Search for Invisible Higgs Boson in CMS

Sunil Bansal

K. Mazumdar

Jasbir Singh

Invisible Decay of Higgs Boson – (I)

- If Higgs decays to weakly interacting and neutral particles → No visible particle in the detector (only missing energy).
- Not possible in SM → Its observation will be indication of "*New Physics*".
- Many BSM incorporate invisible decay of Higgs boson:
  - → Fourth generation neutrino
  - → SUSY
  - → Extra-Dimension

  ………

- Different models give very different branching ratio (BR) to invisible vs Higgs mass, but usually BR is reasonably high for mH < 300 GeV).

Present Analysis is model independent

Invisible Decay of Higgs Boson – (II)

- Trigger and event signature have to come from particle accompanying Higgs production.
- VBF production mode is most suited:
  - → Second Highest production rate
  - → Jets in forward-backward region with large rapidity gap.
  - → Large di-jet invariant mass.
  - → Low hadronic activity between the tagging jets.
- Reconstruction of Higgs mass is not possible → A counting experiment to see excess over expected SM backgrounds.

- Model independent analysis:

  Production rate same as SM rate.

  BR = 100%

Signal rate

MH (GeV):	120	140	160
VBF production cross-section (pb):	4.47	3.83	3.32

Backgrounds

- **W + Jets → charged lepton not get detected and the leading jets satisfy VBF conditions .**
- **Z + Jets → Z decays to neutrino families and the leading jets satisfy VBF conditions.**

CSA07 Alpgen samples with Soft VBF pre-selection at generator level

$\Delta\eta > 2.0$, Mjj > 300 GeV (j1, j2 two highest pT partons) .

Z → $\nu\nu$ and W → l ν (l = e μ τ)

Cross-section after preselection:

Z + 2Jets = 31.01 pb W + 2Jets = 148 pb

Z + 3Jets = 52.55 pb W + 3Jets = 248 pb

- **ttbar : MC@NLO inclusive sample, Cross-section= 840 pb**
- **QCD jets with enormous rate pose as dominant background!**

Trigger Selection

L1 condition : Uncorrected MET > 30 GeV

HLT conditions :

→ MET uncorrected > 60 GeV

→ Leading Jets: corrected pT 1,2 > 40 GeV, $\Delta\eta > 4.2$, $\eta1*\eta2<0$,

Sample	Trigger Efficiency (%)
Signal (m_H = 120 GeV)	16.27
Signal (m_H = 140 GeV)	17.57
Signal (m_H = 160 GeV)	18.65
Z + jets	4.57
W + jets	3.20
$t\bar{t}$(inclusive)	0.58

→ For QCD (Fast Sim) jet sample HLT information is not available.

Offline Selections-(I)

1) Lepton veto :

- ✓ No isolated electron ($p_T > 10$ GeV, $|\eta| < 2.5$ excluding barrel-endcap transition region)
- ✓ No isolated muon ($p_T > 5$ GeV, $|\eta| < 2.1$) .

2) VBF condition:

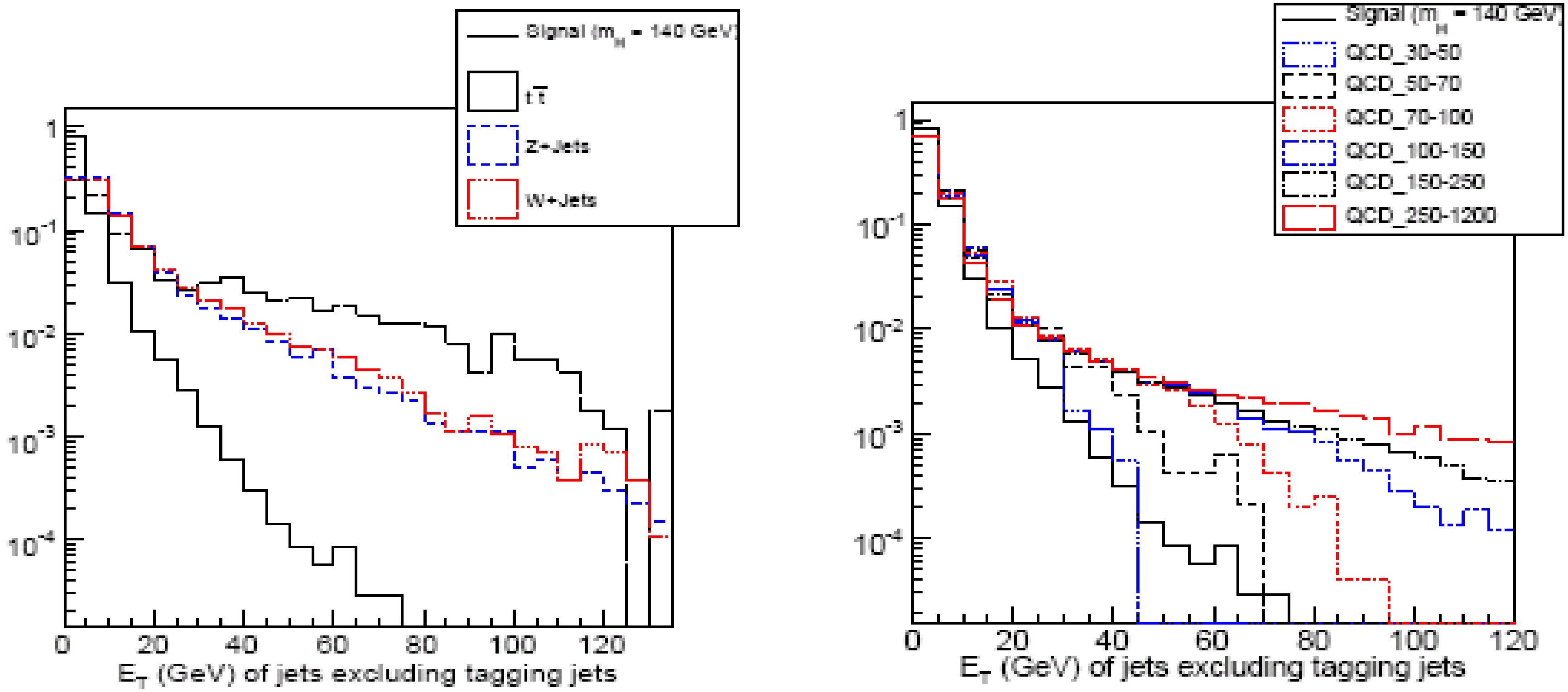
- ✓ p_T (1,2) > 40 GeV, $\eta 1 * \eta 2 < 0$, $|\eta| < 5$
- ✓ $\Delta\eta > 4.4$, Mjj > 1200 GeV

3) MET > 100 GeV

Offline Selections-(II)

4) Central Jet Veto (CJV):

Expected low hadronic activity between tagging jets for signal events



→ Require no jet between (η_{max}-0.5, η_{min}+0.5) tagging jets with E_T (uncorrected) > 15 GeV

Offline selections -(III)

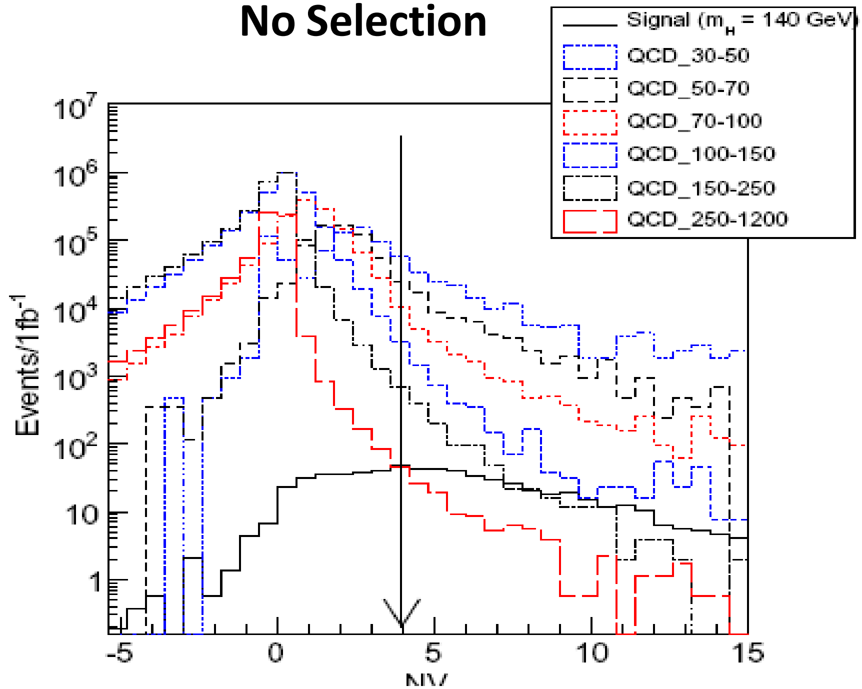
5) NV variable : function of uncorrected E_T of jets and MET (SUSY Group , CMS IN 2007/041)

$$NV = \frac{(E_T^{miss})^2 - (E_T^{j1} - E_T^{j2})^2}{(E_T^{j2})^2}$$

$(E_T^{J1} - E_T^{J2})/E_T^{J2}$ → Related to Jet Energy Resolution

→ **Require NV > 4**

No Selection



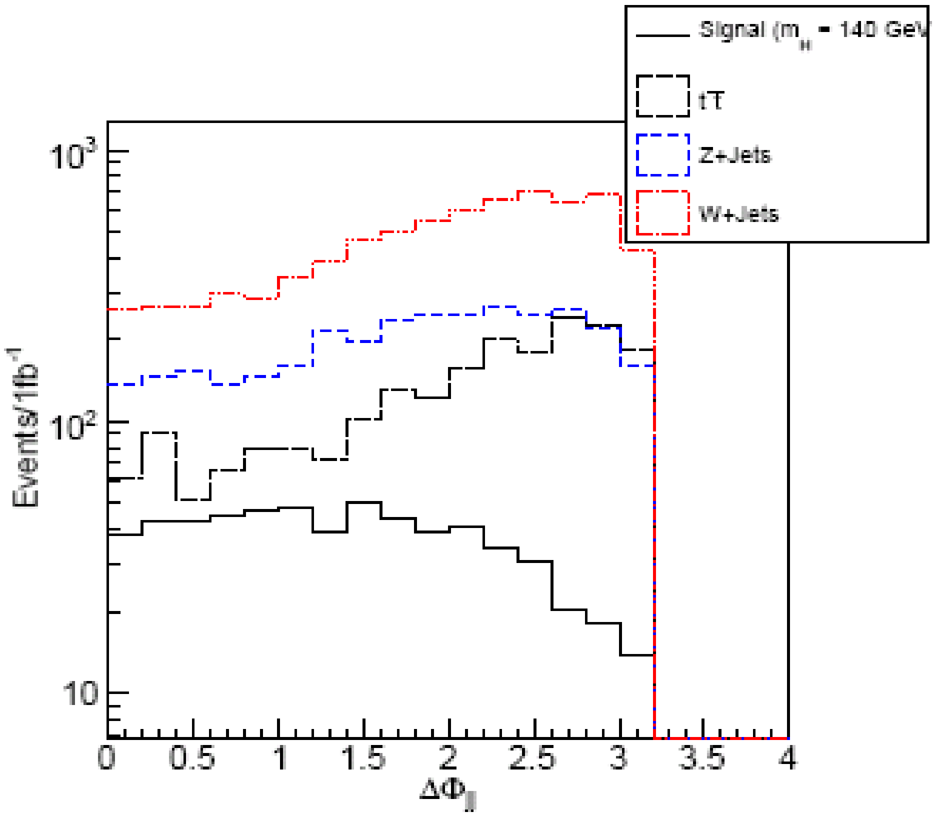
✓ NV cut is most effective for higher QCD (> 70 GeV)

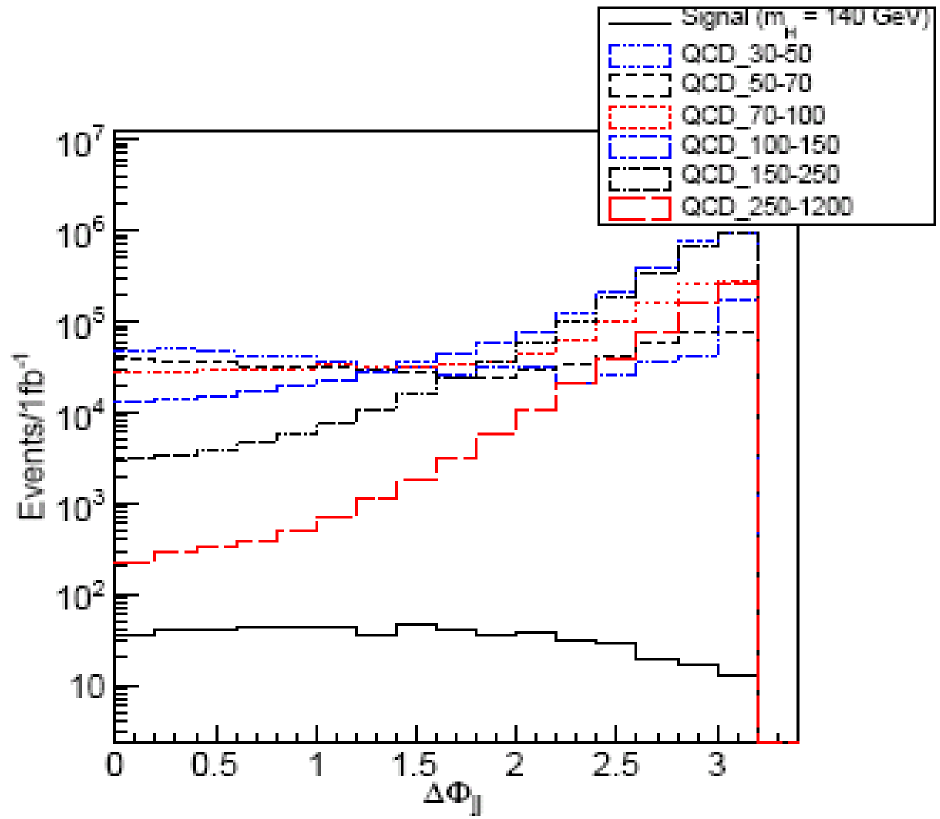
✓ Not much effective for other backgrounds (involve real MET)

Offline Selections-(III)

6) Massive Higgs balances the jets ➔ small angle in transverse plane

($\Delta\phi$) between tagging jets.





→ Accept events for $\Delta\phi$ < 1.5 rad.

Results

- Events surviving after all cuts for integrated luminosity 1 fb^{-1}

m_H = 120 GeV	m_H = 140 GeV	m_H = 160 GeV	Z + jets	W + jets	inclusive $t\bar{t}$	QCD (all $\hat{p}_t$ bins)
109	101	89	64	79	5	5849

Total background ~6000

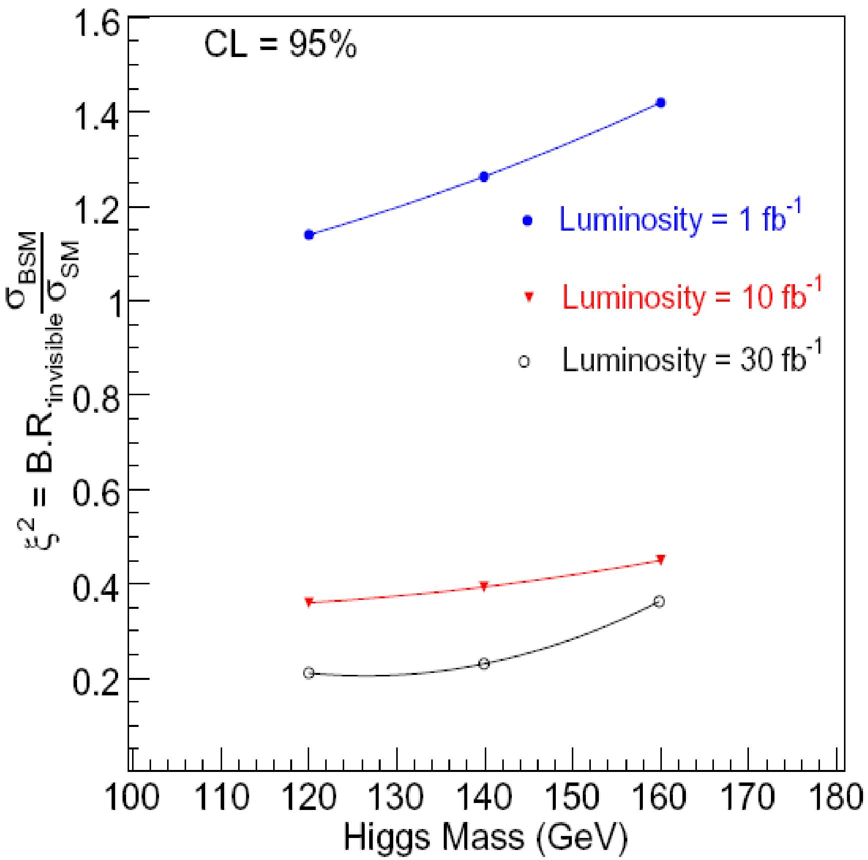
- Systematic uncertainty for selected signal events

Due to Jet Energy Scale = 14.54 % (α_{jet} = 7%)
Due to MET scale = 9.54% (α_{jet} = 7%, α_{calo} = 10%)

Signal Higgs boson mass (GeV)	120	140	160
cross-sction(fb)	4470	3830	3320
Trigger efficiency(%)	16.27	17.57	18.65
Offline selection efficiency (%)	15.30	14.99	14.42
cross-section after all selections (fb)	109	101	89
$S/\sqrt{B}$	1.41	1.30	1.15
Signal Significance ($Scp = Sc12$)	0.38	0.35	0.31

This mode really seems invisible ☺

Discovery Potential



The invisible higgs reach can be defined in term of a model independent parameter:

$$\xi^2 = \mathrm{Br}(H \to Inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$$

For $\sigma_{BSM} = \sigma_{SM}$, $\xi^2 = \mathrm{Br}(H \rightarrow \mathrm{Inv.})$

m_H (GeV) $\rightarrow$	120	140	160
Integrated Luminosity (fb^{-1})↓			
10	0.43	0.47	0.54
30	0.25	0.27	0.31

→ **Invisible search is not possible with integrated luminosity of $1fb^{-1}$**

Data Driven Methods for Background Estimation

Z→$\nu\nu$ + jets background:

→ W ($\mu\nu$)+ jets process can be used, where muon is well identified.

→ Corrections has to be applied for Kinematic selection, isolation efficiency and difference between W and Z production rate

→ Correction factor calculated to be 1.7

→ This method estimate 63 +-10 background events which is in good agreement with MC based estimation of 64 +-9

W→$\mu\nu$ + jets background:

→ W ($\mu\nu$)+ jets process can be used, where muon is well identified.

→ Corrections has to be applied for Kinematic selection, isolation efficiency.

→ Correction factor calculated to be 1.1

→ This method estimate 40+-6 background events which is in agreement with MC based estimation 43+-7.

W→ eν + jets background can be estimated same way.

Estimation of Central Jet Veto Efficiency from Data for V + jet backgrounds

- ✓ Hadronic activity is same in Z + jets and W + jets. So either of these can used for estimation of CJV efficiency for V + jets BG.

For W→ $\mu\nu$ + jets process: select events with
(i) isolated μ, pt > 20 GeV,
(ii) 2 leading jets satisfying VBF conditions
(iii) MET> 100 GeV.
→Efficiency to pass CJV requirement = 36.6 ± 2 %

- ✓ This is in well agreement CJV efficiency (36.1 ± 1.5 %) for W→ $\mu\nu$ + jets background obtained in the analysis.
- ✓ This is also give good estimate of CJV efficiency for Z + jets background which is 34.6 ± 1.8%

Conclusions

✓ A possibility to search for Invisibly decaying Higgs boson in Vector Boson Fusion mode has been studied with a set of selection criteria.

✓ For integrated luminosity 1fb^{-1}, Invisible Higgs search is not possible. For 10 fb^{-1} luminosity, B.R. upto 43% can be explored at 95% CL assuming standard model production rate.

✓ Data driven techniques for various backgrounds have been studied.

✓ Determination of efficiency for Central Jet Veto from data has been discussed.

Back-up Slides

Comparison with ATLAS result (cern-open-2008-020

•Signal & QCD background done with Herwig.
•Signal efficiency for Herwig is similar to Pythia, except for CJV (Herwig selects less signal).
• WZ + jets done with alpgen. ttbar is not considered

Jet Sample	$\sigma(pb)$	$p_T$range [GeV]
J0	1.76×10^{10}	8-17
J1	1.38×10^{9}	17-35
J2	9.33×10^{7}	35-70
J3	5.88×10^{6}	70-140
J4	3.08×10^{5}	140-280
J5	1.25×10^{4}	280-560
J6	3.60×10^{2}	560-1120
J7	5.71×10^{0}	1120-2240

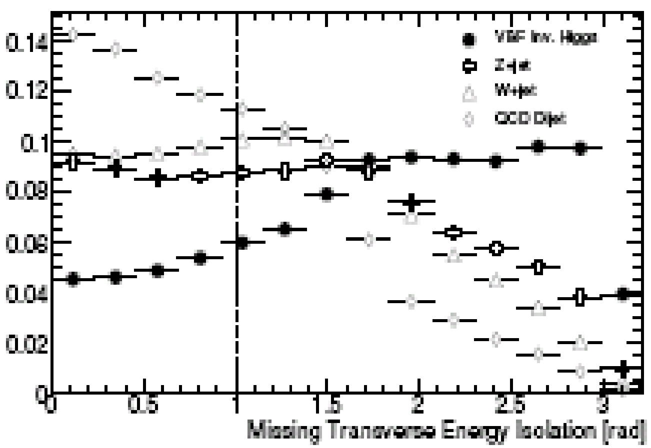
QCD event statistics not mentioned, probably limited!

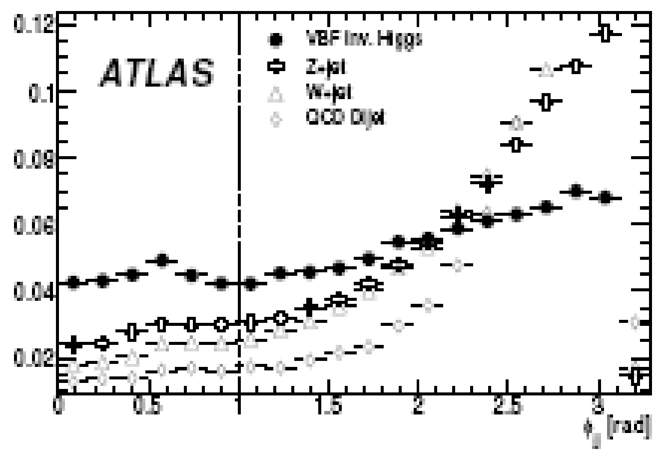
Basic selection cuts are same, other than one variable

CMS: NV

ATLAS: $I = min[\phi(E_T^{miss}) - \phi(j_{1,2})].$

Shape comparison of $\Delta\phi$ distribution accept events for $\Delta\phi$ < 1 rad.





ATLAS Result

Both cut-based and shape analysis tried.
Shape analysis has less systematics ➔ reach is better

Systematics	Higgs boson 130 GeV	Background Cut-Based	Background Shape
Luminosity	3 %	3 %	$\sim 0\%$
Jet energy resolution: $\sigma(E) = 0.45\sqrt{E}$ for $\lvert\eta\rvert < 3.2$; $\sigma(E) = 0.63\sqrt{E}$ for $\lvert\eta\rvert > 3.2$	0.8 %	5.3 %	4.5 %
Jets energy scale: $+7\%$ for $\lvert\eta\rvert < 3.2$; $+15\%$ for $\lvert\eta\rvert > 3.2$	4.0 %	3.2 %	0.2 %
Jets energy scale: -7% for $\lvert\eta\rvert < 3.2$; -15% for $\lvert\eta\rvert > 3.2$	10.0 %	19.5 %	2.8 %
Total	10.5 %	20.4 %	5.3 %

Table 7: Experimental contributions to the systematic uncertainty. The systematic uncertainty on the Jet Energy Scale (JES) is asymmetric. Only the largest (negative) JES systematic uncertainty is included in the total experimental uncertainty shown in the last row of the table.

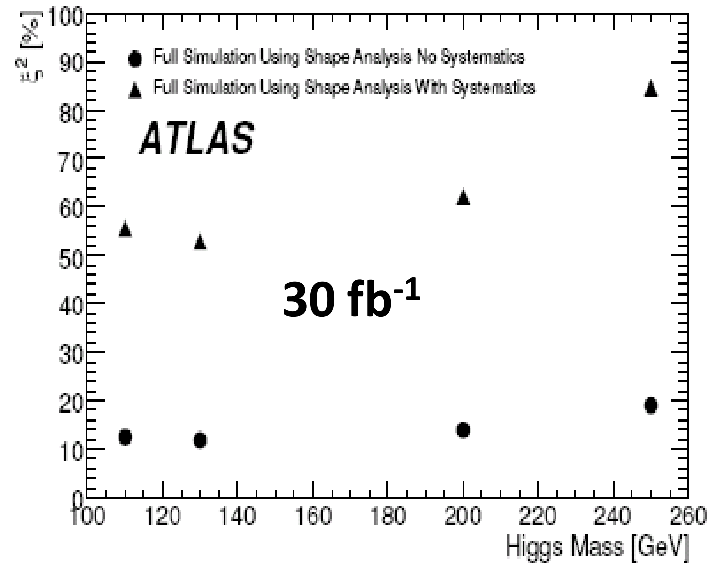


Figure 6: Sensitivity for an invisible Higgs boson at 95% C.L. via the VBF channel using shape analysis for an integrated luminosity of $30 fb^{-1}$ with and without systematic uncertainties. The black triangles (circles) are the results from this analysis with (without) systematic uncertainties.

➔ With systematics, ξ^2 ~50% for Higgs mass 120 GeV

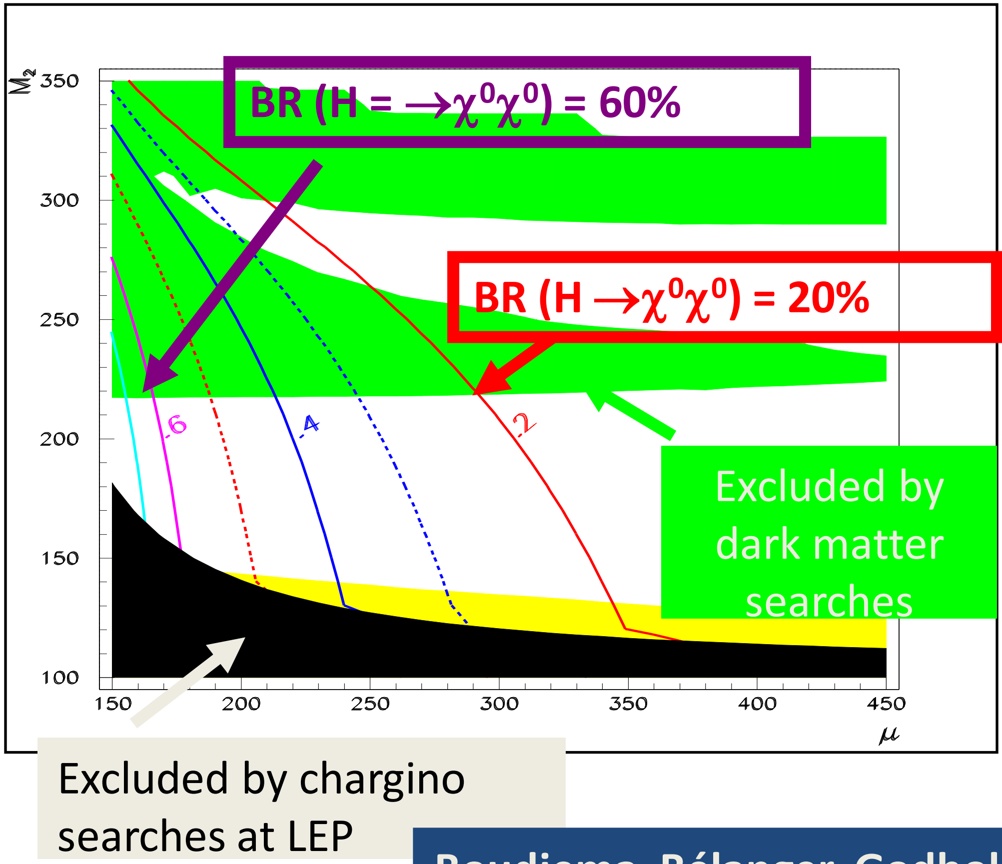
→ different models give very different branching ratio (BR) to invisible vs Higgs mass, but usually BR is reasonably high for mH < 300 GeV).

BR ($H \rightarrow \chi^0\chi^0$) in the M_2-μ plane

χ^0 : neutralino (lighest SUSY particle)

M_2: **gaugino mass**

μ: **Higgs doublet mixing**



Boudjema, Bélanger, Godbole hep-ph/0206311

→ ***Analysis performed is model independent.***

QCD Generation in Fast Simulation

p_T-bins	Cross-section(fb)	Event Generated	Filter Efficiency
QCD[20-30 GeV]	6.37×10^{11}	564M	1.88×10^{-6}
QCD[30-50 GeV]	1.56×10^{11}	328M	6.70×10^{-6}
QCD[50-70 GeV]	1.82×10^{10}	154M	4.29×10^{-5}
QCD[70-100 GeV]	4.84×10^{9}	233M	3.27×10^{-4}
QCD[100-150 GeV]	1.15×10^{9}	148M	2.7×10^{-3}
QCD[150-250 GeV]	2.13×10^{8}	107M	1.25×10^{-2}
QCD[250-400 GeV]	2.02×10^{7}	35M	2.7×10^{-2}
QCD[400-600 GeV]	1.92×10^{6}	4M	4.5×10^{-2}
QCD[600-800 GeV]	2.0×10^{5}	1.5M	4.2×10^{-2}
QCD[800-1200 GeV]	4.4×10^{4}	800K	3.25×10^{-2}

Total events = 1500 M

For 1 fb^{-1} lumi, generated event statistics is still not enough ☹ ➔ very large scale factors. **i.e. ~1100 for 20-30 GeV bin**

QCD sample generated using CMSSW_1_6_7 ➔ No HLT information available

Thanks to Wisconsin Grid -T2!!

Data Samples used for analysis

Sample	filter eff. $\times\sigma$ (fb)	Event Analyzed	Luminosity (fb^{-1})
Signal (m_H = 120 GeV)	4470	21924	4.90
Signal (m_H = 140 GeV)	3830	20088	5.24
Signal (m_H = 160 GeV)	3320	20196	6.08
Z + 2 jets (Alpgen)	31010	42000	1.35
Z + 3 jets (Alpgen)	55520	75000	1.35
W + 2 jets (Alpgen)	148220	150000	1.01
W + 3 jets (Alpgen)	247910	267903	1.08
$t\bar{t}$ (MC@NLO)	840000	350000	0.42
QCD [20-30 GeV]	1197560	1058	0.0009
QCD [30-50 GeV]	1045200	2209	0.002
QCD [50-70 GeV]	891800	7607	0.009
QCD [70-100 GeV]	1582680	75928	0.048
QCD [100-150 GeV]	3105000	399983	0.13
QCD [150-250 GeV]	2662500	1339412	0.5
QCD [250-400 GeV]	545400	940202	1.72
QCD [400-600 GeV]	86400	178786	2.1
QCD [600-800 GeV]	8400	64427	7.7
QCD [800-1200 GeV]	1430	27392	19

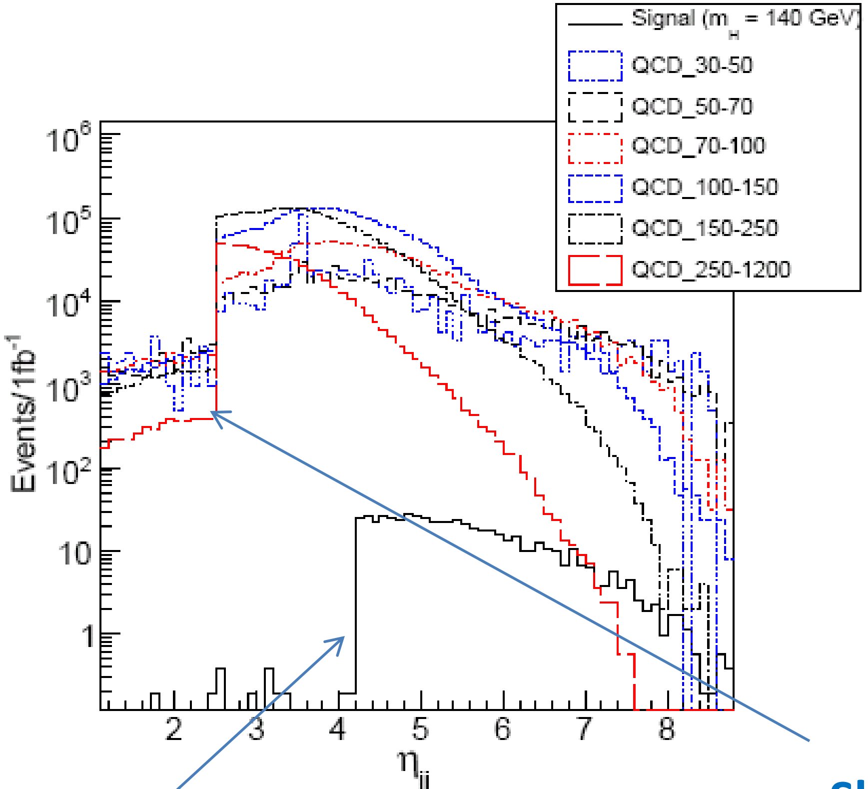
Filter eff. = 1

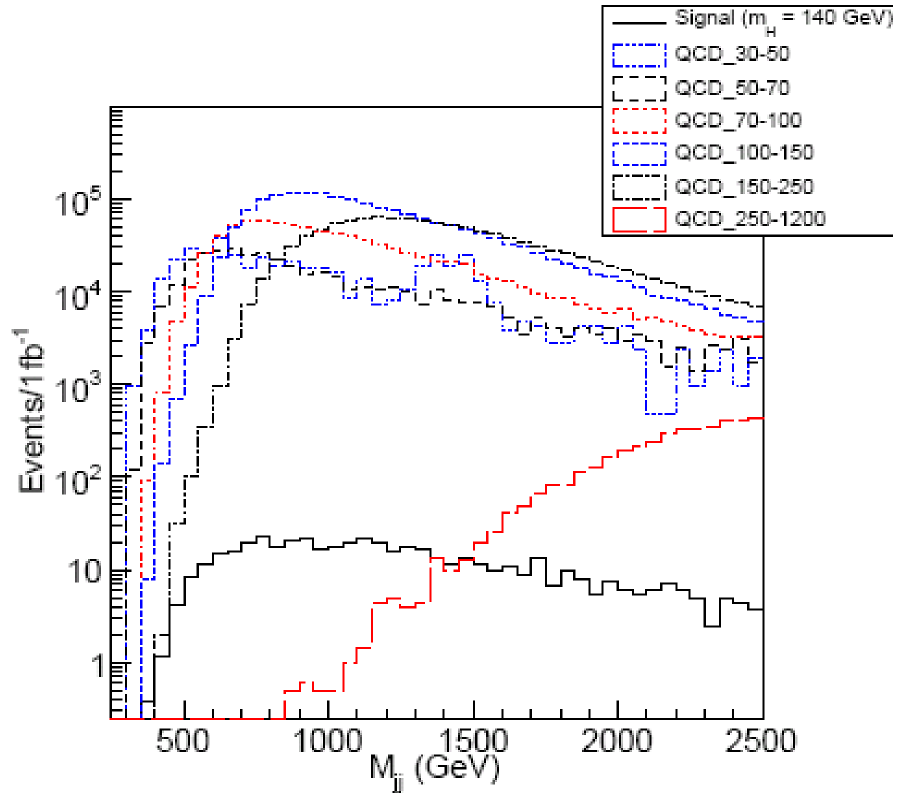
Filter eff. ~ 10^{-4}

Offline Selections (Cont..)

2) VBF conditions on jets:

pT (1,2) > 40 GeV, $\eta 1 * \eta 2 < 0$, $|\eta| < 5$





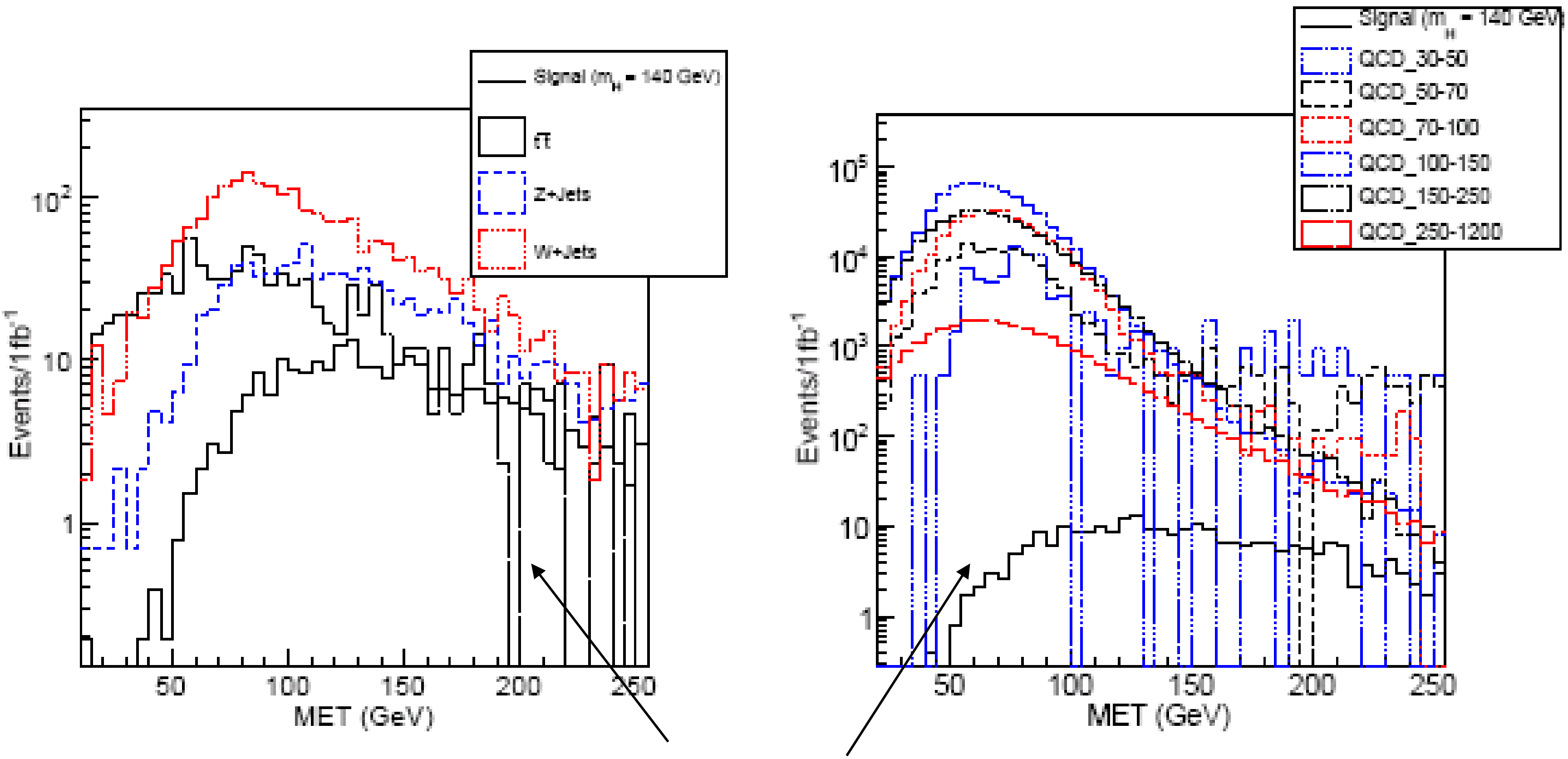
Sharp dip due to pre-selection

Effect of Trigger

➔ Require $\Delta\eta > 4.4$, Mjj > 1200 GeV

Offline selections (cont.)

3) Missing Transverse Energy (MET)



MET distributions after VBF selection

➔ Require MET > 100 GeV

Results

Sample	Signal (m_H = 140 GeV)	Z + jets	W + jets	inclusive $t\bar{t}$
Scale factor	0.19	0.74	1.05	4.17
HLT Condition	673	3800	12680	4870
Lepton veto	660	3717	8388	2449
VBF	286	911	2255	898
$\not{E}_T > 100$ GeV	241	631	1117	355
CJV	190	216	289	38
NV > 4	119	92	95	7
$\Delta\Phi_{jj} < 1.5$ rad.	101	64	79	5

Cross-section (fb) at each stage of selection

Sample	QCD [20-30 GeV]	QCD [30-50 GeV]	QCD [50-70 GeV]	QCD [70-100 GeV]	QCD [100-150 GeV]	QCD [150-250 GeV]	QCD [250-400 GeV]	QCD [400-1200 GeV]
Scale factor	1129	476	118	20.8	7.76	1.99	0.58	0.35
$\sigma\times$Filter Eff. (fb)	1197560	1045200	891800	1582680	3105000	2662500	545400	96230
Lepton veto	1193030	1038156	884646	1564520	3072708	2630640	537546	94527
VBF	46408	98056	142308	318941	625911	352694	27200	1446
$\not{E}_T > 100$ GeV	15847	33320	22302	29016	34544	34562	5383	310
CJV	4528	9520	5782	3648	7634	8767	1205	43
NV > 4	3395	4760	2478	341	54	10	1	1
$\Delta\Phi_{jj} < 1.5$ rad.	3395	476	1770	155	45	8	0	0

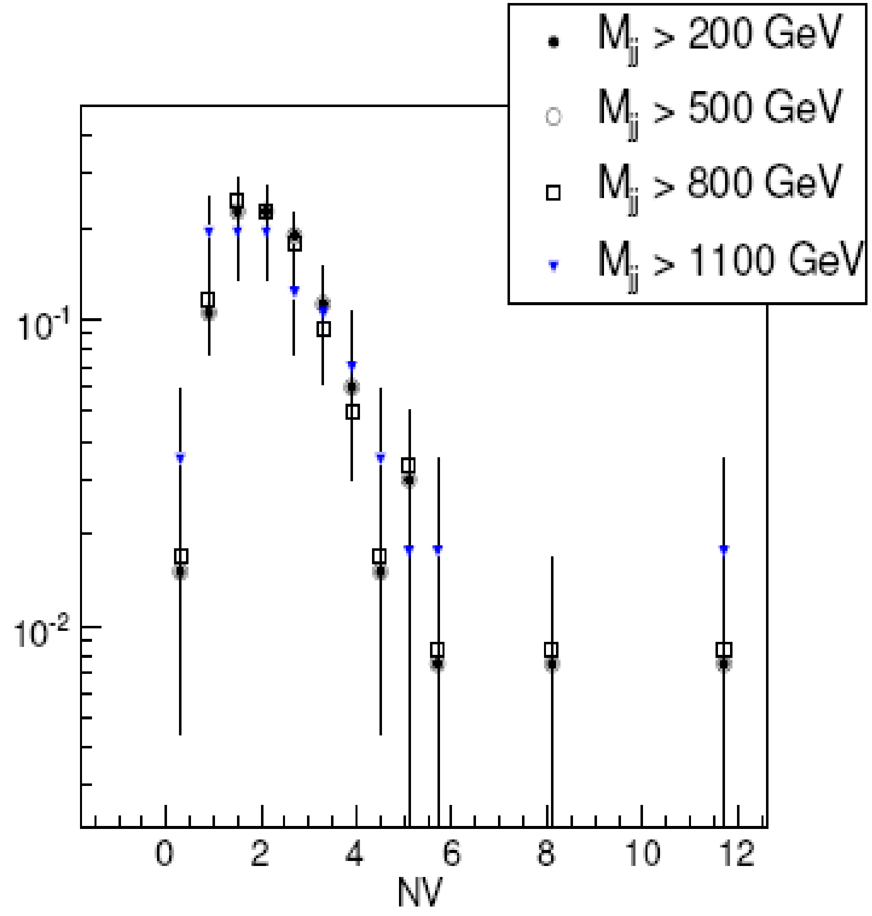
Table 9: Estimated cross-section (fb) for signal and QCD background in various $\hat{p}_T$-bins for various selection cuts.

Estimation of QCD, ttbar + jets backgrounds

Matrix Method

➔ Need 2 independent variables having discriminating power between signal and backgrounds

- **NV distribution for QCD events (70-100 GeV bin) for different values of Mjj cut after all other selections (VBF, MET, CJV, $\Delta\phi$)**

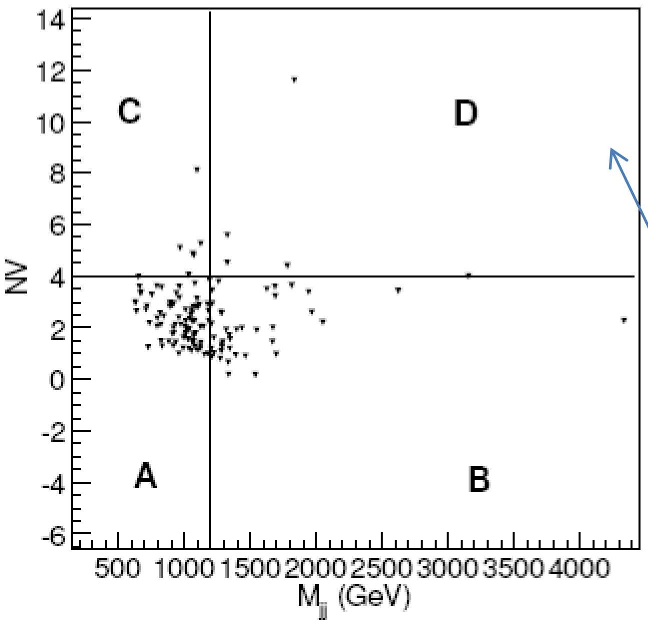


➔ NV and Mjj are un-correlated to good extent

Estimation of QCD, ttbar + jets backgrounds (cont.)

Define four regions A, B, C and D demarcated by NV and Mjj cut values, each region has contribution from all backgrounds and signal

Distribution of QCD (70-100 GeV) events in 4 quadrants



$$N_T^A = N_b^A + N_s^A, \qquad N_T^B = N_b^B + N_s^B$$
$$N_T^C = N_b^C + N_s^C, \qquad N_T^D = N_b^D + N_s^D$$

- ✓ **Signal contribution in each region can be calculated using MC.**
- ✓ **After subtracting signal contribution, background events in region D can be calculated as**

Signal Region

$$N^D = \frac{N^B \times N^C}{N^A}.$$

➔ QCD + ttbar contribution in signal region can be calculated by subtracting contribution of Z/W + jets backgrounds.