Higgs boson properties in the vector boson fusion $H \rightarrow WW^* \rightarrow l\nu l\nu$ channel

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18/12/2018

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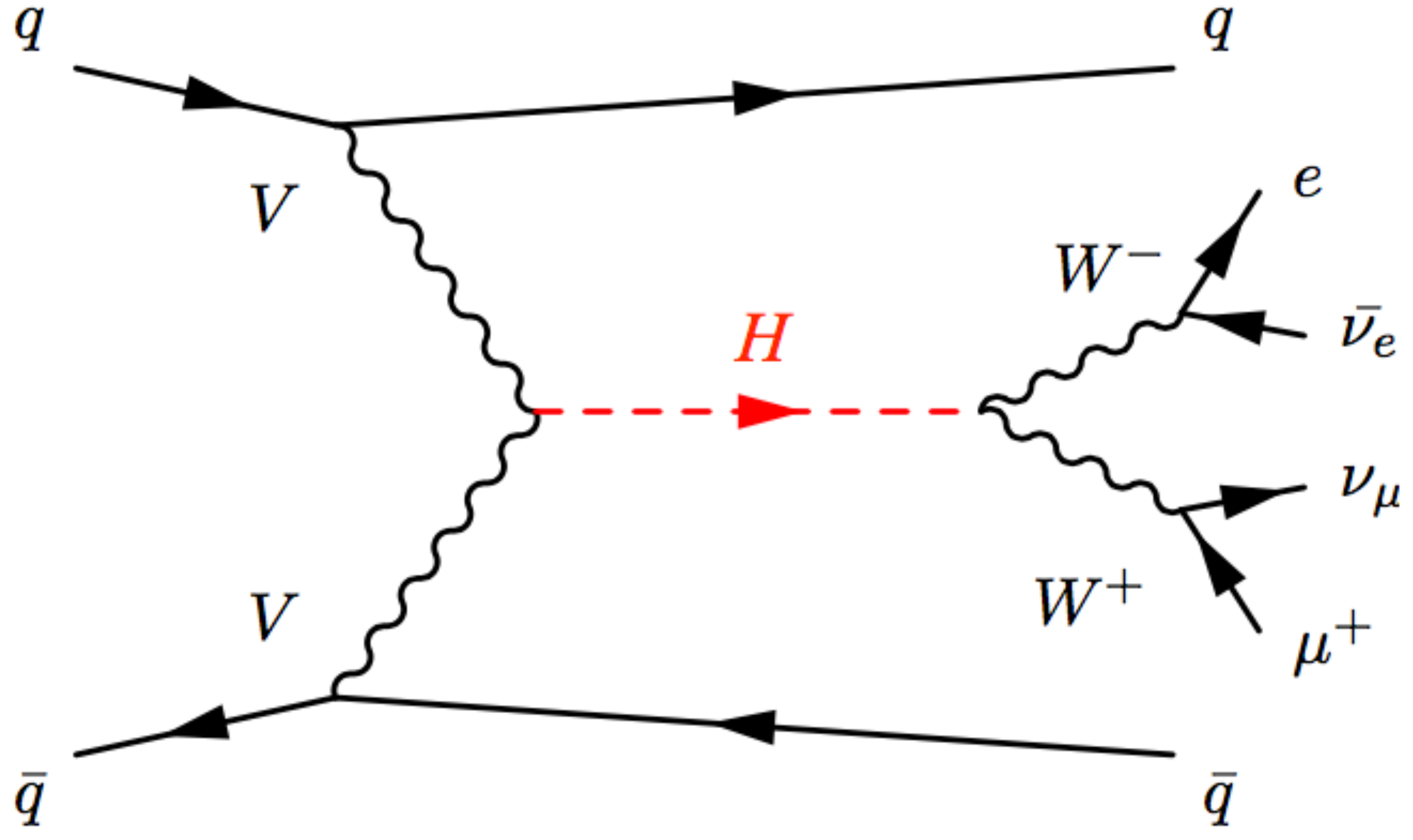
ATLAS EXPERIMENT

The VBF H⟶WW*⟶ lvlv channel

- **Vector Boson Fusion,** after the gluon gluon fusion**, is the second largest Higgs production** mechanism , purely EW process
- **HWW decay** provides a direct access to coupling measurement.



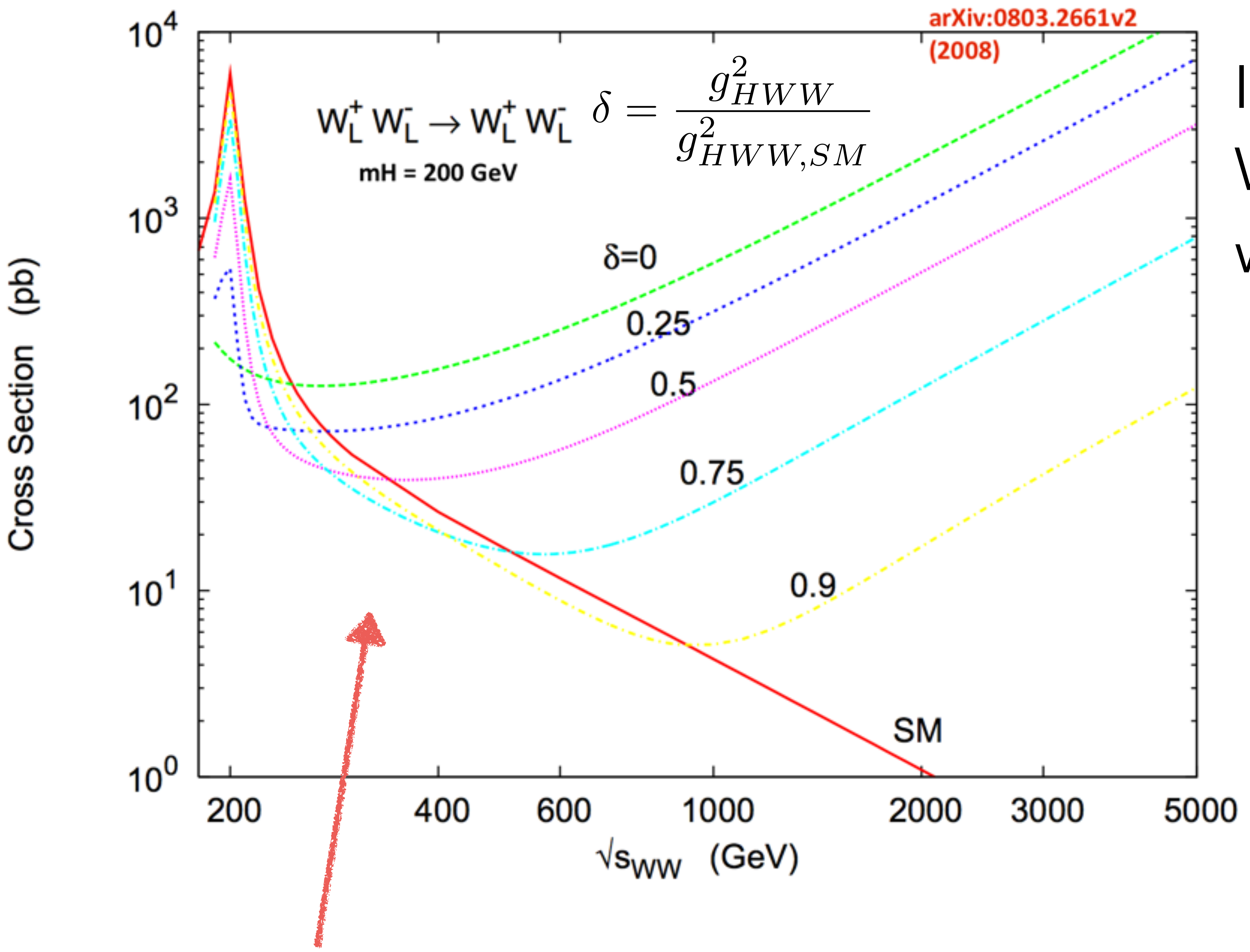
Specific signature:

- Two forward tag jets with high invariant mass
- The Higgs boson is produced centrally:
  - No other jets in the ΔY_{jj} gap
  - The leptons have to be in the gap

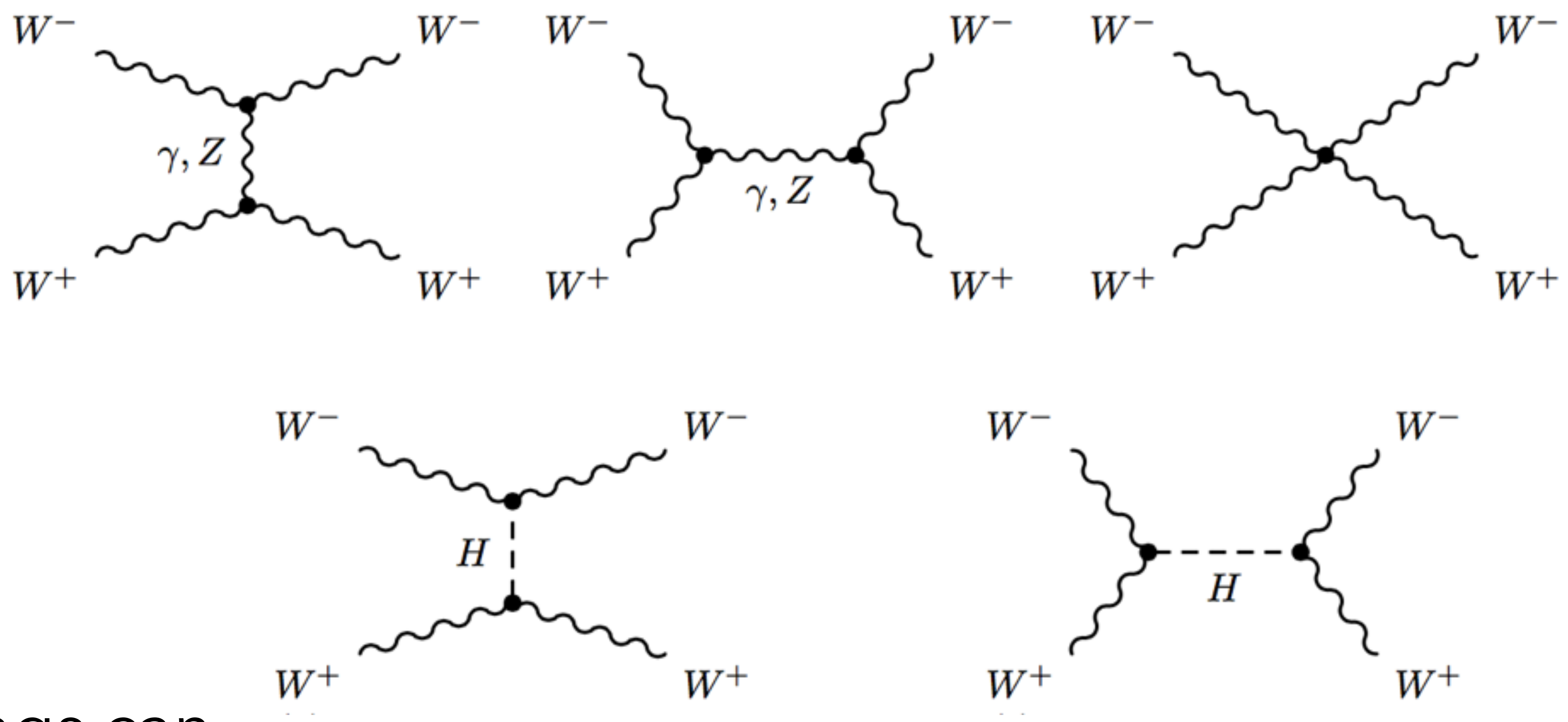
- **First measurement** of the Higgs couplings to **polarized W** bosons
- **Cross-section** measurement

All results with 36.1fb-1 of data (2015+2016)

Motivation for HWW polarised coupling studies



In the SM the Higgs boson unitarizes the cross-section of $W_L W_L \to W_L W_L$ that otherwise would grow infinity large with the center of mass energy



Deviations from SM values of the HWW couplings can still lead to an incomplete unitarisation of the interactions!

HWW couplings are sensitive to new physics in EWSB: extended Higgs sectors (2HDM), Higgs as a composite pseudo-Goldstone boson (SILH) …

Parametrisation of anomalous couplings [arXiv:1404.5951]

- To test the SM EW symmetry breaking → separately test the Higgs couplings to transverse and longitudinal parts of the W bosons

- To measure the polarization we need to choose a reference frame

  → **Higgs rest frame**: no mixed coupling HW_LW_T , only HW_LW_L, HW_TW_T

Couplings parameters

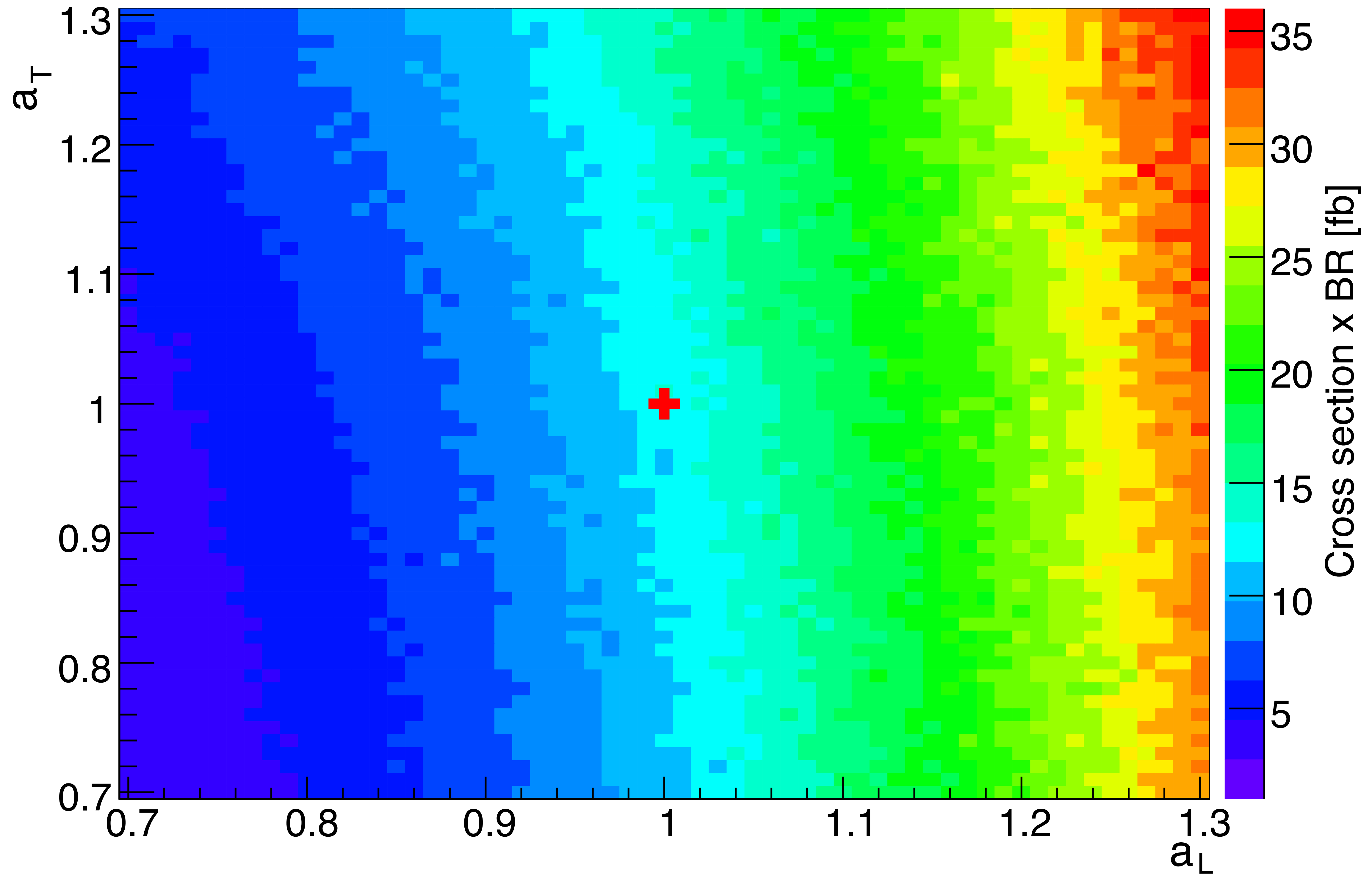
$$a_L = \frac{g_{HW_LW_L}}{g_{HWW}} \qquad a_T = \frac{g_{HW_TW_T}}{g_{HWW}}$$

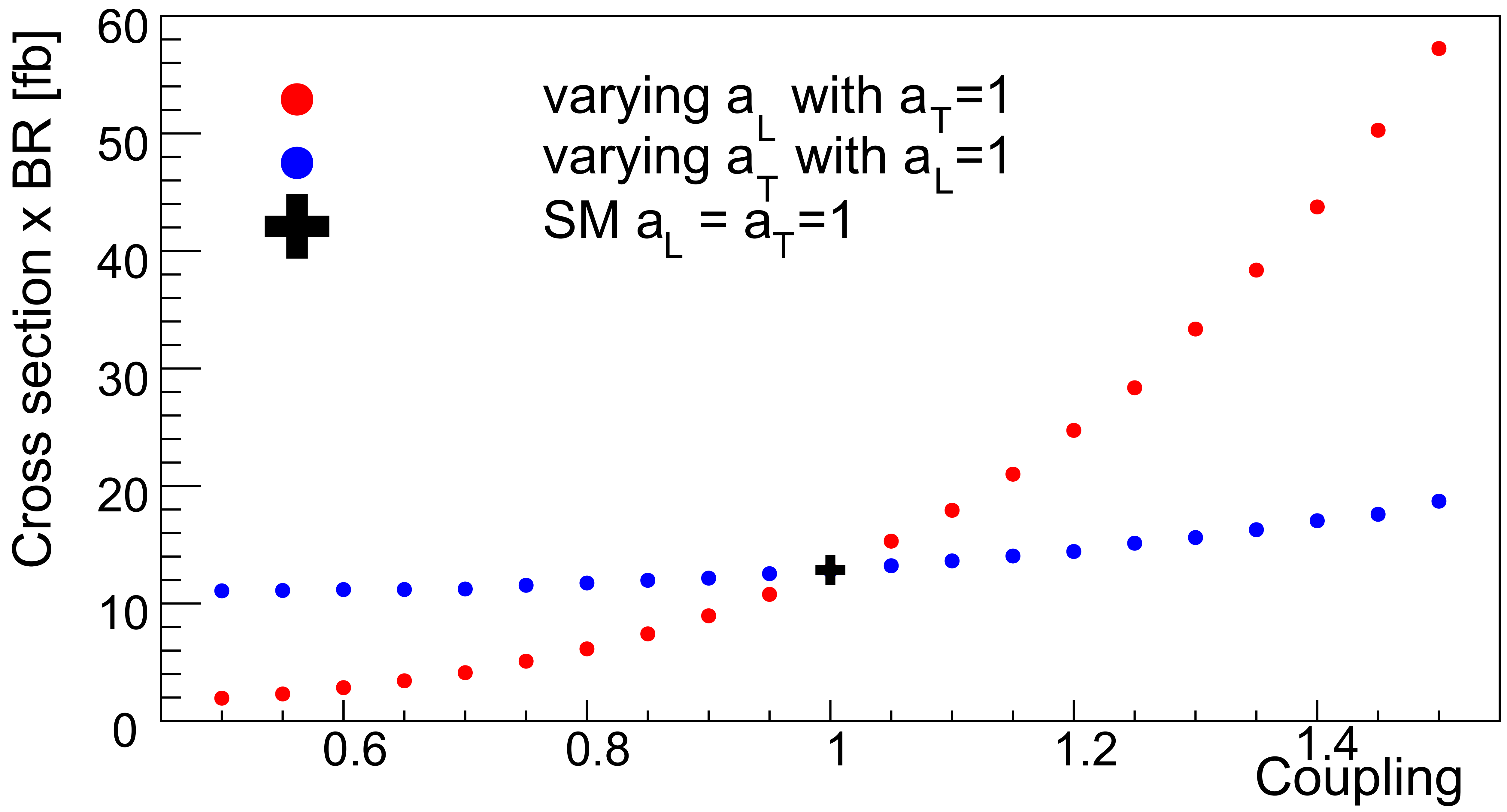
SM case for $a_L = a_T = 1$

Deviations in the coupling parameter can lead to new physics!

How to distinguish different polarization states?

Differences in cross section

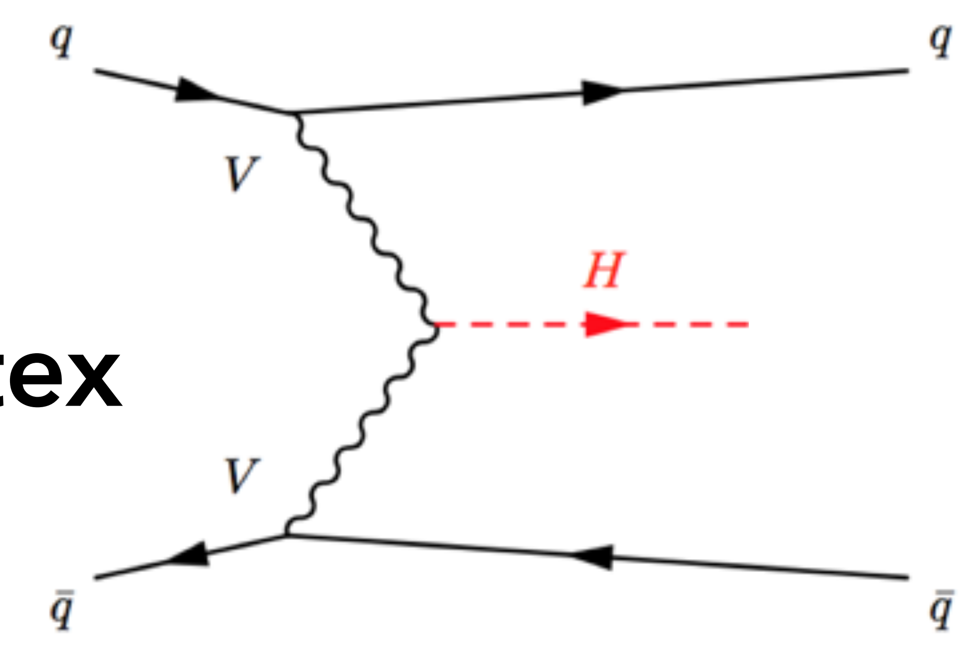




Differences in cross sections are mostly sensitive to **a_L variations**

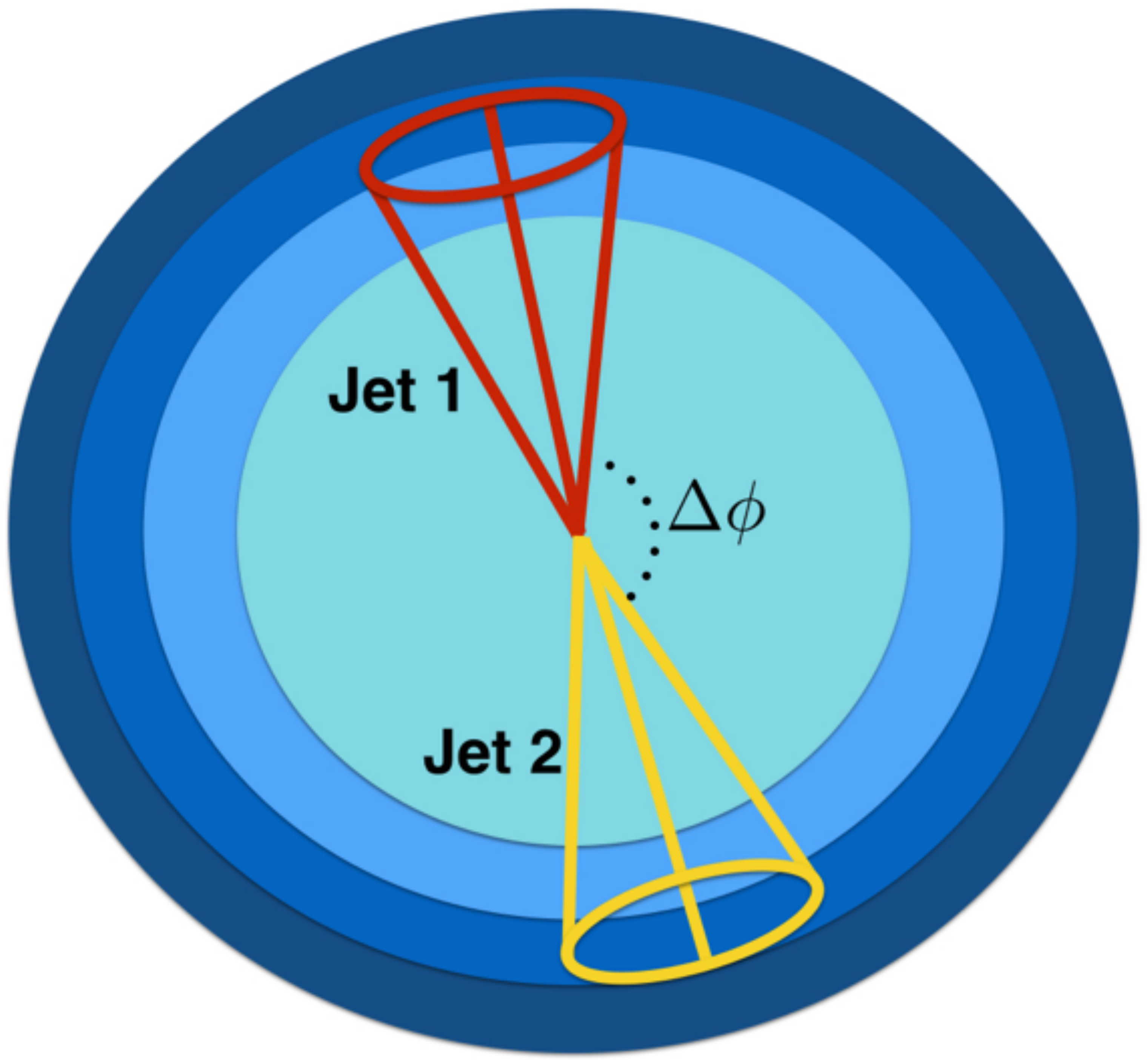
How to distinguish different polarization states?

Shape differences



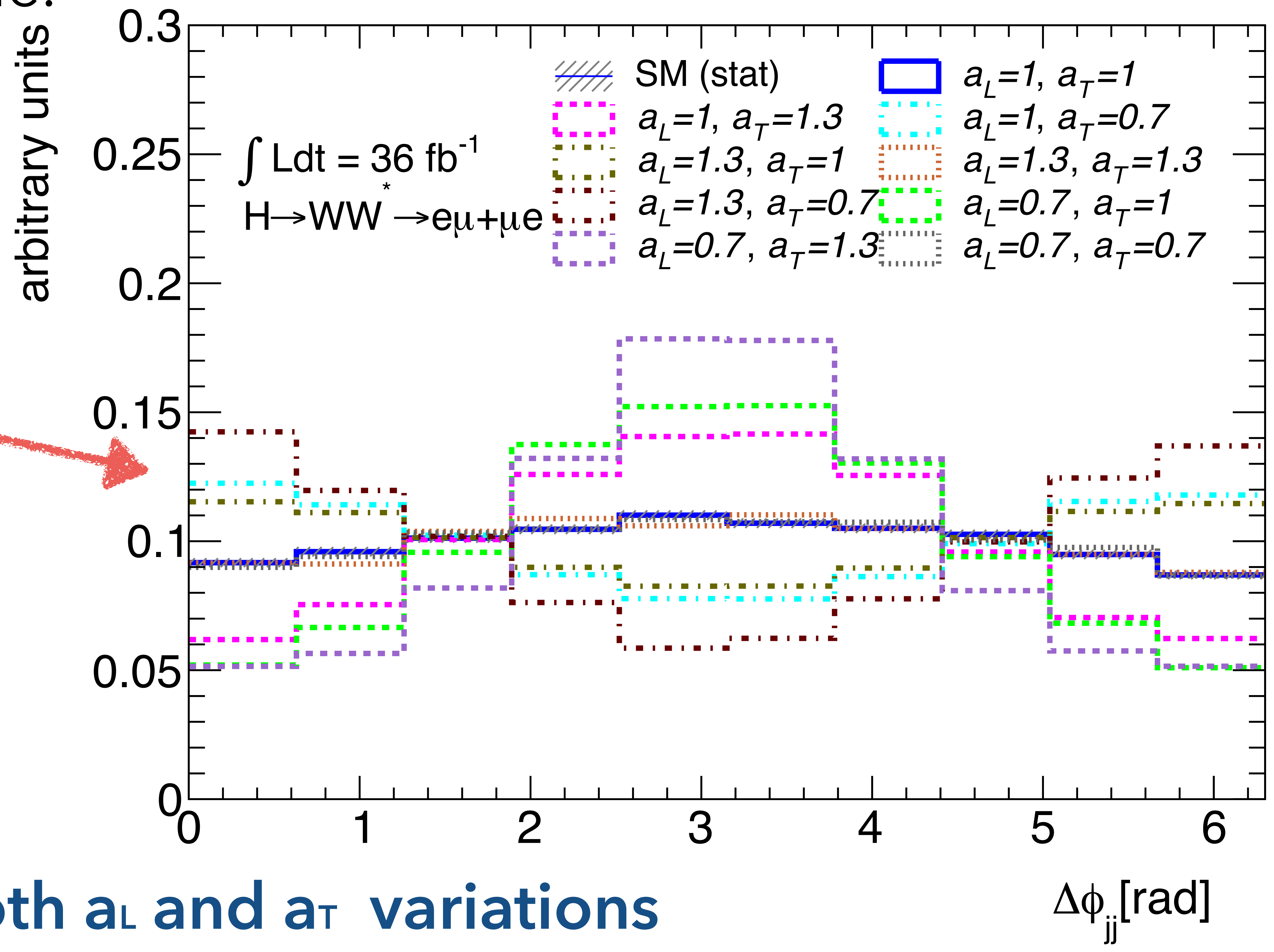
Tagging jets kinematic distributions are sensitive to the initial HWW vertex

the angle between the two leading jets in the plane perpendicular to the beam $\Delta\phi_{jj}$ is the most discriminating variable.



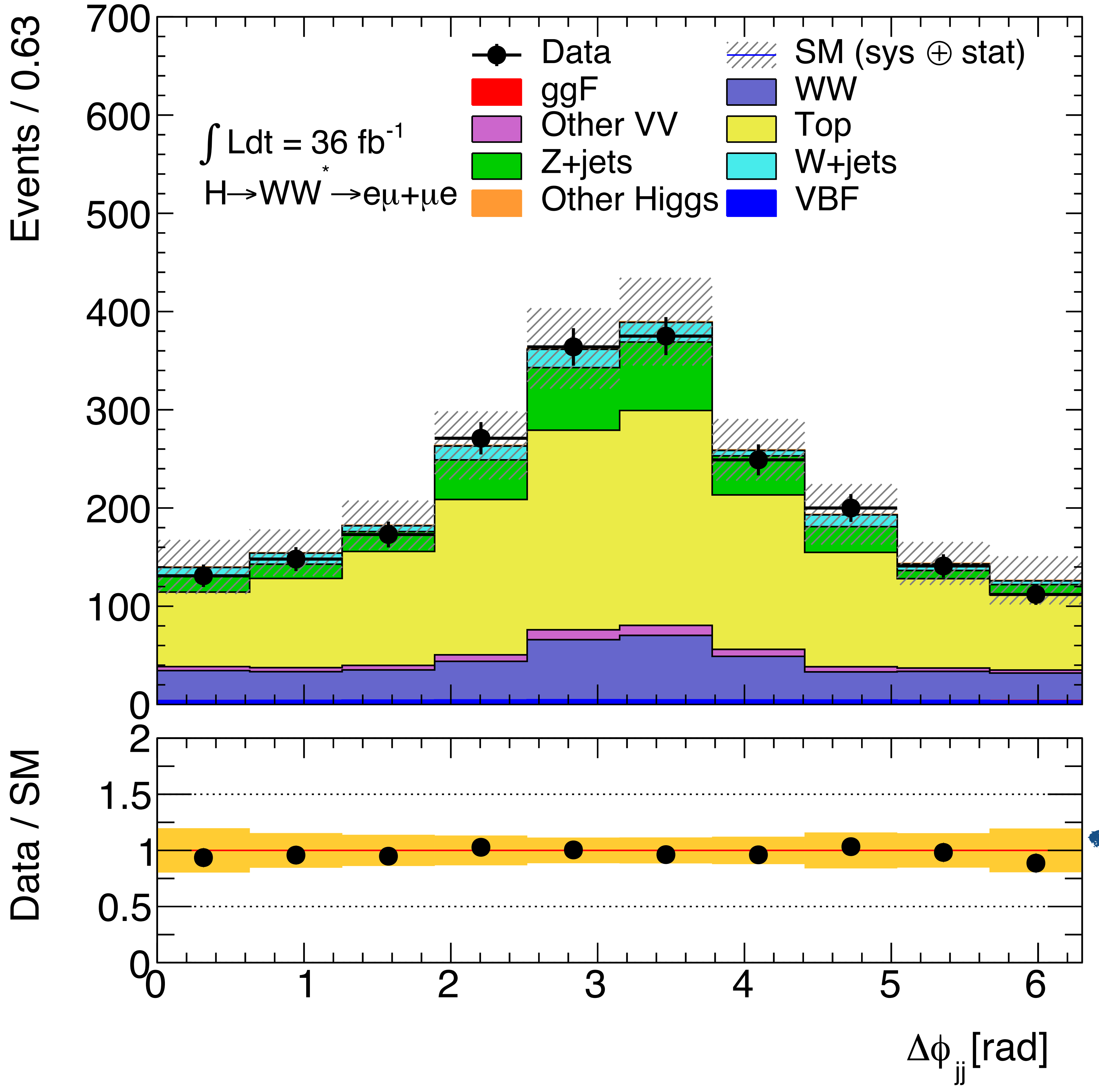
Three different trends:

$a_L < a_T$, $a_L > a_T$ and $a_L = a_T$



→ **Shape is sensitive to both a_L and a_T variations**

Event selection strategy



Pre-selection:

- Two OS leptons: leading lepton p_T > 22 GeV, subleading lepton p_T>15 GeV
- m_{ll}> 10 GeV
- 2jets
- b-jet veto

Definition of a signal enriched region
Signal Region

Definition of bkg enriched regions
Control Regions

Background	Top	Z+jets	Diboson	W+jets	ggF
Relative size	~51%	~22%	~21%	~5%	~1%

Signal Region

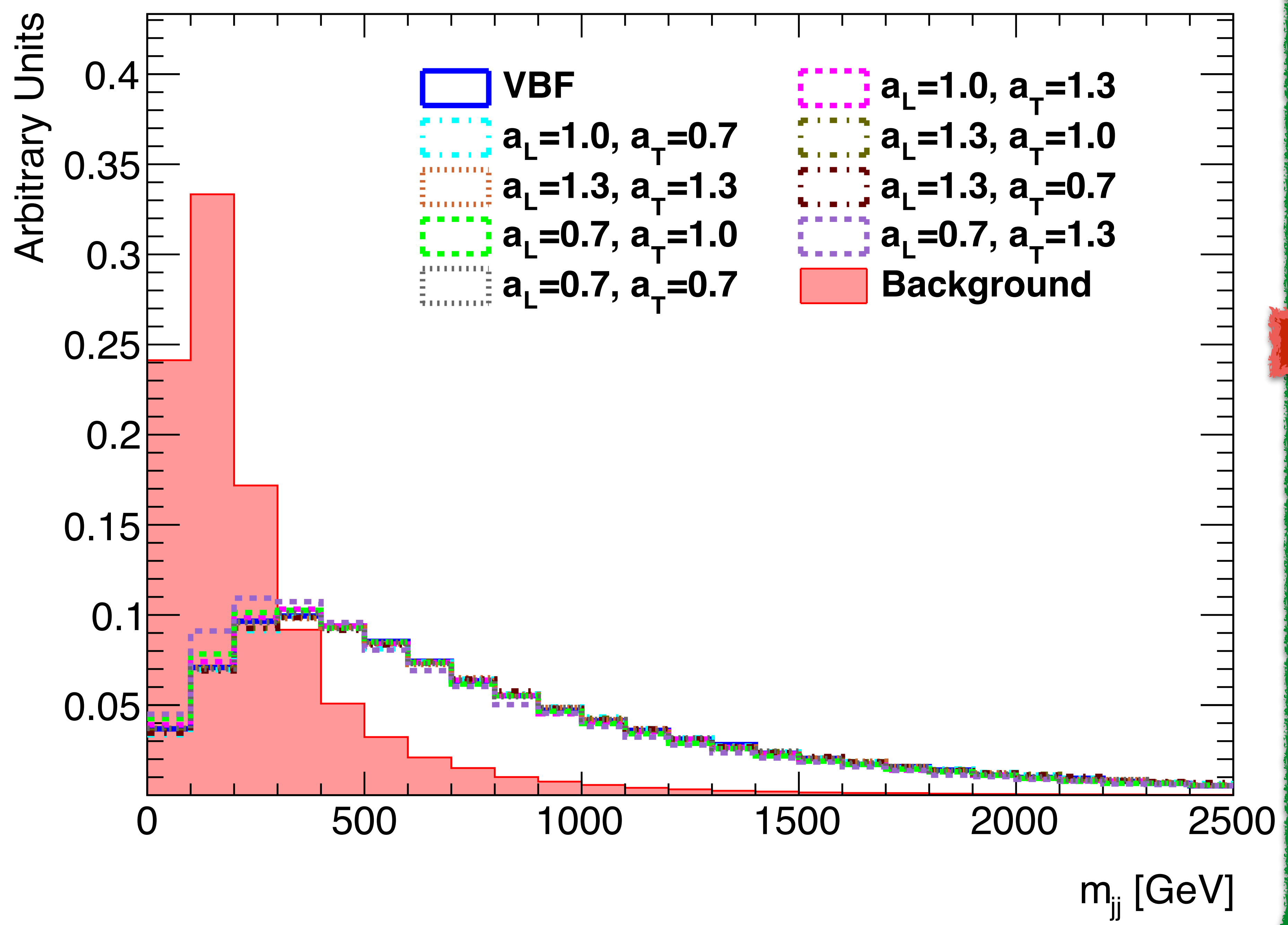
A **Boosted Decision Tree** is trained after pre-selection to decide if an event is **signal-like** or **background-like**

SR definition:

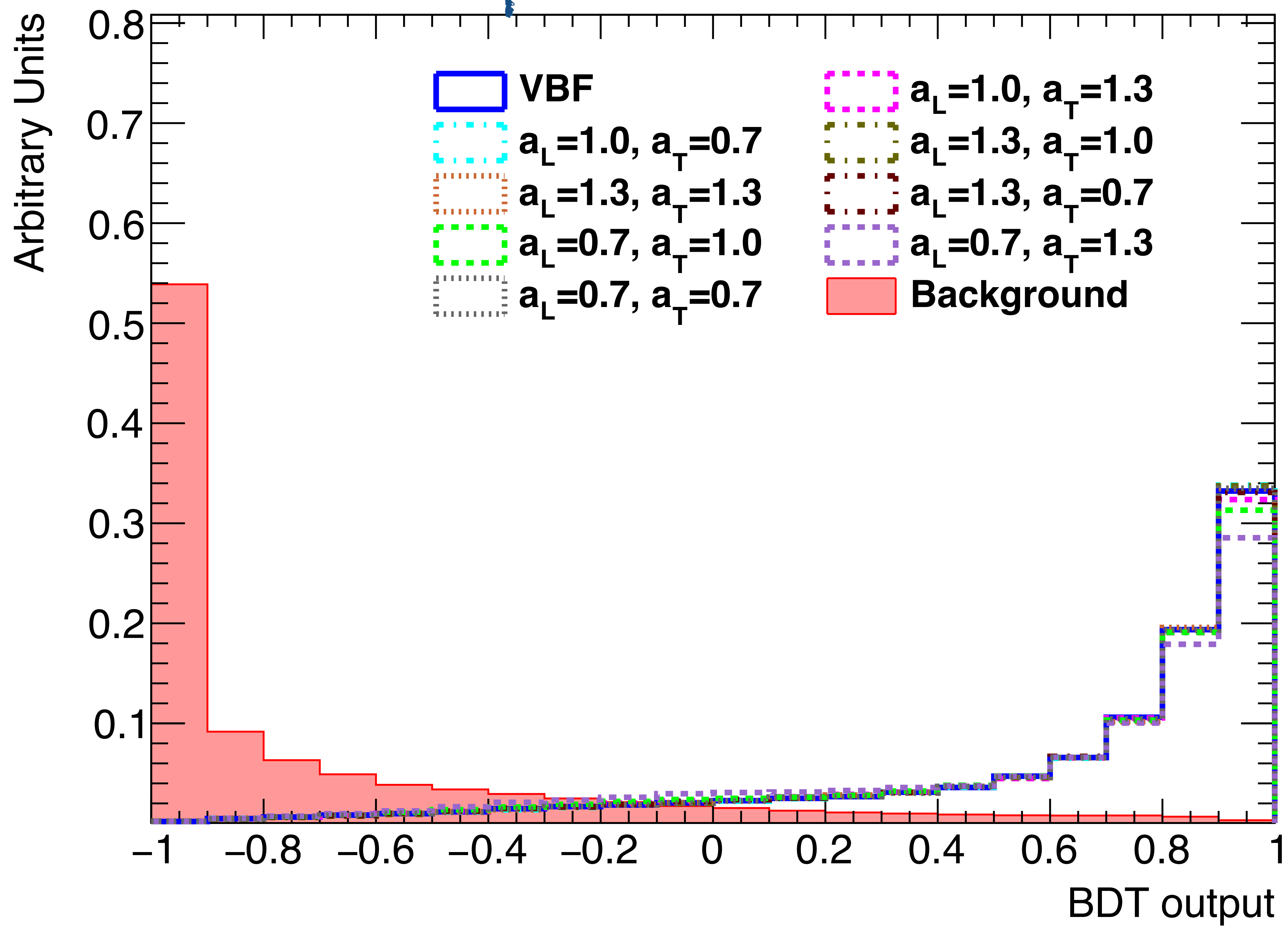
- **Preselection**
- **Central jet veto**.
- **Outside lepton veto**
- **Z →ττ veto→**: $m_{\tau\tau} < m_Z - 25$ GeV

An example of input variable...

M_{jj}: signal presents a high invariant mass of the tag jets

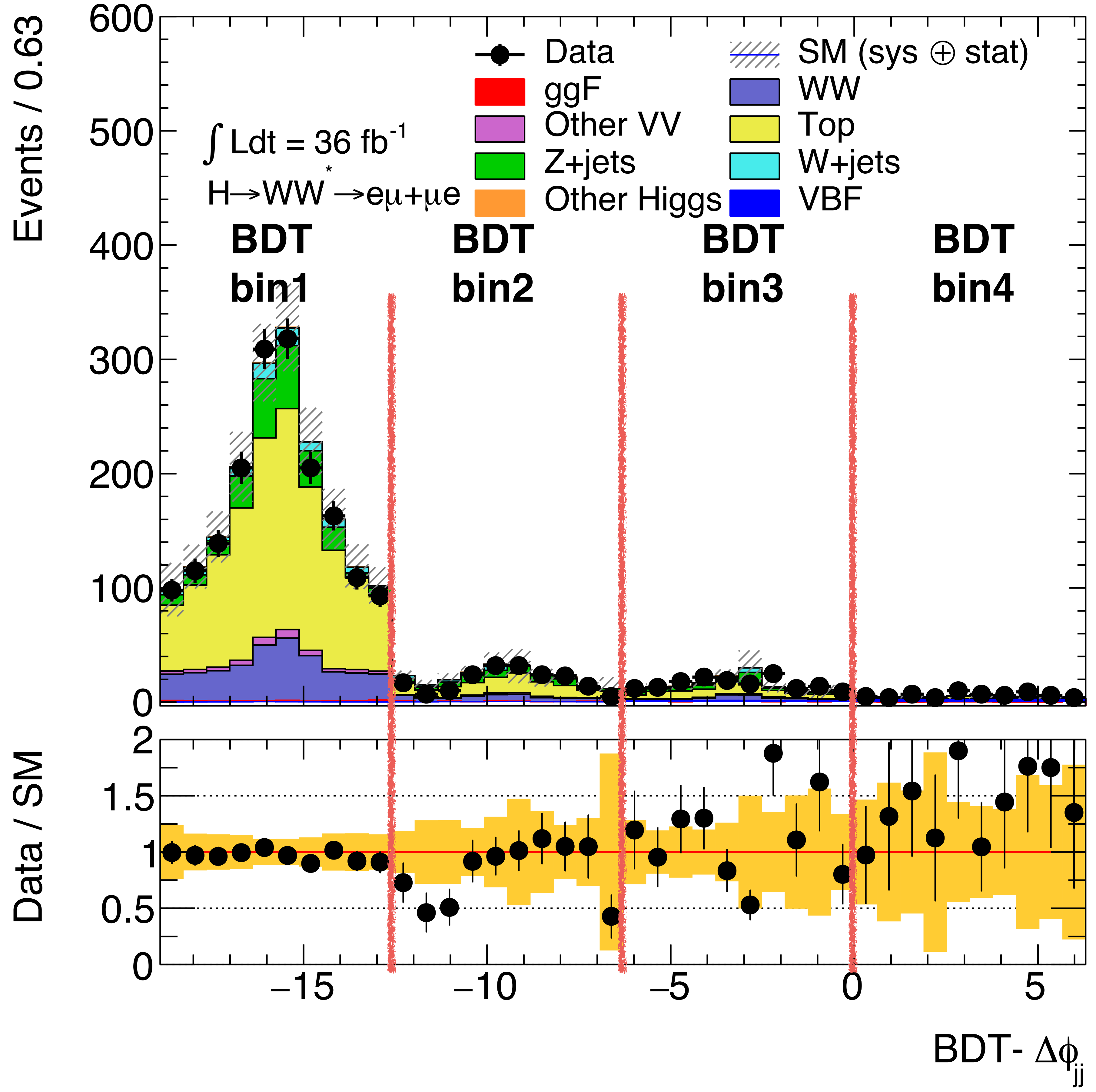


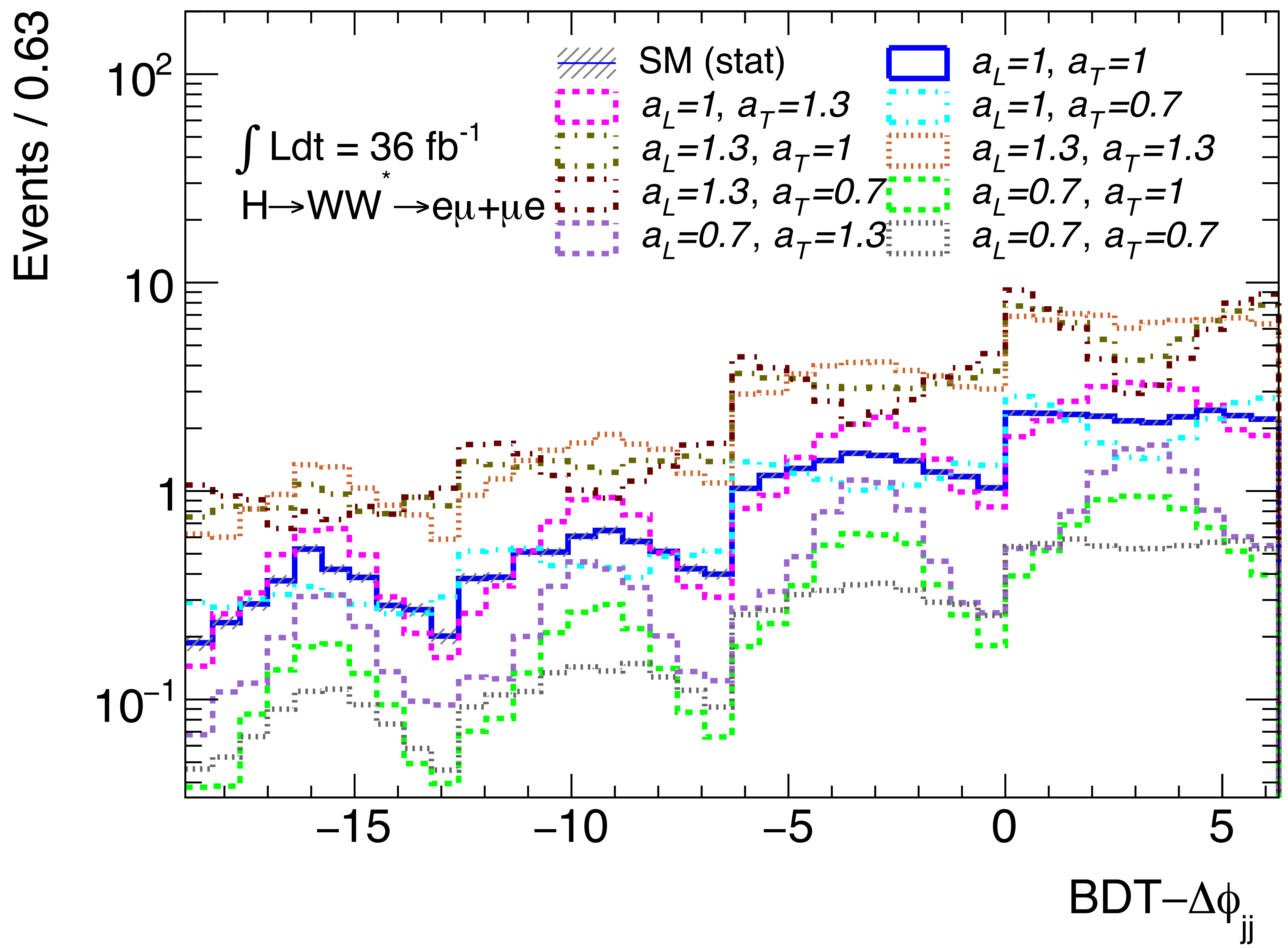
The output distribution...



The BDT -Δφjj distribution

To discriminate the **backgrounds** from the VBF **signal** and the various **BSM** scenarios, an unrolled **BDT -Δφjj distribution** is built : 4 BDT bins x 10 Δφjj bins

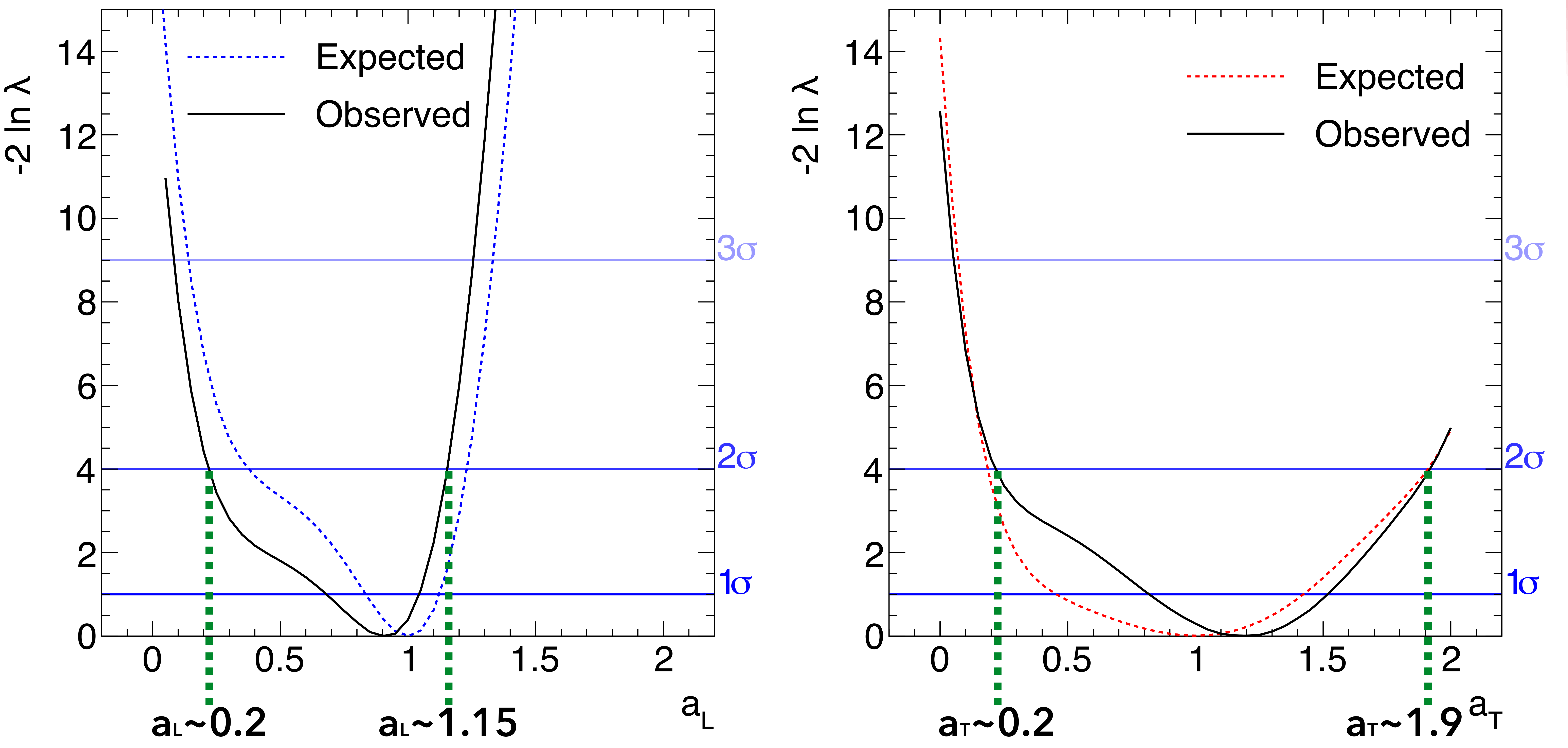




This distribution is used as input for **a maximum likelihood fit**

Results

Likelihood scans over a_L and a_T are performed using both the **rates** and the **shape of the BDT-Δφjj** distribution fixing one coupling to its SM value and profiling the othe one



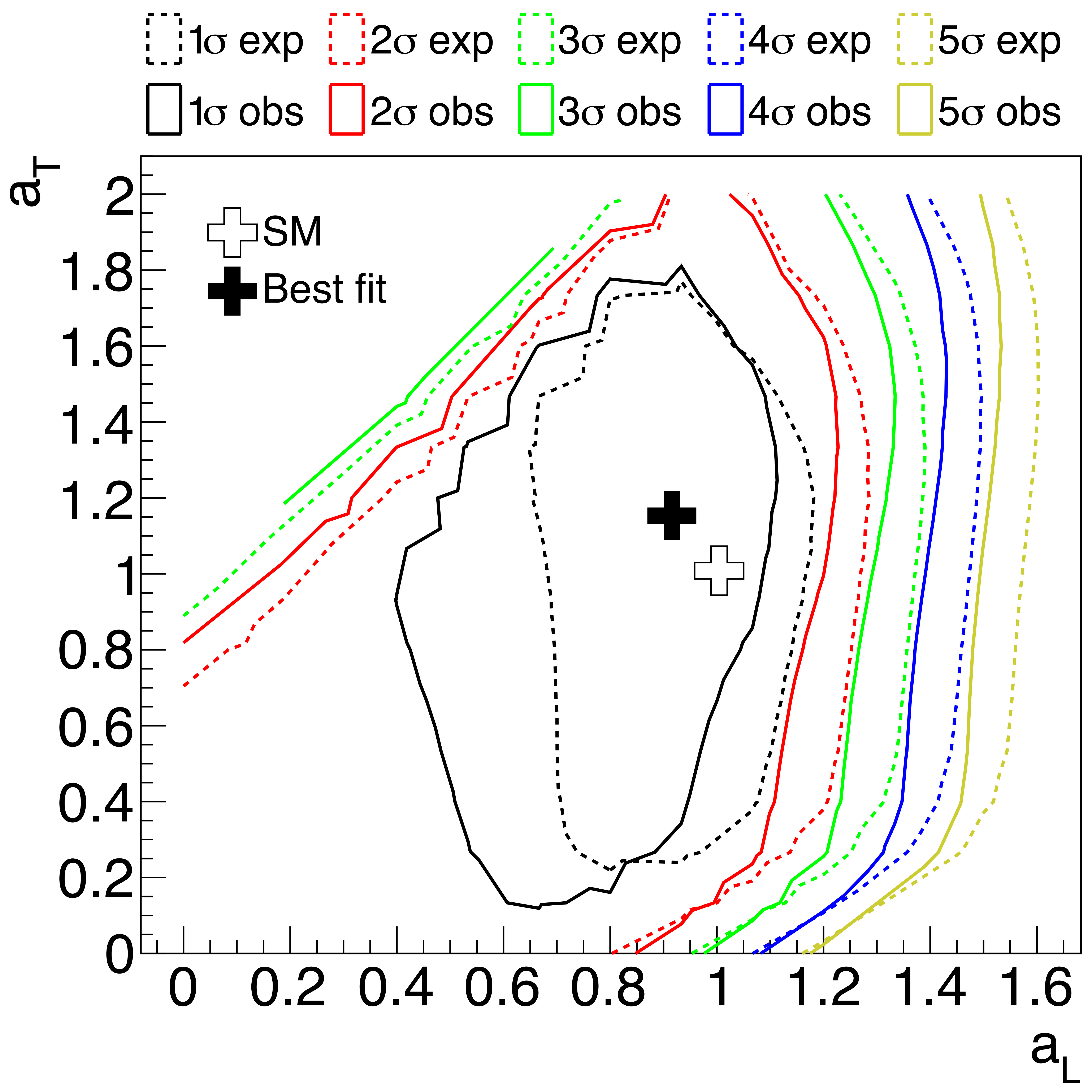
POI	Fit	Expected	Observed
a_L	shape+rate (a_T =1)	$1.00^{+0.12}_{-0.17}$	$0.91^{+0.14}_{-0.23}$
a_T	shape+rate(a_L =1)	$1.00^{+0.43}_{-0.54}$	$1.19^{+0.33}_{-0.37}$

In agreement with the SM within the errors!

Results

- Simultaneous scan over both a_L and a_T are (rates+ shape of the BDT- $\Delta\varphi_{jj}$ distribution)

- Results are **in agreement within 1σ with the SM**



Main uncertainties

- on a_L from the theoretical uncertainties (modelling of top and WW bkg)
- on a_T from data statistical uncertainties

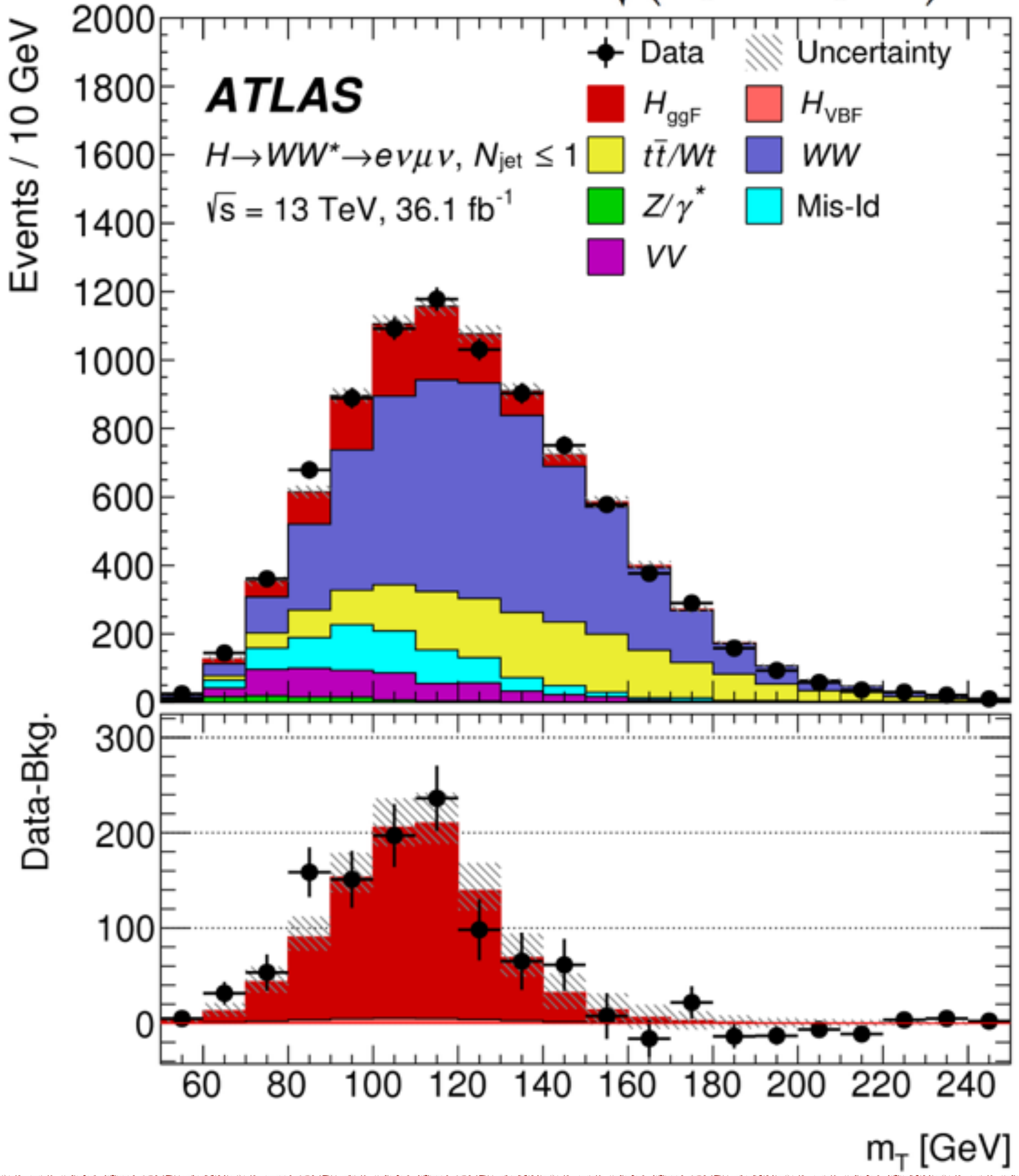
Cross section measurement

Events classified in three Signal Regions

Njets = 0 , Njets = 1

gluon-gluon fusion (ggF)

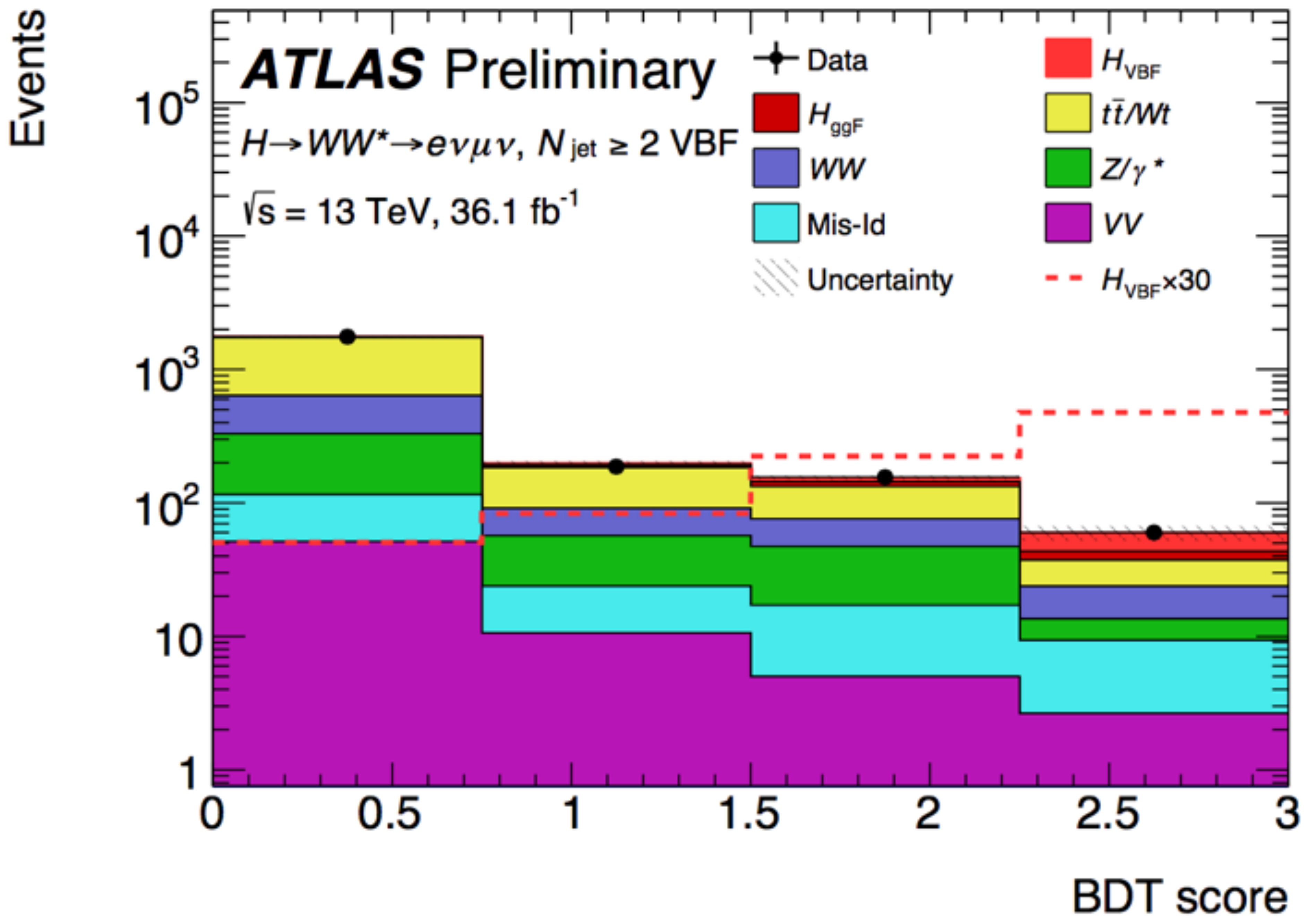
discriminant variable: $m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}\right|^2}$



Njets ≥ 2

Vector Boson Fusion (VBF)

BDT used as discriminant built from jet/lepton kin. quantities



Cross section measurement

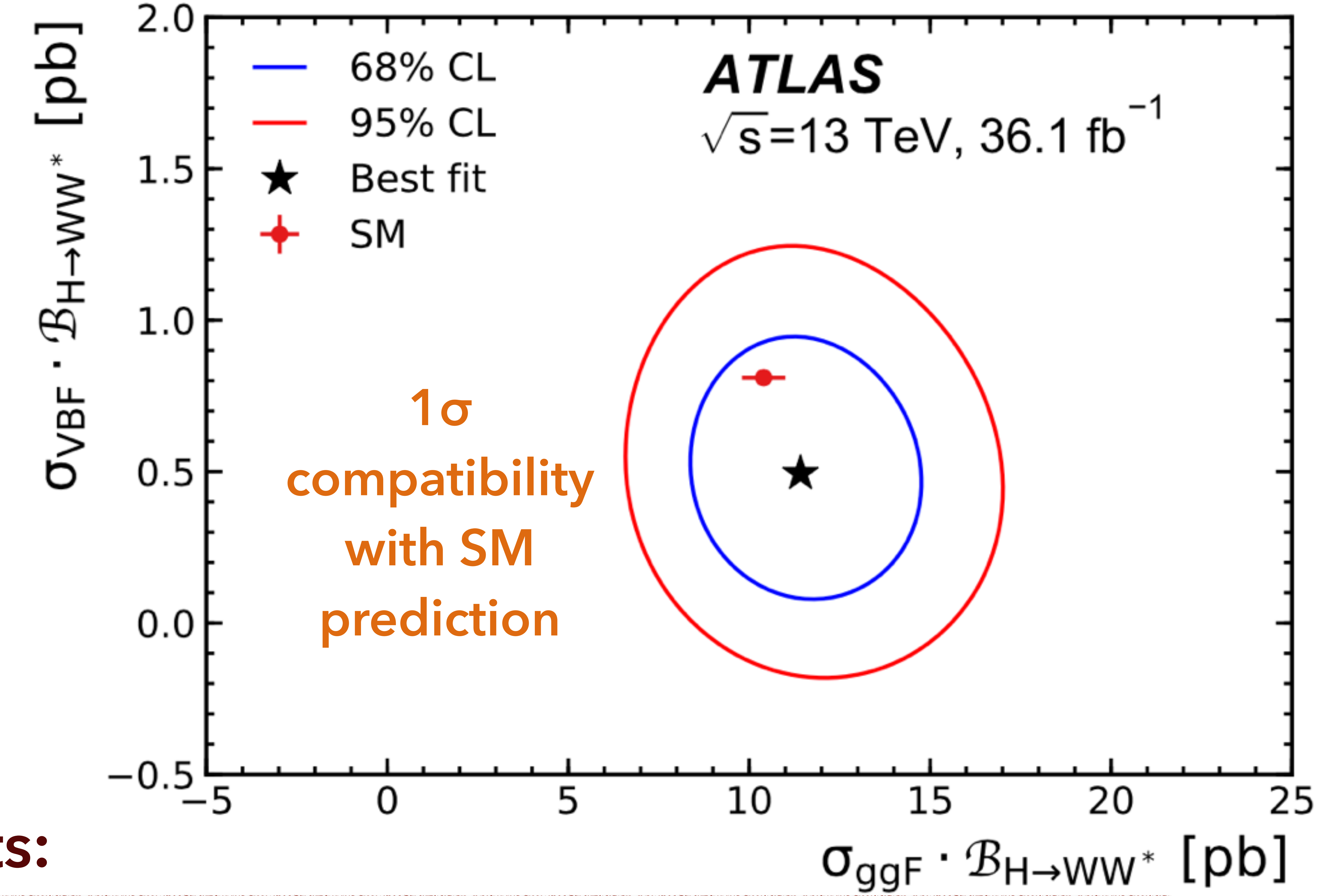
Performed combined maximum likelihood fits of the SR /CR

Significance

ggF: 6.3σ (exp.5.2σ)
VBF: 1.9σ (exp.2.7σ)

Signal strengths:

$$\mu_{ggF} = 1.21^{+0.22}_{-0.21}$$
$$\mu_{VBF} = 0.62^{+0.37}_{-0.36}.$$



Cross section results:

$$\sigma_{ggF} \cdot \mathcal{B}_{H\to WW^*} = 12.6 \pm 1.0(\text{stat.}) \pm 1.1(\text{theo syst.})^{+1.6}_{-1.5}(\text{exp syst.})\ \text{pb} = 12.6^{+2.3}_{-2.1}\ \text{pb}$$
$$\sigma_{VBF} \cdot \mathcal{B}_{H\to WW^*} = 0.50^{+0.24}_{-0.23}(\text{stat.}) \pm 0.11(\text{theo syst.}) \pm 0.13(\text{exp syst.})\ \text{pb} = 0.50^{+0.30}_{-0.29}\ \text{pb}.$$

Predicted σ_{ggF}×BR=10.4±0.6 pb and σ_{VBF}×BR=0.81±0.02

Conclusions

- ggF and VBF cross-section measurement with 36.1 fb-1 of data has been performed
- First measurement of the Higgs couplings to polarized W bosons (a **completely new analysis**!)
  - **First limits** on the couplings parameters a_L and a_T have been set exploiting the shape of the **$\Delta\varphi_{jj}$ distribution** and **the total rates**
  - Results are compatible with the **SM predictions** within the errors
  - **More data** will help in the future to further constrain these coupling parameters: with the full run2 dataset we will be able to exclude at 95% CL variations of 20% on a_L and of 40% on a_T

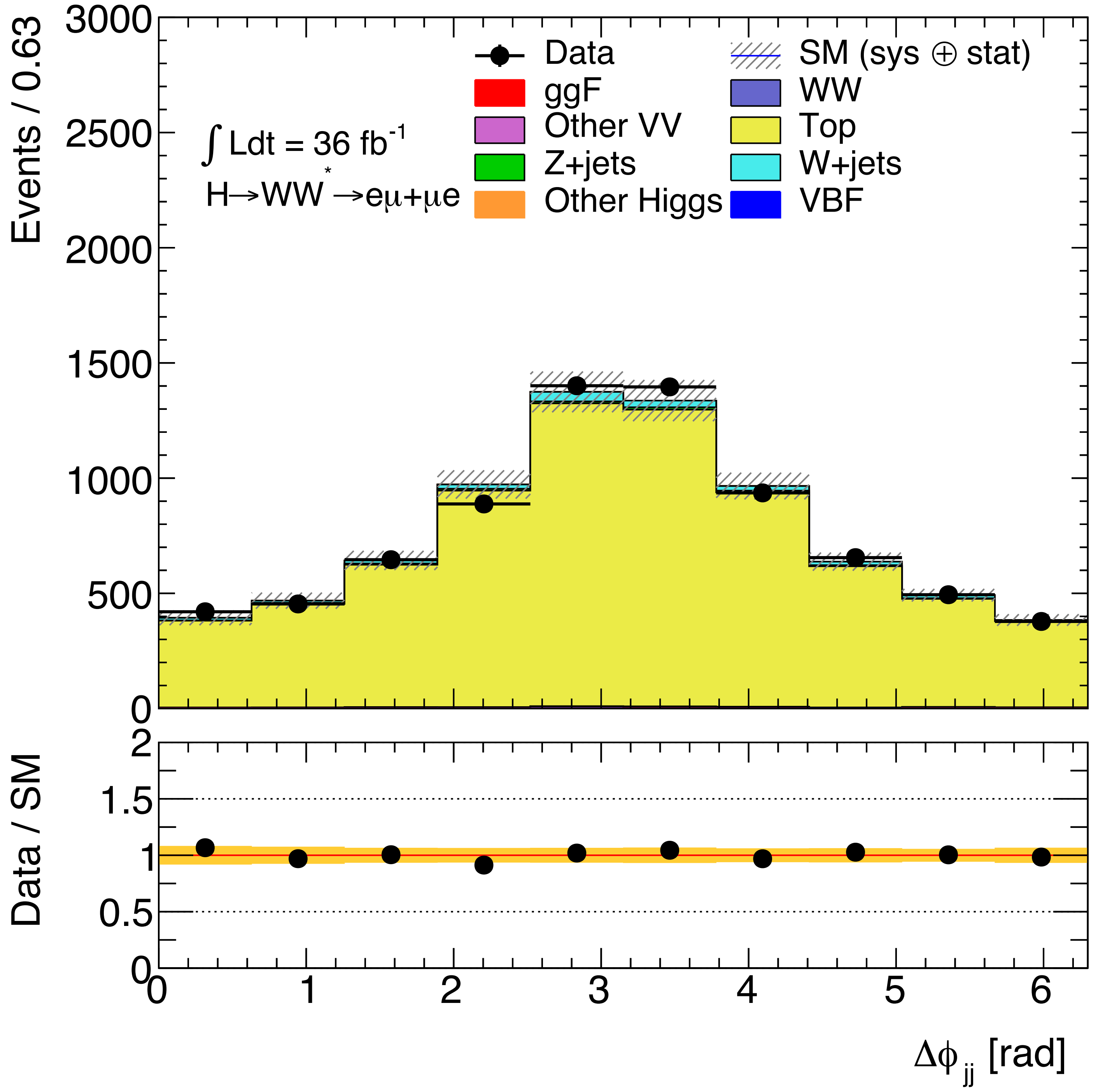
Back-up

Control Regions

Control regions: background enriched region that exist to constrain the MC predictions and extract their normalisation in the signal phase space

Top quark CR:

- Preselection (no b-jet veto)
- **n-bjets =1**
- CJV
- OLV
- Z $\rightarrow\tau\tau$ veto

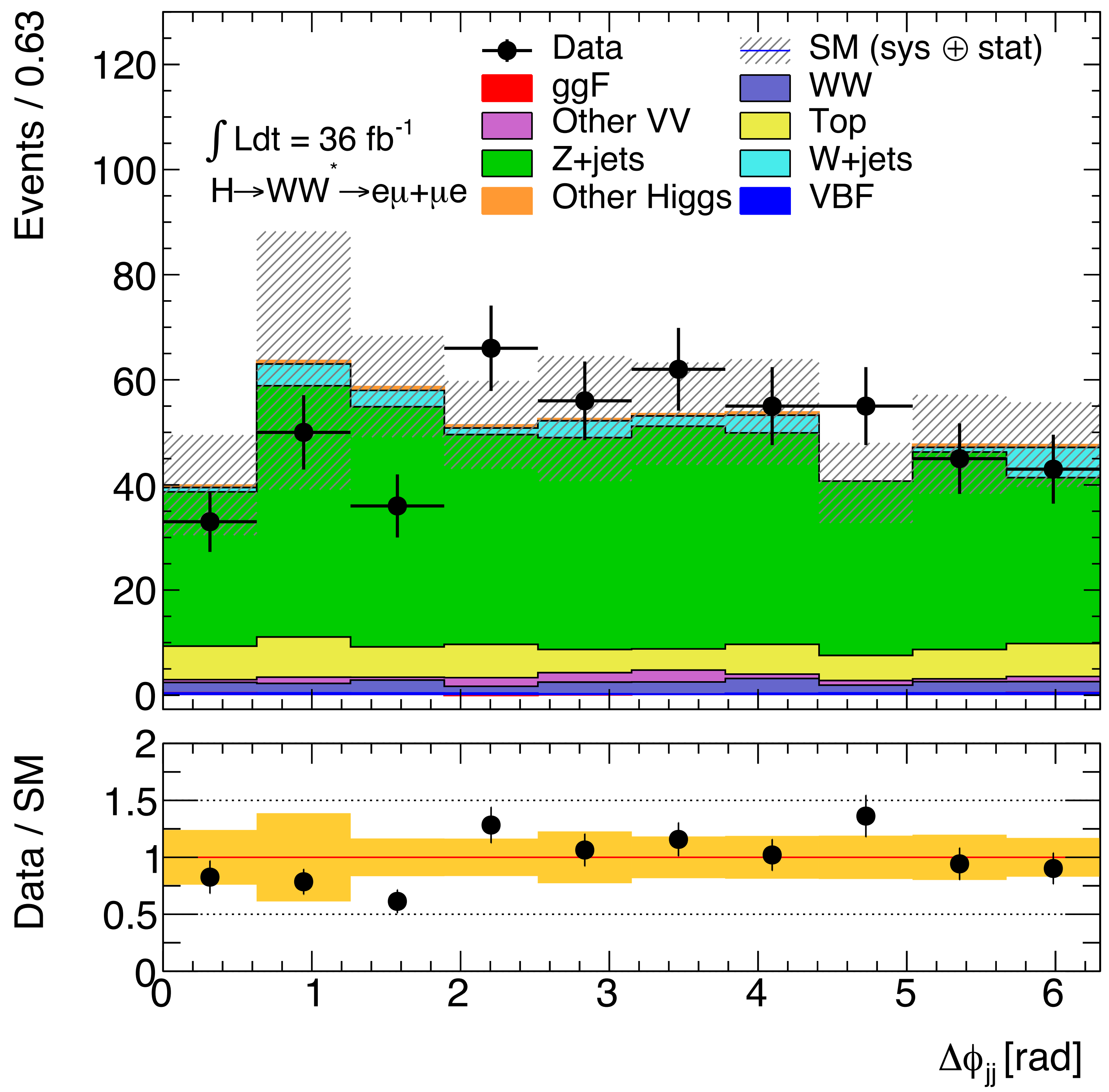


NF = 1.01 ± 0.01(stat).

purity ~96%

Z $\rightarrow\tau\tau$ CR:

- Preselection
- **inverted Z $\rightarrow\tau\tau$ veto**
- mll < 80 GeV
- CJV
- OLV



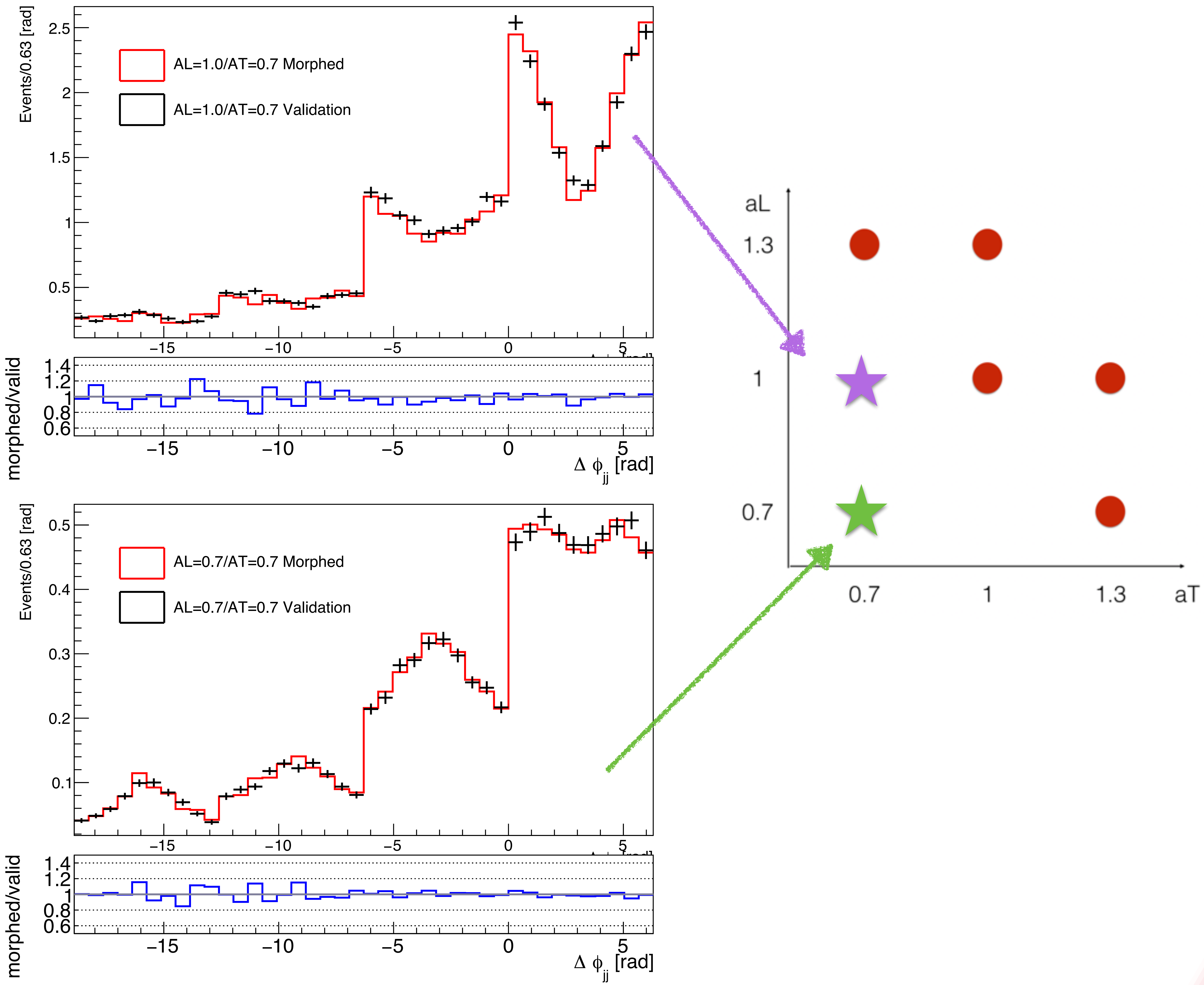
NF = 0.92 ± 0.07(stat).

purity ~74%

Analytic morphing method validation

Five samples given as input to the morphing

Good agreement between the **morphed** distribution and the **validation** one

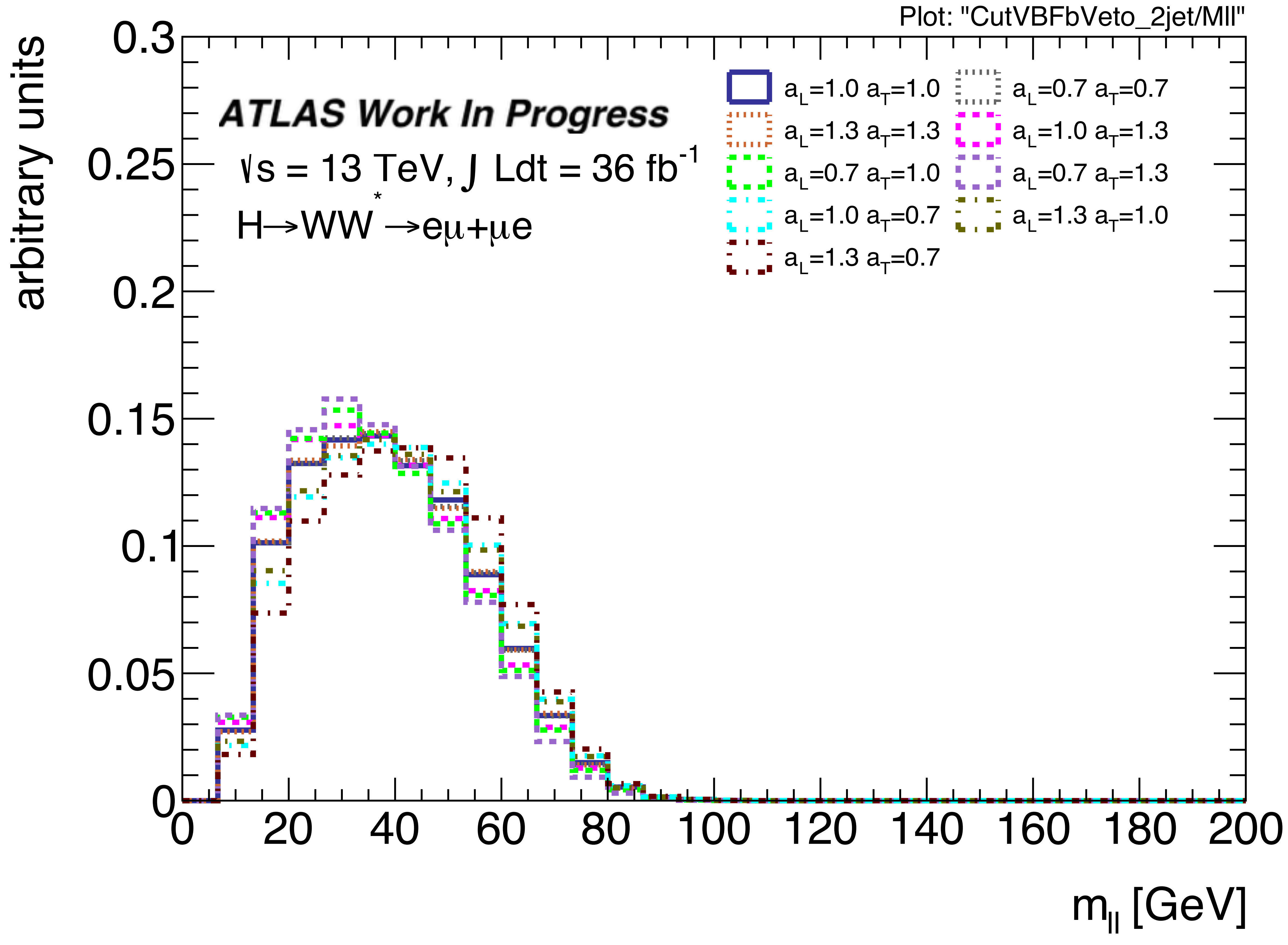


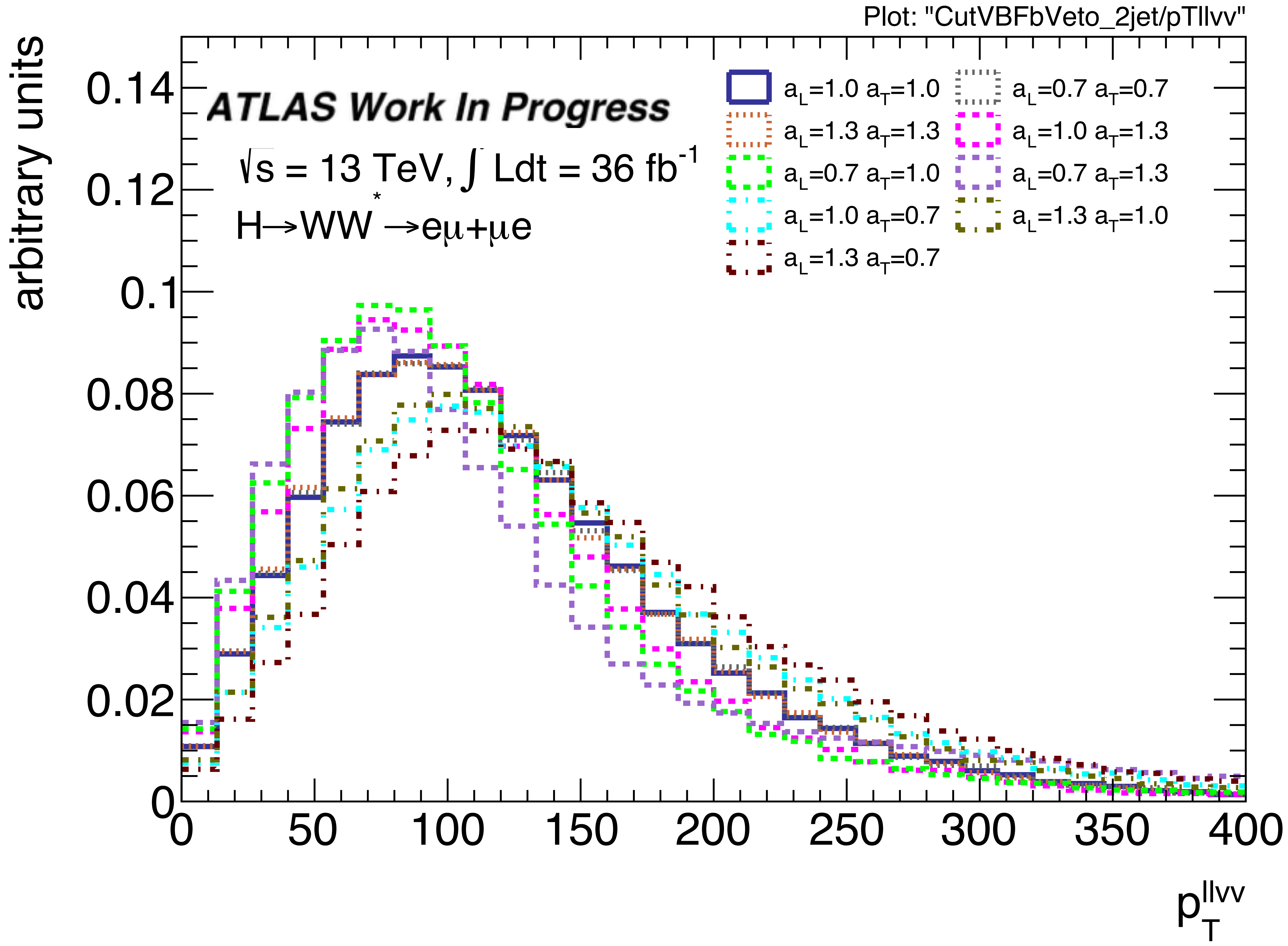
How to distinguish different polarization states?

Differences in shape

Use informations from kinematical distributions to discriminate among the different signals

Leptons kinematic distributions are sensitive to the second HWW vertex





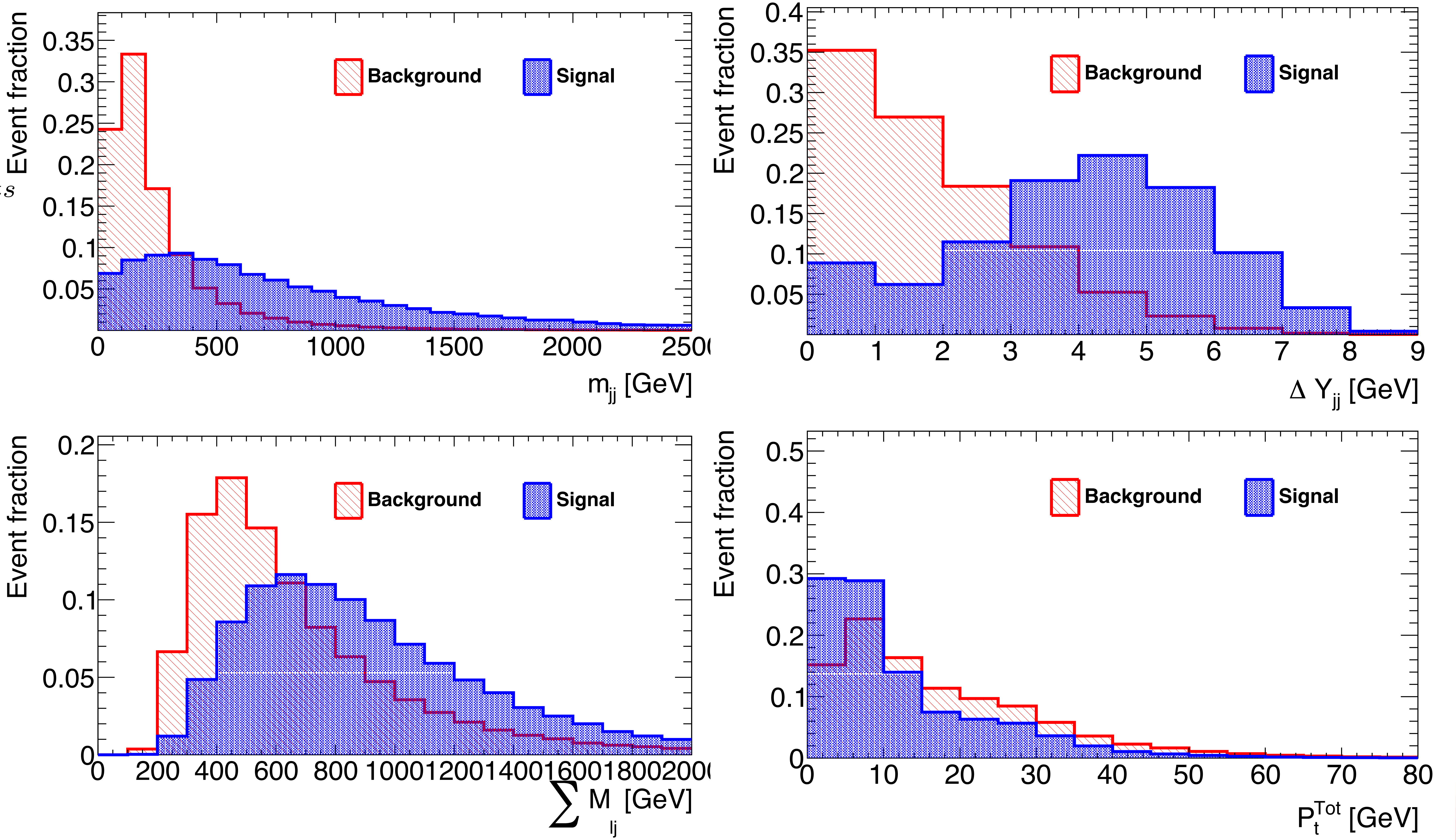
Sources of systematic errors

- Main source of uncertainty on a_L arises from the theoretical uncertainties (modelling of top and WW bkg)
- a_T coupling is dominated by statistical uncertainties from data

Source	a_L [%]	a_T [%]
Data statistics	11	31
Total systematics	14	17
Theoretical uncertainties	12	14
Top theoretical uncertainties	7	7
WW theoretical uncertainties	6	6
VBF theoretical uncertainties	4	6
ggF theoretical uncertainties	4	3
Z+jets theoretical uncertainties	2	3
Experimental systematic uncertainties	6	6
Jet	2	5
Pile-up	< 1	3
b-tagging	1	2
Misidentified leptons	4	2
Leptons	< 1	< 1
Monte Carlo statistics	2	6
Background statistics	2	6
Signal statistics	< 1	< 1
Background normalizations	< 1	< 1

BDT input variables

- A **high invariant mass** of the tag jets is a distinctive signature of the signal events
- The signal is characterised by a **separation of the two tagging jets in rapidity**
- $p_T^{tot} = p_T^{\ell 1} + p_T^{\ell 2} + MET + \Sigma p_T^{jets}$ This variable helps disentangling events with significant **soft gluon radiation** that recoils against the ll+2j system with no high-pT jets (top bkg).
- ΣM_{lj}
Its use is motivated because the jets in the VBF signal topology tend to be in the forward regions while leptons remain central, resulting in **large opening angles between the leptons and the jets**



BDT input variables

- Signal has **small lepton angle** and thus small lepton mass $(m_{ll} \approx \sqrt{E_{l1}E_{l2}(1-cos\Delta\phi_{ll})})$

- Due to the presence of neutrinos in the final state, the invariant mass of the final state products cannot be fully reconstructed but the transverse mass can be evaluated.:

$$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{\nu\nu})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T{}^{\nu\nu}|^2},$$

The mT distribution **peaks just below the Higgs boson mass**

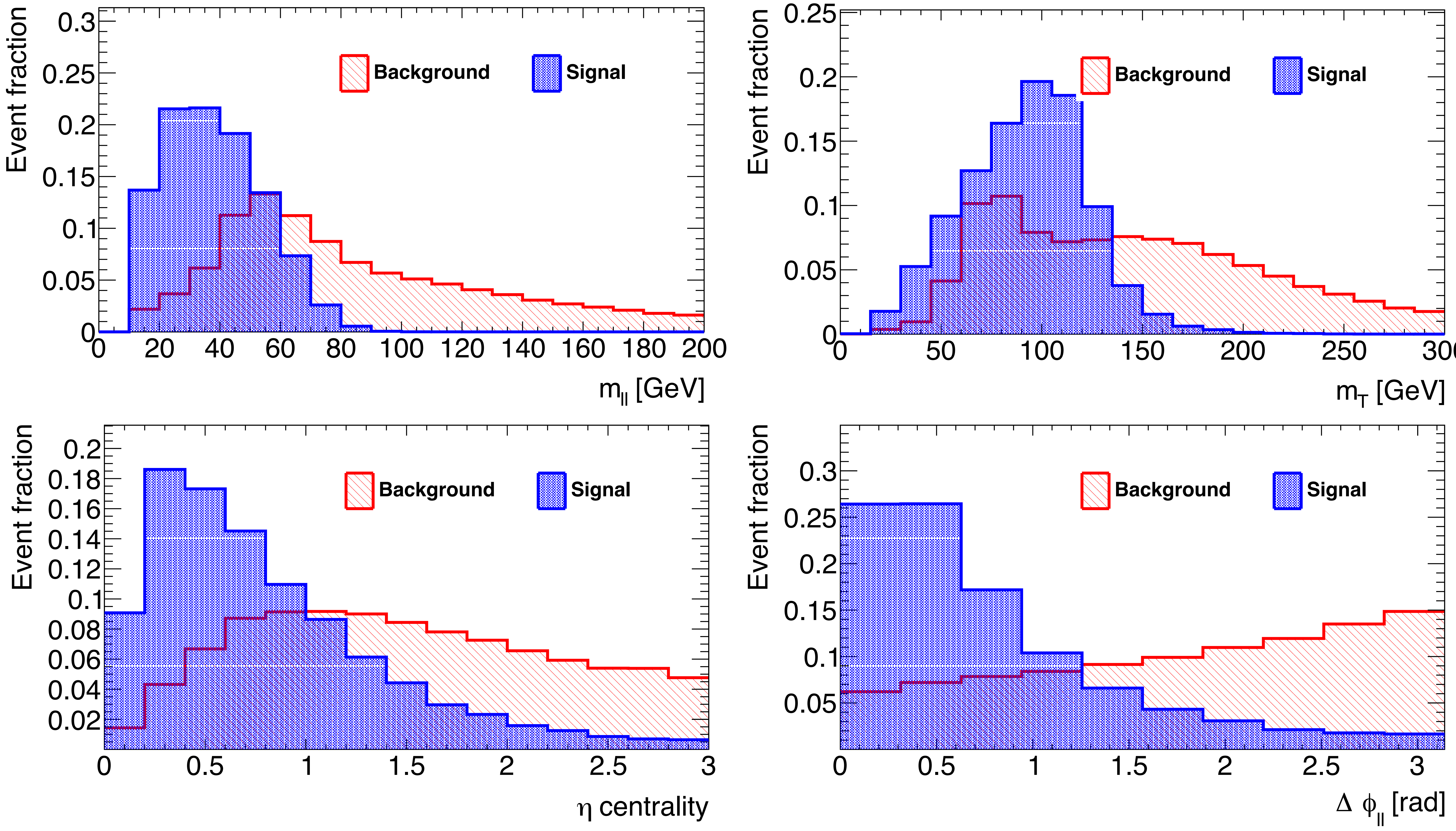
- η centrality: i**t quantifies the exact positions of the leptons with respect to the two tag jets in the η-plane:**

$$\mathrm{OLV}_{l_0} = 2 \cdot |\frac{\eta_{l_0} - \bar{\eta}}{\eta_{j_0} - \eta_{j_1}}|$$

$$\mathrm{OLV}_{l_1} = 2 \cdot |\frac{\eta_{l_1} - \bar{\eta}}{\eta_{j_0} - \eta_{j_1}}|$$

$$\eta_{\mathrm{lep}}\ \mathrm{centrality} = \mathrm{OLV}_{l_0} + \mathrm{OLV}_{l_1}$$

where $\bar{\eta} = (\eta_{j_0} + \eta_{j_1})/2$ is the average η of the two tag jets. For each lepton,



The polarization of the W boson

We say that a **particle is polarized** if its spin has a preferred direction, i.e it has a defined third component on a physically defined axis → To quantify this direction we can use the **helicity** :

$$h = \frac{\vec{S}\cdot\vec{p}}{|p|}$$

The helicity is defined as the projection of the particle's spin S into the direction of its momentum $\vec{p}$

- The W± and Z bosons are spin 1 particles: three possible helicity values: −1, 0, 1
- Boson wave functions are written in terms of the polarization four-vector ϵ^{μ} :

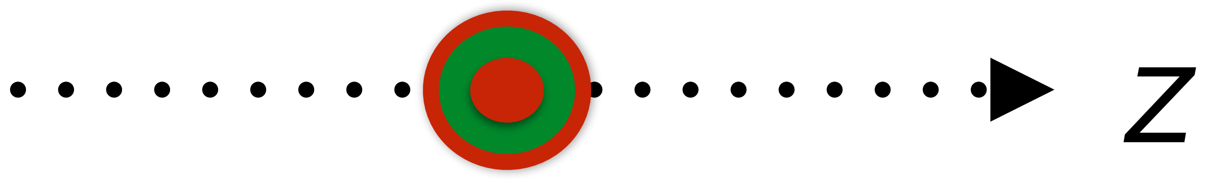
$$B^{\mu} = \epsilon^{\mu} e^{-ipx} = \epsilon^{\mu} e^{i(\vec{p}\vec{x}-Et)}$$

- For a spin-1 boson traveling along the z-axis, the polarization four vectors are:

$$\epsilon^{\mu}_{-} = \frac{1}{\sqrt{2}}(0,1,-i,0) \qquad \epsilon_{L} = \frac{1}{m}(p_z,0,0,E) \qquad \epsilon^{\mu}_{+} = \frac{1}{\sqrt{2}}(0,1,i,0)$$

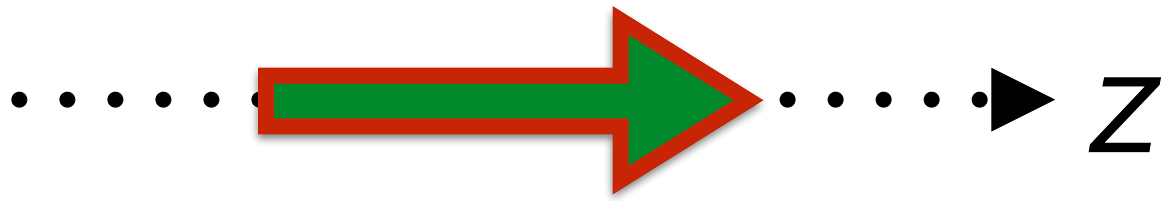
$S_z = -1$

Transverse



$S_z = 0$

Longitudinal



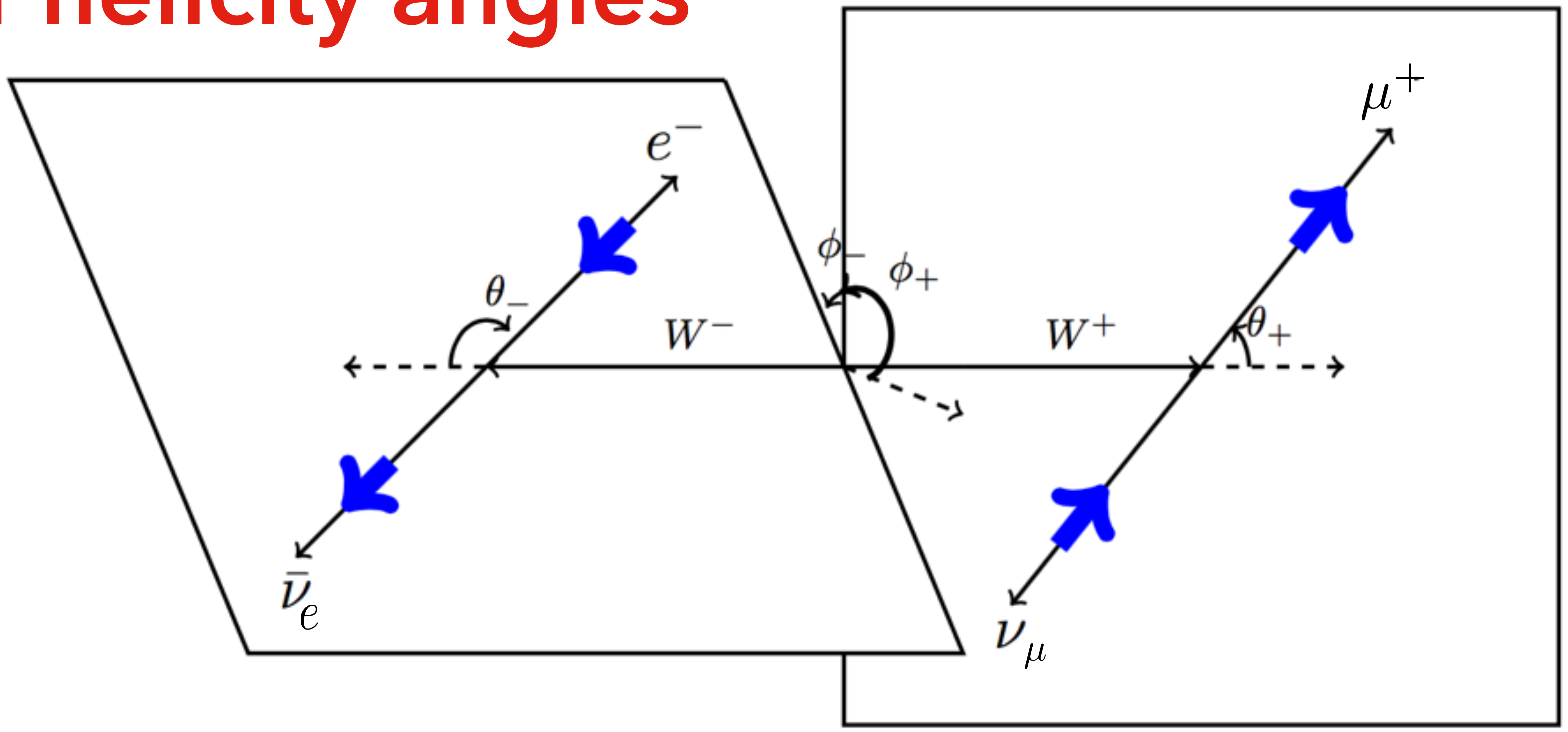
$S_z = 1$

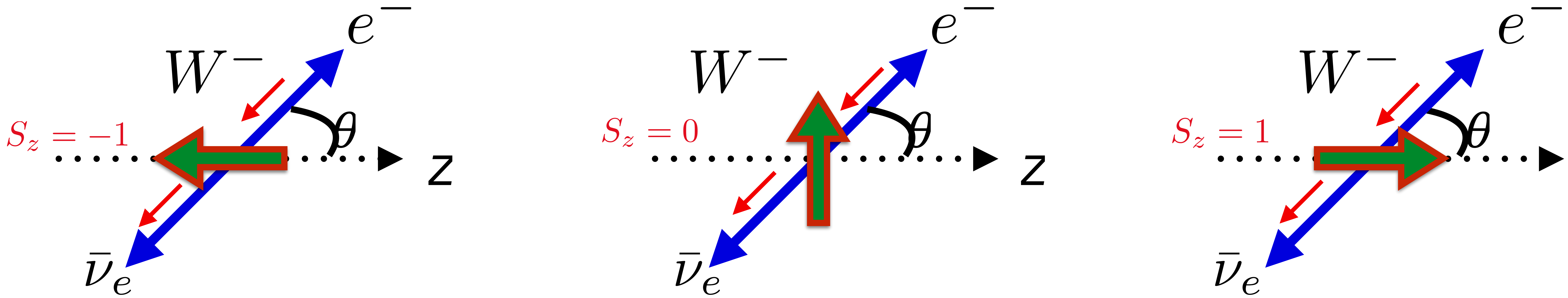
Transverse

Ideas for improvement

Differences in shape: study of helicity angles

- The polar angle θ+(θ−) is the angle of lepton in W rest frame.
- φ+(φ−) is the azimuthal angle of the W+(W−) decay plane measured in the H frame.
- The V-A structure of the charged current in weak decays produces correlations between the final state leptons and the W polarization.





$|M_-|^2 = g_W^2 m_W^2 \frac{1}{4}(1+cos\theta)^2$ $|M_L|^2 = g_W^2 m_W^2 \frac{1}{2} sin^2\theta$ $|M_+|^2 = g_W^2 m_W^2 \frac{1}{4}(1-cos\theta)^2$

Presence of neutrinos in final state ⟶ Higgs rest frame can not be reconstructed without making assumptions on the neutrinos kinematics