CP nature of the top-Yukawa coupling

A study with the $\Delta\phi_{jj}$ distribution in ggF + 2 jets, $h \to WW^* \to e\nu\mu\nu$

Higgs Boson Properties

How can we know that the Higgs boson the Standard Model predicts is really the Higgs boson we have measured?

Measure its properties!

Property	Theory	Experiment
Mass	Unpredicted	125 GeV
Charge	Neutral	Neutral
Spin	0	0
CP	Even	Unknown*
…	…	…

CP

The Higgs Mechanism leaves us several options

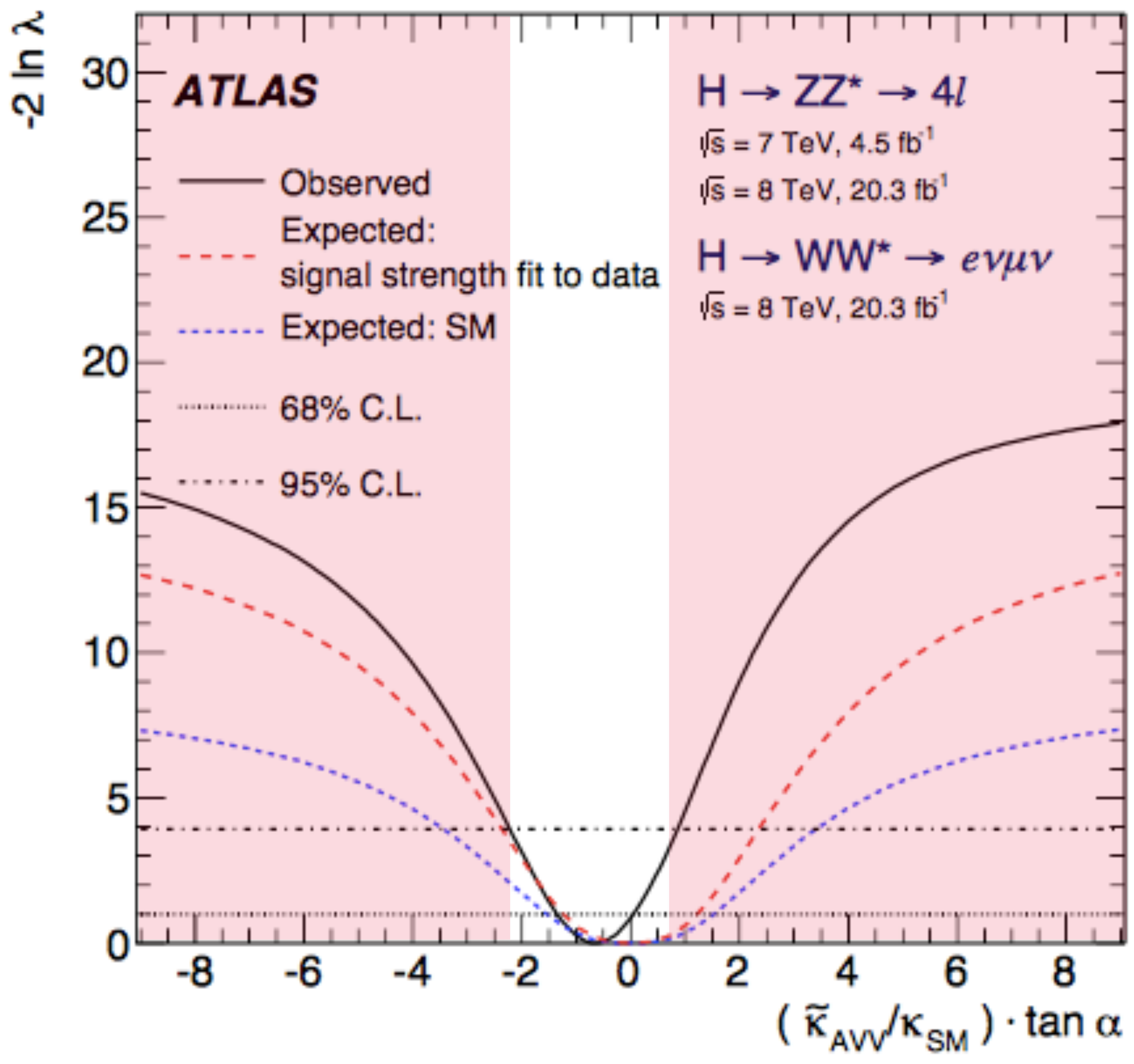
$$\mathscr{L} \propto |D_\mu \phi|^2 - \mu^2|\phi|^2 - \lambda|\phi|^4$$

CP even scalar	$CP|\phi\rangle = +\,|\phi\rangle$	(SM Higgs boson)
CP odd pseudo-scalar	$CP|\phi\rangle = -\,|\phi\rangle$	(BSM Higgs boson)
CP mixed state	$CP|\phi\rangle \neq \pm\,|\phi\rangle$	(BSM, CP violation)

CP mixed is a mixed state between CP even and odd

The amount of mixing is described with a mixing parameter α

*CP Measurement



Run 1

Measurement in HVV vertex

CP even at 0, CP odd at ∞

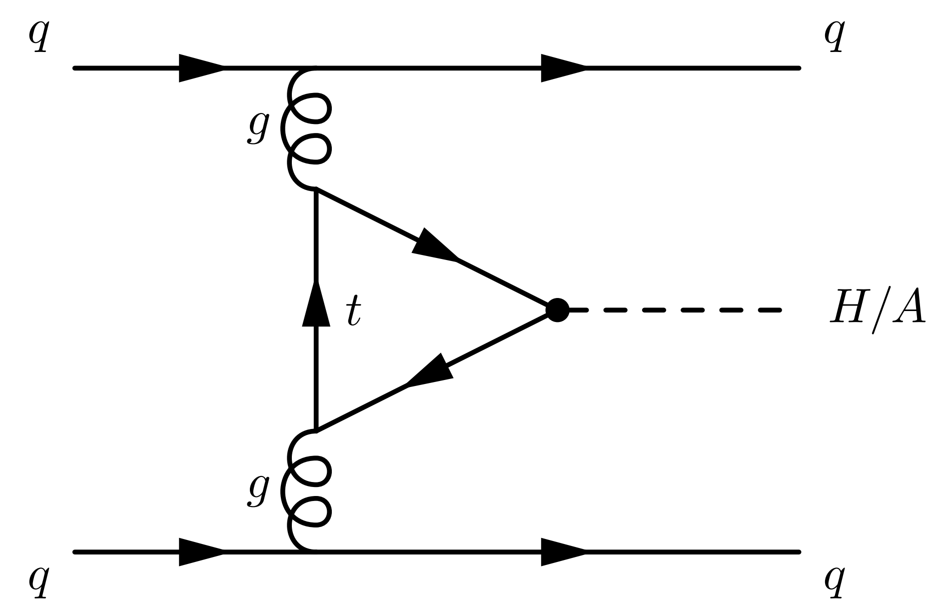
Excluded pure CP odd

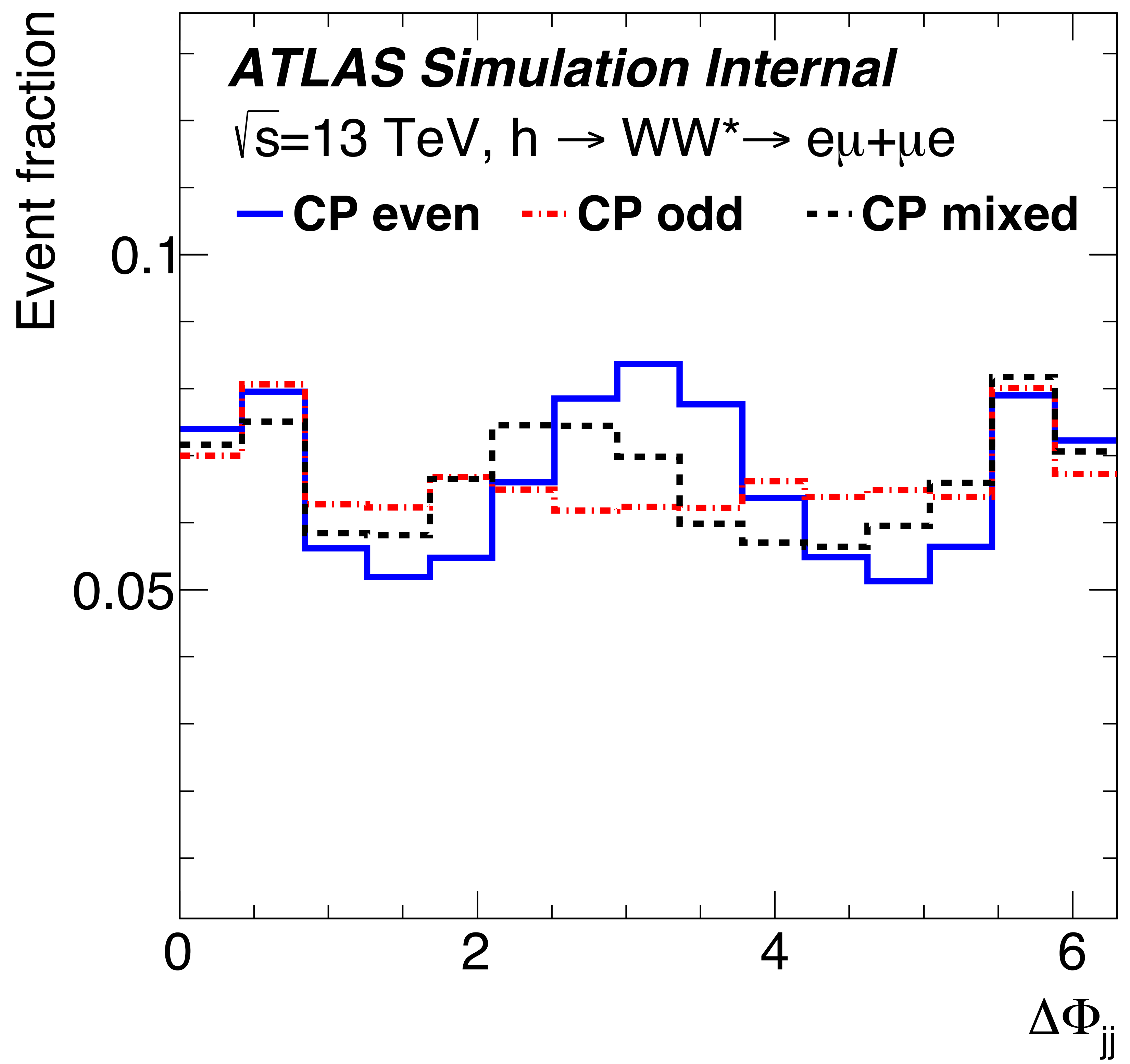
Up to 30% CP odd still possible in a mixed state at 95% C.L.

Top-Yukawa Coupling

Probe the top-Yukawa coupling in ggF + 2 jets

Assume SM decay vertex h → WW* → eνμν





Measurement of $\Delta\phi_{jj}$

Angle between the two jets

Shape depends on CP state

First time CP measurement in top-Yukawa coupling and in > 0 jet!

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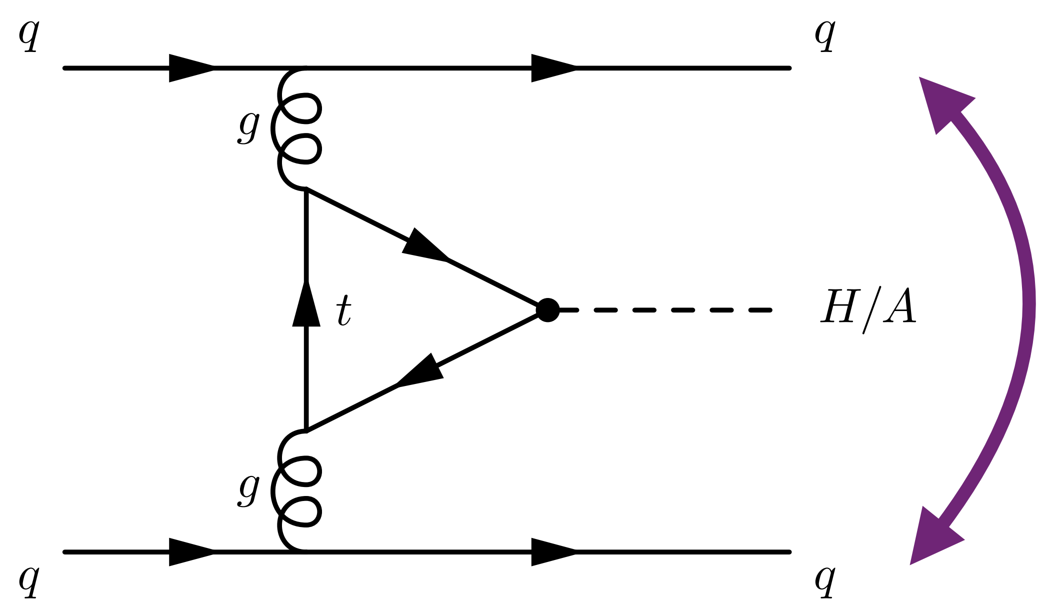

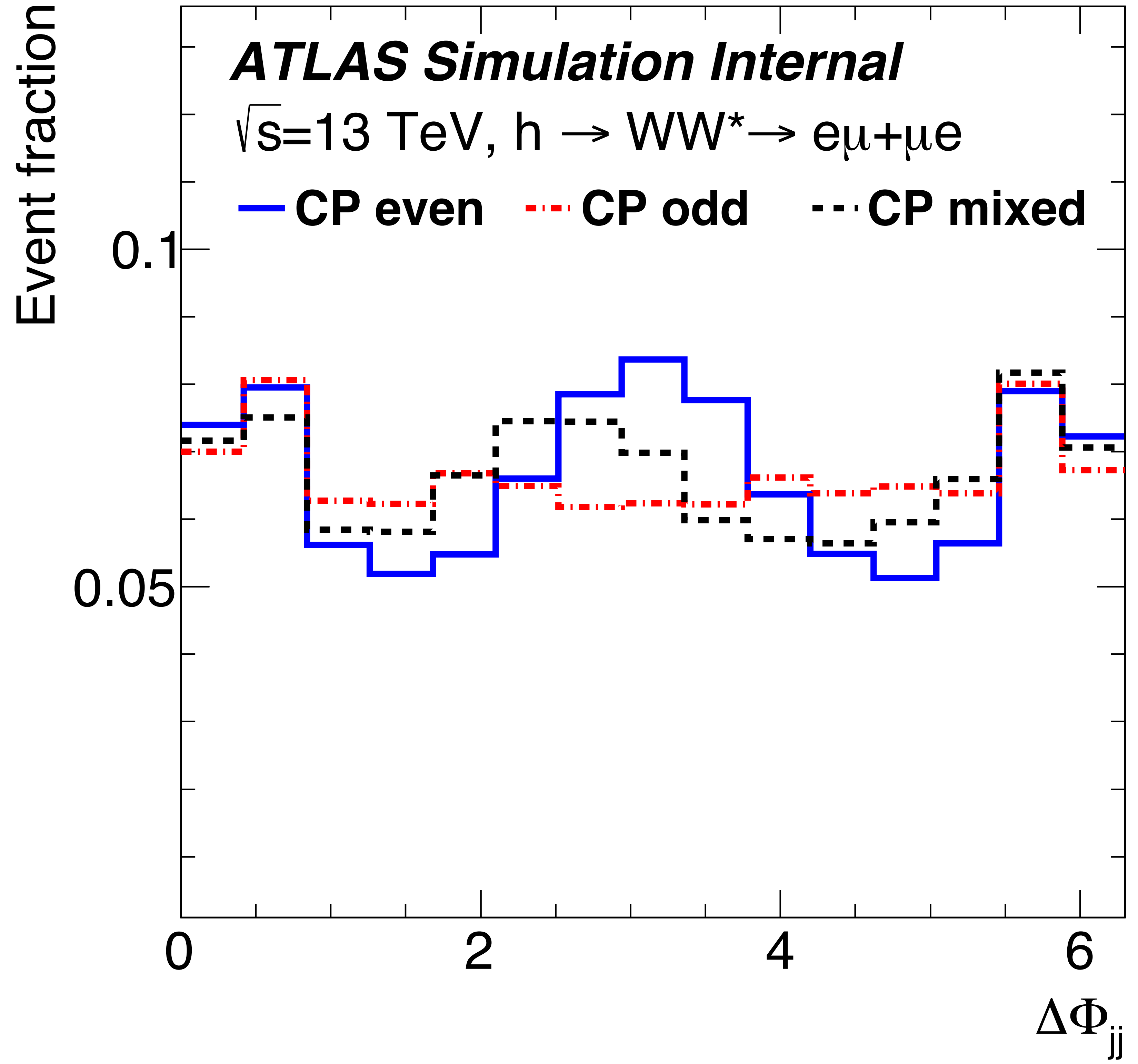

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Simulation of Data

Simulation

Monte Carlo samples

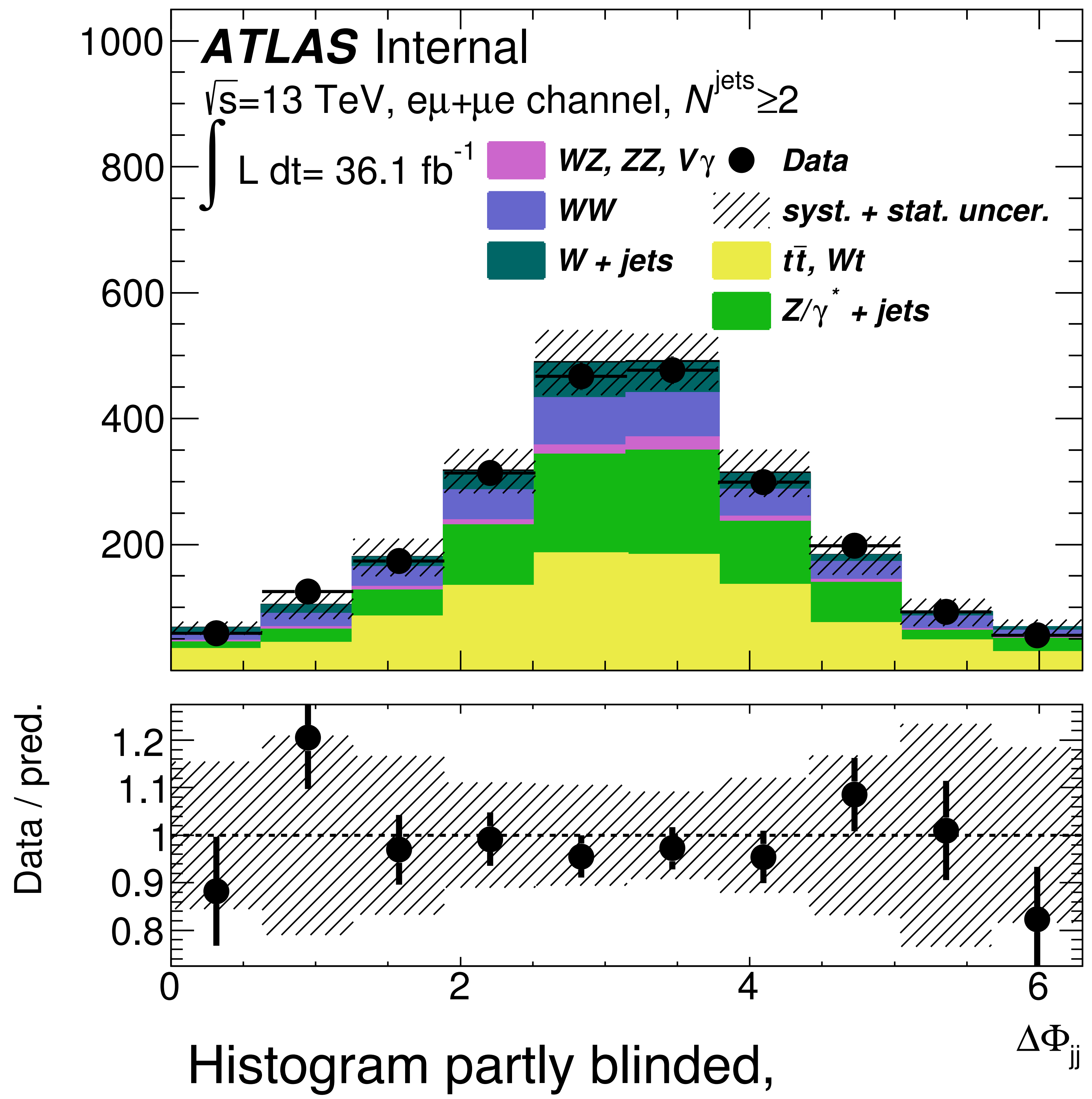
Data driven techniques

CP dependent signal (ggF + 2 jets)

Generate three benchmark samples

- Even
- Odd
- 50/50 Mix

Use morphing technique to find any in-between scenario



Histogram partly blinded, no signal visible

ggF + 2 jets Simulation

Nikhef

Higgs Characterisation model

Effective Langrangian ($m_{top} \rightarrow \infty$) in terms of:

- mixing angle between CP even and CP odd α
- dimensionless tunable couplings κ_{Xgg}

$$\mathscr{L} \propto (\cos\alpha\, \kappa_{Hgg} g_{Hgg} G^a{}_{\mu\nu} G^{a,\mu\nu} + \sin\alpha\, \kappa_{Agg} g_{Agg} G^a{}_{\mu\nu} \tilde{G}^{a,\mu\nu})X$$

Benchmark scenarios

- Even ($\kappa_{Hgg} = 1$, $\kappa_{Agg} = 0$, $\cos\alpha = 1$)
- Odd ($\kappa_{Hgg} = 0$, $\kappa_{Agg} = 1$, $\cos\alpha = 0$)
- Mixed ($\kappa_{Hgg} = 1$, $\kappa_{Agg} = 1$, $\cos\alpha = 1/\sqrt{2}$)

$G^{a,\mu\nu}$ the field strength tensor,

$\tilde{G}^{a,\mu\nu}$ the dual tensor $\propto \varepsilon_{\mu\nu\rho\sigma} G^{a,\rho\sigma}$

g_{Xgg} the coupling of the Higgs field X

ggF + 2 jets Simulation

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Selection of Events

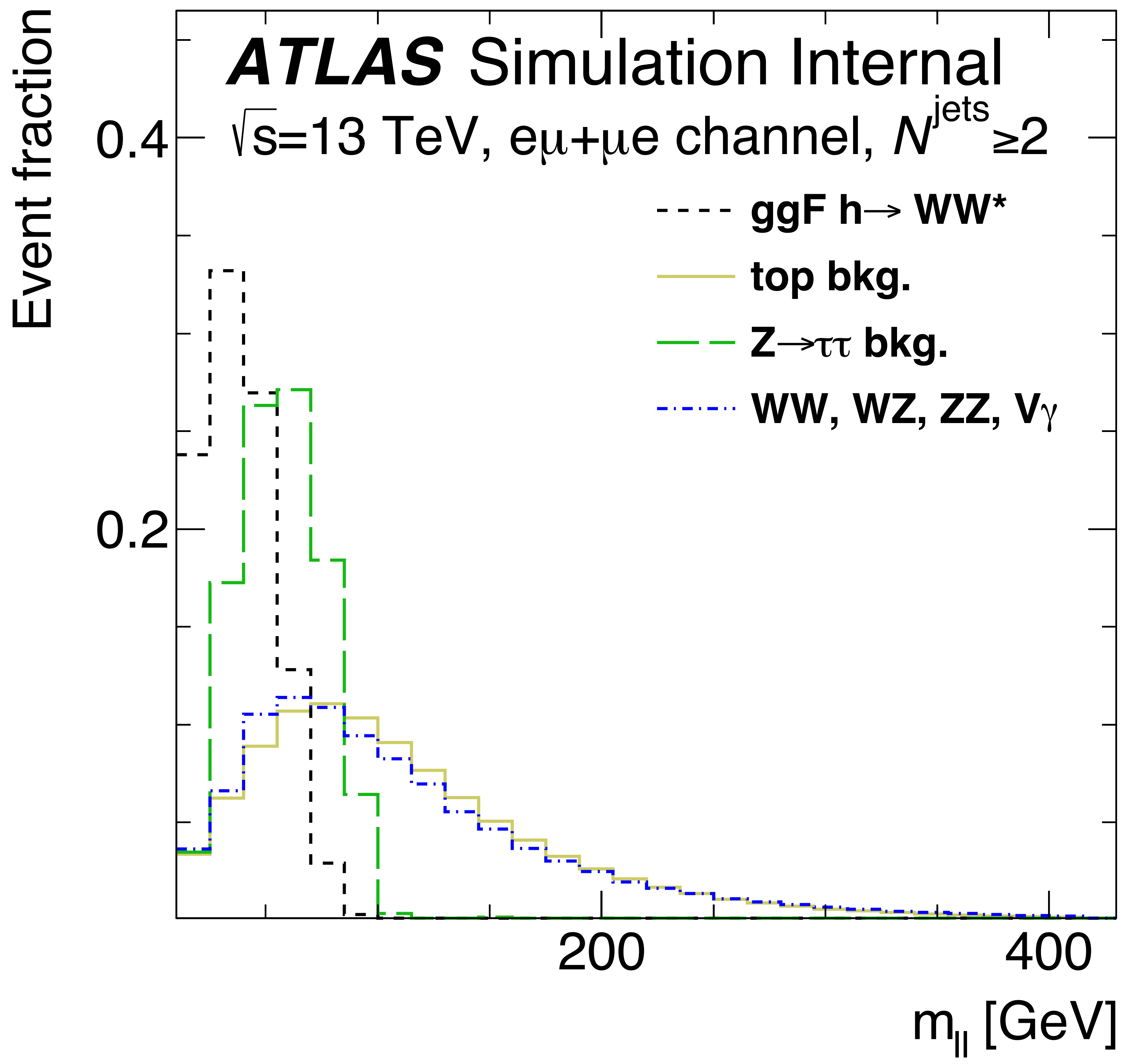
Preselection

ggF + 2 jets, $h \to WW^* \to e\nu\mu\nu$

Select two leptons and two jets

Cuts

Cut away regions that contain little or no signal to reduce backgrounds and so increase sensitivity



Example: m_{ll}

Full selection in back-up

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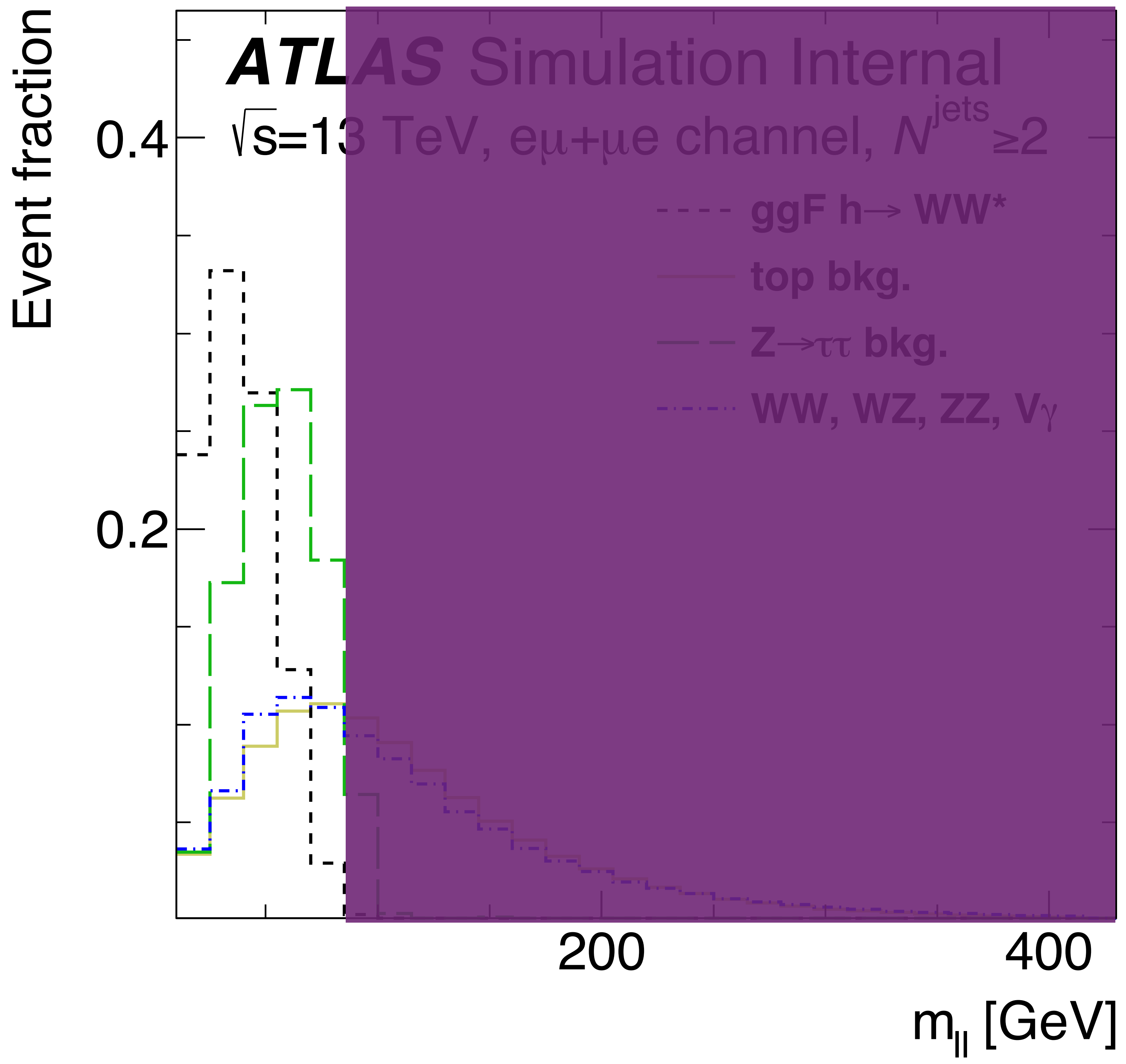


Example: $m_{ll} < 90$ GeV

Full selection in back-up

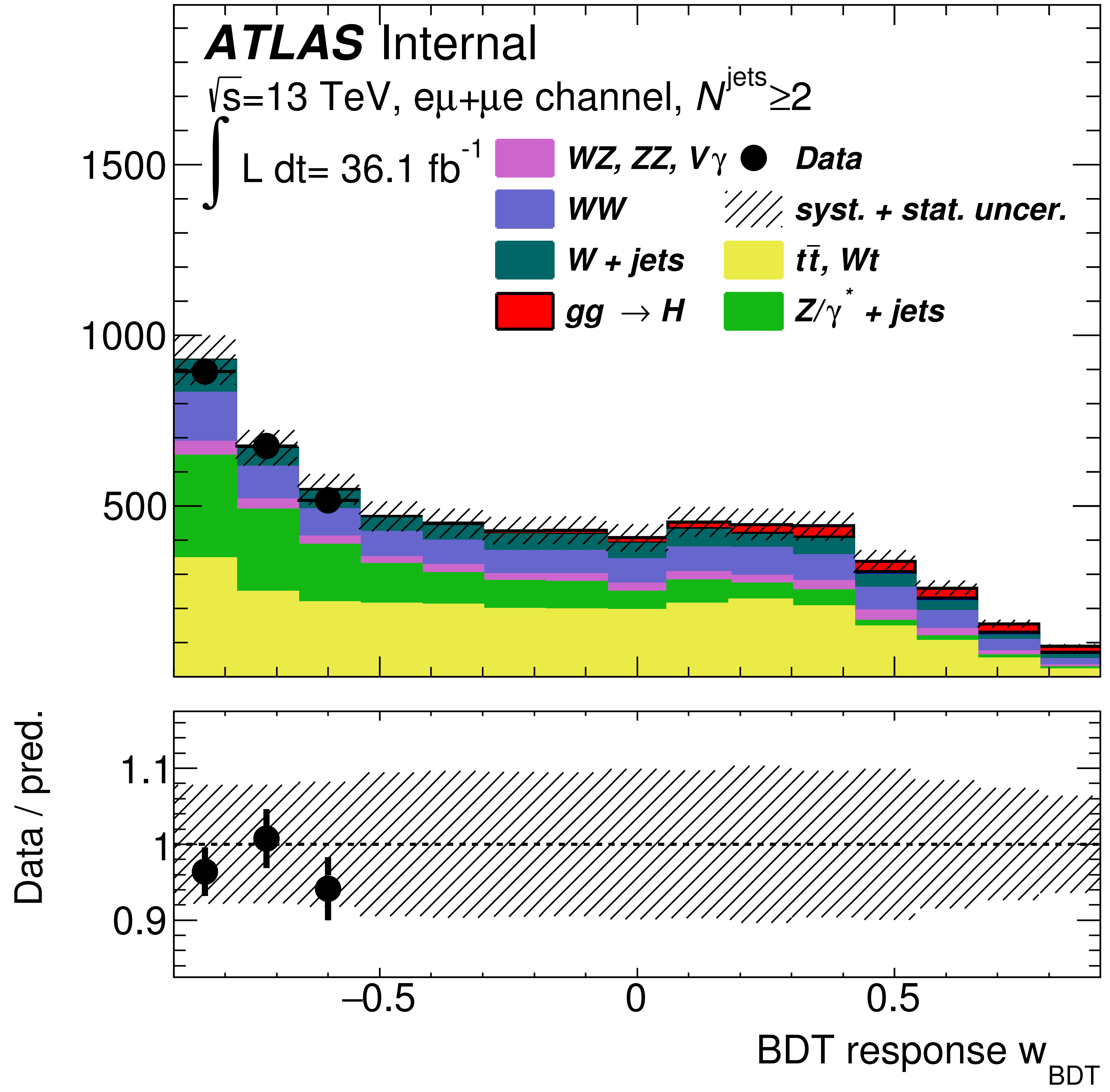
Boosted Decision Tree

Multivariate Technique

Find an as optimal as possible discriminating variable between a chosen signal (ggF + 2 jets) and background (all backgrounds)

BDT response

Cut at 0 leads to large background reduction, so increased sensitivity



Input variables

$\Delta\Phi_{ll}$, M_T, M_{ll}, $Min(\Delta\Phi_{ll,j1})$, $Min(\Delta\Phi_{ll,j2})$

Histogram partly blinded

Validation

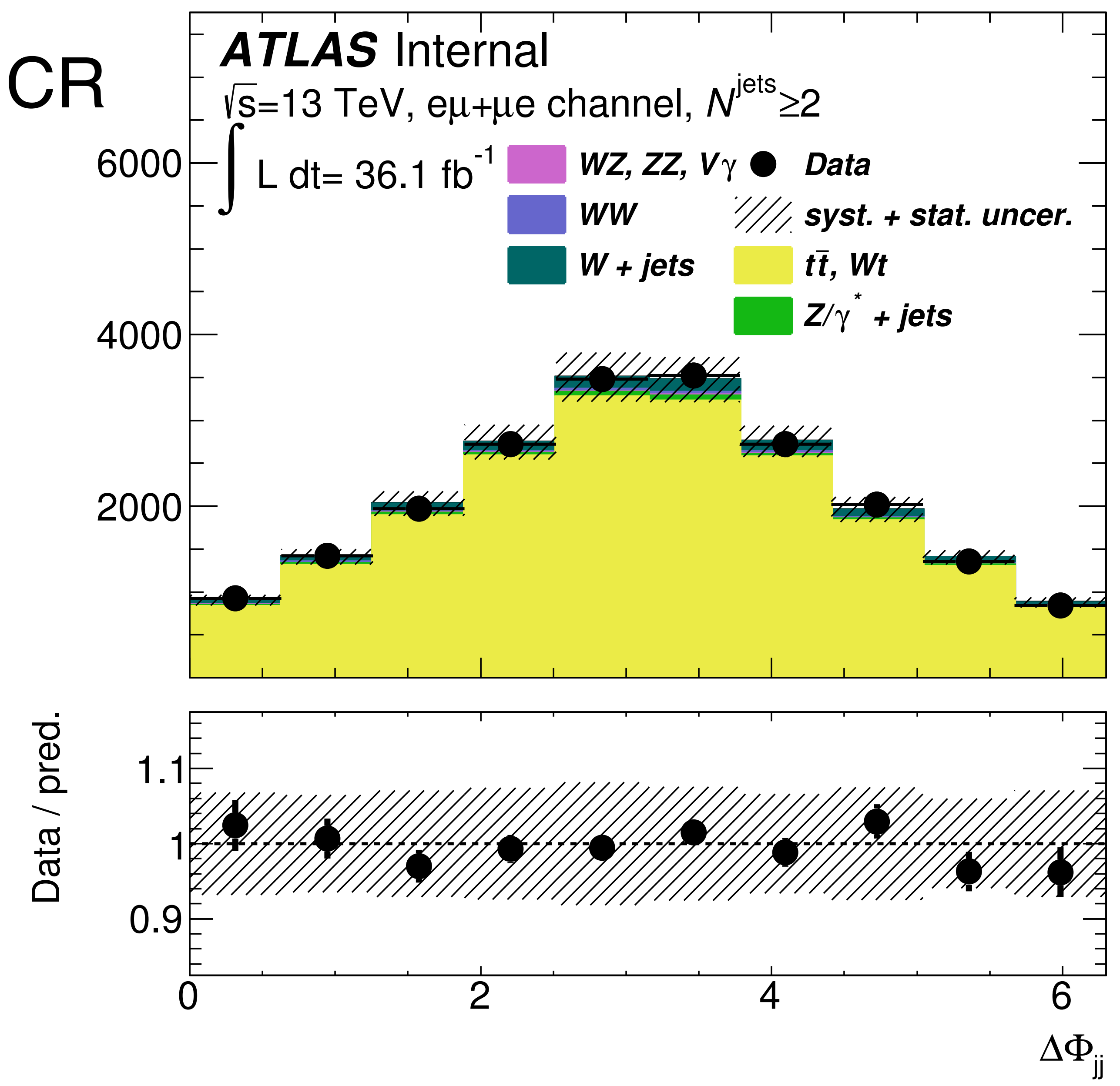
Control Regions

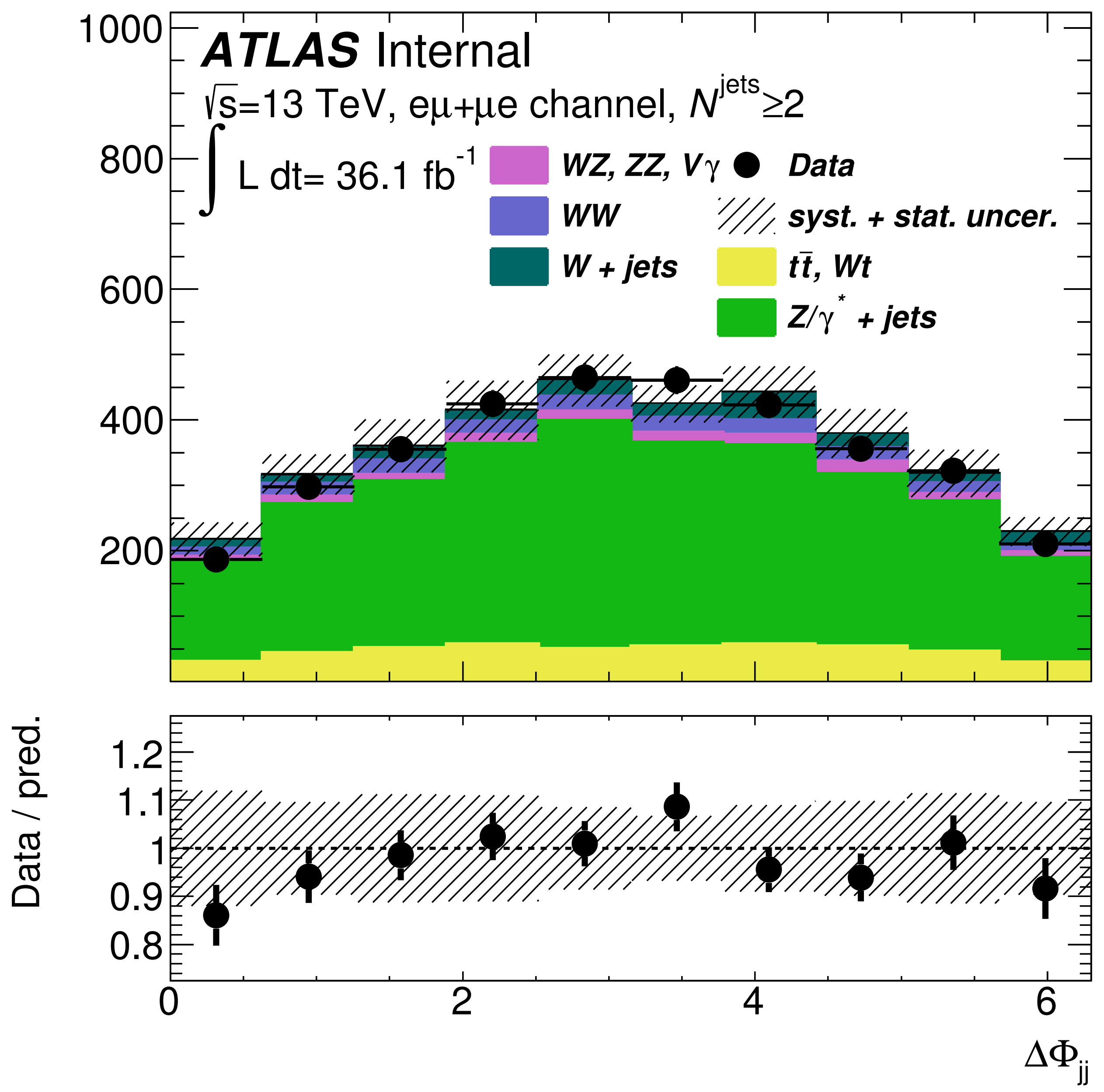
Select a region close, but orthogonal to your signal region

Check the modelling of the backgrounds with real data

Apply scale factor (if needed) to greatly enhance sensitivity

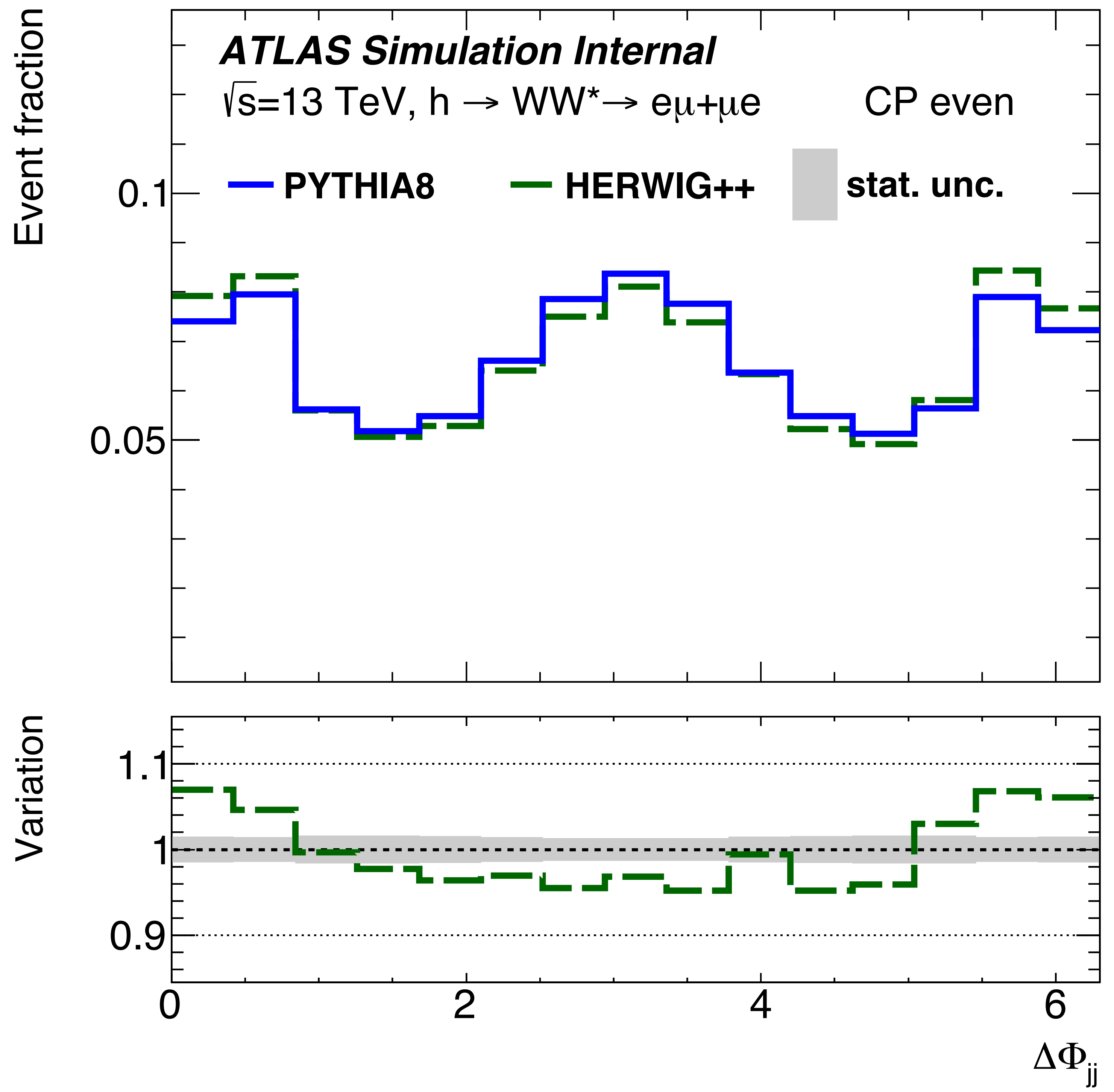
Top CR





Z→ττ CR

Uncertainties



Theory Uncertainties

MC generator

Parton shower

Parton distribution functions

QCD scales

Experimental Uncertainties

Uncertainties related to reconstruction and identification of physics objects such as electrons, muons and jets

Results

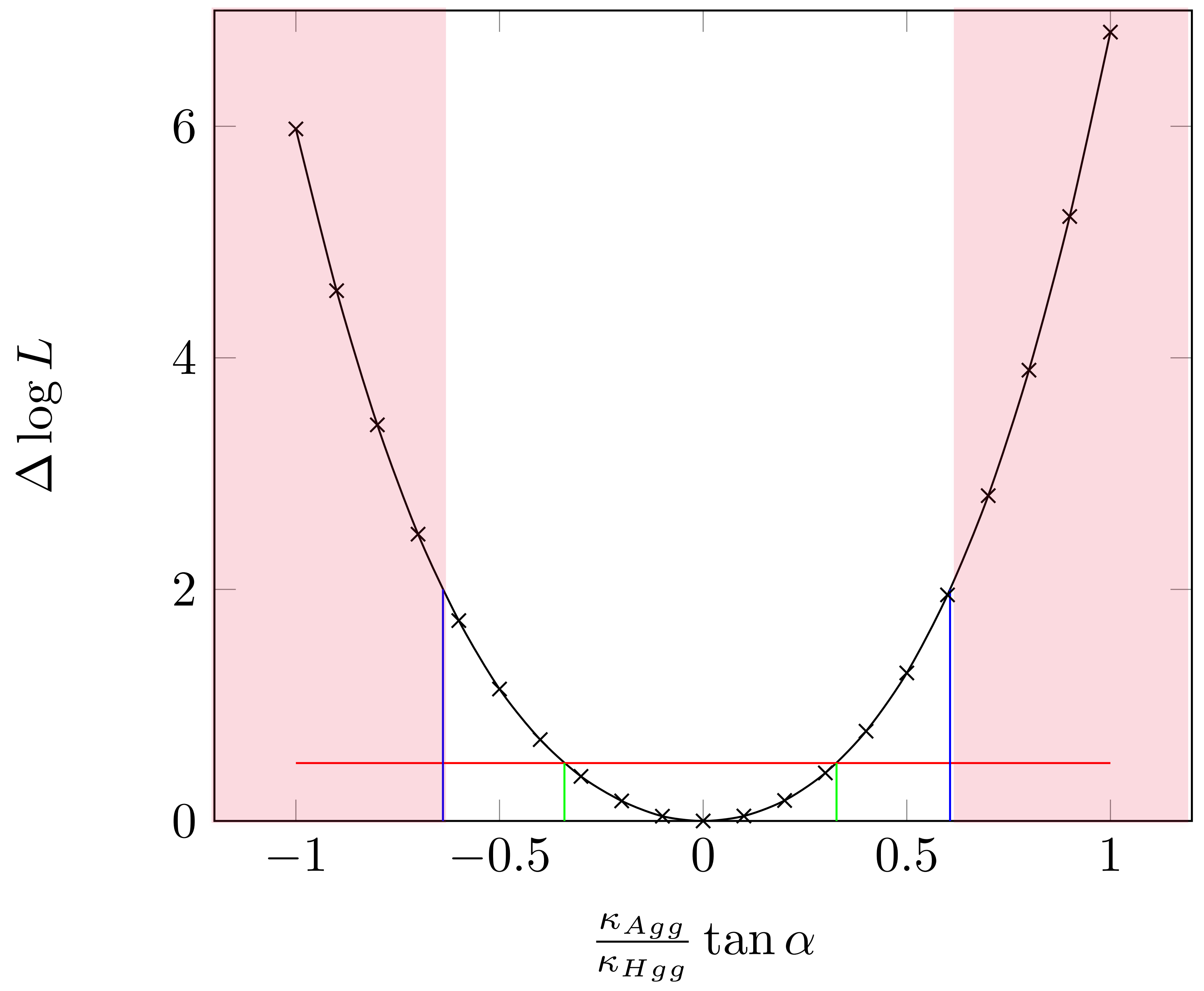
Hypothesis Test

Fit $\Delta\phi_{jj}$ in different CP scenarios

Minimise a log likelihood distribution

Assuming a CP even scenario fractions

$\gtrsim$14% CP odd are excluded at 95% C.L.



Conclusion

For the first time a CP measurement in the top-Yukawa coupling

Four times higher precision than in Run 1*

*Run 1 was a measurement in the HVV vertex, Run 2 in the more challenging top-Yukawa coupling

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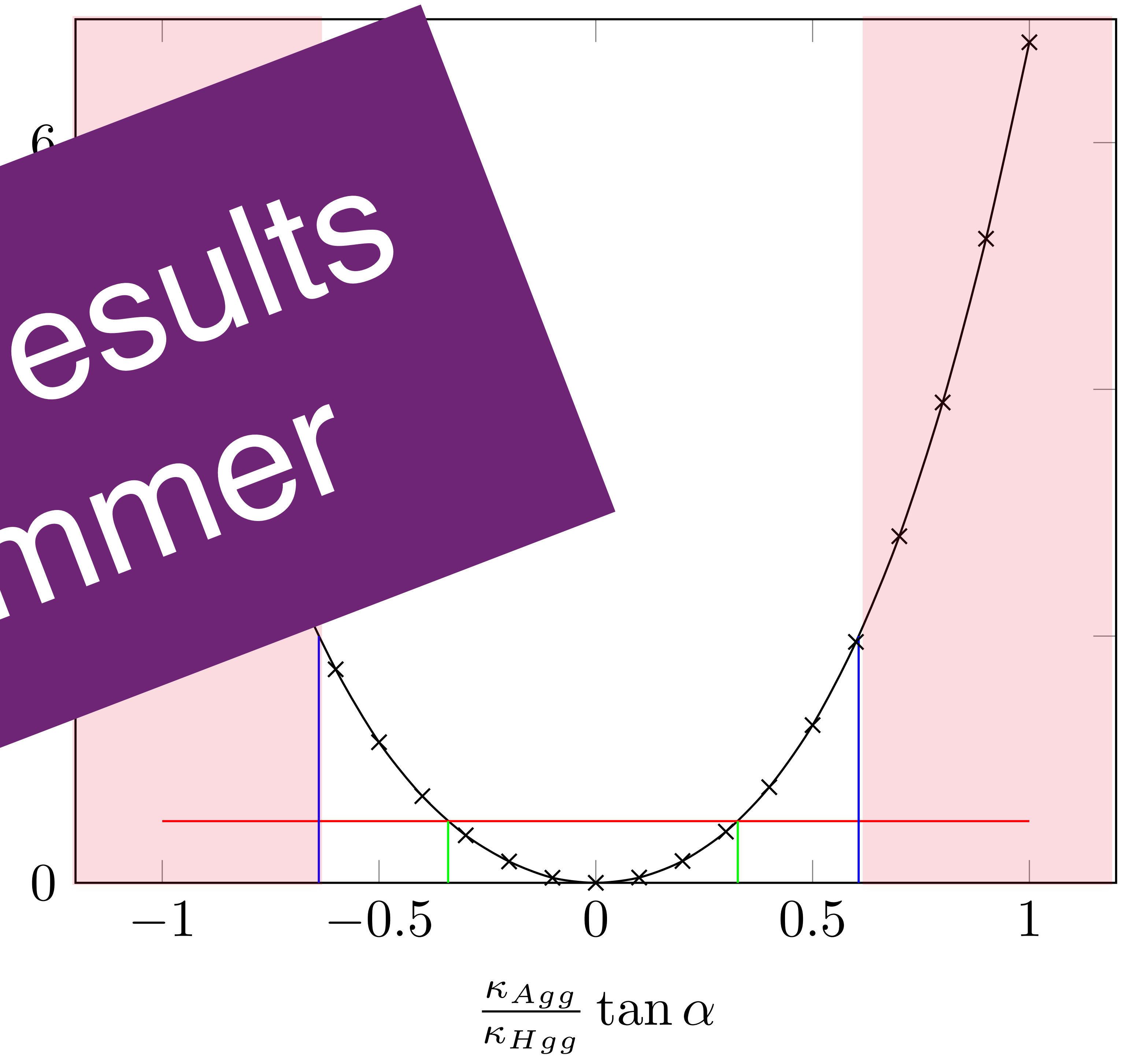
Preliminary, final results expected in summer



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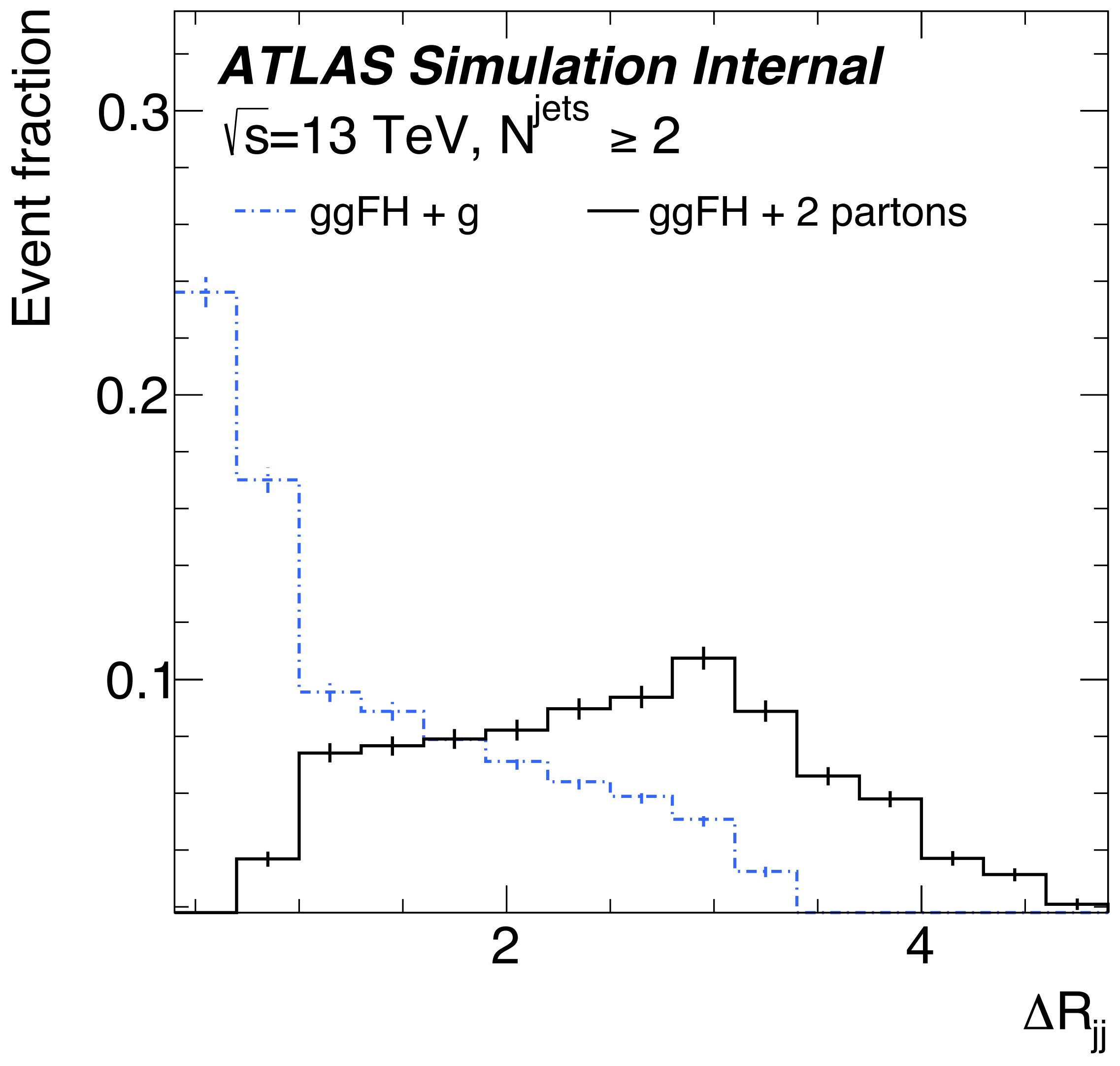
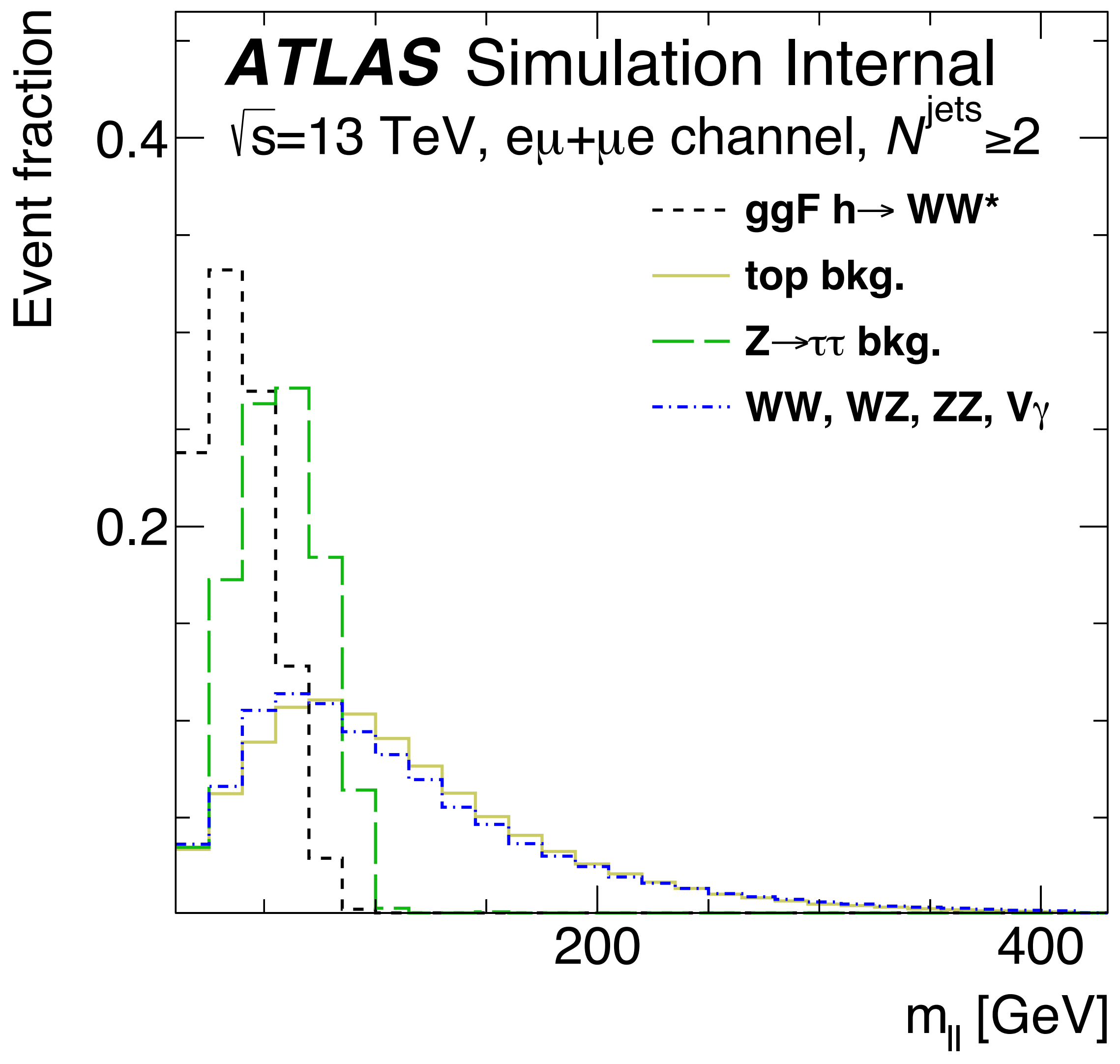
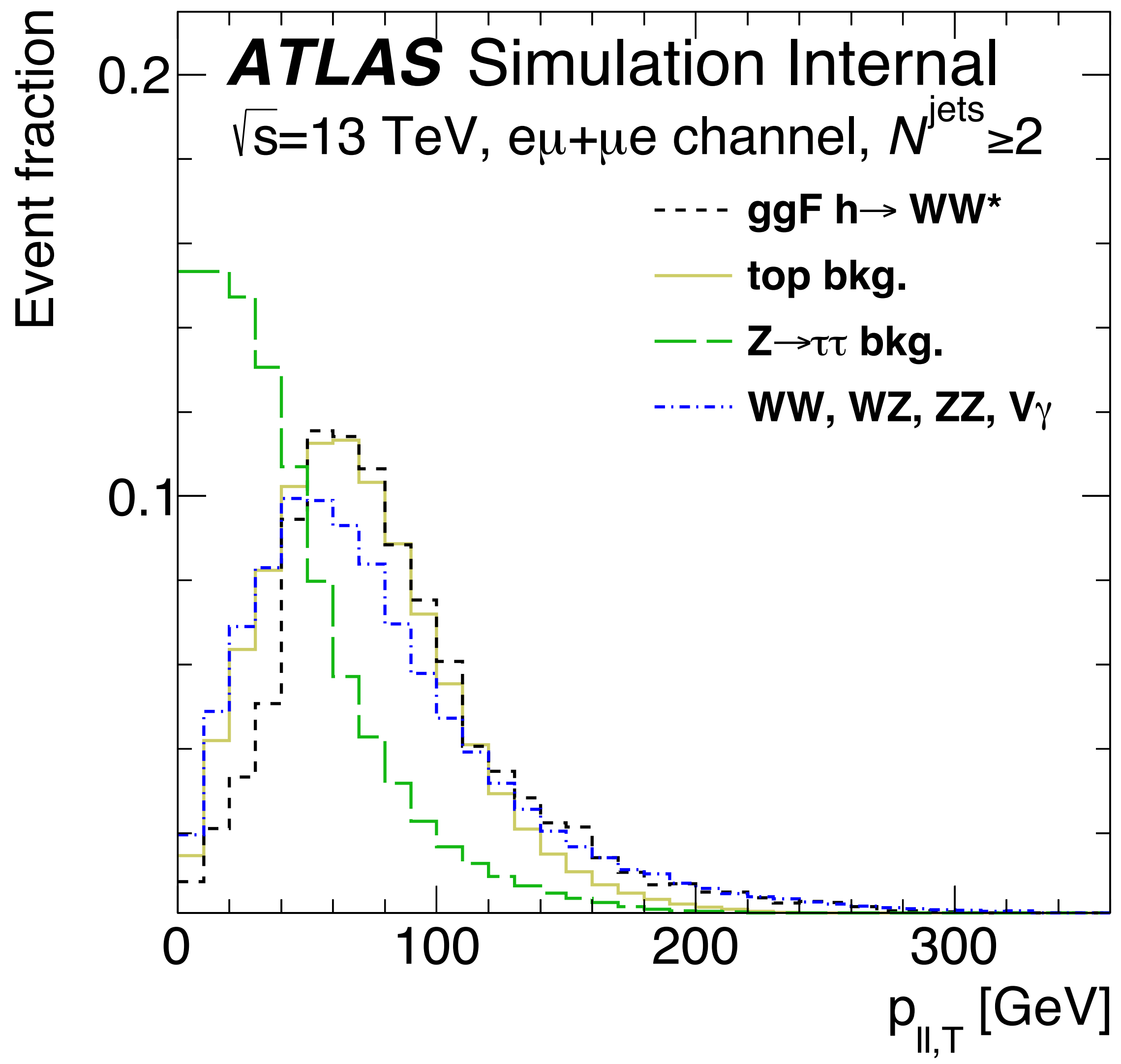
Back-up

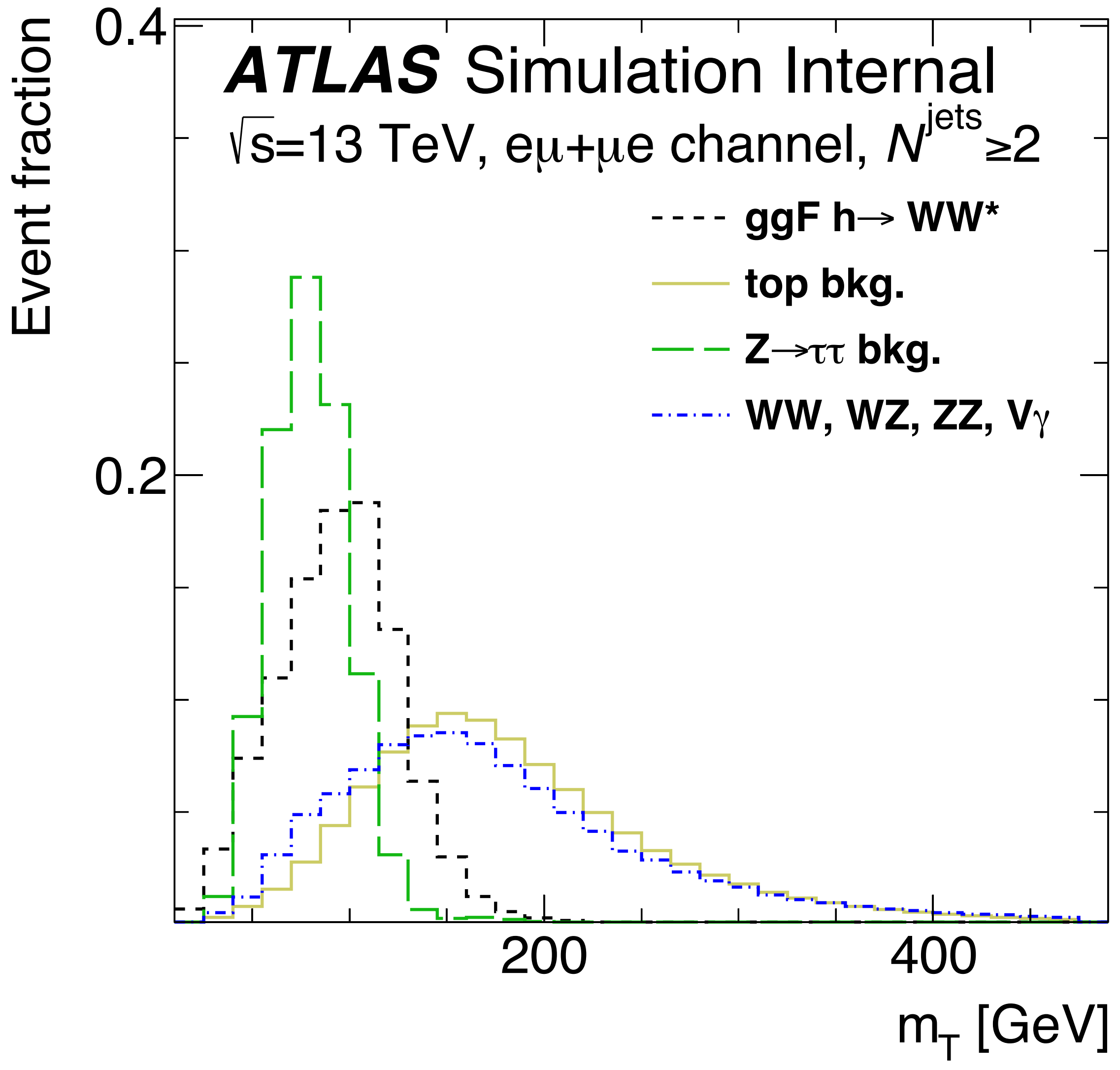
Event Selection Histograms

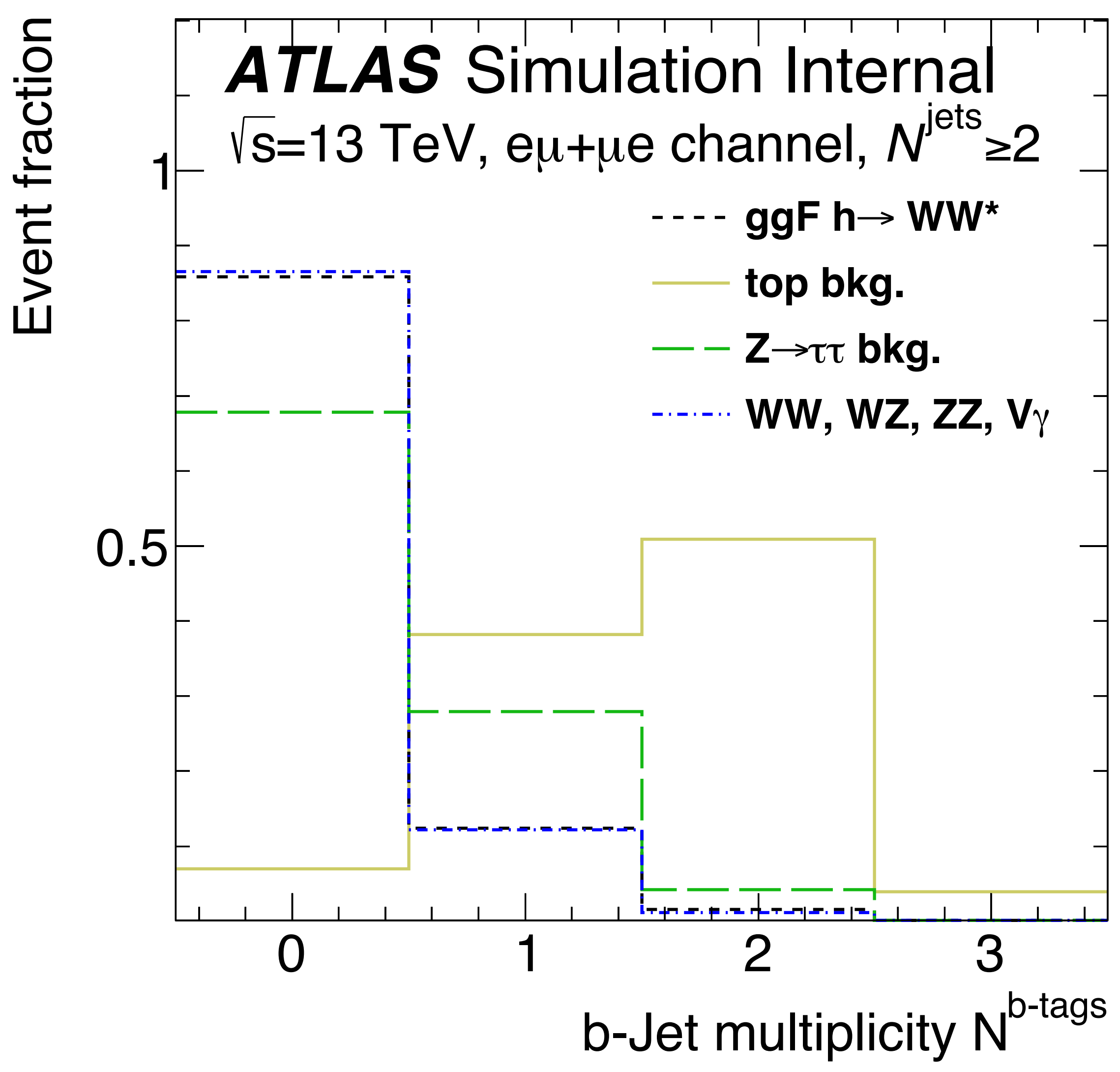


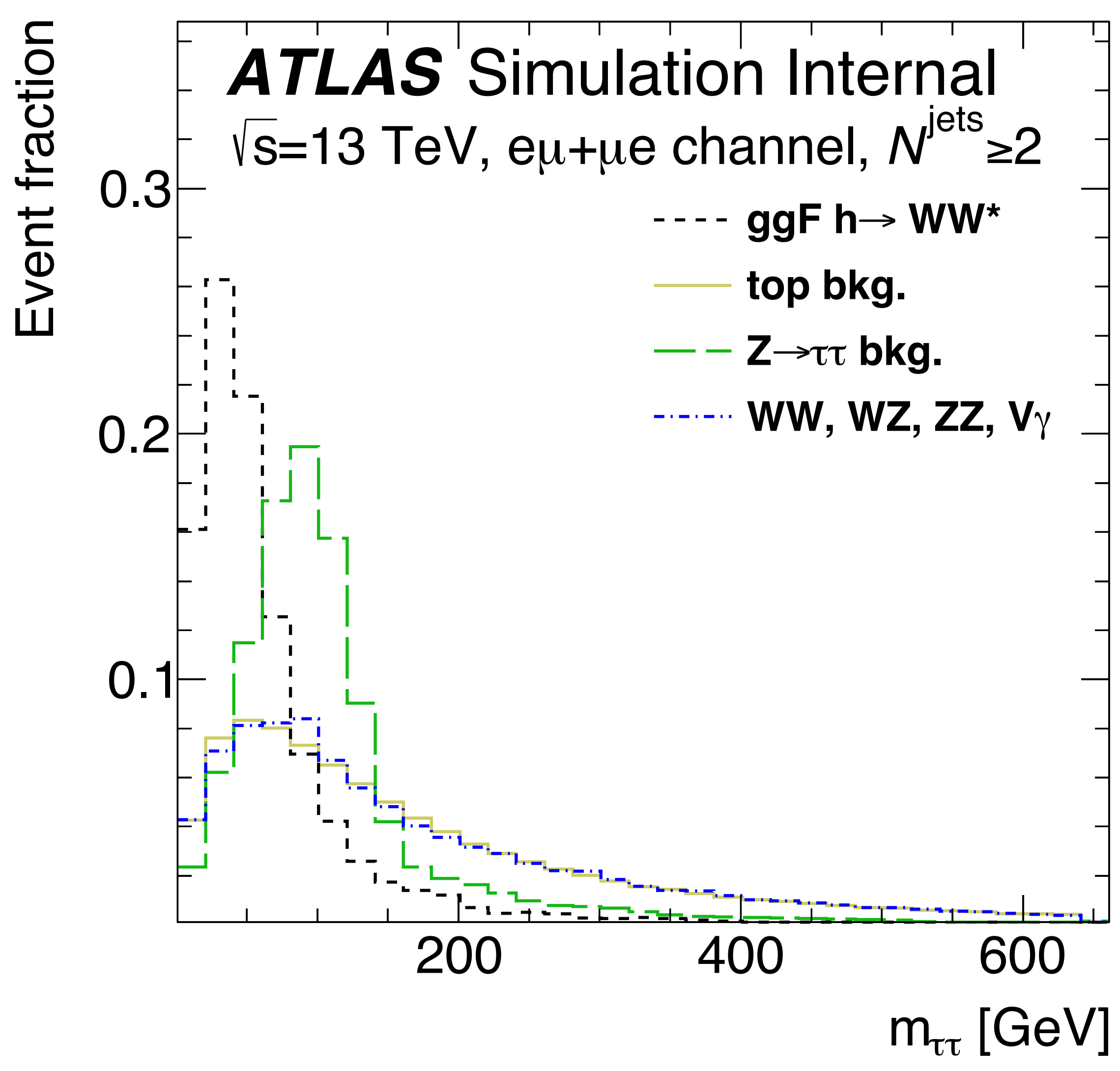




All signals and backgrounds normalised to 1







Event Selection

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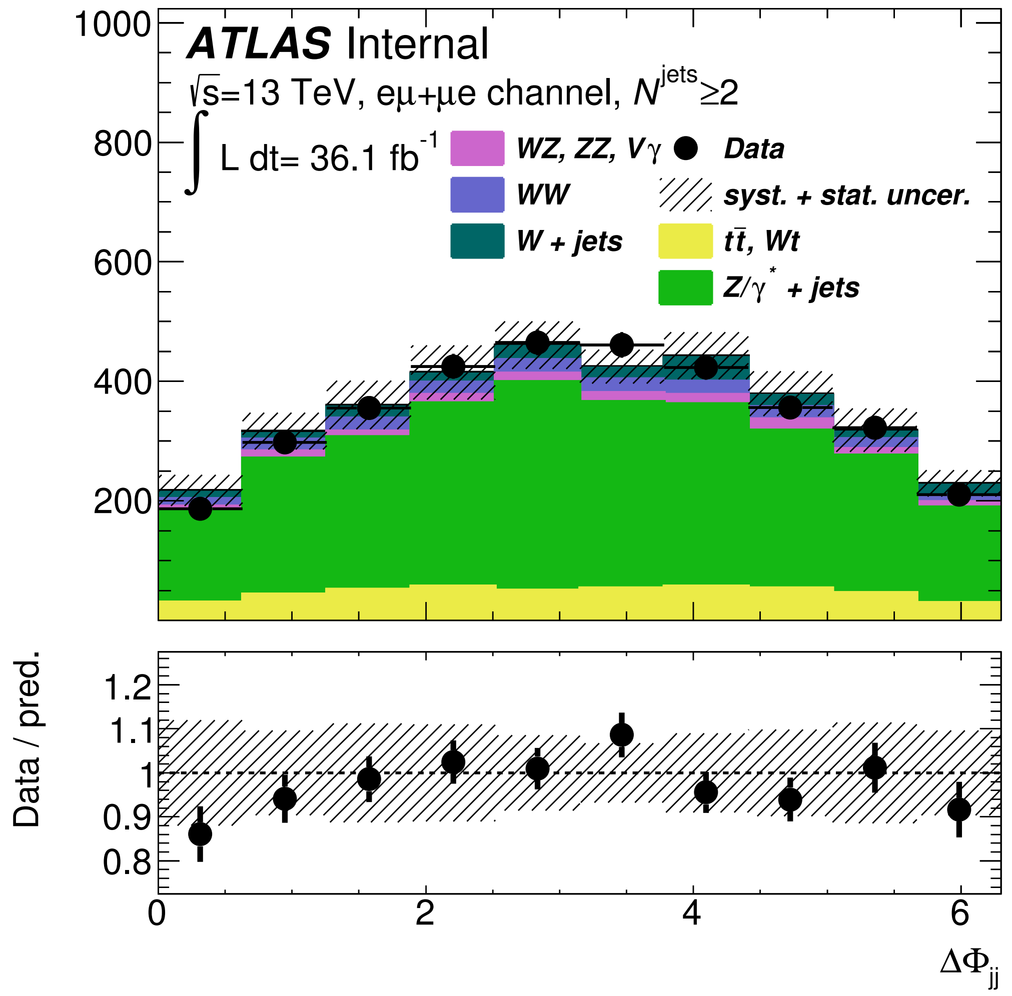
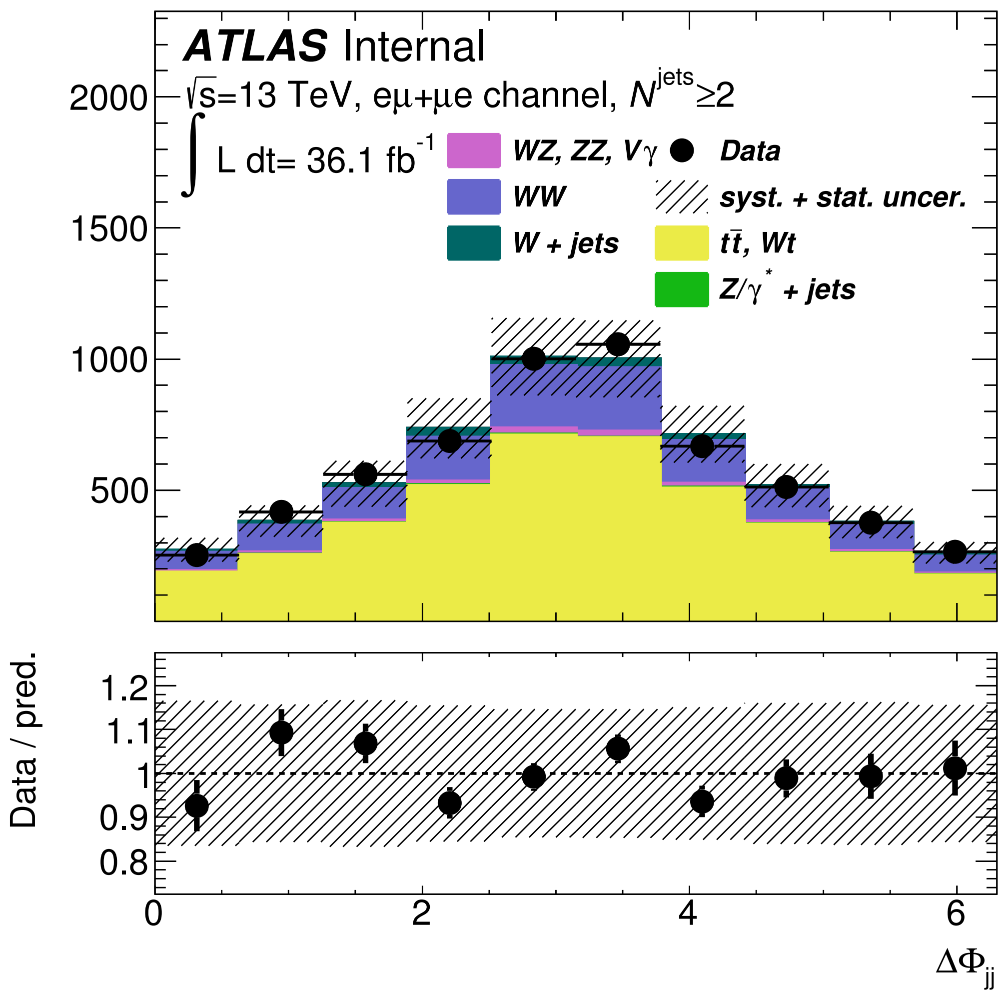
SR Two OS/OF leptons with $p_T > 22$ / 15 GeV (lead / sublead)
$\geqq$ 2 jet with $p_T > 25$ / 30 GeV ($|\eta| < 2.5$ / $2.5 < |\eta| < 4.5$)
$\Delta R_{jj} > 1$
$M_{ll} < 90$ GeV
$p_{T,ll} > 20$ GeV
$M_T < 150$ GeV
b-jet veto
$Z \to \tau\tau$ veto
Possible BDT cut

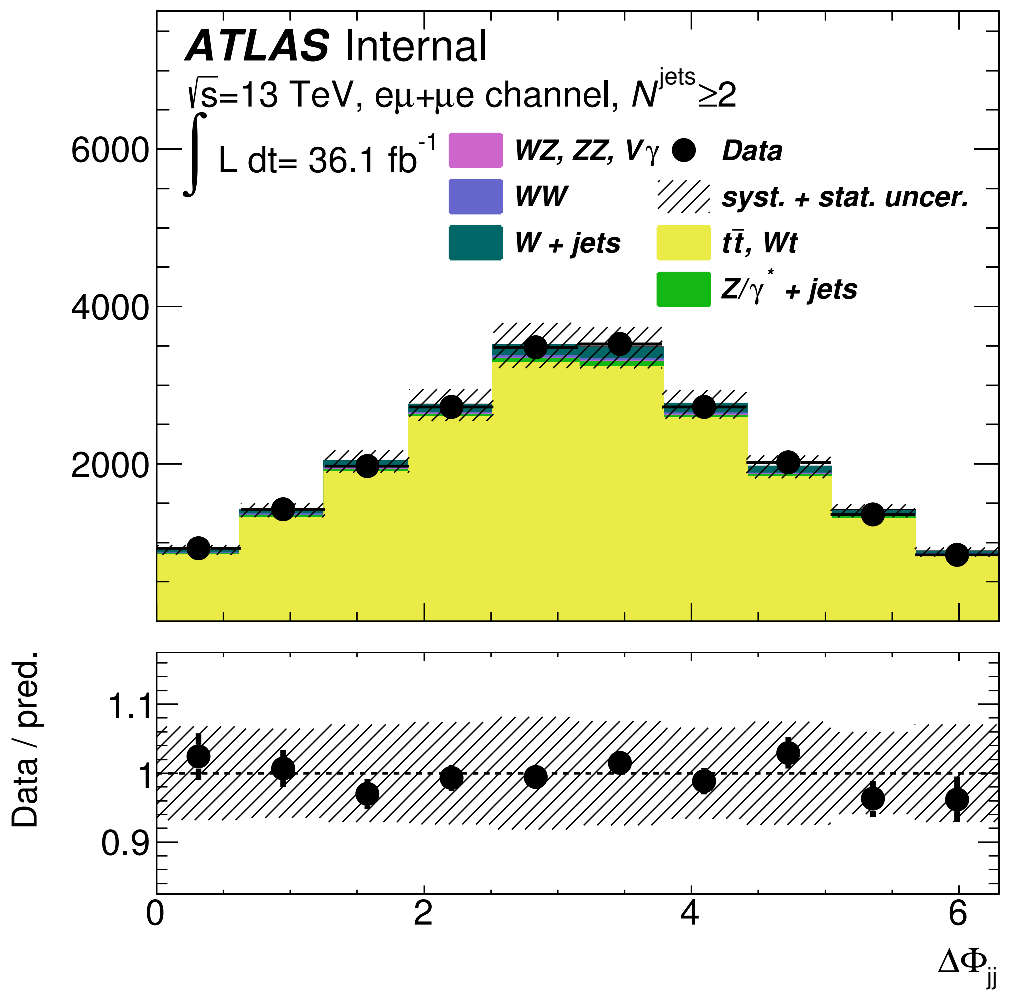
top CR At least one b-jet
$Z \to \tau\tau$ CR Inverted $Z \to \tau\tau$ veto, no $p_{T,ll}$ cut
WW CR Inverted M_{ll} , no M_T cut
SS VR Two SS leptons

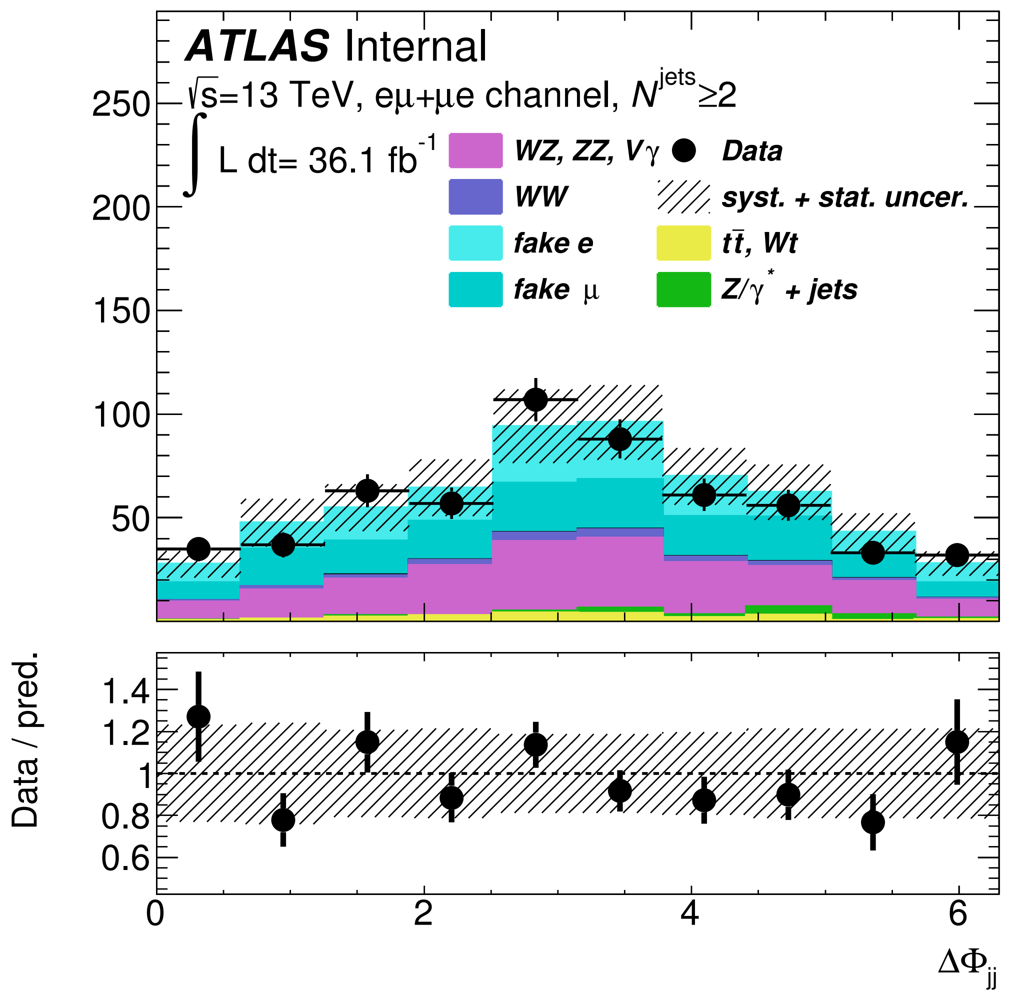
Control and Validation Regions

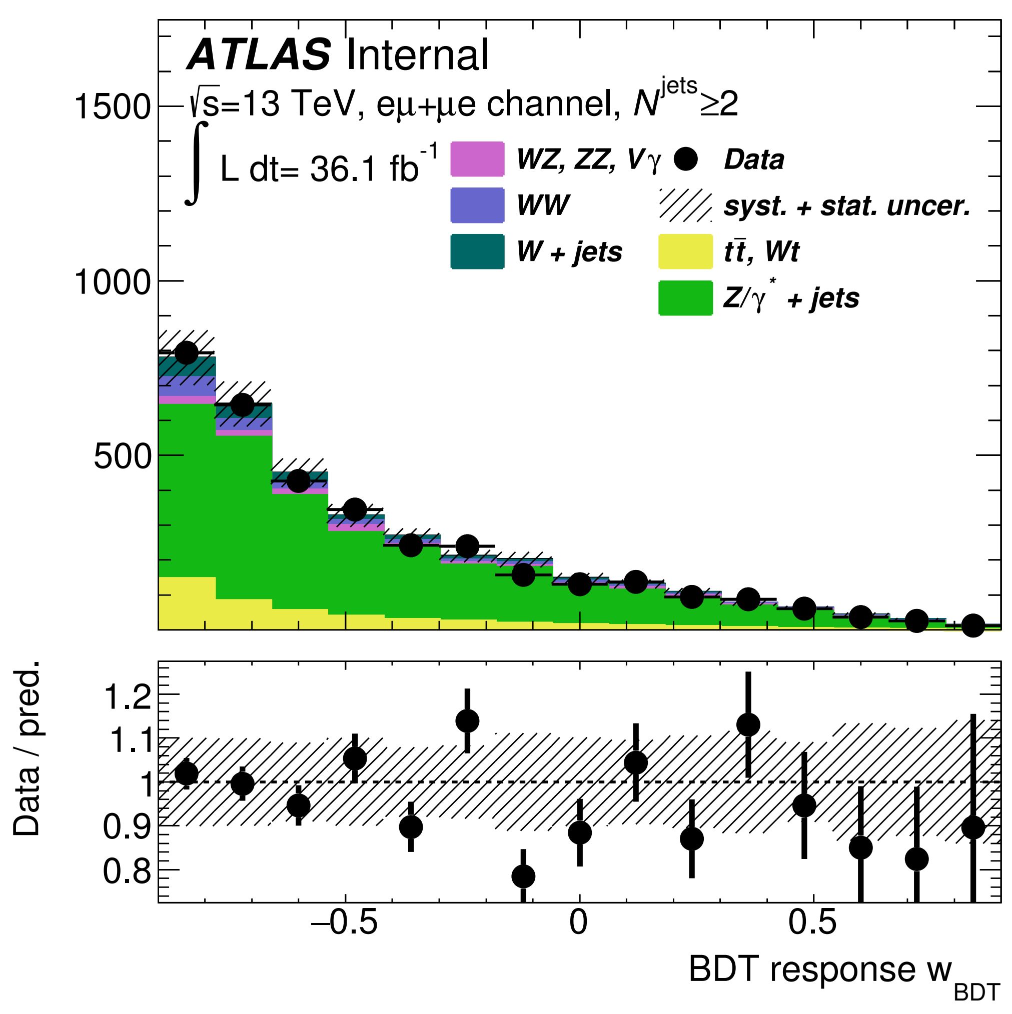
Nikhef

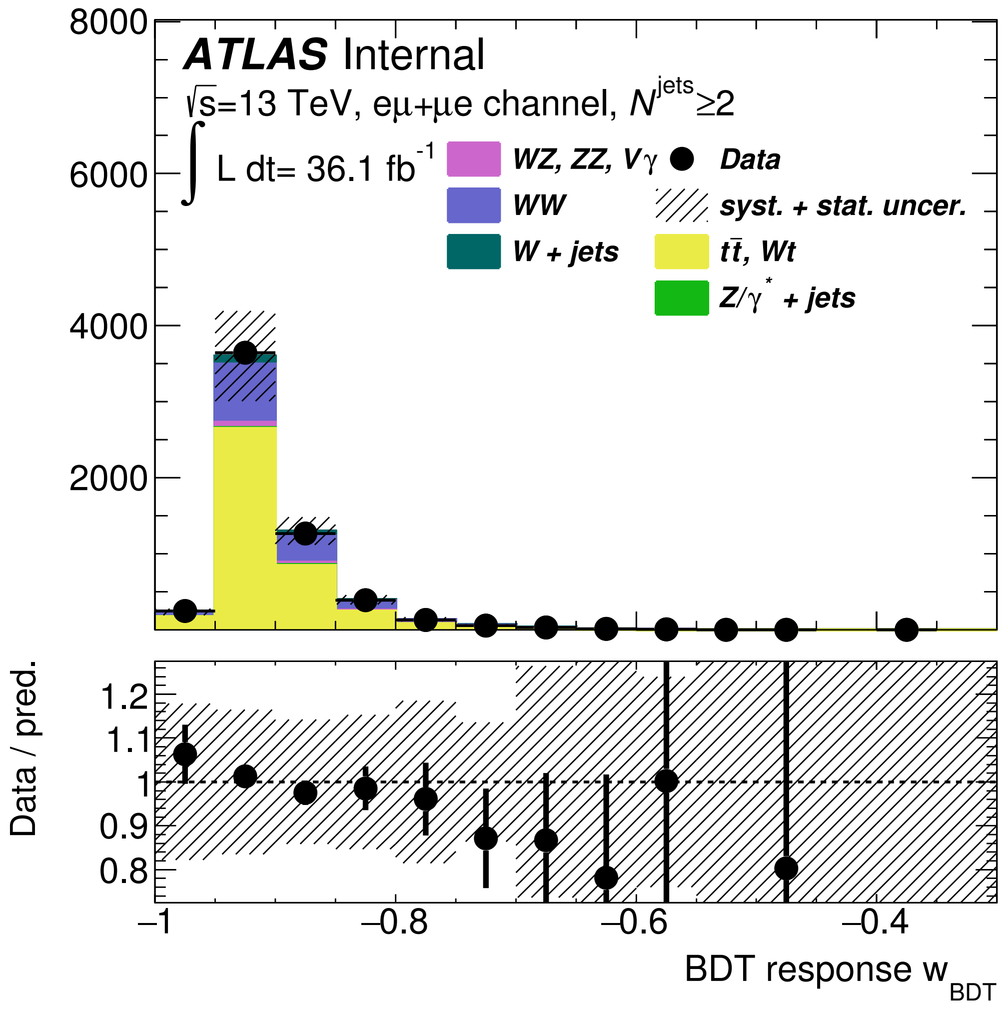


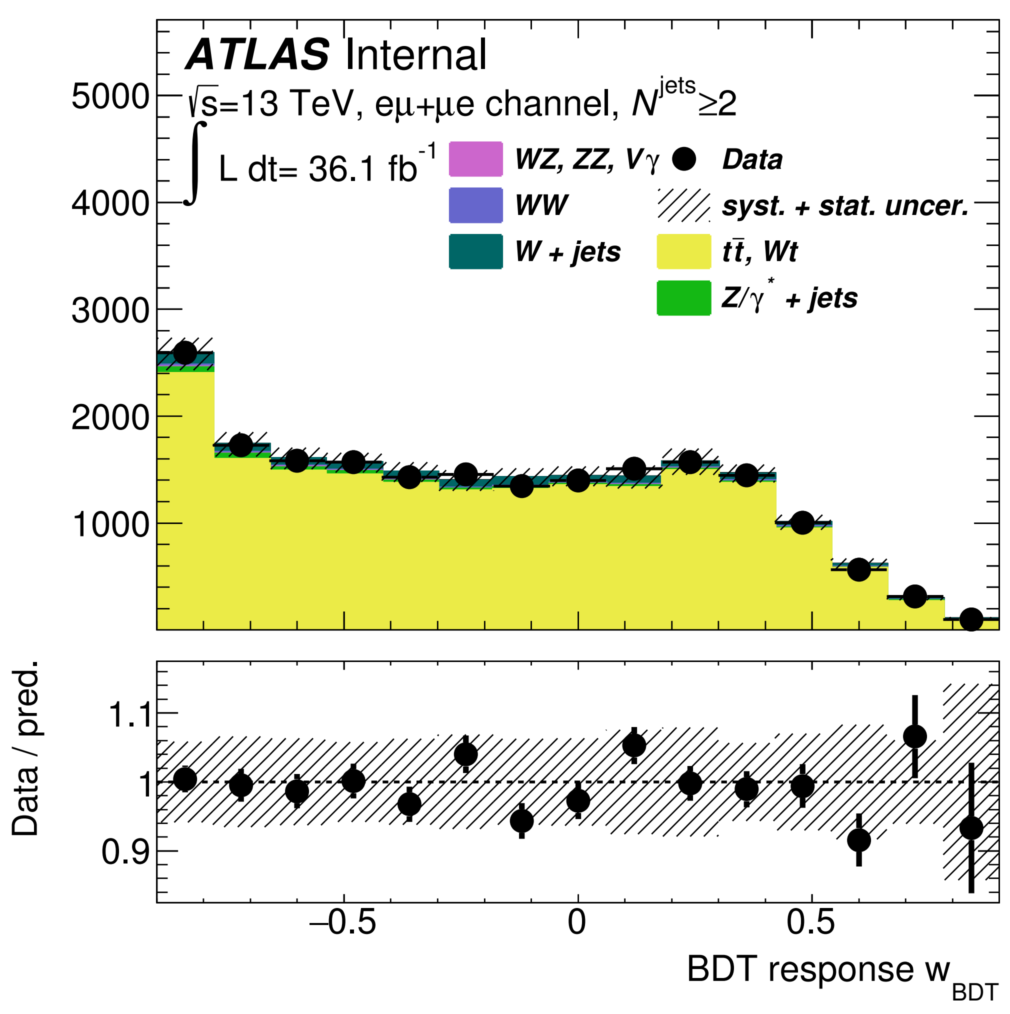


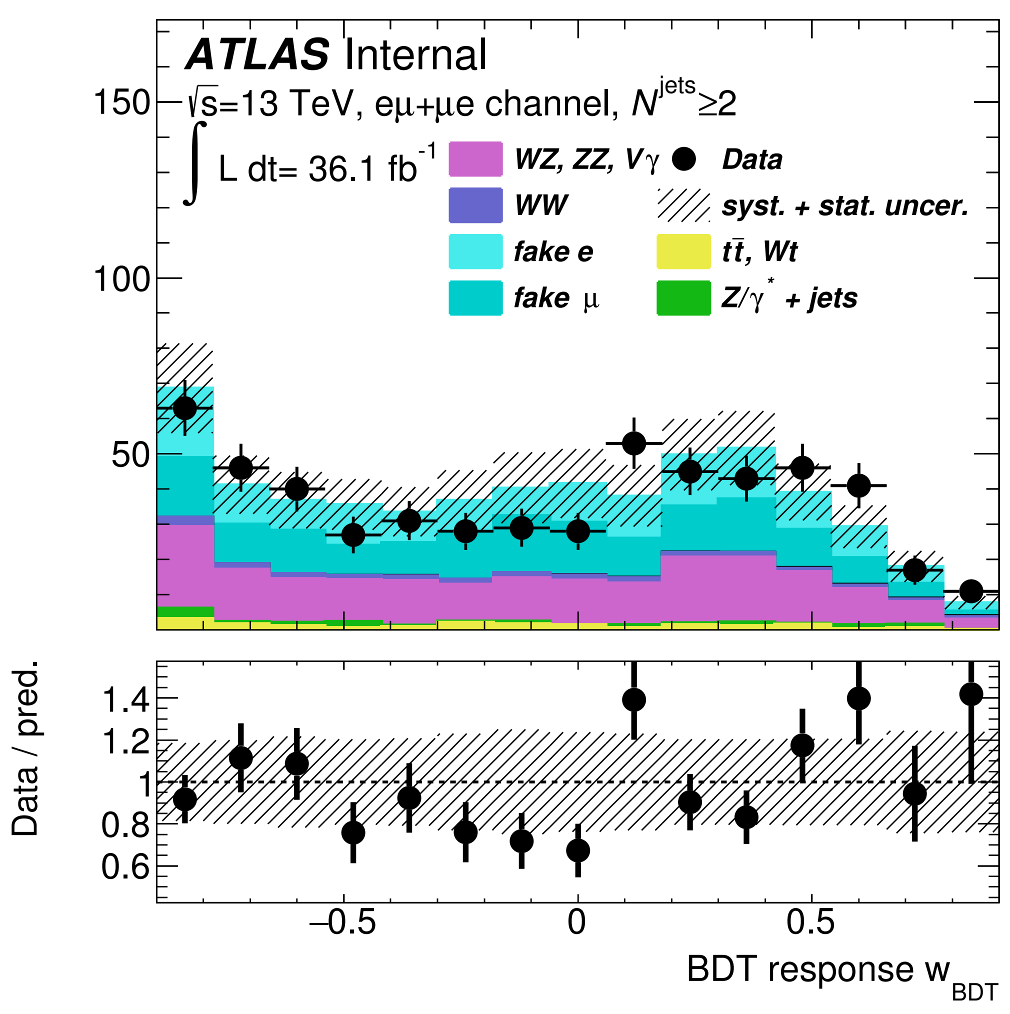












Z→ττ CR

WW CR

Top CR

Same Sign VR

Higgs Characterisation

EFT Lagrangian describes interactions of scalars and pseudo scalars with vector bosons

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big] \\
& - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W}\, \big(W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big] \Big\} X_0
\end{aligned}
$$

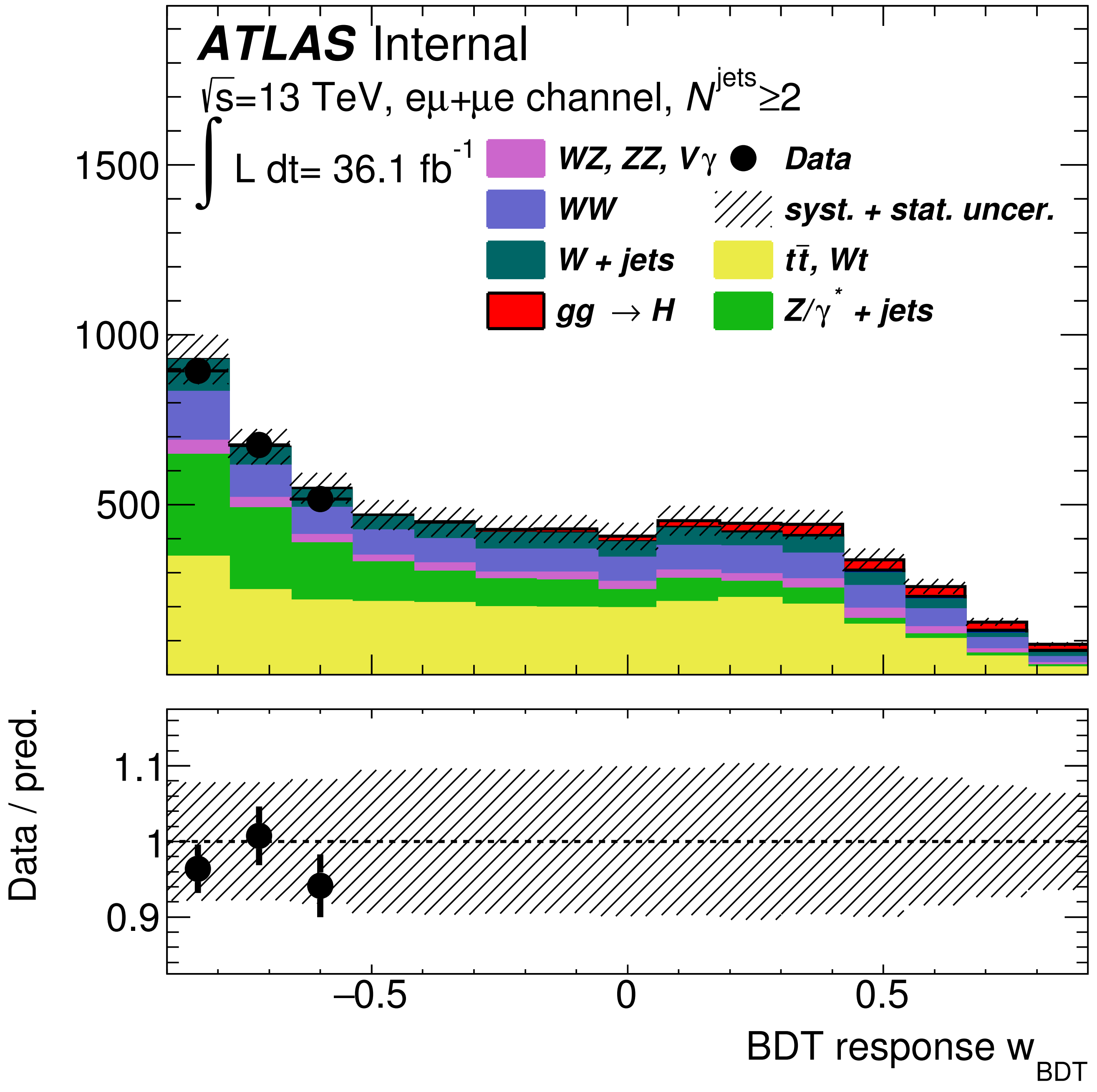
Boosted Decision Tree

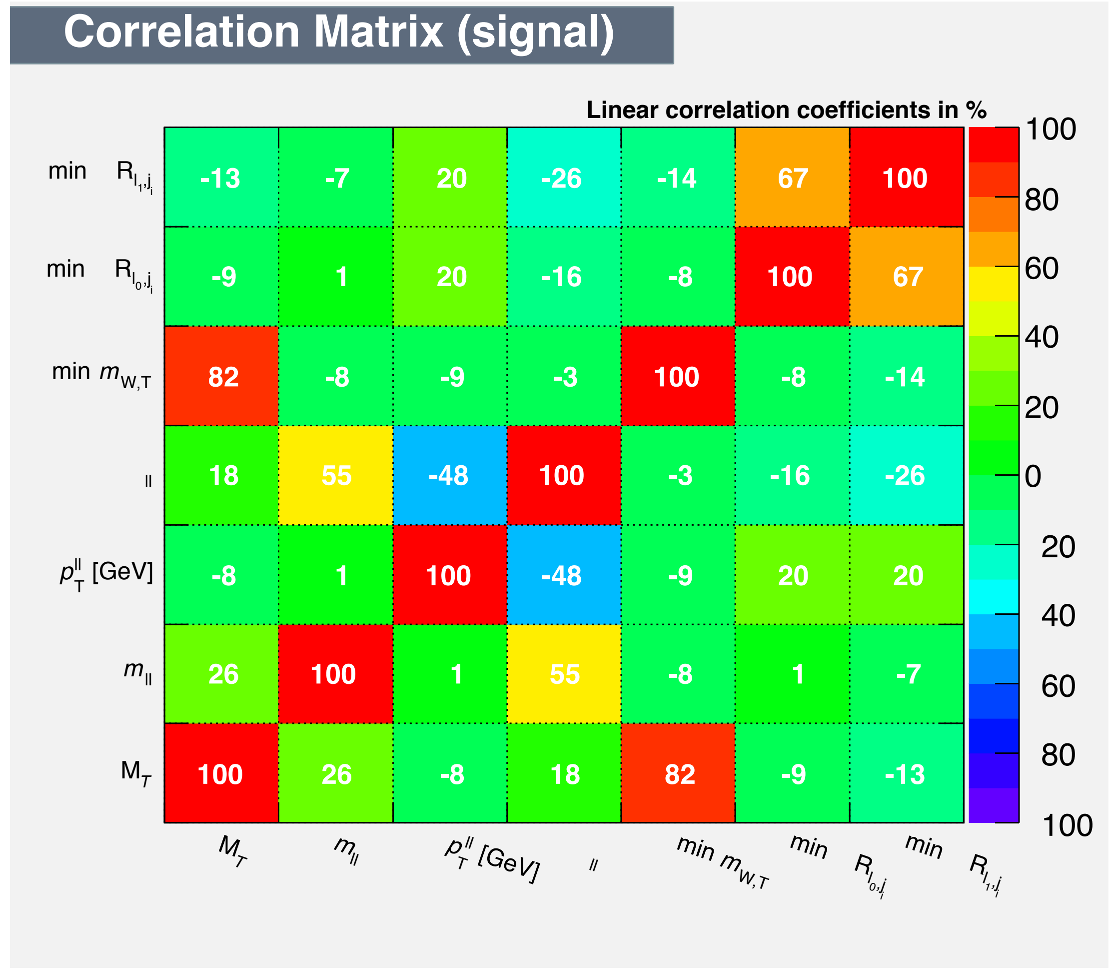
Nikhef

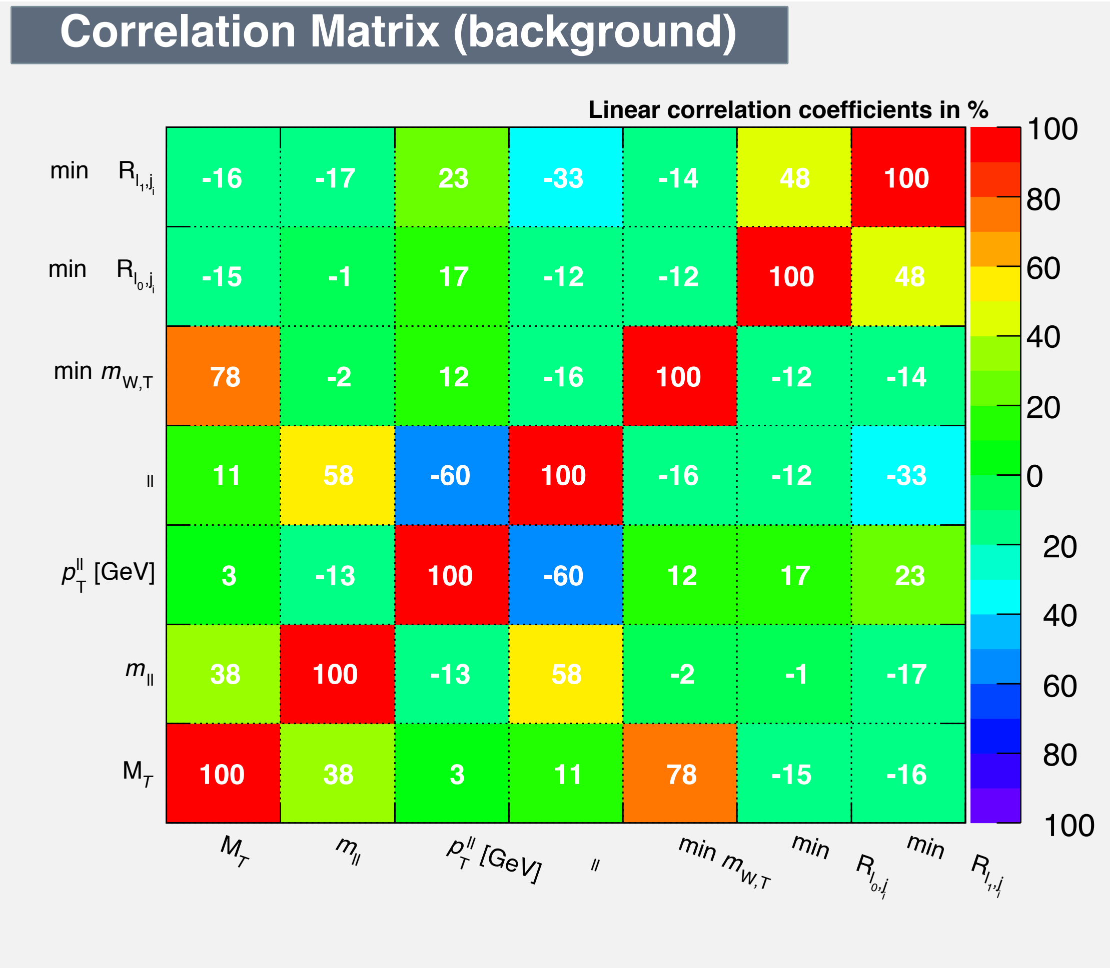
BDT Training

ggF SM vs. backgrounds

Variable name	Variable importance
$m_{\ell\ell}$	0.21
m_{T}	0.20
$\Delta\Phi_{\ell\ell}$	0.17
$\Delta R^{min.}_{\ell_2,j_i}$	0.14
$p_T^{\ell\ell}$	0.14
$\Delta R^{min.}_{\ell_1,j_i}$	0.13







Hypothesis Test

CP Measurements

Run 1: Measurement of HVV vertex

Run 2: Measurement of top-Yukawa coupling

Expected Run 2: $-0.64 < (\kappa_{Agg}/\kappa_{Hgg})\tan\alpha < 0.61$

Measured Run 2: Blinded

Expected Run 1: $-2.33 < (\kappa_{AVV}/\kappa_{SM})\tan\alpha < 2.30$

Measured Run1: $-2.18 < (\kappa_{AVV}/\kappa_{SM})\tan\alpha < 0.83$