CMS search for dark matter particles produced in association with a Higgs boson

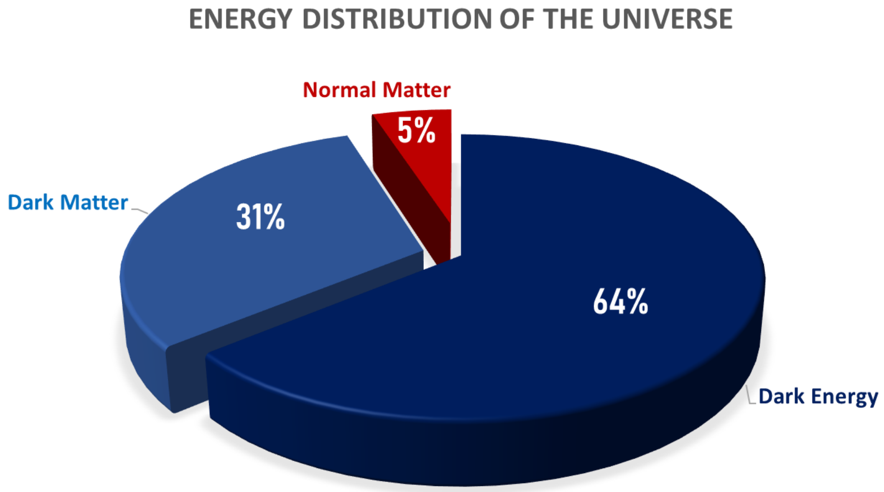
Luca Micheletti

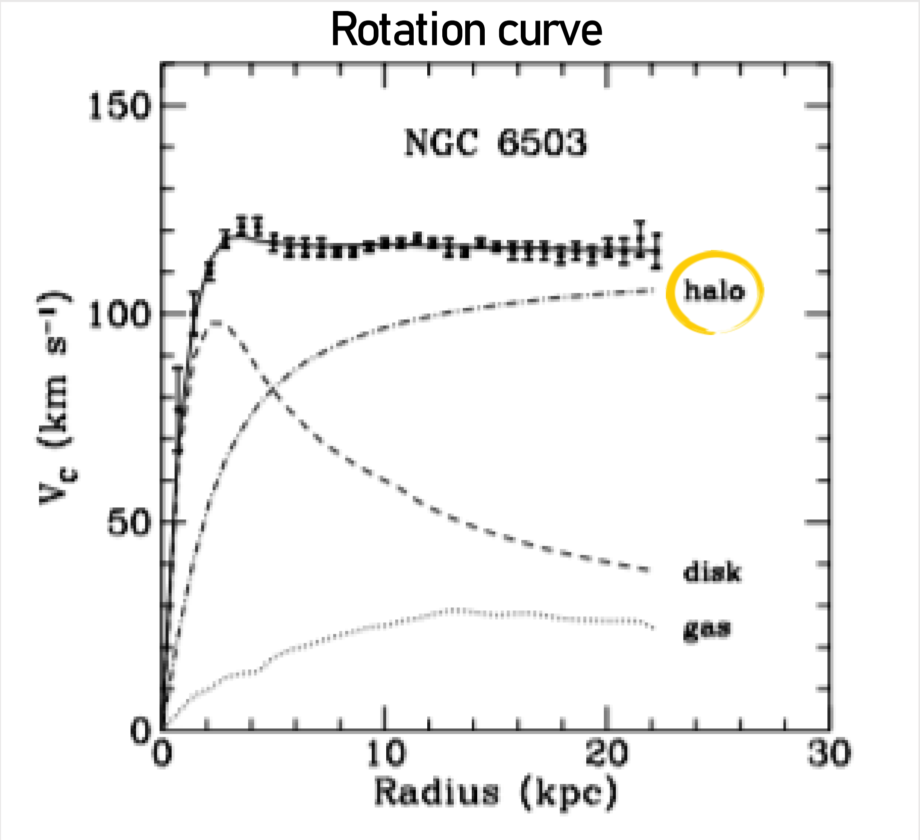
25/10/2019

Introduction

Dark matter: introduction

Astrophysical and cosmological observations confirm that Dark Matter exists and represents a significant part of the total mass of the Universe





DM evidence based on gravitational interaction

Thermal relic of the Universe cooling/expansion process

Hypothesis:

Dark Matter = WIMP?

- ❑ Stable
- ❑ Neutral
- ❑ Massive (few GeV – few TeV)
- ❑ Weakly interacting

➡ DM interacts with standard model particles?

Mono-X searches

Dark Matter
- Neutral
- Weakly interacting

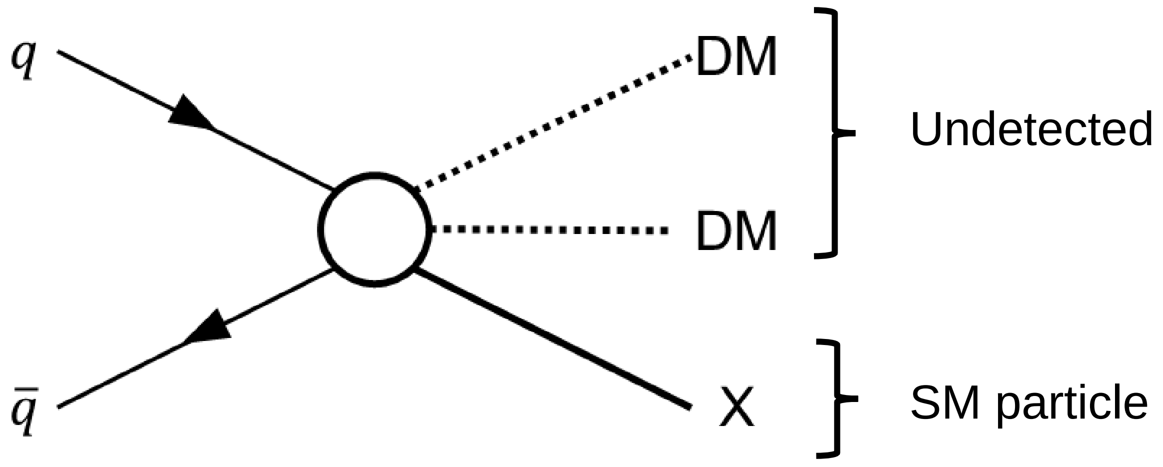
⇒ DM particles do not leave a directly detectable signal in the detector ⇒ Search for non-resonant new physics

Mono-X searches

For triggering events it is necessary that a standard model particle ("X") recolis against the missing transverse momentum (p_{T}^{miss})

Mono-X signature

$$pp \rightarrow \mathrm{X} + p_{\mathrm{T}}^{miss}$$



X can be:

- ❑ Hadronic jet
- ❑ Heavy-flavor quarks
- ❑ Photon
- ❑ W/Z bosons
- ❑ Higgs boson

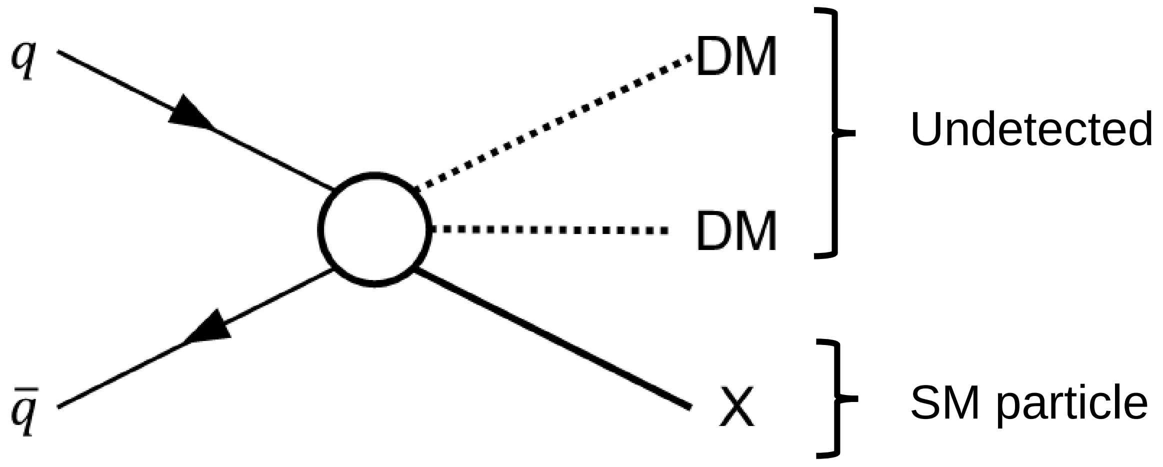
Mono-X searches

Dark Matter
- Neutral
- Weakly interacting

⇒ DM particles do not leave a directly detectable signal in the detector ⇒ Search for non-resonant new physics

Mono-X searches

For triggering events it is necessary that a standard model particle ("X") recolis against the missing transverse momentum (p_{T}^{miss})



Mono-X signature

$$pp \rightarrow \mathrm{X} + p_{\mathrm{T}}^{miss}$$

Normally for mono-X analysis, X emitted as initial-state radiation

Higgs boson

- Process suppressed for small Yukawa cupling of the Higgs boson with light quarks and loop-suppression cupling to gluons
- Higgs can be produced as final state radiation or interacting with DM

The paper

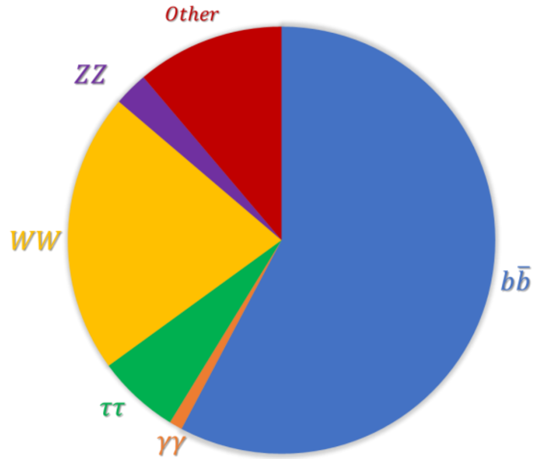
Data sample

- pp collisions at $\sqrt{s} = 13$ TeV collected in 2016
- $L_{int} = 35.9\ fb^{-1}$

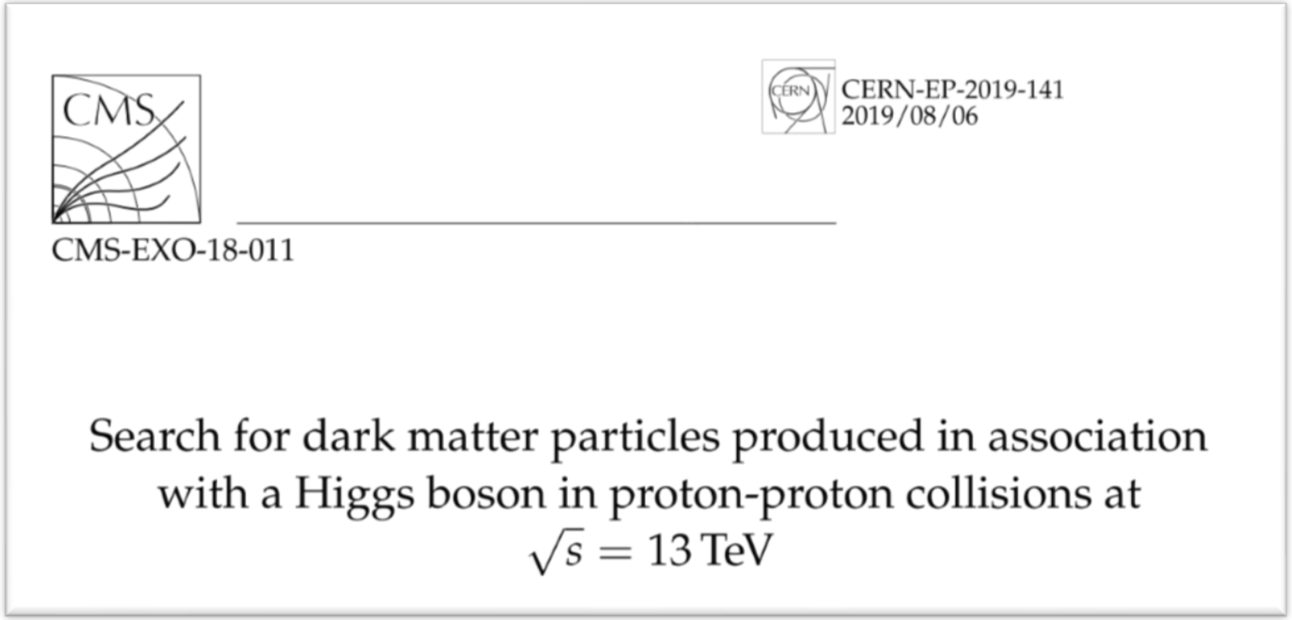
❗ First search of DM particles produced in association with a Higgs boson

❗ First statistical combination based on 5 Higgs boson decay channels

- $h \to b\bar{b}$
- $h \to \gamma\gamma$
- $h \to \tau^+\tau^-$
- $h \to W^+W^-$
- $h \to ZZ$



~ 88% of Higgs deacy channels



CMS

CMS-EXO-18-011

CERN-EP-2019-141
2019/08/06

Search for dark matter particles produced in association with a Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

Different theoretical models are compared to data:

- ❑ Decay of a DM boson into a Higgs boson and a pseudoscalar mediator
- ❑ Higgs boson produced as a final state radiation of a Dark Matter particle

Models

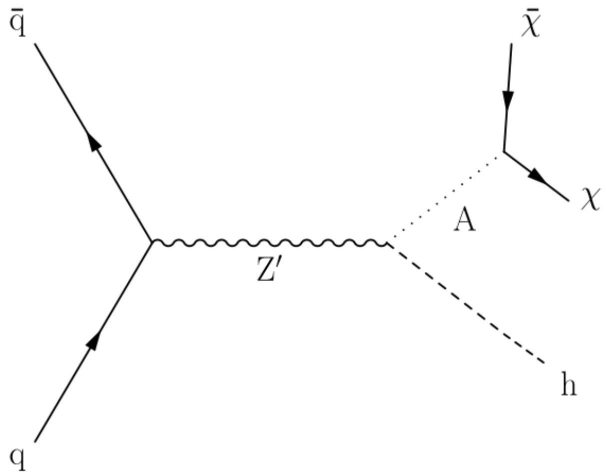
Z' + 2HDM

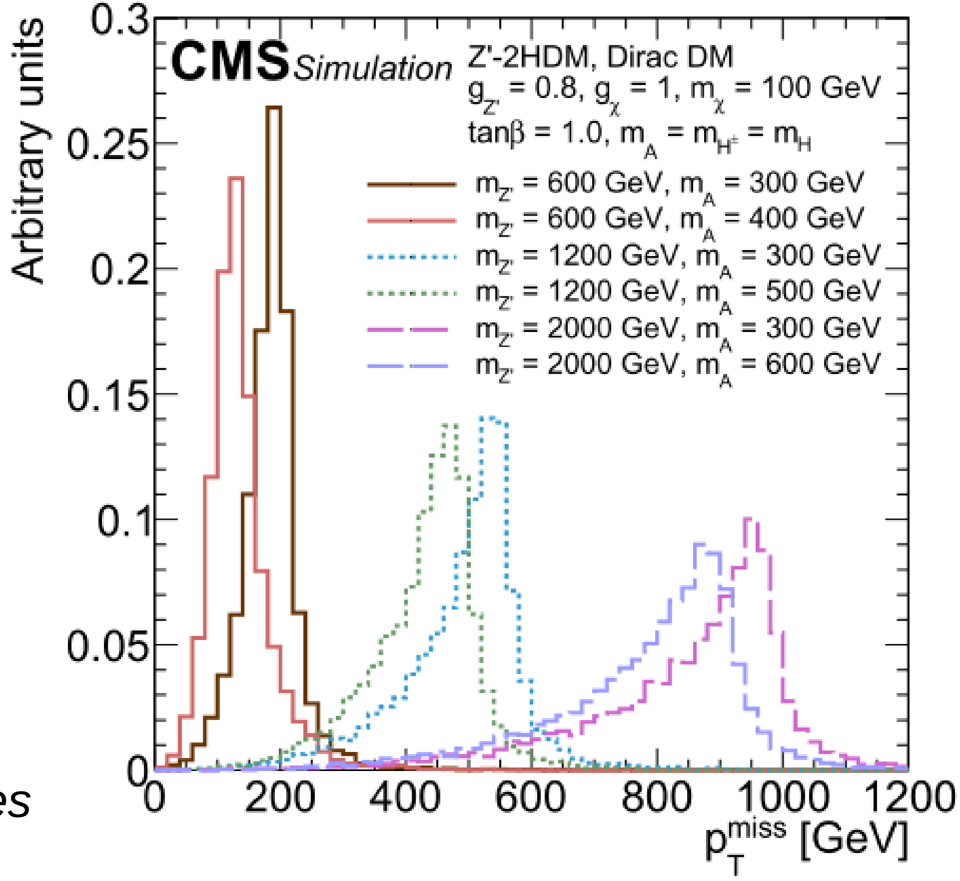
New massive gauge boson corresponding to $U(1)_{Z'}$

simplest extention of SM with 5 Higgs bosons $h, H, A, H^{\pm}$

- $\boldsymbol{h}$ → SM Higgs boson, $m_h \sim 125\ \mathrm{GeV}/c^2$
- $\boldsymbol{H, A, H^{\pm}}$ → Scalars with $m > 300\ \mathrm{GeV}/c^2$

Decay of a DM boson into a Higgs boson and a pseudoscalar mediator





- $\boldsymbol{Z'}$ = *gauge boson corresponding to* $U(1)_{Z'}$
- $\boldsymbol{h}$ = *SM Higgs boson*
- $\boldsymbol{A}$ = *heavy pseudoscalar with large BR in DM particles*
- $\boldsymbol{\chi}$ = *dirac fermion - DM particle*

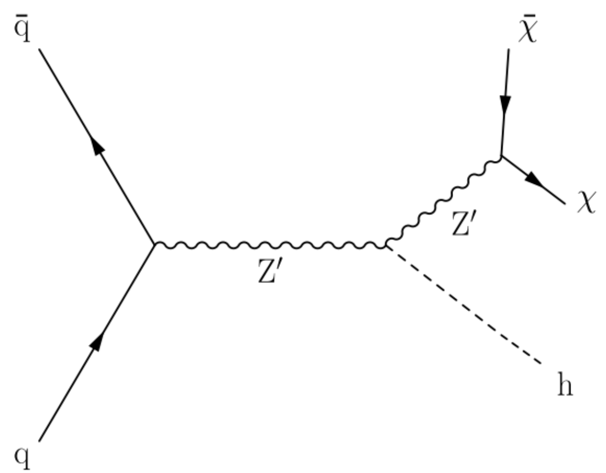
Models

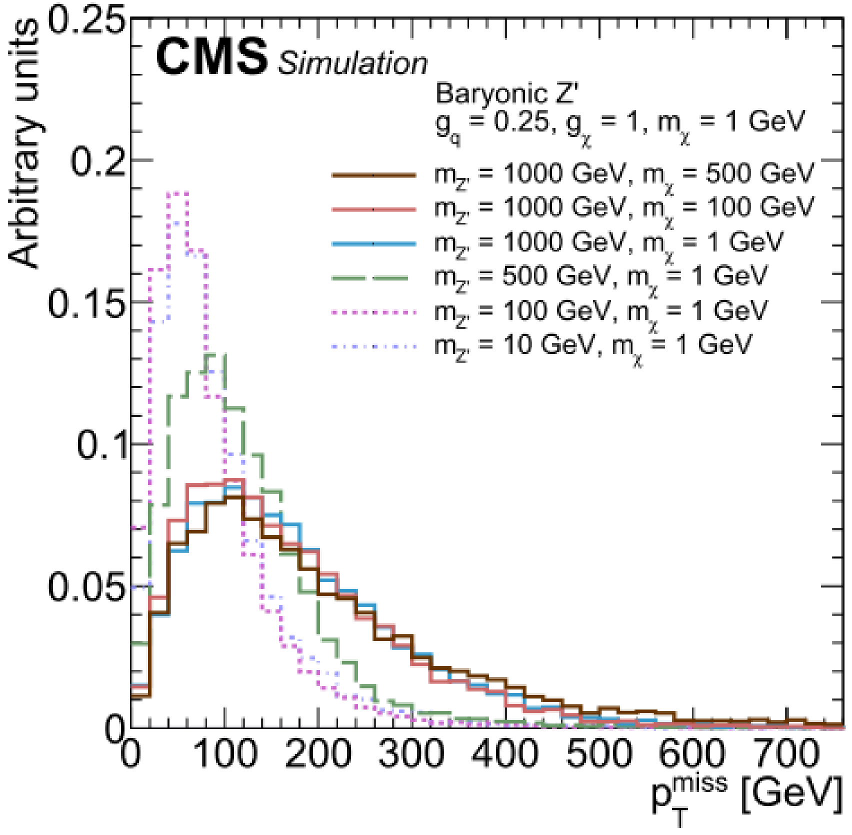
Barionic Z'

Existence of a new stable batyionic state couplig to quarks and DM

Higgs boson produced as a final state radiation of a Dark Matter particle

$$\mathscr{L} \supset g_q \bar{q}\gamma^\mu q Z'_\mu + \begin{cases} i g_\chi \chi^\dagger \overleftrightarrow{\partial^\mu} \chi Z'_\mu + g_\chi^2 |\chi|^2 Z'_\mu Z'^\mu & \text{scalar} \\ g_\chi \bar{\chi}\gamma^\mu \chi Z'_\mu & \text{fermion} \end{cases}$$





- ***Z′*** *= vector boson corresponding to new baryon number associated to the $U(1)_B$ simmetry*
- ***h*** *= radiated Higgs boson*
- ***χ*** *= dirac fermion - DM particle*

Data analysis

$h(\rightarrow b\bar{b}) + p_{\mathrm{T}}^{miss}$

$h(\rightarrow \gamma\gamma) + p_{\mathrm{T}}^{miss}$

$h(\rightarrow \tau\tau) + p_{\mathrm{T}}^{miss}$

$h(\rightarrow WW) + p_{\mathrm{T}}^{miss}$

$h(\rightarrow ZZ) + p_{\mathrm{T}}^{miss}$

Analysis strategy

$h(\to b\bar{b}) + p_T^{miss}$

✓ large B.R. (58.2%)
✗ low S/B

➡ Search for events with $p_T^{miss} > 90\ \mathrm{GeV}/c$

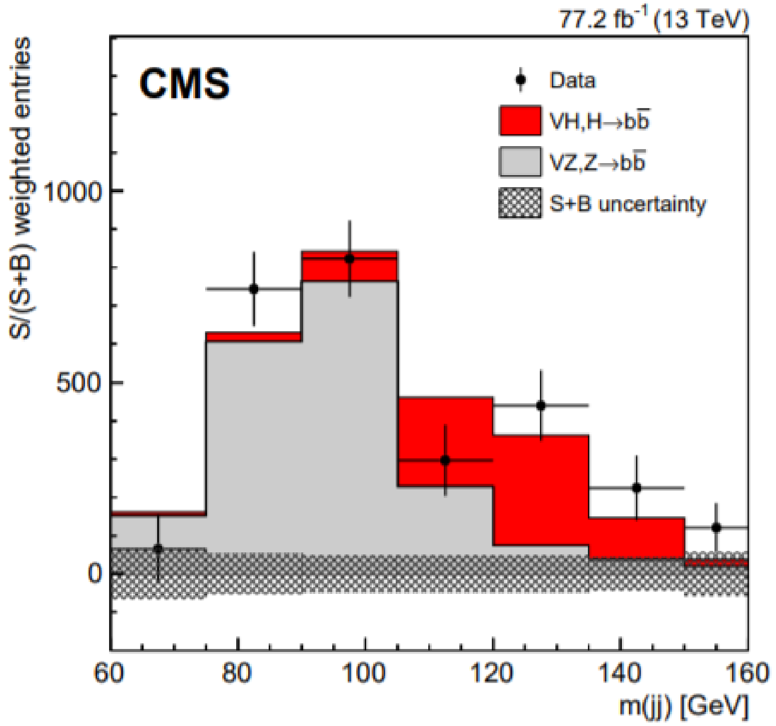
❑ Different boost for the different models ⟹ different jet algorithm:

Z'-2HDM, large boost ⟹ AK8 (distance parameter 0.8)

- Jet $p_T > 200\ \mathrm{GeV}/c$, $|\eta| < 2.4$
- $h \to b\bar{b}$ topology selected requiring at least 1 sub-jet b-tagged
- $105 < m_h < 135\ \mathrm{GeV}/c^2$

Barionic Z', low boost ⟹ CA15 (distance parameter 1.5)

- Multivariate double b-tagging criteria for background and light flavor jet discrimination
- $100 < m_h < 150\ \mathrm{GeV}/c^2$



Higgs production in association with vector boson

Difference in mass given by the difference in the performance of the 2 algorithms for the jet mass resolution

Analysis strategy

$h(\rightarrow \gamma\gamma) + p_{\mathrm{T}}^{miss}$

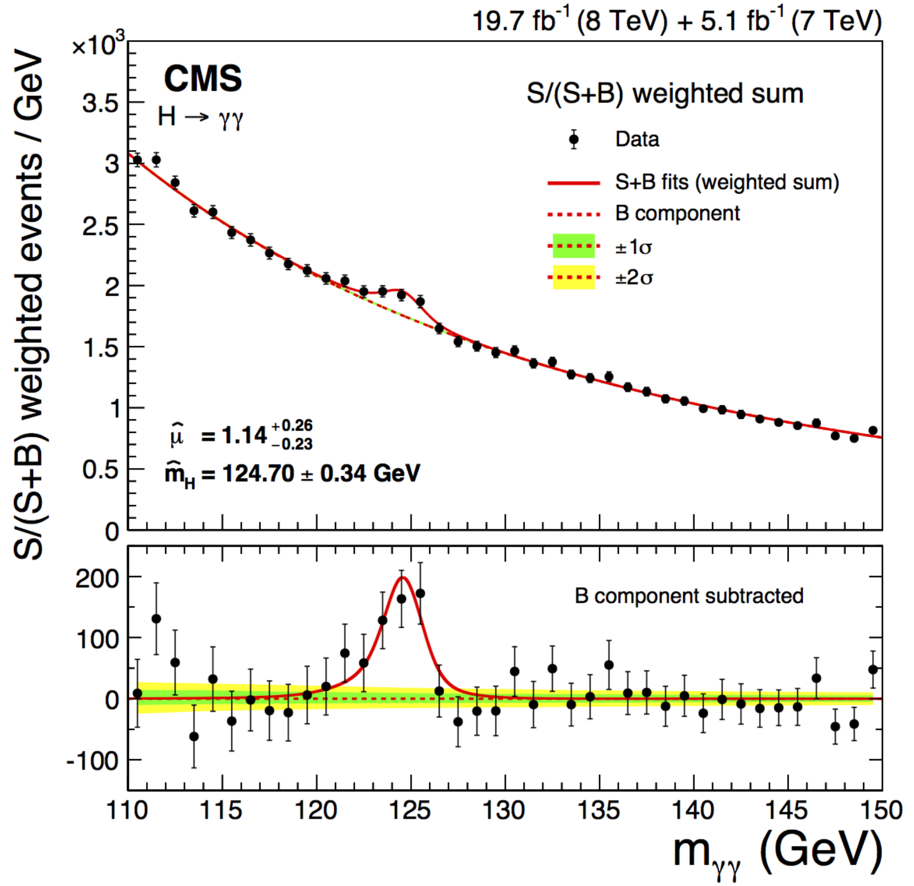
✓ high mass resolution
✗ low B.R. (0.23%)

➡ Search for events with 2 photons and asymmetric p_{T} threshold of 30 and 18 GeV for leading and subleading photons

- $m_{\gamma\gamma} > 90\ \mathrm{GeV}/c^2$
- Photon isolation criteria:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.3$$

- At most 2 jets to with $p_{\mathrm{T}} > 30\ \mathrm{GeV}/c$ to reduce multijet background



$h(\rightarrow \tau\tau) + p_{\mathrm{T}}^{miss}$

✓ large B.R. (6.3%)
✗ low S/B

➡ 3 final states under study: $\tau\tau, \tau\mu, \tau e$

- ❑ Online selection: presence of two isolated τ $(h \rightarrow \tau\tau)$, single muon, single electron $(h \rightarrow \tau + \mu/e)$
- ❑ Offline selection: $p_{\mathrm{T}}^{miss} > 105\ \mathrm{GeV}/c$, $p_{\mathrm{T}}^{\tau\tau} > 65\ \mathrm{GeV}/c$

Analysis strategy

$h(\rightarrow WW) + p_T^{miss}$

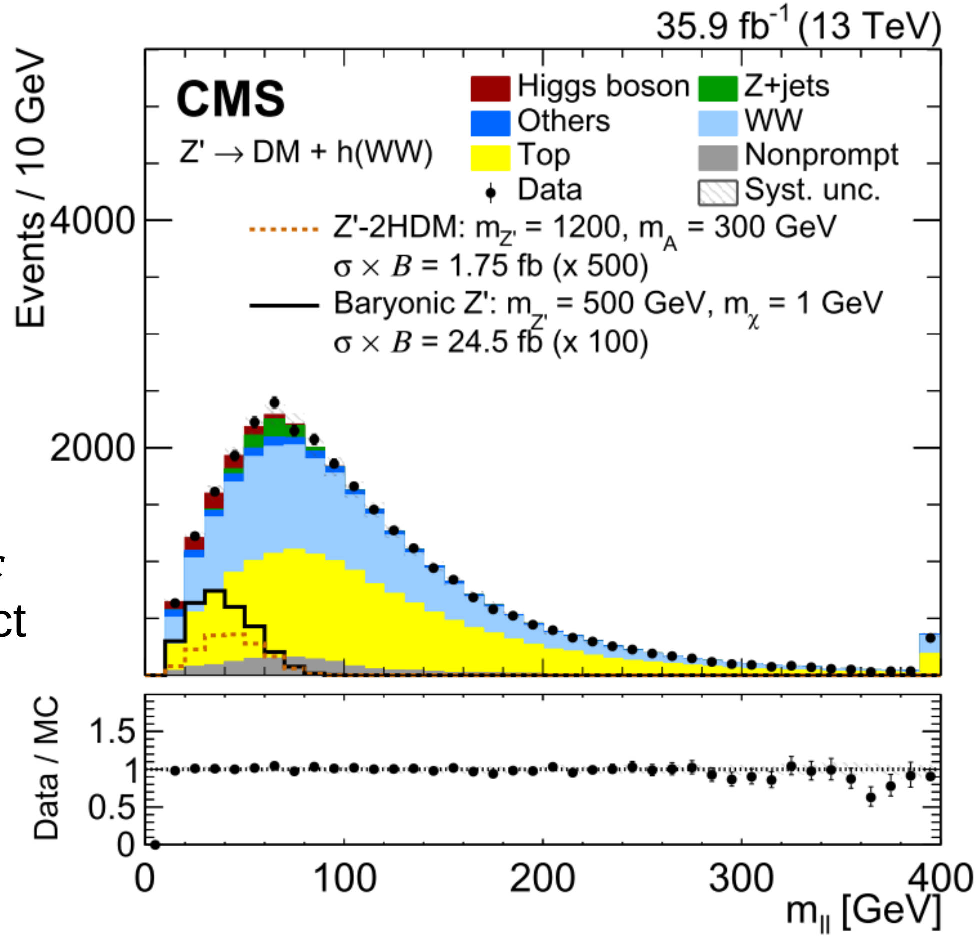
✔ large B.R. (21.4%)
✘ low mass resolution

➡ Search for fully leptonic, different flavor, opposite sign final state

$h \rightarrow WW \rightarrow e\,\mu\,\nu\nu$

Significant contribution of undetected neutrinos to p_T^{miss}

- Online selection: suite of single and double-lepton triggers
- Offline selection:
  - Leading (subleading) lepton required to have $p_T > 25\ (20) \mathrm{GeV}/c$
  - Electron and muon candidate well-identified and isolated to reject background from lepton inside jets
  - $m_{ll} > 12\ \mathrm{GeV}/c^2$ to exclude leptons coming from low mass resonances
  - $p_T^{ll} > 30\ \mathrm{GeV}/c$ to suppress $Z/\gamma^* \rightarrow \tau\tau$ background



Analysis strategy

$$h(\to ZZ) + p_{\mathrm{T}}^{miss}$$

- mass resolution
- backgound under control

small BR (2.6%)

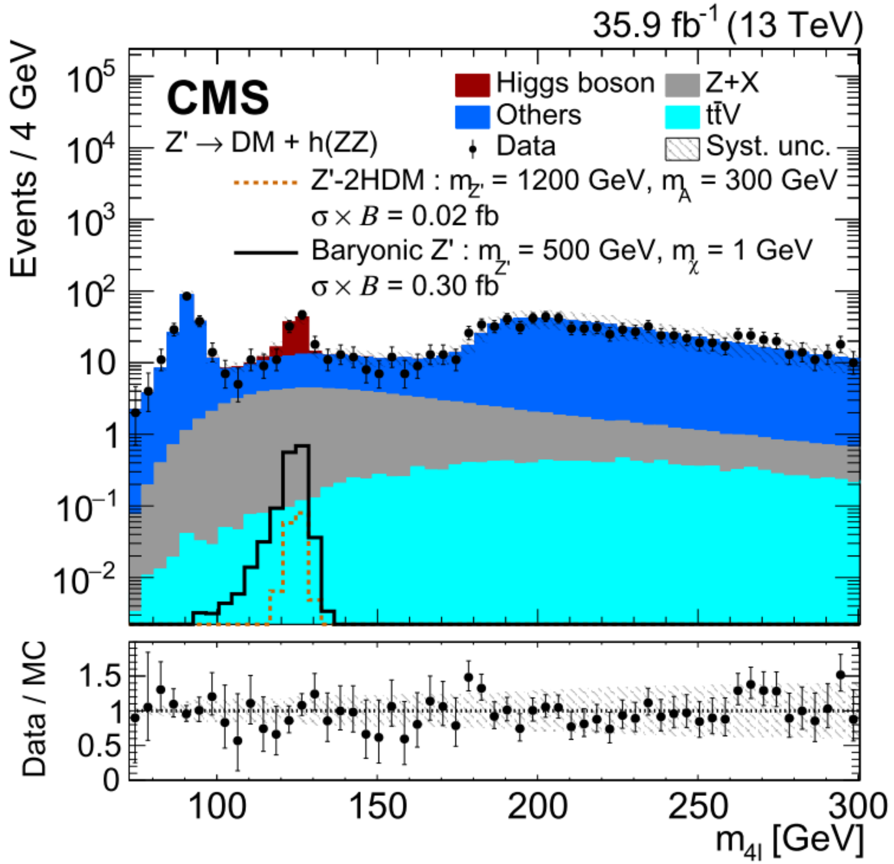
➡ Search for 4-lepton signature

➡ Higgs boson candidates fully reconstructed!

- ❑ Online selection: 2 isolated leptons ($ee, \mu\mu$ o $e\mu$) with asymmetric p_{T} threshold
- ❑ Offline selection:
  - 2 Z boson with $12 < m_{ll} < 120\ \mathrm{Gev}/c^2$
  - ZZ candidates not sharing any of the leptons
  - $m_{ll} > 4\ \mathrm{GeV}/c^2$
  - $m_{4l} > 70\ \mathrm{GeV}/c^2$

  } To suppress low-mass dilepton resonances

  - More than 1 ZZ candidate → event discarded



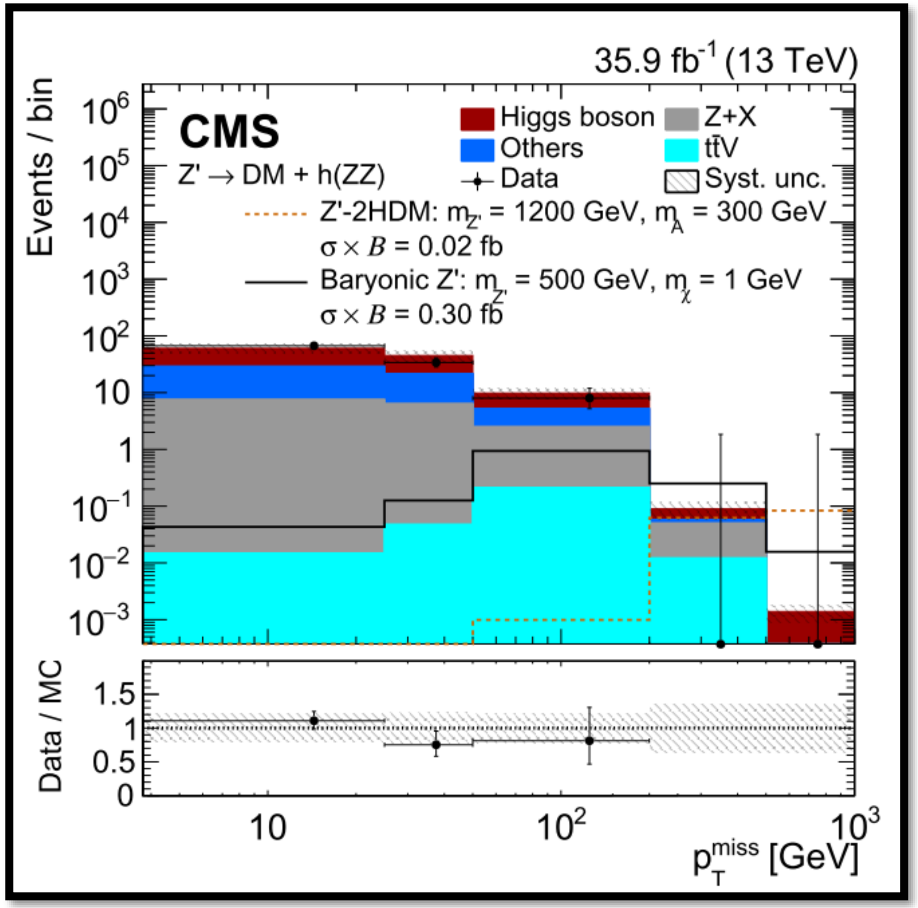
Analysis strategy

$h(\rightarrow ZZ) + p_T^{miss}$

- ✓ mass resolution
- ✓ backgound under control
- ✗ small BR (2.6%)

➔ Search for 4-lepton signature

➔ Higgs boson candidates fully reconstructed!

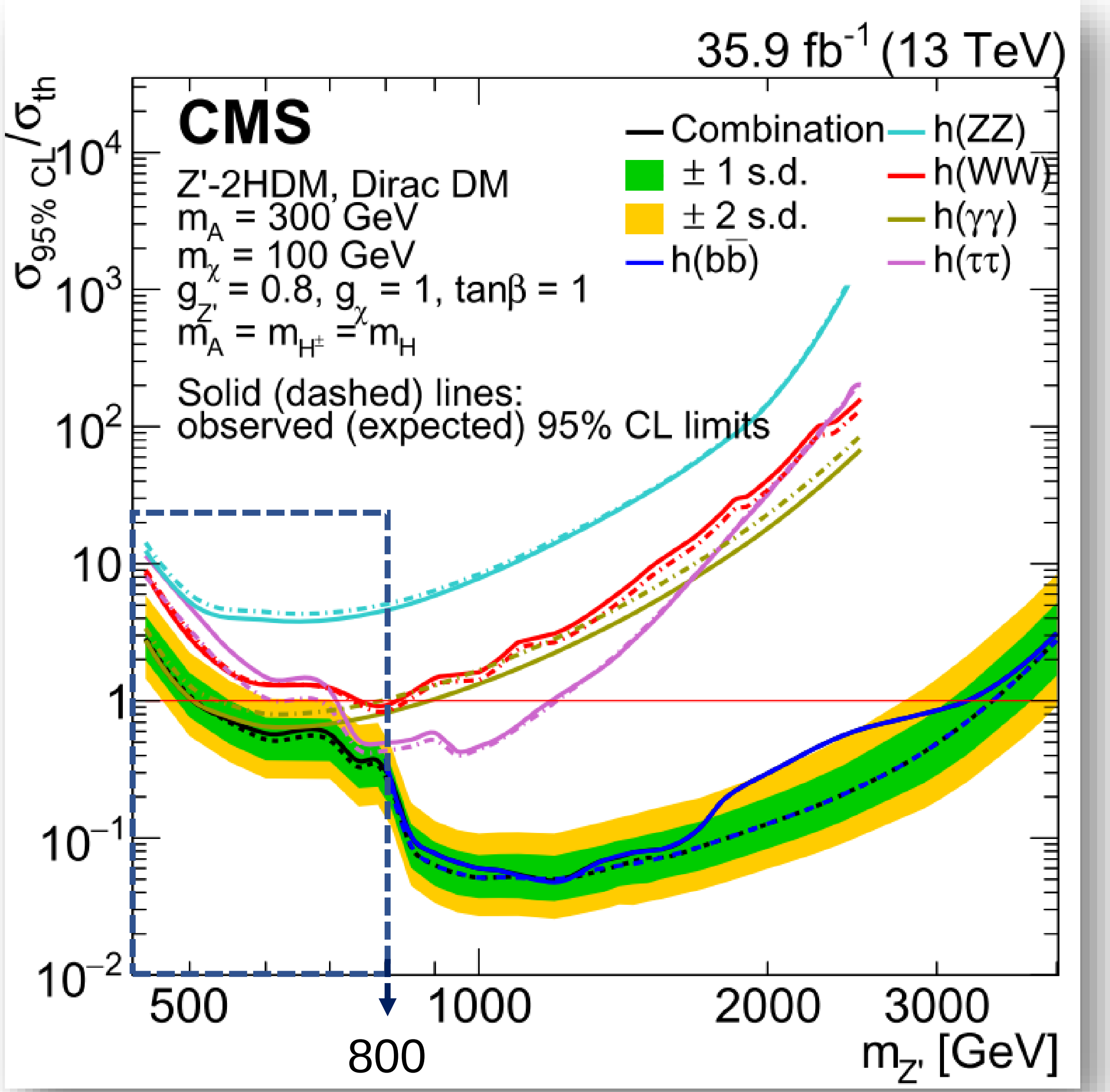


- ❑ Online selection: 2 isolated leptons ($ee, \mu\mu$ o $e\mu$) with asymmetric p_T threshold
- ❑ Offline selection:
  - 2 Z boson with $12 < m_{ll} < 120$ Gev$/c^2$
  - ZZ candidates not sharing any of the leptons
  - $m_{ll} > 4$ GeV$/c^2$
  - $m_{4l} > 70$ GeV$/c^2$

  } To suppress low-mass dilepton resonances
  - More than 1 ZZ candidate → event discarded

Results

Analysis results



The 5 channels are statistically independent

⇩

❗ The analyses can be combined

Z'-2HDM

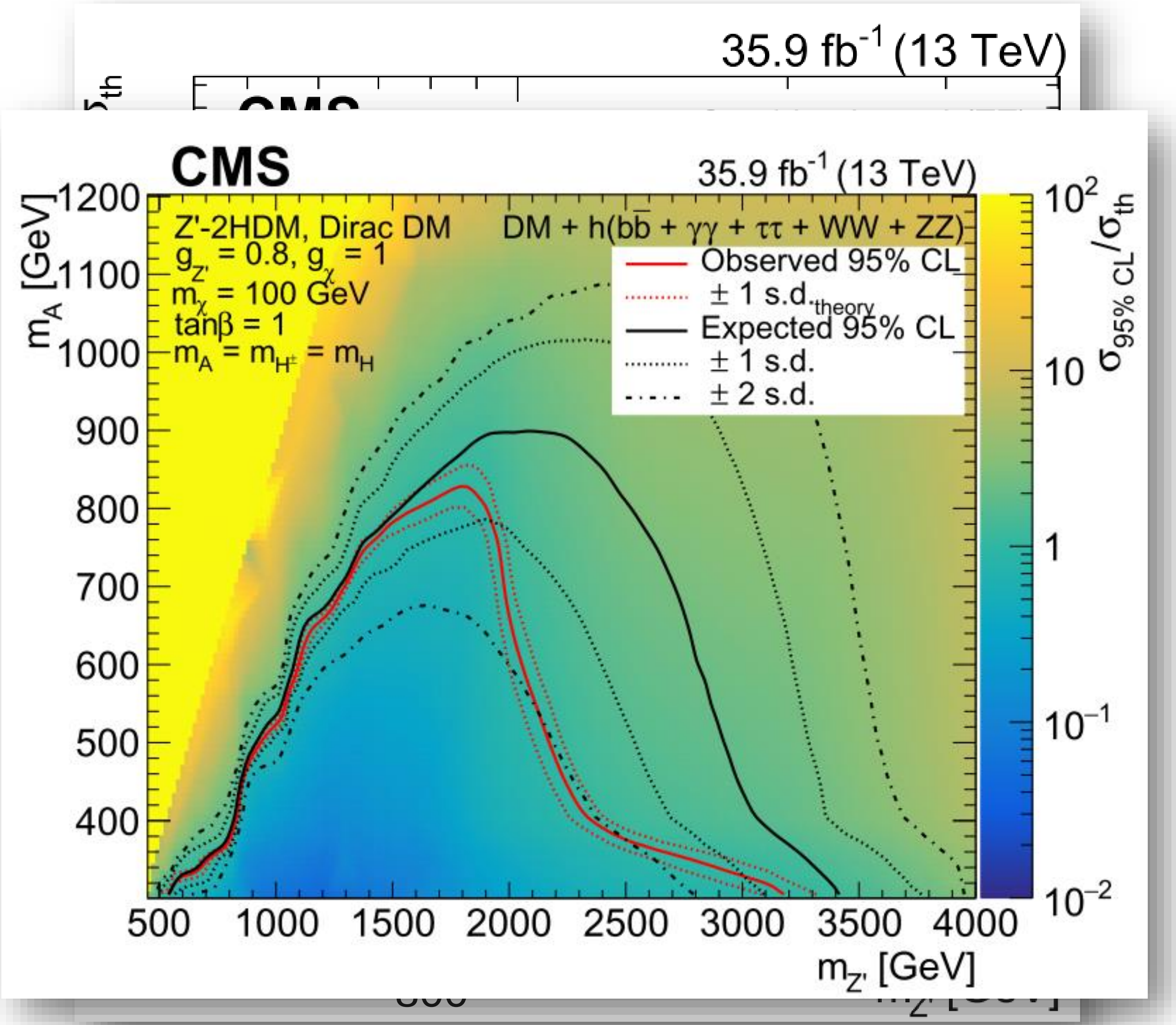
Combination dominated by $h \to \bar{b}b$

- $h \to \bar{b}b$ not valid for $m_{Z'} < 800\ GeV/c^2$
- $h \to \gamma\gamma$
- $h \to \tau\tau$

} significant role for $m_{Z'} < 800\ GeV/c^2$

$500 < m_{Z'} < 3200\ \text{GeV}/c^2$ excluded at 95% CL for $m_A = 300\ GeV/c^2$

Analysis results



The 5 channels are statistically independent

⇩

❗ The analyses can be combined

Z'-2HDM

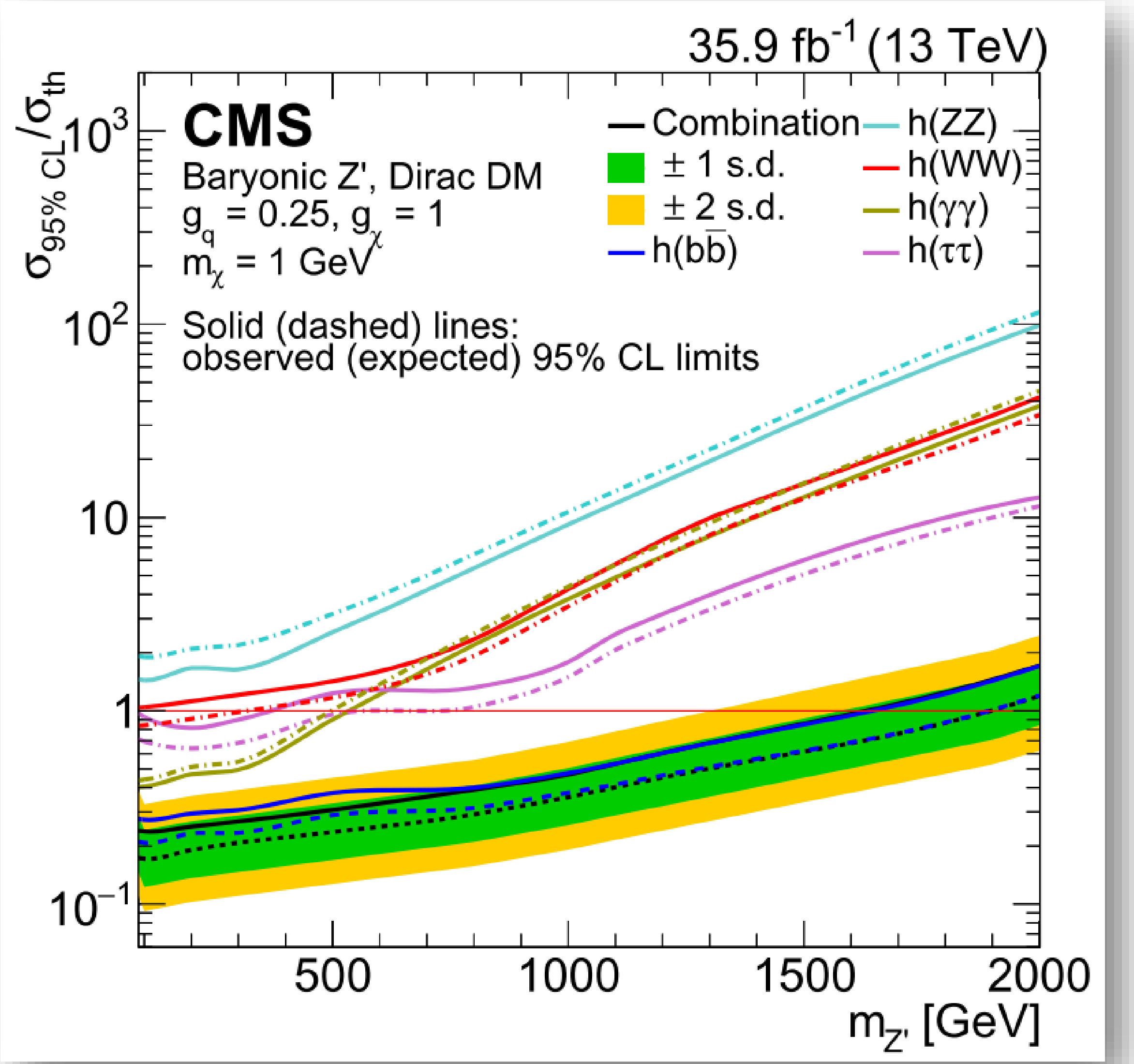
Combination dominated by $h \to \bar{b}b$

- $h \to \bar{b}b$ not valid for $m_{Z'} < 800\ GeV/c^2$
- $h \to \gamma\gamma$
- $h \to \tau\tau$

} significant role for $m_{Z'} < 800\ GeV/c^2$

$500 < m_{Z'} < 3200\ \mathrm{GeV}/c^2$ excluded at 95% CL for $m_A = 300\ GeV/c^2$

Analysis results



The 5 channels are statistically independent

⇩

❗ The analyses can be combined

Barionic Z'

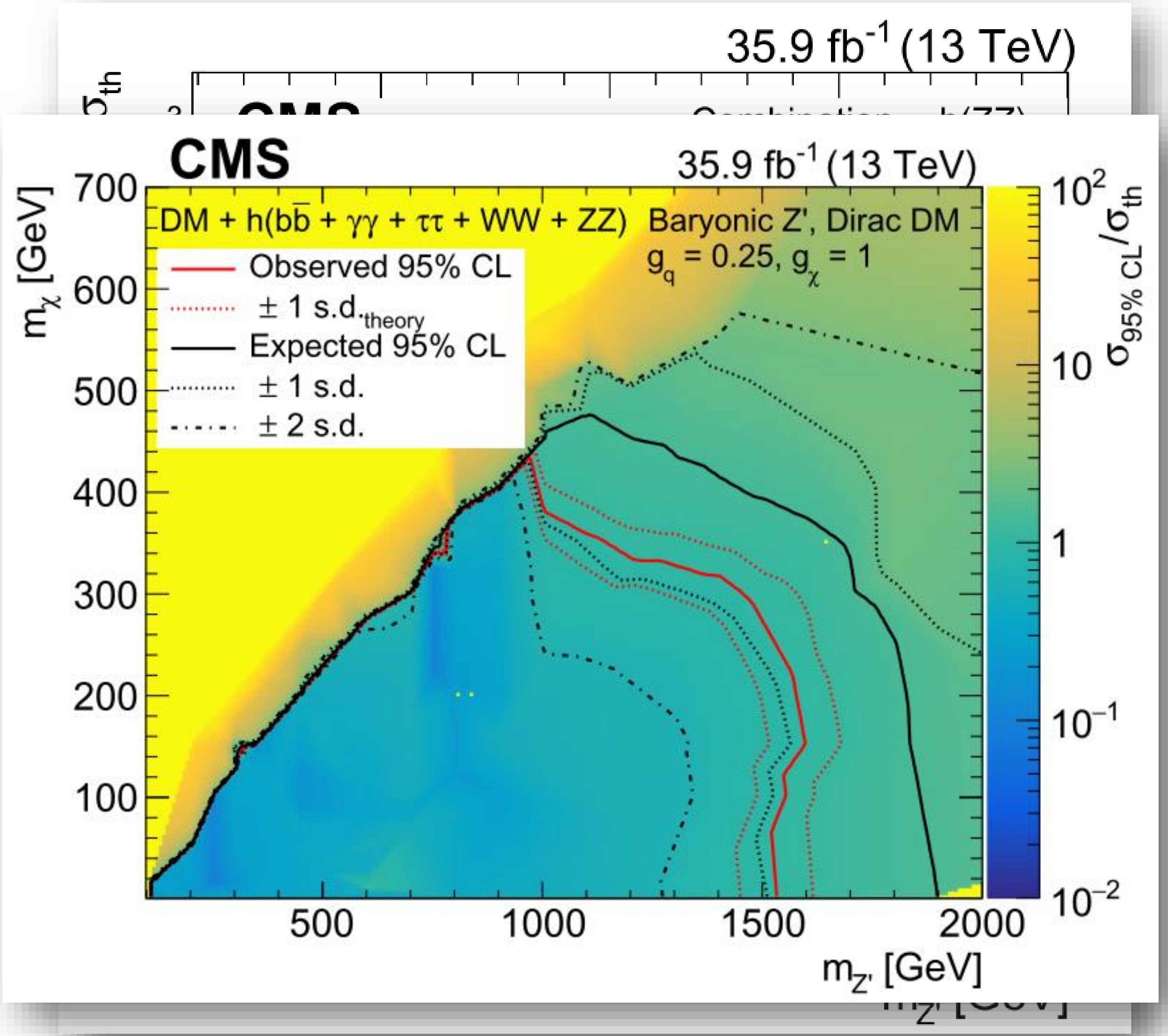
Combination dominated by $h \to \bar{b}b$

- $h \to \gamma\gamma$
- $h \to \tau\tau$

} Non-negligible contribution

$100 < m_{Z'} < 1600\ \mathrm{GeV}/c^2$ excluded at 95% CL for $m_\chi = 1\ GeV/c^2$

Analysis results



The 5 channels are statistically independent

⇩

❗ The analyses can be combined

Barionic Z'

Combination dominated by $h \to \bar{b}b$

- $h \to \gamma\gamma$
- $h \to \tau\tau$

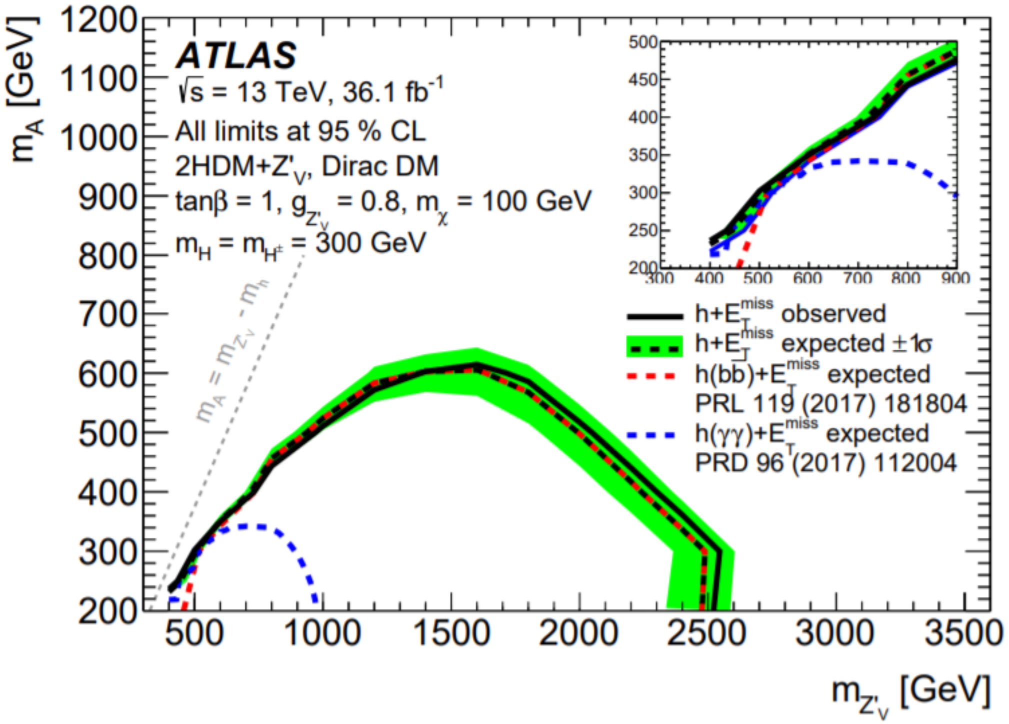
} Non-negligible contribution

$100 < m_{Z'} < 1600\ \mathrm{GeV}/c^2$ excluded at 95% CL for $m_\chi = 1\ GeV/c^2$

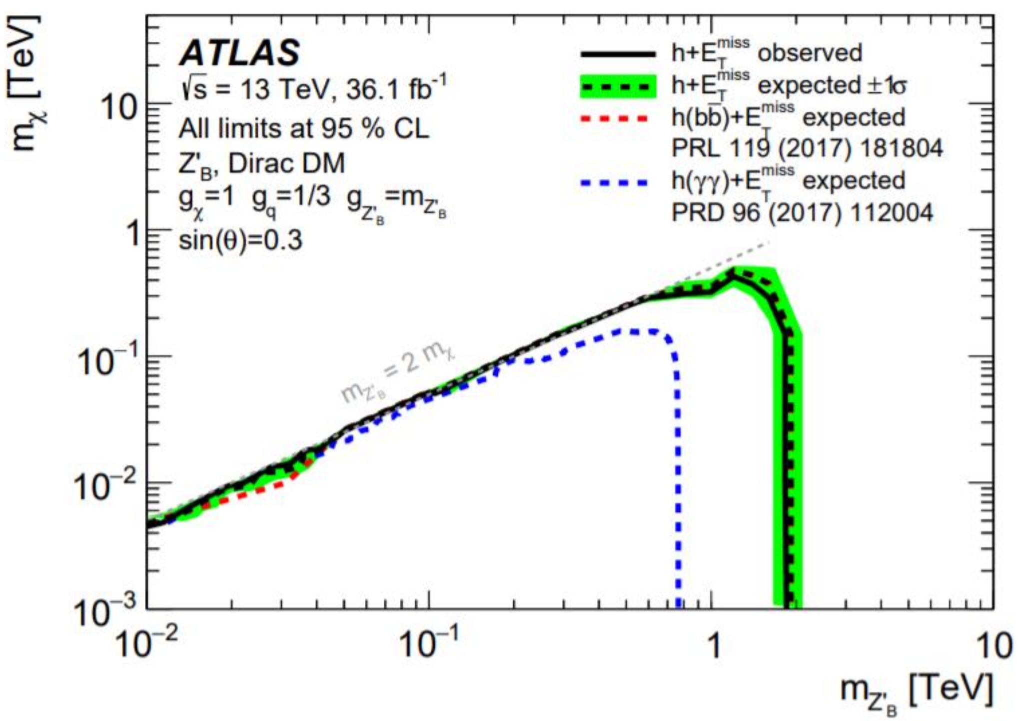
Other searches…

Constraints on mediator-based dark matter and scalar dark energy models using $\sqrt{s}$ = 13 TeV pp collision data collected by the ATLAS detector JHEP 1905 (2019) 142

➡ The ATLAS collaboration perform a similar search considering $h \to b\bar{b} + E_T^{miss}$ and $h \to \gamma\gamma + E_T^{miss}$



$m_{Z'} < 2500\ \mathrm{GeV}/c^2$ excluded



$m_{Z'_B} < 1900\ \mathrm{GeV}/c^2$ excluded

Other searches…

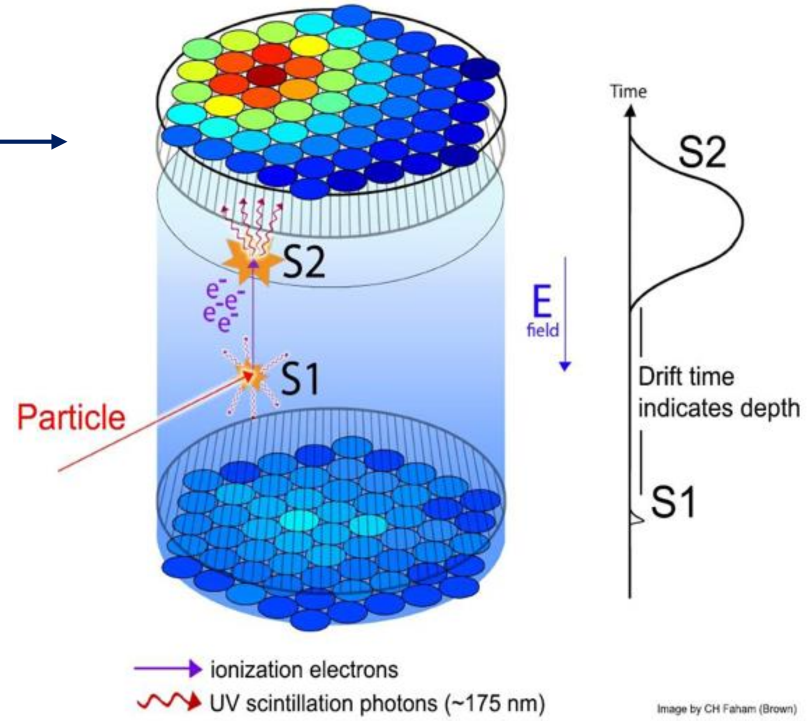
➡ Limits on baryonic Z' model can be interpreted as limit on s-channel simplified DM model

s-channel simplified DM model

- Used for comparison with direct-detection experiments
- Couplig of the Z' mediator with DM Dirac fermions and SM quarks
- Spin-independent DM-nucleon cross section can be calculated as:

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

- m_χ = DM particle mass
- m_{med} = mediator mass
- g_χ = mediator-DM coupling
- $f(g_q)$ = mediator-nucleon clupling
- μ_{nDM} = reduced mass DM-nucleon



Direct detection experiment (LUX,…)

- Two-phases Xe TPC, photomultipliers
- Interaction produce photons & electrons from ionization
- S1, S2 allows to reconstruct 3D vertices
- WIMP interaction would appear as nuclear recoil (electron recoli due to the interaction with photons)

Other searches...

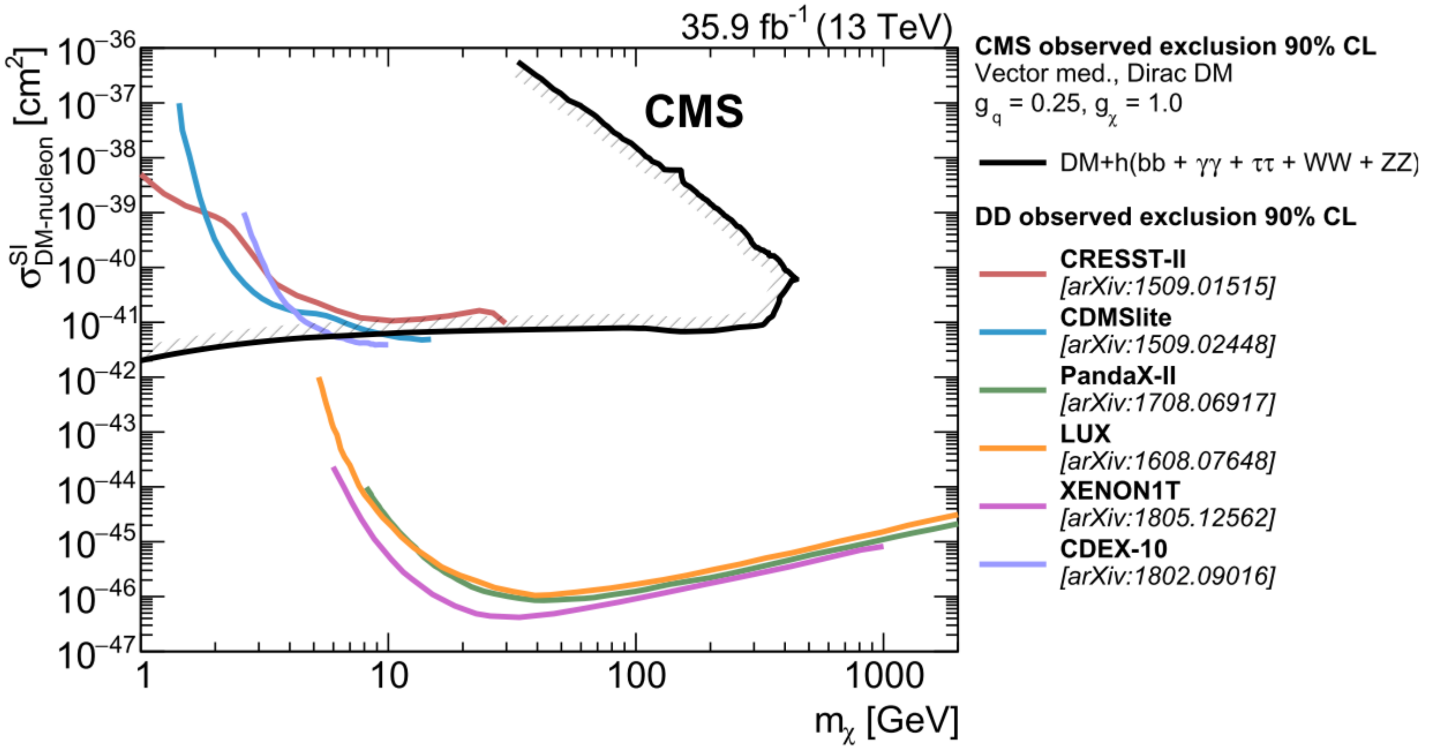
➡ Limits on baryonic Z' model can be interpreted as limit on s-channel simplified DM model

s-channel simplified DM model

- ❑ Used for comparison with direct-detection experiments
- ❑ Couplig of the Z' mediator with DM dirac fermions and SM quarks
- ❑ Spin-independent DM-nucleon cross section can be calculated as:

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

- m_χ = DM particle mass
- m_{med} = mediator mass
- g_χ = mediator-DM coupling
- $f(g_q)$ = mediator-nucleon clupling
- μ_{nDM} = reduced mass DM-nucleon



CMS cross section limit more stringent for $1 < m_\chi < 5\ \mathrm{GeV}/c^2$

Summary & conclusions

- First search of DM particles produced in association with a Higgs boson decaying to a WW and ZZ pairs
  - First statistical combination based on 5 Higgs boson decay channels
  - Exclusion limit at 95% CL set for different DM models:

Z'-2HDM

$$500 < m_{Z'} < 3200 \text{ GeV}/c^2$$
$$300 < m_A < 800 \text{ GeV}/c^2$$

Barionic Z'

$$100 < m_{Z'} < 1600 \text{ GeV}/c^2$$
$$0 < m_\chi < 400 \text{ GeV}/c^2$$

  - Comparison with the spin-independent cross section of direct-detection experiments

→ HL-LHC could be important in order the increase statistics and put more stringent limits on the models

→ Mono-X searches important to:

- ❑ search for deviations w.r.t. SM ↔ SM precision measurements
- ❑ test all the possible final states including new (DM) processes