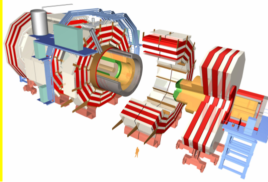

SEARCHES FOR DARK MATTER PRODUCED IN ASSOCIATION WITH THE HIGGS BOSON AT THE CMS EXPERIMENT

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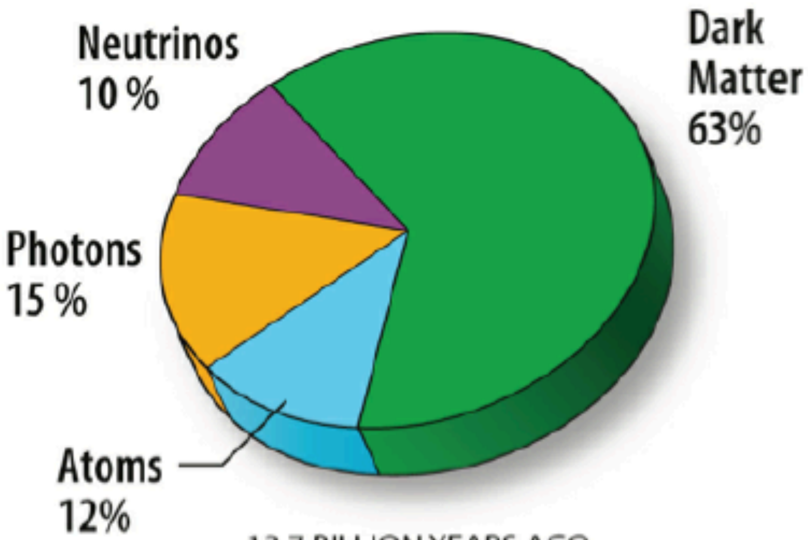
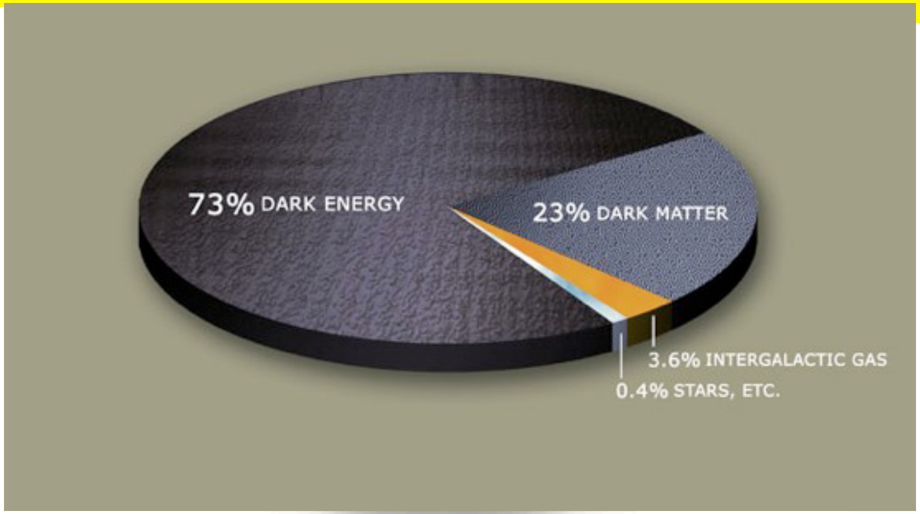
On behalf of CMS Collaboration

Outline

- Introduction
- MonoH models
- Experimental searches
  - $H \rightarrow bb$
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow \tau\tau$
- Conclusions

Introduction: Universe composition

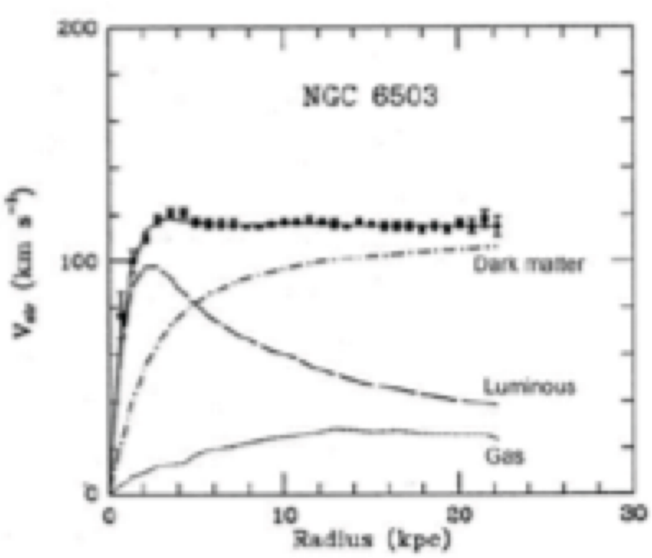




TODAY

Proof of existence of dark matter

- 23% of universe energy/matter i a new type of (non-baryonic) matter
- 73% is a new type of energy (cosmological constant)
- SM is 4%



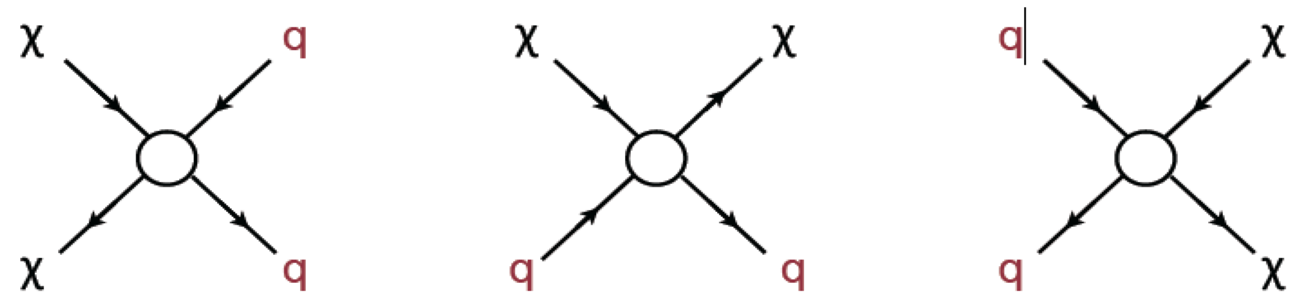
Introduction: Candidate DM particles

- Properties
  - long lived (old)
  - non-relativistic (slow)
  - no electric or color charge
  - very weak interaction with Standard Model particles
  - subject to gravity interaction

No such particle exists in the SM

- Several potential candidates fulfilling these requirements for dark matter
  - Dark: weakly interacting with electromagnetic radiation
  - Hot & dark: ultra-relativistic velocities
    - neutrinos
  - Warm & dark: very high velocity
    - sterile neutrinos, gravitinos
  - Cold & dark: moving slowly
    - Lightest SUSY particle (neutralino, gravitino as LSP), Lightest Kaluza-Klein particles
  - Nonthermal relics:
    - Bose-Einstein condensate (BEC), axions, axion clusters, solitons, supermassive wimpzillas

Introduction: Dark Matter detection

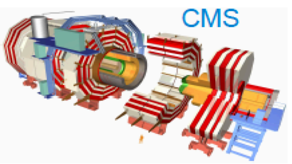


Escapes detector
MET

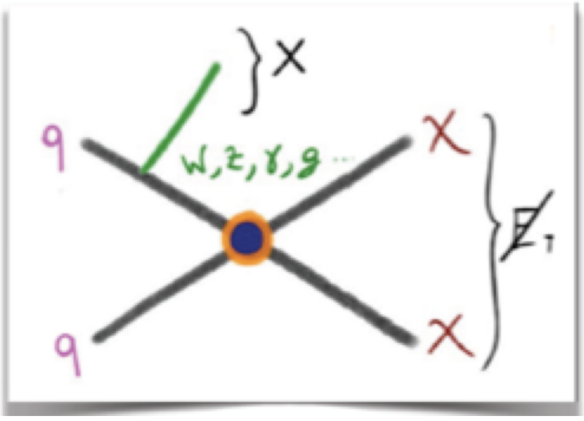
Indirect Detection *Direct Detection* *Production at Colliders*

- Assumption: interaction between SM and DM candidates

@LHC



- Final state with two DM particles and SM particle(s) → Missing transverse momentum (p_T^{miss}) + X signature where X= jet, γ, W, Z, H, tt, tt, t and also Higgs boson → Higgs + MET



- Main candidate for DM: Weakly Interacting Massive Particle (WIMP)

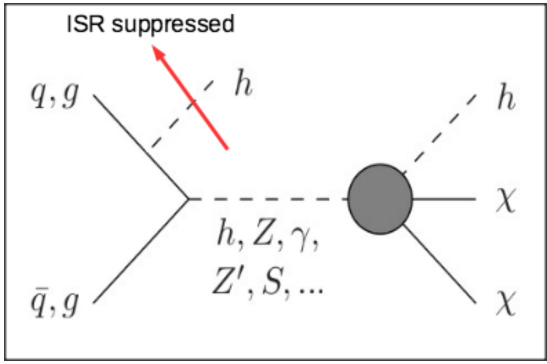
MonoHiggs searches @ LHC

Signature:

- Higgs boson decay products + MET → **Higgs particle used as a TAG**
- Looking for **H decay products + MET**
- Several theoretical models predicts this kind of final state:
  - SUSY production with supersymmetric higgs particles (not studied here)
  - **Higgs-portal, models, EFT, simplified models**

  Reference papers:
  - *10.1103/PhysRevD.89.075017*, 10.1007/JHEP06(2014)078,
  - ATLAS-CMS Dark Matter Forum FINAL REPORT: arXiv:1507.00966

Small coupling of a Higgs to quark → ISR production highly suppressed → a mono-H is preferentially emitted at the effective vertex



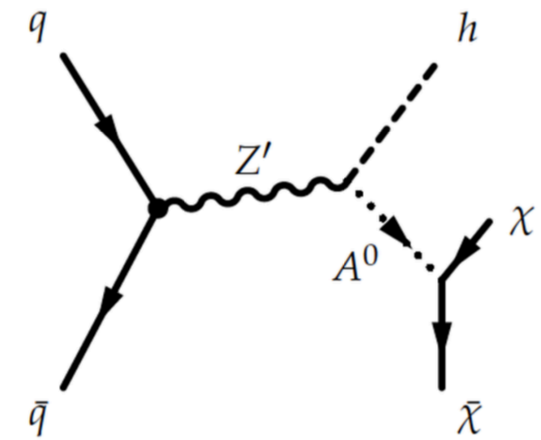
Goals of monoH analyses:

- derive sensitivity of monoHiggs analyses to probe DM mass hypotheses for different models
- probe directly the structure of the effective DM-SM coupling

Z'-2HDM model

Model obtained by extending the 2HDM with an additional $U(1)_{Z'}$ symmetry group that postulates a heavy spin-1 Z' particle with gauge coupling $\mathbf{g}_{Z'}$, and a candidate for dark matter (DM) χ which couples to the A boson with coupling strength $\mathbf{g}_{\chi}$.

Particle	Description	
χ	Fermionic DM particle	
Z'	$U(1)_{Z'}$ gauge boson	
ϕ	Z' sector scalar	
Φ_u, Φ_d	Two Higgs doublets	
h, H	Neutral CP-even scalars	
$H^{\pm}$	Charged heavy Higgs	
A^0	Neutral CP-odd pseudoscalar	
Param.	**Description**	**Value**
m_{χ}	DM mass	100 GeV
$m_{Z'}$	Z' mass	see Table 5
m_{A^0}	A^0 mass	see Table 5
g_z	Z'-quark coupling	0.8 or Eq. 1
$\tan\beta$	$\Phi_{u/d}$ VEV angle	1

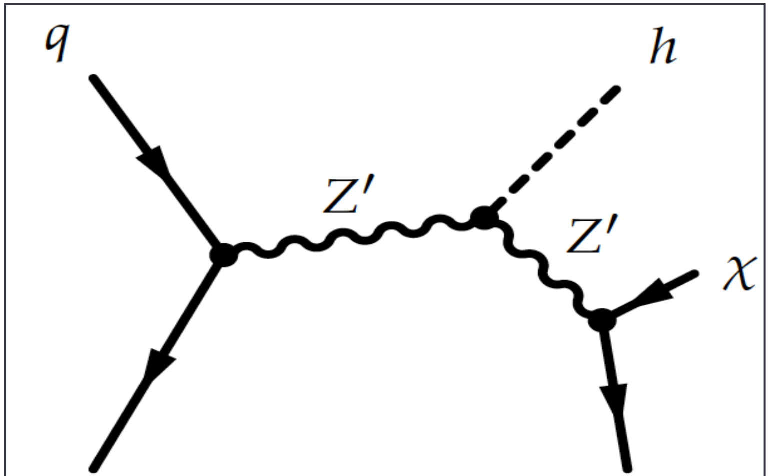


Parameter	Description	Value
m_{A0}	mass of the pseudoscalar Higgs A_0 decaying into two DM candidates	300-800 GeV
m_{χ}	DM Candidate mass	100 GeV
$m_{Z'}$	Z' mass	600-2500 GeV

N.B. Values of m_A below 300 GeV are excluded by constraints on flavor changing neutral currents from measurements of $b \to s\gamma$

Z'-baryonic model

- A baryonic gauge boson Z' arises from a new $U(1)_B$ baryon number symmetry
- Z' emits a Higgs boson and then decays to a pair of Dirac fermionic DM particles.
- A baryonic Higgs boson (h_B) is introduced to spontaneously break the new symmetry and generates the Z' boson mass via a coupling that is dependent on the h_B vacuum expectation value.
- The Z' couplings to quarks and DM are proportional to the $U(1)_B$ gauge couplings. There is a mixing between h_B and the SM Higgs boson, allowing the Z' to radiate an SM-like Higgs boson.
- The stable baryonic states in this model are the candidate DM particles.



(a)

Particle	Description	
χ	Fermionic DM particle	
Z'	$U(1)_B$ gauge boson	
h_B	Baryonic Higgs	
Param.	**Description**	**Value**
m_χ	DM mass	1-1000 GeV
$m_{Z'}$	Z' mass	10-10000 GeV
g_q	Z'-quark coupling	1/3
g_χ	Z'-DM coupling	1
$g_{hZ'Z'}$	Z'-h coupling	$m_{Z'}$

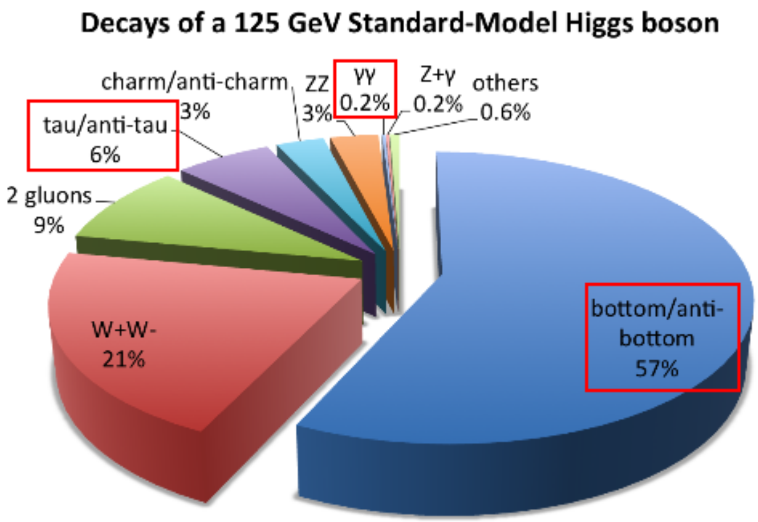
Latest CMS monoHiggs searches

CMS has released several results about monoH searches with 13 TeV data and NEW one combining several final state have been just approved

Channel	Dataset	Luminosity	Model
$h\to \gamma\gamma$ + $h\to$ bb	2015	2.3 fb^{-1}	Z'-2HDM
$h\to \gamma\gamma$ + $h\to \tau\tau$	2016	35.9 fb^{-1}	Z'-2HDM + Z'-Baryonic
$h\to$ bb	2016	35.9 fb^{-1}	Z'-2HDM

- **h→bb** is the most probable channel because of the BR (58%)
- **h→γγ** channel benefits from higher precision in reconstructed invariant mass
- **h→ττ** channel benefits from smaller SM background.

Both **h→γγ** and **h→ττ** are not dependent on p_T^{miss} trigger thresholds → probe DM scenarios with lower p_T^{miss}



MonoHiggs searches with 2016 data:

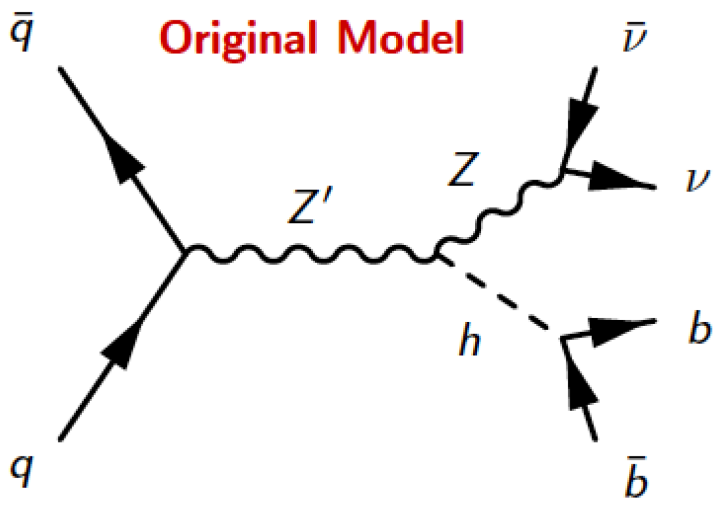
H→bb

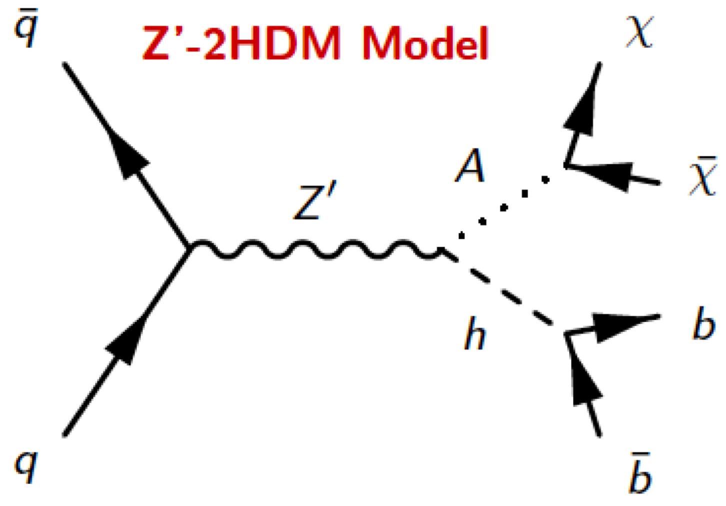
CMS-B2G-17-004

H→bb strategy

The current CMS analysis in the h→bb final state is a **reinterpretation** of a search for heavy resonances V' decaying to Vh, where:

- V = W,Z
  - W→lν
  - Z→ ll or Z→νν
- h→bb
- V' is **a heavy resonance**:
  - Only the Z'-2HDM is considered in the reinterpretation
  - **The Higgs boson is considered to be highly boosted ($m_{Z'}$ > 1 TeV)**





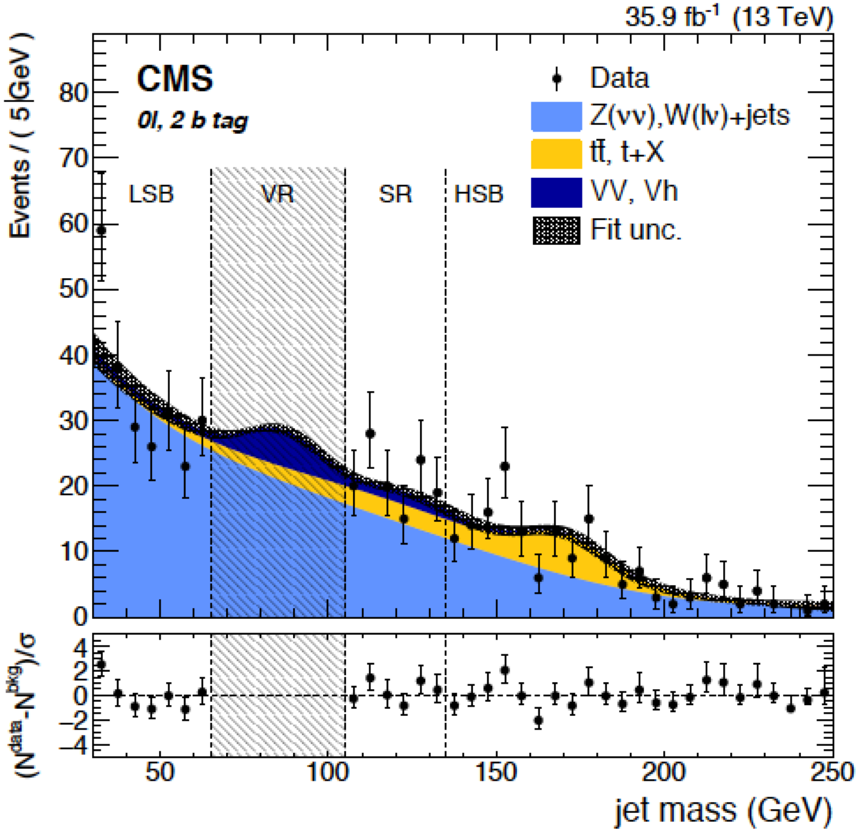
H→bb selection

The basic selection of the h→bb analysis requires one AK8 jet compatible with the decay of a Higgs boson to a pair of b quarks and large p_T^{miss}

- HLT based on p_T^{miss} > 90–110 GeV

A boosted h→bb candidate with:

- p_T^J > 200 GeV
- Two b-tag categories
  - 1 or 2 AK4 sub-jets b-tagged
- $|\eta^J|$ < 2.5
- 105 GeV < m^J < 135 GeV
- p_T^{miss} > 250 GeV
- Events with leptons or additional AK4 b-tagged jets are rejected



To ensure the Higgs boson is produced back-to-back with respect to the dark matter system, and to reduce the QCD multijet production:

$|\Delta\phi(\text{jet}, p_T^{miss})| > 0.5$rad for every jet and $|\Delta\phi(\text{jet}, p_T^{miss})| > 2$rad for the h-tagged AK8 jet

H→bb: background and signal extraction

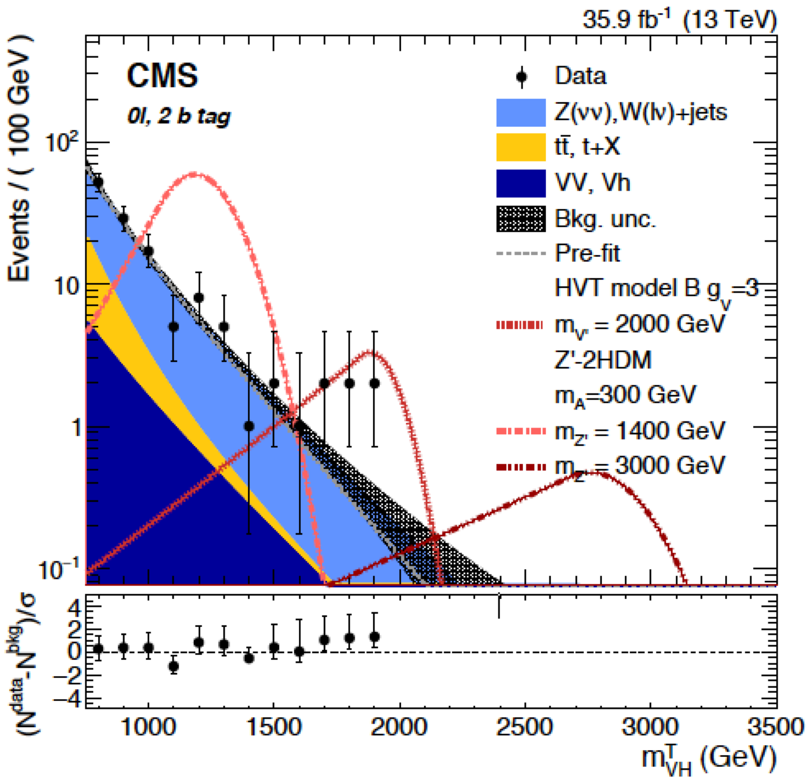
The main backgrounds affecting the h→bb signal region:

- Z→νν + b-jets :
  - Estimated in m_J sidebands by fitting with a polynomial function
  - Yields and shape in signal region obtained by applying a transfer factor

$$\alpha(m^{T}_{Vh}) = \frac{F_{SR}^{sim,V+jets}(m^{T}_{Vh})}{F_{SB}^{sim,V+jets}(m^{T}_{Vh})}$$

- Top :
  - Normalized in control region
  - Relax m^J cut
  - At least one additional AK4 b-jet

- VV and VH :
  - Taken from simulation



Signal and background yields are obtained through a fit to the signal region and the control regions to the m^{T}_{Vh} distribution

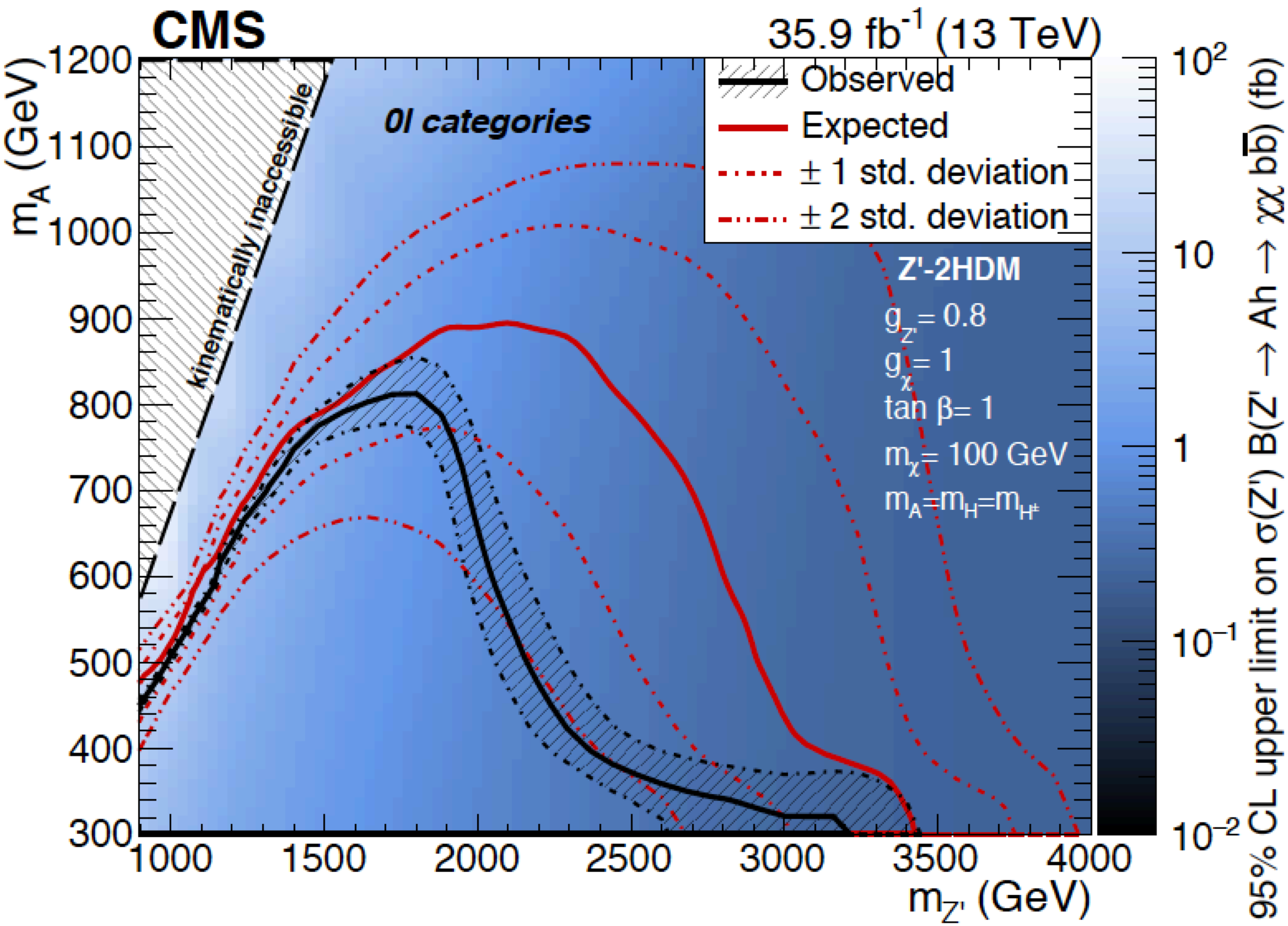
$$m^{T}_{Vh} = \sqrt{2p_T^{miss} E_T^J [1 - \cos\Delta\phi(J, \vec{p}_T^{miss})]}$$

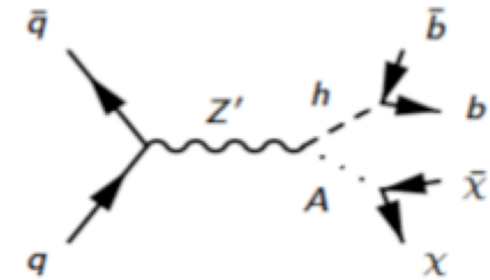
H→bb: systematic uncertainties

Different sources of uncertainty are considered in the analysis:

- **Jets:**
  - Energy scale and resolution: 1-11%
  - Jet energy corrections: 1%
  - b-tag efficiency: 2-7% for signal
  - Parton shower: 6% for signal
- **Trigger efficiency:** 3%
- **Data-driven background estimation:**
  - Z+jets: 2-15%
  - Top: 2-17%
- **PDF, μ_R, μ_F**: 21-30%
- **Top p_T uncertainty**: 14%
- **Pile-up**: 1%
- **Luminosity**: 2.5%

H→bb results: Z'-2HDM





$m_{Z'}$ up to 3.3 TeV and m_A up to 0.8 TeV are excluded at 95%CL

MonoHiggs searches with 2016 data:

H→γγ

JHEP09(2018)046

$H \rightarrow \gamma\gamma$ selection

The $h \rightarrow \gamma\gamma$ exploits events with two energetic photons compatible with the decay of a Higgs boson, and large missing transverse momentum p_T^{miss}:

- $E_T^{\gamma 1} > 30$ GeV, $E_T^{\gamma 2} > 20$ GeV
- $m_{\gamma\gamma} > 95$ GeV
- $p_T^{miss} > 50$ GeV

Events are further categorized in a high-sensitivity and a low-sensitivity regions, depending on the p_T^{miss}, with optimized selections:

Variable	Low-p_T^{miss} Category	High-p_T^{miss} Category
p_T^{miss}	> 50 GeV, < 130 GeV	≥ 130 GeV
$p_{T1}/m_{\gamma\gamma}$	> 0.45	> 0.5
$p_{T2}/m_{\gamma\gamma}$	> 0.25	> 0.25
$p_T^{\gamma\gamma}$	> 75 GeV	> 90 GeV

To select events in which the Higgs boson is produced back to back with the invisible system and to reduce the multi-jet background contamination →

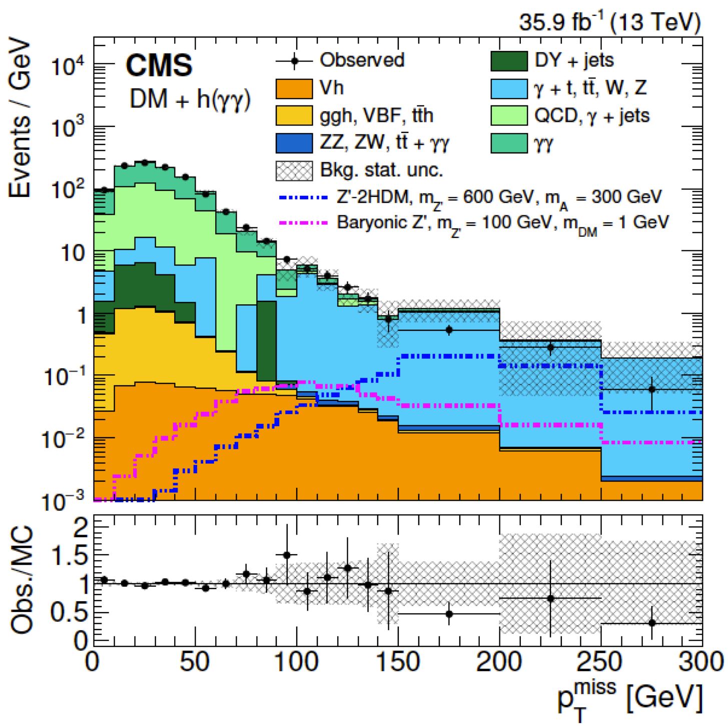
- $|\Delta\phi(p_{\gamma\gamma}, p_T^{miss})| > 2.1$rad
- $|\Delta\phi(p_{jet}, p_T^{miss})| > 0.5$rad for jets with $p_T > 50$ GeV
- Events with 3 or more jets with $p_T > 30$ GeV are rejected

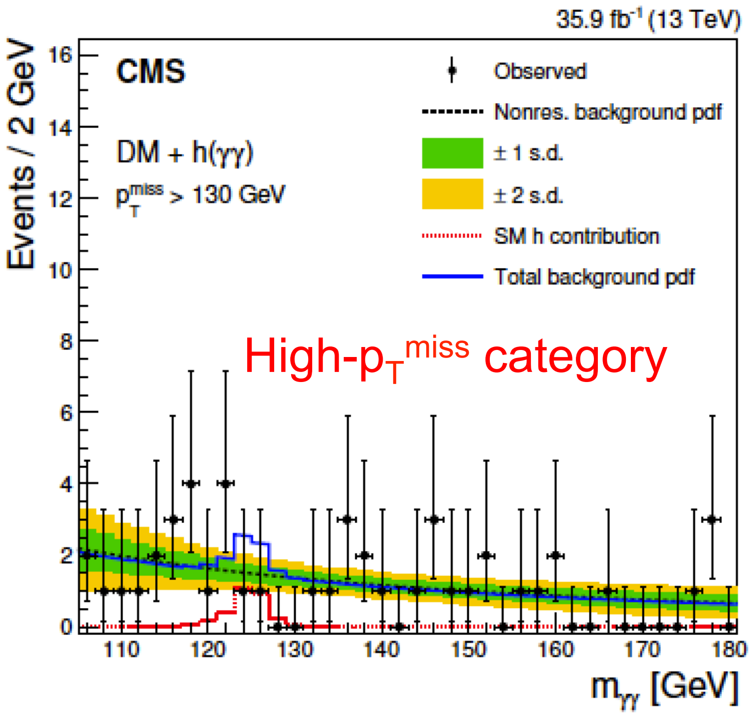
H→γγ background estimation

The main backgrounds of the h→γγ channel involves the production of two photons. The signal and background yields are estimated through a fit to the $m_{\gamma\gamma}$ spectrum

- Resonant backgrounds (SM Higgs boson) and signal
  - Shape taken from MC simulation
- Non-resonant backgrounds
  - Shape given by a smooth function
  - Bias studies are performed to test the dependence of the fit on the fitting function: negligible with respect to statistical uncertainty

p_T^{miss} spectrum after selections





MonoHiggs searches with 2016 data:

H→ττ

JHEP09(2018)046

$H \rightarrow \tau\tau$ selection

The three final states of τ lepton pairs with the highest branching fractions are considered

- $e\tau_h$ or $\mu\tau_h$
  - $p_T^{e/\mu} > 26$ GeV, $p_T^{\tau} > 20$ GeV
  - $e/\mu/\tau$ must pass dedicated MVA ID or ISO selection
  - e/μ must be isolated
- $\tau_h\tau_h$
  - $p_T^{\tau 1} > 55$ GeV, $p_T^{\tau 2} > 40$ GeV
  - Looser MVA isolation selection required

To select events with a highly boosted Higgs boson recoiling against the dark matter system, some more selections are required

- $p_T^{miss} > 105$ GeV
- $P_T^{\tau\tau} > 65$ GeV
- $m_{\tau\tau} < 125$ GeV
- $\Delta R_{\tau\tau} < 2.0$

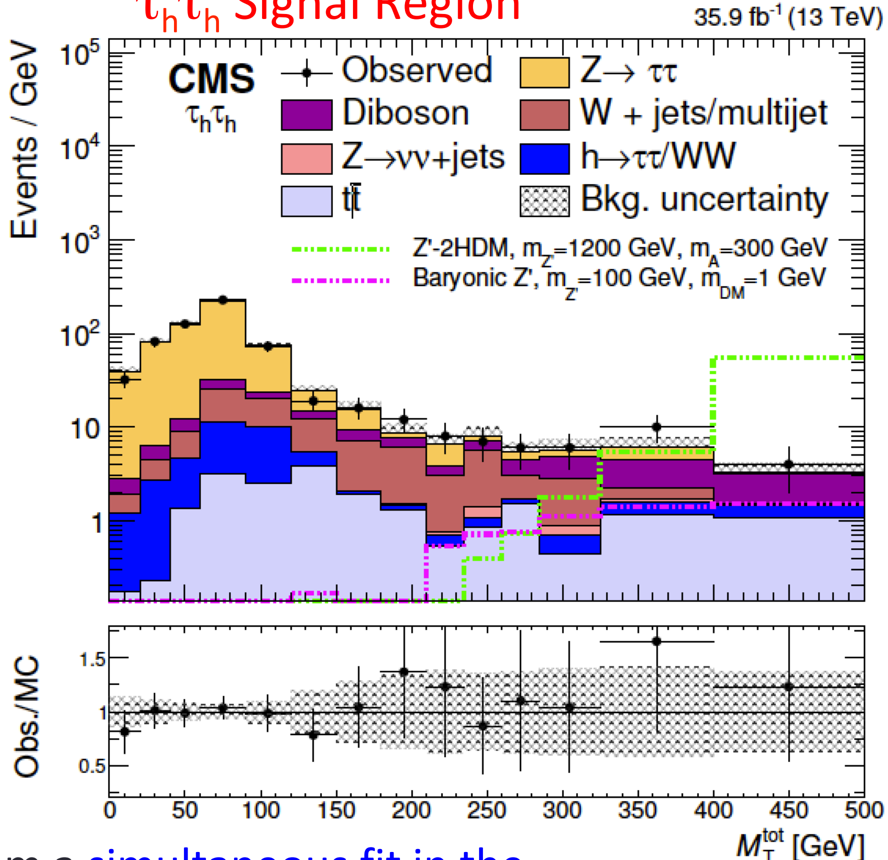
To further reduce top and multilepton backgrounds, events with b-tagged jets or additional leptons are vetoed

H→ττ background estimation

The main processes contaminating the signal region of this final state are:

- W+Jets: estimated in control region
  - Relax τ_h ISO to take shape from MC with enhanced statistics
  - Invert τ_h ISO to define a CR used to normalize the process
- QCD multijet: normalized in control region
  - Normalization extracted in same-sign control region
  - SS→OS scale factor extracted from MC in CR with low-p_T^{miss} and inverted τ_h ISO selection
- SM Higgs boson, Top and di-boson: taken from simulation

$\tau_h\tau_h$ Signal Region



Signal and backgrounds yields are extracted from a simultaneous fit in the signal region and the control regions to the total transverse mass

$$M_T^{tot} = \sqrt{(E_T^{\tau_1} + E_T^{\tau_2} + |p_T^{miss})^2 - (p_x^{\tau_1} + p_x^{\tau_2} + p_x^{miss})^2 - (p_y^{\tau_1} + p_y^{\tau_2} + p_y^{miss})^2}$$

H→γγ + H→ττ systematics uncert.

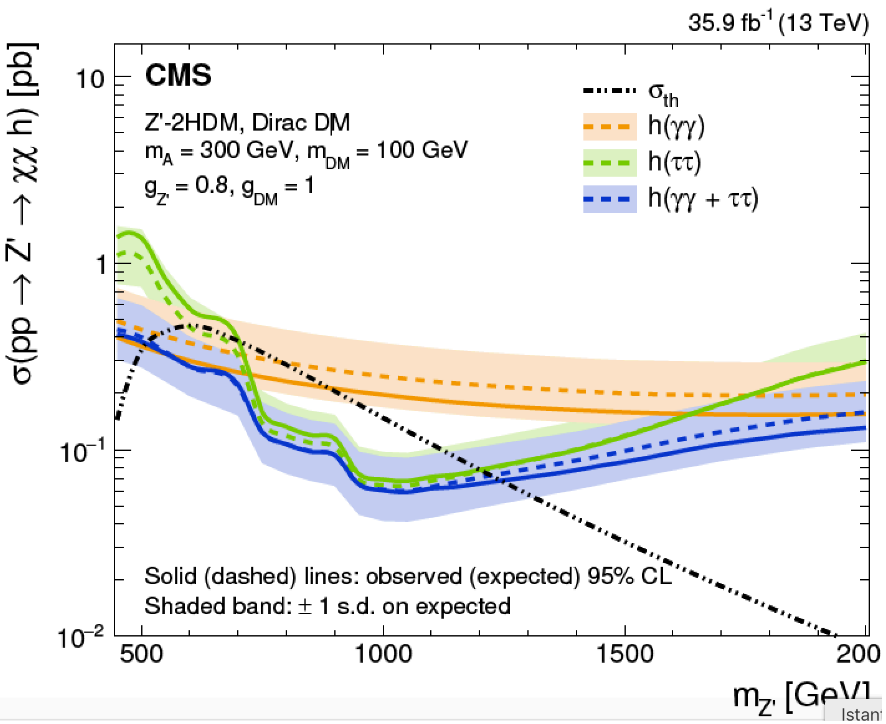
Both the analyses are mainly limited by statistics. Since some resuls are combined , some of the nuisances are considered fully correlated:

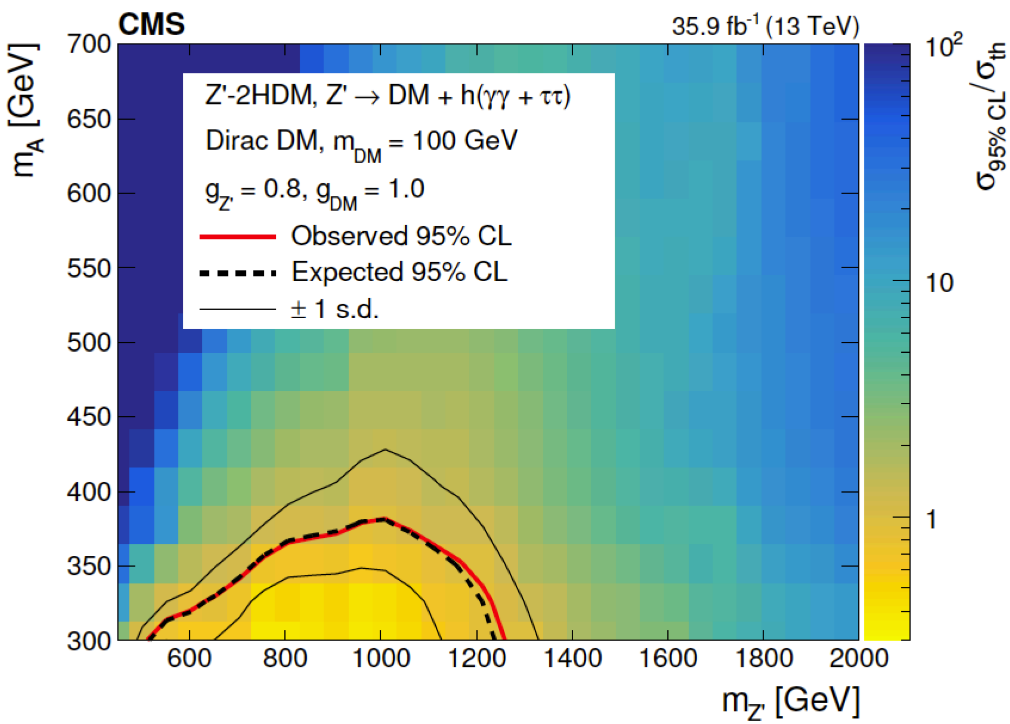
- **Luminosity**: 2.5%
- **Higgs boson production cross sections**
- **PDF, μ_R, μ_F**: 0.3-9%

Additional sources of uncertainty are considered separately for the two channels:

- **h→γγ**
  - ggh cross section for events with $p_T^{\gamma\gamma}$ > 70 GeV: 20%
  - h→γγ BR: 1.73%
  - Trigger efficiency: 1%
  - Photo ID efficiency: 2%
  - Photon energy scale: 0.5%
  - p_T^{miss} mismeasurement (ggh and VBF): 50%
  - $\Delta\phi$ selection efficiency (ggh and VBF): 1-4%
- **h→ττ**
  - e, μ, τ_h ID, iso, trigger: 2-9%
  - e, μ, jet faking a τ_h : 12-25%
  - τ_h jet, p_T^{miss} en.scale: 1-11% 12-25%
  - Backgrounds normalization: 5-20%
  - W+jets, WW, ZZ NLO EW corrections: 2-12%
  - Z+Jets LO-NLO corrections: up to 26%
  - Top quark p_T reweighting: up to 5%

H→γγ + H→ττ results for Z'-2HDM

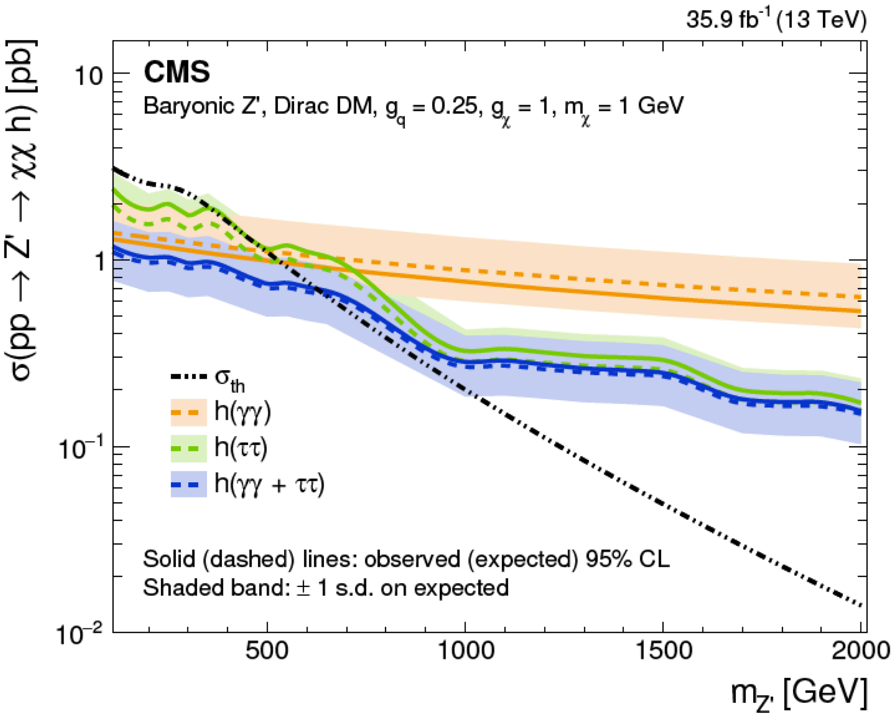


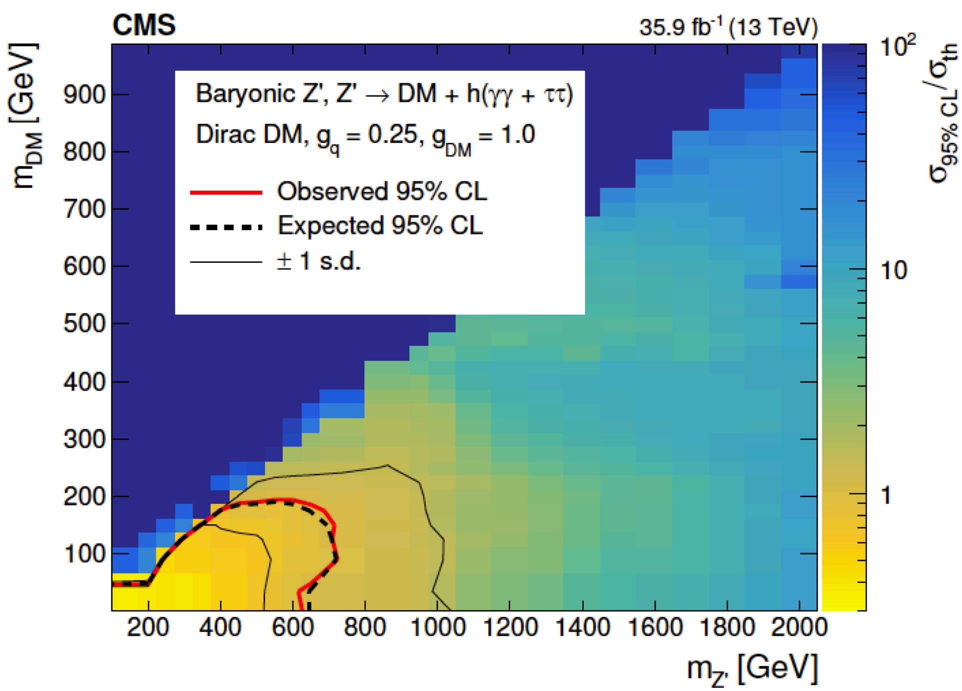


The combination of the two decay channels excludes the Z' masses from 550 GeV to 1265 GeV for m_A = 300 GeV.

N.B. These upper limits, although obtained with a DM mass of 100 GeV, can be considered valid for any DM mass below 100 GeV since the BR for decays of A to DM particles decreases as the dark matter mass increases.

H→γγ + H→ττ results for Z'-Baryonic

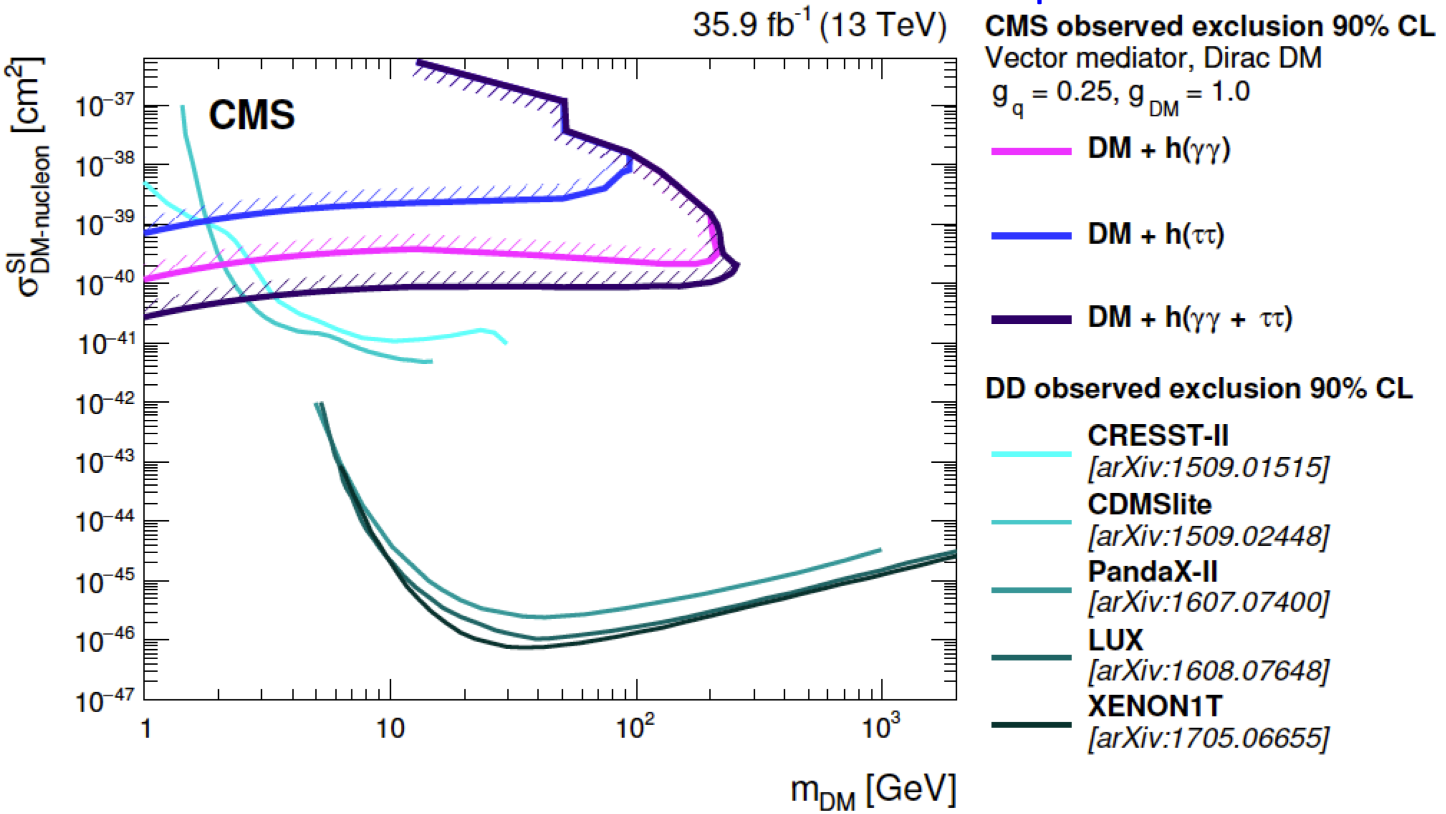




The combination of the two decay channels excludes $m_{Z'}$ up to 615 GeV for m_{DM} = 1 GeV

H→γγ + H→ττ: σ^{SI} interpretation

The limits on the Z'-Baryonic model are reinterpreted in terms of spin-independent cross section for dark matter scattering off a nucleus, allowing a comparison with direct detection experiments.



$$\sigma^{\rm SI} = \frac{f^2(g_{\rm q}) g_{\rm DM}^2 \mu_{\rm nDM}^2}{\pi m_{\rm med}^4}$$

- $f(g_q)$ = mediator-nucleon coupling
- $\mu^2_{n\chi}$ = reduced mass of nucleon-DM system

For the baryonic Z' model,

the limits are more stringent than direct detection experiments for m_{DM} < 2.5 GeV

Summary/Conclusions

The current CMS searches for mono-Higgs signature have been presented:

- **Z'-2HDM**:
  - Z' mediator of mass from 1 TeV to 3 TeV and pseudoscalar A mediator of mass up to 800 GeV are excluded by the $h \rightarrow bb$ analysis
  - Z' masses from 550 GeV to 1265 GeV are excluded by the combination of $h \rightarrow \gamma\gamma$ and $h \rightarrow \tau\tau$ with m_A =300 GeV
- **Z'-baryonic**: with m_{DM} = 1 GeV, Z' masses up to 615 GeV are excluded by the combination of $h \rightarrow \gamma\gamma$ and $h \rightarrow \tau\tau$
- **Spin-Independent DM-nucleus cross section s^{SI}** limits:
  - Values of σ^{SI} larger than 10^{-41} cm^2 are excluded at 95%CL for light DM particles (better w.r.t. direct detection experiments)
- **Short term plans:**
  - Results for the two models in the $\gamma\gamma$, $\tau\tau$, bb, WW and ZZ final states are combined and will become public shortly
  - A paper of the combination will be published early next year

Backup

References

- “Search for heavy resonances decaying into a vector boson and a Higgs boson in final states with charged leptons, neutrinos and b quarks at $\sqrt{s}$ = 13 TeV”, **CMS-B2G-17-004**, arXiv:1807.02826v1 (2018)

- “Search for dark matter produced in association with a Higgs boson decaying to gg or $\tau\tau$ at $\sqrt{s}$ = 13 TeV”, **JHEP09(2018)046**

- “Search for associated production of dark matter with a Higgs boson decaying to bb or gg at $\sqrt{s}$ = 13 TeV”, **JHEP10(2017)180**

Theory papers:

- *arXiv:1312.2592v2 [hep-ph], arXiv:1404.3716v2* [hep-ph]

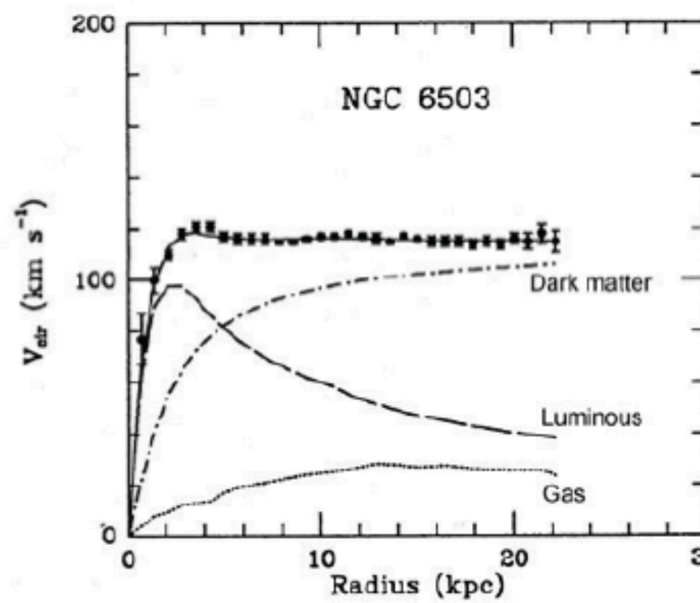
Evidence for Dark Matter: Coma cluster

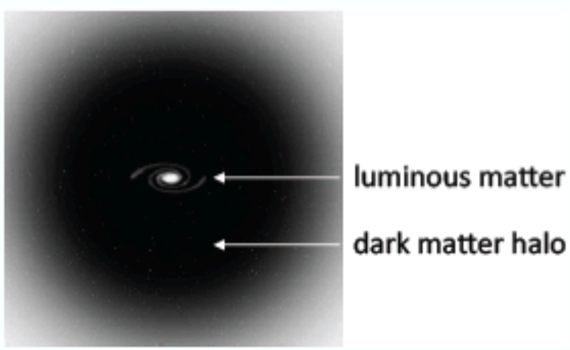
In 1933, Fritz Zwicky calculated the mass of the Coma cluster using galaxies on the outer edge, and came up with a number 400 times larger than expected.

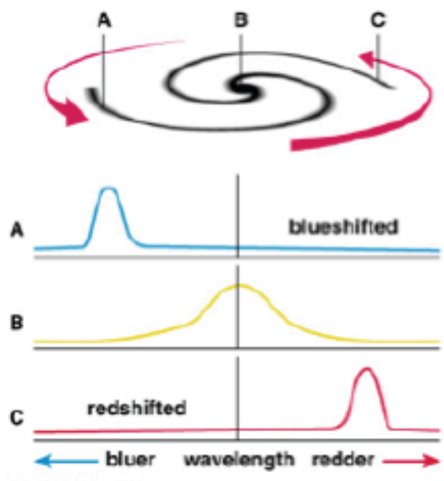
Now we know 90% of its mass due to Dark Matter

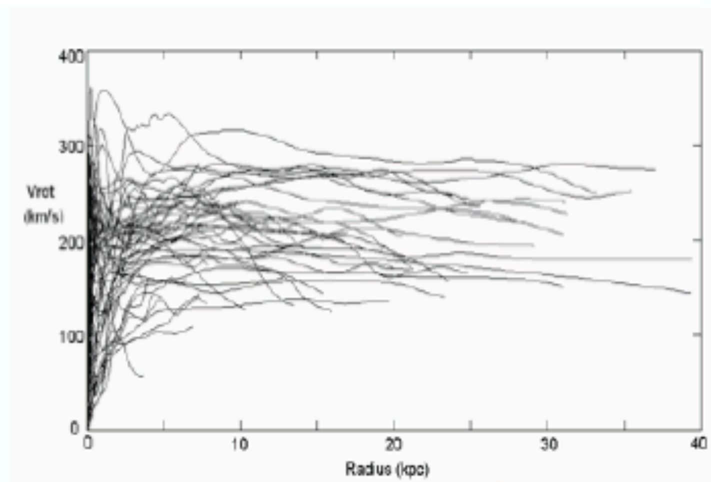
Evidence for Dark Matter: Galactic rotation

- Starting in 1970's, first measurements of the velocity curve of edge-on spiral galaxies
- Velocity found to be flat, consistent with ~10x as much "dark" mass for more than one galaxy







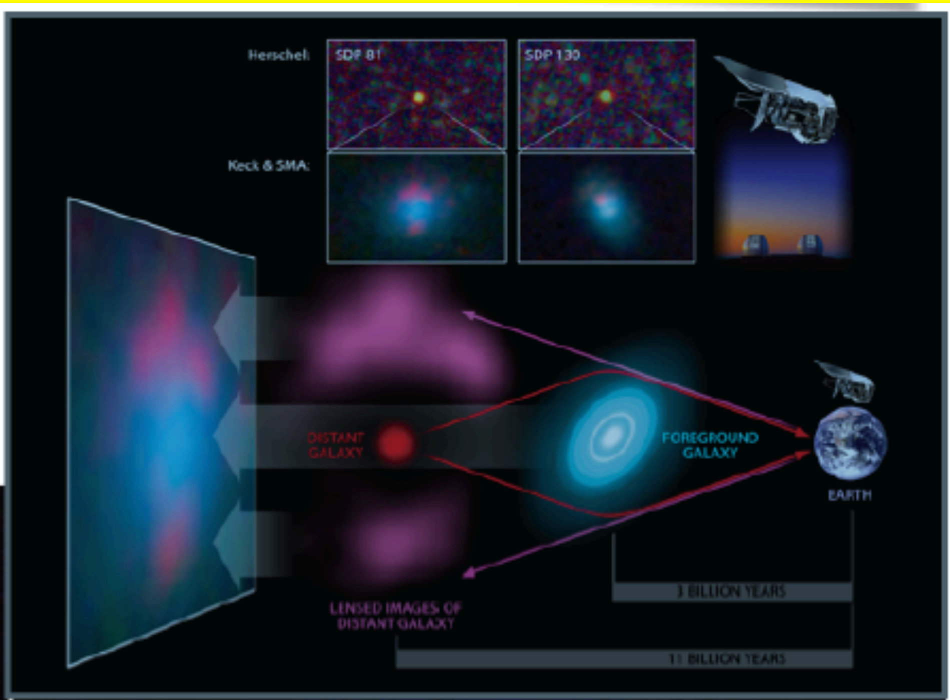


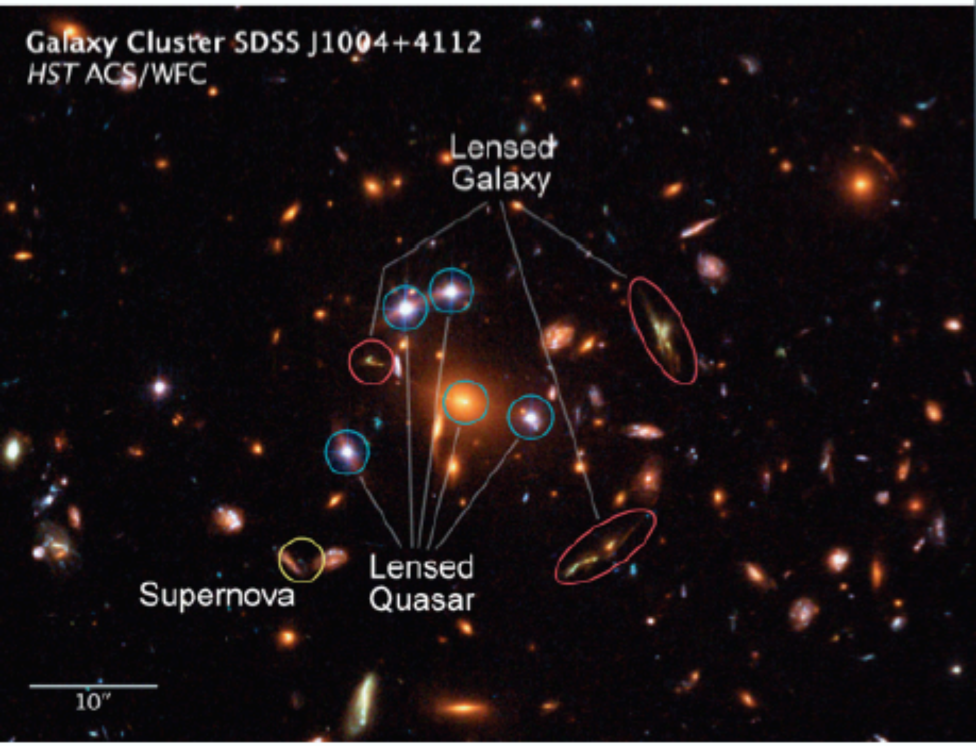
Evidence for Dark Matter: Bullet cluster

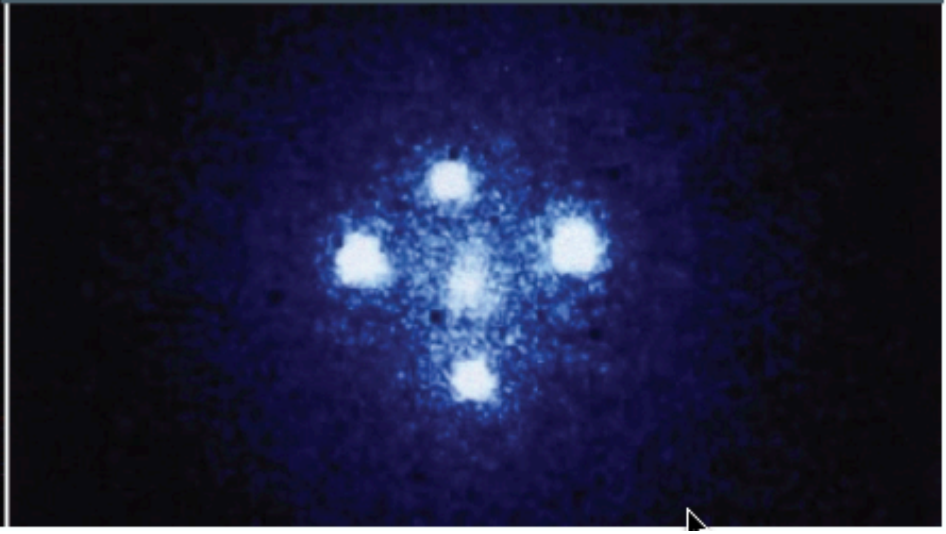
- Collision of galaxies in bullet cluster
  - lensing of background objects suggest at least 10x more Dark matter than visible mass

Evidence for Dark Matter: Gravitation lensing

- visible mass not sufficient to explain observed lensing effect

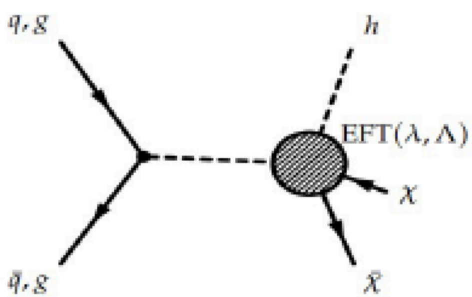






MonoHiggs models

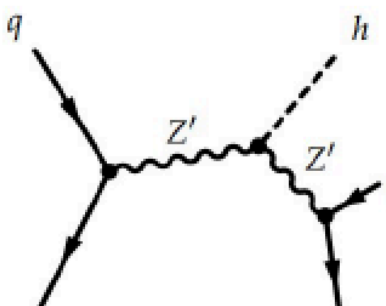
- Models consist of the union of models from Phenom papers arXiv:1312.2592 arXiv:1402.7074 and ATLAS-CMS DM Forum, with phenomenology studies for new models comir
- Six EFTs: dimension 4 to 8 contact operators valid below cutoff scale Λ



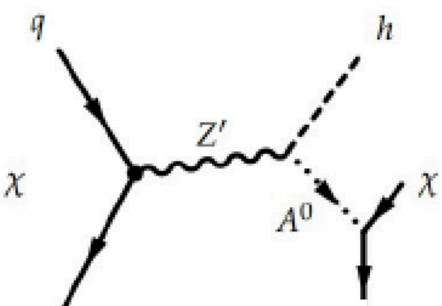
$$\lambda|H|^2\chi^2 \qquad \frac{1}{\Lambda}|H|^2\bar{\chi}\chi \qquad \frac{1}{\Lambda}|H|^2\bar{\chi}i\gamma_5\chi \qquad \frac{1}{\Lambda^2}\chi i\partial^\mu\chi H^\dagger iD_\mu H$$

$$\frac{1}{\Lambda^2}\chi^\dagger i\overleftrightarrow{\partial^\mu}\chi H^\dagger iD_\mu H \qquad \frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H\,.$$

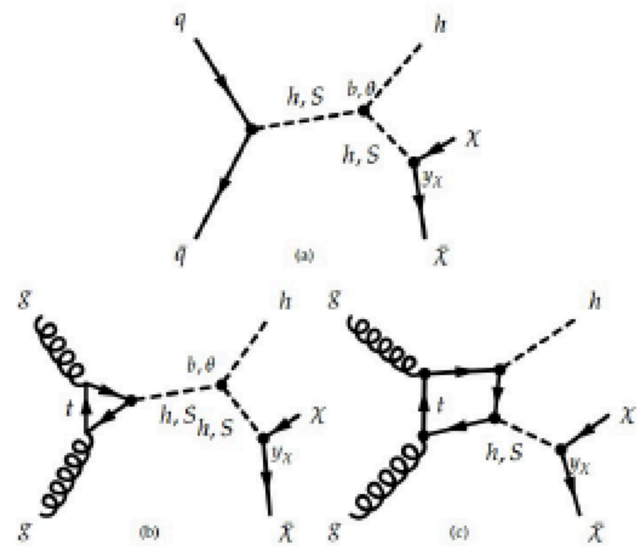
- Four simplified models: new massive mediator – Z', S, A^0 – for Higgs-DM coupling



Z' - baryonic

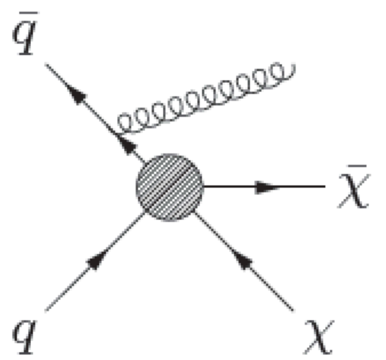


Z'- 2HDM



EFT for mono-Higgs

- Effective Field Theory (EFT)
  - Assume heavy particle mediating interaction: contact interaction (integrate out mediator)
  - For M → ~40 TeV, where $\Lambda \equiv M/\sqrt{g_\chi g_q}$

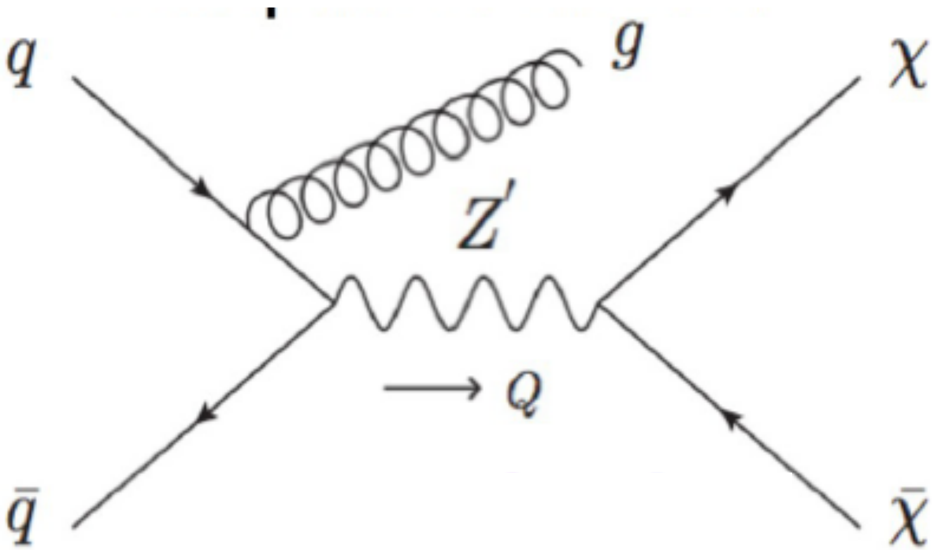


$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2 \approx \Lambda^{-4} E^2$$

- Simple model for comparison
  - ✓ Only a few parameters; dark matter mass m_χ and cut-off scale Λ
  - ✓ Much easier than e.g. a full SUSY model
  - ✓ Easy comparison to direct or indirect DM experiments
  - ✓ DM can be fermion (Dirac or Majorana) or scalar (complex or real)
  - ✗ Limitations on model validity ⇦ EFT lacks validity for high Q^2 since it violates unita
  - ✗ Probe only one interaction at a time

Simplified models for mono-Higgs

- Complete enough:
  - explicitly include mediators
- Simple enough:
  - minimal number of renormalizable interactions
- Valid enough:
  - satisfy all non-high pT constraints within parameter space



Dark matter models

- EFT
  - Dim 4: $\lambda |H|^2 \chi^2$,
  - Dim 5: $\frac{1}{\Lambda}|H|^2\bar{\chi}\chi$, $\frac{1}{\Lambda}|H|^2\bar{\chi}i\gamma_5\chi$,

    Constrained by Br(H > invisible)
  - Dim 6:

    $$\frac{1}{\Lambda^2}\chi^\dagger i\overleftrightarrow{\partial^\mu}\chi H^\dagger iD_\mu H \quad \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi H^\dagger iD_\mu H , \quad \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi H^\dagger iD_\mu H .$$

    Constrained by Br(Z > invisible)
  - Dim 8:

    $$\frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H , \quad \frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi W^a_{\mu\nu}H^\dagger t^a D^\nu H$$

    $$\frac{1}{\Lambda^4}\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu}H^\dagger H , \quad \frac{1}{\Lambda^4}\bar{\chi}\sigma^{\mu\nu}\chi W^a_{\mu\nu}H^\dagger t^a H$$

    Derivative couplings lead to more MET, better acceptance efficiency
- Simplified
  - Z' from extended gauge group: Gauge Baryon number B. Z' is (leptophobic) gauge boson of corresponding U(1)_B symmetry, spontaneously broken by "Baryonic Higgs" hB, which mixes with SM H.

    $$\mathscr{L}_{\rm eff} = -\frac{g_q g_\chi}{m^2_{Z'}}\bar{q}\gamma^\mu q\bar{\chi}\gamma_\mu\chi\left(1 + \frac{g_{hZ'Z'}}{m^2_{Z'}}h\right)$$

  - Z' from hidden sector mixing with SM: DM charged under new U(1)', SM states neutral. Mass mixing between Z and Z' induces hZ' coupling.

    $$\mathscr{L} \supset \frac{g_2}{2c_W}J^\mu_{\rm NC}Z_\mu + g_\chi\bar{\chi}\gamma^\mu\chi Z'_\mu , \qquad \mathscr{L} \supset \frac{m^2_Z s_\theta}{v}hZ'_\mu Z^\mu$$

  - Scalar S coupling to H: Real scalar singlet S with Yukawa coupling to DM mixes with SM through H only (renormalizability, gauge invariance). hS coupling from scalar potential:

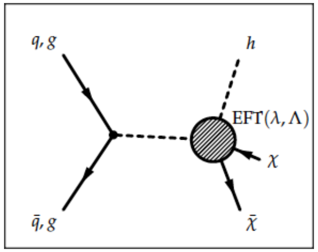
    $$V_{\rm cubic} \approx \frac{\sin\theta}{v}(2m_h^2 + m_S^2)h^2 S + bvhS^2 + \ldots$$

  - Z' coupled to a 2HDM: Type 2 2HDM with Z' gauge boson of U(1)_z'. Z' on shell decays to H and pseudoscalar A0. A0 has large branching fraction to DM

Mono-Higgs models

EFT approach (model-independent approach):

- non-renormalizable n-dim operators for X+E_T generation,
- valid at energies below cutoff scale Λ
- no underlying UV physics specifications



fermionic DM dim-5 | fermionic DM dim-6

$$\lambda|H|^2\chi^2 \qquad \frac{1}{\Lambda}|H|^2\bar{\chi}\chi \qquad \frac{1}{\Lambda}|H|^2\bar{\chi}i\gamma_5\chi \qquad \frac{1}{\Lambda^2}\chi i\partial^\mu\chi H^\dagger iD_\mu H$$

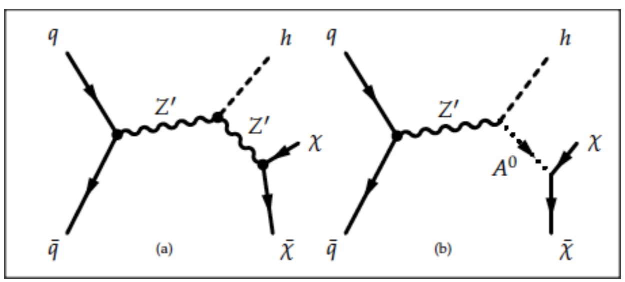
$$\frac{1}{\Lambda^2}\chi^\dagger i\overleftrightarrow{\partial^\mu}\chi H^\dagger iD_\mu H \qquad \frac{1}{\Lambda^4}\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H\,.$$

scalar DM dim-4

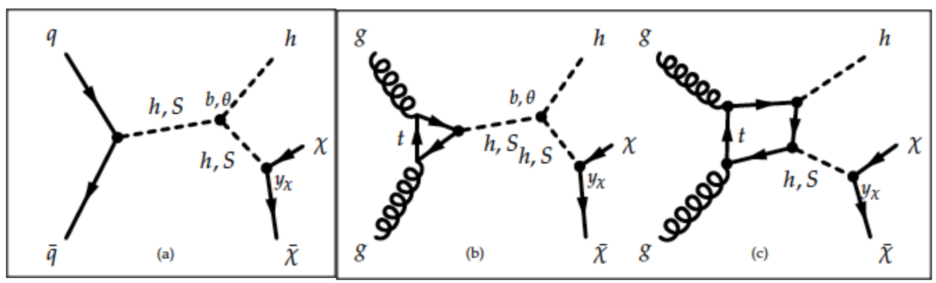
scalar DM dim-6 | fermionic DM dim-8

Simplified Model:

- A *new* massive particle (Z', S, A^0) mediates DM-H interaction

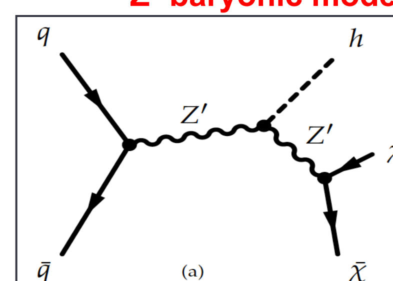


Vector mediator | 2HDM model



Scalar mediator

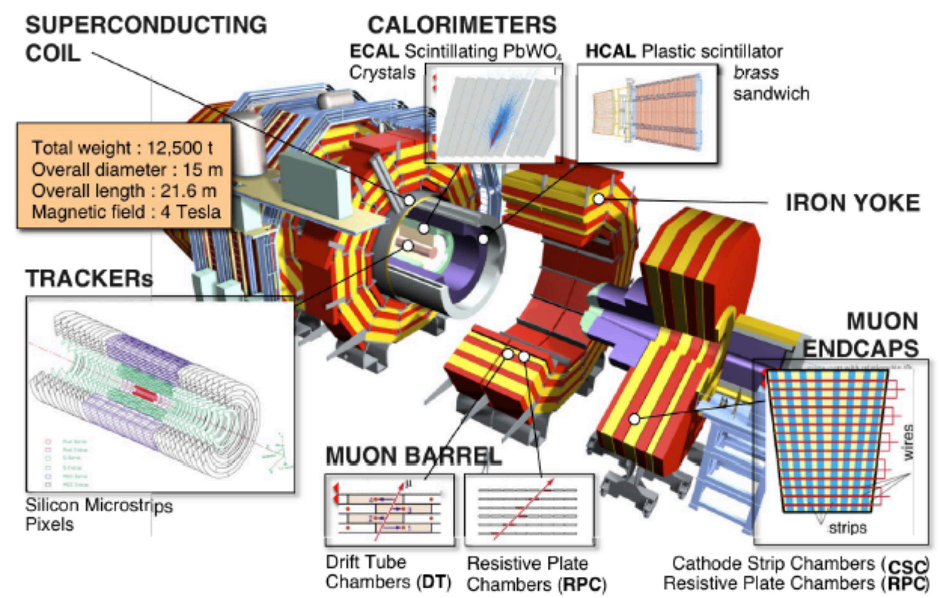
Z'-baryonic model

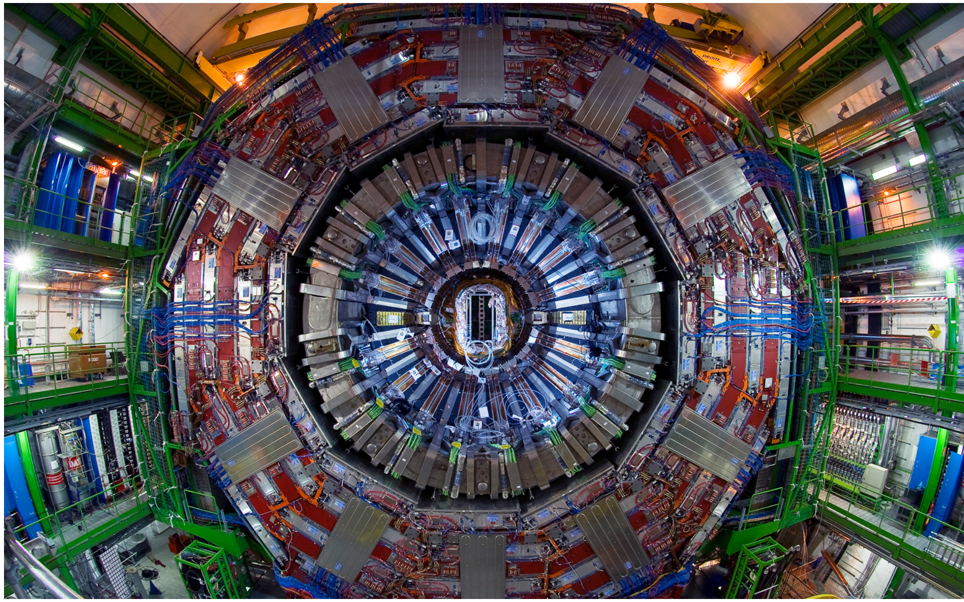


Two simplified models used for this analysis:

- Z'-2HDM: a Z' produce as a on-shell resonance decaying into a Higgs and a pseudoscalar A_0, with $A_0 \rightarrow \chi\chi$
- Z'-baryonic: a vector mediator Z'_B decays into $\chi\chi$ after radiating a H

CMS in a nutshell





|η|<2.5 : Tracker

$\sigma / p_T \approx 10^{-4} p_T \oplus 0.005$

|η|<4.9 : EM Calorimeter

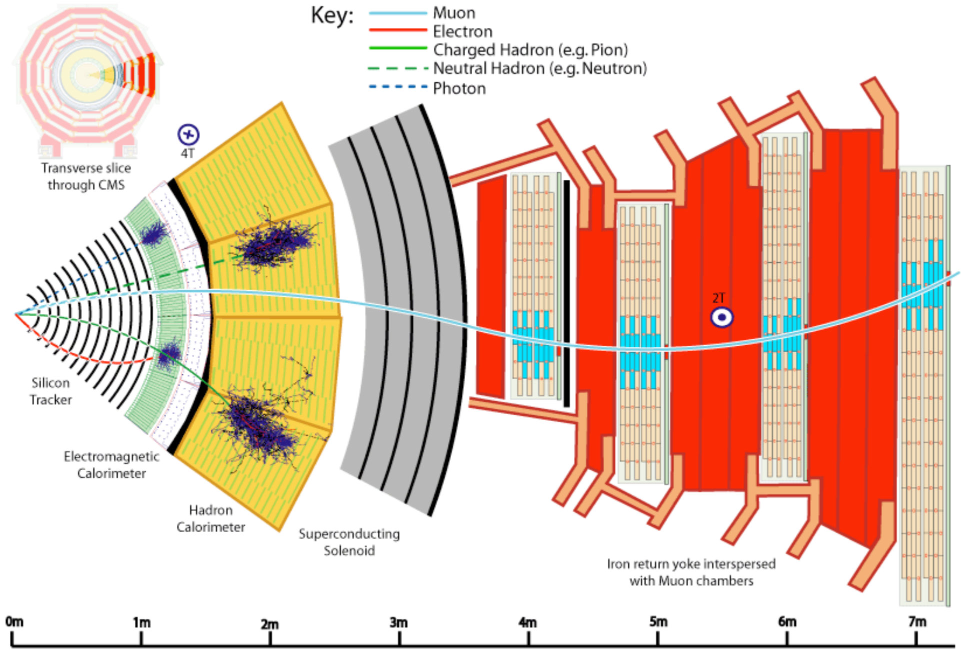
$\sigma / E \approx 0.03/\sqrt{E} + 0.003$

|η|<4.9 : HAD Calorimeter

$\sigma / E \approx 1.0/\sqrt{E} + 0.05$

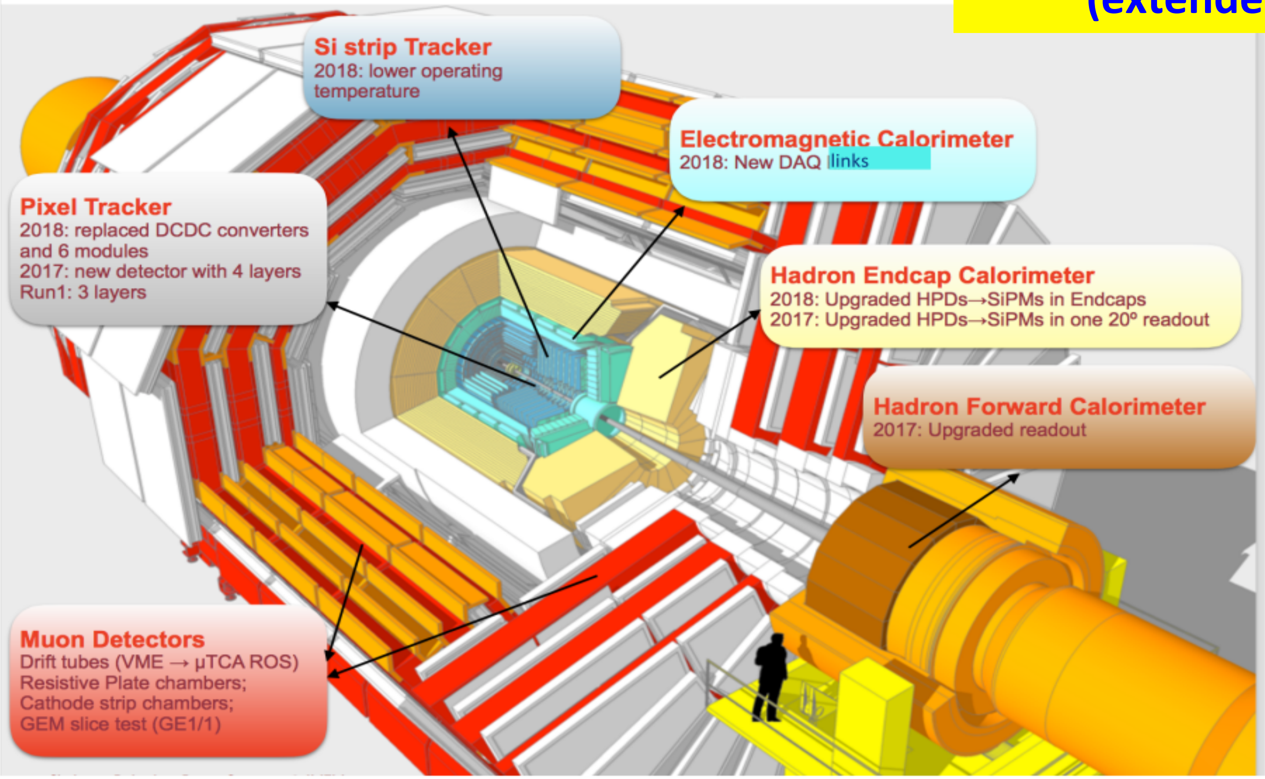
|η|<2.4 : Muon spectrometer

$\sigma / p_T \approx 0.10$ *(1TeV muons)*



CMS upgrade in 2017/2018 after the EYETS

(extended year-end technical stop)



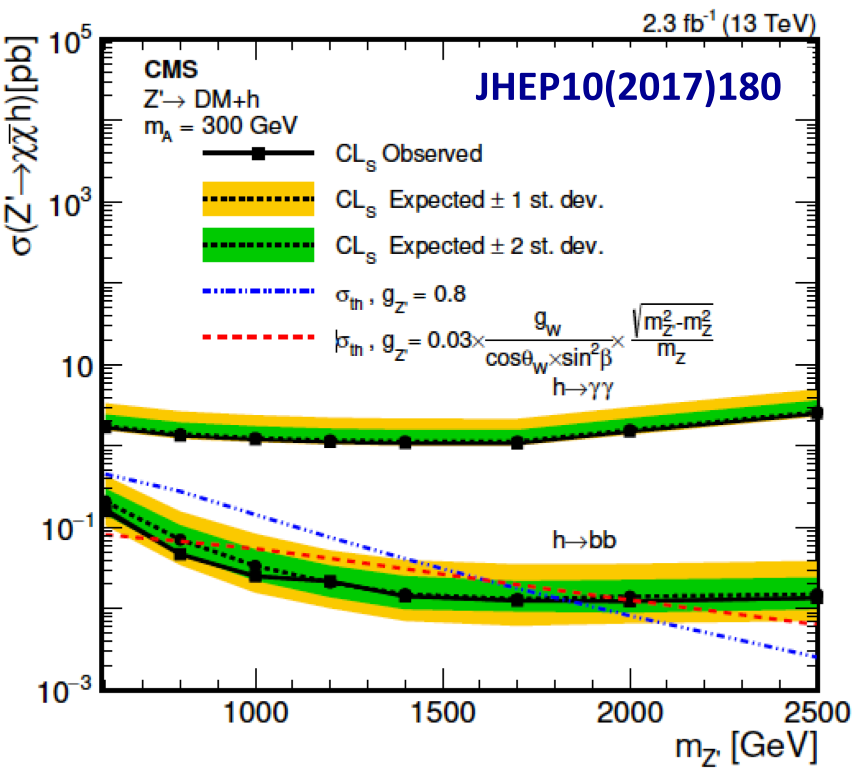
The original pixel detector replaced with a new device, the **"Phase-1" pixel detector** to address dynamic inefficiencies in the readout chip at high rates →

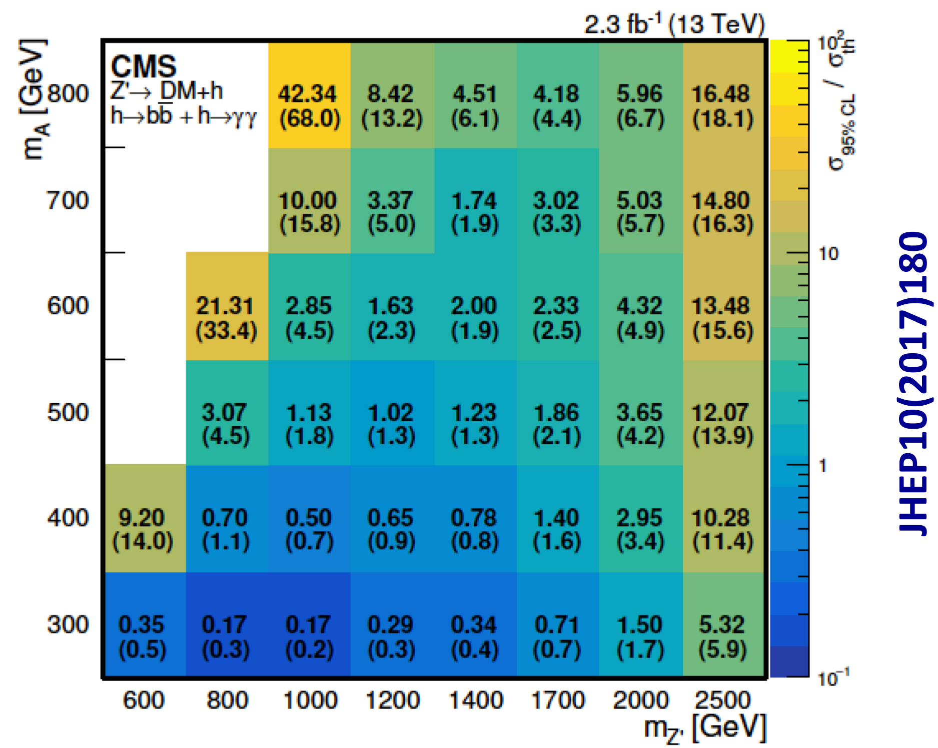
1 more pixel layer in barrel and 1 more disk in endcap

CMS is continuously upgraded to handle higher luminosity and do better physics

MonoHiggs results with 2015 data

CMS presented results of the **combination of the h→γγ and h→bb** final states with 2.3 fb^{-1} taken in 2015 for the **Z'-2HDM model**





For m_A = 300 GeV, the observed data exclude the **Z' mass range of 600 to 1860 GeV** for $g_{Z'}$ = 0.8

$H \rightarrow \gamma\gamma + H \rightarrow \tau\tau$ yields

$H \rightarrow \gamma\gamma$

Expected background	Low-p_T^{miss} category	High-p_T^{miss} category
SM $h \rightarrow \gamma\gamma$ (Vh)	2.9 ± 0.1 (stat) ± 0.2 (syst)	1.26 ± 0.05 (stat) ± 0.09 (syst)
SM $h \rightarrow \gamma\gamma$ (ggh, $t\bar{t}h$, VBF)	5.3 ± 0.3 (stat) ± 1.2 (syst)	0.11 ± 0.01 (stat) ± 0.01 (syst)
Nonresonant background	125.1 ± 11.2 (stat)	4.5 ± 2.1 (stat)
Total background	133 ± 11 (stat) ± 1 (syst)	5.9 ± 2.1 (stat) ± 0.1 (syst)
Observed events	159	6

$H \rightarrow \tau\tau$

Expected background	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
W + jets/QCD multijet	13.1 ± 2.2	32.5 ± 6.2	3.8 ± 2.6
$t\bar{t}$	13.7 ± 1.6	24.8 ± 2.0	4.2 ± 1.3
SM Higgs boson	0.48 ± 0.08	0.72 ± 0.06	1.21 ± 0.08
Diboson	12.3 ± 1.0	21.5 ± 1.5	7.3 ± 0.6
$Z \rightarrow \tau\tau$	0.00 ± 0.01	0.0 ± 0.5	3.6 ± 1.2
$Z \rightarrow \ell\ell$	0.9 ± 1.9	2.0 ± 1.3	—
$Z \rightarrow \nu\nu$	—	—	0.4 ± 0.3
Total background	40.5 ± 3.3	81.8 ± 6.3	20.5 ± 3.0
Observed events	38	81	26

	$h \rightarrow \gamma\gamma$ channel		$h \rightarrow \tau^+\tau^-$ channel		
Signal	Low-p_T^{miss}	High-p_T^{miss}	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
Z′-2HDM					
Expected yield	0.1 ± 0.4	4.5 ± 0.6	6.5 ± 0.3	11.1 ± 0.5	14.3 ± 1.2
$A\epsilon$ [%]	0.1	42.6	2.2	3.6	4.4
Baryonic Z′					
Expected yield	14.7 ± 6.7	13.8 ± 6.4	8.6 ± 0.3	16.8 ± 0.5	20.9 ± 0.8
$A\epsilon$ [%]	6.4	6.0	0.1	0.3	0.3