Invisible Higgs decays

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and Jennifer Thompson

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UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL
PT FS
FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

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
- Conclusion and outlook

work in progress

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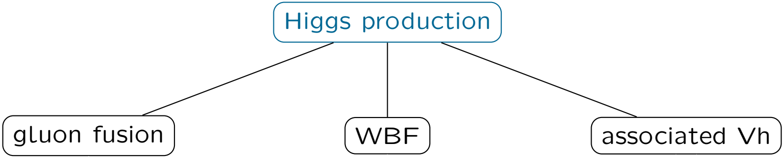
- Weak boson fusion and its backgrounds
- Quark gluon discrimination
- BDT analysis
- Conclusion and **outlook**
- **Discussion:** Your input?

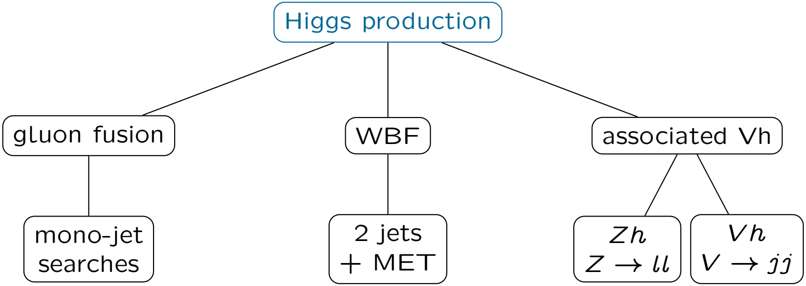
work in progress

Introduction

Invisible Higgs decays



Invisible Higgs decays



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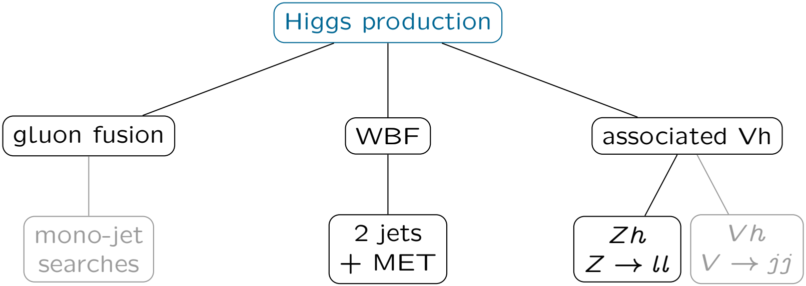


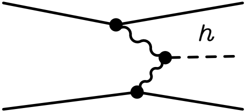
strongest channels [ATLAS: CERN-PH-EP-2015-191]

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



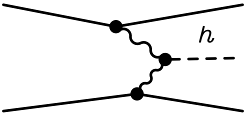
Trigger

- 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?

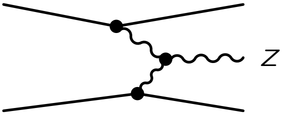
[Eboli, Zeppenfeld, 2000]

[Bernaciak, Plehn, Schichtel, Tattersall, 2014]

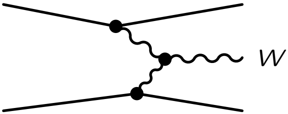
WBF backgrounds



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



Z EW



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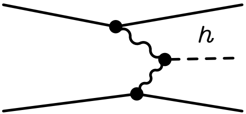

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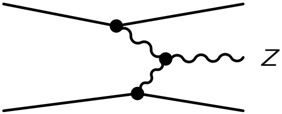

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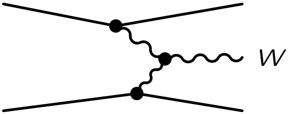

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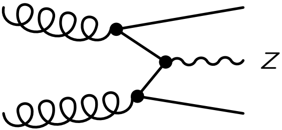
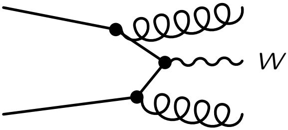
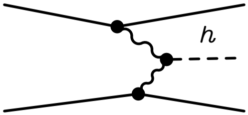


Z QCD



W QCD

WBF backgrounds



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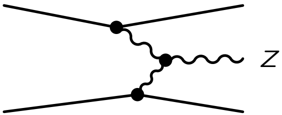
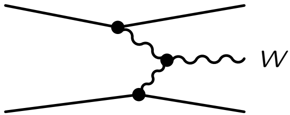
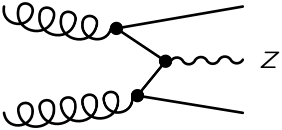
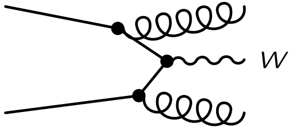
	
Z EW	W EW losing a lepton
	
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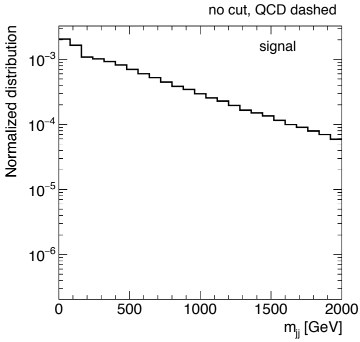
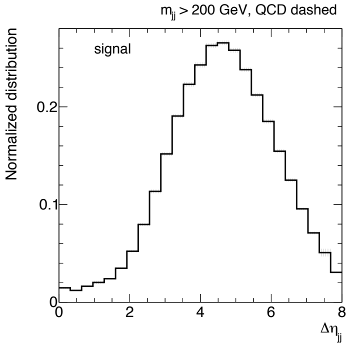
WBF distributions

merged sample (2 + 3) jets





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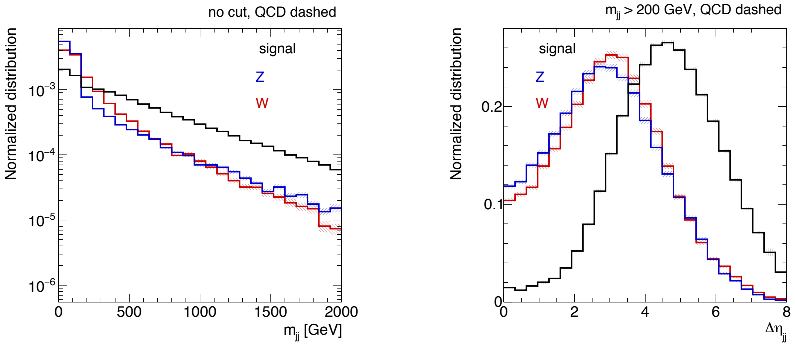

W and *Z* backgrounds similar in signal region

WBF distributions

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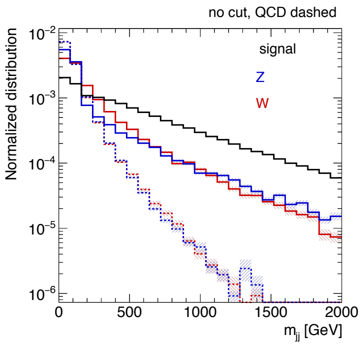
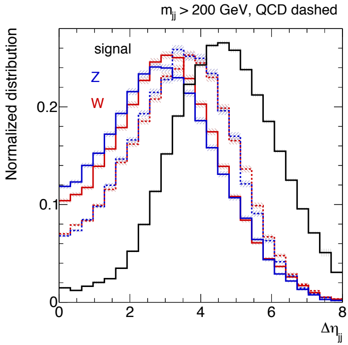
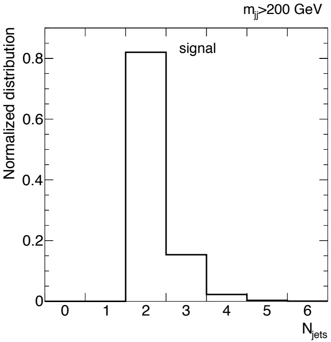




WBF distributions - N_{jets}

merged sample (2 + 3) jets



- W background peaks at 3 jets

WBF distributions - N_{jets}

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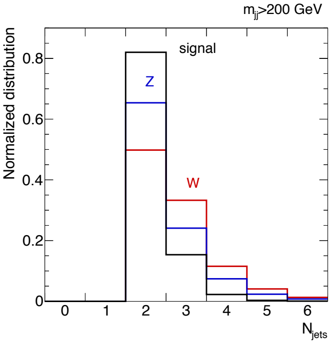

W and *Z* backgrounds different for N_{jets} distribution

- *W* background peaks at 3 jets

WBF distributions - N_{jets}

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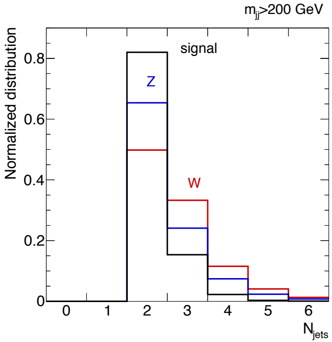

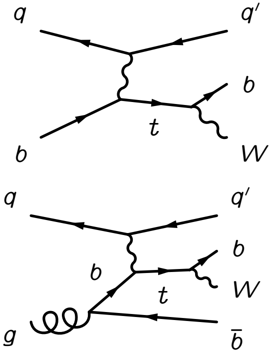

W and Z backgrounds different for N_{jets} distribution

- W background peaks at 3 jets
- 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, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$, $p_T(V) > 80$ GeV

WBF distributions - N_{jets}

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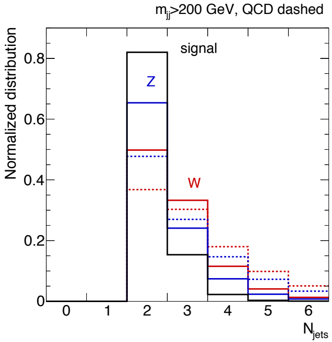

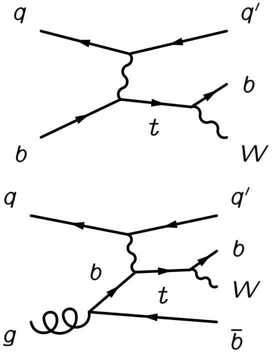

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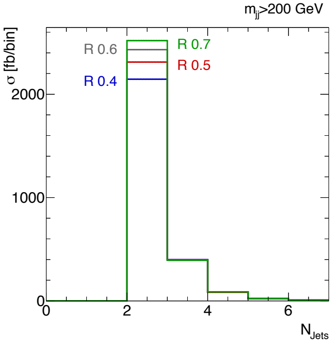
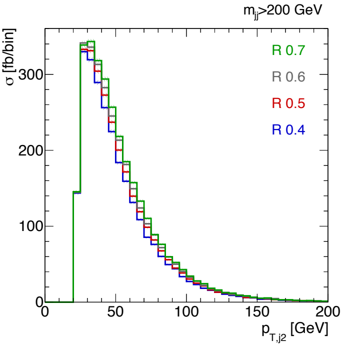
WBF - dependence on jet cone size

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

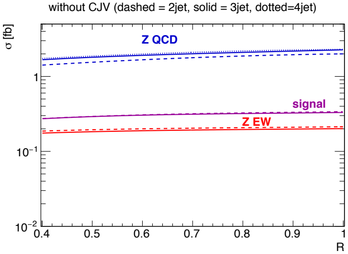
variation of jet cone size in Delphes

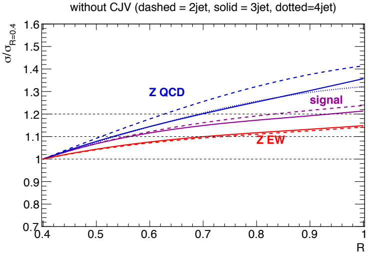




kinematics unchanged

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

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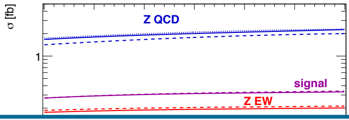
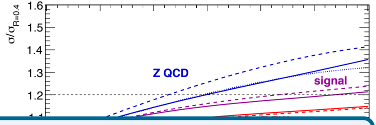
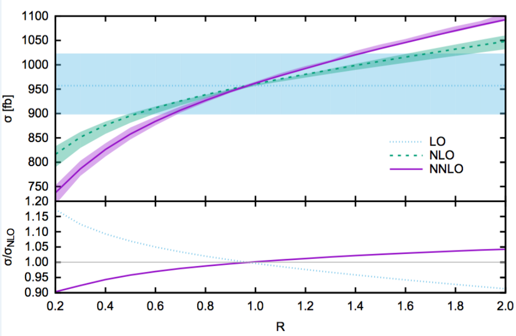






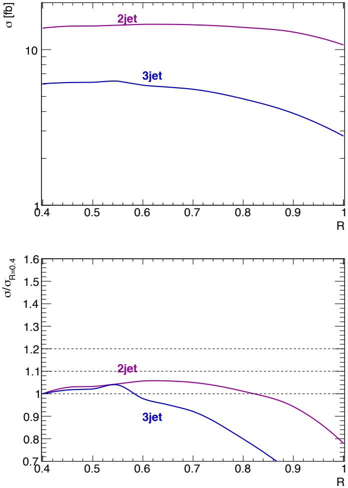
similar results in fixed-order calculation [Rauch, Zeppenfeld, 2017]

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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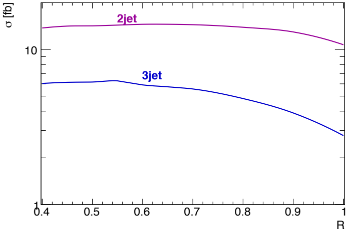

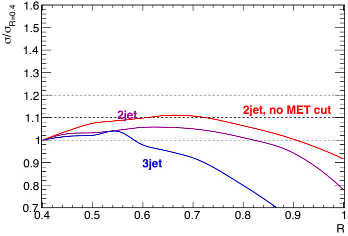

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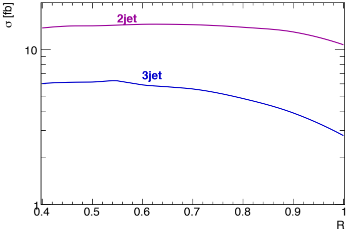
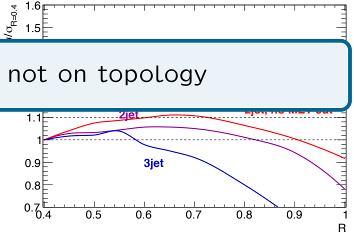




depends on **phase space**, not on topology

No strong dependence on R visible

Quark gluon discrimination

QCD backgrounds more likely to have hard gluon jets

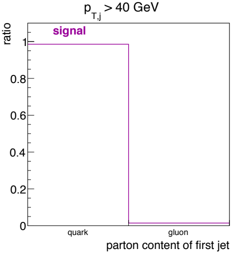
- wider angle soft emissions
- more splittings in parton evolution

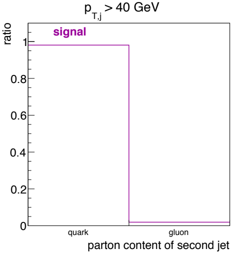
Variables for quark gluon discrimination

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

[ATLAS-CONF-2016-034]

Parton content in WBF





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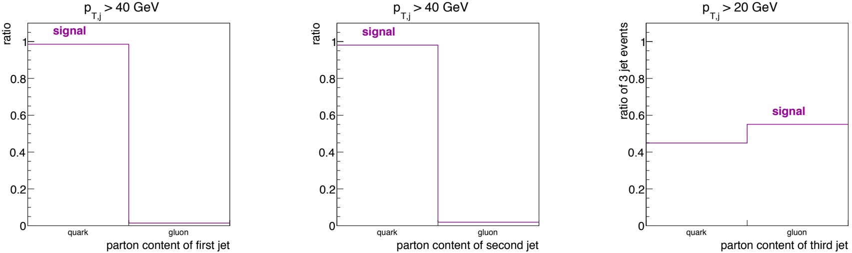

Expect best discrimination power for second jet.

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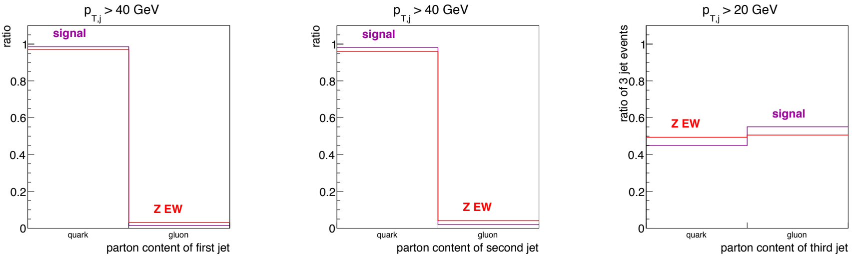

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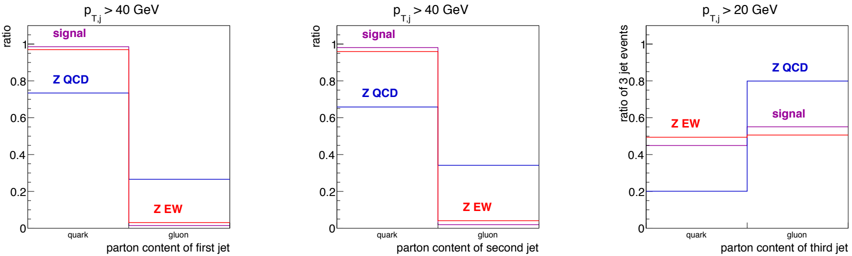

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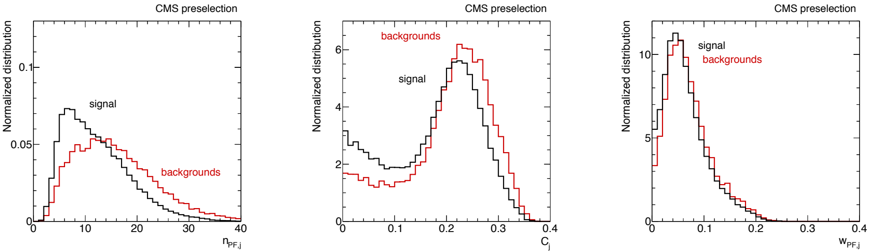
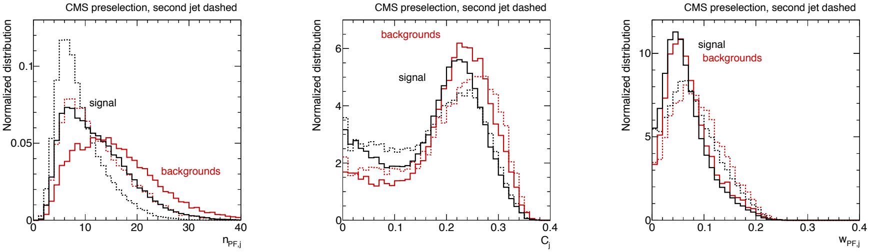
Quark gluon discrimination - distributions



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

Quark gluon discrimination - distributions



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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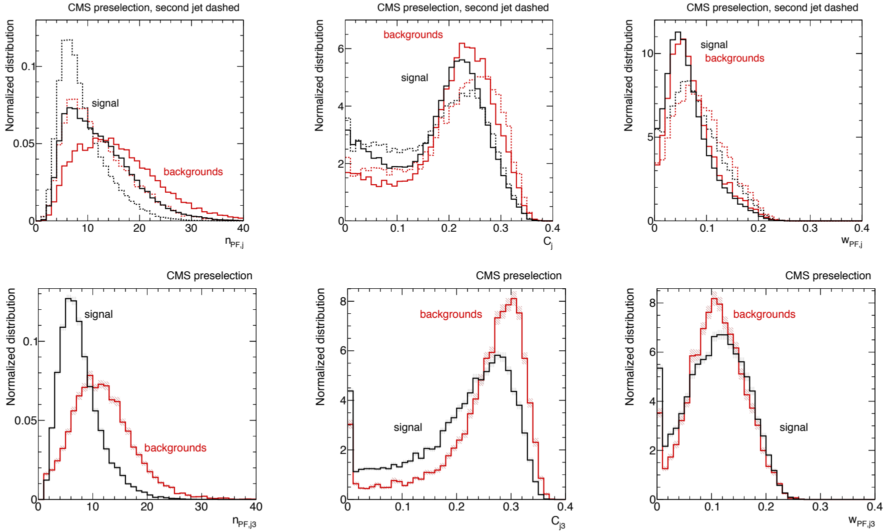
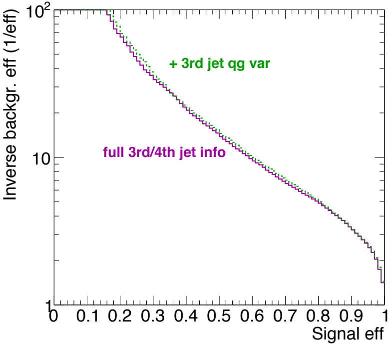


Third jet gives best separation (here: $p_T > 20$ GeV)

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

BDT - WBF

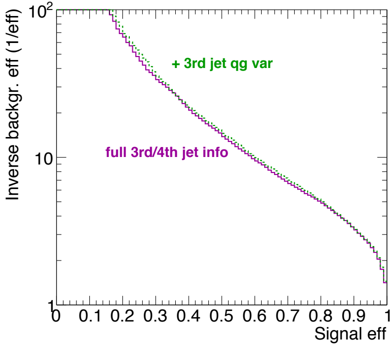


p_T, η, ϕ of third jet + p_T of fourth jet

same + C + n_{PF} of jet 1 - 3

preselection: $p_{T,j} > 40$ GeV, $m_{jj} > 600$ GeV, $E_T^{\text{miss}} > 140$ GeV, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$
variables used: $p_T(j)$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$ of leading two jets,
E_T^{miss}, $\Delta\phi(E_T^{\text{miss}}, j1)$, $\Delta\phi(E_T^{\text{miss}}, j2)$, m_{jj}, $N_{\text{jets}}(p_T > 20\text{GeV})$

BDT - WBF



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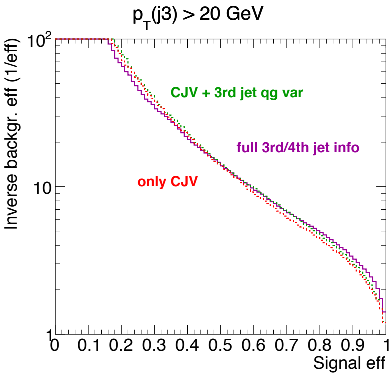

CJV ($p_T > 20$ GeV)

CJV + C + $n_{\rm PF}$ of jet 1 - 3

p_T, η, ϕ of third jet

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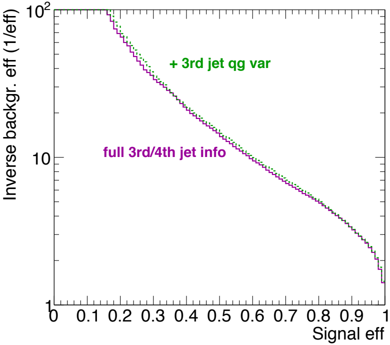
variables used: $p_T(j)$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$ of leading two jets,

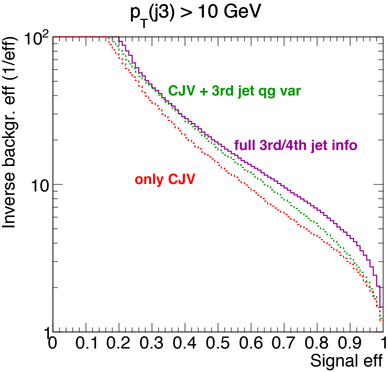
$E_T^{\rm miss}$, $\Delta\phi(E_T^{\rm miss}, j1)$, $\Delta\phi(E_T^{\rm miss}, j2)$, m_{jj}, $N_{\rm jets}(p_T > 20{\rm GeV})$

BDT - WBF



p_T, η, ϕ of third jet + p_T of fourth jet

same + C + n_{PF} of jet 1 - 3



CJV ($p_T > 20$ GeV)

CJV + C + n_{PF} of jet 1 - 3

p_T, η, ϕ of third jet

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

variables used: $p_T(j)$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$ of leading two jets,

E_T^{miss}, $\Delta\phi(E_T^{\mathrm{miss}}, j1)$, $\Delta\phi(E_T^{\mathrm{miss}}, j2)$, m_{jj}, $N_{\mathrm{jets}}(p_T > 20\mathrm{GeV})$

Outlook

Conclusion

WBF

- Backgrounds: different behavior for N_{jets}
- Signal cross section growing with **R**
- 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

Conclusion

WBF

- Backgrounds: different behavior for N_{jets}
- Signal cross section growing with **R**
- 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

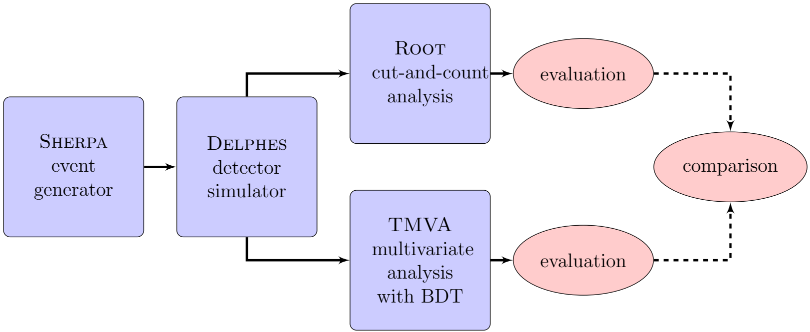
Outlook

- Compare to Zh, $Z \to ll$
- WBF still most sensitive channel 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

BDT settings

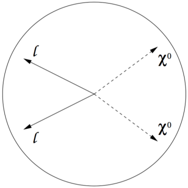
Use TMVA with

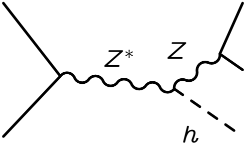
- 70 trees
- 3 layers
- nCuts = 20
- minimum node size 5 %
- preselection

Associated Zh production

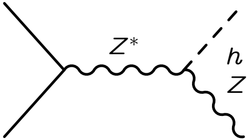
Zh production - signature

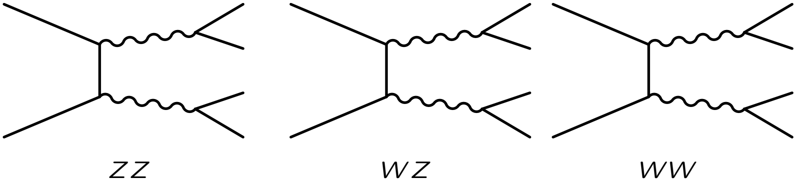
- boosted SFOS leptons $m_{ll} \sim m_Z$
- $Z+$ jets not taken into account (irrelevant at high MET)



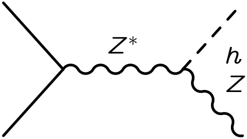


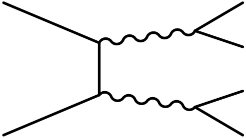
Zh production - backgrounds



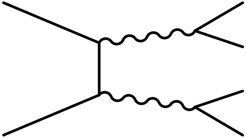


Zh production - backgrounds

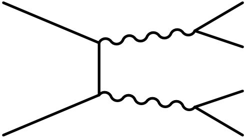




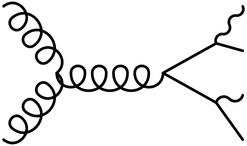
ZZ



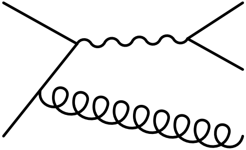
WZ



WW

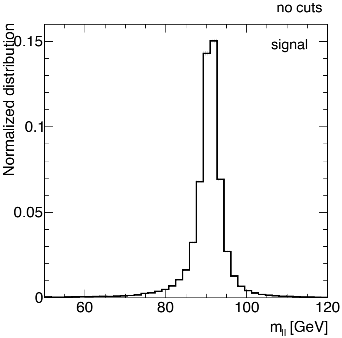


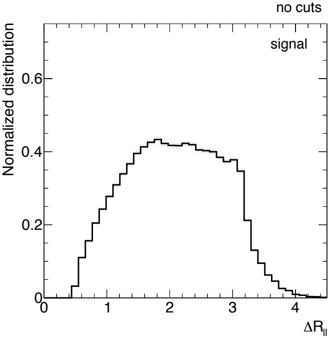
$t\bar{t}$



Z+jets

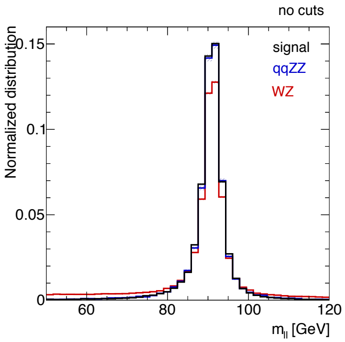
Zh - distributions

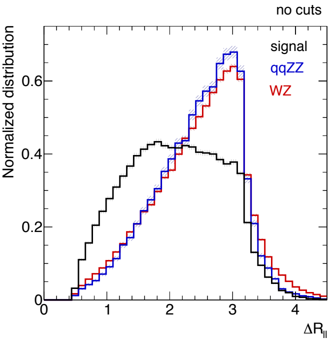




signal: Z boosted

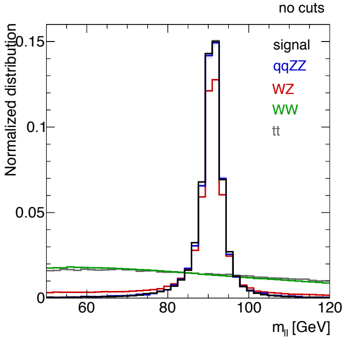
Zh - distributions



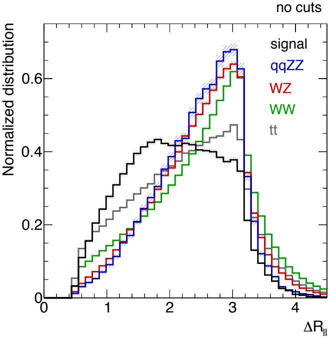


signal: Z boosted

Zh - distributions



non-resonant bkgs flat



signal: Z boosted