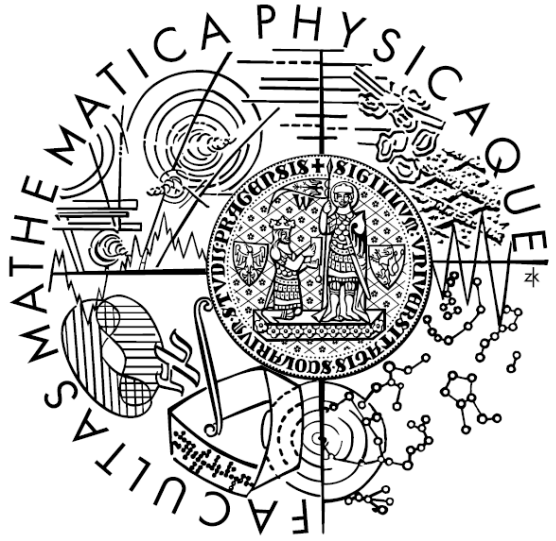
Faculty of Mathematics and Physics

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



Tomáš Kello

Supervisor of the master thesis: Mgr. Daniel Scheirich, Ph.D.

Institute of Particle and Nuclear Physics

Výjezdní seminář, Malá Skála, 2018

Content

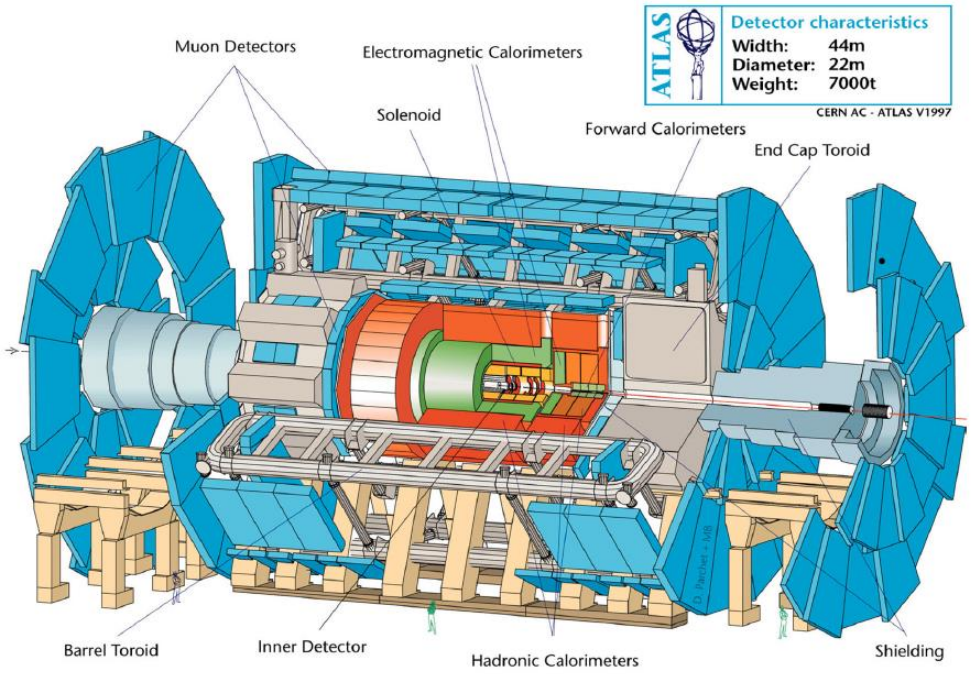
1) ATLAS detector subsystems
2) Higgs boson mechanism
3) Data & MC – preselection and categorisation
4) MVA – Boosted Decision Trees
5) BDT Training
6) Final BDT score cut

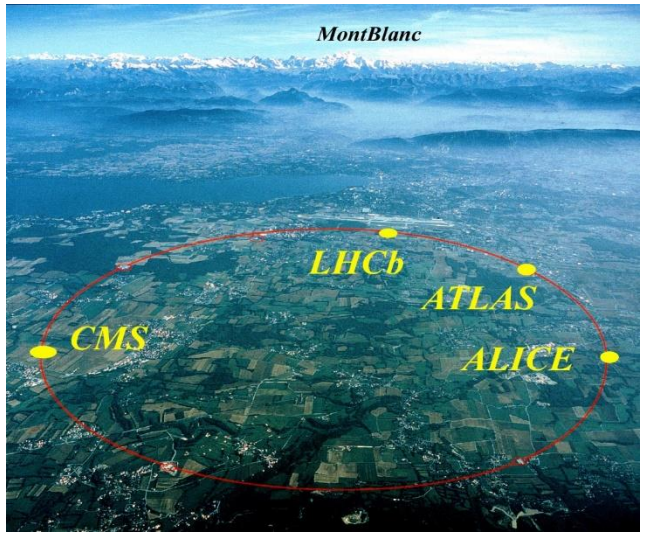
Content

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

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

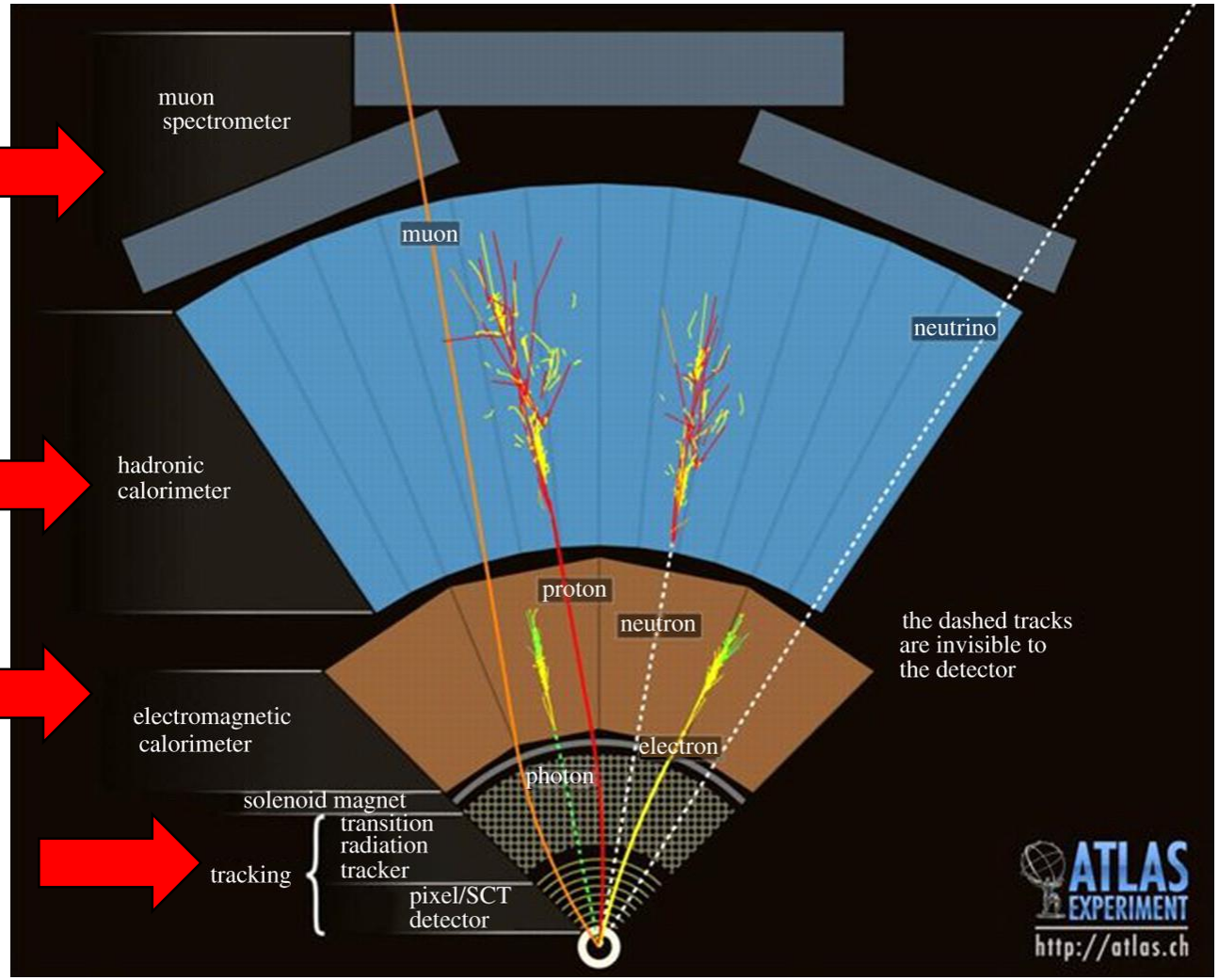
Muon spectrometer

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

System of calorimeters

Inner detector

Solenoid (B=2T)



Content

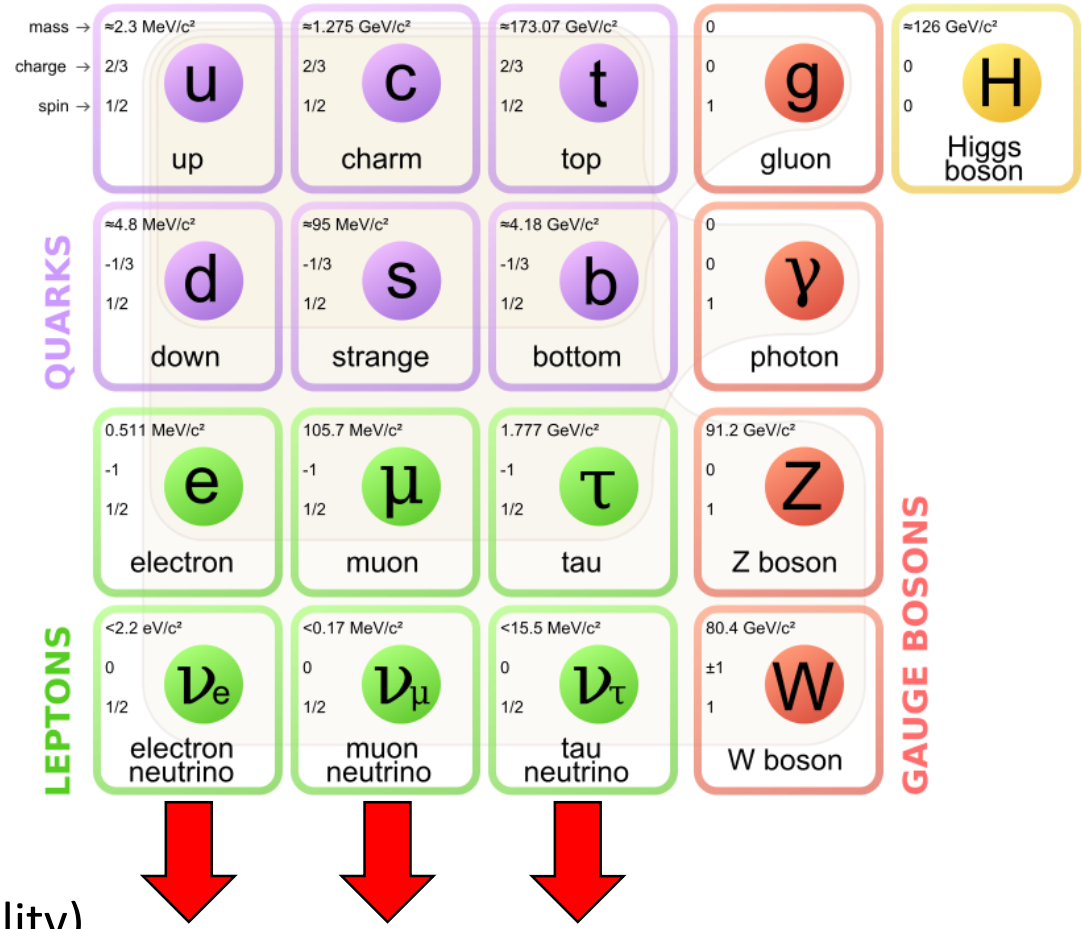
1) ~~ATLAS detector subsystems~~
2) Higgs boson mechanism
3) Data & MC – preselection and categorisation
4) MVA – Boosted Decision Trees
5) BDT Training
6) Final BDT score cut

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)



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 $U(1)$)

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

- **The Goldstone model**

➢ $SU(2) \times U(1)$ symmetry requirement

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

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

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

- $\boldsymbol{SU(2) \times U(1)}$ **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

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

...

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

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

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

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

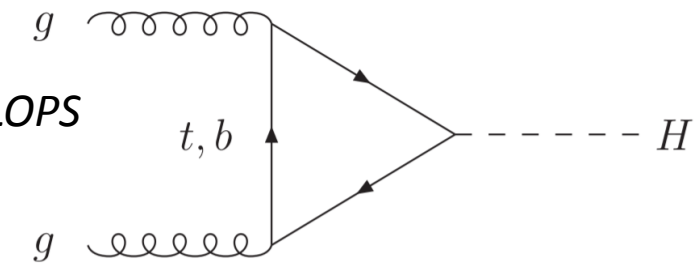
$$m_W = \frac{1}{2}gv \qquad m_Z = \frac{1}{2}v\sqrt{(g^2 + g'^2)}$$

Higgs production

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

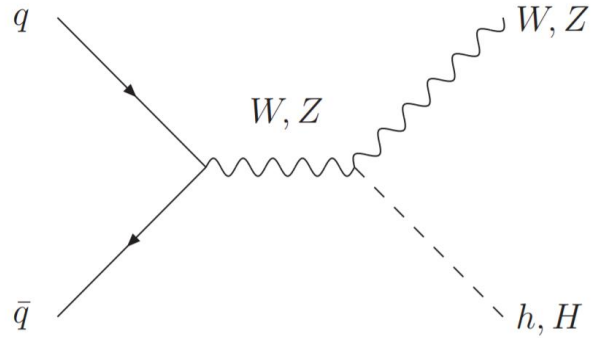
ggF (gluon-gluon fusion)

PowhegNNLOPS



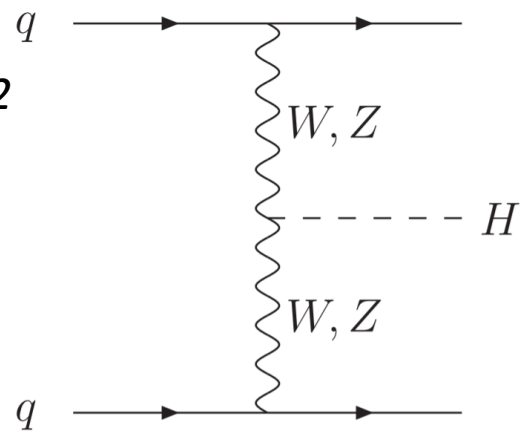
Higgs Strahlung VH

Powheg Box2 (NLO)



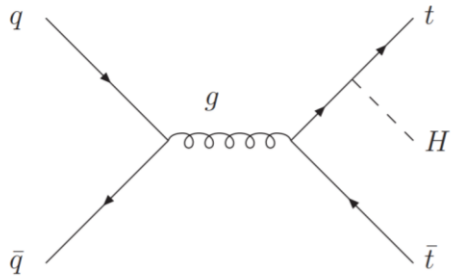
VBF (vector-boson fusion)

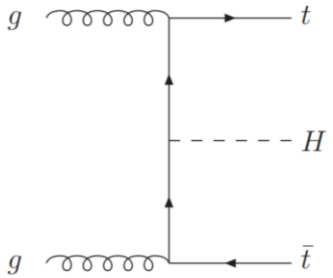
Powheg Box2 (NLO)



$t\bar{t}H$ 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]

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

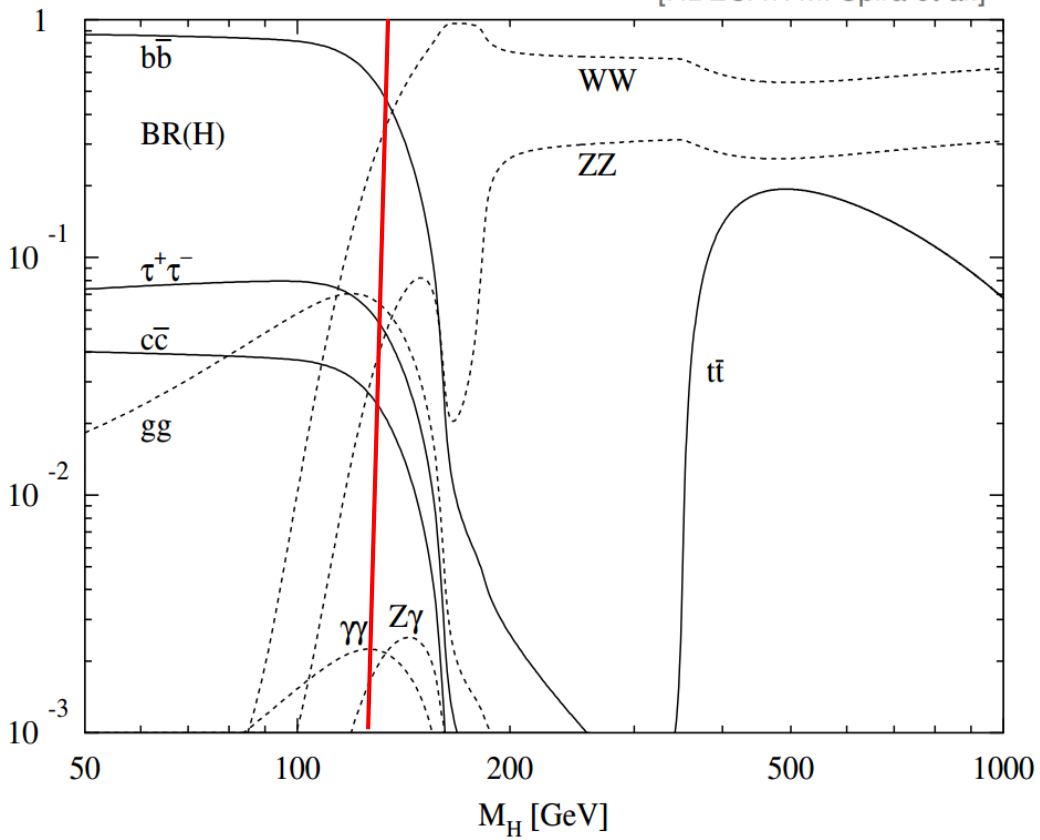
$H^0 \to W^+W^-$

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

$H^0 \to \gamma\gamma$

...

[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)

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

Content

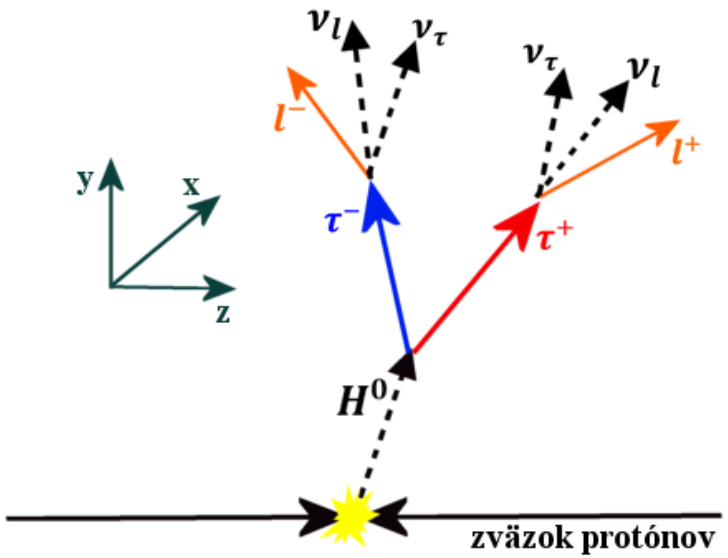
1) ~~ATLAS detector subsystems~~
2) ~~Higgs boson mechanism~~
3) Data & MC – preselection and categorisation
4) MVA – Boosted Decision Trees
5) BDT Training
6) Final BDT score cut

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

$$p_T^{jet2} > 30\text{GeV}$$
$$|\eta_{jj}| > 3$$
$$m_{jj} > 400\text{GeV}$$

Boosted

not VBF

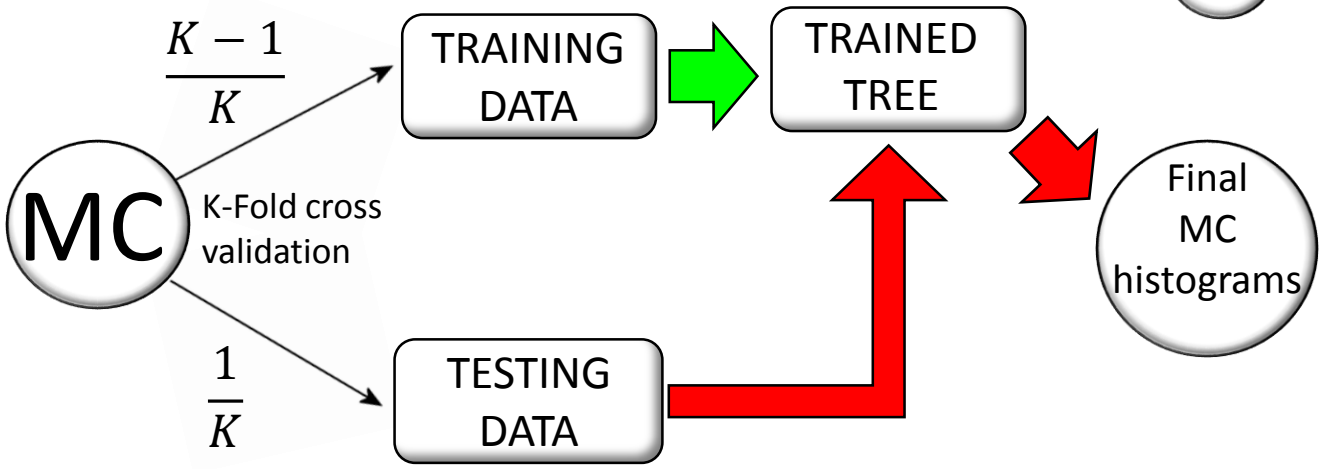
$$p_T^{\tau\tau} > 100\text{GeV}$$

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

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

=

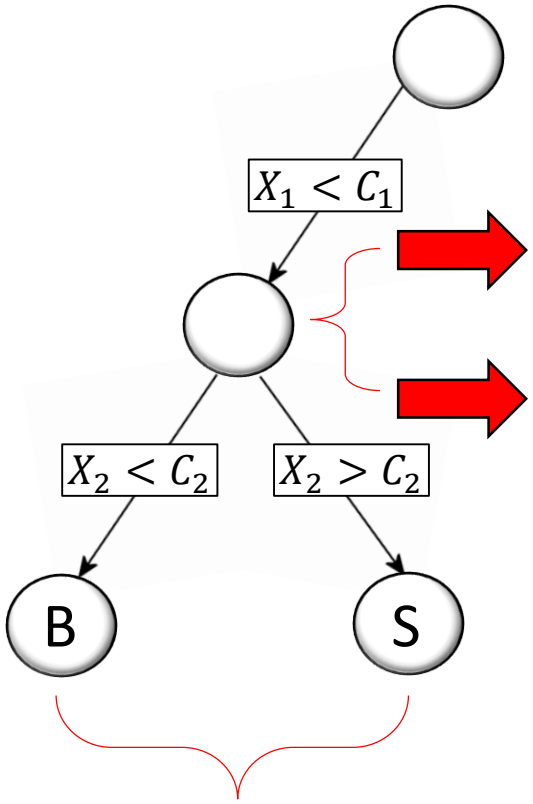
Determining the one variable and the corresponding cut value to get the best MC data separation at each node.

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

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

Training algorithm

TRAINED TREES → Final MC histograms



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 x ... testing sample
P... parameters y ... training sample

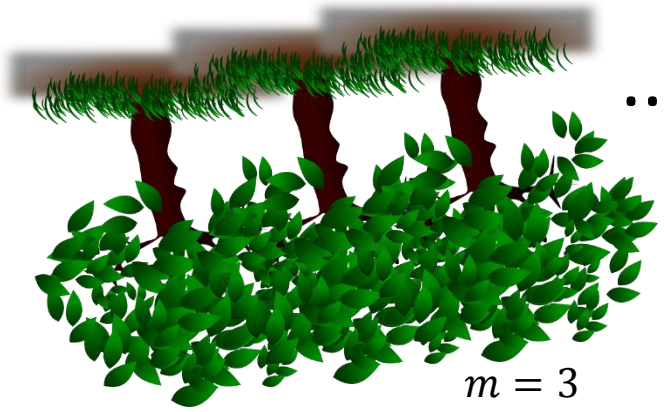
- **loss function minimization**

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

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

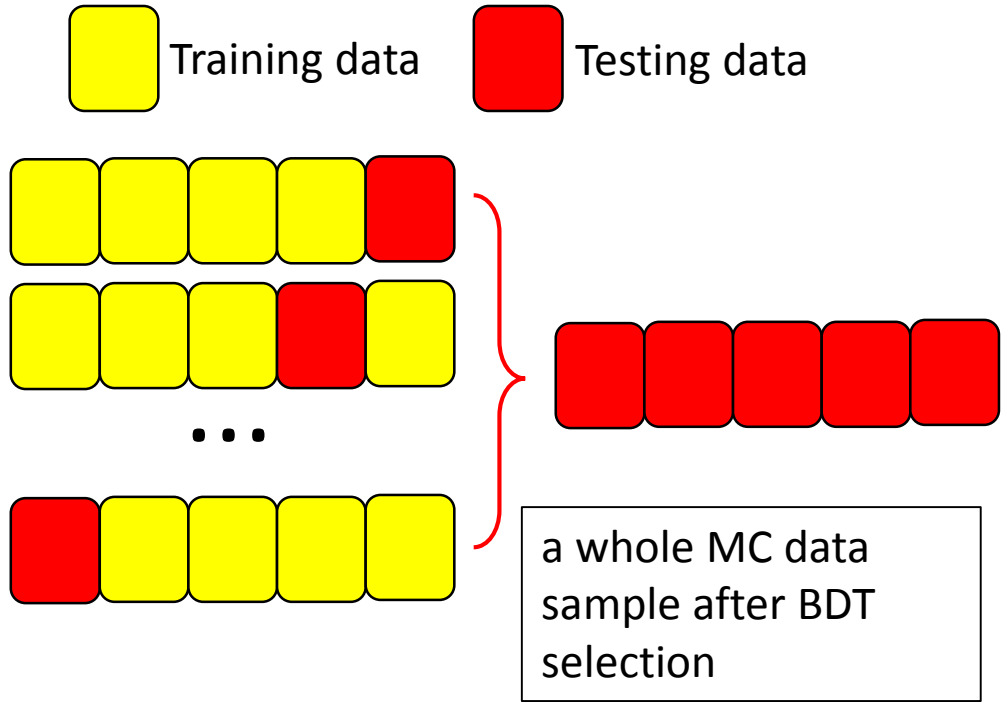
- executed by loss function **gradient calculation**

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



M number of trees in the forest

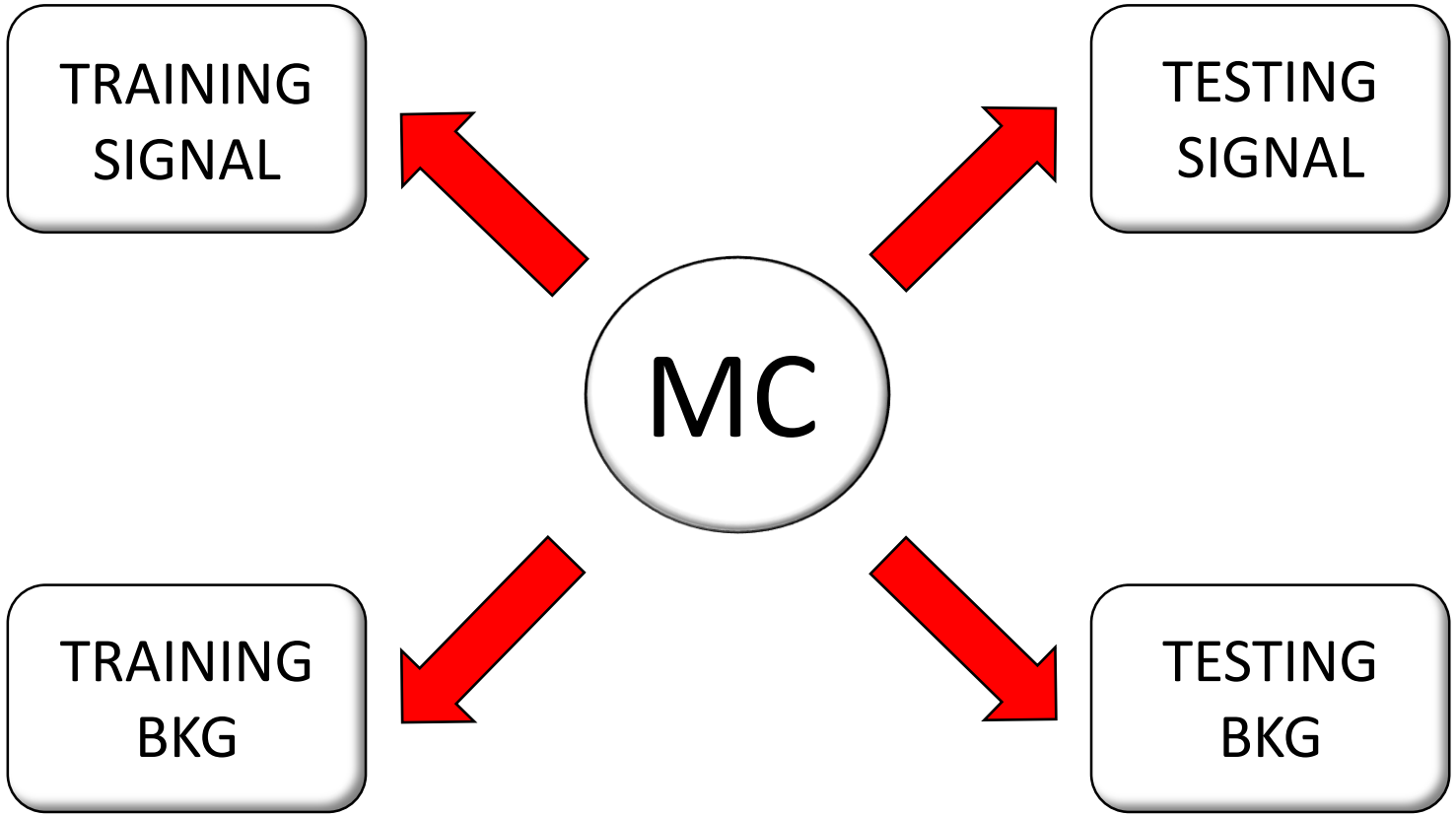
K-Fold cross validation (K=5)



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

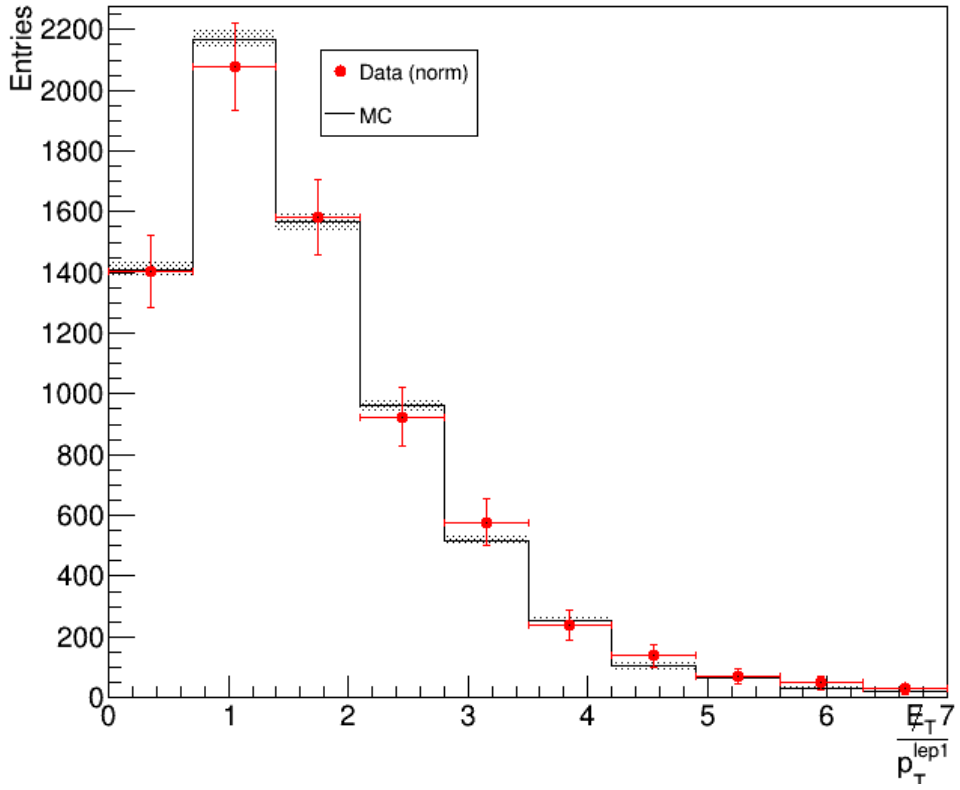
BDT training – splitting data randomly

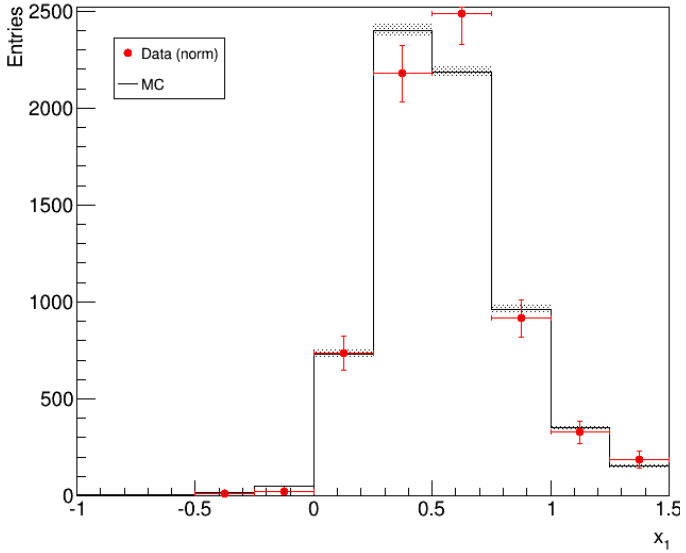


BDT training – DQ and variables selection

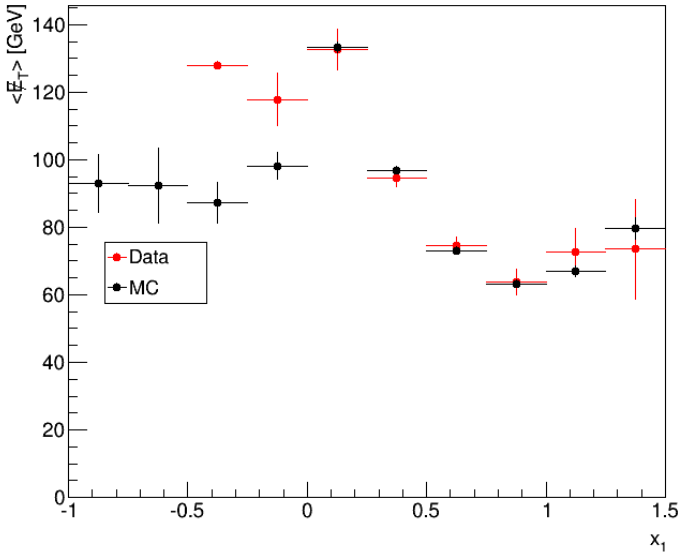
Starter Pack Selection

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

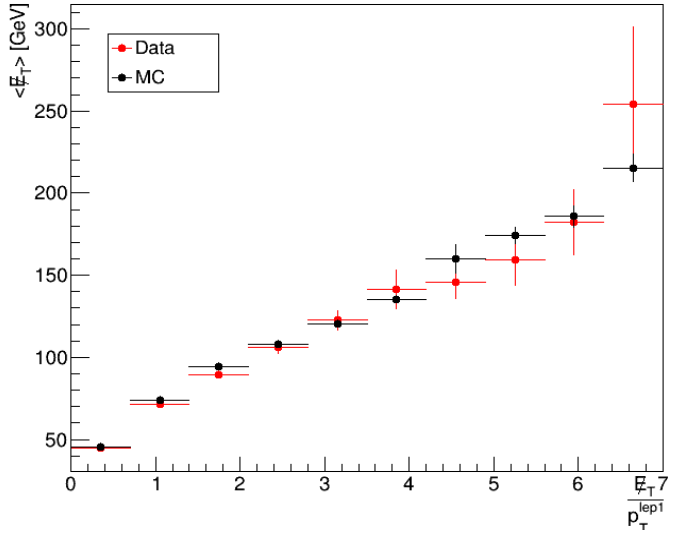




KS test: 0.000000



KS test: 0.776448

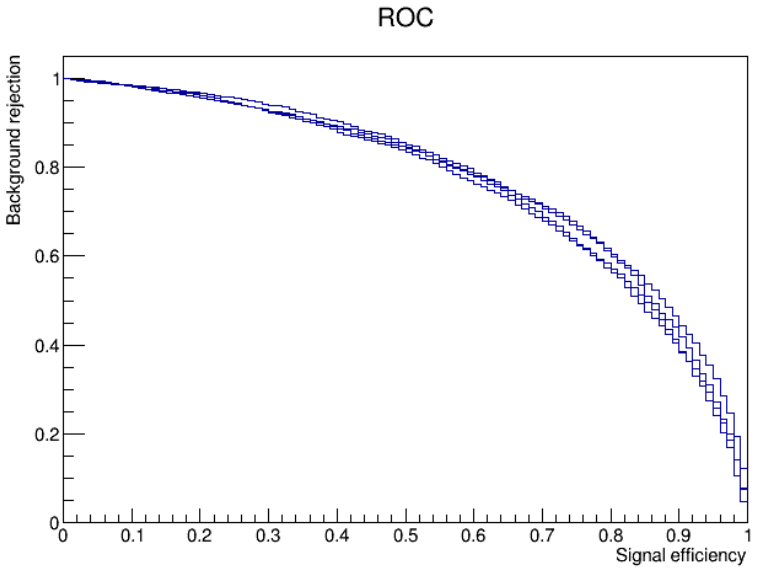


NONE was excluded

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

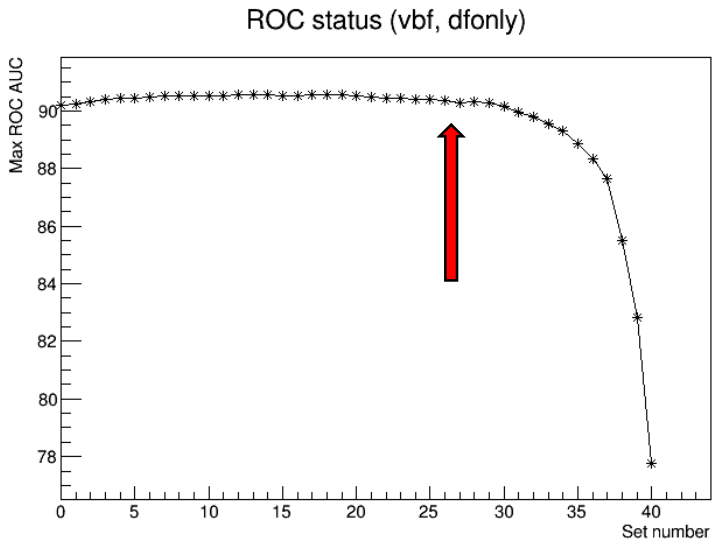
SF

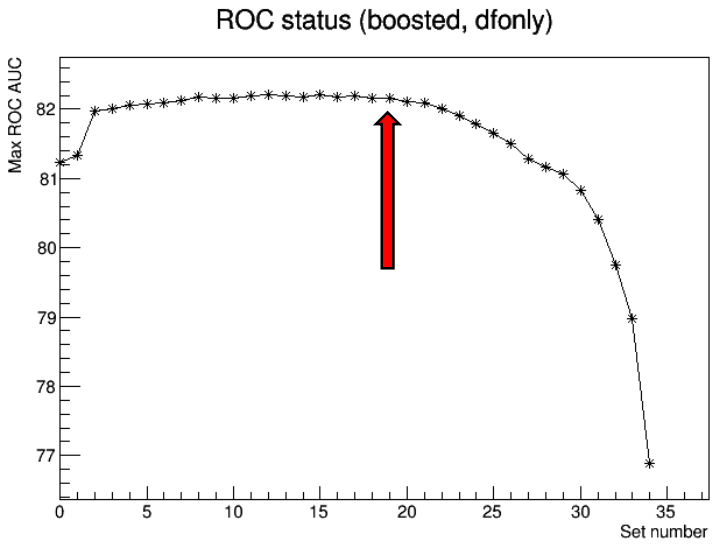
m_{ll}, m_{jj}
p_T^{jet2}
p_T^{tot}
$m_{ll,jet1}$
m_T^{lep1}
x_1, x_2
η_{ll}
Sphericity
$\min \Delta R\ (l_1, jets)$
ΔR_{ll}
E_T^{miss}/p_T^{lep1}
E_T^{miss}/p_T^{lep2}

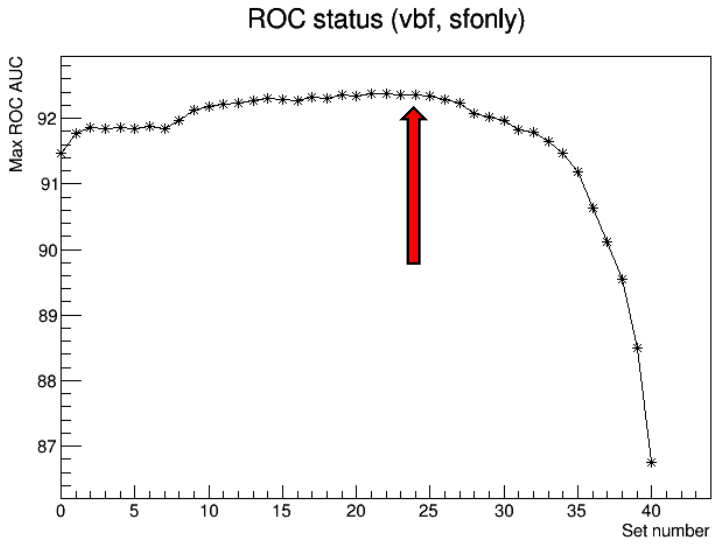
DF

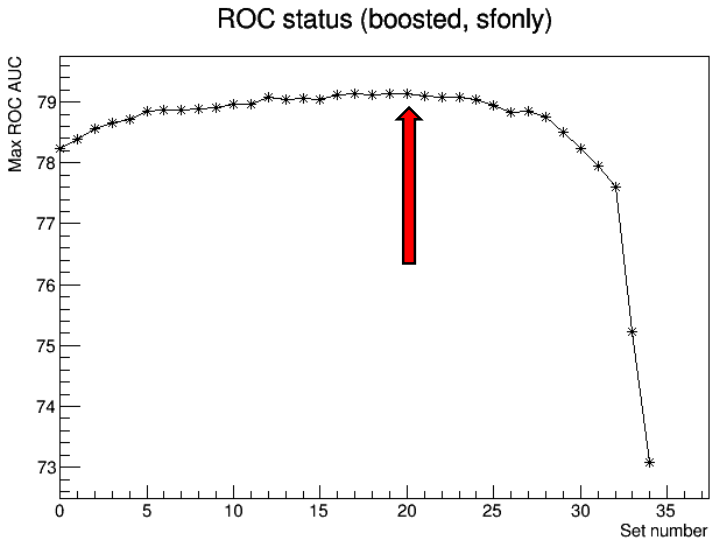
m_{ll}
p_T^{jet1}, p_T^{jet2}
p_T^{tot}
$m_{ll,jet1}, m_{l1,l2,j1}$
m_T^{lep1}
x_1, x_2
p_T^{Higgs}
Sphericity
$\min \Delta R\ (l_1, jets)$
ΔR_{ll}
E_T^{miss}/p_T^{lep1}
E_T^{miss}/p_T^{lep2}

BDT training – DQ and variables selection



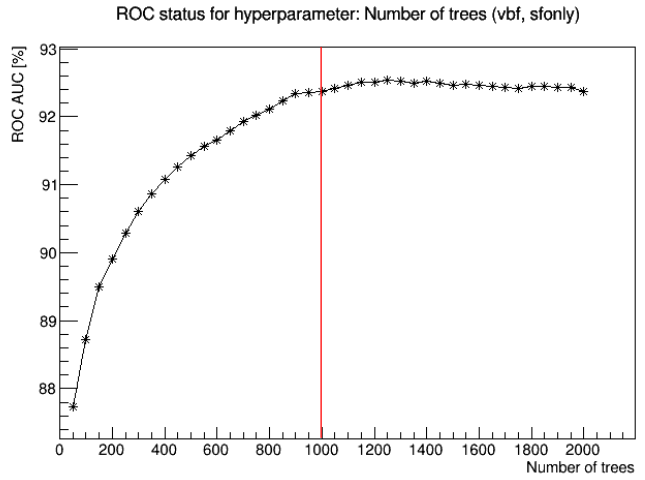


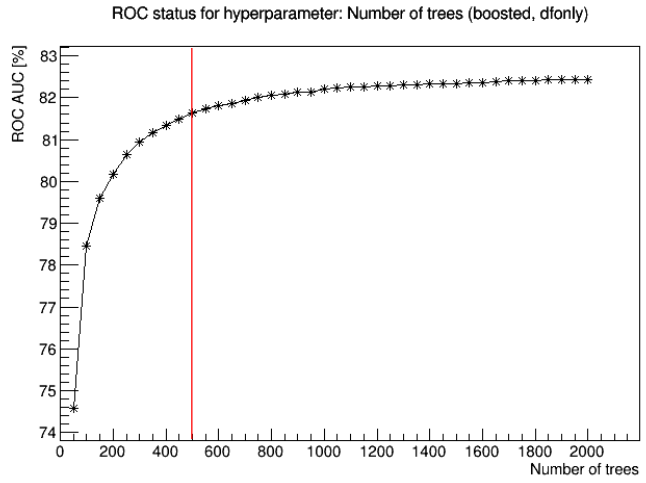




BDT training – Hyperparameters optimization

	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

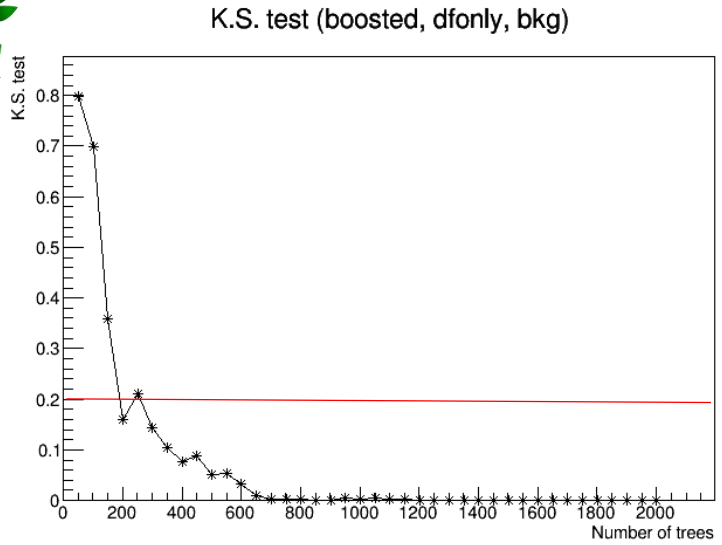


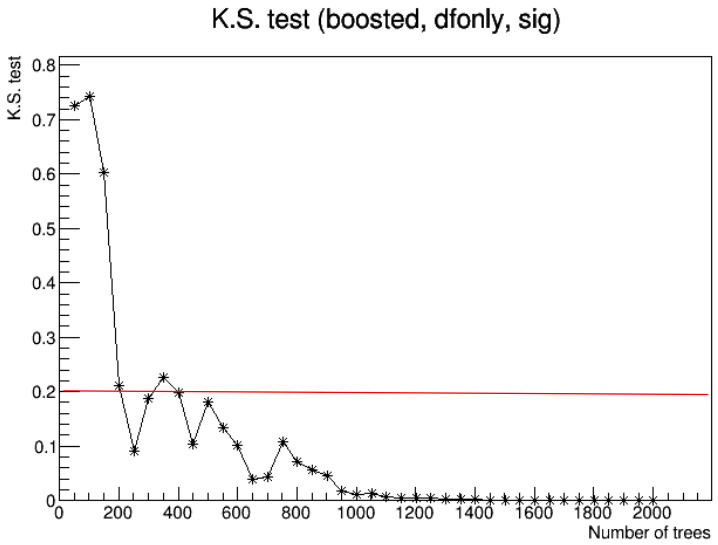


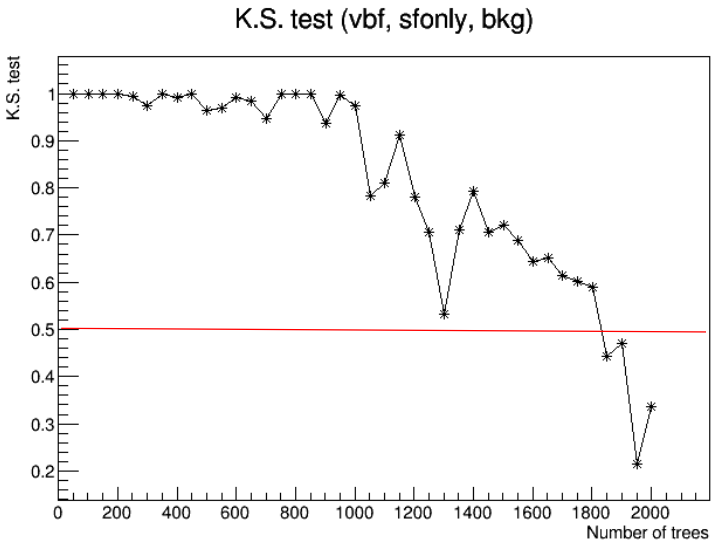
Other parameters

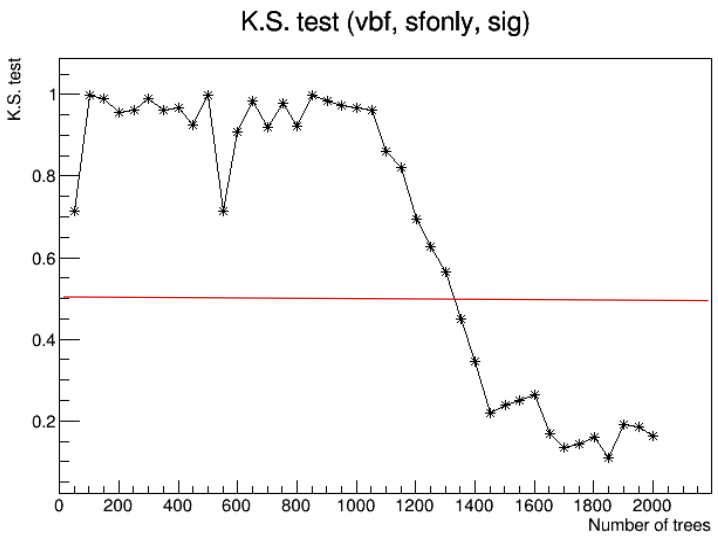
number of selection cuts per node $N_C = 20$
negative weights treatment: we have **PRAY**ed
pre-training transformation: **Gauss**

BDT training – Hyperparameters optimization









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

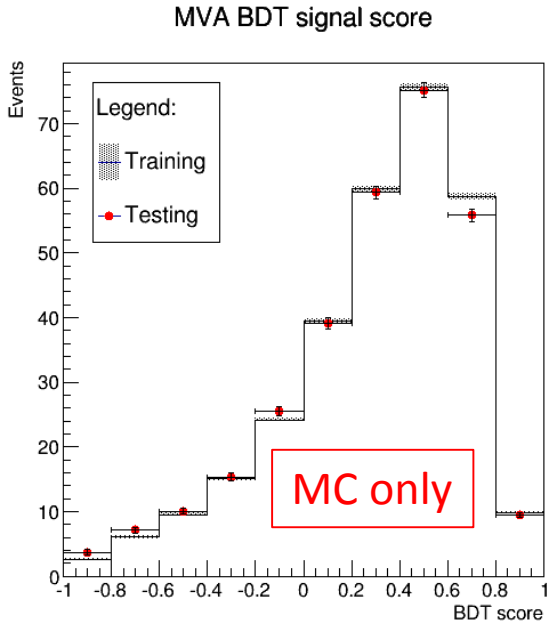
BDT score

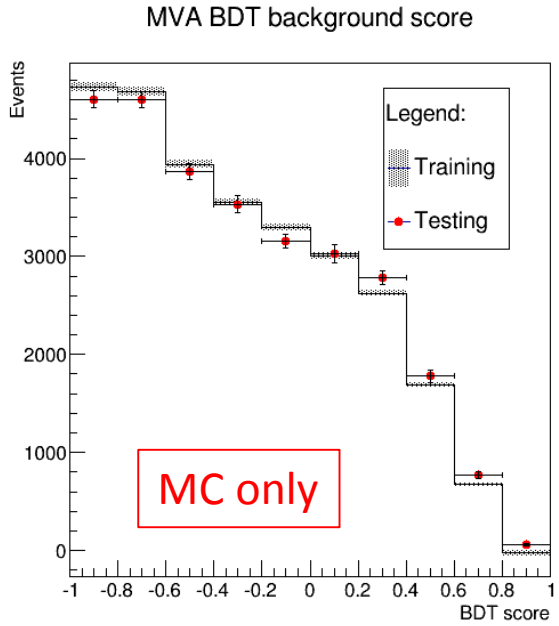
Boosted DF

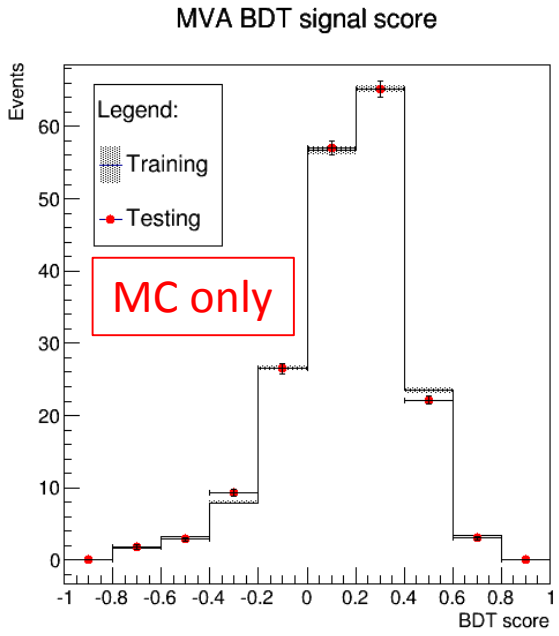
Boosted SF

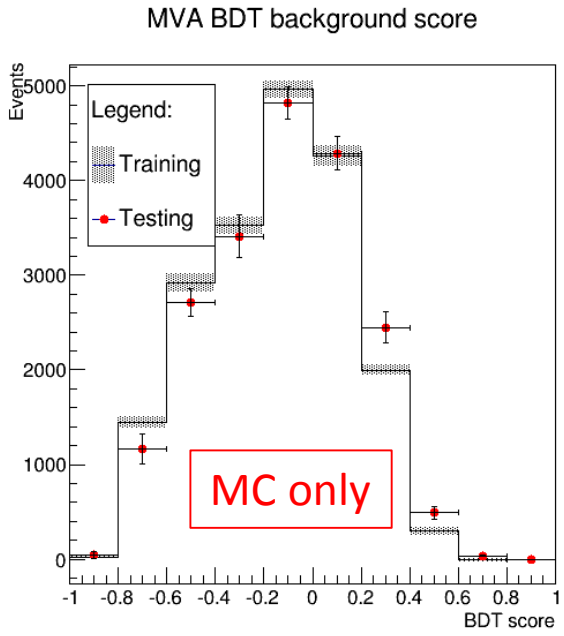
Workflow

- 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**









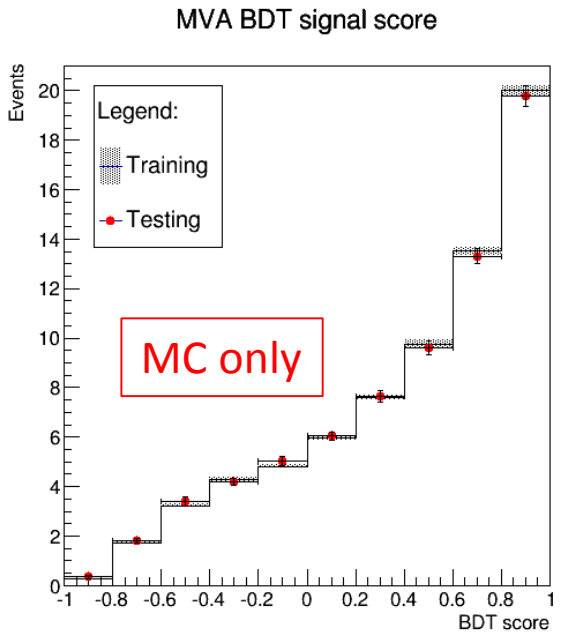
BDT score

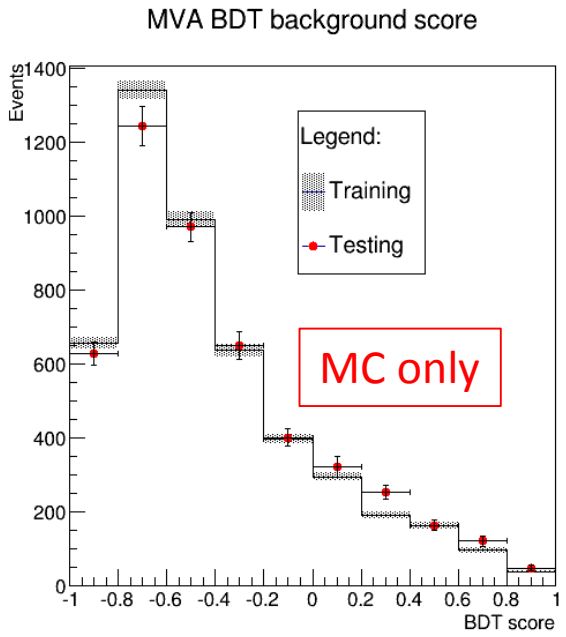
VBF DF

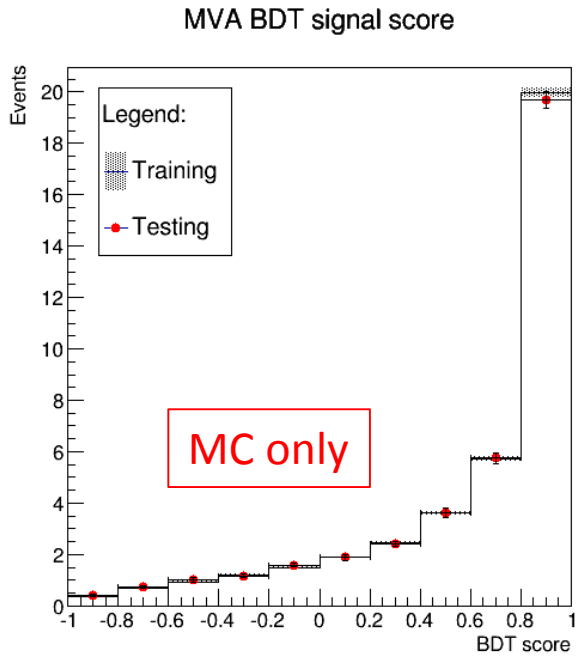
Workflow

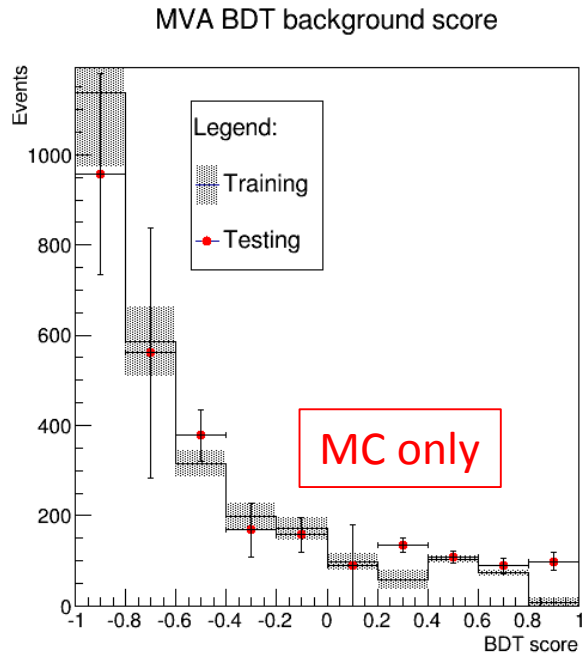
- trigger selection and preselection
- MC modelling profiles
- variables reduction
- BDT hyperparameter optimization
- overtraining test
- **BDT score calculation (event by event – testing data)**
- **the best BDT score cut – the best SIG vs. BKG separation**

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

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

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

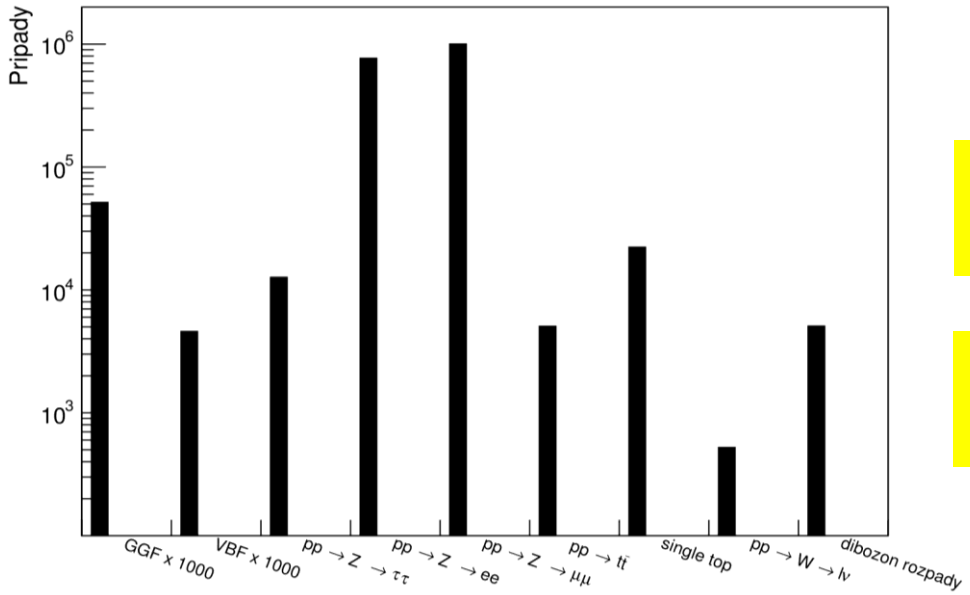
luminosity $\mathcal{L}$

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

$$\frac{dN}{dt} = \sigma\mathcal{L}(\text{t}) \rightarrow N = \sigma\mathcal{L}_{int}$$

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

$$\sigma \rightarrow \sigma'$$



branching ratio Br

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

detector efficiency ε

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

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

Appendices – Preselection (2016)

Trigger selection

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

Quality of lepton reconstruction

- purity ↔ reconstruction efficiency

Lepton isolation

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

Invariant mass

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

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

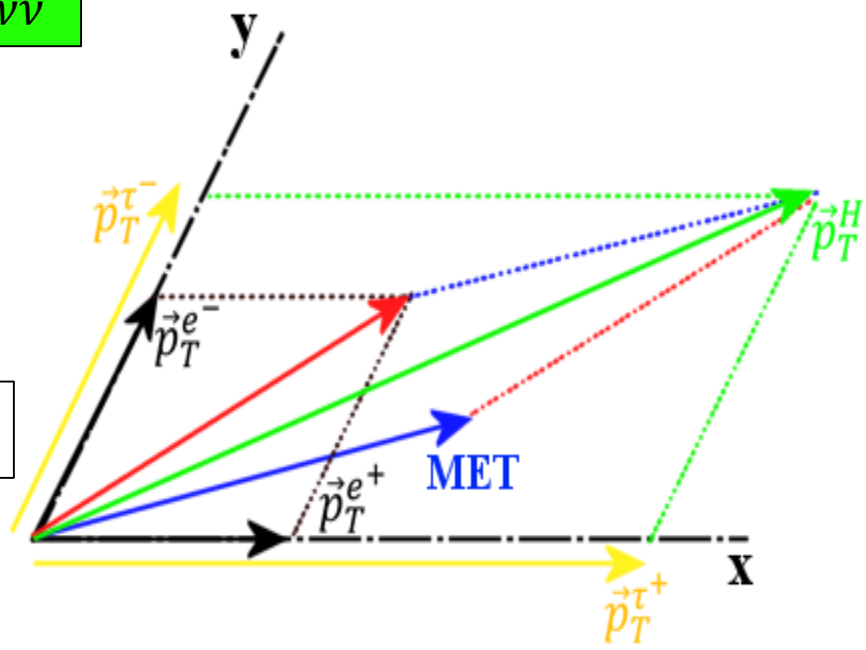
$H^0 \rightarrow \tau^+\tau^- \rightarrow l^+\bar{\nu}\nu l^-\bar{\nu}\nu$

- 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

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



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

MET ... missing energy transversal