VBF Higgs to Invisible - Update

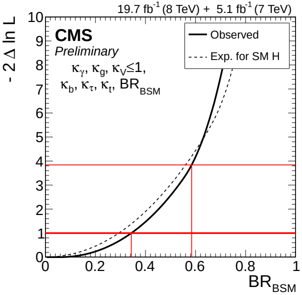
AN-14-243

P. Dunne on behalf of the VBF H→invisible analysis group

Why Higgs to Invisible?

Experimental motivation

- Current measurements of the 125 GeV Higgs boson are compatible with Standard Model (SM) expectations
  - large uncertainties can still accommodate significant beyond the SM (BSM) properties
- Additional Higgs bosons with exotic decays are not excluded

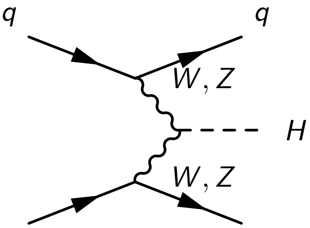


Theoretical motivation

- Many BSM theories predict Higgs boson decays to invisible final states:
  - e.g. SUSY, extra dimensions, fourth-generation neutrinos
- These final state particles are often dark matter candidates

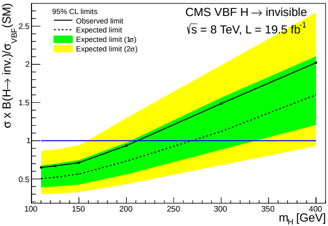
Talk outline

- For run 1 we had two sets of triggers
  - Prompt trigger used for current published result: HIG-13-30
  - Parked triggers analysis progress presented today



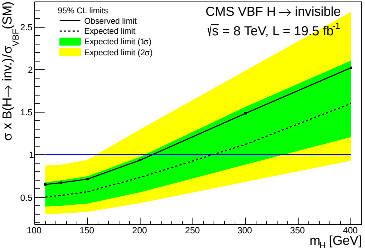
Overview

- Reminder of prompt analysis
- Why we chose our new analysis strategy
- Details of parked analysis
  - Emphasis on changes from established prompt analysis
- Brief look at some other analysis techniques we are investigating



Prompt Analysis

- 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
- Expected limit 49% at $m_H = 125$ GeV



Data driven background estimation

W: $N_S = N_S^{MC} \frac{N_C^{Data} - N_C^{Bkg}}{N_C^{MC}}$

Z:

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

Parked Triggers

- Use already analysed prompt trigger for run A
- One parked trigger for runs B and C, another for run D
- All parked and prompt triggers are seeded by L1ETM40
- Parked triggers have looser HLT thresholds
- This allows us to look at new regions of phase space and different analysis techniques

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

Software framework strategy

Prompt analysis

- Two frameworks: Analyses A and B
- independent ntuples and analysis code

Parked analysis

- Insufficient manpower to maintain and develop two frameworks
- Moved to one fully developed framework
  - New framework is development of analysis B and uses same ntuples
- Synchronised yields in signal and control regions between new framework and old analyses A and B
- Repeated expected limit calculation from HIG-13-030 analysis with the new framework and parked data
  - Agrees with HIG-13-030 to within 2%, which is good given rereco, and change of global tag and triggers

Analysis strategy

Initial investigations

- Planned to define a loose pre-selection and model QCD shape
- Several options for analysis strategy:
  - Rectangular cuts and counting experiment
  - Rectangular cuts and shape experiment
  - MVA and counting experiment
  - MVA and shape experiment
- Due to trigger conditions no appropriate QCD control region found - details later

Final plan for parked data

- During QCD studies found new variables which remove QCD
  - Signal efficiency significantly higher than prompt selection
- Remaining backgrounds very signal like in variables studied so far
  - Opted for cut and count analysis

QCD options tried

Several methods tried to model QCD

Standard MC

- doesn't have enough events

Private VBF+MET enriched QCD MC sample

- Can only enrich in events with real met
- Can't model met from mismeasurement

Data-driven shape using different jet pairs in the event

- Jet kinematics are very biased
- Ordering in p_T and angle have been tried
- Reweighting individual distributions to fix others has been tried

Changes since prompt analysis

Trigger

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

Signal region

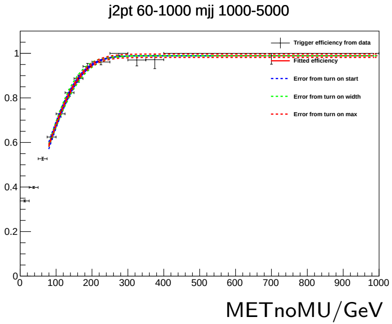
- The signal region has been reoptimised for the looser parked triggers
  - New region uses new variable has higher signal efficiency with much less QCD

Background estimation

- A top control region has been added
- Minor modifications made to $W \to \tau\nu$ background estimation method
- QCD background estimation method changed
- Wγ contribution found to be modelled already by our $W \to \ell\nu$ Monte Carlo

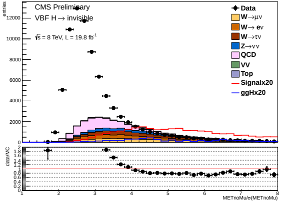
Trigger efficiency

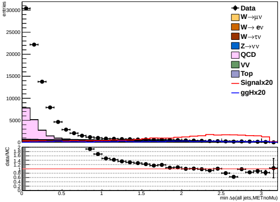
- The variables used in prompt and parked triggers are highly correlated:
  - dijet mass, METnoMU, jet 2 p_T
- In the prompt analysis we neglected correlations and cut to ensure trigger was $> 95\%$ efficient
- For the parked analysis we use a 2D binning in dijet mass and jet 2 p_T
  - MJJ: 0,600,800,900,1000,5000
  - 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

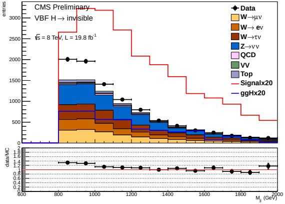


Preselection choice

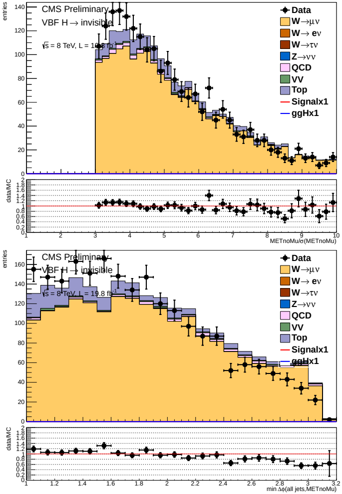
- Trigger turn ons and detector acceptance impose the following cuts:
  - $\eta_{j1} \cdot \eta_{j2} < 0$, $|\eta_{j1,2}| < 4.7$, jet 1 $p_T > 50$ GeV, $\Delta\eta_{jj} > 3.6$, jet 2 $p_T > 40$ GeV, METnomu > 90 GeV, $M_{jj} > 800$ GeV
- As in the prompt analysis we also veto events with 'veto' electrons or muons
- QCD in plots is VBF enriched MC doesn't model all QCD
- Poor data-MC agreement from QCD contamination motivates the following additional cuts:
- $\frac{METnomu}{\sigma_{METnomu}} > 3.0$, Min$\Delta\phi$(*all jets* $p_T > 30$ *GeV*, *METnomu*) > 1.0, $M_{jj} > 1000$ GeV







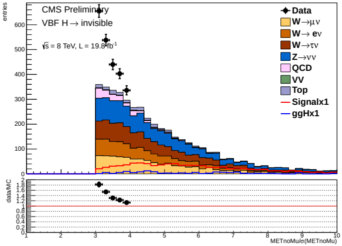
Signal region selection

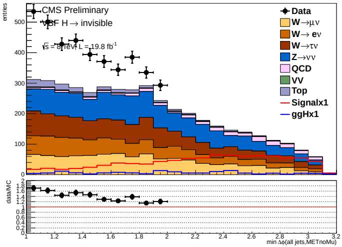


- Can't model QCD shape so alter cuts to remove most QCD
  - Can then tolerate a larger uncertainty on QCD estimation
- Remaining QCD in region $\frac{METnoMU}{\sigma_{METnoMU}} < 4$ and $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, METnomu) < 2.0$
- Signal contribution also large for some regions of parameter space
  - We blind these regions 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, dijet mass and $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu})$
- Best limit was found for:
  - No additional jet 2 p_T cut
  - $\frac{\mathit{METnoMU}}{\sigma_{\mathit{METnoMU}}} > 4$
  - $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu}) > 2.5$
- This was used as our "signal region"
- Discrepancy outside signal region is from QCD

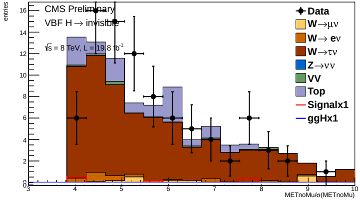


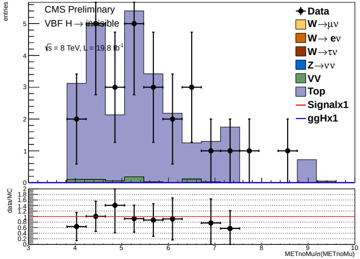


Top control region

- Top contribution to V+jets control regions is non-negligible
  - up to 16% in $W \to \tau\nu$
- Use method used for W backgrounds in prompt analysis
- Region: signal region with lepton veto replaced with requirement for 1 tight muon and 1 tight electron
  - Very few events in $e\mu$ region so also removed $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu})$ cut

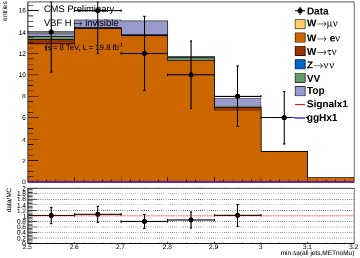
N_C^{data}	28 ± 5.3(stat.)
N_C^{bkg}	0.6 ± 0.2(MC stat.)
$N_S^{top\ MC}$	9.6 ± 1.8(MC stat.)
$N_C^{top\ MC}$	42.6 ± 5.2(MC stat.)
N_S^{top}	6.1 ± 1.2(stat.) ± 1.4(MC stat.)

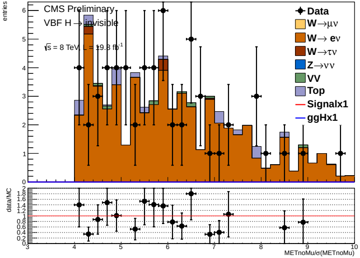




$W \rightarrow e\nu$

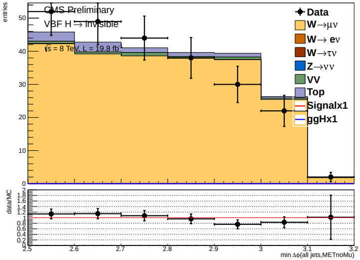
- Data-MC agreement good
- Same method used as for prompt analysis

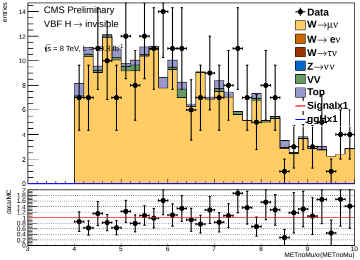




$W \to \mu\nu$

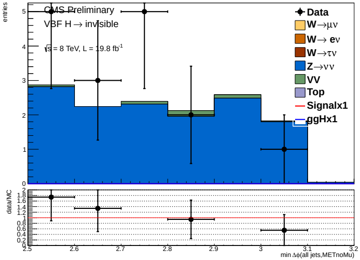
- Data-MC agreement good
- Same method used as for prompt analysis

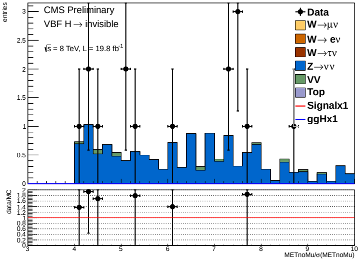




$Z \to \nu\nu$

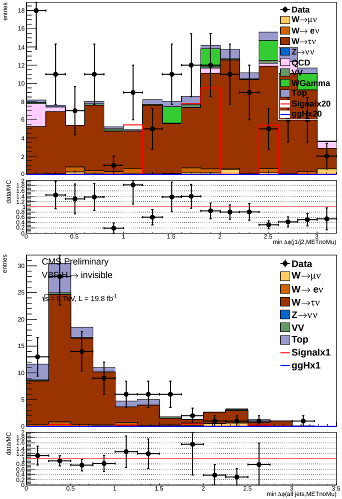
- Data-MC agreement good for limited statistics
- Same method used as for prompt analysis





$W \to \tau\nu$ control region

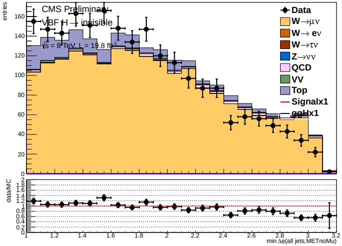
- For other W+jets backgrounds control region is:
  - signal region with lepton veto replaced with a requirement for a single lepton
- For $W \to \tau\nu$ there are not enough events in this region: 2 events for N_C^{Data}
  - In prompt analysis we removed the central jet veto (CJV)
- CJV no longer used, so we remove the $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu})$ cut
- This leads to QCD contamination so we require:
  - $\mathrm{Min}\Delta\phi(\mathit{leading\ 2\ jets}, \mathit{METnomu}) > 1.0$
  - We also add an $m_T > 20$ GeV cut on the lepton-MET system to remove QCD contamination

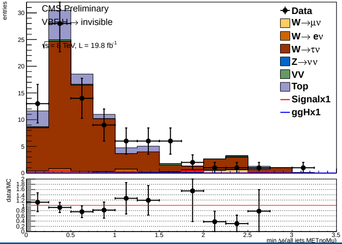


$W \to \tau\nu$ control region

- Estimate error from difference between control region and signal region cuts
- $W \to \mu\nu$ has enough events to see data driven weight variation with $\mathrm{Min}\Delta\phi(all\ jets, METnomu)$ cut
  - weight changes by 20% when loosening cut from 2.5 to 1.0.
  - We add a 20% systematic on the $W \to \tau\nu$ background

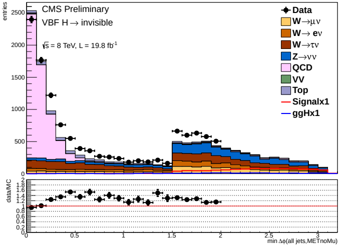
N_C^{data}	$88 \pm 9.4(stat.)$
N_C^{bkg}	$15.2 \pm 4.8(MCstat.)$
N_S^{MC}	$176.1 \pm 10.5(MCstat.)$
N_C^{MC}	$133.9 \pm 8.0(MCstat.)$
N_S^{W}	$95.7 \pm 12.3(stat.) \pm 10.2(MCstat.)$

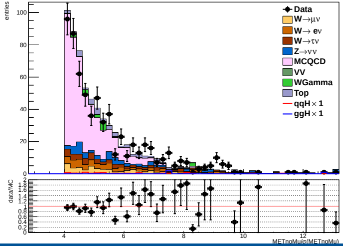




QCD background estimation: Shape region choice

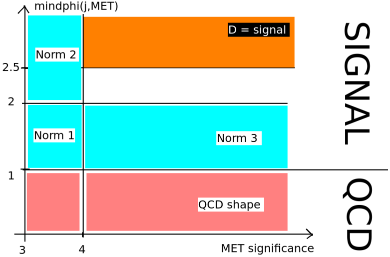
- Try modelling QCD shape in preselection region
- QCD met must come from a jet, use region with low $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu})$
- Try inverted region with:
  - $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu}) < 1.0$
  - $\mathrm{Min}\Delta\phi(\mathit{leading\ jets}, \mathit{METnomu}) > 1.0$
- Has good shape agreement with enriched QCD MC
- Use shape taken from requiring:
  - $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu}) < 1.0$
- And replacing $\mathrm{Min}\Delta\phi(\mathit{all\ jets}, \mathit{METnomu})$ with $\mathrm{Min}\Delta\phi(\mathit{leading\ jets}, \mathit{METnomu})$





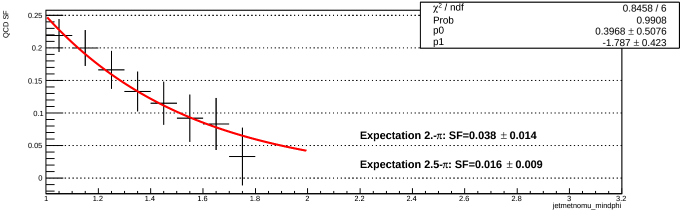
QCD background estimation: Scale factor

- Cannot use ABCD to normalise
- Scale factor 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 opposite the met in phi
- Fit scale factor variation in norm 1
- Check consistency in norm 2 and 3

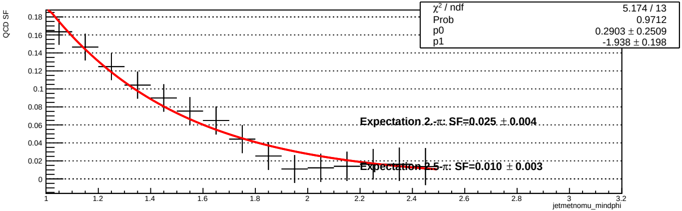


Scale factor variation

Norm 1



Norm 1+2



QCD background estimation: Result and systematics

Region	Factor	Extrapolation mindphi$>$ 2.5	Extrapolation metsig$>$ 4
Norm 1	0.22 ± 0.03	0.016 ± 0.009	0.04 ± 0.03
Norm 1+2	0.15 ± 0.02	0.010 ± 0.003	0.03 ± 0.02
Norm 1+3	0.41 ± 0.03	0.036 ± 0.062	1.10 ± 0.10
Norm 2	0.08 ± 0.02	-	0.05 ± 0.04
Norm 3	1.22 ± 0.15	0.60 ± 0.25	-

- Good agreement in all Min$\Delta\phi$(*all jets*, *METnomu*) 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: $N_S^{QCD} = 14 \pm 10$
- Expected limit 0.5% better with no QCD, 0.5% worse with double error

Results

Process	Number of events
$Z \to \nu\nu$	$141.9 \pm 36.4(\text{stat.}) \pm 15.0(\text{MC stat.})$
$W \to e\nu$	$59.7 \pm 7.7(\text{stat.}) \pm 5.2(\text{MC stat.})$
$W \to \mu\nu$	$81.2 \pm 5.6(\text{stat.}) \pm 5.8(\text{MC stat.})$
$W \to \tau\nu$	$95.7 \pm 12.3(\text{stat.}) \pm 10.2(\text{MC stat.})$
QCD	14 ± 10
Top	$6.1 \pm 1.2(\text{stat.}) \pm 1.4(\text{MC stat.})$
VV	$6.0 \pm 0.6(\text{MC stat.})$
Total bkg.	$405 \pm 39.6(\text{stat.}) \pm 19.8(\text{MC stat.})$
VBF signal	$313.5 \pm 9.4(\text{MC stat.})$
ggH signal	$22.5 \pm 6.0(\text{MC stat.})$
Total signal	$336 \pm 11.1(\text{MC stat.})$

Expected limits

- Used Higgs combine package with Asymptotic CLs method
- Performed a single bin counting experiment
- Analysis blind so have expected limits only
- 95% C.L. Median limit on B(H→inv.) for $m_H = 125$ GeV is: 31%
  - 1σ band is 23-42%
  - 2σ band is 17-57%
- Prompt analysis expected limit was 49%
- We intend to run other mass points:
- 110, 150, 200, 300 and 400 GeV

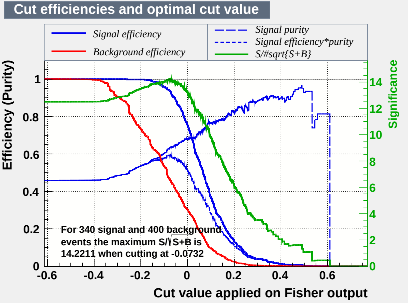
Uncertainties by decreasing impact
Control region statistics
$Z \to \nu\nu$-$Z/\gamma^* \to \mu\mu$ extrapolation
nb above to be revisited
JES
$W \to \tau\nu$ extrapolation
MC statistics
QCD systematics
lepton ID efficiency
JER
UES
luminosity
PU weighting
theory uncertainties

Uncertainty impact table - impacts larger than 0%

Median expected limit with:		
All Nuisances: 30.8%	No Nuisances: 12.2%	
Nuisance	Removal impact/%	Addition impact/%
CMS_VBFHinv_zvv_stat:	-12.7%	64.6%
CMS_VBFHinv_zvv_extrapfacunc:	-7.6%	47.4%
CMS_scale_j:	-6.3%	19.2%
CMS_VBFHinv_tau_extrapfacunc:	-4.7%	24.9%
CMS_VBFHinv_zvv_norm:	-1.9%	18.4%
CMS_VBFHinv_wtau_stat:	-1.9%	12.0%
CMS_VBFHinv_wtau_norm:	-1.3%	8.8%
CMS_VBFHinv_wel_stat:	-1.3%	4.8%
CMS_VBFHinv_qcd_norm:	-1.3%	4.0%
CMS_VBFHinv_tau_eff:	-0.6%	5.6%
CMS_VBFHinv_wmu_norm:	-0.6%	3.2%
CMS_eff_m:	-0.6%	2.4%
CMS_VBFHinv_wmu_stat:	-0.6%	2.4%
CMS_VBFHinv_wel_norm:	-0.6%	2.4%
CMS_res_j:	-0.6%	0.8%
CMS_scale_met:	0.0%	0.8%

BDT Study

- Had a quick look at MVA analysis
- Started from cut based signal region
  - Only region with negligible QCD
- Best expected limit obtained 30%
  - Does not take into account any increased systematic
  - Therefore unlikely to be worthwhile
- New variables could make MVA worthwile
- Ability to model QCD would enable looser starting selection which may make MVA worthwhile



Summary

Parked analysis

- New cut based analysis found with negligible QCD and higher signal efficiency
  - Can then accept remaining QCD estimate with large error
  - Made possible by looser parked trigger thresholds
- MVA investigated
  - Not sufficient benefit without new variables or looser preselection
- Full cut based analysis presented
  - Expected limit 31%
  - Improved from 49% for prompt analysis

Run 2 prospects

- Prescaled looser control triggers planned to enable better QCD control region
- Will reinvistigate shape analysis and MVA

Backup

VBF enriched QCD MC

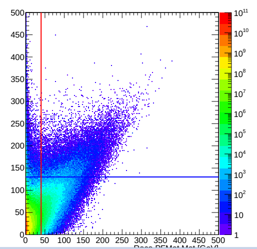
MC Filter: Vectorial sum of neutrino E_T

- $\sum E_{\perp}(\vec{\nu}) > 40\ GeV$

MC Filter: Dijet Filter

- Select jets with:
  - $p_{\perp} > 20\ GeV$
  - $|\eta| < 5.0$
- From selected jets at least one pair with:
  - $m_{jj} > 700\ GeV$
  - $\Delta\eta > 3.2$

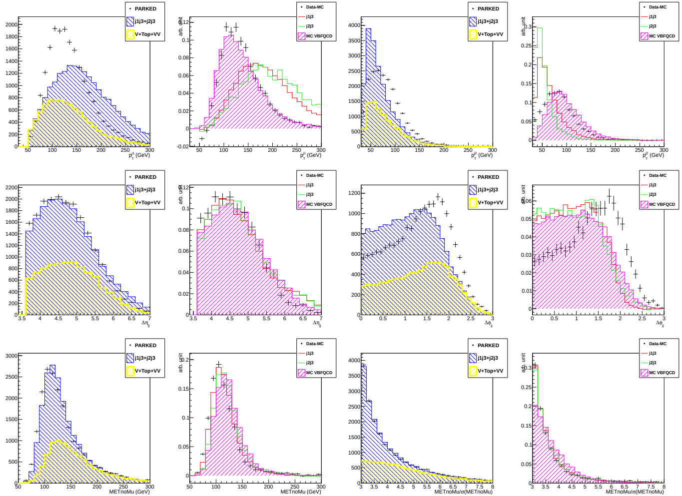
QCD Inc 80-600 *GeV*



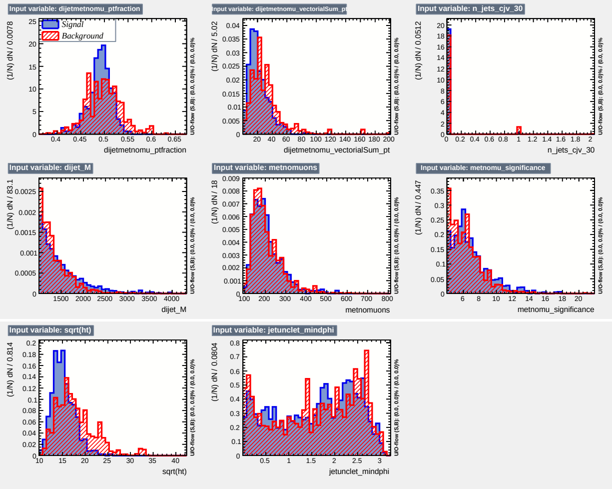
There 2 distict populations of events: real and fake met.

Sample	Ev. Gen.	Filter Eff.	Events	XS [*pb*]	Eq. Lumi. [fb^{-1}]
QCD-Pt-80to120	39376000000	0.000049	1614416	1033680	38.09
QCD-Pt-120to170	7000000000	0.000283	2051000	156293.3	44.79
QCD-Pt-170to300	1375000000	0.000987	1391500	34138.15	40.28
QCD-Pt-300to470	80000000	0.002659	207840	1759.549	45.47
QCD-Pt-470to600	25000000	0.004127	104675	113.8791	219.53

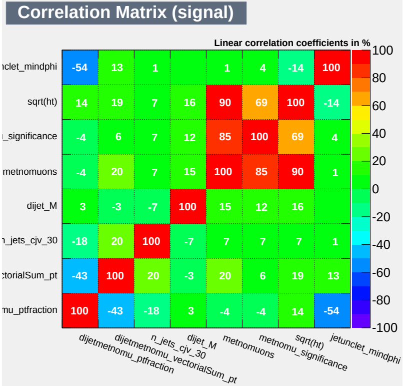
QCD Data-Driven: j1j3, j2j3 shape

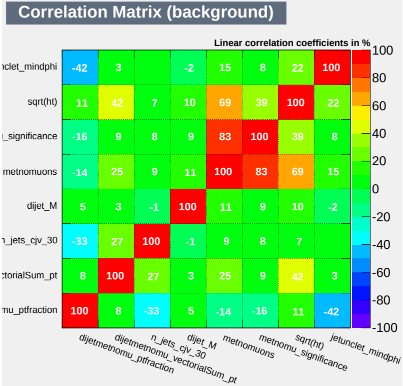


MVA Details

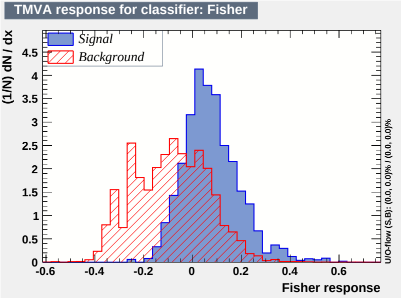

Input variable: dijetmetnomu_ptfraction
Signal
Background
(1/N) dN / 0.0078
dijetmetnomu_ptfraction
Input variable: dijetmetnomu_vectorialSum_pt
(1/N) dN / 5.02
dijetmetnomu_vectorialSum_pt
Input variable: n_jets_cjv_30
(1/N) dN / 0.0512
n_jets_cjv_30
Input variable: dijet_M
(1/N) dN / 83.1
dijet_M
Input variable: metnomuons
(1/N) dN / 18
metnomuons
Input variable: metnomu_significance
(1/N) dN / 0.447
metnomu_significance
Input variable: sqrt(ht)
(1/N) dN / 0.814
sqrt(ht)
Input variable: jetunclet_mindphi
(1/N) dN / 0.0804
jetunclet_mindphi
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%

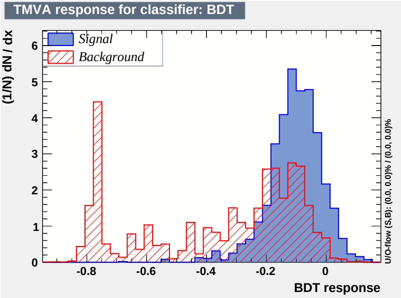
MVA Details


Correlation Matrix (signal)
Linear correlation coefficients in %
nclet_mindphi
sqrt(ht)
_significance
metnomuons
dijet_M
n_jets_cjv_30
ctorialSum_pt
mu_ptfraction
-54 13 1 1 4 -14 100
14 19 7 16 90 69 100 -14
-4 6 7 12 85 100 69 4
-4 20 7 15 100 85 90 1
3 -3 -7 100 15 12 16
-18 20 100 -7 7 7 7 1
-43 100 20 -3 20 6 19 13
100 -43 -18 3 -4 -4 14 -54
dijetmetnomu_ptfraction
dijetmetnomu_vectorialSum_pt
n_jets_cjv_30
dijet_M
metnomuons
metnomu_significance
sqrt(ht)
jetunclet_mindphi
100
80
60
40
20
0
-20
-40
-60
-80
-100

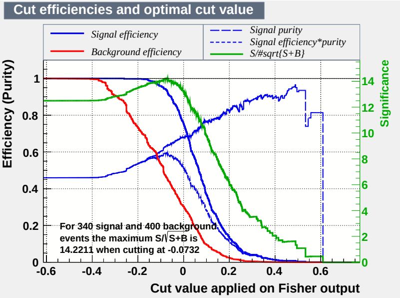

Correlation Matrix (background)
Linear correlation coefficients in %
nclet_mindphi
sqrt(ht)
_significance
metnomuons
dijet_M
n_jets_cjv_30
ctorialSum_pt
mu_ptfraction
-42 3 -2 15 8 22 100
11 42 7 10 69 39 100 22
-16 9 8 9 83 100 39 8
-14 25 9 11 100 83 69 15
5 3 -1 100 11 9 10 -2
-33 27 100 -1 9 8 7
8 100 27 3 25 9 42 3
100 8 -33 5 -14 -16 11 -42
dijetmetnomu_ptfraction
dijetmetnomu_vectorialSum_pt
n_jets_cjv_30
dijet_M
metnomuons
metnomu_significance
sqrt(ht)
jetunclet_mindphi
100
80
60
40
20
0
-20
-40
-60
-80
-100

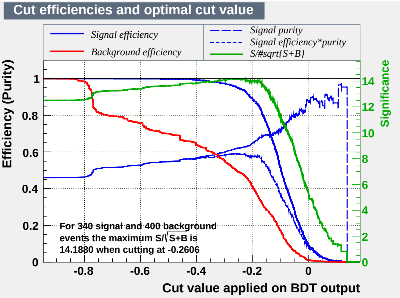
MVA Details


TMVA response for classifier: Fisher
Signal
Background
(1/N) dN / dx
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
Fisher response
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%


TMVA response for classifier: BDT
Signal
Background
(1/N) dN / dx
0
1
2
3
4
5
6
-0.8
-0.6
-0.4
-0.2
0
BDT response
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%

MVA Details


Cut efficiencies and optimal cut value
Signal efficiency
Background efficiency
Signal purity
Signal efficiency*purity
S/#sqrt{S+B}
Efficiency (Purity)
Significance
For 340 signal and 400 background events the maximum S/√S+B is 14.2211 when cutting at -0.0732
Cut value applied on Fisher output


Cut efficiencies and optimal cut value
Signal efficiency
Background efficiency
Signal purity
Signal efficiency*purity
S/#sqrt{S+B}
Efficiency (Purity)
Significance
For 340 signal and 400 background events the maximum S/√S+B is 14.1880 when cutting at -0.2606
Cut value applied on BDT output

No systematics limits

- Prompt limit with no systematics 16.6%