Matematicko-fyzikální fakulta

Study of the Higgs boson decay at the ATLAS experiment at the LHC

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Ústav částicové a jaderné fyziky

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Content

1) Structure of the ATLAS detector,
2) Standard model, Higgs boson,
3) Principals of the selection process,
4) Optimized selection cuts,
5) (Boosted) Decision Tree method,
6) Strategy for the further analysis.

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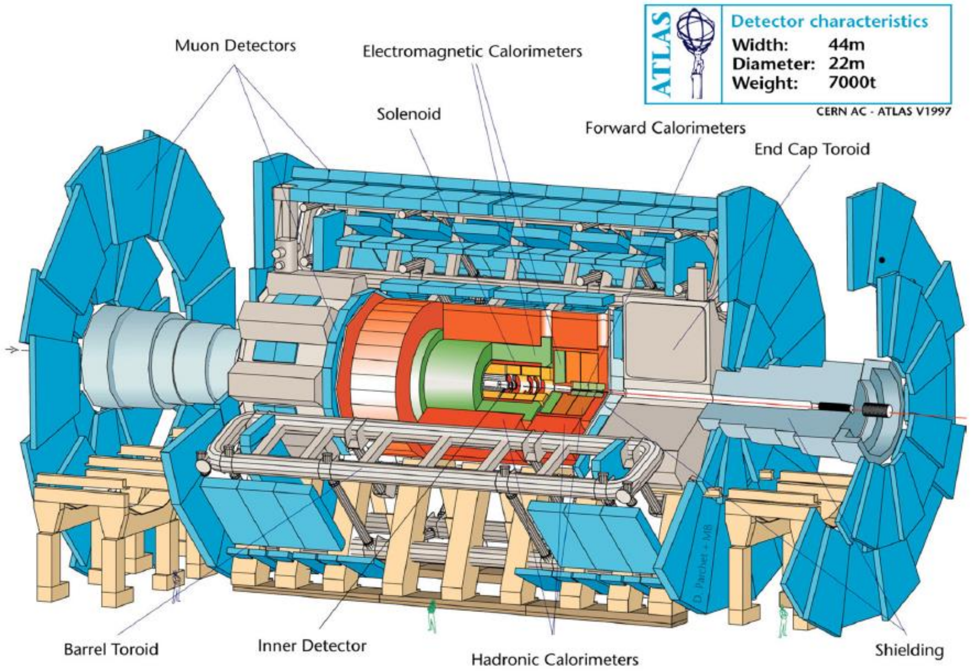
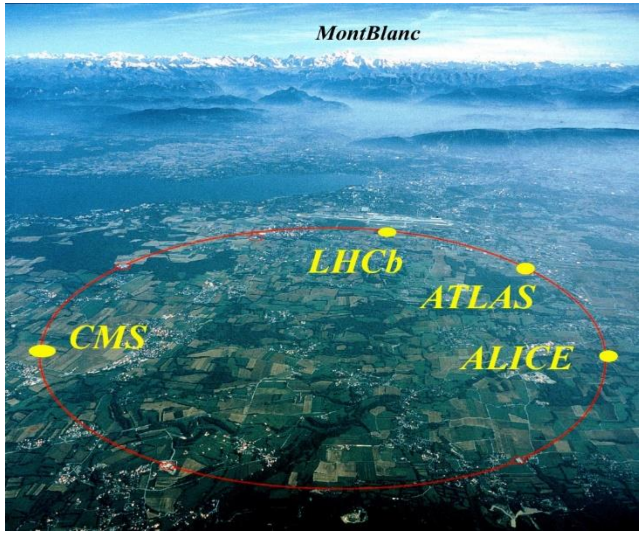
The ATLAS experiment at the LHC

- **Inner detector** (trajectory and momentum **of charged particles**),
- **Electromagnetic calorimeter** (energy of **EM** interacting particles – electrons, photons, tauons...),
- **Hadron calorimeter** (energy of **strong** inter. particles – hadrons),
- **Muon spectrometer** (trajectory, muon momentum),
- **Magnetic system, Trigger, shielding...**





The ATLAS experiment at the LHC

MET

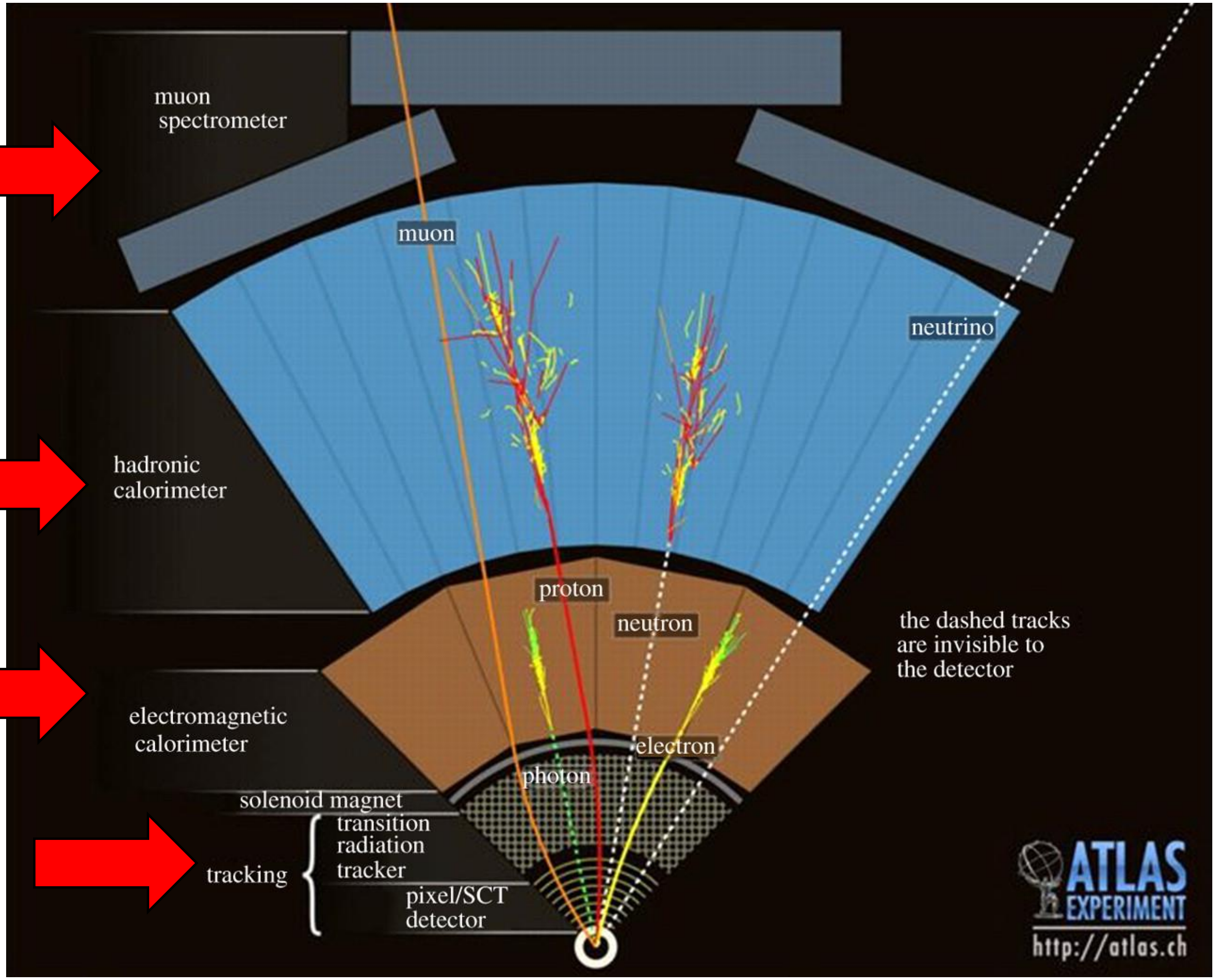
Muon spectrometer

Toroid (B=2-8T)

System of calorimeters

Inner detector

Solenoid (B=2T)



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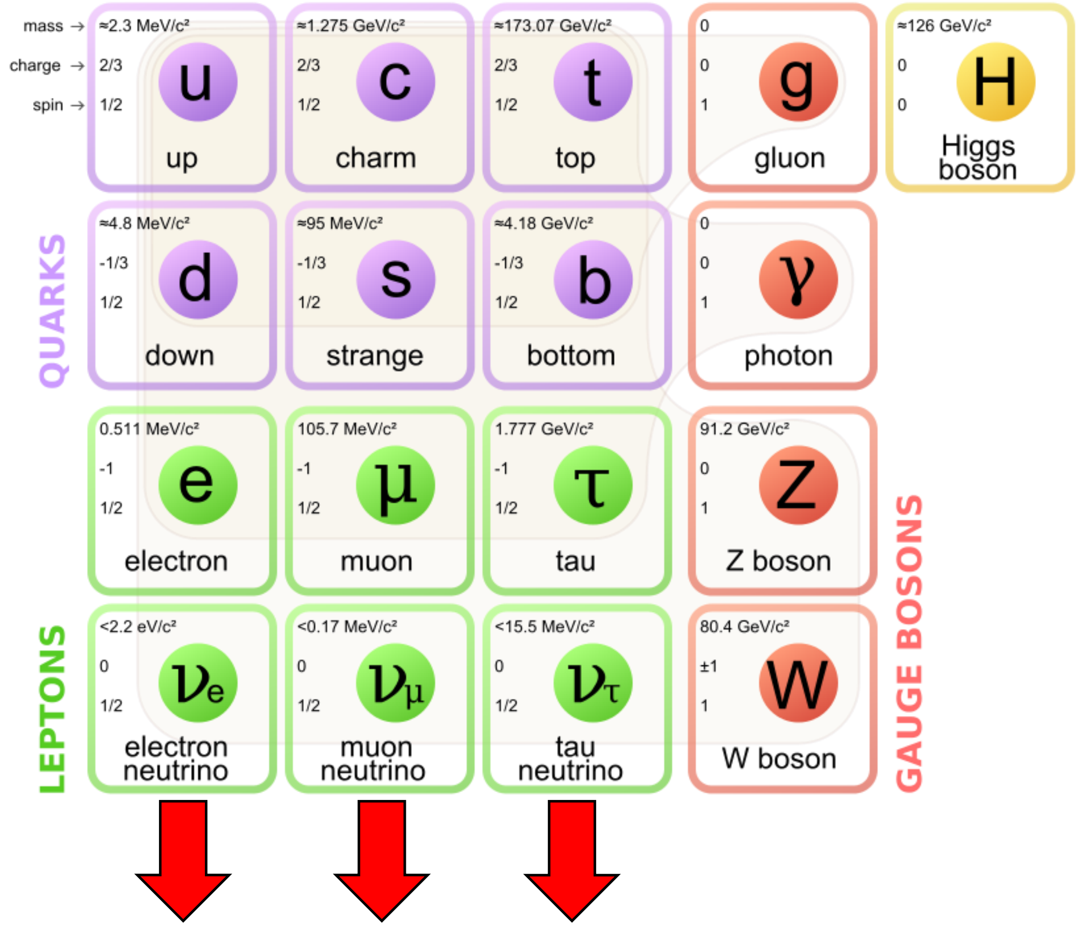
Standard model. Elementary particles

- **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** (neutral charge, spin 0)



3 fermion generations

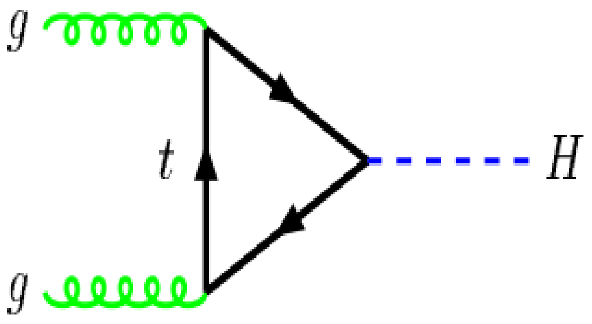
Higgs boson

- **mass** ↔ **given by interaction** with Higgs field,
- **explains** measured mass of the gauge bosons $W^{\pm}(\sim 80\text{ GeV})$, $Z^0(\sim 91\text{ GeV})$,
- **Standard model** predicts only H^0 existence, but not its mass

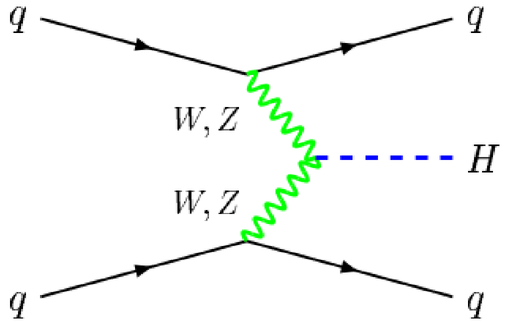
PDG 2016, [9]: $m_{H_0} \doteq (125.09 \pm 0.24)\text{GeV}$

Main Higgs production processes

ggF (gluon-gluon fusion)



VBF (vector-boson fusion)



Higgs boson

Decay modes

$H^0 \rightarrow f\bar{f}$ → $H^0 \rightarrow b\bar{b}$

→ $H^0 \rightarrow \tau\bar{\tau}$

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

$H^0 \rightarrow Z^0Z^0$

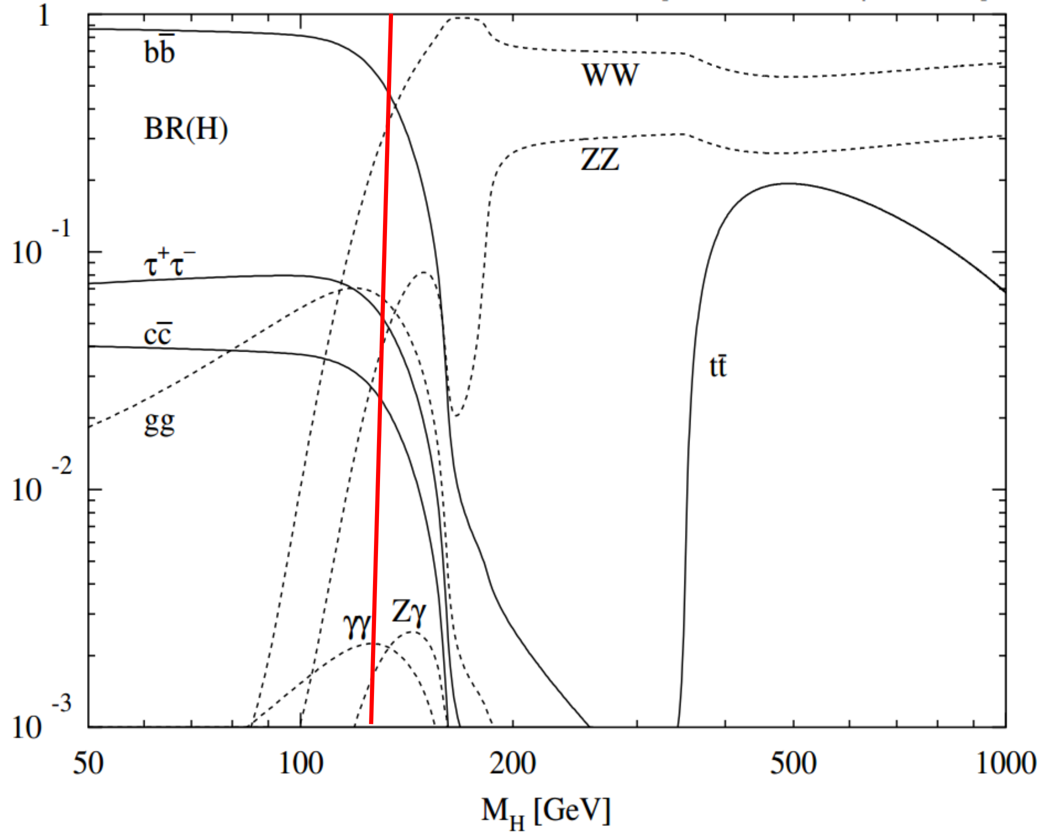
$H^0 \rightarrow \gamma\gamma$

14. august 2012, [6]:

$$m_{H_0} = 126.0 \pm 0.4\,(\text{stat}) \pm 0.4\,(\text{sys})\; GeV$$

…

[HDECAY: M. Spira et al.]



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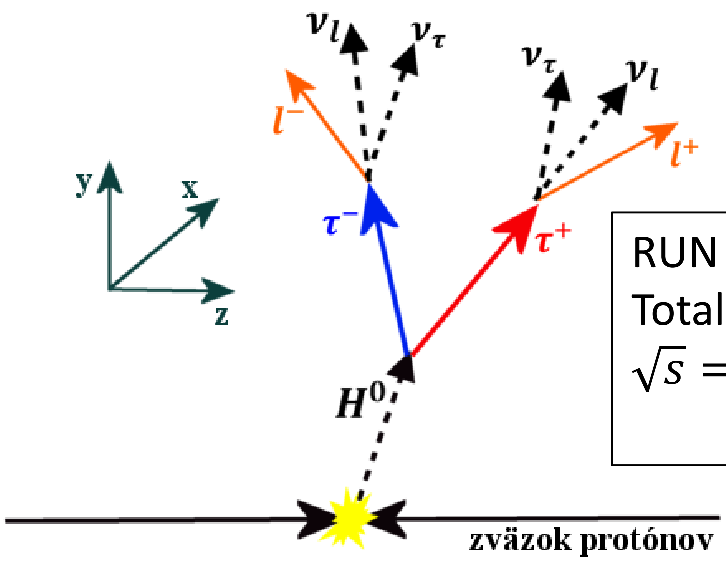
Higgs boson $H \to \tau\tau$ decay analysis

Signal

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

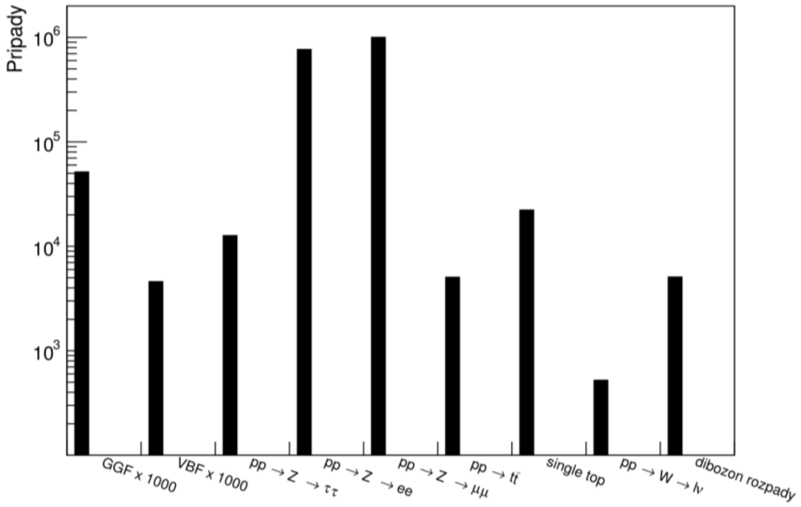
- ggF
- VBF



RUN 2
Total collision energy
$\sqrt{s} = 13$ TeV

Background

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



Higgs boson $H \rightarrow \tau\tau$ decay analysis

Significance

- figure of merit of the process of optimization,

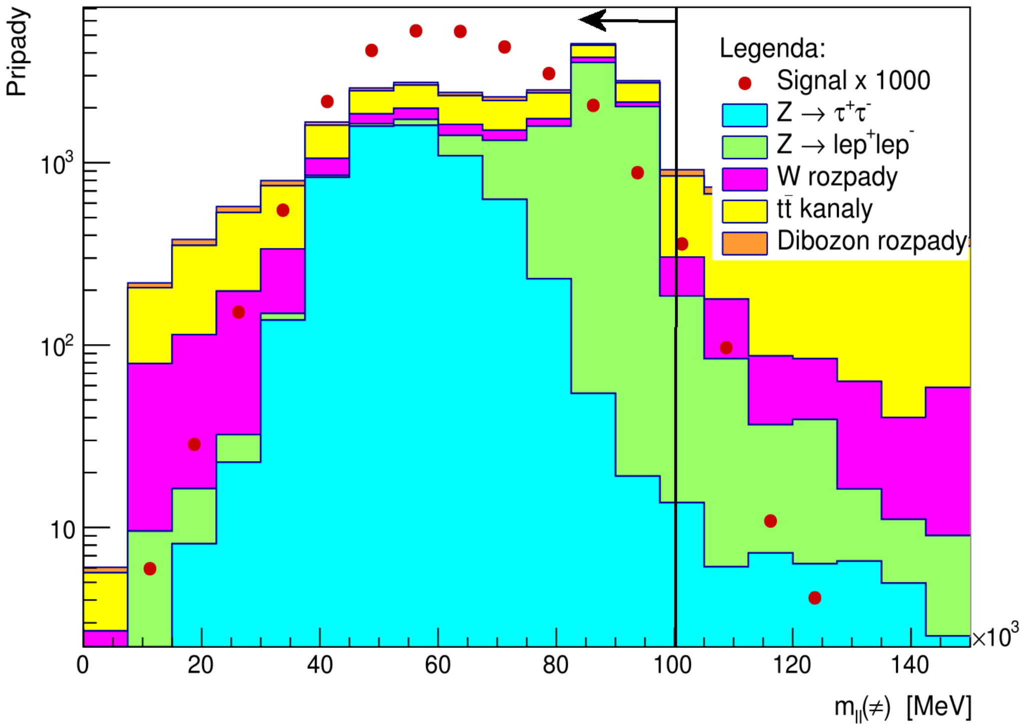
$$Z = \frac{N_S}{\sqrt{N_B}}$$

number of signal events N_S after selection

number of background events N_B after selection

- Task: **to maximize Z_{C_i}** within an interval of requirements $(C_1, .., C_n)$ sequentially applied to individual observables,
- significance is evaluated for each bin separately

$$Z = \left[\sum_i \left(\frac{N_{S_i}}{\sqrt{N_{B_i}}}\right)^2\right]^{\frac{1}{2}}$$



An example of the selection on invariant lepton mass in case $l_1 \neq l_2$

$$m_{ll} < 100 \text{ GeV}$$

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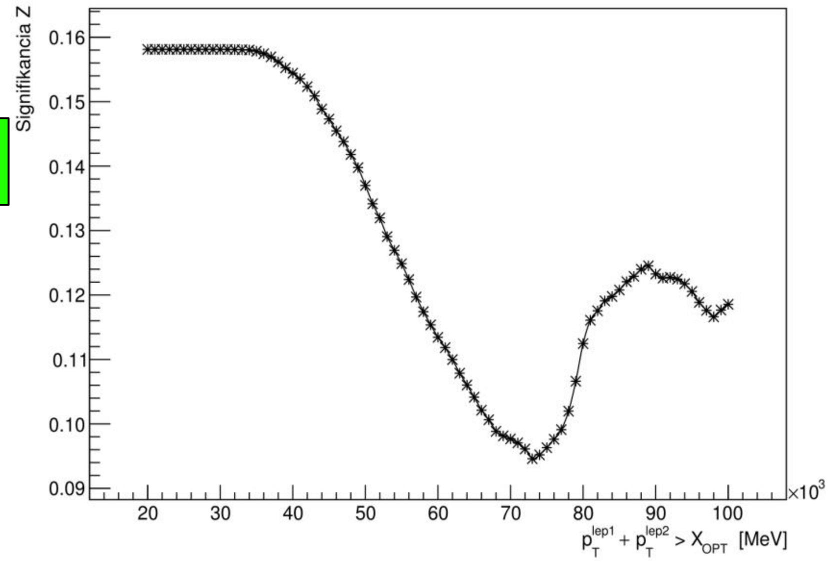
Optimization I & II

Sum of the Transverse Lepton momentum $p_T^{l1} + p_T^{l2} > X$

- already used in RUN1 [17] ($\sqrt{s} = 7$ TeV),
- background suppression (leptons created in hadronic decays),
- interval $X \in (20{,}100)$ GeV, accuracy 1 GeV,
- constant trend observed until ~ 36 GeV

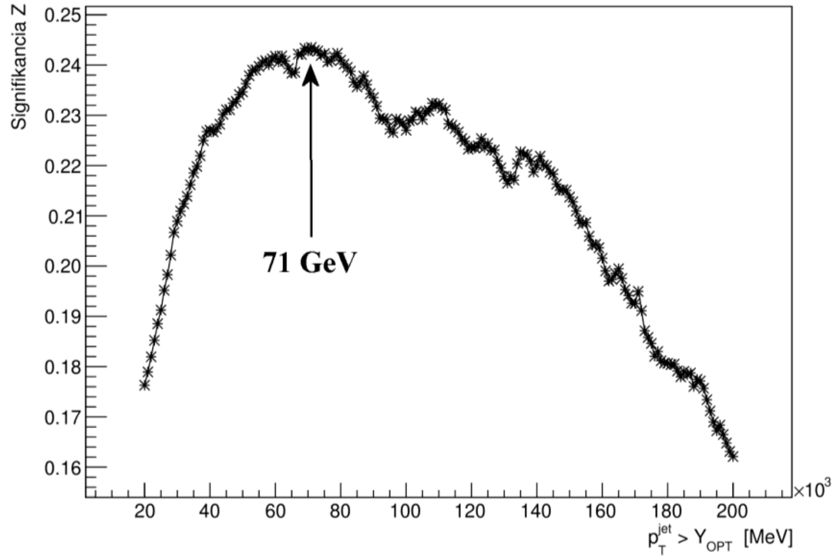
INEFFICIENT



Transverse momentum of the jets from H^0 production $p_T^{jet} > Y$

- requirement for a big H^0 transverse momentum (otherwise „back-to-back“ decay appears),
- Big jets‘ transverse momentum $\Rightarrow$ big H^0 trans. momentum,
- two jets are produced, the selection is applied to more energetic one

$$p_T^{jet} > 71\ \mathrm{GeV}$$

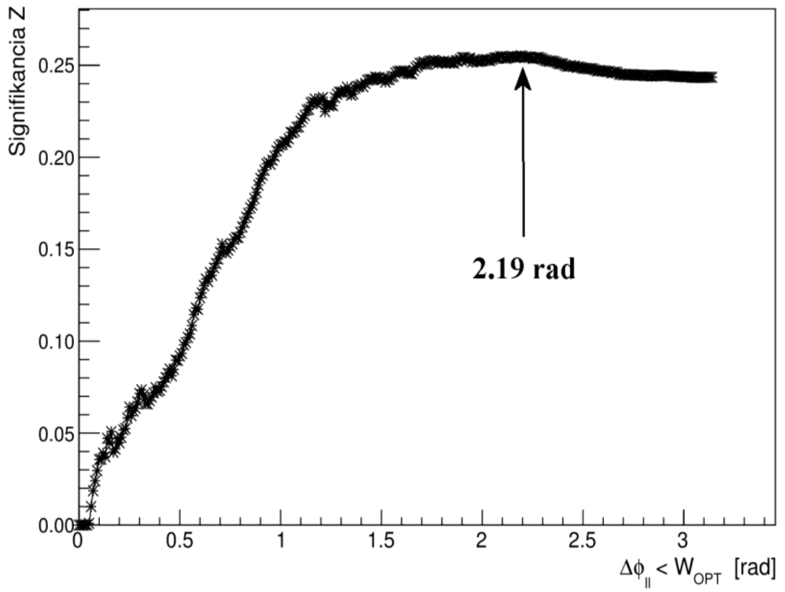


Optimization III & IV

Mutual Leptonic Azimuthal angle $\Delta\phi_{ll} < W$

- obvious but strict requirement $\cos\phi > -1$ may not be ideal,
- it is required by collinear approximation used in mass calculation,
- accuracy 0.01 rad

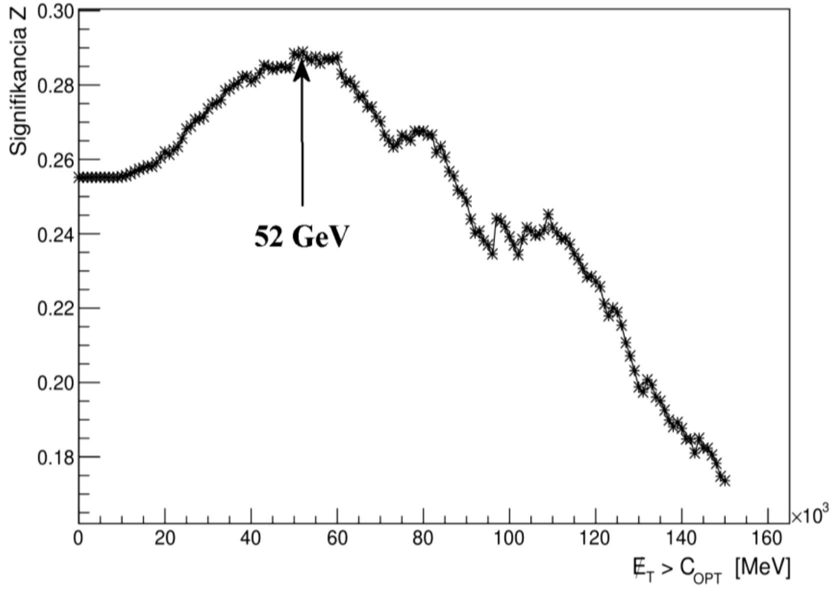
$$\Delta\phi_{ll} < 2.19 \text{ rad}$$



Missing Energy Transversal $E_T^{miss} > M$

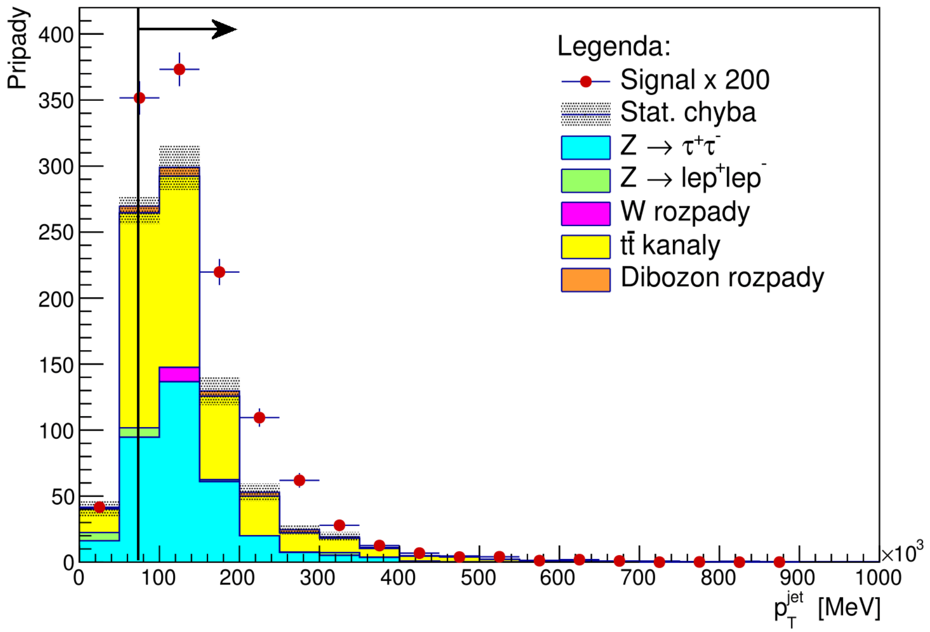
- implies neutrino appearance,
- motivated by $Z \to l^+l^-$ background suppression,
- accuracy 1 GeV

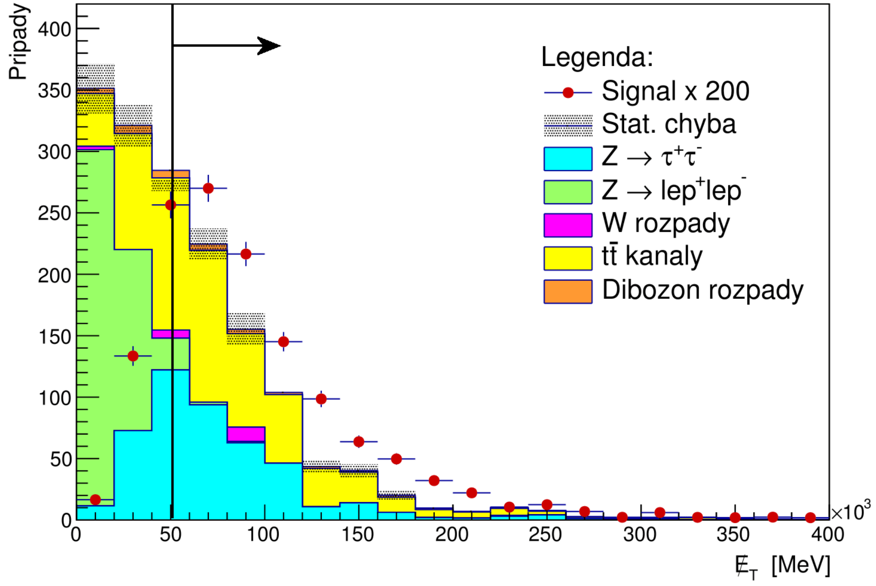
$$E_T^{miss} > 52 \text{ GeV}$$

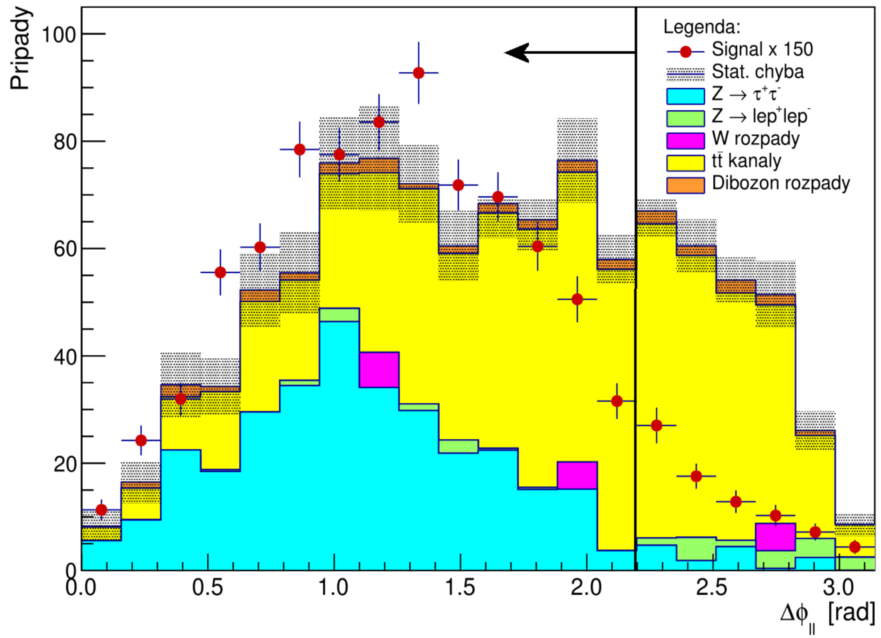


Selection results

Selection	RUN2 (2016)	RUN1 [17]
$p_T^{l1} + p_T^{l2} > X$	inefficient	35 GeV
$p_T^{jet} > Y$	71 GeV	40 GeV
$\Delta\phi_{ll} < W$	2.19 rad	2.5 rad
$\not{E}_T > M$	52 GeV	40 GeV







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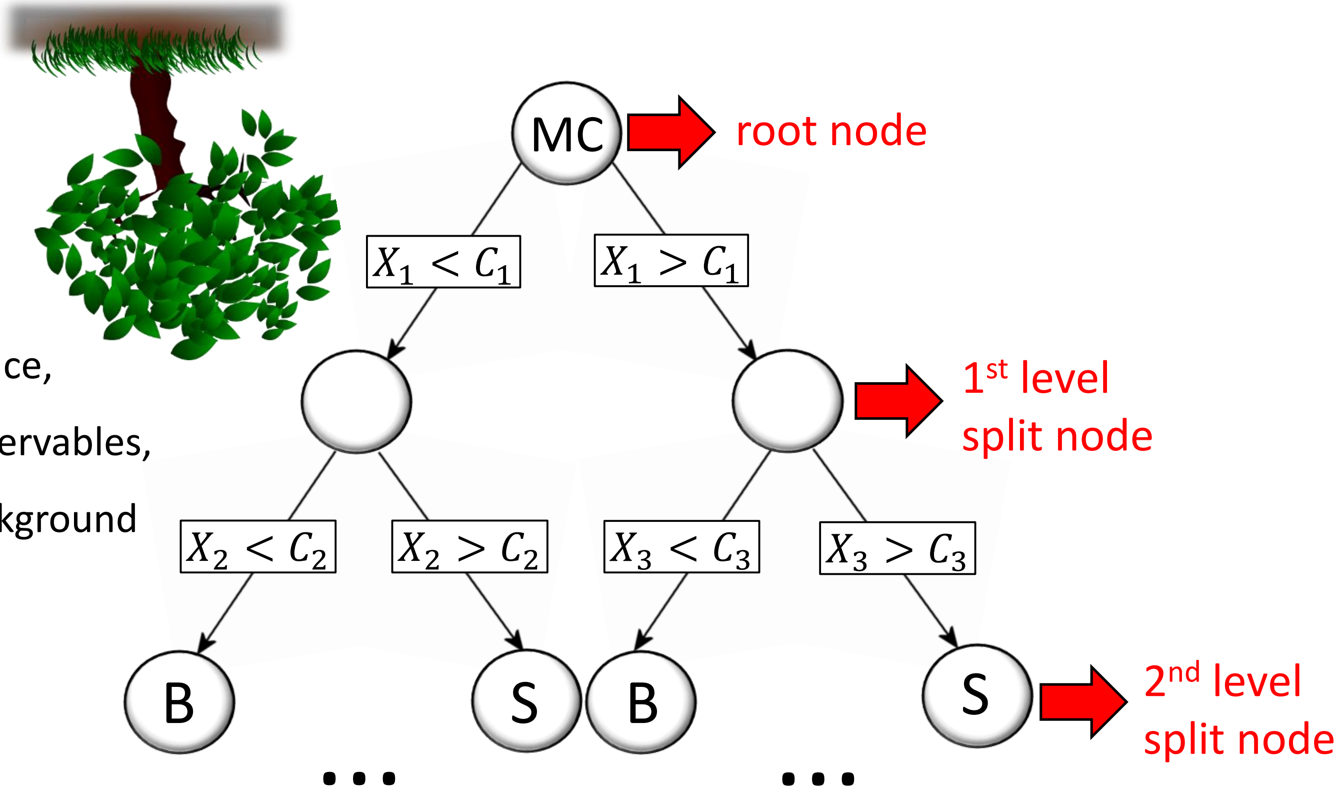
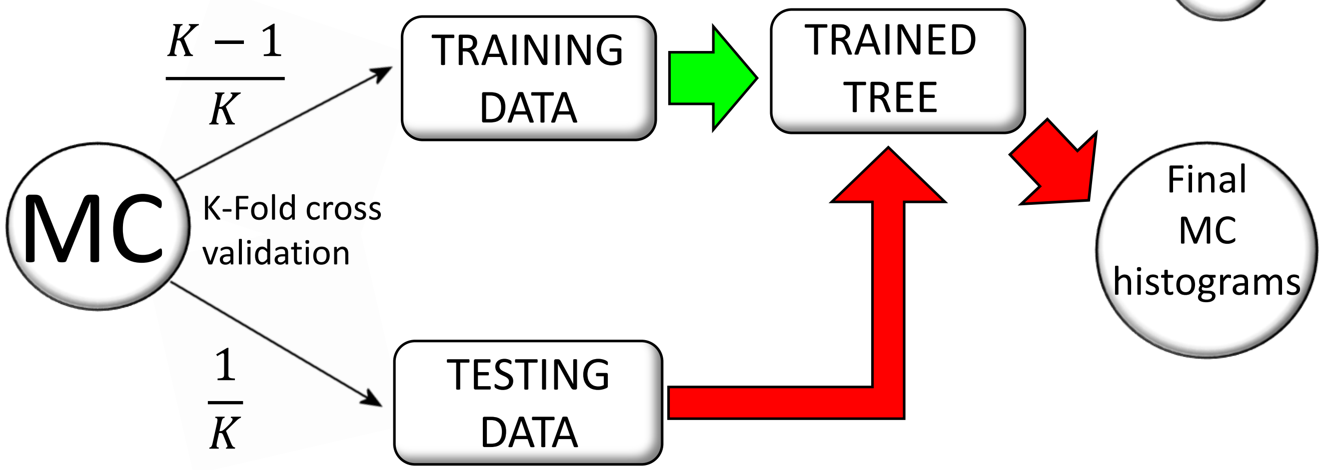
Decision Tree

- 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

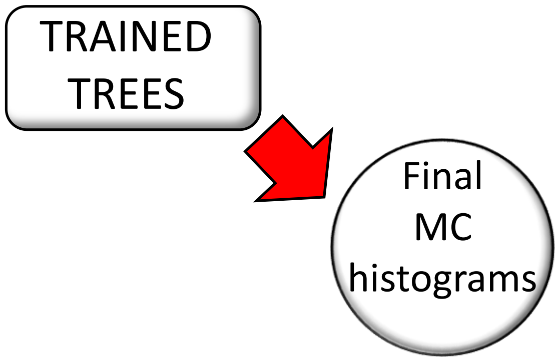
=

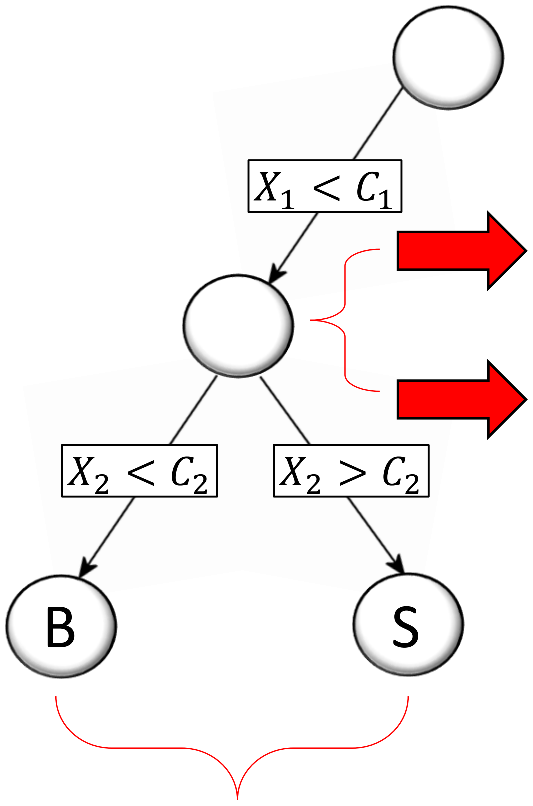
Determining the one variable and the corresponding cut value to get the best MC data separation at each node.

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

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

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
(AdaBoost)

- previously misclassified events are given a larger weight

$$w_m = w_{m-1} \cdot \exp(\alpha_m)$$

α_m ... the weight of a classifier m

$$\alpha_m = \beta \cdot \ln\left(\frac{1 - err_{m-1}}{err_{m-1}}\right)$$

err_{m-1} ... the fraction of previously misclassified events

β ... learning rate

- the whole process is then $M\times$ iterated and the final classifier is averaged and prepared for application of the testing sample:

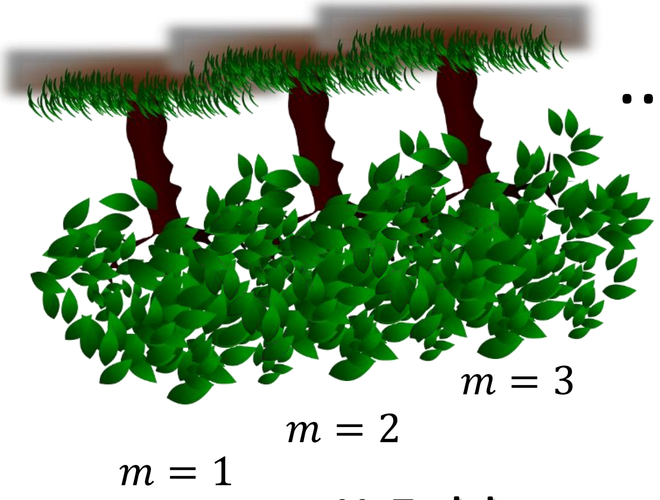
$$y_{Boost}(\boldsymbol{x}) = \frac{1}{M}\sum_{m}^{M} \alpha_m \cdot b_m(\boldsymbol{x})$$

$+1$ Signal

-1 Background

$\boldsymbol{x}$ ... event from the testing sample

$b_m(\boldsymbol{x}) = \pm 1$ ... the result of an individual classifier m for signal $(+1)$ and background (-1)



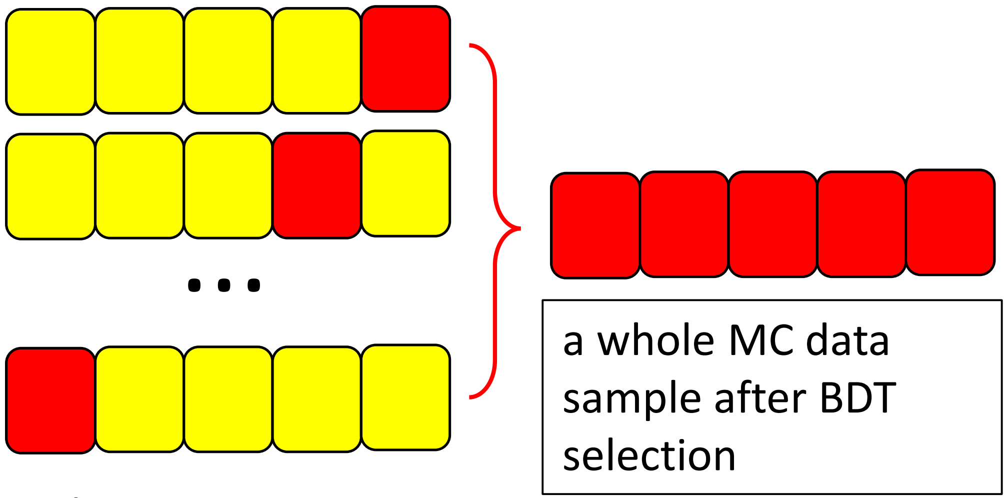
...

M number of trees in the forest

K-Fold cross validation (K=5)

Training data

Testing data



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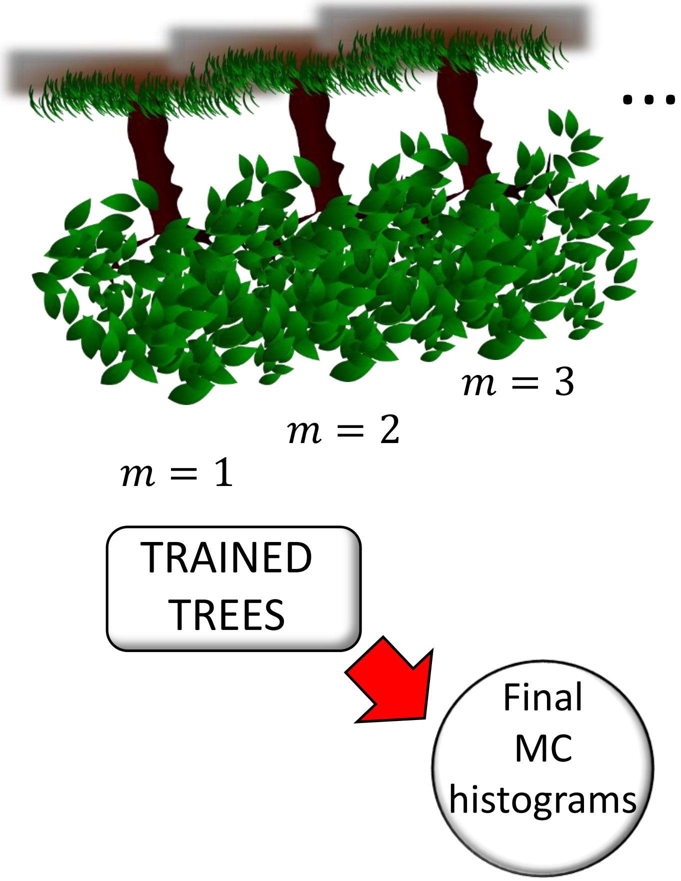
Strategy

- To train the particular decision tree with as many available variables as possible,
- to optimize training and boosting parameters (a number of tree levels/a minimum number of events in the final leaves, a number of trained trees...),
- to exclude non contributing variables from the selection process with respect to the given ranking,
- to use testing data samples and apply them to the prepared BDTs; to create histograms,
- (during further analysis) to use measured data and apply them to the prepared BDTs; to create histograms.

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



Conclusion

- The Higgs boson mass is one of the Standard model free parameters that needs to be specified,

- $H \rightarrow \tau\tau$ decay mode requires a challenging but promising analytic approach to Higgs boson reconstruction,

- The signal vs. background separation process:

⇨ Significance maximization ⇔ optimization of the selection criteria

⇨ BDT method ⇔ a search for the optimal selection variable and the corresponding cut value using multivariate classifier, reweighting of the previously misclassified events

YOU MATTER

UNLESS YOU MULTIPLY YOURSELF TIMES c^2

THEN YOU ENERGY

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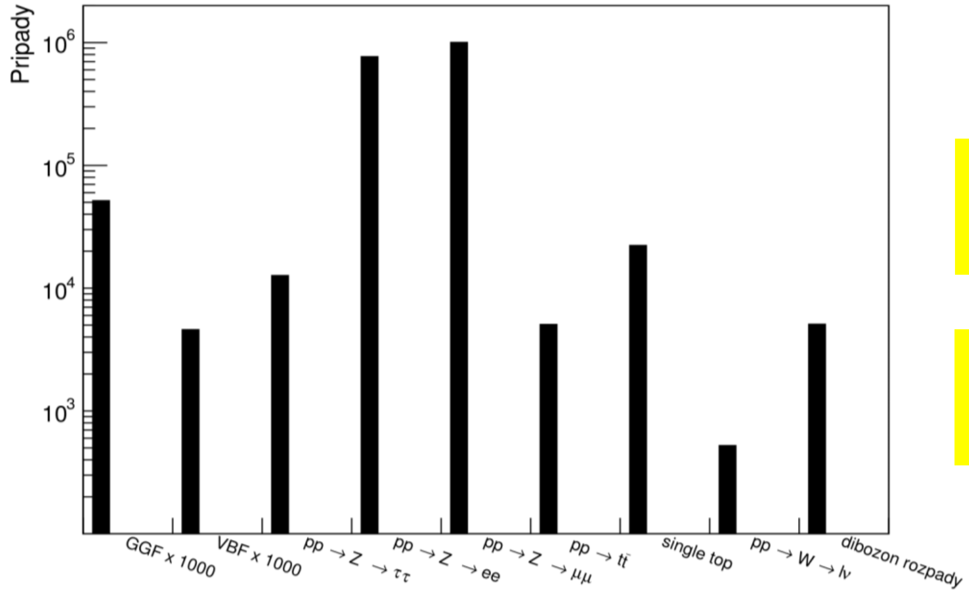
Appendices

Monte Carlo simulation

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



cross section σ

luminosity $\mathcal{L}$

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

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

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

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

$$\sigma \to \sigma'$$

branching ratio Br

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

detector efficiency ε

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

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

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

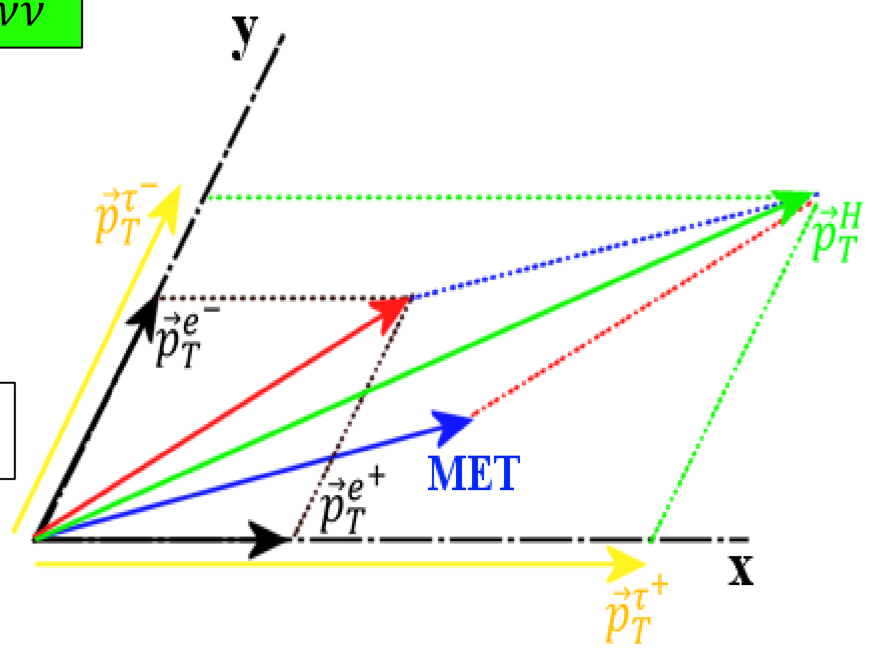
$H^0 \to \tau^+\tau^- \to l^+\bar{\nu}\nu l^-\bar{\nu}\nu$

- 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

$$x_1 = \frac{p_T^{l1}}{p_T^{\tau1}} \quad x_2 = \frac{p_T^{l2}}{p_T^{\tau2}} \quad x_{1,2} \in (0,1)$$



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

MET ... missing energy transversal