Imperial College London

Searches for invisible decays of the Higgs boson with the CMS detector

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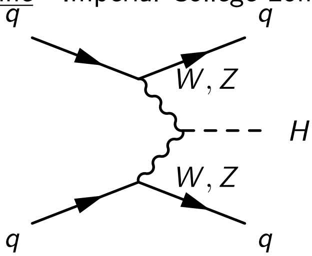
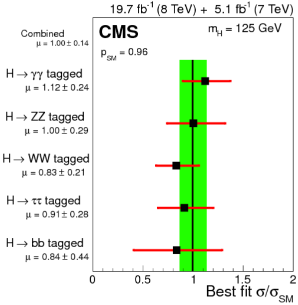


Outline

- Why look for invisibly decaying Higgs bosons?
- Higgs to invisible at CMS so far
- Parked update to VBF channel
- Combination with ZH channel

Why look for invisibly decaying Higgs bosons?

- SM compatible 125 GeV Higgs boson does not mean BSM incompatible

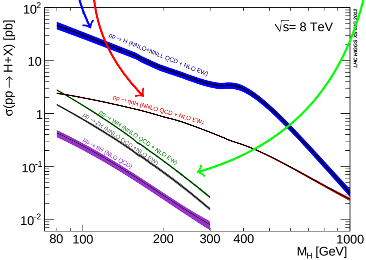


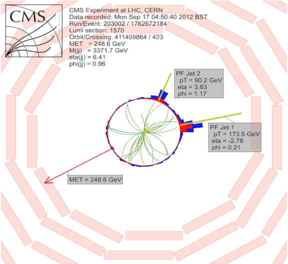
CMS-HIG-14-009

- Many BSM theories predict Higgs to invisible, e.g. SUSY
  - Often provide good DM candidates

Higgs to invisible at CMS

- Indirect: Look for effect of BSM Higgs decays on Higgs total width
- Direct: Use channels where the Higgs recoils against a visible system
  - ggH: high rate, no visible products (unless ISR/FSR, i.e. mono-X)
  - VBF: medium rate, jets+MET final state
  - ZH: low rate, leptons/b jets+MET final state





CMS VBF History

- CMS ran two sets of triggers in 2012:
  - prompt: reconstructed immediately
  - parked: looser thresholds, reconstructed in long shutdown
- CMS published result using full run I prompt dataset
- Parked analysis presented today

Parked Triggers

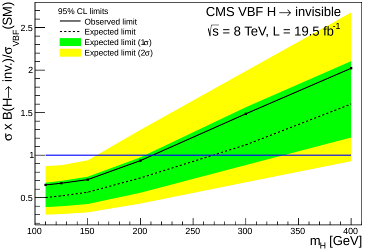
- Use already analysed prompt trigger for run A
- One parked trigger for runs B and C, another for run D
  - Parked trigger cuts are looser so prompt trigger not used where parked trigger is available
- All parked and prompt triggers are seeded by L1_ETM40
- Parked triggers have looser HLT thresholds
- This allows us to look at new regions of phase space and different analysis techniques
- Use prompt analysis as a base:
  - e.g. same objects and MC samples

HLT

Run period	MET cut	dijet p_T cut	dijet mass cut
A	METnoMuons>65 GeV	DiPFJet40	MJJ800
B&C	N/A	DiJet35	MJJ700
D	N/A	DiJet30	MJJ700

Prompt Analysis

- Standard object definition
- Single bin counting experiment
  - Signal region chosen to eliminate QCD and be above trigger turn ons
- Major backgrounds use data driven estimates:
  - $Z \to \nu\nu, W \to \ell\nu$, QCD
- Minor backgrounds taken from MC:
  - VV, Wγ, $t\bar{t}$, single top
- Observed (Expected) limit 65 (49)% at $m_H = 125$ GeV



Parked Analysis Changes

Trigger

- Parked trigger efficiency has been measured including correlation between variables
  - This allows the trigger turn on region to be used

Signal region

- QCD hard to model, signal region cuts are chosen to make remaining QCD small whilst enhancing real-MET using new Min$\Delta\phi$(jet,MET) variable
- The signal region has been reoptimised for the looser parked triggers
  - New region uses new variable has higher signal efficiency with much less QCD

Background estimation and limit setting

- Minor modifications made to $W \rightarrow \tau\nu$ background estimation method
- QCD background estimation method changed
- Wγ contribution found to be modelled already by our $W \rightarrow \ell\nu$ Monte Carlo
- We removed the $Z/\gamma^* \rightarrow \mu\mu$ to $Z \rightarrow \nu\nu$ after more studies with aMC@NLO
- Remaining backgrounds very signal like in variables studied so far
  - Stayed with cut and count analysis

Prompt vs Parked selection

- Summary of differences in signal region selection

Variable	Prompt cut	Parked cut
Lepton veto	no veto e or μ	
$\eta_{j1,2}$	< 4.7	
$\eta_{j1} \cdot \eta_{j2}$	< 0	
jet 1 p_T	> 50 GeV	
jet 2 p_T	> 50 GeV	> 45 GeV
$\Delta\eta_{jj}$	> 4.2	> 3.6
M_{jj}	> 1100 GeV	> 1200 GeV
METnomu	> 130 GeV	> 90 GeV
Central jet veto	yes	no
$\Delta\phi_{jj}$	< 1.0	no cut
$\frac{METnoMU}{\sigma_{METnoMU}}$	no cut	> 4
Min$\Delta\phi(all\ jets, METnomu)$	no cut	> 2.3

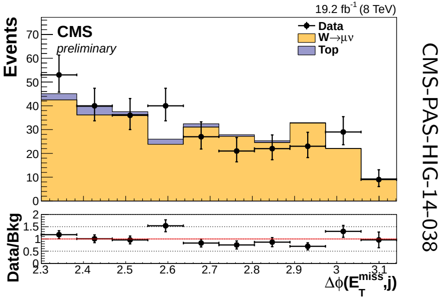
Background estimation

- All major backgrounds have data driven normalisation

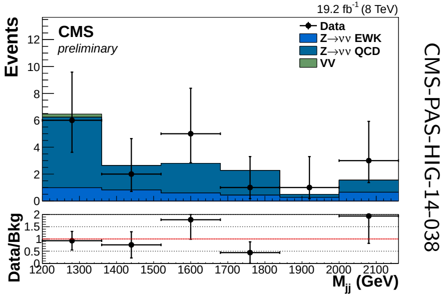
$$N^{W}_{bkg} = \frac{(N^{control}_{obs} - N^{control}_{other\ bkgs})}{N^{control}_{MC}} \cdot N^{sig}_{MC},\ N^{Z}_{Bkg} = \left(N^{control}_{obs} - N^{control}_{otherbkgs}\right) \cdot \frac{\sigma(Z\to\nu\nu)}{\sigma(Z/\gamma^{*}\to\mu\mu)} \cdot \frac{\epsilon^{ZMC}_{S}}{\epsilon^{ZMC}_{C}}$$

- Most backgrounds from missed lepton or misreconstructed jet
  - use control region where object is reconstructed

$W \to \mu\nu$ control region



$Z \to \nu\nu$ control region

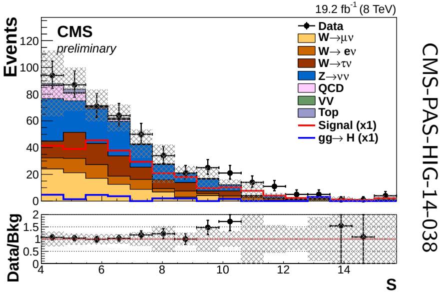


VBF results

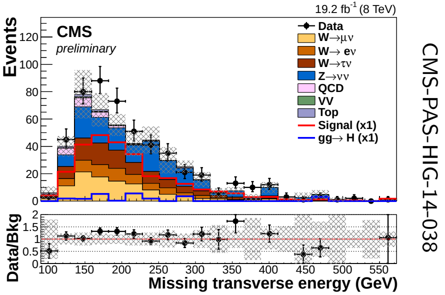
Total background	$439.7 \pm 41.0(stat.) \pm 55.8(syst.)$
VBF H(inv.) assuming B(H→inv)=100%	$273.4 \pm 31.2(syst.)$
ggF H(inv.) assuming B(H→inv)=100%	$22.6 \pm 15.6(syst.)$
Observed data	508

- Compatible with the background hypothesis

Signal region

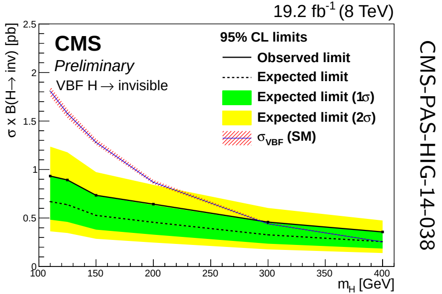


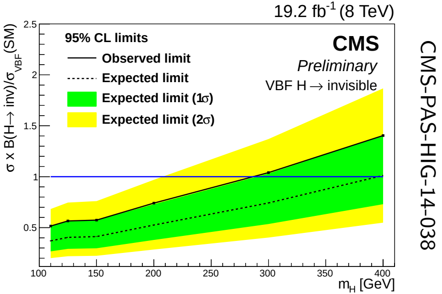
Signal region



VBF limits

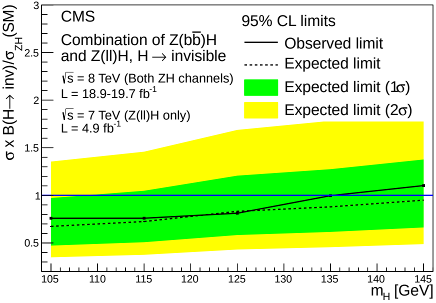
- Perform a single bin counting experiment using CL_S method
- Observed(expected) 95% C.L. limit on $B(H \rightarrow inv)$ for m_H=125 GeV is 57(40)%





ZH: summary

- Search also performed in $ZH \rightarrow \ell\ell inv$ and $ZH \rightarrow b\bar{b}inv$ channels at CMS
- Observed(expected) 95% C.L. limit on $B(H \rightarrow inv)$ for m_H=125 GeV is 81(83)%



Eur. Phys. J. C 74 (2014) 2980

Combined Results

- Separate limits on $\sigma x B(H \rightarrow inv)$ are combined at 125 GeV
- Assume SM production cross-sections to interpret as a limit on B(H$\rightarrow$inv)

Observed (expected) limits on B(H$\rightarrow$inv) at 95% C.L. for m_H=125 GeV

Channel	Limit/%
VBF	57(40)
ZH($\ell\ell$+bb)	81(83)
VBF + ZH	47(35)

Conclusions

- A direct search for Higgs boson decays to invisible final states has been carried out in the VBF channel
  - No significant excesses are seen over the background predictions
- This has been combined with the results in the $Z(\ell\ell)H$ and Z(bb)H channels
- The combined limit is 47(35)% observed (expected) at 95% C.L. for $m_H = 125$GeV

Backup

References

- CMS Higgs combination - CMS–HIG-14-009
- CMS VBF Higgs to invisible parked data PAS - CMS-PAS-HIG-14-038
- CMS Higgs to invisible paper - Eur. Phys. J. C 74 (2014) 2980

Comparison to recent ATLAS result

- We see an excess where ATLAS see a deficit:
  - observed can move the post-fit expected limit
  - were we to see a similar deficit our expected limit improves by $\sim$10%
- ATLAS use a single data driven normalisation factor for all V+jets backgrounds
  - statistical uncertainty on the factor is therefore lower
  - reducing our $Z \rightarrow \nu\nu$ statistical uncertainty to the level we see in $W \rightarrow \mu\nu$ our expected limit improves by $\sim$10%

W+jets

- $W \to e/\mu\nu$ control region formed by swapping lepton veto for e/μ requirement
- $W \to \tau\nu$ control region formed by requiring a hadronic tau
  - not many events with hadronic taus, need to loosen requirements
  - assign a 20% systematic to $W \to \tau\nu$ to compensate

$$N^{sig}_{bkg} = (N^{control}_{obs} - N^{control}_{other\ bkgs}) \cdot \frac{N^{sig}_{MC}}{N^{control}_{MC}}$$

$W \to \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \to e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \to \tau\nu$	$94.6 \pm 13.1 \pm 23.8$

Z+jets

- Use $Z \to \mu\mu$ MC ignoring muons to emulate $Z \to \nu\nu$
- Correct for difference in cross-section
- Efficiency correction takes into account EWK vs QCD difference

$$N_S^{Z\to\nu\nu} = \left(N_C^{Data} - N_C^{bkg}\right) \cdot \frac{\sigma(Z\to\nu\nu)}{\sigma(Z\to\mu\mu)} \cdot \frac{\epsilon_S^{ZMC}}{\epsilon_C^{ZMC}}$$

$Z \to \nu\nu$	$158.1 \pm 37.3 \pm 21.2$

QCD

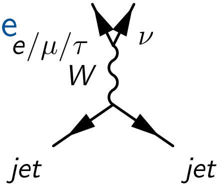
- Take shape from region with third jet near MET
- Normalise in sideband region
- normalisation highly selection dependent
- parameterise as function of selection and extrapolate
- Final estimate 17 ± 14

Other backgrounds

- Taken from MC

top	5.5 ± 1.8
VV	3.9 ± 0.7

$Z(\ell\ell)H$ outline

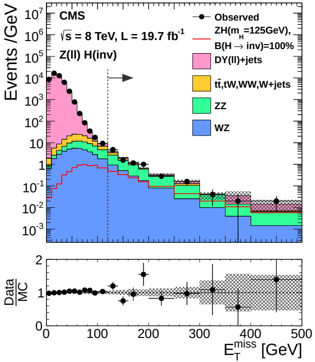


Signal Topology and Selection

- Two same flavour opposite sign electrons or muons
  - $p_T > 20$ GeV, $|M_{\ell\ell} - m_Z| < 15$ GeV
- Large MET
  - $MET > 120$ GeV

Backgrounds and Rejection Cuts

- $ZZ(\ell\ell\nu\nu)$+jets, $WW(\ell\nu\ell\nu)$+jets
- $WZ(\ell\nu\ell\ell)$+jets
  - Veto events with >3 leptons, $p_T>10$ GeV
- $Z(\ell\ell)$+jets
  - MET cut, MET-$\ell\ell$ balance requirement
- $t\bar{t}$, single top, $W(\ell\nu)$, QCD
  - ≤ 1 jet, $p_T>30$ GeV
  - no b-tagged jets, $p_T > 30$ GeV

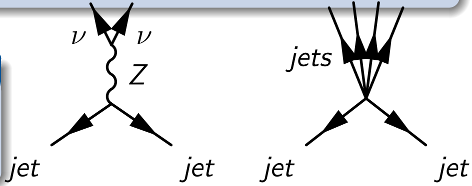


arXiv:1404.1344

$Z(\ell\ell)$H background estimation

ZZ($\ell\ell\nu\nu$)+jets and WZ($\ell\nu\ell\ell$+jets)

- Estimated from MC prediction



Z($\ell\ell$)+jets

- Estimated from photon + jets events
  - Photon p_T spectrum reweighted to match Z spectrum

WW($\ell\nu\ell\nu$)+jets, single top, $t\bar{t}$, $Z(\tau\tau)$

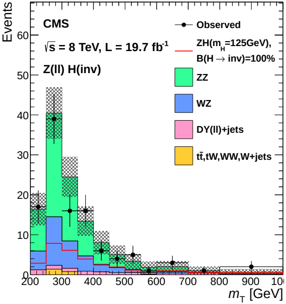
- Estimated from $e\mu$ events and Z peak sidebands:
  - $m_{\ell\ell}$ 40-70 and 110-200 GeV
  - $N^{sig}_{\ell\ell} = N^{sig}_{e\mu} \cdot N^{SB}_{\ell\ell} / N^{SB}_{e\mu}$

Z($\ell\ell$)H results

	Process	$\sqrt{s}=7$TeV ee	$\sqrt{s}=7$TeV $\mu\mu$	$\sqrt{s}=8$TeV ee	$\sqrt{s}=8$TeV $\mu\mu$
0 jets	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 for B(H→inv) 100%	0.26	0.28	0.28	0.24
1 jet	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 for B(H→inv) 100%	0.15	0.18	0.15	0.18

- Limits obtained from a 2D fit to m_T and $\Delta\phi(\ell\ell)$
  - 1D fit to m_T for 7 TeV data
- Assuming SM Higgs production cross-section and acceptance:
  - observed(expected) 95% C.L. limit on $B(H \to inv)$ for m_H=125 GeV is 83(86)%

arXiv:1404.1344



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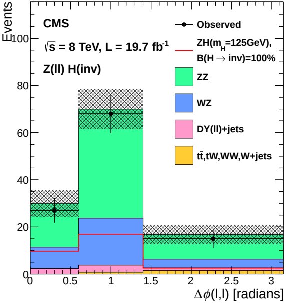


Z(bb)H outline and backgrounds

Signal Topology and Selection

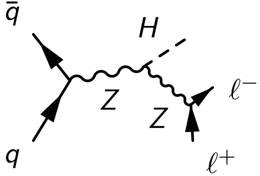
- Two b-tagged jets:
  - $p_T > 30/60$ GeV, $p_{Tjj} > 100 - 130$ GeV
- Three bins in MET
  - 100-130, 130-170, $>$ 170 GeV

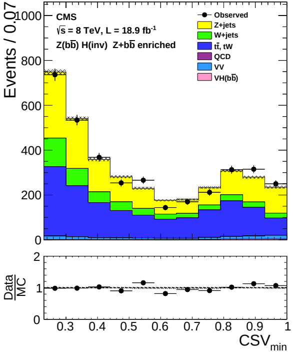
Backgrounds and Rejection Cuts

- $Z(\nu\nu)$+jets, $W(\ell\nu)$+jets
- $ZZ(\nu\nu b\bar{b})$
- $WZ(\ell\nu b\bar{b})$, $t\bar{t}$, single top
  - Veto events with leptons, p_T>15 GeV
- QCD
  - MET quality requirements

Background estimation - data normalised MC

- Normalisation from a simultaneous fit in seven control regions:
  - Z+jets (0,1,2 b-jets), W+jets (0,1,2 b-jets), $t\bar{t}$





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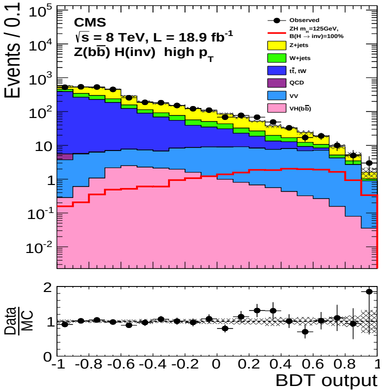
Z($b\bar{b}$)H results

Process	High $p_T(V)$	Intermediate $p_T(V)$	Low $p_T(V)$
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

- Multivariate analysis (BDT):
  - performed for each mass hypothesis and boost region
- Limits from a fit to the BDT output distribution
- Assuming SM Higgs production cross-section and acceptance:
  - observed(expected) 95% C.L. limit on $B(H \to inv)$ for m_H=125 GeV is 182(199)%



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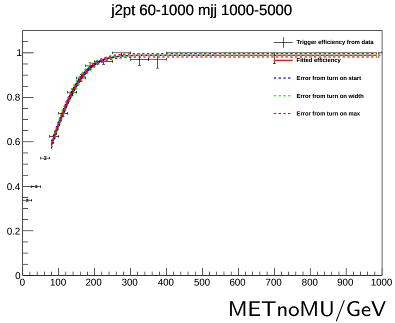
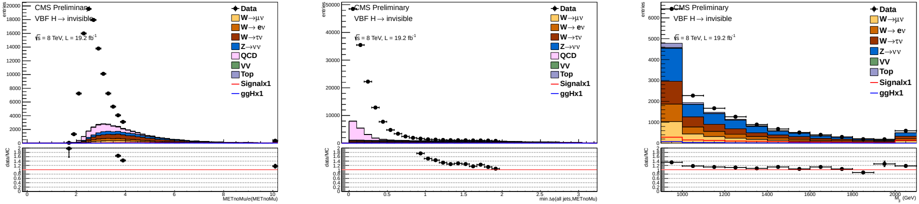
Trigger efficiency

- Variables used in prompt and parked triggers are highly correlated:
  - dijet mass, METnoMU, jet 2 p_T
- In the prompt analysis correlations were neglected as we cut to ensure trigger was $> 95\%$ efficient
- For the parked analysis we use a 2D binning in dijet mass and jet 2 p_T
  - MJJ: 0,600,800,900,1000,5000
  - Jet 2 p_T: 30,40,50,60,1000
- In each bin we fit the METnoMU trigger turn on using an error function
- We then combine the turn ons from runs A, BC and D weighted by luminosity and apply this to MC events



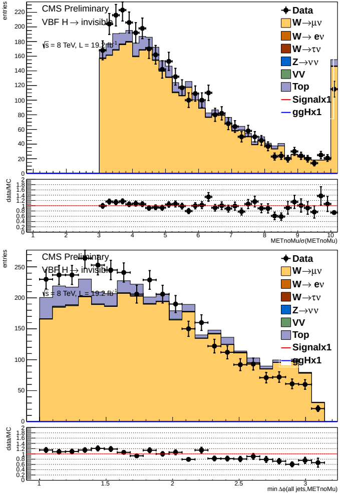
Starting point for region choice

- Trigger turn ons and detector acceptance impose the following cuts:
  - $\eta_{j1} \cdot \eta_{j2} < 0$, $|\eta_{j1,2}| < 4.7$, jet 1 $p_T > 50$ GeV, $\Delta\eta_{jj} > 3.6$, jet 2 $p_T > 40$ GeV, METnomu > 90 GeV, $M_{jj} > 800$ GeV
- QCD in plots is VBF enriched MC doesn't model all QCD
- Following cuts added due to poor data-MC agreement from QCD contamination:
- $\frac{METnomu}{\sigma_{METnomu}} > 3.0$, Min$\Delta\phi(all\ jets\ p_T > 30\ GeV, METnomu) > 1.0$, $M_{jj} > 1000$ GeV



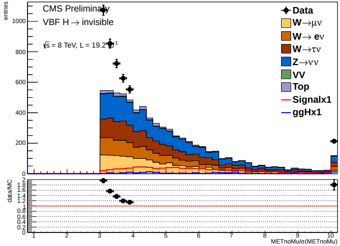
Signal region selection

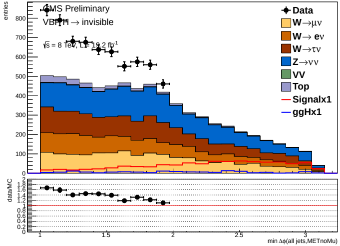
- As in the prompt analysis we veto events with 'veto' electrons or muons
  - Taus are not vetoed due to low ($\sim$55%) ID efficiency and high ($\sim$2-3%) fake rate
- Can't model QCD shape so cut hard to remove most QCD
  - Can then tolerate a larger uncertainty on QCD estimation
- Remaining QCD in region $\frac{METnoMU}{\sigma_{METnoMU}} < 4$ and $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu}) < 2.0$
- Select region $\frac{METnoMU}{\sigma_{METnoMU}} > 4$ and $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu}) > 2.0$
- Signal contribution also large in this region of parameter space
  - We blind this region and use as a basis for signal region optimisation



Signal region selection

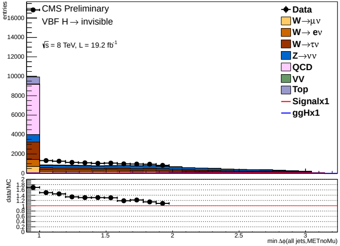
- We optimise by choosing the cut values with the best 95% C.L. expected limit
  - Limit calculation details later
- We scanned through jet 2 p_T, $\frac{METnoMU}{\sigma_{METnoMU}}$, $\mathrm{Min}\Delta\phi(all\ jets, METnomu)$ and M_{jj}
- Best limit was found for:
  - jet 2 $p_T > 45$ GeV
  - $\frac{METnoMU}{\sigma_{METnoMU}} > 4$
  - $\mathrm{Min}\Delta\phi(all\ jets, METnomu) > 2.3$
  - $M_{jj} > 1200$ GeV
- We defined this as our "signal region"
- Discrepancy outside signal region is from QCD

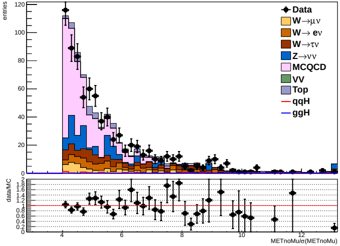




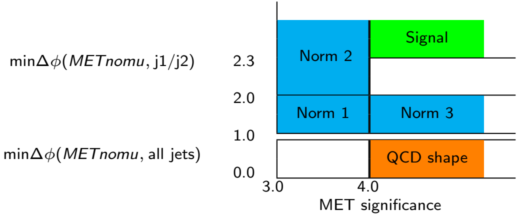
QCD background estimation: Shape

- Other background methods estimate unreconstructed contribution from reconstructed
- For QCD use MET near reconstructed jets to model MET from unreconstructed/mismeasured jets
- Use region with low Min$\Delta\phi$(*all jets*, *METnomu*) but high Min$\Delta\phi$(*leading jets*, *METnomu*)
  - Min$\Delta\phi$(*all jets*, *METnomu*) < 1.0
  - Min$\Delta\phi$(*leading jets*, *METnomu*) > 1.0
- Has good shape agreement with enriched QCD MC
- Use shape from this region





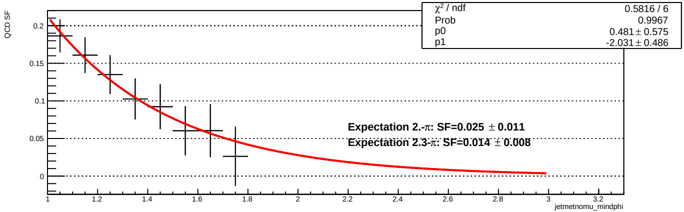
QCD background estimation: Normalisation



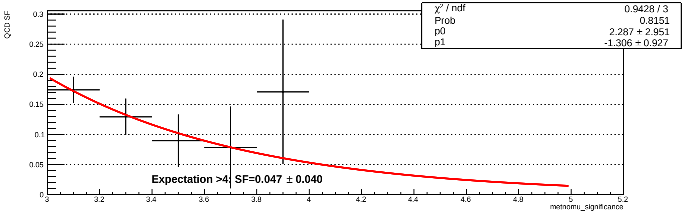
- MET significance and $\min\Delta\phi(METnomu, \text{all jets})$ correlated
  - Cannot use ABCD to normalise
- Normalisation shows strong dependence on cut variables
- Norm 2 and 3 have large signal contamination
  - Norm 3 also has low stats and odd because we forbid jets recoiling against significant met
- Fit normalisation variation in norm 1
- Check consistency in norm 2 and 3

Normalisation variation

Jet met dphi



MET significance



QCD background estimation: Result and systematics

Region	Factor	Extrapolation mindphi>2.5	Extrapolation metsig>4
Norm 1	0.17 ± 0.02	0.014 ± 0.008	0.05 ± 0.04
Norm 1+2	0.12 ± 0.01	0.013 ± 0.004	0.01 ± 0.01
Norm 1+3	0.24 ± 0.03	0.03 ± 0.01	0.55 ± 0.06
Norm 2	0.06 ± 0.01	-	0.01 ± 0.02
Norm 3	0.5 ± 0.1	0.21 ± 0.11	-

- Good agreement in mindphi extrapolations
- Norm 3 agreement in metsig is poor
  - As norm 3 has low statistics and is an odd region: drop
- Use envelope of norm 1 scale factors
- Final prediction: $N_S^{QCD} = 17 \pm 14$

Systematics

- Uncertainties considered are mostly the same as the prompt analysis
- Changes are:
  - New $W \rightarrow \tau\nu$ extrapolation error
  - QCD background error procedure now as described above
- We removed the $Z/\gamma^* \rightarrow \mu\mu$ to $Z \rightarrow \nu\nu$ after more studies with aMC@NLO