Invisible Higgs decays

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RESEARCH SCHOOL

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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

Invisible Higgs decays

- Signatures of invisible Higgs decays
- Understanding the backgrounds to WBF
- BDT analysis
- Conclusion and outlook

Outline

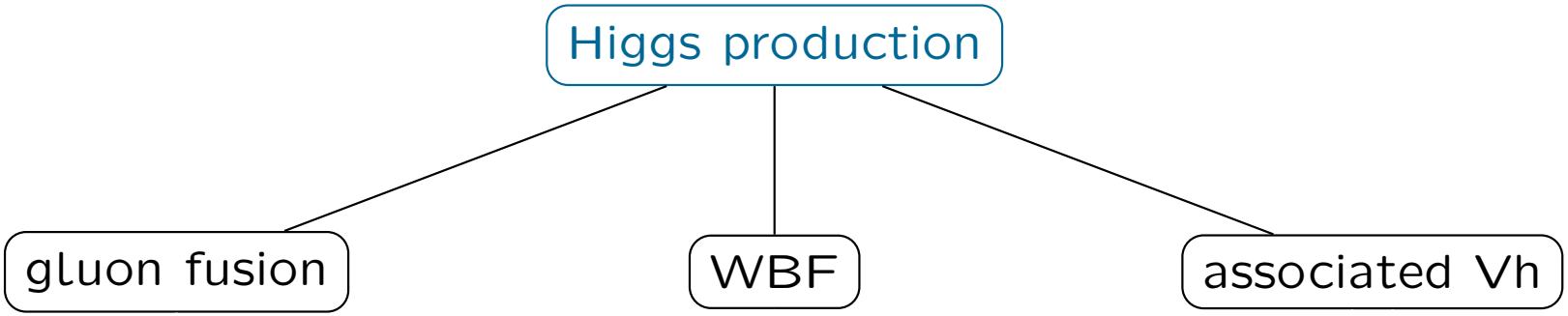
~~Invisible Higgs decays~~

Understanding WBF

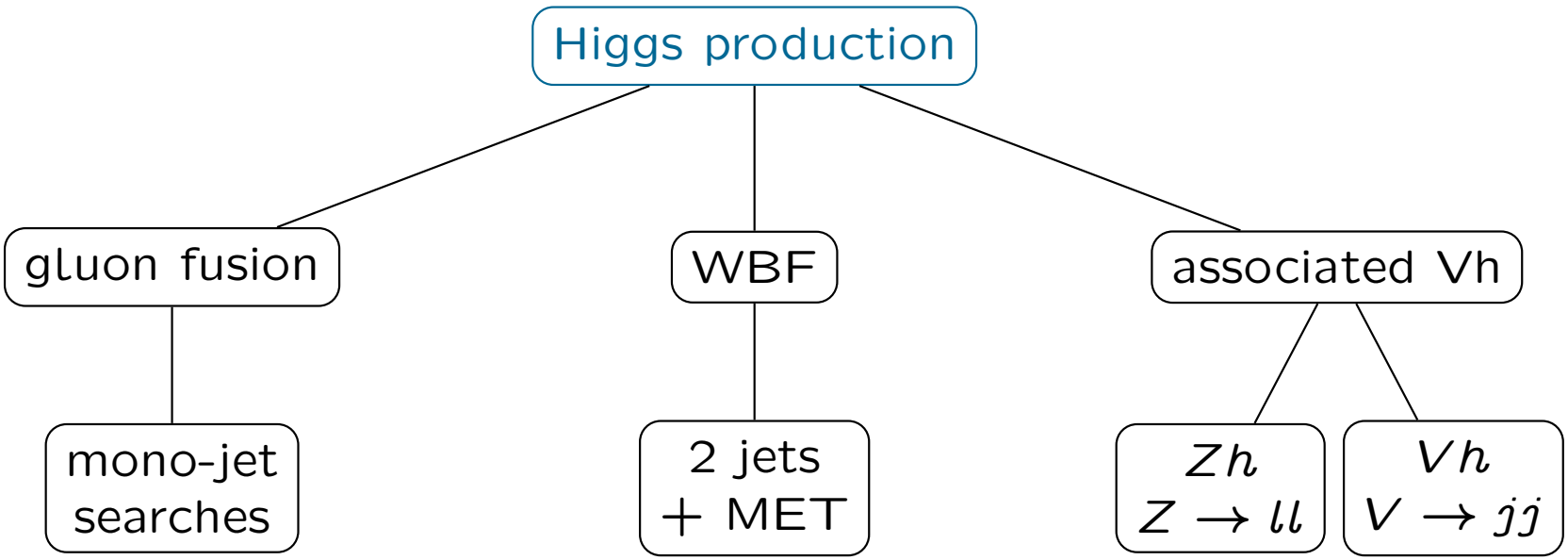
- Signatures of invisible Higgs decays
- Understanding the backgrounds to WBF
- BDT analysis
- Conclusion and **outlook**

Introduction

Invisible Higgs decays



Invisible Higgs decays



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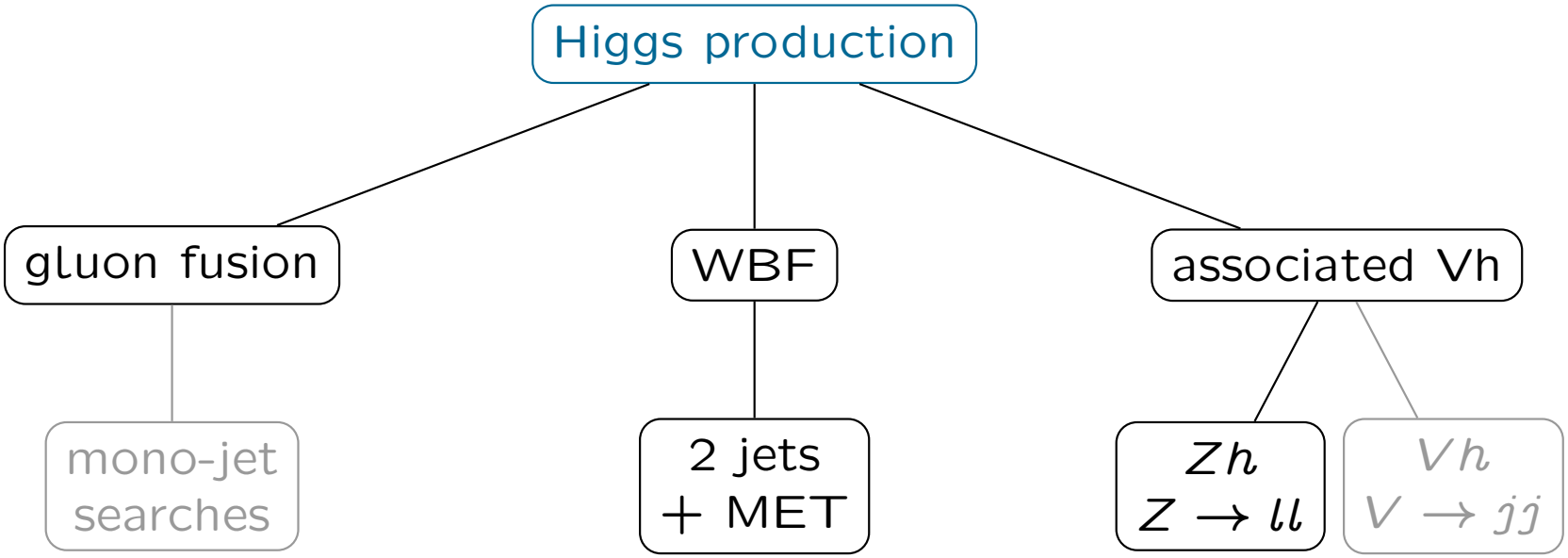


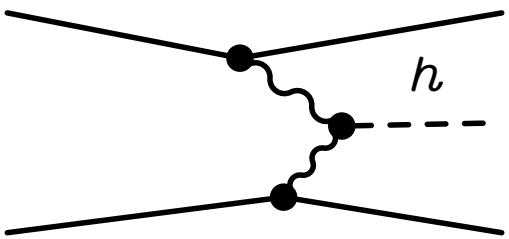
strongest channels [ATLAS: CERN-PH-EP-2015-191]

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



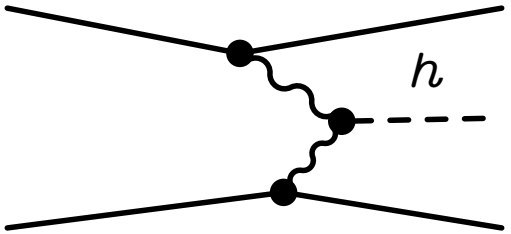
[Eboli, Zeppenfeld, 2000]

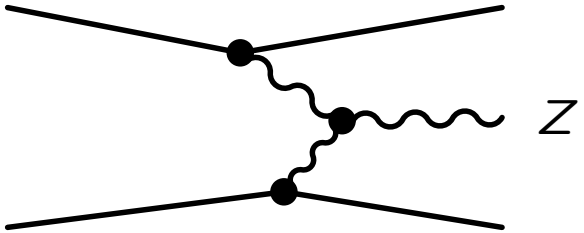
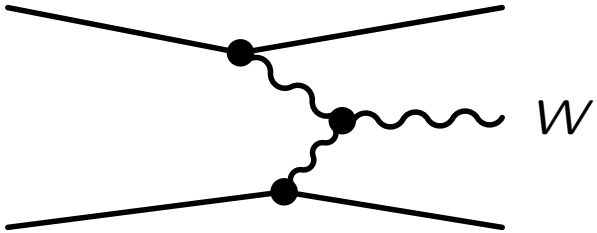
[Bernaciak, Plehn, Schichtel, Tattersall, 2014]

Trigger

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

WBF backgrounds



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

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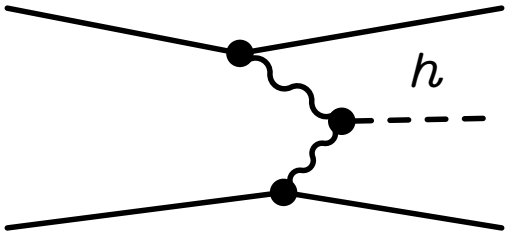

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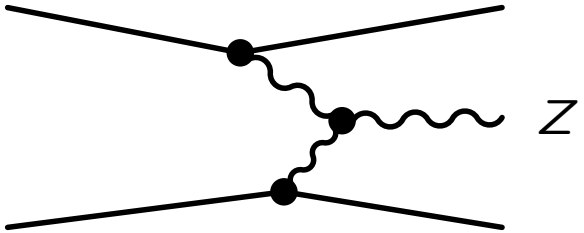	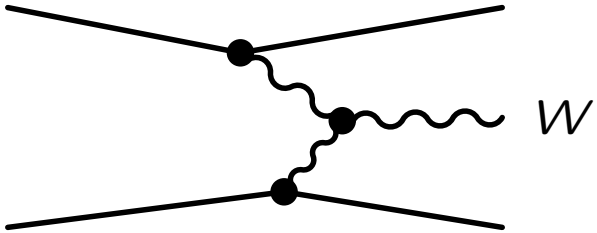
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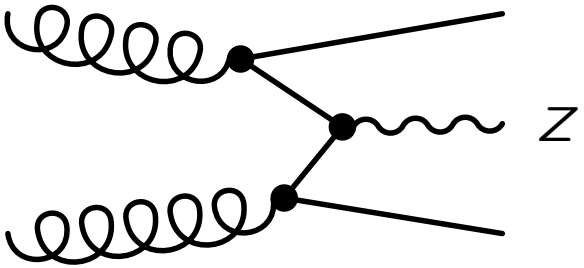	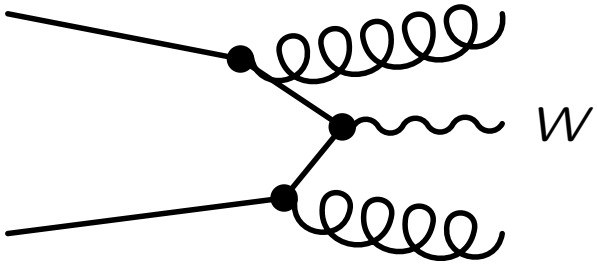
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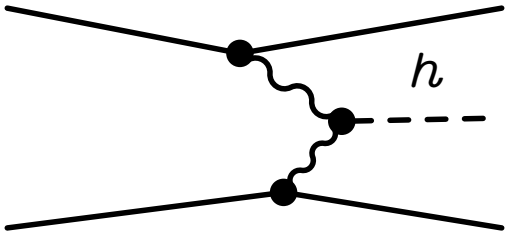

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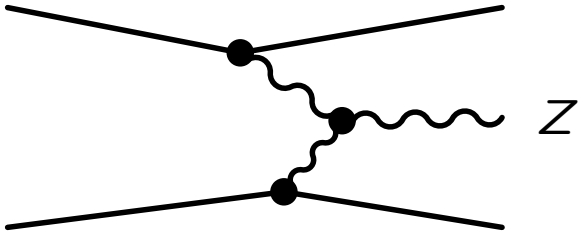	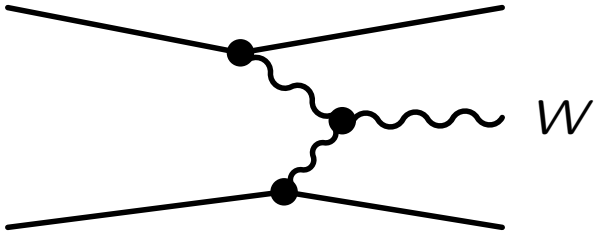
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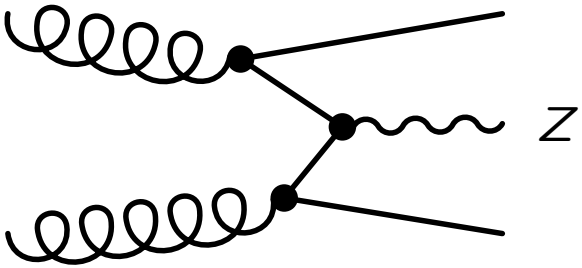	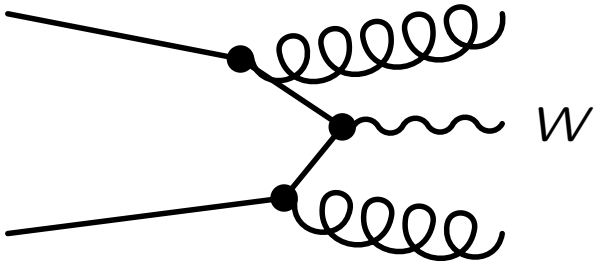
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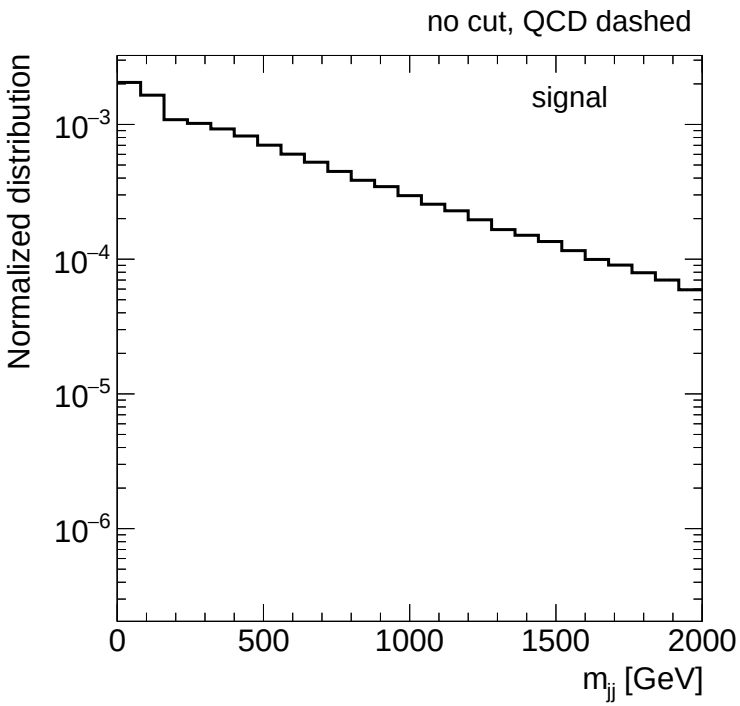
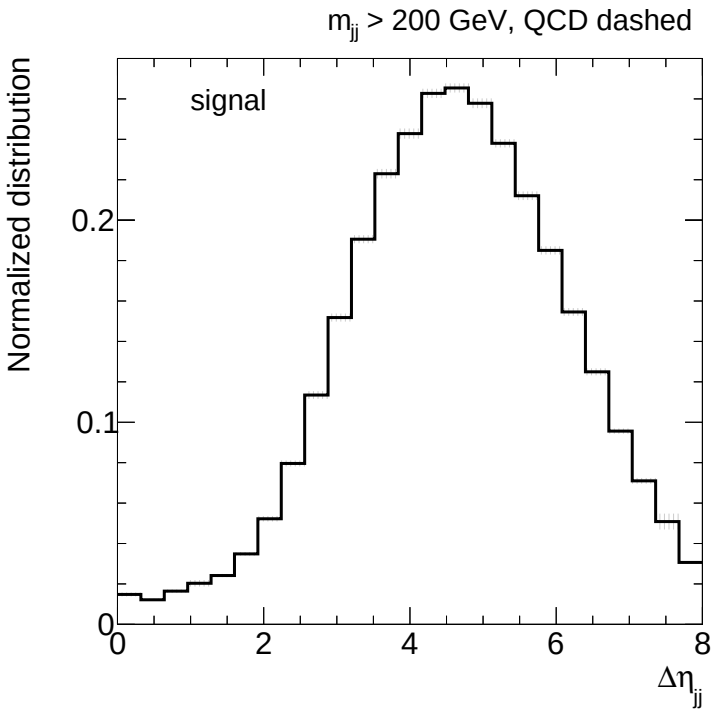
WBF - distributions

merged sample (2 + 3) jets





W and *Z* backgrounds similar in signal region

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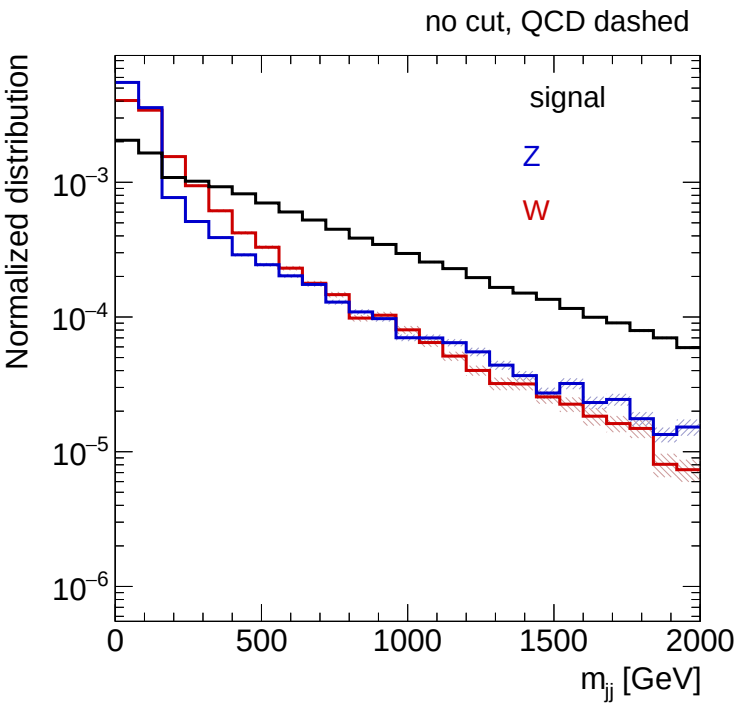

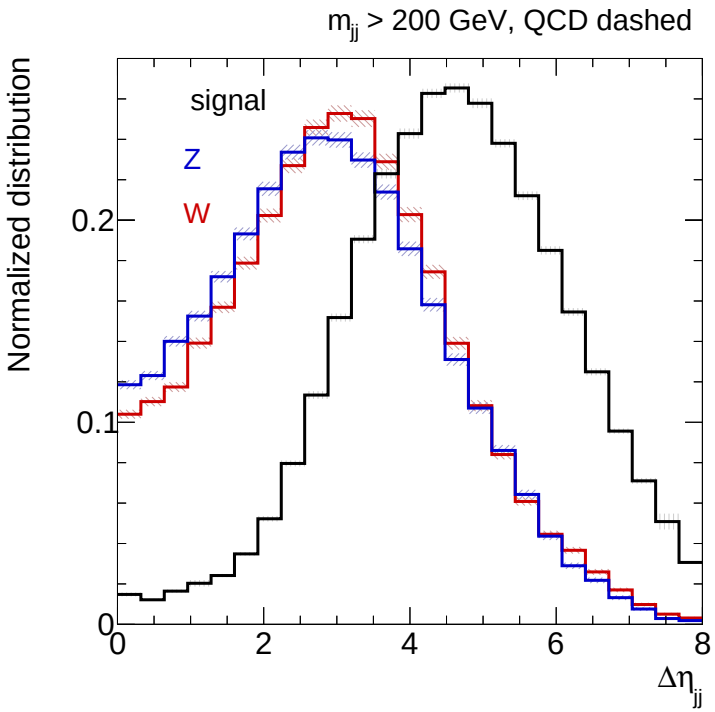

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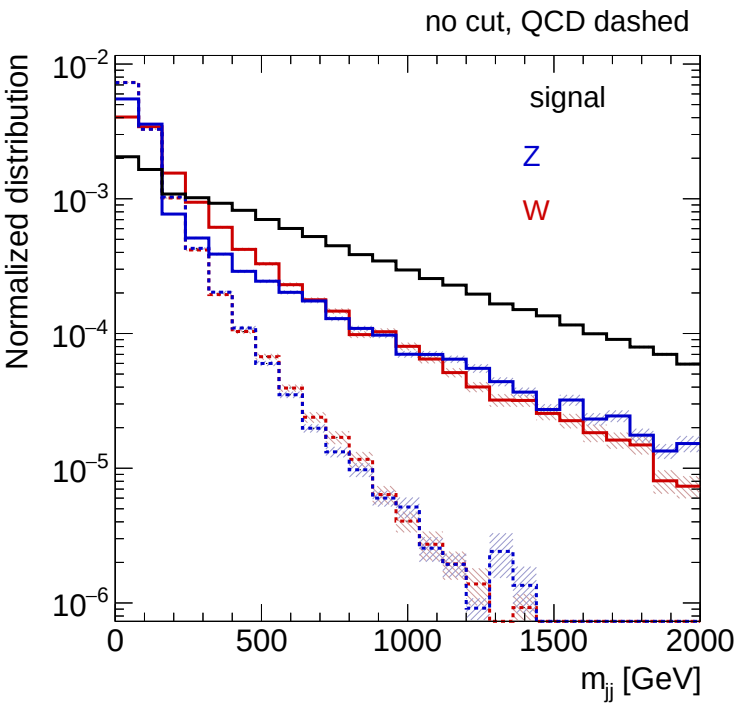

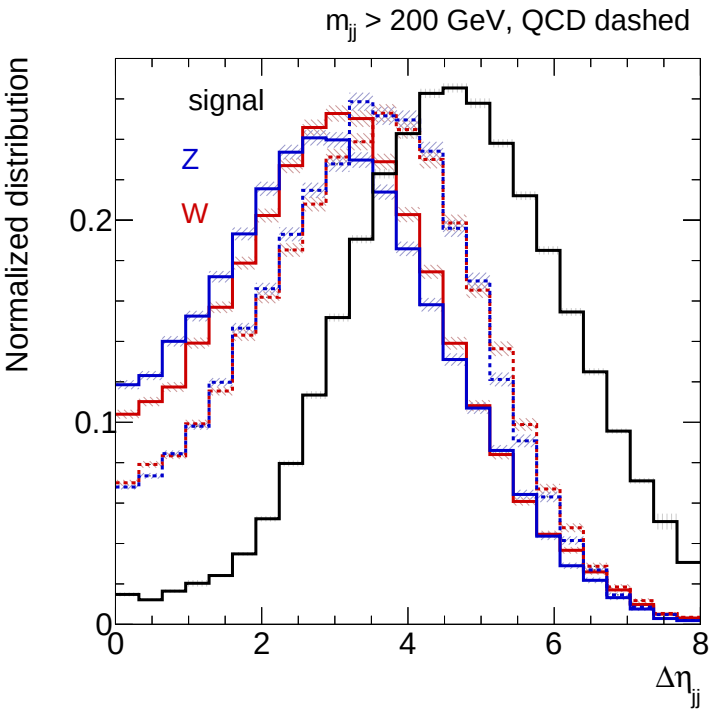

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WBF - distributions (2)

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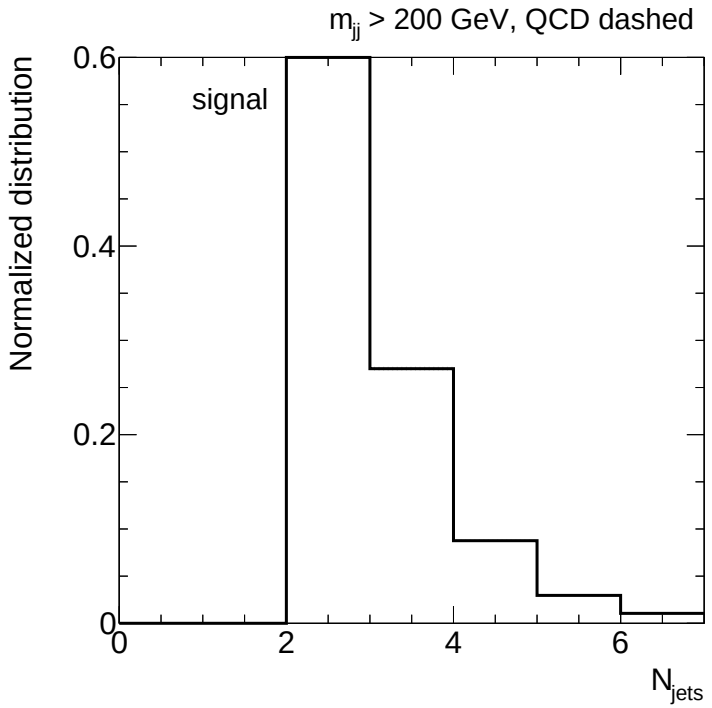

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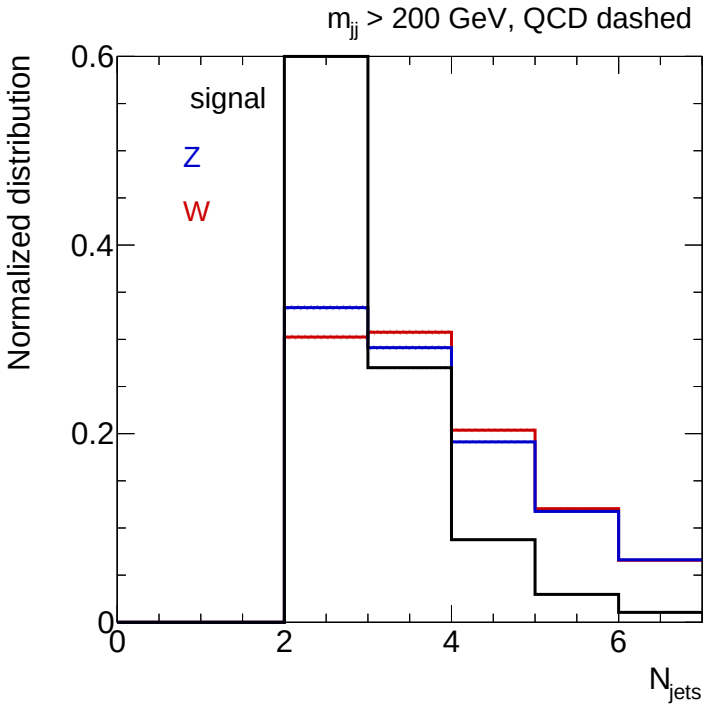
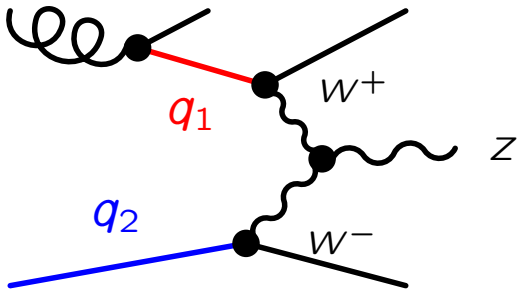


Z bkg: q_1 and q_2 need opposite charges



W and Z backgrounds different for N_{jets} distribution

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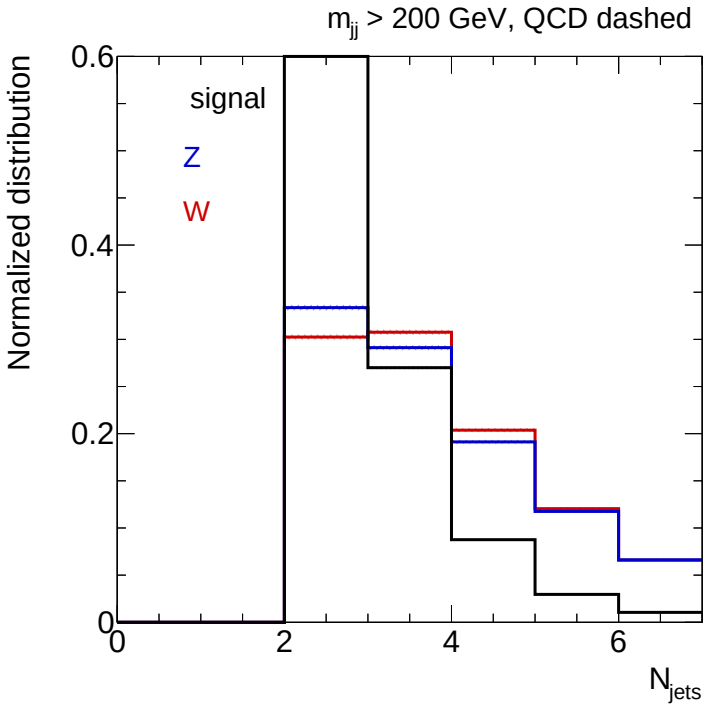

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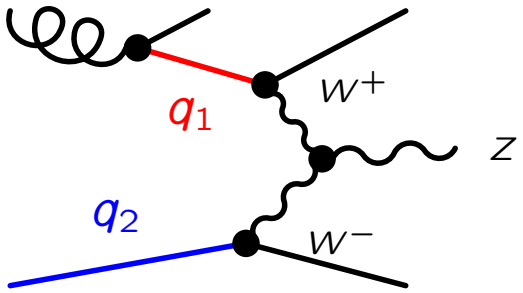

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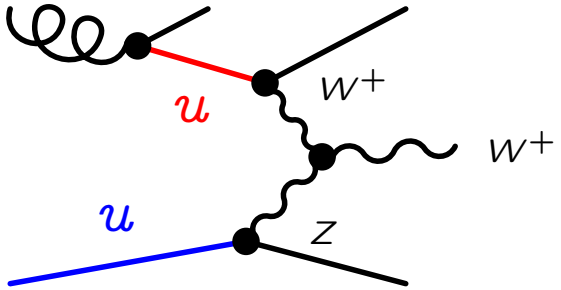

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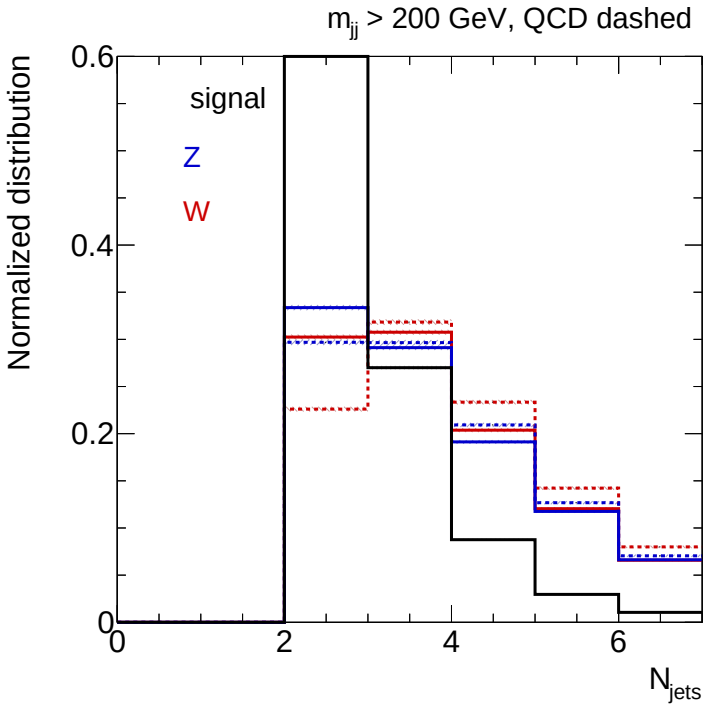

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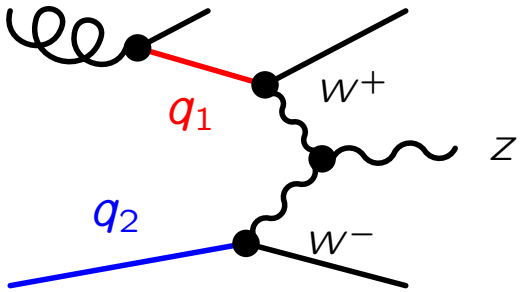

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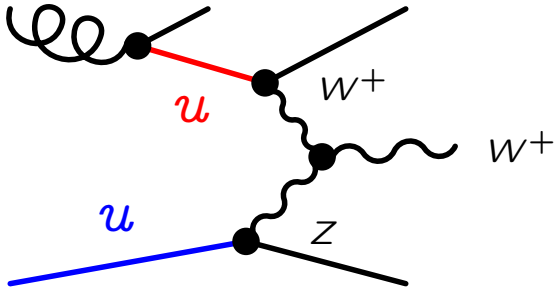

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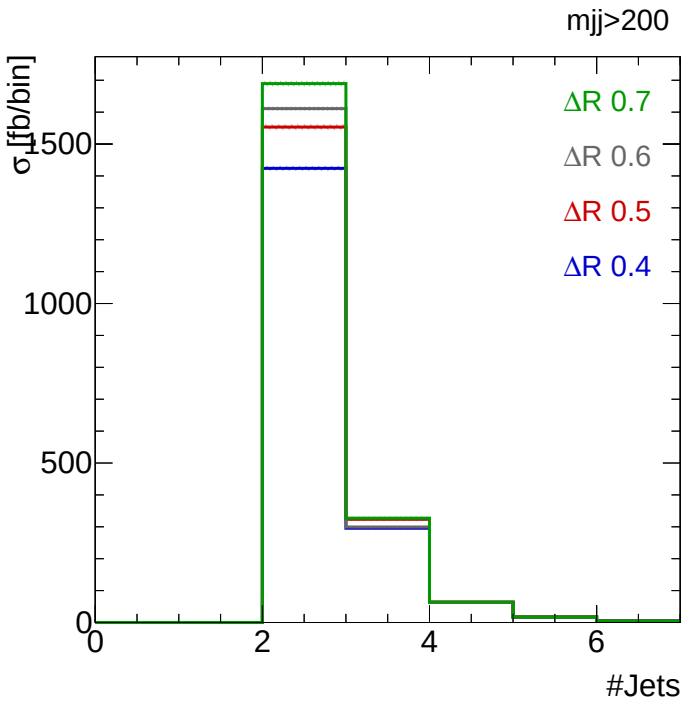
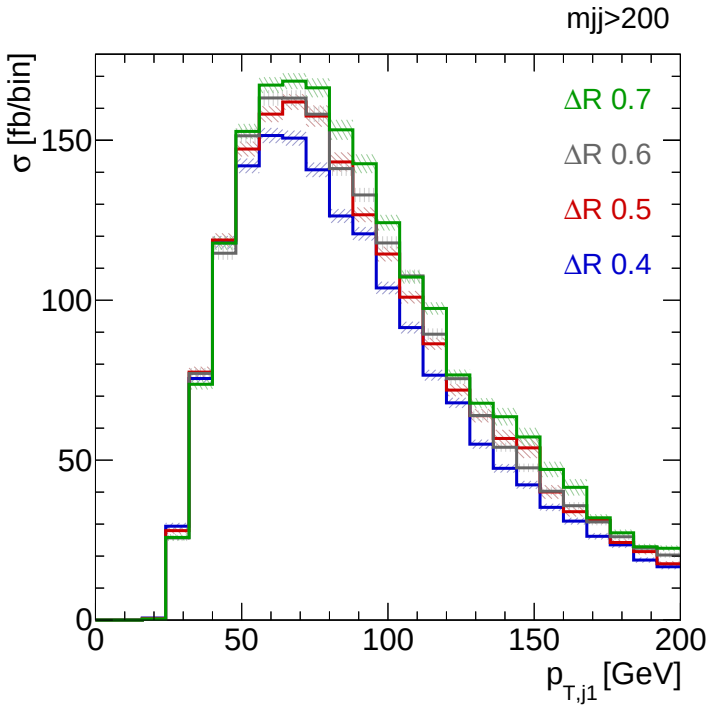
WBF - dependence on jet cone size

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

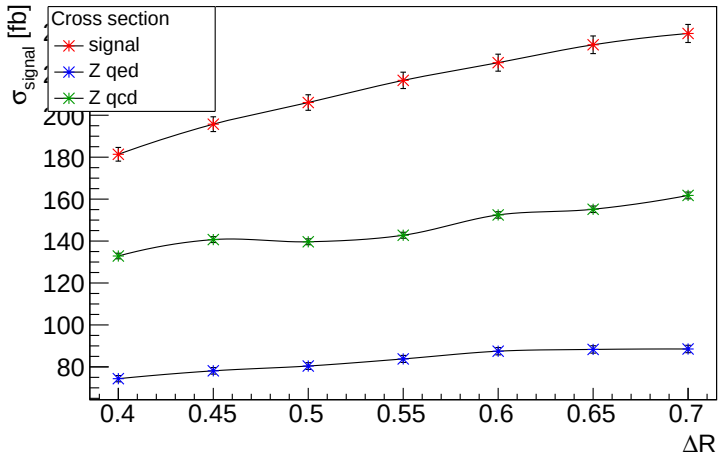
variation of jet cone size in Delphes

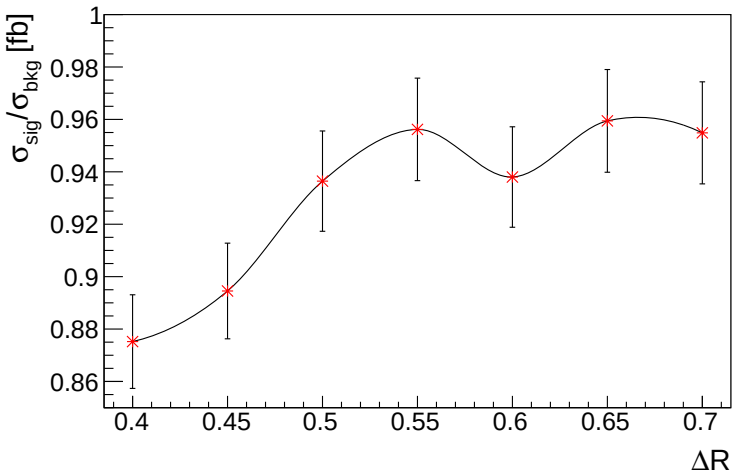




kinematics unchanged

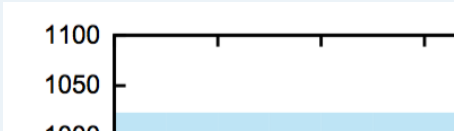
WBF - dependence on jet cone size (2)

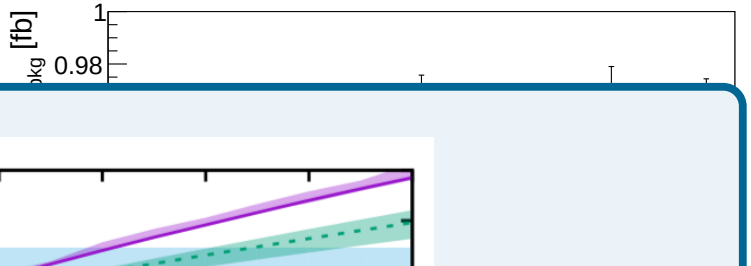




Signal grows stronger with ΔR than the backgrounds

WBF - dependence on jet cone size (2)

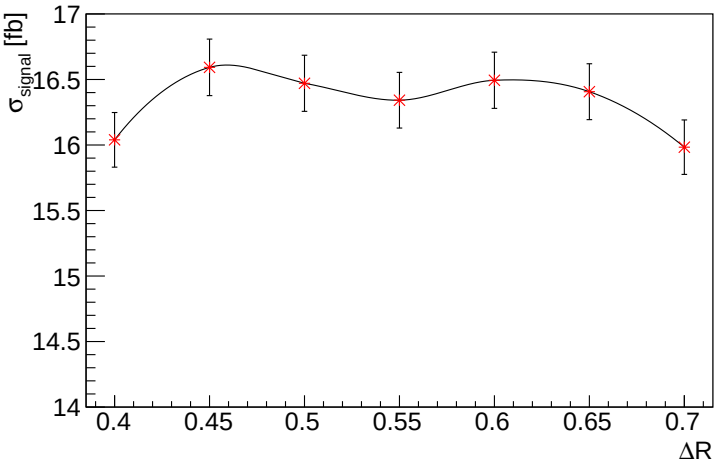




similar results in fixed-order calculation [Rauch, Zeppenfeld, 2017]

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

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 ΔR visible

Quark gluon discrimination

two hardest jets in WBF are quarks

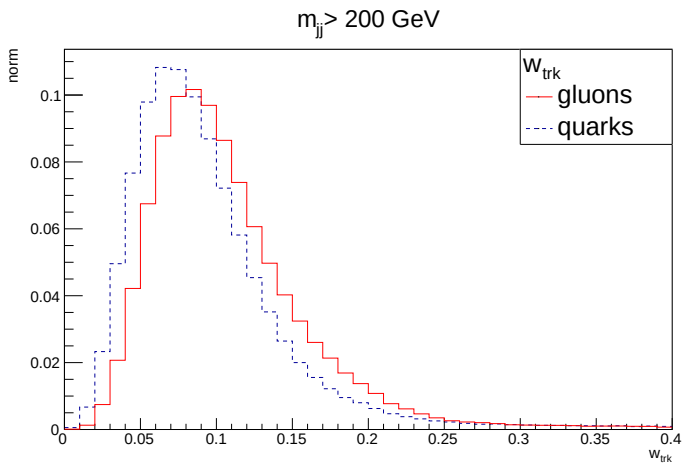
QCD backgrounds can have hard gluon jets

- quarks and gluons have different color and electric charge
- gluons:
  - wider angle soft emissions
  - more splittings in parton evolution
- variables used for discrimination
  - number of tracks
  - fraction of energy carried by largest energy constituent
  - p_T weighted width of jet from tracks w_{trk}
  - ...

$$w_{\text{trk}} = \frac{\sum_{\text{trk}\in\text{jet}} p_{T,\text{trk}} \Delta R_{\text{trk,jet}}}{\sum_{\text{trk}\in\text{jet}} p_{T,\text{trk}}}$$

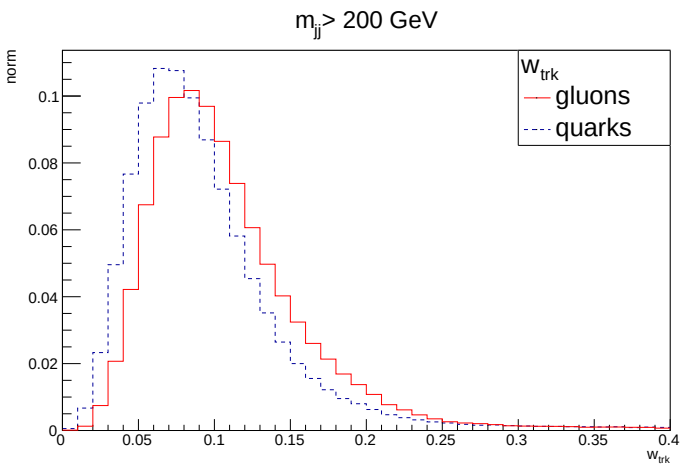
[ATLAS-CONF-2016-034]

Quark gluon discrimination (2)



Z QCD bkg (2jet): pure gluon and and pure quark final states

Quark gluon discrimination (2)



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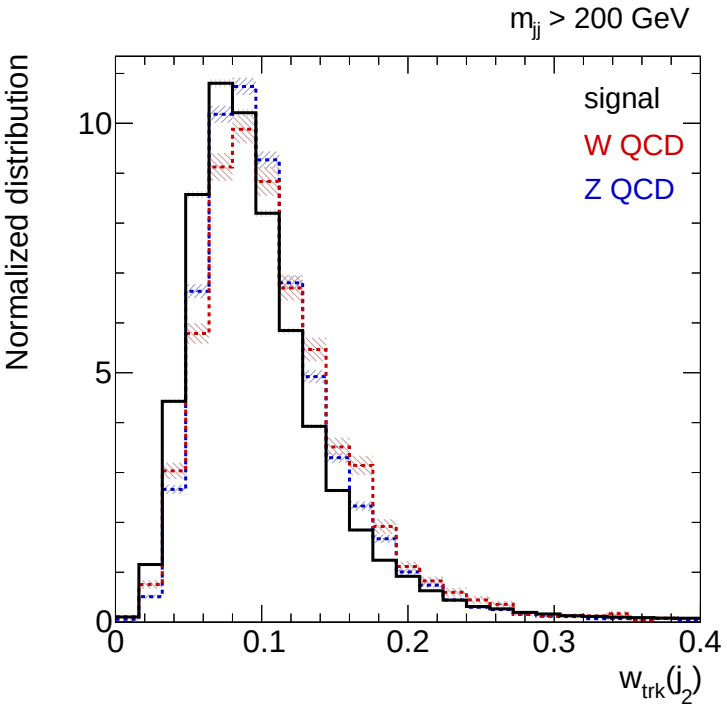


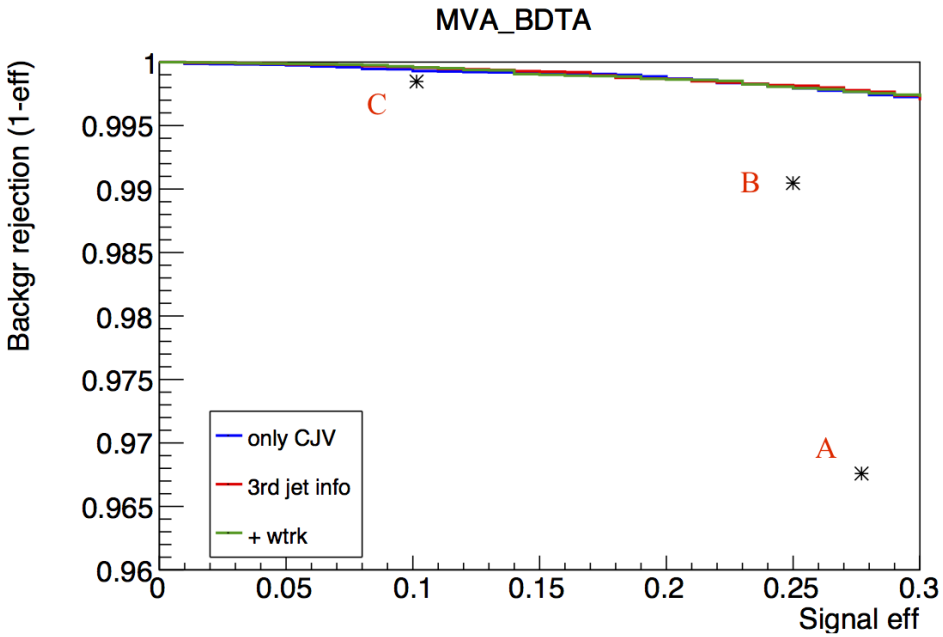
(2 + 3) jets merged, WBF signal and QCD backgrounds

BDT analysis

BDT - WBF work in progress

Observable	Requirement
Number of Leptons	$= 0$
Number of Jets	≥ 2
$p_{T,1}, p_{T,2}$	> 40 GeV
$\lvert\Delta\eta_{1,2}\rvert$	> 4.4
$\eta_1 \cdot \eta_2$	< 0
E_T^{miss}	> 100 GeV
$m_{1,2}$ A	> 1.2 TeV
$\eta_j \notin (\eta_{min}, \eta_{max})$ if $p_{T,j}$ B	> 20 GeV
$\lvert\Delta\phi_{1,2}\rvert$ C	< 1

[Éboli, Zeppenfeld, 2000]



jet cone size $\Delta R = 0.4$

preselection: $p_{T,j} > 30\,\text{GeV}$, $m_{jj} > 500\,\text{GeV}$, $E_T^{\text{miss}} > 90\,\text{GeV}$

variables used: p_T, η, ϕ of leading two jets,

E_T^{miss}, $\phi(E_T^{\text{miss}})$, m_{jj}, N_{leptons}, N_{jets}

plus:

CJV ($p_T > 20\,\text{GeV}$) or p_T, η, ϕ of third jet or in addition w_{trk} info

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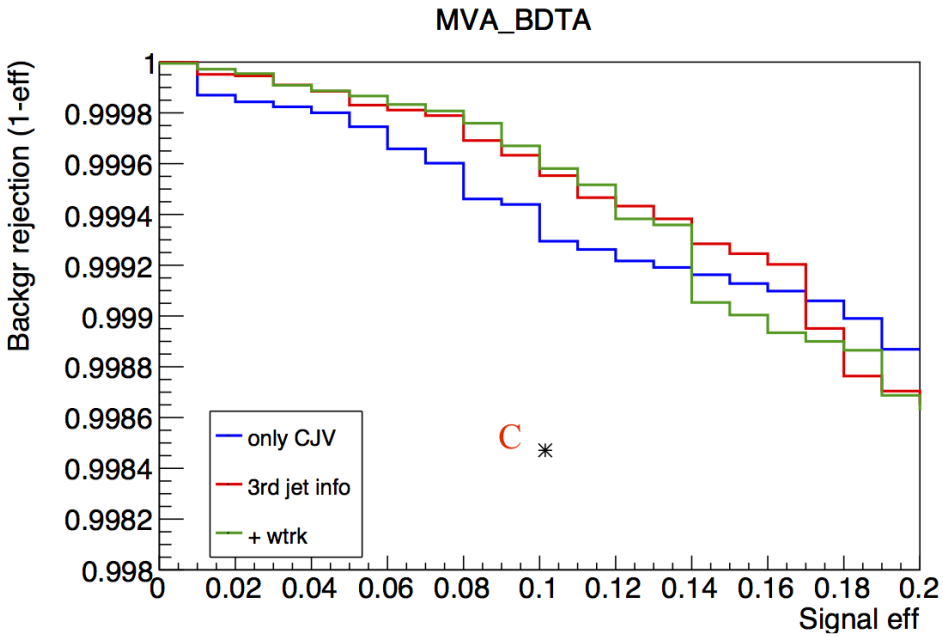

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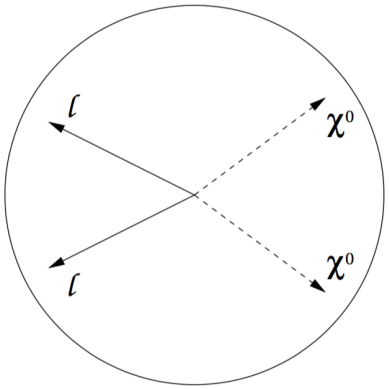
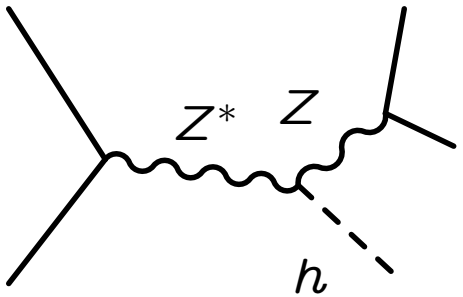
Associated Zh production

Zh production - signature

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





Outlook

Conclusion

WBF

- backgrounds: different behavior for N_{jets}
- signal cross section growing with ΔR
- use quark gluon discrimination variable w_{trk}
- profits from use of BDTs

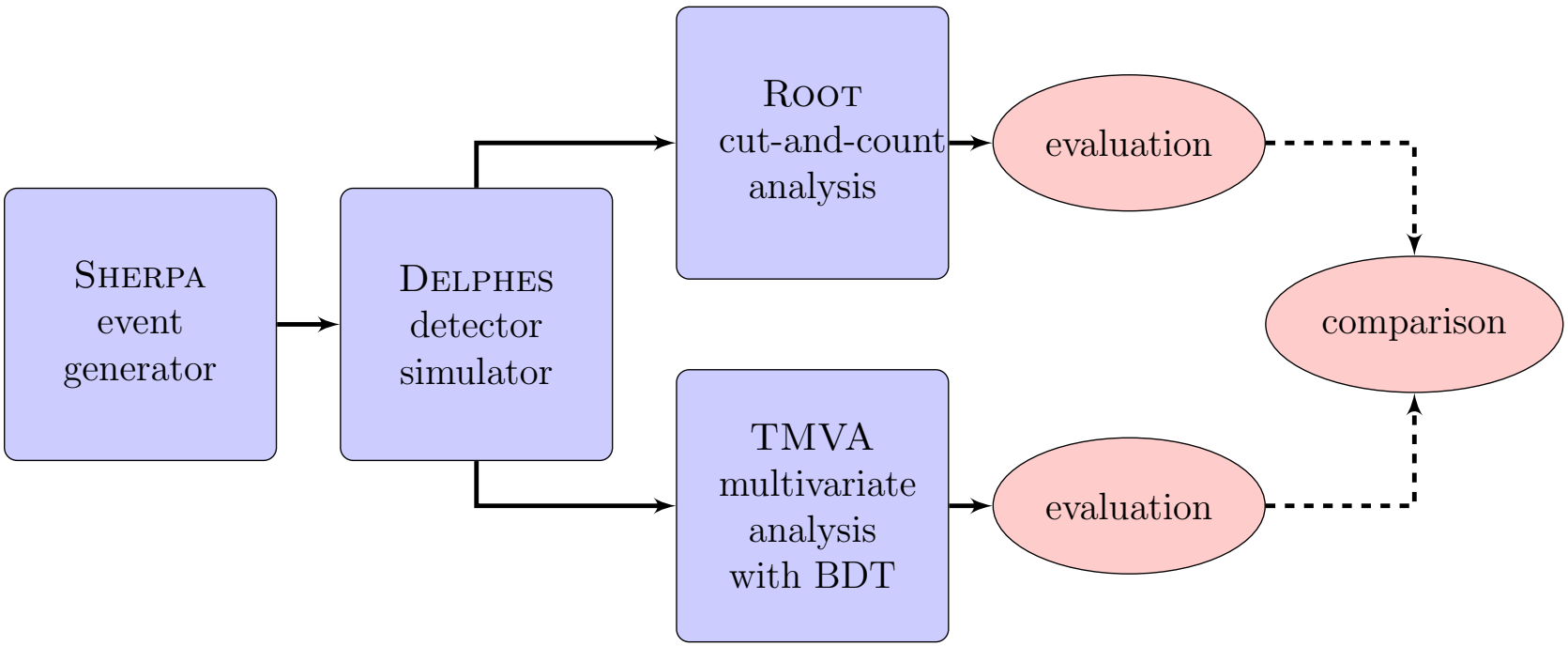
Outlook

- WBF still most sensitive channel after trigger update?

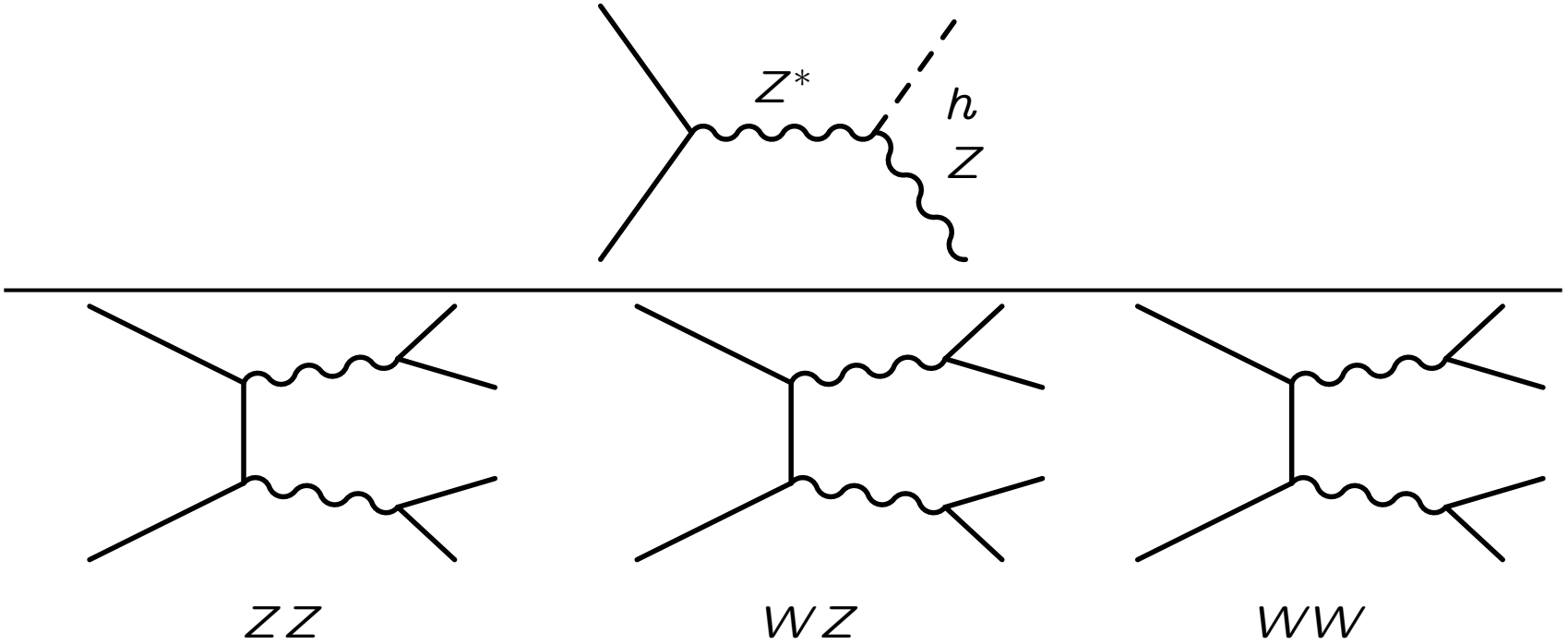
Thank you for your attention!

Backup

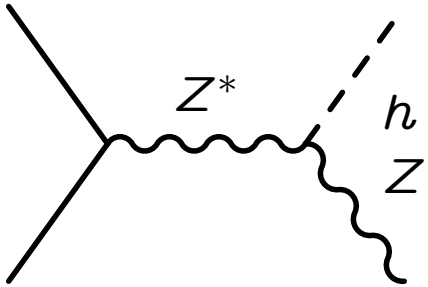
Tool chain

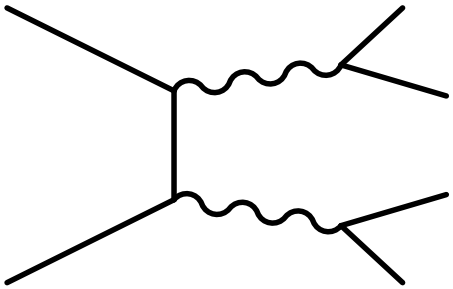

Sherpa
event
generator
Delphes
detector
simulator
Root
cut-and-count
analysis
TMVA
multivariate
analysis
with BDT
evaluation
evaluation
comparison

Zh production - backgrounds

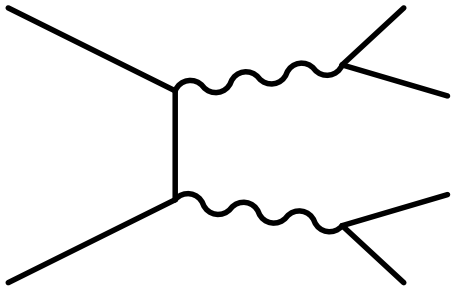


Zh production - backgrounds

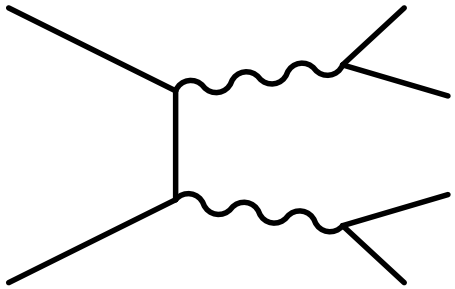




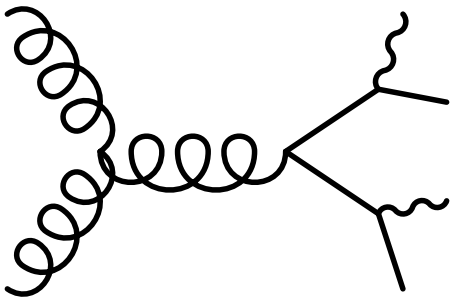
ZZ



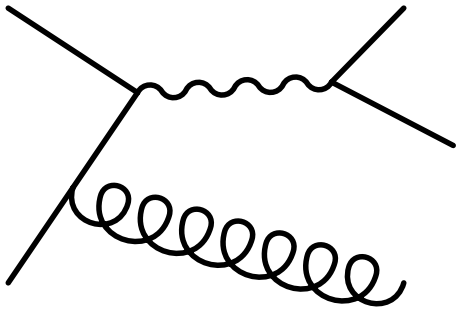
WZ



WW

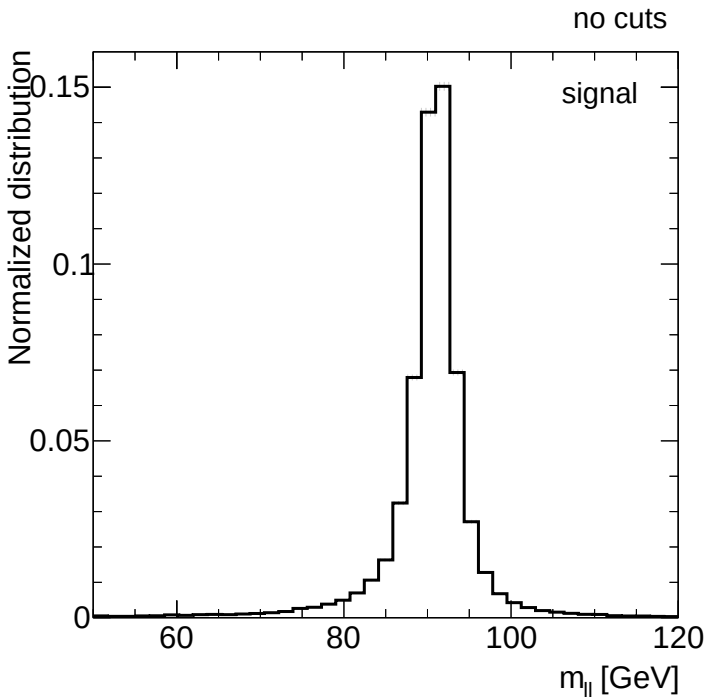


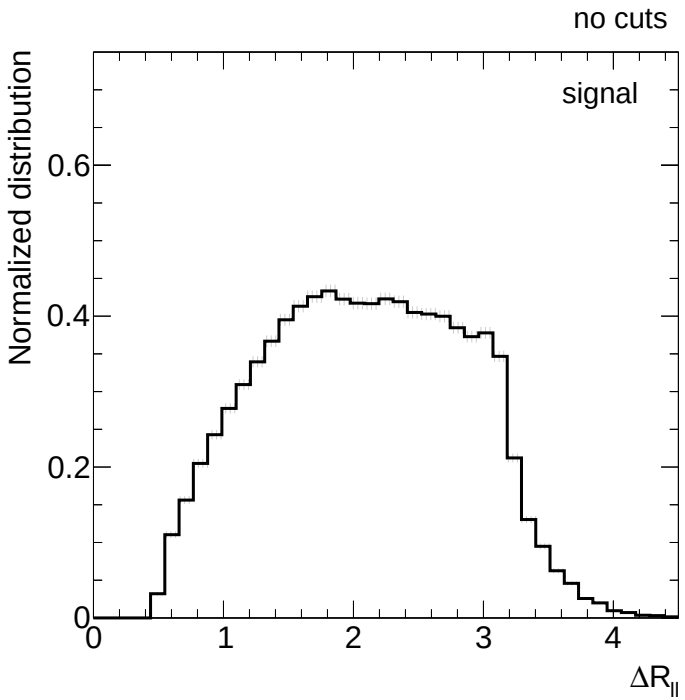
$t\bar{t}$



Z+jets

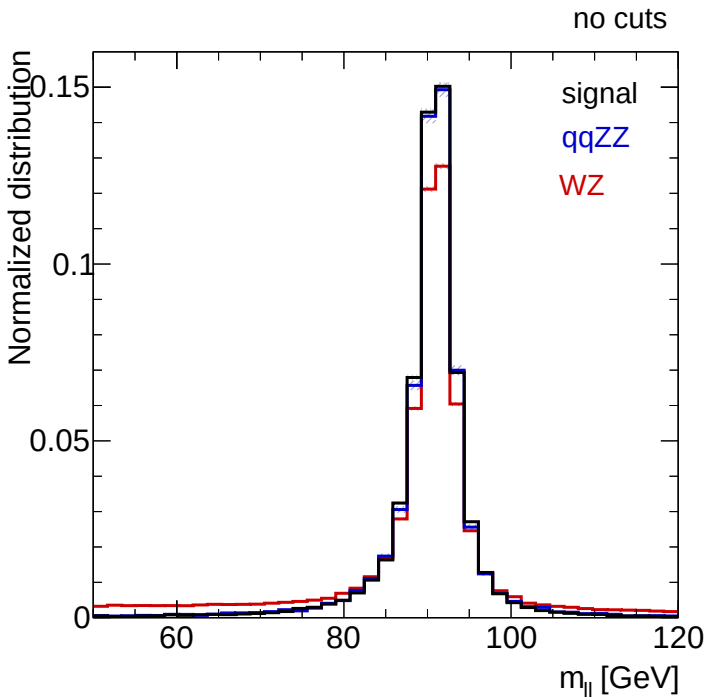
Zh - distributions

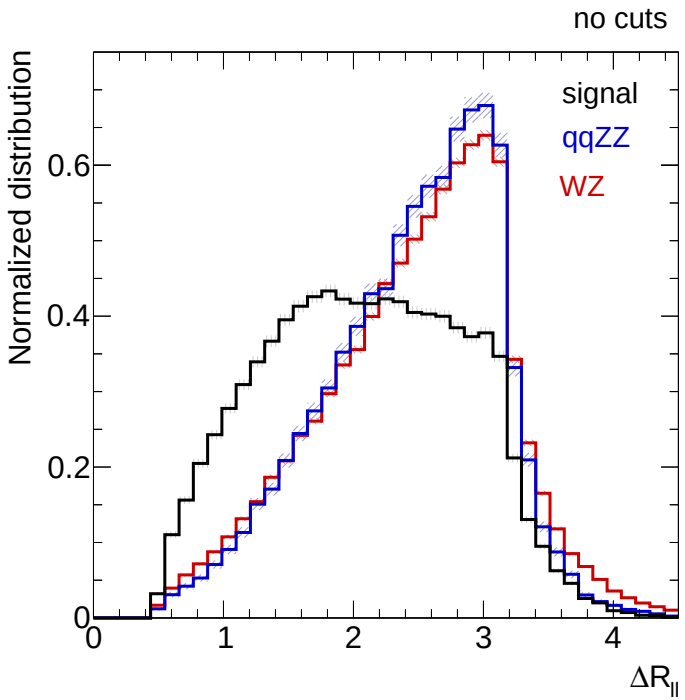




signal: Z boosted

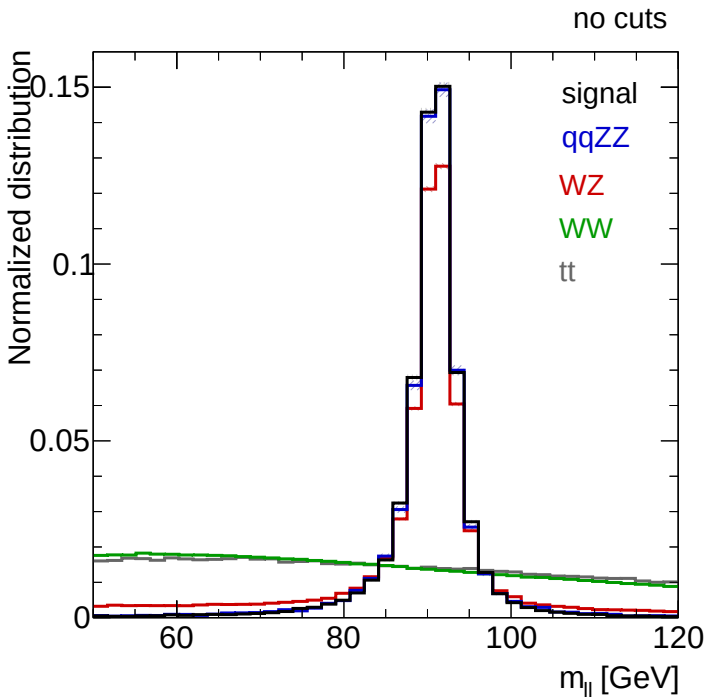
Zh - distributions



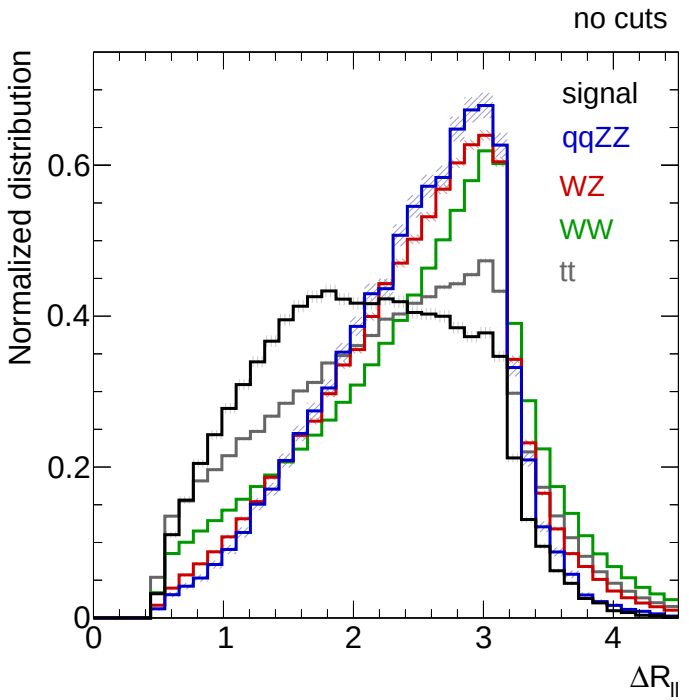


signal: Z boosted

Zh - distributions



non-resonant bkgs flat



signal: Z boosted

BDT settings

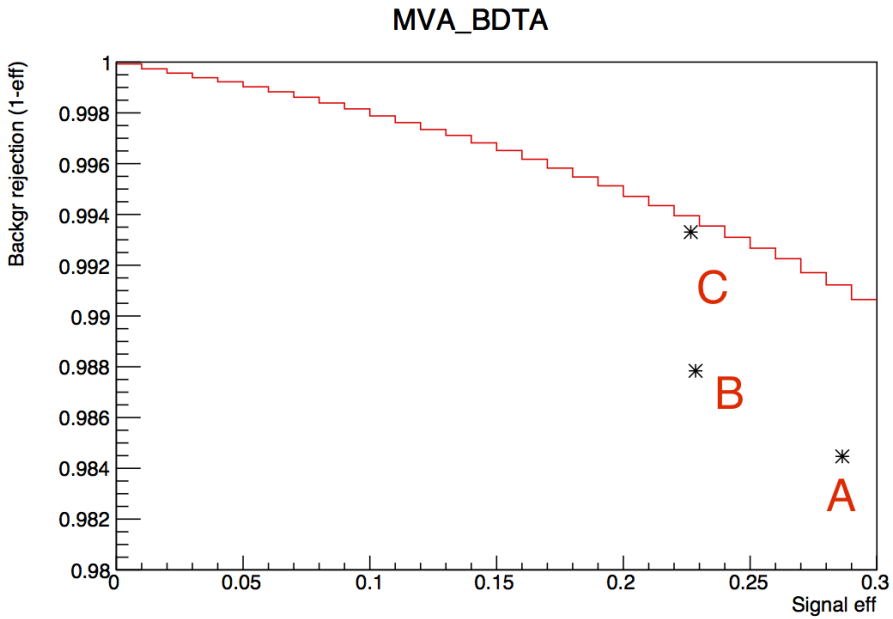
Use TMVA with

- 400 trees
- 3 layers
- nCuts = 20
- minimum node size of 1000 events
- preselection

BDT - Zh work in progress

Observable	Requirement
Number of SFOS Leptons	$= 2$
$p_{\mathrm{T},1}$	> 30 GeV
$p_{\mathrm{T},2}$	> 20 GeV
$\lvert m_{1,2} - m_Z \rvert$	< 15 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 120 GeV
$\Delta R_{1,2}$ A	< 1.8
$\lvert \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{1,2}) \rvert$	> 2.7
$\lvert p_{\mathrm{T}}^{\mathrm{miss,jet}} - p_{\mathrm{T}}^{1,2} \rvert / p_{\mathrm{T}}^{1,2}$	< 0.2
$\lvert \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}) \rvert$	< 0.7
$p_{\mathrm{T}}^{1,2}/m_T$ B	< 0.9
B-tagged Jets C	veto

[ATLAS-CONF-2016-056]



variables used: p_T, η, ϕ of two leptons, E_T^{miss}, $\phi(E_T^{\mathrm{miss}})$, m_{ll}, N_{bjets}

preselection: SFOS leptons with $p_T > 10\,\mathrm{GeV}$

cuts in plot: $\Delta R_{ll} < 1.8$, $\frac{p_T^{ll}}{m_T} < 0.9$, b veto

total signal cross section: $\sigma = 59.1$ fb

no large improvement by BDT analysis