Search for doubly charged Higgs bosons via the VBF production mode

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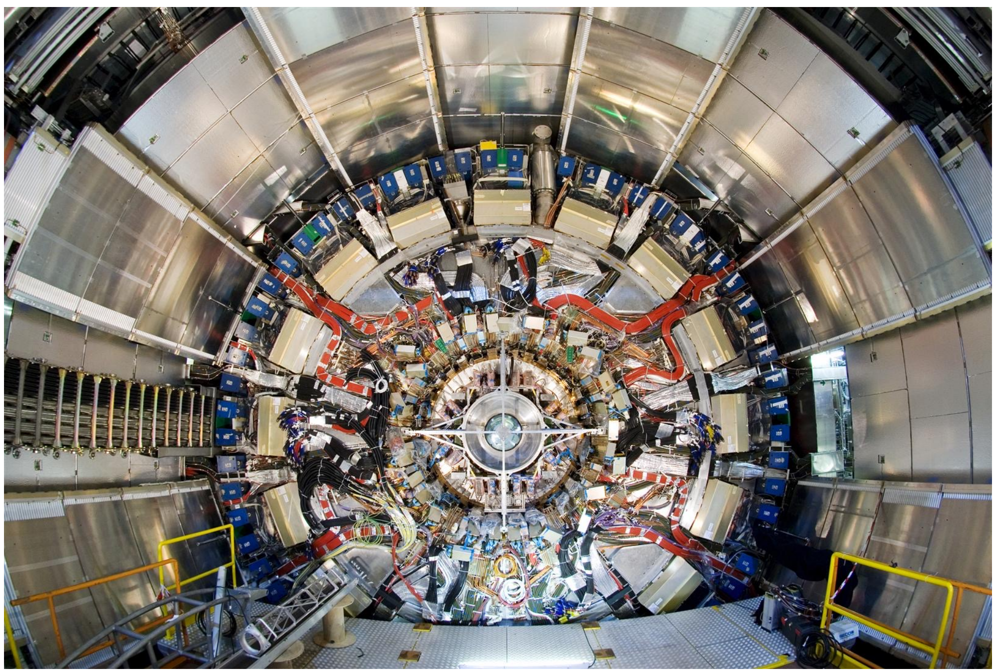
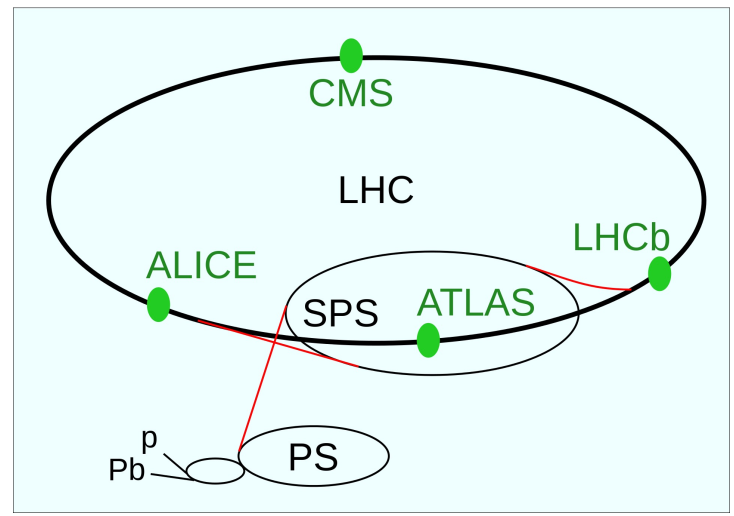
ATLAS detector (I)

Front view of **ATLAS**: one of four LHC experiments, multipurpose particle detector with forward-backward symmetric cylindrical geometry

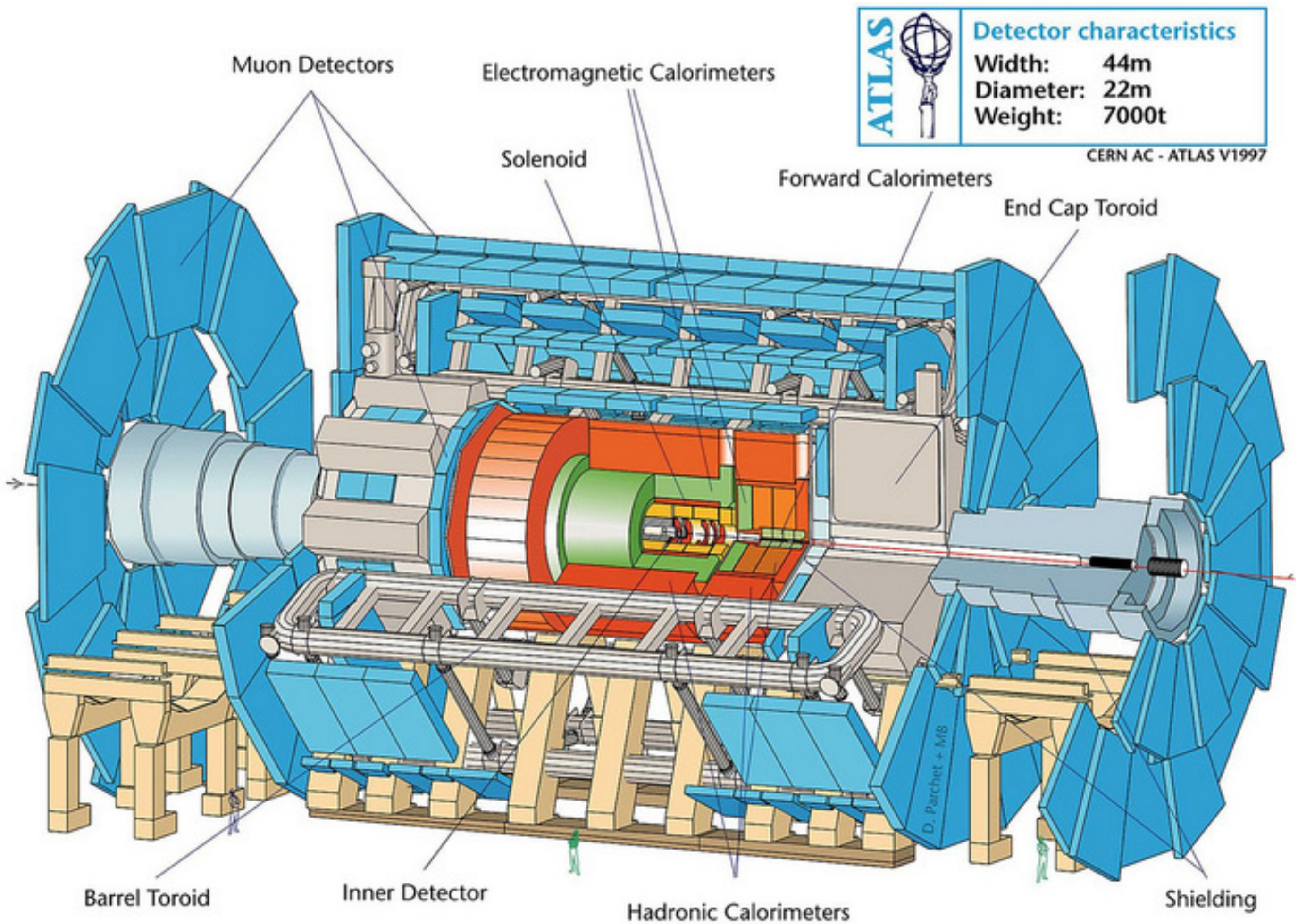


[1]



[2]

ATLAS detector (II)



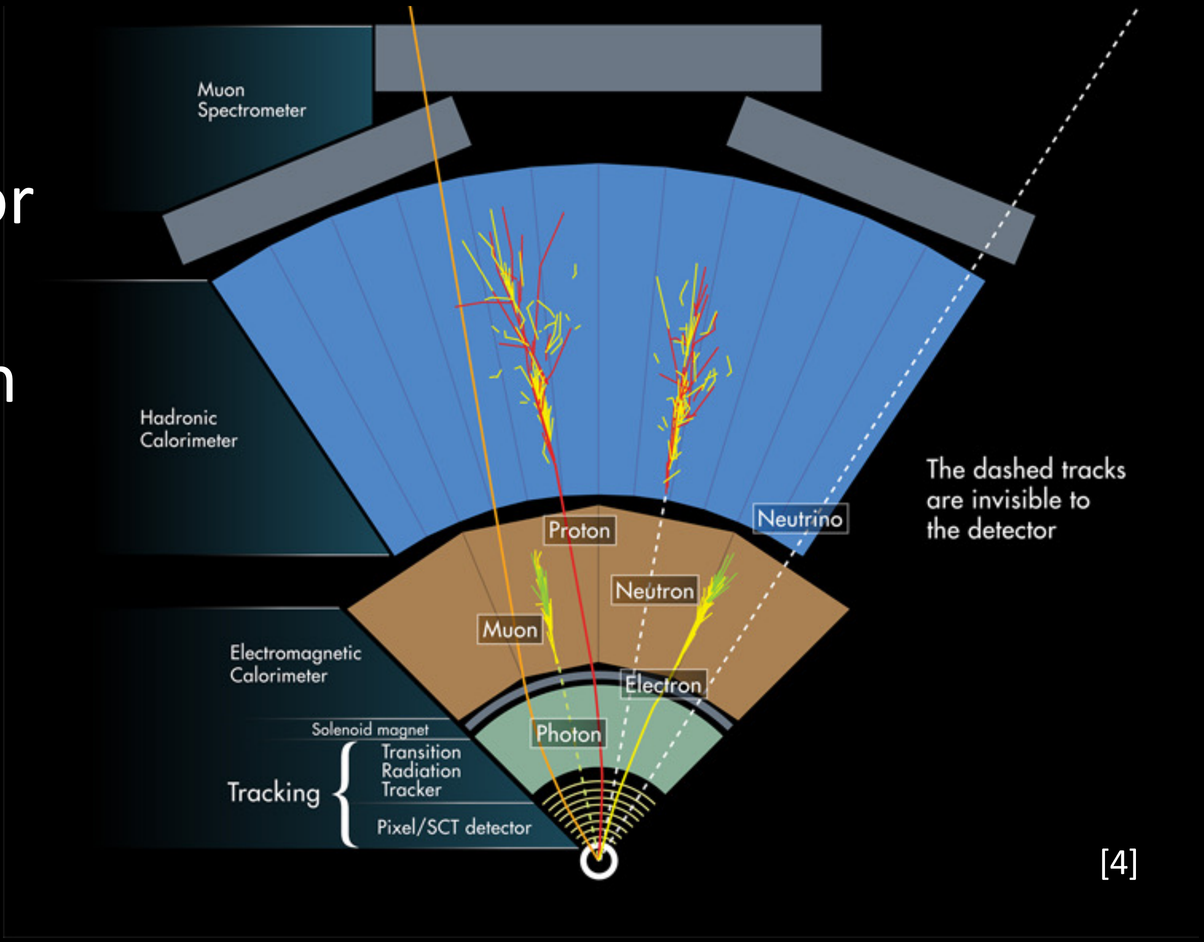
[3]

ATLAS detector (III)

Combination of detector data for

- particle identification
- momentum
- energy

determination



[4]

Standard-Model Higgs (I)

- Gauge Bosons are massless → local gauge symmetry of $\mathscr{L}$ is conserved
- $W^{\pm}$, Z Bosons acquire their mass by interacting with the background-field
- Introduce scalar Higgs-field:

$$\begin{array}{cc} & I_3 \\ \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} & \begin{array}{c} +\frac{1}{2} \\ -\frac{1}{2} \end{array} \end{array}$$

Standard-Model Higgs (II)

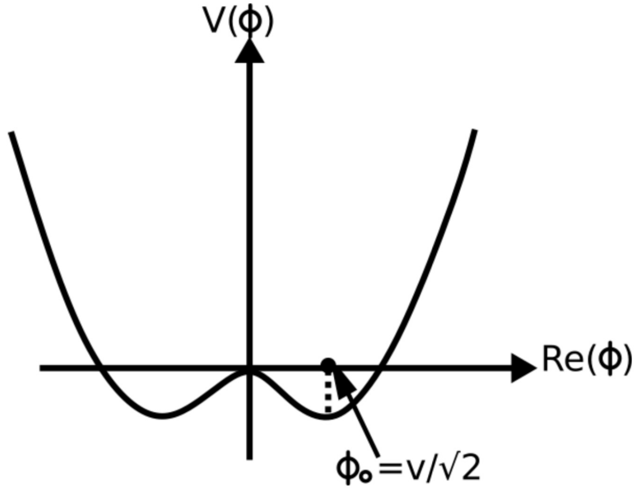
- Second component of the doublet with non vanishing **VEV** (Vacuum expectation value) → Spontaneous symmetry breaking (**SSB**)

$$V = \mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4$$

- Development of the complex field:

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) + i\zeta(x) \end{pmatrix}$$

VEV Higgs-B Goldstone-B



[5]

Standard-Model Higgs (III)

Covariant derivative:

$$D_\mu = \partial_\mu \cdot \mathbb{1} + ig'YB_\mu \cdot \mathbb{1} + i\frac{g}{2}\vec{\sigma} \cdot \vec{W}_\mu$$

Coupling between the massless gauge bosons and the Higgs-field lead to mass term in $\mathscr{L}$

GM-Model (I)

Georgi-Machecek model

- Expansion of the minimal Higgs sector → **BSM** (Beyond the standard model)
- 2 additional isospin triplet scalar fields, with non vanishing VEV for the neutral field:

Real

$$\xi = \begin{pmatrix} \xi^{+} \\ \xi^{0} \\ \xi^{+*} \end{pmatrix}, \qquad \chi = \begin{pmatrix} \chi^{0} \\ \chi^{-} \\ \chi^{--} \end{pmatrix} \qquad \longrightarrow \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & -\xi^{-} & \chi^{0} \end{pmatrix}$$

- Additional kinetic terms in $\mathscr{L}$ (Covariant field derivatives)

GM-Model (II)

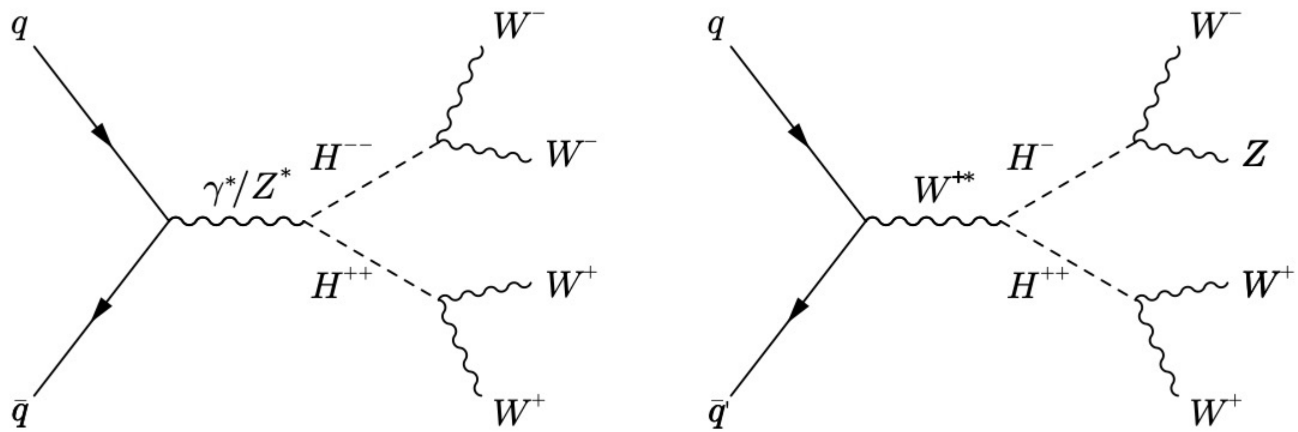
After SSB, rearranging of the fields under custodial symmetry transformations (comparable to spin addition)

- SM Higgs (Φ^*, Φ →bidoublet): $2 \otimes 2 \longrightarrow 3 \oplus 1$
- GM Higgs: $3 \otimes 3 \longrightarrow 5 \oplus 3 \oplus 1$

Singlet corresponds to SM Higgs (125 GeV)

5-plet can be identified with physical Higgs
$\mathbf{H_5 = (H_5^{\pm\pm}, H_5^{\pm}, H_5^{0})}$

Production Modes $\boldsymbol{\gamma}^*$/Z*,W*



[6]

Experimental useful final states (W → $l\nu_l$/q$\bar{q}$):

2 same charged leptons (2l^sc)

3 leptons (3l) + Quarks (Jets)

4 leptons (4l)

Characteristic Event Variables $\boldsymbol{\gamma}$/Z

$\boldsymbol{p_{T,L}}$, $\boldsymbol{p_{T,j}}$ Transvers jet/lepton momentum

$\boldsymbol{N_{jets}}$, $\boldsymbol{N_{b-jet}}$ Number of (b-)jets,

$\boldsymbol{E^{T}_{miss}}$ Missing transvers momentum (Neutrinos)

$\boldsymbol{m_{jets}}, \boldsymbol{m_{xl}}$ Jet mass, lepton mass

$\Delta\boldsymbol{R} = \sqrt{\Delta\boldsymbol{\phi}^{2} + \Delta\boldsymbol{\eta}^{2}}$ η- ϕ angular separation of two objects

Event Selection (Preselection)

1. Detector specific restrictions
2. Improve **signal-background ratio** (more in detail later)

Selection criteria	$2\ell^{sc}$	3ℓ	4ℓ
At least one offline tight lepton with $p_T^\ell > 30$ GeV that triggered the event			
N_ℓ (type L)	=2	=3	=4
N_ℓ (type L*)	–	–	=4
N_ℓ (type T)	=2	≥2 ($\ell_{1,2}$)	≥1
$\lvert \sum Q_\ell \rvert$	=2	=1	≠4
Lepton p_T	$p_T^{\ell_1,\ell_2} > 30, 20$ GeV	$p_T^{\ell_0,\ell_1,\ell_2} > 10, 20, 20$ GeV	$p_T^{\ell_1,\ell_2,\ell_3,\ell_4} > 10$ GeV
E_T^{miss}	> 70 GeV	> 30 GeV	> 30 GeV
N_{jets}	≥ 3	≥ 2	–
$N_{b\text{-jets}}$	=0		
Low SFOC $m_{\ell\ell}$ veto	–	$m_{\ell\ell}^{oc} > 15$ GeV	
Z boson decay veto	$\lvert m_{ee}^{sc} - m_Z \rvert > 10$ GeV	$\lvert m_{\ell\ell}^{oc} - m_Z \rvert > 10$ GeV	

Type L: "Loose"
Type T: "Tight" (Isolation)

[6]

Event Selection (Selection)

1. Detector specific restrictions
2. Improve **signal-background ratio** (more in detail later)

Charged Higgs boson mass	$m_{H^{\pm\pm}}$ = 200 GeV	$m_{H^{\pm\pm}}$ = 300 GeV	$m_{H^{\pm\pm}}$ = 400 GeV	$m_{H^{\pm\pm}}$ = 500 GeV
Selection criteria	$2\ell^{sc}$ channel			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
S	<0.3	<0.6	<0.6	<0.9
$\Delta R_{\ell^\pm\ell^\pm}$	<1.9	<2.1	<2.2	<2.4
$\Delta\phi_{\ell\ell,E_T^{miss}}$	<0.7	<0.9	<1.0	<1.0
$m_{x\ell}$ [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
E_T^{miss} [GeV]	>100	>130	>170	>200
Selection criteria	3ℓ channel			
$\Delta R_{\ell^\pm\ell^\pm}$	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$m_{x\ell}$ [GeV]	>160	>190	>240	>310
E_T^{miss} [GeV]	>30	>55	>80	>90
$\Delta R_{\ell jet}$	[0.1, 1.5]	[0.1, 2.0]	[0.1,2.3]	[0.5, 2.3]
$p_T^{leading\ jet}$ [GeV]	>40	>70	>100	>95
Selection criteria	4ℓ channel			
$m_{x\ell}$ [GeV]	>230	>270	>360	>440
E_T^{miss} [GeV]	>60	>60	>60	>60
$p_T^{\ell_1}$ [GeV]	>65	>80	>110	>130
$\Delta R_{\ell^\pm\ell^\pm}^{min}$	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
$\Delta R_{\ell^\pm\ell^\pm}^{max}$	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]

[6]

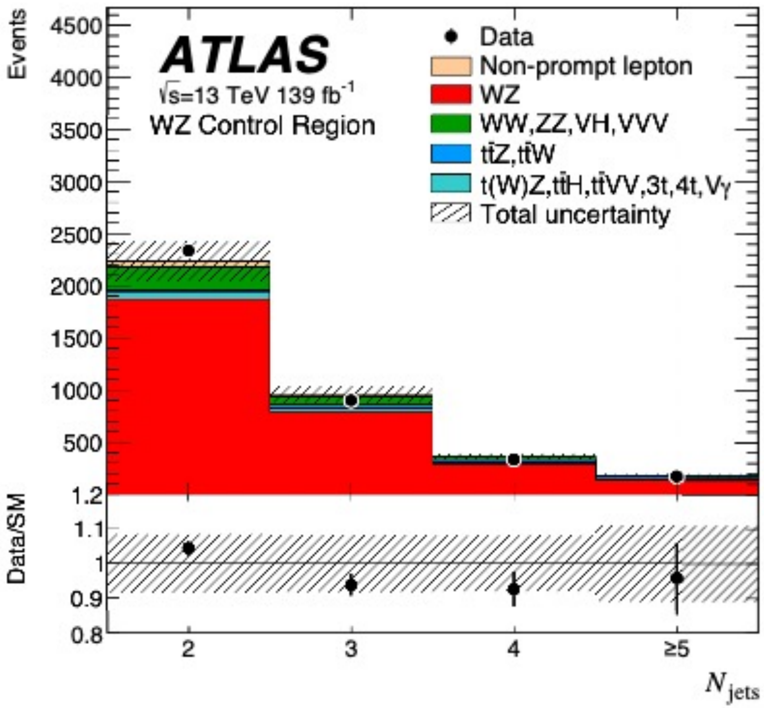
State of the art – Analysis (I)

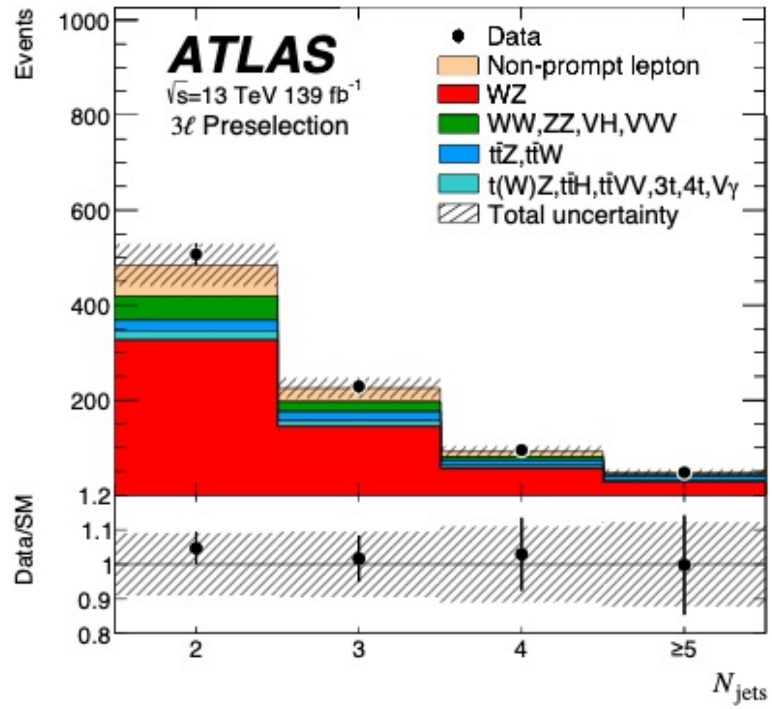
Techniques to estimate contributions from the dominant background processes.

Relevant contributions:

- WZ production (dominant for $2l^{sc}$, 3l)
- Electron charge flip (misidentification of $e^{\pm}$ charge for $2l^{sc}$)
- Non-prompt-lepton (misidentification of jets as leptons in all channels)
- Other SM contributions (MC simulations)

Analysis (II)

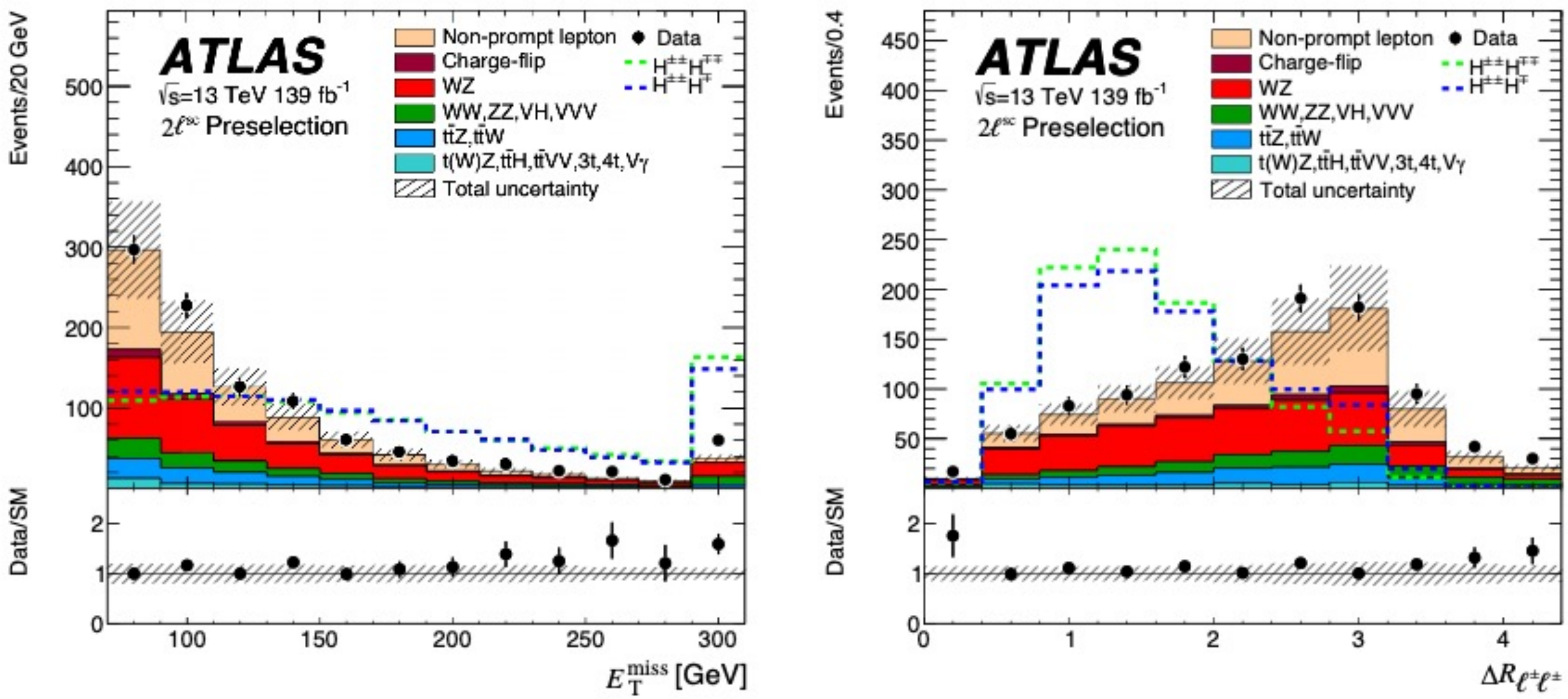




[6]

Data and prediction in good agreement for control region as well as in the 3l Signal region (**SR**)

Analysis (III)

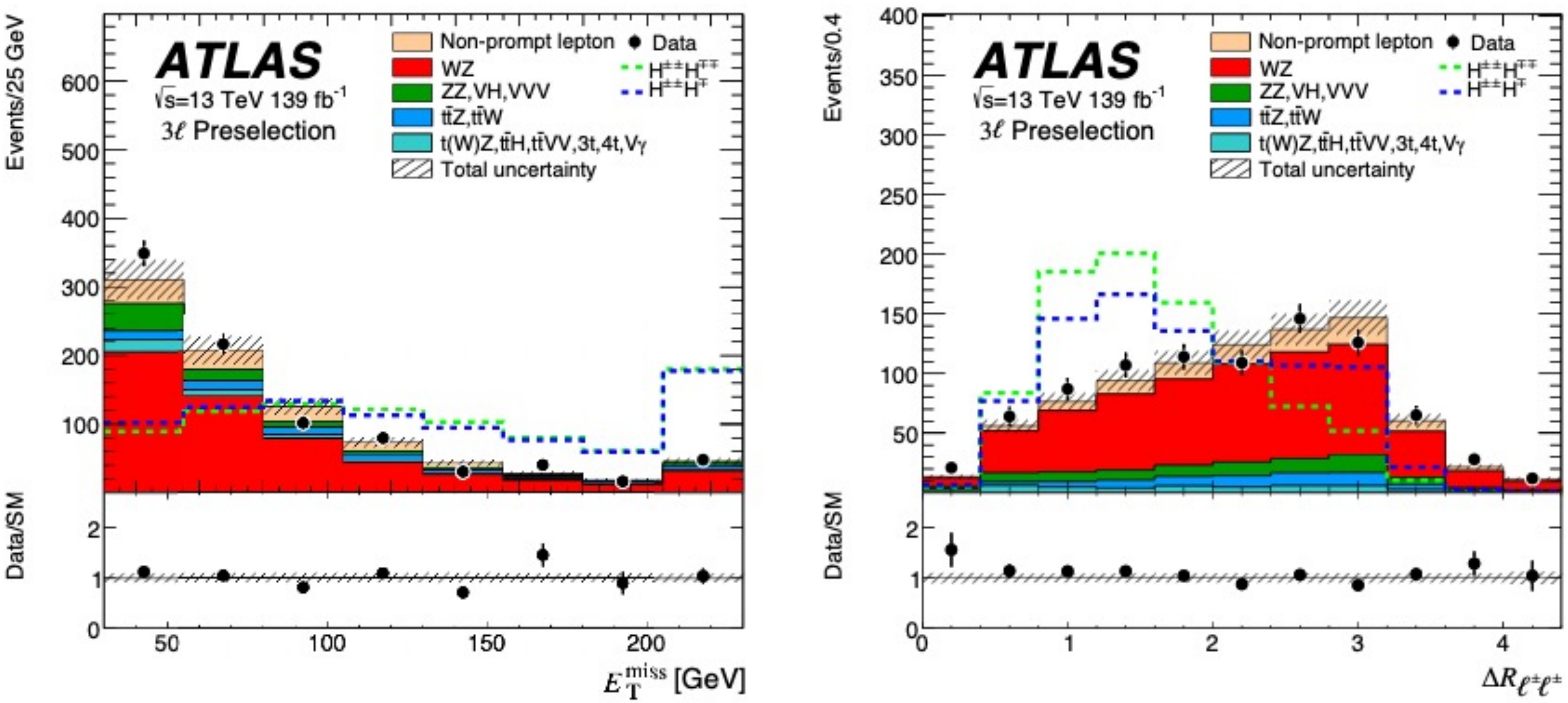


[6]

Data in agreement with background ($2l^{sc}$ channel), but not with (double) charged Higgs hypothesis.

Same results for m_{xl}, m_{jets}.

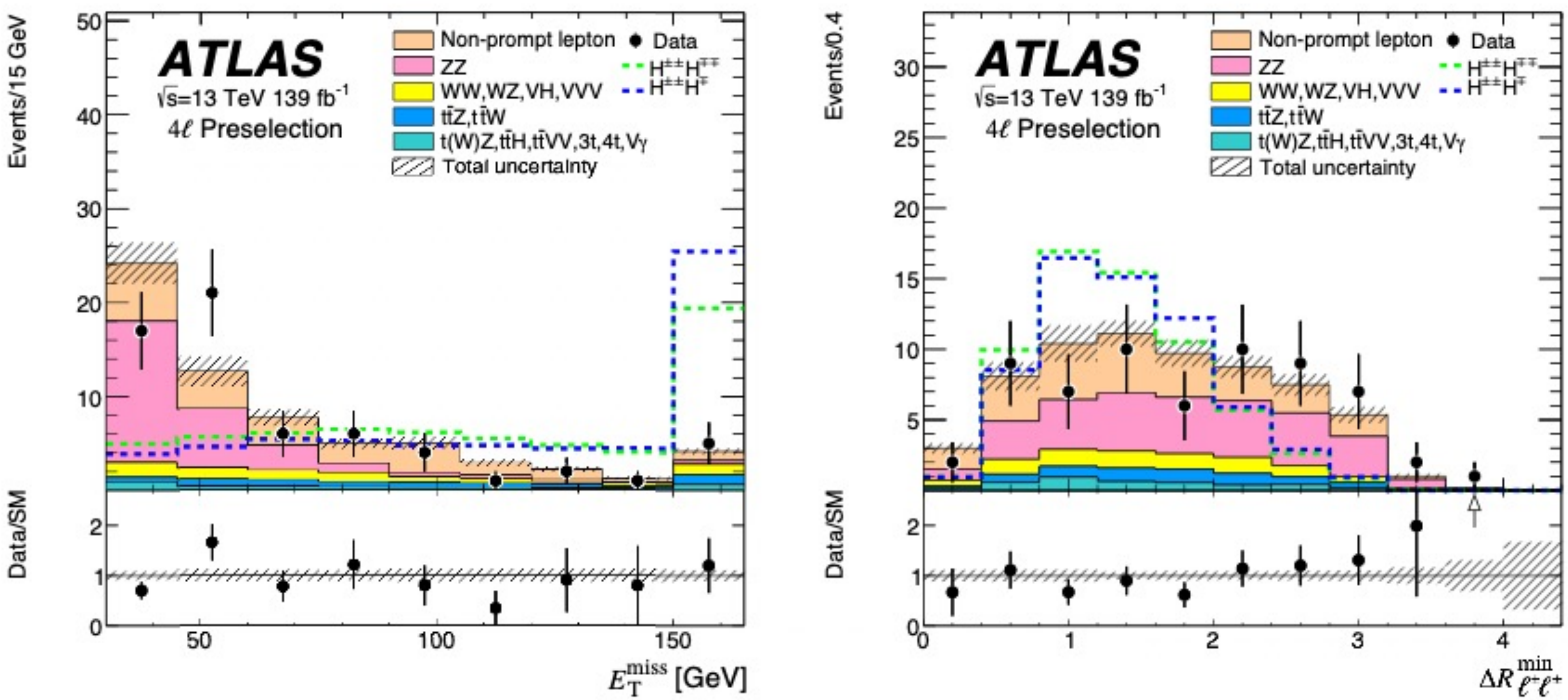
Analysis (IV)



[6]

The measured data are in agreement with the background predictions for the 3l channel.

Analysis (V)

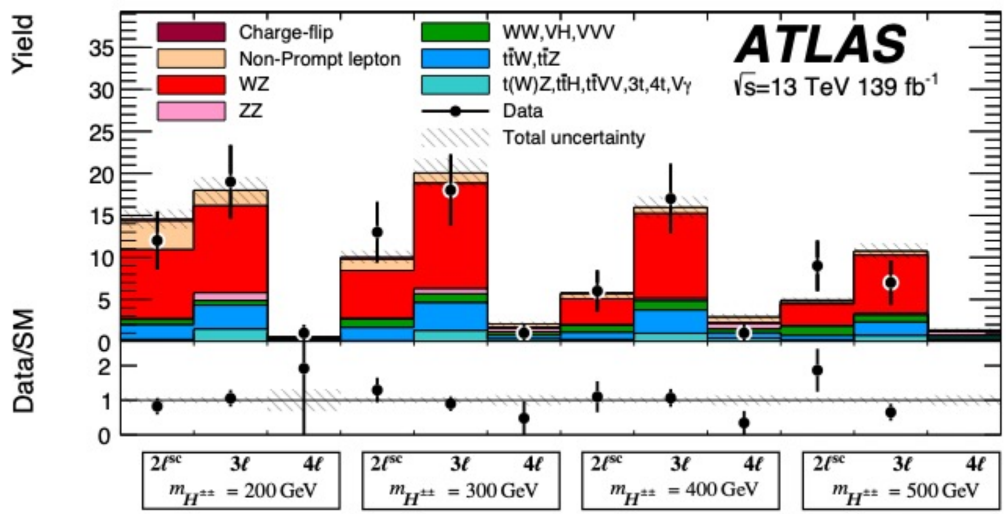


[6]

Data consistent with background predictions in the 4l channel, with small statistical fluctuations .

Analysis (VI)

Combination of results:



[6]

Observations and Monte Carlo predictions are consistent to each other considering the total uncertainties

Input for upper limit determination for $\sigma\ x\ B$.

Statistical Analysis

Likelihood (function): measures goodness of a fit

Likelihood ratio test: Comparing goodness of a fit for two competing statistical models upon likelihood ratio

Maximization of free parameter space (signal strength → σ)

Additional constraints: Nuisance parameters (stat. uncertainties)

Define **upper limits & confidence level (CL)** on model parameters.

Analysis (VII)

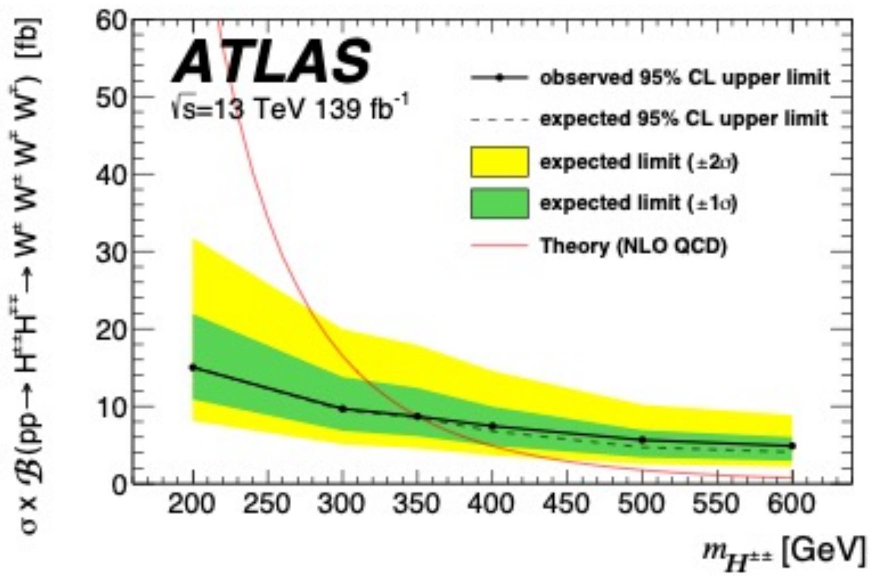
Expected limit:

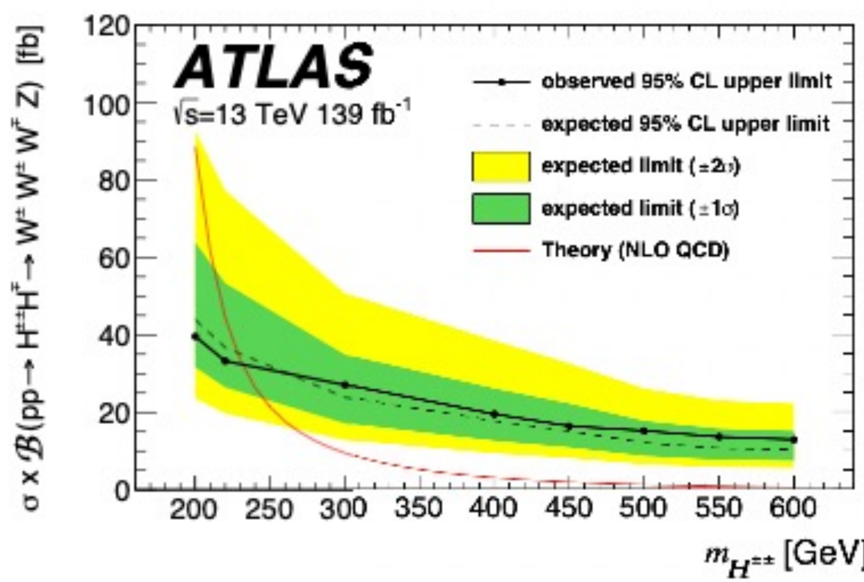
$\mu \times$ Signal + Background vs. Background

Observed limit:

$\mu \times$ Signal + Background vs. Data

The combined data are not sensitive for heavy $H^{\pm\pm}$ bosons with masses > 320 GeV





[6]

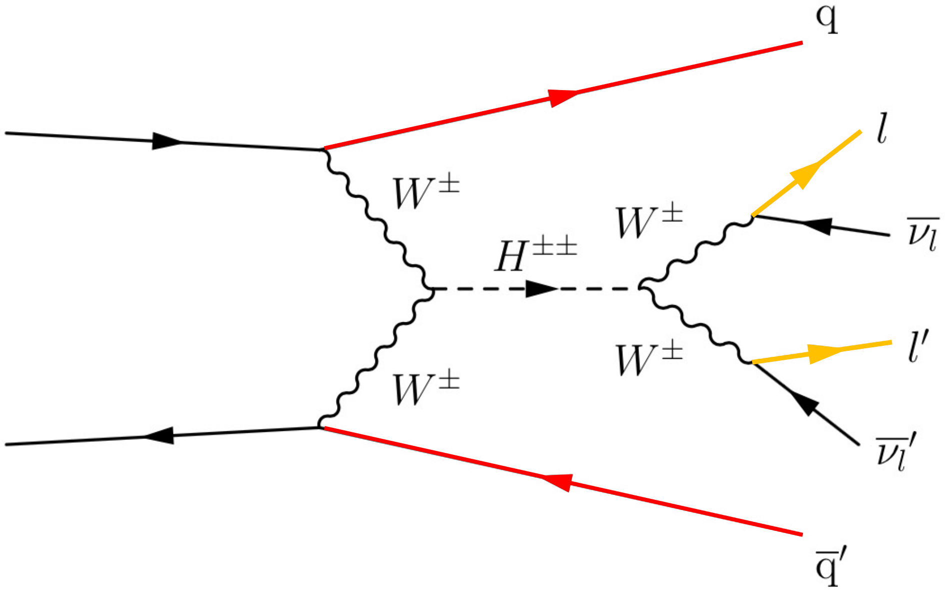
Results

No significant excess over expected yields.

Considered model can be excluded

- **at a 95% confidence level for $m_{H^{\pm\pm}}$ < 350 GeV (pair production)**
- **at a 95% confidence level for $m_{H^{\pm\pm}}$ < 230 GeV (mixed production)**

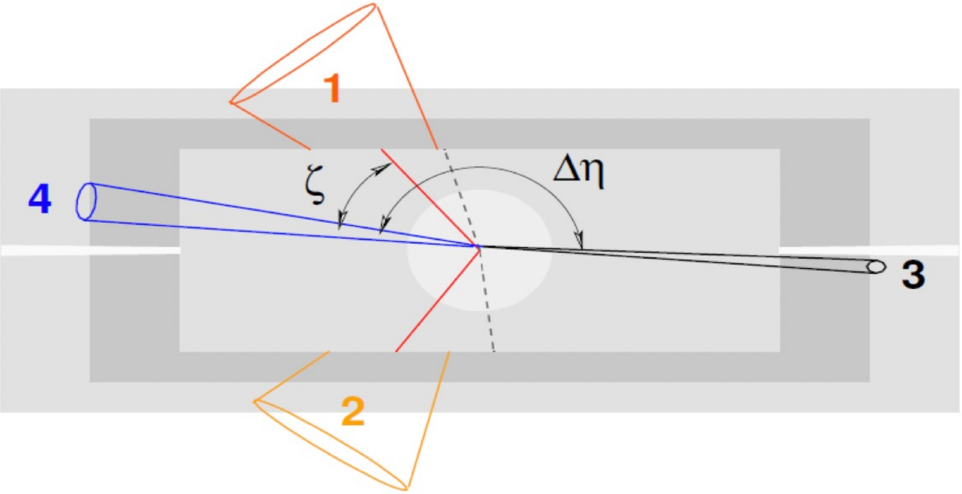
PART B: Vector Boson Fusion (VBF)



- 2 jets + central dileptons
- Large values of transverse momentum p_T/mass m_T
- Jets in different hemispheres (~ back to back)

→ Expect clear signature of the signal process [8]

Event Variables VBF $H^{\pm\pm}$ (I)



[9]

Centrality (W/Leptons boosted in transversal direction) → $\zeta > 0$ for VBF

$$\zeta = min\left[min(\eta_{l1}, \eta_{l2}) - min(\eta_{l1}, \eta_{l2}), \quad max(\eta_{j1}, \eta_{j2}) - max(\eta_{l1}, \eta_{l2})\right]$$

$\Delta\boldsymbol{\eta_{jj}}$ (Pseudorapidity gap, jets back to back)

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

Event Variables VBF $H^{\pm\pm}$ (II)

$\boldsymbol{m_T} = |pT|$ (Transversal mass)

$\boldsymbol{m_{jj}} = |p_{j1} + p_{j1}|$ (Dijet mass)

$\Delta\boldsymbol{\phi_{jj}}$ (Azimuth angle between jets)

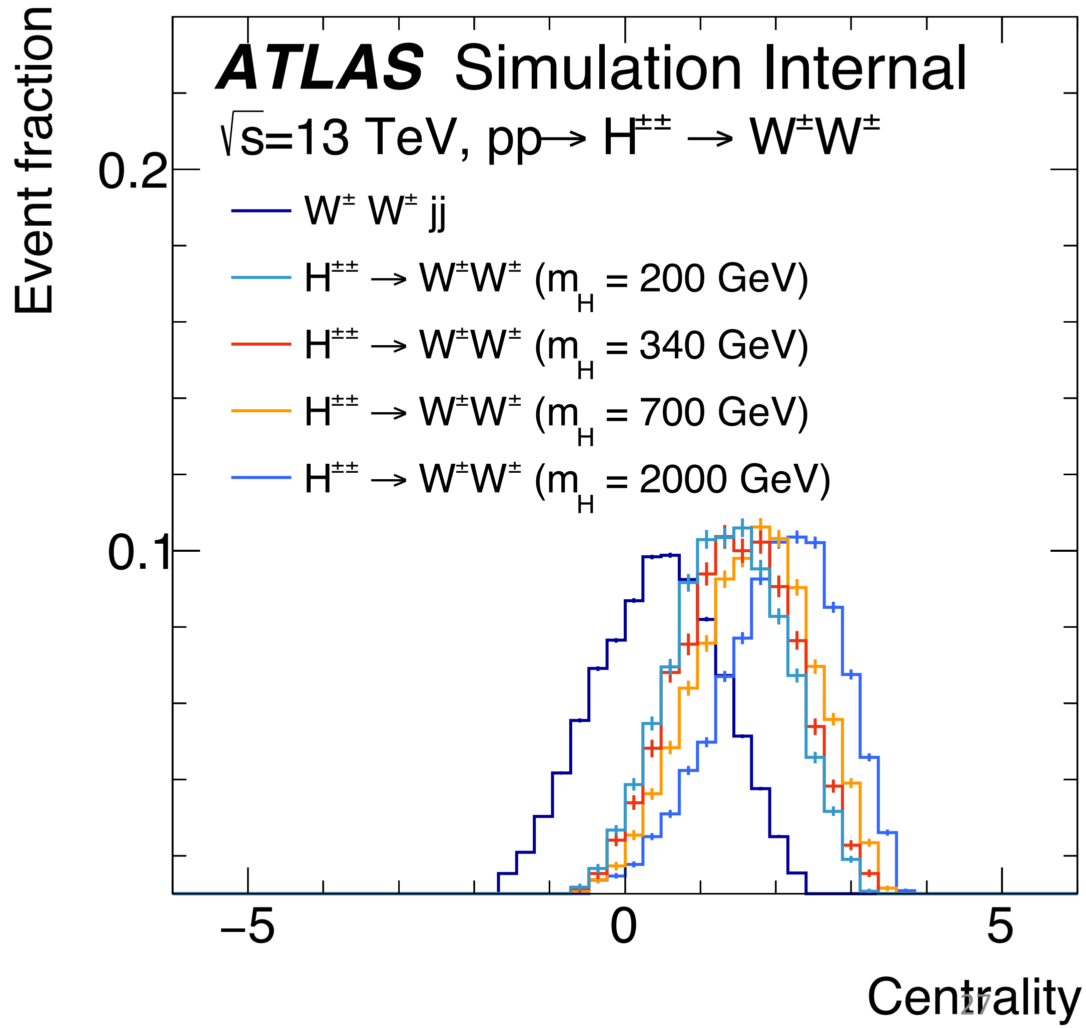
→ Choose variables with the best background separation

Event Variables VBF $H^{\pm\pm}$ (III)

Centrality

Leptons boosted transversally
→ Centrality > 0

Clear distinction - especially for higher masses



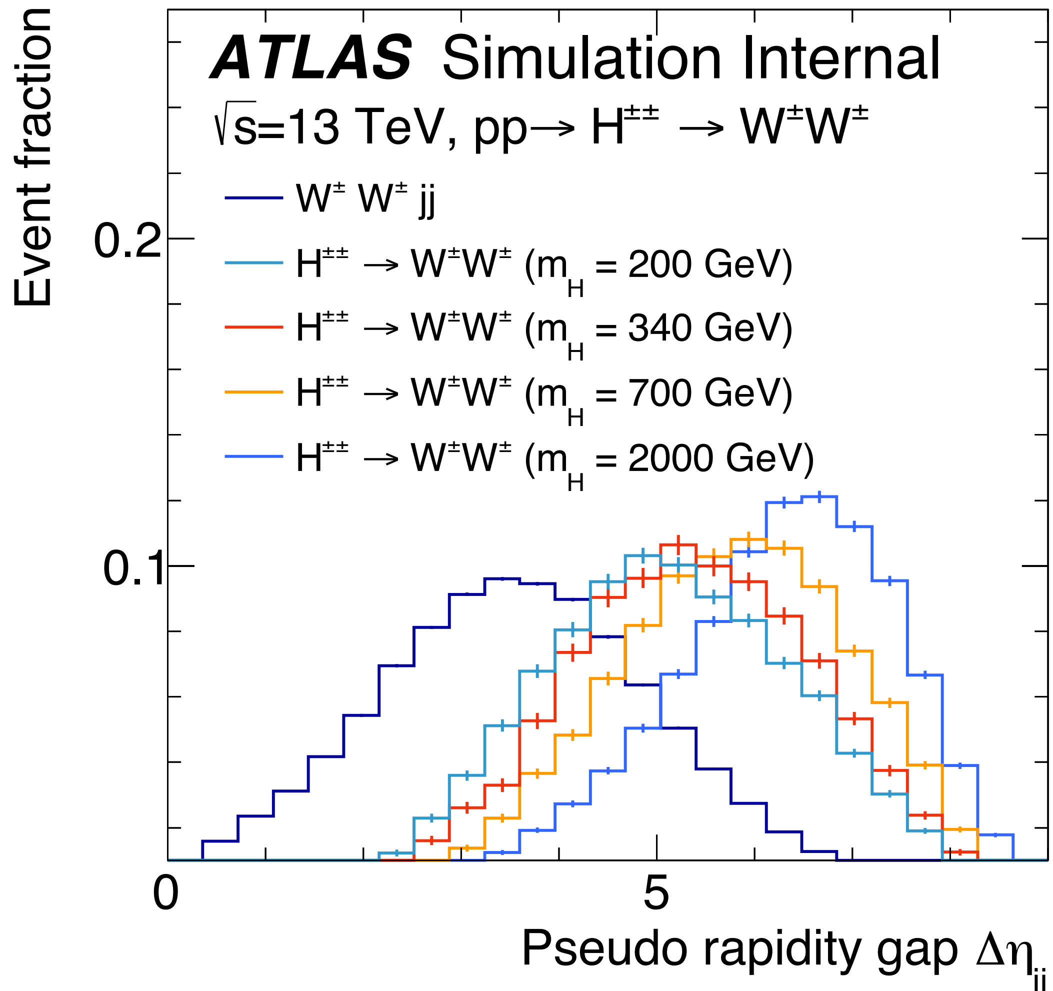
Event Variables VBF $H^{\pm\pm}$ (IV)

$\Delta\eta_{jj}$

Jets back to back

→Large pseudo-rapidity gap

Valid for all masses

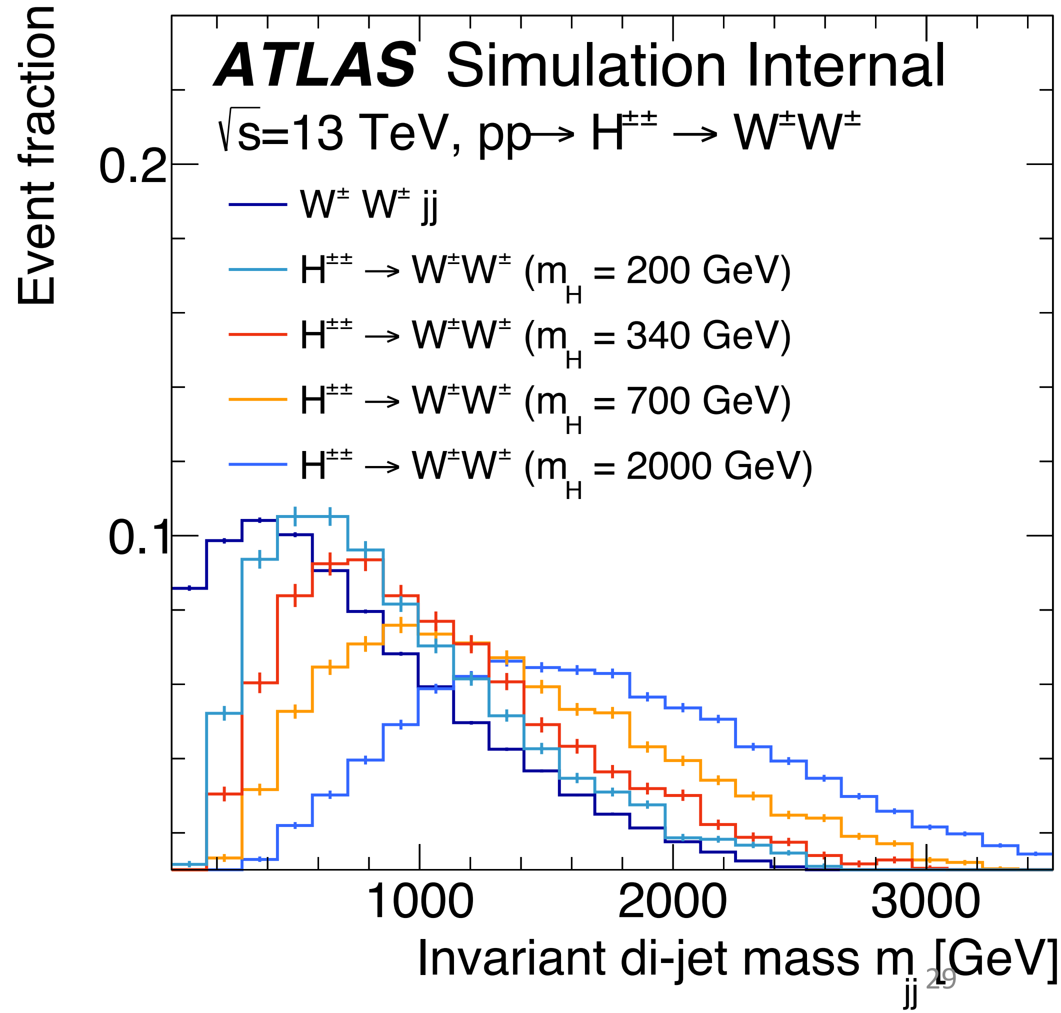


Event Variables VBF $H^{\pm\pm}$ (VI)

m_{jj}

Separation difficult for low masses.

Better suited for possible heavy $H^{\pm\pm}$.



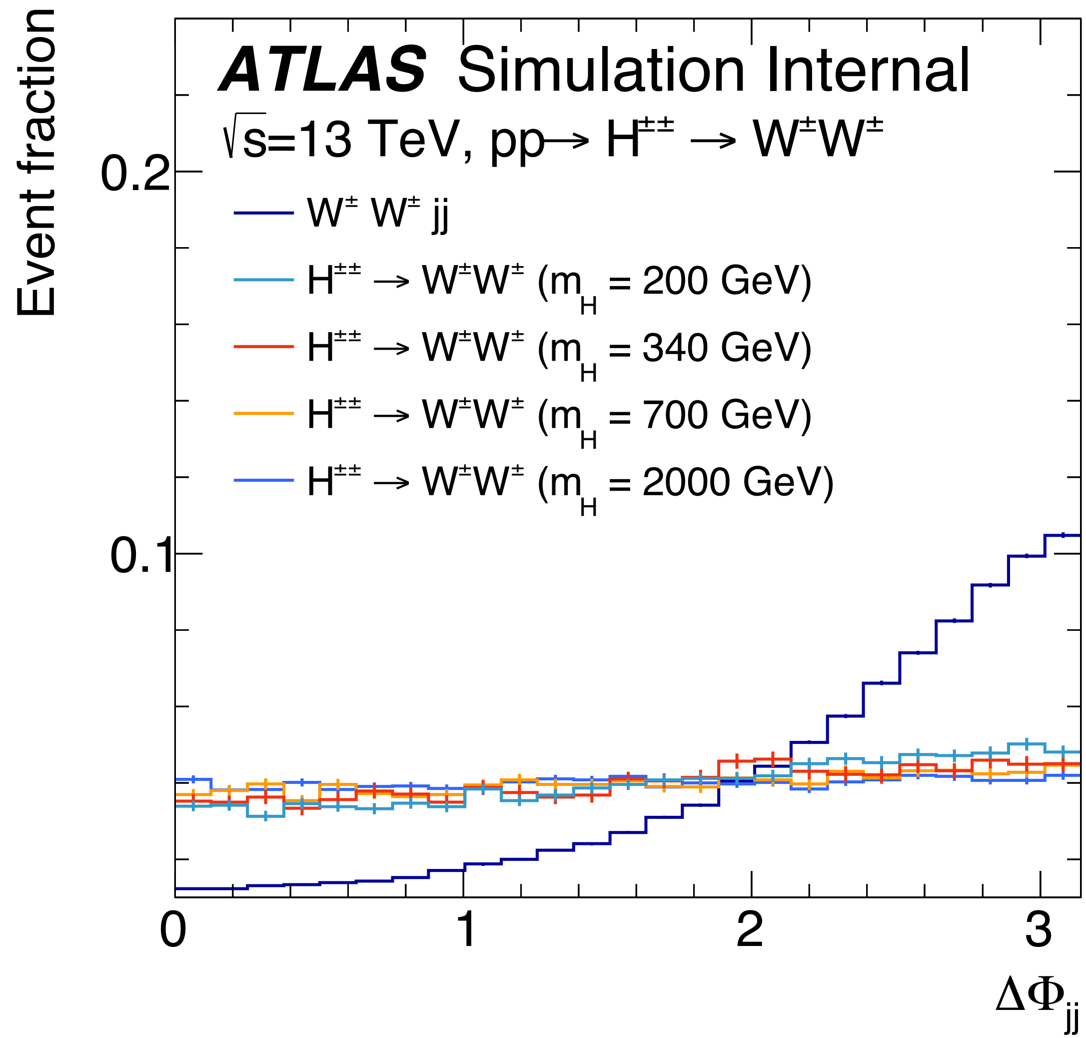
Event Variables VBF $H^{\pm\pm}$ (VII)

$\Delta\phi_{jj}$

Good separation for small angles

Independent of $H^{\pm\pm}$ mass

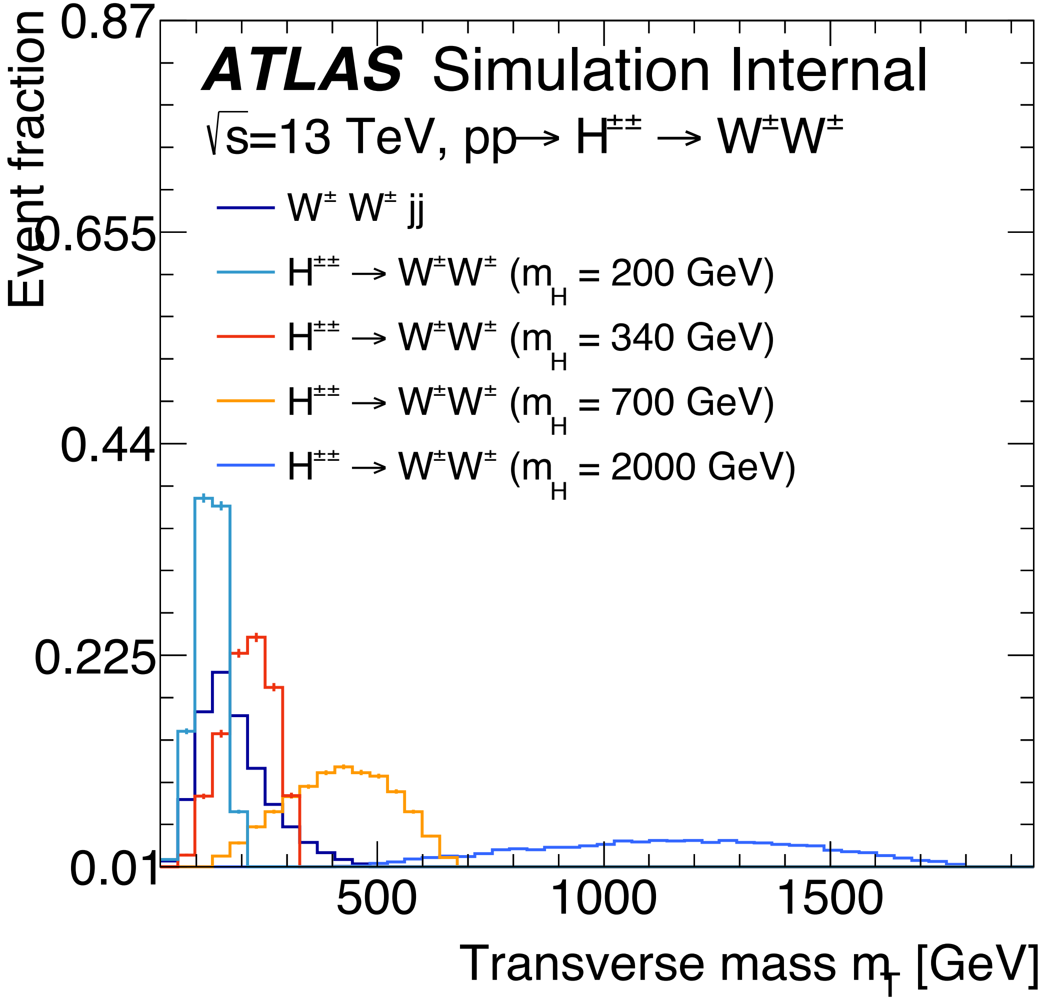
→ Well qualified



Event Variables VBF $H^{\pm\pm}$ (V)

$\boldsymbol{m_T}$

Candidate as input for maximum likelihood fit

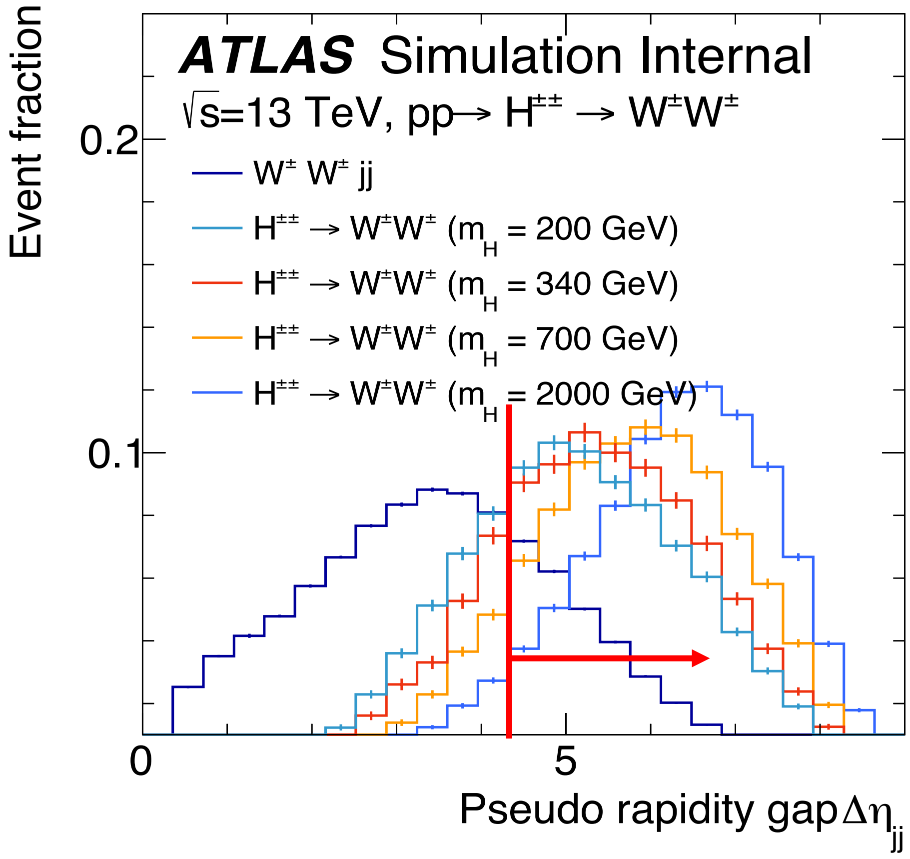


Event Selection (I)

Limiting the available signal region (Cuts)

→ Improves the signal/ background ratio

Mostly lower bounds, for $\Delta\boldsymbol{\phi}_{jj}$ upper bound



Event Selection (II)

Improve ratio ⟷ Maximise signal

Quantified by significances, e.g.:

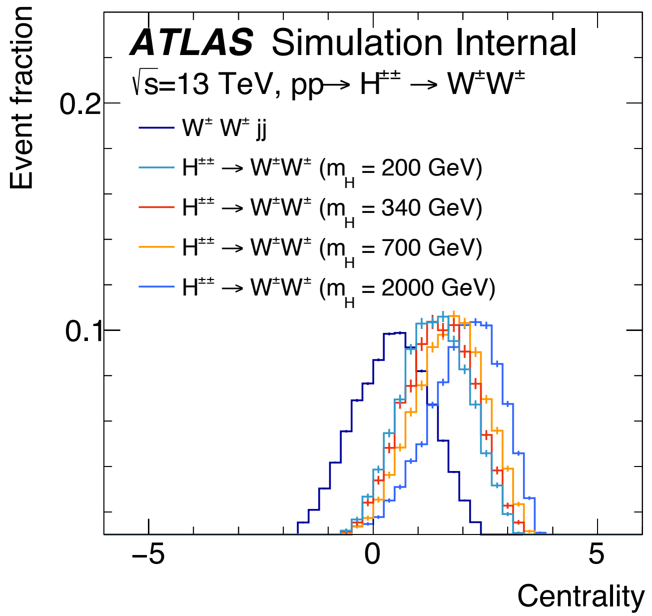
$\frac{s}{\sqrt{b}}$ s (b) = Number of signal (background) events

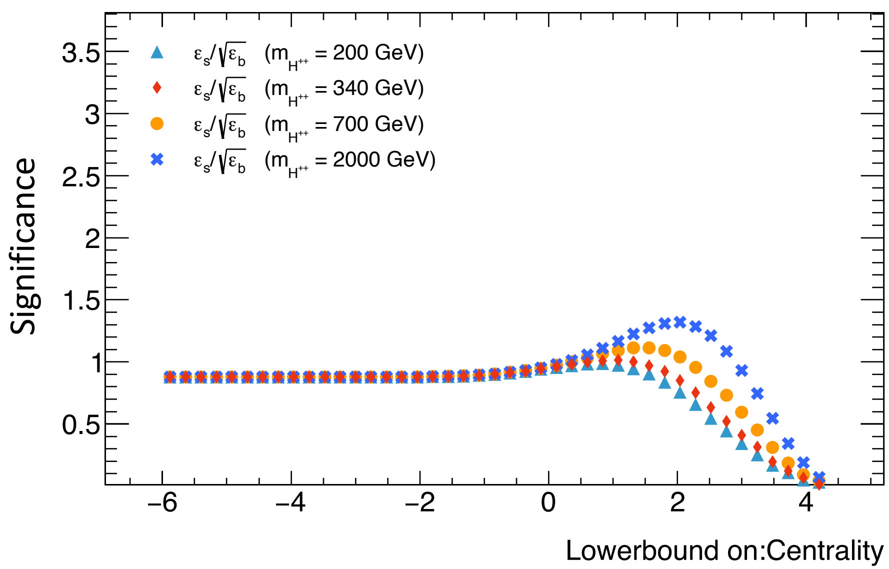
$$\sqrt{2\left[(n+b)\log\left(1+\frac{n}{b}\right)-n\right]}$$

→ Determine max. value

Event Selection (III)

$$\sqrt{2\left[(n+b)\log\left(1+\frac{n}{b}\right)-n\right]}$$





Maximum significance close to intersection from signal to background.

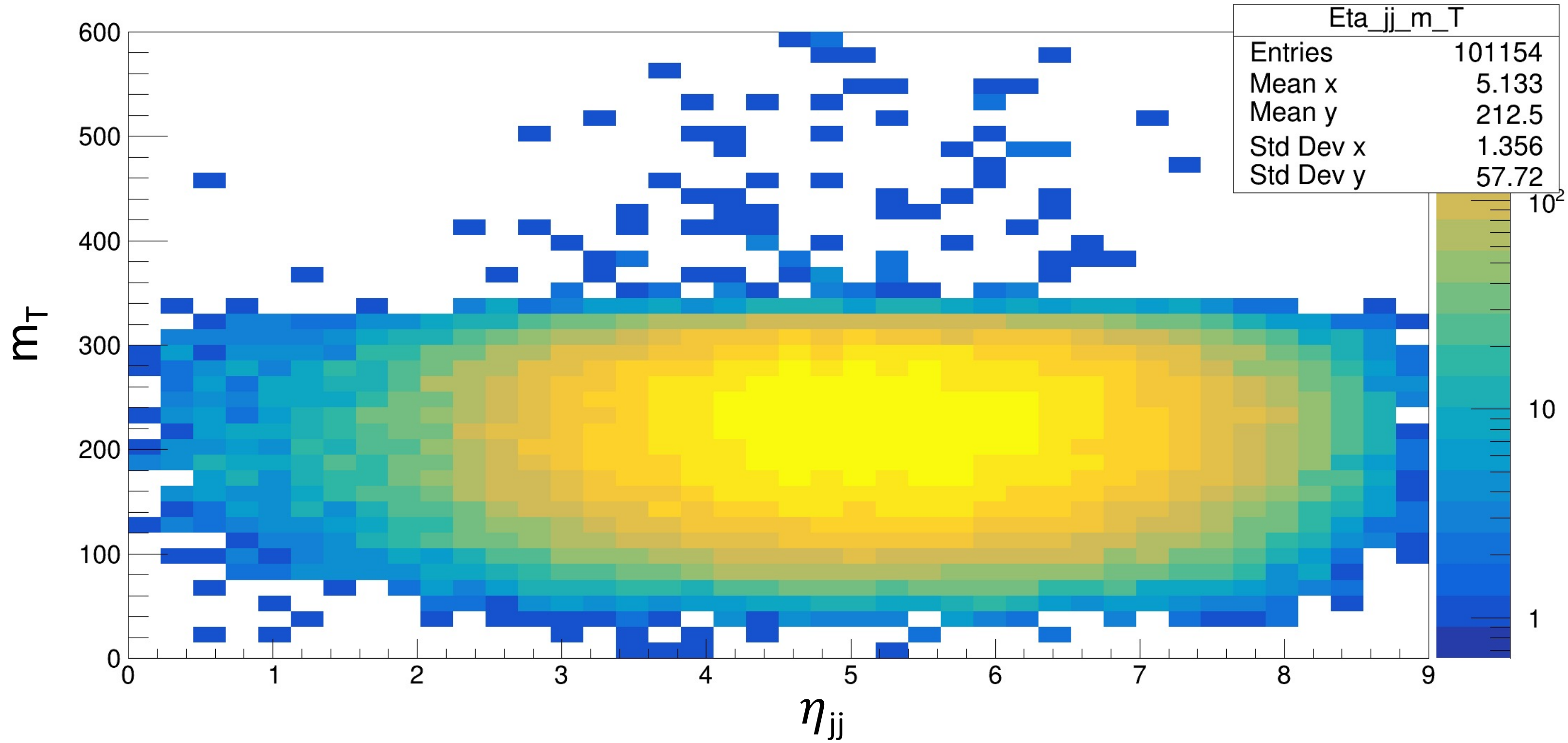
Event Selection (IV)

Problem: if variables depend on each other

Cuts may influence other variables → low signal

Analyse correlation in **2D-Histograms**

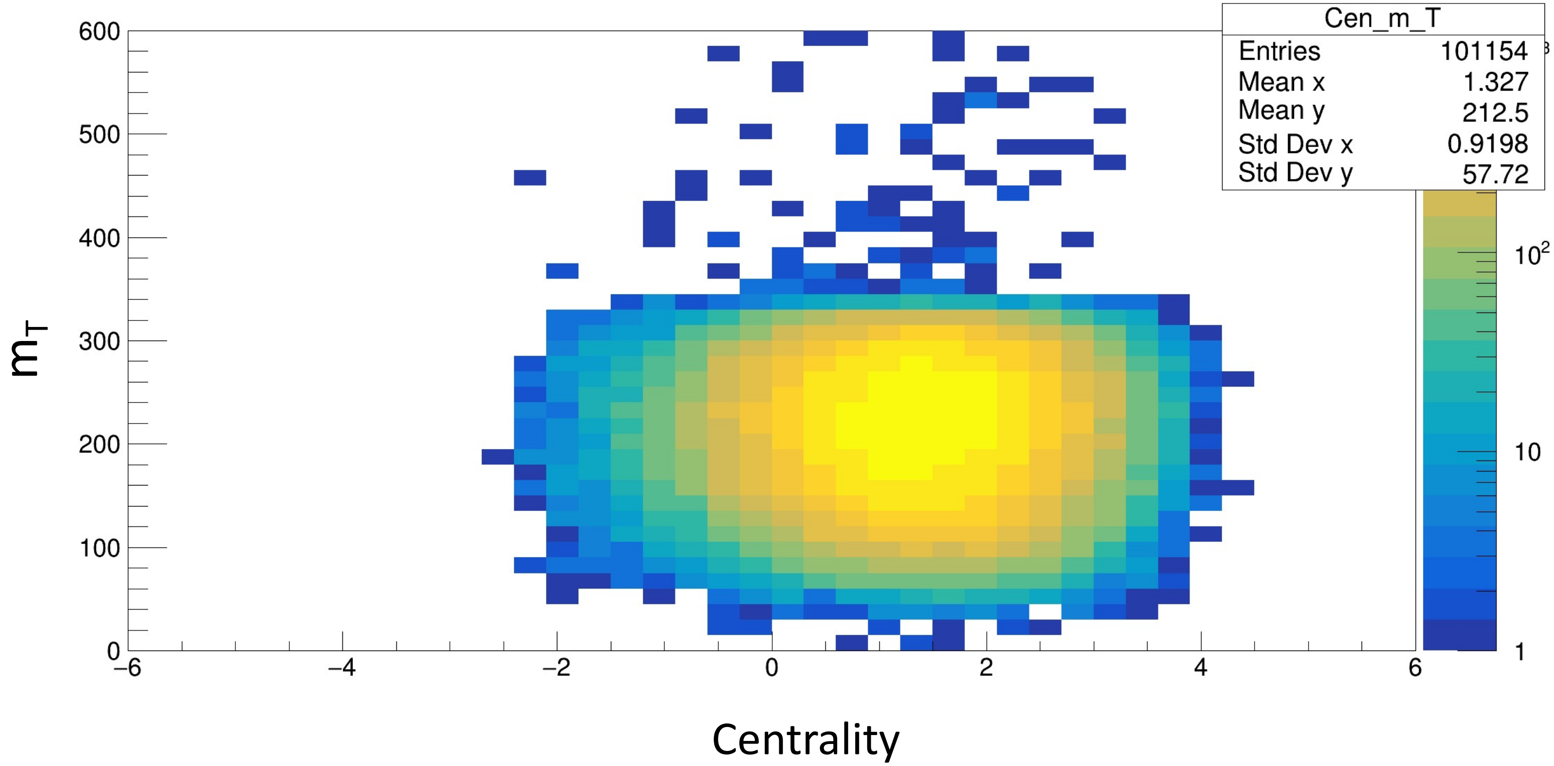
Event Selection (V)



Probably no correlation between the variables.

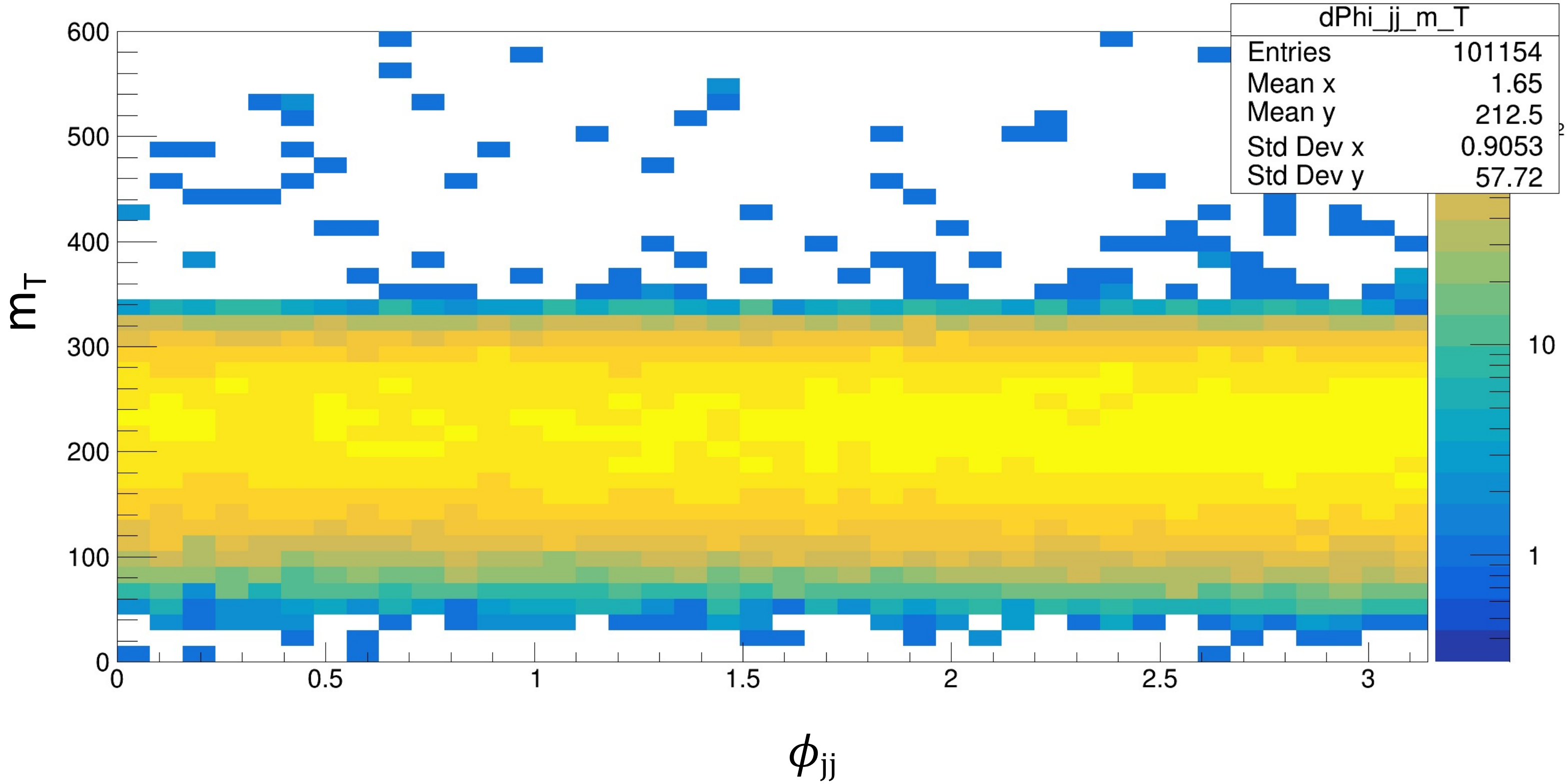
m_T is limited by Higgs Mass (340 GeV).

Event Selection (VI)



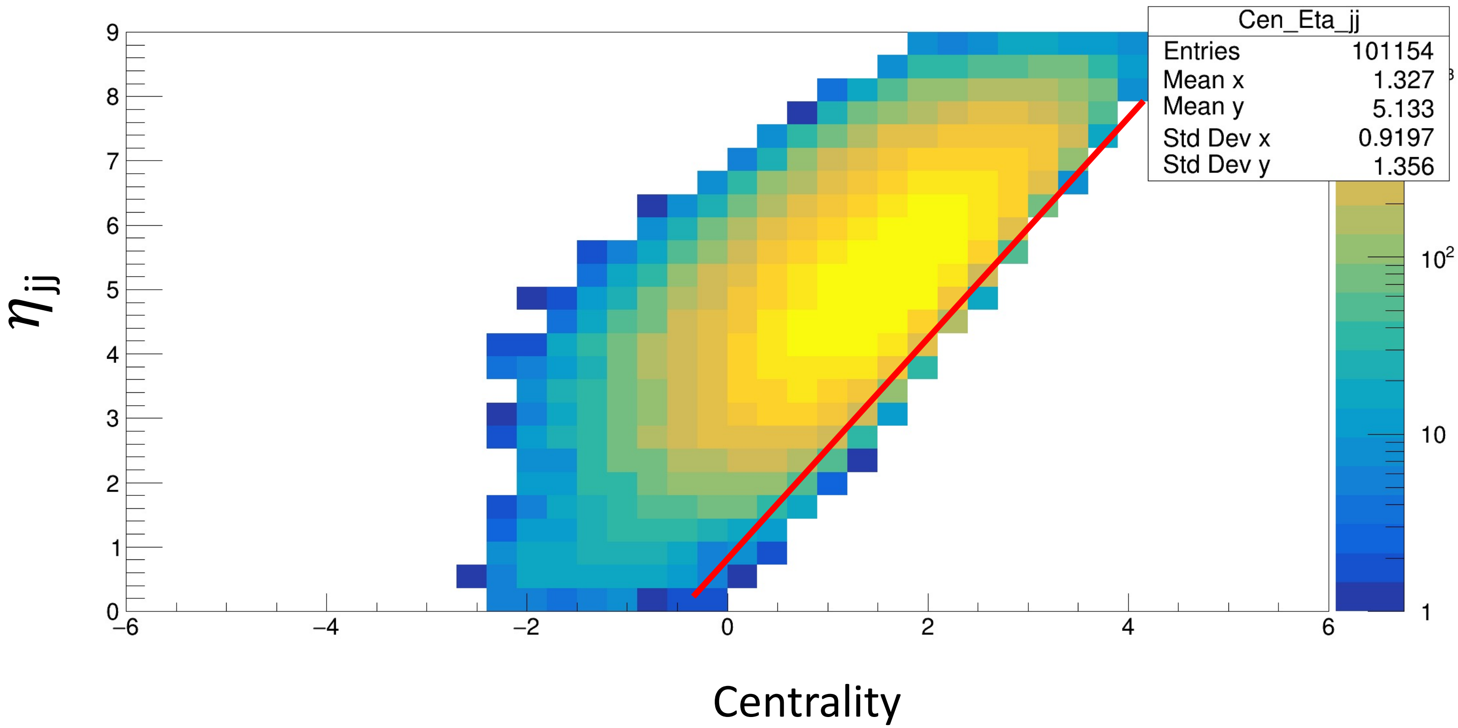
Probably no correlation (no visible function dependence) → Further in depth analysis

Event Selection (VII)



Clearly no correlation → Cuts possible for ϕ_{jj}

Event Selection (IIIX)



Strongly correlated, linear dependence → Caution with cuts for centrality **and** η_{jj}

Background Estimation (I)

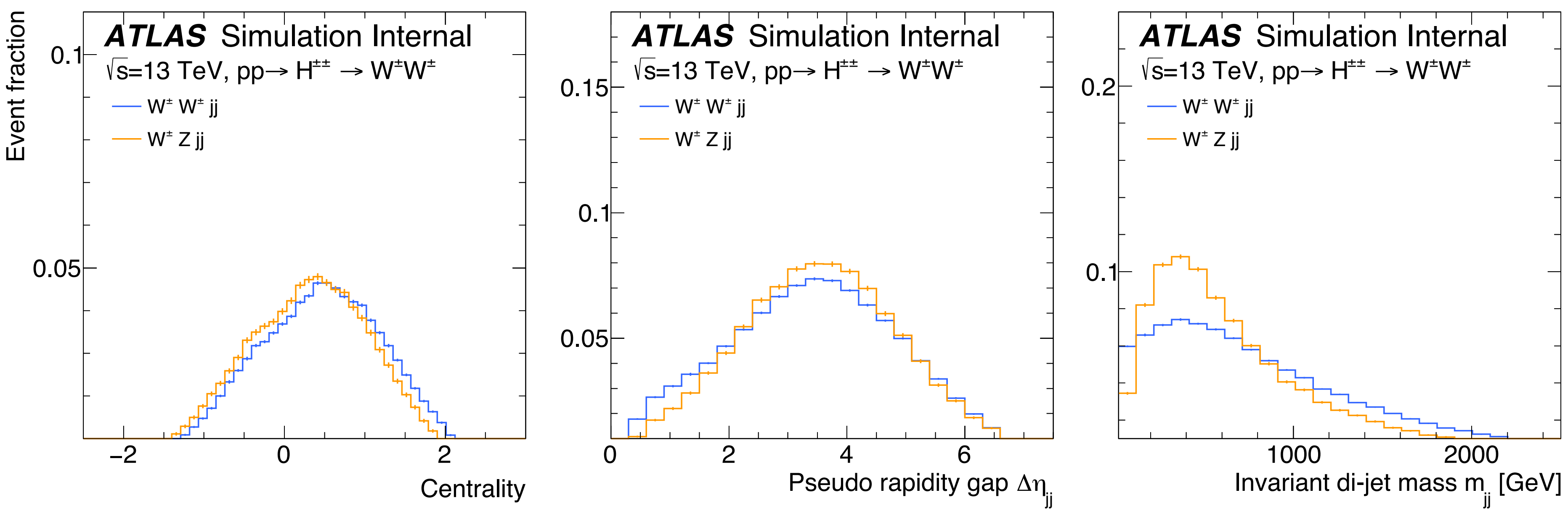
$\mathbf{W^{\pm}W^{\pm}\,jj}$ (so far) + $\mathbf{W^{\pm}Z\,jj}$

Restrict possible events for better separation:

- Jets in different hemispheres
- Number of jets/leptons
- Leptons of same charge (Z resonance)

Background Estimation (II)

Small difference between different channels for all variables → Same cuts and event variables



MVA Training

Multi variant analysis training

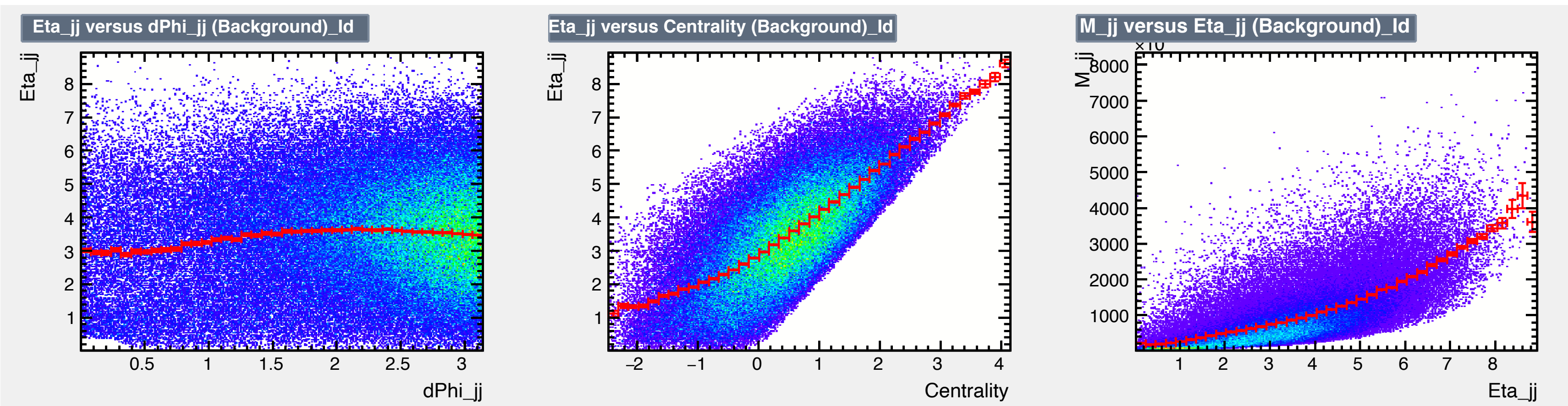
Separation signal background via MVA:

ϕ_{jj}	ϕ_{ll}	η_{jj}	M_{jj}
Centrality	j_T^{Lead}	$j_T^{sublead}$	

$\mathbf{m_T}$ is needed for maximum likelihood fit, $\mathbf{m_{ll}}$ is not independent → m_T, m_{ll} not included in training (no cuts)

Variable Correlation

Determine dependencies between variables: Prevent cut interferences (as before)



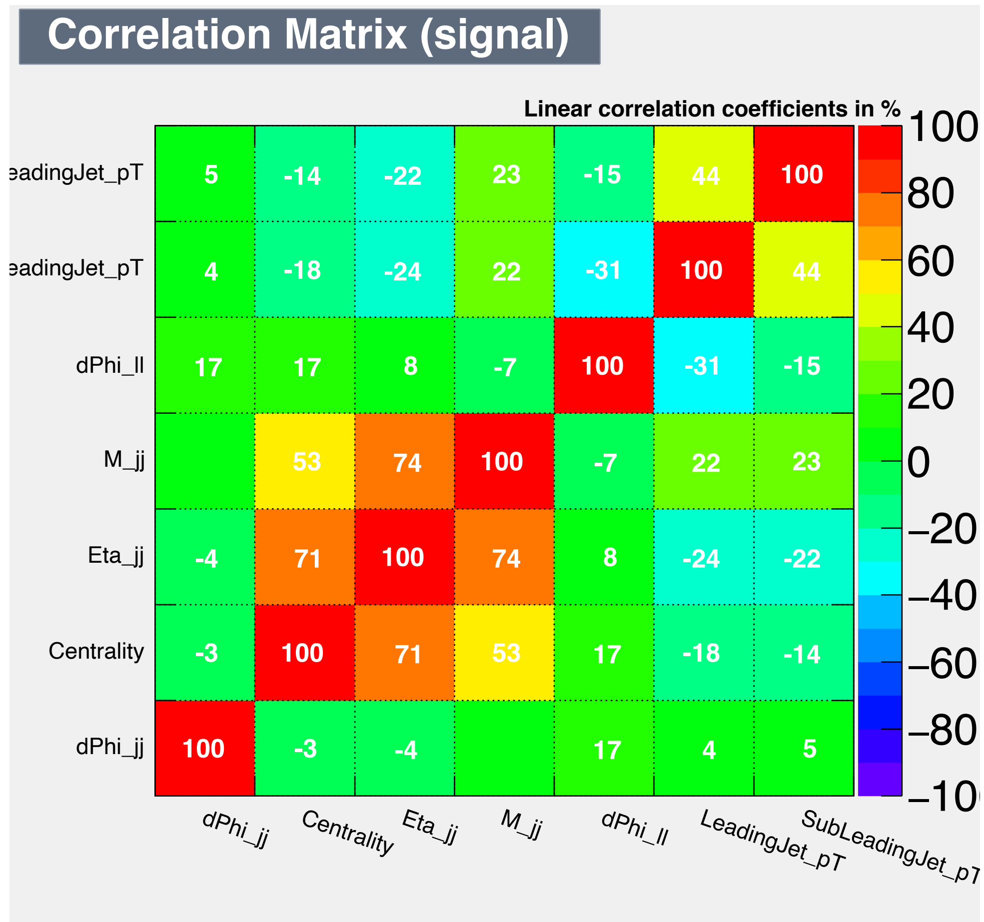
Quantification: Linear dependence coefficients from mean value (in gradient percentage $m = 1 \triangleq 100$)

Correlation Matrix

Summary of linear correlation coefficients (signal) in correlation matrix for m_H = 340 GeV

Example from before: Centrality $\longleftrightarrow$ η_{jj}

Strongly dependent

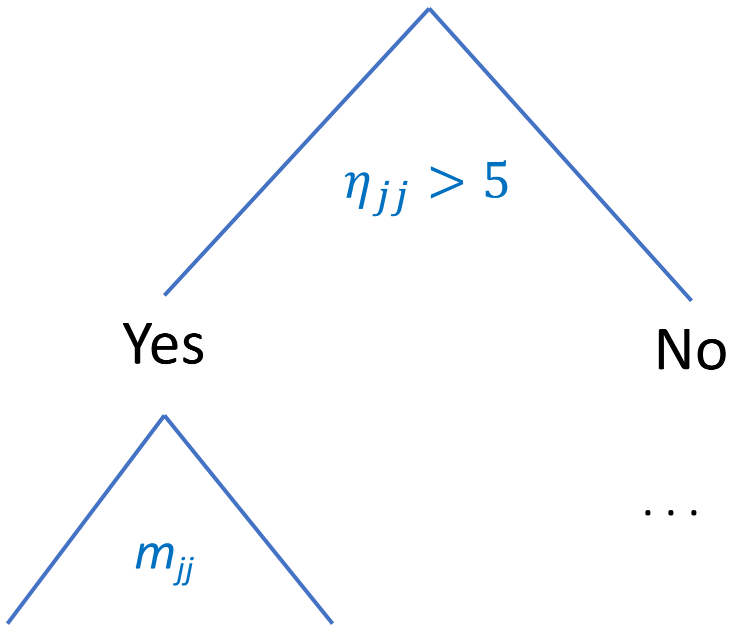


Decision Trees

Separation background signal via **decision trees** [10]:

- Training/Testing with simulations
- Reconstruct more signal (no exclusion because of one variable)
- Combination of multiple trees

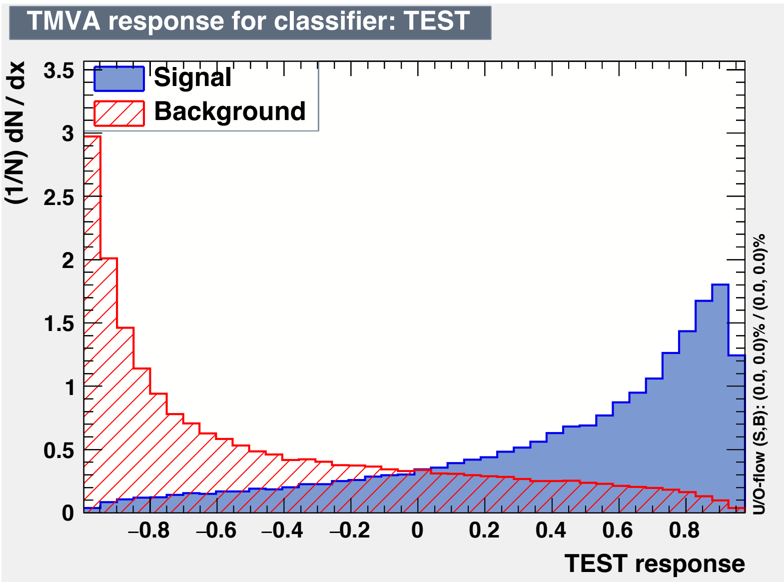
→ **Boosted decision trees**

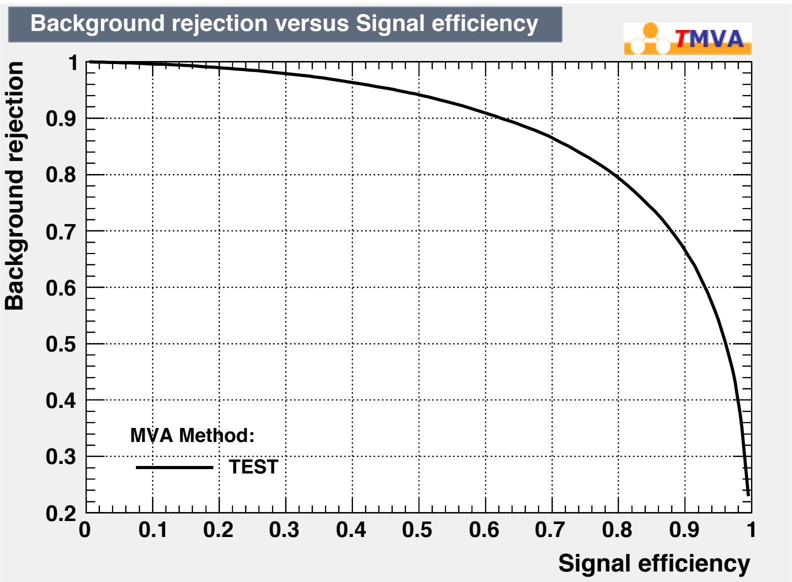


Signal/Background response

Ratio of trees identifying event as signal ≡ **Response**

Results for training set (m_H = 340 GeV):

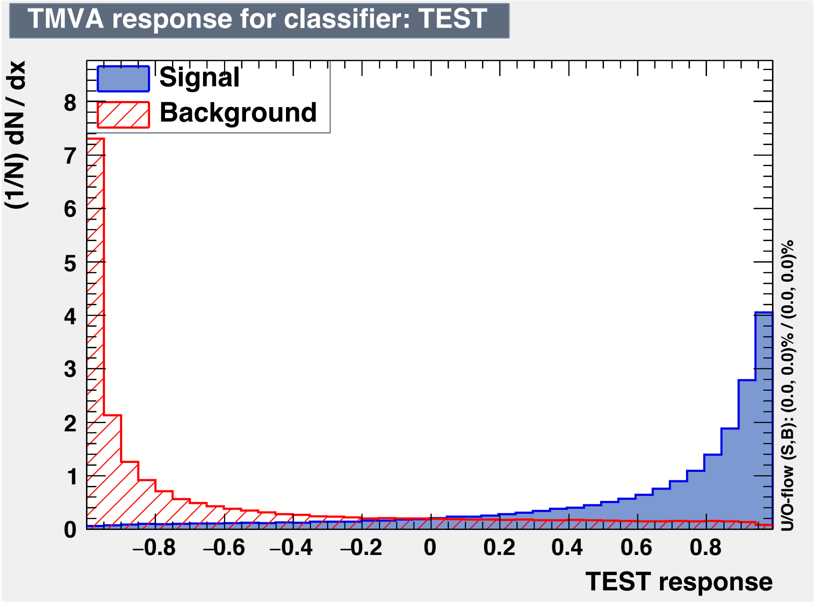


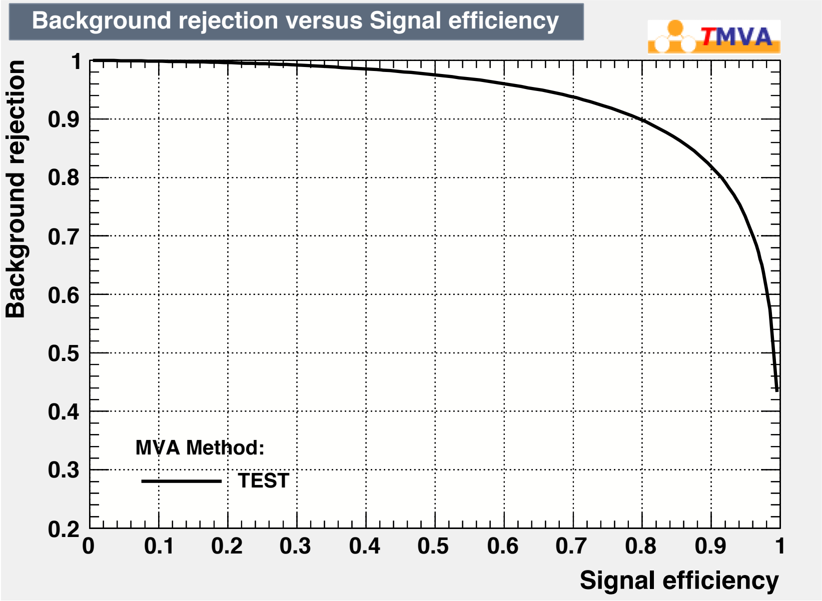


Integration for a given boundary determines signal efficiency (ratio) & Background rejection

Signal/Background Response (II)

Results for training set (m_H = 700 GeV):



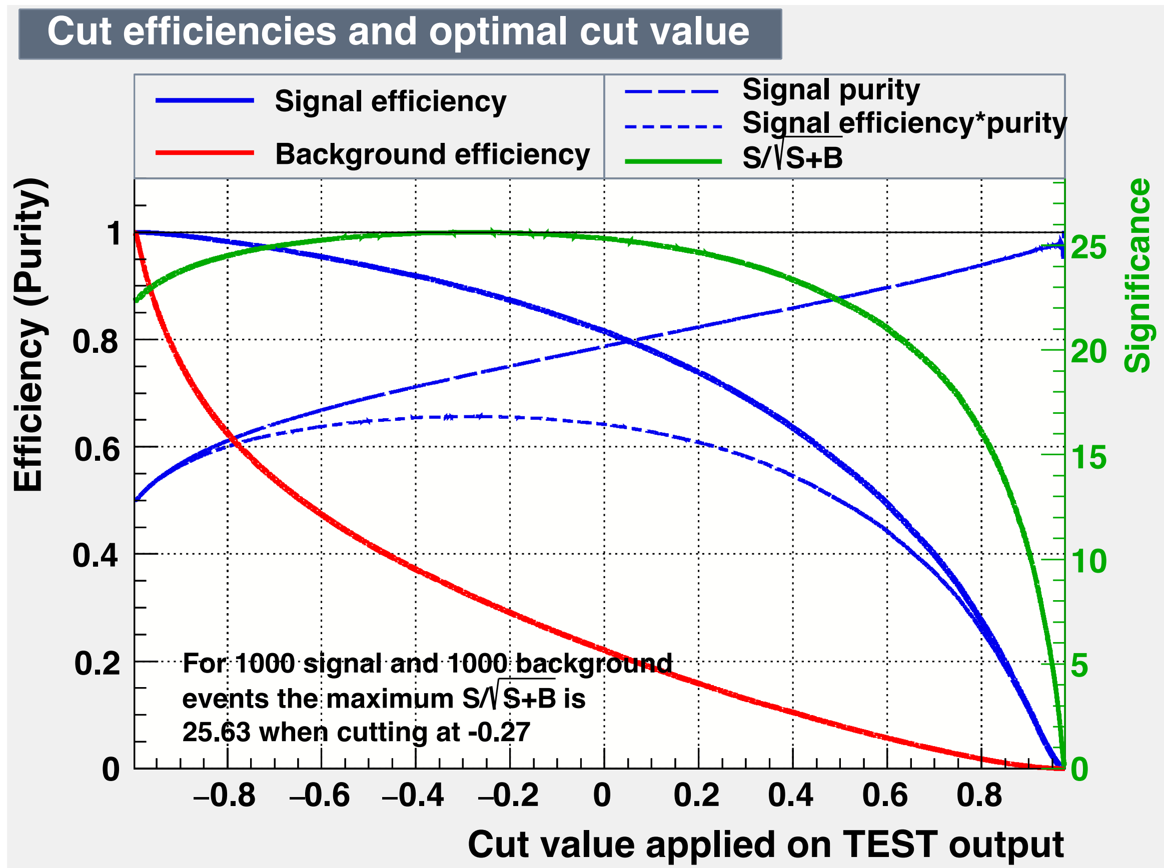


Even better signal (background) identification (High ratio with clear signal (background) response ≅ 1 (-1))

Defining Cuts

Boundary (Cut) is set according to the used **metric** (e.g.: $\frac{s}{\sqrt{s+b}}$)

Suggested cut for significance at a response of –0.27 (background region)



Outlook

1.

Add/sum different backgrounds with relative weight to each other and signal

2.

Calculate expected upper limits for

$\sigma \times B$

with 95% CL

Acknowledgments

Prof. Hubert Kroha

Dr. Dominik Duda

Thank your for your attention!

Sources

[1] https://atlas.cern/discover/detector

[2] https://de.wikipedia.org/wiki/ATLAS_(Detektor)#/media/Datei:LHC_02.svg

[3] httpa://www.lhc-closer.es/taking_a_closer_loos_at_lhc/0.atlas

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[5] Testing the Standard Model, lecture by D. Duda

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