Tagging Jets in Invisible Higgs Searches

[1712.03973]

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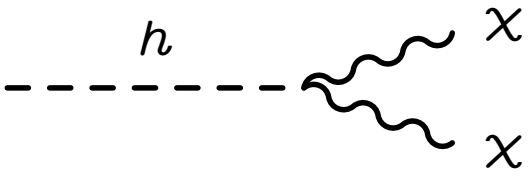
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

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
- Comparison to associated Zh production
- Conclusion and discussion

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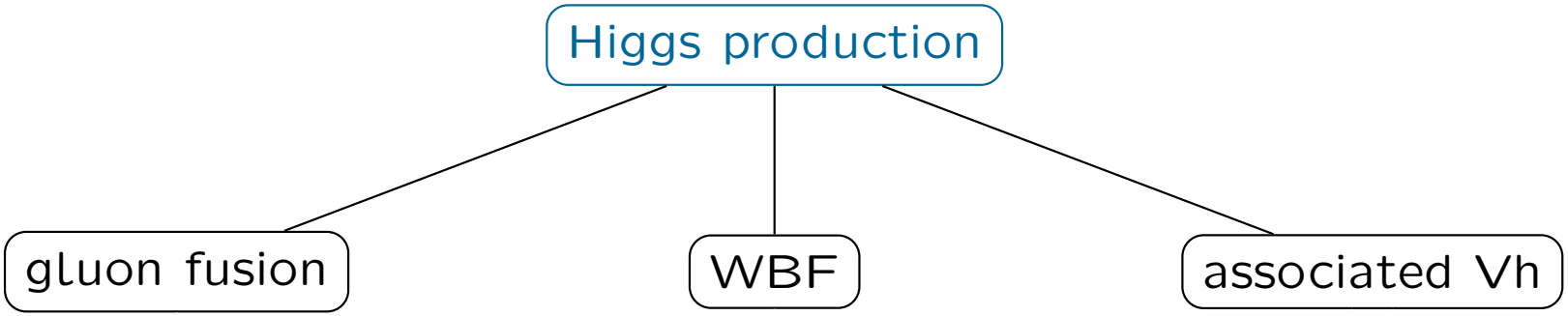
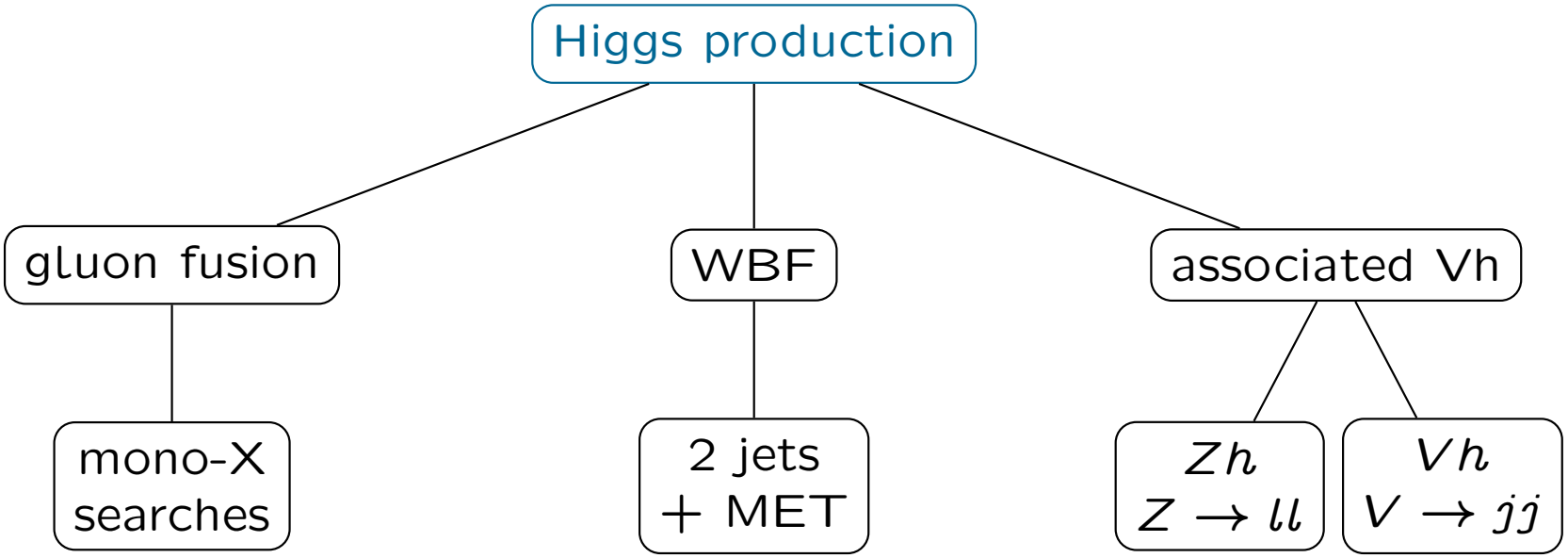
Introduction

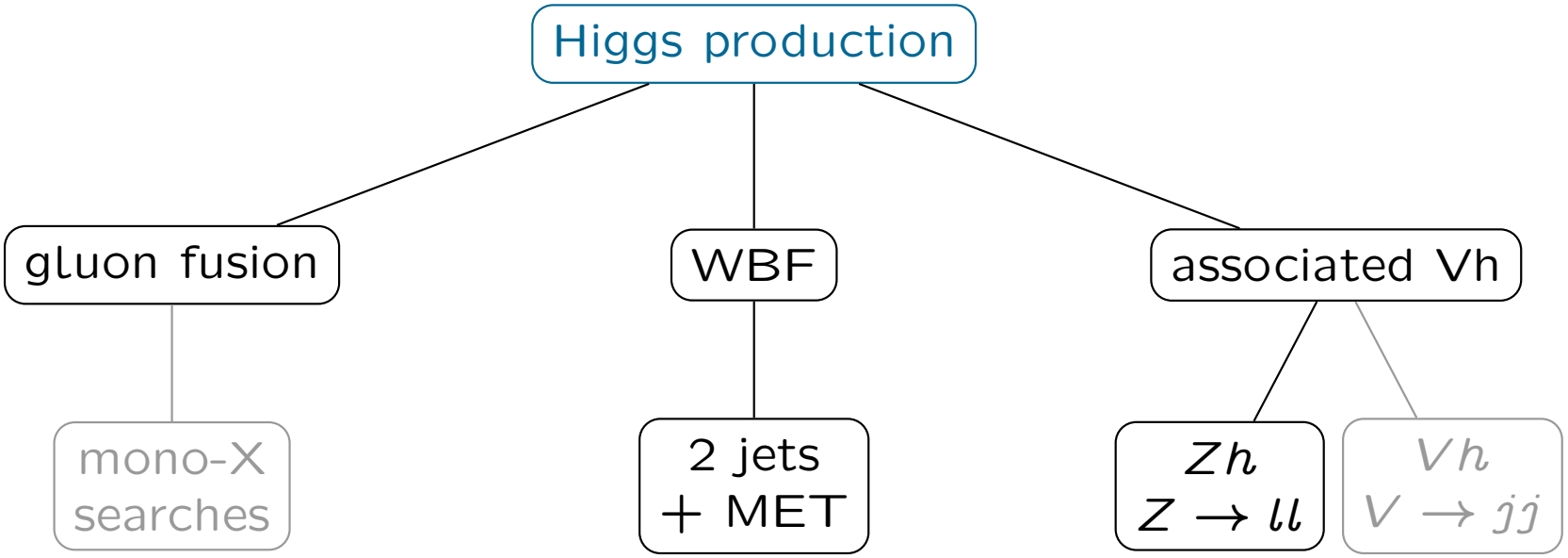
Invisible Higgs decays



Invisible Higgs decays



Invisible Higgs decays



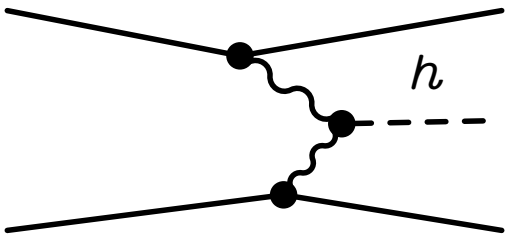
strongest channels [ATLAS: CERN-PH-EP-2015-191]

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



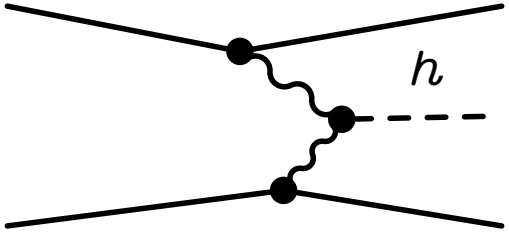
[Eboli, Zeppenfeld, 2000]

[Bernaciak, Plehn, Schichtel, Tattersall, 2014]

Trigger

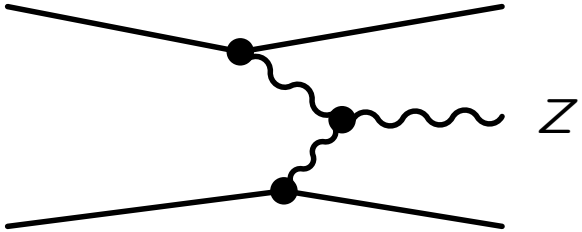
- CMS-HIG-16-016:
  - $p_{T,j} > 40\,\text{GeV}$
  - $m_{jj} > 600\,\text{GeV}$
  - $E_T^{\text{miss}} > 140\,\text{GeV}$
  - $\Delta\eta_{jj} > 3.5$
  - $\eta_{j1} * \eta_{j2} < 0$
- outlook for HL-LHC
  - $E_T^{\text{miss}} > 200\,\text{GeV}$?
  - . . . ?
  - How dangerous is this?

WBF backgrounds

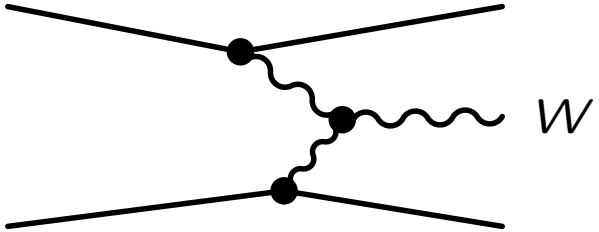


$Z \to \nu\nu$

$W \to (l)\nu$



Z EW



W EW

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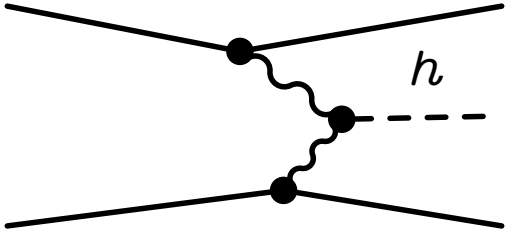

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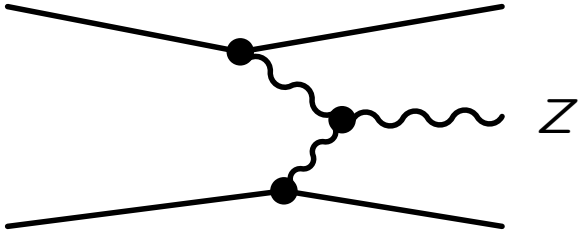	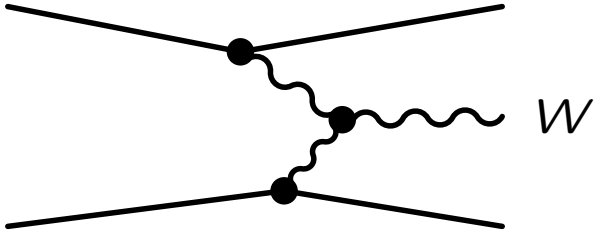
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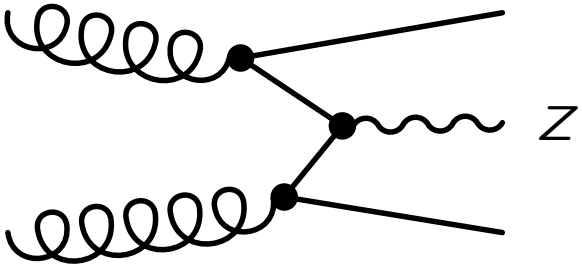	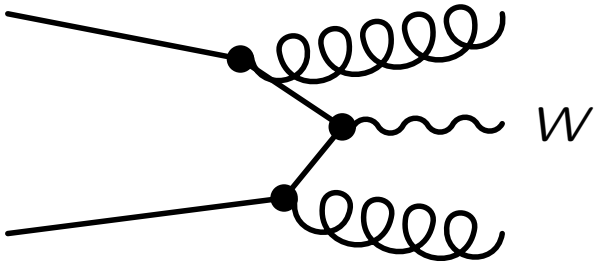
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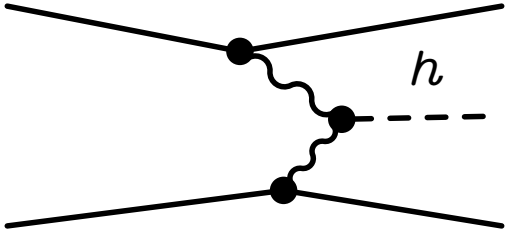

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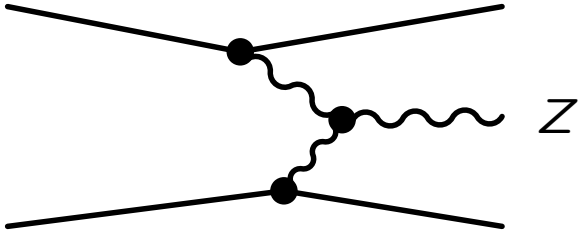	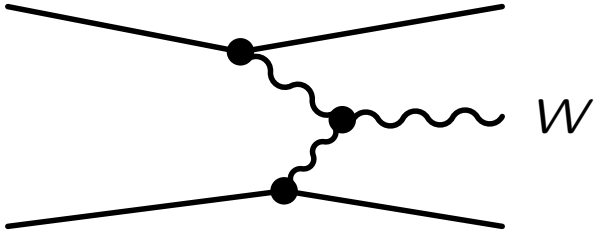
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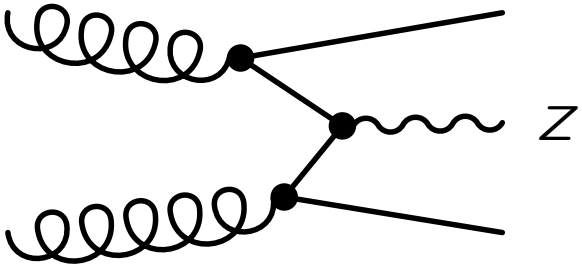	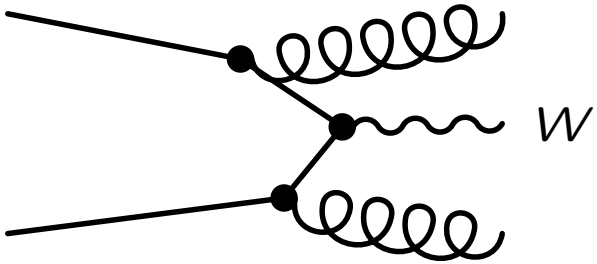
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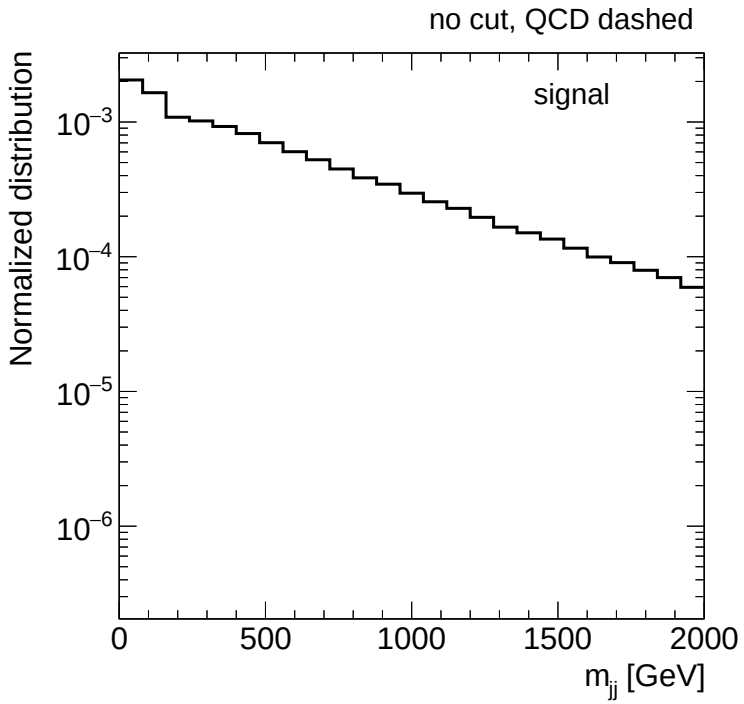
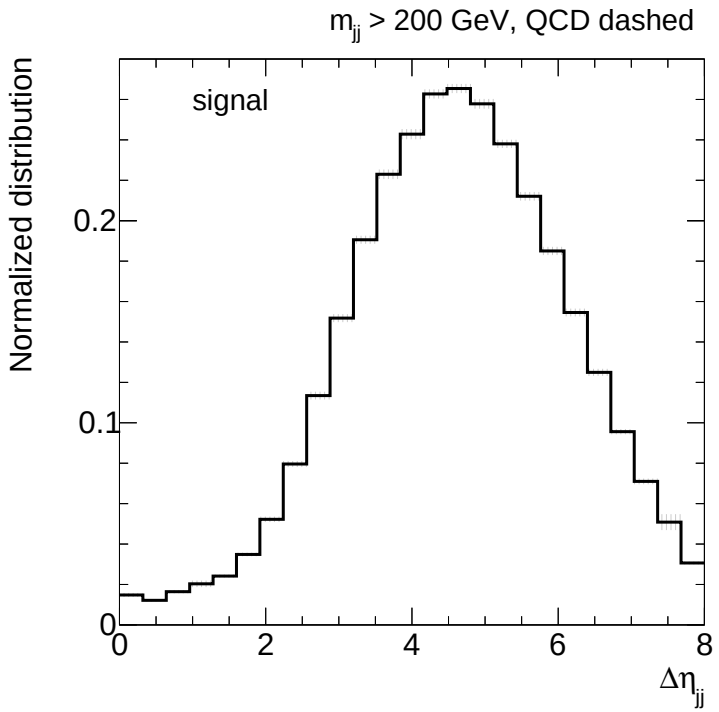
WBF distributions

Sherpa + Delphes,

merged sample (2 + 3) jets





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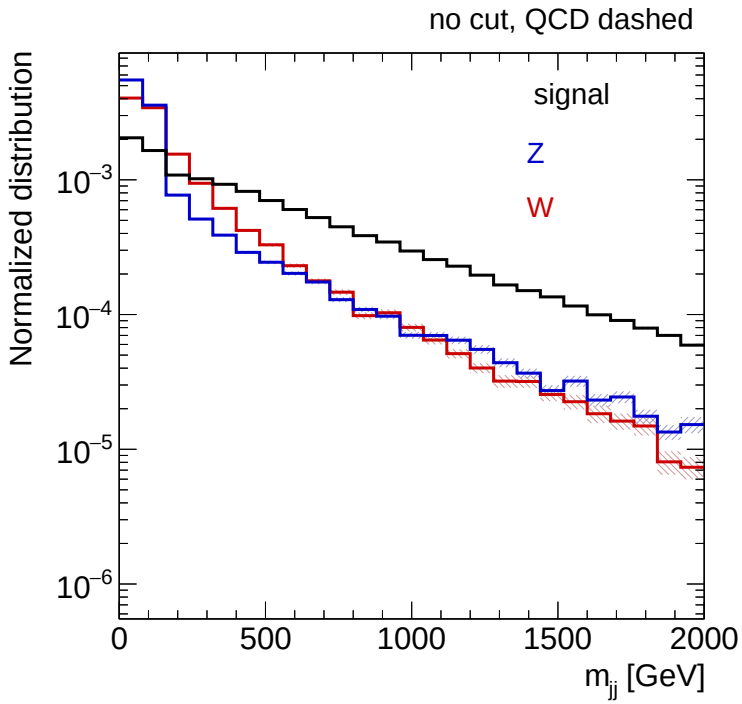

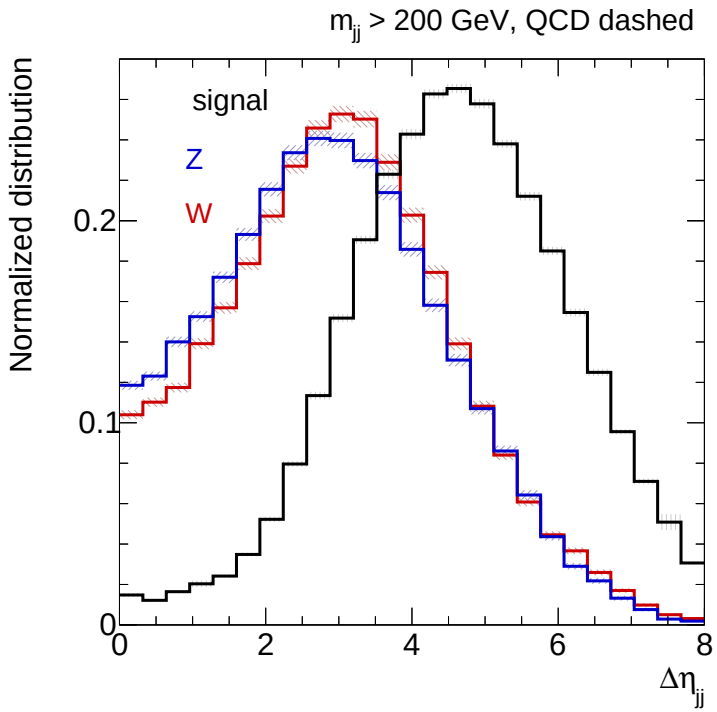

W and Z backgrounds similar in signal region

WBF distributions

Sherpa + Delphes,

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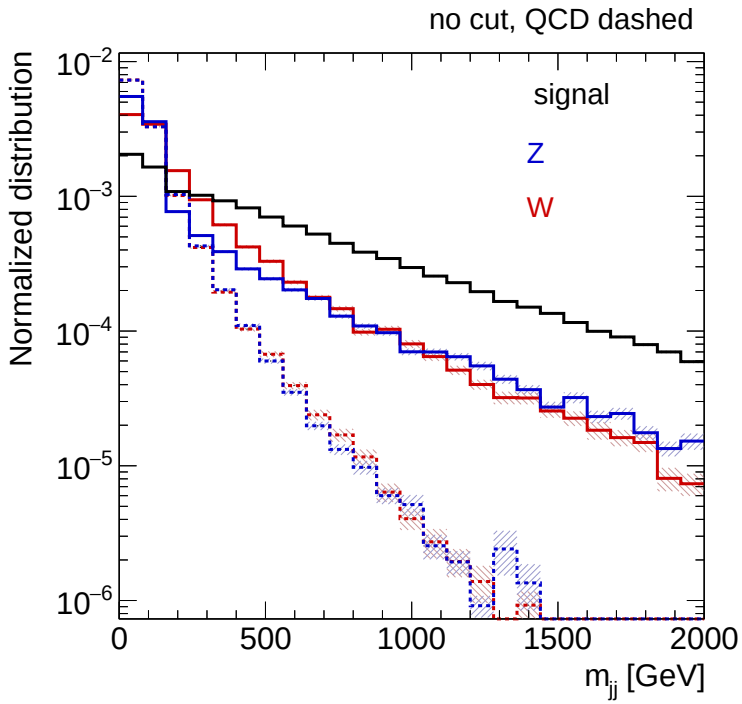
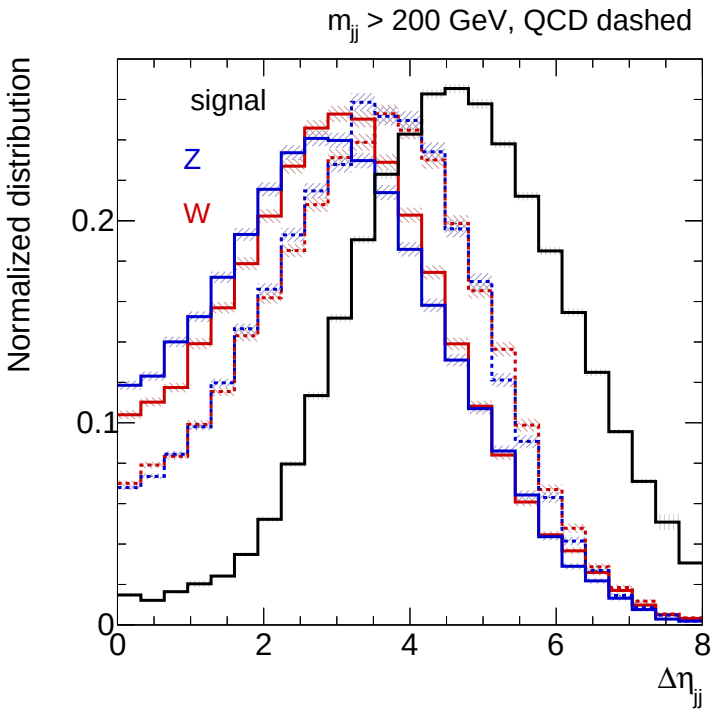
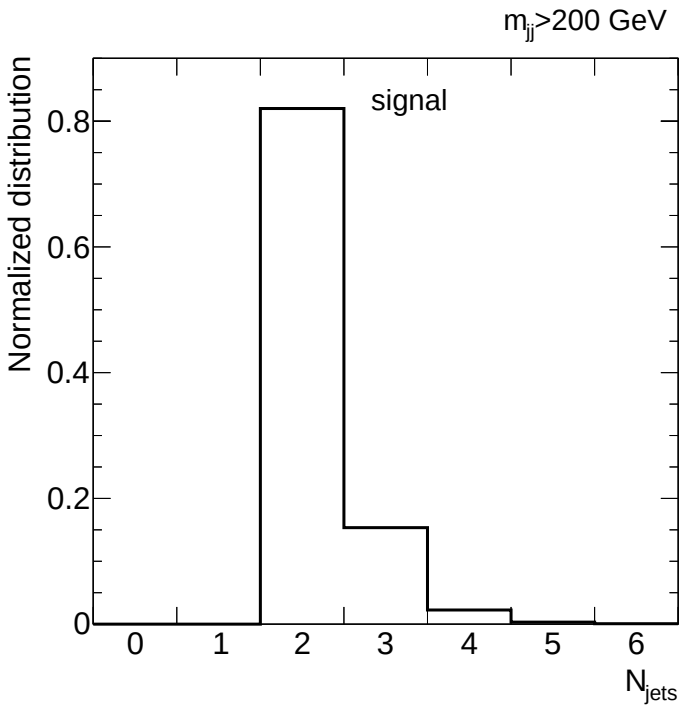




WBF distributions - N_{jets}

merged sample (2 + 3) jets



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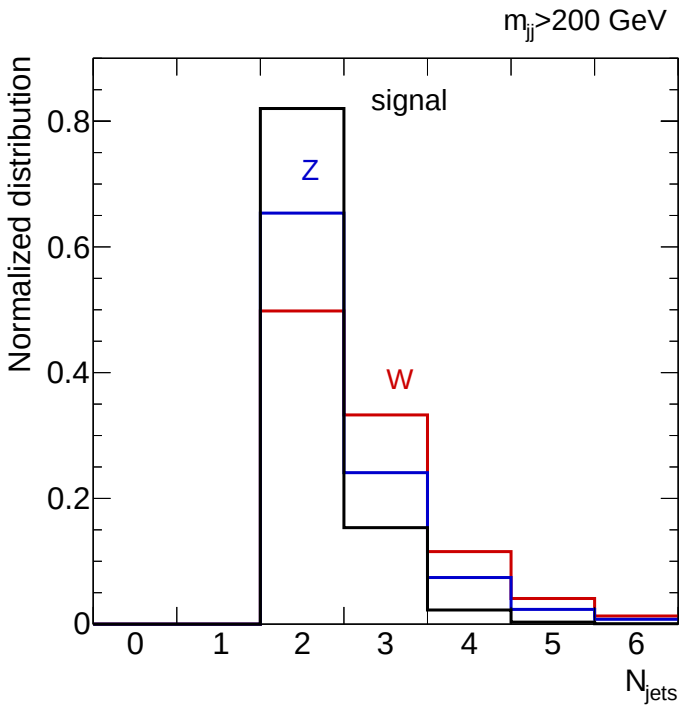

W and Z backgrounds different for N_{jets} distribution

- W background has more 3-jet events

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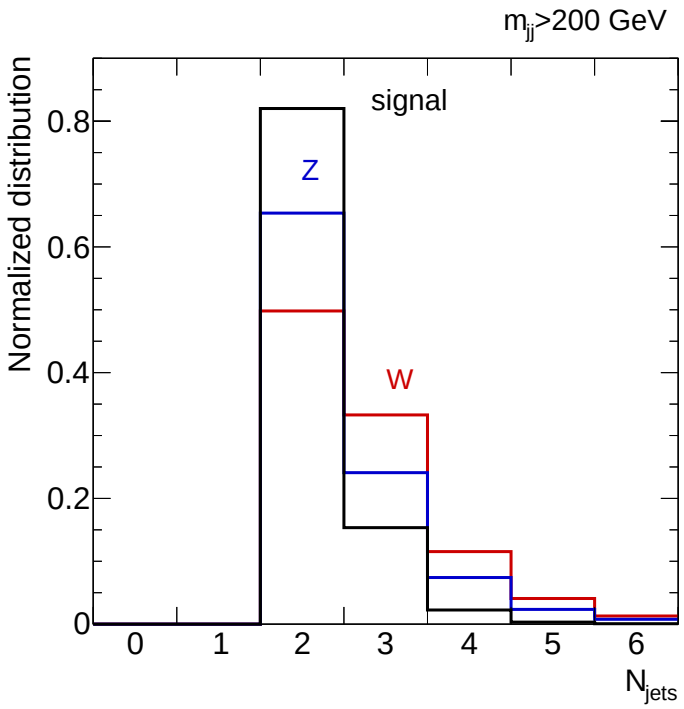

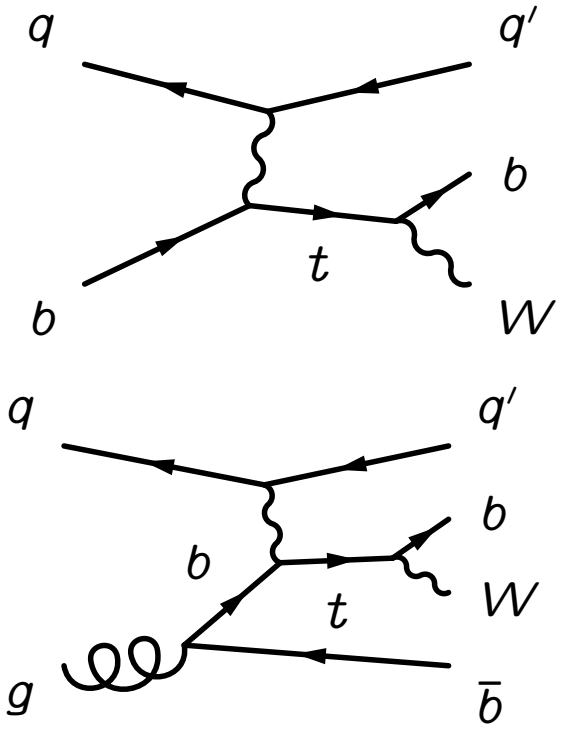

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- W background contains **single-top** events

($m_{jj} > 200$ 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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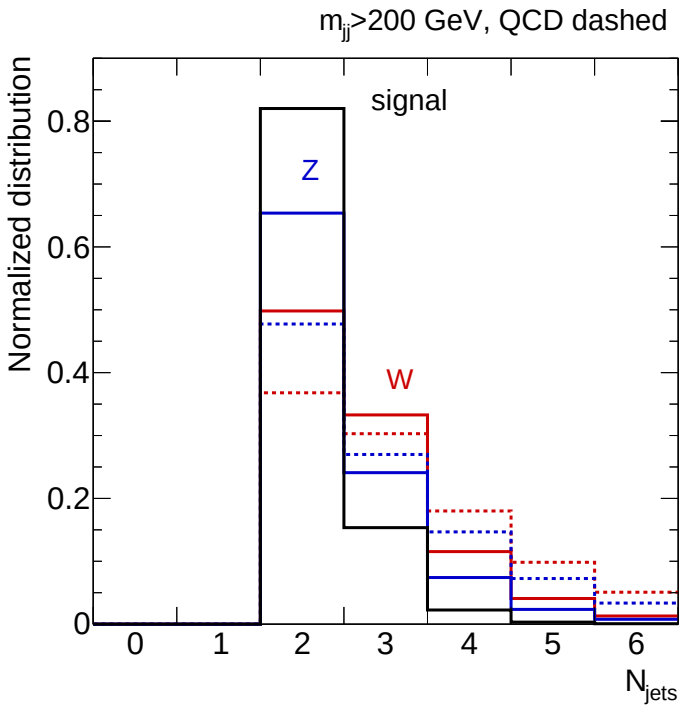

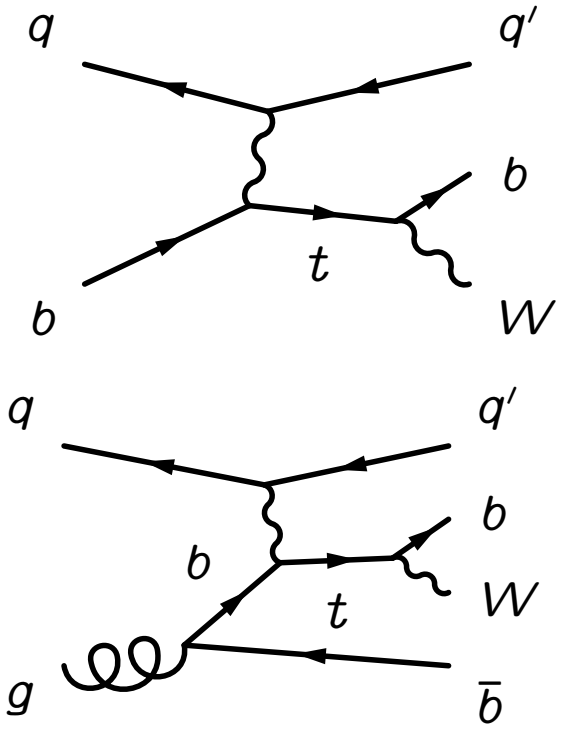

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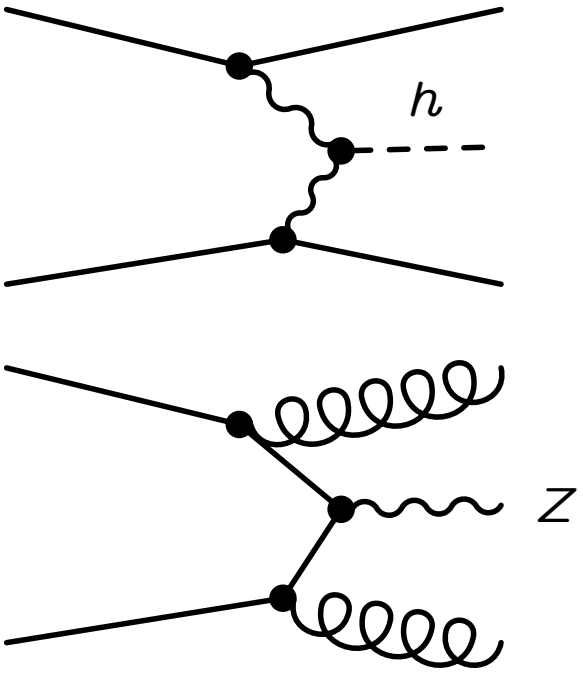
Tagging jet content

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

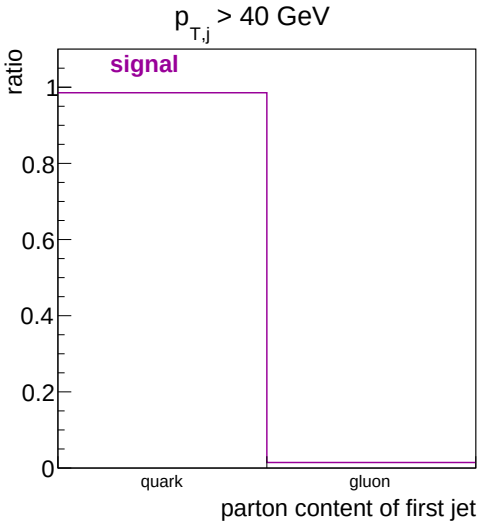
- wider angle soft emissions
- more splittings in parton evolution

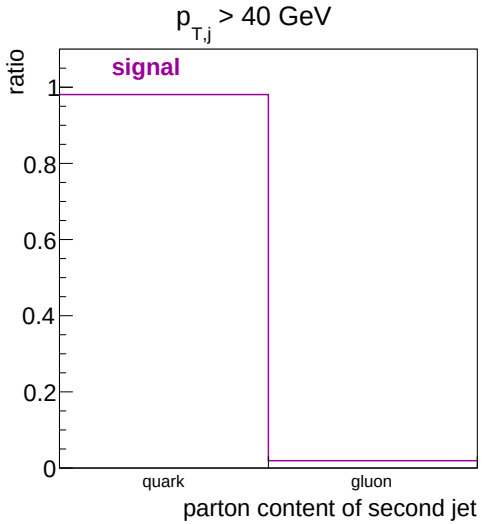
Variables for quark gluon discrimination

- 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]

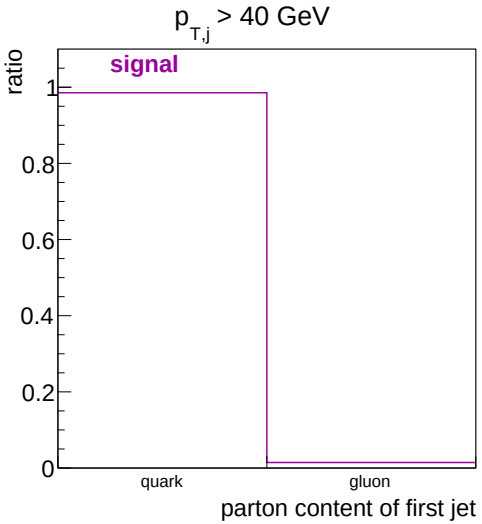
Parton content in WBF

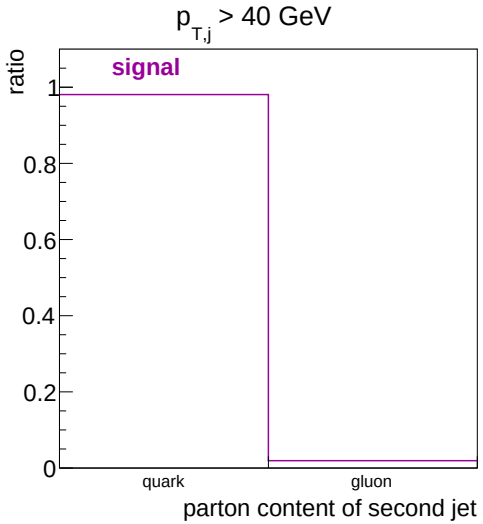


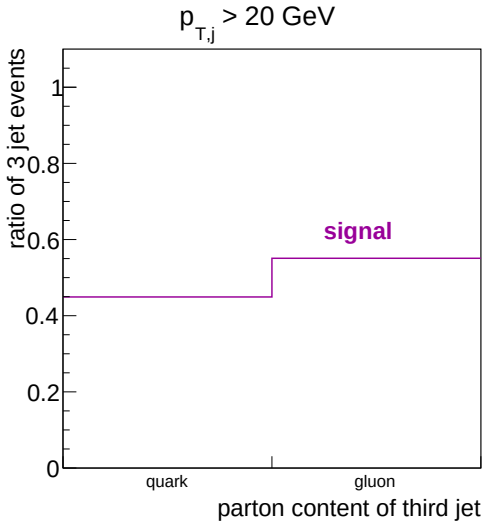


preselection: $p_{T,j} > 40\,\text{GeV}$, $m_{jj} > 600\,\text{GeV}$, $\Delta\eta_{jj} > 3.5$, $N_{\text{Lep}} = 0$, $p_T(V) > 80\,\text{GeV}$

Parton content in WBF







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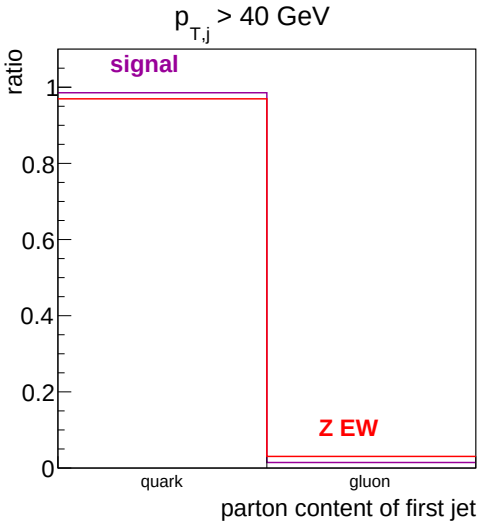

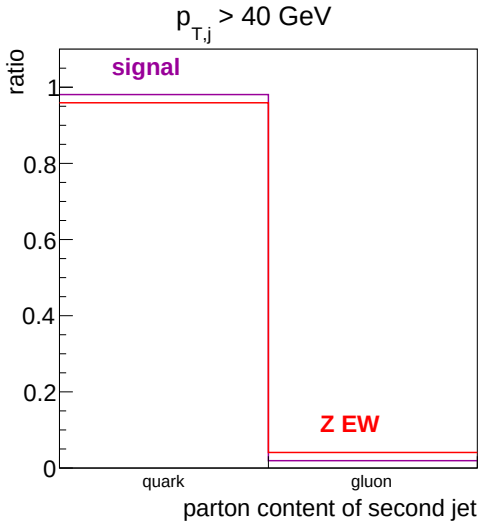

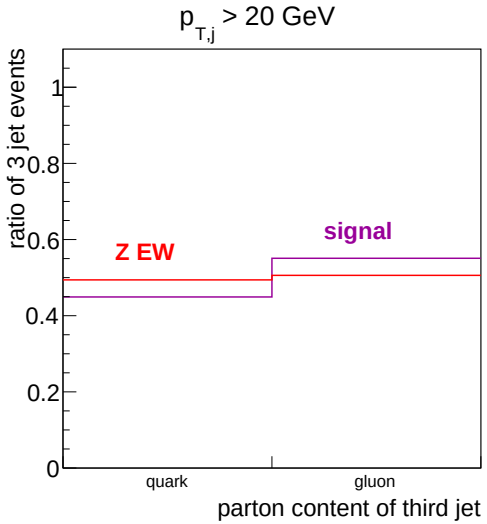

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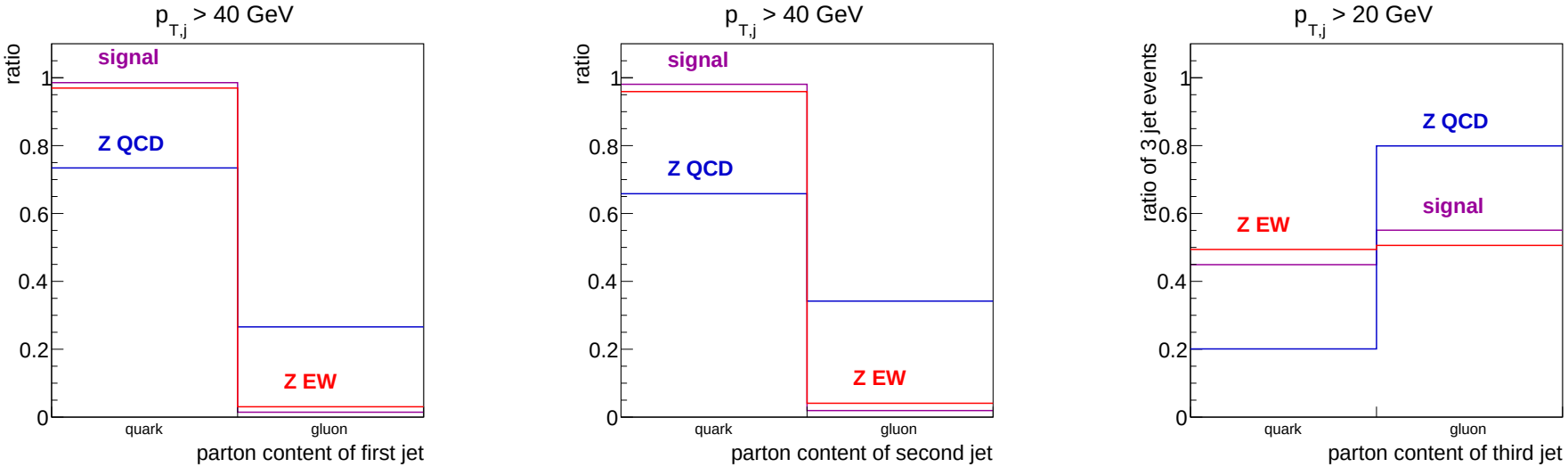
Parton content in WBF



Expect best discrimination power for second jet.

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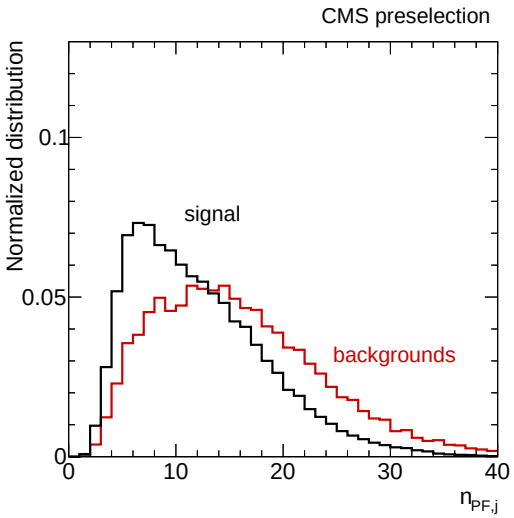
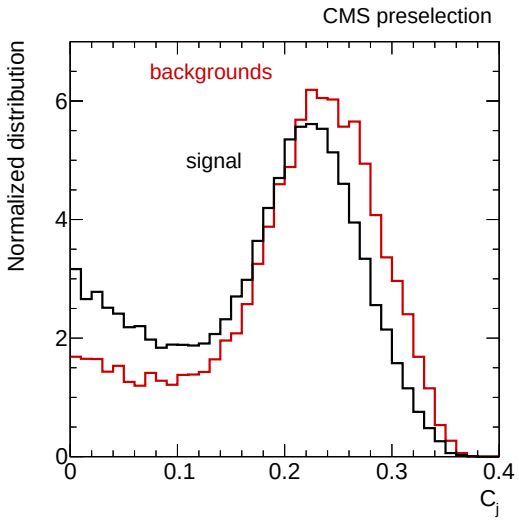
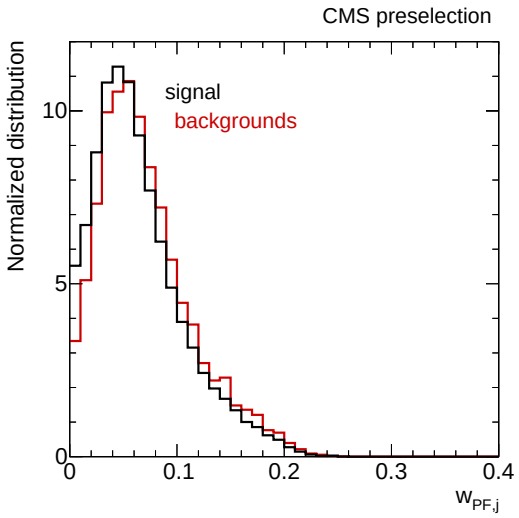
Quark gluon discrimination - distributions







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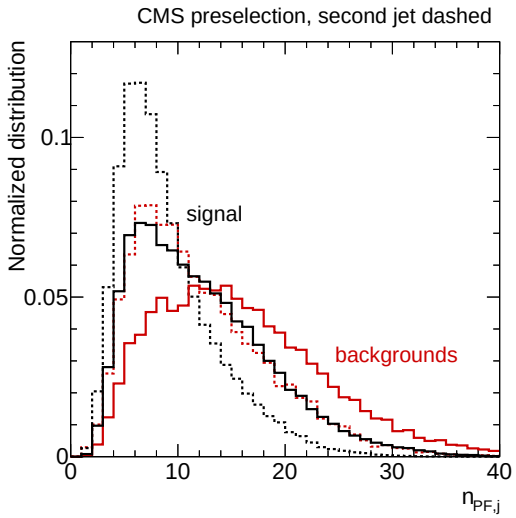
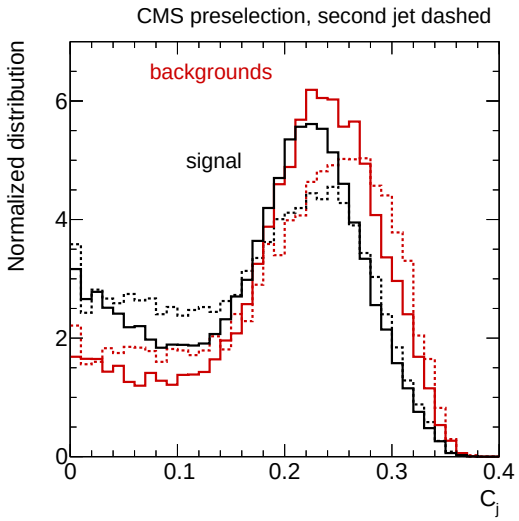
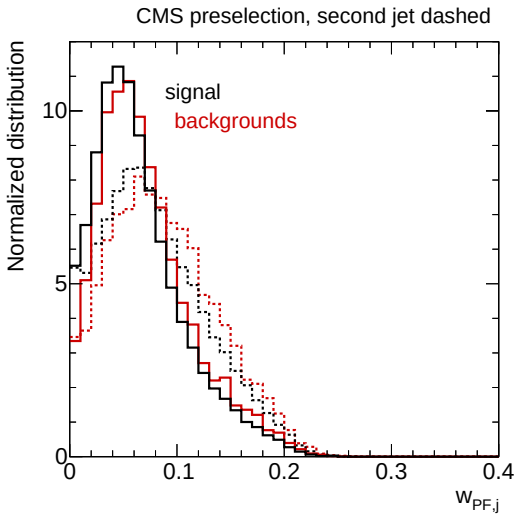
Quark gluon discrimination - distributions







Quark gluon discrimination variables are p_T dependent

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

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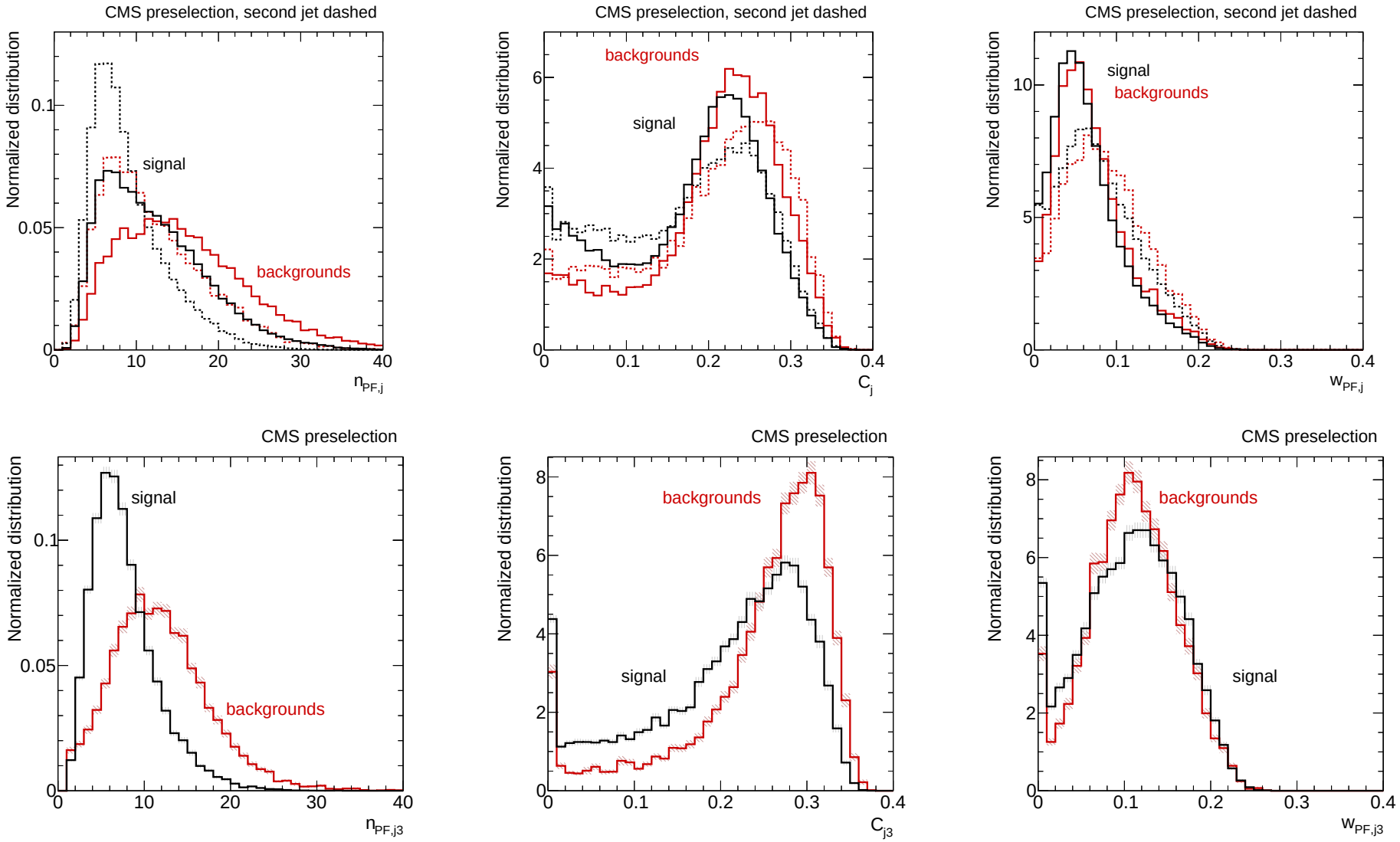

Third jet gives best separation (here: $p_T > 20$ GeV)

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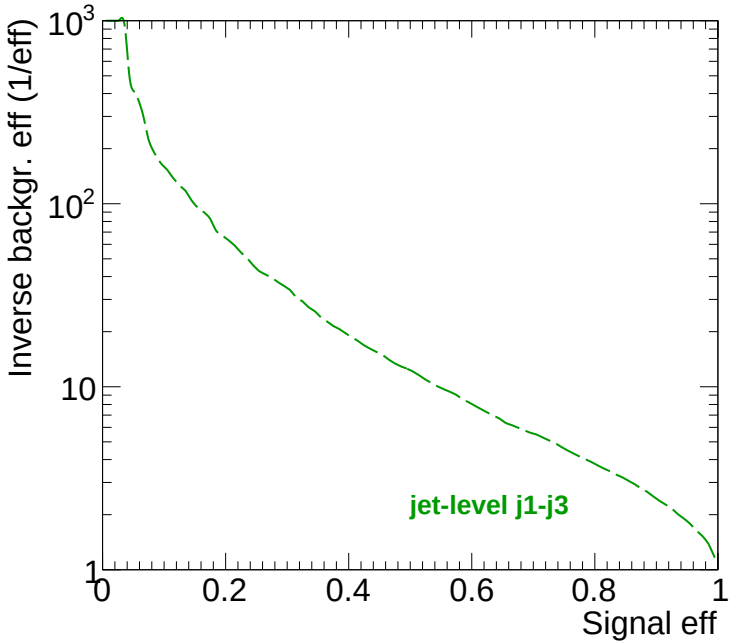
BDT analysis

Boosted decision tree analysis

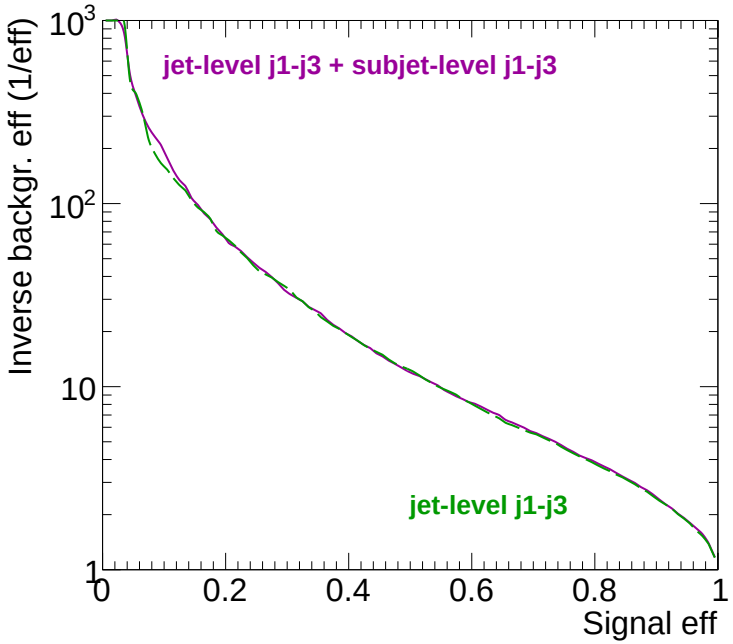


Set	Variables
jet-level j_1, j_2	p_{T,j_1} p_{T,j_2} $\Delta\eta_{jj}$ $\Delta\phi_{jj}$ m_{jj} $\not{E}_T$ $\Delta\phi_{j_1,\not{E}_T}$ $\Delta\phi_{j_2,\not{E}_T}$
subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
j_3 angular information	$\Delta\eta_{j_1,j_3}$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

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

Boosted decision tree analysis



Set	Variables
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subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
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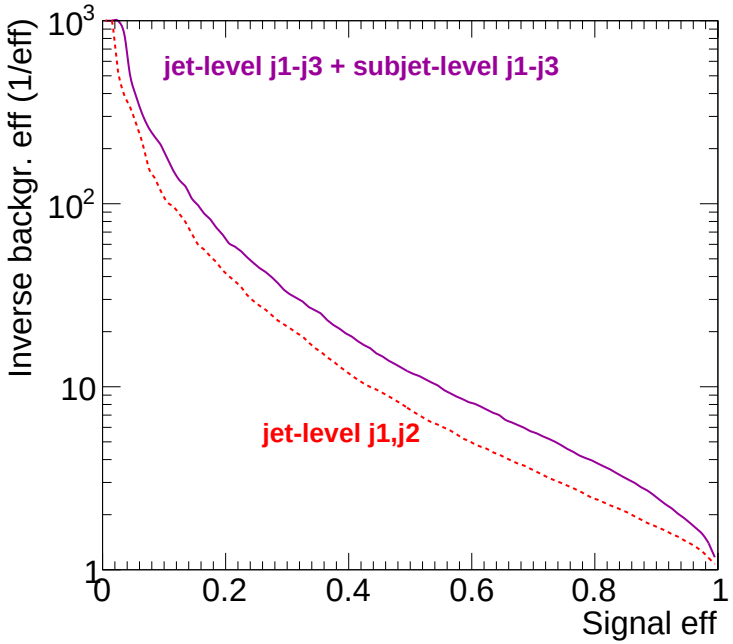

Set	Variables
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subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
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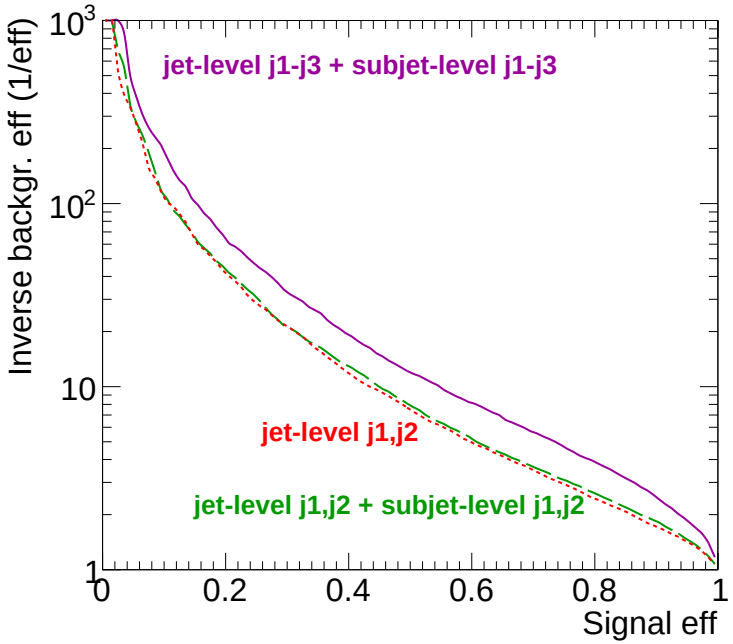

Set	Variables
jet-level j_1, j_2	p_{T,j_1} p_{T,j_2} $\Delta\eta_{jj}$ $\Delta\phi_{jj}$ m_{jj} $\not{E}_T$ $\Delta\phi_{j_1,\not{E}_T}$ $\Delta\phi_{j_2,\not{E}_T}$
subjet-level j_1, j_2	n_{PF,j_1} n_{PF,j_2} C_{j_1} C_{j_2} $p_T D_{j_1}$ $p_T D_{j_2}$
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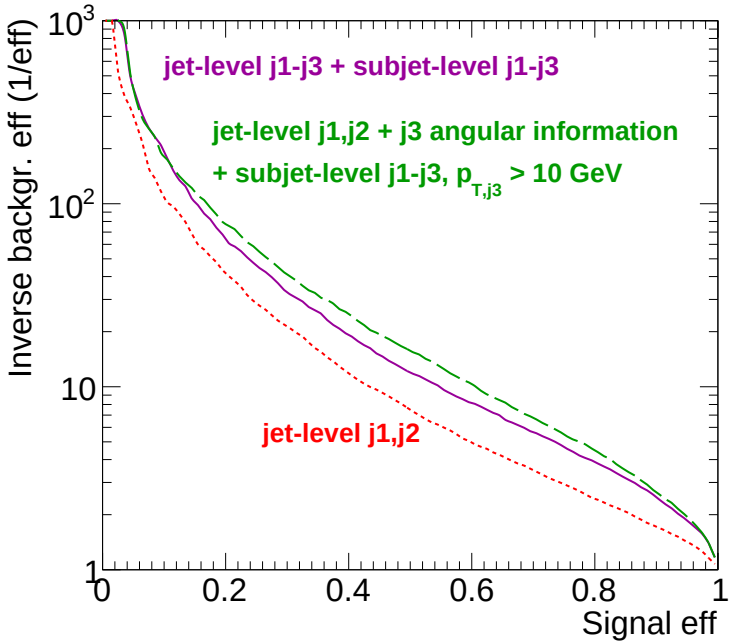
Boosted decision tree analysis



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	$\Delta\eta_{j_1,j_3}$ $\Delta\eta_{j_2,j_3}$ $\Delta\phi_{j_1,j_3}$ $\Delta\phi_{j_2,j_3}$, $p_{T,j3} > 10$ GeV
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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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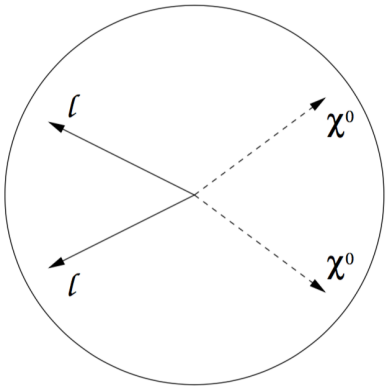
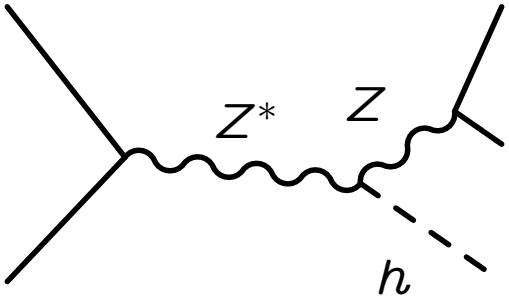
Associated Zh production

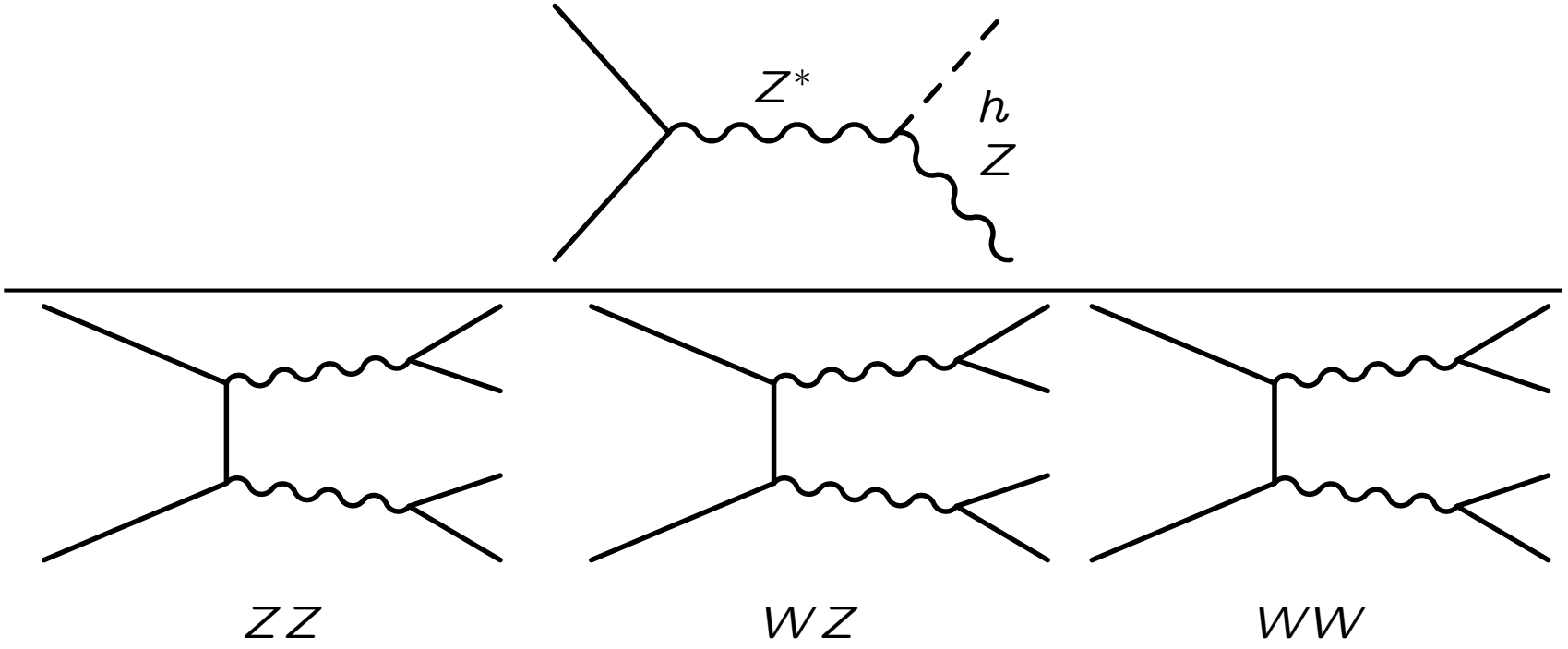
Zh production - signature

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

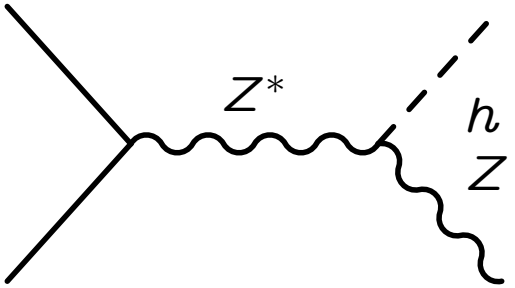


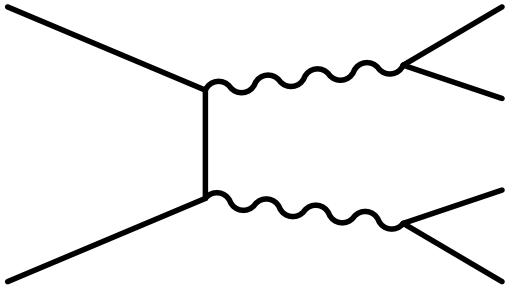


Zh production - backgrounds

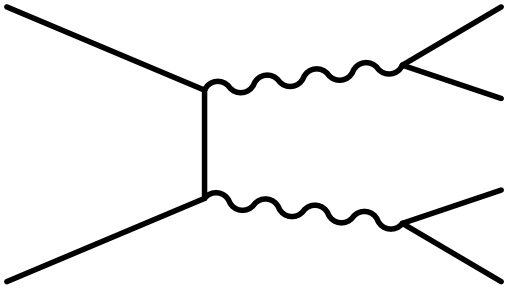


Zh production - backgrounds

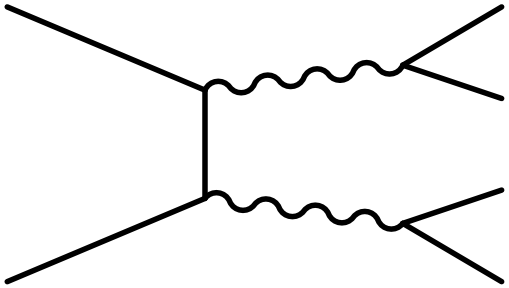




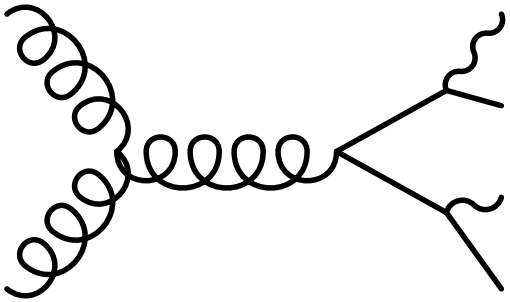
ZZ



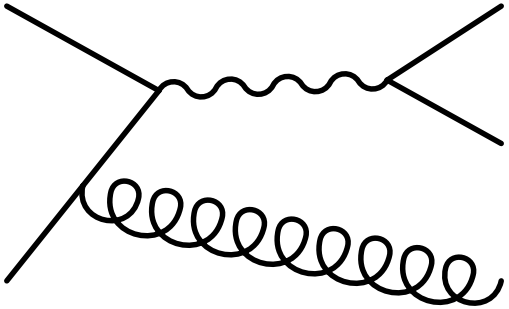
WZ



WW

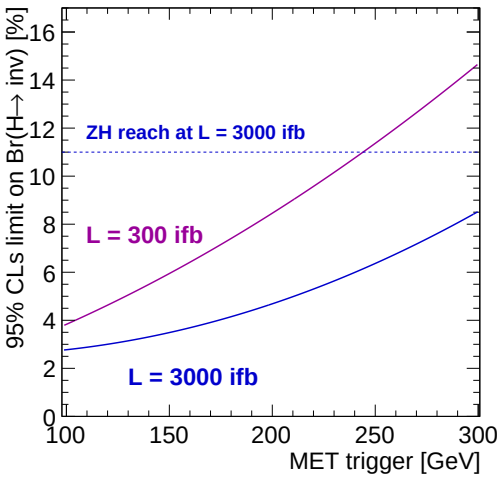


$t\bar{t}$



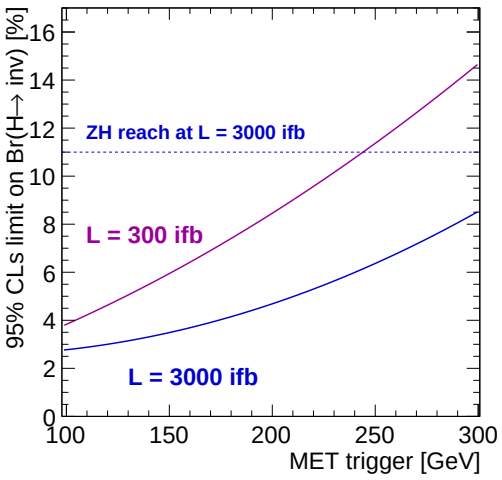
Z+jets

WBF and Zh reach - triggering



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

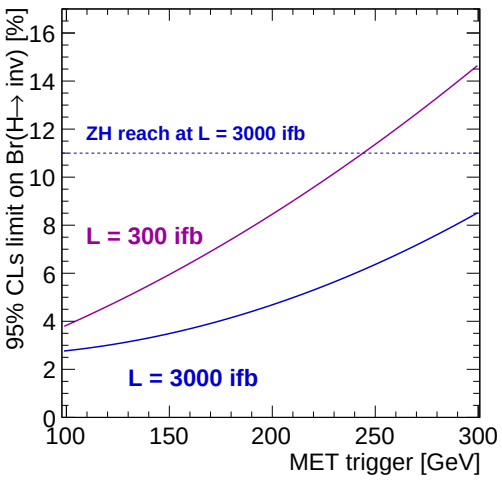
WBF and Zh reach - triggering

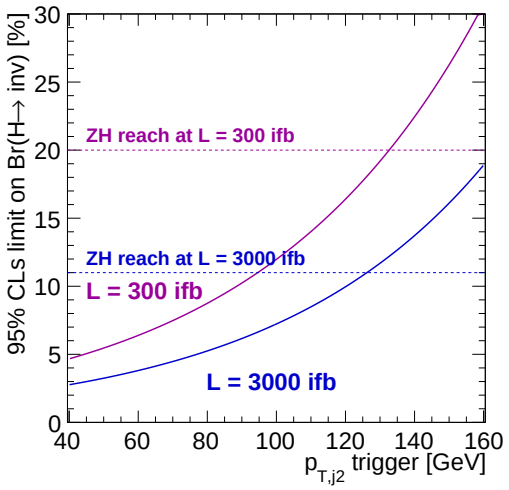


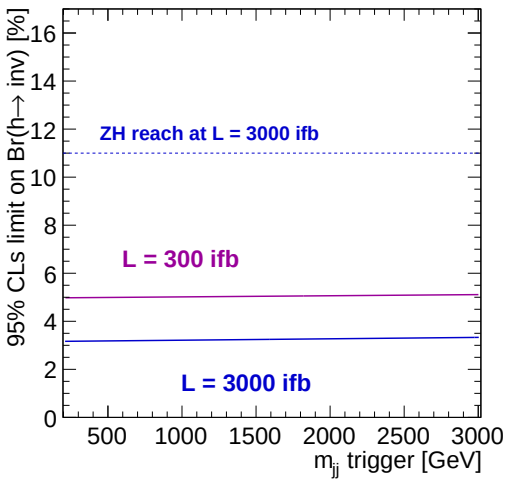
WBF constraints stronger for MET trigger $\lesssim$ 350 GeV

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

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

Conclusions

Conclusions

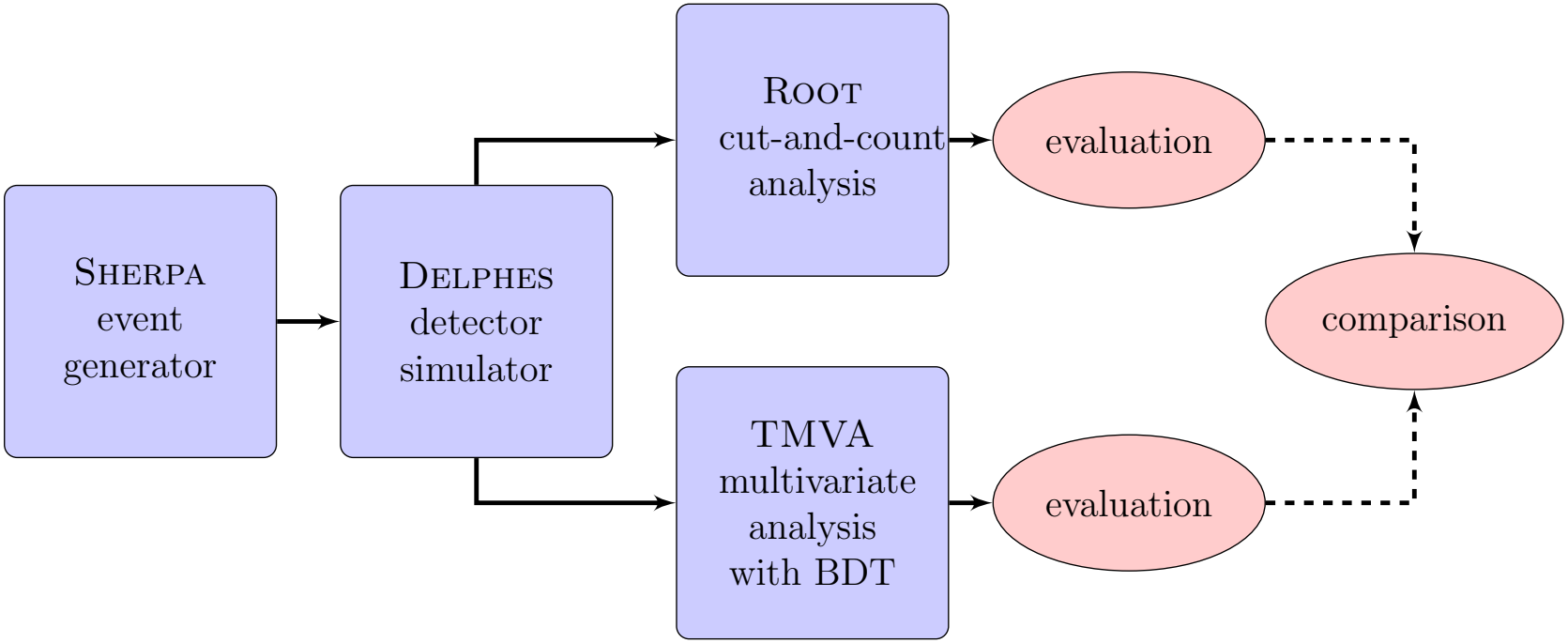
WBF

- 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 (overconstrained)
- **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

BDT settings

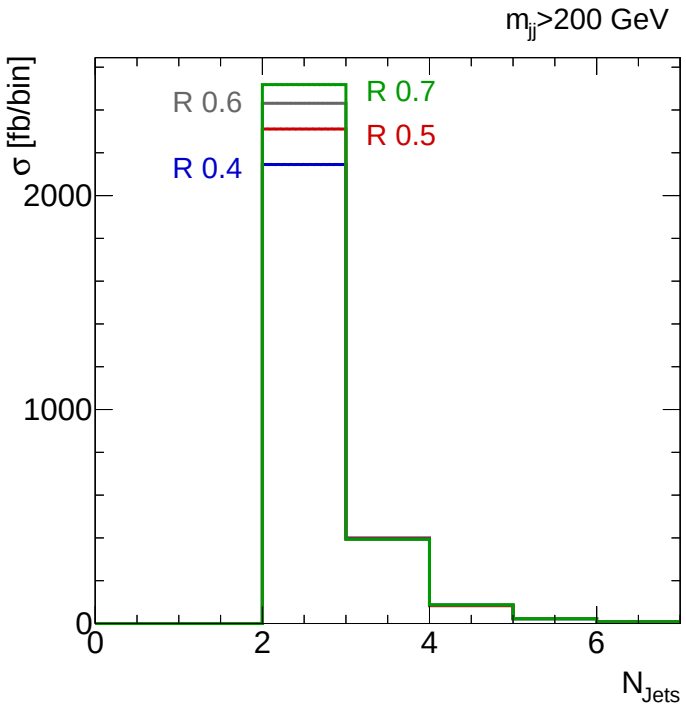
Use TMVA with

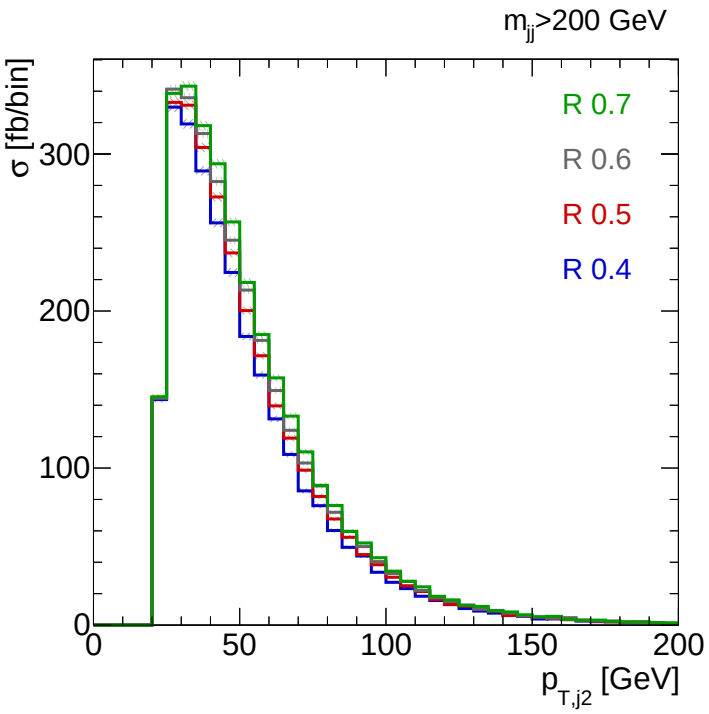
- 70 trees
- 3 layers
- nCuts = 20
- minimum node size 5 %
- preselection

WBF - dependence on jet cone size

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

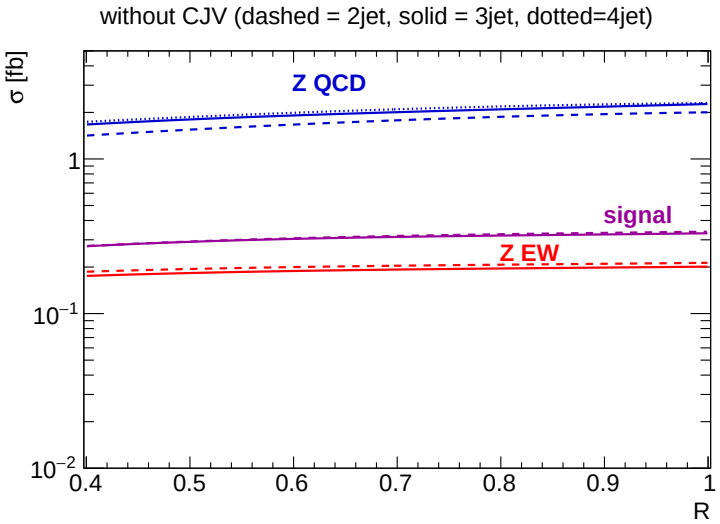
variation of jet cone size in Delphes

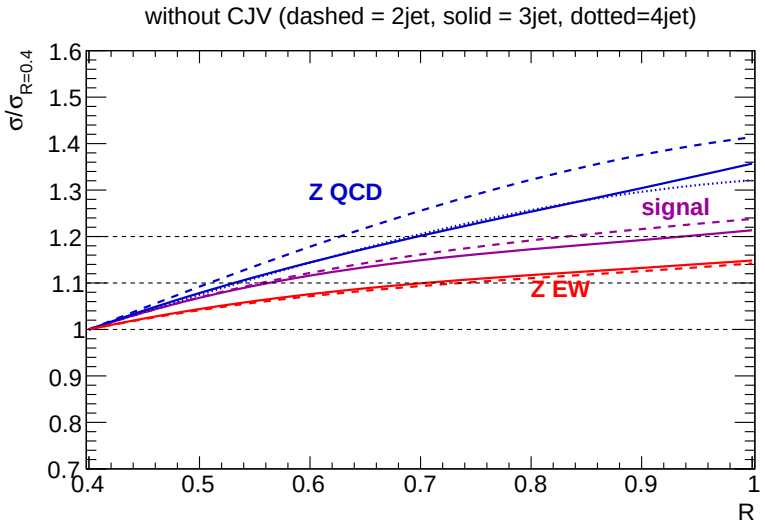




kinematics unchanged

WBF - dependence on jet cone size (2)

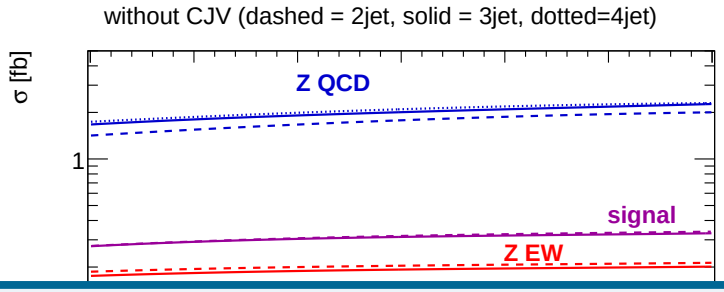


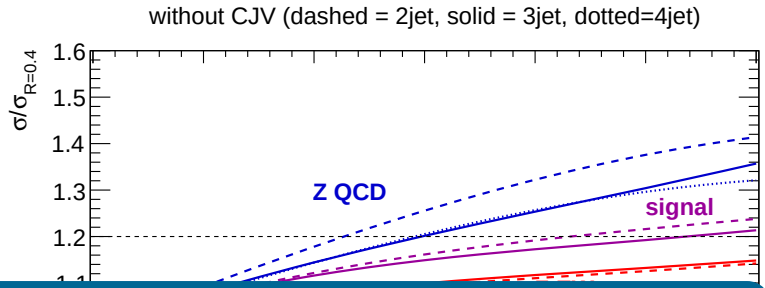


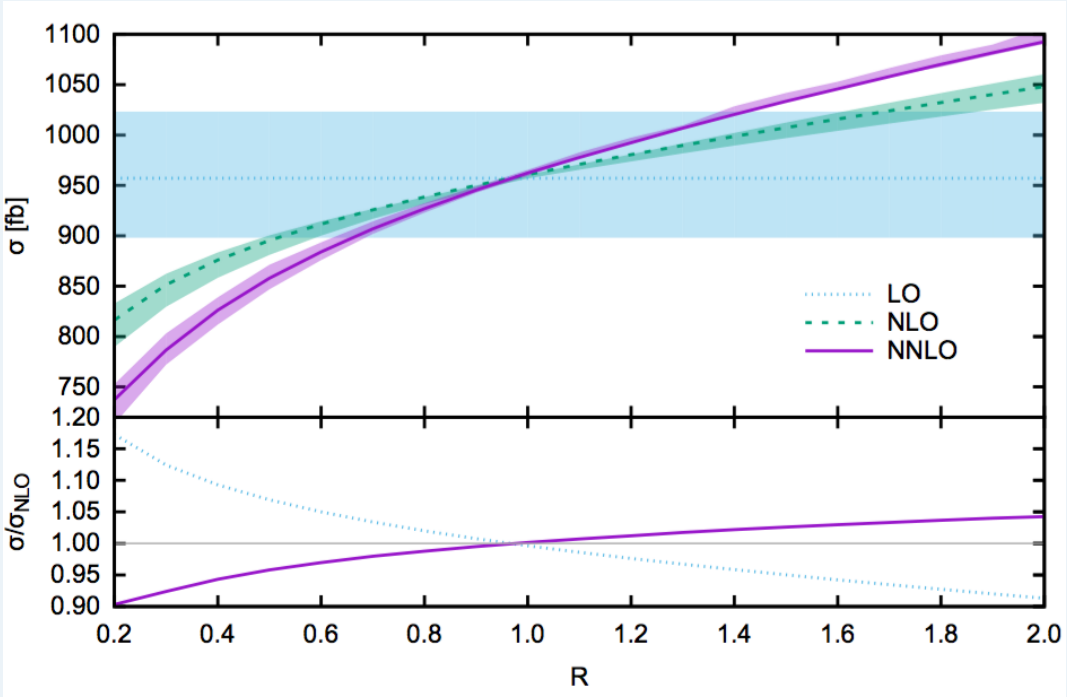
Signal grows stronger with R than EW background

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

WBF - dependence on jet cone size (2)







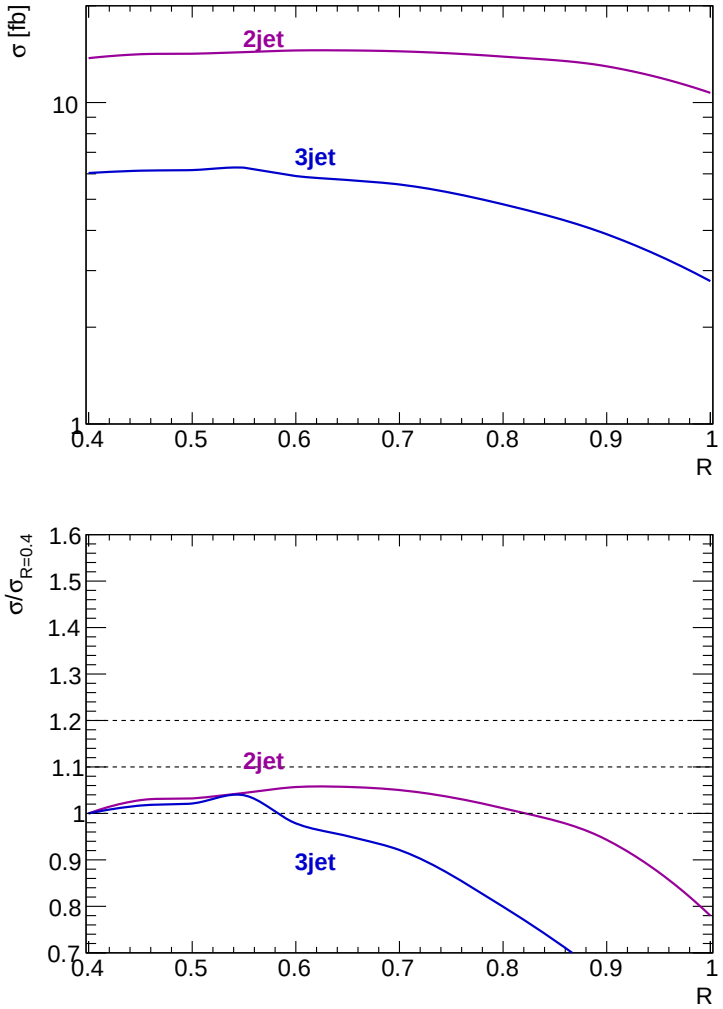
similar results in fixed-order calculation [Rauch, Zeppenfeld, 2017]

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

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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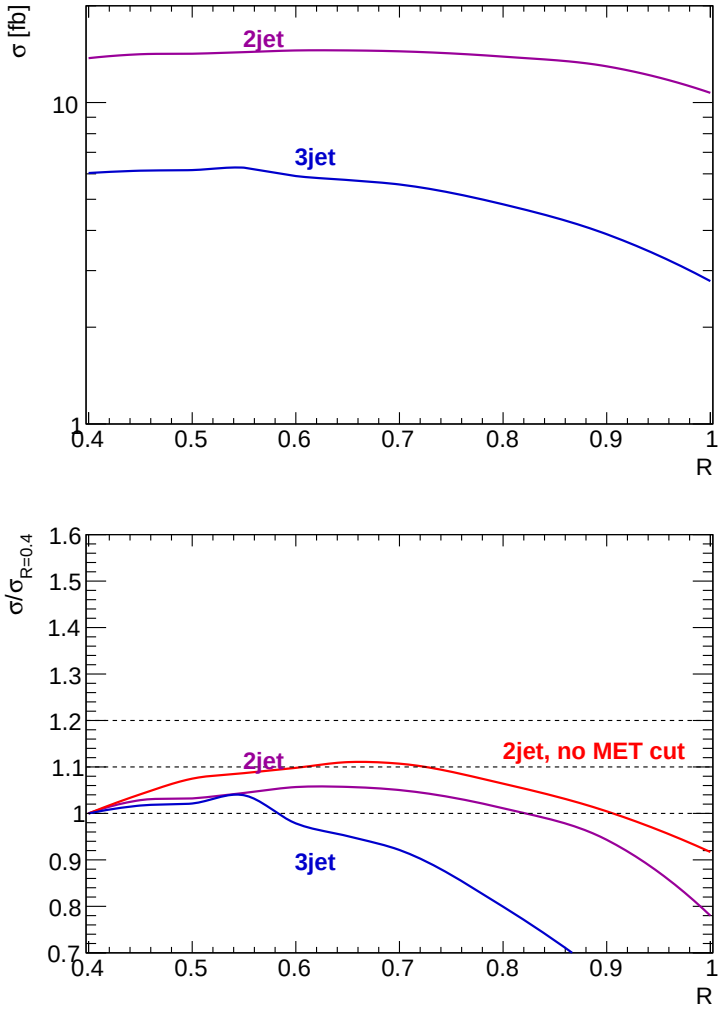

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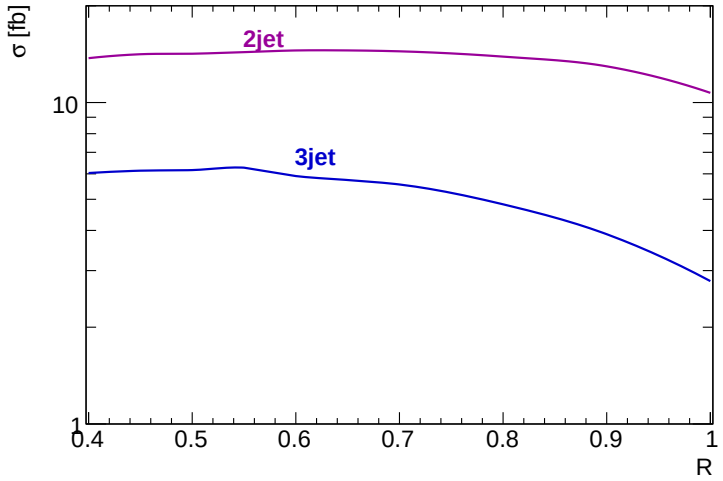

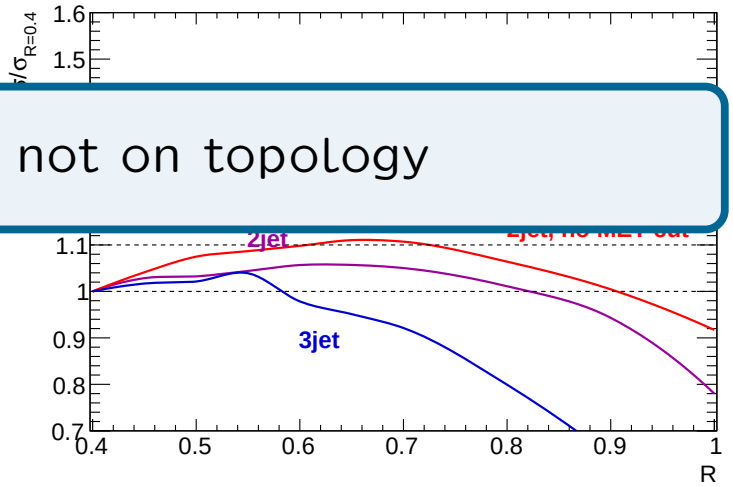

depends on **phase space**, not on topology

No strong dependence on R visible