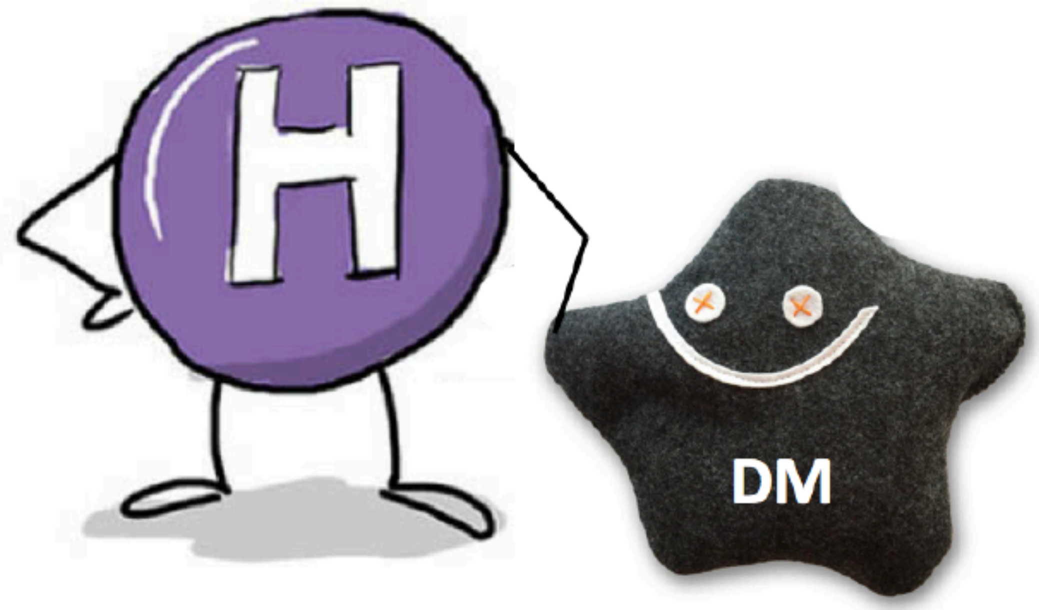
The Higgs Boson as a tool to search for dark matter at CMS



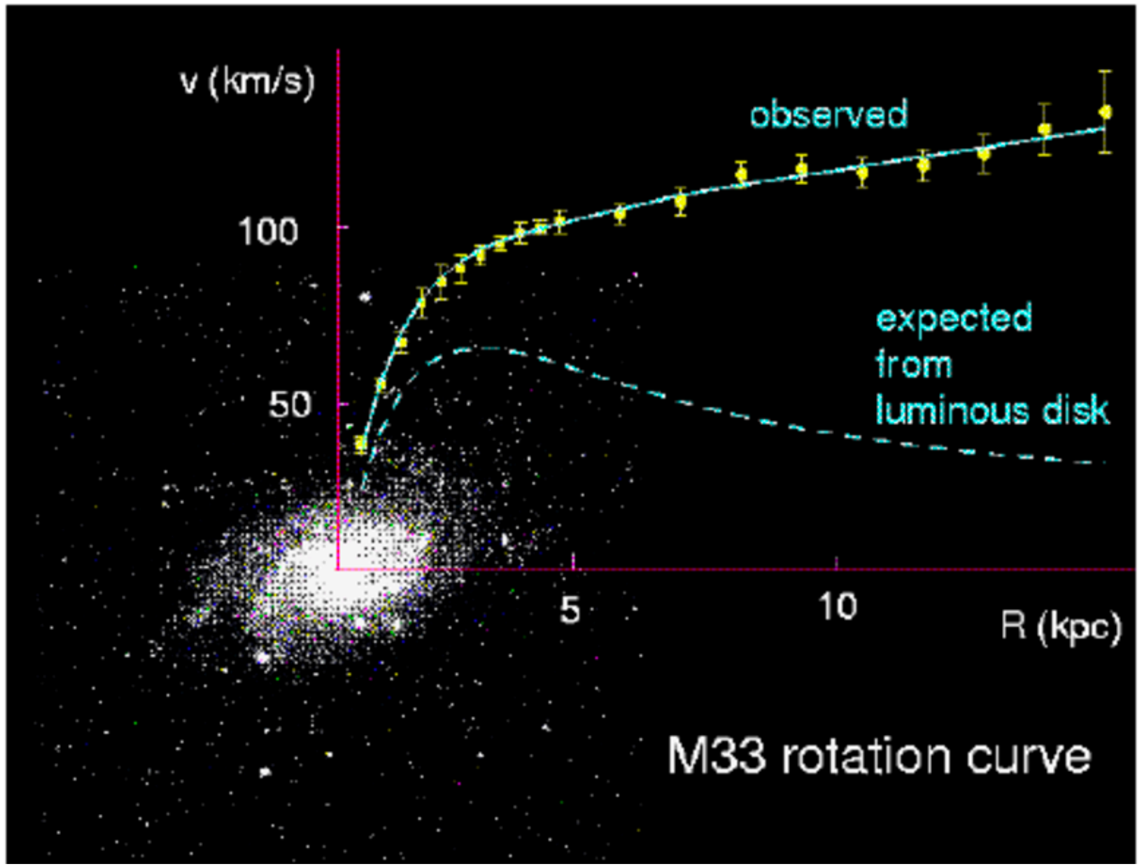
Raman Khurana
on behalf of CMS Collaboration

National Taiwan University, Taiwan

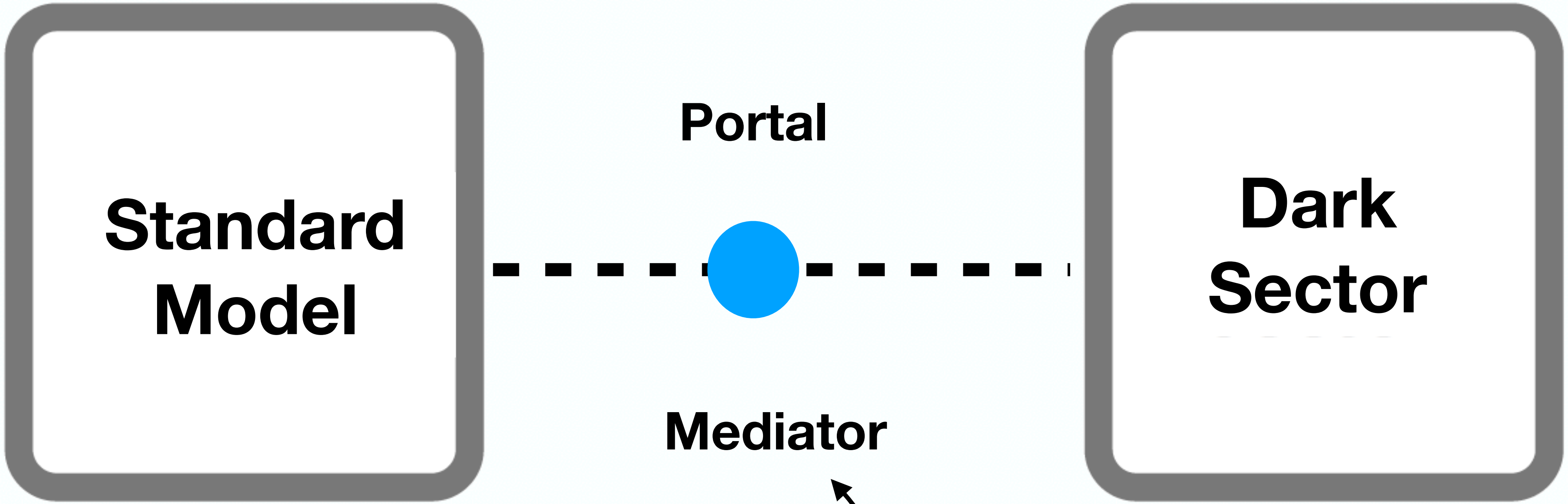
7th July 2022

ICHEP 2022, Bologna, Italy.

Evidence for Dark Matter



Portals to Dark Sector



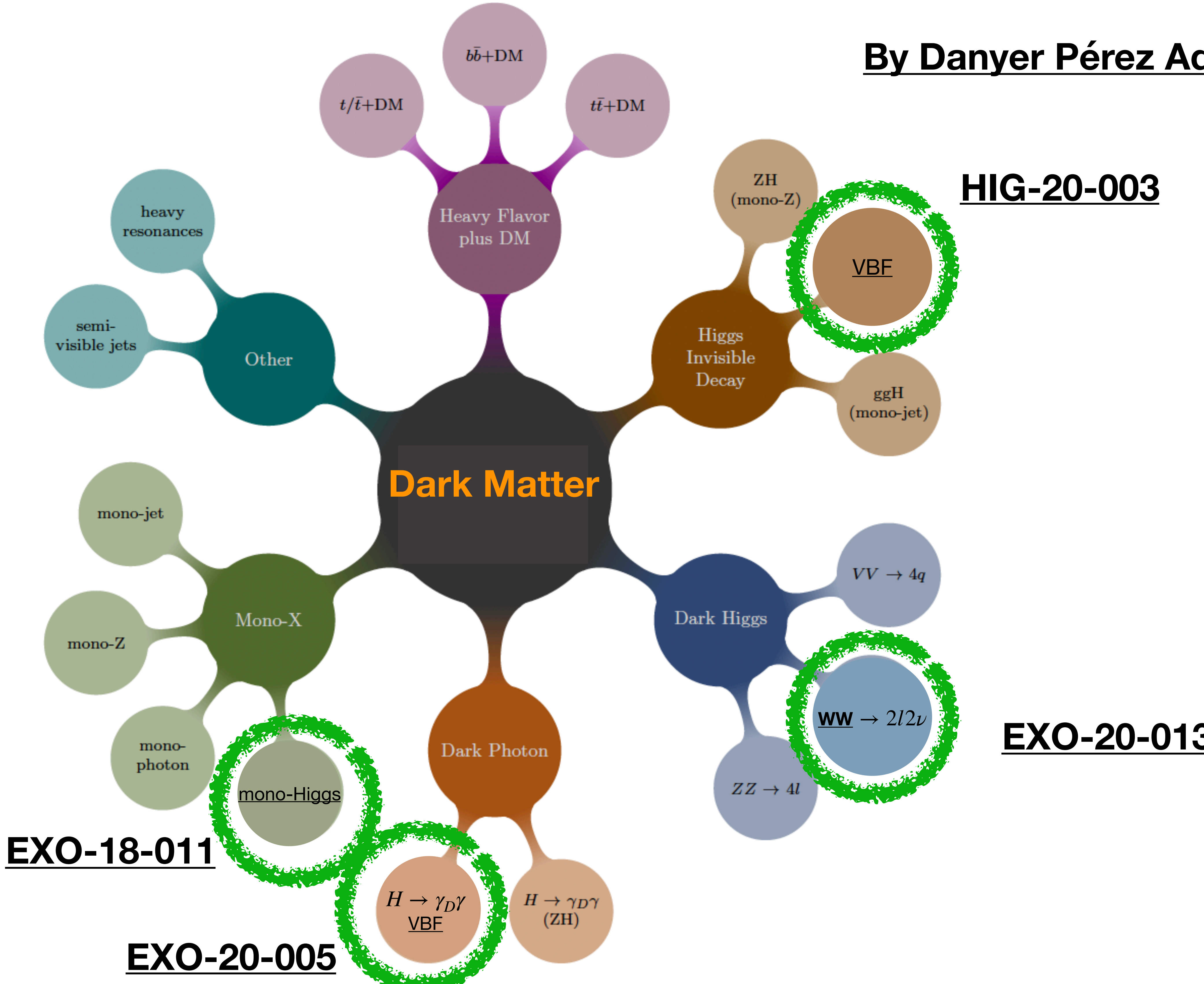
Non-gravitational interaction with ordinary matter

- **Dark matter**
- **Dark forces**
- **Other dark particles**

The new mediator governs the non-gravitational interactions between dark matter and ordinary matter

List of DM searches

By Danyer Pérez Adán

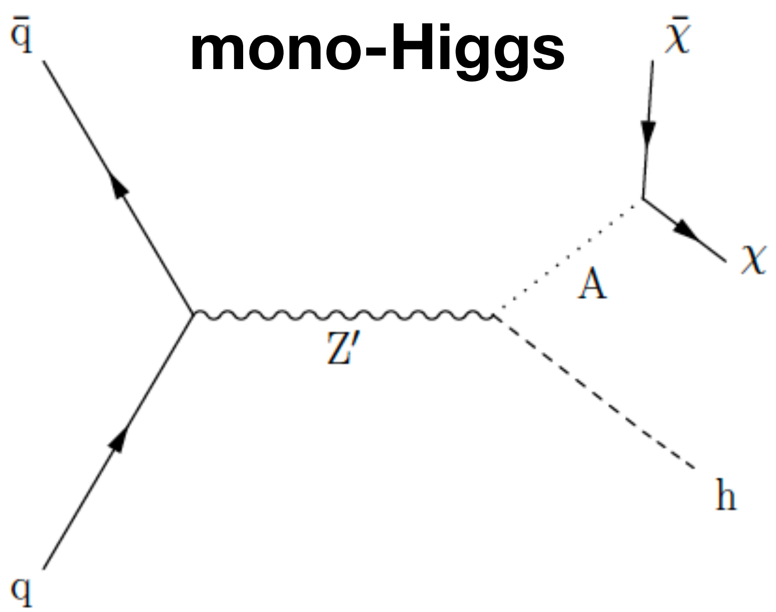


Other mono-X searches are covered in talk by D. Kumar

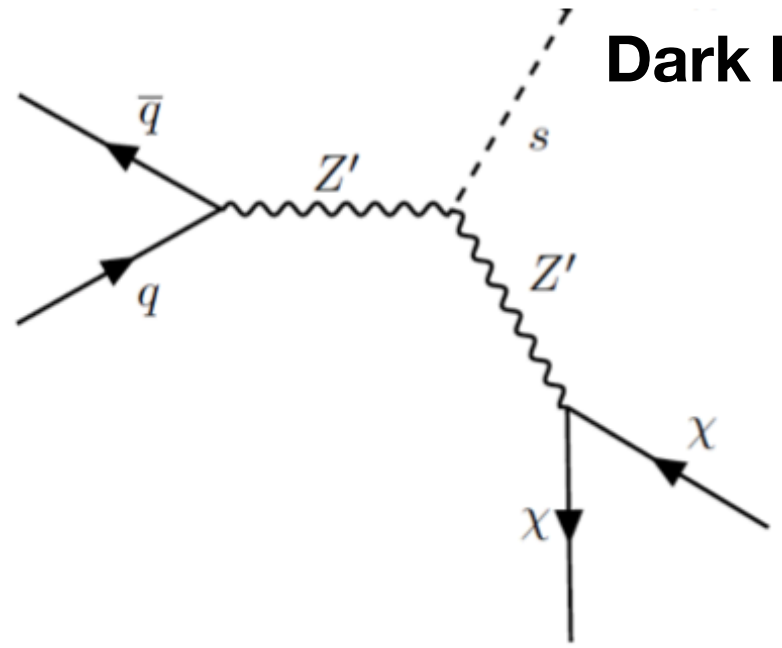
Outline

- Focus here is on the scenarios where Higgs boson is involved in probing the dark sector.

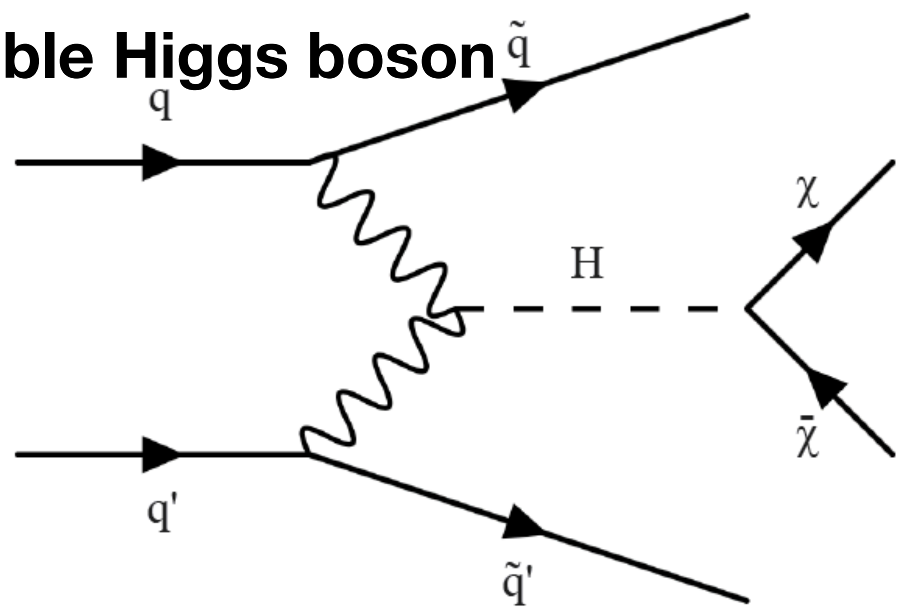
mono-Higgs



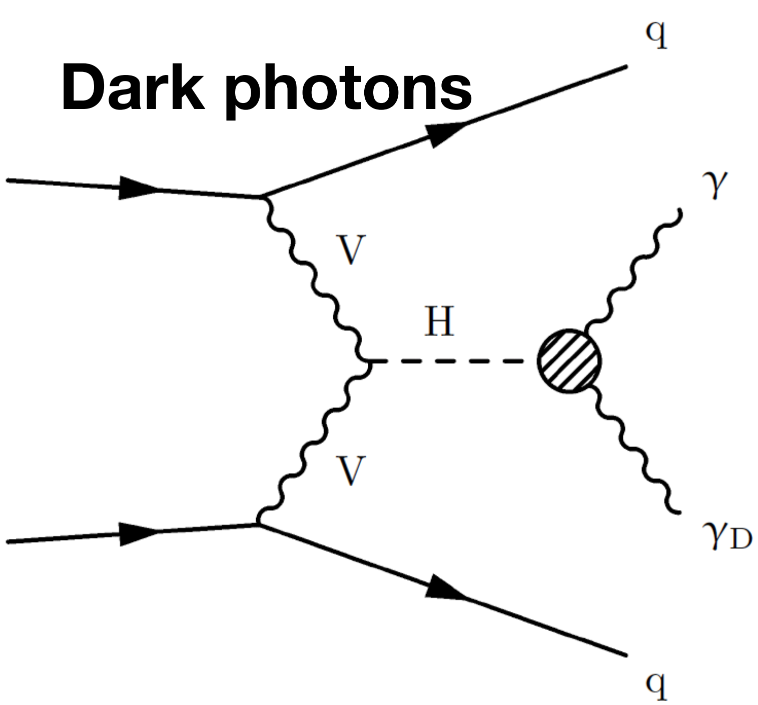
Dark Higgs boson



Invisible Higgs boson



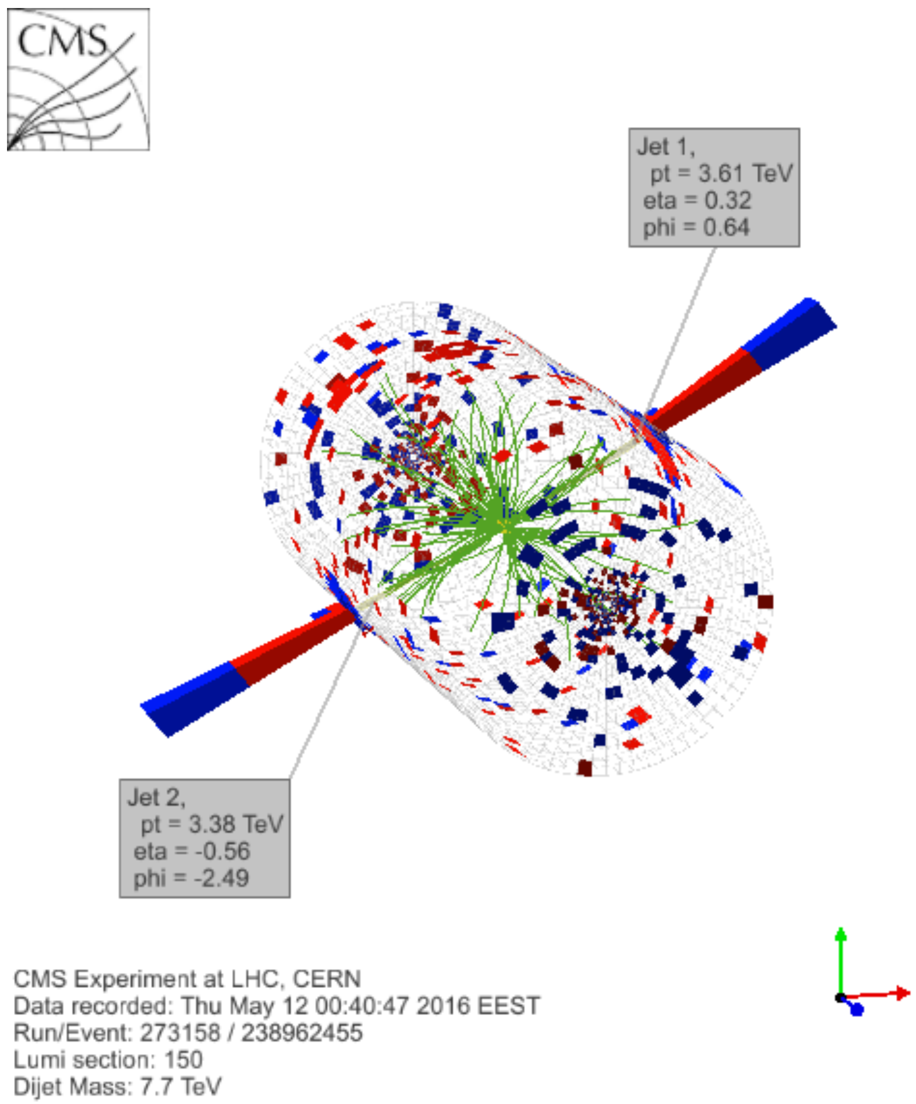
Dark photons

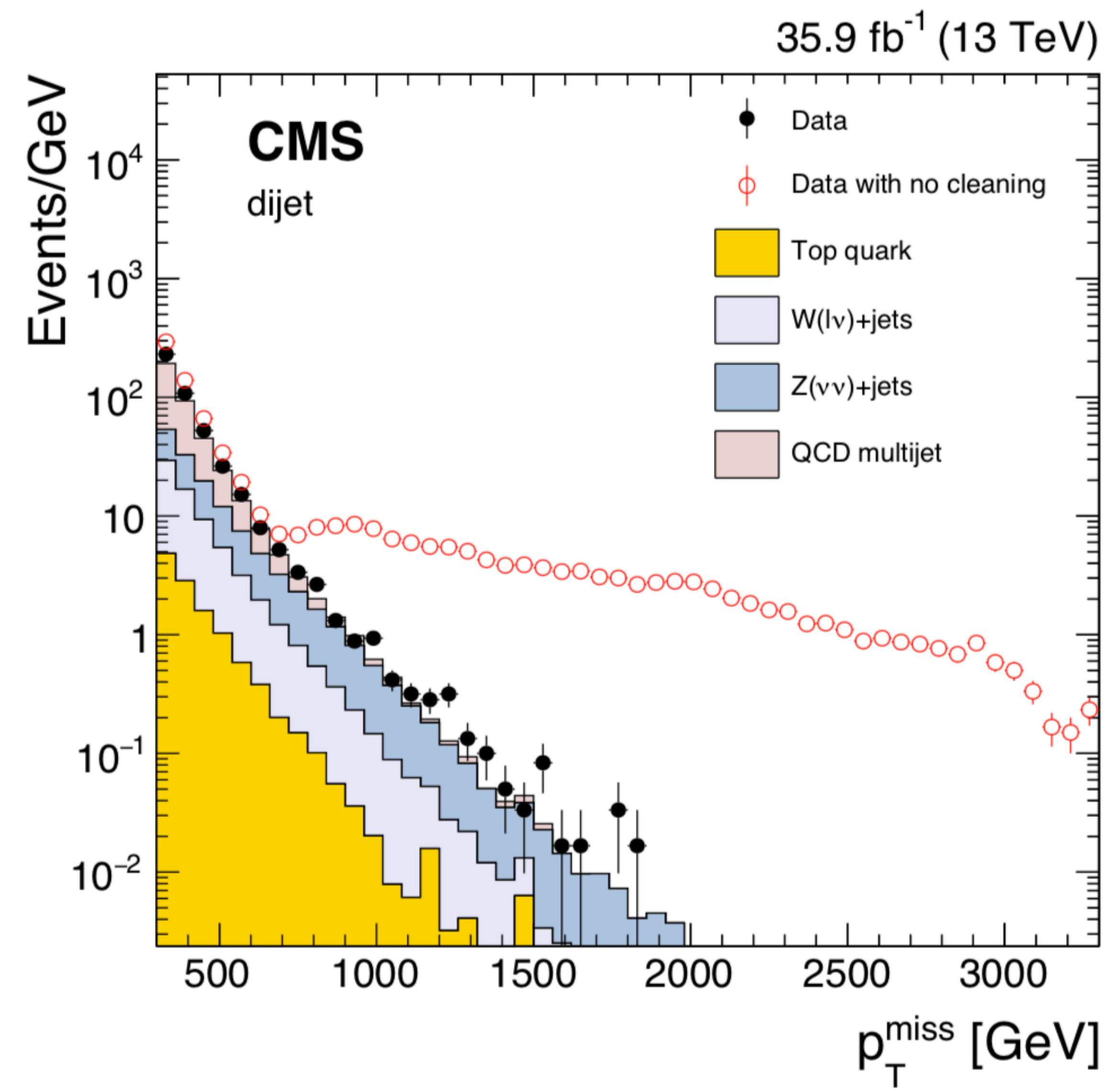


p_T^{miss} **: missing transverse momentum; negative vector sum of all the visible particles in the detector.**

Performance of p_T^{miss}

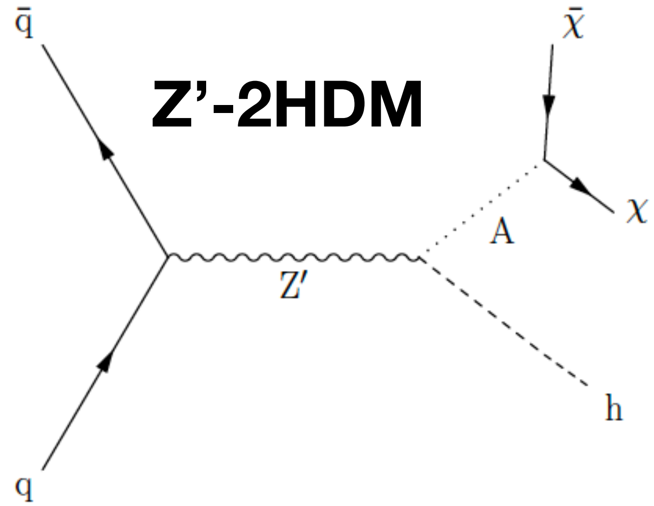
- All DM search analysis use p_T^{miss} as the main observable.
- p_T^{miss} reconstruction highly affected by instrumental effects.
- A set of noise filters are used to reject the events with mis-measured p_T^{miss} from various instrumental and reconstruction effects.
- Filters clean up the tails of p_T^{miss} significantly at a cost of <1% of signal.

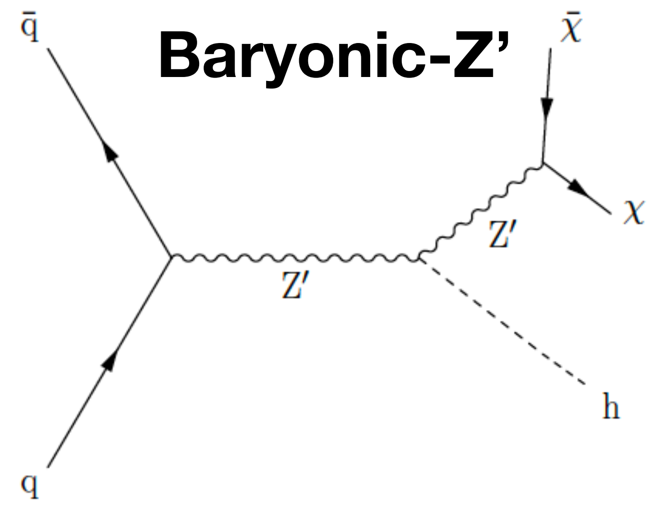


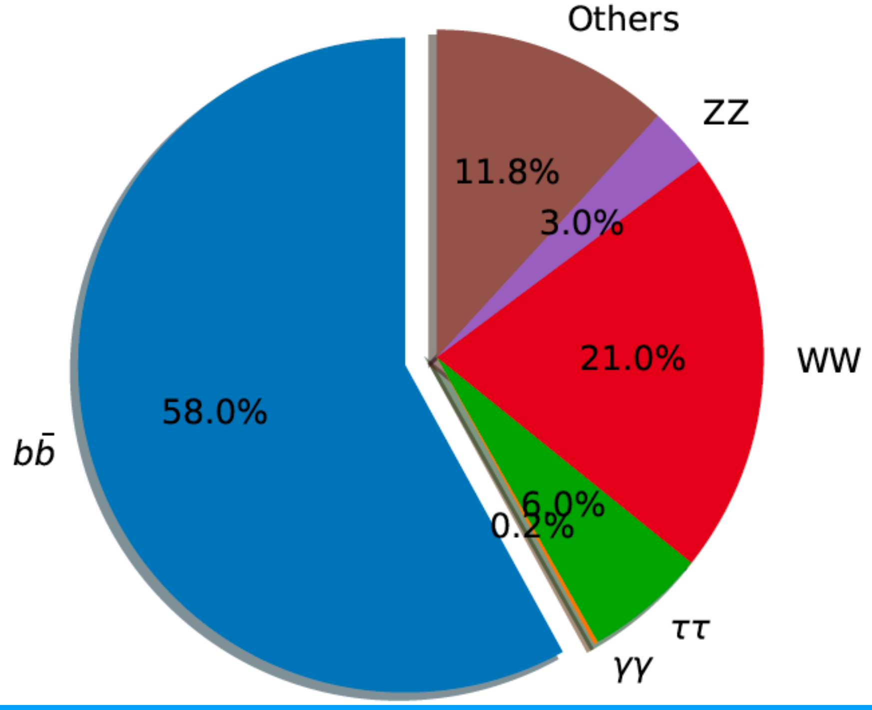


mono-Higgs

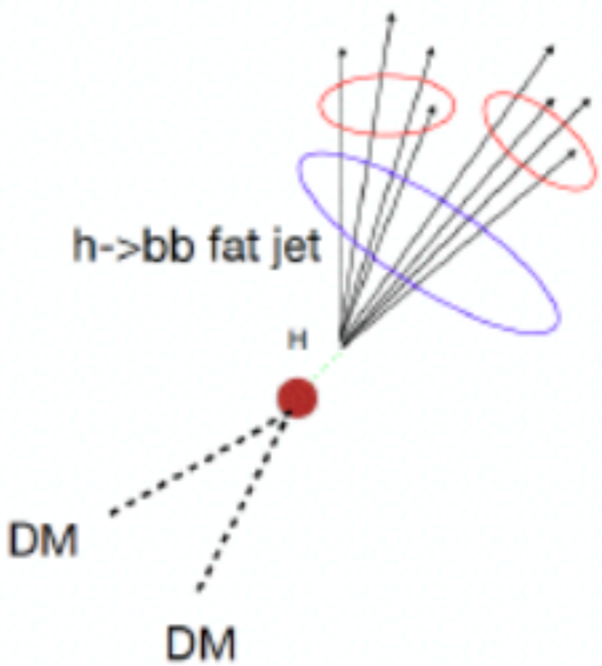
- After the discovery of the **Higgs boson (125 GeV)** it is possible to probe the DM using this new handle.
- **New massive particle** mediates the **Higgs**-**DM** interaction.
- Search performed in 5 decay channels and statistically combined.
  - $b\bar{b}, \gamma\gamma, WW, ZZ \ and \ \tau\tau$
- Results interpreted using three simplified models.
  - Z'-2HDM
  - Baryonic-Z'
  - 2HDM+a







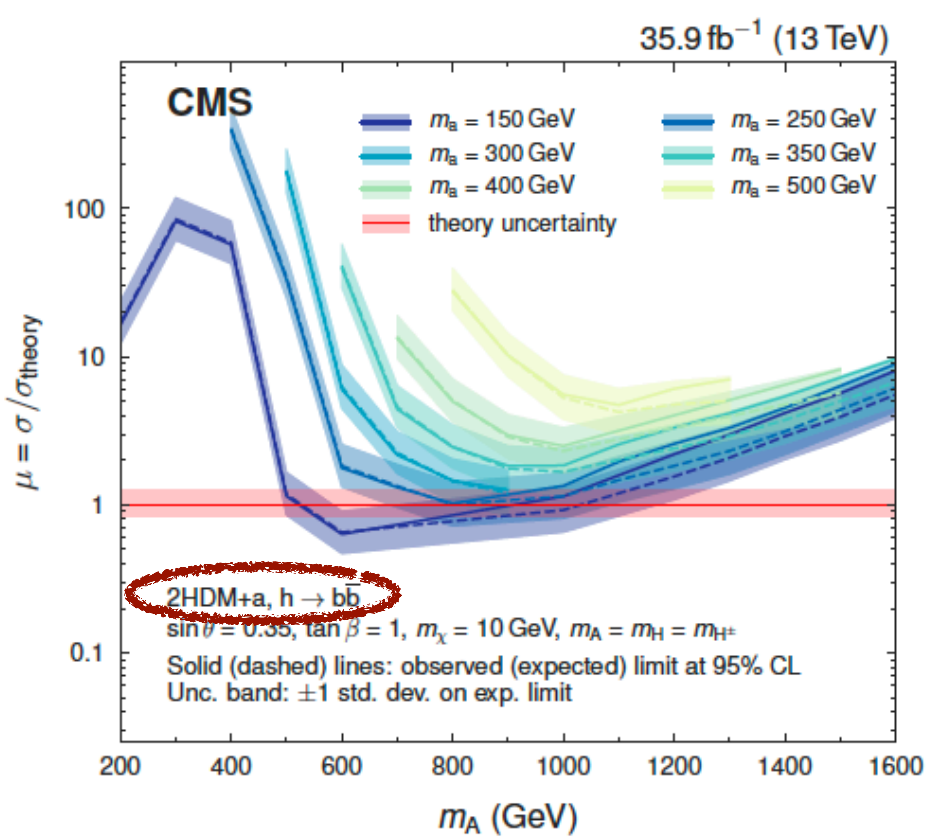
mono-Higgs

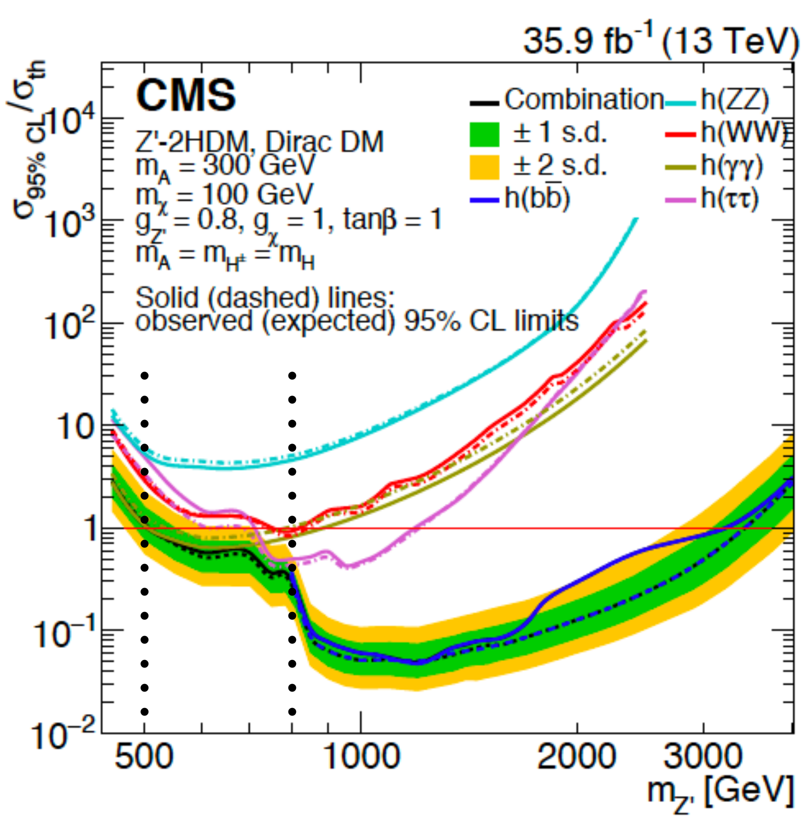


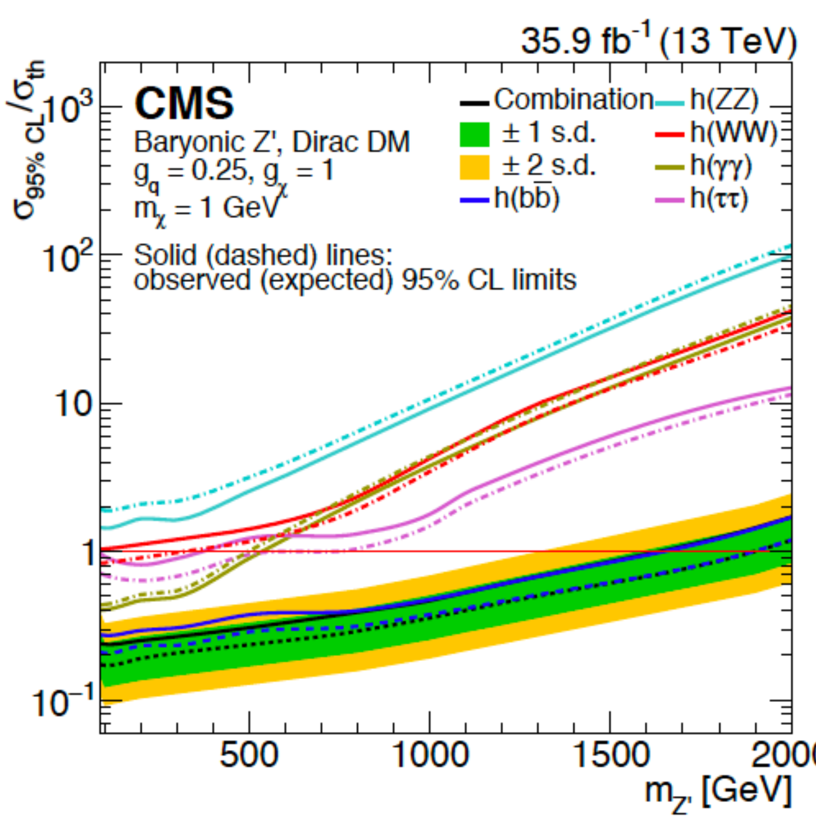
H→bb	most sensitive
2HDM+a	CA15 jets
Baryonic-Z'	CA15 jets
Z'-2HDM	AK8 jets

Decay channel	Final state or category
$h \to bb$	AK8 jet (Z'-2HDM) CA15 jet (Baryonic Z')
$h \to \gamma\gamma$	$p_T^{miss} \in 50\text{–}130\,GeV$ $p_T^{miss} > 130\,GeV$
$h \to \tau\tau$	$\tau_h\tau_h$ $\mu\tau_h$ $e\tau_h$
$h \to WW$	$e\nu\mu\nu$
$h \to ZZ$	4e 4μ $2e2\mu$

Final states orthogonal to each other

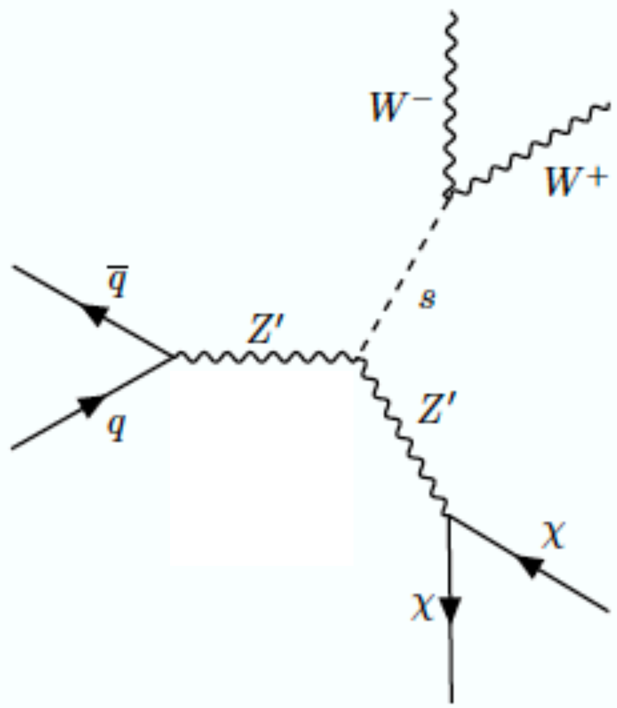


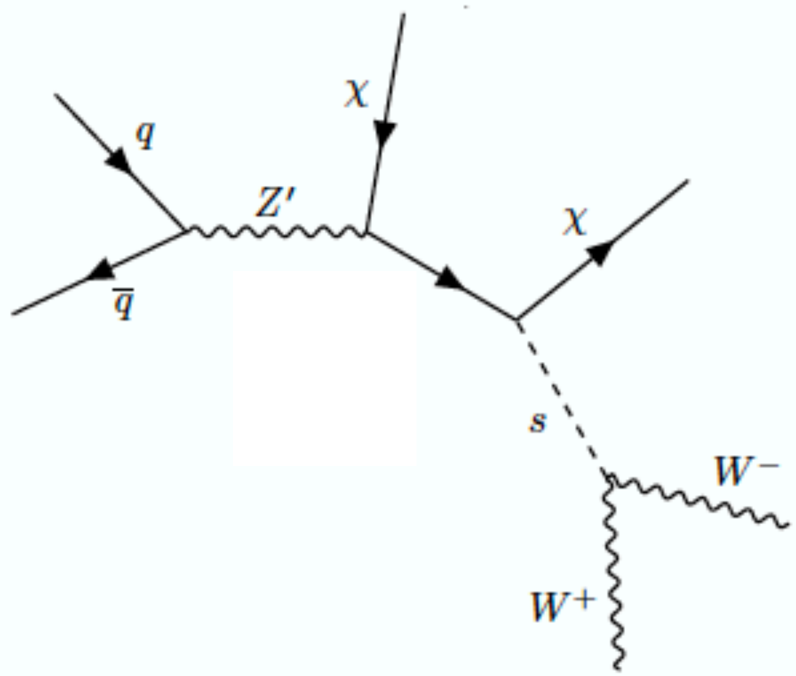


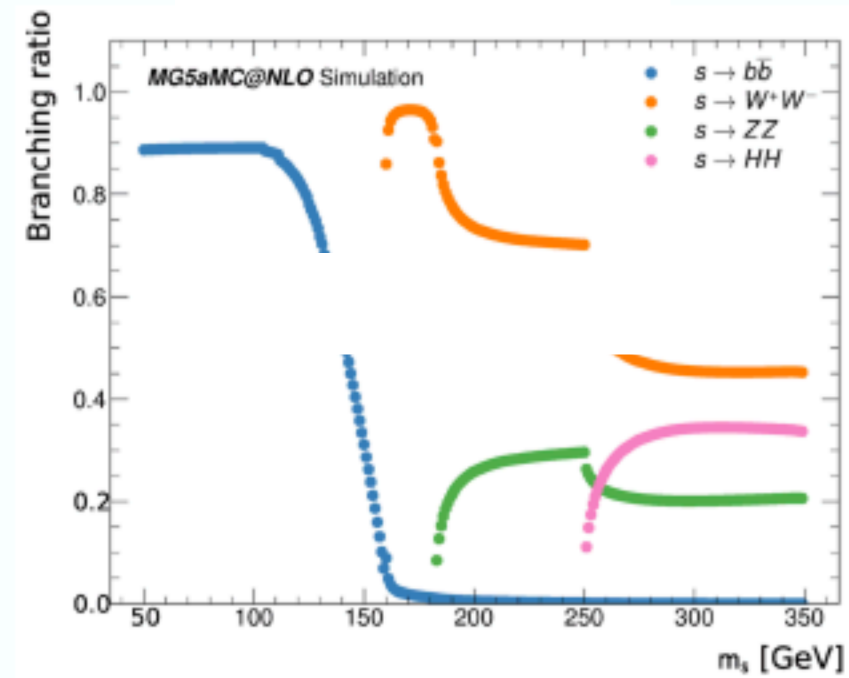


Dark Higgs boson (WW) + MET

- Dark Higgs boson model: Dark Matter particle acquire mass through their interaction with a dark Higgs boson (paper).







- WW decay mode dominates for **m_s>160 GeV.**

- s→WW search performed for the first time in fully leptonic final state.

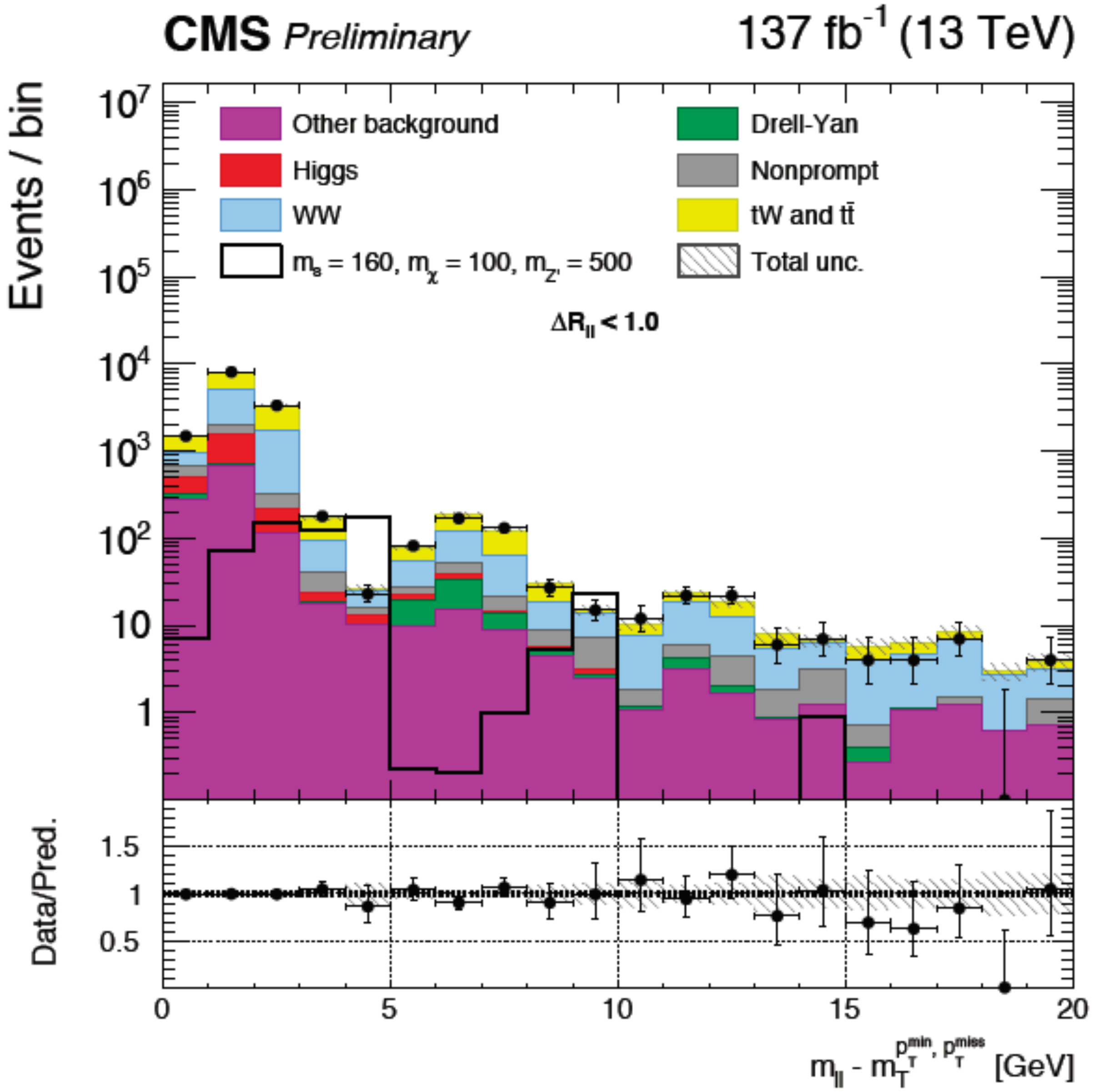
- Major backgrounds:

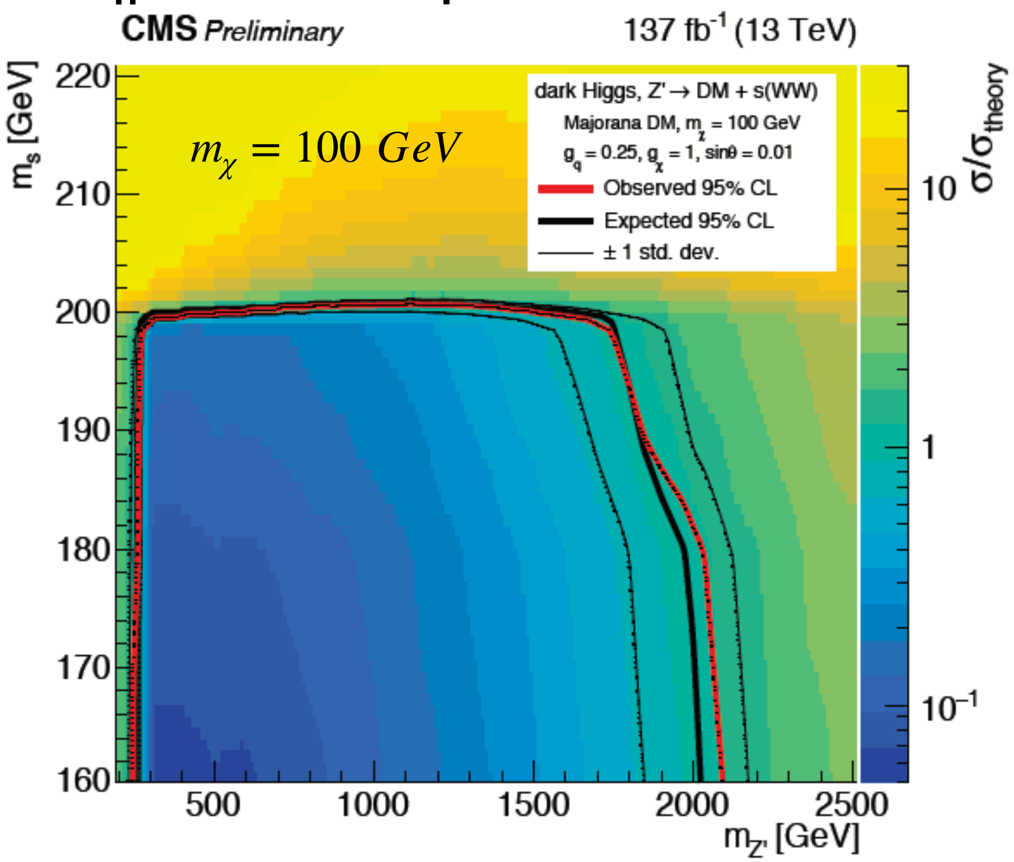
    - Non-prompt leptons: estimated using data.

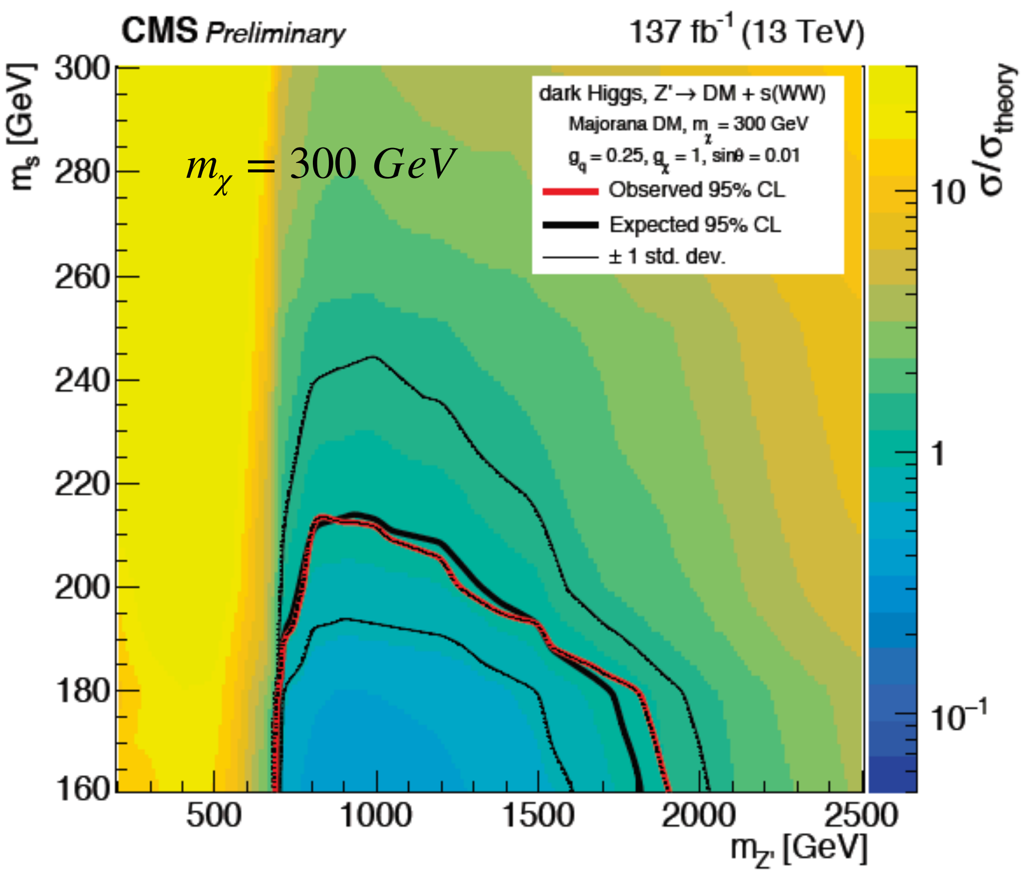
    - WW, Top and Z→ττ rate estimated from dedicated control regions,

Dark Higgs boson (WW) + MET

3-dimensional fit performed using ΔR, m_{ll} and m_T

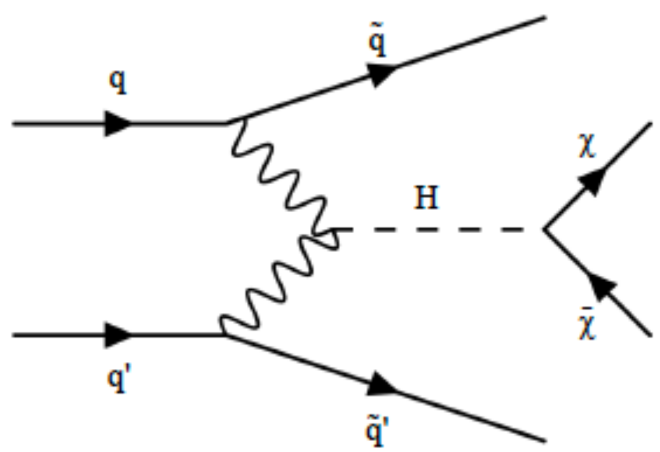






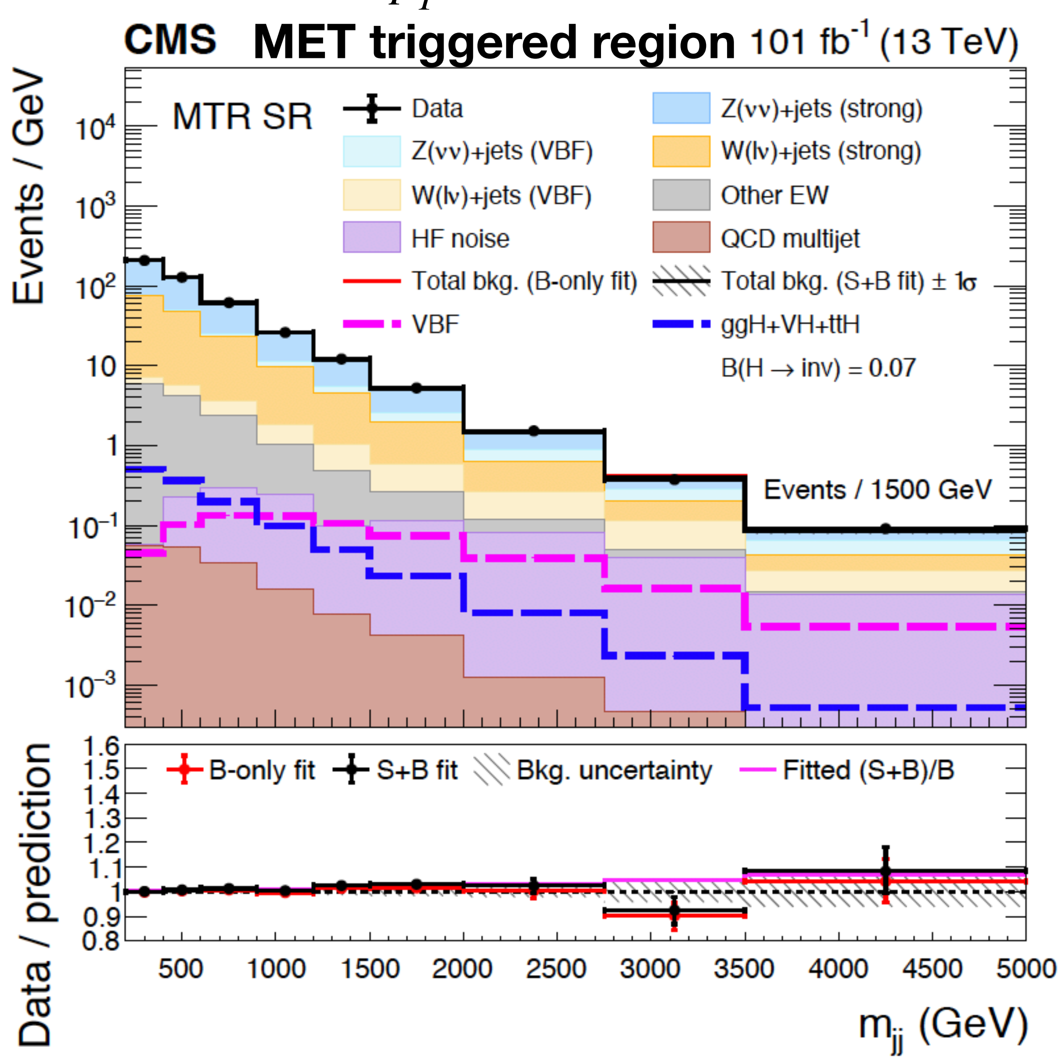
— No significant excess of events observed.
— most stringent limit for mχ=100 GeV in dark Higgs framework.

Higgs → invisible

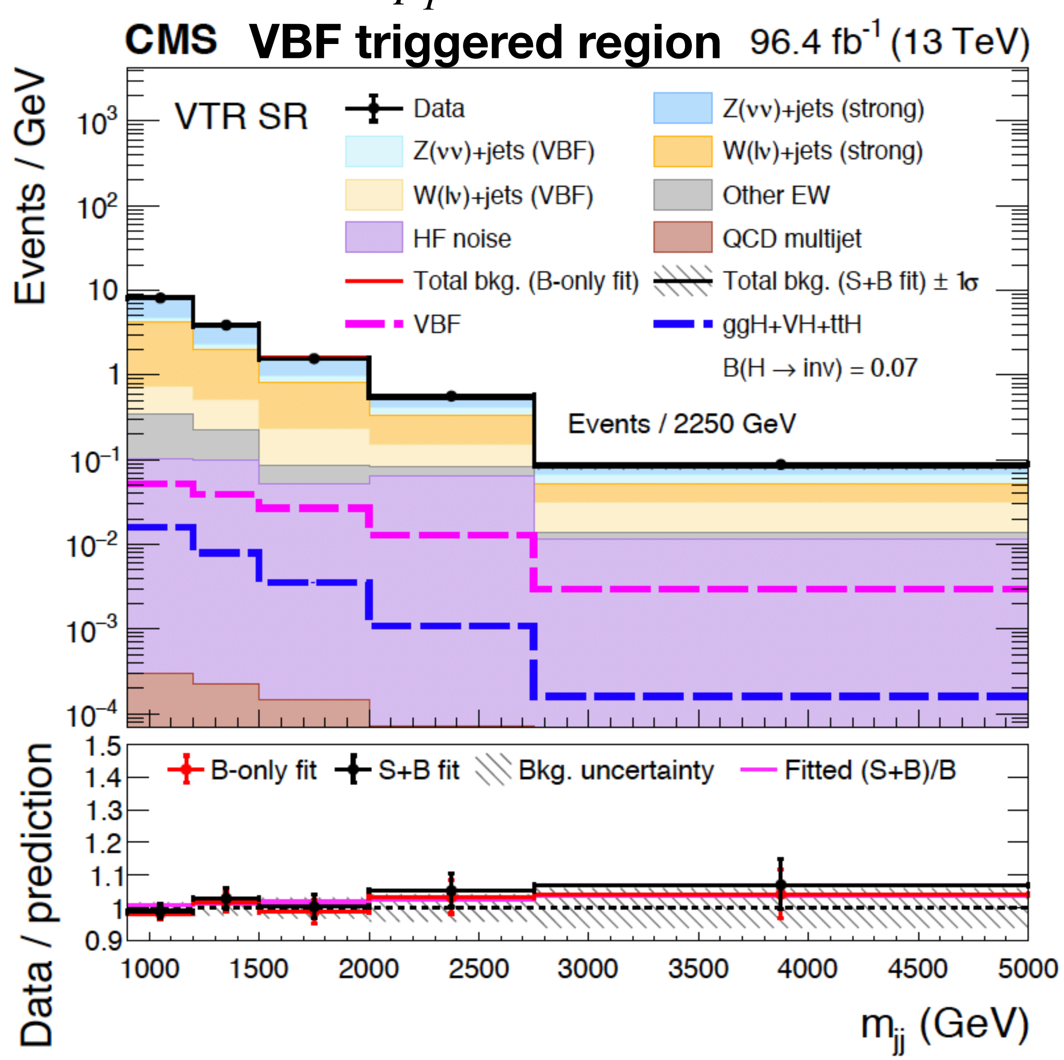


- New trigger strategy: using jet properties from VBF production in addition to p_T^{miss} trigger.
- Using V+jets and $\gamma + jets$ CRs to constrain major backgrounds (Z(νν)+jet and W(lν)+jets).

p_T^{miss}>250 GeV

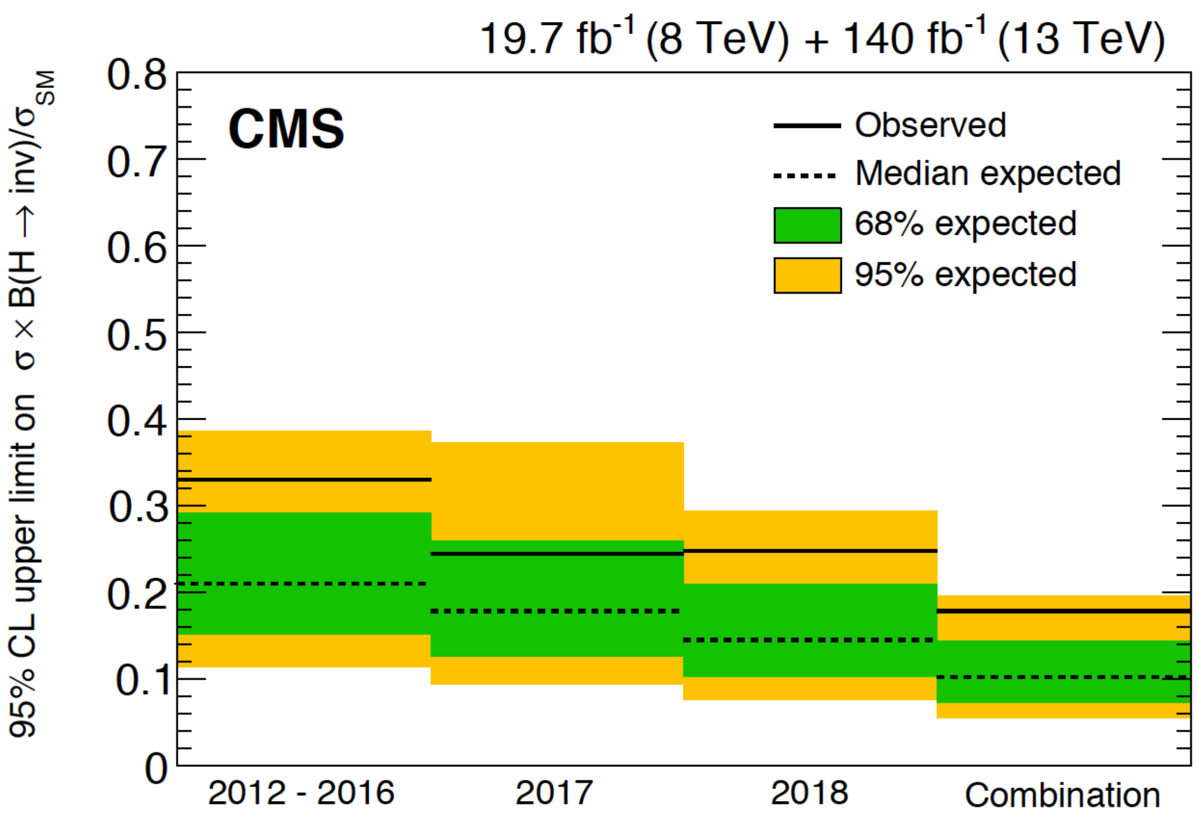


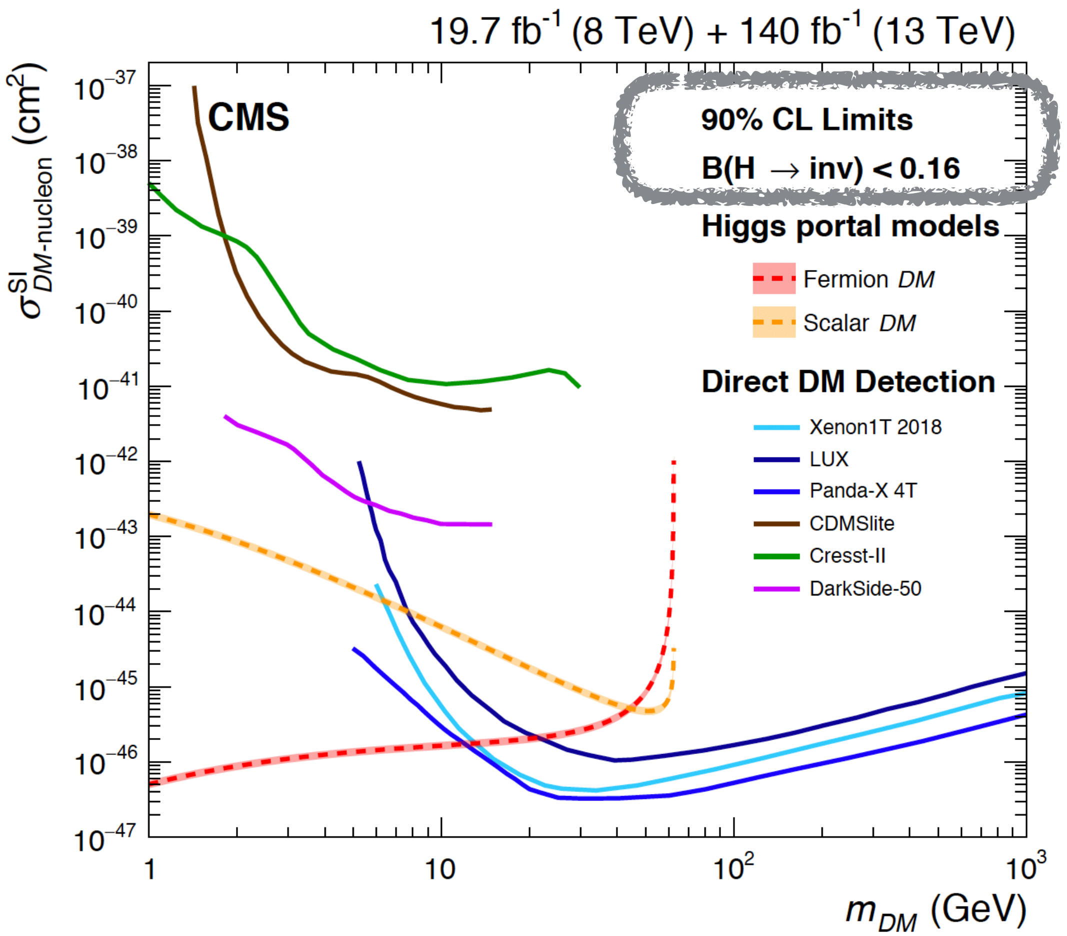
160 <p_T^{miss}<250 GeV



Higgs → invisible

- Combination of Run 1 and Run2
  - **95% CL** upper limit on the in **BR (H→invisible) < 0.18 (0.10)**



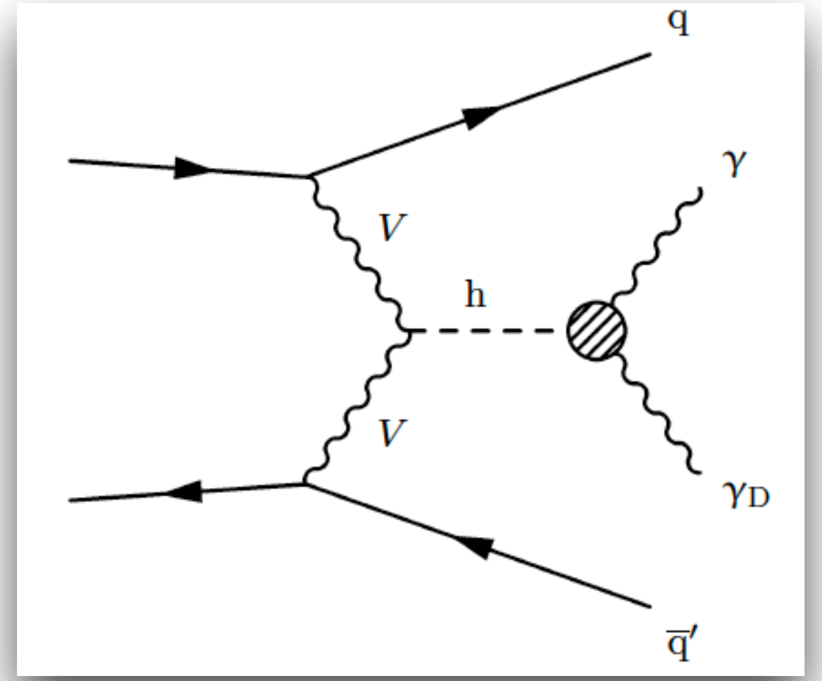


Constraints are compatible with SM H → invisible branching ratio.

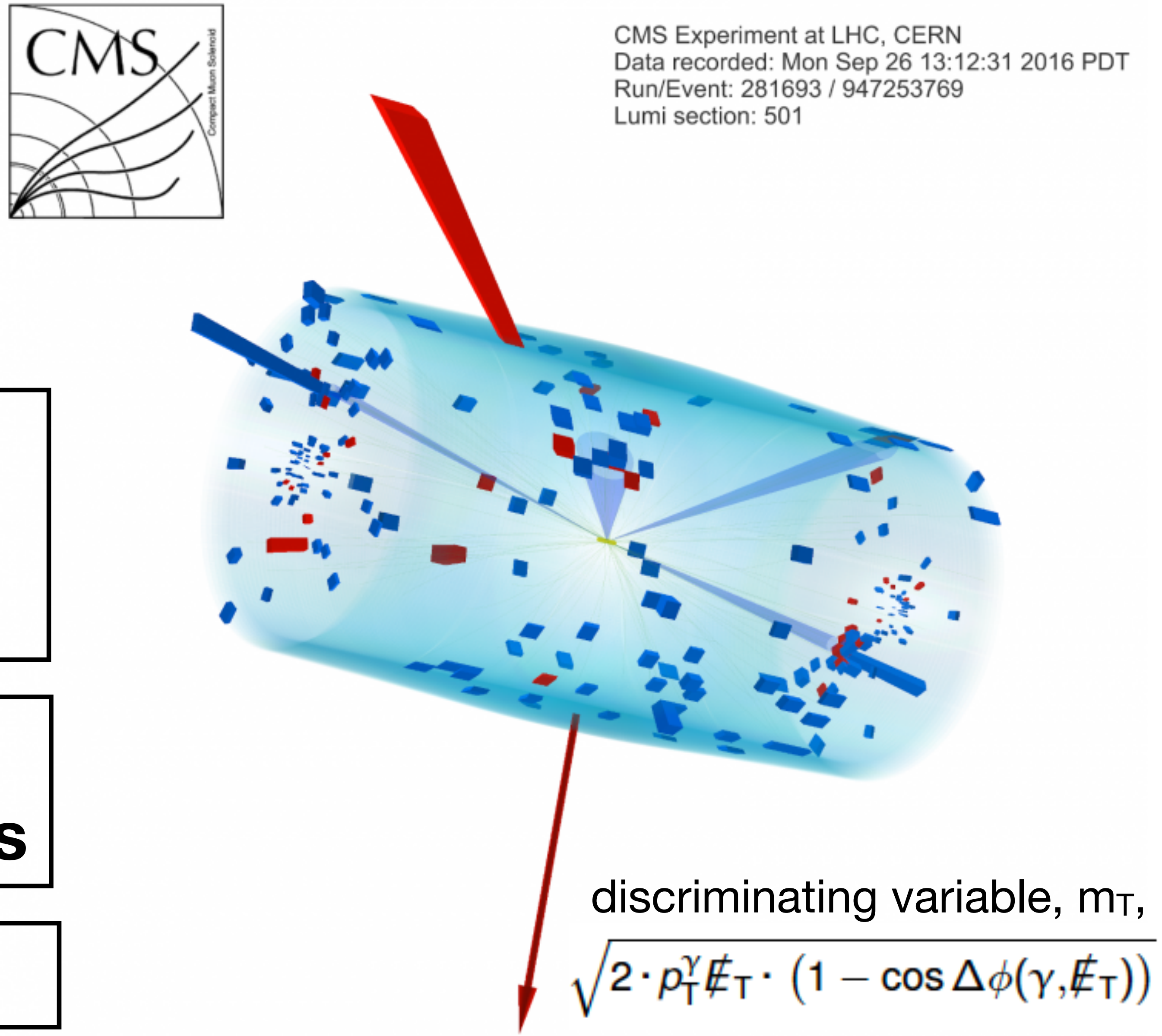
Constraints on spin independent DM-neucleon cross-section

Dark photon in VBF Higgs

Search for dark photon in VBF Higgs boson events.



Year	Triggering object
2016	VBF photon
2017/2018	MET Photon



h(125 GeV) is of particular interest but higher masses are also considered.

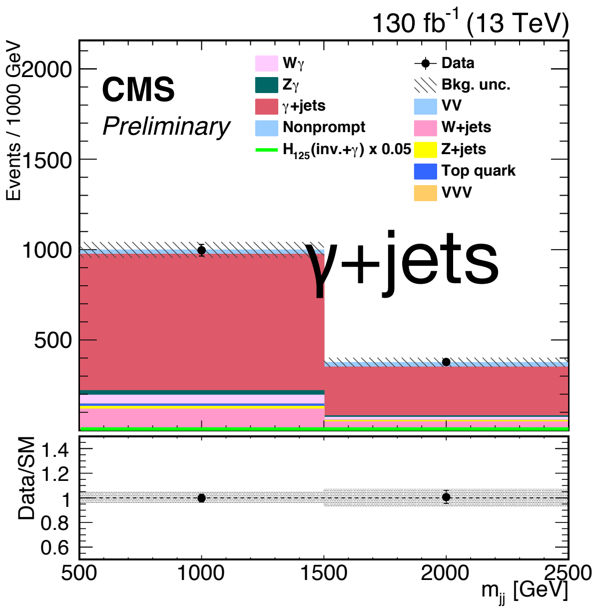
Dedicated CRs for major background: **W+jets, Wγ, Zγ, γ+jets**

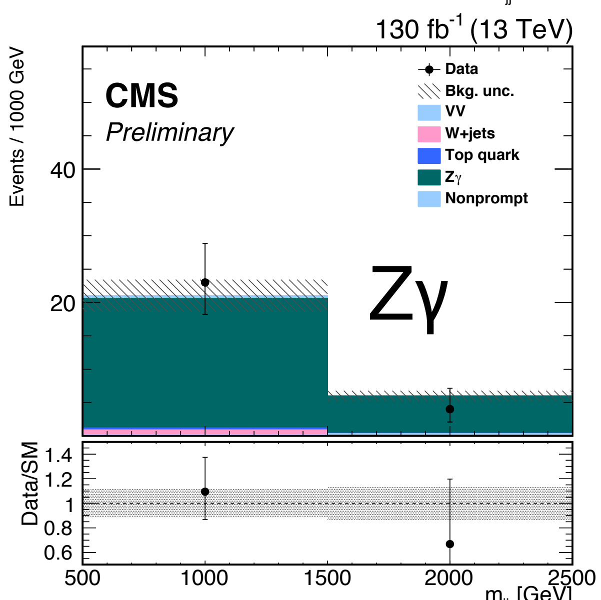
Simultaneous fit of SR and CRs

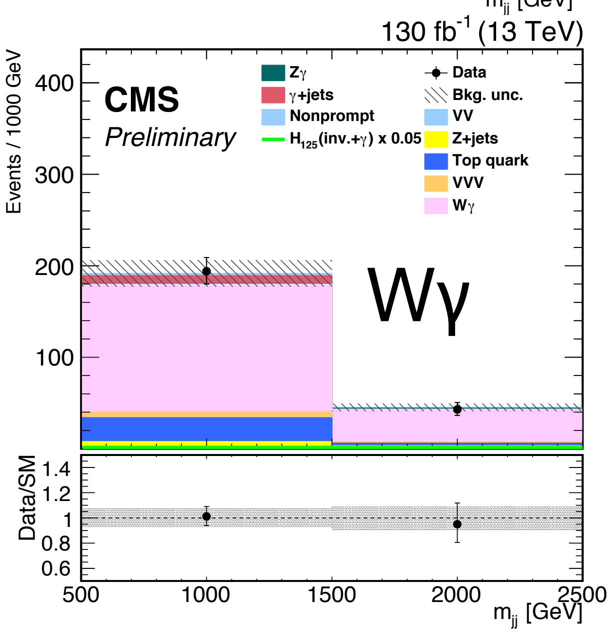
discriminating variable, m_T,

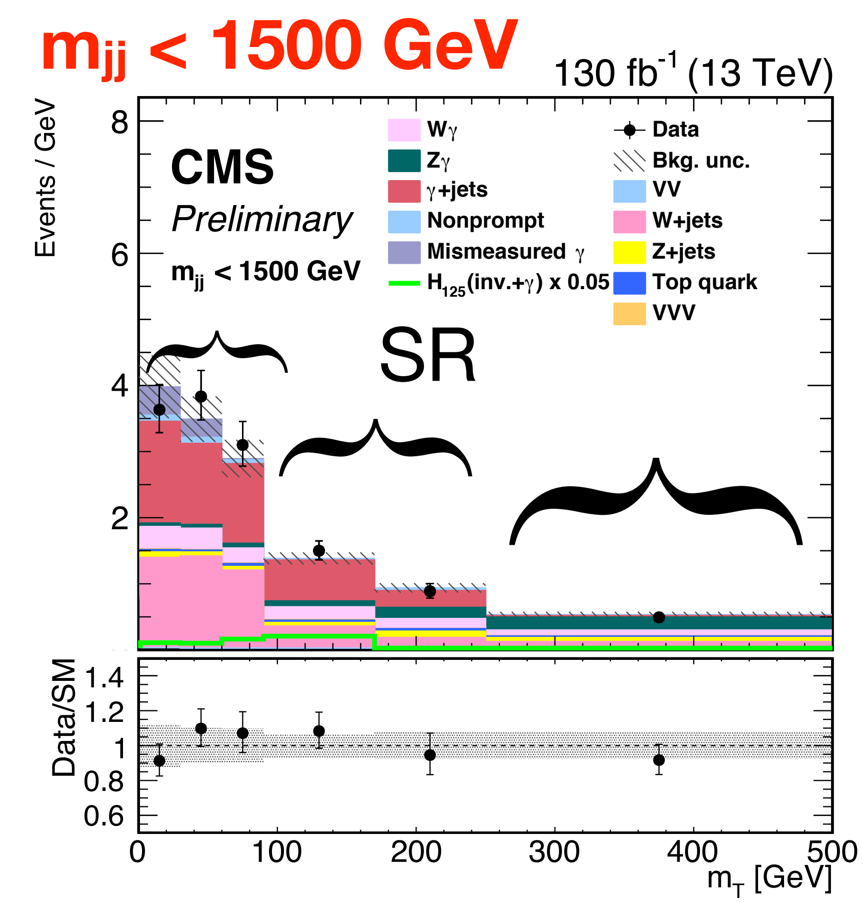
$$\sqrt{2 \cdot p_T^{\gamma} \not{E}_T \cdot (1 - \cos\Delta\phi(\gamma, \not{E}_T))}$$

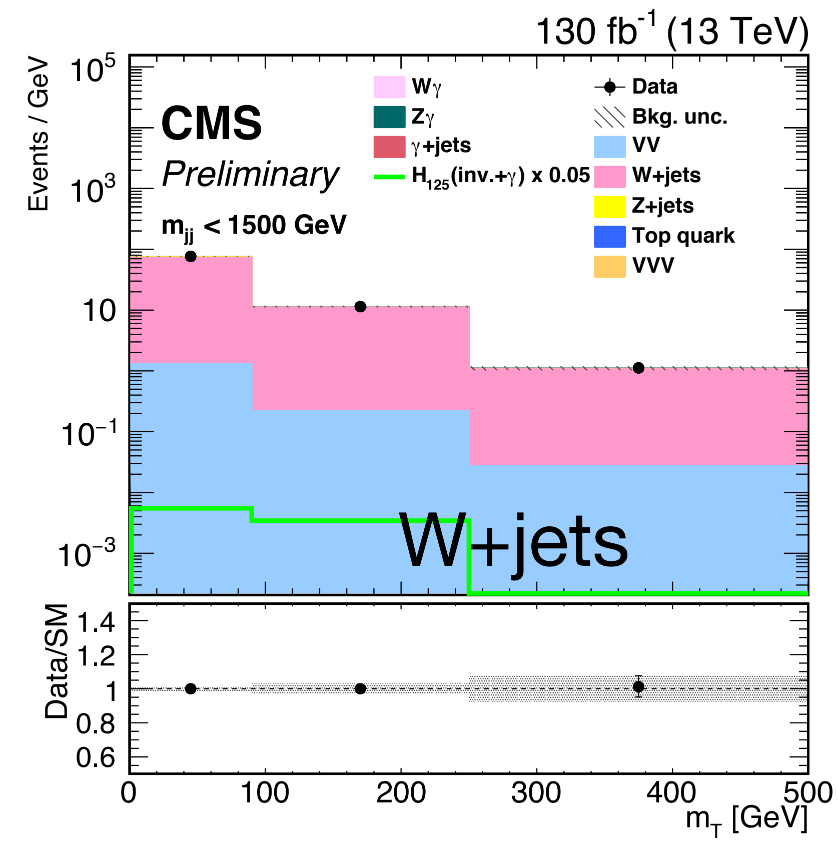
Dark photon in VBF Higgs

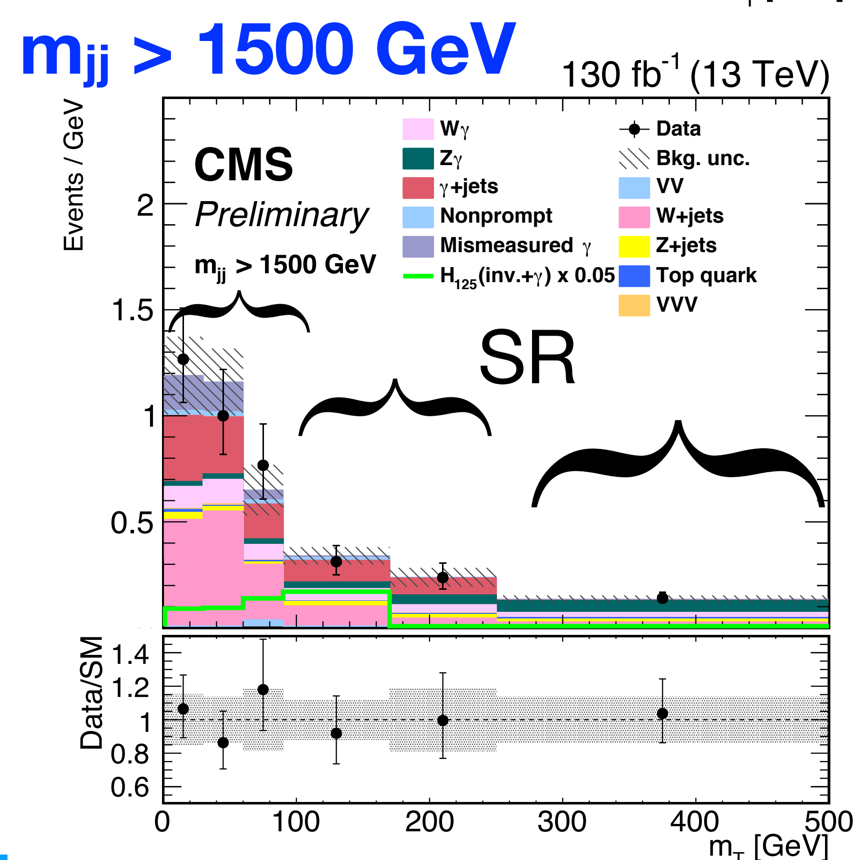


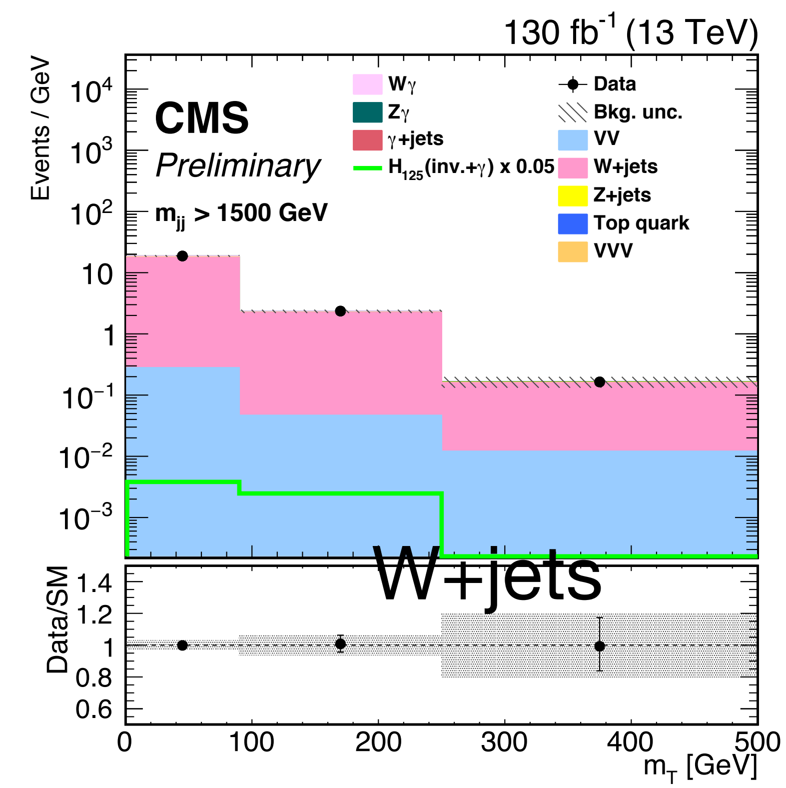




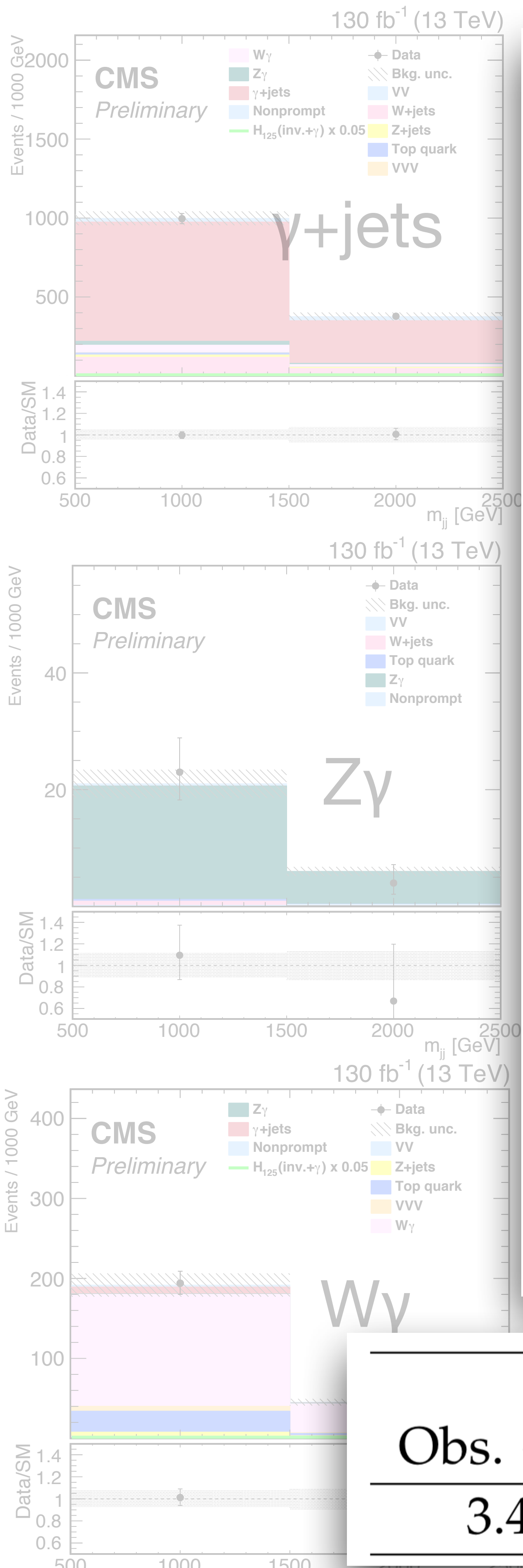


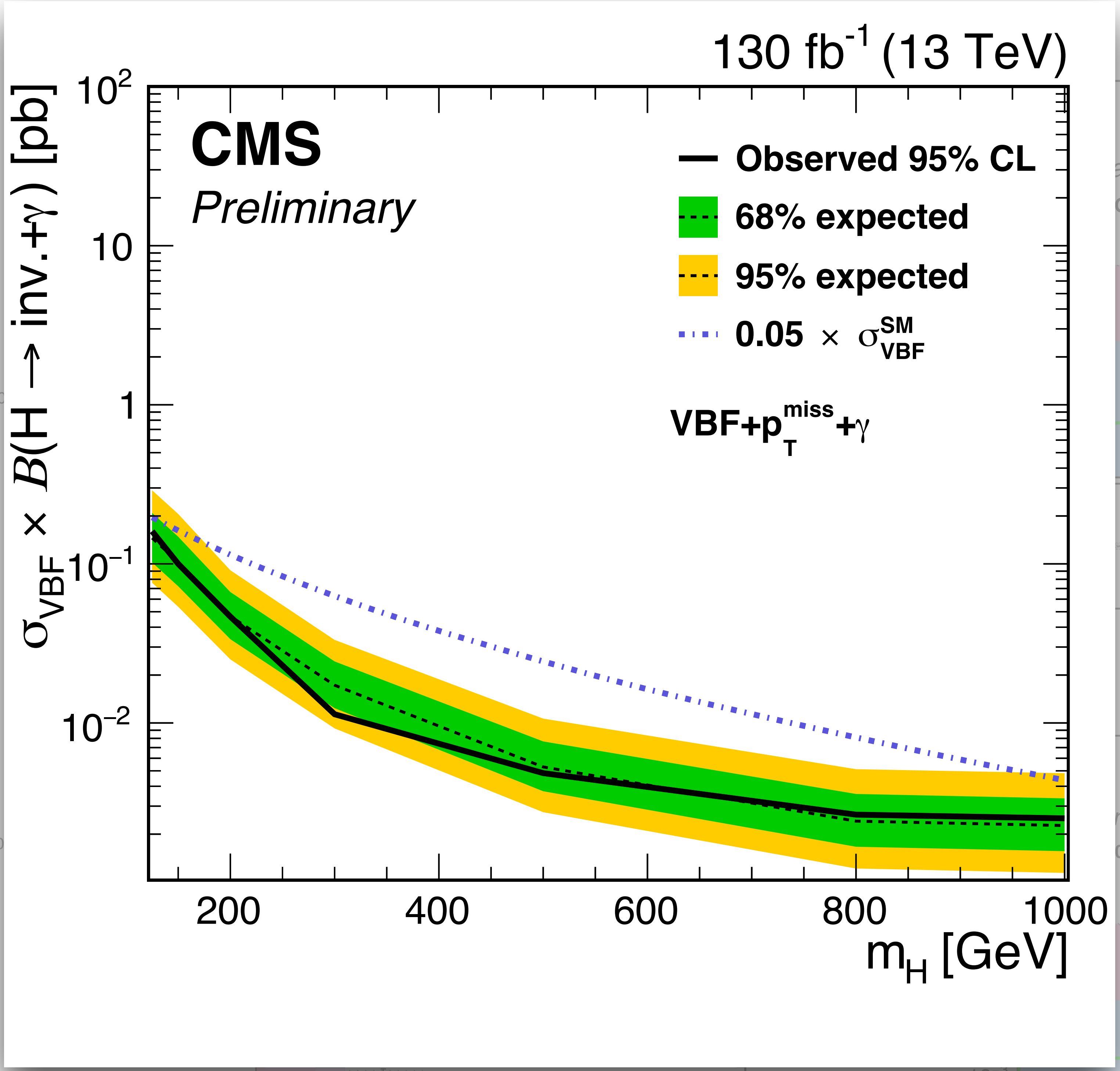


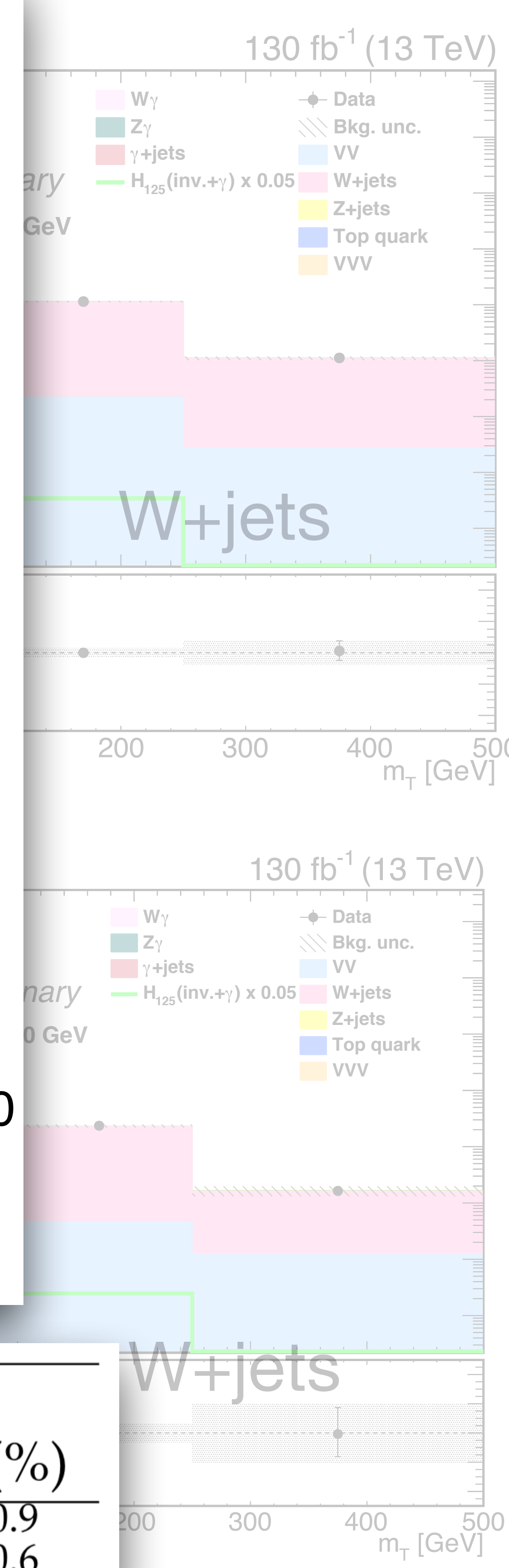




Dark photon in VBF Higgs







VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.4	$2.7^{+1.2}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+0.9}_{-0.6}$

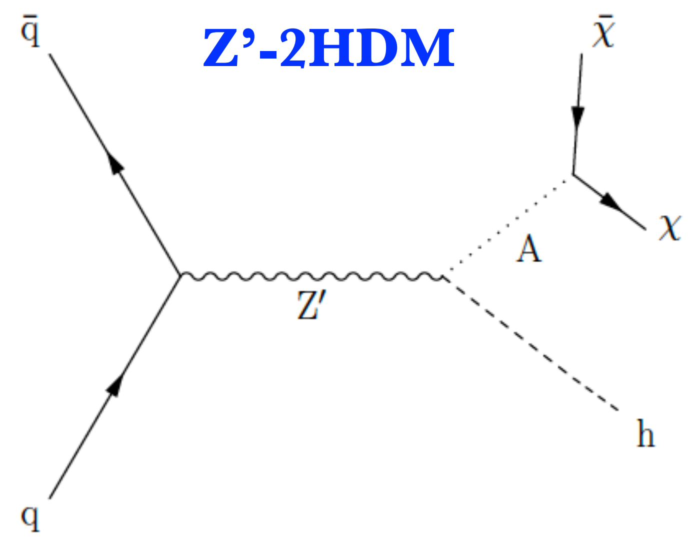
Summary

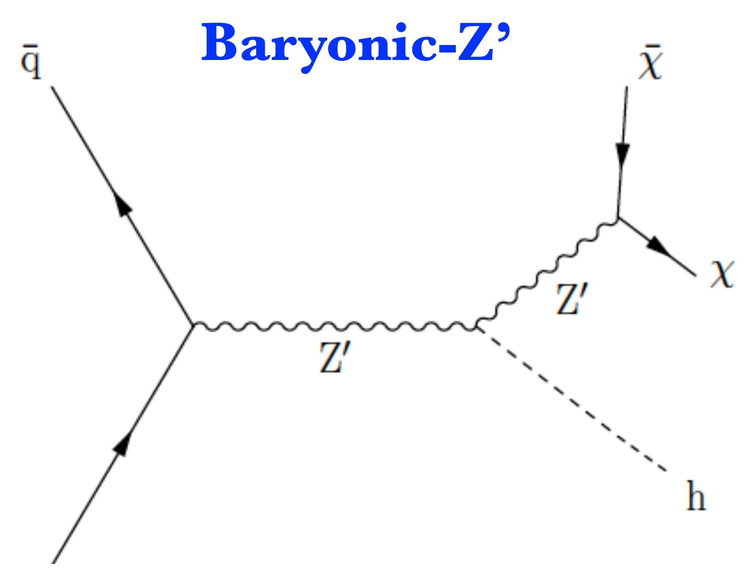
- **Showcasing the selected dark matter searches using Higgs boson.**
  - Higgs boson to Invisible and MET based signatures are key to DM search at CMS.
  - A big phase space has been excluded using Run 2 dataset for the Dark Higgs model.
- Results for Dark Higgs WW (semi-leptonic) and mono-Higgs bb using the Run-2 dataset are expected to be public soon
- For more details

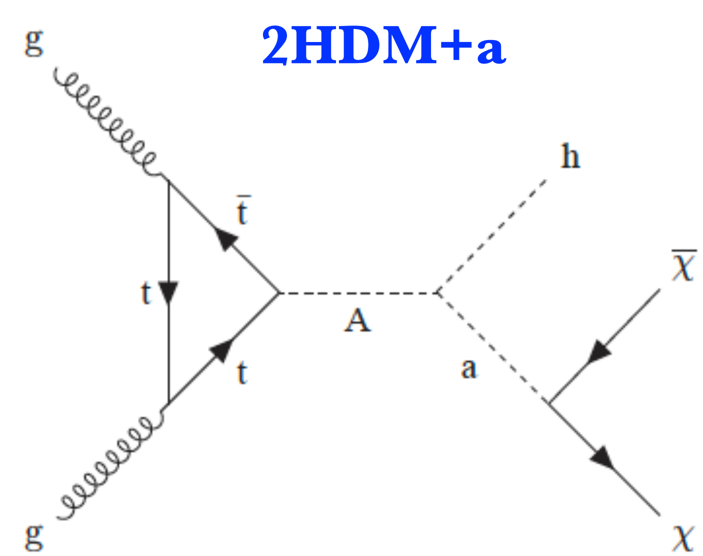
Backup

mono-Higgs: Interpretations

- **There are three simplified models available which predicts the mono-H signal.**
  - **Z'-2HDM:**
    - ➡ Heavy vector mediator is produced resonantly and decays into a SM-like Higgs boson and an intermediate pseudoscalar particle A.
  - **Baryonic-Z':**
    - ➡ A "baryonic-Higgs" boson mixes with the SM Higgs boson. A vector mediator Z' is produced in s-channel and decays into a pair of DM particles after radiating a Higgs boson.
  - **2HDM+a:**
    - ➡ Two-Higgs-doublet model extended by an additional pseudoscaler ***a*** which mixes with the scalar and pseudoscalar partner of the new Higgs boson and decays into a pair of DM particles.

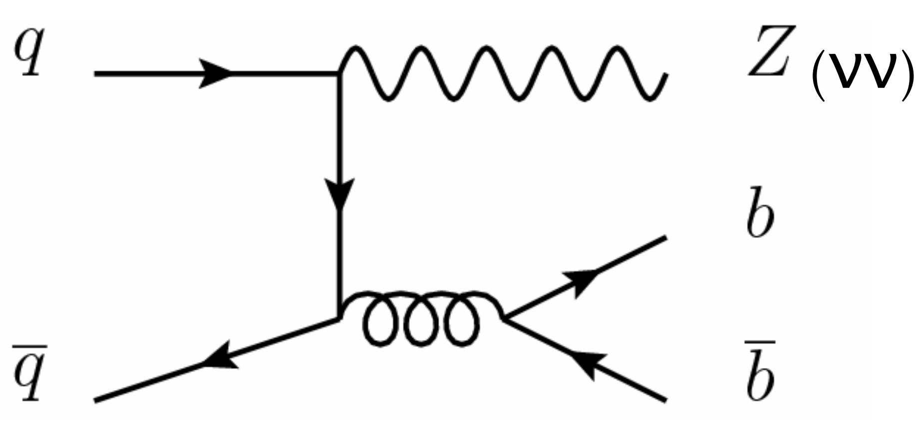


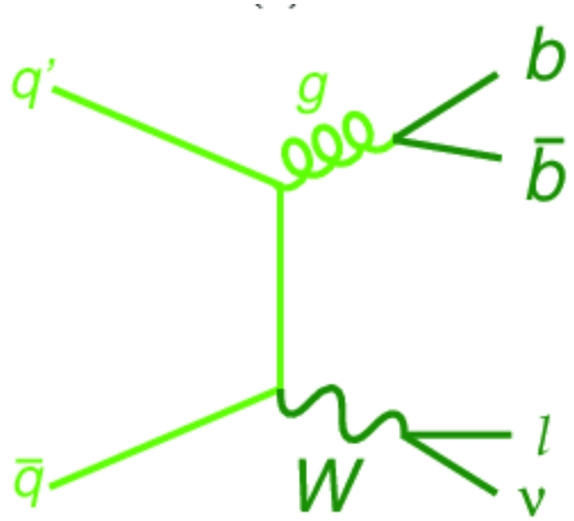


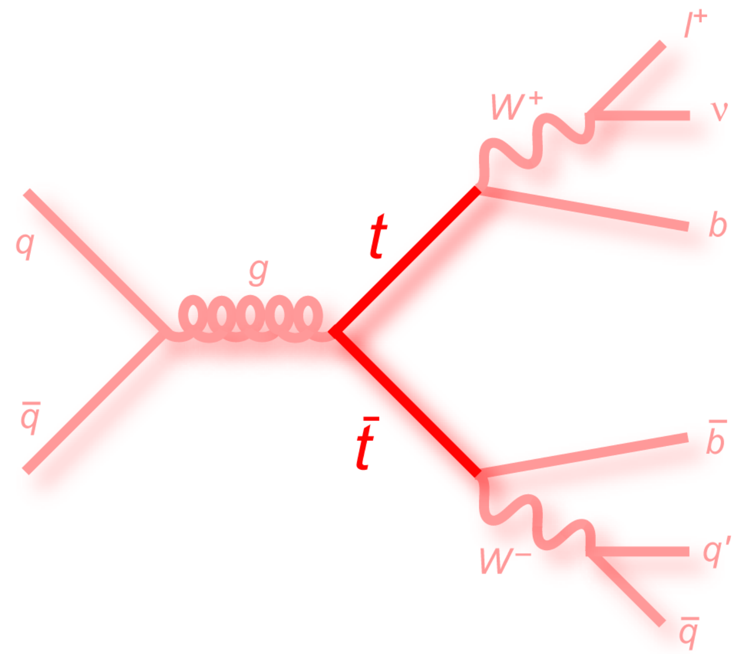


Major backgrounds

- There are three SM processes which can mimic the signal like detector signature.





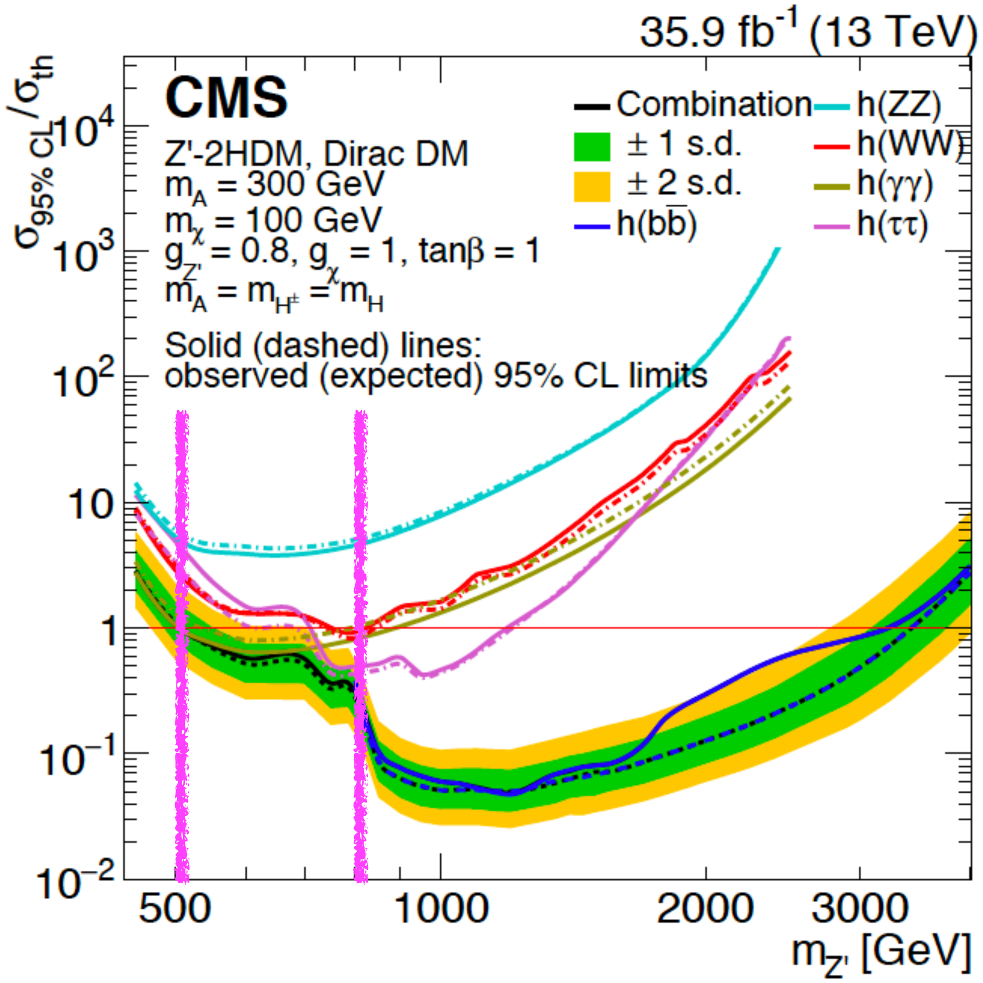


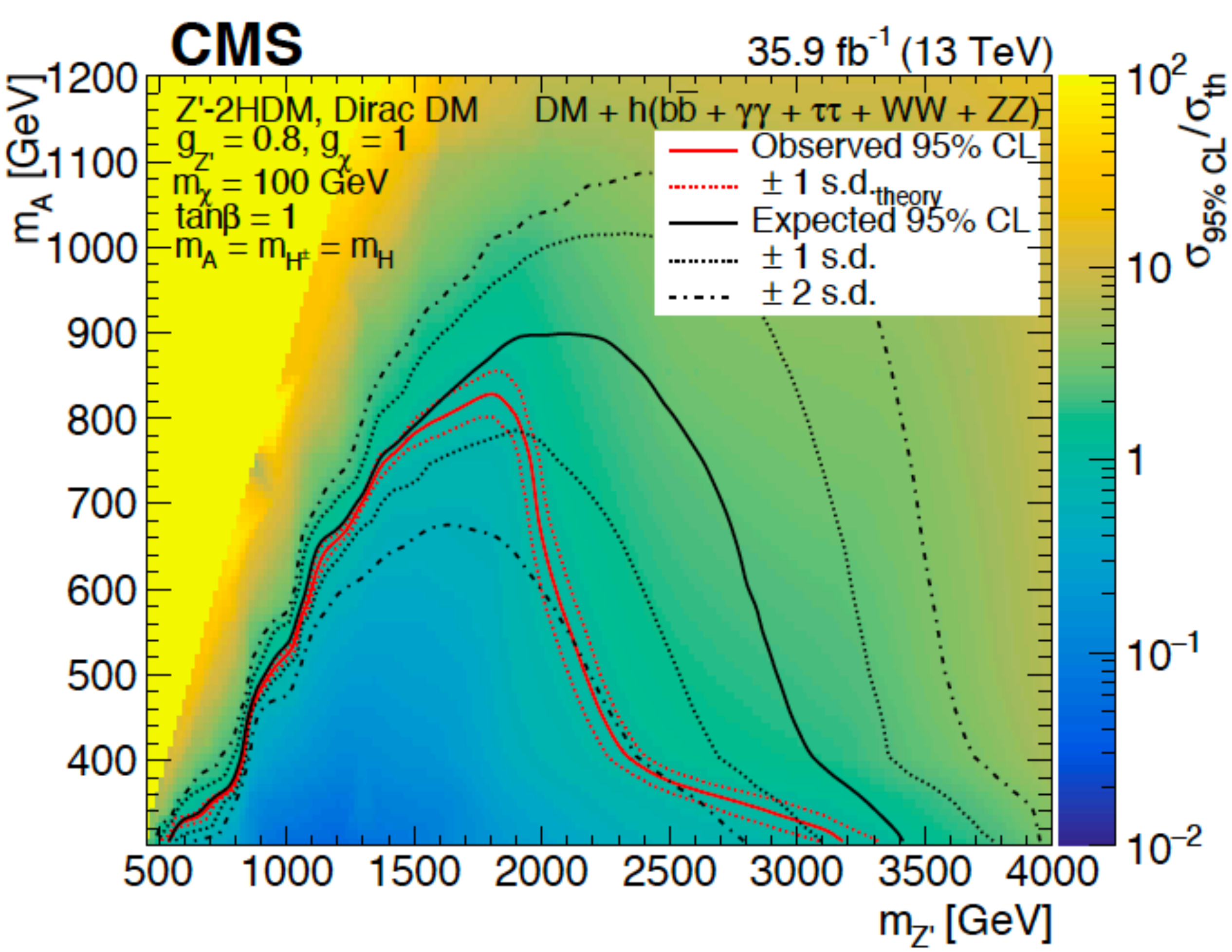
mono-Higgs Combination

Third mono-H publication
10.1007/JHEP03(2020)025

- The search is extended by a statistical combination of 5 analyses.
  - bb, γγ,ττ,WW and ZZ
- The analyses the required to be orthogonal to each other to avoid double counting.

Object	$h \to bb$	$h \to \gamma\gamma$	$h \to \tau\tau$	$h \to WW$	$h \to ZZ$
Electron	=0	—	=0	=0	=0
Muon	=0	—	=0	=0	=0
τ lepton	=0	—	—	=0	—
Photon	=0	—	—	—	—
AK4 Jet	≤1	≤2	—	—	—
b tagged AK4 jet	=0	—	=0	=0	≤1





Source	$h \to bb$		$h \to \gamma\gamma$	$h \to \tau\tau$	$h \to WW$	$h \to ZZ$
	Z′-2HDM	Baryonic Z′				
AK4 jet b tagging	} 3–11%	Uncorr. (3–4%)	—	4%	Shape (1%)	1%
AK4 jet b mistag		Shape (5–7%)	—	2–5%	Shape (1%)	—
e ident. efficiency	4%	2%	—	2%	Shape (2%)	2.5–9.0%
μ ident. efficiency	4%	2%	—	2%	Shape (2%)	2.5–9.0%
τ_h ident. efficiency	3%	3%	—	4.5%	Shape (1%)	—
e energy scale	1%	—	—	—	Shape (1%)	3%
μ energy scale	1%	—	—	—	Shape (1%)	0.4%
JES	—	Uncorr. (4%)	—	Shape (<10%)	Shape (3%)	2–3%
Int. luminosity	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
Signal (PDF, scales)	0.3–9.0%	0.3–9.0%	0.3–9.0%	0.3–9.0%	0.3–9.0%	0.3–9.0%

Decay channel	Final state or category	Reference
$h \to bb$	AK8 jet (Z'-2HDM)	[30]
	CA15 jet (Baryonic Z')	[31]
$h \to \gamma\gamma$	$p_T^{miss} \in 50$–$130\,GeV$	[32]
	$p_T^{miss} > 130\,GeV$	[32]
$h \to \tau\tau$	$\tau_h\tau_h$	[32]
	$\mu\tau_h$	[32]
	$e\tau_h$	[32]
$h \to WW$	$e\nu\mu\nu$	—
$h \to ZZ$	4e	—
	4μ	—
	$2e2\mu$	—

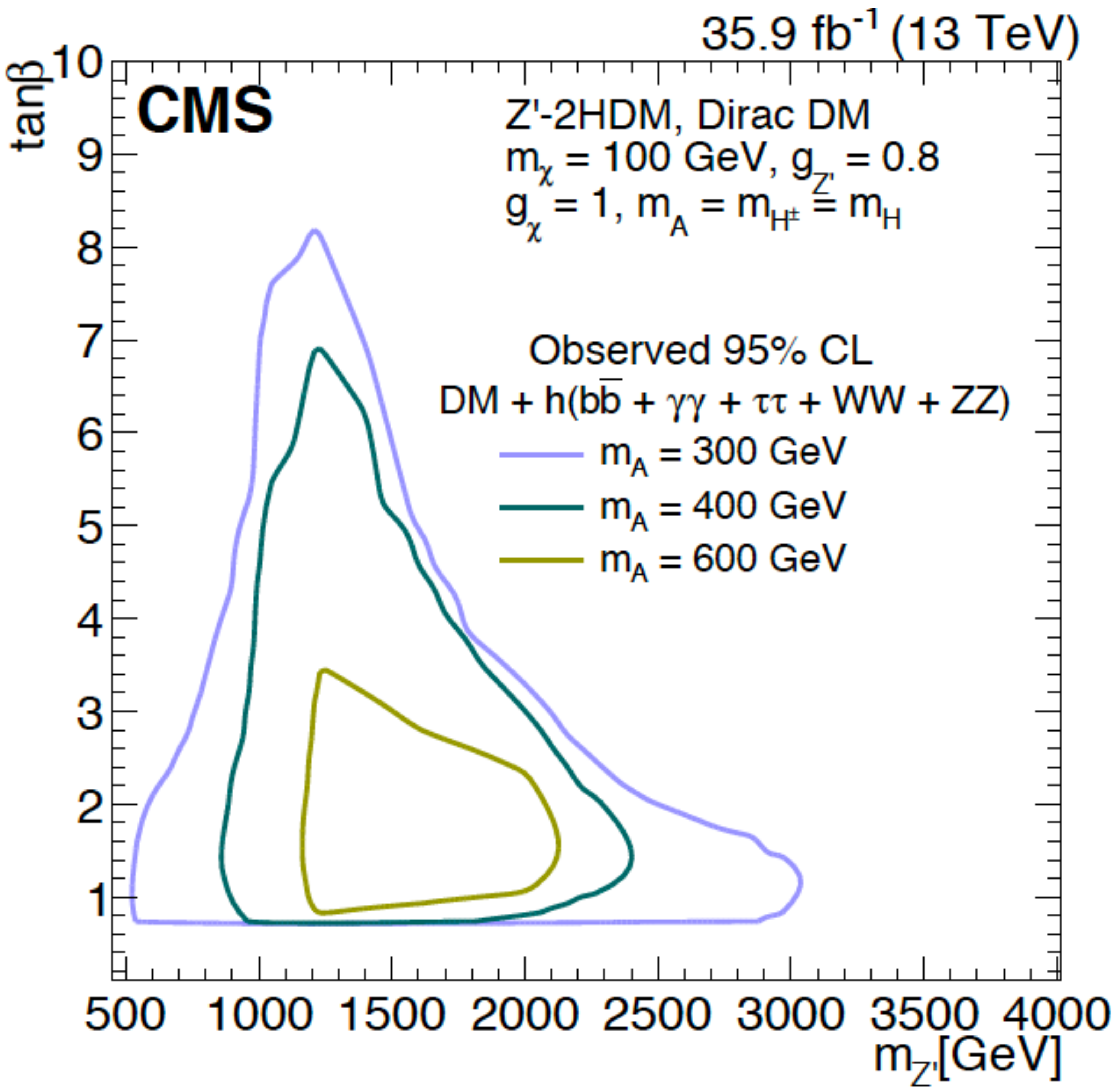

35.9 fb^{-1} (13 TeV)
CMS
Z'-2HDM, Dirac DM
m_χ = 100 GeV, $g_{Z'}$ = 0.8
g_χ = 1, m_A = $m_{H^\pm}$ = m_H
Observed 95% CL
DM + h($b\bar{b}$ + $\gamma\gamma$ + $\tau\tau$ + WW + ZZ)
m_A = 300 GeV
m_A = 400 GeV
m_A = 600 GeV
tanβ
$m_{Z'}$[GeV]
500 1000 1500 2000 2500 3000 3500 4000
1 2 3 4 5 6 7 8 9 10

Table 2: Summary of the kinematic selections used to define the SR for both the MTR and the VTR categories.

Observable	MTR	VTR
Choice of pair	leading-p_T jets	leading-m_{jj} jets
Leading (subleading) jet	$p_T > 80\,(40)$ GeV, $\lvert\eta\rvert < 4.7$	$p_T > 140\,(70)$ GeV, $\lvert\eta\rvert < 4.7$
p_T^{miss}	>250 GeV	$160 < p_T^{miss} < 250$ GeV
$\min(\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet}))$	>0.5	>1.8
$\lvert\Delta\phi_{jj}\rvert$	<1.5	<1.8
m_{jj}	>200 GeV	>900 GeV
$\lvert p_T^{miss} - \text{calo } p_T^{miss}\rvert / p_T^{miss}$	<0.5	
Leading/subleading jets $\lvert\eta\rvert < 2.5$	NHEF < 0.8, CHEF > 0.1	
HF noise jet candidates	0 (using the requirements from Table 1)	
τ_h candidates	$N_{\tau_h} = 0$ with $p_T > 20$ GeV, $\lvert\eta\rvert < 2.3$	
b quark jet	$N_{jet} = 0$ with $p_T > 20$ GeV, DeepCSV Medium	
$\eta_{j1}\eta_{j2}$	<0	
$\lvert\Delta\eta_{jj}\rvert$	>1	
Electrons (muons)	$N_{e,\mu} = 0$ with $p_T > 10$ GeV, $\lvert\eta\rvert < 2.5\,(2.4)$	
Photons	$N_{\gamma} = 0$ with $p_T > 15$ GeV, $\lvert\eta\rvert < 2.5$	

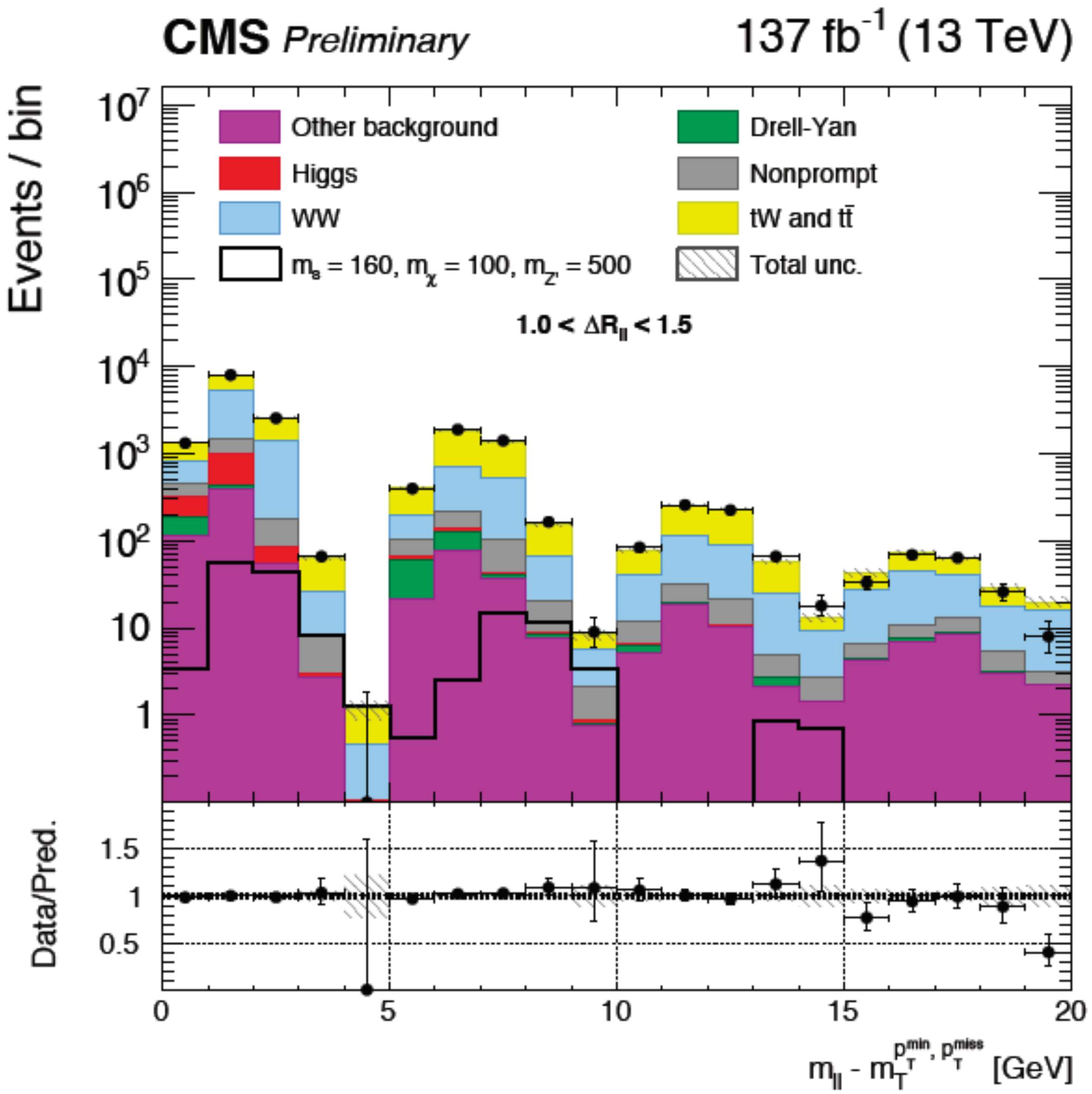
Source of uncertainty	Ratios	Uncertainty vs. m_{jj}
	Theoretical uncertainties	
Ren. scale V+jets (VBF)	$f_i^{W/Z,VBF}$	7.5%
Ren. scale V+jets (strong)	$f_i^{W/Z,strong}$	8.2%
Fac. scale V+jets (VBF)	$f_i^{W/Z,VBF}$	1.5%
Fac. scale V+jets (strong)	$f_i^{W/Z,strong}$	1.3%
PDF V+jets (VBF)	$f_i^{W/Z,VBF}$	0%
PDF V+jets (strong)	$f_i^{W/Z,strong}$	0%
NLO EW corr. V+jets (strong)	$f_i^{W/Z,strong}$	0.5%
Ren. scale γ+jets (VBF)	$f_i^{\gamma/Z,VBF}$	6–10%
Ren. scale γ+jets (strong)	$f_i^{\gamma/Z,strong}$	6–10%
Fac. scale γ+jets (VBF)	$f_i^{\gamma/Z,VBF}$	2.5%
Fac. scale γ+jets (strong)	$f_i^{\gamma/Z,strong}$	2.5%
PDF γ+jets (VBF)	$f_i^{\gamma/Z,VBF}$	2.5%
PDF γ+jets (strong)	$f_i^{\gamma/Z,strong}$	2.5%
NLO EW corr. γ+jets	$f_i^{\gamma/Z,strong}$	3%
	Experimental uncertainties	
Electron reco. eff.	$R_i^{CR,proc}$, CR=Z(ee) or W($e\nu$)	≈0.5% (per lepton)
Electron id. eff.	$R_i^{CR,proc}$, CR=Z(ee) or W($e\nu$)	≈1% (per lepton)
Muon id. eff.	$R_i^{CR,proc}$, CR=Z($\mu\mu$) or W($\mu\nu$)	≈0.5% (per lepton)
Muon iso. eff.	$R_i^{CR,proc}$, CR=Z($\mu\mu$) or W($\mu\nu$)	≈0.1% (per lepton)
Photon id. eff.	$f_i^{\gamma/Z,proc}$	5%
Electron veto (reco)	$f_i^{W/Z,proc}$, $R_i^{CR,proc}$, CR=W($\ell\nu$)	≈1.5 (1)% for VBF (strong)
Electron veto (id)	$f_i^{W/Z,proc}$, $R_i^{CR,proc}$, CR=W($\ell\nu$)	≈2.5 (2)% for VBF (strong)
Muon veto	$f_i^{W/Z,proc}$, $R_i^{CR,proc}$, CR=W($\ell\nu$)	≈0.5%
τ_h veto	$f_i^{W/Z,proc}$, $R_i^{CR,proc}$, CR=W($\ell\nu$)	≈1%
Electron trigger	$R_i^{CR,proc}$, CR=Z(ee) or W($e\nu$)	≈ 1%
p_T^{miss} trigger	$R_i^{CR,proc}$, CR=Z($\mu\mu$) or W($\mu\nu$)	≈ 2%
Photon trigger	$f_i^{\gamma/Z,proc}$	1%
JES	$f_i^{W/Z,proc}$	1–2%
	$R_i^{CR,proc}$, CR=W($e\nu$) or W($\mu\nu$)	1.0–1.5%
	$R_i^{CR,proc}$, CR=Z(ee) or Z($\mu\mu$)	1%
	$f_i^{\gamma/Z,proc}$	3%
JER	$f_i^{W/Z,proc}$	1.0–2.5%
	$R_i^{CR,proc}$, CR=W($e\nu$) or W($\mu\nu$)	1.0–1.5%
	$R_i^{CR,proc}$, CR=Z(ee) or Z($\mu\mu$)	1%
	$f_i^{\gamma/Z,proc}$	1–4%

Dark Photon

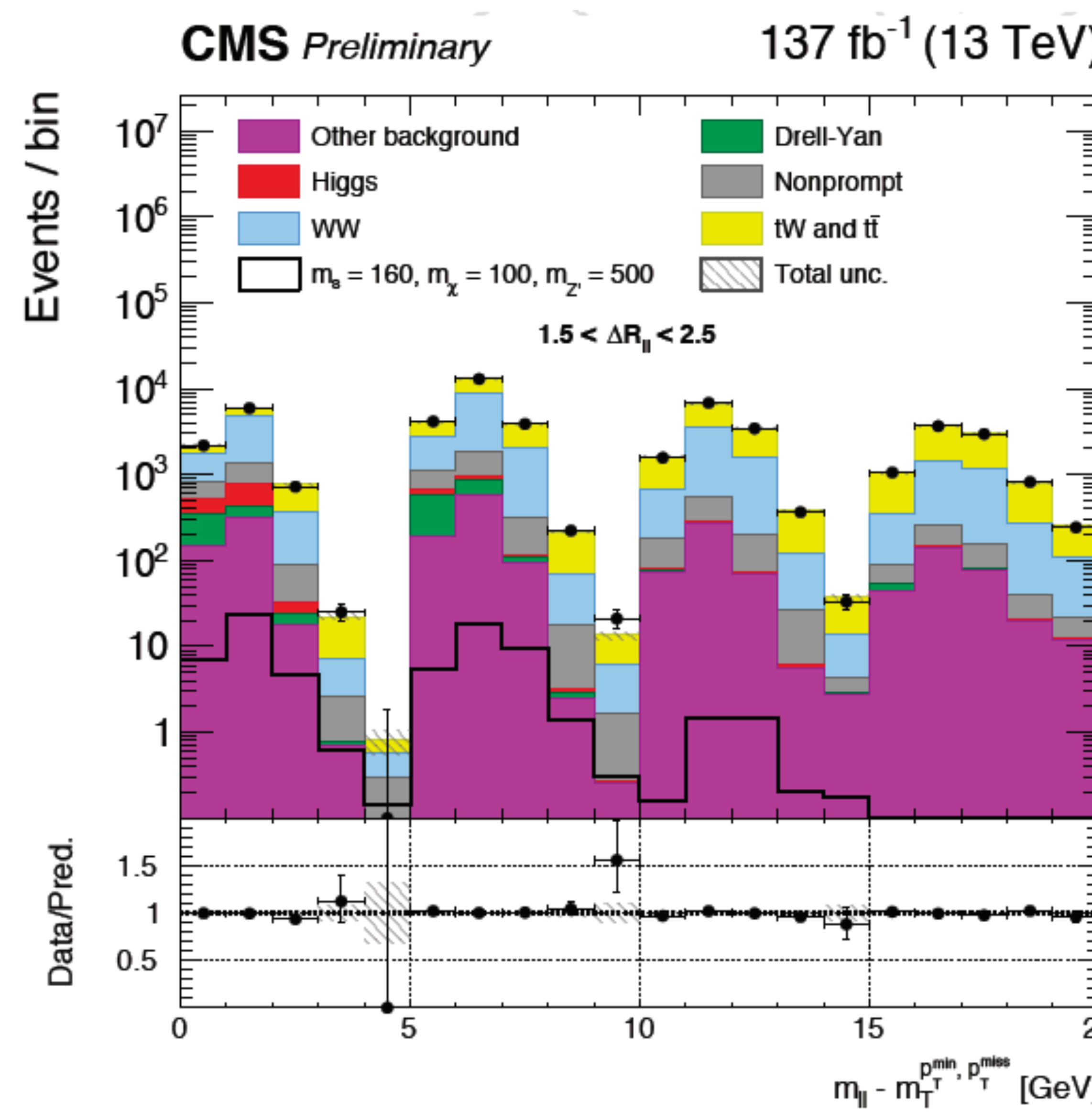
Data-taking year	2016	2017/2018	
Variable	VBF+γ	Single photon	p_T^{miss}
Number of photons		$\geq$1 photon	
p_T^{γ}	$>$80 GeV	$>$230 GeV	$>$80 GeV
Number of leptons		0	
p_T^{miss}	$>$100 GeV	$>$140 GeV	$>$140 GeV
Jet counting		2-5	
m_{jj}		$>$500 GeV	
$\lvert\Delta\eta_{jj}\rvert$		$>$3.0	
$\eta_{j_1} \times \eta_{j_2}$		$<$0	
$\Delta\phi_{jet,\vec{p}_T^{miss}}$		$>$1.0	
z_{γ}^{*}		$<$0.6	
p_T^{tot}		$<$150 GeV	

Region	Bins	Range (GeV)
SR, $m_{jj} < 1500$ GeV	6	[0,30,60,90,170,250,inf]
SR, $m_{jj} \geq 1500$ GeV	6	[0,30,60,90,170,250,inf]
W + jets CR, $m_{jj} < 1500$ GeV	3	[0,90,250,inf]
W + jets CR, $m_{jj} \geq 1500$ GeV	3	[0,90,250,inf]
$Z(\ell\bar{\ell}) + \gamma$ CR, $m_{jj} < 1500$ GeV	1	[0,inf]
$Z(\ell\bar{\ell}) + \gamma$ CR, $m_{jj} \geq 1500$ GeV	1	[0,inf]
$W(\rightarrow \ell\nu) + \gamma$ CR, $m_{jj} < 1500$ GeV	1	[0,inf]
$W(\rightarrow \ell\nu) + \gamma$ CR, $m_{jj} \geq 1500$ GeV	1	[0,inf]
γ + jets CR, $m_{jj} < 1500$ GeV	1	[0,inf]
γ + jets CR, $m_{jj} \geq 1500$ GeV	1	[0,inf]

Dark Higgs

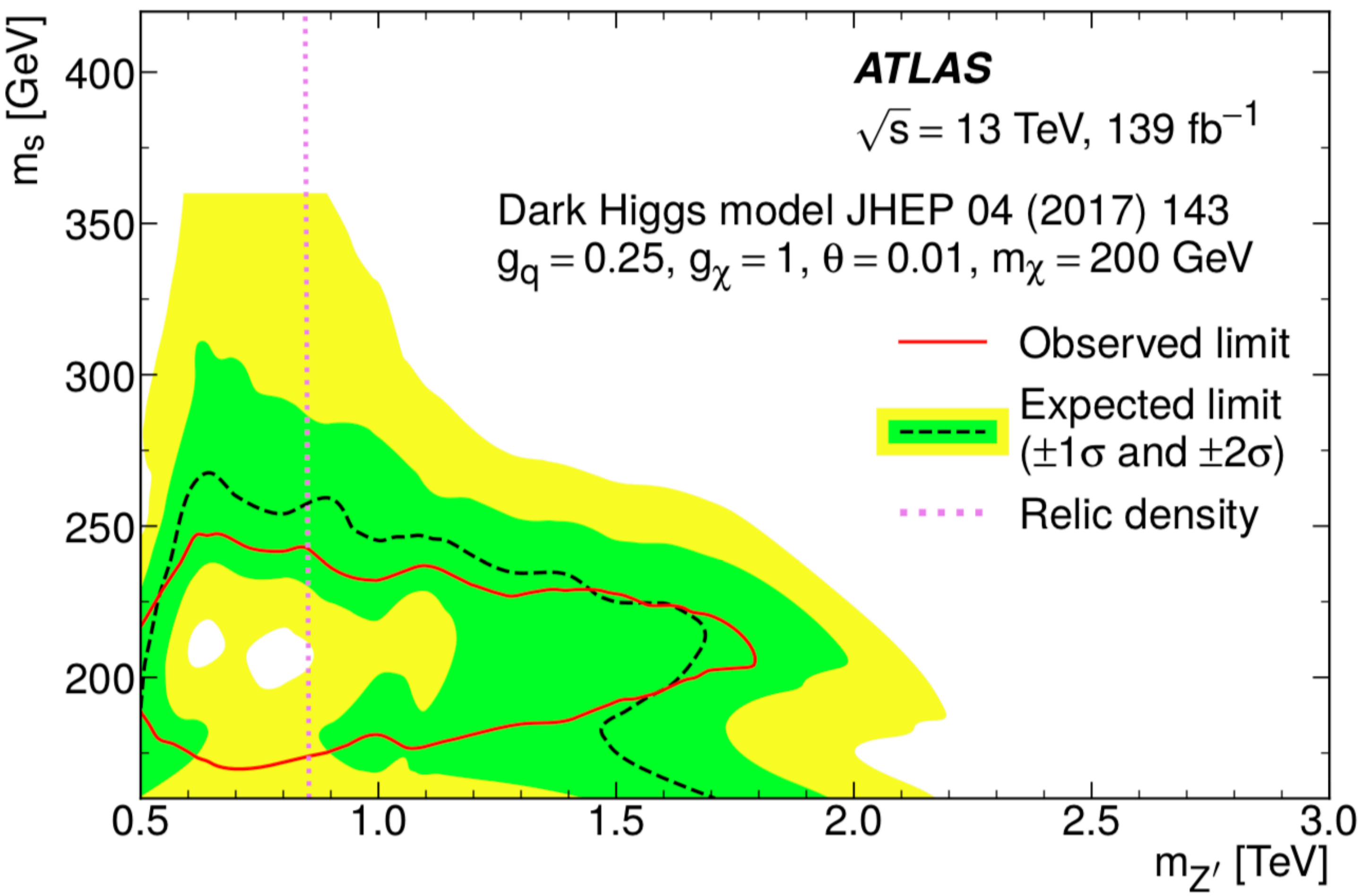


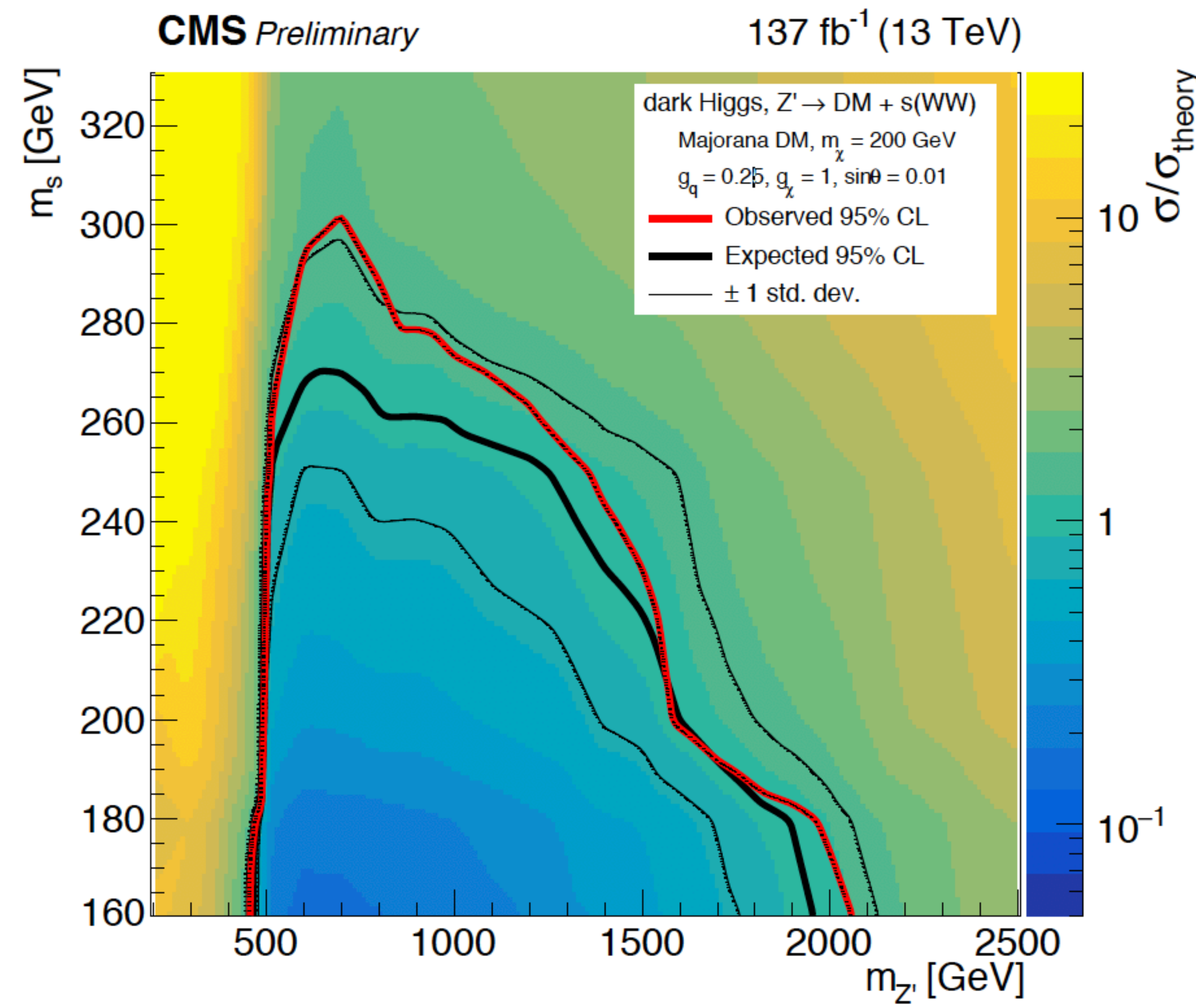
CMS Preliminary
137 fb-1 (13 TeV)
Events / bin
Other background
Higgs
WW
ms = 160, mχ = 100, mZ' = 500
Drell-Yan
Nonprompt
tW and tt̄
Total unc.
1.0 < ΔRll < 1.5
Data/Pred.
mll - mT pTmin, pTmiss [GeV]



CMS Preliminary
137 fb-1 (13 TeV)
Events / bin
Other background
Higgs
WW
ms = 160, mχ = 100, mZ' = 500
Drell-Yan
Nonprompt
tW and tt̄
Total unc.
1.5 < ΔRll < 2.5
Data/Pred.
mll - mT pTmin, pTmiss [GeV]

Dark Higgs comparison





VBF Higgs Invisible ATLAS

$H \rightarrow invisible$ **95% upper limit at 15%**