Faculty of Mathematics and Physics

Multivariate analysis of decays of the Higgs boson into pairs of tau leptons using the ATLAS detector at the LHC

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Content

1) ATLAS detector subsystems
2) Higgs boson mechanism
3) Data & MC – preselection and categorisation
4) MVA – Boosted Decision Trees
5) BDT Training
6) Final BDT score cut

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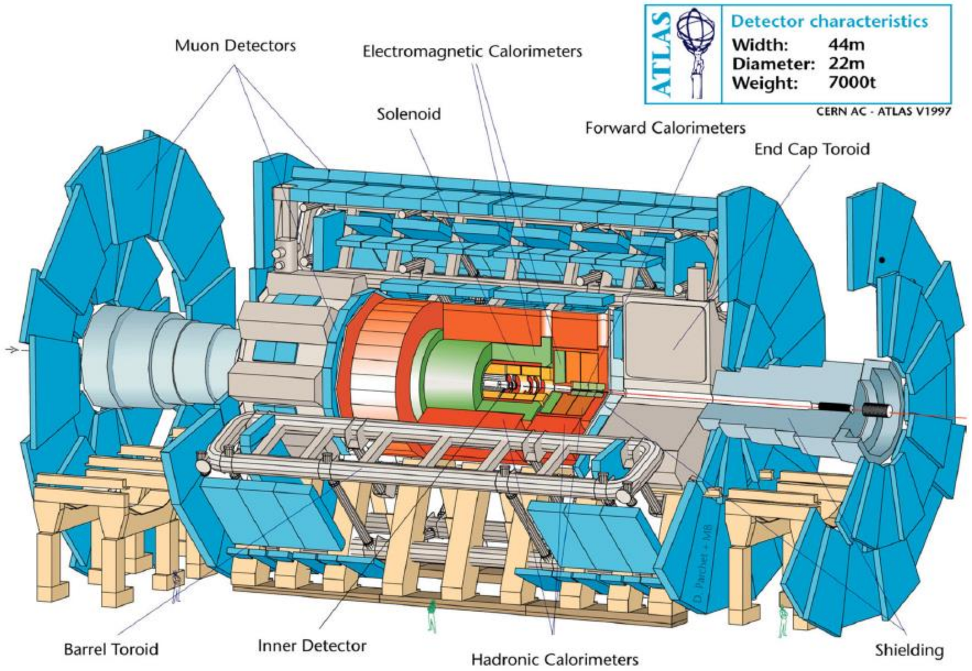
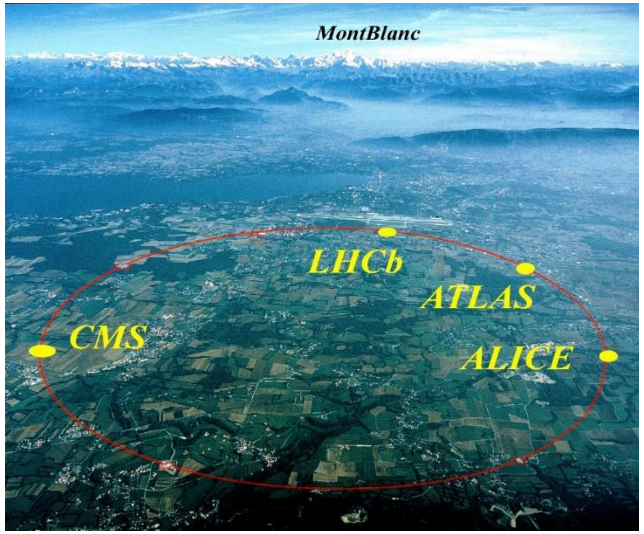
The ATLAS experiment at the LHC

- **Inner detector** (pixel detector, semiconductor tracker, transition radiation tracker, solenoid, $|\eta| < 2.5$)
- **Electromagnetic calorimeter** (absorber: lead layer, active medium: liquid argon, $|\eta| < 3.2$, FCal $3.1 < |\eta| < 4.9$)
- **Hadron calorimeter** (absorber: steel layer, active medium: liquid argon, $|\eta| < 4.9$),
- **Muon spectrometer** (monitored drift tube chambers, cathode strip chambers, thin gap chambers, toroid, $|\eta| < 2.7$),
- **Trigger** (75kHz -> 1kHz reduction, L1 (hardware), L2 + event filter (software))





The ATLAS experiment at the LHC

MET

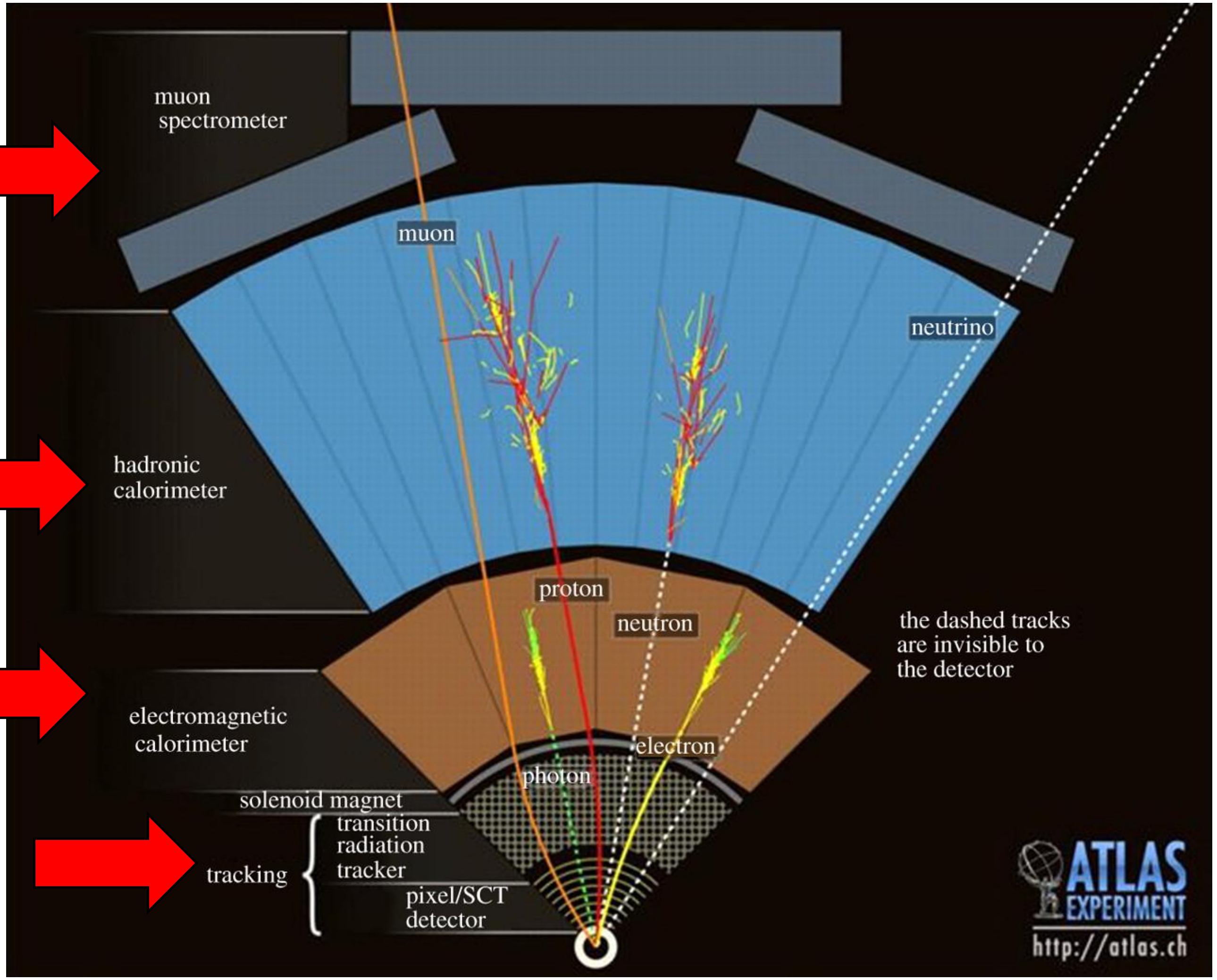
Muon spectrometer

Toroid B=0.5T (barrel)
B=1.0T (end-cup)

System of calorimeters

Inner detector

Solenoid (B=2T)



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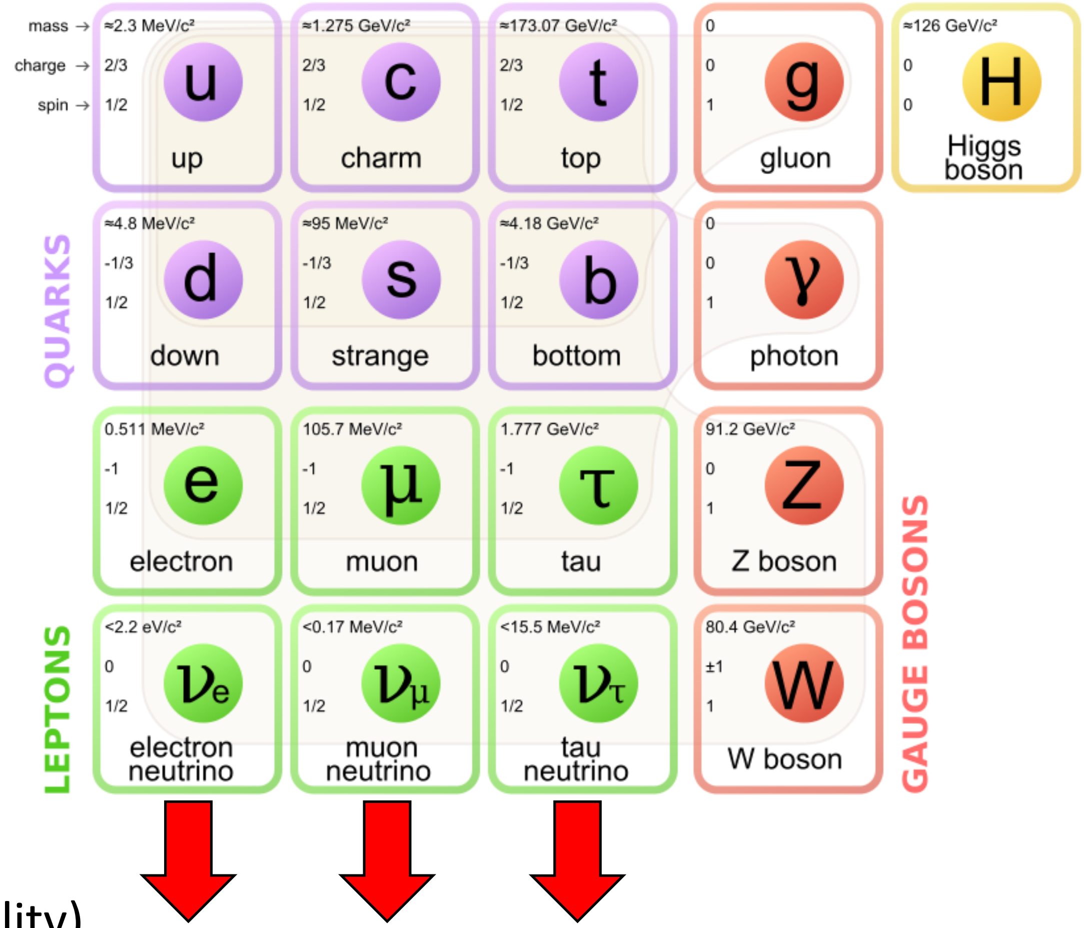
Standard model. Elementary particles

- **Fermions** (half-integer spin)
  - ➢ quarks (u, d, c, s, t, b),
  - ➢ leptons $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$,

- **Bosons** (integer spin)
  - ➢ gluon g (strong interaction),
  - ➢ photon γ (electromagnetic interaction),
  - ➢ $W^{\pm}, Z^{0}$ bosons (weak interaction),

- **Higgs boson H^0** (scalar particle (renormalizability), neutral charge, spin 0)



3 fermion generations

Higgs mechanism

- **The minimal Higgs-Goldstone sector of EW theory**
- 3 massive vector bosons + 1 physical scalar boson ⇒ 4 real scalar fields
- $SU(2) \times U(1)$ gauge theory (1 complex weak isospin $SU(2)$ doublet; transformation properties under weak hypercharge $U(1)$)

$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix}$$

- **The Goldstone model**
- $SU(2) \times U(1)$ symmetry requirement

$$\mathcal{L}_{\text{Goldstone}} = \left(\partial_\mu \Phi^\dagger\right)\left(\partial^\mu \Phi\right) - V(\Phi)$$
$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda\left(\Phi^\dagger \Phi\right)^2$$

μ ... mass dimension
λ ... dimensionless coupling constant

- space-time constant Φ ⇔ minimum of energy density for $\Phi_0^\dagger \Phi_0 = \frac{v^2}{2}$ $v = \frac{\mu}{\sqrt{\lambda}}$ v... „vacuum value“

Higgs mechanism

- **A deviation from the „vacuum value“**

$$\Phi(x) = \exp\left(\frac{i}{v}\pi^a(x)\tau^a\right)\begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{pmatrix}$$

„angular“ variable — shifted „radial“ variable

$H(x)$ ... massive Higgs field
$\pi^a(x)$ ... Goldstone boson representatives
τ^a ... Pauli matrices

➢ mass term appears with a correct sign, Goldstone bosons become massless

$$\mathcal{L} = kin.terms + interactions \; - \lambda v^2 H^2 \quad \Leftrightarrow \quad m_H^2 = 2\lambda v^2 \quad m_\pi = 0$$

- **$SU(2) \times U(1)$ local symmetry requirement ⇒ *U*-gauge**

$$\Phi_U(x) = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{pmatrix}$$

Higgs mechanism

- **The *U*-gauge Higgs Lagrangian**

A_μ^a ... Yang-Mills fields corresponding to $SU(2)$
B_μ... Yang-Mills fields corresponding to $U(1)$
Y ... weak hypercharge
g, g' ... coupling constants

$$\mathcal{L}_{Higgs}^{(U)} = \Phi_U^\dagger \left(\overleftarrow{\partial}_\mu + igA_\mu^a \frac{\tau^a}{2} + ig'YB_\mu \right) \left(\vec{\partial}_\mu - igA^{b\mu} \frac{\tau^b}{2} - ig'YB^\mu \right) \Phi_U - \lambda \left(\Phi_U^\dagger \Phi_U - \frac{v^2}{2} \right)^2 + kin. + selfinter.$$

...

$$\mathcal{L}_{Higgs}^{(U)} = \frac{1}{2} \partial_\mu H \partial^\mu H - \lambda v^2 H^2 - \lambda v H^3 - \frac{1}{4} \lambda H^4 + \frac{1}{8} (v + H)^2 \left(g^2 A_\mu^a A^{a\mu} - 4Ygg' A_\mu^3 B^\mu + 4Y^2 g'^2 B_\mu B^\mu \right)$$

$$Z_\mu = \frac{1}{\sqrt{g^2 + g'^2}} (gA_\mu^3 - g'B_\mu)$$

$$Y = \frac{1}{2}$$

$$\mathcal{L}_{mass}^{(IVB)} = \frac{1}{4} g^2 v^2 W_\mu^- W^{+\mu} + \frac{1}{8} (g^2 + g'^2) v^2 Z_\mu Z^\mu$$

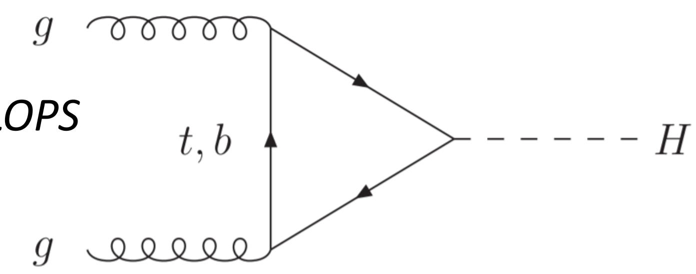
$$m_W = \frac{1}{2} gv \qquad m_Z = \frac{1}{2} v \sqrt{(g^2 + g'^2)}$$

Higgs production

PDG 2016, [9]: $m_{H_0} \doteq (125.09 \pm 0.24)\mathrm{GeV}$

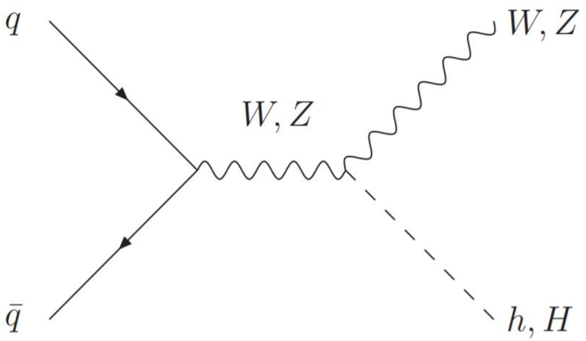
ggF (gluon-gluon fusion)

PowhegNNLOPS



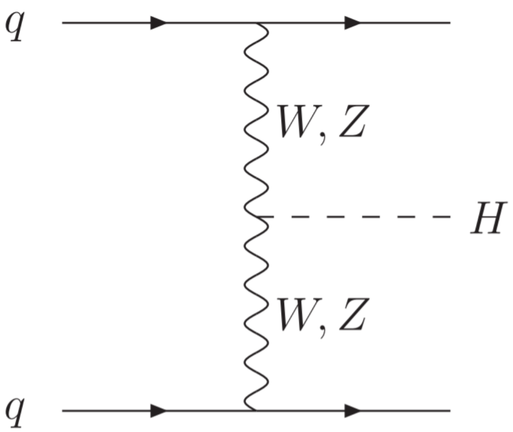
Higgs Strahlung VH

Powheg Box2 (NLO)



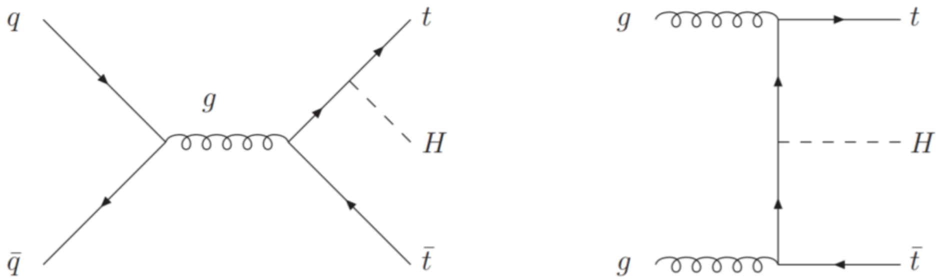
VBF (vector-boson fusion)

Powheg Box2 (NLO)



$t\bar{t}H$ production

MG5_aMC@NLO v2.2.2



Higgs decay modes

$H^0 \to f\bar{f}$

- $H^0 \to b\bar{b}$ $5.84 \times 10^{-1}{}^{+3.3\%}_{-3.2\%}$ [9]
- $H^0 \to \tau\bar{\tau}$ $6.27 \times 10^{-2}{}^{+5.7\%}_{-5.7\%}$ [9]
- $H^0 \to \mu^+\mu^-$

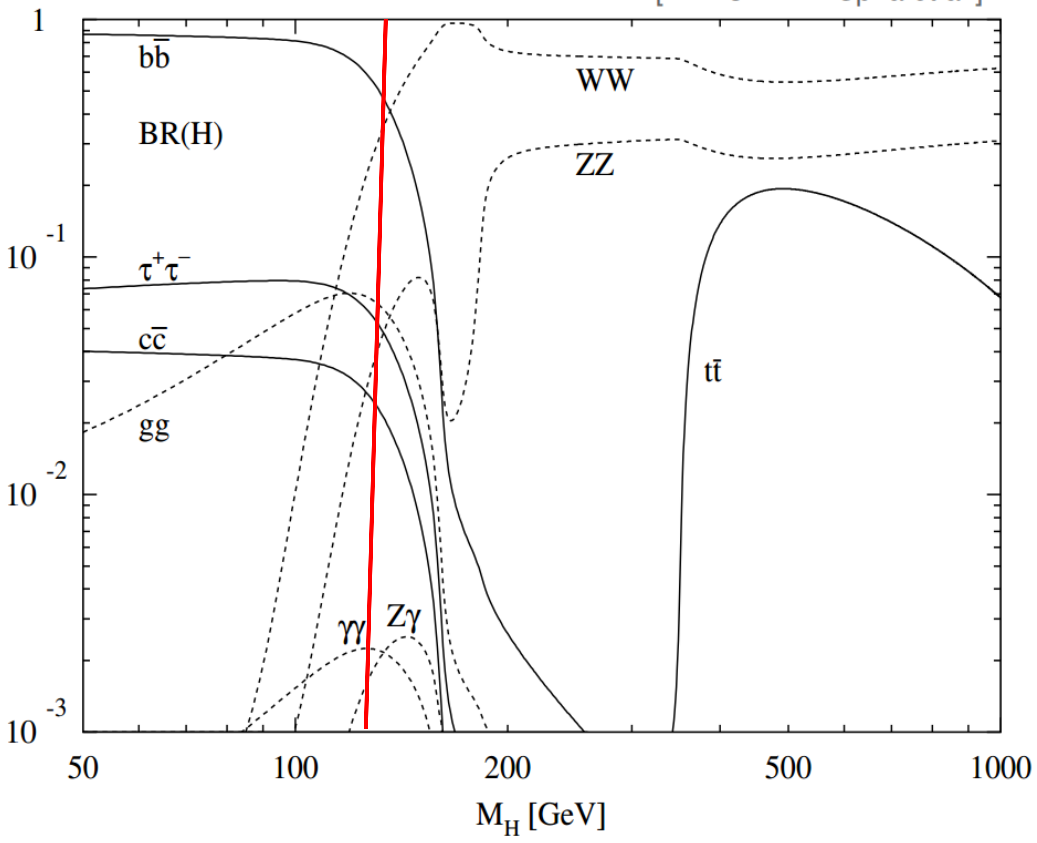
$H^0 \to W^+W^-$

$H^0 \to Z^0Z^0$

$H^0 \to \gamma\gamma$

…

[HDECAY: M. Spira et al.]



$H^0 \to \tau^+\tau^- \to l^+\bar{\nu}\nu l^-\bar{\nu}\nu$

$\sqrt{s} = 13$ TeV

integrated luminosity $= 36.2\ \text{fb}^{-1}$

Run 2 (2015 & 2016)

$\text{DF} = e\mu$

$\text{SF} = ee/\mu\mu$

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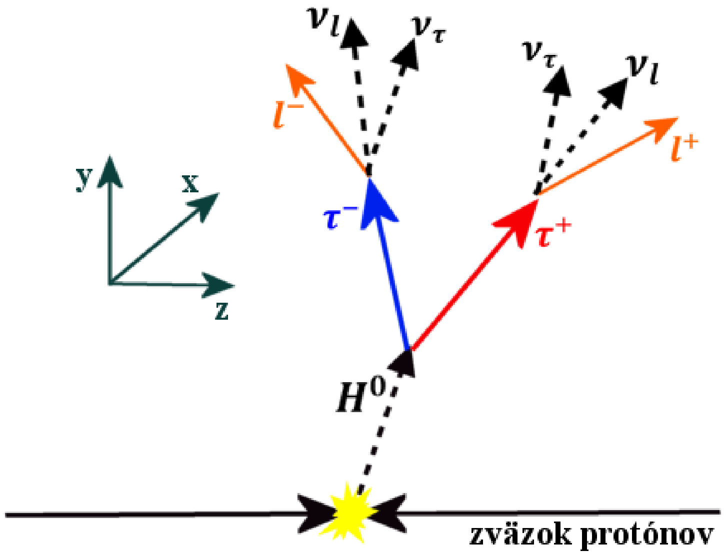
Data&MC

Signal

$$H^0 \rightarrow \tau^+\tau^- \rightarrow l^+\bar{\nu}\nu l^-\bar{\nu}\nu$$

- ggF
- VBF
- VH
- $t\bar{t}H$



Background

- $pp \rightarrow Z^0 \rightarrow \tau^+\tau^-$,
- $pp \rightarrow Z^0 \rightarrow e^+e^-$,
- $pp \rightarrow Z^0 \rightarrow \mu^+\mu^-$,
- $pp \rightarrow t\bar{t}$,
- „single top“,
- $pp \rightarrow \mathrm{W}^\pm \rightarrow \mathrm{l}^\pm\nu_\mathrm{l}$,
- „diboson decays“

Sherpa 2.2.1

- jet associated W/Z production
- VBF Z production
- diboson

Powheg-Box v2 & Powheg-Box v1 NLO

- $t\bar{t}$ & single top

Data&MC

Object reconstruction requirements
- primary vertices
- electrons, muons
- jets
- missing transversal energy E_T^{miss}

Trigger selection
- Single electron/Single muon p_T threshold
- Di-electron/Di-muon/electron-muon p_T threshold

Preselection requirements
- number of leptons
- opposite charge
- lepton (medium) gradient isolation criteria
- ...

$\tau_{lep}\tau_{lep}$ preselection criteria

$$m_{\tau\tau}^{coll} < m_Z - 25\text{GeV}$$

SF	DF
$30 < m_{ll} < 75$ GeV	$30 < m_{ll} < 100$ GeV
$E_T^{miss} > 55$ GeV	$E_T^{miss} > 20$ GeV

$$p_T^{jet1} > 40\text{GeV}$$
$$N_{b-jets} = 0$$

VBF	Boosted
$p_T^{jet2} > 30\text{GeV}$	not VBF
$\lvert\eta_{jj}\rvert > 3$	$p_T^{\tau\tau} > 100\text{GeV}$
$m_{jj} > 400\text{GeV}$	

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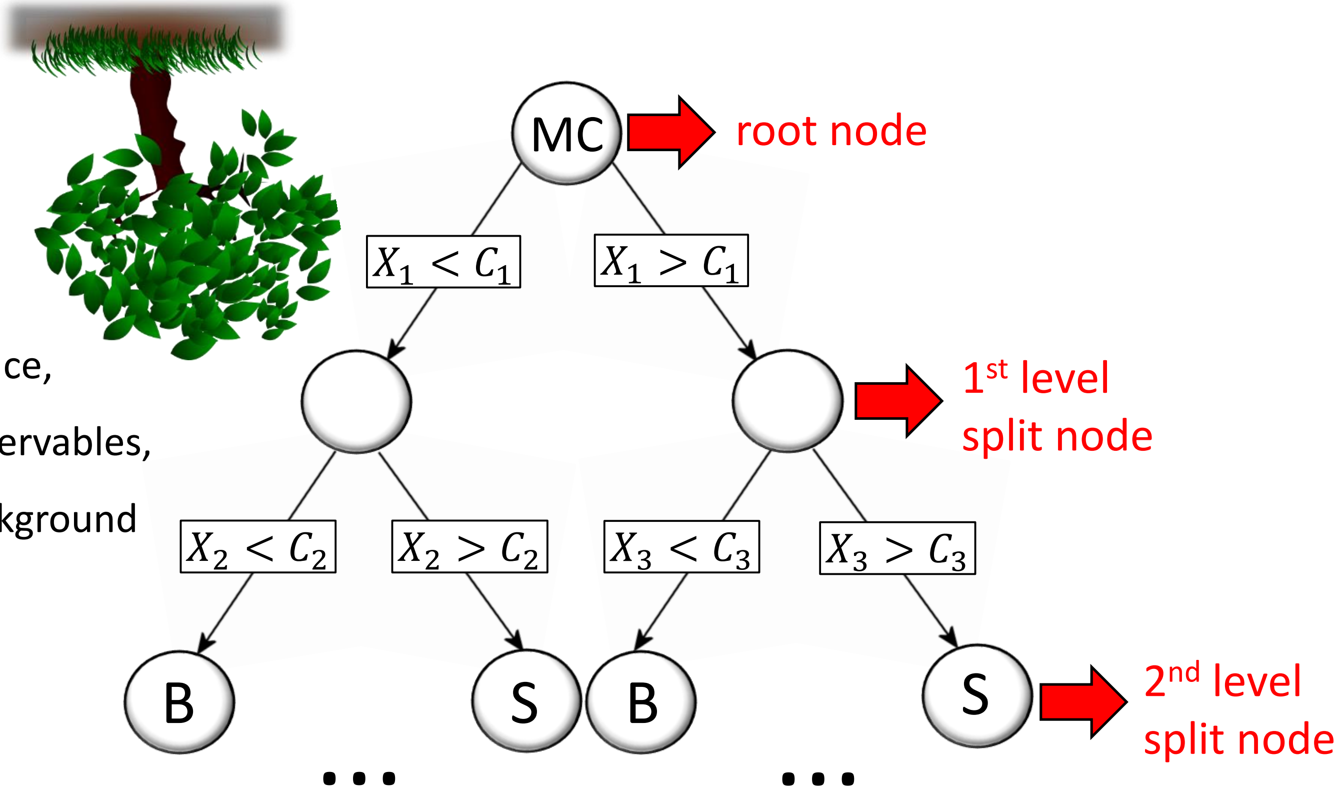
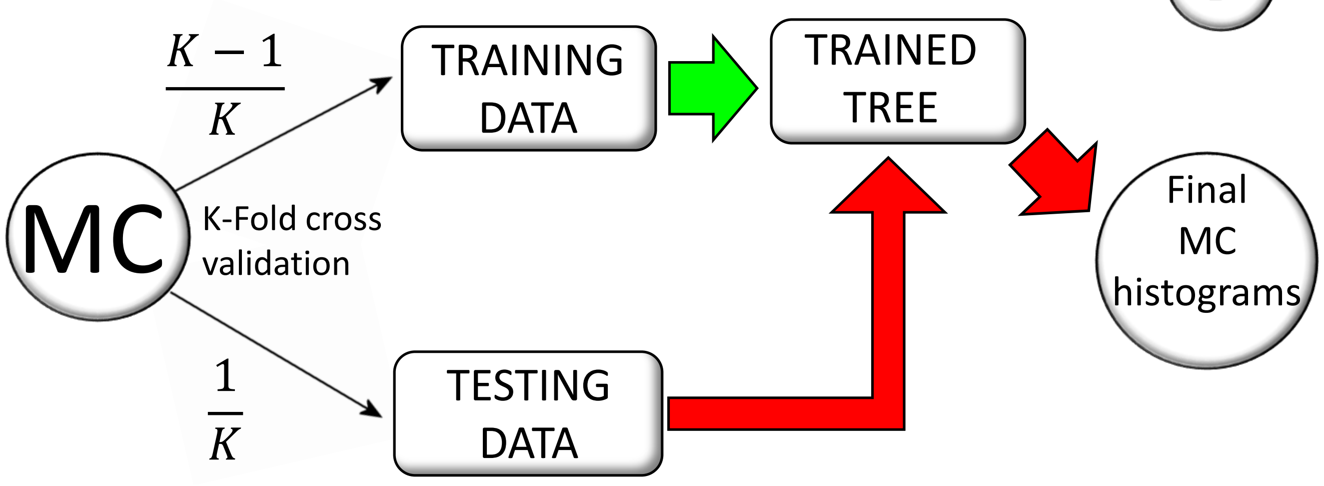
Decision Tree

- multivariate classification algorithm,
- operates within a multi-dimensional observable space,
- more sophisticated non sequential approach to observables,
- Task: **to maximize a figure of merit** of signal vs. background selection.





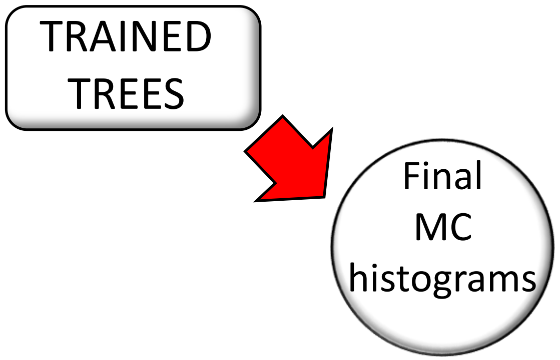
TRAINING

=

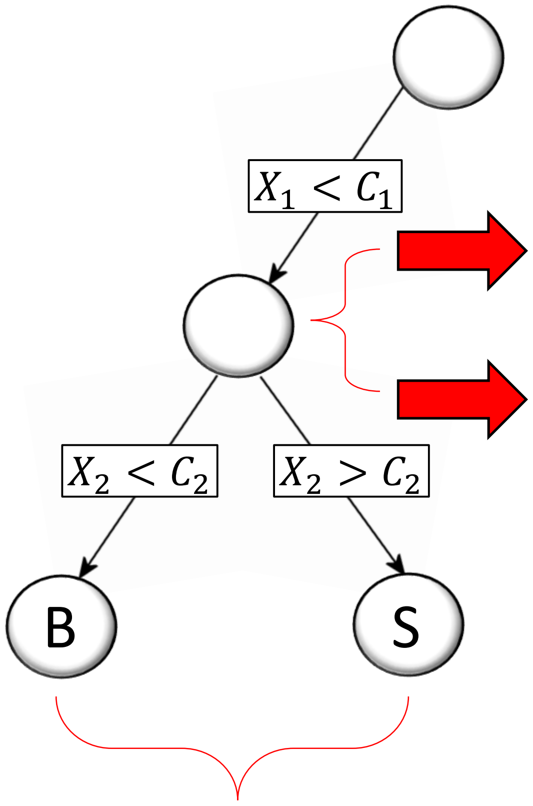
Determining the one variable and the corresponding cut value to get the best MC data separation at each node.

$X_j \in \{X_1, \ldots, X_n\}$

$C_j \in \{C_1(X_1), C_2(X_2), \ldots, C_n(X_n)\}$



Training algorithm



Gini index is evaluated **AFTER & BEFORE** each split node to determine the most contributing selection variable with the corresponding cut value.

$X_j \in \{X_1, \dots, X_n\}$

$C_j \in \{C_1(X_1), C_2(X_2), \dots, C_n(X_n)\}$

$Gini\ index = p(1-p)$

purity ... $p = \frac{N_S}{N}$

the difference of Gini indices is being maximized $(G_L - G_{L-1})_{max}$

The number of split node levels L is a fixed parameter.

Each event from the training data is then classified according to the label of the final leaf node.

Boosted Decision Tree

(Gradient Boost)

- **sequential method** – learning from the mistakes of previous classifiers
- **tree ensemble model construction**

$$F(x;P)=\sum_{m=1}^{M}\beta_m f(x;a_m)\quad P\in\{\beta_m;a_m\}_0^M$$

$f(x;a_m)$ ... weak classifiers
P... parameters
x ... testing sample
y ... training sample

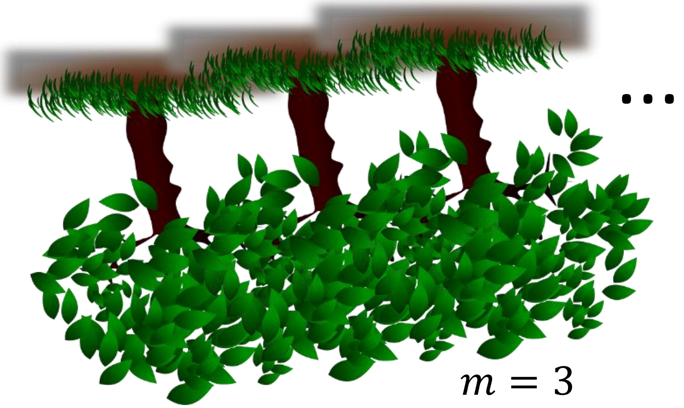
- **loss function minimization**

basic $L(F(x),y)=(F(x)-y)^2$

gradient $L(F(x),y)=\ln\left(1+e^{-2F(x)y}\right)$

- executed by loss function **gradient calculation**

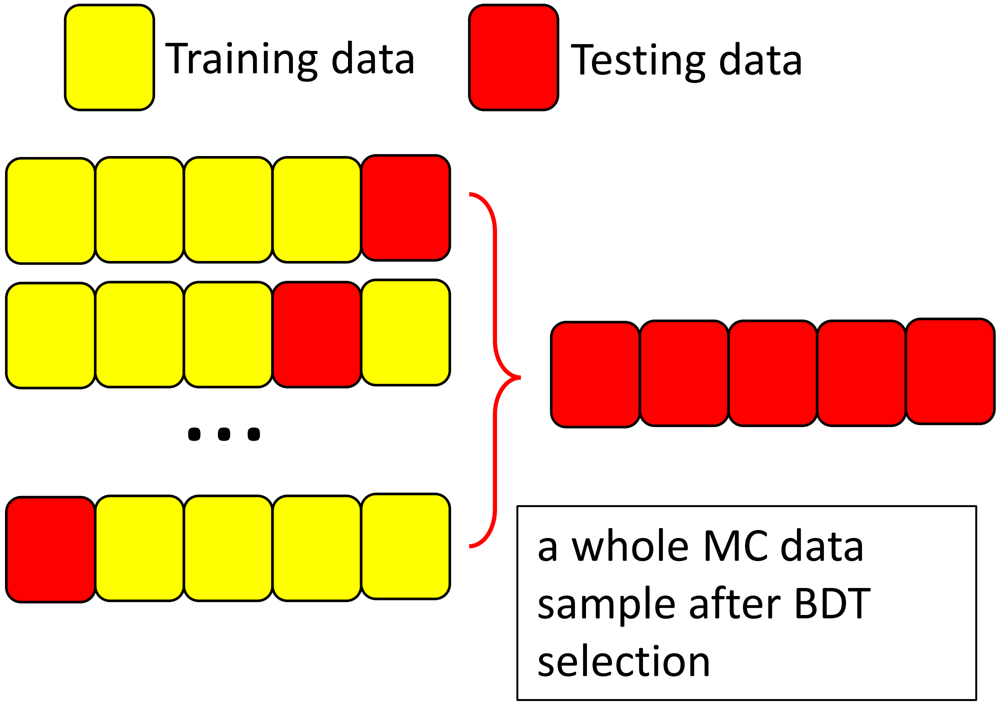
$$F(x)\approx F(x)+k\frac{\delta L(F(x),y)}{\delta F(x)}$$



$m=3$
$m=2$
$m=1$

M number of trees in the forest

K-Fold cross validation (K=5)



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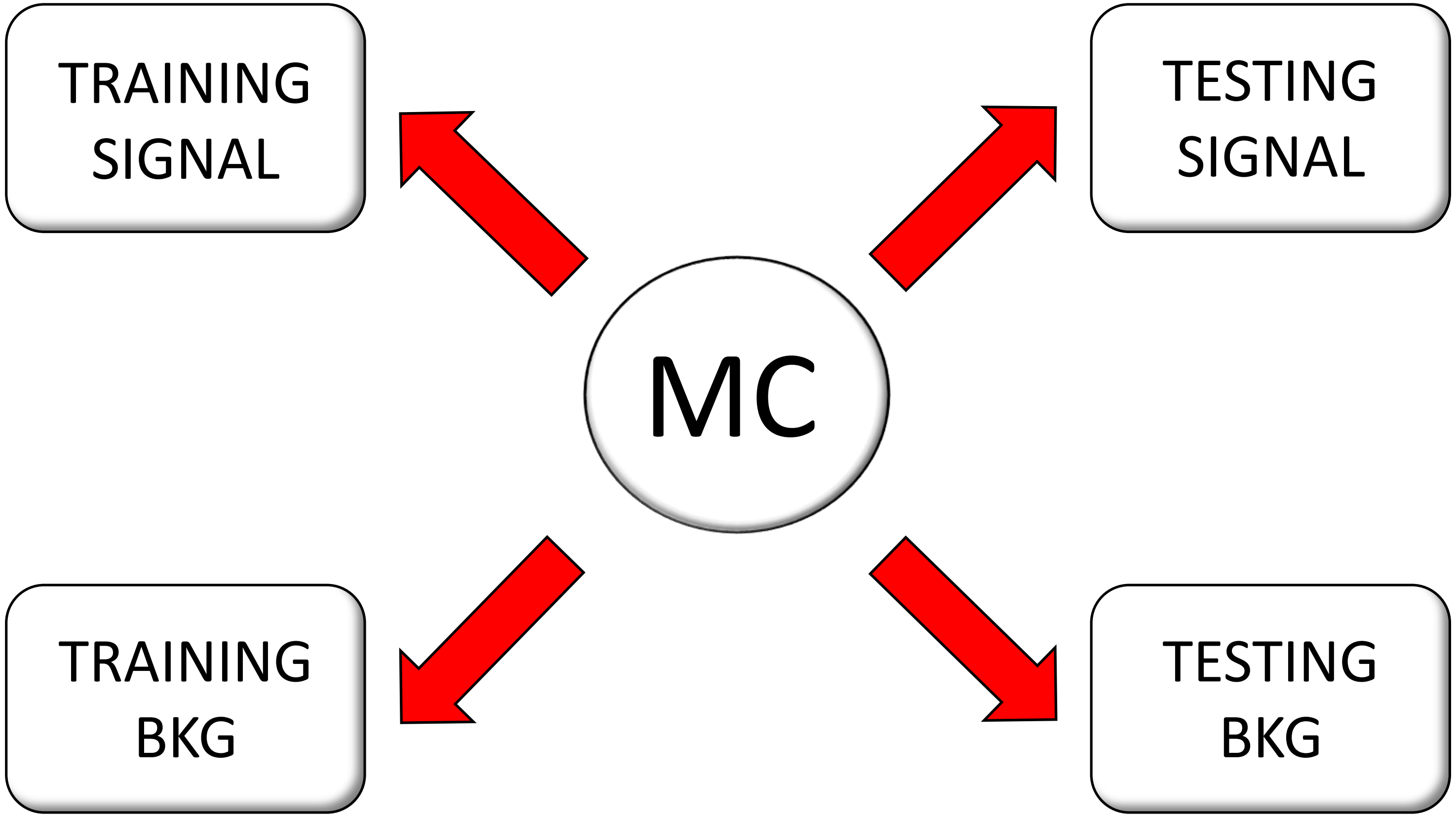
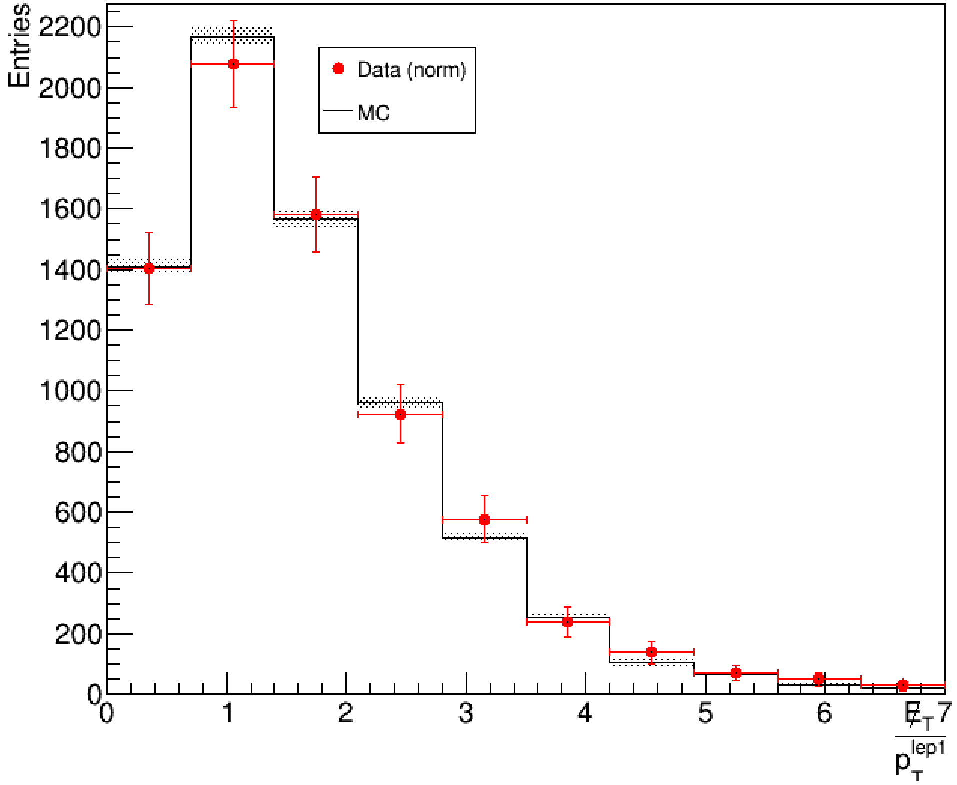
BDT training – splitting data randomly

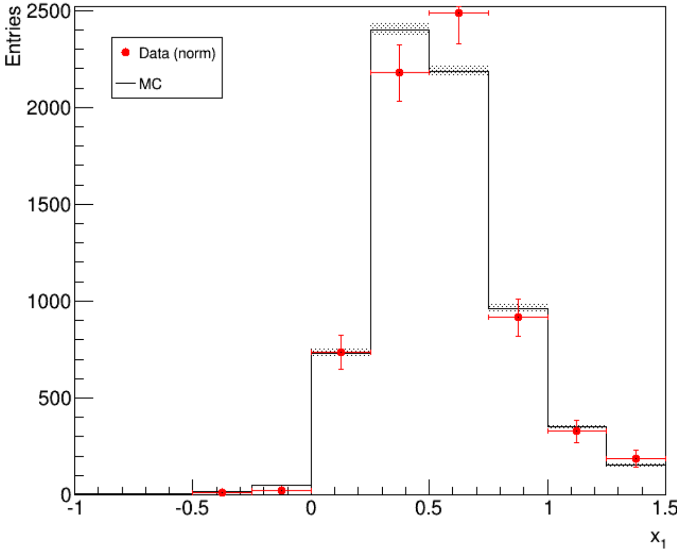


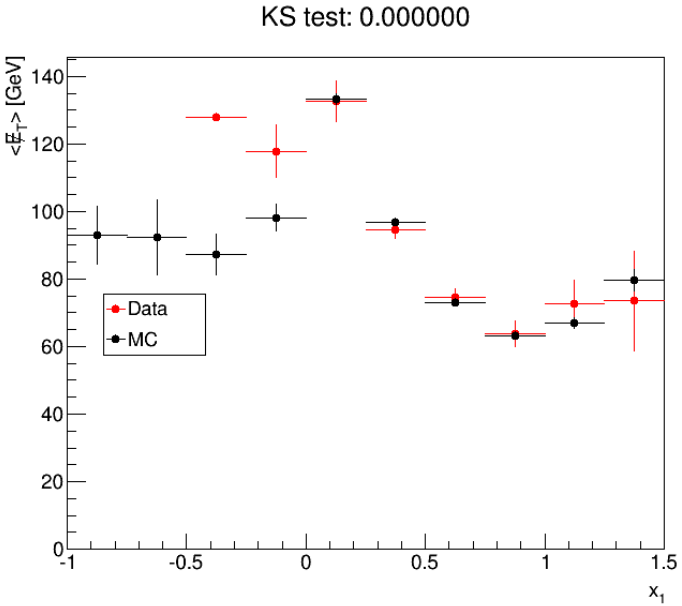
BDT training – DQ and variables selection

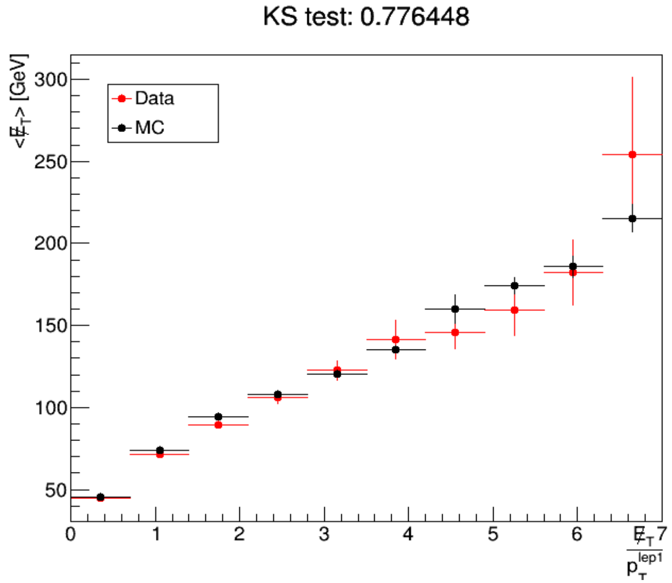
Starter Pack Selection

- Boosted SF – 34 variables
- Boosted DF – 34 variables
- VBF SF – 40 variables
- VBF DF – 40 variables







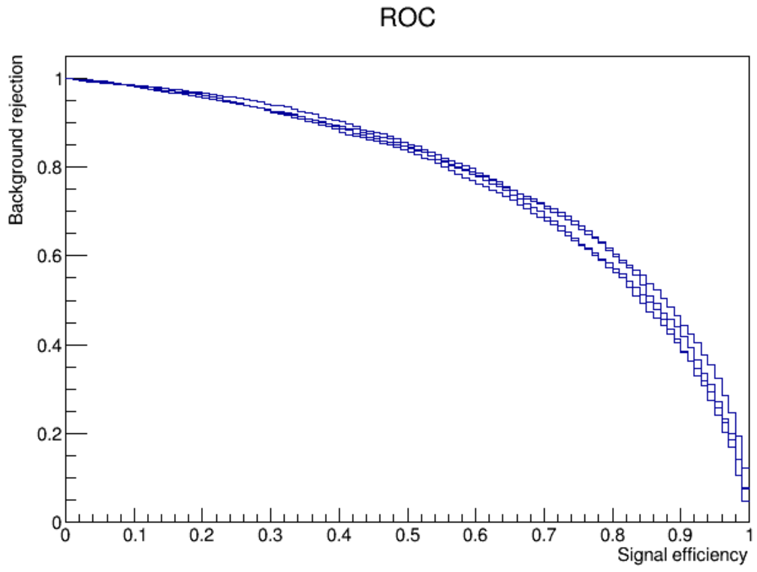


NONE was excluded

BDT training – DQ and variables selection

Starter Pack Selection

- Boosted SF – 34 variables
- Boosted DF – 34 variables
- VBF SF – 40 variables
- VBF DF – 40 variables



Final List of Variables

VBF

SF

E_T^{miss}
m_{ll}, m_{jj}
p_T^{jet1}, p_T^{jet2}
p_T^{tot}
$m_{ll,jet1}$
$m_{l1,l2,j1}, m_{l1,l2,j2}$
x_1, x_2
$\min \Delta\eta \, (l_1, l_2, jets)$
$\min \Delta R \, (l_2, jets)$
ΔR_{ll}
$N(jets > 30\text{GeV})$
E_T^{miss}/p_T^{lep2}

DF

E_T^{miss}
m_{ll}, m_{jj}
m_T^{lep1}, m_T^{lep2}
p_T^{jet1}, p_T^{jet2}
p_T^{tot}
$m_{l1,l2,j2}$
$\min \Delta\eta \, (l_1, l_2, jets)$
ΔR_{ll}
$N(jets > 30\text{GeV})$
E_T^{miss}/p_T^{lep1}
E_T^{miss}/p_T^{lep2}

Boosted

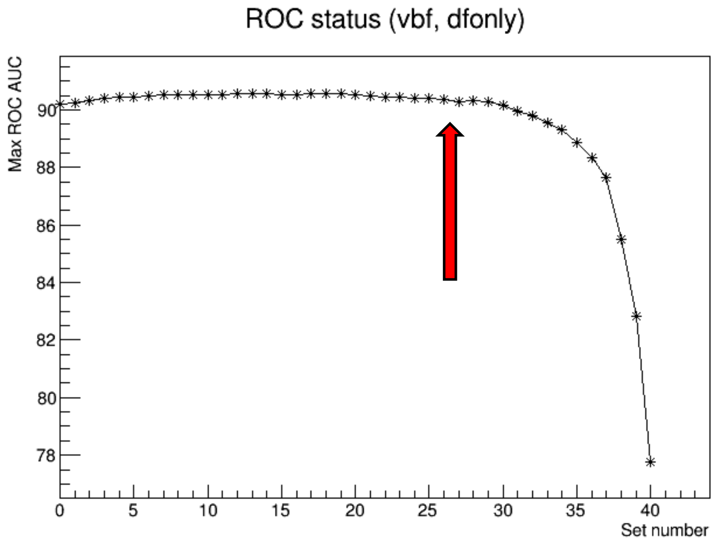
SF

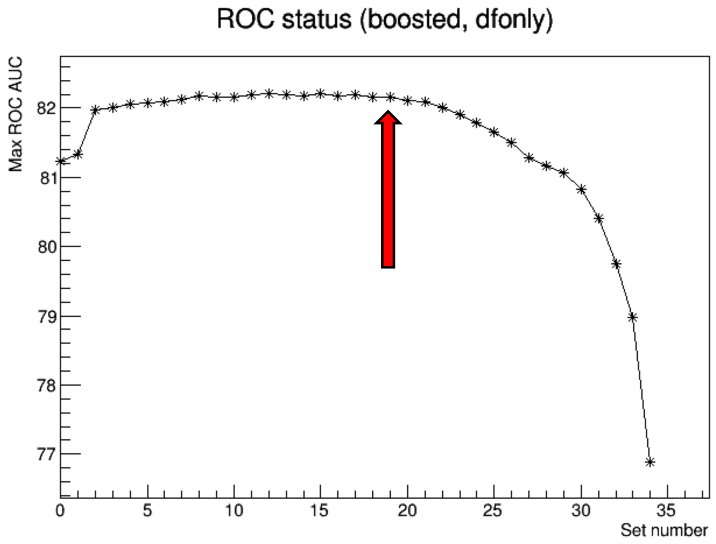
m_{ll}, m_{jj}
p_T^{jet2}
p_T^{tot}
$m_{ll,jet1}$
m_T^{lep1}
x_1, x_2
η_{ll}
$Sphericity$
$\min \Delta R \, (l_1, jets)$
ΔR_{ll}
E_T^{miss}/p_T^{lep1}
E_T^{miss}/p_T^{lep2}

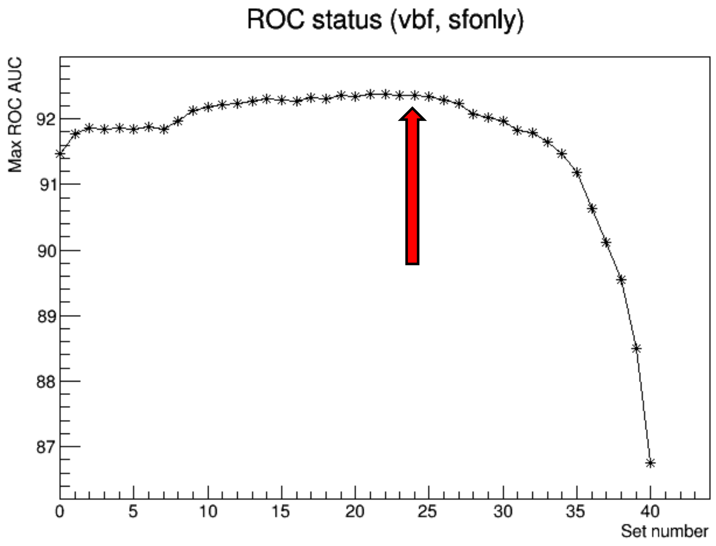
DF

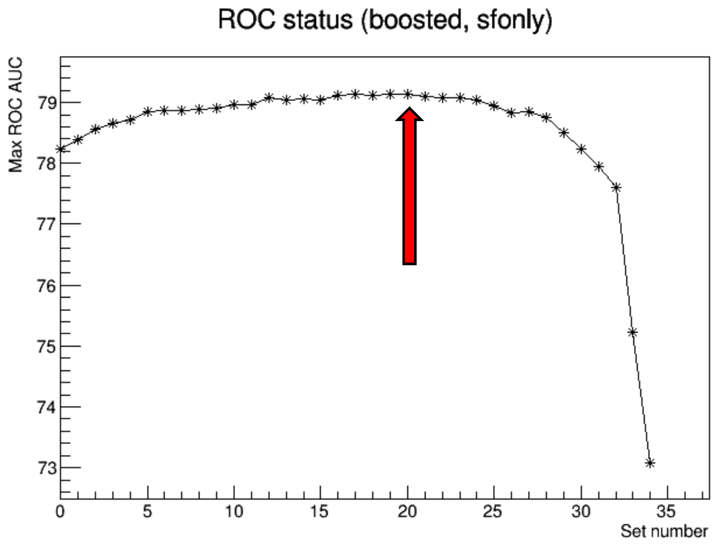
m_{ll}
p_T^{jet1}, p_T^{jet2}
p_T^{tot}
$m_{ll,jet1}, m_{l1,l2,j1}$
m_T^{lep1}
x_1, x_2
p_T^{Higgs}
$Sphericity$
$\min \Delta R \, (l_1, jets)$
ΔR_{ll}
E_T^{miss}/p_T^{lep1}
E_T^{miss}/p_T^{lep2}

BDT training – DQ and variables selection



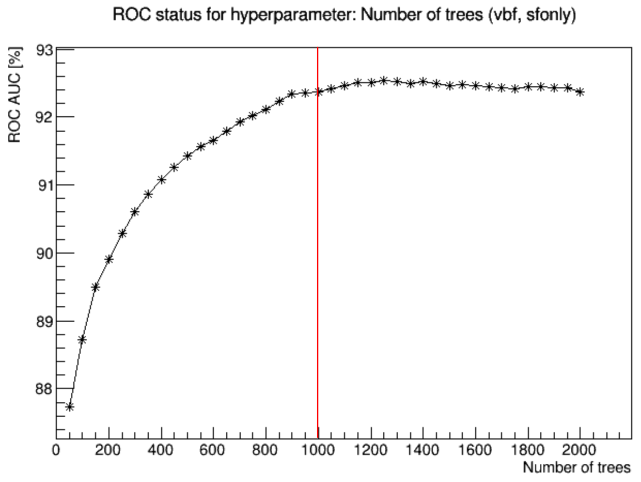


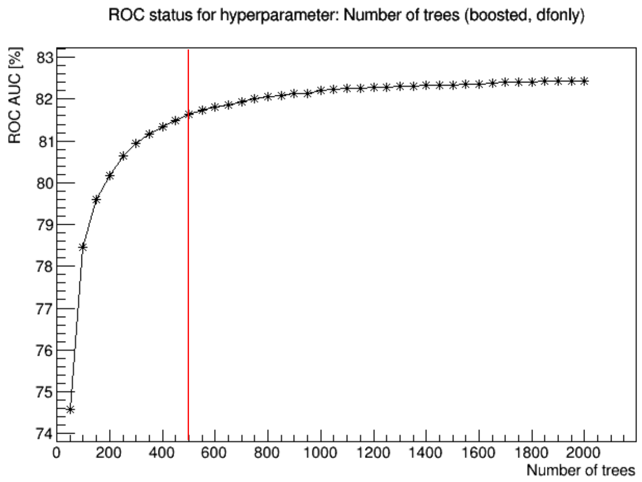




BDT training – Hyperparameters optimization

	BOOSTED		VBF	
	SF	DF	SF	DF
number of trees	400	550	1000	250
tree depth	3	5	3	3
minimum node size	6%	7%	3.5%	6%
shrinkage	0.3	0.2	0.3	0.3

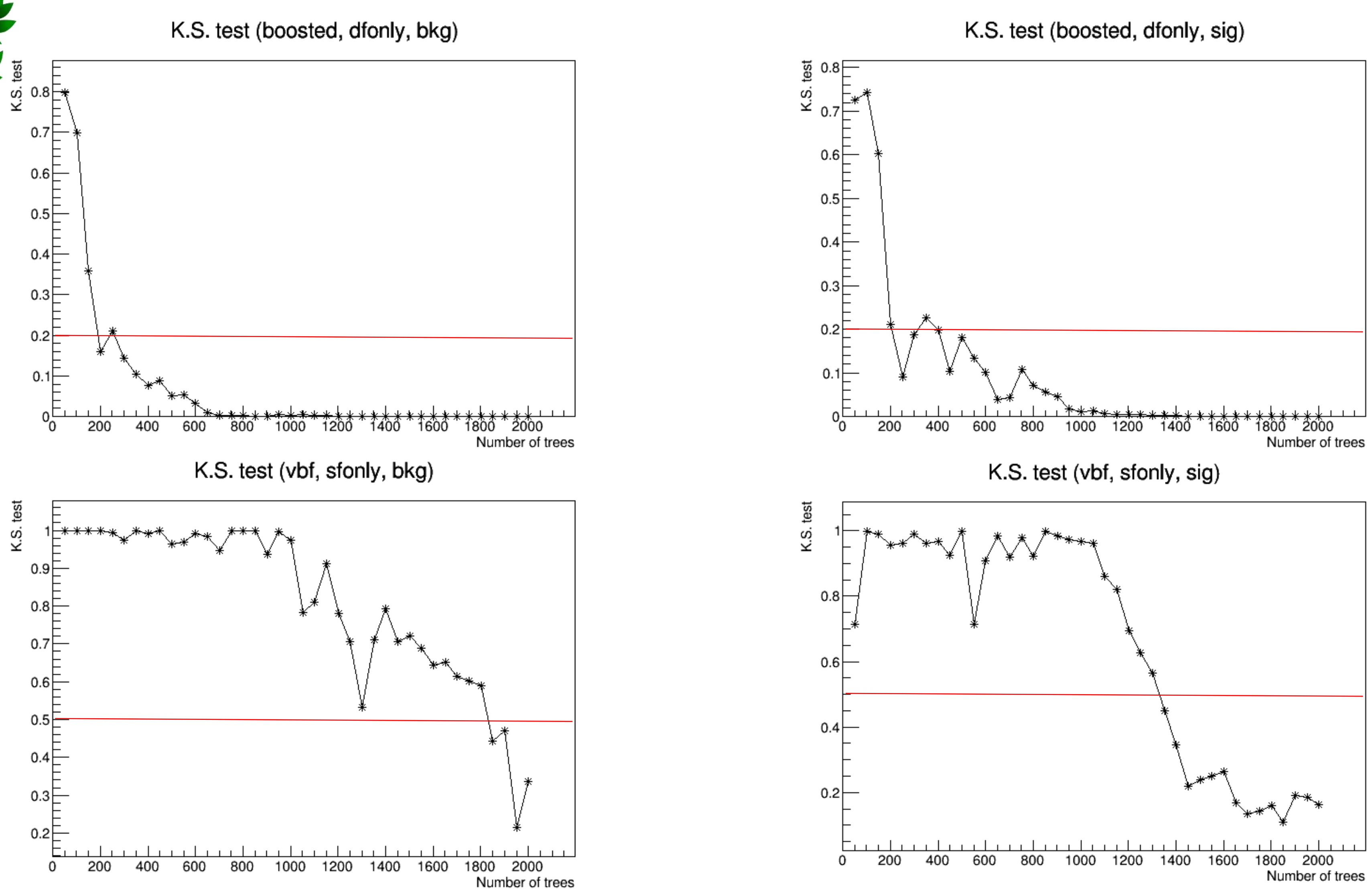




Other parameters

number of selection cuts per node $\boldsymbol{N_C = 20}$
negative weights treatment: we have **PRAY**ed
pre-training transformation: **Gauss**

BDT training – Hyperparameters optimization



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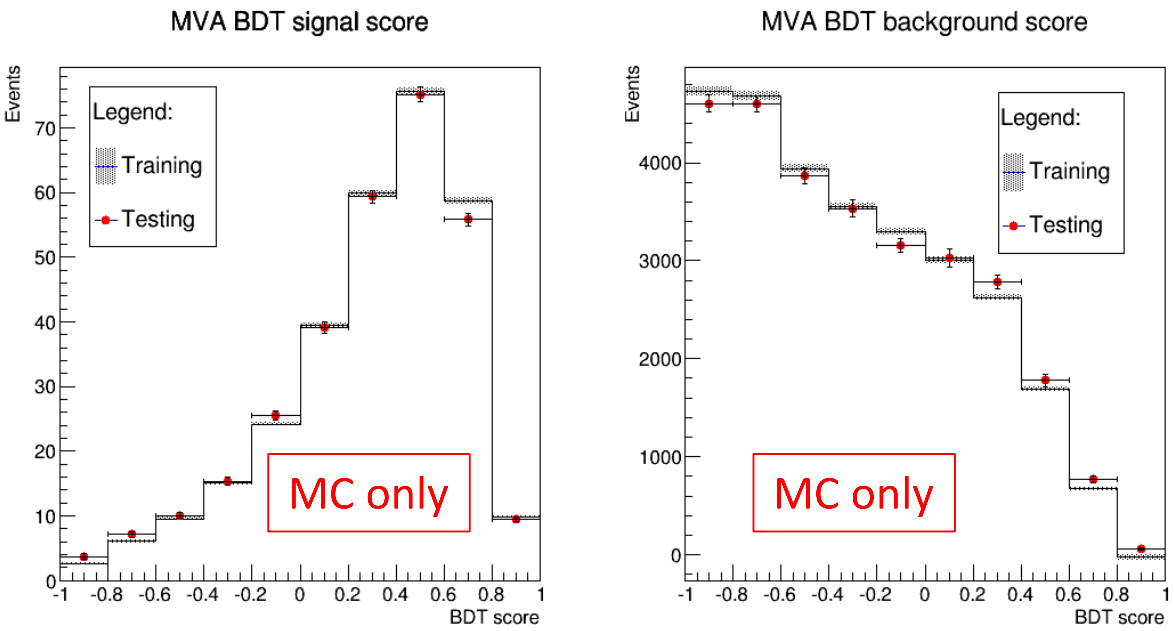
BDT score

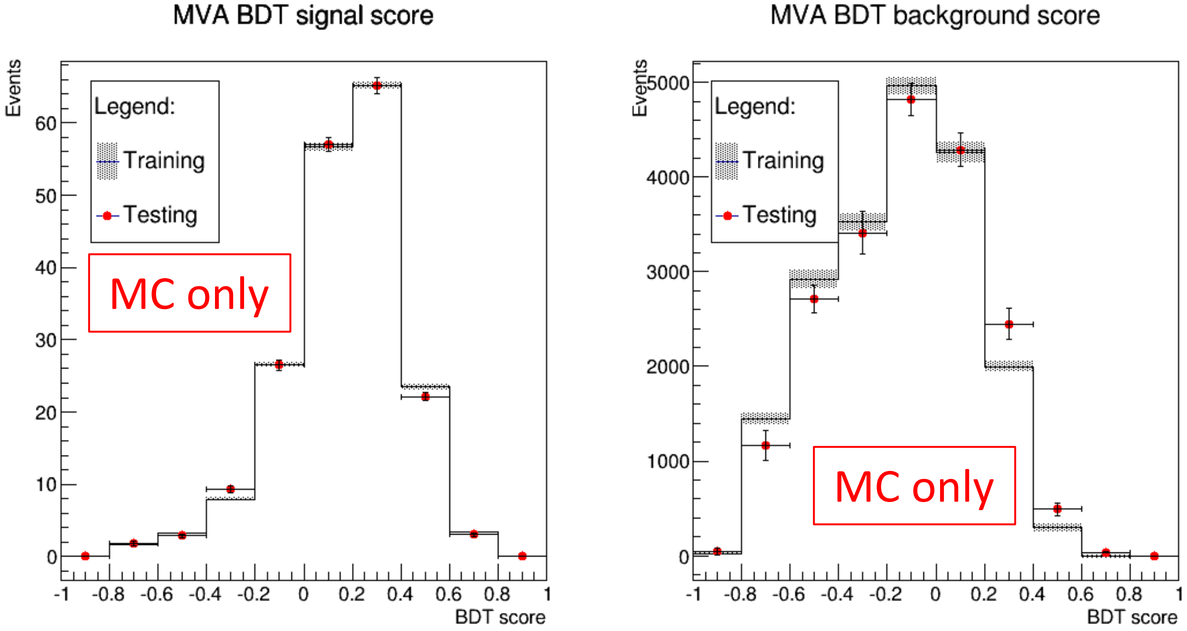
Boosted DF



Workflow

- trigger selection and preselection
- MC modelling profiles
- variables reduction
- BDT hyperparameter optimization
- overtraining test
- **BDT score calculation (event by event – testing data)**
- **the best BDT score cut – the best SIG vs. BKG separation**

Boosted SF



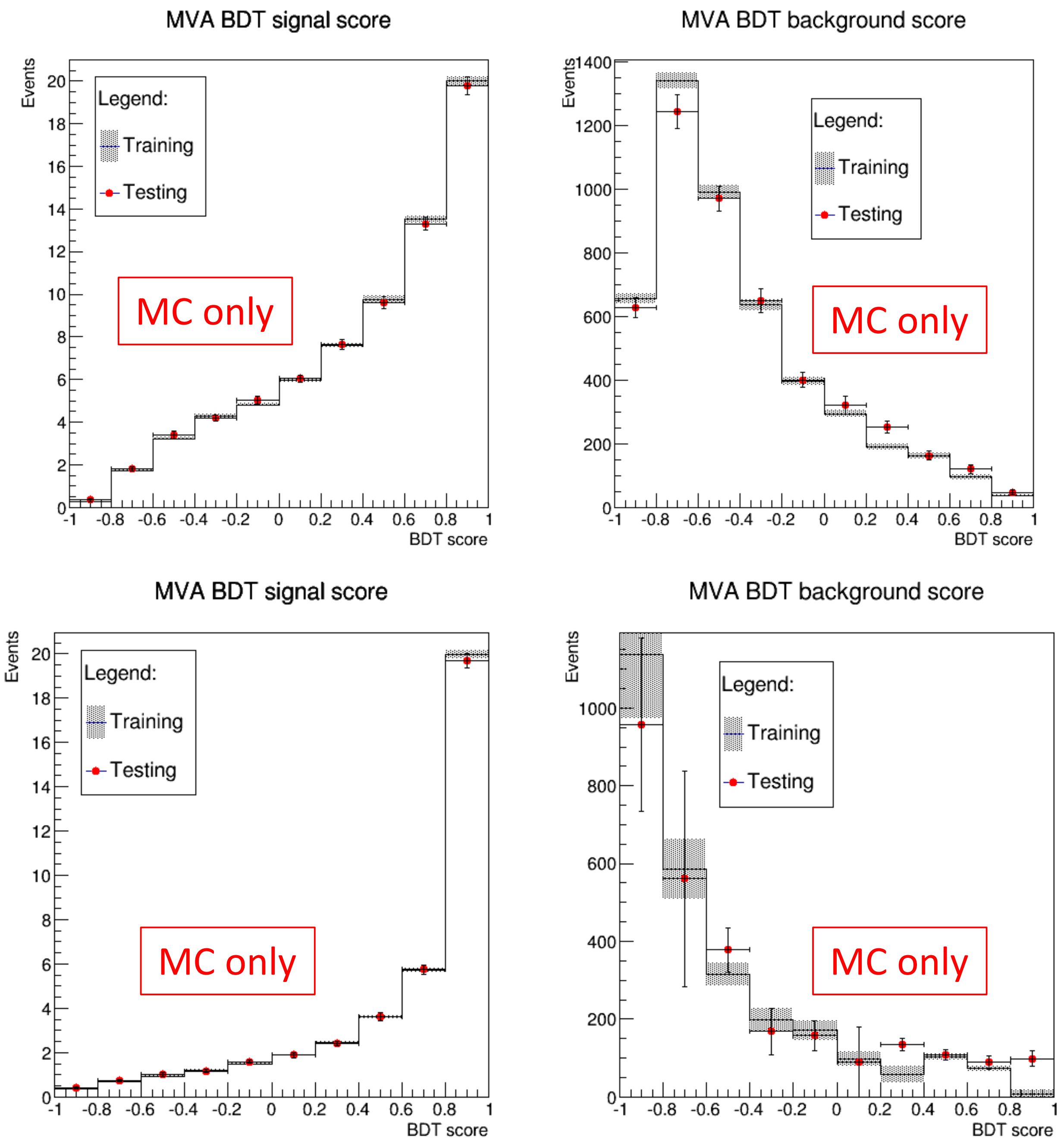
BDT score

VBF
DF

Workflow

- ➢ trigger selection and preselection
- ➢ MC modelling profiles
- ➢ variables reduction
- ➢ BDT hyperparameter optimization
- ➢ overtraining test
- ➢ **BDT score calculation (event by event – testing data)**
- ➢ **the best BDT score cut – the best SIG vs. BKG separation**

VBF
SF



BDT score

+1 -1

Definition: Likelihood estimation of event being signal or background

the better BDT cut – the better SIG/BKG selection

determined by calculation of

Profile Likelihood Ratio

Expected significance *Z*

Express how likely it is, that expected signal has outreached background noises only by chance

Significance estimation

Systematic errors

- Theoretical systematics
  - signal cross section uncertainties (higher order corrections)
  - ggH + 1 or 2 exclusive jets (QCD corrections)
  - background acceptances (higher order corrections)
  - PDFs uncertainties
  - parton shower distribution

- Experimental systematics
  - triggering efficiencies
  - object identification and reconstruction uncertainties
  - energy scale
  - luminosity uncertainties

- Background modelling
  - $Z \rightarrow \tau\tau$ control region
  - shape of the $m_{\tau\tau}^{MMC}$ distribution
  - Shape and normalization of the fake-lepton background

BDT score

Final BDT selection and Significance (expected)

	BDT score >	$Z_{expected}$
Boosted SF	-0.1	0.18
Boosted DF	-1.0	0.42
VBF SF	0.6	0.44
VBF DF	0.8	0.88

$$Z_{expected}^{combined} = 1.16$$

Summary

Final BDT selection and Significance (expected)

	BDT score >	$Z_{expected}$
Boosted SF	-0.1	0.18
Boosted DF	-1.0	0.42
VBF SF	0.6	0.44
VBF DF	0.8	0.88

MVA BDT $\tau_{lep}\tau_{lep}$ $\quad Z_{expected}^{combined} = 1.16$

Cut based $\tau_{lep}\tau_{lep}$ $\quad Z_{expected}^{combined} = 1.18$

Reference

[1] SCHEIRICH, Daniel, 2013. *Measurements of* Λ *and* Λ_b *baryon properties in the ATLAS experiment*. Michigan. Dissertation thesis. University of Michigan.

[2] VIRDEE, T. S., 2012. Physics requirements for the design of the ATLAS and CMS experiments at the Large Hadron Collider. *Phil. Trans. R. Soc.* **370**, s. 876-891. ISSN 1364-503X.

[3] DAVÍDEK, Tomáš a LEITNER, Rupert, 2012. *Elementární částice od prvních objevů po současné experimenty*. Praha: MATFYZPRESS. ISBN 978-80-7378-205-4.

[4] THE ATLAS COLLABORATION, 2008. *Expected performance of the ATLAS experiment: detector, trigger and physics* [online]. CERN-OPEN-2008-020 [cit. 16.4.2017]. Available: http://cds.cern.ch/record/1125884

[5] HOŘEJŠÍ, Jiří. *Historie standardního modelu mikrosvěta* [online]. Praha: Ústav částicové a jaderné fyziky MFF UK [cit. 16.4.2017]. Available: http://www-ucjf.troja.mff.cuni.cz/new/wp-content/uploads/2014/02/smodel.pdf

Reference

[6] THE ATLAS COLLABORATION, 2012. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B.* **716(**1), s. 1-29.

[7] CEJNAR, Pavel, 2013. *A Condensed Course of Quantum Mechanics.* Praha: Karolinum Press. ISBN 978-80-246-2321-4.

[8] *Standard Model*, 2016 [online]. Wikipedia. Posledná zmena 12.05.2016 10:22 [cit. 16.4.2017]. Available: https://en.wikipedia.org/wiki/Standard_Model

[9] C. Patrignani et al. (Particle Data Group). The Review of Particle Physics, 2016. Chin. Phys. C, **40**, 100001.

[10] BARGER, V., MARFATIA, D. a WHISNANT, K. L., 2012. *The Physics of Neutrinos.* Princeton University Press. ISBN 978-06-9112-853-5.

[11] CONTEMPORARY PHYSICS EDUCATION PROJECT, český preklad KOTRBOVÁ, Olga. *Standardní model: Základní částice a interakce* [online], [cit. 16.4.2017]. Available: http://www-ucjf.troja.mff.cuni.cz/dolejsi/outreach/standardni_model_1.pdf

Reference

[12] BELYAEV, Alexander, 2014. *Nuclei and Particles* [online], [cit. 16.4.2017]. Available: http://www.personal.soton.ac.uk/ab1u06/webpage/phys3002.html

[13] BENTVELSEN, Stan, LAENEN, Eric a MOTYLINSKI, Patrick, 2005. *Higgs production through gluon fusion at leading order* [online]. Amsterdam: National Institute for Subatomic Physics [cit. 16.4.2017]. Available: http://www.nikhef.nl/pub/services/biblio/preprints/05-007.pdf

[14] KRÄMER, Michael, 2005. *Higgs Production at the LHC* [online]. Universität Bielefeld [cit. 16.4.2017]. Available: https://web.physik.rwth-aachen.de/~mkraemer/Higgs-Production-at-the-LHC.pdf

[15] GRAZZINI, Massimiliano, 2011. *Higgs cross sections: a brief overview* [online]. Zurich: Institute for Theoretical Physics, University of Zurich [cit. 16.4.2017].
Available: https://indico.in2p3.fr/event/6004/session/8/contribution/111/material/paper/0.pdf

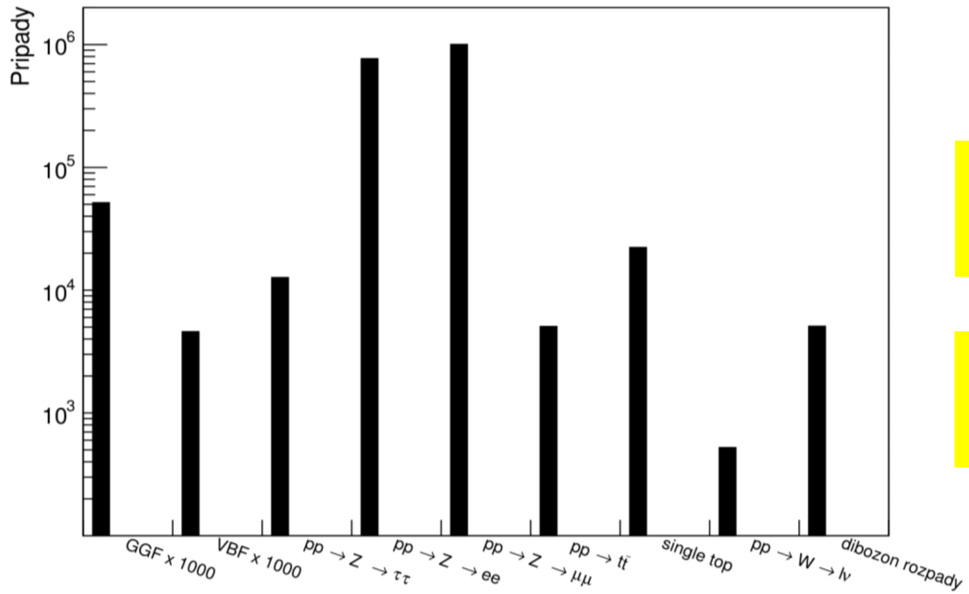
[16] DJOUADI, A., KALINOWSKI, J. a SPIRA, M., 1998. HDECAY: a program for Higgs boson decays in the Standard Model and its supersymmetric extension. *Computer Physics Communications.* **108**(1), s. 56-74. ISSN 0010-4655.

[17] THE ATLAS COLLABORATION, 2015. Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector. *JHEP* **04**, s. 117. ISSN 1029-8479.

Appendices

Monte Carlo simulation

- signal + background,
- various processes ↔ various weights,
- perturbative method



cross section σ

luminosity $\mathcal{L}$

integrated luminosity $\mathcal{L}_{\text{int}}$

$$\frac{dN}{dt} = \sigma\mathcal{L}(\mathrm{t})$$

$$N = \sigma\mathcal{L}_{int}$$

$$\mathcal{L}_{int} = 1411.26\ \mathrm{pb}^{-1}$$

$$\sigma \to \sigma'$$

branching ratio Br

$$\sigma' = \sigma(pp \to Z) \cdot Br(Z^0 \to e^+e^-)$$

detector efficiency ε

$$\varepsilon = \frac{\sum_{rec,i} w_i{}^{MC}}{\sum_{gen,i} w_i{}^{MC}}$$

$$N = \sum_{rec,i} \underbrace{\frac{\sigma' \mathcal{L}_{int} w_i{}^{MC}}{\sum_{gen,i} w_i{}^{MC}}}_{\substack{MC\ event \\ total\ weight}}$$

Appendices – Preselection (2016)

Trigger selection

- $p_T^e > 15$ GeV,
- $p_T^\mu > 10$ GeV,
- $|\eta| < 2{,}47$,

Quality of lepton reconstruction

- purity ↔ reconstruction efficiency

Lepton isolation

- „free isolation“ $\varepsilon = \frac{N_{iso,lep}}{N_{lep}} = 99\%$,

Invariant mass

- $m_{ll} < 100$ GeV ($l_1 \neq l_2$),
- $m_{ll} < 80$ GeV ($l_1 = l_2$),

Charge conservation, dilepton decays

pseudorapidity η

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

θ polar angle

invariant mass

$$m_{ll}{}^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

$E_i, \vec{p_i}$ lepton energy and momentum

Appendices – Preselection (2016)

Collinear approximation

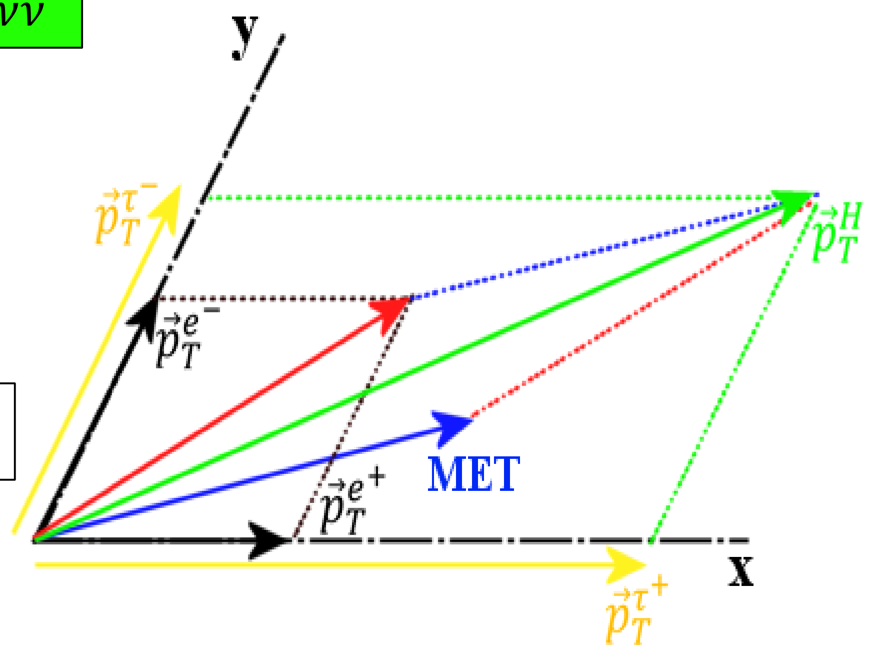
$H^0 \to \tau^+\tau^- \to l^+\bar{\nu}\nu l^-\bar{\nu}\nu$

- neutrino flight direction ≈ lepton direction ($m_H \gg m_\tau$),
- ν, l, τ mass neglected,
- azimuthal angle between leptons $\cos\phi > -1$,

$$m_{coll}^2 = \left(p_{l,1} + p_{\nu,1} + p_{l,2} + p_{\nu,2}\right)^2 - \left(\vec{p}_{l,1} + \vec{p}_{\nu,1} + \vec{p}_{l,2} + \vec{p}_{\nu,2}\right)^2$$

- leads to excluding of non physical event reconstruction

$$x_1 = \frac{p_T^{l1}}{p_T^{\tau 1}} \qquad x_2 = \frac{p_T^{l2}}{p_T^{\tau 2}} \qquad \boxed{x_{1,2} \in (0,1)}$$



H^0 mass reconstruction with respect to the collinear approx.

MET ... missing energy transversal