Higgs-to-Invisible and Dark Matter Searches with the CMS experiment at the LHC

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on behalf of the CMS Collaboration

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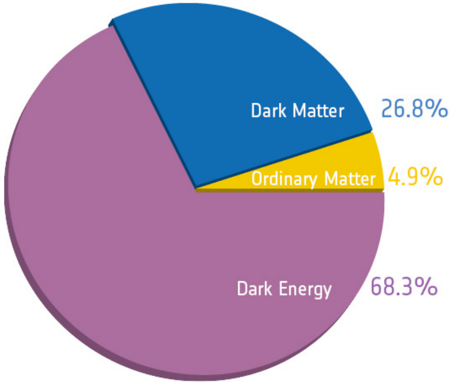
Higgs Couplings 2017, 6-10 November 2017, Heidelberg (Germany)

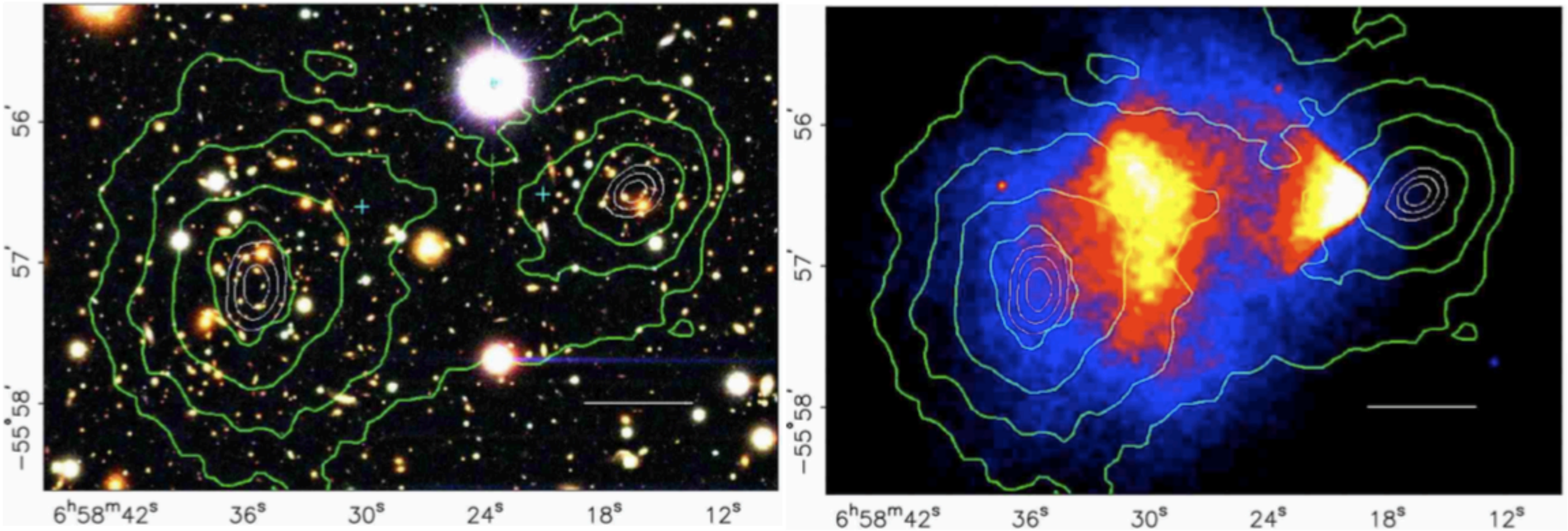
Contents

Motivation

- Strong astrophysical evidence indicates that dark matter (DM) exists [1].

- There is no evidence yet for non-gravitational interactions between DM and standard model (SM) particles.





arXiv:astro-ph/0608407

- The LHC provides an opportunity to probe these interactions by directly producing DM particles.

Why Higgs to Invisible?

- Higgs boson decays to invisible final states predicted by many beyond the SM (BSM) theories, where final state particles can be DM candidates.

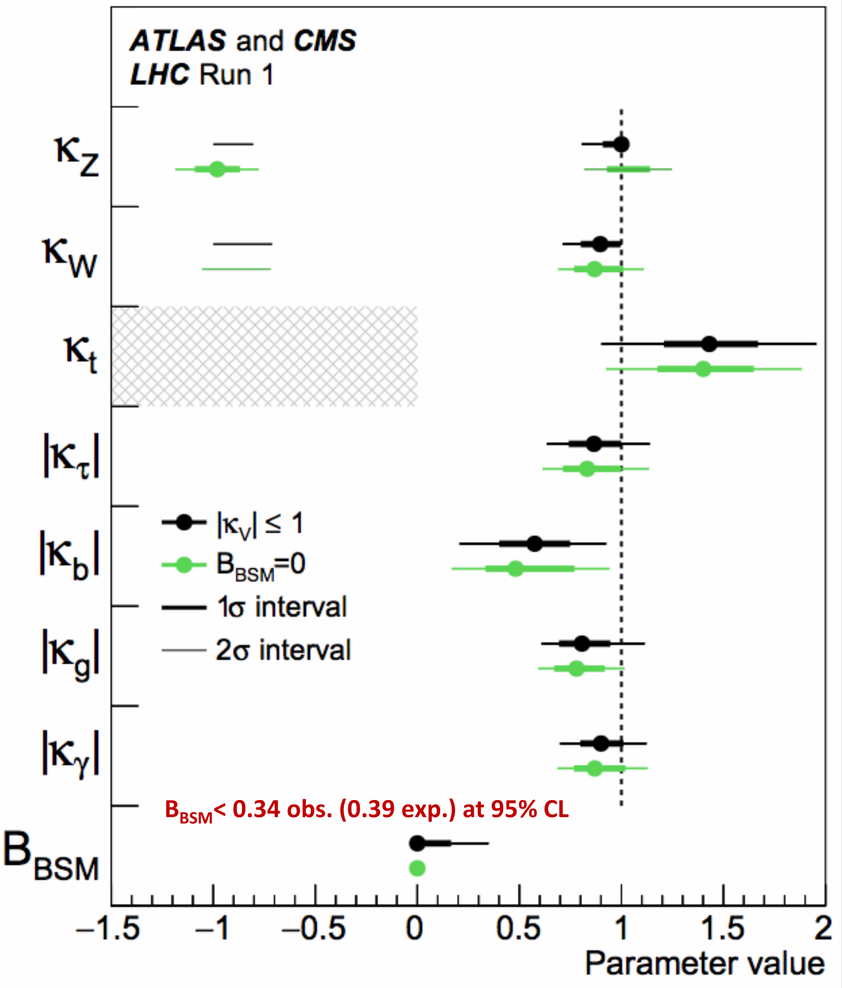
- The Higgs boson (125 GeV) measurements are compatible with SM expectations.

- However, large uncertainties can accommodate BSM properties.

- BSM Higgs decays affect the total Higgs boson width.

- The SM branching ratio H(inv.) is ~0.12% (H(4ν)).

- Invisibly decaying Higgs boson is a hint of new physics.

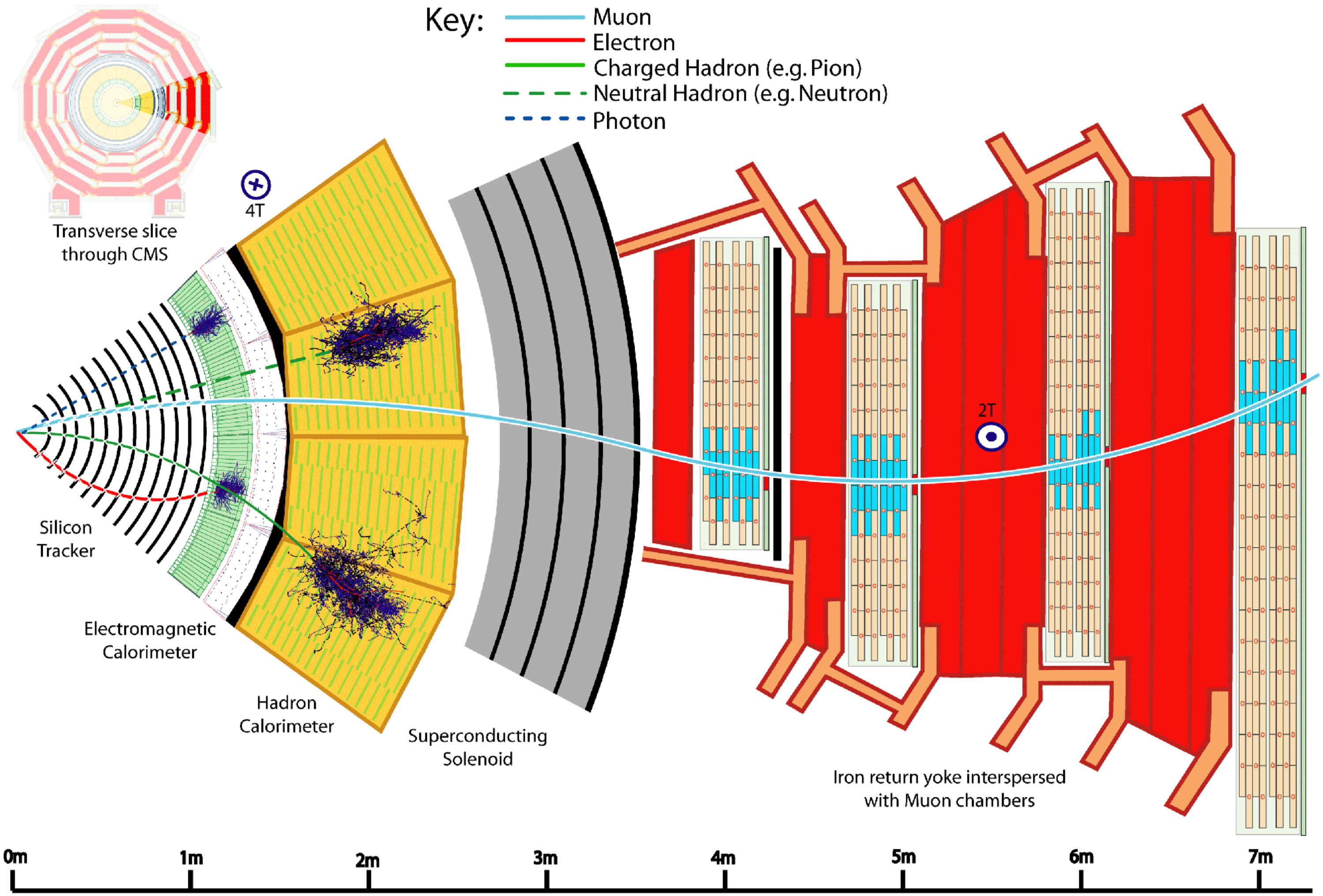


B_{BSM}< 0.34 obs. (0.39 exp.) at 95% CL

arXiv.: 1606.02266

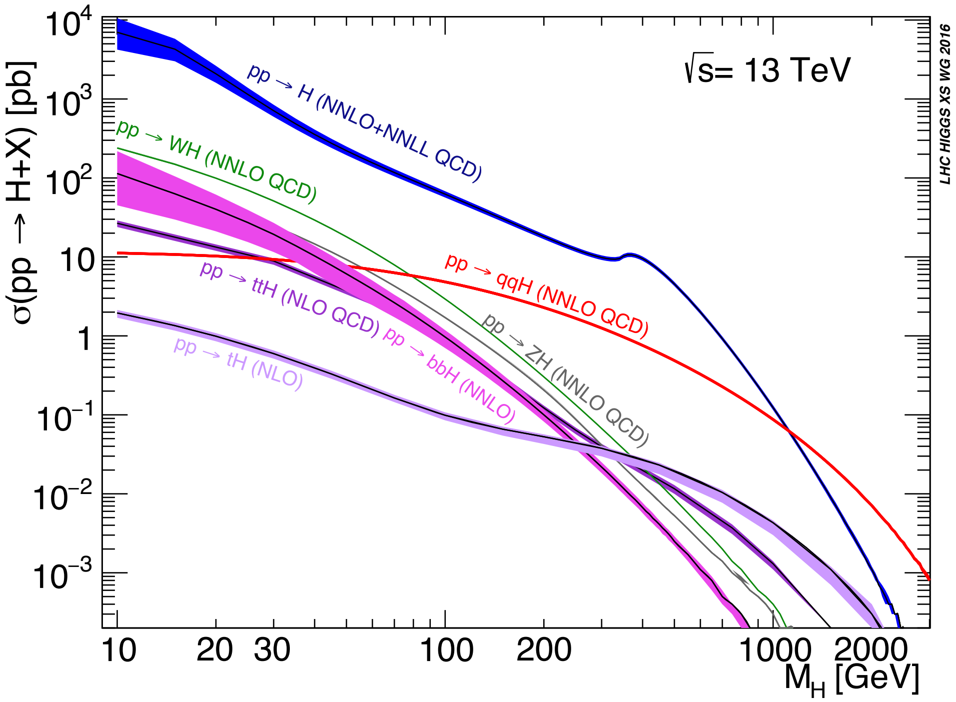
The CMS experiment

- All the CMS sub-detectors are vital for MET-searches.



Direct Searches

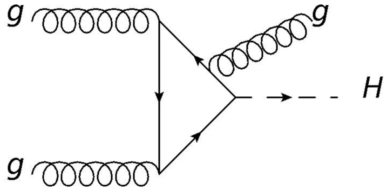
- Higgs boson has to recoil against a visible system.
- Missing transverse energy (MET) has to be present in the final state.



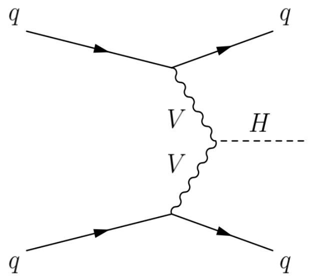
YR4: arXiv:1610.07922

higher production cross-section

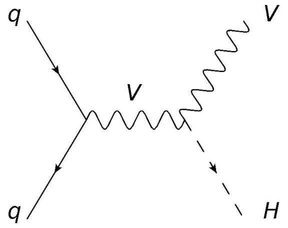
gluon-gluon fusion (ggH)



vector boson fusion (VBF)



vector boson associated production (VH)



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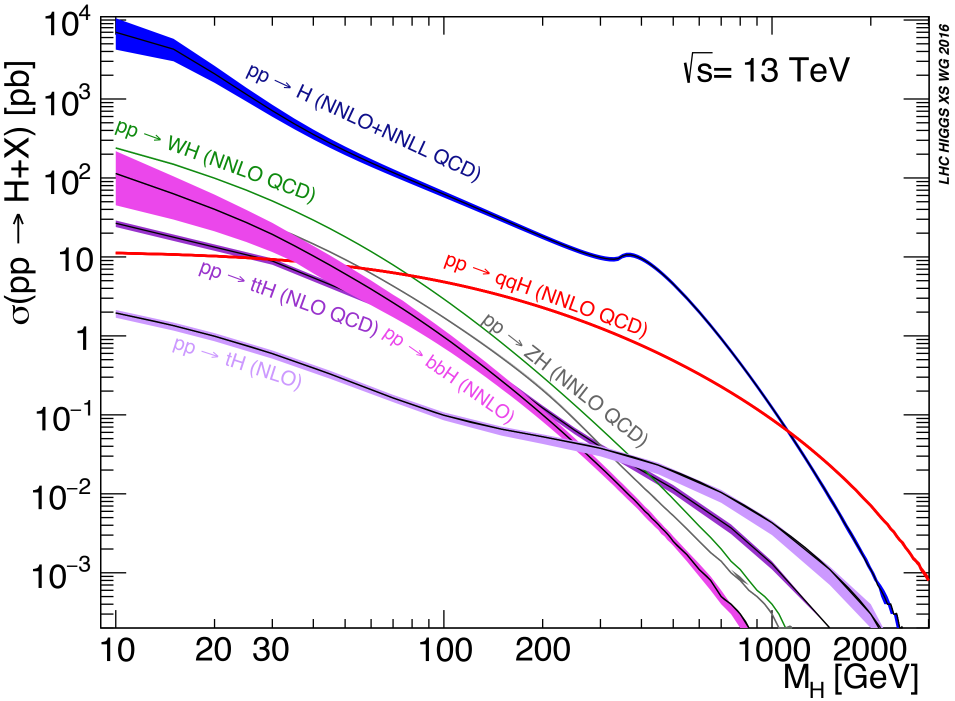

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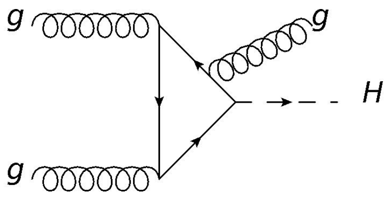

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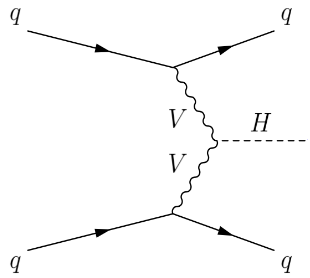

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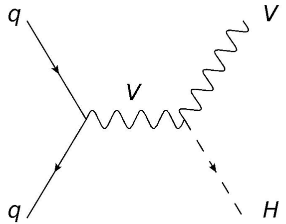


Z($\ell^+\ell^-$)H(inv.)

- **CMS EXO-16-052** [Submitted to Eur. Phys. J. C] uses 35.9/fb (2016 data).

- Leptons (opposite-sign same-flavour) coming from Z boson decay are expected to be isolated from hadronic activity in the event.

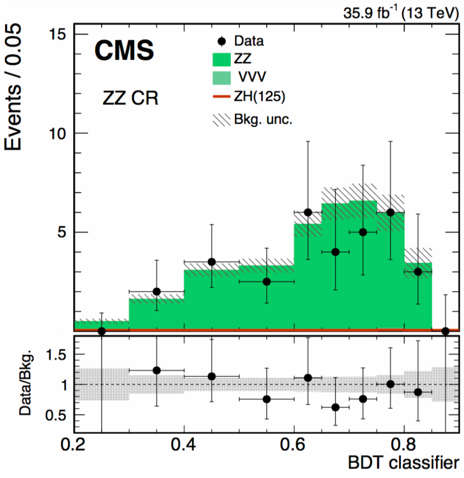
- There are many SM processes that mimic the dilepton+MET final state:
  - continuum ZZ(2ℓ2ν), irreducible background (60%);
  - WZ(ℓνℓℓ), where ℓ from W is mis-identified (25%);
  - others: WW(ℓνℓν), Top quark, Drell Yang Z/γ*(ℓℓ).
- Methods based on control samples in data are used to estimate backgrounds.
- min$\Delta\phi$(jet,MET) > 0.5 rad is used to further reduce background due to jet mismeasurement.

- *Method A*: A shape-based analysis binned in MET is employed to extract the final result.

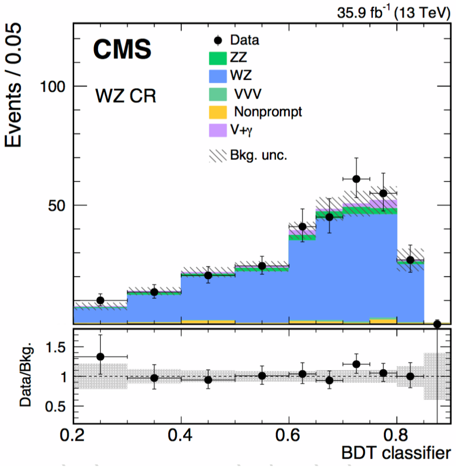
- *Method B*: A multivariate classifier is employed to increase the sensitivity, using a set of 12 variables to train a multiclass boosted decision tree (BDT).

- $|m_{\ell\ell} - m_Z|$ (dilepton mass);
- $p_T^{\ell 1}$ (leading lepton transverse momentum);
- $p_T^{\ell 2}$ (subleading lepton transverse momentum);
- $p_T^{\ell\ell}$ (dilepton transverse momentum);
- $|\eta^{\ell 1}|$ (leading lepton pseudorapidity);
- $|\eta^{\ell 2}|$ (subleading lepton pseudorapidity);
- E_T^{miss} (missing transverse energy);
- $m_T(p_T^{\ell 1}, E_T^{\text{miss}})$ (leading lepton transverse mass);
- $m_T(p_T^{\ell 2}, E_T^{\text{miss}})$ (subleading lepton transverse mass);
- $\Delta\phi(\vec{p_T}^{\ell\ell}, \vec{p_T}^{\text{miss}})$ (azimuthal separation between dilepton and missing energy);
- $\Delta R_{\ell\ell}$ (separation between leptons); and
- $|\cos\theta_{\ell 1}^{CS}|$ (cosine of Collins–Soper angle for leading lepton).

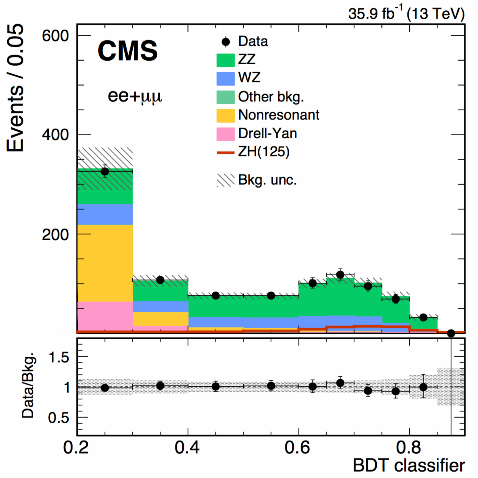
$Z(\ell^+\ell^-)H(\text{inv.})$



ZZ control region

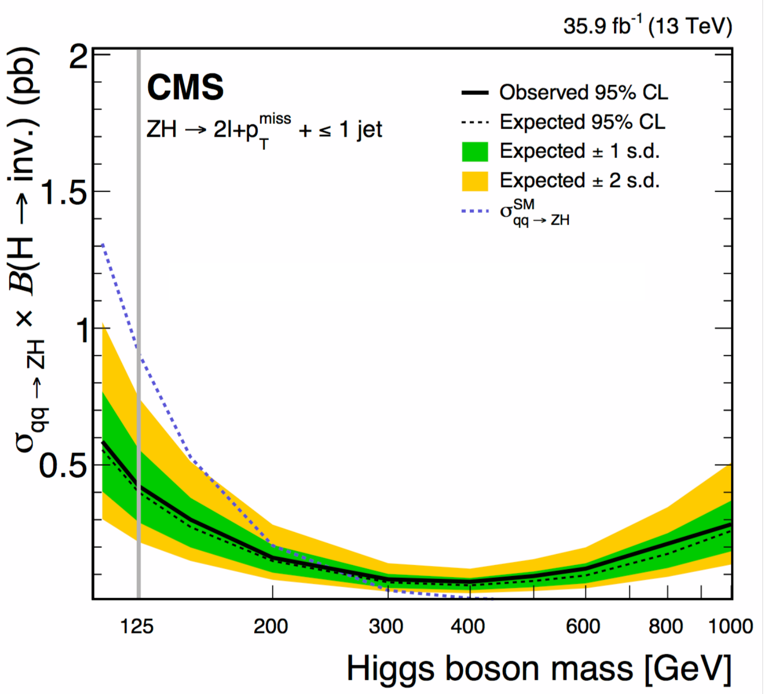


WZ control region



signal region

- No significant excess of events is observed over the SM expectation.
- The observed (expected) 95% confidence level upper limit on $\mathcal{B}$(H(inv.)) assuming SM production rate is:
  - *Method A*: 0.45 (0.44);
  - *Method B*: 0.40 (0.42).



Direct Searches

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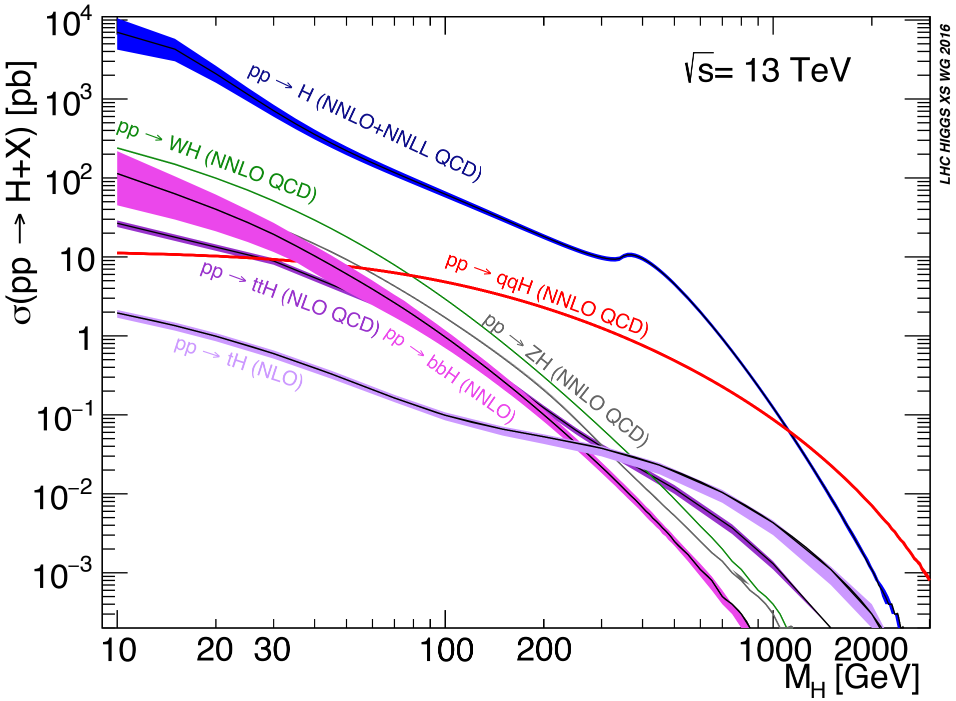
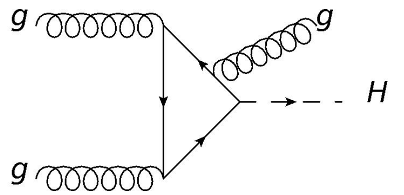


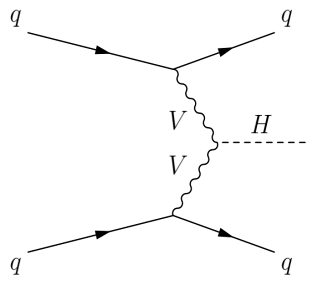
YR4: arXiv:1610.07922

higher production cross-section

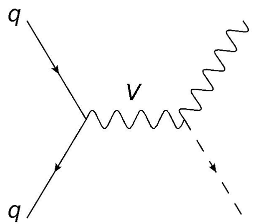
gluon-gluon fusion (ggH)



vector boson fusion (VBF)



vector boson associated production (VH)



ggH(inv.)/V(jj)H(inv.)

- **CMS PAS EXO-16-048** uses 35.9/fb (2016 data).

- The final state is characterised by: no leptons, at least one energetic jet (from ISR, or hadronic decays of a W or Z boson), and large MET.

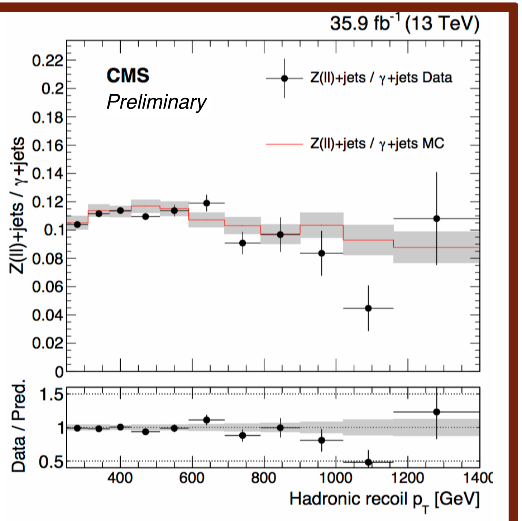
- mono-V: MET > 250 GeV, conditions on leading fat-jet ($p_T > 250$ GeV, $\eta < 2.4$, $65 < m_J < 105$ GeV).
- mono-jet: MET > 200 GeV, fails any of the mono-V fat-jet requirements.

Category	Expected signal composition
mono-jet	72.82% ggH, 21.52% VBF, 3.31% WH, 1.94% ZH, 0.63% ggZH
mono-V	38.71% ggH, 7.05% VBF, 32.90% WH, 14.62% ZH, 6.72% ggZH

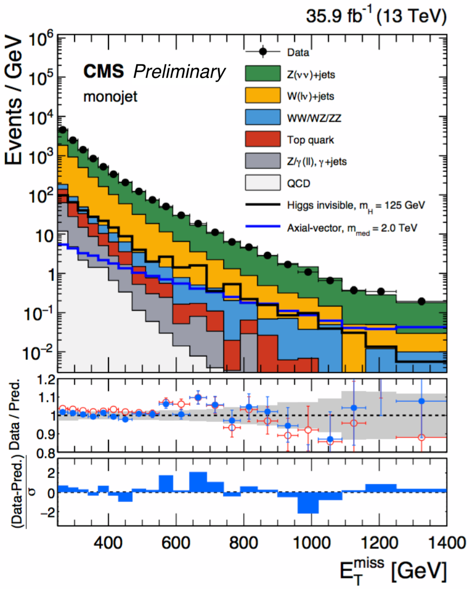
- Backgrounds to this search are: Z(νν)+jets, irreducible background, and W($\ell\nu$)+jets, where ℓ from W is mis-identified (90%).
- CRs: dimuon, dielectron, single-muon, single-electron, and γ+jets.
- minΔϕ(jet,MET) > 0.5 rad is used to reduce QCD multijet background in which large MET arises from jet mismeasurement.

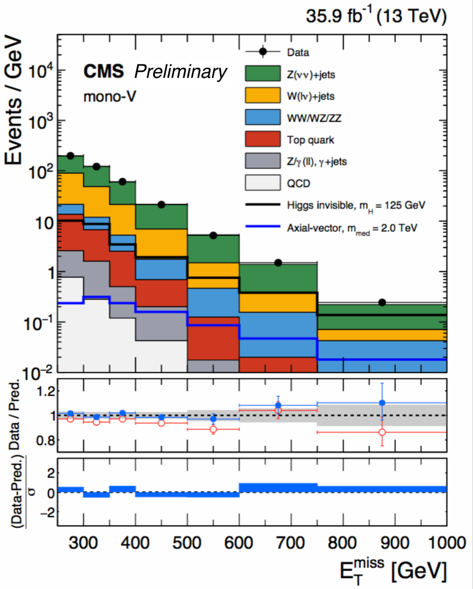
- V+jets backgrounds are determined through a simultaneous maximum likelihood fit to all the CRs (hadronic recoil p_T, proxy) and SRs (MET).

ggH(inv.)/V(jj)H(inv.)



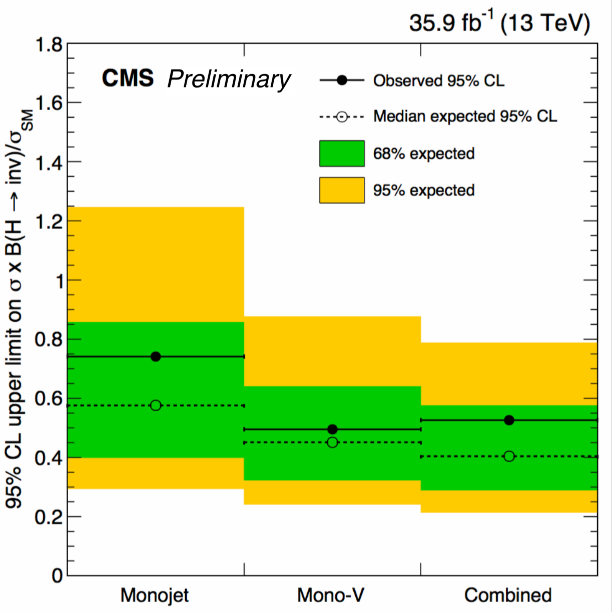
- Major improvement in theory calculations for γ/Z, W/Z.





- No significant excess of events is observed over the SM expectation.

- The observed (expected) 95% confidence level upper limit on $\mathcal{B}$(H(inv.)) is:
  mono-jet 0.74 (0.57),
  mono-V 0.49 (0.45),
  combined 0.53 (0.40).



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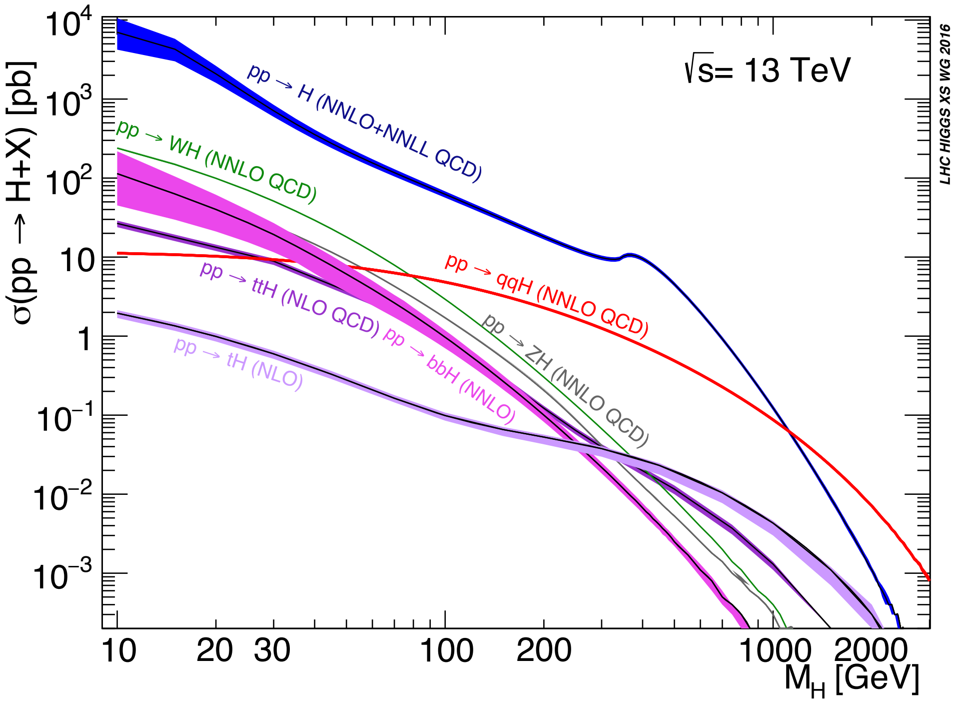
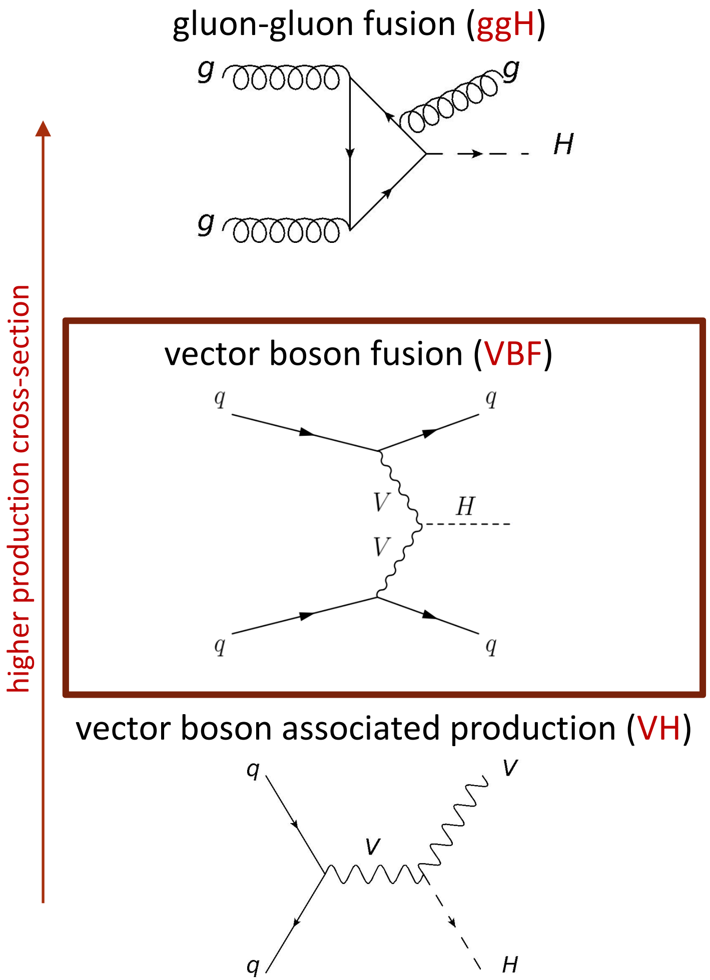


YR4: arXiv:1610.07922


gluon-gluon fusion (ggH)

vector boson fusion (VBF)

vector boson associated production (VH)

VBF H(inv.)

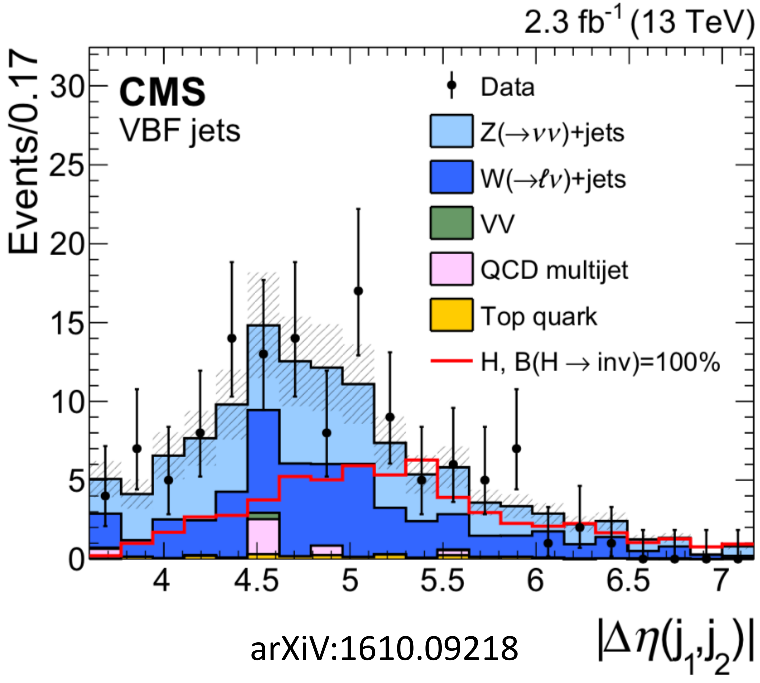
- **CMS HIG-16-016** [JHEP 02 (2017) 135] uses 5.1, 19.7, and 2.3/fb (2015 data).

- The VBF channel is the most sensitive, with no colour connection between the jets which have a large pseudo-rapidity gap.

- The final state is characterised by: two jets with large pseudo-rapidity separation and large MET well-separated from any jets.

- The major backgrounds are:
  - Z(νν)+jets, irreducible background;
  - W(ℓν)+jets, where ℓ from W is missed;
  - QCD multijet.

- minΔϕ(jet,MET) > 2.3 rad is used to reduce QCD multijet background in which large MET arises from jet mismeasurement.



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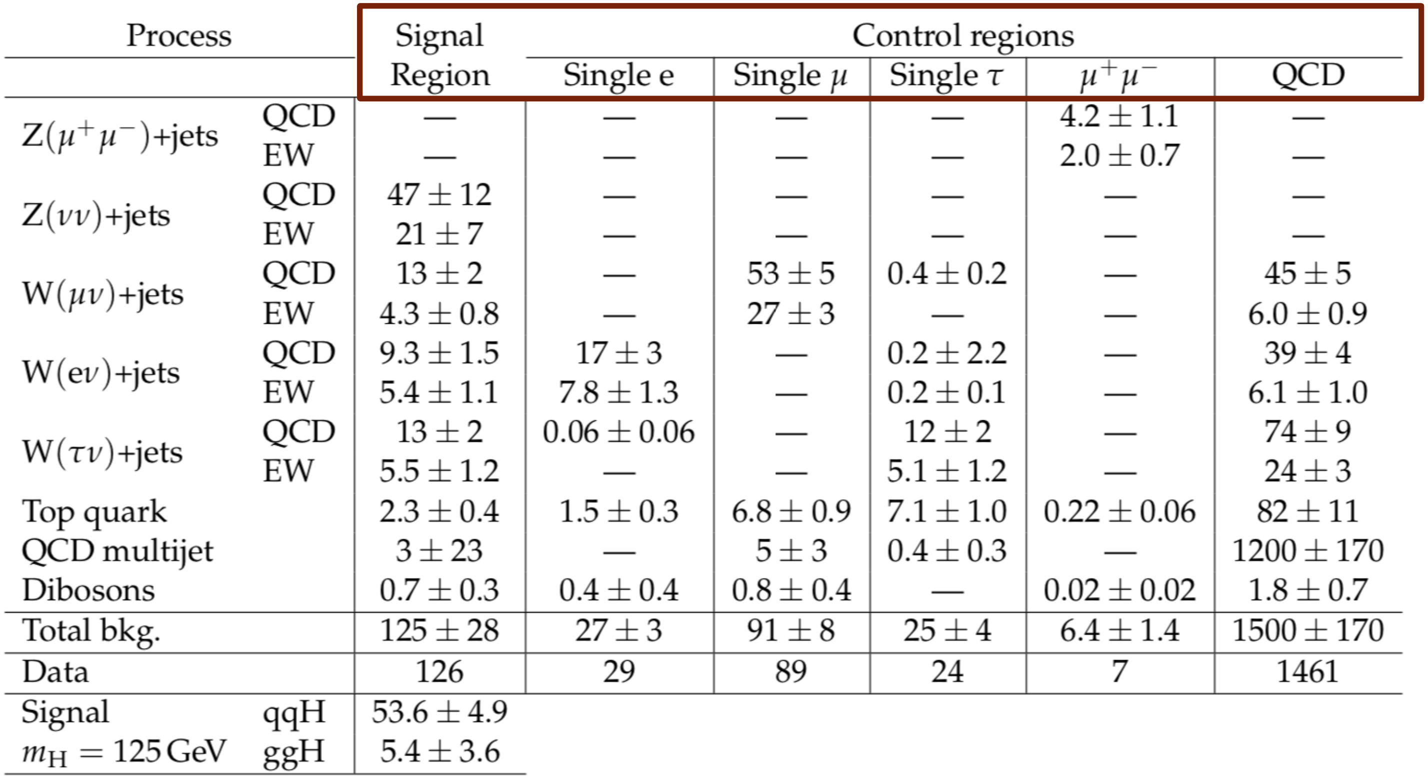
VBF H(inv.)



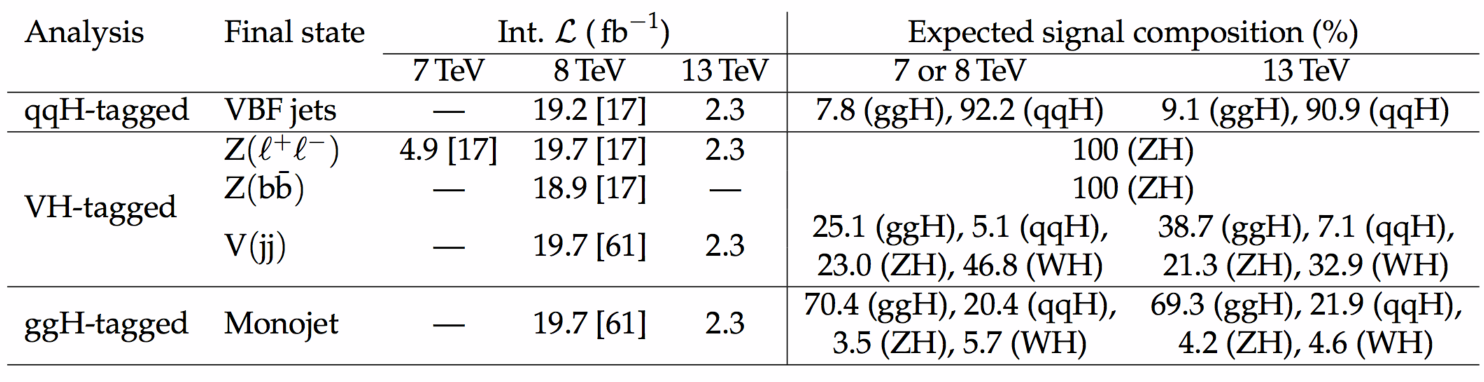
Process		Signal Region	Control regions				
			Single e	Single μ	Single τ	$\mu^+\mu^-$	QCD
Z($\mu^+\mu^-$)+jets	QCD	—	—	—	—	4.2 ± 1.1	—
	EW	—	—	—	—	2.0 ± 0.7	—
Z($\nu\nu$)+jets	QCD	47 ± 12	—	—	—	—	—
	EW	21 ± 7	—	—	—	—	—
W($\mu\nu$)+jets	QCD	13 ± 2	—	53 ± 5	0.4 ± 0.2	—	45 ± 5
	EW	4.3 ± 0.8	—	27 ± 3	—	—	6.0 ± 0.9
W($e\nu$)+jets	QCD	9.3 ± 1.5	17 ± 3	—	0.2 ± 2.2	—	39 ± 4
	EW	5.4 ± 1.1	7.8 ± 1.3	—	0.2 ± 0.1	—	6.1 ± 1.0
W($\tau\nu$)+jets	QCD	13 ± 2	0.06 ± 0.06	—	12 ± 2	—	74 ± 9
	EW	5.5 ± 1.2	—	—	5.1 ± 1.2	—	24 ± 3
Top quark		2.3 ± 0.4	1.5 ± 0.3	6.8 ± 0.9	7.1 ± 1.0	0.22 ± 0.06	82 ± 11
QCD multijet		3 ± 23	—	5 ± 3	0.4 ± 0.3	—	1200 ± 170
Dibosons		0.7 ± 0.3	0.4 ± 0.4	0.8 ± 0.4	—	0.02 ± 0.02	1.8 ± 0.7
Total bkg.		125 ± 28	27 ± 3	91 ± 8	25 ± 4	6.4 ± 1.4	1500 ± 170
Data		126	29	89	24	7	1461
Signal	qqH	53.6 ± 4.9					
$m_H = 125\,\mathrm{GeV}$	ggH	5.4 ± 3.6					

- The search is based on a cut-and-count method, and no significant excess of events is observed over the SM expectation.

- The observed (expected) 95% confidence level upper limit on $\mathcal{B}$(H(inv.)) assuming SM production rate is: 0.44 (0.31) for the combination of Run1 + Run2-2015 VBF-only H(inv.).

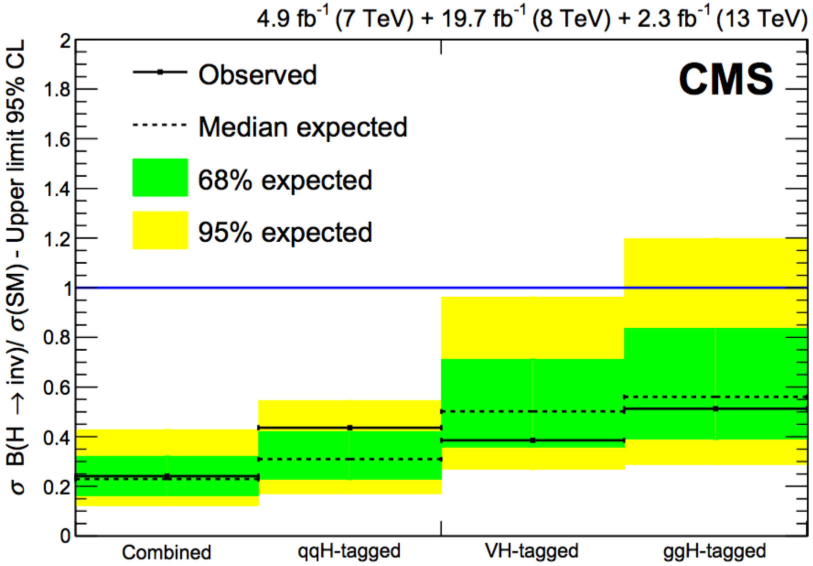
Combination of H(inv.) searches

- **CMS HIG-16-016** [JHEP 02 (2017) 135]
- The data collected corresponds to integrated luminosities of 5.1, 19.7, and 2.3 /fb at centre-of-mass energies of 7, 8, and 13 TeV respectively.



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), 23.0 (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)

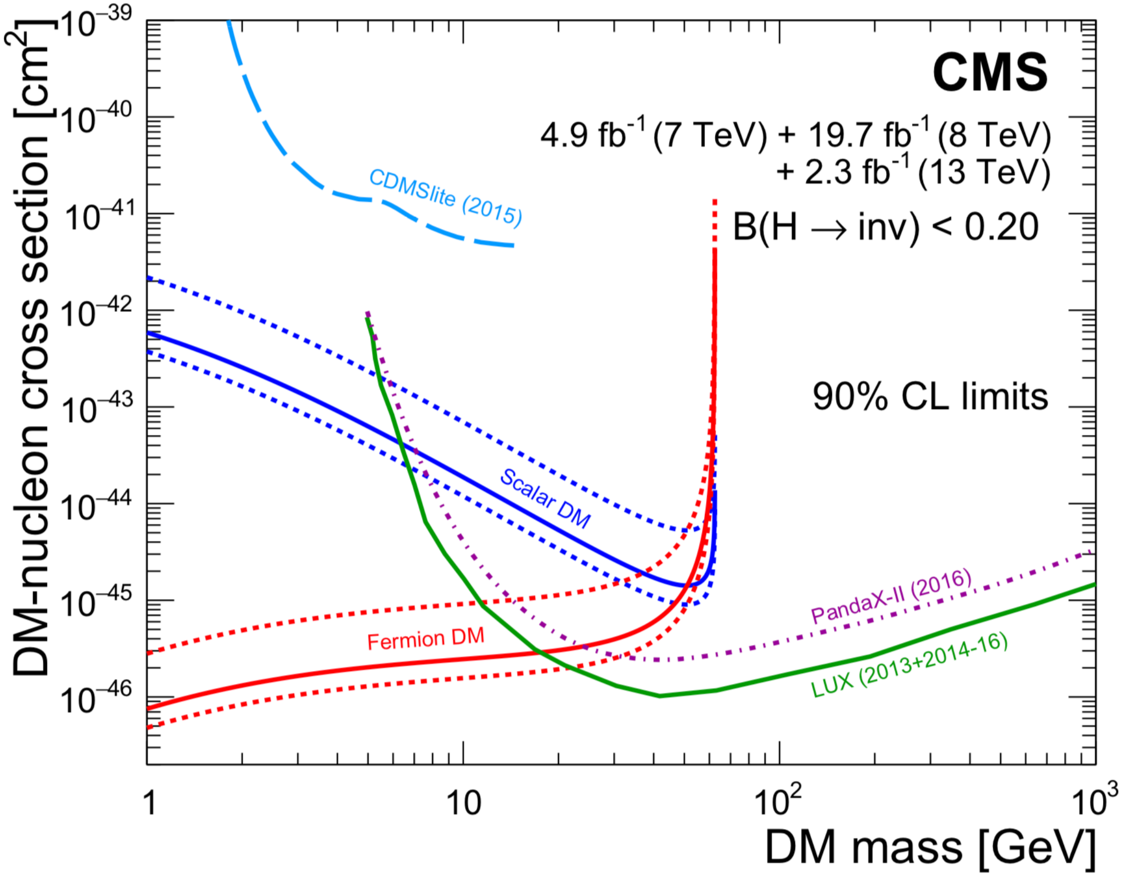
- The observed (expected) 95% confidence level upper limit on $\mathcal{B}$(H(inv.)) assuming SM production rate is: 0.24 (0.23).



DM Interpretation

- $\mathcal{B}$(H(inv.)) translated into DM-nucleon spin-independent cross-section limits as a function of DM mass (90% CL to compare to direct detection experiments).
- Use Higgs-Portal models [9] assuming **scalar**/**fermion** DM.

- LHC limits complementary to direct detection experiments.



mono-H(bb+γγ) + DM

- **CMS EXO-16-012** [accepted by JHEP, arXiv 1703.05236] uses 2.3/fb (2015 data).

- ***H(bb)***:
  - It has the largest branching fraction (~58%), but with relatively poor mass resolution (~10%).
  - The final state is characterised by: jet(s) in the boosted (resolved) regime with $p_T^{j(j)} > 150$ (200) GeV, and large MET.
  - Backgrounds:
    - VH is an irreducible background;
    - Z(νν)+jets, Top quark, and W+jets CRs (or Top quark + W+jets) for the resolved (boosted) regime.
  - Signal and backgrounds events are compared to data and fitted simultaneously in the SR and CRs in three p_T^{miss} bins for both resolved and boosted regimes.

mono-H(bb+γγ) + DM

- **CMS EXO-16-012** [accepted by JHEP, arXiv 1703.05236] uses 2.3/fb (2015 data).

- ***H(γγ)***:
  - It has a small branching fraction (~0.2%), but with high precision in reconstructed $m_{\gamma\gamma}$ (resolution 1-2%).

  - The search seeks excess of events over SM prediction in spectrum $m_{\gamma\gamma}$, large MET.

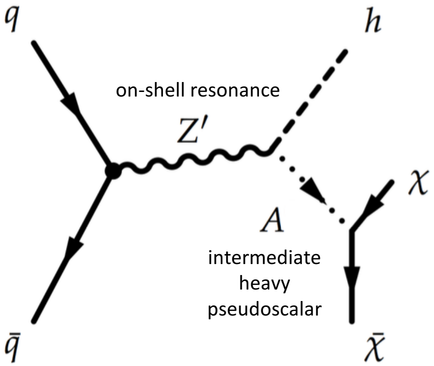
  - Backgrounds:
    - main source arises from jets with high-EM energy content;
    - VH is an irreducible background;
    - resonant backgrounds arise from decays of the SM Higgs boson to two photons;
    - there are several non-resonant backgrounds: dijet and multijet; EWK (t)t, (Z)Z, or W+(γ)γ; γγ and γ+jets; and DY+jets.

  - Signal and resonant backgrounds are estimated through counting approach in SR, using $p_T^{\gamma\gamma}$,$m_{\gamma\gamma}$ and MET as discriminating variables.

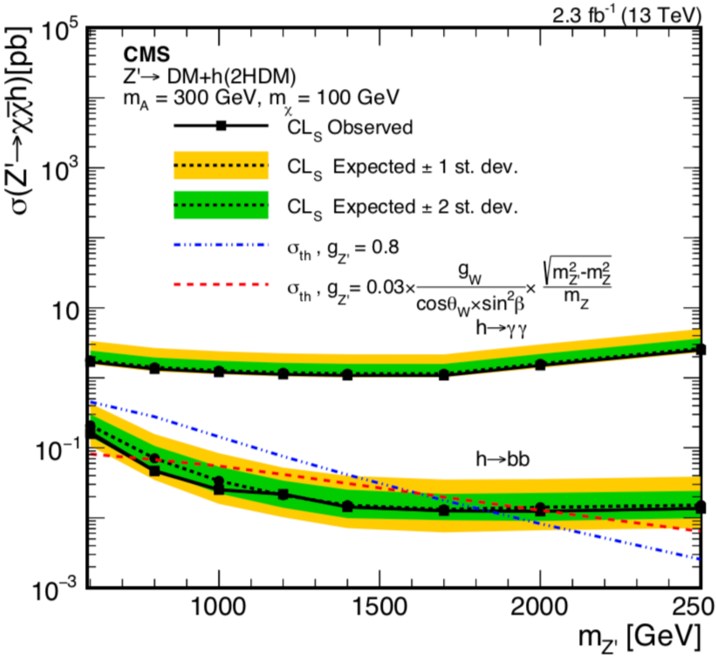
  - Control samples in data are used to estimate reducible background.

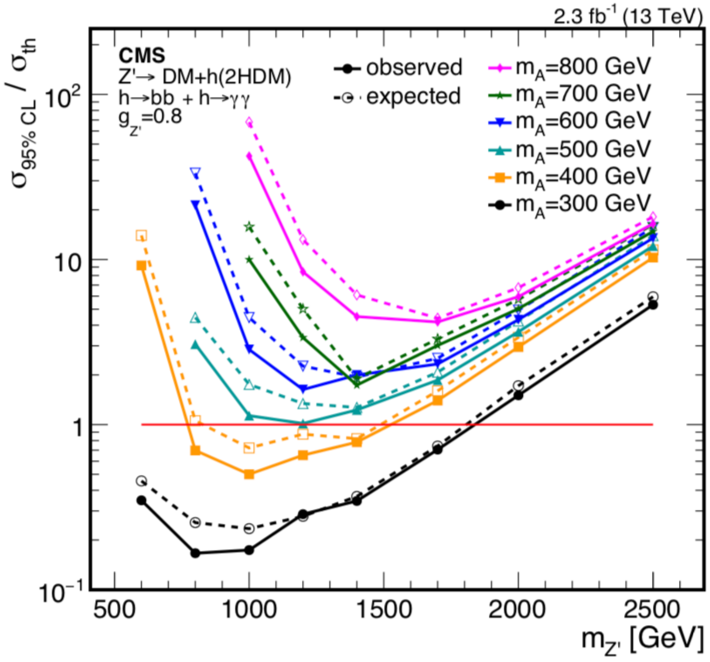
mono-H(bb+γγ) + DM

- The results have been interpreted using a benchmark “simplified model” [7]: Z’-two-Higgs-doublet-model [8].
- The results are interpreted in terms of an upper limit on the production cross section of DM candidates in association with a Higgs boson via Z’(AH).



- For m_A=300 GeV, the observed data exclude 600 < $m_{Z'}$ < 1860 GeV using $g_{Z'}$=0.8, and 770 < $m_{Z'}$ < 2040 GeV using the constrained value of $g_{Z'}$.

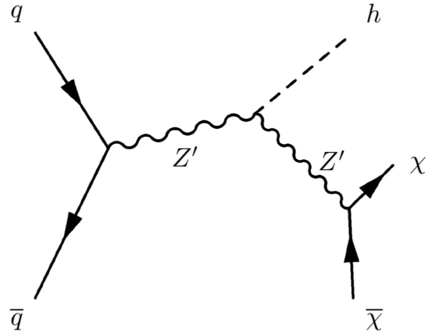




mono-H(γγ) + DM

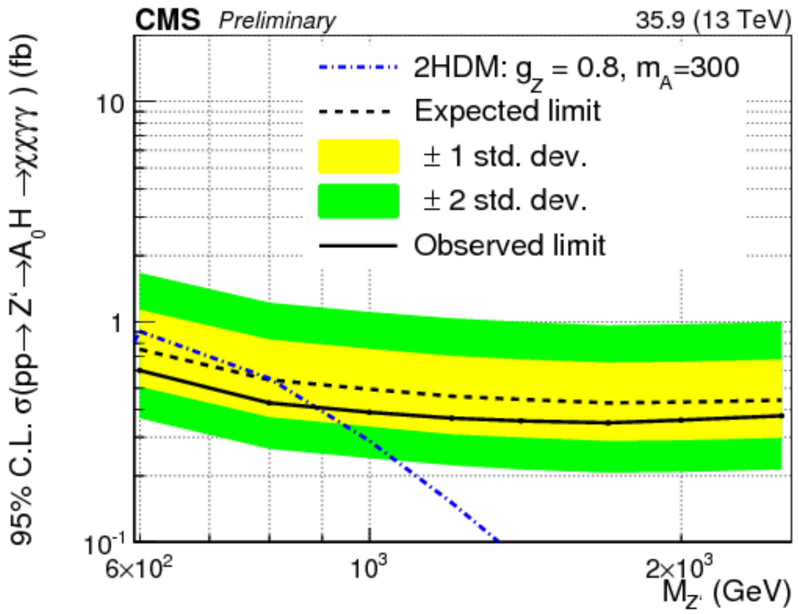
- **CMS PAS EXO-16-054** uses 35.9/fb (2016 data).

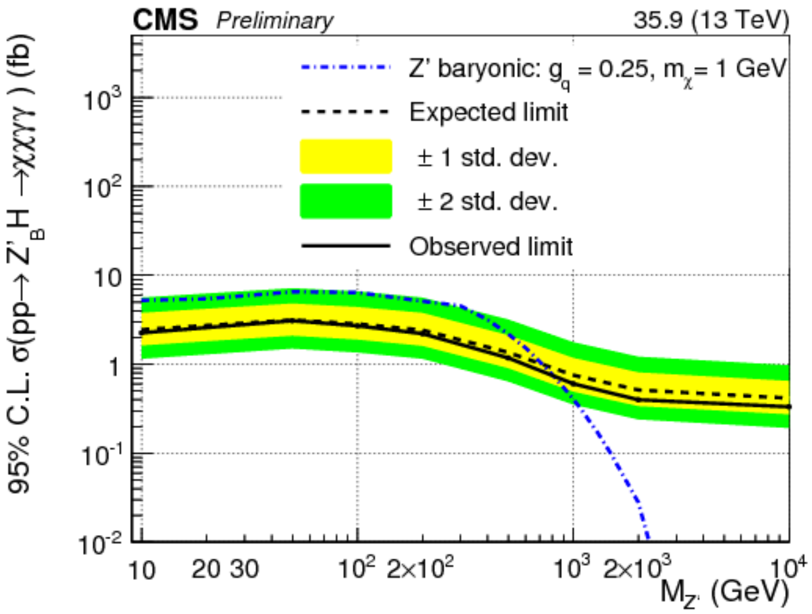
- A new result for H(γγ) using an additional interpretation (Baryonic Z’ model).



- Z’-2HDM: for m_A = 300 GeV, the observed data exclude $m_{Z'} < 900$ GeV using $g_{Z'}=0.8$

- Z_B’: for m_χ = 1 GeV, the observed data exclude $m_{Z'} < 800$ GeV using $g_q=0.25$.





Conclusions

- Direct searches for Higgs boson decays to invisible final states have been carried out in the three main production channels.

Channel	Observed (Expected) Upper Limit @ 95% CL on $\mathcal{B}$(H(inv.))
ZH (MVA-BDT)	0.40 (0.42)
mono-jet + mono-V	0.53 (0.40)
VBF (Run1 + Run2-2015)	0.44 (0.31)
Combination	**0.24 (0.23)**

- Using Z’-two-Higgs-doublet-model, a combination of mono-H searches excludes:
  - $600 < m_{Z'} < 1860$ GeV using $g_{Z'}=0.8$;
  - $770 < m_{Z'} < 2040$ GeV using the constrained value of $g_{Z'}$.

- Using Z_B’ model, mono-H(γγ) excludes $m_{Z'} < 800$ GeV.

Backup Slides

References

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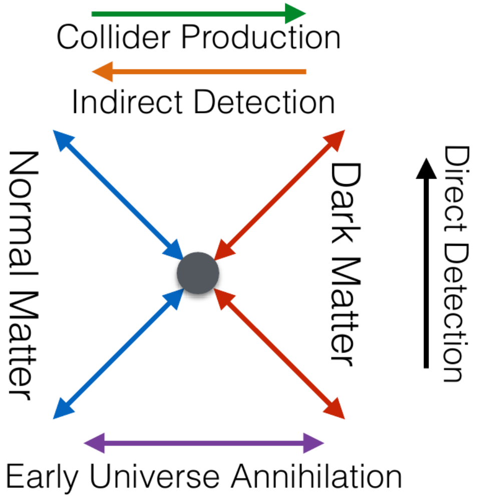
Dark Matter

- The dark matter is supposed to be a thermal relic of the early Universe.
- The comparison between direct and indirect detection is model dependent.
- A theoretical guidance is needed (LHC DM forum).



Collider Production

Indirect Detection

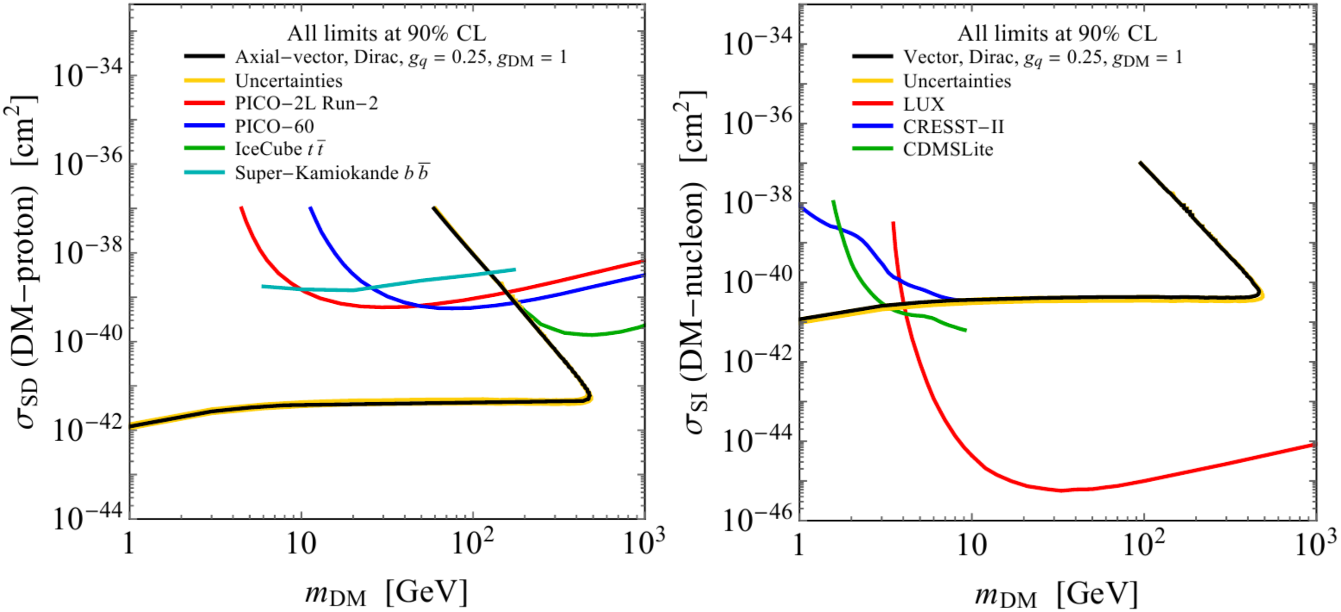
Normal Matter

Dark Matter

Direct Detection

Early Universe Annihilation

arXiv:1603.04156



$\mathrm{CL_S}$ method

- The limit is computed using the modified frequentist approach $\mathrm{CL_s}$ (confidence level) [2,3] based on asymptotic formulas [4,5], exploiting a simultaneous maximum likelihood fit to the signal region as well as the control regions, in which the systematic uncertainties are incorporated as nuisance parameters.

- Perform a single bin counting experiment assuming B(H → inv.) = 100%.

- $\mathrm{CL_S}$ statistic is used, which is the number of times more likely the signal hypothesis is than the background hypothesis.

$$CL_s = \frac{P(q_\mu \geqslant q_\mu^{obs} | \mu \cdot s + b)}{P(q_\mu \geqslant q_\mu^{obs} | b)} \qquad q_\mu = -2 \ln \frac{\mathcal{L}(obs | \mu \cdot s + b, \hat{\theta}_\mu)}{\mathcal{L}(obs | \hat{\mu} \cdot s + b, \hat{\theta})}$$

- Excluding signal models which are less than 5% likely to give data means to exclude everything with $\mathrm{CL_{S+B}} < 5\%$.

$Z(\ell^+\ell^-)H(\text{inv.})$

- The final state is characterised by:

  - pair of same-flavour, oppositely charged, isolated electrons or muons;
  - $m_{\ell\ell}$ within Z mass window (+-15 GeV);
  - no additional leptons;
  - no high-p_T jets or b-tagged jets;
  - large MET.

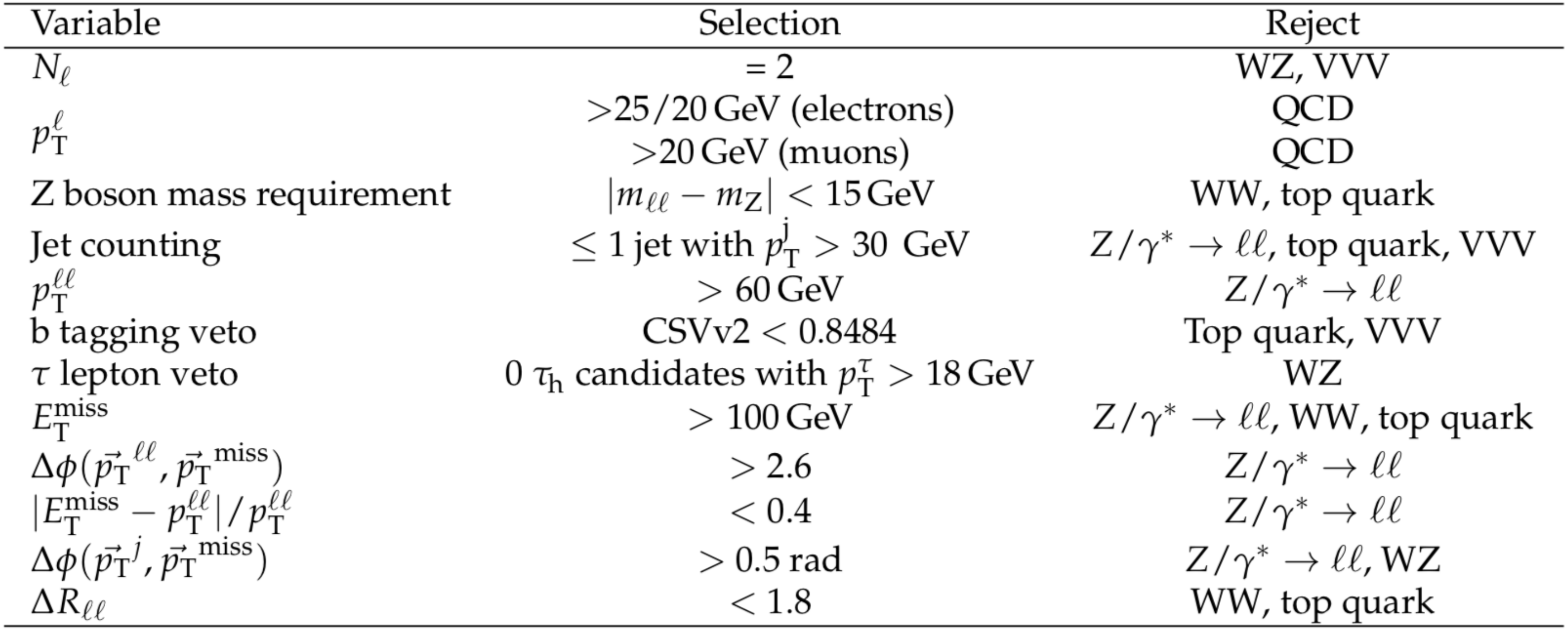
- The event selection is optimised using three main variables (to mainly face DY and Top quark), and leading to the criteria:

  - MET > 100 GeV;
  - $\Delta\phi(\ell\ell,\text{MET}) > 2.6$ (2.8, CMS PAS EXO-16-038) rad;
  - $|\text{MET}-p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.4$.

- min$\Delta\phi(\text{jet},\text{MET}) > 0.5$ rad is used to further reduce background due to jet mismeasurement.

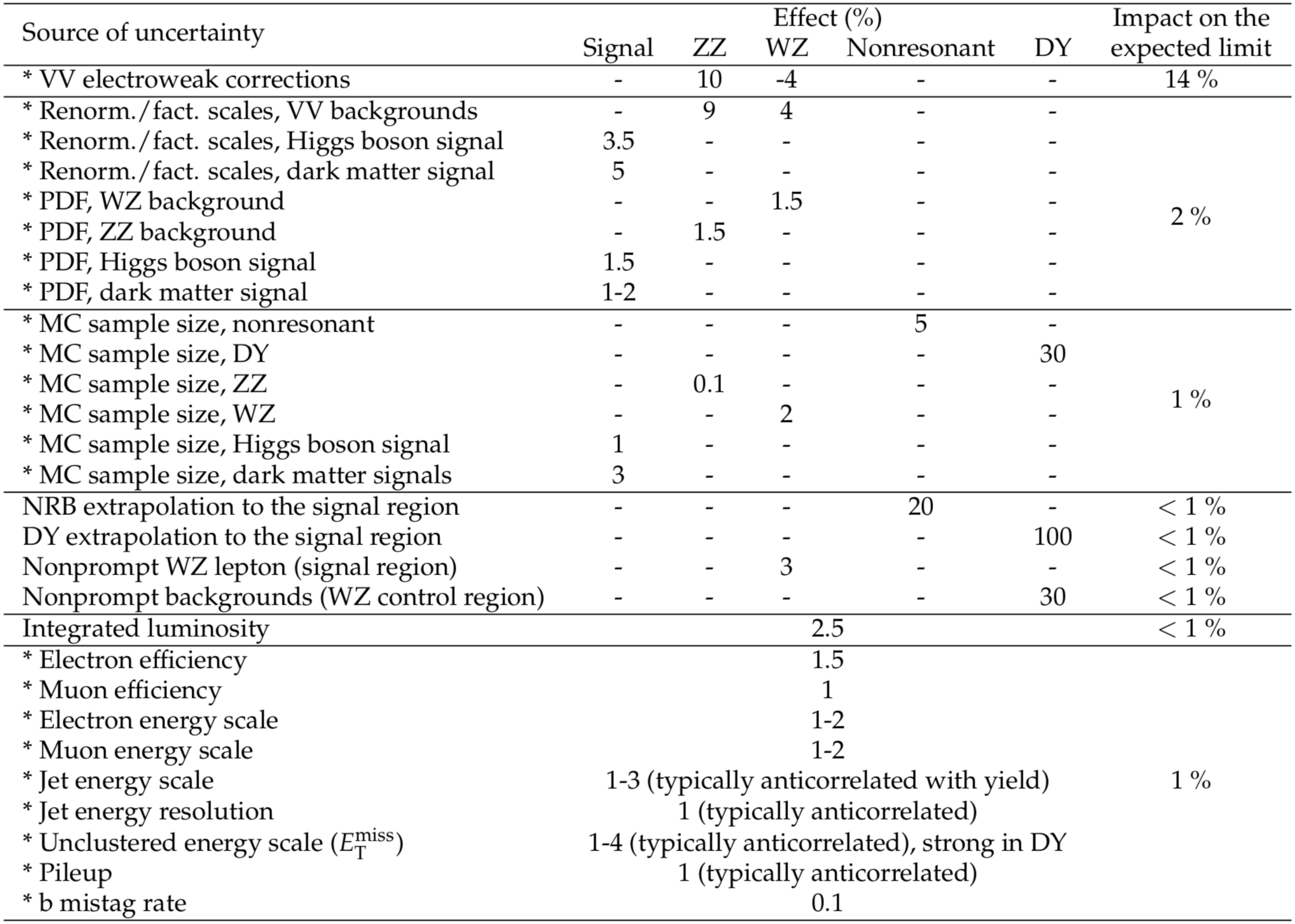
Z($\ell^+\ell^-$)H(inv.)

- The kinematic selection requirements for the MET-based analysis are:



Variable	Selection	Reject
N_ℓ	$= 2$	WZ, VVV
p_T^ℓ	$>25/20$ GeV (electrons) >20 GeV (muons)	QCD QCD
Z boson mass requirement	$\lvert m_{\ell\ell} - m_\mathrm{Z} \rvert < 15$ GeV	WW, top quark
Jet counting	≤ 1 jet with $p_\mathrm{T}^\mathrm{j} > 30$ GeV	$Z/\gamma^* \to \ell\ell$, top quark, VVV
$p_\mathrm{T}^{\ell\ell}$	> 60 GeV	$Z/\gamma^* \to \ell\ell$
b tagging veto	CSVv2 < 0.8484	Top quark, VVV
τ lepton veto	0 τ_h candidates with $p_\mathrm{T}^\tau > 18$ GeV	WZ
$E_\mathrm{T}^\mathrm{miss}$	> 100 GeV	$Z/\gamma^* \to \ell\ell$, WW, top quark
$\Delta\phi(\vec{p_\mathrm{T}}^{\ell\ell}, \vec{p_\mathrm{T}}^\mathrm{miss})$	> 2.6	$Z/\gamma^* \to \ell\ell$
$\lvert E_\mathrm{T}^\mathrm{miss} - p_\mathrm{T}^{\ell\ell} \rvert / p_\mathrm{T}^{\ell\ell}$	< 0.4	$Z/\gamma^* \to \ell\ell$
$\Delta\phi(\vec{p_\mathrm{T}}^{j}, \vec{p_\mathrm{T}}^\mathrm{miss})$	> 0.5 rad	$Z/\gamma^* \to \ell\ell$, WZ
$\Delta R_{\ell\ell}$	< 1.8	WW, top quark

Z($\ell^+\ell^-$)H(inv.)



Source of uncertainty	Effect (%)					Impact on the expected limit
	Signal	ZZ	WZ	Nonresonant	DY	
* VV electroweak corrections	-	10	-4	-	-	14 %
* Renorm./fact. scales, VV backgrounds	-	9	4	-	-	2 %
* Renorm./fact. scales, Higgs boson signal	3.5	-	-	-	-	
* Renorm./fact. scales, dark matter signal	5	-	-	-	-	
* PDF, WZ background	-	-	1.5	-	-	
* PDF, ZZ background	-	1.5	-	-	-	
* PDF, Higgs boson signal	1.5	-	-	-	-	
* PDF, dark matter signal	1-2	-	-	-	-	
* MC sample size, nonresonant	-	-	-	5	-	1 %
* MC sample size, DY	-	-	-	-	30	
* MC sample size, ZZ	-	0.1	-	-	-	
* MC sample size, WZ	-	-	2	-	-	
* MC sample size, Higgs boson signal	1	-	-	-	-	
* MC sample size, dark matter signals	3	-	-	-	-	
NRB extrapolation to the signal region	-	-	-	20	-	< 1 %
DY extrapolation to the signal region	-	-	-	-	100	< 1 %
Nonprompt WZ lepton (signal region)	-	-	3	-	-	< 1 %
Nonprompt backgrounds (WZ control region)	-	-	-	-	30	< 1 %
Integrated luminosity	2.5					< 1 %
* Electron efficiency	1.5					1 %
* Muon efficiency	1					
* Electron energy scale	1-2					
* Muon energy scale	1-2					
* Jet energy scale	1-3 (typically anticorrelated with yield)					
* Jet energy resolution	1 (typically anticorrelated)					
* Unclustered energy scale ($E_{\mathrm{T}}^{\mathrm{miss}}$)	1-4 (typically anticorrelated), strong in DY					
* Pileup	1 (typically anticorrelated)					
* b mistag rate	0.1					

* shape uncertainty

ggH(inv.)/V(jj)H(inv.)

$$
\begin{aligned}
\mathcal{L}_k(\boldsymbol{\mu}^{Z(\nu\overline{\nu})},\boldsymbol{\mu},\boldsymbol{\theta}) = &\prod_i \text{Poisson}\left(d_i^{\gamma}|B_i^{\gamma}(\boldsymbol{\theta}) + \frac{\boldsymbol{\mu}_i^{Z(\nu\overline{\nu})}}{R_i^{\gamma}(\boldsymbol{\theta})}\right) \\
&\times \prod_i \text{Poisson}\left(d_i^{\mu\mu}|B_i^{\mu\mu}(\boldsymbol{\theta}) + \frac{\boldsymbol{\mu}_i^{Z(\nu\overline{\nu})}}{R_i^{\mu\mu}(\boldsymbol{\theta})}\right) \\
&\times \prod_i \text{Poisson}\left(d_i^{\text{ee}}|B_i^{\text{ee}}(\boldsymbol{\theta}) + \frac{\boldsymbol{\mu}_i^{Z(\nu\overline{\nu})}}{R_i^{\text{ee}}(\boldsymbol{\theta})}\right) \\
&\times \prod_i \text{Poisson}\left(d_i^{\mu}|B_i^{\mu}(\boldsymbol{\theta}) + \frac{f_i(\boldsymbol{\theta})\boldsymbol{\mu}_i^{Z(\nu\overline{\nu})}}{R_i^{\mu}(\boldsymbol{\theta})}\right) \\
&\times \prod_i \text{Poisson}\left(d_i^{\text{e}}|B_i^{\text{e}}(\boldsymbol{\theta}) + \frac{f_i(\boldsymbol{\theta})\boldsymbol{\mu}_i^{Z(\nu\overline{\nu})}}{R_i^{\text{e}}(\boldsymbol{\theta})}\right) \\
&\times \prod_i \text{Poisson}\left(d_i|B_i(\boldsymbol{\theta}) + (1+f_i(\boldsymbol{\theta}))\boldsymbol{\mu}_i^{Z(\nu\overline{\nu})} + \boldsymbol{\mu}S_i(\boldsymbol{\theta})\right)
\end{aligned}
$$

- Poisson(x|y) = $y^x e^{-y}/x!$
- d_i = observed number of events
- f_i = transfer factor/constrain between V+jets backgrounds
- R_i = transfer factor from the CR
- B_i = contributions from other backgrounds
- $\mu_i^{Z(\nu\nu)}$ = yield of Z(νν)+jets in each bin i of MET in SR – this parameter is left floating in the fit
- S_i = nominal signal prediction
- $\mu_i^{Z(\nu\nu)}$ = signal strength parameter

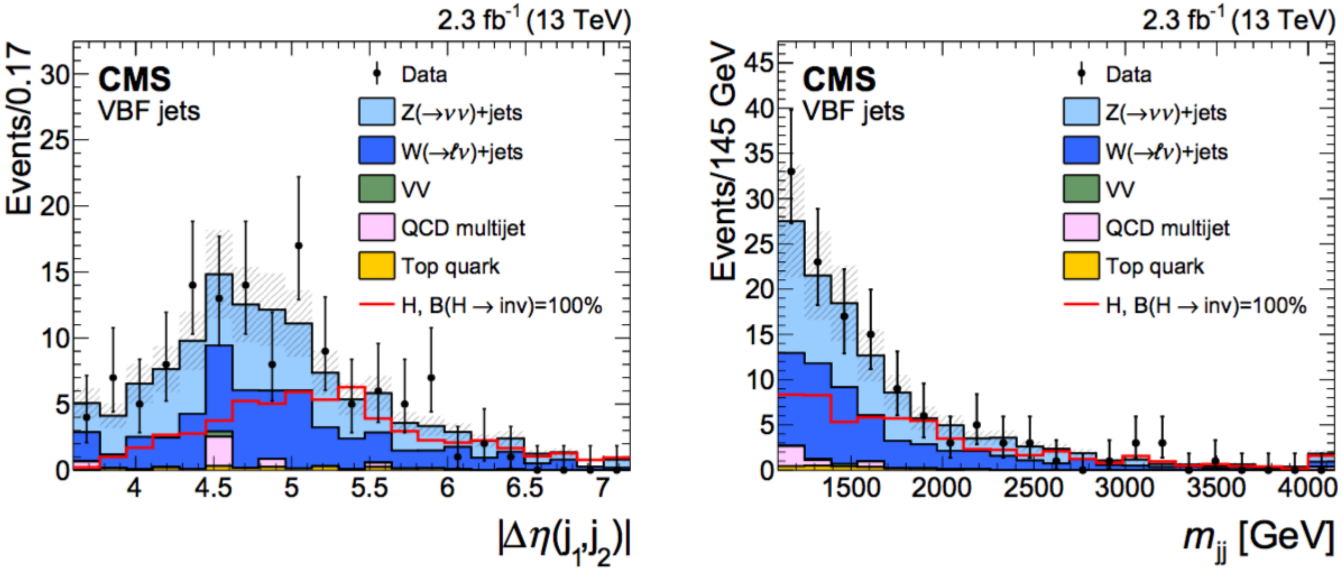
- The systematic uncertainties are modeled as nuisance parameters (θ)

VBF H(inv.)

- Dedicated VBF trigger selects events with two jets with high rapidity gap and large dijet mass.
- Event selections for the VBF H(inv.) search at 8 and 13 TeV:

	8 TeV	13 TeV
$p_{\mathrm{T}}^{\mathrm{j}_1}$	$>50\,\mathrm{GeV}$	$>80\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\mathrm{j}_2}$	$>45\,\mathrm{GeV}$	$>70\,\mathrm{GeV}$
m_{jj}	$>1200\,\mathrm{GeV}$	$>1100\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$>90\,\mathrm{GeV}$	$>200\,\mathrm{GeV}$
$S(E_{\mathrm{T}}^{\mathrm{miss}})$	$>4\sqrt{\mathrm{GeV}}$	—
$\min\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{j})$	>2.3	>2.3
$\Delta\eta(\mathrm{j}_1,\mathrm{j}_2)$	>3.6	>3.6

optimised for H(125)

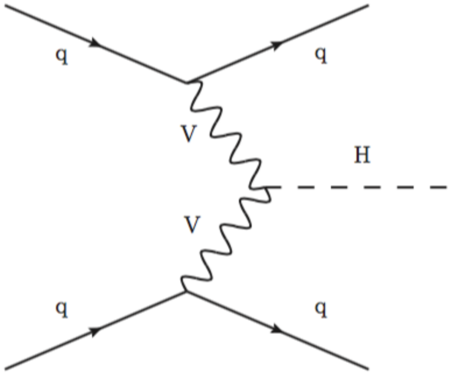


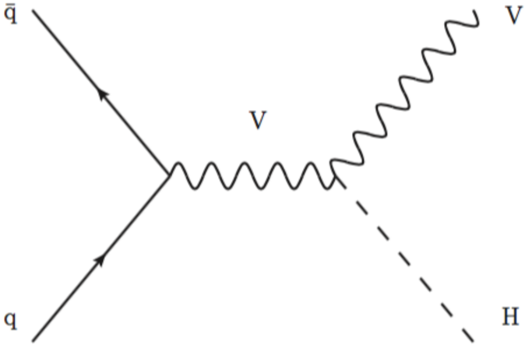
VBF H(inv.)

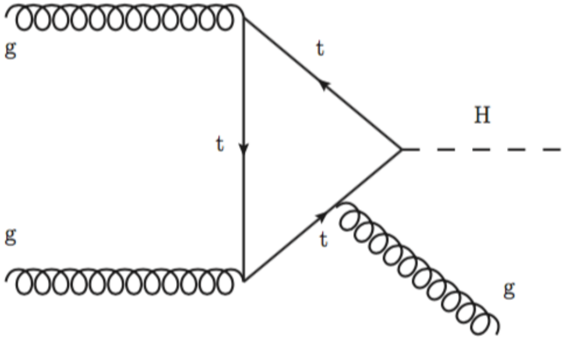
- Dominant sources of systematic uncertainties and their impact on the fitted value of $\mathcal{B}$(H(inv.)) in the VBF analysis at 13 TeV are:

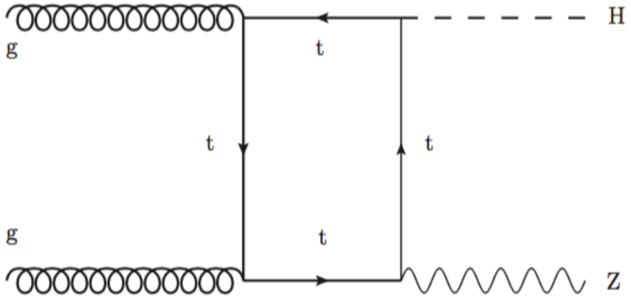
Systematic uncertainty	Impact
Common	
W to Z ratio in QCD produced V+jets	13%
W to Z ratio in EW produced V+jets	6.3%
Jet energy scale and resolution	6.0%
QCD multijet normalisation	4.3%
Pileup mismodelling	4.2%
Lepton efficiencies	2.5%
Integrated luminosity	2.2%
Signal specific	
ggH acceptance	3.8%
Renorm. and fact. scales and PDF (qqH)	1.8%
Renorm. and fact. scales and PDF (ggH)	$<$0.2%
Total systematic	$^{+15}_{-19}\%$
Total statistical only	$^{+28}_{-27}\%$
Total uncertainty	$^{+32}_{-33}\%$

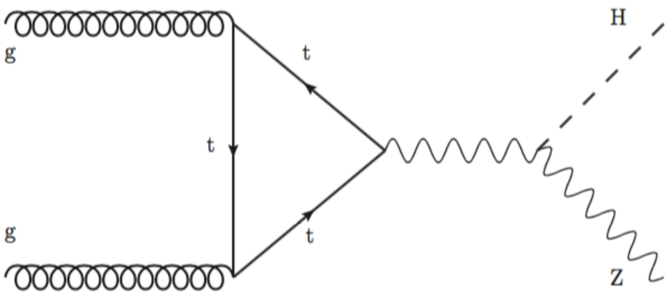
Feynman diagrams for the combination of H(inv.) searches



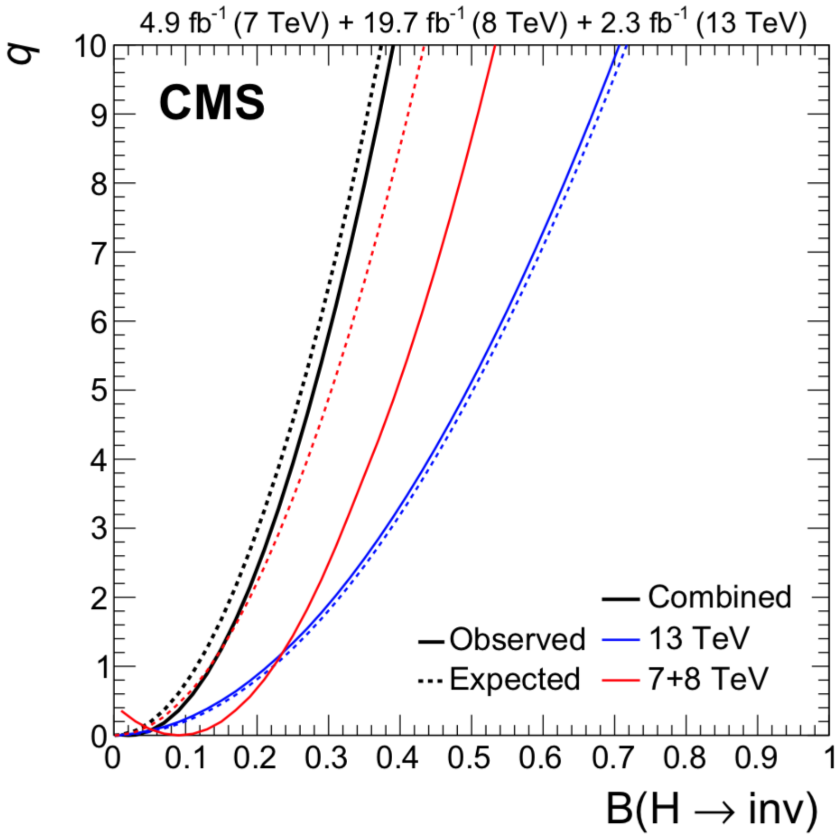


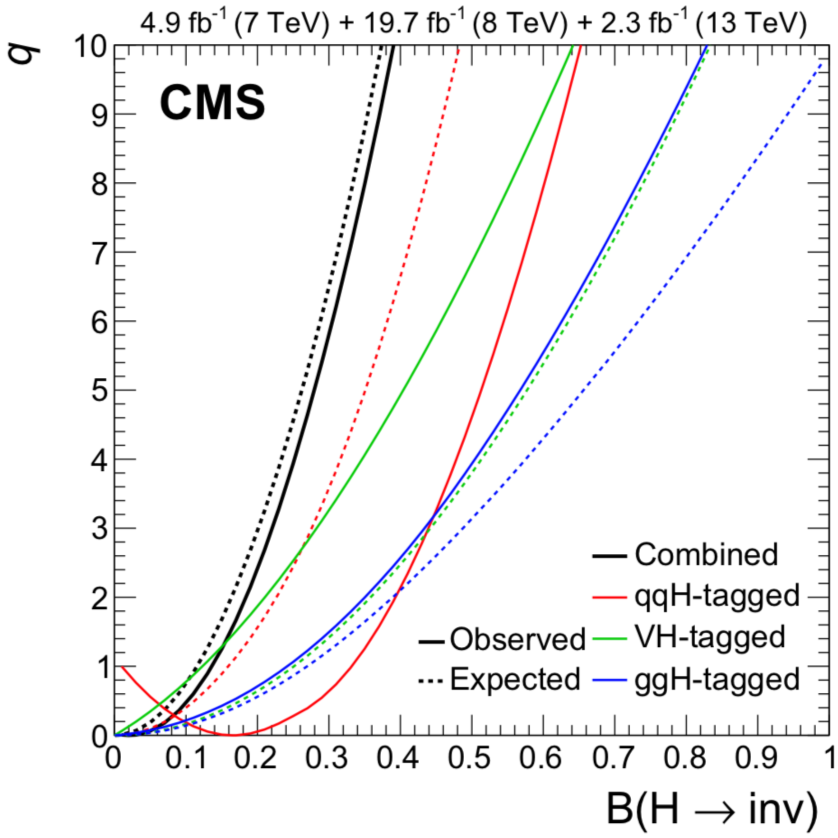




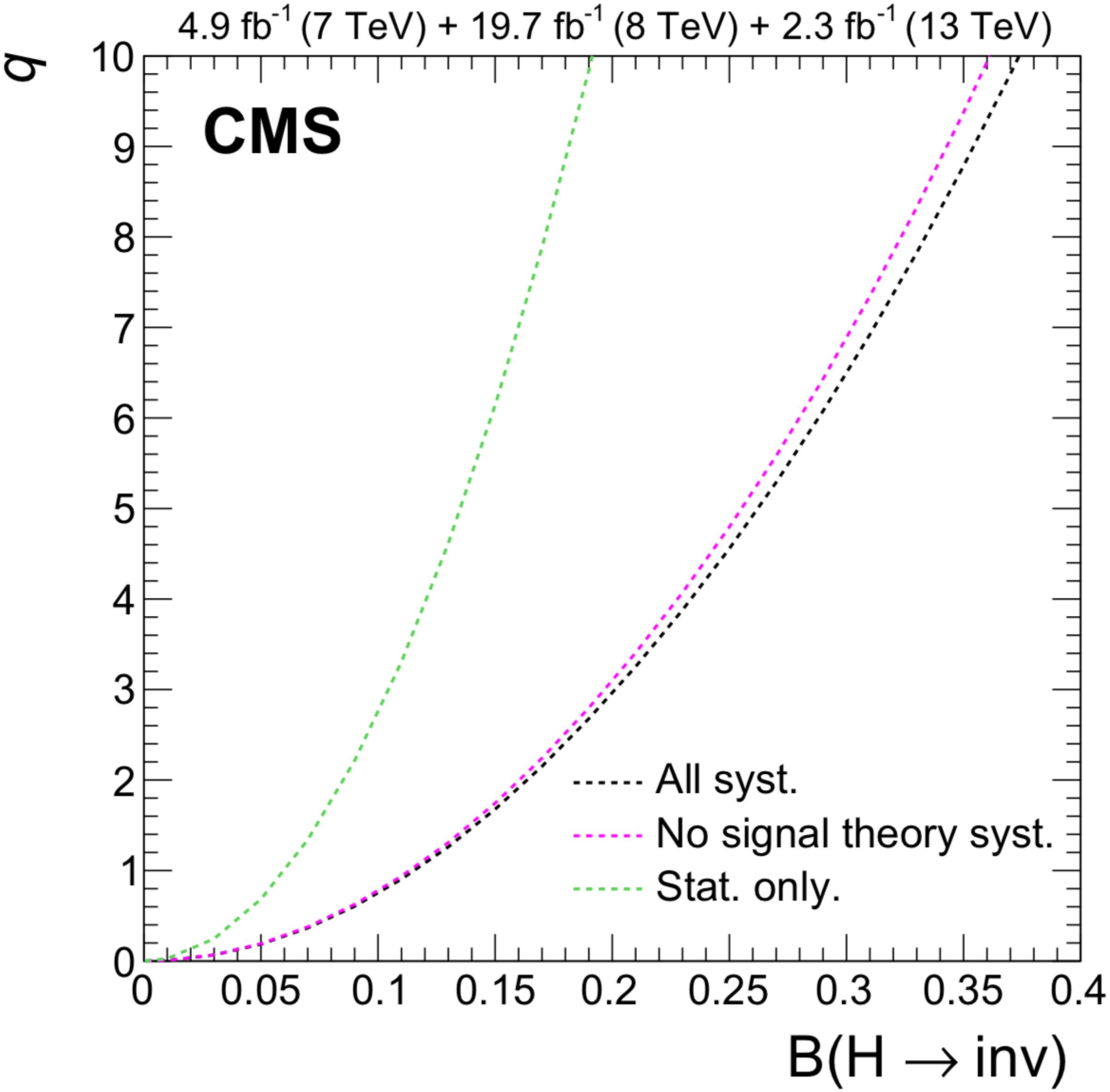


Combination of H(inv.) searches





Combination of H(inv.) searches

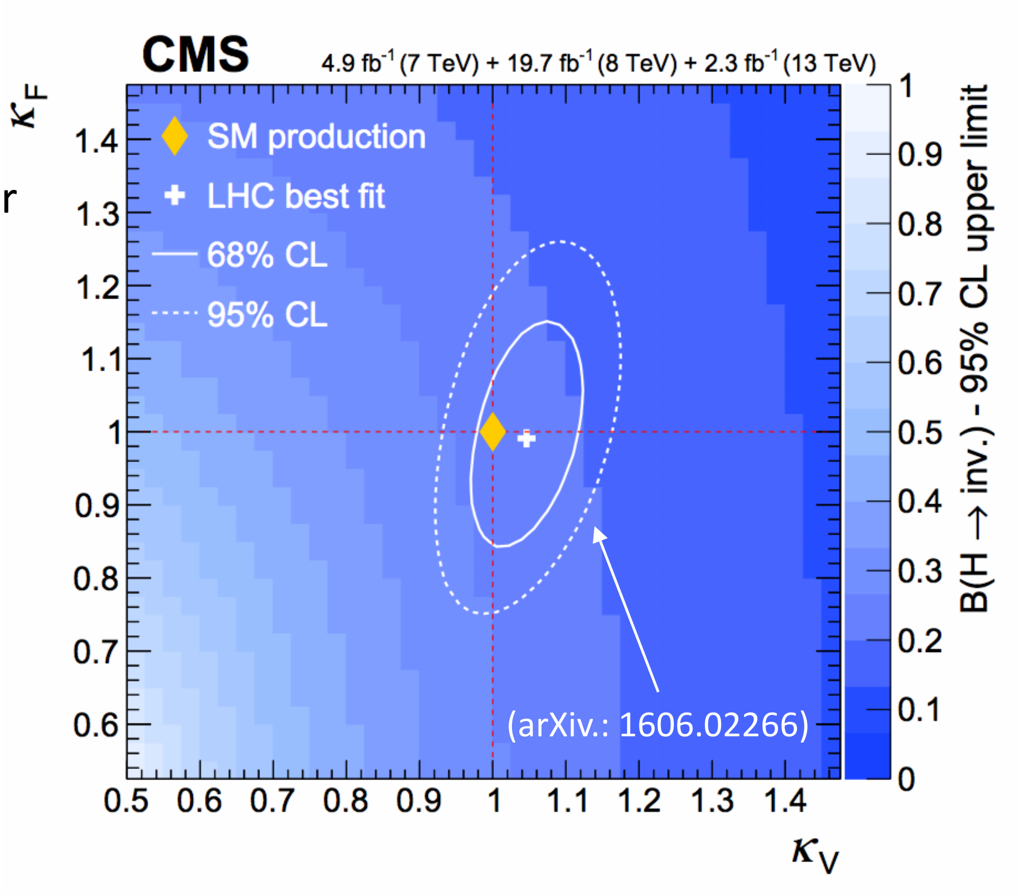


Combination of H(inv.) searches

- The 95% confidence level upper limit on $\mathcal{B}$(H(inv.)) is expressed as for different assumptions on production (non-SM).

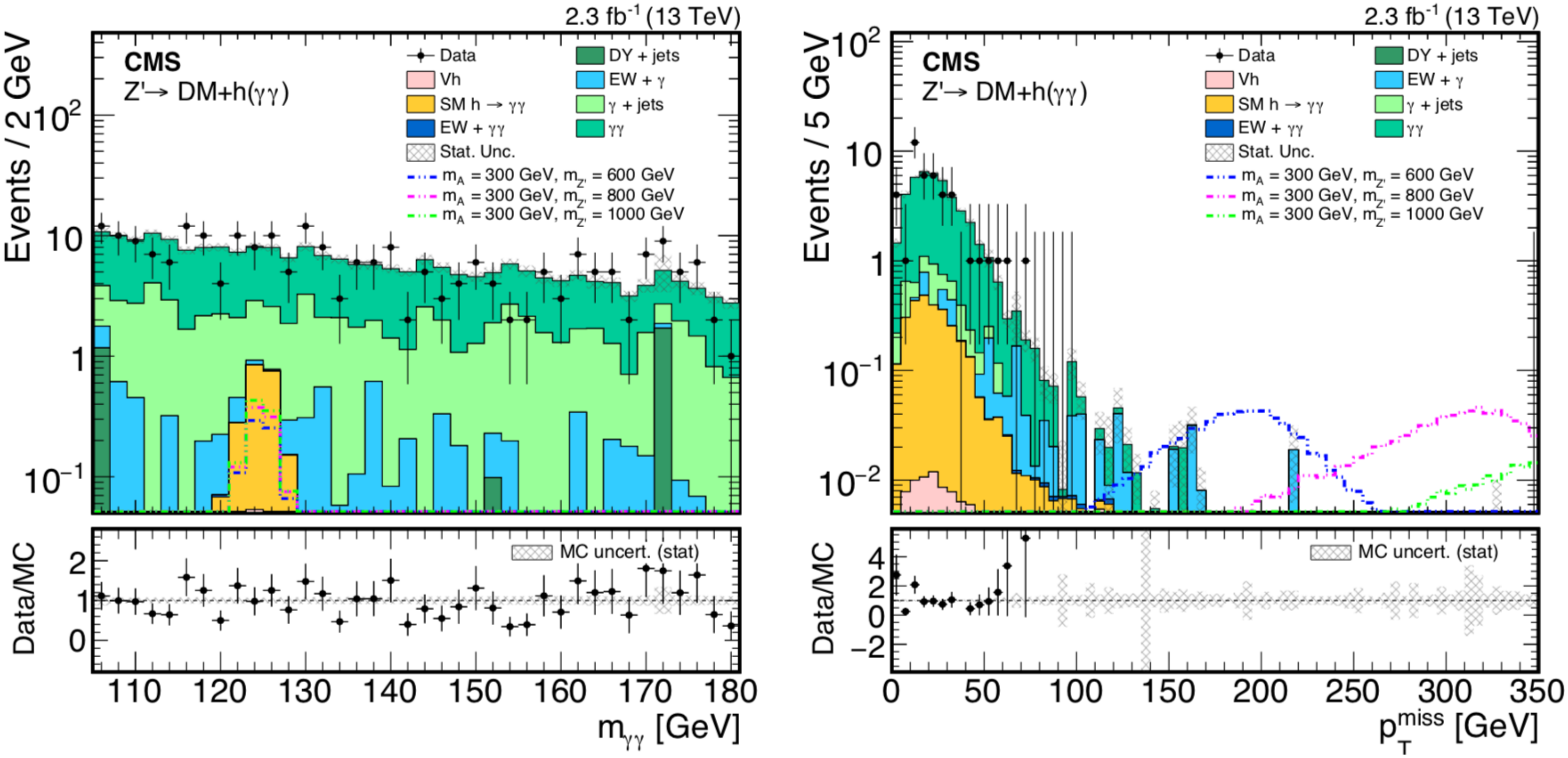
- It shows the result of varying coupling modifiers of Higgs boson to SM fermions (**κ_F**) and vector bosons (**κ_V**).

- The 95% confidence level upper limit on $\mathcal{B}$(H(inv.)) varies between 20-30% within LHC couplings constraints.



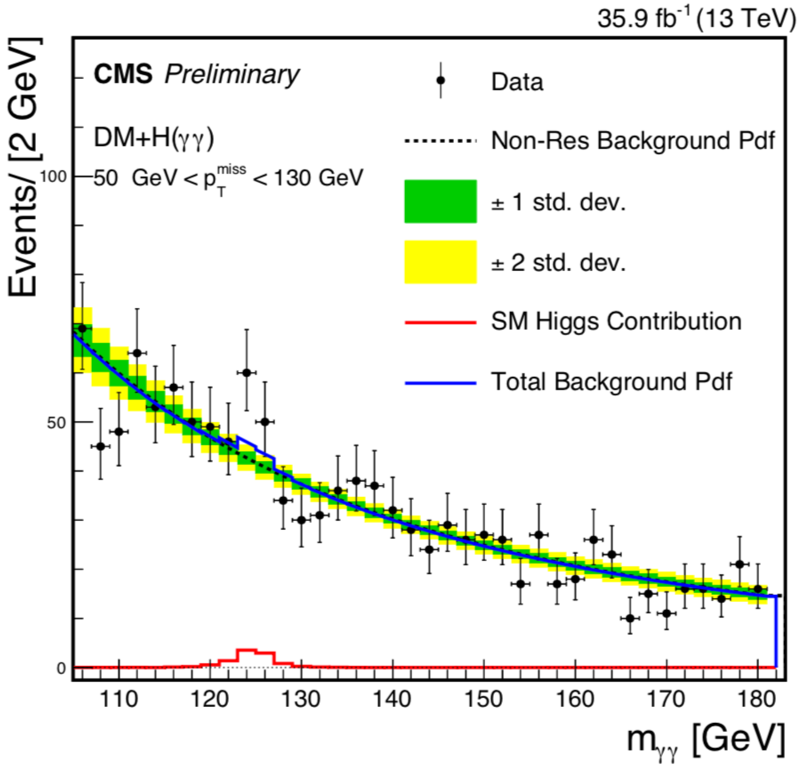
(arXiv.: 1606.02266)

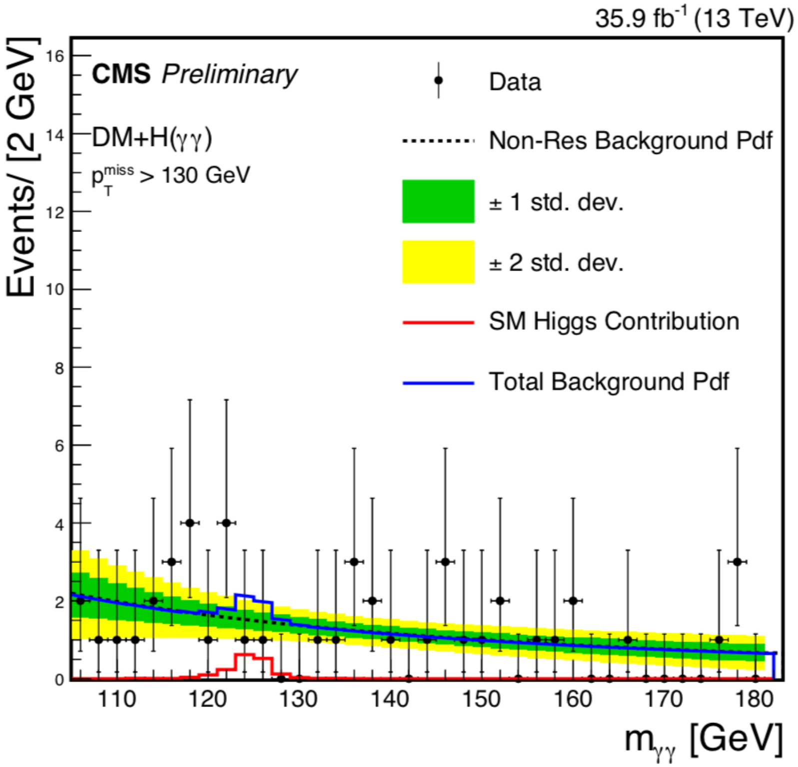
mono-H(γγ) + DM


2.3 fb^{-1} (13 TeV)
CMS
Z'→ DM+h(γγ)
Data
Vh
SM h → γγ
EW + γγ
Stat. Unc.
DY + jets
EW + γ
γ + jets
γγ
m_A = 300 GeV, $m_{Z'}$ = 600 GeV
m_A = 300 GeV, $m_{Z'}$ = 800 GeV
m_A = 300 GeV, $m_{Z'}$ = 1000 GeV
Events / 2 GeV
10^2
10
1
10^{-1}
MC uncert. (stat)
Data/MC
2
1
0
110
120
130
140
150
160
170
180
$m_{\gamma\gamma}$ [GeV]
2.3 fb^{-1} (13 TeV)
CMS
Z'→ DM+h(γγ)
Events / 5 GeV
10^2
10
1
10^{-1}
10^{-2}
MC uncert. (stat)
Data/MC
4
2
0
−2
0
50
100
150
200
250
300
350
p_T^{miss} [GeV]

mono-H($\gamma\gamma$) + DM

Variable	Low-$p_{\mathrm{T}}^{\mathrm{miss}}$ Category	High-$p_{\mathrm{T}}^{\mathrm{miss}}$ Category
$p_{\mathrm{T}1}/m_{\gamma\gamma}$	> 0.45	> 0.5
$p_{\mathrm{T}2}/m_{\gamma\gamma}$	> 0.25	> 0.25
$p_{\mathrm{T}\gamma\gamma}$	> 75 GeV	> 90 GeV
$p_{\mathrm{T}}^{\mathrm{miss}}$	$[50, 130]$ GeV	> 130 GeV





Higgs to invisible decays constraints

- LHC indirect limits on $\mathcal{B}$(H(inv.)) (HIG-15-002): 0.34 (exp. 0.35) @ 95% CL
- VBF, VH and ggH production modes combined in Run-1
  CMS HIG-15-012: 0.36 (exp. 0.30) @ 95% CL
- ATLAS JHEP 1511 (2015) 206: 0.25 (exp. 0.27) @ 95% CL