Search for Dark Matter recoiling from the SM Higgs boson at CMS

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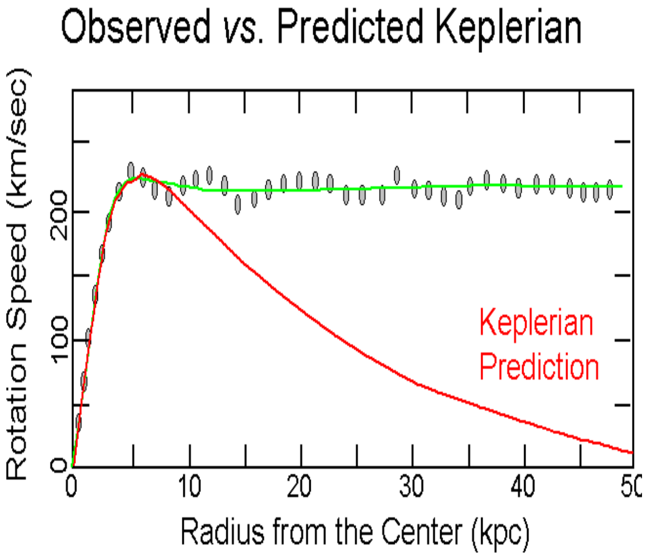
Tata Institute of Fundamental Research

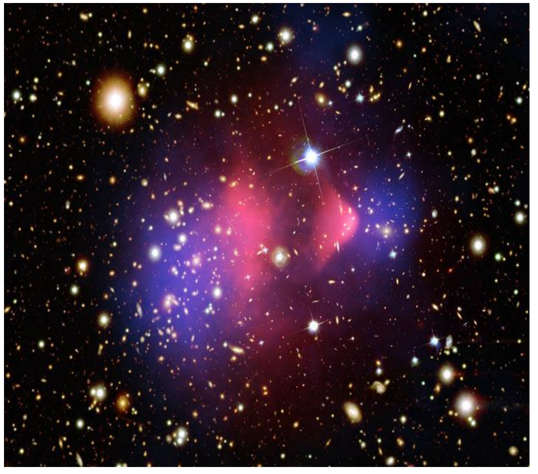
+ Evidence for dark matter

- Strong astrophysical evidence for the existence of dark matter
  - From rotational curves, gravitational lensing/bullet cluster, CMB power spectrum

Rotation curve of galaxies



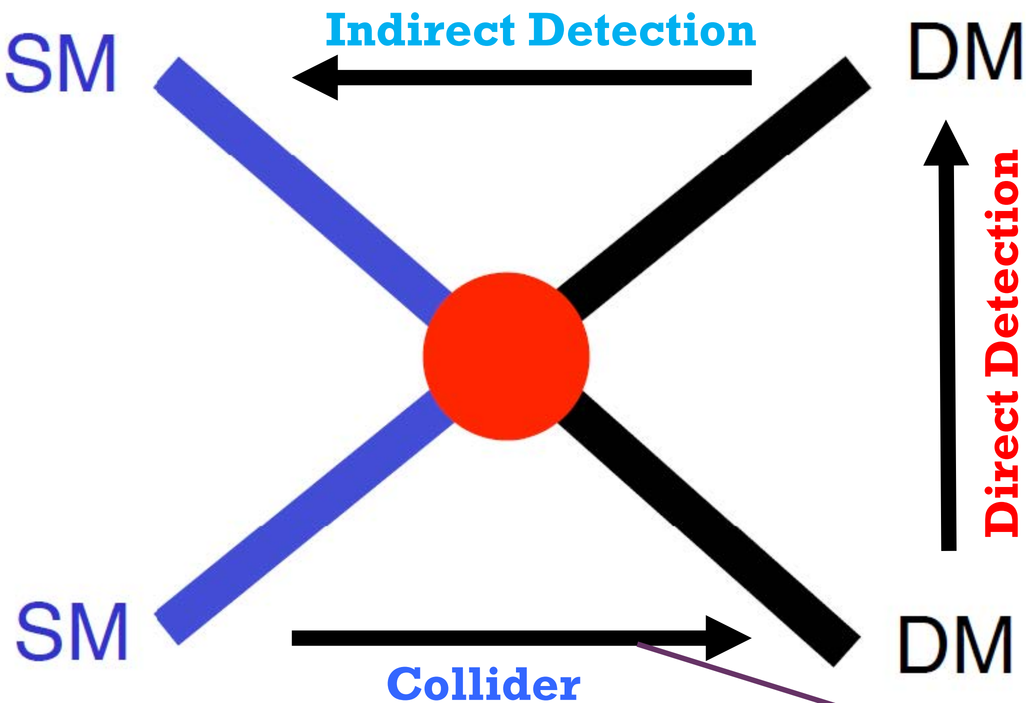
Gravitation Lensing



- Increasing number of observations consistent with DM existence
  - No direct observation yet

Detection Techniques

Assume annihilation of DM particles, eg. In the sun. Detect annihilation products.



Scattering of DM particles on nuclei of detector material; Detect recoil. For a given cross section sensitivity scales with detector size.

DM may be pair produced in pp collisions at the LHC, with masses <1/2 parton-parton c.o.m. Yields experimental signature of MET

My talk

Dark Matter search using SM Higgs boson

- Two kind of searches can be performed using SM Higgs boson
  - Invisible Higgs Boson decay (Higgs Portal)
    - Invisible Higgs recoiling from Z-boson (ZH production mode)
    - Invisible Higgs associated with forward jets (VBF production mode)
  - Higgs recoil from dark matter (Mono-higgs)
    - MonoH (bb)
    - MonoH($\gamma\gamma$)
    - MonoH (bb + $\gamma\gamma$) combination

- *Both method require measurement of 125 GeV Higgs boson*

Status of 125 GeV Higgs boson

- Re-discovered the Higgs boson using Run-II data in both $\gamma\gamma$ and ZZ final states.
- ATLAS and CMS published combined results of the Higgs mass measurement in 2016
  - Combined bb+$\tau\tau$ gives 5 sigma observation of fermionic decays

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

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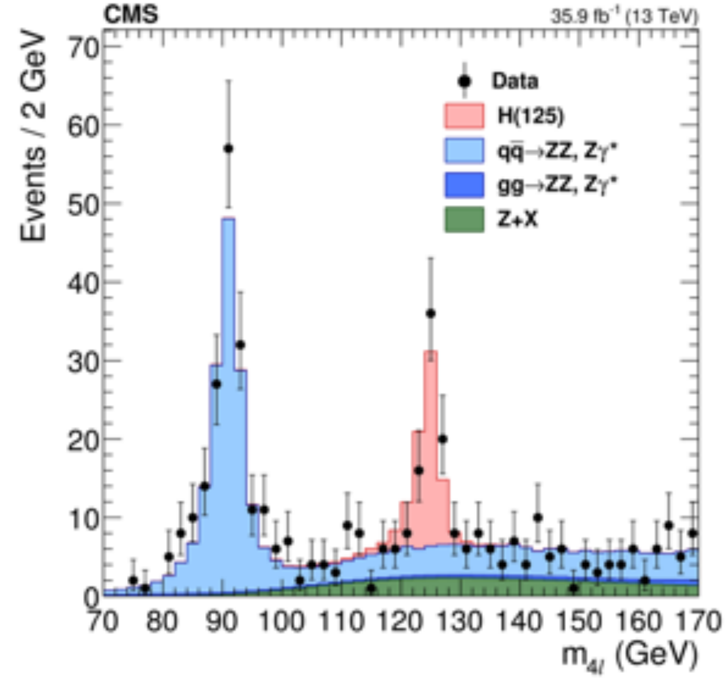
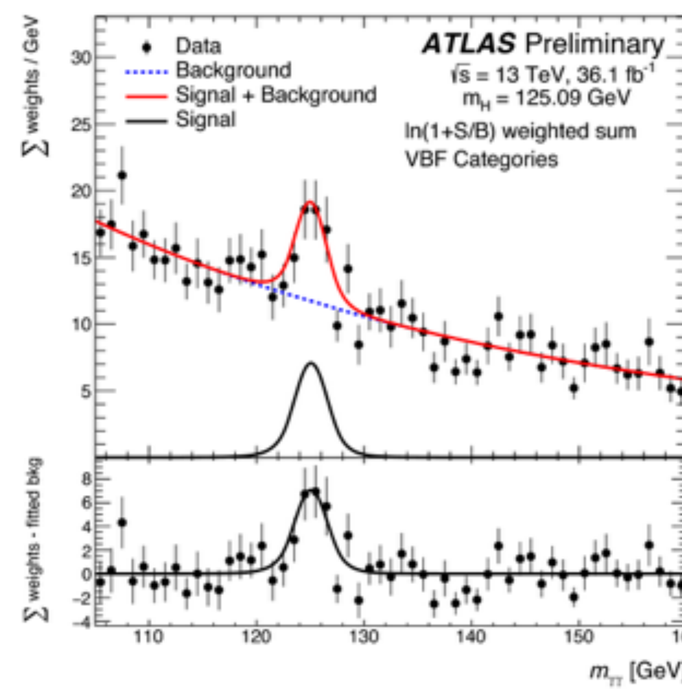




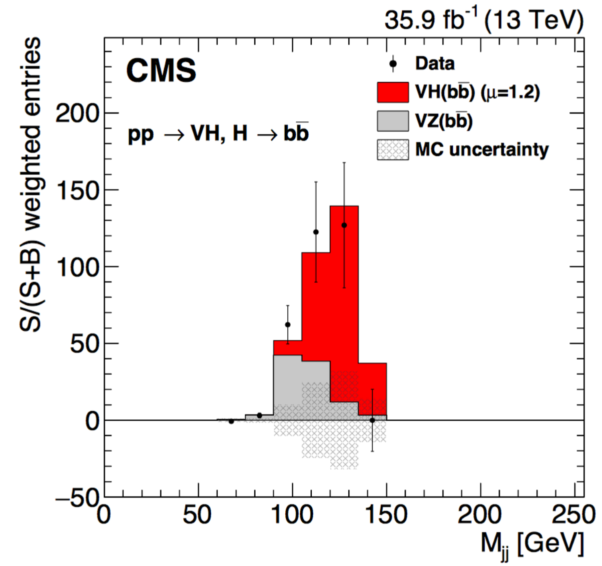
Status of 125 GeV Higgs boson

- Further confirmation of the yukawa-coupling arrives from VH(bb) and H(ττ) Run-II results

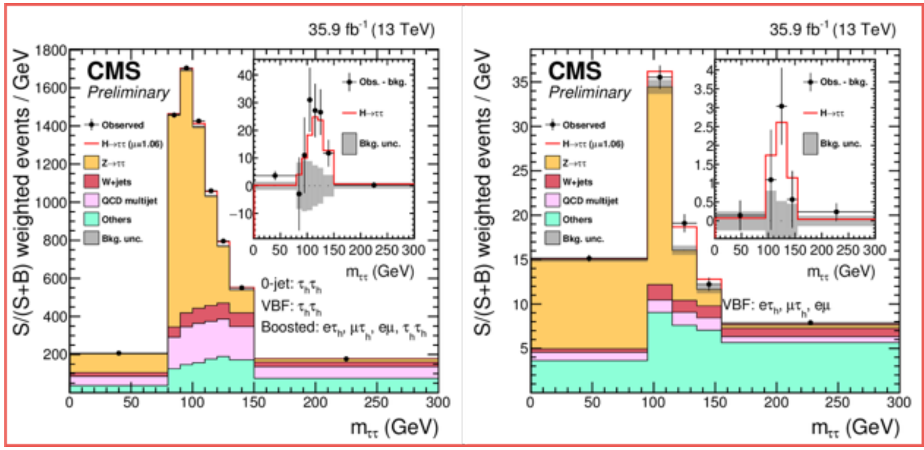
- VH(bb) Run-II evidence from CMS with 3.3(2.8) σ observed(expected) with a signal strength μ=1.2+/- 0.4 at 13 TeV. Combined with Run-1 measurement the significance improves to 3.8(3.8) σ observed(expected) with μ= 1.06+0.31-0.29

- H(ττ) Run-II evidence with 4.9(4.7) σ observed(expected) at CMS using 2016 data (μ= 1.06 + 0.25 – 0.24)

CMS-PAS-HIG-16-044



CMS-PAS-HIG-16-043

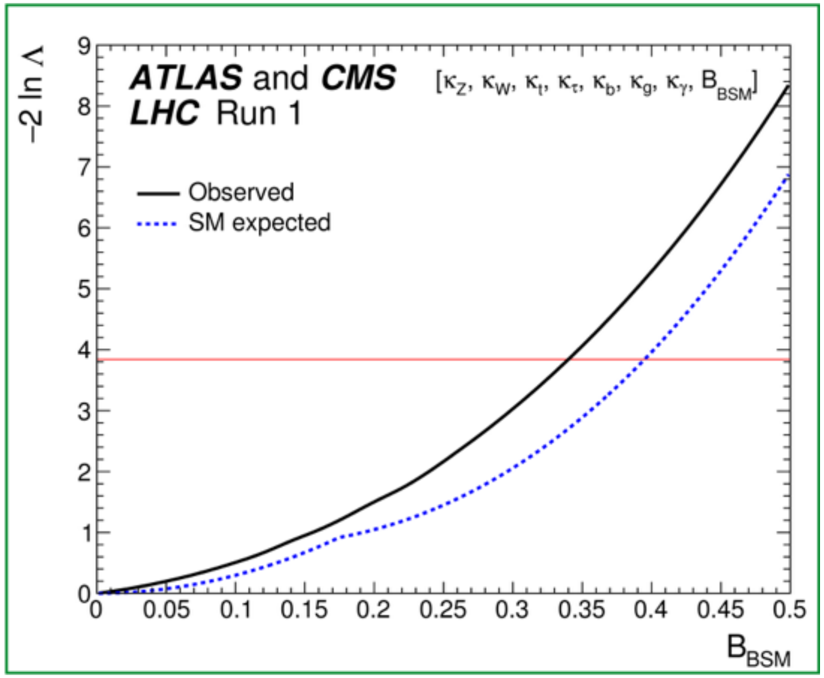


Status of 125 GeV Higgs boson

- With Run-I combination results, the indirect searches constrain the overall branching fraction of the Higgs boson into BSM decays to be less than 34% at 95% CL.

Indirect searches

- Compare visible width to total width:
  - $BR_{BSM} = \frac{\Gamma_H - \Gamma_{vis}}{\Gamma_H}$
- No measurement of Γ_H, need to make an assumption
  - Usually assume SM width
- ATLAS+CMS combination gives an observed (expected) limit on BR_{BSM} of 0.34 (0.35)



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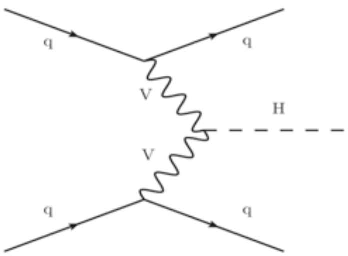
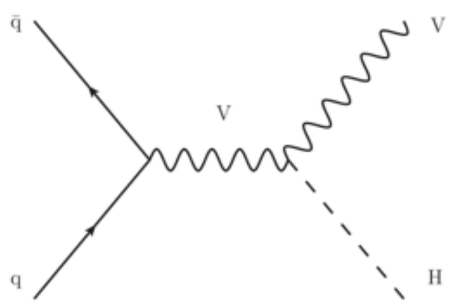
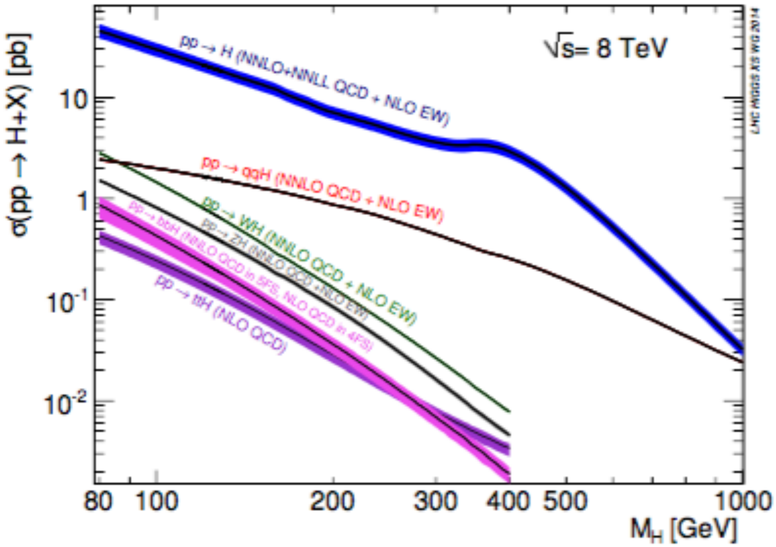
Invisible Higgs Decays

- Look for associated Higgs boson products plus Missing transverse energy (MET)

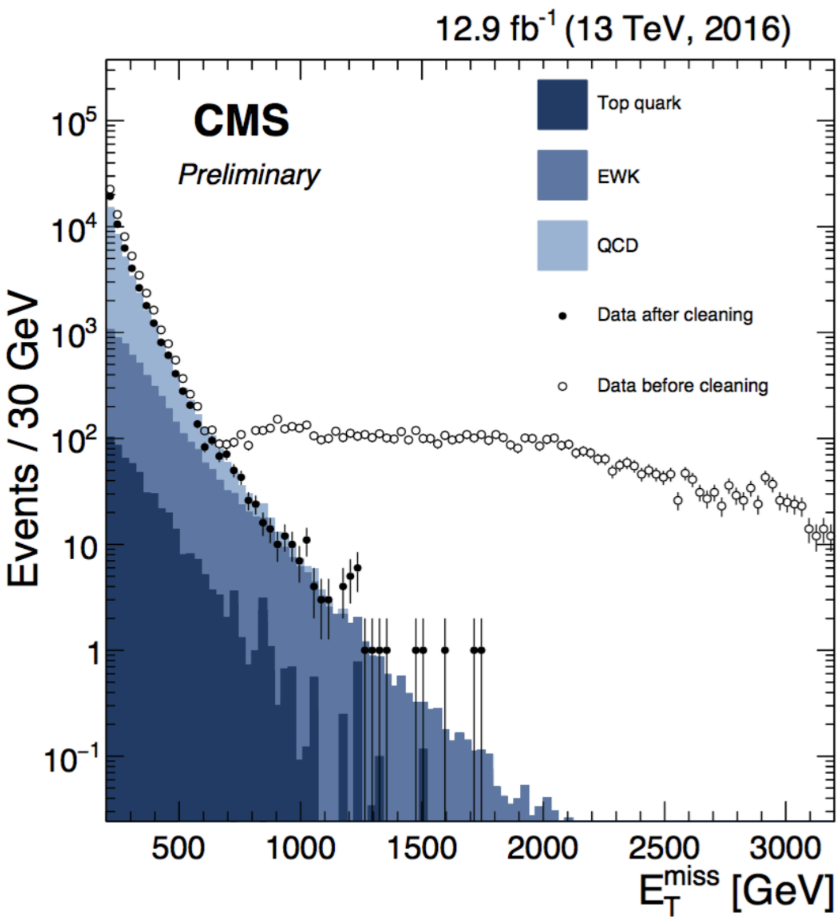


  - VBF mode is most sensitive
    - Second highest rate and distinctive topology
  - Gluon fusion has no visible products, needs ISR
    - High rate, but difficult final state
  - VH has clean final states but low rate





Challenges with Missing Transverse Energy

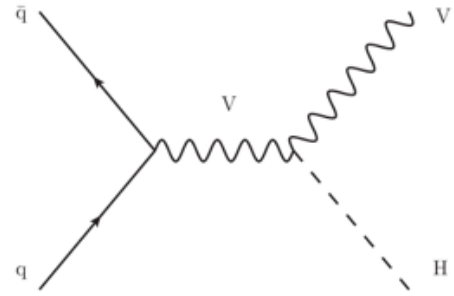


Spurious detector signals can cause fake MET signatures that must be identified and suppressed.

Anomalous high MET can be due to:

- Particles striking sensors in the ECAL photodetectors
- Beam halo particles
- ECAL dead cells (real energy to have been missed)
- Noise in photodiode & readout box electronics in HCAL

+ Higgs Invisible : ZH

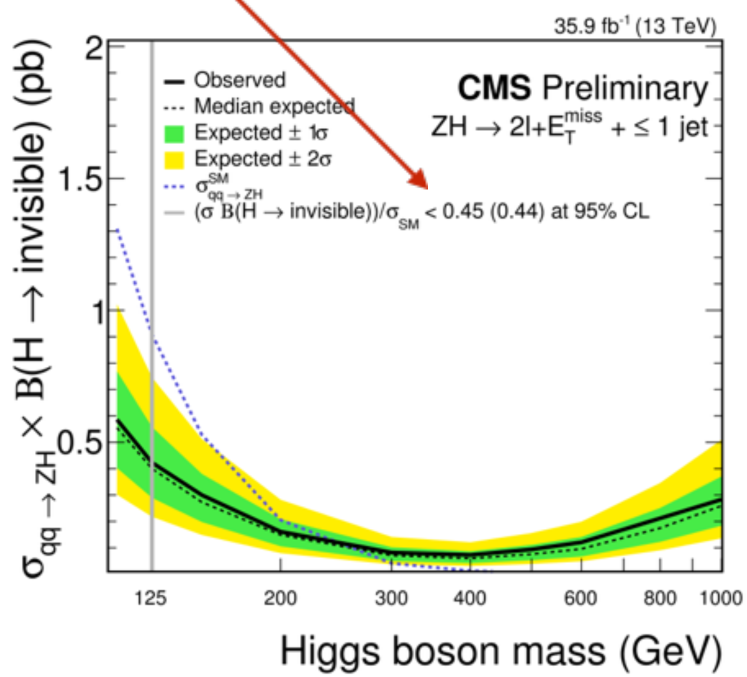


- Traditional MET+X searches can be interpreted for Higgs+X
- MET+Z (MonoZ) dark matter search can be interpreted for ZH (invisible)
  - Target Z->ll final state
  - 2D shape analysis with leading backgrounds estimated using MC
- MET+jet dark matter search can be interpreted for gH (invisible)

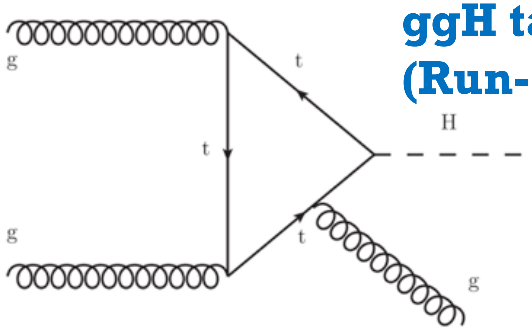
VH tagged : Z(ll)H

ggZH +qqZh B (H->inv) (125 GeV) < 45%

CMS-PAS-EXO-16-052

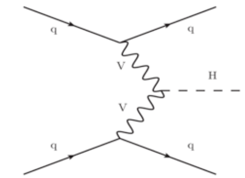


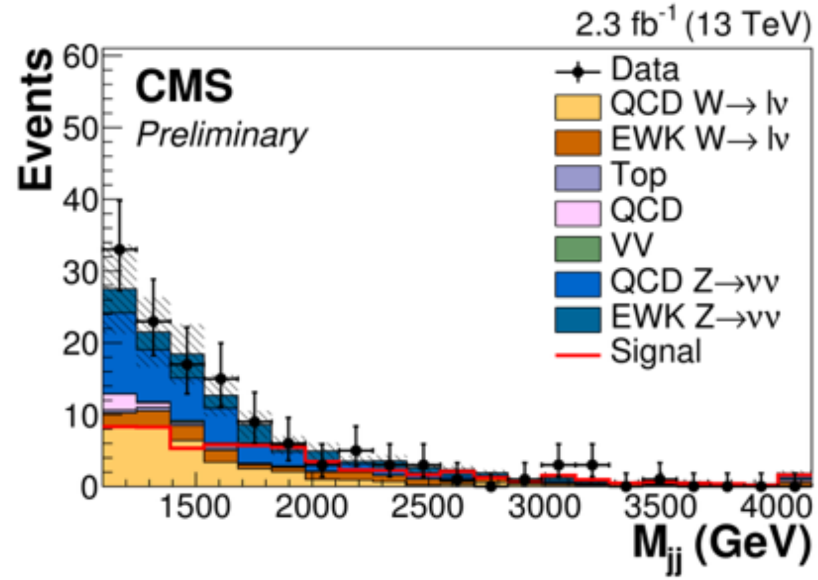
ggH tagged : monojet (Run-2 Ongoing)



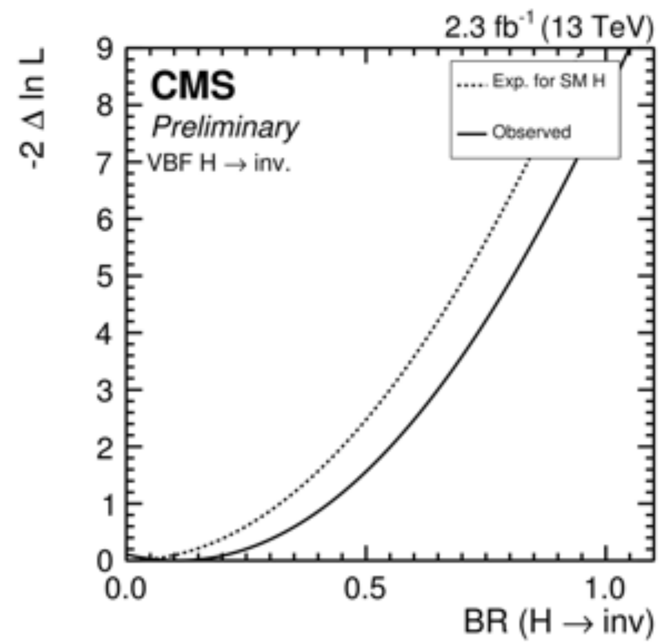
Higgs Invisible : VBF

CMS-PAS-HIG-16-009





- Events with 2 high-p_T forwards jets
- Special trigger with VBF topology
  - Level1 trigger : ETM trigger with 60 GeV
  - HLT : dijet mass 600 GeV and well separated in $\Delta\eta$
- Offline Cuts
  - Di-jet mass > 800 GeV
  - MET > 200 GeV
  - $\Delta\eta$ (j_1,j_2) > 3.6
- Observed(expected) limit
  - ***B(H->inv) for m_H=125 GeV is 69 (62) %***



Higgs Invisible : Combination

- First CMS analysis combining 8 and 13 TeV results
- Limit calculated both by production mode and overall
- qqH + VH + ggH tagged (using 4.9fb^{-1}(7 TeV), 19.6fb^{-1} (8TeV) + 2.3 fb^{-1} (13 TeV)

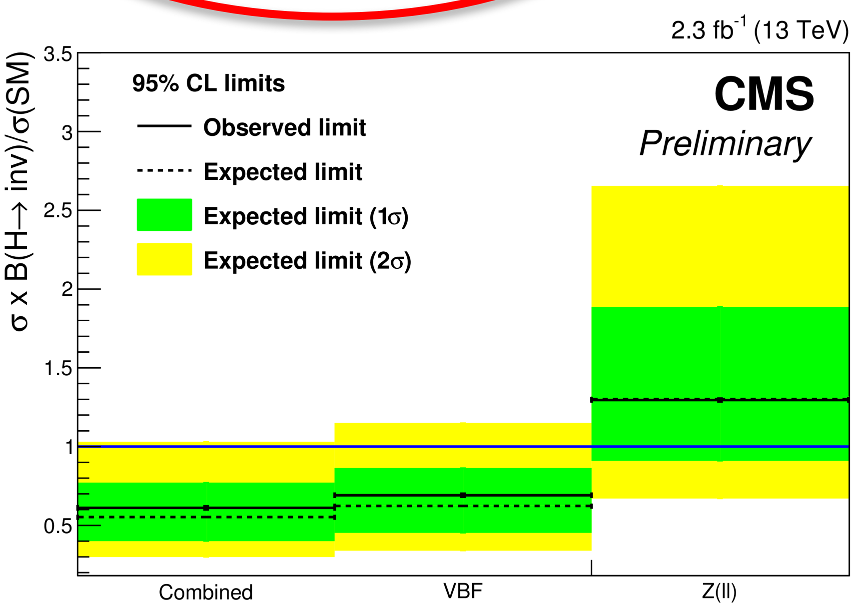
CMS-PAS-HIG-16-016

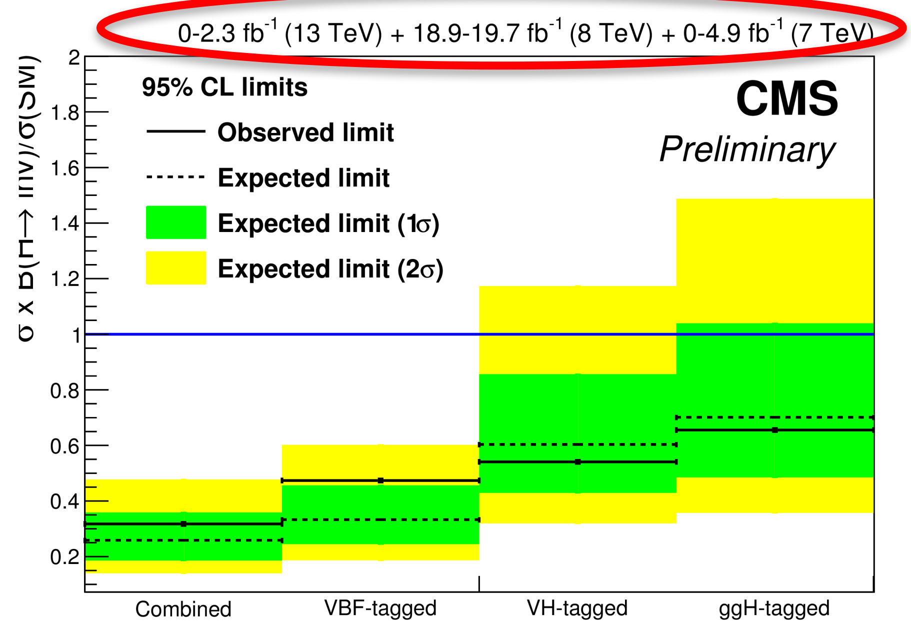
Higgs Invisible : Combination

Table 2: Summary of the expected composition of production modes of a Higgs boson with a mass of 125 GeV in each analysis included in the combination. The relative contributions assume SM production cross sections.

Analysis	Final state	Int. $\mathcal{L}$ (fb^{-1})			Expected signal composition (%)	
		7 TeV	8 TeV	13 TeV	7 or 8 TeV	13 TeV
qqH-tagged	VBF jets	—	19.2 [17]	2.3	7.8 (ggH), 92.2 (qqH)	9.1 (ggH), 90.9 (qqH)
VH-tagged	$Z(\ell^+\ell^-)$	4.9 [17]	19.7 [17]	2.3	100 (ZH)	
	$Z(b\bar{b})$	—	18.9 [17]	—	100 (ZH)	
	V(jj)	—	19.7 [61]	2.3	25.1 (ggH), 5.1 (qqH), 22.0 (ZH), 46.8 (WH)	38.7 (ggH), 7.1 (qqH), 21.3 (ZH), 32.9 (WH)
ggH-tagged	Monojet	—	19.7 [61]	2.3	70.4 (ggH), 20.4 (qqH), 3.5 (ZH), 5.7 (WH)	69.3 (ggH), 21.9 (qqH), 4.2 (ZH), 4.6 (WH)

Combined observed(expected) limits on B (H->inv) for m_H =125 GeV is 20 (21)%





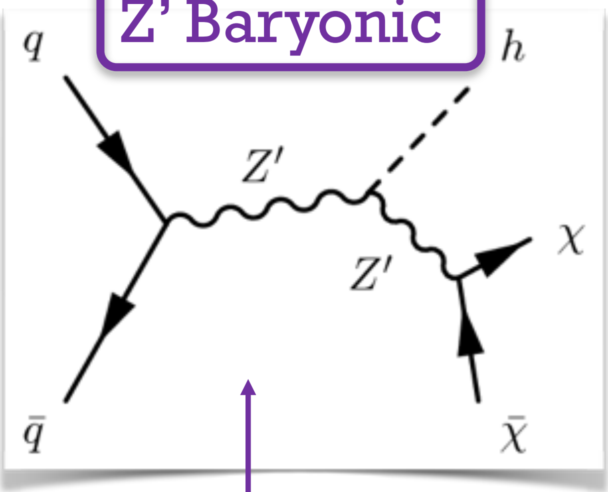
CMS-PAS-HIG-16-016

Higgs Recoil from Dark Matter

- Higgs decays in association with dark matter
- Higgs ISR is Yukawa suppressed, instead H can be emitted by the mediator
  - Direct test of the SM-DM coupling structure
- Any Higgs final state can be probed
  - bb+MET, $\gamma\gamma$+MET, $\tau\tau$+MET, WW+MET, ZZ+MET
  - I will present results from bb+MET and $\gamma\gamma$+MET final state
  - bb+MET : largest branching fraction (~58%), but poor mass resolution
  - $\gamma\gamma$+MET : Small branching fraction (~0.2%), but resolution of ~1-2%
  - Rest of the analysis are not yet approved
- Different final states allow for different trigger strategies as some final states can probe lower MET ranges than others.

Higgs Recoil from Dark Matter

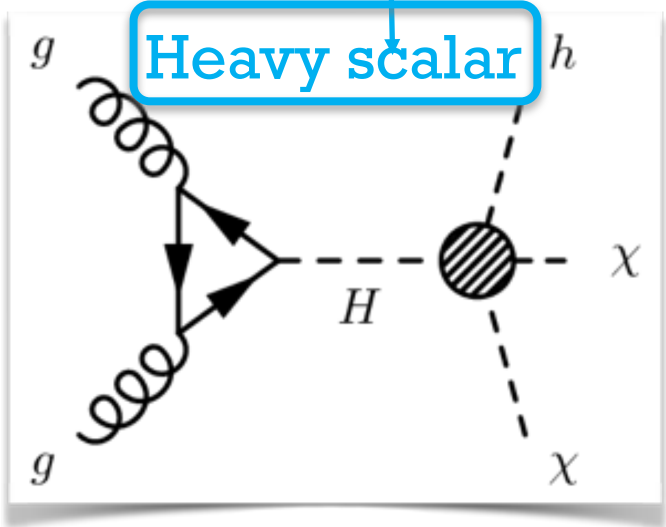
Z' Baryonic



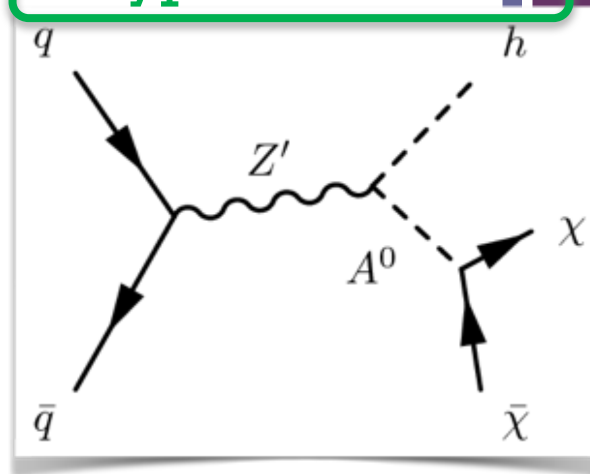
S-channel vector mediator Z' radiates off Higgs boson and decays to DM

produced via ggF
2mh < mH < 2mtop

Heavy scalar



Z' Type-II 2HDM



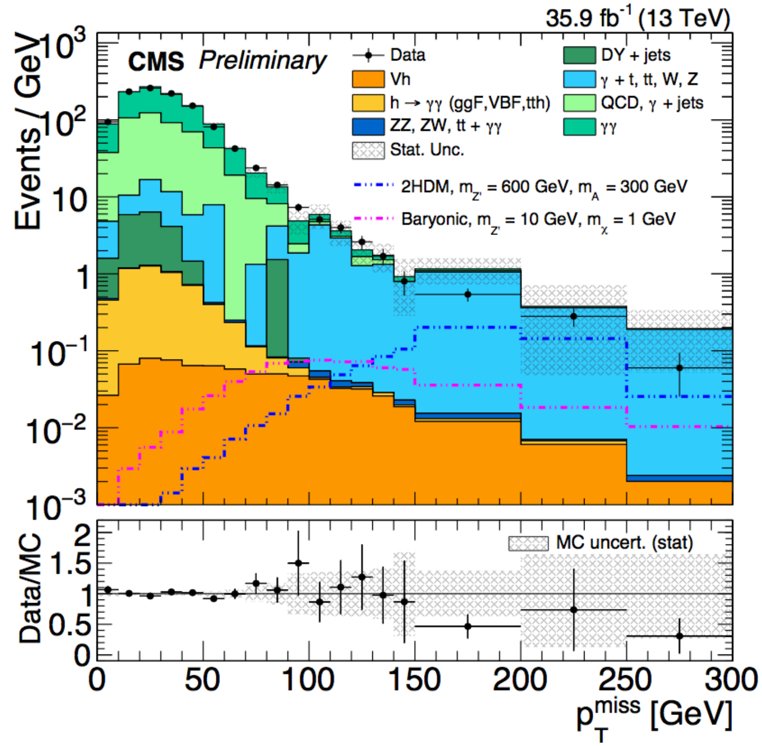
0.2 TeV < mZ′ < 3 TeV
0.3 TeV < mA < 0.8 TeV
mχ =100GeV, tanβ=1,
gZ′=0.8,
BR(A→χχ̄)=100%

arXiV:1507.00966
arXiV:1706.03948

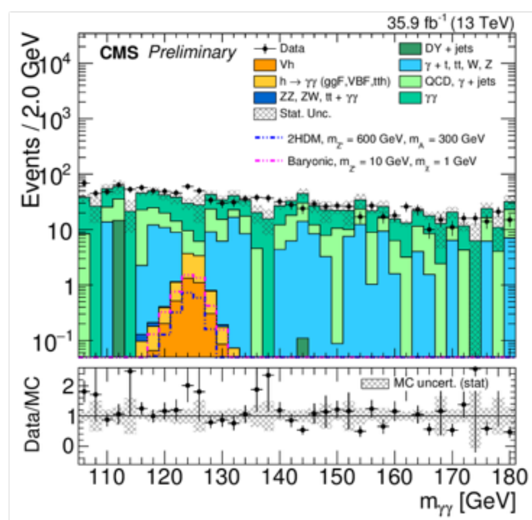
H(γγ)+MET : 2016

- 2HDM and Z' Baryonic models considered
- γγ good at probing low pT_{miss} final state, use di-photon trigger
  - no MET trigger required
- Higgs SM contribution includes as resonant background
- 2 categories are considered :
  - Low MET : 50-130 GeV
  - High MET : >130 GeV

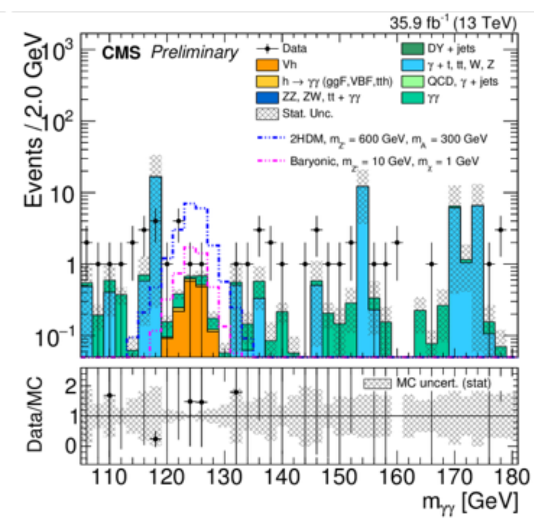
Signal extraction by fitting analytic function to m(γγ) distribution



low MET(pTmiss)



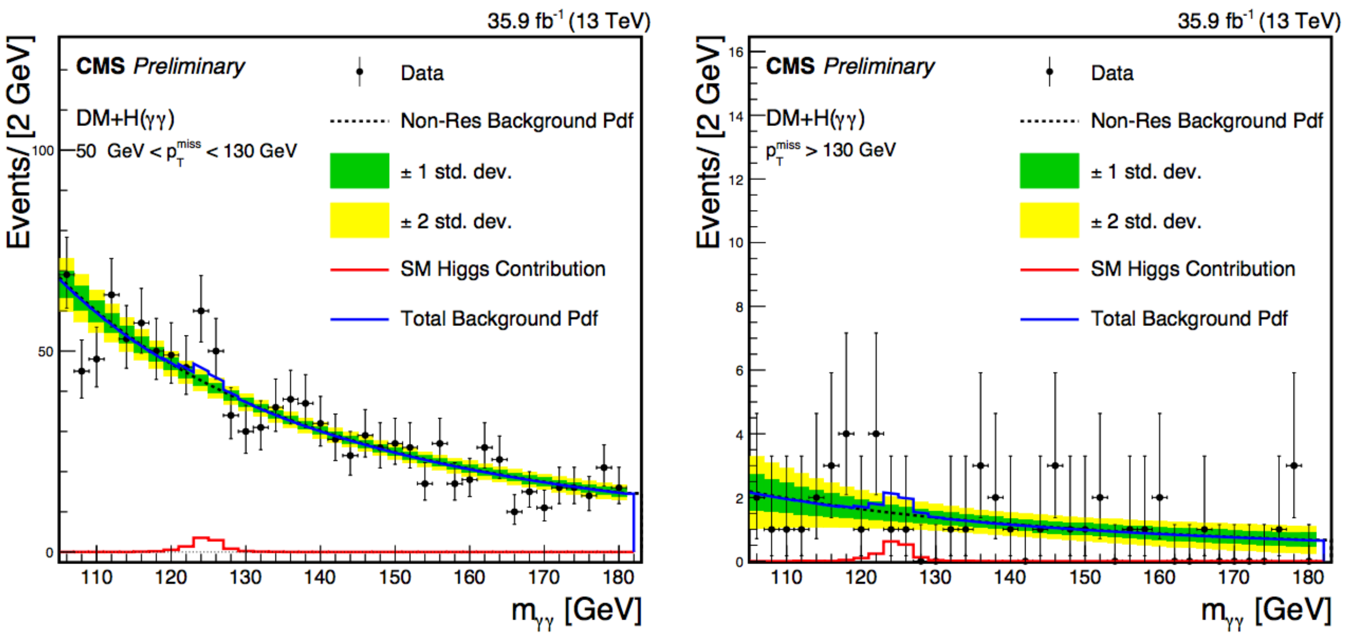
high MET(pTmiss)



CMS-PAS-EXO-16-054

H(γγ)+MET : 2016

- Diphoton invariant mass distribution of the background processes modelled as a smooth function of m(γγ) and fitted directly in data
- Resonant backgrounds from decays of the SM Higgs boson to 2 photons
  - Estimated from MC simulation
- Non-resonant background due to QCD and EWK contributions
  - Diphoton mass spectrum in data is fit with a power law function $P(x) = \sum_{i=1}^{N} \beta_i x^{-\alpha_i}$

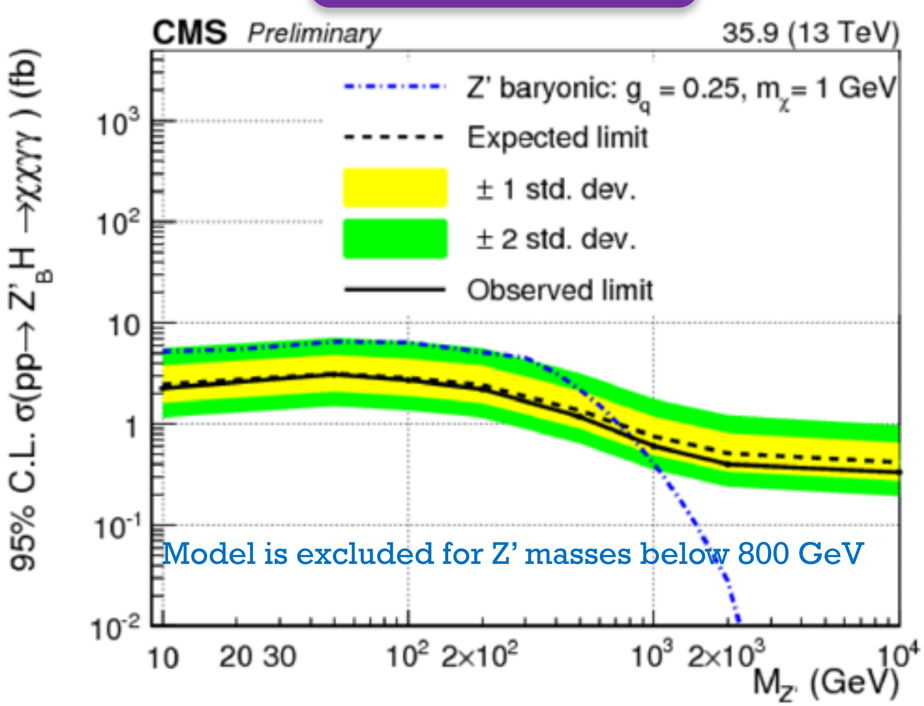


H(γγ)+MET : 2016

Dominated by statistical uncertainties

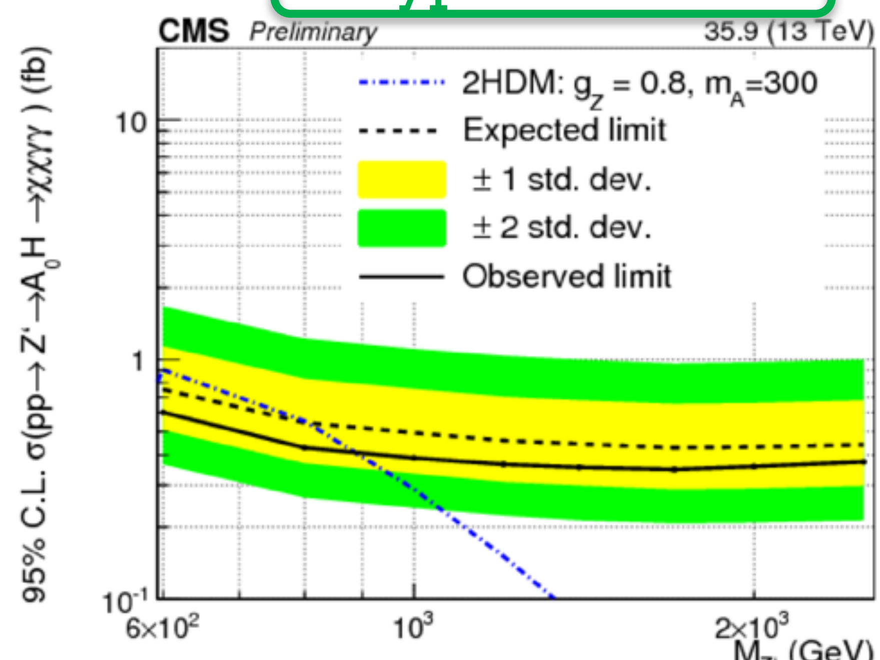
Sample	Low-p_T^{miss} Yield	High-p_T^{miss} Yield
SM h→ $\gamma\gamma$ (Vh)	3.2 ± 0.1(stat) ± 0.2(syst)	1.41 ± 0.10(stat) ± 0.09(syst)
SM h→ $\gamma\gamma$ (ggF,tth,VBF)	5.7 ± 0.3(stat) ± 1.2 (syst)	0.11 ± 0.01(stat) ± 0.01(syst)
Non-resonant Background	125.1 ± 11.2(stat)	4.5 ± 2.1(stat)
Data	190	6

Z' Baryonic



Model is excluded for Z' masses below 800 GeV

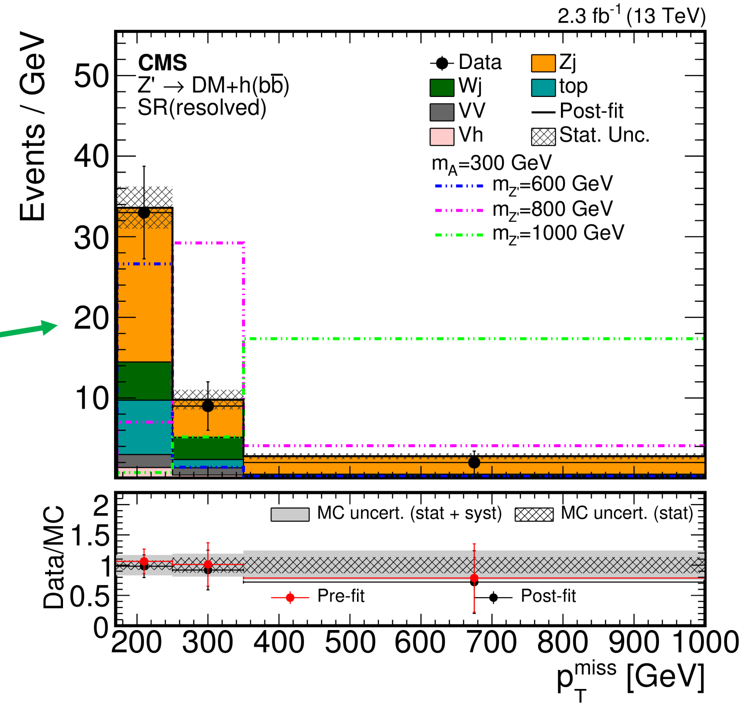
Z' Type-II 2HDM



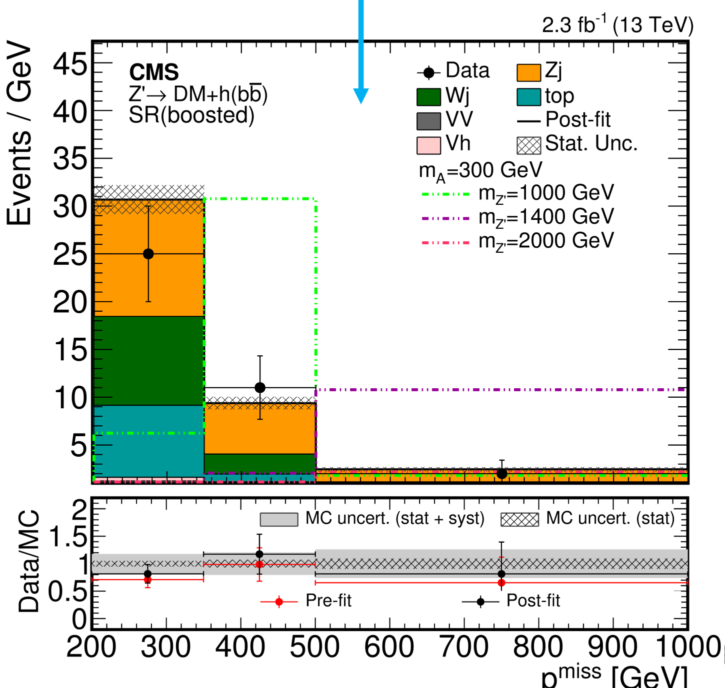
2HDM signal with mA=300 GeV are excluded with Z' mass below 900 GeV

+ H(bb)+MET : 2015

- Two categories are considered
  - Resolved : H decays to 2 distinct reconstructed b jets
  - Merged : H is reconstructed as fat jet



- For Resolved category
  - pT >30 GeV, |η| <2.4, MET > 170 GeV
  - aK4 jets with R=0.4, used for MZ' < 1000 GeV
- For Merged category
  - pT >200 GeV, |η| <2.4, MET > 200 GeV
  - Fat jets with R = 0.8, user for MZ'>1000 GeV



Signal extraction is performed in bins of MET by simultaneously fitting the SR and CR

Background Normalization Strategy

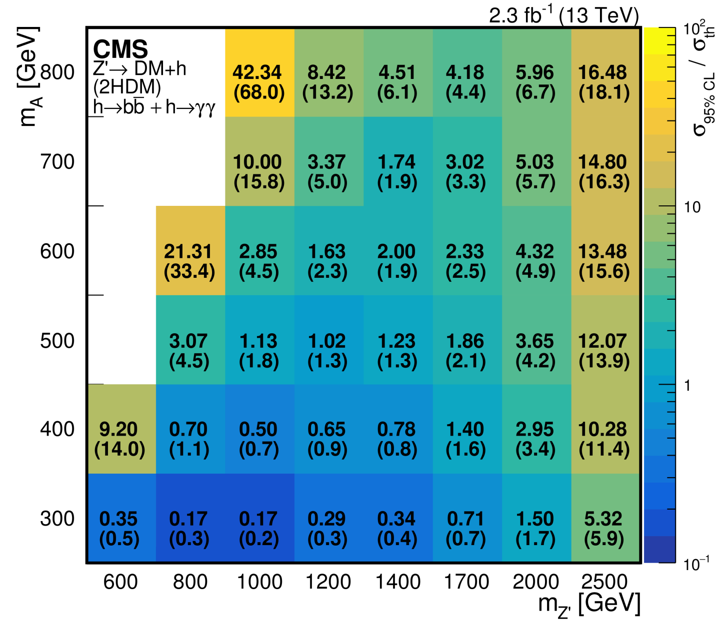
	CMS (resolved)	CMS (boosted)
Z+jets	Mass sideband	
W+jets	1l+0j CR	1l CR
Top	1l+1j CR	

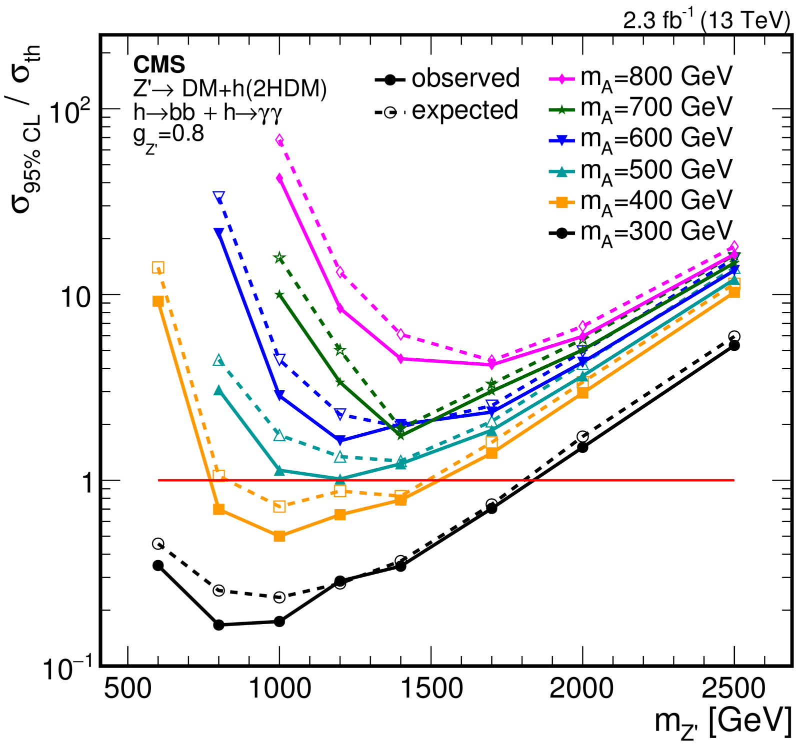
...s boson

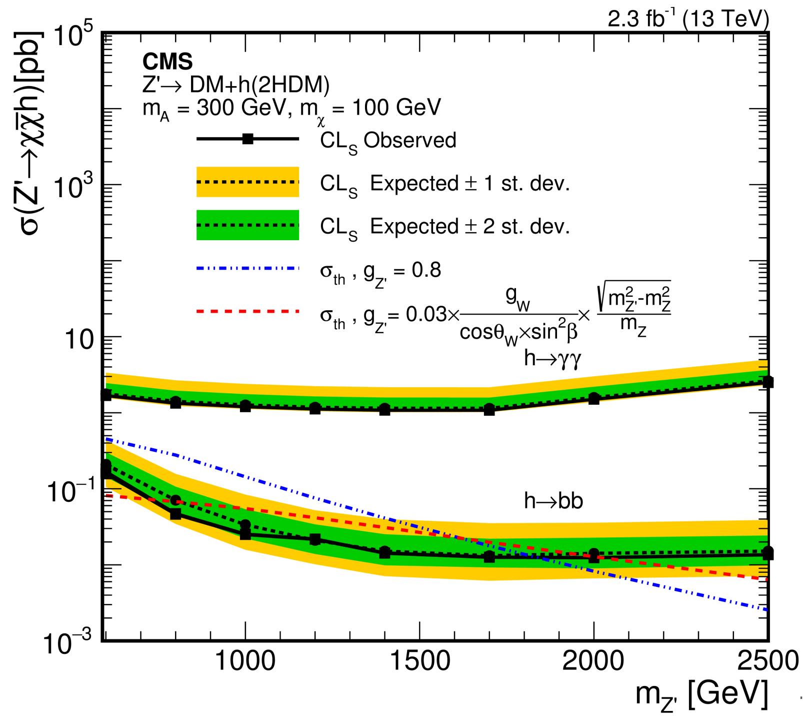
CMS-PAS-EXO-16-012

H(bb)+MET : 2HDM Limits

- Limits are put on 2HDM model
- Combined MonoH (bb) and MonoH(γγ) on 2015 data
  - Exclusion is driven by bb final state
  - Inclusion of γγ improves the low pT_{miss} results up to 20%







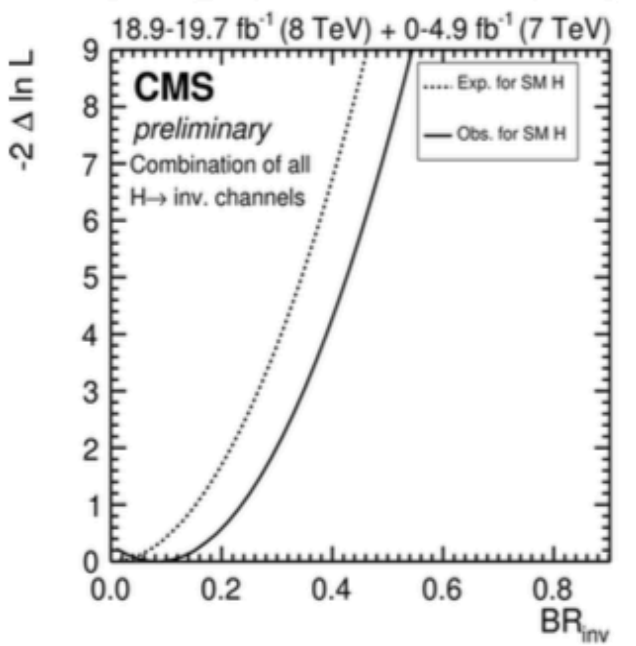
Summary

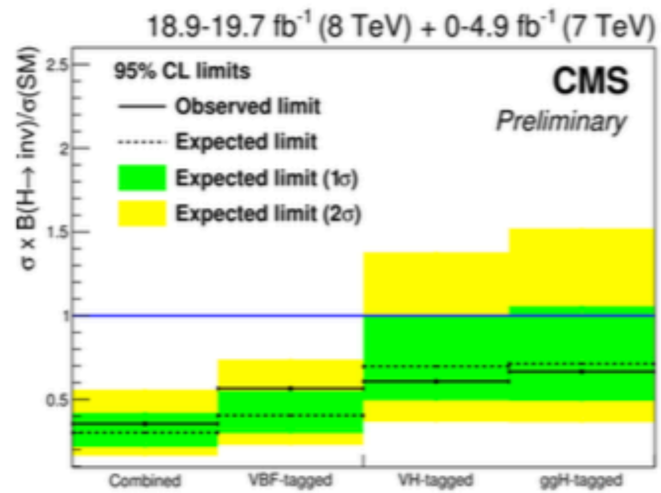
- No dark matter found yet!
- Still looking
  - Continue Higgs measurements and indirect searches
  - Exploring the invisible Higgs decays using full 2016 data
  - Higgs+Dark matter results are on-going using full 2016 data for different final states
  - Stay tuned!

Backup

Run 1 CMS direct searches - Combination

- Combine by production mode as well as full combination
  - ggH-tagged is monojet, VH-tagged is Z($\ell\ell$)H+Z(bb)H+V(had)H, VBF-tagged is VBF
- Obs. (exp.) limit on $\mathcal{B}(H \to inv.)$ at m_H =125 GeV is 36 (30)%

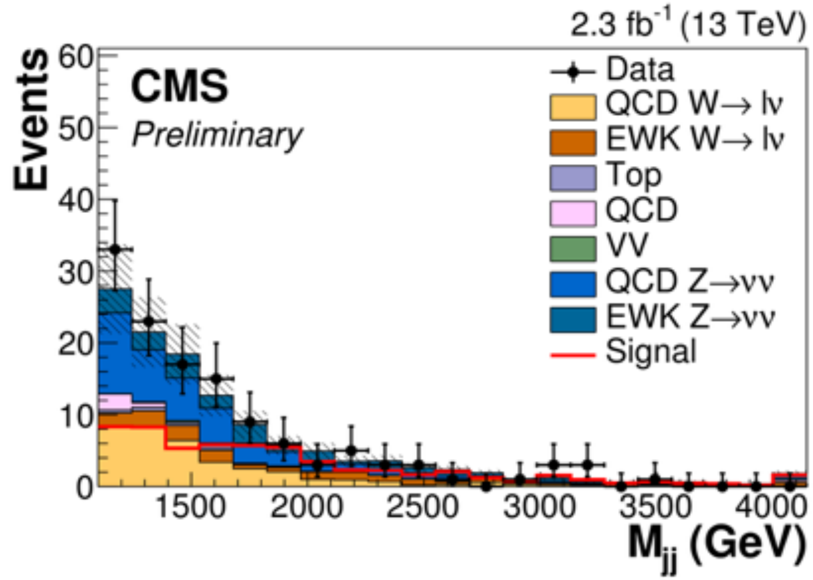




CMS-PAS-HIG-15-012

Higgs Invisible : VBF Mode

CMS-PAG-HIG-16-009



- Events with 2 high-pT forwards jets
- Special trigger with VBF topology
  - Level1 trigger : ETM trigger with 60 GeV
  - HLT : dijet mass 600 GeV and well separated in DR
- Offline Cuts
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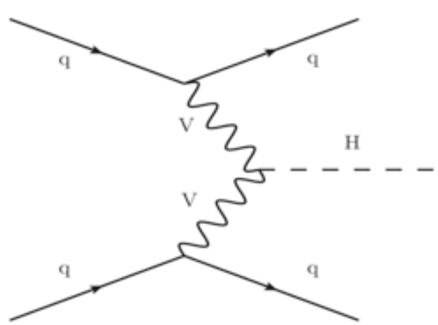
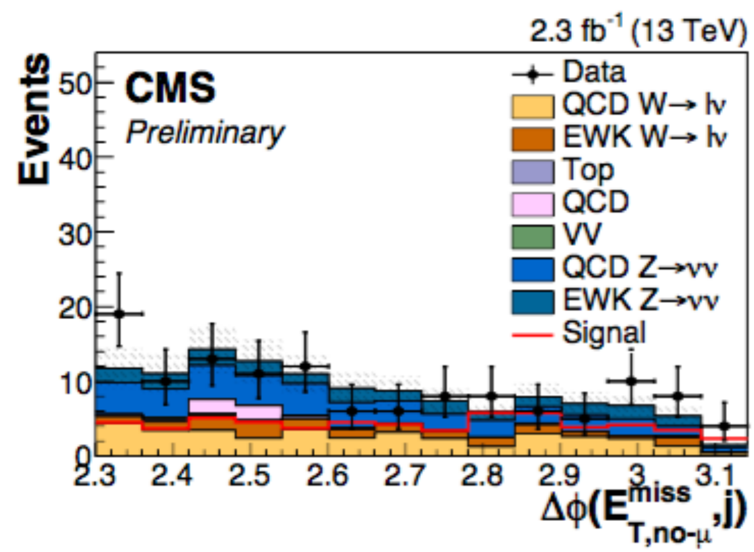




MonoHiggs (gg)

Table 4: Efficiency times acceptance and statistical uncertainty for the 2HDM in both the low- and high-p_T^{miss} categories. Samples that have negligible efficiencies in the low-p_T^{miss} category are shown with a dash (/).

Low-p_T^{miss} Efficiencies [%]						
m_A [GeV] / $m_{Z'}$ [GeV]	300	400	500	600	700	800
600	2.9 ± 2.0	11.3 ± 3.7	-	-	-	-
800	0.4 ± 0.7	0.7 ± 1.0	2.0 ± 1.6	7.2 ± 3.0	-	-
1000	0.1 ± 0.4	0.2 ± 0.5	0.3 ± 0.6	0.6 ± 0.9	1.7 ± 1.5	4.7 ± 2.5
1200	/	/	0.1 ± 0.4	0.1 ± 0.4	0.2 ± 0.6	0.5 ± 0.9
1400	/	/	/	/	0.1 ± 0.3	0.1 ± 0.4
1700	/	/	/	/	/	/
2000	/	/	/	/	/	/
2500	/	/	/	/	/	/

High-p_T^{miss} Efficiencies [%]						
m_A [GeV] / $m_{Z'}$ [GeV]	300	400	500	600	700	800
600	28.9 ± 5.4	14.9 ± 4.2	-	-	-	-
800	38.8 ± 5.8	37.0 ± 5.7	32.4 ± 5.5	23.0 ± 5.0	-	-
1000	42.6 ± 5.8	41.6 ± 5.8	40.4 ± 5.8	38.4 ± 5.7	35.0 ± 5.6	29.3 ± 5.4
1200	45.2 ± 5.9	44.8 ± 5.9	43.5 ± 5.9	43.1 ± 5.9	41.8 ± 5.8	39.6 ± 5.8
1400	46.6 ± 5.9	46.5 ± 5.9	45.8 ± 5.9	45.9 ± 5.9	44.6 ± 5.9	43.9 ± 5.9
1700	48.0 ± 5.9	48.2 ± 5.9	47.8 ± 5.9	47.7 ± 5.9	47.2 ± 5.9	47.0 ± 5.9
2000	47.4 ± 5.9	47.7 ± 5.9	47.5 ± 5.9	47.7 ± 5.9	47.9 ± 5.9	48.5 ± 5.9
2500	45.9 ± 5.9	45.8 ± 5.9	45.9 ± 5.9	46.5 ± 5.9	46.9 ± 5.9	46.7 ± 5.9

MonoHiggs (gg)

Table 5: Efficiency times acceptance and statistical uncertainty for the Baryonic Z' model in both the low- and high-p_T^{miss} categories. Efficiencies are calculated for several Z' mass points for a fixed $m_\chi = 1$ GeV.

$m_{Z'}$ [GeV]	Low-p_T^{miss} Efficiencies [%]	High-p_T^{miss} Efficiencies [%]
10	6.6 ± 2.9	7.0 ± 3.0
50	6.0 ± 2.8	5.6 ± 2.7
100	6.4 ± 2.9	5.9 ± 2.8
200	6.1 ± 2.8	7.1 ± 3.0
500	7.5 ± 3.1	12.6 ± 3.9
1000	5.4 ± 2.7	22.6 ± 4.9
2000	3.1 ± 2.1	32.0 ± 5.5
10000	1.0 ± 1.2	40.1 ± 5.8

MonoHiggs (gg)

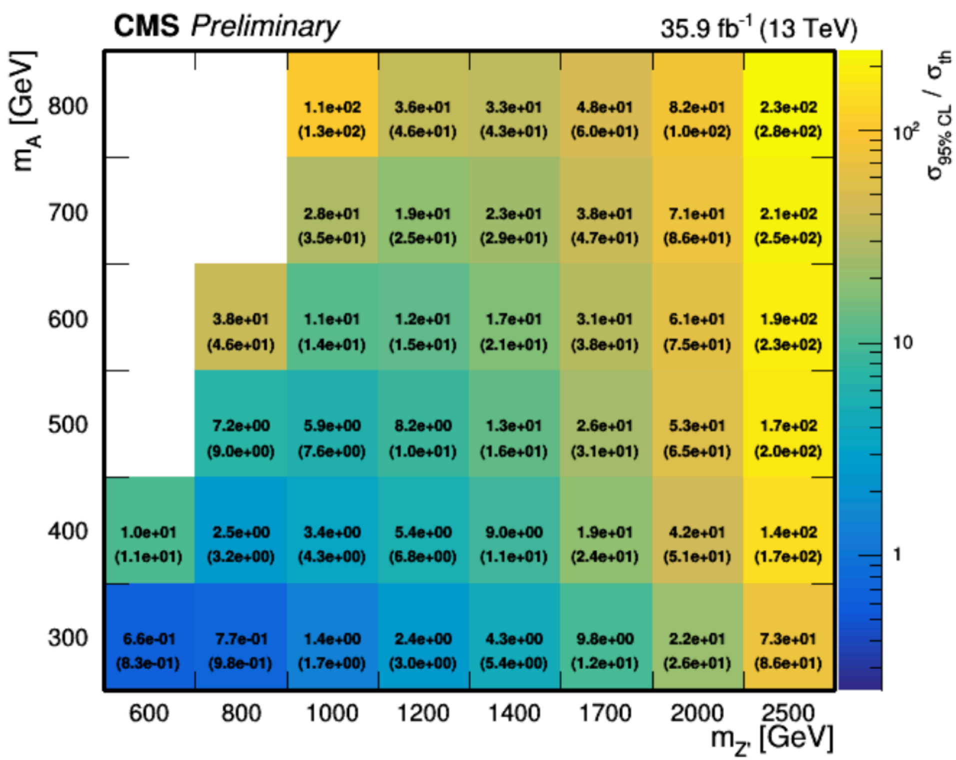


Figure 6: The observed (expected) 95% CL limits on the signal strength ($\sigma_{95\%CL}/\sigma_{th}$) for all 2HDM mass points shown in a grid of m_A and $m_{Z'}$. The theoretical cross section for each point is calculated assuming $g_{Z'} = 0.8$.

MonoHiggs

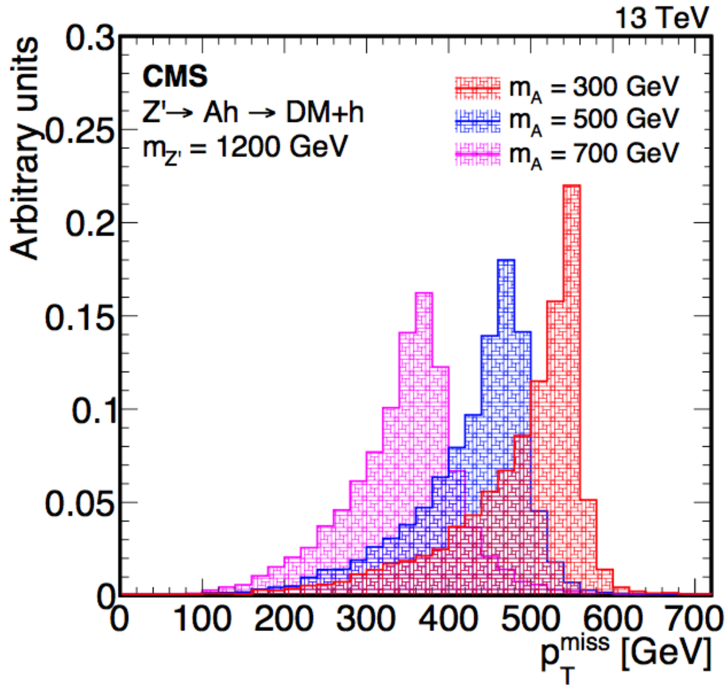


Figure 2: Distribution of p_T^{miss} at generator level for $Z' \to$ A h $\to$ DM+h with $m_A = 300$, 500, and 700 GeV with $m_{Z'} = 1200$ GeV. All other parameters of the model are fixed, as mentioned in the text.

MonoHiggs

The signal cross section is calculated for two assumptions on $g_{Z'}$: (i) a fixed value of $g_{Z'} = 0.8$, as considered in Ref. [9] and recommended in Ref. [11], and (ii) using the maximum value from electroweak global fits and constraints from dijet searches [7]:

$$g_{Z'} = 0.03 \frac{g_W}{\cos\theta_W \sin^2\beta} \frac{\sqrt{m_{Z'}^2 - m_Z^2}}{m_Z}, \quad (1)$$

yielding $g_{Z'} = 0.485$ for $m_{Z'} = 1$ TeV, and $g_{Z'} = 0.974$ for $m_{Z'} = 2$ TeV. It can be seen from Eq. 1 that $g_{Z'} = 0.8$ is the maximum allowed value of $g_{Z'}$ for $\tan\beta = 1$ and $m_{Z'} = 1.7$ TeV (the best reach of LHC as estimated by Ref. [7]). Note that this analysis does not consider the

contribution of another decay that gives a similar mono-h signature: $Z' \rightarrow Zh$ where $Z \rightarrow \nu\bar{\nu}$. The ratio of branching fractions, $\mathcal{B}(Z' \rightarrow Zh, Z \rightarrow \nu\bar{\nu})/\mathcal{B}(Z' \rightarrow Ah, A \rightarrow \chi\bar{\chi})$, is a function of $\tan\beta$ and $m_{Z'}$ and does not depend on $g_{Z'}$ since the value of $g_{Z'}$ cancels in the ratio.

How To Translate (Vector)

In general, the SI DM-nucleon scattering cross section takes the form

$$\sigma_{\mathrm{SI}} = \frac{f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}\,, \tag{4.1}$$

where $\mu_{n\chi} = m_n m_{\mathrm{DM}}/(m_n + m_{\mathrm{DM}})$ is the DM-nucleon reduced mass with $m_n \simeq 0.939\,\mathrm{GeV}$

For the vector mediator,

$$f(g_q) = 3 g_q\,,$$

and hence

$$\sigma_{\mathrm{SI}} \simeq 6.9 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2 .$$

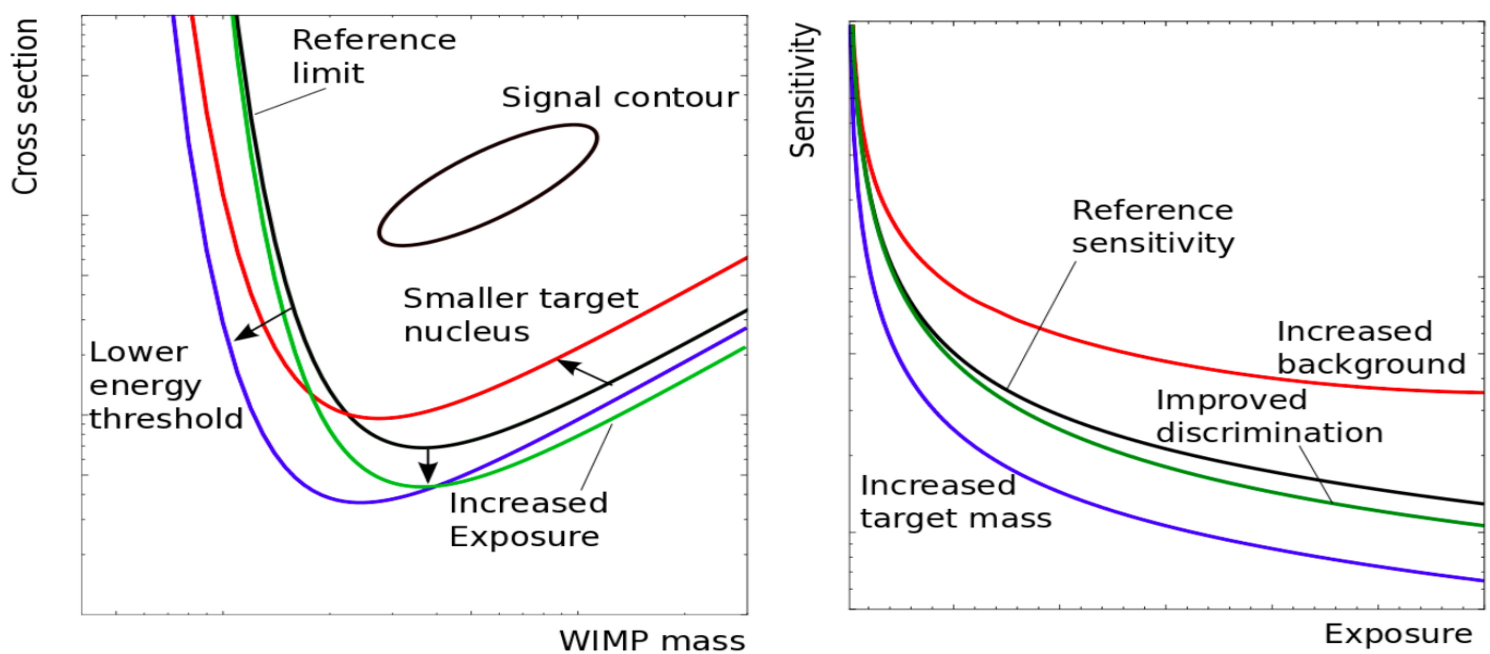
Direct detection

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{2\mu_A^2 \cdot m_\chi} \cdot \sigma_0 \cdot A^2 \cdot F^2 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v},t)}{v}\, \mathrm{d}^3 v, \tag{13}$$

with v_{esc} the escape velocity (see section 3.4) and the minimal velocity defined as

$$v_{min} = \sqrt{\frac{m_A \cdot E_{thr}}{2\mu_A^2}}. \tag{14}$$

The parameter E_{thr} describes the energy threshold of the detector and μ_{A} is the reduced mass of the WIMP-nucleus system. The left plot in figure 6 shows a generic limit (open black curve) on the dark matter cross-section with respect to the dark matter mass which can be calculated with equation 13. At low WIMP masses the sensitivity is reduced



+ Couplings

Most prominent couplings

Spin-independent vector coupling (V) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi \quad \xi_i\bar{q}_i\gamma_{\mu}q_i$

Spin-dependent axial-vector coupling (AV) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\gamma^5\chi \quad \xi_i\bar{q}_i\gamma_{\mu}\gamma^5 q_i$

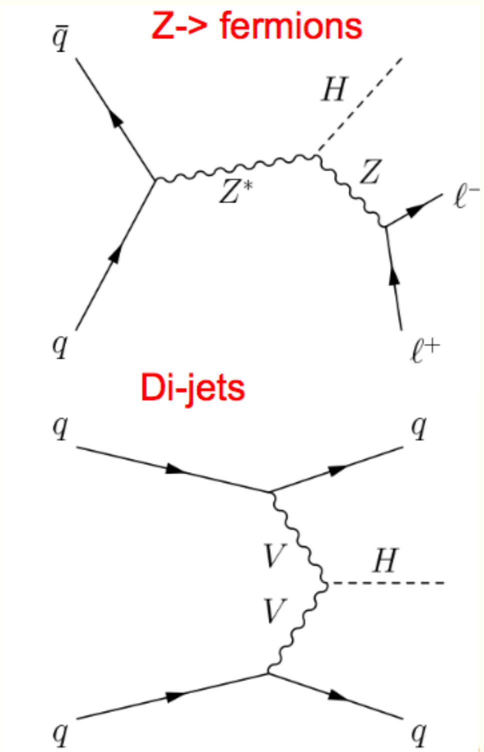
Name	Type	Operator	Coefficient
D1	scalar (qq)	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D5	vector	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	$1/M_*^2$
D8	axial-vector	$\bar{\chi}\gamma^{\mu}\gamma^5\chi\bar{q}\gamma_{\mu}\gamma^5 q$	$1/M_*^2$
D9	tensor	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D11	scalar (gg)	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	scalar	$\chi^{\dagger}\chi\bar{q}q$	m_q/M_*^2

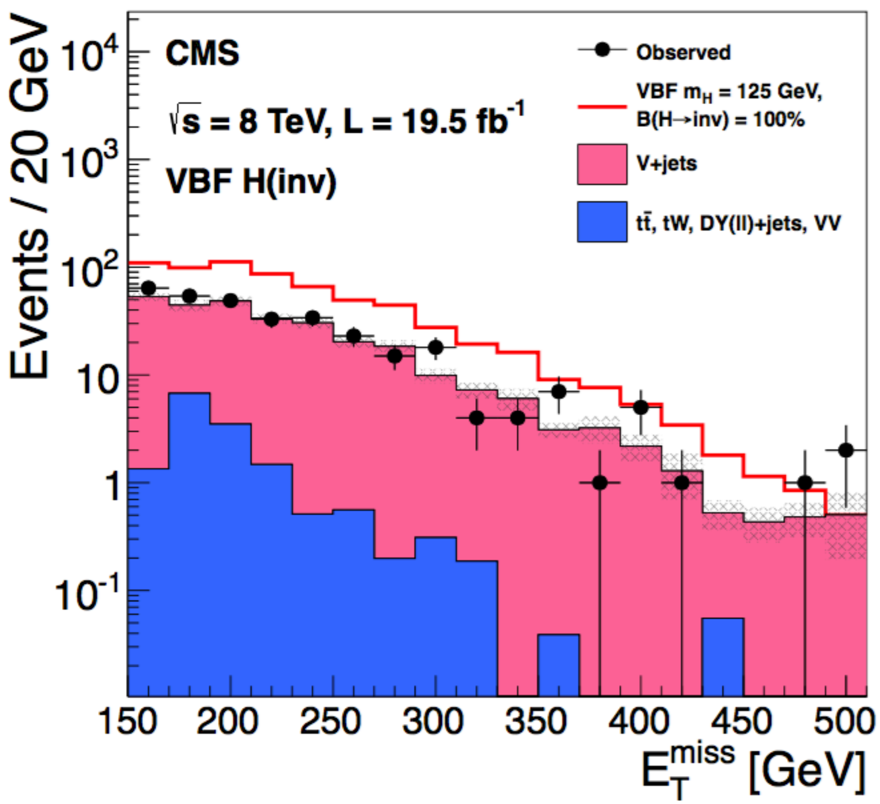
According to [J. Goodman et al., Phys. Rev D 82, 116010 (2010)]

The masses of strange and charm quarks are relevant for the cross sections of the D1 operator and they are set to 0.1 GeV and 1.42 GeV, respectively.

+ Higgs Modes : CMS VBF

Depending on its nature, DM will couple to theHiggs in various ways. Assuming a Higgs -> Invisible branching, one can search in several channels.



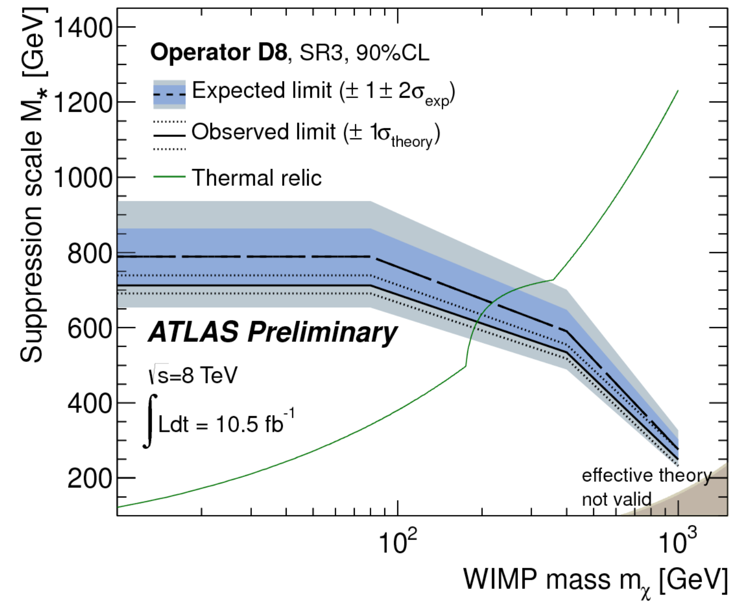


Validity of the EFT

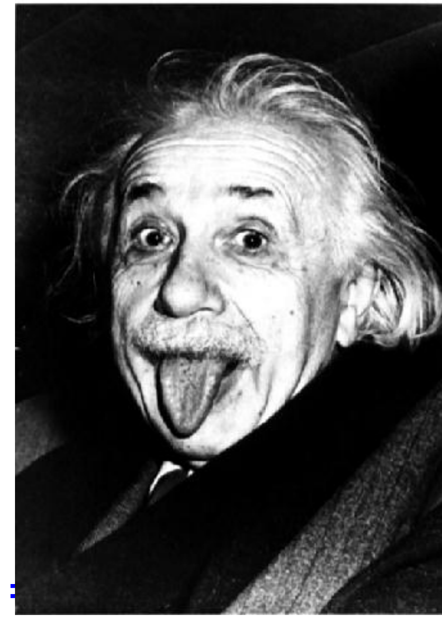
Busoni, De Simone, Morgante, Riotto, arXiv: 1307.2253

- EFT is strictly valid when $q^2 << M^2$ and $M > m_\chi$
- For the theory to be calculable, one further needs $g_\chi, g_q < 4\pi$, which implies : $\Lambda > m_\chi/4\pi$
- Further, from kinematics of the s-channel exchange, $q^2 > (2m_\chi)^2$
- Now since $2m_\chi < q < M$, implies $\Lambda > m_\chi/2\pi$
- This is important condition to keep in mind
  - This is the ATLAS monojet limit; it applies for m_χ <~ 1 TeV

ATLAS , arXiv: 1309.4017



Relativistic World



- Mass-energy equivalence – a grand idea!

Einstein's famous equation: $E = M$

The collision energy can manifest as mass!

For particles in motion: $E^2 - P_x^2 - P_y^2 - P_z^2$ =

Energy-Momentum is conserved in collisions

Low mass, but energetic particles create high mass ones

Relativity and Natural Measurement Units

Speed of light, $c = 1$

Instead of using kg, kilo-watt-hour …

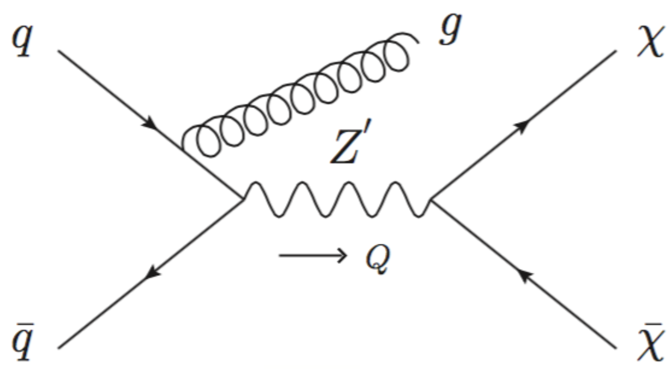
we can use a common unit for mass, energy and momentum called eV

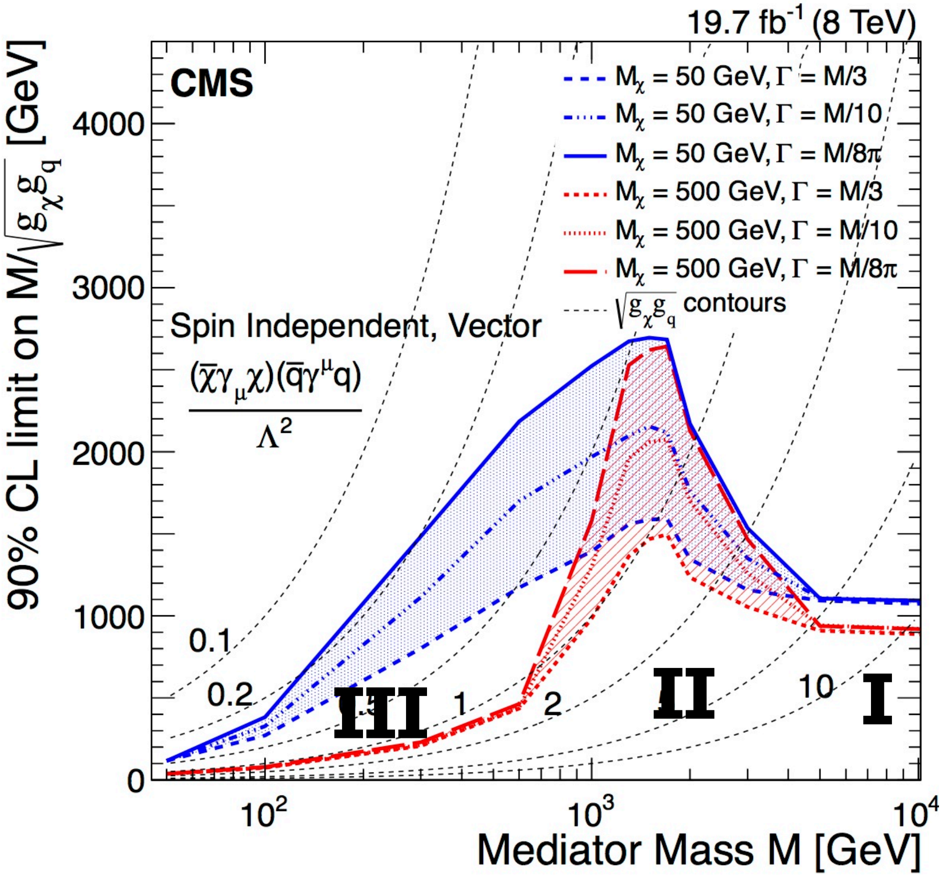
A common AA battery cell accelerates electrons to 1.5 eV

LHC accelerates protons (938 million eV mass) to 6.5 trillion eV

Light Mediator Case

- The most tricky case is that of light mediator
- First step : put in a mediating particle (e.g s-channel Z') and look at limits vs m_z





- EFT gives good/conservative results above a few hundred GeV (high M)
  - Region I – EFT is good
  - Region II – EFT underestimate
  - Region III – EFT overestimate