Exotic Higgs Decays at CMS

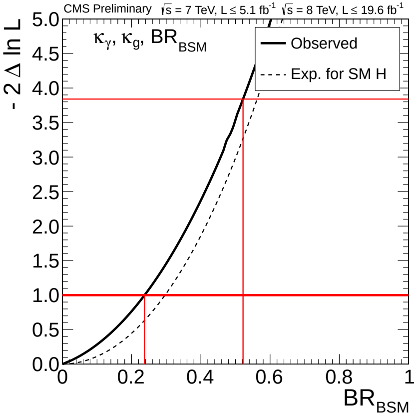
Aysen Tatarinov for CMS Collaboration
Texas A&M University

Dark Interactions 2014
Brookhaven National Laboratory
June 11–13, 2014

Introduction (1/2)

- Higgs-like particle with mass ∼125 GeV was observed at LHC
- Critical question: is it the SM Higgs boson?

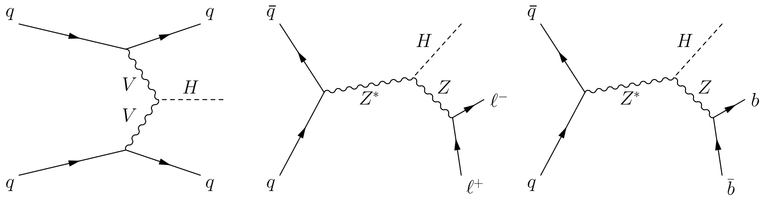
- (1) Precise measurements of its branching ratios:
  - This may take many years
  - Current 95% CL limit: $\mathcal{B}_{BSM} \leq 0.52$
- (2) Direct searches for non-SM decays of SM-like Higgs:
  - In case of observation: this is non-SM Higgs!
  - In case of no signal: restrict broad class of scenarios beyond the SM



CMS-PAS-HIG-13-005

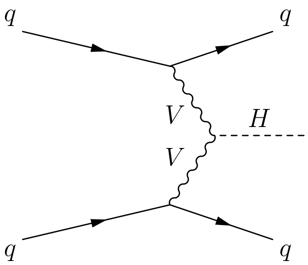
Introduction (2/2)

- Searches for invisible decays of the Higgs boson:
  - Vector Boson Fusion production
  - ZH production with the Z boson decaying to a pair of charged leptons
  - ZH production with the Z boson decaying to bottom quarks
  - Interpretation in terms of Higgs-portal models of DM interactions



- Search for non-SM Higgs decays to a pair of new light bosons, each of which decays to boosted muon pairs: $h \to 2a \to 4\mu$
  - Interpretation in the context of SUSY with hidden dark sector

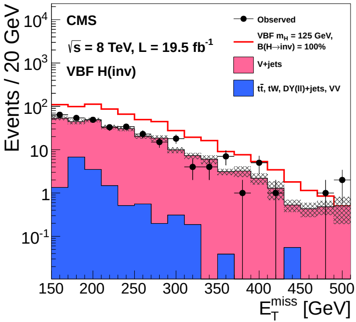
Invisible Higgs Decays in Vector Boson Fusion Channel

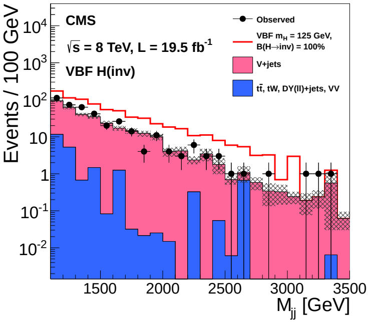


- Experimental signature:
  - Two jets with high transverse momentum, p_T, well separated in pseudorapidity
  - Large missing transverse evergy, E_T^{miss}
- CMS-PAS-HIG-13-013, arXiv:1404.1344v2

Vector Boson Fusion Channel: Results (1/2)

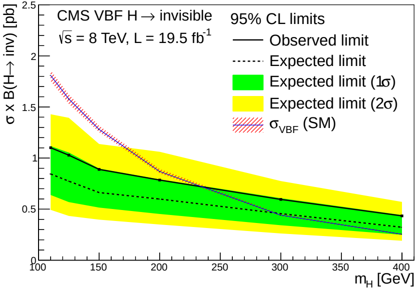
- E_T^{miss} and M_{jj} in data and simulation after the full selection:
  - Signal contribution for $m_H = 125$ GeV and $\mathcal{B}(H \to inv) = 100\%$
  - Background estimates and signal predictions shown cumulatively

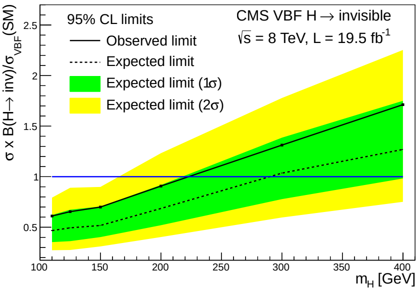




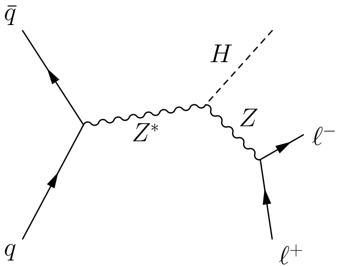
Vector Boson Fusion Channel: Results (2/2)

- No significant excess in data over total background
- Set upper limit on invisible Higgs decays in VBF channel
  - Assuming SM VBF production cross section, 95% CL observed (expected) upper limit on $\mathcal{B}(h \to inv)$ for $m_H = 125$ GeV is 0.65 (0.49)





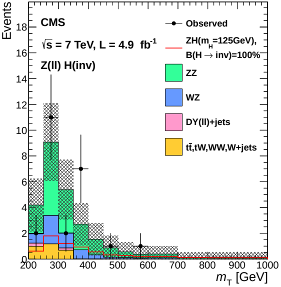
Search for Invisible Higgs Decays in Z(ll)H Channel



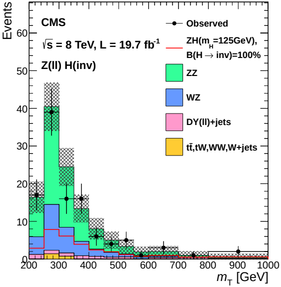
- Experimental signature:
  - Two leptons (e^+e^- or $\mu^+\mu^-$) with invariant mass consistent with Z mass
  - Large missing transverse evergy, E_T^{miss}
- CMS-PAS-HIG-13-018, arXiv:1404.1344v2

Results (1/2)

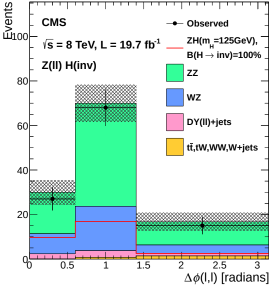
- m_T and $\Delta\phi(ll)$ in data and simulation after the full selection:
  - Signal contribution for $m_H = 125$ GeV and $\mathcal{B}(H \to inv) = 100\%$
  - Background estimates shown cumulatively
  - Signal predictions shown separately
  - For limit setting at 7 TeV 1D distribution of m_T is used
  - For limit setting at 8 TeV 2D distribution of m_T and $\Delta\phi(ll)$ is used
  - Limit on invisible Higgs decays in Z(ll)H channel to be shown later in combination with limit $Z(b\bar{b})H$ channel



7 TeV

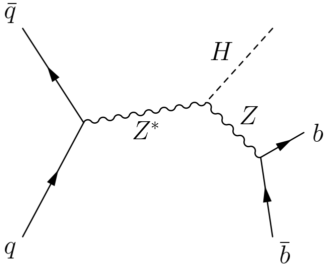


8 TeV



8 TeV

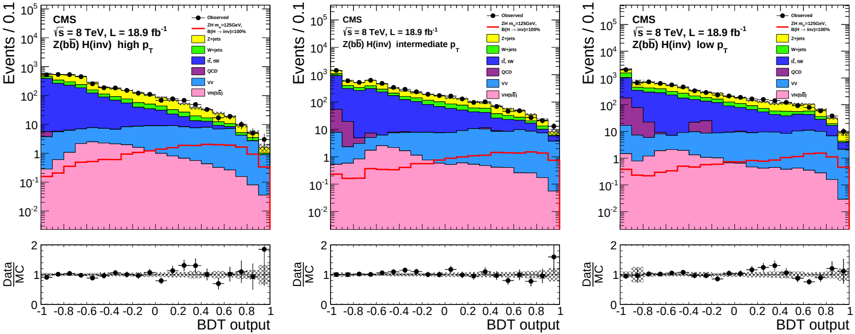
Search for Invisible Higgs Decays in Z($b\bar{b}$)H Channel



- Experimental signature:
  - Two jets consistent with $Z \to b\bar{b}$
  - Large missing transverse evergy, E_T^{miss}
- CMS-PAS-HIG-13-028, arXiv:1404.1344v2

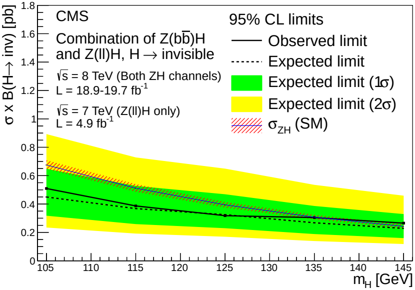
$Z(b\bar{b})H$ Channel: Results (1/2)

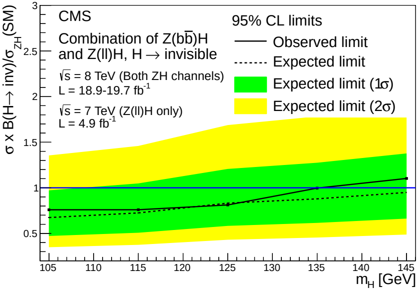
- Multivariate Analysis: Boosted Decision Trees (BDT)
- BDT output in high-, intermediate-, low- dijet p_T regions in data and simulations after the full selection
  - Signal contribution for $m_H = 125$ GeV and $\mathcal{B}(H \to inv) = 100\%$
  - Background estimates shown cumulatively
  - Signal predictions shown separately



ZH Channel: Results (2/2)

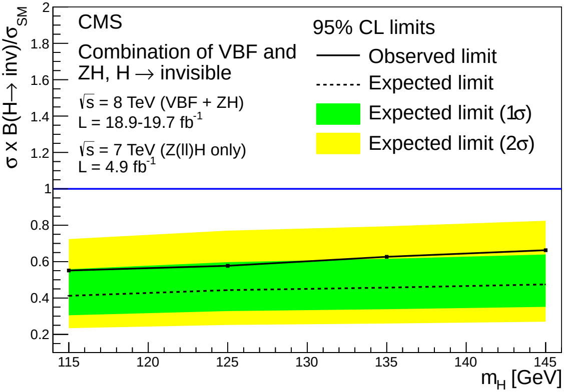
- Combine limits on invisible Higgs decays in Z($b\bar{b}$)H channel and Z(ll)H channel
  - Assuming SM ZH production cross section, 95% CL observed (expected) upper limit on $\mathcal{B}(h \to inv)$ for $m_H = 125$ GeV is 0.81 (0.83)





Combination of VBF, Z(ll)H, Z($b\bar{b}$)H channels

- Combine limits on invisible Higgs decays of all three searches
  - Assuming SM ZH production cross section, 95% CL observed (expected) upper limit on $\mathcal{B}(h \to inv)$ for $m_H = 125$ GeV is 0.58 (0.44)
- The best direct measurement of $\mathcal{B}(h \to inv)$ to date



Interpretation (1/2)

- Interpret the limit on $\mathcal{B}(h \to inv)$, assuming SM production cross section, in the context of a Higgs-portal model of dark matter interactions
- If $M_\chi < m_H/2$, the width of invisible Higgs decays, Γ_{inv} relates to spin-independent DM-nucleon elastic cross section as follows for scalar(S), vector (V), fermionic (F) DM:

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

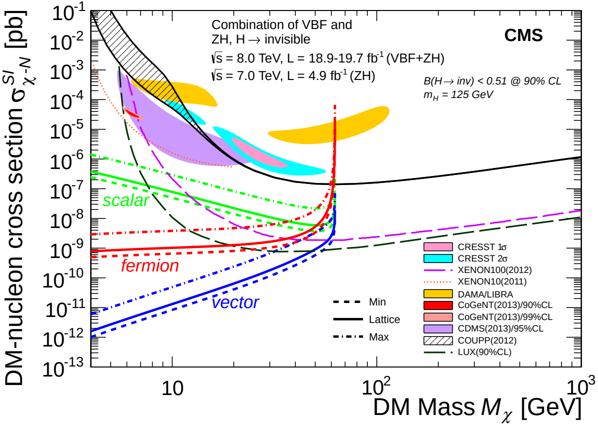
$$\sigma^{\mathrm{SI}}_{\mathrm{V}} - \mathrm{N} = \frac{16\Gamma_{\mathrm{inv}} M_\chi^4}{m_{\mathrm{H}}^3 v^2 \beta (m_{\mathrm{H}}^4 - 4M_\chi^2 m_{\mathrm{H}}^2 + 12 M_\chi^4)} \frac{m_{\mathrm{N}}^4 f_{\mathrm{N}}^2}{(M_\chi + m_{\mathrm{N}})^2},$$

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

Here, m_{N} represents the nucleon mass, taken as the average of proton and neutron masses, 0.939 GeV, while $\sqrt{2}v$ is the Higgs vacuum expectation value of 246 GeV, and $\beta = \sqrt{1 - 4M_\chi^2/m_{\mathrm{H}}^2}$ The dimensionless quantity f_{N} [8] parameterizes the Higgs-nucleon coupling; we take the central values of $f_{\mathrm{N}} = 0.326$ from a lattice calculation [68], while we use results from the MILC Collaboration [69] for the minimum (0.260) and maximum (0.629) values. We convert the invisible branching fraction to the invisible width using $\mathcal{B}(\mathrm{H} \to \mathrm{inv}) = \Gamma_{\mathrm{inv}}/(\Gamma_{\mathrm{SM}} + \Gamma_{\mathrm{inv}})$, where $\Gamma_{\mathrm{SM}} = 4.07$ MeV.

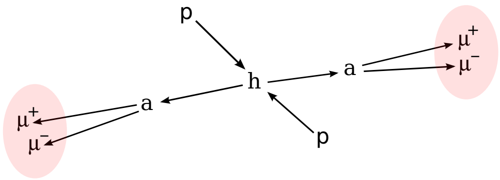
Interpretation (2/2)

- Upper limits on the DM-nucleon cross section for $m_H = 125$ GeV and $\mathcal{B}(h \to inv) < 0.51$ at 90%CL as a function of the DM mass
  - Severeley restrict the DM-nucleon cross section for light DM



Search for muon (leptin) jets

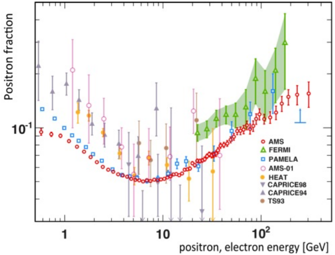
- Search for non-SM Higgs decays to a pair of new light bosons, each of which decays to boosted and isolated muon pairs (dimuons): $h \to 2a \to 4\mu$ (CMS-PAS-HIG-13-010)
  - m_a within the range 0.25–3.55 GeV (roughly between $2m_\mu$ and $2m_\tau$)



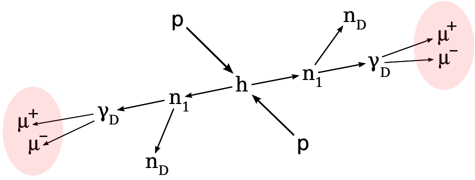
- Analysis is designed to remain model independent
  - Allows easy reinterpretation in the context of any scenario with the same signature
- Example interpretation: SUSY + hidden sector

SUSY + hidden sector

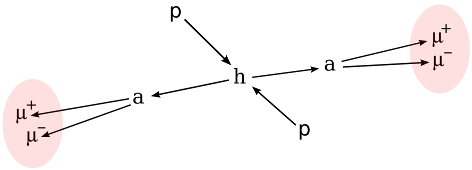
- Recent observation of rising positron fraction at high energies by satellite experiments
- Dark matter annihilation: new light γ_D as an attractive long-distance force between slow moving WIMPs
- Simplified implementation of dark sector (for simulation only):
  - dark neutralino n_D (new LSP) + dark photon γ_D
- if $m_{n_1} < \frac{m_h}{2}$: $h \to 2n_1$
- n_1 decays into dark sector particles: $n_1 \to n_D \gamma_D$
- γ_D weakly couples to SM via kinetic mixing with photon



Phys. Rev. Lett. 110, 141102 (2013)



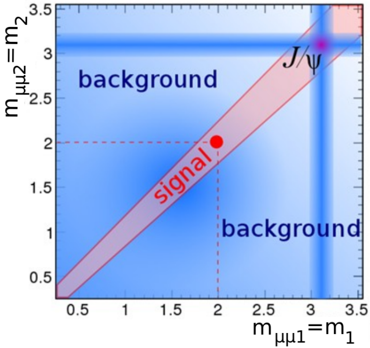
Analysis Selection



- At least four muons: $p_T > 8$ GeV/c, $|\eta| < 2.4$, good track quality
  - At least one good quality muon with $p_T > 17$ GeV/c, $|\eta| < 0.9$
- Assign two opposite-sign muons to a dimuon
  - $m_{\mu\mu} < 5$ GeV/c^2 **and** (good common vertex **or** $\Delta R_{\mu\mu} < 0.01$)
- Further consider events with exactly two dimuons
- Apply isolation requirement to dimuons: supresses background by a factor of 50, reject about 20% of signal

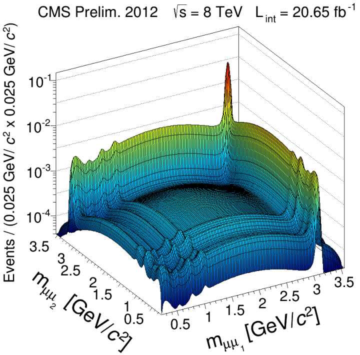
Signal Region

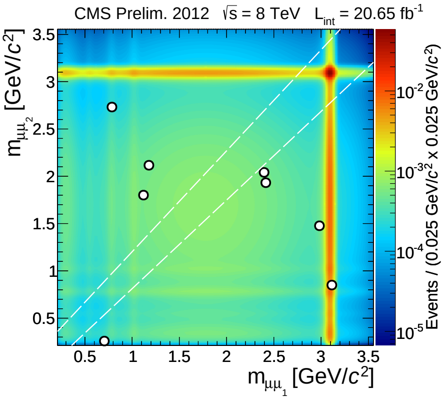
- Target events where dimuons are produced in decays of new light bosons with the same mass
- Signal region: reconstructed dimuon masses consistent with each other:
  - $|m_1 - m_2| \leq 5 \cdot \sigma(\frac{m_1+m_2}{2})$ (where $\sigma(m)$ — dimuon mass resolution)
- Study of dimuon mass resolution: $\sigma(m) \sim 0.026 + 0.013 \cdot m$
  - Use narrow SM resonances in data: ω, ϕ, J/ψ, ψ'



SM Background (1/2): $b\bar{b}$

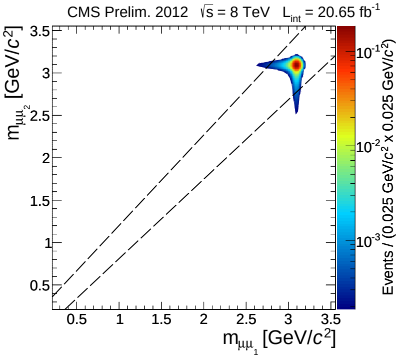
- 2D background template obtained from $b\bar{b}$ enriched data: events with one dimuon and one muon (no isolation requirement)
- Off-diagonal part of $b\bar{b}$ 2D shape is normalized to 8 events observed in off-diagonal region in data
- 1.8 ± 0.6 of $b\bar{b}$ events expected in the signal region

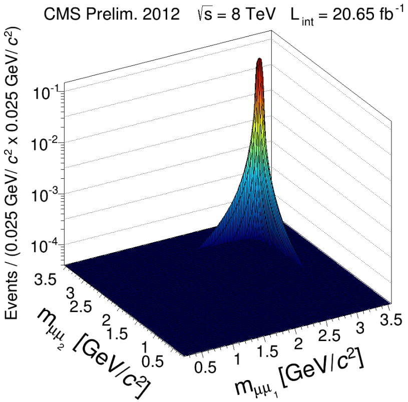




Background Estimation (2/2): Prompt Double J/ψ

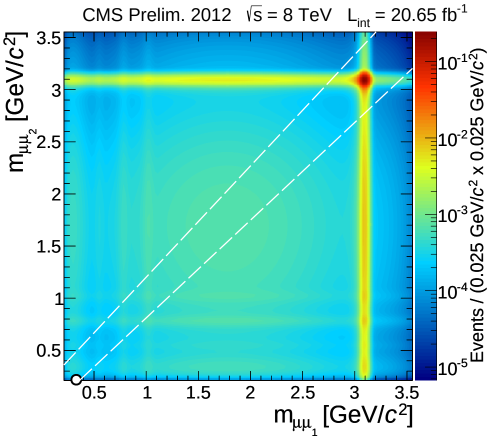
- Prompt double J/ψ production
  - 2D Crystal Ball template normalized to data
  - 2.0 ± 2.0 prompt double J/ψ events expected in the signal region





Signal Region Yields

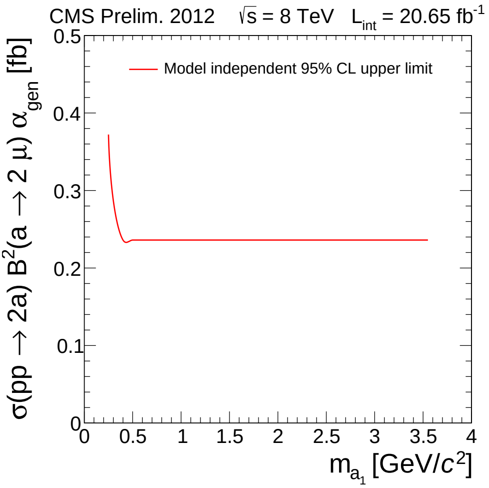
- Unblind the signal region (diagonal region)
- One event is observed in the signal region
- 3.8 ± 2.1 background events expected in the signal region (1.8 ± 0.6 $b\bar{b}$, 2.0 ± 2.0 double J/ψ)



Model Independent Limit

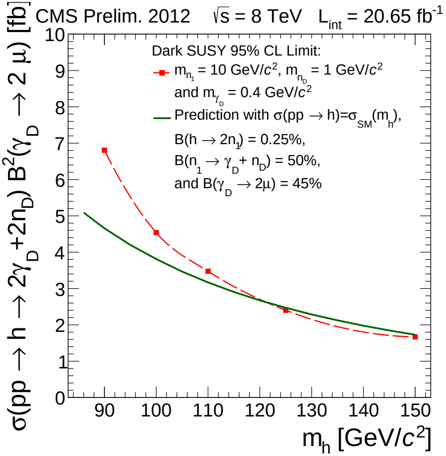
95% CL limit on $\sigma(pp \to h \to 2a) \times \mathcal{B}^2(a \to 2\mu) \times \alpha_{gen}$

- α_{gen} — kinematic and geometric acceptance on generator level
- We use flat $\frac{\epsilon_{full}}{\alpha_{gen}} = 0.63 \pm 0.05$ observed in all MC samples we used
- Applicable to models with 4μ coming from new light bosons with mass in range 0.25–3.55 GeV, where new light bosons typically isolated and spatially separated



Results: SUSY with Hidden Dark Sector Scenario

- 95% CL limit on $\sigma(pp \to h \to 2a)\mathcal{B}^2(a \to 2\mu)$ vs m_h



Conclusions

Searches for invisible Higgs decays in VFB and ZH channels with 7 and 8 TeV data collected at CMS experiment

- The best direct measurement of $\mathcal{B}(h \rightarrow inv)$ to date
- Severe restriction on DM-nucleon cross section for low mass DM ($M_\chi < m_H/2$) in the context of Higgs-portal model of dark matter interactions

Search for non-SM Higgs decays to a pair of new light bosons, which decay to boosted and isolated muon pairs: $h \rightarrow 2a \rightarrow 4\mu$ ($2m_\mu \lesssim m_a \lesssim 2m_\tau$)

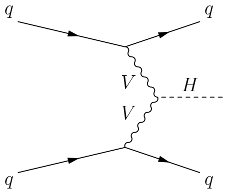
- Model independent limit is set:
  - Can be applied to any model with the same signature
  - Interpreted in the context of SUSY with hidden dark sector

BACKUP SLIDES

Search for Invisible Higgs Decays in VBF Channel

Event selection:

- Two jets with $p_T^{j_1}, p_T^{j_2} > 50$ GeV
- Forward/backward: $\eta_{j_1} \cdot \eta_{j_2} < 0$
- Well separated in pseudorapidity: $\Delta\eta_{jj} > 4.2$
- High invariant mass: $M_{jj} > 1100$ GeV
- Missing transverse energy: $E_T^{miss} > 130$ GeV
- Veto events with e, μ with $p_T > 10$ GeV — supress Z and W backgrounds
- $\Delta\phi_{jj} < 1.0$ — supress multijet backgrounds
- Central jet veto (CJV): veto events with additional jet with $p_T > 30$ GeV and $\eta_{j_1} < \eta < \eta_{j_2}$



VBF Channel: Background Estimation

- Main backgrounds: Z($\nu\nu$)+jets and W(lν)+jets (not identified lepton)
- Data-driven estimation with Z and W decays to well identified leptons
  - Z($\nu\nu$)+jets control region: require oppositely charged pair of muons, veto additional leptons, relax some selections
    - Number of Z($\nu\nu$) events in the signal region:

$$N^{s}_{\nu\nu} = (N^{c}_{\mu\mu\mathrm{obs}} - N^{c}_{\mathrm{bkg}}) \cdot \frac{\sigma(Z \to \nu\nu)}{\sigma(Z/\gamma^{*} \to \mu\mu)} \cdot \frac{\varepsilon^{s}_{\mathrm{ZMC}}}{\varepsilon^{c}_{\mathrm{ZMC}}}$$

    - $N^{c}_{\mu\mu obs}$ — observed yield in the control region
    - N^{c}_{bkg} — background estimation from $t\bar{t}$, single-top, diboson MC
  - W(eν)+jets and W($\mu\nu$)+jets control region: require electron or muon, veto additional leptons
  - W($\tau\nu$)+jets control region: require hadronic tau, veto additional leptons, do not apply CJV
- QCD multijet backgrounds — data-driven (ABCD method)
- Minor backgrounds ($t\bar{t}$, signle-top, diboson, DY(ll)) — MC simulation

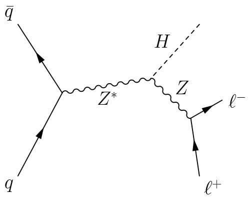
Vector Boson Fusion Channel: Results

Process	Event yields
$Z(\nu\nu)$+jets	$99 \pm 29\,(\text{stat.}) \pm 25\,(\text{syst.})$
$W(\mu\nu)$+jets	$67 \pm 5\,(\text{stat.}) \pm 16\,(\text{syst.})$
$W(e\nu)$+jets	$63 \pm 9\,(\text{stat.}) \pm 18\,(\text{syst.})$
$W(\tau_h\nu)$+jets	$53 \pm 18\,(\text{stat.}) \pm 18\,(\text{syst.})$
QCD multijet	$31 \pm 2\,(\text{stat.}) \pm 23\,(\text{syst.})$
Sum ($t\bar{t}$, single top quark, VV, DY)	$20.0 \pm 8.2\,(\text{syst.})$
Total background	$332 \pm 36\,(\text{stat.}) \pm 46\,(\text{syst.})$
VBF H(inv.)	$210 \pm 30\,(\text{syst.})$
ggF H(inv.)	$14 \pm 11\,(\text{syst.})$
Observed data	390
S/B (%)	70

Search for Invisible Higgs Decays in Z(ll)H Channel

Event selection:

- e^+e^- or $\mu^+\mu^-$, each lepton with $p_T > 20$ GeV, invariant mass m_{ll} within ± 15 GeV from Z boson mass
- Reject events with two or more jets with $p_T > 30$ GeV — reduce DY(ll)+jets background
- Veto events with additional e, μ with $p_T > 10$ GeV — supress Z and W backgrounds
- Reject events identified to have b quark — supress top-quark background
- Final requirements optimized for best expected exclusion limit for $m_H = 125$ GeV:
  - $E_T^{miss} > 130$ GeV, $\Delta\phi(ll, E_T^{miss}) > 2.7$, $|E_T^{miss} - p_T^{ll}|/p^{ll_T} < 0.25$



Z(ll)H Channel: Background estimation

- Main backgrounds: WZ and ZZ — estimate using MC simulation
- DY(ll)+jets — use orthogonal control sample of γ+jets events
- Minor backgrounds — $t\bar{t}$, Wt, WW, W+jets
  - Control sample with opposite-charge different-flavor dileptons ($e^{\pm}\mu^{\mp}$)
  - Multiply number of events in the control region, $N_{e\mu}$, by scale factors α_{ee} and $\alpha_{\mu\mu}$ to estimate backgrounds in e^+e^- and $\mu^+\mu^-$ final states

$$N_{\mathrm{ee}} = \alpha_{\mathrm{ee}} \times N_{\mathrm{e}\mu}, \qquad N_{\mu\mu} = \alpha_{\mu\mu} \times N_{\mathrm{e}\mu}$$

  - Measure α_{ee} and $\alpha_{\mu\mu}$ in the sidebands (SB) of the Z peak ($40 < m_{ll} < 70$ GeV and $110 < m_{ll} < 200$ GeV):

$$\alpha_{\mathrm{ee}} = \frac{N^{\mathrm{SB}}_{\mathrm{ee}}}{N^{\mathrm{SB}}_{\mathrm{e}\mu}}, \qquad \alpha_{\mu\mu} = \frac{N^{\mathrm{SB}}_{\mu\mu}}{N^{\mathrm{SB}}_{\mathrm{e}\mu}}$$

  - N^{SB}_{ee}, $N^{SB}_{\mu\mu}$, $N^{SB}_{e\mu}$ — number of events in e^+e^-, $\mu^+\mu^-$, $e^{\pm}\mu^{\mp}$ final states in top-quark enriched sample

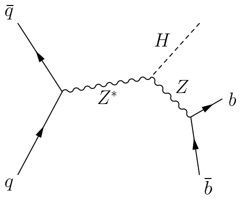
Z(ll)H Channel: Results

Process	$\sqrt{s} = 7\,\text{TeV}$		$\sqrt{s} = 8\,\text{TeV}$	
	ee	$\mu\mu$	ee	$\mu\mu$
		0 jet selection		
$Z/\gamma^* \to \ell^+\ell^-$	0.1 ± 0.1	0.2 ± 0.2	0.2 ± 0.3	0.9 ± 1.4
$WZ \to 3\ell\nu$	1.7 ± 0.2	2.0 ± 0.3	10.4 ± 1.6	14.1 ± 1.7
$ZZ \to 2\ell 2\nu$	5.8 ± 0.7	7.8 ± 0.9	26.4 ± 3.0	35.9 ± 3.6
$t\bar{t}$, Wt, WW & W+jets	1.1 ± 6.4	1.0 ± 3.1	0.4 ± 1.5	0.7 ± 2.1
Total backgrounds	8.7 ± 6.5	11.0 ± 3.3	37.4 ± 3.7	51.6 ± 4.8
ZH(125)	2.3 ± 0.2	3.1 ± 0.3	10.3 ± 1.2	14.7 ± 1.5
Observed data	9	10	36	46
S/B(%)	26	28	28	24
		1 jet selection		
$Z/\gamma^* \to \ell^+\ell^-$	0.2 ± 0.2	$0.0 \pm ^{1.3}_{0.0}$	2.0 ± 3.8	3.0 ± 5.6
$WZ \to 3\ell\nu$	0.8 ± 0.1	0.9 ± 0.2	3.3 ± 0.4	3.8 ± 0.5
$ZZ \to 2\ell 2\nu$	1.1 ± 0.2	1.4 ± 0.2	4.8 ± 0.5	6.3 ± 0.7
$t\bar{t}$, Wt, WW & W+jets	0.5 ± 0.6	0.5 ± 0.8	0.4 ± 1.7	0.7 ± 1.3
Total backgrounds	2.6 ± 0.7	2.8 ± 0.9	10.6 ± 4.2	13.8 ± 5.8
ZH(125)	0.4 ± 0.1	0.5 ± 0.1	1.6 ± 0.2	2.5 ± 0.3
Observed data	1	4	11	17
S/B (%)	15	18	15	18

Search for Invisible Higgs Decays in Z(bb)H Channel

- Events with two jets consistent with $Z \to b\bar{b}$, large E_T^{miss} due to invisible Higgs decay
- Summary of selection criteria:

Variable	Selection		
	Low p_T	Intermediate p_T	High p_T
E_T^{miss}	100–130 GeV	130–170 GeV	>170 GeV
p_T^{j1}	>60 GeV	>60 GeV	>60 GeV
p_T^{j2}	>30 GeV	>30 GeV	>30 GeV
p_T^{jj}	>100 GeV	>130 GeV	>130 GeV
M_{jj}	<250 GeV	<250 GeV	<250 GeV
CSV_{max}	>0.679	>0.679	>0.679
CSV_{min}	>0.244	>0.244	>0.244
N additional jets	<2	—	—
N leptons	=0	=0	=0
$\Delta\phi(Z,H)$	>2.0 radians	>2.0 radians	>2.0 radians
$\Delta\phi(E_T^{miss},j)$	>0.7 radians	>0.7 radians	>0.5 radians
$\Delta\phi(E_T^{miss},E_{T\,trk}^{miss})$	<0.5 radians	<0.5 radians	<0.5 radians
E_T^{miss} significance	>3	not used	not used



Z(bb)H Channel: Background Estimation & BDT Training

- All backgrounds are estimated from MC simulation
- Train BDT using simulated samples for signal and backgrounds after all selections
- Set of BDT input variables is the subset of the following variables chosen in iterative optimization:

Variable	
p_T^{j1}, p_T^{j2}	Transverse momentum of each Z boson daughter
M_{jj}	Dijet invariant mass
p_T^{jj}	Dijet transverse momentum
E_T^{miss}	Missing transverse energy
N_{aj}	Number of additional jets ($p_T > 25$ GeV and $\lvert\eta\rvert < 4.5$)
CSV_{max}	Value of CSV for the Z boson daughter with largest CSV value
CSV_{min}	Value of CSV for the Z boson daughter with second largest CSV value
$\Delta\phi(Z, H)$	Azimuthal angle between E_T^{miss} and dijet
$\Delta\eta_{jj}$	Difference in η between Z daughters
ΔR_{jj}	Distance in η-ϕ between Z daughters
$\Delta\theta_{pull}$	Color pull angle [62]
$\Delta\phi(E_T^{miss}, j)$	Azimuthal angle between E_T^{miss} and the closest jet
CSV_{aj}	Maximum CSV of the additional jets in an event
$\Delta R(H, aj)$	Minimum distance between an additional jet and the Z boson candidate
m_T	Transverse mass of the ZH system

$Z(b\bar{b})H$ Channel: Results

Process	High $p_T(V)$	Intermediate $p_T(V)$	Low $p_T(V)$
$Z(\nu\bar{\nu})H(b\bar{b})$(SM)	2.0 ± 0.3	0.4 ± 0.1	0.1 ± 0.0
$W(\ell\nu)H(b\bar{b})$(SM)	0.5 ± 0.1	0.1 ± 0.0	0.1 ± 0.0
ZZ(bb)	27.7 ± 3.1	11.6 ± 1.3	5.5 ± 0.7
WZ(bb)	10.2 ± 1.6	7.3 ± 0.9	3.1 ± 0.5
VV(udscg)	5.3 ± 1.1	0.3 ± 0.2	0.1 ± 0.1
$Z+b\bar{b}$	61.8 ± 7.1	21.1 ± 2.4	13.2 ± 1.6
Z+b	16.7 ± 1.7	3.2 ± 1.4	0.7 ± 0.9
Z+udscg	7.1 ± 0.3	0.6 ± 0.4	3.1 ± 2.5
$W+b\bar{b}$	15.8 ± 2.2	5.8 ± 0.8	3.0 ± 1.4
W+b	4.7 ± 1.2	0.2 ± 0.3	0.0 ± 0.0
W+udscg	4.9 ± 0.2	1.1 ± 0.3	0.2 ± 0.3
$t\bar{t}$	20.4 ± 1.8	9.6 ± 1.0	8.9 ± 1.1
Single-top-quark	4.1 ± 2.4	3.5 ± 2.0	2.5 ± 0.7
QCD	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Total backgrounds	181.3 ± 9.8	64.8 ± 4.1	40.5 ± 4.1
$Z(b\bar{b})H$(inv)	12.6 ± 1.1	3.6 ± 0.3	1.6 ± 0.1
Observed data	204	61	38
S/B (%)	6.9	5.6	3.9