Tagging Jets in Invisible Higgs Searches

[1712.03973]

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INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

Higgs physics

What has been measured yet?

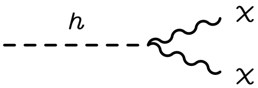
- h $\to \gamma\gamma$ [ATLAS-CONF-2017-045]
- h $\to ZZ^* \to 4l$ [ATLAS-CONF-2017-043]
- h $\to WW^* \to l\nu l\nu$ [ATLAS-CONF-2016-112]
- h $\to \tau\tau$ ([708.00373], $4.9\,\sigma$($4.5\,\sigma$) evidence)
- h $\to b\bar{b}$ ([1708.03299], $3.5\,\sigma$ evidence)
- $t\bar{t}$h ([1804.02610], $5.2\,\sigma$)

not measured yet

- h $\to \mu\mu$ ([CMS PAS HIG-17-019], upper limit 2.6(2.8) times SM pred.)
- h $\to Z\gamma$ ([CMS PAS HIG-17-007], upper limit 3.9(6.6) times SM pred.)
- h $\to$ invisible? ([CMS PAS HIG-17-023], upper limit 0.24)

Motivation

- Higgs decays to invisible particles
  - [Shrock, Suzuki, 1982]
- Higgs portal models
  - [Silveira, Zee, 1985]
  - [Burgess, Pospelov, Veldhuis, 2001]
  - [Patt, Wilczek, 2006]
  - [Englert, Plehn, Zerwas, Zerwas, 2011]
- Dark matter candidates
  - Scalar (minimal/extended Higgs sector)
  - Fermion (MSSM) [Butter, Murgia, Plehn, Tait, 2016]
  - ...



Outline

- Introduction: Signatures of invisible Higgs decays
- Weak boson fusion and its backgrounds
- Quark gluon discrimination
- BDT analysis
- Comparison to associated Zh production
- Conclusion and discussion

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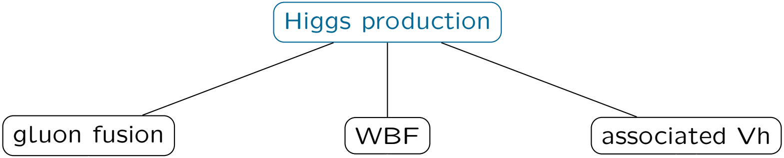
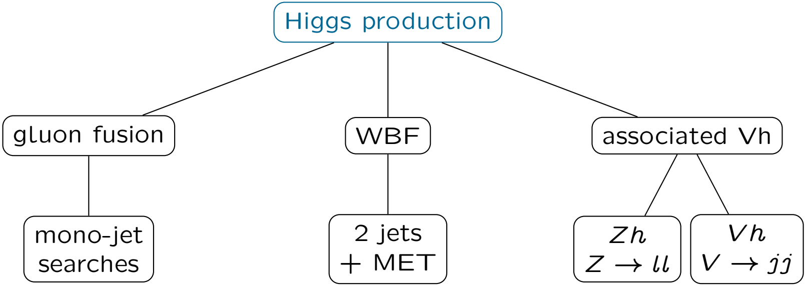
Introduction

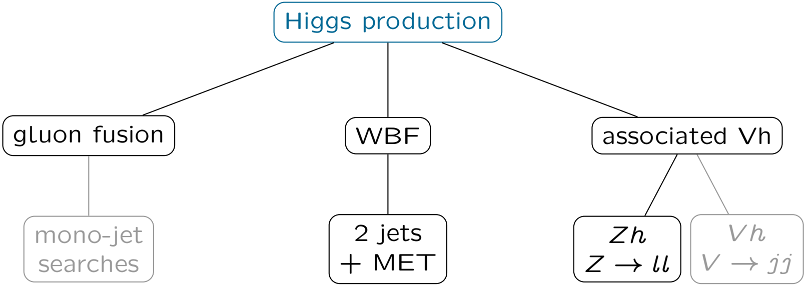
Invisible Higgs decays



Invisible Higgs decays



Invisible Higgs decays



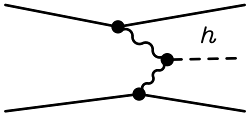
strongest channels [ATLAS: CERN-PH-EP-2015-191]

Weak boson fusion

WBF signature

EW process: Jets + missing energy

- 2 jets with large η separation
- opposite hemispheres $\eta_1 \cdot \eta_2 < 0$
- large MET
- no central jet activity



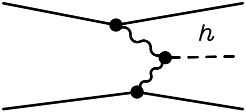
Trigger

- CMS-HIG-16-016:
  - $p_{T,j} > 40$ GeV
  - $m_{jj} > 600$ GeV
  - $E_T^{\text{miss}} > 140$ GeV
  - $\Delta\eta_{jj} > 3.5$
  - $\eta_{j1} * \eta_{j2} < 0$
- outlook for HL-LHC
  - $E_T^{\text{miss}} > 200$ GeV?
  - ...?
  - How dangerous is this?

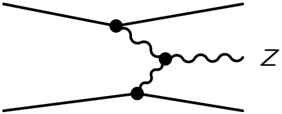
[Eboli, Zeppenfeld, 2000]

[Bernaciak, Plehn, Schichtel, Tattersall, 2014]

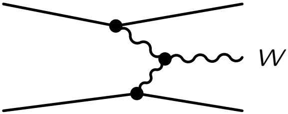
WBF backgrounds



$Z \to \nu\nu$	$W \to (l)\nu$

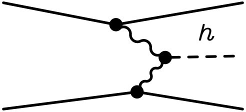


Z EW



W EW

WBF backgrounds



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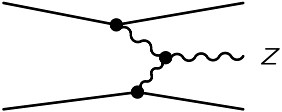

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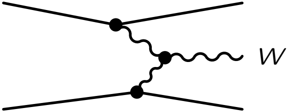

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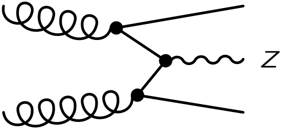
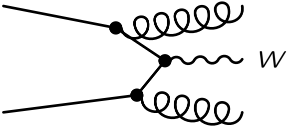


Z QCD



W QCD

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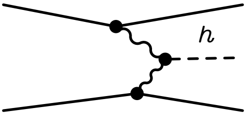

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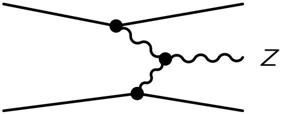

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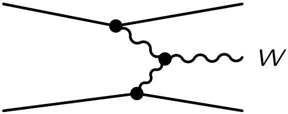
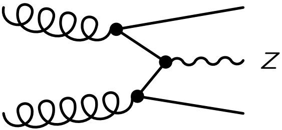
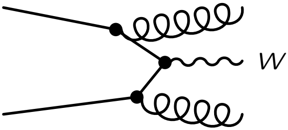


W EW losing a lepton



Z QCD

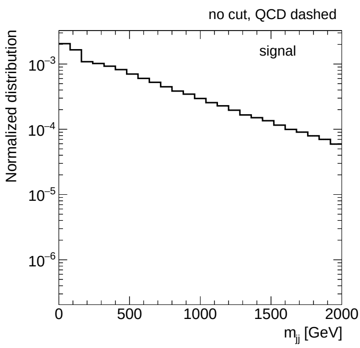


W QCD losing a lepton

WBF distributions

Sherpa + Delphes,

merged sample (2 + 3) jets



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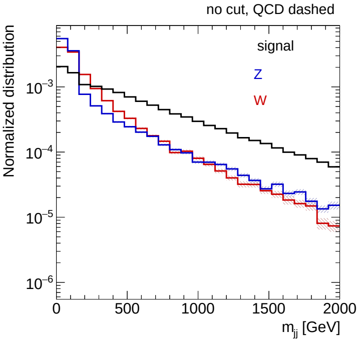
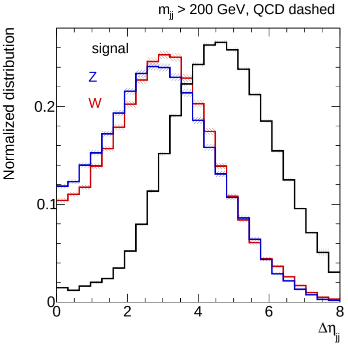


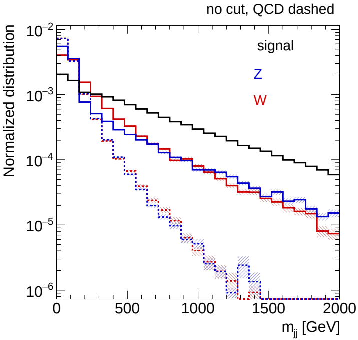


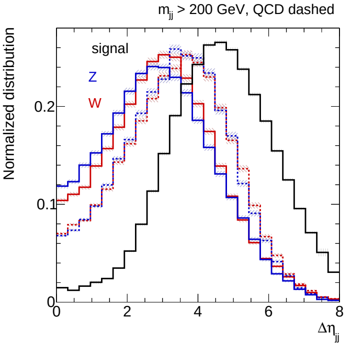
W and Z backgrounds similar in signal region

WBF distributions

Sherpa + Delphes,

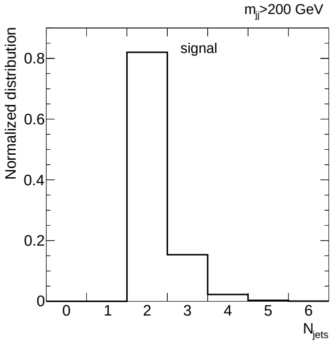
merged sample (2 + 3) jets





WBF distributions - N_{jets}

merged sample (2 + 3) jets



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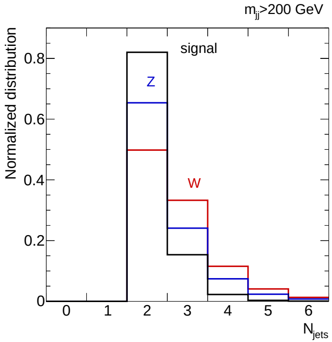

W and Z backgrounds different for N_{jets} distribution

- W background has more 3-jet events

WBF distributions - N_{jets}

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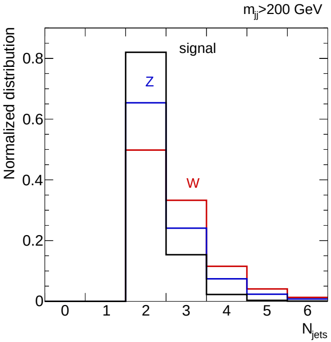

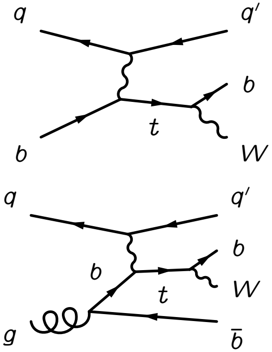

W and Z backgrounds different for N_{jets} distribution

- W background has more 3-jet events
- W background contains **single-top** events

($m_{jj} > 200$ GeV: 30% 2jet, 50% 3jet; preselection: 5%, 12%)

preselection: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $\Delta\eta_{jj} > 3.5$, $p_T(V) > 80$ GeV

WBF distributions - N_{jets}

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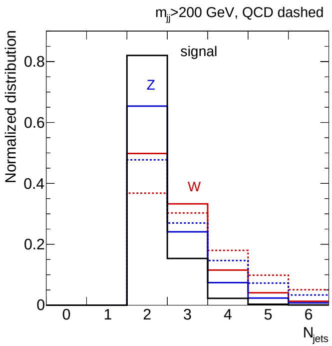

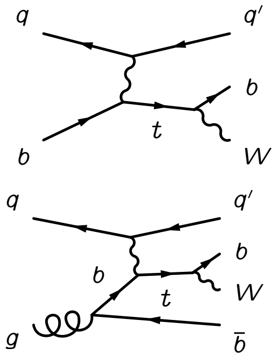

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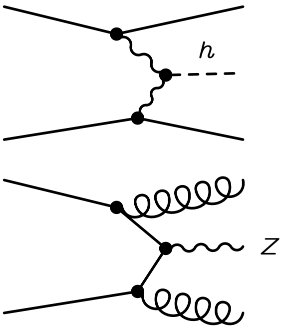
Tagging jet content

How to suppress QCD backgrounds?

- QCD dominates over EW processes (L**H**C)
- central jet veto
- recall: for QCD background tagging jets can be quarks
  ➜ can we use this to suppress QCD backgrounds?



Quark gluon discrimination

QCD backgrounds more likely to have hard gluon jets

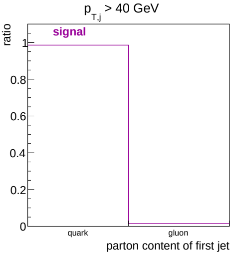
- wider angle soft emissions
- more splittings in parton evolution

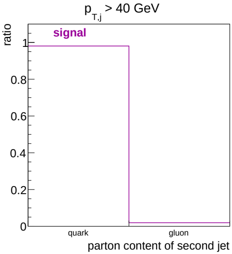
Variables for quark gluon discrimination

- n_{PF}: number of particle flow (PF) objects (tracks and towers)
- $$w_{\mathrm{PF}} = \frac{\sum_{\mathrm{PF}\in\mathrm{jet}} p_{T,\mathrm{PF}} \Delta R_{\mathrm{PF,jet}}}{\sum_{\mathrm{PF}\in\mathrm{jet}} p_{T,\mathrm{PF}}}$$
- $$C = \frac{\sum_{i_{\mathrm{PF}}, j_{\mathrm{PF}}} \; p_{T,i} p_{T,j} \; (\Delta R_{ij})^{0.2}}{\left(\sum_{i_{\mathrm{PF}}} p_{T,i}\right)^2}$$
- $$p_T D = \frac{\sqrt{\sum_{\mathrm{PF}\in\mathrm{jet}} \; p_{T,\mathrm{PF}}^2}}{\sum_{\mathrm{PF}\in\mathrm{jet}} \; p_{T,\mathrm{PF}}}$$

[ATLAS-CONF-2016-034, CMS-PAS-JME-13-002]

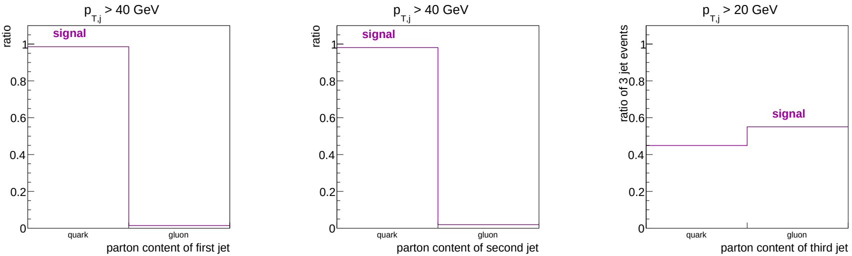
Parton content in WBF





preselection: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$, $p_T(V) > 80$ GeV

Parton content in WBF



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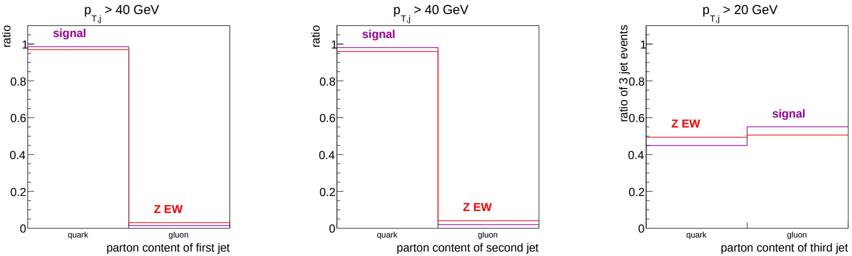

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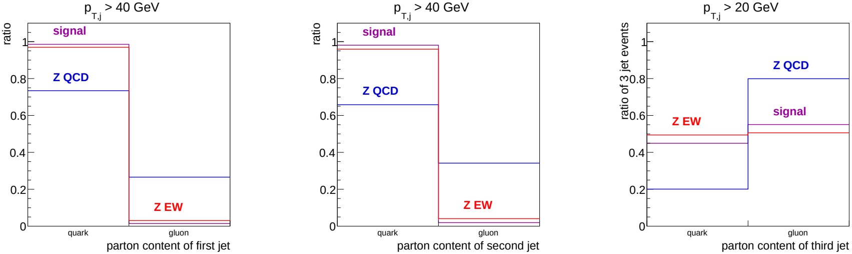
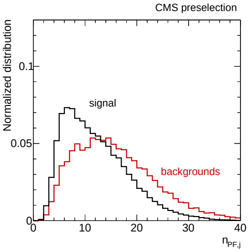
Parton content in WBF

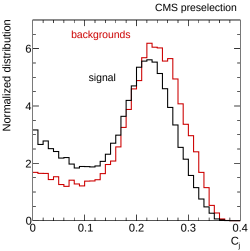


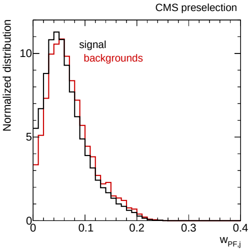
Expect best discrimination power for second jet.

preselection: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$, $p_T(V) > 80$ GeV

Quark gluon discrimination - distributions







preselection: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $E_T^{\text{miss}} > 140$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$

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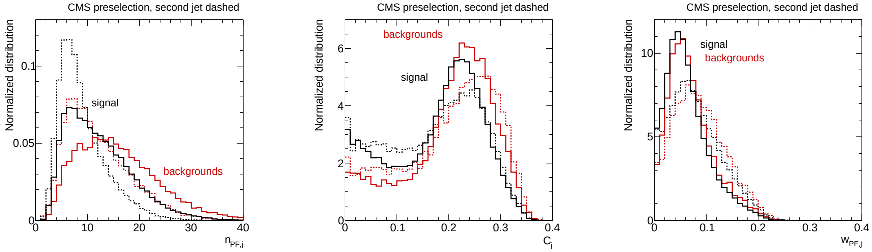

Quark gluon discrimination variables are p_T dependent

preselection: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $E_T^{\text{miss}} > 140$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$

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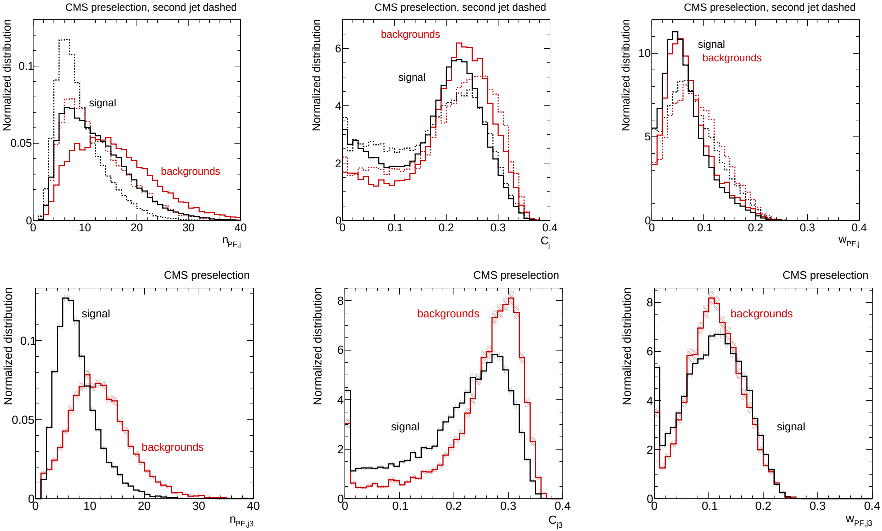
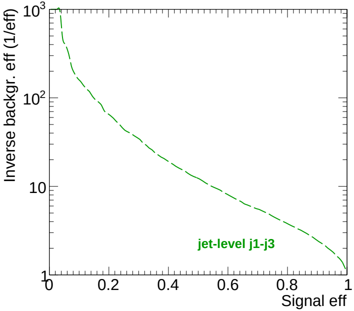


Third jet gives best separation (here: $p_T > 20$ GeV)

preselection: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $E_T^{\text{miss}} > 140$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$

BDT analysis

Boosted decision tree analysis



Set	Variables
jet-level j_1, j_2	p_{T,j_1} p_{T,j_2} $\Delta\eta_{jj}$ $\Delta\phi_{jj}$ m_{jj} $\not{E}_T$ $\Delta\phi_{j_1,\not{E}_T}$ $\Delta\phi_{j_2,\not{E}_T}$
subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
j_3 angular information	$\Delta\eta_{j_1,j_3}$ $\Delta\eta_{j_2,j_3}$ $\Delta\phi_{j_1,j_3}$ $\Delta\phi_{j_2,j_3}$
jet-level j_1-j_3	jet-level j_1, j_2 $+$ j_3 angular information $+$ p_{T,j_3}
subjet-level j_1-j_3	subjet-level j_1, j_2 $+$ n_{PF,j_3} C_{j_3} $p_T D_{j_3}$

preselection:

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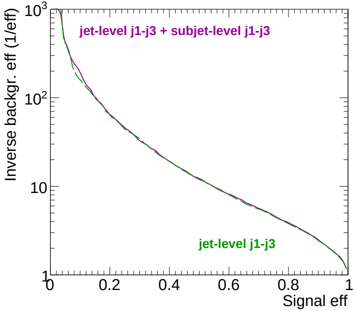

Set	Variables
jet-level j_1, j_2	p_{T,j_1} p_{T,j_2} $\Delta\eta_{jj}$ $\Delta\phi_{jj}$ m_{jj} $\not{E}_T$ $\Delta\phi_{j_1,\not{E}_T}$ $\Delta\phi_{j_2,\not{E}_T}$
subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
j_3 angular information	$\Delta\eta_{j_1,j_3}$ $\Delta\eta_{j_2,j_3}$ $\Delta\phi_{j_1,j_3}$ $\Delta\phi_{j_2,j_3}$
jet-level j_1-j_3	jet-level j_1, j_2 $+$ j_3 angular information $+$ p_{T,j_3}
subjet-level j_1-j_3	subjet-level j_1, j_2 $+$ n_{PF,j_3} C_{j_3} $p_T D_{j_3}$

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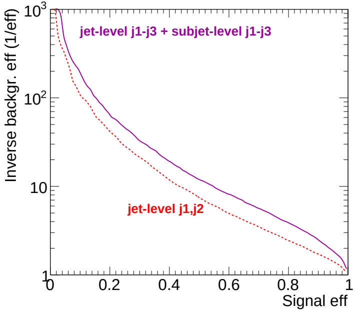

Set	Variables
jet-level j_1, j_2	p_{T,j_1} p_{T,j_2} $\Delta\eta_{jj}$ $\Delta\phi_{jj}$ m_{jj} $\not{E}_T$ $\Delta\phi_{j_1,\not{E}_T}$ $\Delta\phi_{j_2,\not{E}_T}$
subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
j_3 angular information	$\Delta\eta_{j_1,j_3}$ $\Delta\eta_{j_2,j_3}$ $\Delta\phi_{j_1,j_3}$ $\Delta\phi_{j_2,j_3}$
jet-level j_1-j_3	jet-level j_1, j_2 + j_3 angular information + p_{T,j_3}
subjet-level j_1-j_3	subjet-level j_1, j_2 + n_{PF,j_3} C_{j_3} $p_T D_{j_3}$

preselection:

$p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $E_T^{\text{miss}} > 140$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$, $p_{T,j3} > 20$ GeV

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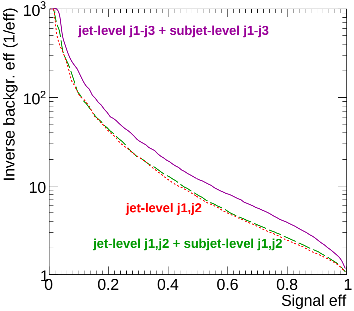

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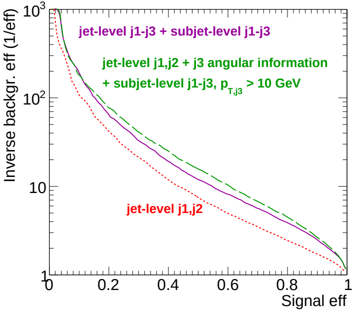
jet-level j_1, j_2	p_{T,j_1} p_{T,j_2} $\Delta\eta_{jj}$ $\Delta\phi_{jj}$ m_{jj} $\not{E}_T$ $\Delta\phi_{j_1,\not{E}_T}$ $\Delta\phi_{j_2,\not{E}_T}$
subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
j_3 angular information	$\Delta\eta_{j_1,j_3}$ $\Delta\eta_{j_2,j_3}$ $\Delta\phi_{j_1,j_3}$ $\Delta\phi_{j_2,j_3}$
jet-level j_1-j_3	jet-level j_1, j_2 $+$ j_3 angular information $+$ p_{T,j_3}
subjet-level j_1-j_3	subjet-level j_1, j_2 $+$ n_{PF,j_3} C_{j_3} $p_T D_{j_3}$

preselection:

$p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $E_T^{\text{miss}} > 140$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$, $p_{T,j3} > 20$ GeV

Boosted decision tree analysis



Set	Variables
jet-level j_1, j_2	p_{T,j_1} p_{T,j_2} $\Delta\eta_{jj}$ $\Delta\phi_{jj}$ m_{jj} $\not{E}_T$ $\Delta\phi_{j_1,\not{E}_T}$ $\Delta\phi_{j_2,\not{E}_T}$
subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
j_3 angular information	$\Delta\eta_{j_1,j_3}$ $\Delta\eta_{j_2,j_3}$ $\Delta\phi_{j_1,j_3}$ $\Delta\phi_{j_2,j_3}$
jet-level j_1-j_3	jet-level j_1, j_2 $+$ j_3 angular information $+$ p_{T,j_3}
subjet-level j_1-j_3	subjet-level j_1, j_2 $+$ n_{PF,j_3} C_{j_3} $p_T D_{j_3}$

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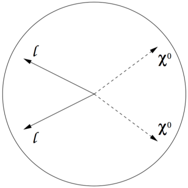
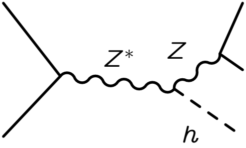
Associated Zh production

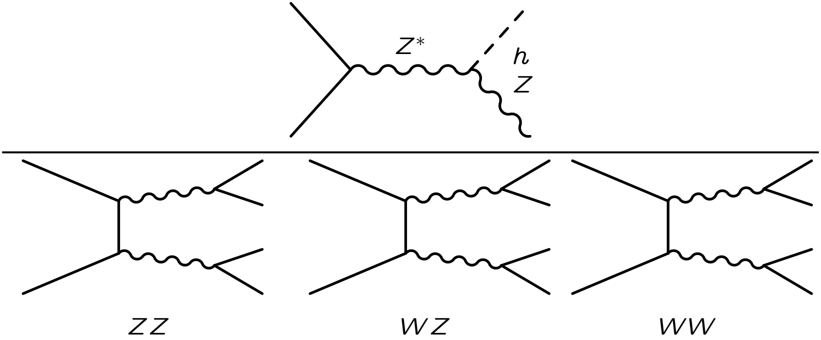
Zh production - signature

- boosted SFOS leptons $m_{ll} \sim m_Z$
- $Z+$ jets not taken into account (irrelevant at high MET)

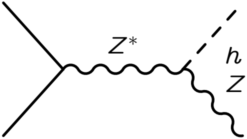


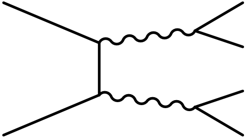


Zh production - backgrounds

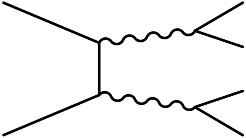


Zh production - backgrounds

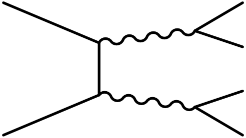




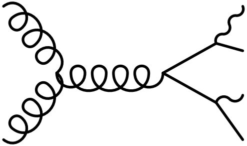
ZZ



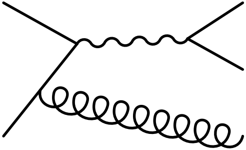
WZ



WW

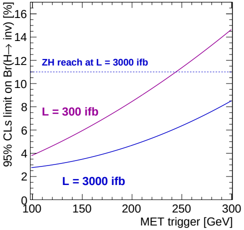


$t\bar{t}$



Z+jets

WBF and Zh reach - triggering



default: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $E_T^{\text{miss}} > 140$ GeV

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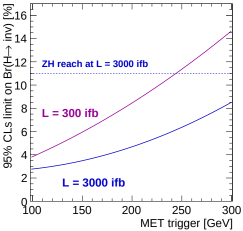
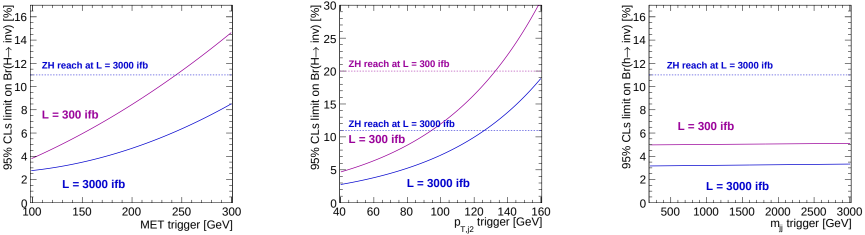


WBF constraints stronger for MET trigger $\lesssim$ 350 GeV

default: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $E_T^{\text{miss}} > 140$ GeV

WBF and Zh reach - triggering



WBF constraints stronger for MET trigger $\lesssim$ 350 GeV

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Conclusions

Conclusions

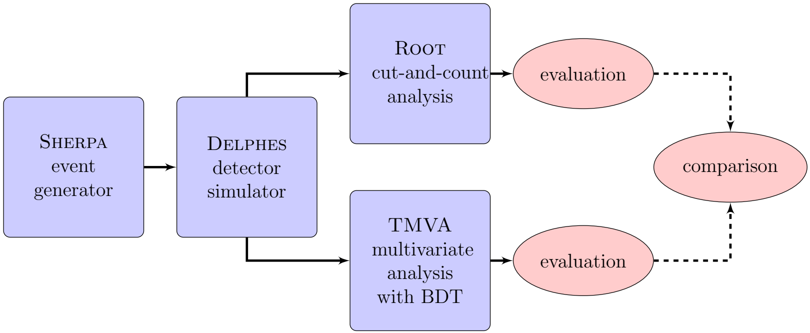
WBF

- Backgrounds: different behavior for N_{jets}
- Useful **quark gluon discrimination** variables: n_{PF}, C
- **Third jet** best for quark gluon discrimination $\mathbf{p_T > 10\ GeV}$
- However, no large improvement by QG variables when full information of additional jets is present
- **WBF** will still provide strongest constraints after trigger update

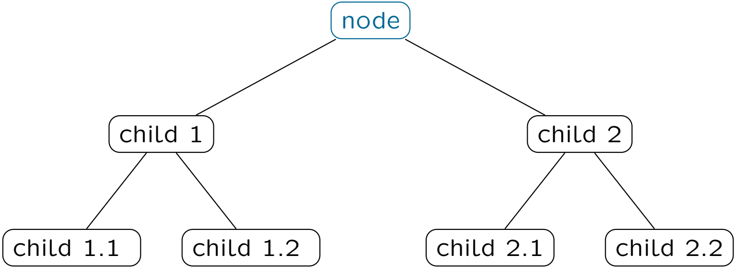
Thank you for your attention!

Backup

Tool chain


Sherpa
event
generator
Delphes
detector
simulator
Root
cut-and-count
analysis
TMVA
multivariate
analysis
with BDT
evaluation
evaluation
comparison

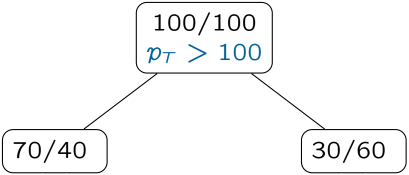
Boosted decision trees



Boosted decision trees

- used for **classification** problems (S/B)
- every node corresponds to decision
- always use the variable and the splitting that gives the **largest purity** of the classified samples

$$P = \frac{\sum w_S}{\sum w_S + \sum w_B}$$



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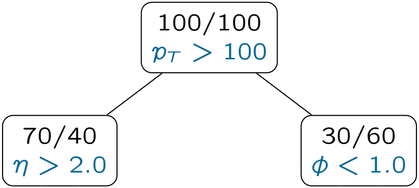

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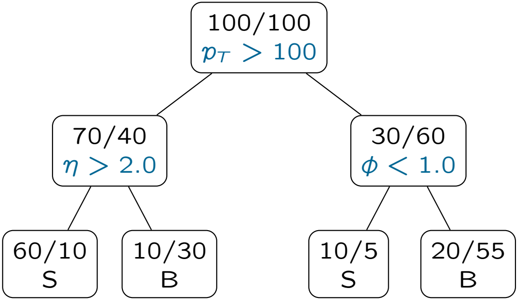

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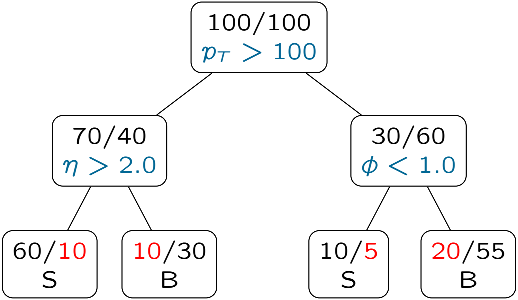

misclassified events

Boosted decision trees

- decision trees are unstable (sensitive to statistical fluctuations)
- generate more than one tree and average
- **boosting** = modifying the **weights** of misclassified events
- different variables and splittings may be chosen at each node

$$\boxed{\begin{array}{c} P = 0.48 \\ p_T > 90 \end{array}}$$

Boosted decision trees

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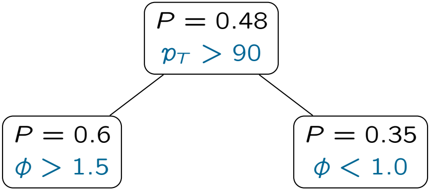


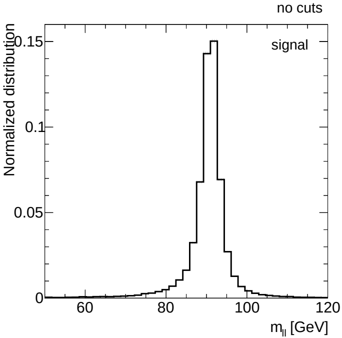
events used for classification are the same for each tree - only the weights change

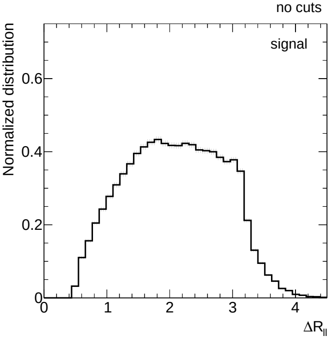
BDT settings

Use TMVA with

- 70 trees
- 3 layers
- nCuts = 20
- minimum node size 5 %
- preselection

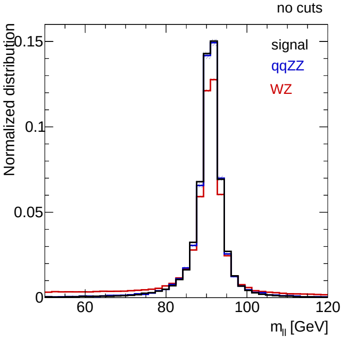
Zh - distributions

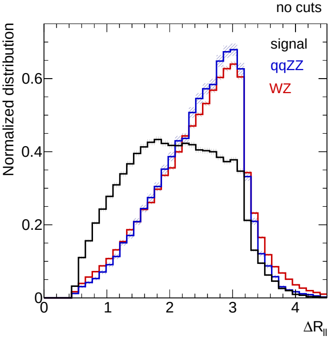




signal: Z boosted

Zh - distributions





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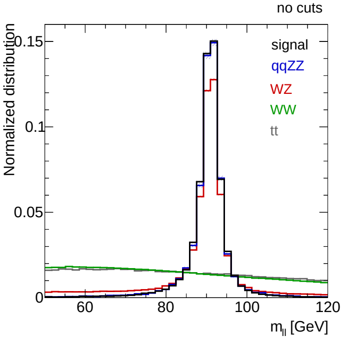
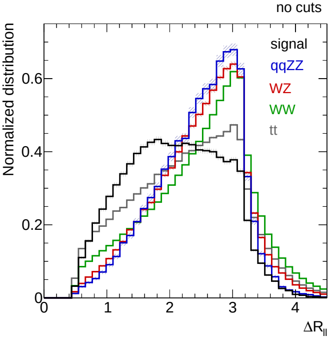


non-resonant bkgs flat

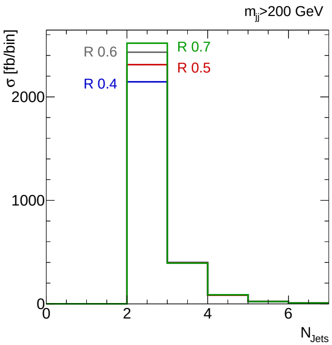


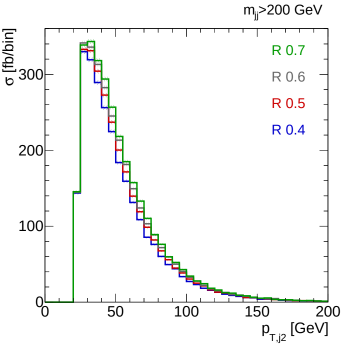
signal: Z boosted

WBF - dependence on jet cone size

Simulated process: $h + 2/3$ jets merged (Sherpa, parton shower)

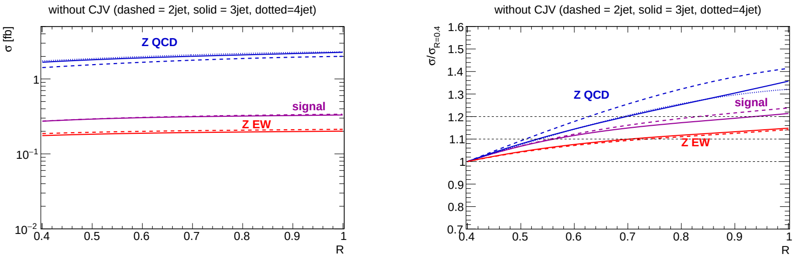
variation of jet cone size in Delphes





kinematics unchanged

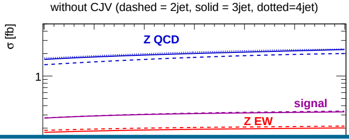
WBF - dependence on jet cone size (2)

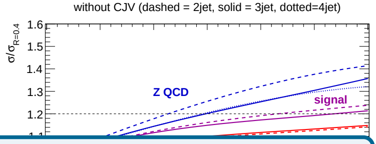


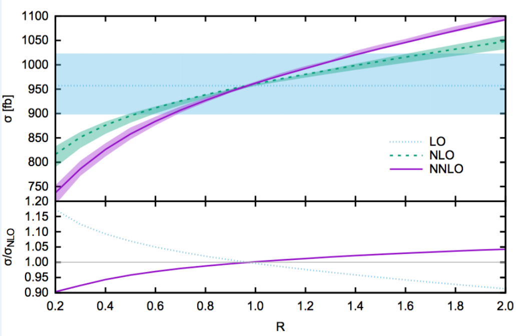
Signal grows stronger with R than EW background

preselection: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$, $p_T(V) > 80$ GeV

WBF - dependence on jet cone size (2)







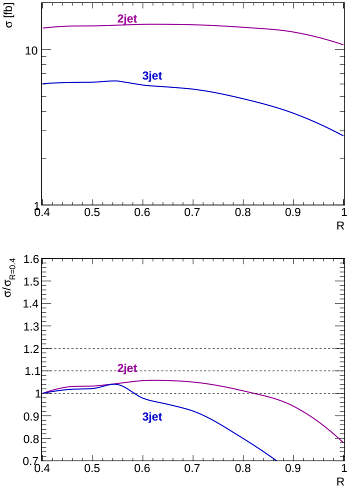
similar results in fixed-order calculation [Rauch, Zeppenfeld, 2017]

Dependence on jet cone size - hZ, $Z \to j\ j$

same final state,

different topology

variable	cut
MET	$120 - 160$ GeV
N_{jets}	$2 - 3$
ΔR_{jj}	$0.7 - 2.0$
m_{jj}(2jets)	$70 - 100$
m_{jj}(3jets)	$50 - 100$



No strong dependence on R visible

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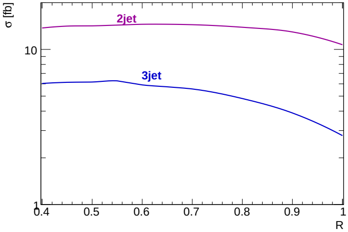

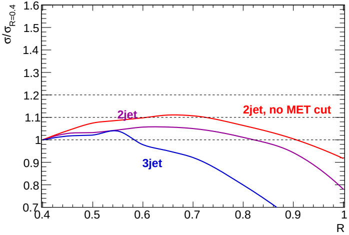

No strong dependence on R visible

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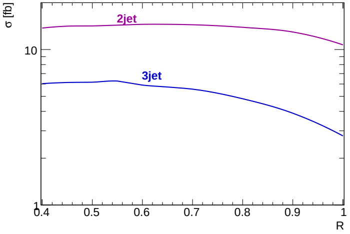

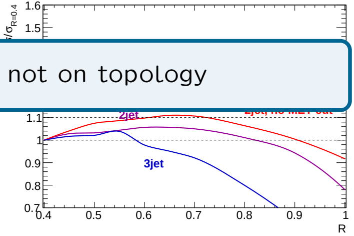

depends on **phase space**, not on topology

No strong dependence on R visible