Determination of spin and parity of the Higgs boson in the $WW^* \rightarrow e\nu\mu\nu$ decay channel with the ATLAS detector

Nikos Karastathis
NTUA, Nikhef

HEP2015
Athens, Greece

European Union
European Social Fund
OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS, CULTURE & SPORTS
MANAGING AUTHORITY
NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND
Co-financed by Greece and the European Union

Introduction

CERN-PH-EP-2015-075

- Newly discovered resonance at 125.09±0.21(stat.)±0.11(syst.) GeV :
  Determining the *spin* & CP → establish the nature of the boson : *Is it the (a) Standard Model Higgs or not?*

- Using ATLAS Run-I $\sqrt{s}$=8TeV data to test the SM ($J^{CP} = 0^{++}$) hypothesis vs alternative spin/CP models :

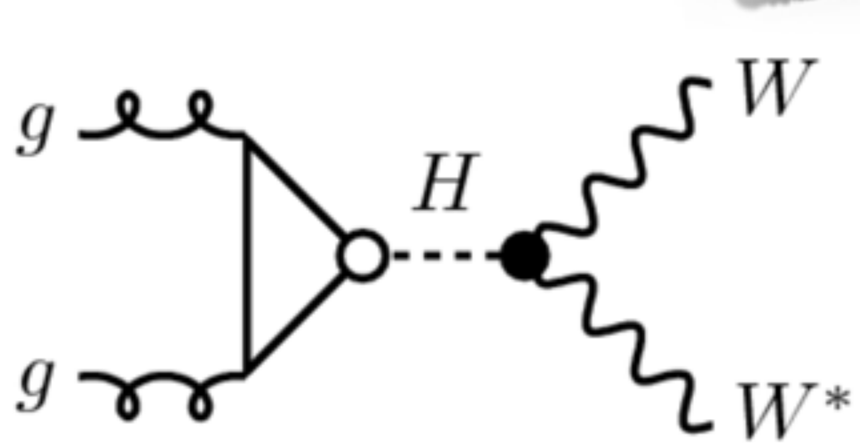
  - ***Spin Analysis***
    - Spin 2^{+} graviton-like model

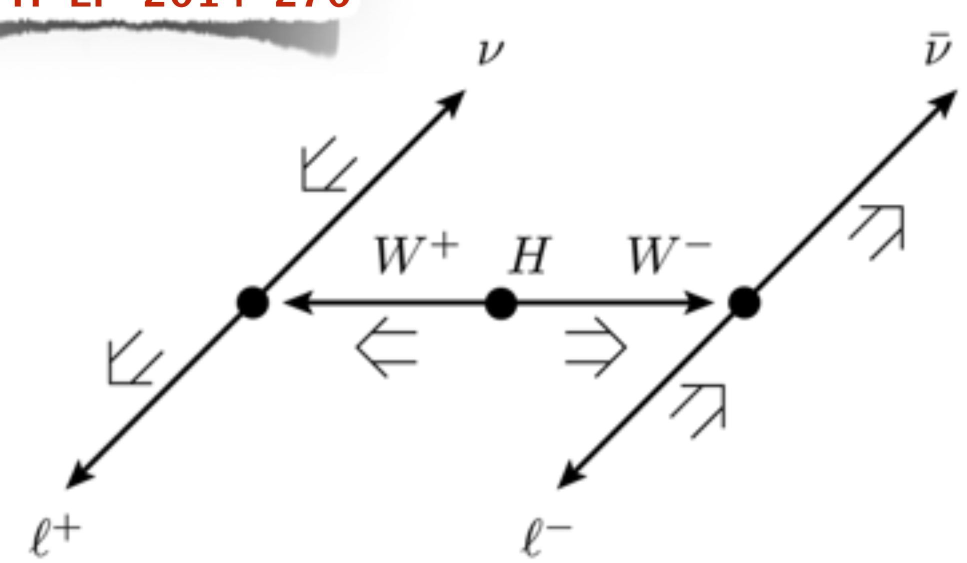
  - ***CP Analysis:***
    - Spin 0^{+-} BSM
    - Spin 0_h^{++} BSM
    - CP-Mixing :
      Implying CP violation in the Higgs sector → *Observed resonance is a mass, but not a CP eigenstate.*

Event Selection

- Share object definition, background estimates and some systematic uncertainties with the H→WW* couplings analysis
- Analysis restricted to the **<u>eνμν</u>** final state
  - 0 and 1 jet-bin for spin analysis
  - 0 jet-bin only for CP analysis

CERN-PH-EP-2014-270





(+ 1jet)

	Variable	Requirements
		Preselection
	N_{leptons}	Exactly 2 with $p_T > 10$ GeV, $e\mu$, opposite sign
	$p_T^{\ell_1}$	> 22 GeV
	$p_T^{\ell_2}$	> 15 GeV
	$m_{\ell\ell}$	> 10 GeV
	p_T^{miss}	> 20 GeV
		0-jet selection
DY	$p_T^{\ell\ell}$	> 20 GeV
WW	$m_{\ell\ell}$	< 80 GeV
DY	$\Delta\phi_{\ell\ell}$	< 2.8
non-U.C.	p_T^{H}	< 125 or 300 GeV (*)
		1-jet selection
top	b−veto	No b-jets with $p_T > 20$ GeV
Z/γ*→ττ	$m_{\tau\tau}$	$< m_Z - 25$ GeV
W+jets	m_T^{ℓ}	> 50 GeV
	$m_{\ell\ell}$	< 80 GeV
	$\Delta\phi_{\ell\ell}$	< 2.8
top WW	m_T	< 150 GeV
	p_T^{H}	< 125 or 300 GeV (*)

CERN-PH-EP-2015-037	N_{ggF}	N_{WW}	$N_{t\bar{t}}$	N_t	$N_{DY,\tau\tau}$	$N_{W+\text{jets}}$	N_{VV}	$N_{DY,SF}$	N_{bkg}	Data	Data/N_{bkg}
0j SR	218	2796	235	135	515	366	311	32	4390	4730	1.08 ± 0.02
1j SR:	77	555	267	103	228	123	131	5.8	1413	1569	1.11 ± 0.03
1j SR: $p_T^H < 300$ GeV	77	553	267	103	228	123	131	5.8	1411	1567	1.11 ± 0.03
1j SR: $p_T^H < 125$ GeV	76	530	259	101	224	121	128	5.8	1367	1511	1.11 ± 0.03

Spin Analysis

Theoretical Framework

- Effective Field Theory with a cut-off scale at Λ=1 TeV
  (Higgs Characterization Model within MadGraph5_aMC@NLO)

$$\mathcal{L}_2^p = \sum_{p=V,f} -\frac{1}{\Lambda}\kappa_p T_{\mu\nu}^p X_2^{\mu\nu}$$

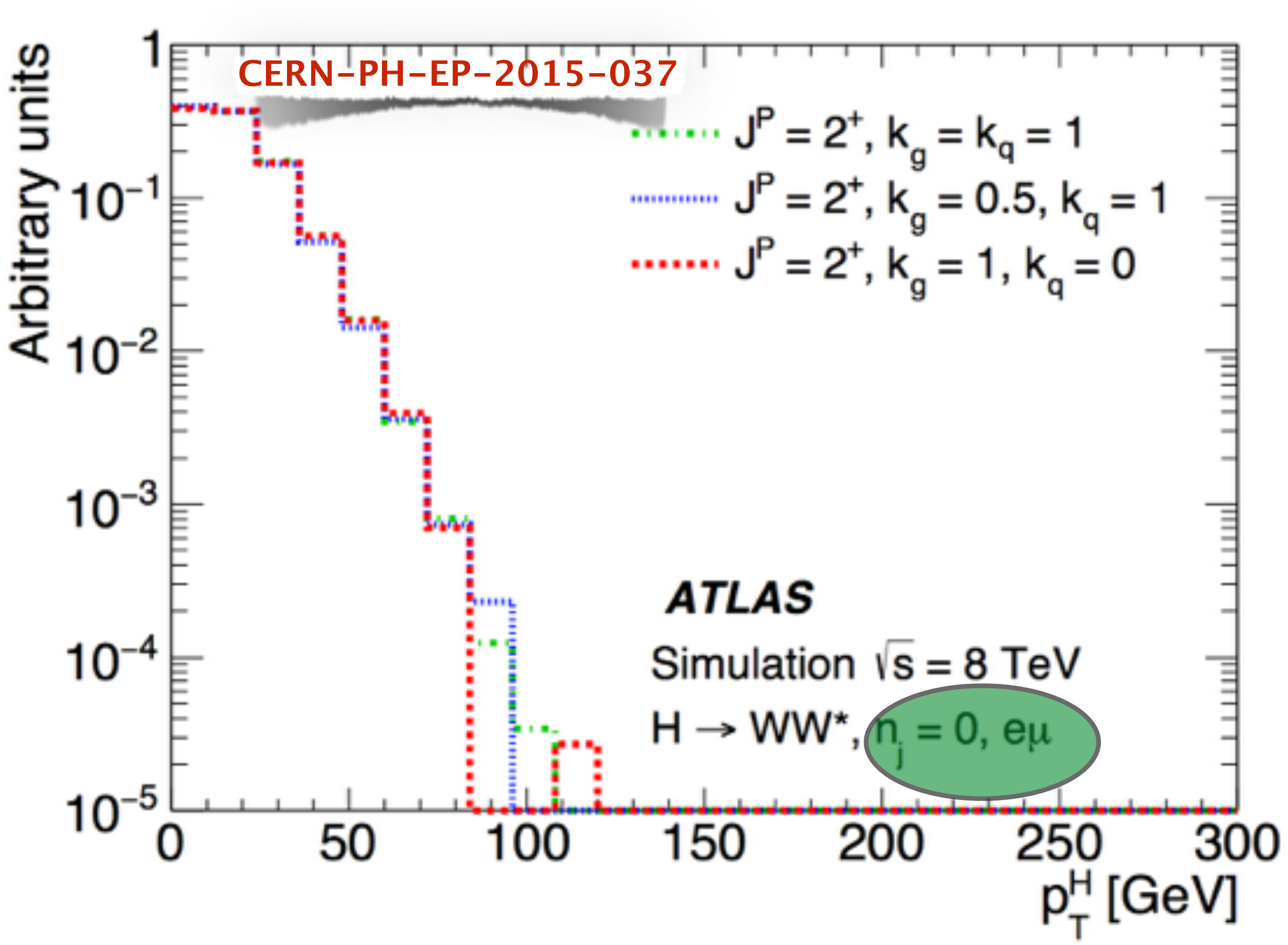
- Gravity is insensitive to the nature of other particle fields:
  - ➡ all κ-couplings should be equal (universal)
    - ✳ but observed BRs to gg, WW, ZZ not reproduced
  - still worth investigating
- need to consider benchmarks with non-universal couplings
  - ➡ cannot constrain $\kappa_g, \ \kappa_q$ separately with data→try various cases

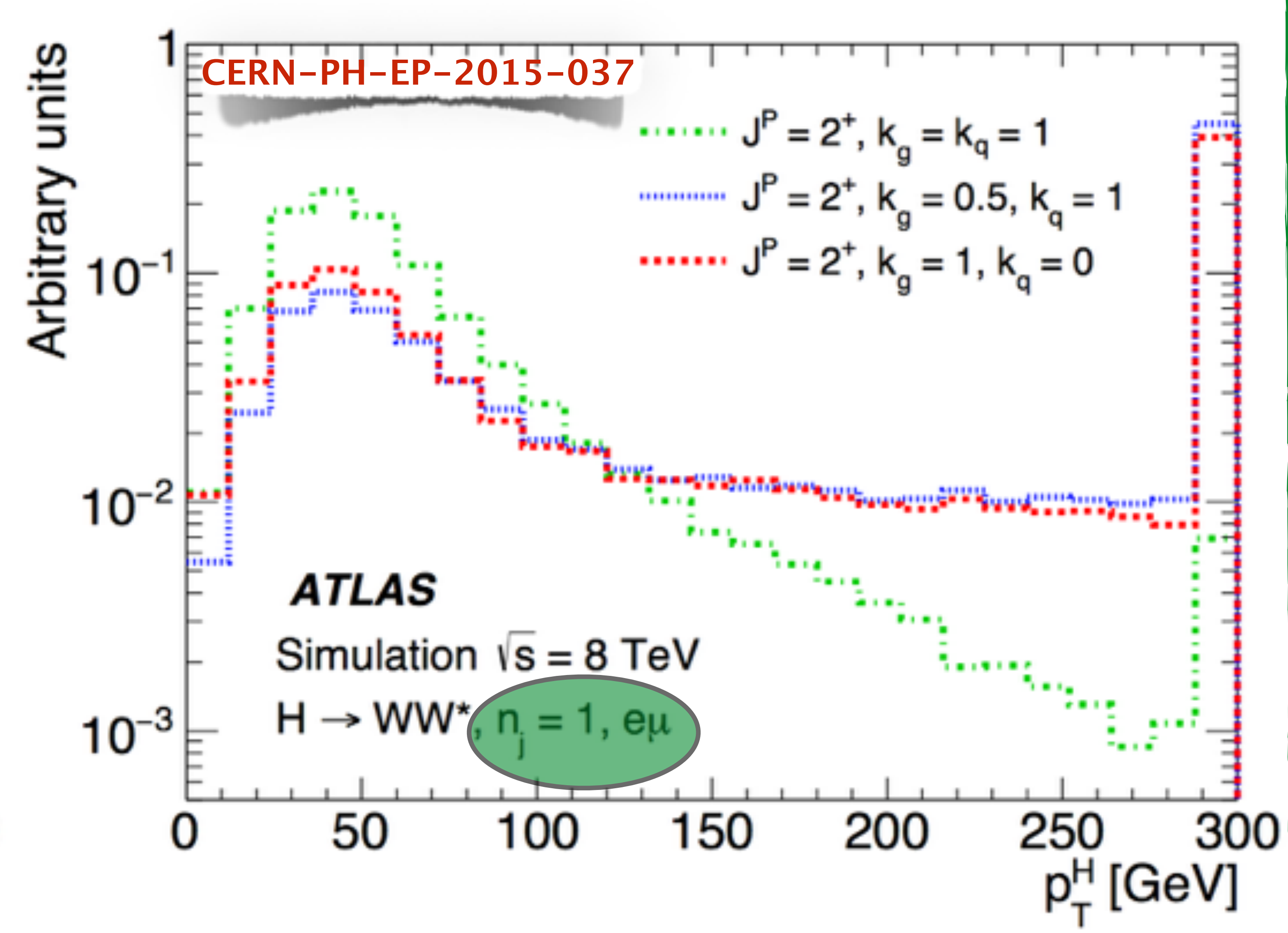
- Spin-2 Benchmarks (fixed-hypothesis test)
  - *universal couplings* (U.C.) $\kappa_g = \kappa_q$ (ggF 96% at LO)
  - *non-universal couplings:*

$\kappa_g = 0.5 \quad \kappa_q = 1$

$\kappa_g = 0 \quad \kappa_q = 1$

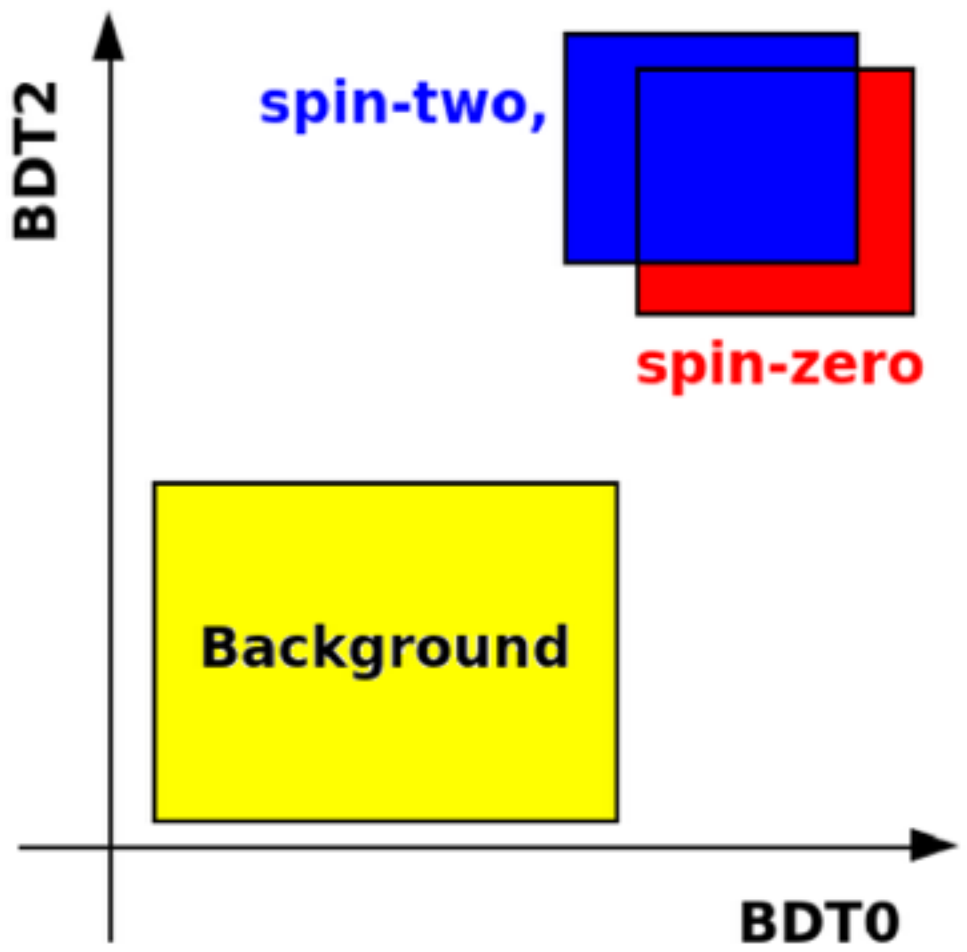
} $p_{\mathrm{T}}^{\mathrm{H}} < 125\ (300)\ GeV$





- NLO effects lead to a tail in $p_{\mathrm{T}}^{\mathrm{H}}$ when jets are in the final state
- Apply a selection on $p_{\mathrm{T}}^{\mathrm{H}}$ to preserve unitarity

Analysis Strategy

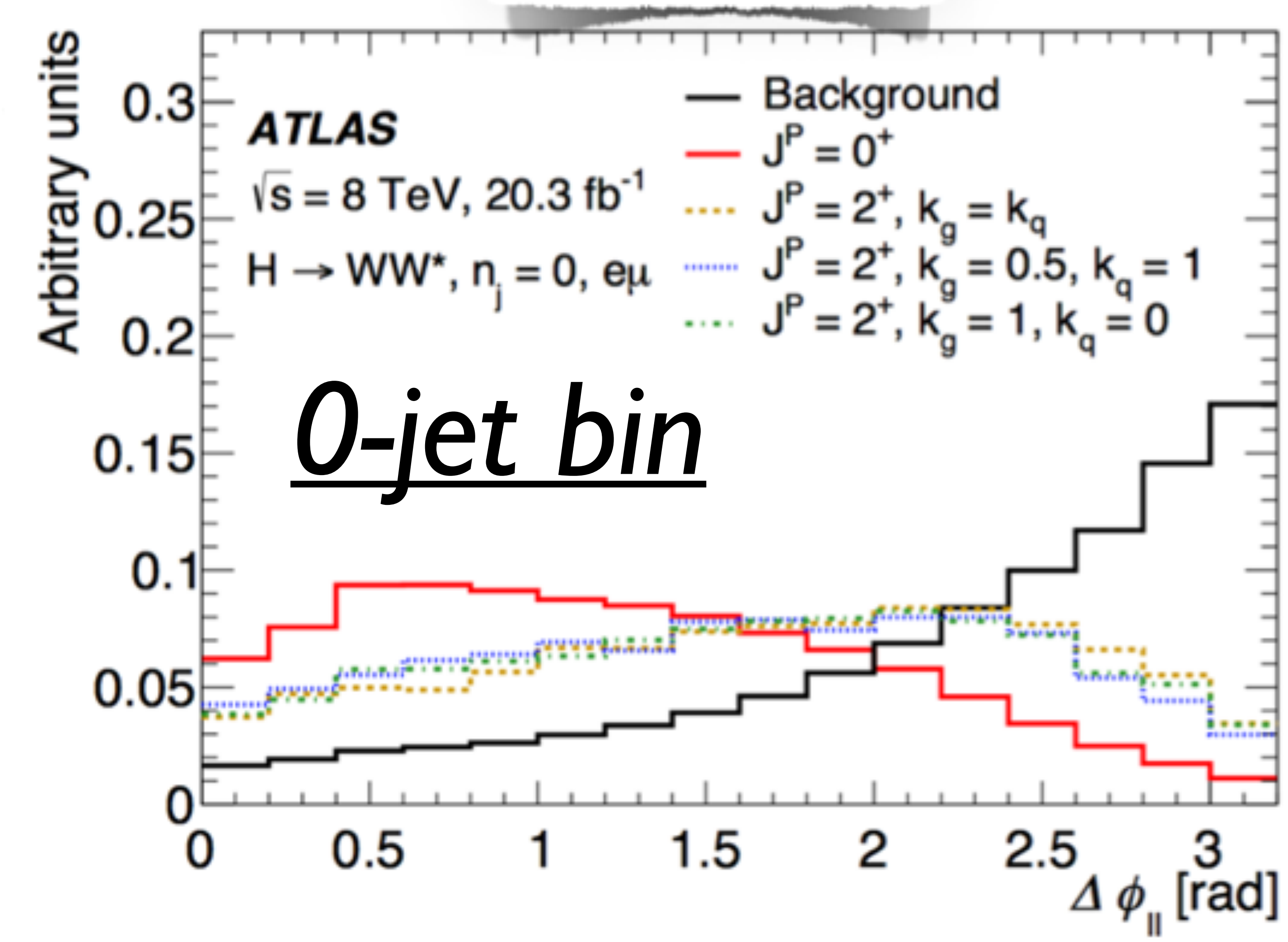


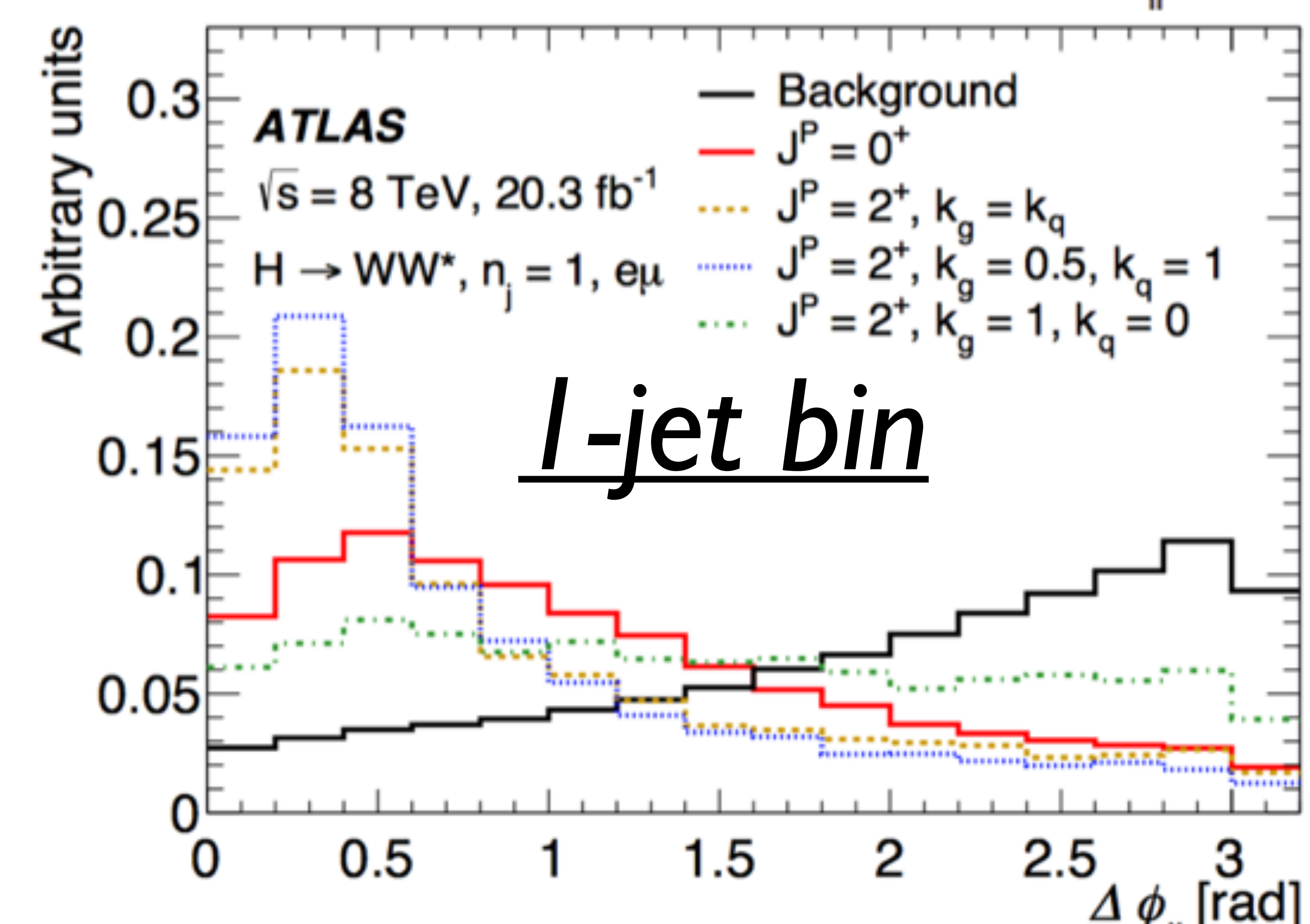
- Exploiting *shape* and **correlation** variations with BDT analysis.

- Build two BDTs : $m(\ell\ell)$, $\Delta\phi^{\ell\ell}$, $p_T^{\ell\ell}$, m_T
  - **BDT0:** Trained with the SM signal vs SM backgrounds
  - **BDT2:** Trained with the spin-2 signal vs SM backgrounds

- Combine the BDT responses in a 2D space

CERN-PH-EP-2015-037

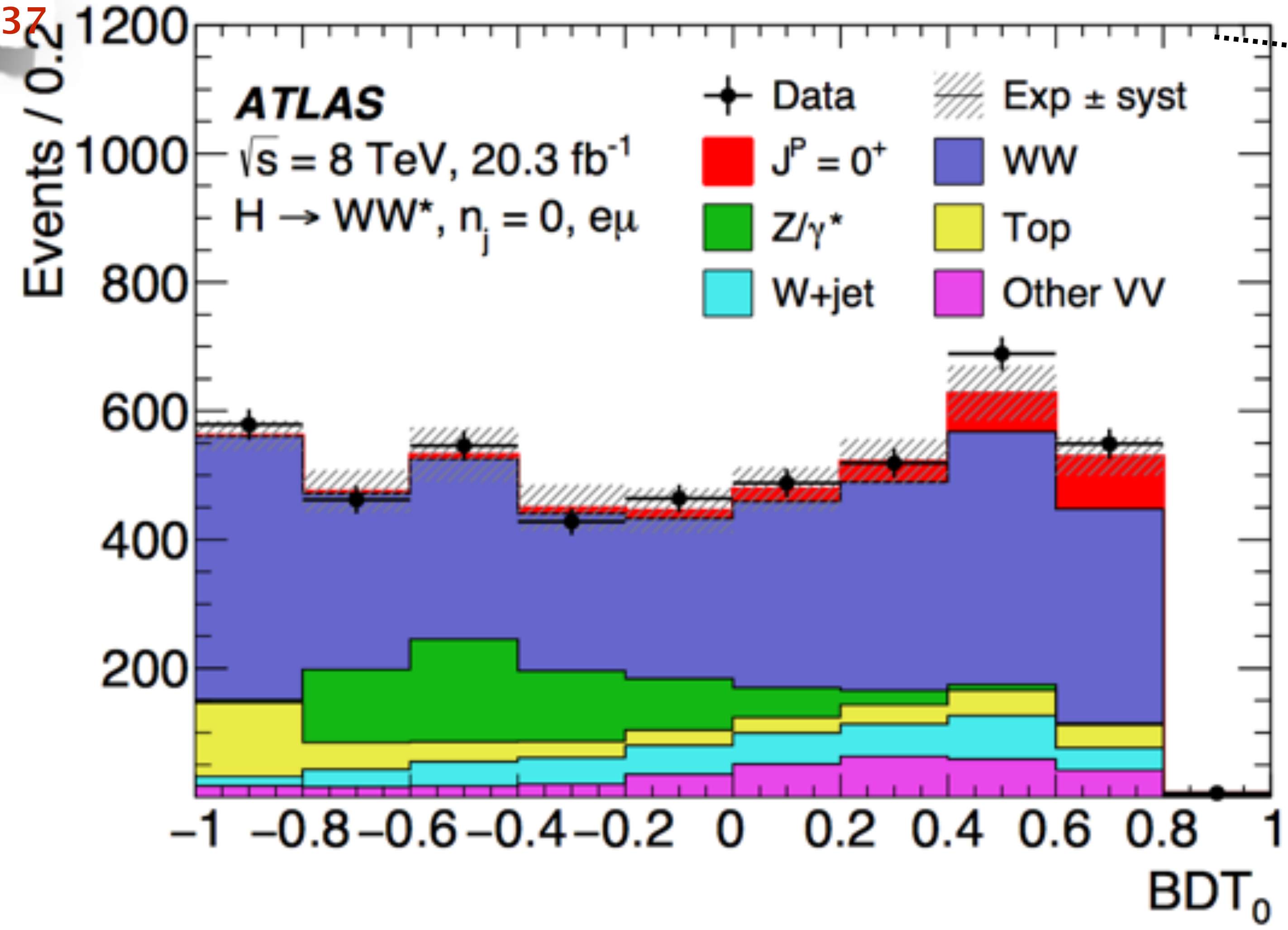


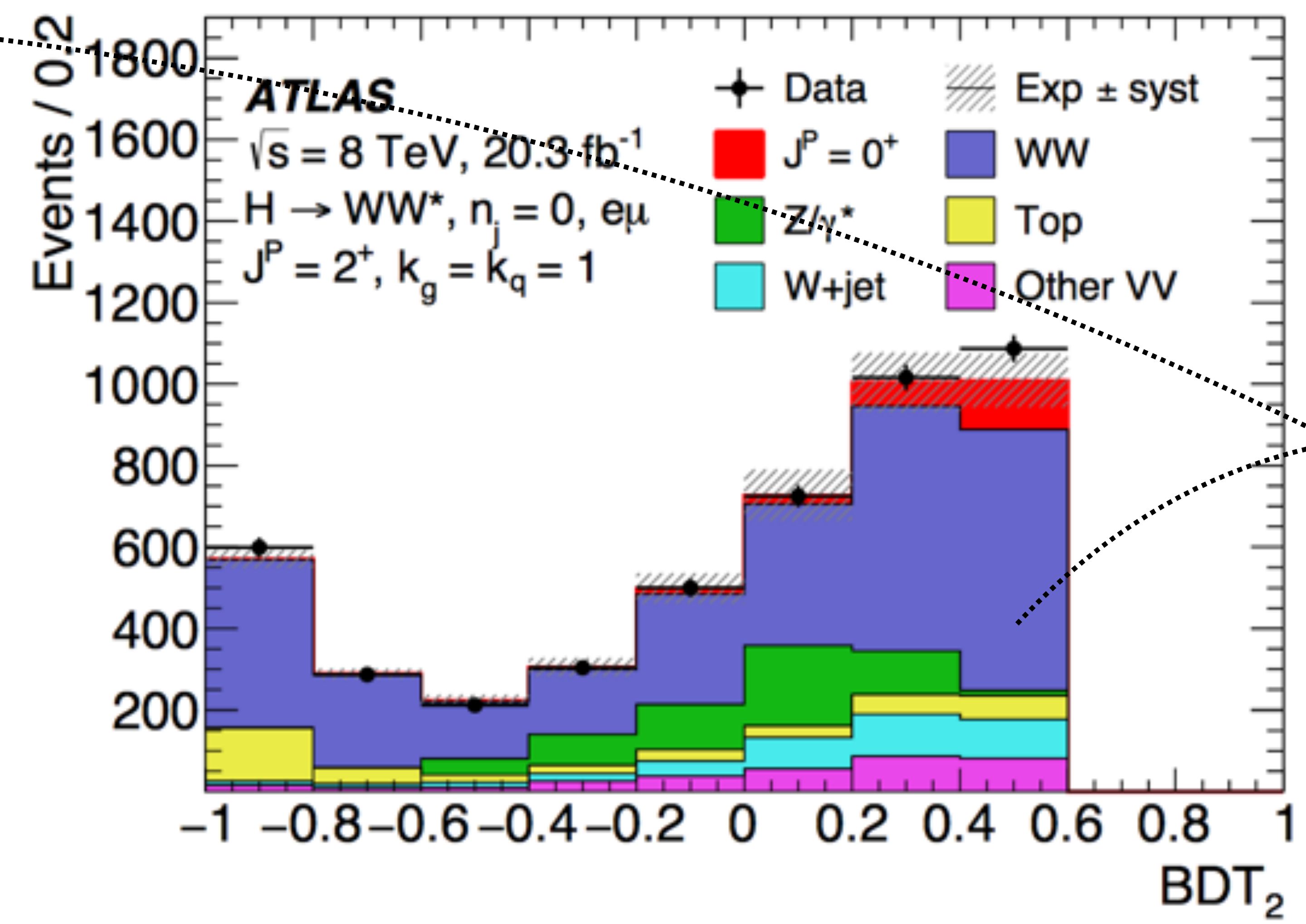


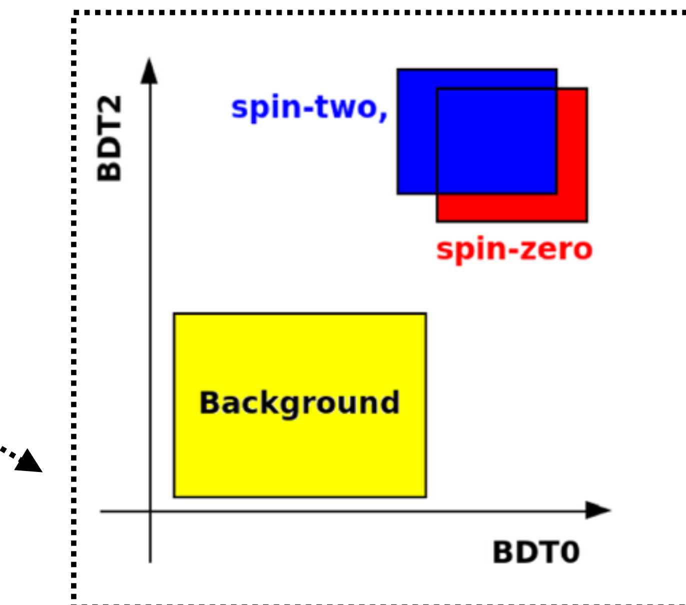
BDT Response: Univ. Couplings

CERN-PH-EP-2015-037

0-jet

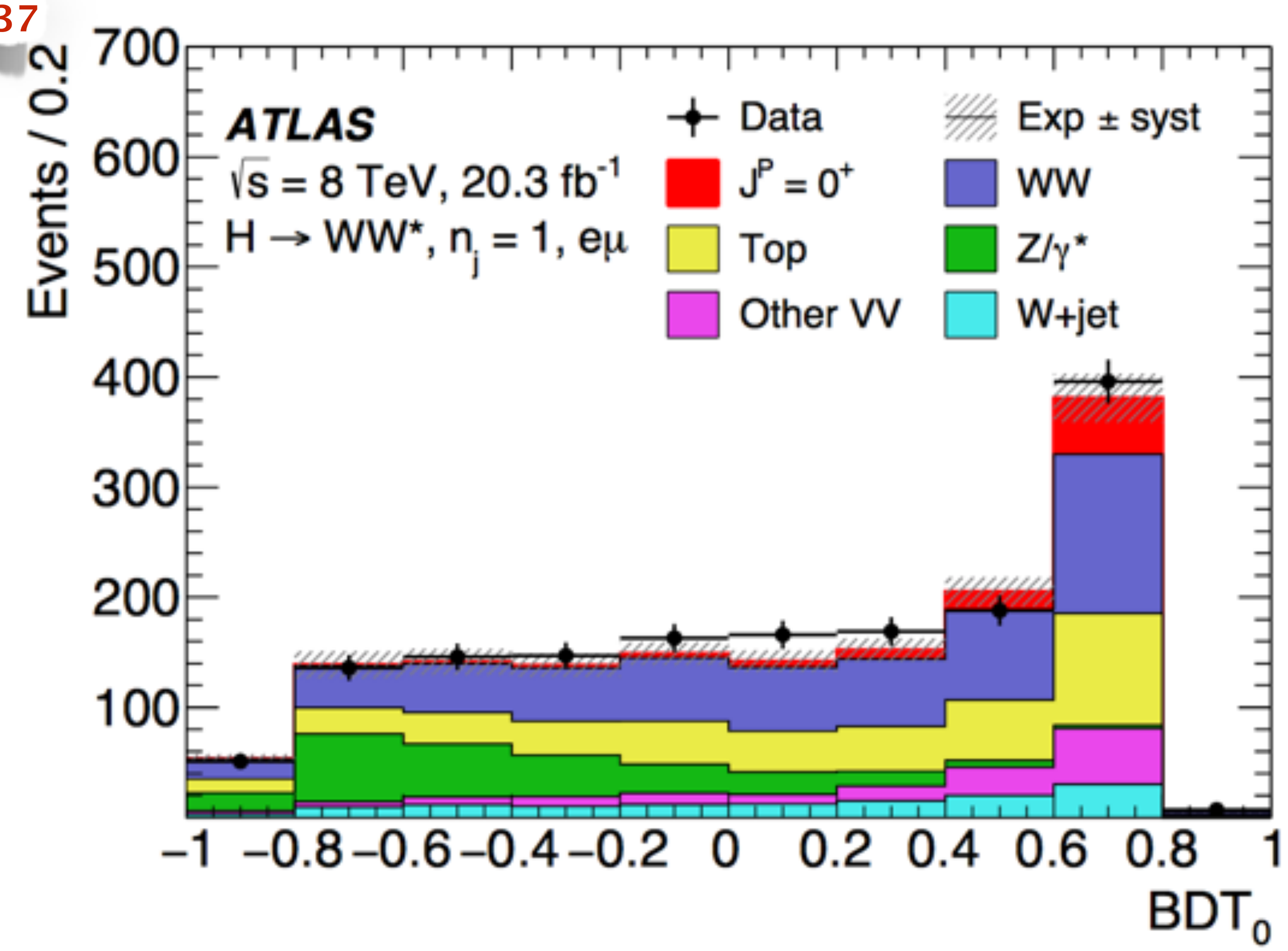


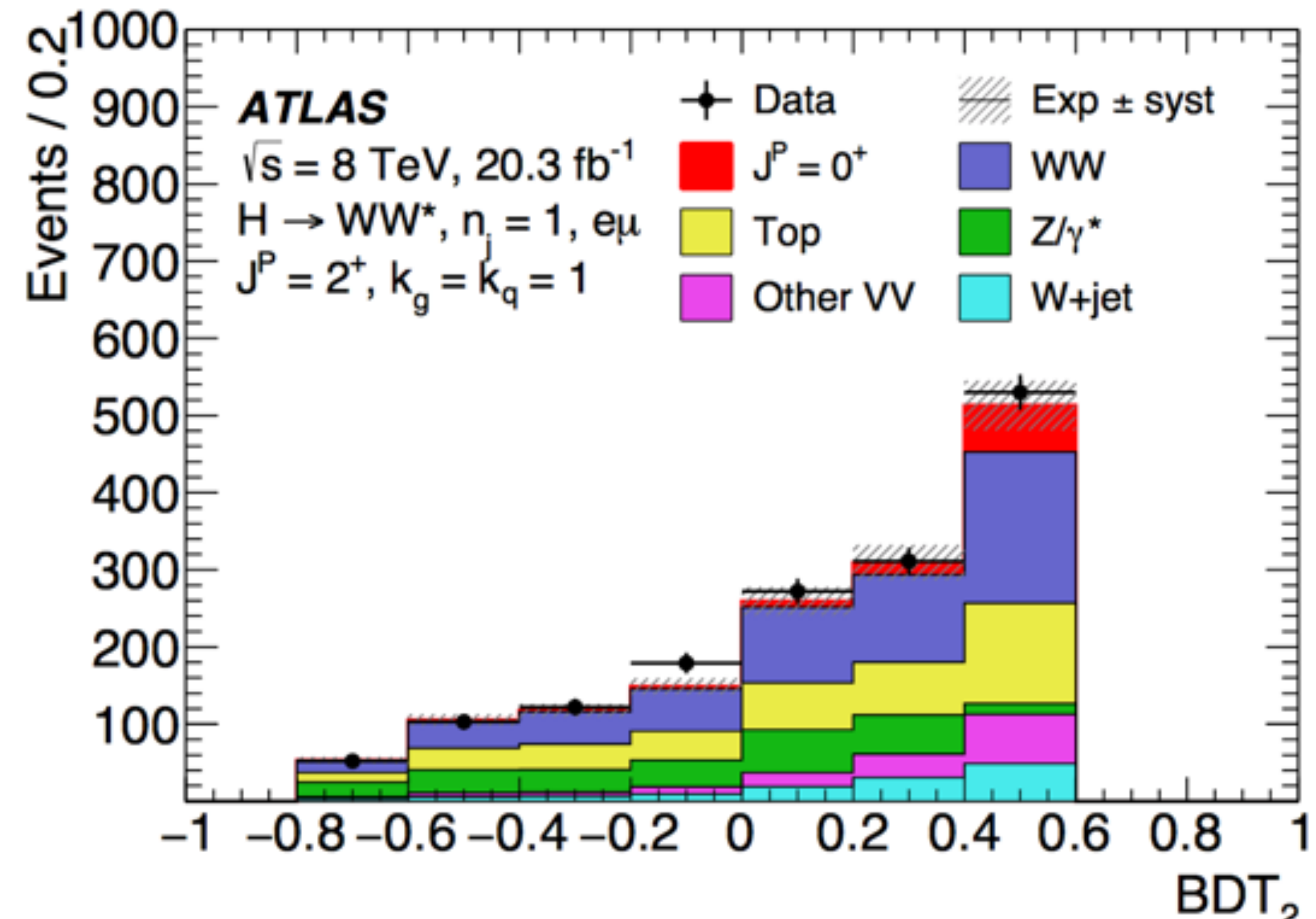




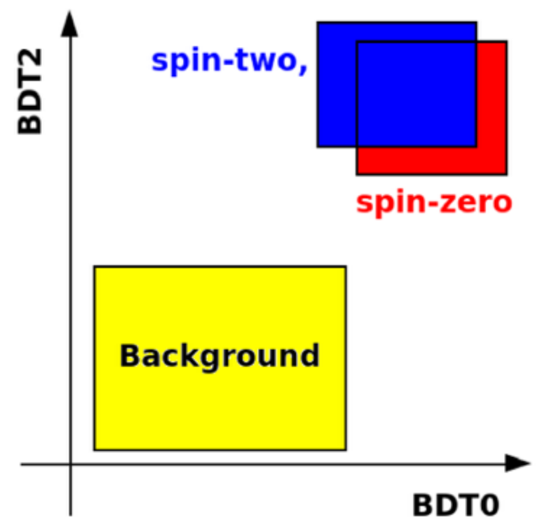
CERN-PH-EP-2015-037

1-jet





Statistical Interpretation



- The 2D space created out of the two BDTs is then **unrolled** row-by-row in a 1D distribution
- This unrolled 1D distribution is used for the fit.

- *For the fit of the fixed hypothesis tests:*
  - Binned likelihood with P.O.I. **ε**, *the fraction of SM events with respect to the expected.*
  - Template histograms for nominal signal and background rates construct the likelihood, while systematic uncertainties are treated as nuisance parameters

$$\mathcal{L}(\varepsilon, \mu, \boldsymbol{\theta}) = \prod_i^{N_{\text{bins}}} P(N_i | \mu(\varepsilon\, S_{\text{SM},i}(\boldsymbol{\theta}) + (1-\varepsilon)\, S_{\text{ALT},i}(\boldsymbol{\theta})) + B_i(\boldsymbol{\theta})) \times \prod_i^{N_{\text{sys}}} \mathcal{A}(\tilde{\theta}_i | \theta_i)$$

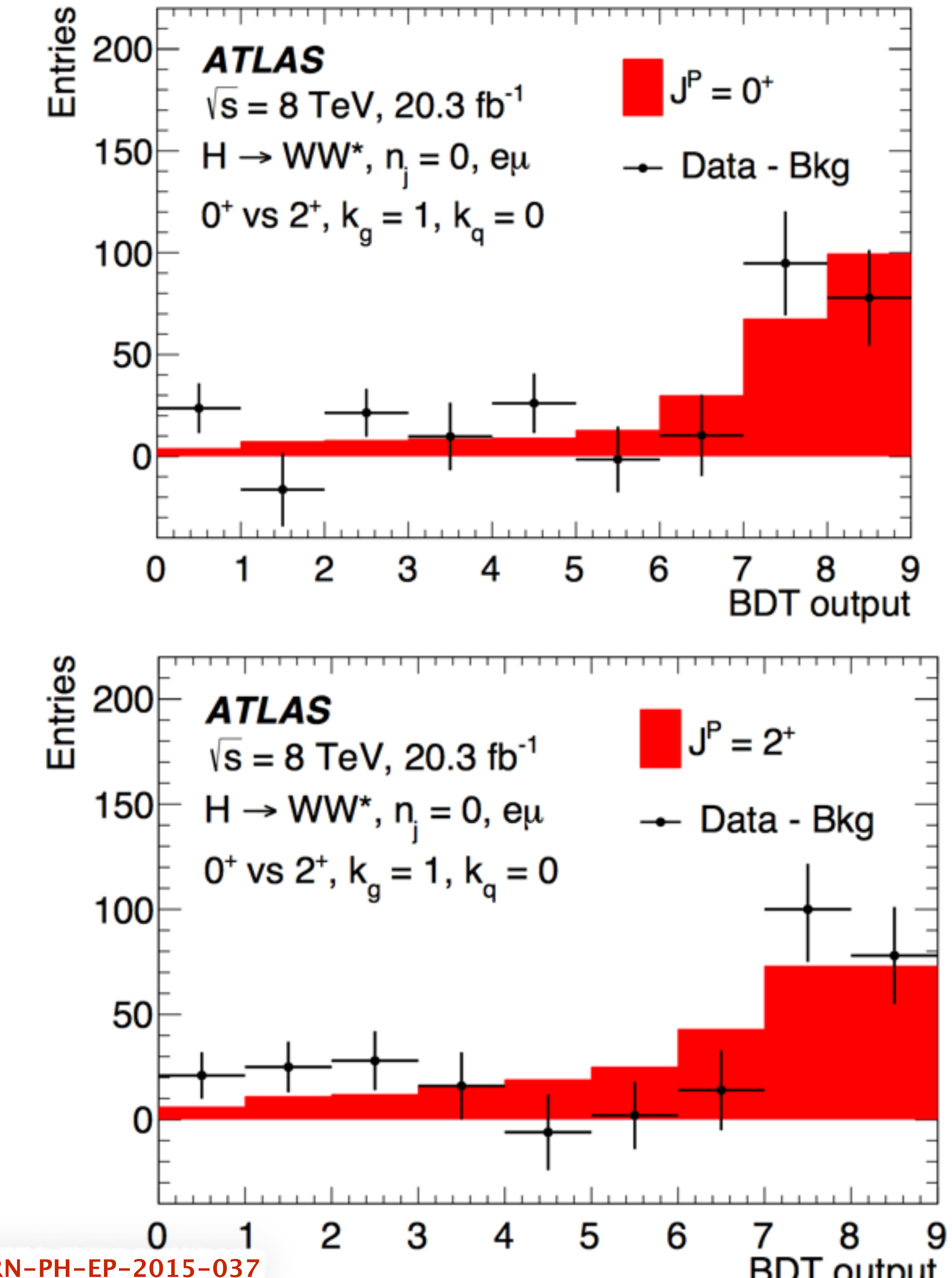
  - The compatibility with the data is estimated with the statistic test

$$q = \ln \frac{\mathcal{L}(\varepsilon = 1, \hat{\hat{\mu}}_{\varepsilon=1}, \hat{\hat{\boldsymbol{\theta}}}_{\varepsilon=1})}{\mathcal{L}(\varepsilon = 0, \hat{\hat{\mu}}_{\varepsilon=0}, \hat{\hat{\boldsymbol{\theta}}}_{\varepsilon=0})} \qquad \text{CL}_s = \frac{p_{\text{obs}}^{\text{ALT}}}{1 - p_{\text{obs}}^{\text{SM}}}$$

and pseudo-experiments are used to calculate the *p0*-values and the CLs

Spin Results

Channel	$p^{SM}_{exp,\ \mu=1}$	$p^{SM}_{exp,\ \mu=\hat{\mu}}$	$p^{ALT}_{exp,\ \mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	$1 - CL_s$
Spin-2, $\kappa_g = \kappa_q$						
0+1-jet	0.131	0.039	0.033	0.246	0.117	84.5%
Spin-2, $\kappa_g = 0.5$, $\kappa_q = 1$, $p_T^H < 125$ GeV						
0+1-jet	0.105	0.047	0.022	0.685	0.007	97.8%
Spin-2, $\kappa_g = 0.5$, $\kappa_q = 1$, $p_T^H < 300$ GeV						
0+1-jet	0.023	0.014	0.004	0.524	0.003	99.3%
Spin-2, $\kappa_g = 1$, $\kappa_q = 0$, $p_T^H < 125$ GeV						
0+1-jet	0.109	0.041	0.029	0.421	0.044	92.5%
Spin-2, $\kappa_g = 1$, $\kappa_q = 0$, $p_T^H < 300$ GeV						
0+1-jet	0.015	0.016	0.004	0.552	0.003	99.4%



CERN-PH-EP-2015-037

CP Analysis

Theoretical Framework

$$\mathcal{L}_0^W = \left\{ c_\alpha \kappa_{SM} \left[\frac{1}{2} g_{HWW} W_\mu^+ W^{-\mu} \right] - \frac{1}{2}\frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu} \right] \right\} X_0$$

SM: $\kappa_{SM} = 1,\ \kappa_{HWW} = \kappa_{AWW} = 0,\ c_\alpha = 1$

BSM CP-Even: $\kappa_{SM} = 0,\ \kappa_{HWW} = 1,\ \kappa_{AWW} = 0,\ c_\alpha = 1$

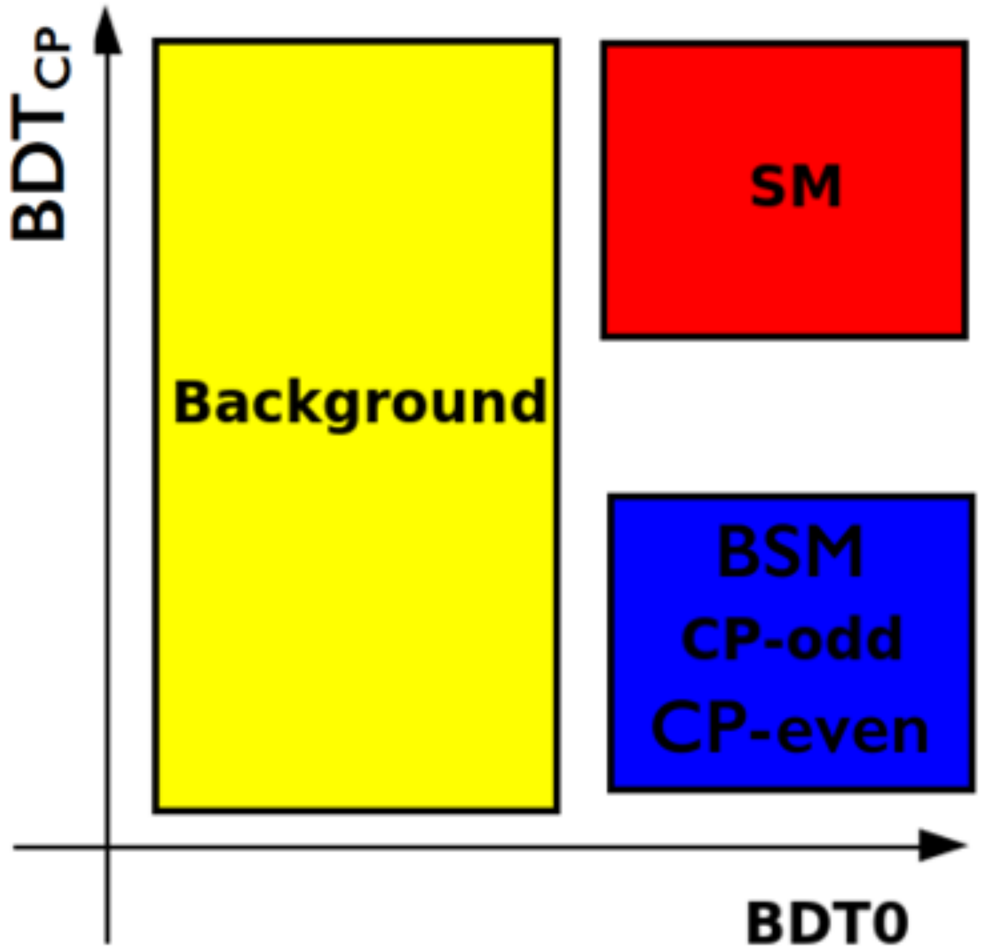
BSM CP-Odd: $\kappa_{SM} = 0,\ \kappa_{HWW} = 0,\ \kappa_{AWW} = 1,\ c_\alpha = 0$

1. ***Fixed Hypothesis Tests:***
   - SM *vs* pure CP-Odd & SM *vs* pure CP-Even

2. ***BSM CP-Even Scan*** : Scan on $\frac{\tilde{\kappa}_{HWW}}{\kappa_{SM}}$ where $\tilde{\kappa}_{HWW} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HWW}$
3. ***BSM CP-Odd Scan*** : Scan on $\frac{\tilde{\kappa}_{AWW}}{\kappa_{SM}} \tan\alpha$ where $\tilde{\kappa}_{AWW} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AWW}$

} *CP Mixed States*

Analysis Strategy



- <u>We build 2 BDT's:</u>
  - *BDT0:* Same as for spin
  - *BDTCP:* Trained with the SM signal vs the ALTernative signal
    No backgrounds in the training
- *Inputs for the BDTCP :*
  - *CP-Even* ($m_{\ell\ell},\ \Delta\phi_{\ell\ell},\ p_{\mathrm{T}}^{\ell\ell},\ p_{\mathrm{T}}^{\mathrm{miss}}$)
  - *CP-Odd* ($m_{\ell\ell},\ \Delta\phi_{\ell\ell},\ E_{\ell\ell\nu\nu},\ \Delta p_{\mathrm{T}}$)

$$\Delta p_{\mathrm{T}} = |p_{\mathrm{T}}^{\ell_1} - p_{\mathrm{T}}^{\ell_2}|$$

$$E_{\ell\ell\nu\nu} = p_{\mathrm{T}}^{\ell_1} - 0.5 p_{\mathrm{T}}^{\ell_2} + 0.5 p_{\mathrm{T}}^{\mathrm{miss}}$$

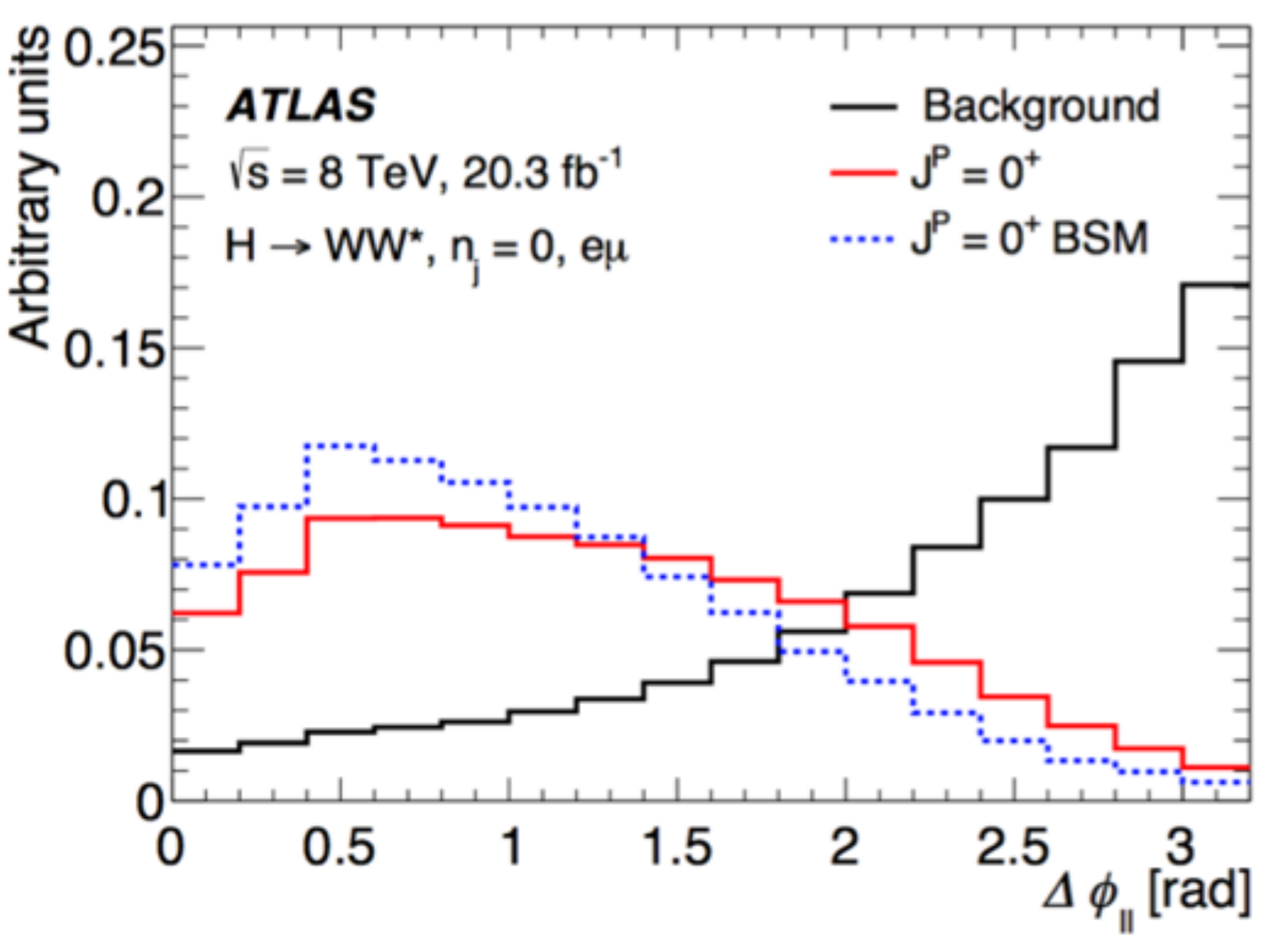
- *Training is performed only on the pure CP cases - no retraining on the mixed signal hypotheses*

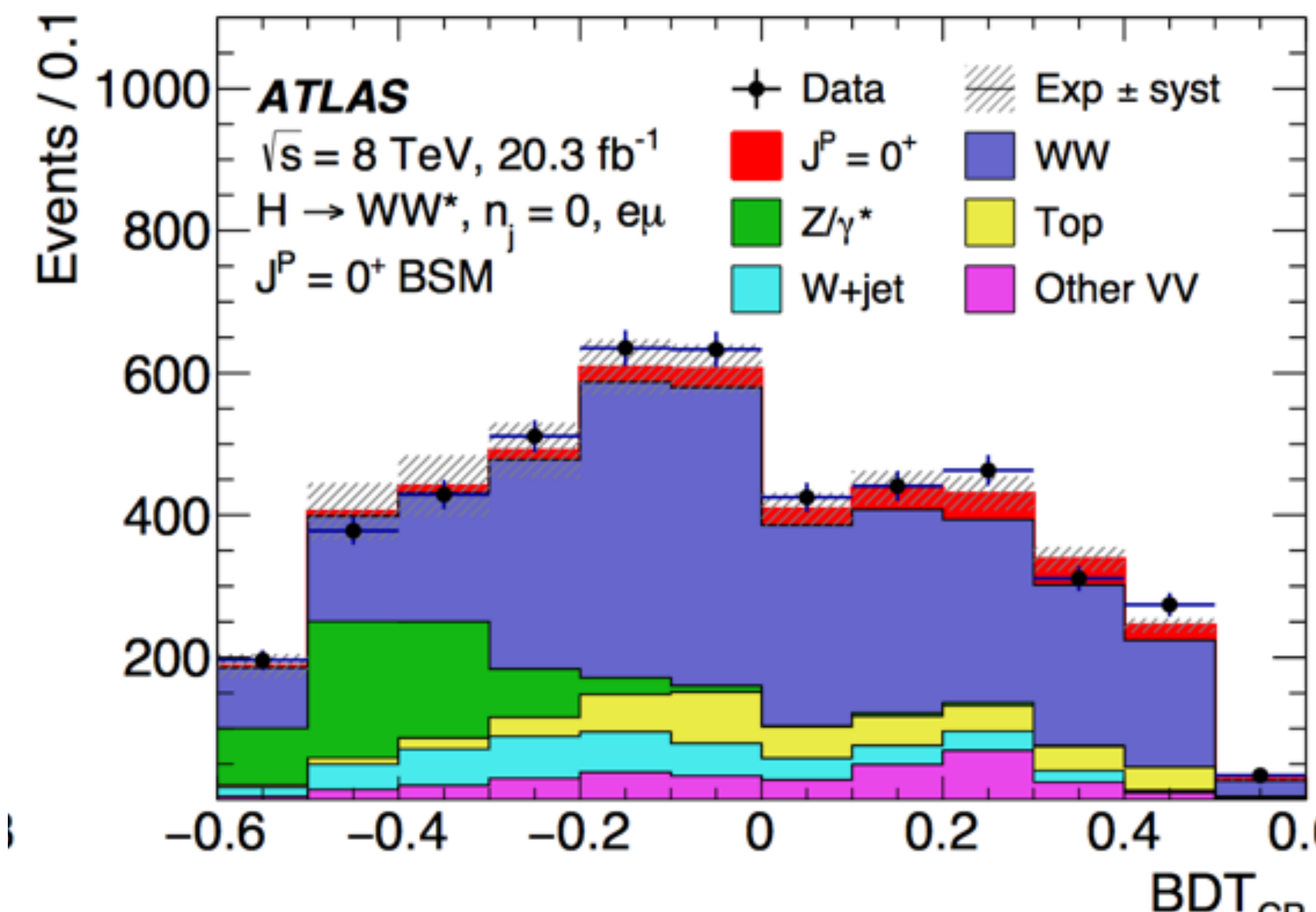
- The statistical treatment for the fixed hypothesis test is the same as for spin where now the POI ε corresponds to CP
- For the CP Mixing scans:
  - the likelihood definition is the **same**
  - **the asymptotic approximation** is used and the results are given as -2ΔLL vs the scan parameter

Input Shapes & BDT Responses

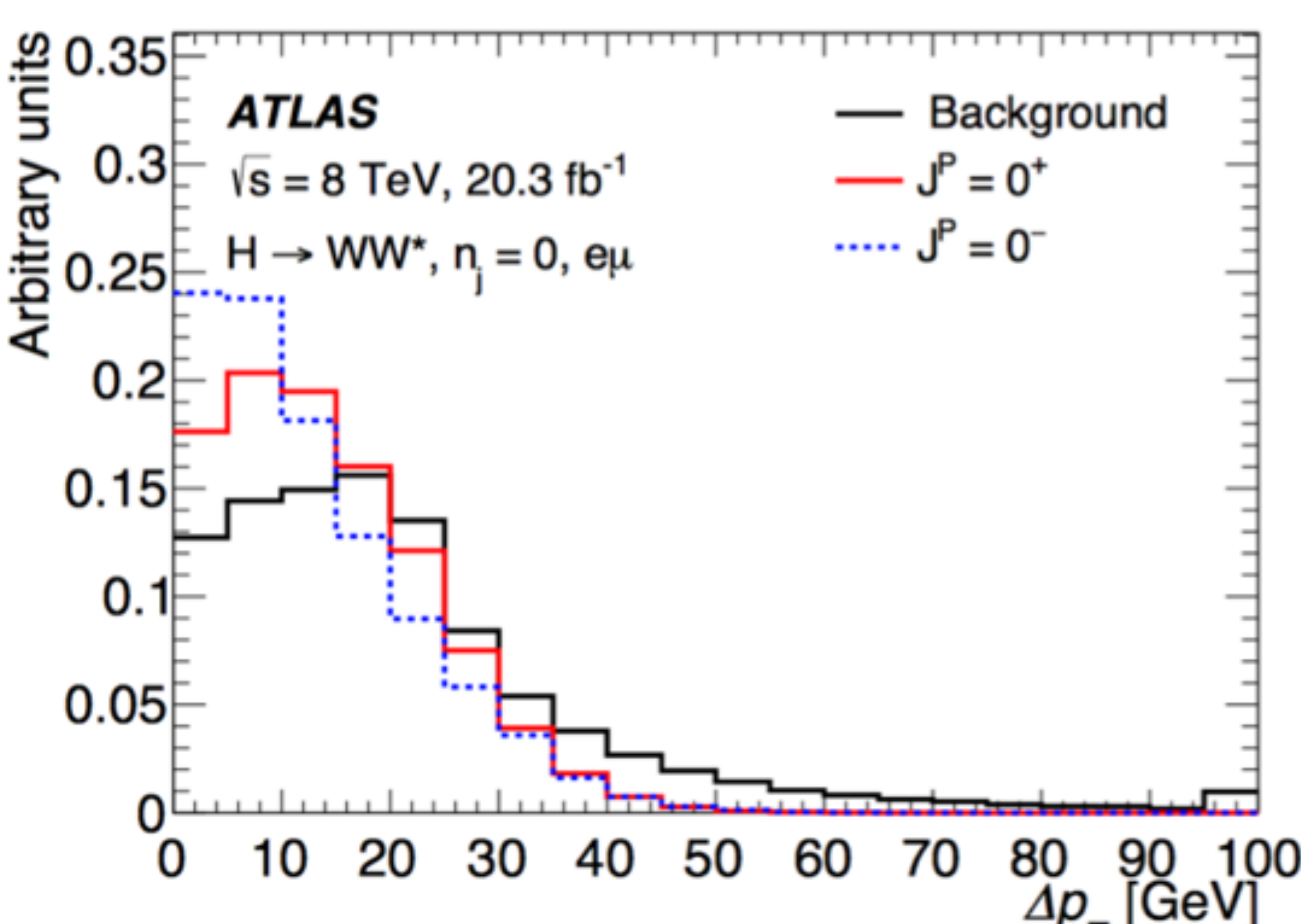
CERN-PH-EP-2015-037

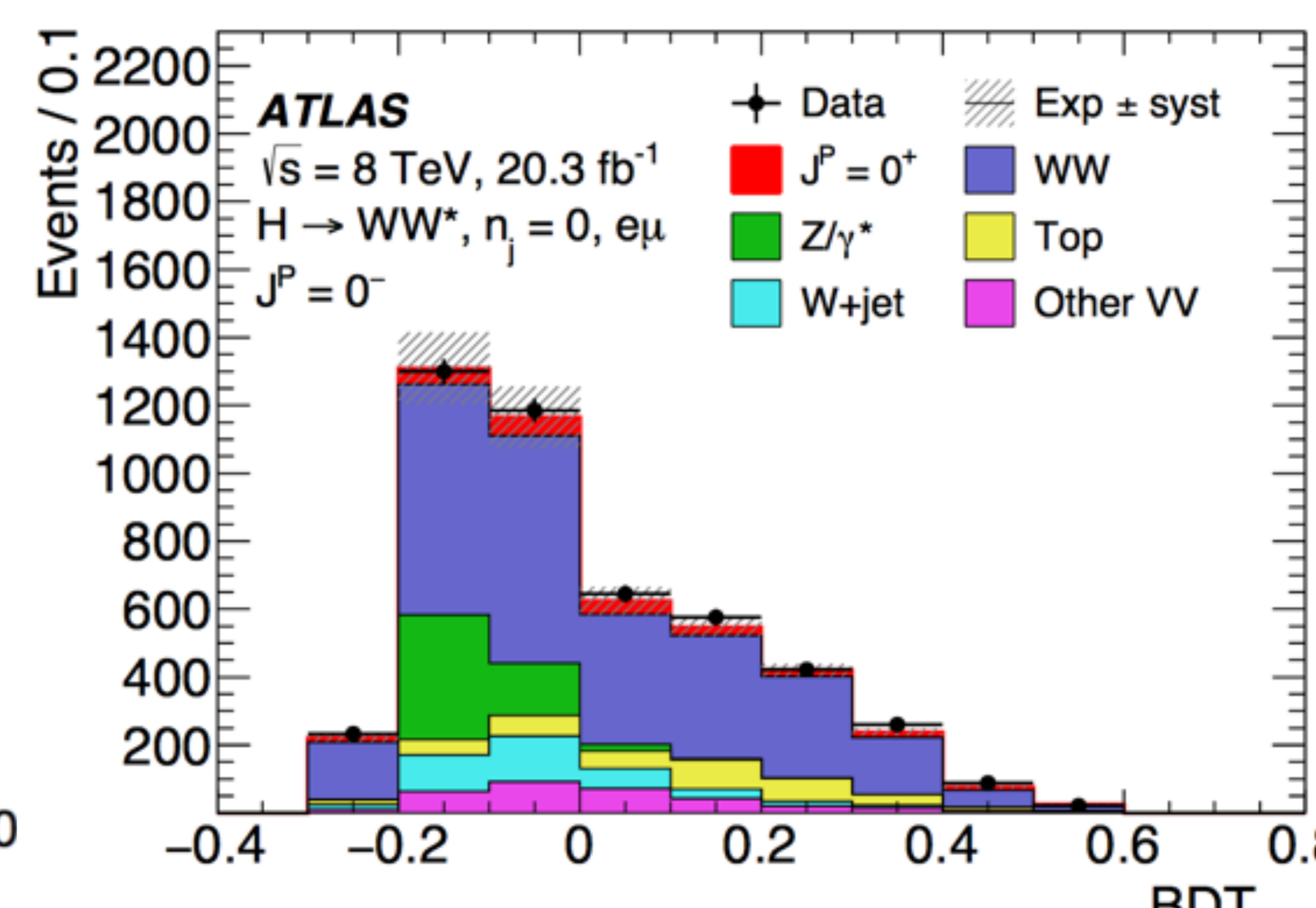
CP Even





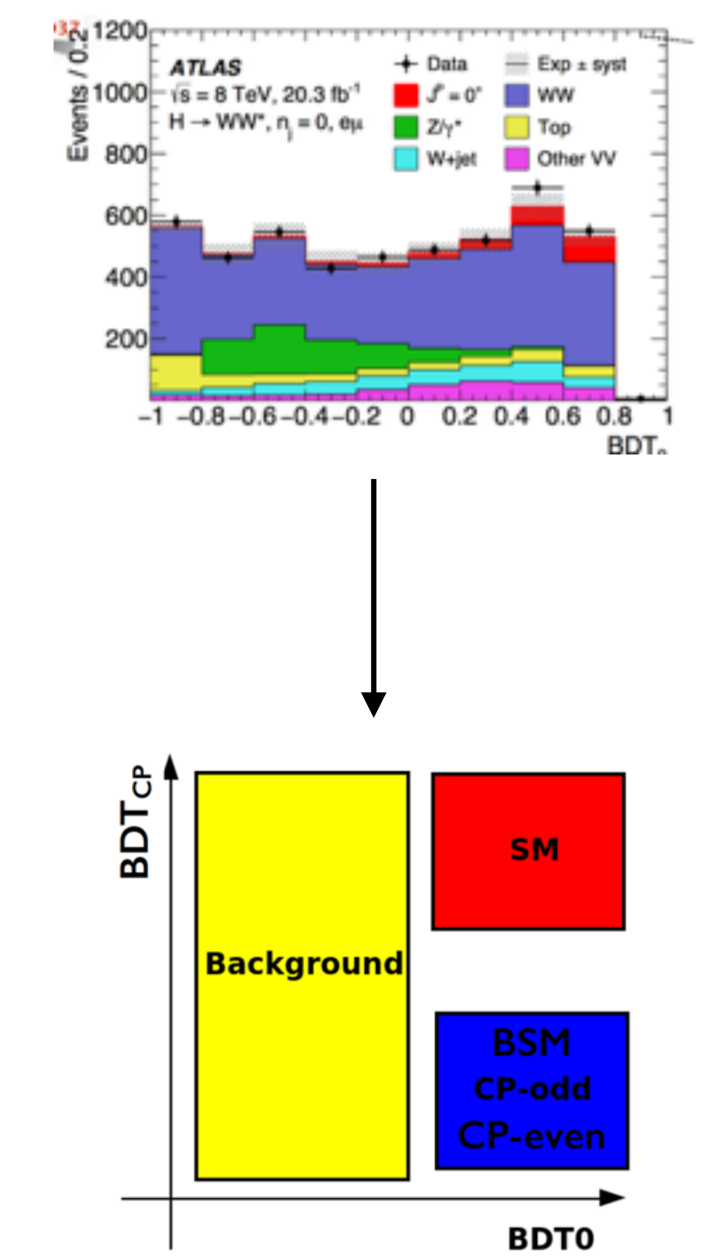
CP Odd





for each

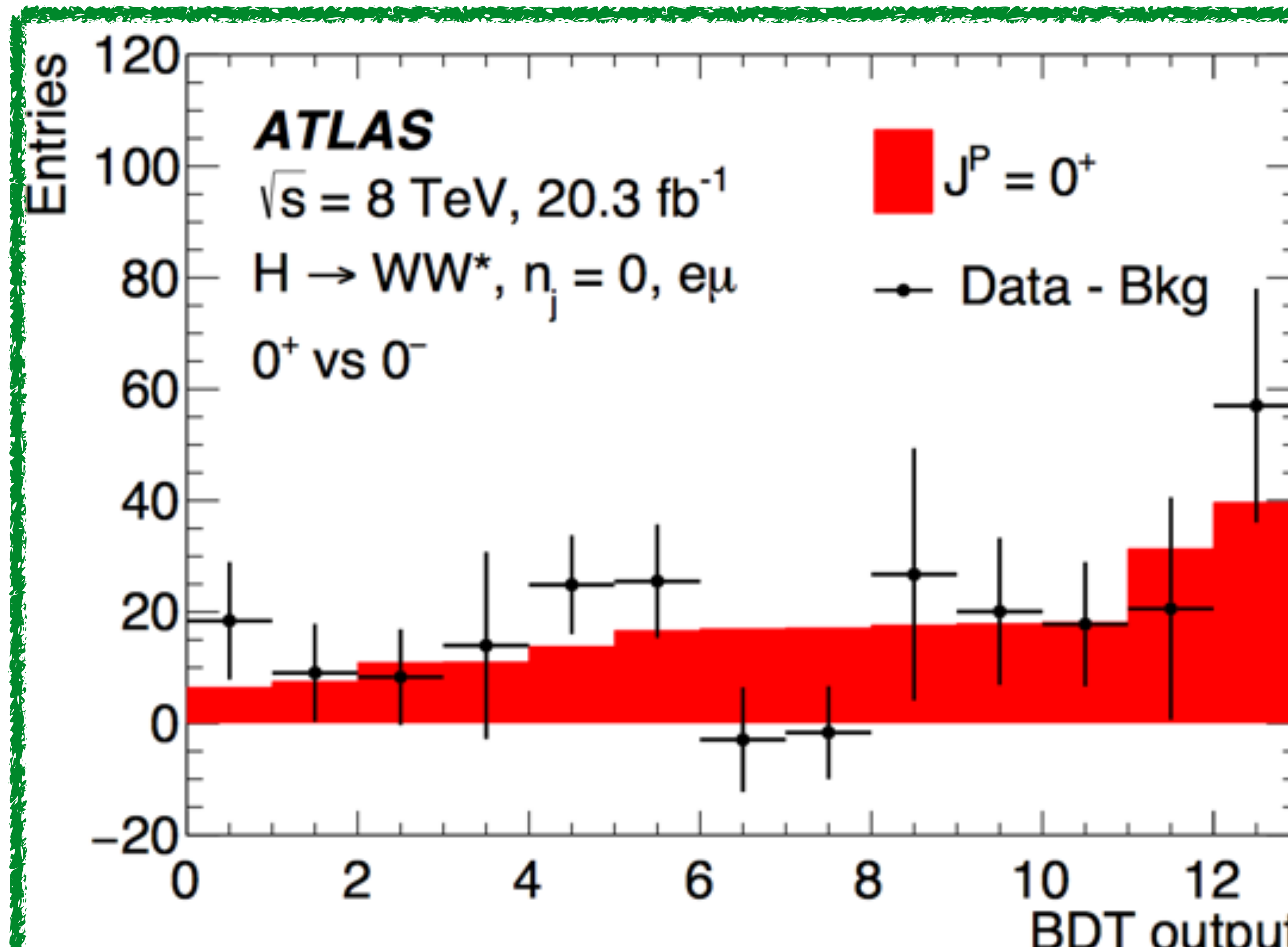
+

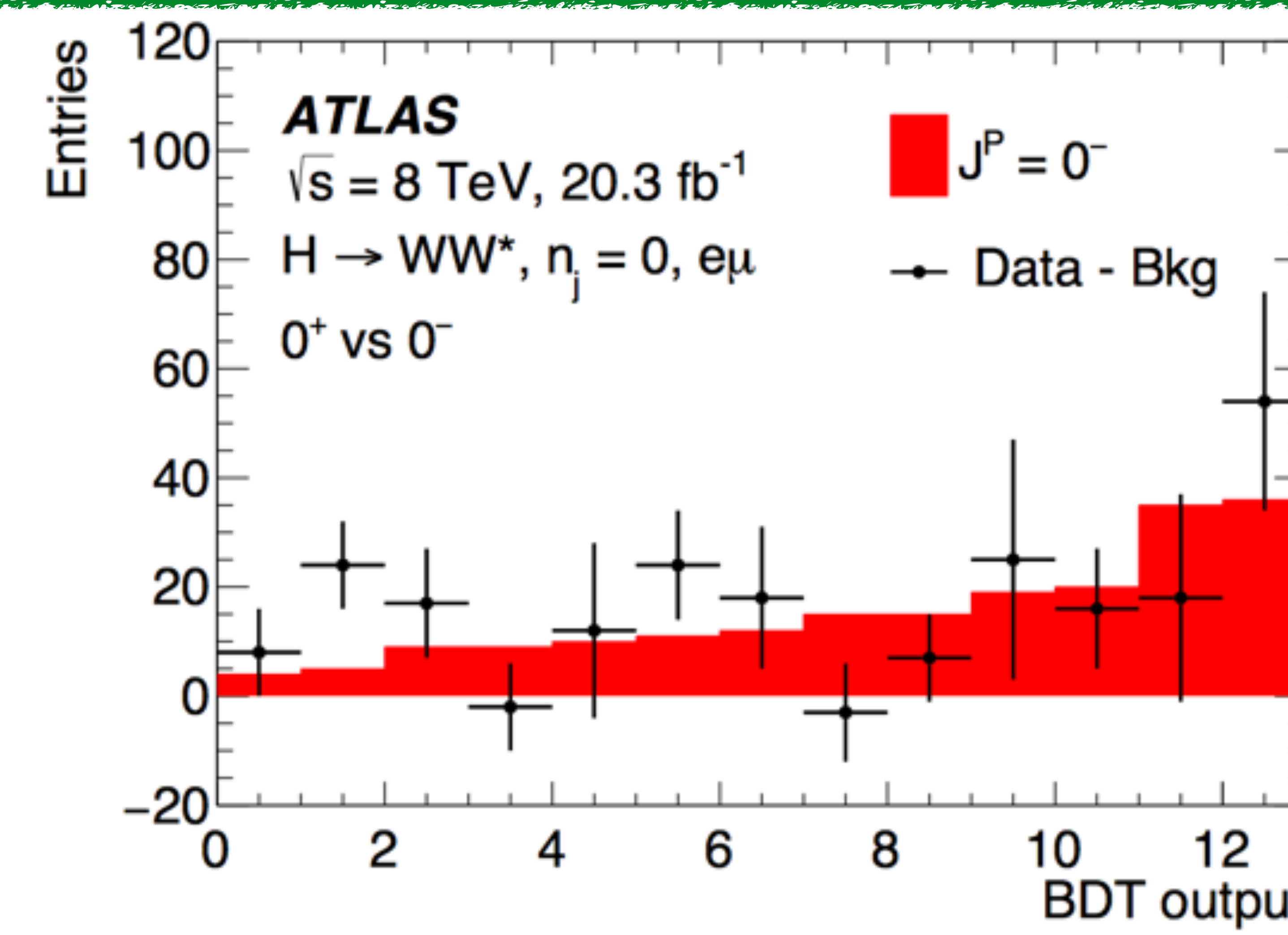


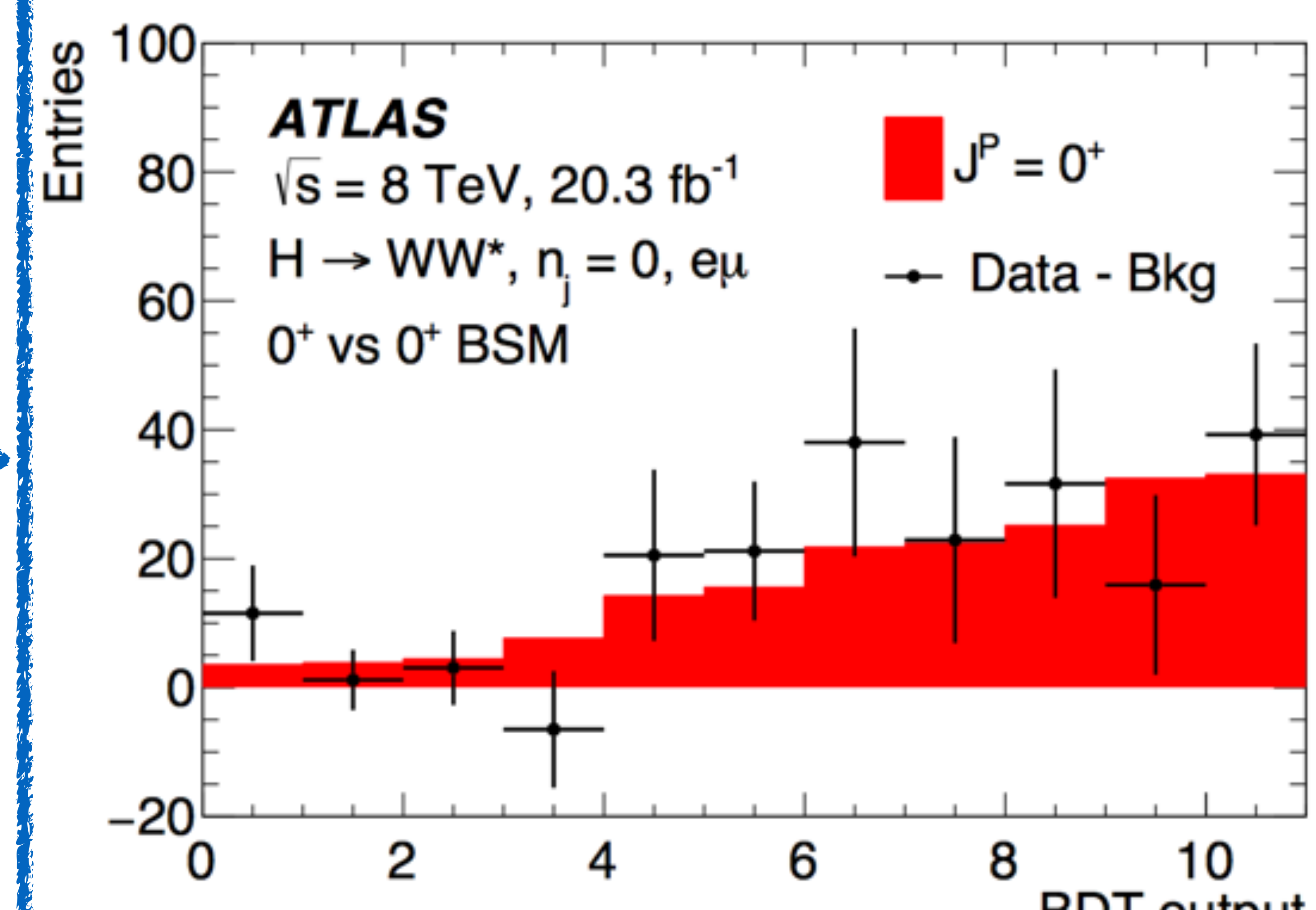
CP: Fixed Results

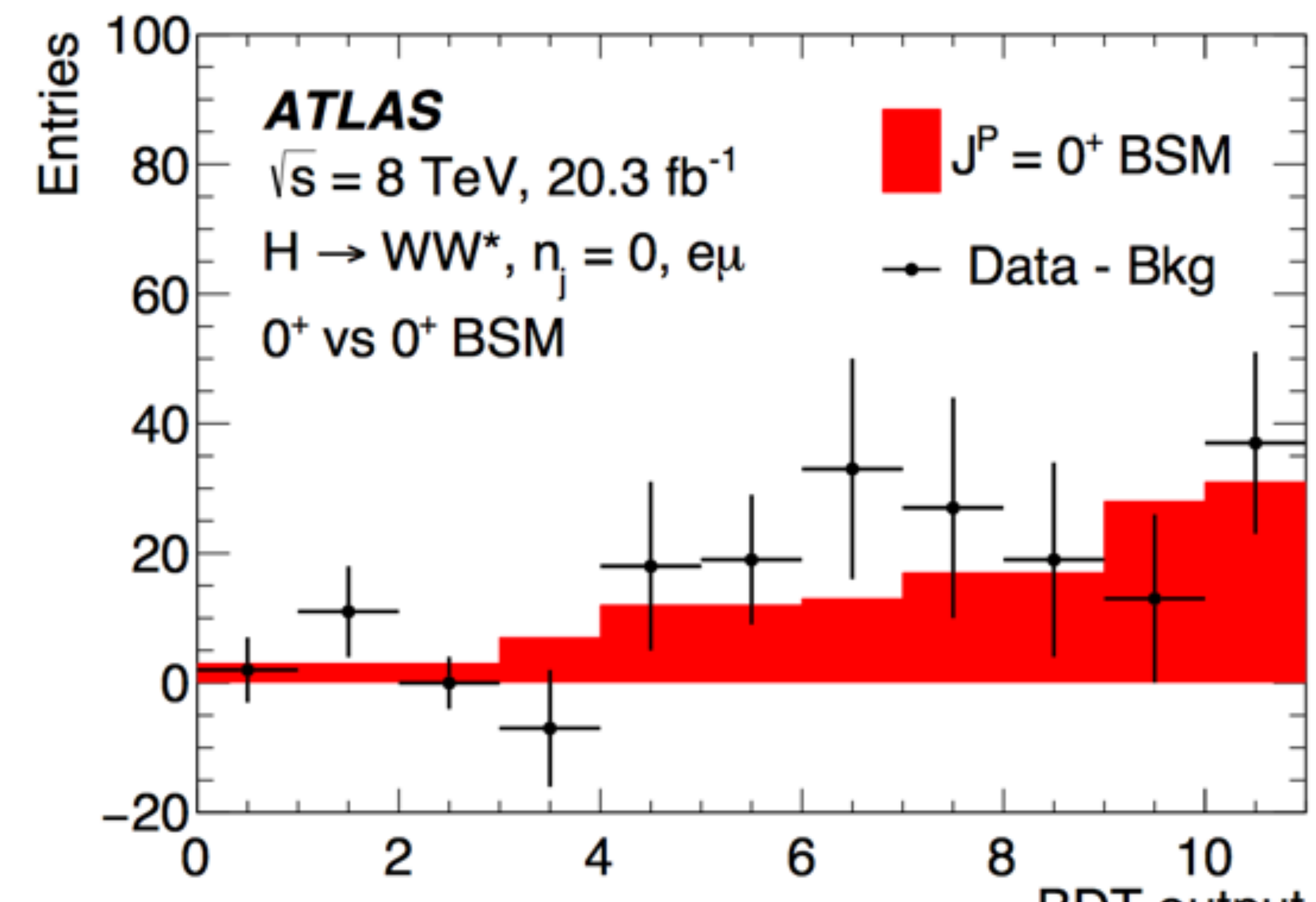
CERN-PH-EP-2015-037

Channel	$p^{SM}_{exp,\,\mu=1}$	$p^{SM}_{exp,\,\mu=\hat{\mu}}$	$p^{ALT}_{exp,\,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	– CL_s
BSM CP-odd						
0-jet	0.078	0.062	0.032	0.652	0.012	96.5%
BSM CP-even						
0-jet	0.271	0.310	0.287	0.907	0.027	70.8%



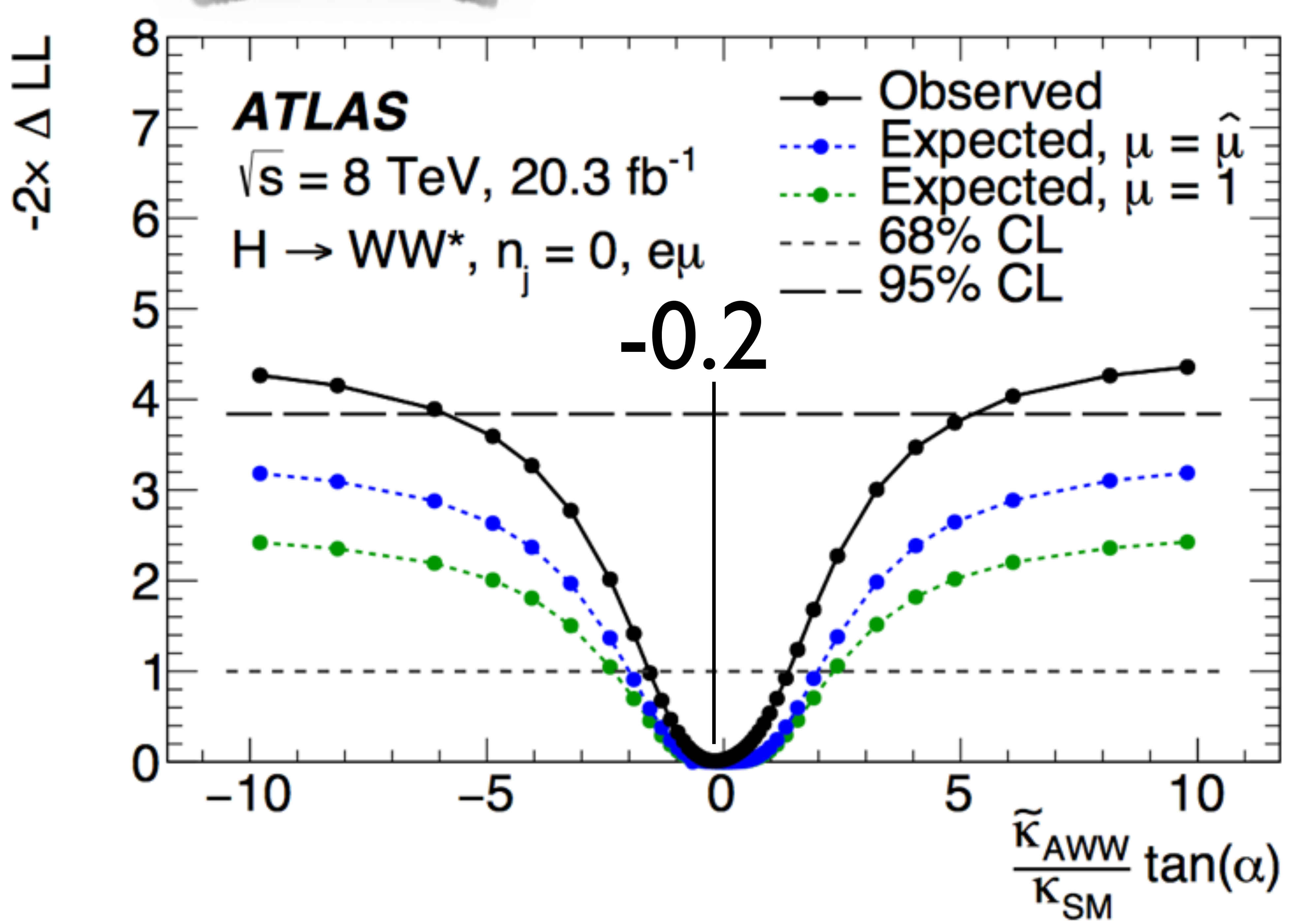




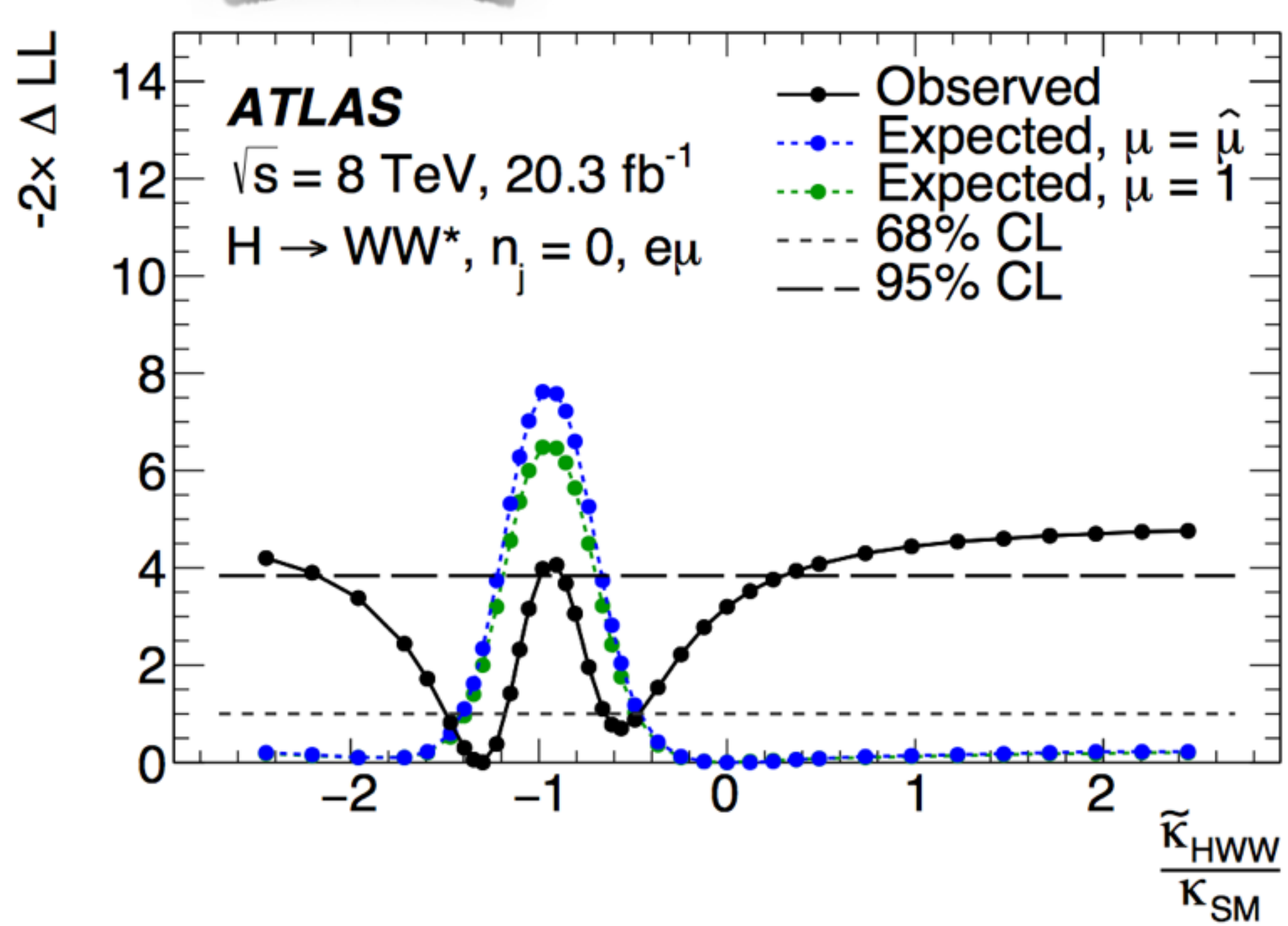


CP-Mixing Scan Results

CERN-PH-EP-2015-037



CERN-PH-EP-2015-037



95% CL $\frac{\tilde{\kappa}_{AWW}}{\kappa_{SM}} tan\alpha < -6.0$ and $\frac{\tilde{\kappa}_{AWW}}{\kappa_{SM}} tan\alpha > 5.0$

68% CL $\frac{\tilde{\kappa}_{AWW}}{\kappa_{SM}} tan\alpha < -1.6$ and $\frac{\tilde{\kappa}_{AWW}}{\kappa_{SM}} tan\alpha > 1.3$

$\frac{\tilde{\kappa}_{HWW}}{\kappa_{SM}} < -2.2$, $\frac{\tilde{\kappa}_{HWW}}{\kappa_{SM}} > 0.4$ and $\frac{\tilde{\kappa}_{HWW}}{\kappa_{SM}} \in [-0.85, -1]$

$\frac{\tilde{\kappa}_{HWW}}{\kappa_{SM}} < -1.5$, $\frac{\tilde{\kappa}_{HWW}}{\kappa_{SM}} > -0.5$ and $\frac{\tilde{\kappa}_{HWW}}{\kappa_{SM}} \in [-1.20, -0.65]$

Summary

- The SM Hypothesis for the Higgs boson have been tested against the alternative spin-2 hypothesis, and different CP states.

- ***For the spin-2 benchmarks the alternative model is :***
  - disfavoured at 84.5% CLs for the universal couplings
  - excluded up to 99.4% CL for the non-universal couplings case.

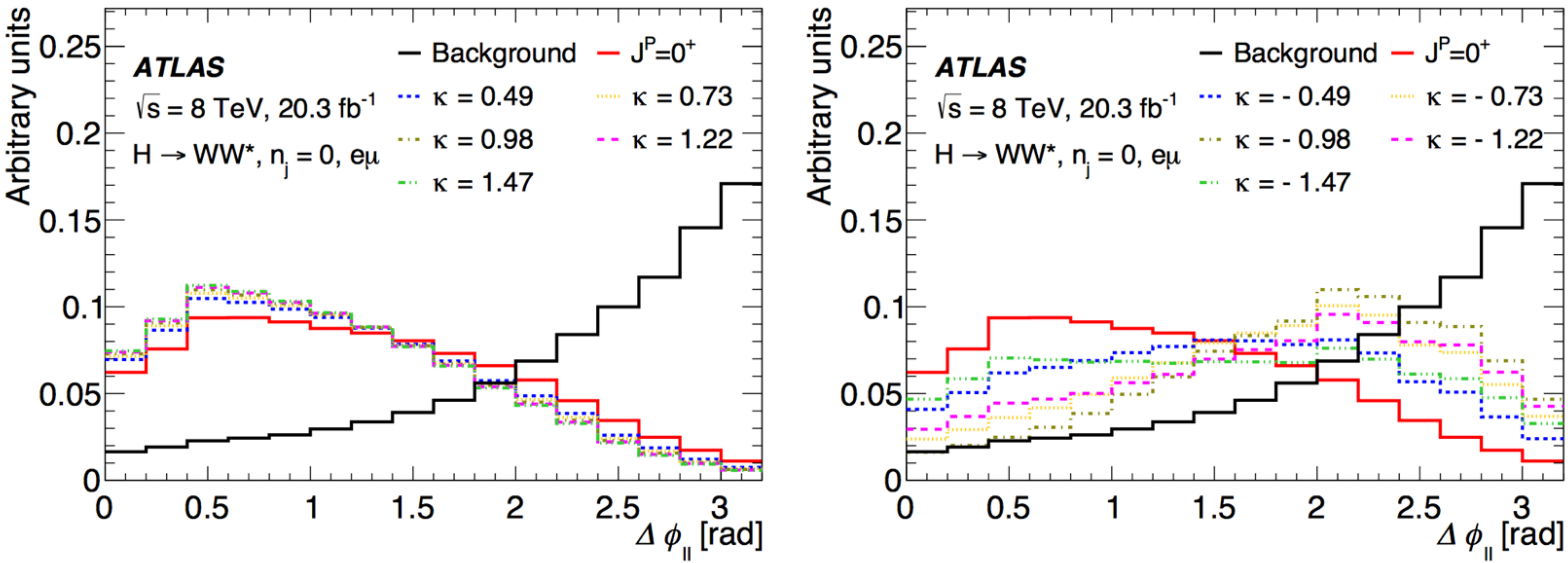
- ***For the CP study***
  - *For fixed hypotheses:*
    CP-Even alternative hypothesis is disfavoured at 70.8% && the CP-Odd is excluded at 96.5% CLs.
  - *For the CP-mixing case:*
    CP-Even : compatible with SM within 1.9σ

    CP-Odd : compatible with SM within 0.5σ

Backup

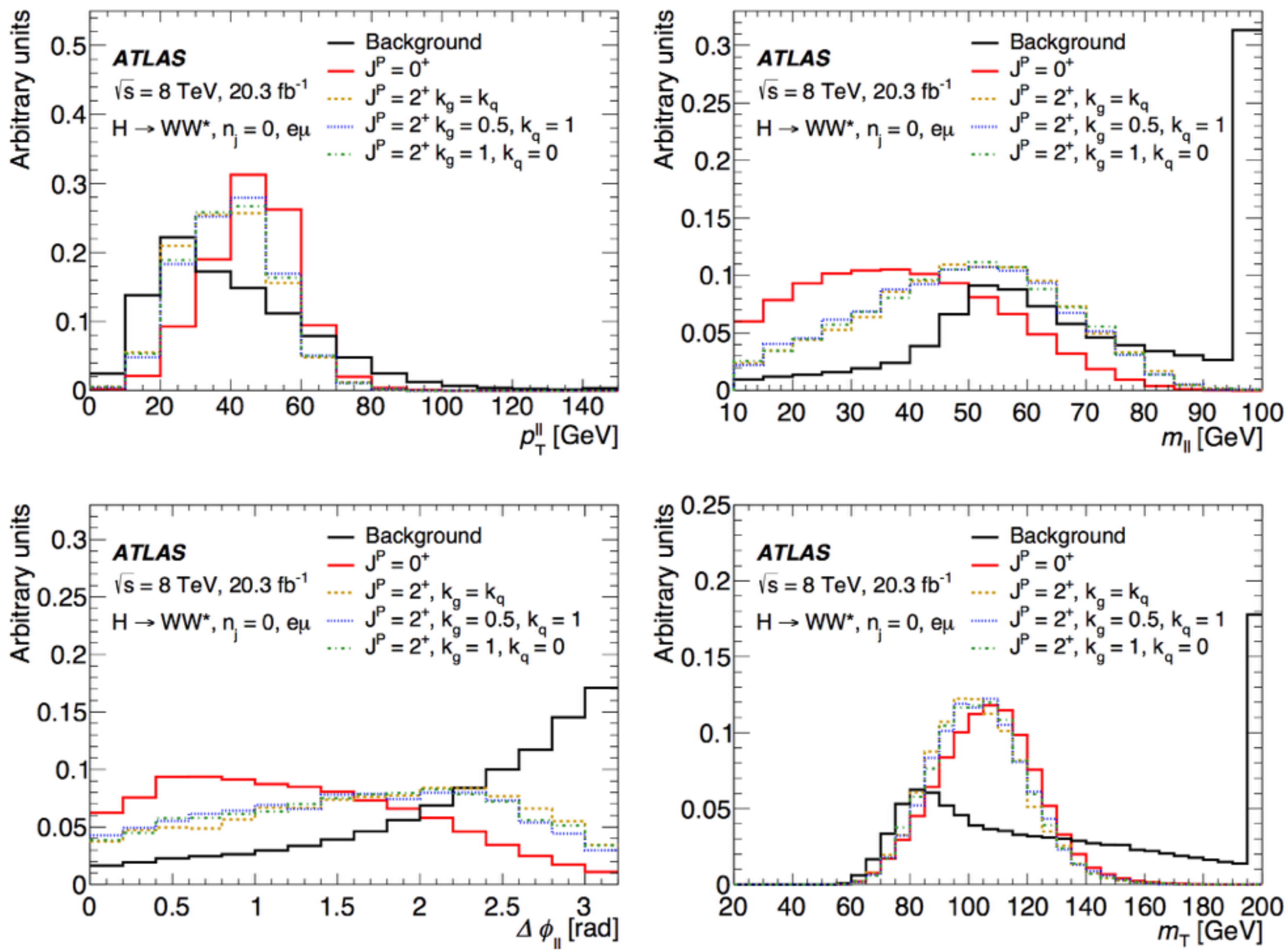
kHWW Interference

CERN-PH-EP-2015-037



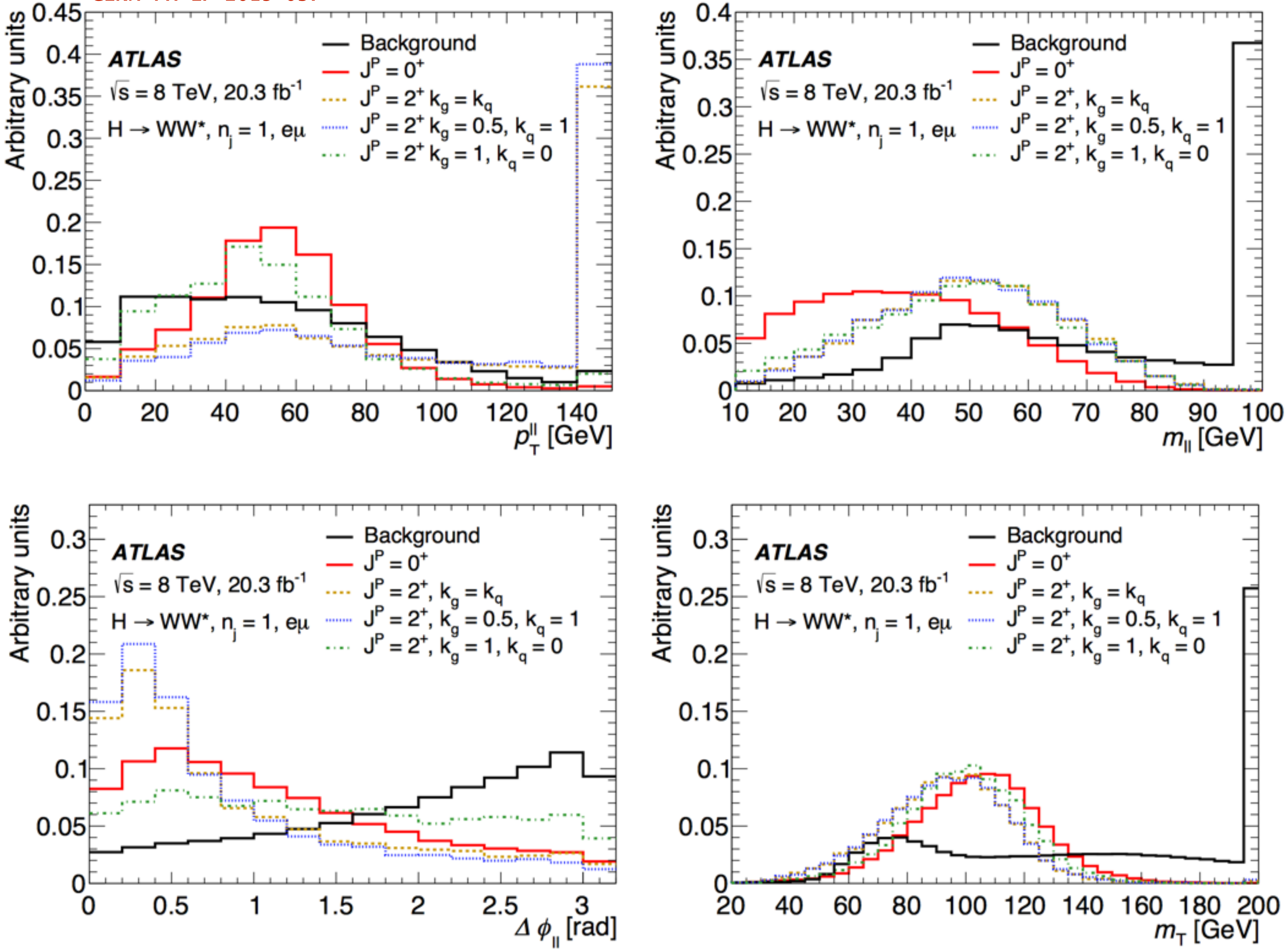
- In negative κ values a negative interferance appears which cancels out the amplitudes of SM/BSM -> Huge discrimination as ***shape*** but normalization (x-sect) falls dramatically.

Spin.Input Shapes.0j



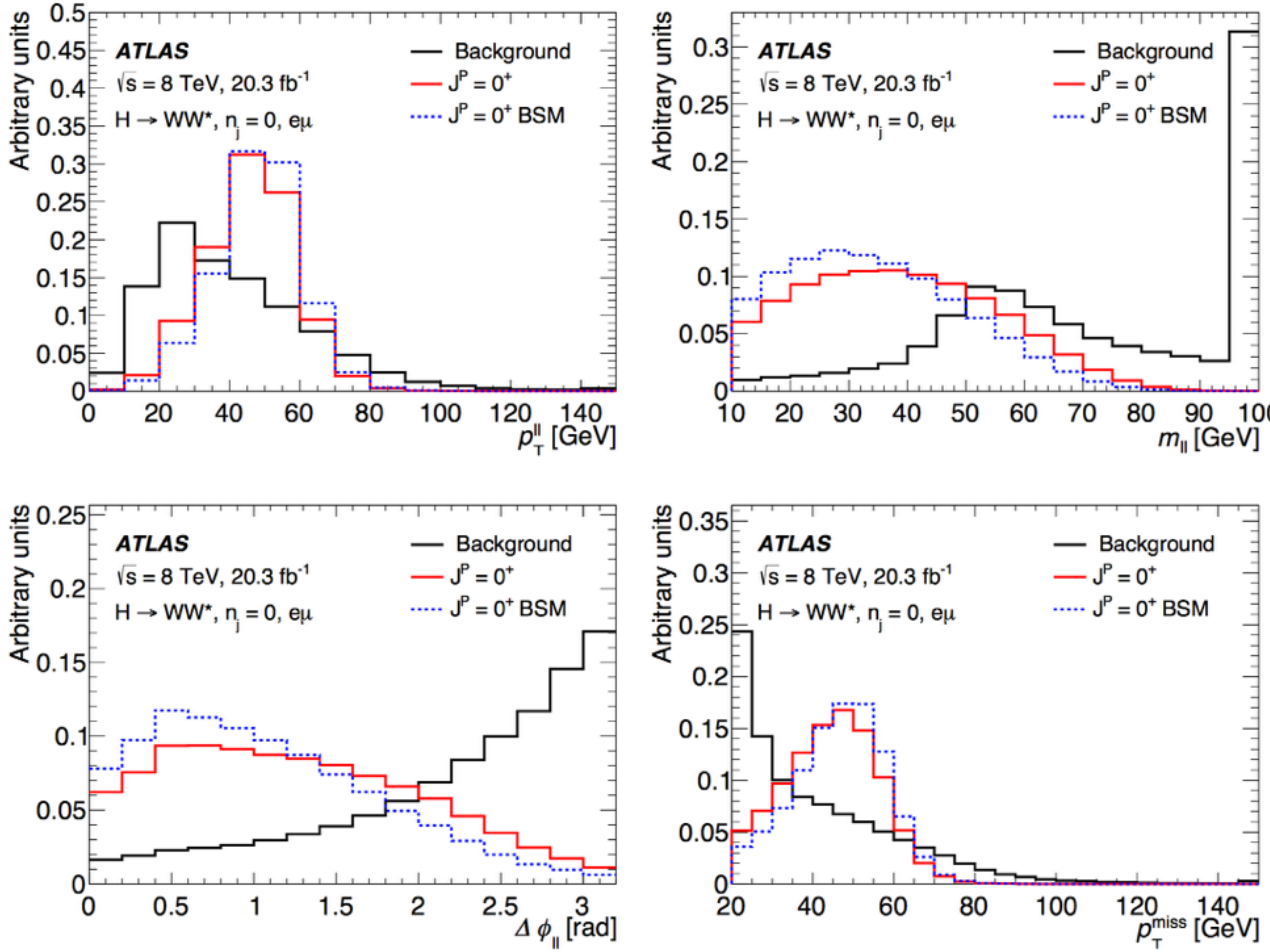
1-jet Input Shapes

CERN-PH-EP-2015-037

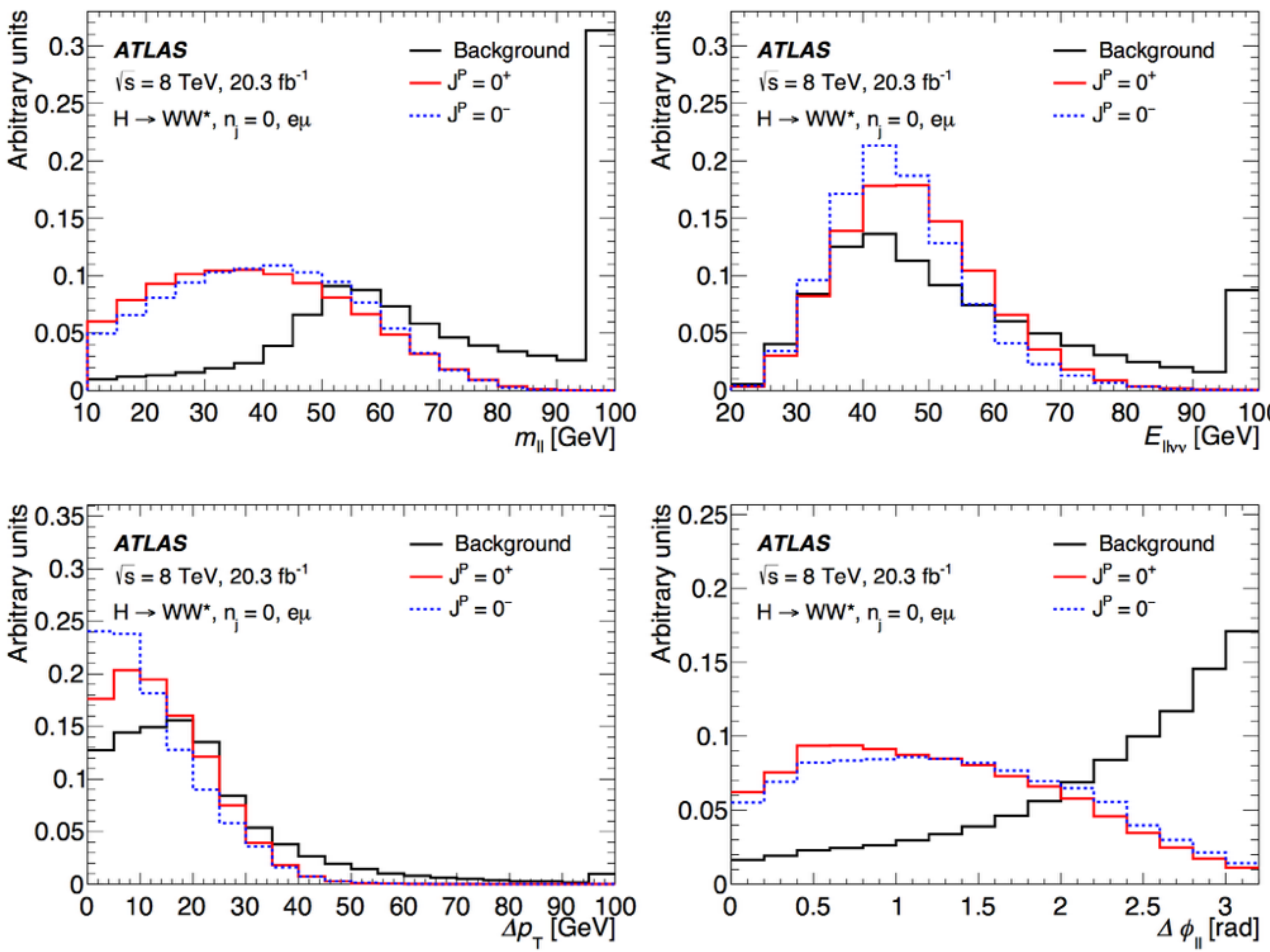


Variations on the shapes for the alternative case more apparent!

CP even input shapes



CP odd input shapes

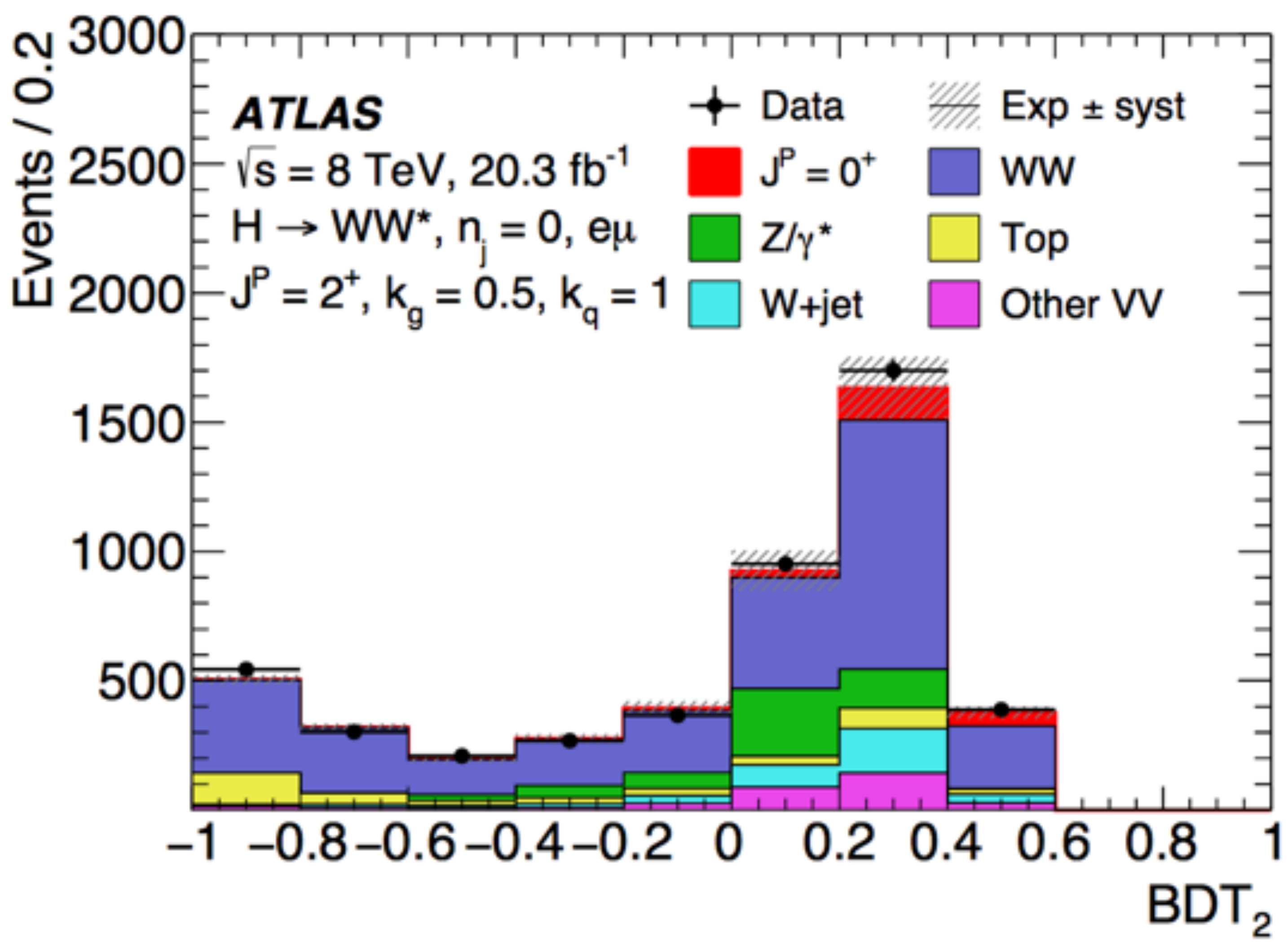


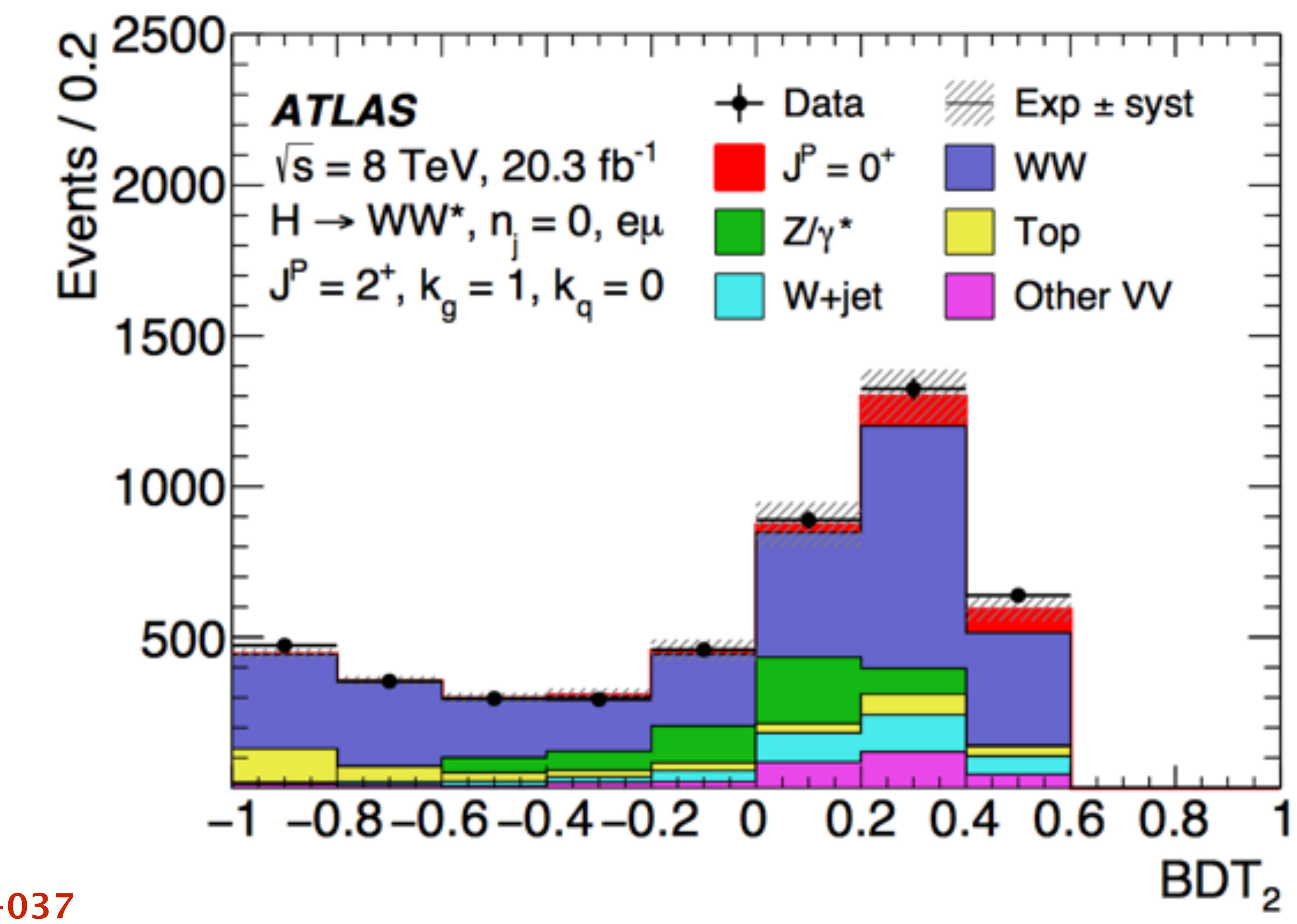
Non U.C - BDT Output

$\kappa_g = 0.5\,,\ \kappa_q = 1\,,\ p_{\mathrm{T}}^{\mathrm{H}} > 125\ GeV$

$\kappa_g = 0\,,\ \kappa_q = 1\,,\ p_{\mathrm{T}}^{\mathrm{H}} > 125\ GeV$

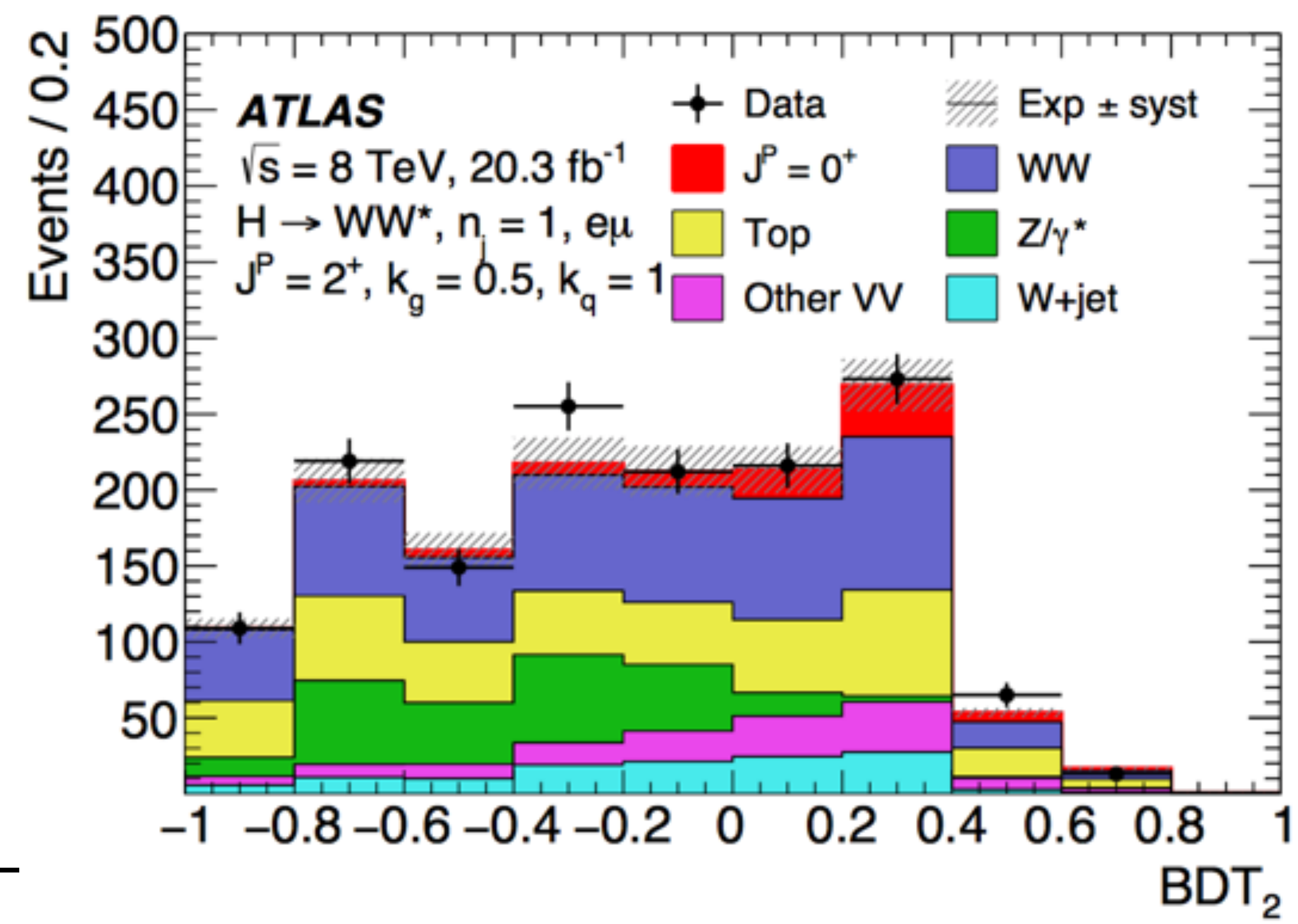
0-jet

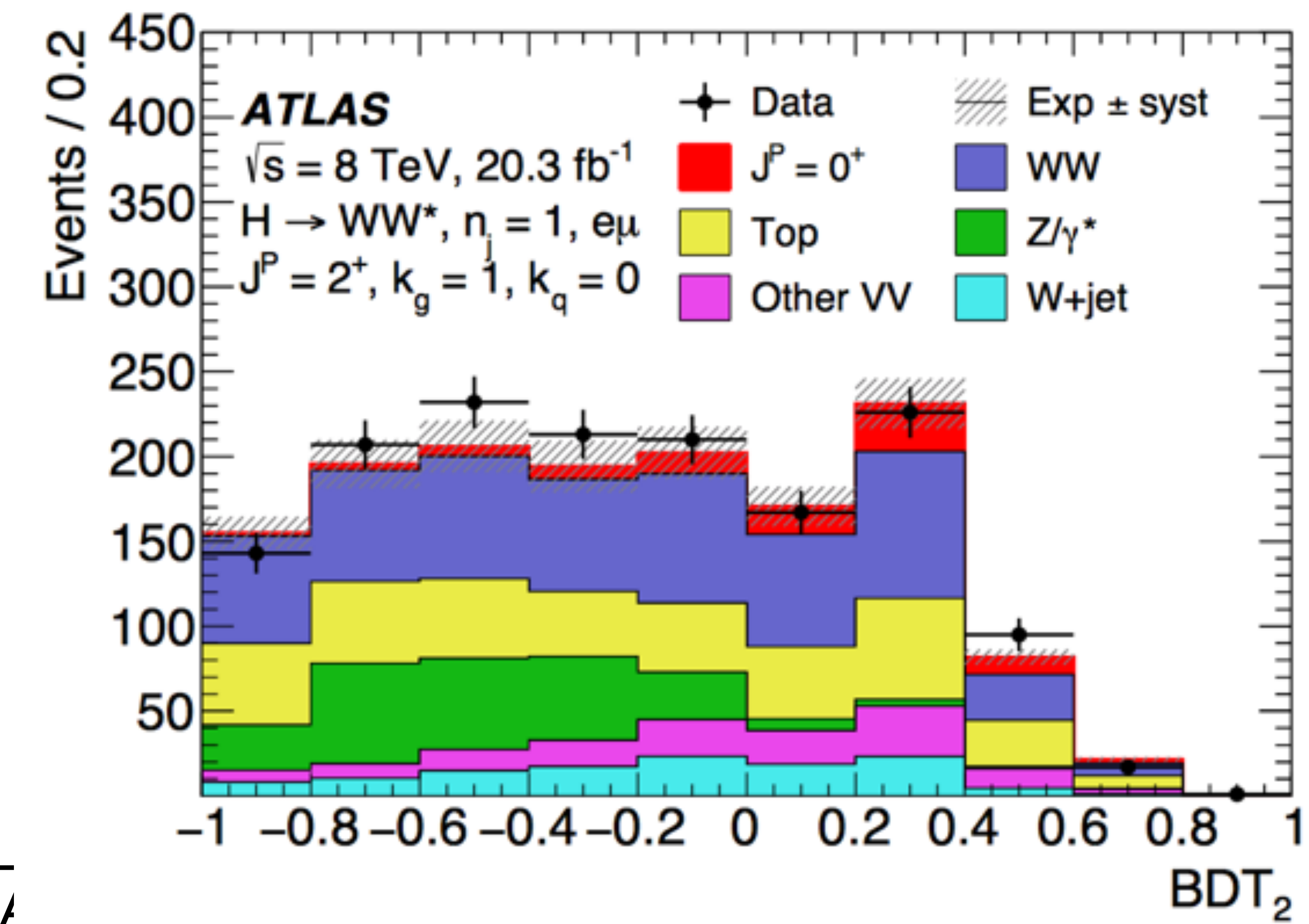




CERN-PH-EP-2015-037

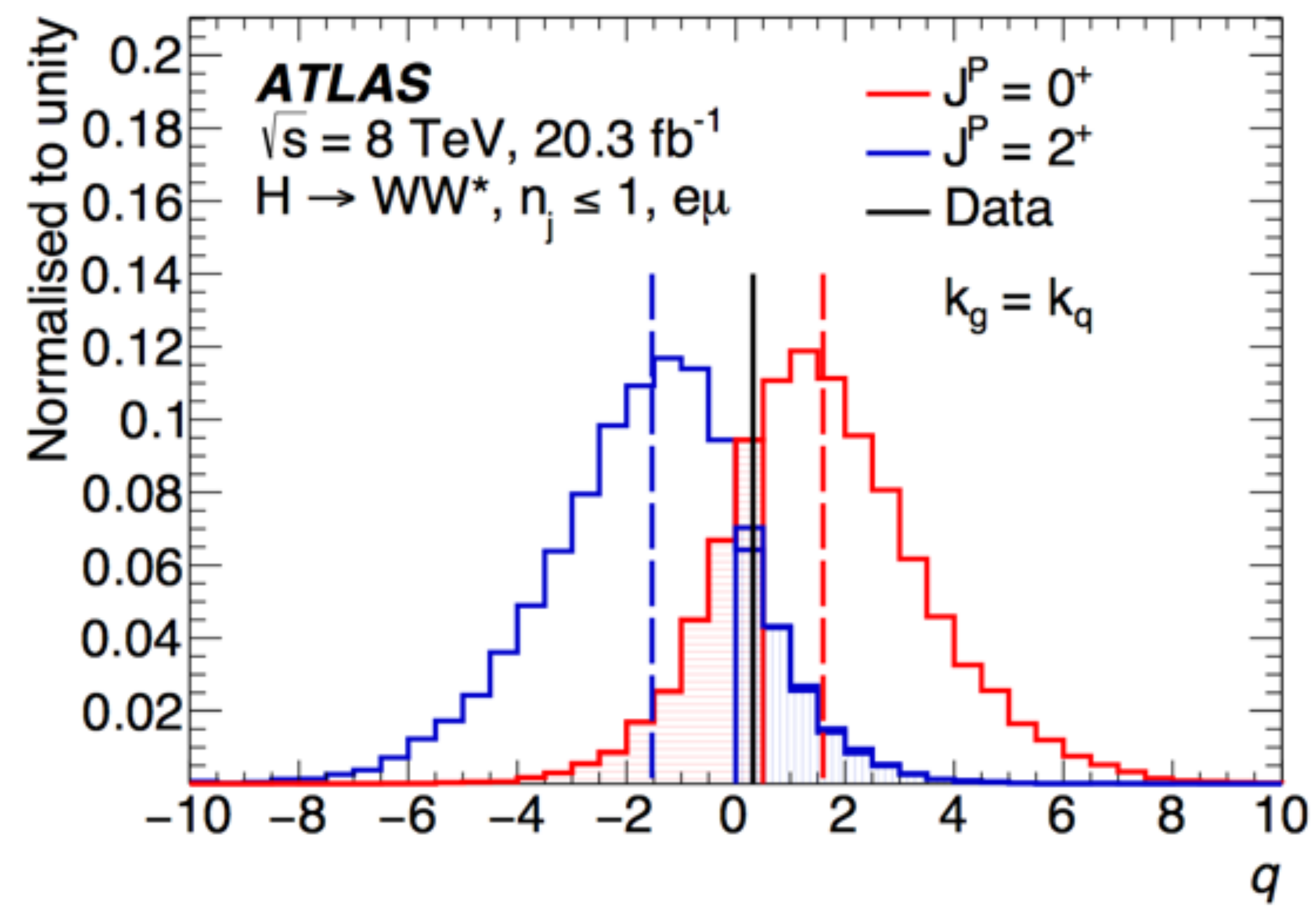
1-jet



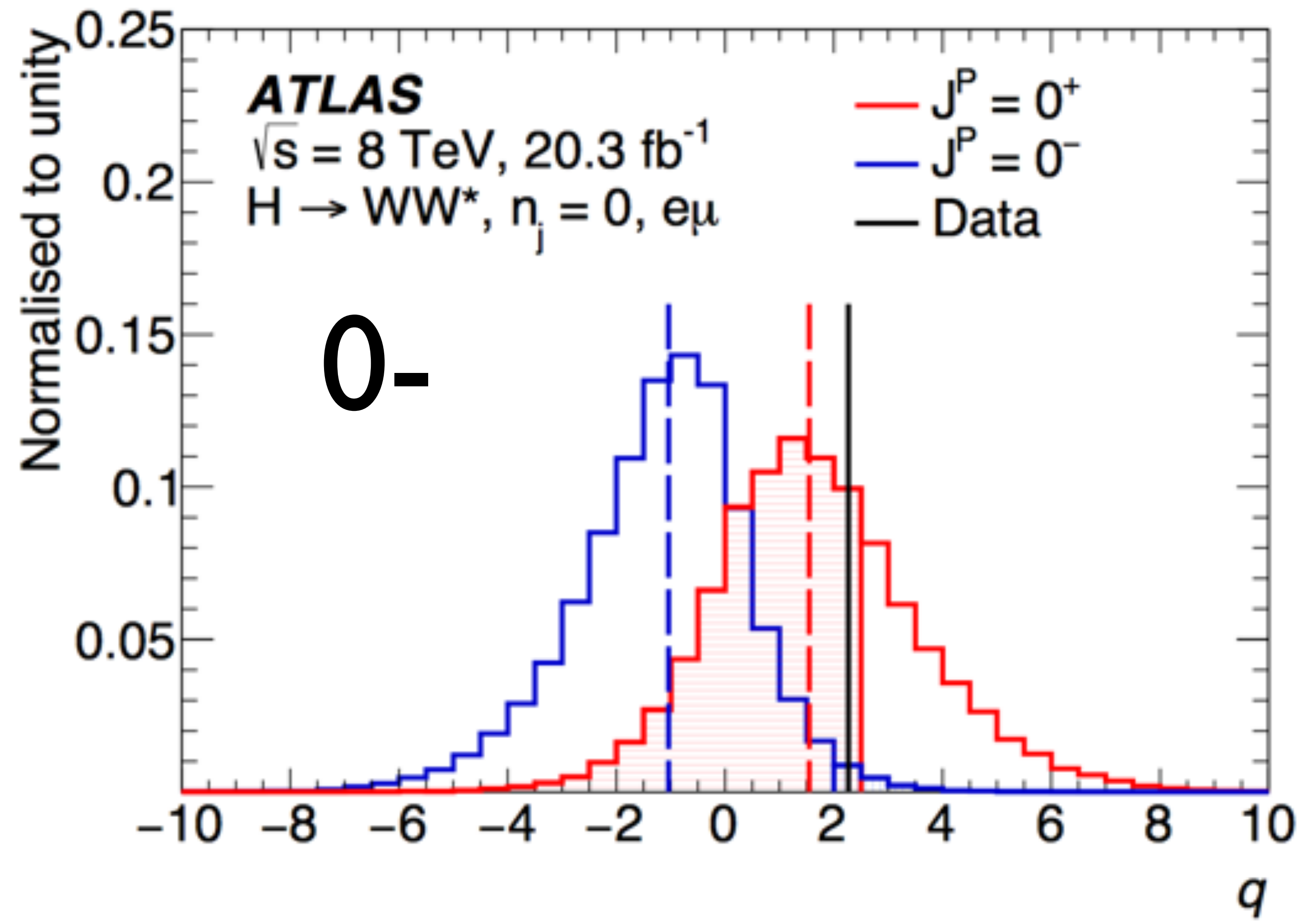


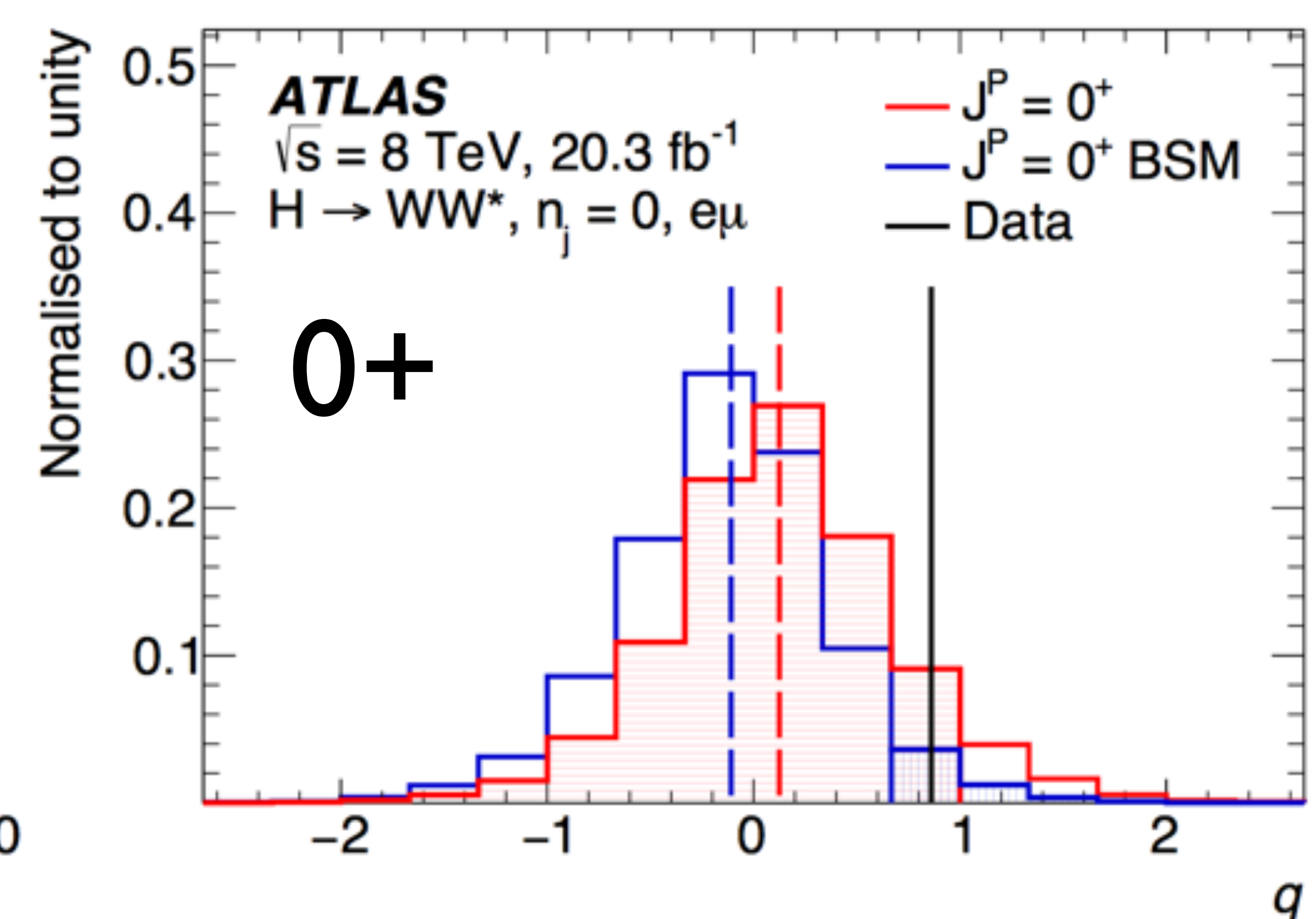
Test Statistics

CERN-PH-EP-2015-037



spin-2 0+1j





Post-fit event yields - U.C.

CERN-PH-EP-2015-037

Benchmark	Signal 0-jet	Signal 1-jet	Total background 0-jet	Total background 1-jet
$\kappa_g = \kappa_q$	360 ± 100	126 ± 34	4370 ± 240	1430 ± 60
$\kappa_g = 0.5, \kappa_q = 1, p_T^H < 125$ GeV	300 ± 100	103 ± 33	4430 ± 240	1390 ± 60
$\kappa_g = 0.5, \kappa_q = 1, p_T^H < 300$ GeV	230 ± 80	82 ± 29	4490 ± 230	1460 ± 70
$\kappa_g = 1, \kappa_q = 0, p_T^H < 125$ GeV	320 ± 90	111 ± 32	4410 ± 240	1390 ± 60
$\kappa_g = 1, \kappa_q = 0, p_T^H < 300$ GeV	200 ± 80	71 ± 28	4520 ± 240	1480 ± 70
BSM CP-odd	240 ± 80	–	4490 ± 260	–
BSM CP-even	180 ± 60	–	4530 ± 240	–

	Data	Signal	Tot. bkg.	*WW*	Top	DY	*W*+jets	Other
SM 0-jet	4730	270 ± 70	4460 ± 240	2904	376	464	370	345
SM 1-jet	1569	95 ± 26	1450 ± 70	607	355	233	124	133

Systematic Uncertainties

CERN-PH-EP-2015-037

Table 6: Sources of experimental systematic uncertainty considered in the analysis. The source and magnitude of the uncertainties and their impact on the reconstructed objects is indicated.

Source of uncertainty	Treatment in the analysis and its magnitude
Jet energy scale	1 –7% in total as a function of jet η and p_T
Jet energy resolution	5 –20% as a function of jet η and p_T Relative uncertainty on the resolution is 2 –40%
b-tagging	b-jet identification: 1 –8% decomposed in p_T bins Light-quark jet misidentification: 9 –19% as a function of η and p_T c-quark jet misidentification: 6 –14% as a function of p_T
Leptons	Reconstruction, identification, isolation, trigger efficiency: below 1% except for electron identification: 0.2 –2.7% depending on η and p_T Momentum scale and resolution: < 1%
Missing transverse momentum	Propagated jet-energy and lepton-momentum scale uncertainties Resolution (1.5 –3.3 GeV) and scale variation (0.3 –1.4 GeV)
Pile-up	The number of pile-up events is varied by 10%
Luminosity	2.8% [47]

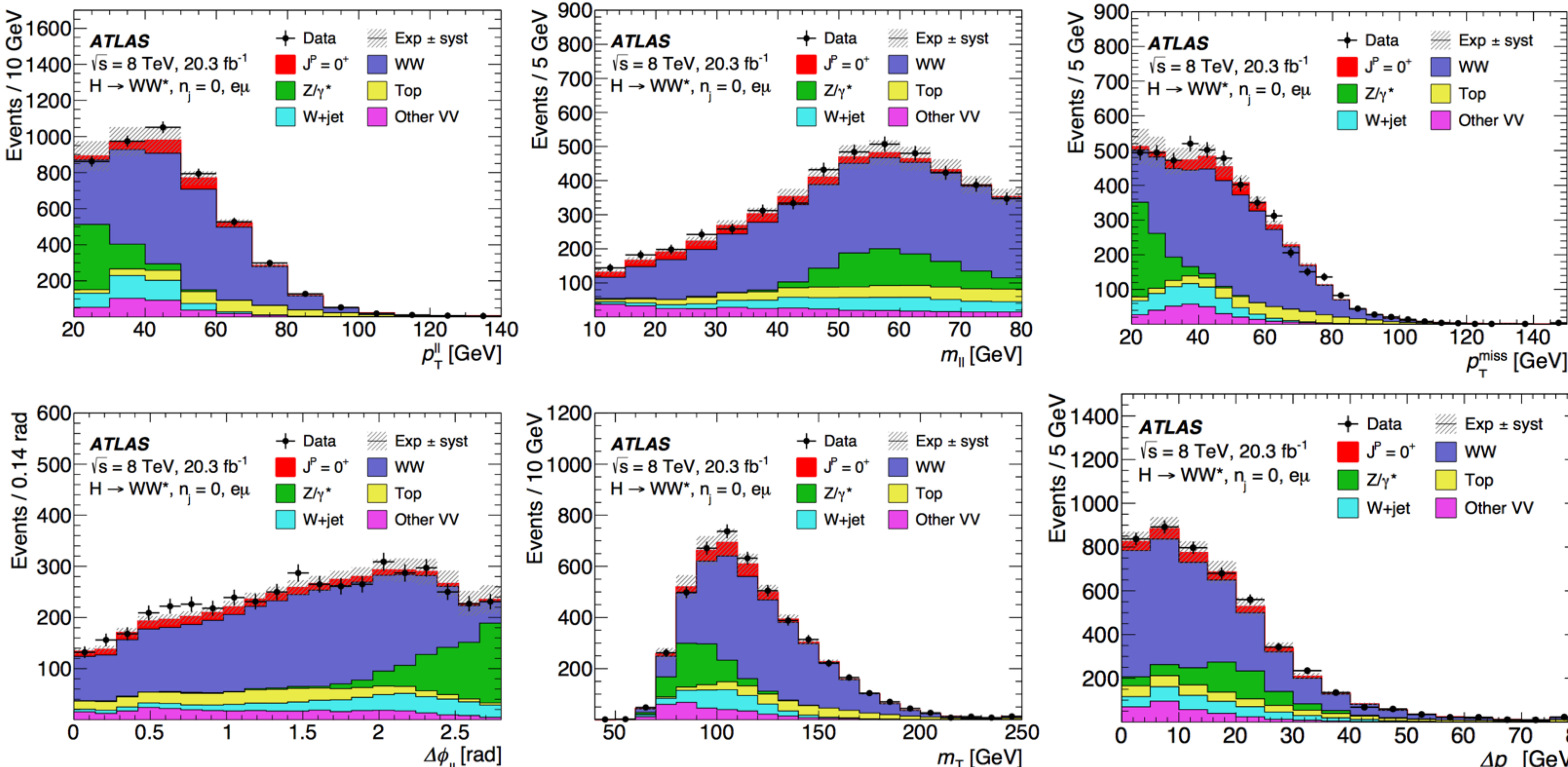
Category	Scale	PDF	Gen	EW	UE/PS	p_T^Z	Total
WW background							
SR 0-jet	0.9	3.8	6.9	–0.8	–4.1	–	8.2
SR 1-jet	1.2	1.9	3.3	–2.1	–3.2	–	5.3
Top-quark background							
SR 1-jet	–0.8	–1.4	1.9	–	2.4	–	3.5
WW CR 1-jet	0.6	0.3	–2.4	–	2.0	–	3.2
$Z/\gamma^* \to \tau\tau$ background							
SR 0-jet	–7.1	1.3	–	–	–6.5	19	21.3
SR 1-jet	6.6	0.66	–	–	–4.2	–	7.9
WW CR 0-jet	–11.4	1.7	–	–	–8.3	16	21.4
WW CR 1-jet	–5.6	2.2	–	–	–4.8	–	7.7

Table 7: From top to bottom, systematic uncertainties (in %) with the largest impact on the spin-2 universal couplings, BSM CP-odd and CP-even Higgs-boson fixed-hypothesis tests. This ranking is based on the impact of each systematic uncertainty on the CL_s estimator (see Sect. 7). For the exact meaning of the different uncertainties related to the misidentified lepton rates (the W+jets background estimate uncertainty), see Sect. 5.4 and Ref. [9].

Spin-2		BSM CP-odd		BSM CP-even	
WW generator:	2.6	*WW* generator:	0.73	*WW* UE/PS:	21
p_T^Z reweighting:	1.2	*WW* UE/PS:	0.66	Misid. rate (elec. stats):	9.2
Misid. rate (elec. stats):	1.1	QCD scale Wg^*:	0.45	Misid. rate (elec. flavour):	8.4
Misid. rate (elec. flavour):	1.0	p_T^Z reweighting:	0.43	Misid. rate (muon flavour):	7.4
WW UE/PS:	0.86	QCD scale VV :	0.39	Misid. rate (muon stats):	7.3
Misid. rate (muon stats):	0.81	QCD scale Wg:	0.38	Misid. rate (elec. other):	7.3
$Z/\gamma^* \to \tau\tau$ generator:	0.76	Misid. rate (elec. stats):	0.37	*WW* PDF qq-production:	6.9
Misid. rate (muon flavour):	0.75	Misid. rate (elec. other):	0.34	*WW* PDF gg-production:	6.9
Misid. rate (elec. other):	0.67	Misid. rate (elec. flavour):	0.33	*WW* generator:	3.6

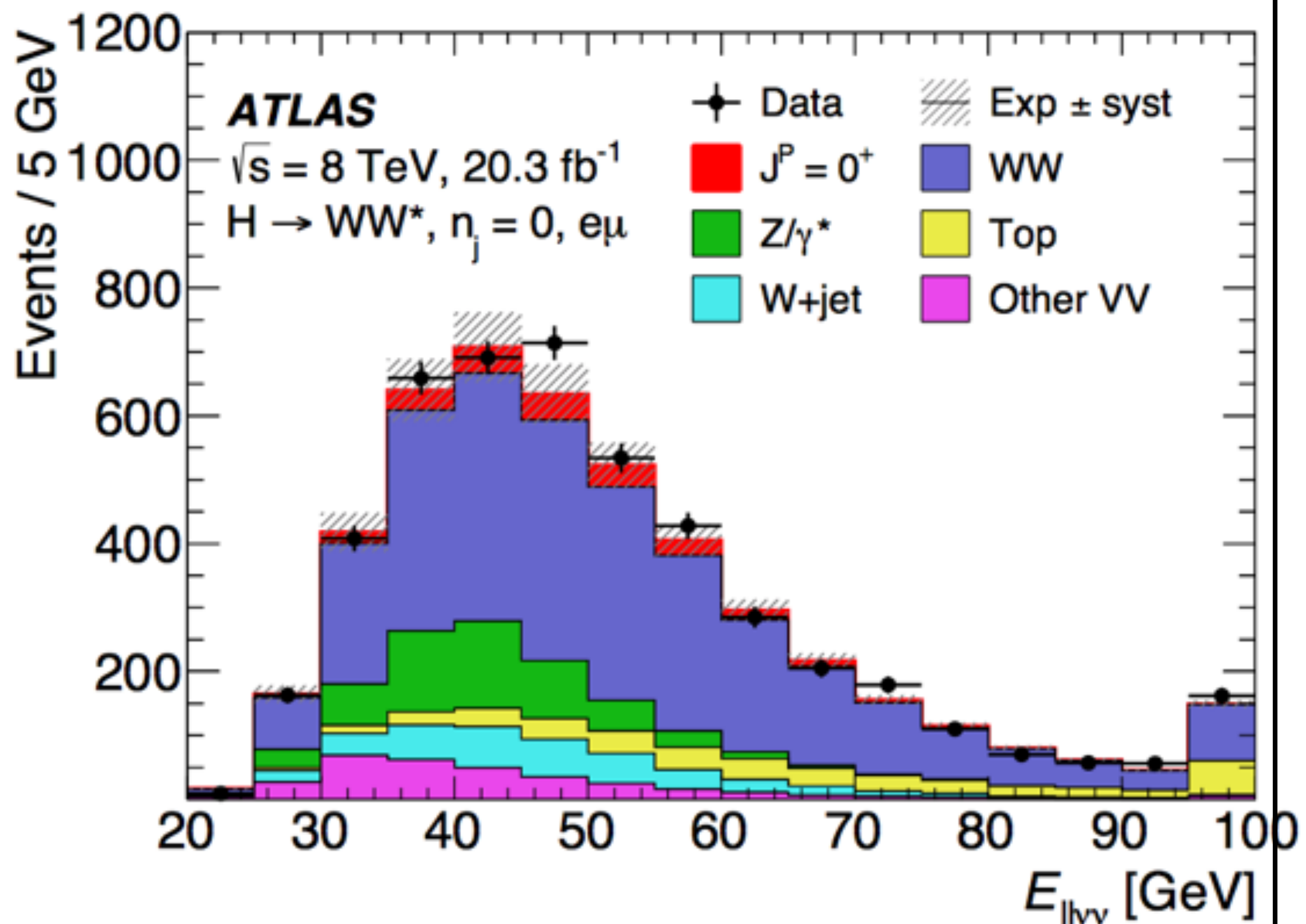
0jet Inputs

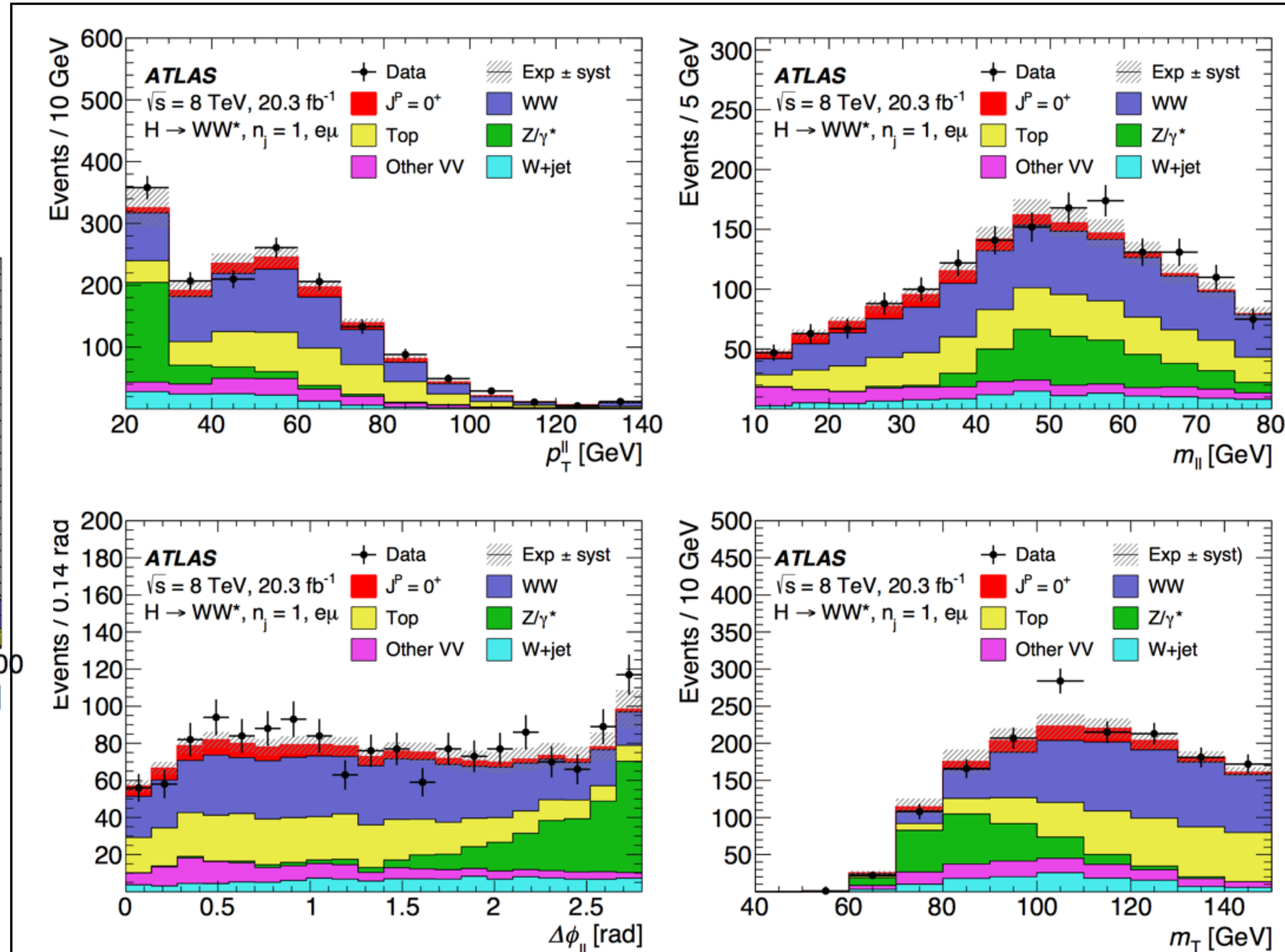
CERN-PH-EP-2015-037



0jet Ellvv & 1jet Inputs

CERN-PH-EP-2015-037





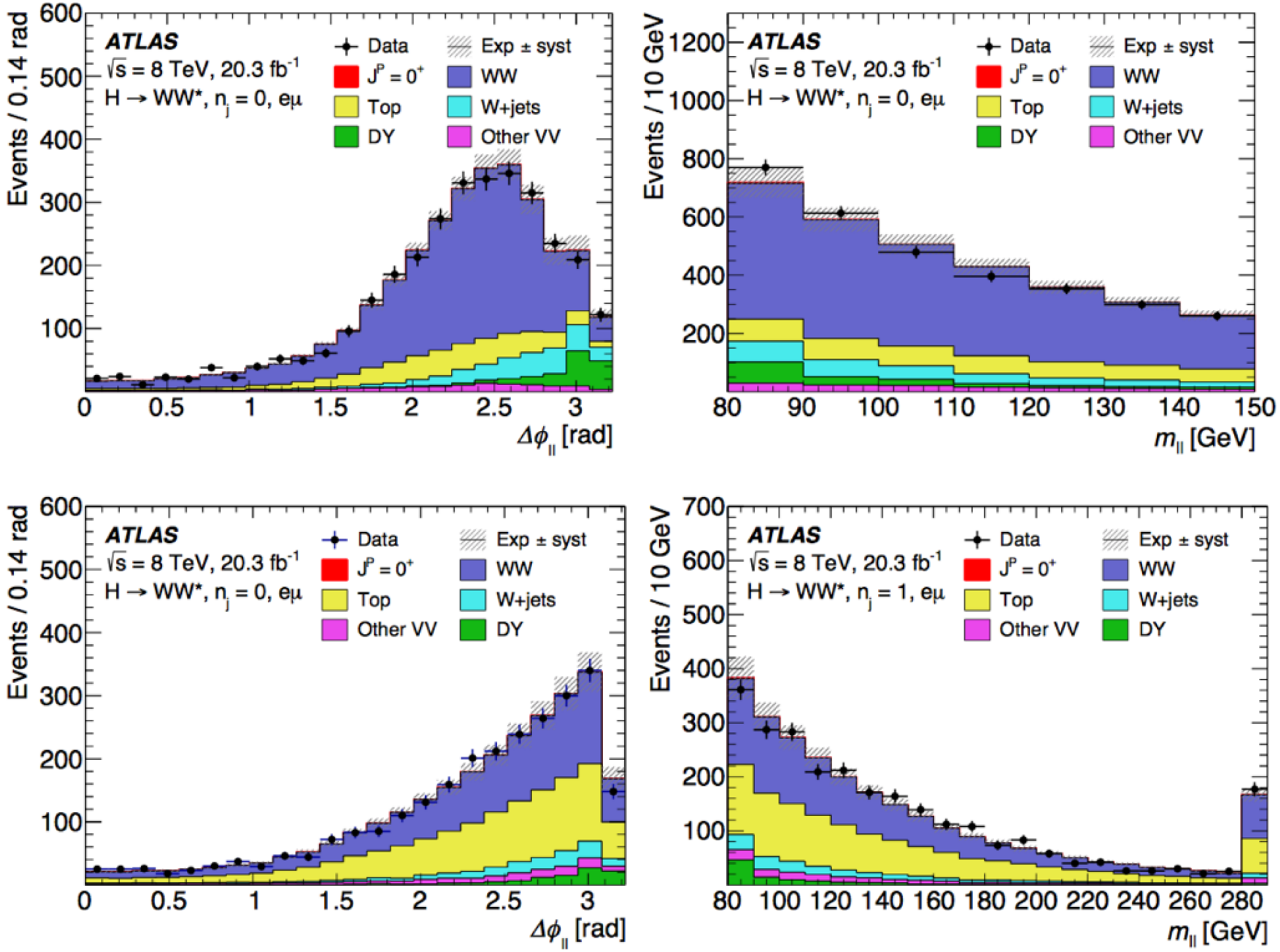
CR Definition

CERN-PH-EP-2015-037

Control region	Selection
WW CR 0-jet	Preselection, $p_T^{\ell\ell} > 20$ GeV, $80 < m_{\ell\ell} < 150$ GeV
WW CR-1 jet	Preselection, b-veto, $m_{\tau\tau} < m_Z - 25$ GeV $m_T^{\ell} > 50$ GeV, $m_{\ell\ell} > 80$ GeV
Top CR 0-jet	Preselection, $\Delta\phi_{\ell\ell} < 2.8$, all jets inclusive
Top CR 1-jet	At least one b-jet, $m_{\tau\tau} < m_Z - 25$ GeV
$Z/\gamma^* \to \tau\tau$ CR 0-jet	Preselection, $m_{\ell\ell} < 80$ GeV, $\Delta\phi_{\ell\ell} > 2.8$
$Z/\gamma^* \to \tau\tau$ CR 1-jet	Preselection, b-veto, $m_T^{\ell} > 50$ GeV, $m_{\ell\ell} < 80$ GeV, $\|m_{\tau\tau} - m_Z\| < 25$ GeV

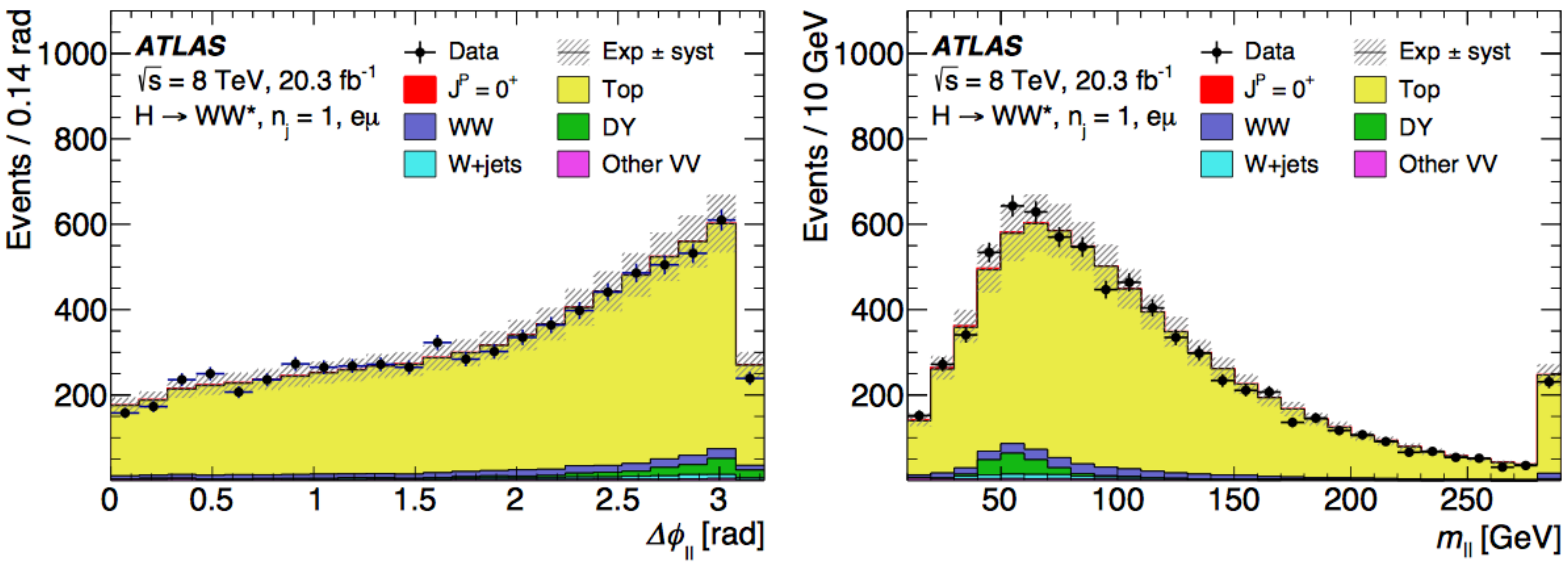
WW CR

CERN-PH-EP-2015-037



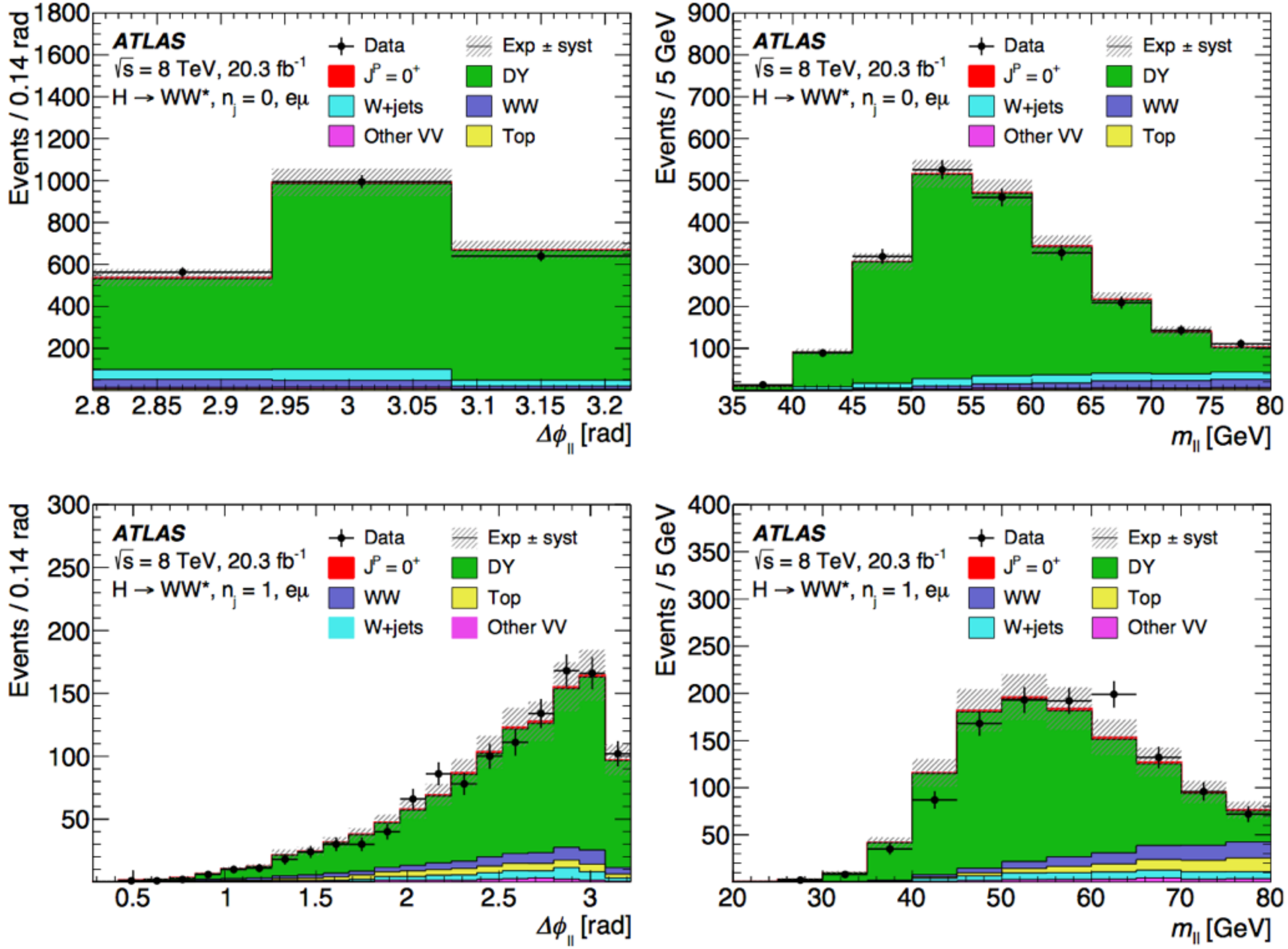
Top CR

CERN-PH-EP-2015-037



Zττ CR

CERN-PH-EP-2015-037



Samples

CERN-PH-EP-2015-037

Table 1: Monte Carlo samples used to model the signal and background processes. The corresponding cross-sections times branching fractions, $\sigma \cdot \mathcal{B}$, are quoted at $\sqrt{s} = 8$ TeV. The branching fractions include the decays $t \to Wb$, $W \to \ell\nu$, and $Z \to \ell\ell$ (except for the process $ZZ \to \ell\ell\,\nu\nu$). Here ℓ refers to e, μ, or τ. The neutral current $Z/\gamma^* \to \ell\ell$ process is denoted Z or γ^*, depending on the mass of the produced lepton pair. The parameters κ_g, κ_q are defined in Sect. 2.1.1, while κ_{SM}, κ_{HWW}, κ_{AWW}, c_α are defined in Sect. 2.2.1.

Process	MC generator	Filter	$\sigma \cdot \mathcal{B}$ (pb)
Signal samples used in $J^P = 2^+$ analysis			
SM $H \to WW^*$	Powheg+Pythia8		0.435
$\kappa_g = \kappa_q$	MadGraph5_aMC@NLO+Pythia6		-
$\kappa_g = 1, \kappa_q = 0$	MadGraph5_aMC@NLO+Pythia6		-
$\kappa_g = 0.5, \kappa_q = 1$	MadGraph5_aMC@NLO+Pythia6		-
Signal samples used in CP-mixing analysis			
$c_\alpha = 0.3, \kappa_{SM} = 1$ $\kappa_{HWW} = 2, \kappa_{AWW} = 2$	MadGraph5_aMC@NLO+Pythia6		-
Background samples			
WW			
$q\bar{q} \to WW$ and $gg \to WW$	Powheg+Pythia6		5.68
$gg \to WW$	gg2VV+Herwig		0.196
Top quarks			
$t\bar{t}$	Powheg+Pythia6		26.6
Wt	Powheg+Pythia6		2.35
$tq\bar{b}$	AcerMC+Pythia6		28.4
$t\bar{b}$	Powheg+Pythia6		1.82
Other dibosons (VV)			
$W\gamma$	Alpgen+Herwig	$p_T^\gamma > 8$ GeV	369
$W\gamma^*$	Sherpa	$m_{\ell\ell} \leq 7$ GeV	12.2
WZ	Powheg+Pythia8	$m_{\ell\ell} > 7$ GeV	12.7
$Z\gamma$	Sherpa	$p_T^\gamma > 8$ GeV	163
$Z\gamma^*$	Sherpa	min. $m_{\ell\ell} \leq 4$ GeV	7.31
ZZ	Powheg+Pythia8	$m_{\ell\ell} > 4$ GeV	0.733
$ZZ \to \ell\ell\,\nu\nu$	Powheg+Pythia8	$m_{\ell\ell} > 4$ GeV	0.504
Drell –Yan			
Z/γ^*	Alpgen+Herwig	$m_{\ell\ell} > 10$ GeV	16500