Search for Invisible Higgs at LHC

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on behalf of

CMS collaboration, LHC, CERN

SUSY 2017

Introduction

- After the Higgs(125) discovery, the next imperative is to learn about the properties of the resonance.

- Main issue: is it ***THE*** Standard Model Higgs or one of the Higgs of beyond Standard Model physics?

- All measurements related to Higgs boson are in very good agreement with Standard Model, eg.,various cross section measurements in a variety of final states indicate the observed signal strength for Higgs to be compatible with SM values.

- However data volume delivered by LHC is still limited for precision measurements in the Higgs sector.

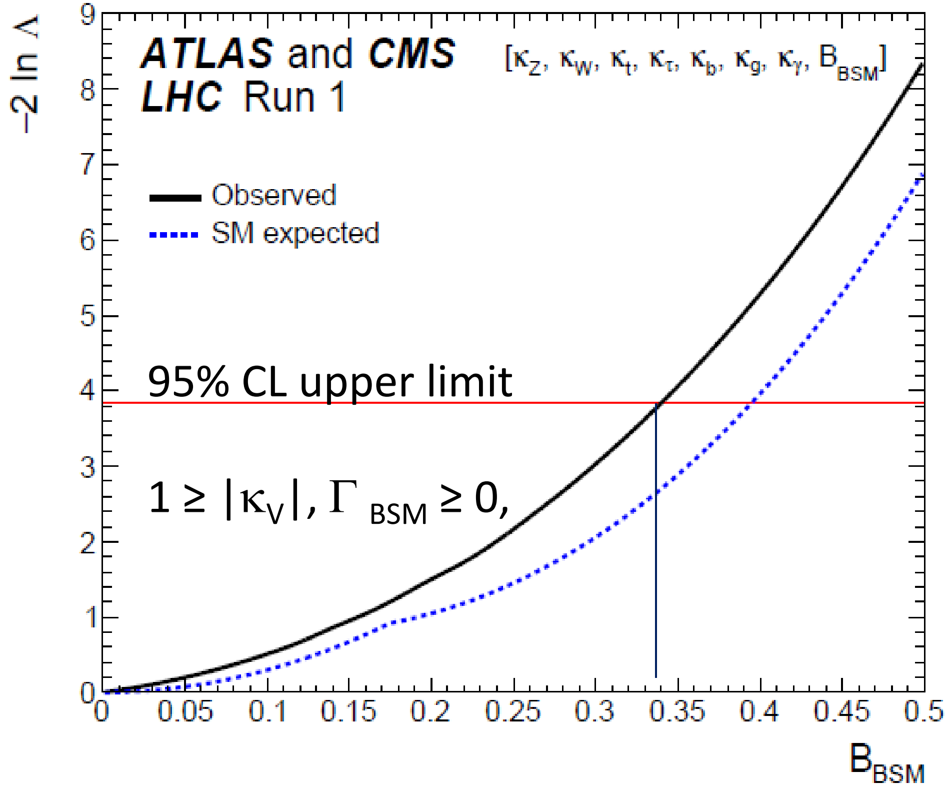
➔ provides lee way to accommodate various ideas of beyond Standard Model (BSM)

- Determination of Higgs total decay width provide indirect constraint on additional decay modes to invisible as well as other particles which are not detected.

Constraint on Higgs width from Run1 data

- Accommodate beyond standard model physics in terms of coupling strength modifiers κ :

$$\sigma_i \cdot \mathrm{B}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}, \quad \kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \text{ or } \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}, \qquad \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{B}_{\mathrm{BSM}}}$$



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B_{BSM} < 0.34 at 95% confidence limit

$\Gamma_H = \Gamma_H\,(\mathrm{SM}) + \Gamma_H\,(\mathrm{BSM})$
where $\Gamma_H\,(\mathrm{BSM}) = \Gamma_H\,(\mathrm{invisible})$

[in SM, the branching ratio for Γ_H(invisible) is ~ 0.12% due to H → ZZ* → 4ν.
→ beyond detection capability of experiments at present.]

- In general interaction between Higgs boson and the dark matter (DM) sector leads to invisible decay mode of Higgs eg., a pair of neutralinos in SUSY models.

“invisible” decay of Higgs

- In Higgs portal model, the role of mediator between SM particles and DM particles is played by the Higgs. ➔ allows “direct production” of DM at LHC!
  ➔ potentially establishes non-gravitational interaction of DM particles!

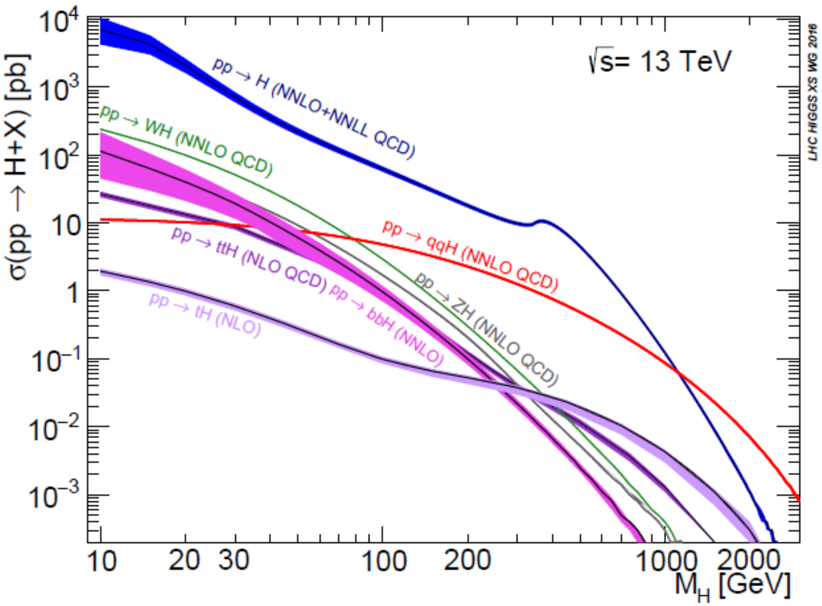
- In the early universe, Higgs is expected to have played a role in the evolution as per several cosmological models.

- Direct search for invisible decay of Higgs is more interesting, since it has more sensitivity to invisible decay width compared to indirect constraint.

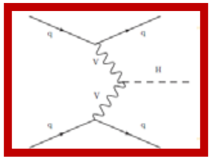
- Signature for invisible decay of Higgs ➔ large missing transverse energy E_T^{miss}
- For experimental “tag/identification” of invisible decay of Higgs, it has to recoil against a “visible” system in the detector ➔ Higgs should be produced accompanied with a detectable object.

- All production processes at LHC can be utilized, with varying efficiency:

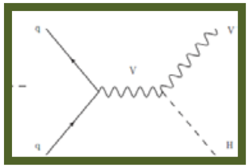
Suitable Higgs production processes at LHC



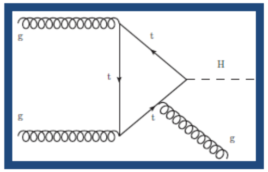
i) Vector boson fusion (VBF):
qq → qqH



ii) Associated production with a vector boson (VH): qq → VH
V = W/Z, with W/Z → qq
& Z → ee, μμ, bb



iii) Gluon-gluon fusion (ggH) at higher orders: gg → Hg
→ use mono-jet signal



Expected signal composition (%)

Analysis	Final state	7 or 8 TeV	at 13 TeV
qqH tagged	VBF jets	7.8 (ggH), 92.2 (qqH)	9.1 (ggH), 90.9 (qqH)
VH tagged	Z → ℓℓ Z → bb W/Z → qq	100 (ZH) 100 (ZH) 25.1 (ggH), 5.1 (qqH) , 23.0(ZH), 46.8(WH)	100 (ZH) 100(ZH) 38.7 (ggH), 7.1 (qqH) , 21.3(ZH), 32.9(WH)
ggH-tagged	Mono-jet	70.4(ggH), 20.4(qqH) , 3.5(ZH), 5.7(WH)	69.3(ggH), 21.9 (qqH) , 4.2(ZH), 4.6(WH)

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Gluon PDF increases significantly for √s = 8 to 13 TeV

Search for H(inv) in VBF mode

$\mathcal{L}$ = 5.1, 19.7 & 2.3 /fb : 2011, 2012 & 2015 data at √s =7, 8 & 13 TeV

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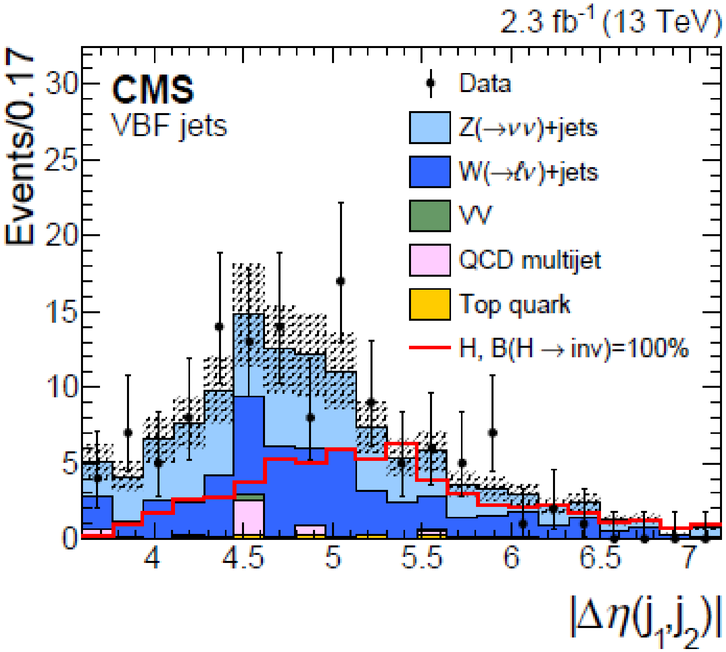
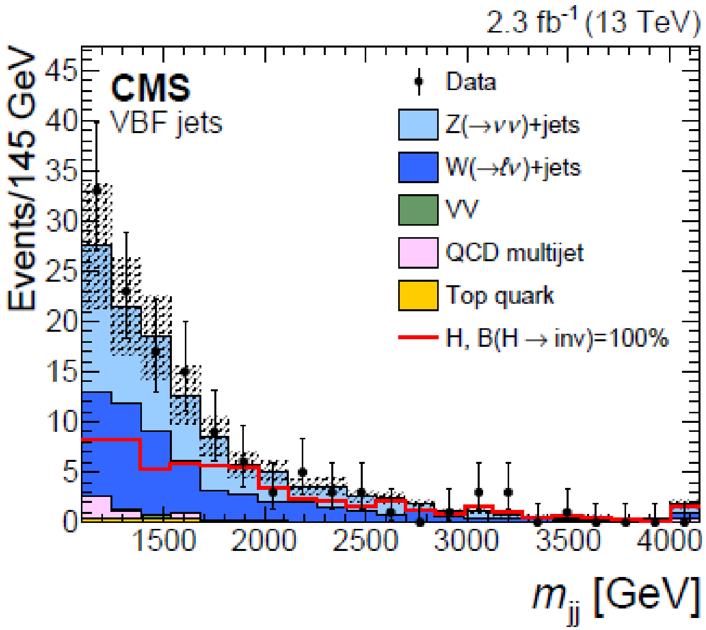
- Most sensitive search channel: unique event topology of signal
- 2 forward-backward jets with large invariant mass (m_{jj}), large pseudo-rapidity gap ($\Delta\eta$)
- Outgoing jets are not colour connected ➔ hadronically quiet central region occupied by only missing energy (essentially p_T^{miss})
- Cut and count analysis





VBF analysis: event yield in signal and control regions

$\sqrt{s}$ =13 TeV, 2.3 /fb

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					
$m_H = 125$ GeV	ggH	5.4 ± 3.6					

NO excess of events

VBF selections

	8 TeV	13 TeV
$p_T^{j_1}$	>50 GeV	>80 GeV
$p_T^{j_2}$	>45 GeV	>70 GeV
m_{jj}	>1200 GeV	>1100 GeV
E_T^{miss}	>90 GeV	>200 GeV
$S(E_T^{miss})$	$>4\sqrt{GeV}$	—
$\min \Delta\phi(\vec{p}_T^{miss}, j)$	>2.3	>2.3
$\Delta\eta(j_1, j_2)$	>3.6	>3.6

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Signal extraction for VBF

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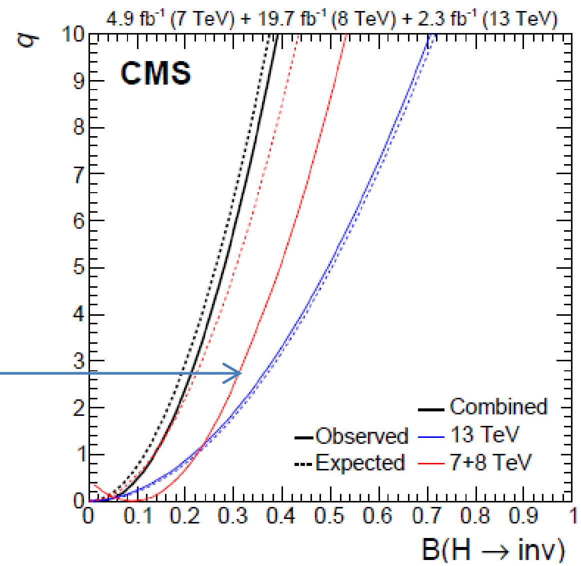
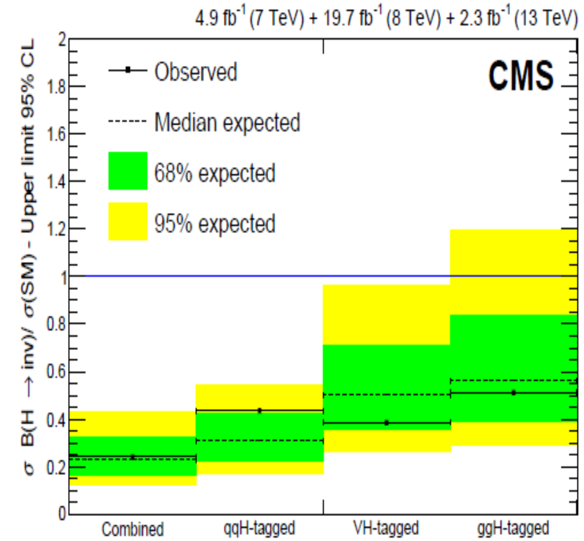
data at √s = 7, 8 & 13 TeV

- Simultaneous fit to signal and control regions
- Profile likelihood ratio:

$$q = -2\ln\frac{L(\mathrm{data}|\sigma\,\mathcal{B}(\mathrm{H}\to\mathrm{inv})/\sigma(\mathrm{SM}),\hat{\hat{\theta}})}{L(\mathrm{data}|\sigma\,\hat{\mathcal{B}}(\mathrm{H}\to\mathrm{inv})/\sigma(\mathrm{SM}),\hat{\theta})},$$

Expected = no invisible decay





- VBF is most sensitive
- presented result mostly driven by 8 TeV data which showed a small excess!

Utilizing all channels Run1 + Run2 combined observed (expected) upper limit on $\mathcal{B}$(H→inv.) < 0.24 (0.23) at 95% CL, assuming SM production rate.

Results from VBF analysis of 2016 data (36 /fb) coming soon!

Interpretation in Higgs-portal model

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- SM particles communicate with dark matter particles via Higgs & tree level coupling ➔ invisible decay of H (produced acc. to SM)
- Interpretation of limit in terms of spin-independent DM-nucleon cross section.

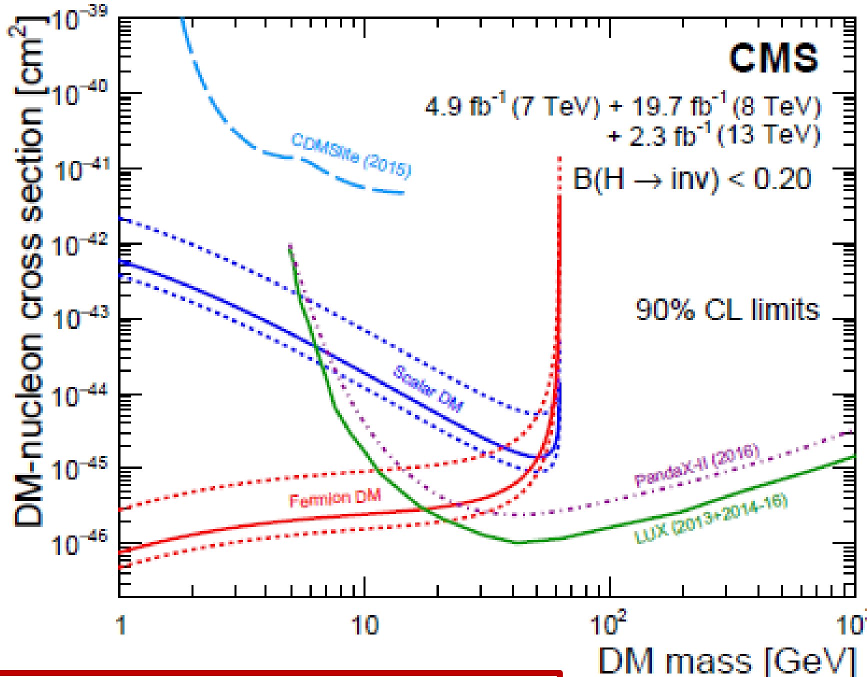
- Assumptions: nature of DM particle → either scalar or fermion;
  + effective interaction does not depend on spin

- Use 90% CL limit to compare collider reach with constrains from direct detection Experiments ➔ **$\mathcal{B}$(H(inv)) < 0.20**

$$\sigma^{\mathrm{SI}}_{\mathrm{S-N}} = \frac{4\Gamma_{\mathrm{inv}}}{m_{\mathrm{H}}^3 v^2 \beta} \frac{m_{\mathrm{N}}^4 f_{\mathrm{N}}^2}{(m_\chi + m_{\mathrm{N}})^2}$$

$$\sigma^{\mathrm{SI}}_{\mathrm{f-N}} = \frac{8\Gamma_{\mathrm{inv}} m_\chi^2}{m_{\mathrm{H}}^5 v^2 \beta^3} \frac{m_{\mathrm{N}}^4 f_{\mathrm{N}}^2}{(m_\chi + m_{\mathrm{N}})^2}$$

f_{N} : nuclear form factor = [0.260, 0.629]

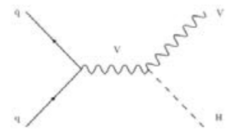


Collider sensitivity most significant for low mass DM below ~ 10 GeV

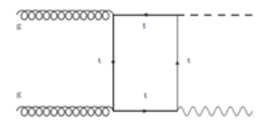
CMS-EXO-16-052
arXiv: 1711.00431
Submitted to Euro. Phys. J. C

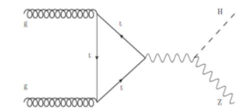
Z (→ $\ell^+\ell^-$) H(inv)

$\mathcal{L}$ = 35.9 /fb : 2016 data



additional ZH processes





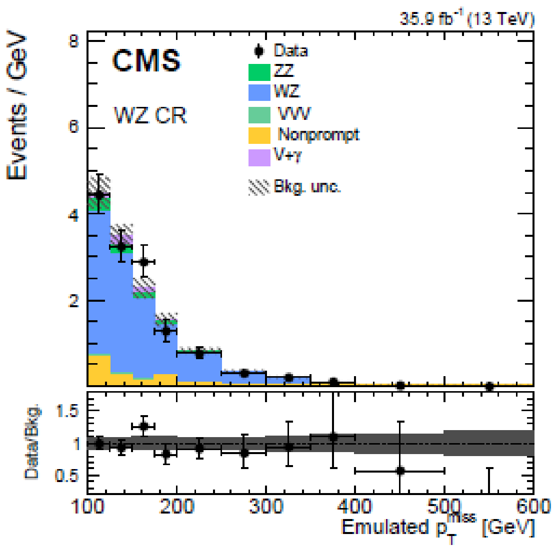
- Same flavour, opposite sign isolated lepton pair, recoiling against large p_T^{miss}
- Several background processes: estimated using control samples.

→ Continuum production of ZZ → $2\ell\, 2\nu$, irreducible (60% of total bkg)

→ WZ → $\ell'\nu'\ \ell^+\ell^-$ where ℓ' is mis-identified (25%)

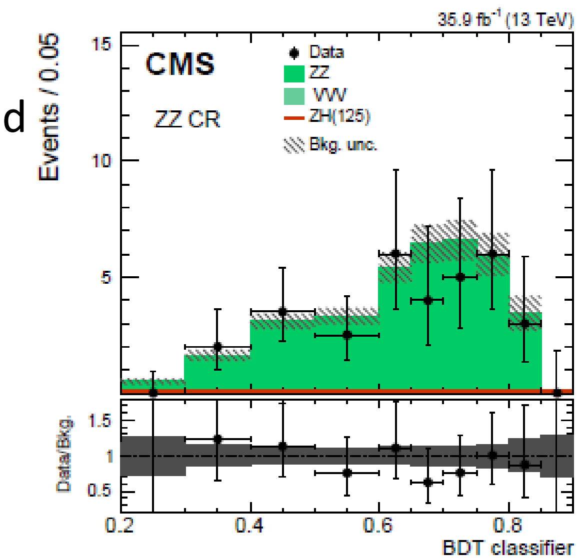
→ leptonic decays of top quark, WW → $\ell\nu\ \ell\nu$, Drell -Yan ($Z/\gamma^* \rightarrow \ell^+\ell^-$), WWW,...

- Shape based analysis → final result from binned fit of p_T^{miss} distribution
- Multivariate analysis → several input variables to train a boosted decision tree



Control regions used for background estimation in signal region

"Emulated W pT" = p_T^{miss} + p_T (l3)



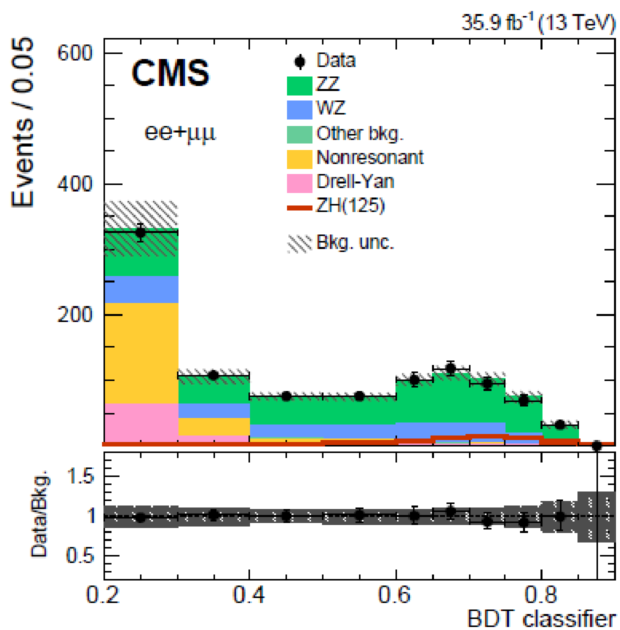
Event selection for Z (→ $\ell^+\ell^-$) H(inv)

Selection	Requirement	Reject
N_ℓ	$=2$	WZ, VVV
p_T^ℓ	$>25/20$ GeV for electrons >20 GeV for muons	QCD
Z boson mass requirement	$\lvert m_{\ell\ell} - m_Z \rvert < 15\ (30)$ GeV	WW, top quark
Jet counting	≤ 1 jet with $p_T^j > 30$ GeV	$Z/\gamma^* \to \ell\ell$, top quark, VVV
$p_T^{\ell\ell}$	>60 GeV	$Z/\gamma^* \to \ell\ell$
b tagging veto	CSVv2 < 0.8484	Top quark, VVV
τ lepton veto	0 τ_h cand. with $p_T^\tau > 18$ GeV	WZ
p_T^{miss}	>100 GeV (130 GeV, training only)	$Z/\gamma^* \to \ell\ell$, WW, top quark
$\Delta\phi(\vec{p}_T^{\,j}, \vec{p}_T^{\,miss})$	>0.5 rad	$Z/\gamma^* \to \ell\ell$, WZ
$\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,miss})$	>2.6 rad (omitted)	$Z/\gamma^* \to \ell\ell$
$\lvert p_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	<0.4 (omitted)	$Z/\gamma^* \to \ell\ell$
$\Delta R_{\ell\ell}$	<1.8 (omitted)	WW, top quark

$\mathcal{L}$ = 35.9 /fb : 2016 data

(…) ➔ *for BDT analysis*

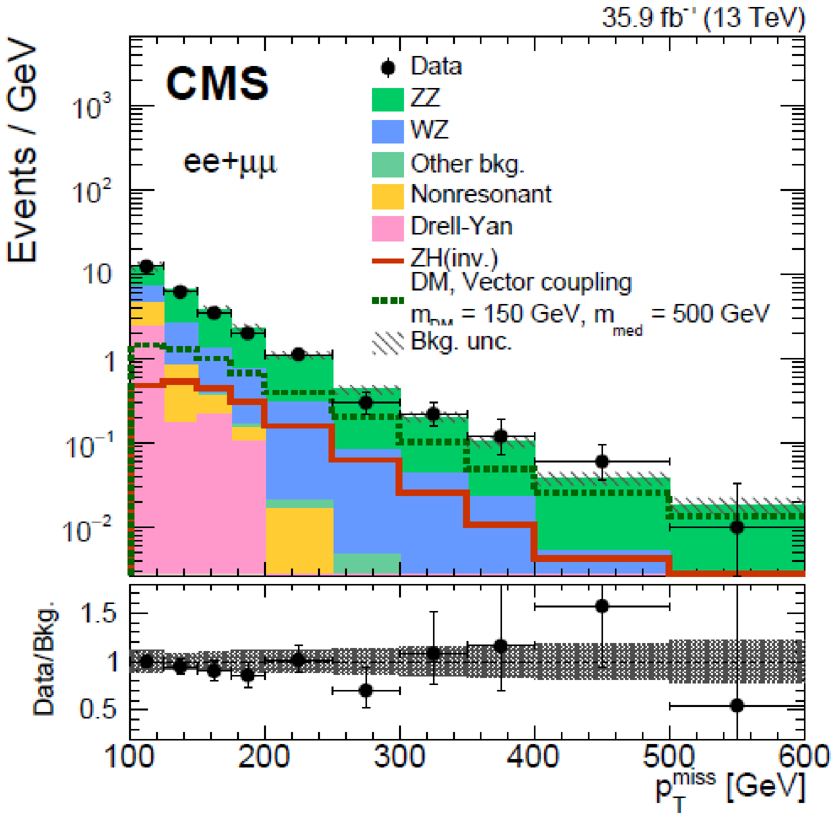
BDT distribution for signal region in MVA



No excess of events above SM expectation

CMS-EXO-16-052
arXiv: 1711.00431
Submitted to Euro. Phys. J. C

ZH analysis: prediction for signal, background and event yield using p_T^{miss} spectrum



$\mathcal{L}$ = 35.9 /fb : 2016 data

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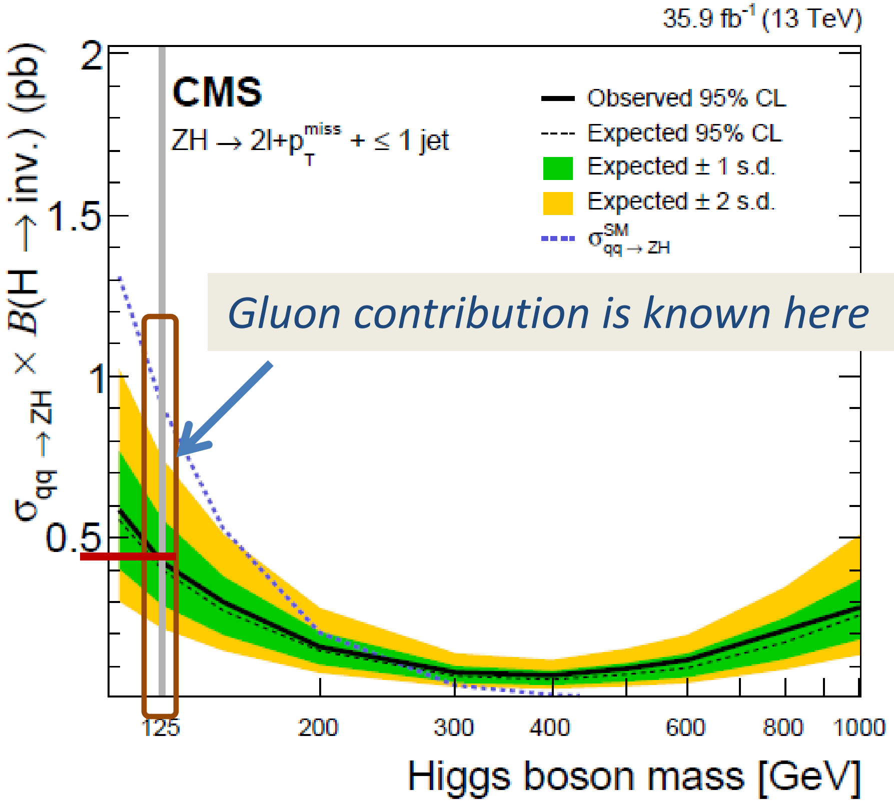
Process	$ee + \mu\mu$
qqZH(inv.) $m_H = 125\,\text{GeV}, \mathcal{B}(H \to \text{inv.}) = 1$	158.6 ± 5.4
ggZH(inv.) $m_H = 125\,\text{GeV}, \mathcal{B}(H \to \text{inv.}) = 1$	42.7 ± 4.9

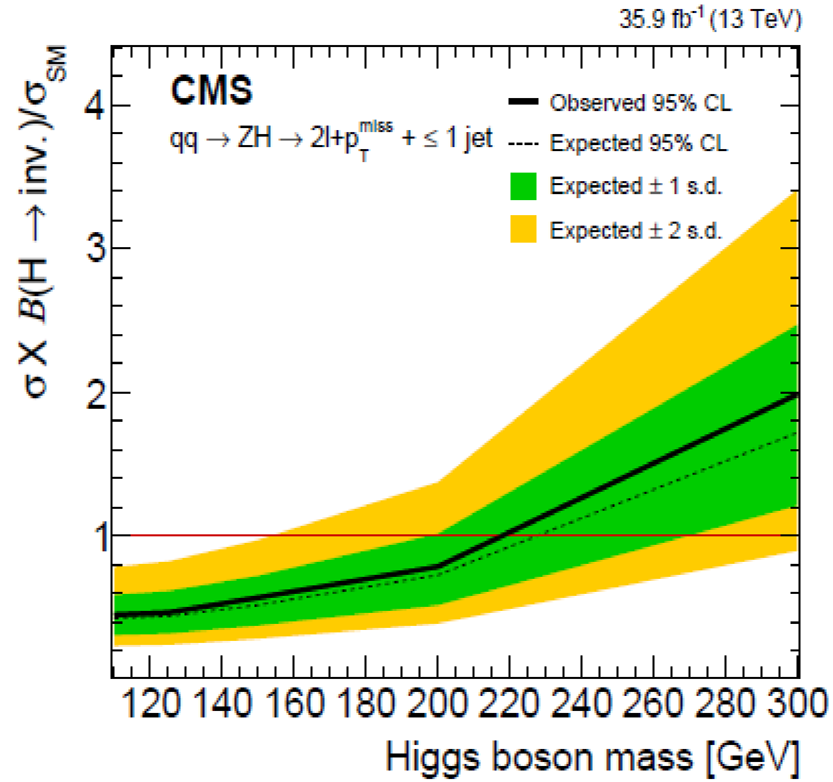
ZZ	379.8 ± 9.4
WZ	162.5 ± 6.8
Nonresonant bkg.	75 ± 15
Drell–Yan	72 ± 29
Other bkg.	2.6 ± 0.2
Total bkg.	692 ± 35
Data	698

No excess of events above SM expectation

Z (→ ℓ⁺ℓ⁻) H(inv): Results

$\mathcal{L}$ = 35.9 /fb : 2016 data





Assuming SM rate for Higgs production, observed (expected) 95% CL upper limit on $\mathcal{B}$(H(inv)) = 0.45 (0.44) from shape analysis
= 0.40 (0.42) from MVA

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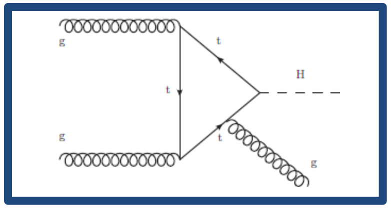
Mono-jet final state targeting gg →H(inv) + g

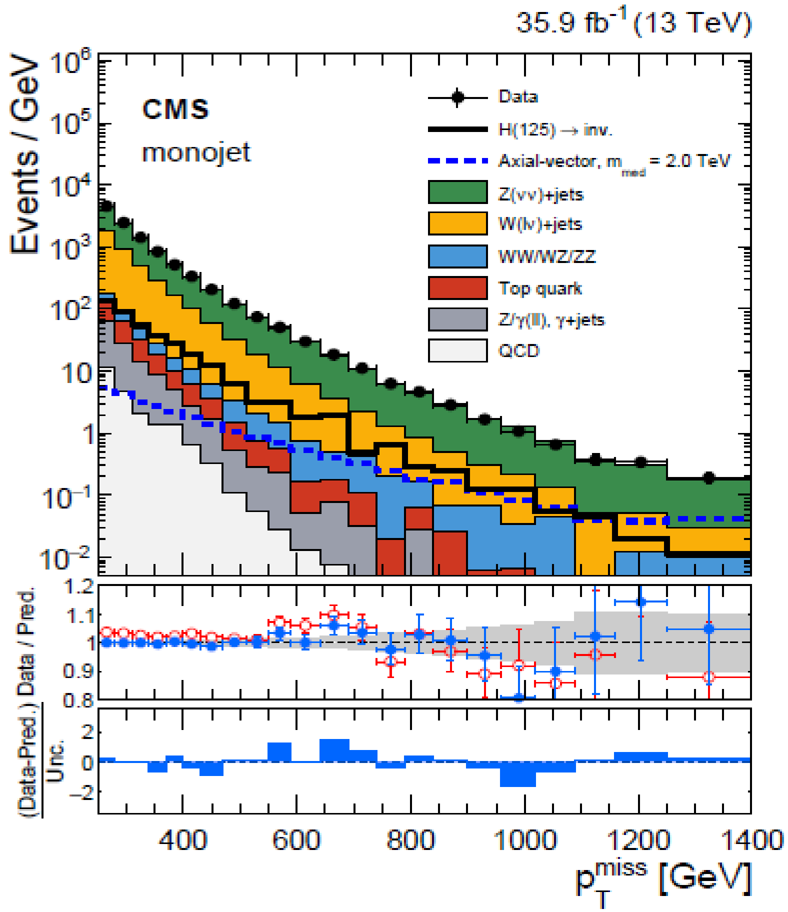
$\mathcal{L}$ = 35.9 /fb : 2016 data

CMS Paper EXO-16-048
arXiv: 1712.02345, to PRD



- Jets + p_T^{miss} in final state, no lepton
  → at least 1 jet from ISR , NOT fat jet! + p_T^{miss} > 200 GeV
- 90% Backgrounds: irreducible Z (→νν) + jet and W → ℓν, where ℓ is misidentified
- Control regions include various final states : μμ, ee, single μ, single e and γ + jets
  → simultaneous fit to both signal region and all backgrounds from V+jets processes
- to reduce QCD background due to mis-measurement of jets, demand
  min Δϕ (jet ,p_T^{miss}) > 0.5 rad.

Search for H(inv) in 1jet + E_t^{miss} final state



$\mathcal{L}$ = 35.9 /fb : 2016 data

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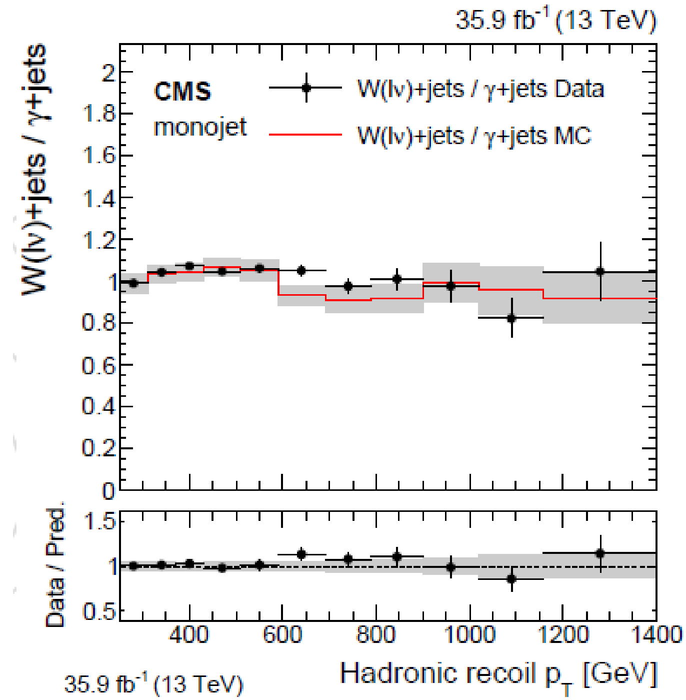
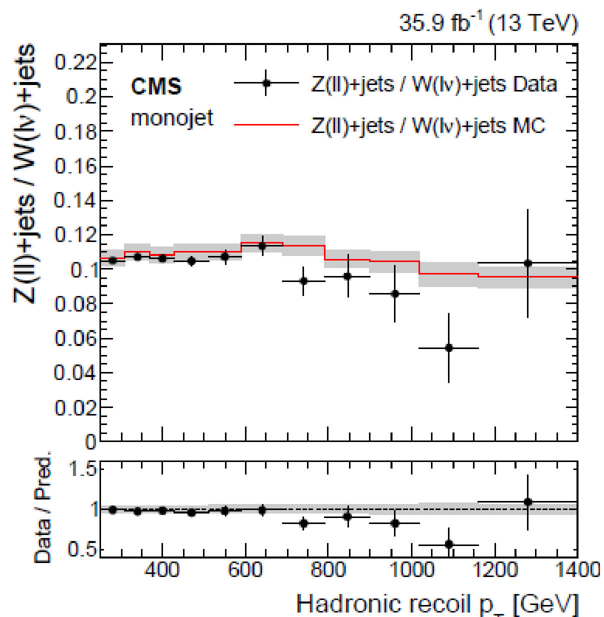
Control regions

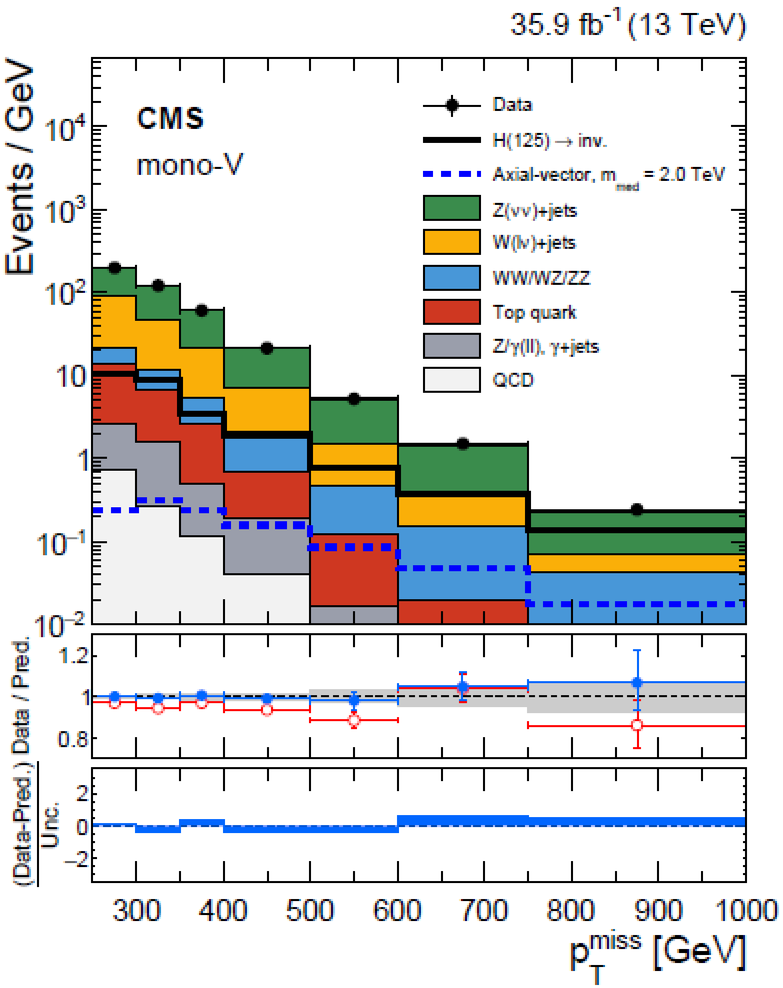




Mono V: W/Z(→jj) H(inv)

$\mathcal{L}$ = 35.9 /fb : 2016 data

- Large p_t^{miss}, no lepton, 2 jets from W/Z decay peaking at respective masses



Expected & observed upper limit on $\mathcal{B}$ (H(inv))

Category	Observed (expected)	68% expected	Expected signal composition
Monojet	0.74 (0.57)	0.40–0.86	72.8% ggH, 21.5% VBF, 3.3% WH, 1.9% ZH, 0.6% ggZH
Mono-V	0.49 (0.45)	0.32–0.64	38.7% ggH, 7.0% VBF, 32.9% WH, 14.6% ZH, 6.7% ggZH
Combined	0.53 (0.40)	0.29–0.58	N/A

CMS Paper EXO-16-048
arXiv: 1712.02345, to PRD

Combined result from mono V and mono-jet final states

$\mathcal{L}$ = 35.9 /fb : 2016 data

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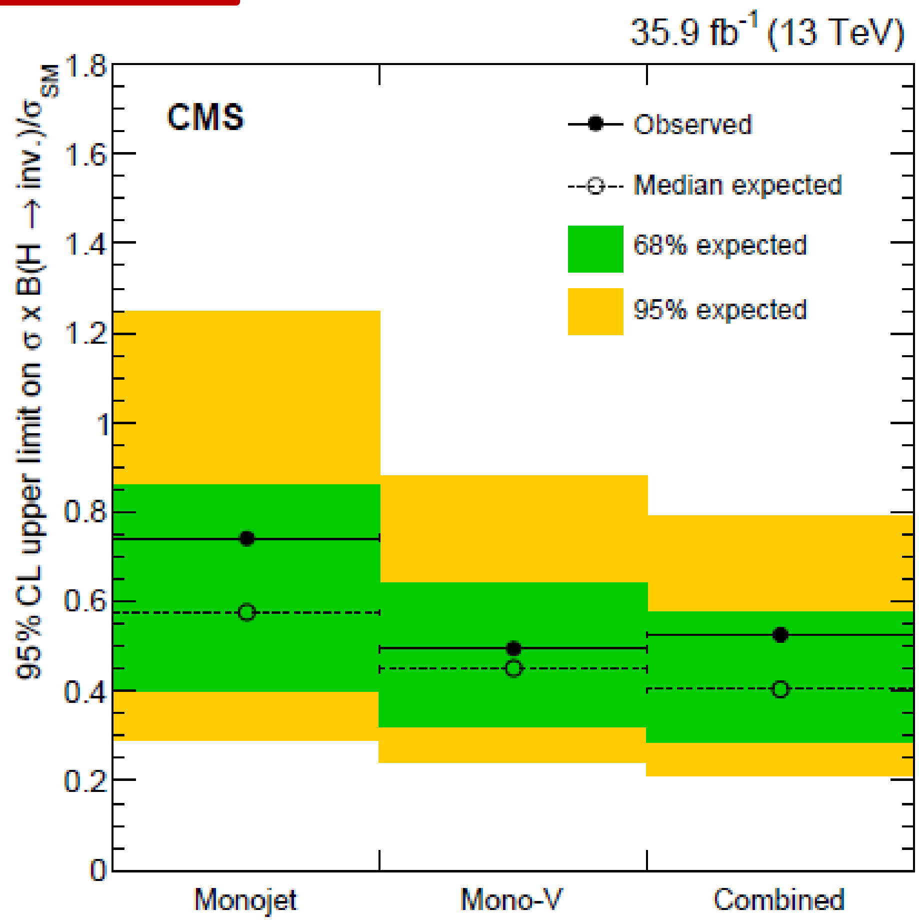


Assuming SM production rate for Higgs, from mono-V(→ jj) and mono-jet searches the observed (expected) 95% CL upper limit on **$\mathcal{B}$(H(inv)) = 0.53 (0.40)**

Outlook

- New results from VBF analysis, based on 2016 data is expected in near future.

- Analysis of 2017 data is in progress.

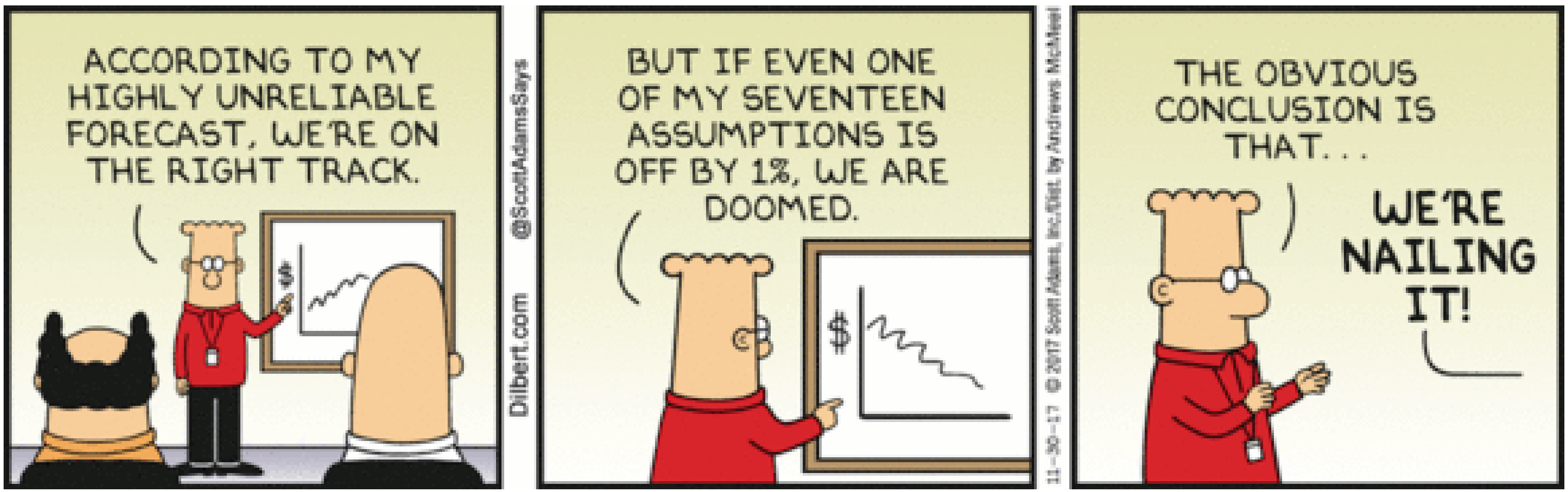
- **Expect very interesting results during next several years using total Run2 data, corresponding to at least 120 fb^{-1} at $\sqrt{s}$= 13 TeV.**

- However LHC roadmap is drawn till 2030s with total expected data volume of ~ 3000-5000 /fb. LHC has delivered till now less than 3% of the total data ➔ Precision measurement of Higgs properties will be complementary to constrain the branching to invisible decay.

➔ **Stay tuned, exciting times ahead!**

Conclusion

- Invisible decay of Higgs is an important probe of physics beyond Standard Model. If established, has very significant implications .
- Experimental data analysed so far leaves room for such a speculation.



Thank you!

Backup

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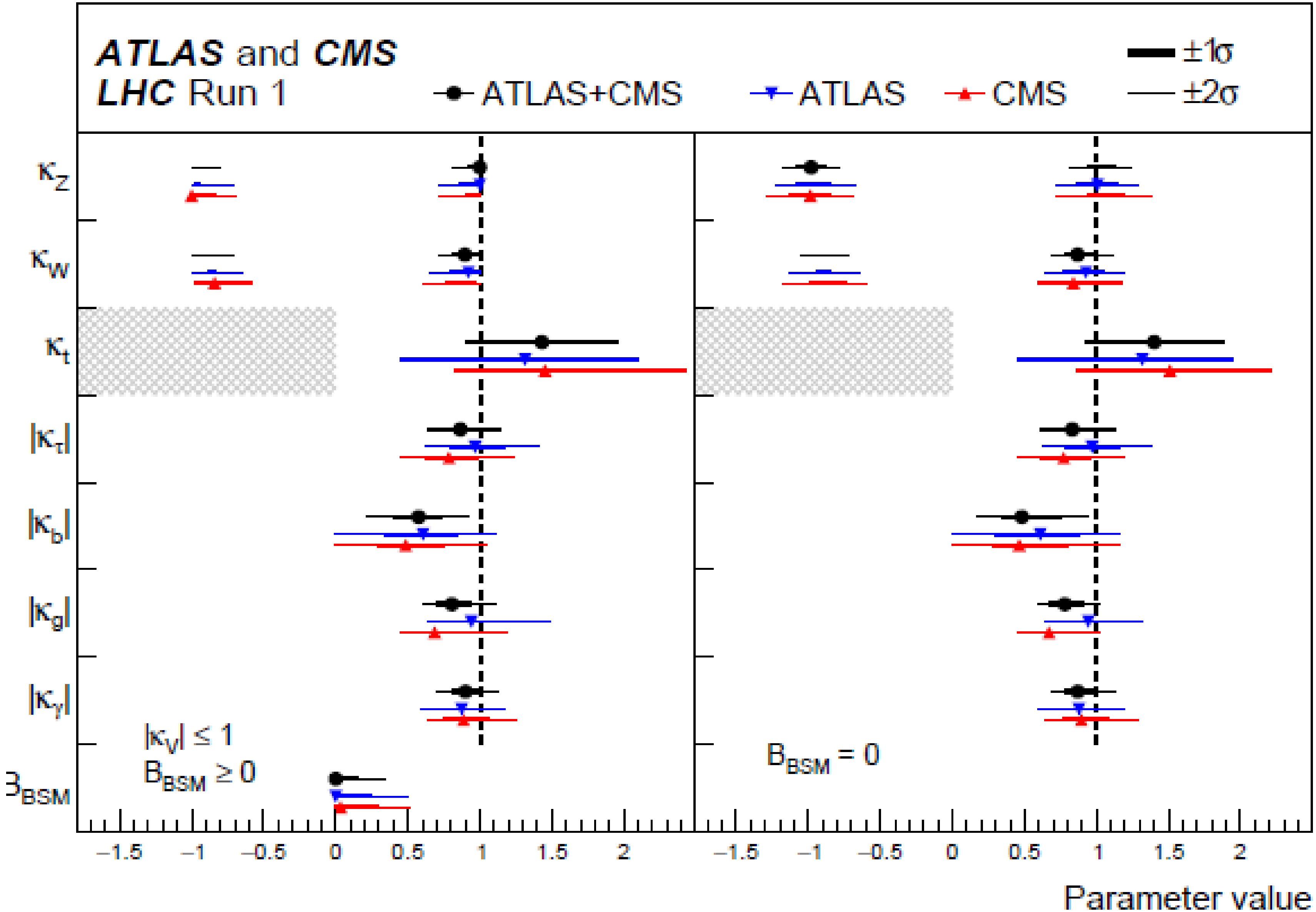
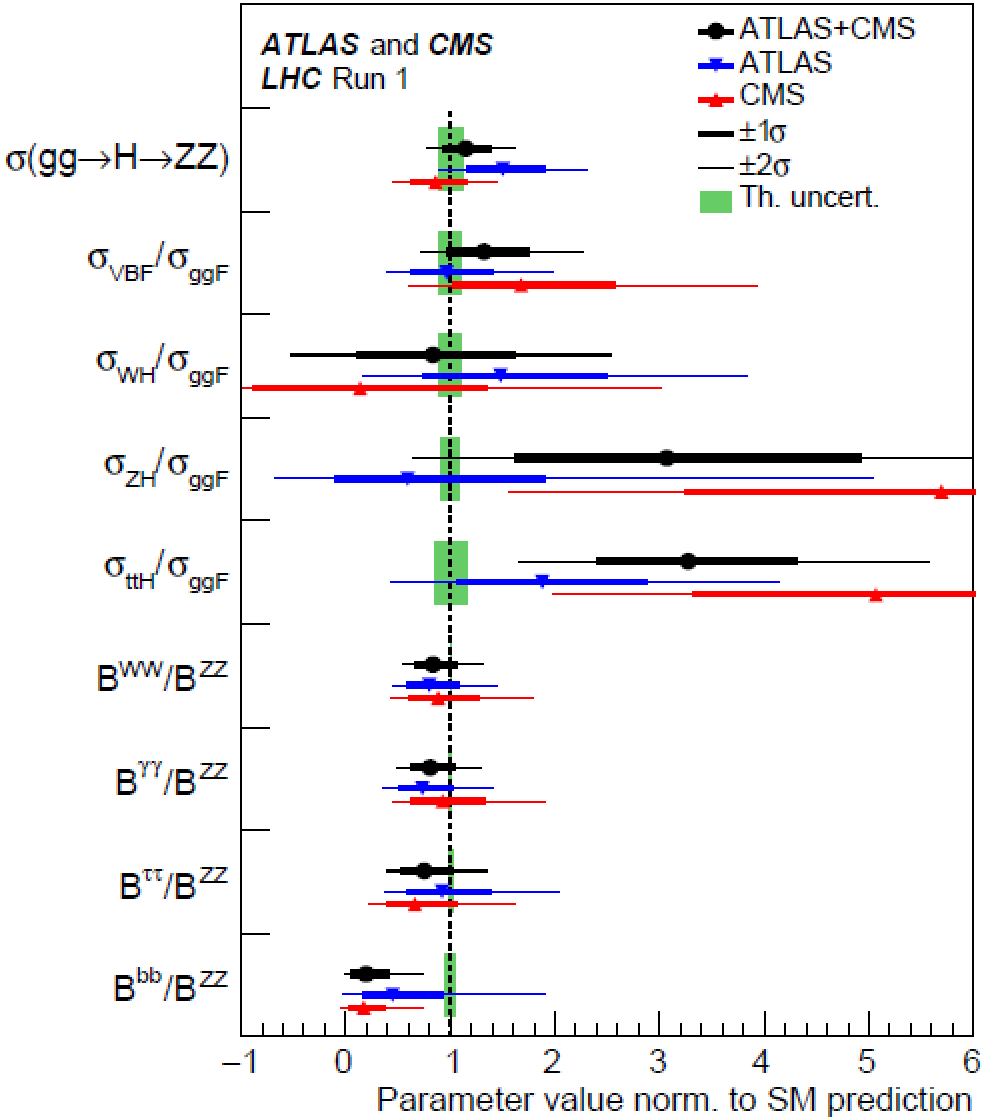


Run1 measurements



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Combination of ATLAS and CMS analyses

$\mathcal{B}$(H(inv)) < 34 (39)%, obs.(exp.)

→ unitarity-inspired constrained k_v <1

ZH analysis multiclass BDT classifier

Backgrounds: ZZ, WZ, DY, flavour symmetric or non-resonant p

- $|m_{\ell\ell} - m_{\mathrm{Z}}|$ (dilepton mass);
- $p_{\mathrm{T}}^{\ell 1}$ (leading lepton transverse momentum);
- $p_{\mathrm{T}}^{\ell 2}$ (subleading lepton transverse momentum);
- $p_{\mathrm{T}}^{\ell\ell}$ (dilepton transverse momentum);
- $|\eta^{\ell 1}|$ (leading lepton pseudorapidity);
- $|\eta^{\ell 2}|$ (subleading lepton pseudorapidity);
- $p_{\mathrm{T}}^{\mathrm{miss}}$ (missing transverse momentum);
- $m_T(p_{\mathrm{T}}^{\ell 1}, p_{\mathrm{T}}^{\mathrm{miss}})$ (leading lepton transverse mass);
- $m_T(p_{\mathrm{T}}^{\ell 2}, p_{\mathrm{T}}^{\mathrm{miss}})$ (subleading lepton transverse mass);
- $\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\ell}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$ (azimuthal separation between dilepton and missing momentum);
- $\Delta R_{\ell\ell}$ (separation between leptons); and
- $|\cos\theta_{\ell 1}^{\mathrm{CS}}|$ (cosine of the polar angle in the Collins–Soper frame [71] for the leading lepton).

Systematic uncertainties for ZH analysis

Source of uncertainty	Effect (%) Signal	ZZ	WZ	NRB	DY	Impact on the exp. limit (%)
* VV EW corrections	—	10	−4	—	—	14 (12)
* Renorm./fact. scales, VV	—	9	4	—	—	2 (1)
* Renorm./fact. scales, ZH	3.5	—	—	—	—	
* Renorm./fact. scales, DM	5	—	—	—	—	
* PDF, WZ background	—	—	1.5	—	—	
* PDF, ZZ background	—	1.5	—	—	—	
* PDF, Higgs boson signal	1.5	—	—	—	—	
* PDF, DM signal	1–2	—	—	—	—	
* MC sample size, NRB	—	—	—	5	—	1
* MC sample size, DY	—	—	—	—	30	
* MC sample size, ZZ	—	0.1	—	—	—	
* MC sample size, WZ	—	—	2	—	—	
* MC sample size, ZH	1	—	—	—	—	
* MC sample size, DM	3	—	—	—	—	
* Electron efficiency	1.5					1 (<1)
* Muon efficiency	1					
* Electron energy scale	1–2					
* Muon energy scale	1–2					
* Jet energy scale	1–3 (typically anticorrelated w/ yield)					
* Jet energy resolution	1 (typically anticorr.)					
* Unclustered energy ($p_{\mathrm{T}}^{\mathrm{miss}}$)	1–4 (typically anticorr.), strong in DY					
* Pileup	1 (typically anticorrelated)					
* b tagging eff. & mistag rate	1					
* BDT: electron energy scale	1.1	2.9	2.6	—	—	— (2)
* BDT: muon energy scale	1.5	4.3	2.7	—	—	
* BDT: $p_{\mathrm{T}}^{\mathrm{miss}}$ scale	1.0	3.2	4.1	—	—	
NRB extrapolation to the SR	—	—	—	20	—	<1
DY extrapolation to the SR	—	—	—	—	100	<1
Lepton efficiency (WZ CR)	—	—	3	—	—	<1
Nonprompt bkg. (WZ CR)	—	—	—	—	30	<1
Integrated luminosity	2.5					<1

Affecting the shape