Direct and Indirect Searches of New Physics in Multi-Bosons Final States at ATLAS

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Jan 2008 - July 2008

★ Master thesis at Rome University “La Sapienza”

- title: Development of the muon isolation algorithm at ATLAS
- supervisors: prof. Carlo Dionisi, prof. Stefano Giagu

Oct 2008 - Jan 2012

★ Ph.D. thesis at Rome University “La Sapienza”

- title: $J/\psi \rightarrow \mu^+\mu^-$ cross-section and B-lifetime determination at ATLAS
- supervisors: prof. Carlo Dionisi, prof. Stefano Giagu, doct. Marco Rescigno

Feb 2012 - Feb 2014/2016

★ Post-Doctorate at CEA Saclay within Samira Hassani’s ERC-DIBOSON project

- project goal: diboson production for SM measurements and new physics searches at ATLAS

Presentation Outline

- **Indirect new physics searches using diboson production at ATLAS**
  - cross-section and Triple Gauge Coupling (TGC) measurement in $W\gamma$
  - first anomalous Quartic Gauge Couplings (QGC) measurement in $W\gamma\gamma$
- **Direct new physics searches using diboson production at ATLAS**
  - model independent searches for new resonances decaying to $W\gamma$
- **Other ways: using the Higgs-candidate as a probe at ATLAS**
  - spin-parity measurement in the $H\rightarrow ZZ^{(*)}\rightarrow 4\ell$ decay channel

Introducing Triple Gauge Couplings (TGC)

- Triple gauge couplings are a direct consequence of the SU(2) x U(1) structure of the electroweak sector

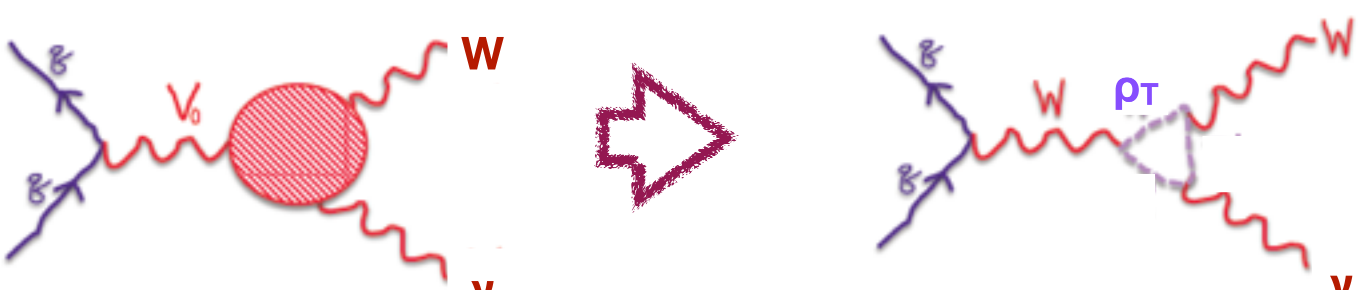
- Defining an effective Lagrangian:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V (W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2} W^\dagger_{\rho\mu} W^\mu_\nu V^{\nu\rho}\right]$$

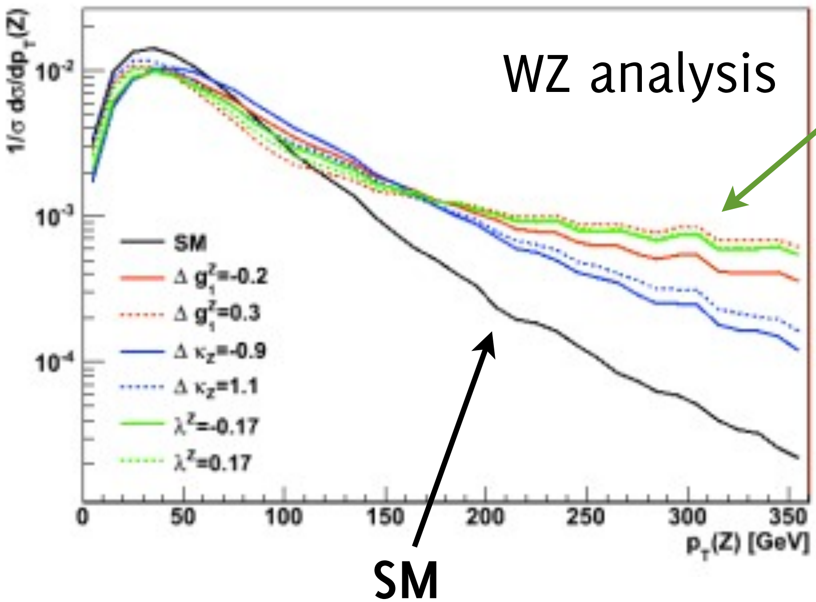
In the Standard Model:

- $g_1^V = \kappa^V = 1$ (set limits on $\Delta g = g - 1$, $\Delta\kappa = \kappa - 1$)
- $\lambda^V = f_4^V = f_5^V = h_3^V = h_4^V = 0$

- Measurement of TGCs
  - study of di-boson production → high stat, clean measurements
  - gives access to new physics in the high energy range



TGC Sensitivity to New Physics



Deviations from the SM could:

→ **modify** allowed triple gauge couplings

→ **introduce** new ones...

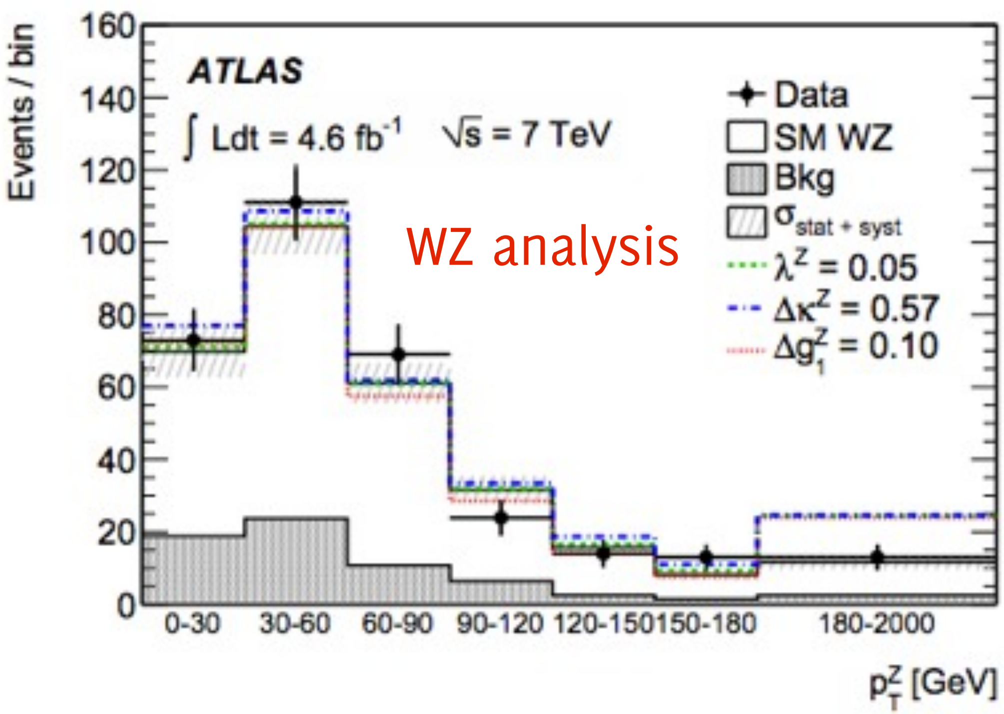
How do new physics processes relate to aTGCs?

parameters measurable in Wγ

Theoretical predictions	$\Delta\kappa$	λ
2HDM (Two Higgs doublet model)	0,016	0,0014
E6 (→ Z′, W′)	2,5 . 10^{-5}	0,003
SuperSymmetry	0,005	5 . 10^{-5}
Technicolor	0,002	-

How do we Measure TGCs

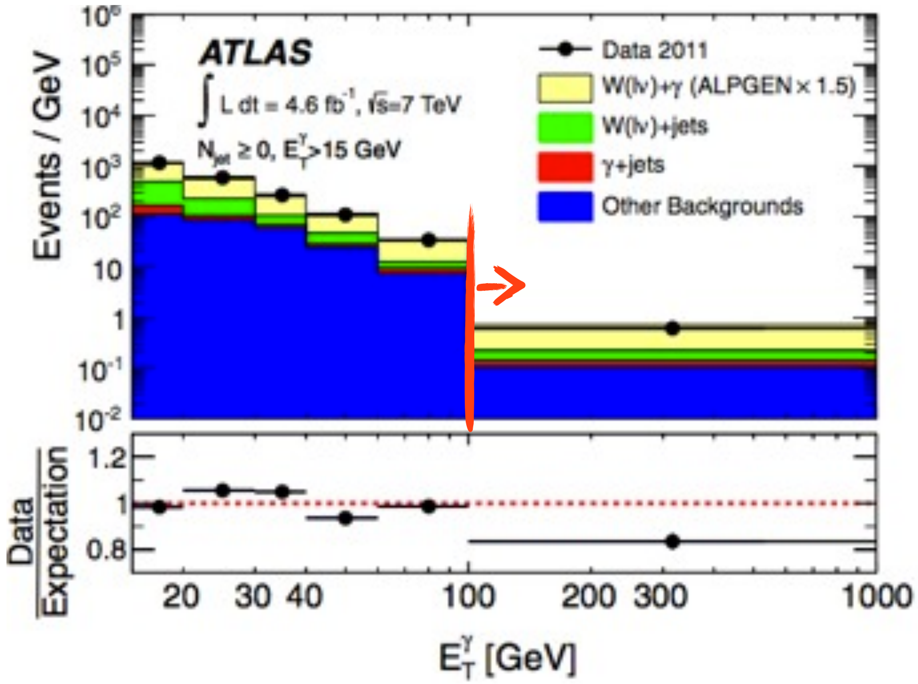
- Goal: set limits on TGC parameters → using WW, WZ, ZZ, Wγ, Zγ
  - all parameters expected to be zero
- Experimentally
  - we check deviations of the cross-section from the SM prediction
  - higher deviations are expected in the high energy range
  - maximum likelihood defined to set limits



WZ analysis

Wγ Analysis Overview

- ★ Analyzing ATLAS 2011 dataset
- ★ Signal:
  - Wγ → ℓνγ
- ★ Backgrounds estimated from data
  - W+jets, γ+jets → ABCD method
- ★ Other backgrounds (from MC)
  - Drell-Yan, WW/WZ/ZZ, top
- ★ Main systematic uncertainties
  - luminosity ~3.9%
  - photon identification ~6%
  - jet energy scale ~2-3%
  - EM scale and resolution ~1.5-3%
  - will improve with more stats!



ex-fid cross-section measurement [pb]

Njet ≥ 0: 2.77 ± 0.03 (stat.) ± 0.33 (syst.) ± 0.14 (lumi.)

Njet ≥ 0 (MCFM): 1.96 ± 0.17

Njet = 0: 1.76 ± 0.03 (stat.) ± 0.21 (syst.) ± 0.08 (lumi.)

Njet = 0 (MCFM): 1.39 ± 0.13

aTGC extraction: $p_T(\gamma)$ > 100 GeV, N_{jet} = 0

Defining the Likelihood

The probability that the number of **expected signal and background events** gives the number of **events observed** is regulated by a Poissonian function:

Number of expected signal and background events..

$$N_s^i(\sigma_{W\gamma}^{tot}, \{x_k\}) = \sigma_{W\gamma}^{tot} \cdot A \cdot C \cdot \int \mathcal{L}(t)dt \cdot (1 + \sum_{k=1}^{n} x_k S_k^i)$$

systematic uncertainties

$$N_b^i(\{x_k\}) = N_b^i(1 + \sum_{k=1}^{n} x_k B_k^i)$$

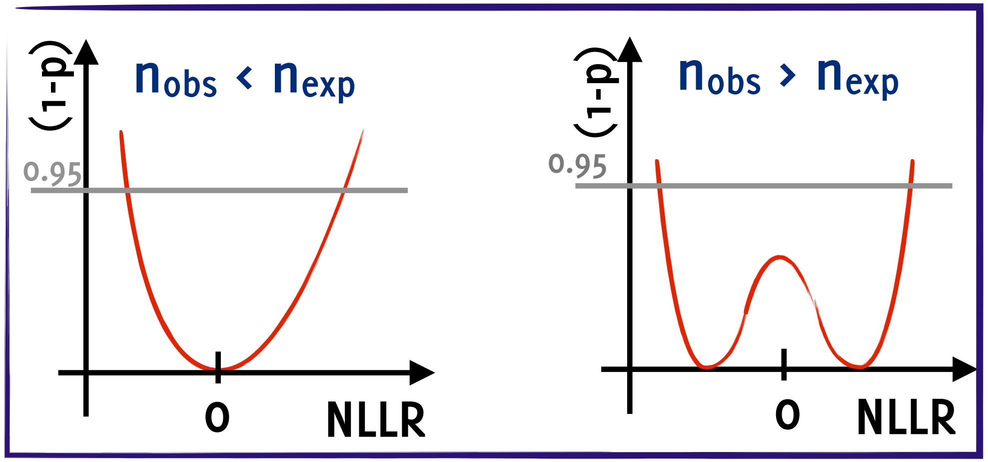
SM cross-sec

$$(p_0 + p_1 * \lambda_\gamma + p_2 * \Delta\kappa_\gamma$$
$$+ p_3 * \lambda_\gamma^2 + p_4 * \lambda_\gamma * \Delta\kappa_\gamma$$
$$+ p_5 * \Delta\kappa_\gamma^2) \cdot A \cdot C$$

→ **p_i** extracted from a multi-dimensional fit on MCFM MC

Using Frequentist Method for Limits Extraction

- TGC likelihood functions can have more than one minimum



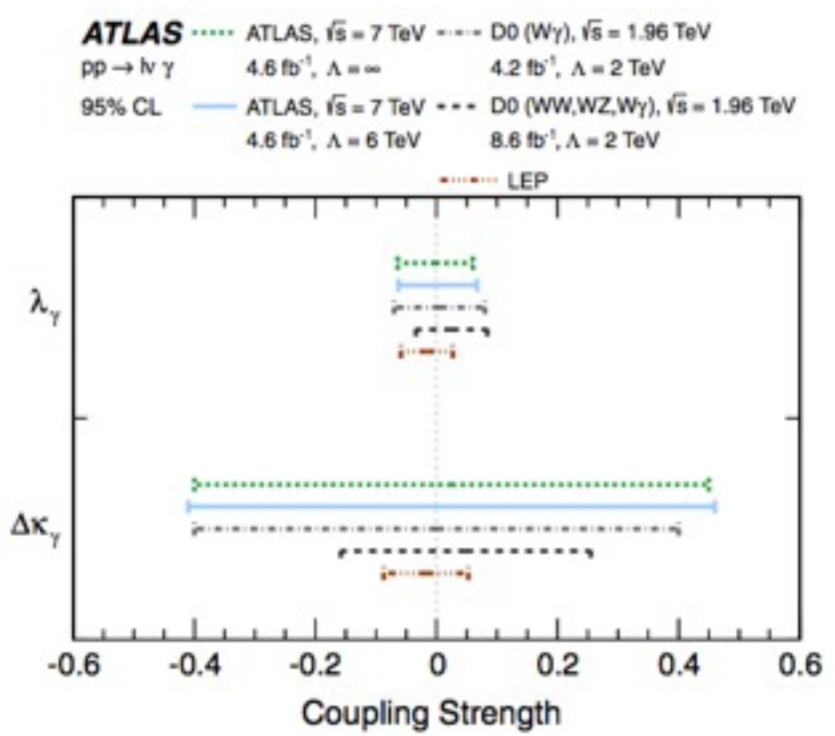
→ Maximizing the likelihood is not enough!

- Limits extraction
  - using negative log-likelihood ratio, function of:
    - → aTGC parameter (POI)
    - → nuisance parameters (systematic uncertainties)
  - applying frequentist procedure to look for 95% CLs interval
- Developed a tool for the extraction of TGC limits here at Saclay
  - now used in many other diboson analyses

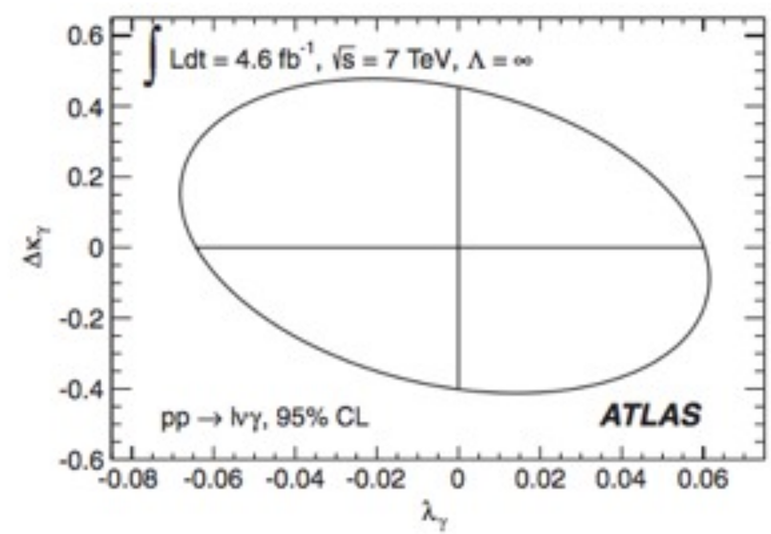
★ Indirect searches
★ Direct searches
★ Other ways: using the Higgs

Wγ Observed TGC Limits

1D limits



correlation



compatible with SM predictions

★ **My role:**
- Wγ background data driven estimates
- W/Zγ cross-section extraction
- W/Zγ TGC limits setting

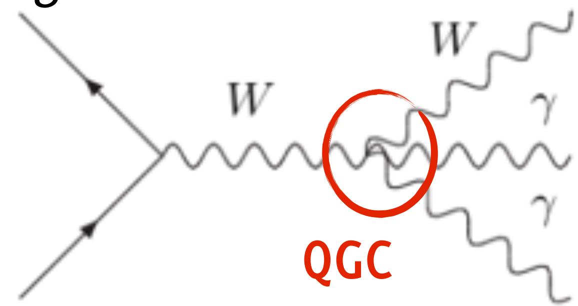
→ publications: [Phys. Rev. D 87, 11 (2013)]
→ one conference talk

Perspectives on aTGC and aQGC Measurements

- ★ **All channels studied with 2011 data @ 7 TeV → 4.7 fb^{-1} @ 7 TeV**
  - no deviations found wrt the Standard Model
- ★ **Sensitivity is still low!**
  - the channel with highest statistics Wγ gives $\Delta\kappa_\gamma < 0.4$ and $\lambda_\gamma < 0.05$
  - the "interesting" range is a factor 10 away → **$\Delta\kappa_\gamma \sim 0.01$ and $\lambda_\gamma \sim 0.001$**
- ★ **Improvements expected soon**
  - analyzing full 2012 data sample → **20.3 fb^{-1} @ 8 TeV**
  - **combining channels sensitive to the same couplings**
- ★ **Need to run at 13 TeV (→ higher sensitivity) and 100 fb^{-1} to probe the interesting region → 2 to 3 years of data taking**

First Look at Quartic Gauge Couplings: Wγγ

- LHC has opened **new era of Quartic Gauge Coupling** (QGC) measurements:
  - Vector Boson Scattering of particular interest → confirm unitarization
  - search for new resonances in the multi-TeV range
- Wγγ paper in preparation: **→ 20.3 fb^{-1} @ 8 TeV**
  - fiducial Wγγ production cross-section
  - first QGC limits at ATLAS
- QGC **extraction**:
  - same techniques as for TGCs

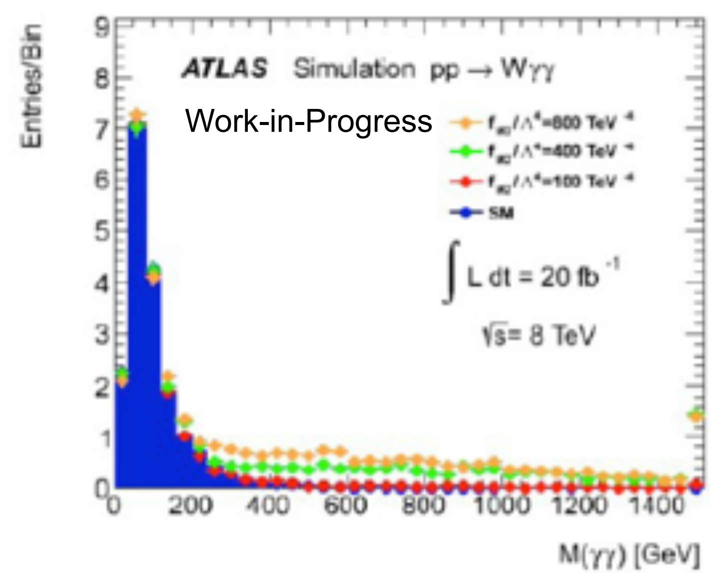


...many other vertices

★ **My role:**

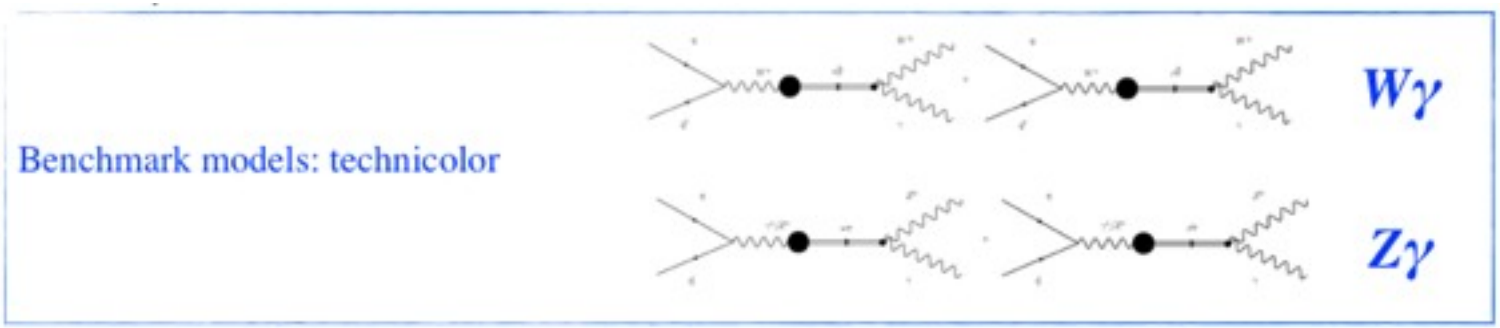
- contact person of the analysis and editor of the publication
- responsible for the cross-section measurement

→ **publication on PLB forseen before March 2014**



Direct, Model Independent Searches

★ **Goal: perform model-independent searches for new resonances decaying to W(ℓν)γ or Z(ℓ)γ final states**



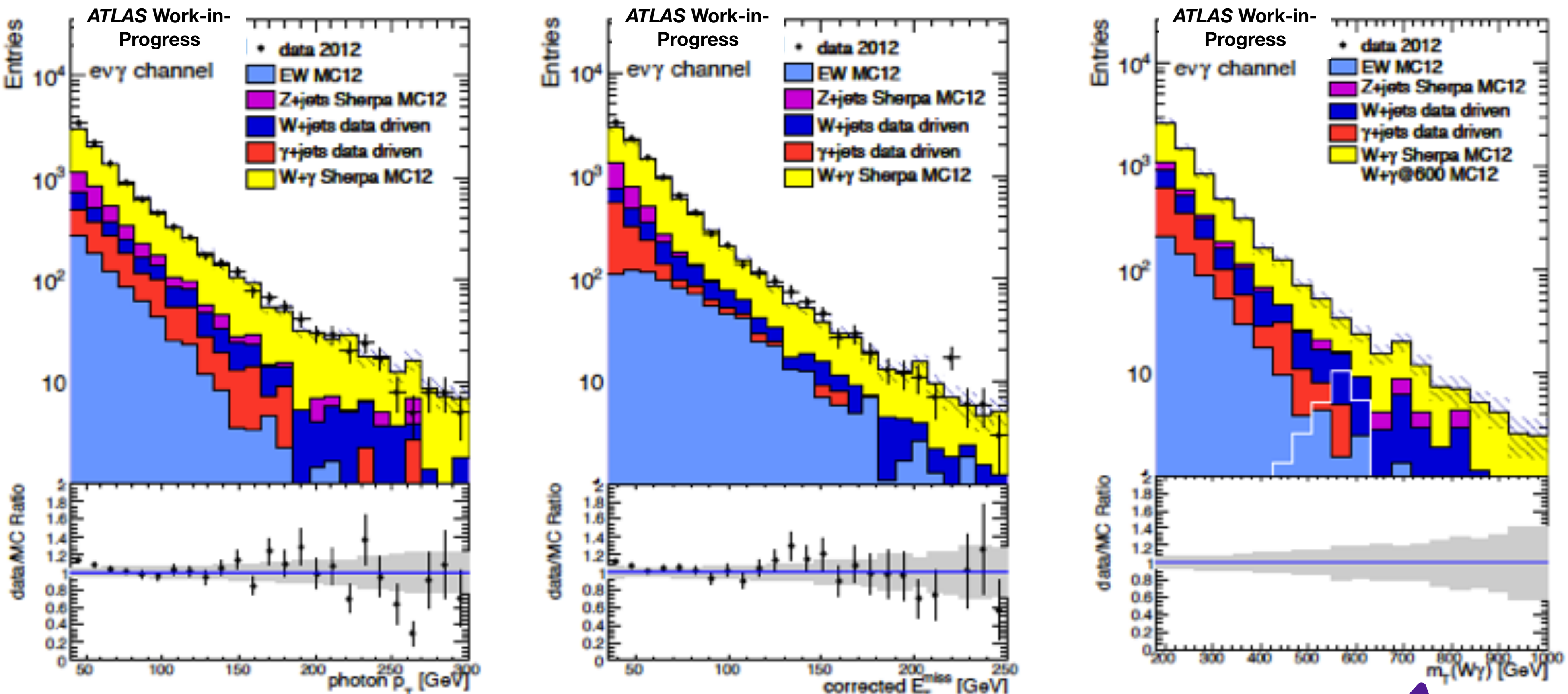
★ **Strategy:**

- Study background composition in "SM" dominated region
- Perform signal+background fit on $m_T(W\gamma)$ for different signal massese
- Extract exclusion/discovery limits by using ATLAS frequentist approach

★ **My role:**

- Main author of Wγ analysis: from background estimates to statistical treatment
- Editor of the publication (PLB in preparation)

Background Composition



Checking data-MC agreement, $m_T(W\gamma)$ is blind

MASS MODELLING FOR SIGNAL EXTRACTION

- Performing unbinned extended maximum likelihood mass fit

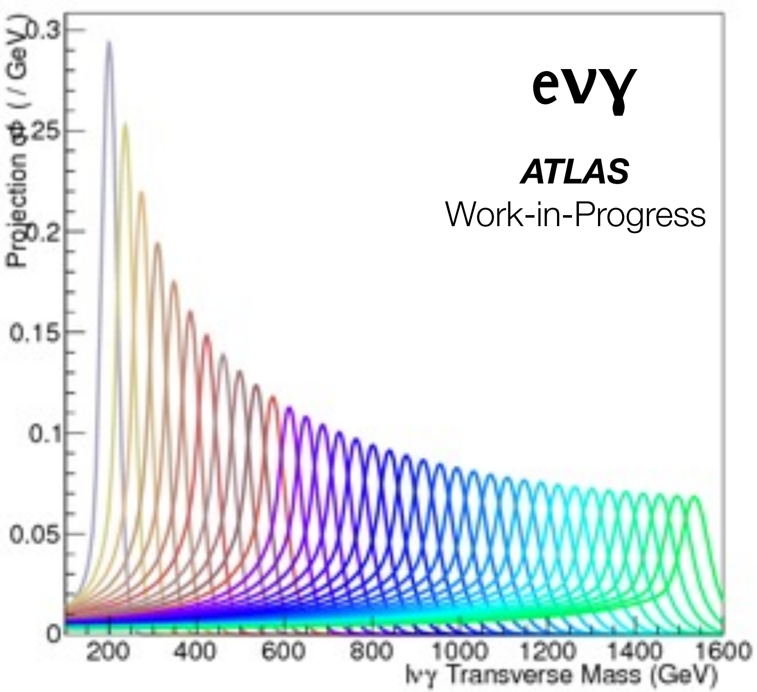
$$\mathcal{L} = \prod_{categories} \text{Pois}(N_{sig} + N_{bkg}) \cdot \prod_{\text{events}} f_{sig} \cdot PDF_{sig}(m_T(W\gamma)) + (1 - f_{sig}) \cdot PDF_{bkg}(m_T(W\gamma))$$

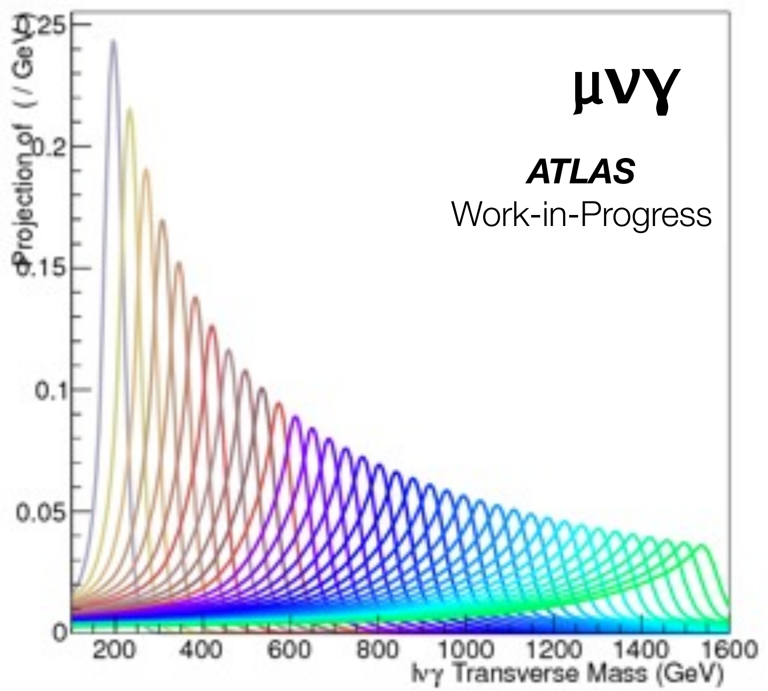
- Signal pdf: Gaussian + Crystal Ball (CB)
- Background pdf:
  - **baseline:** sum of two exponentials

empirical

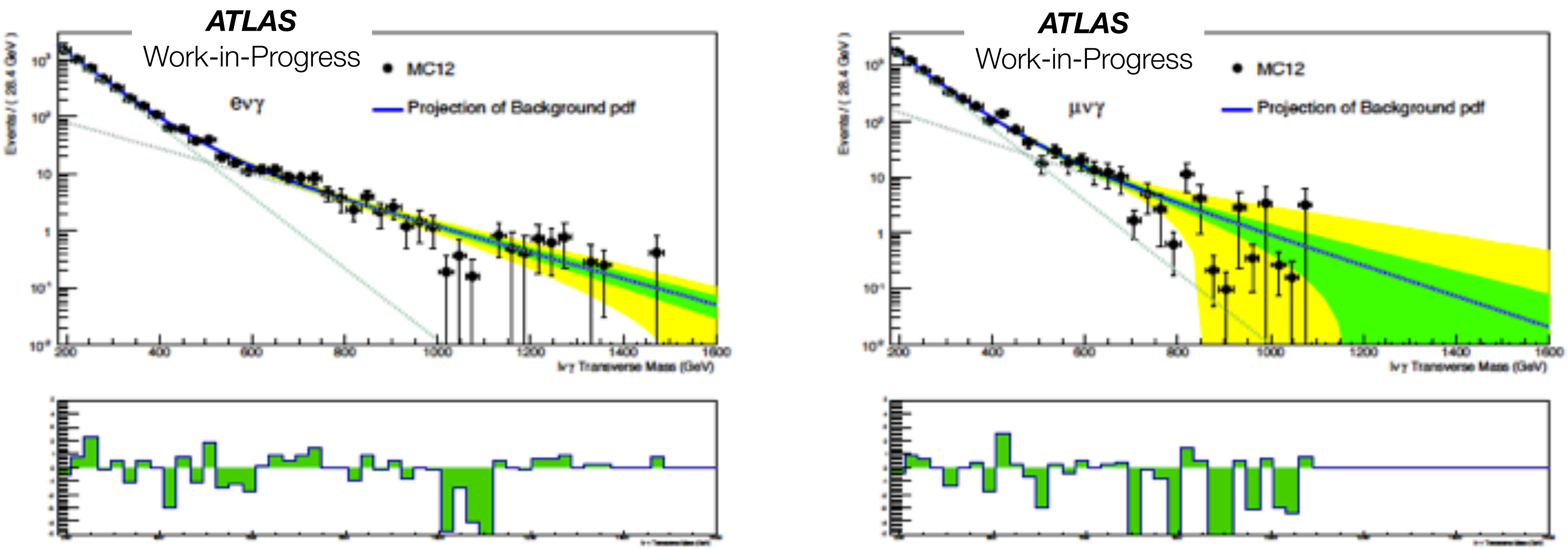
Signal Modelling Overview

- **Wγ signal pdf:**
  - empirical model optimized on benchmark MC samples
  - extrapolation for masses in between
  - very different resolutions at low and high mass and between decay channels





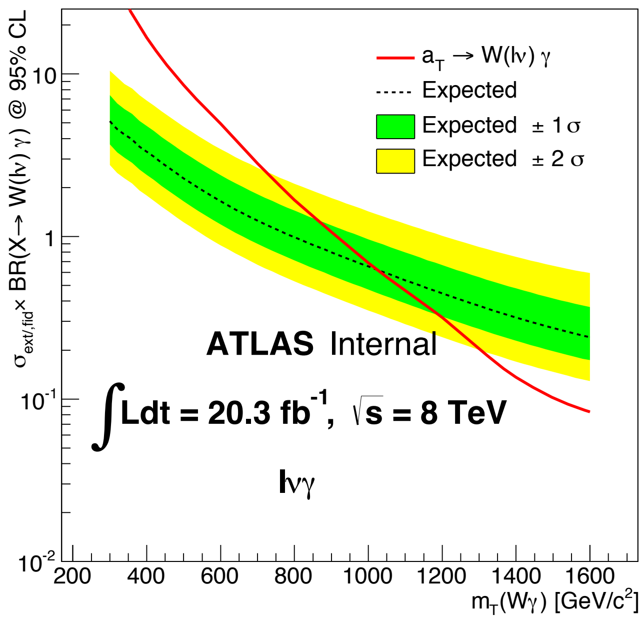
Background Modelling Overview



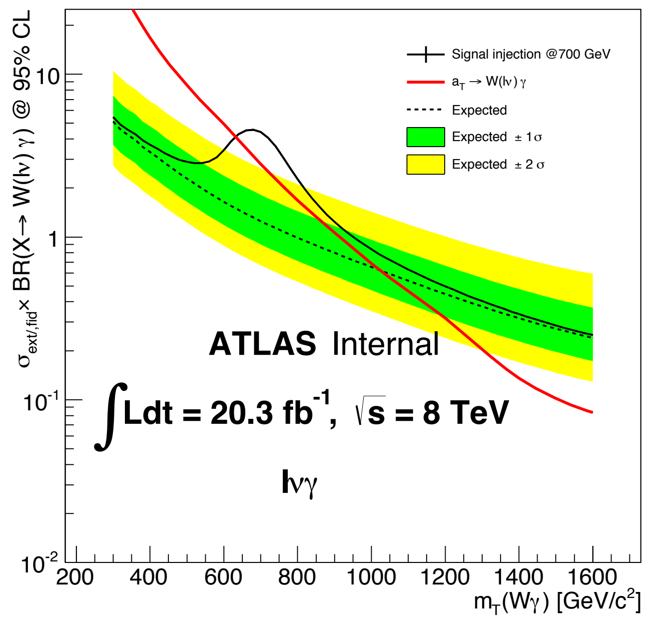
- **Wγ background pdf:**
  - using background expectations (from MC and data driven estimates) to optimize the background shape
- **NB:** the parameters used in the final limits extraction will be those taken from a **direct fit on data**

Expected Limits @ 8 TeV

expected for background only hypothesis



signal injection at $m_T(W\gamma)$ = 700 GeV



- **Main systematics:**
  - normalization: luminosity, γ ID, γ isolation
  - shape: small uncertainty on resolution
- **Final steps of the analysis on-going:**
  - unblinding of 2012 data → **expected next week**

2011 exclusion ~ 700 GeV

Higgs-Candidate as a Probe to Look for New Physics

in summer 2012 a new Higgs-like particle is found

- The discovery of a new Higgs-like particle opens a number of measurements
  - ★ significance, mass and couplings
  - ★ **spin-parity**
- These allow to test the new particle → is it a SM Higgs? Is it new physics (composite Higgs)? **Does it point to new physics (CP violation terms, supersymmetric partners)?**

★ **My role:**

- development of the MELA framework on $H \to ZZ^{(*)} \to 4\ell$
- understanding of detector acceptance and selection effects
- contribution to systematic uncertainties estimate
- extraction of signal/background hypotheses separations
- **editor** of the spin-parity part of ATLAS-CONF-2013-013

→ publications: ATLAS-CONF-2012-169, ATLAS-CONF-2013-013, Phys. Lett. B 726, 1–3 (2013)

→ one talk at LHC France

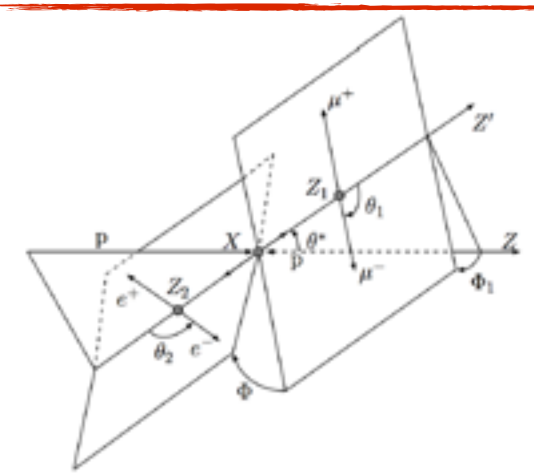
Observables and Separation Power

$H \to ZZ^{(*)} \to 4\ell$ is very clean, and the full decay kinematic is measured

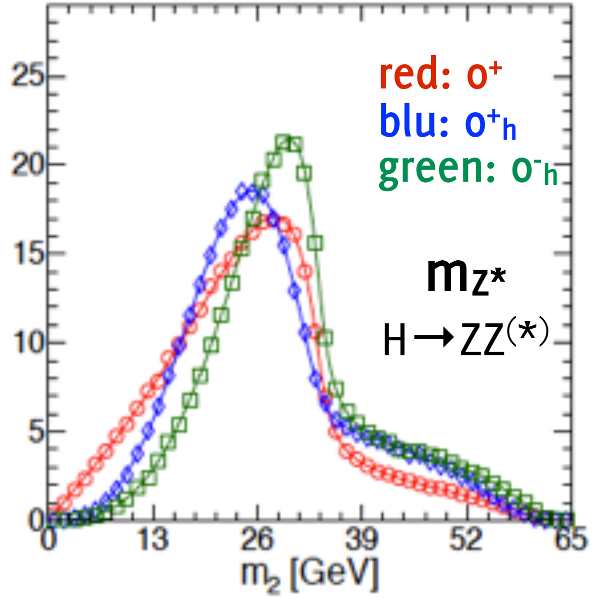
Defining a 1D discriminant from all the observables sensitive to J^P:

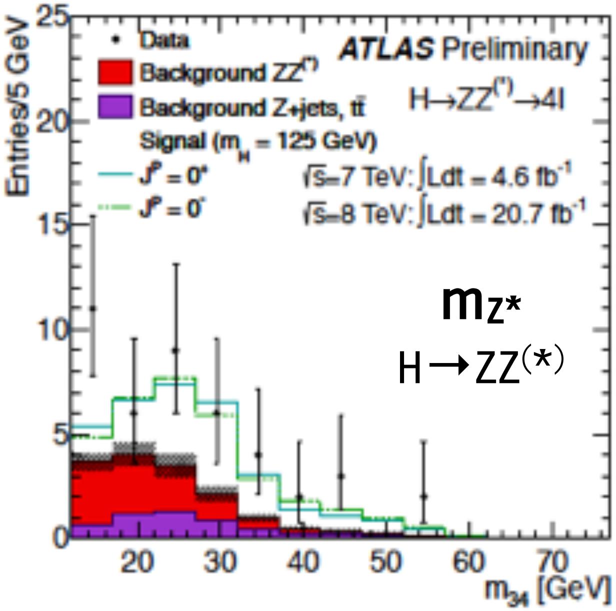
m_1, m_2, $\cos\theta^*$, ϕ_1, $\cos\theta_1$, $\cos\theta_2$, ϕ

Separation power is altered by background presence and selection effects



production and decay angles definition





Spin Measurement in $H \to ZZ^{(*)} \to 4\ell$ Decay

- Discriminant definition: **two independent methods are used**
  - ★ **BDT approach:** Boosted Decision Tree trained on MC signal samples
  - ★ **MELA approach:** Bayes Likelihood Ratio multivariate discriminant from **matrix element** description of the decay

→ **using full theoretical description of signal final state**
→ **includes corrections for detector/selection effects: inefficiencies, ZZ mis-pairing [extracted from fully simulated JHU MC]**

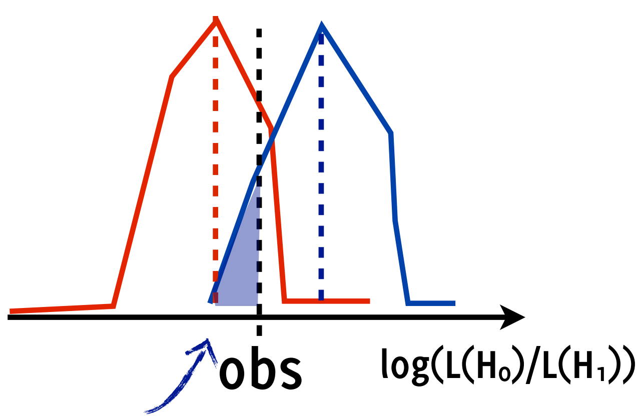
- Main systematic uncertainties
  - ★ reconstruction: electron ES, mis-pairing fraction
  - ★ signal/background modelling: MC/control regions statistics, MC cross-sections
  - ★ mass regions migration

Separations in $H \to ZZ^{(*)} \to 4\ell$

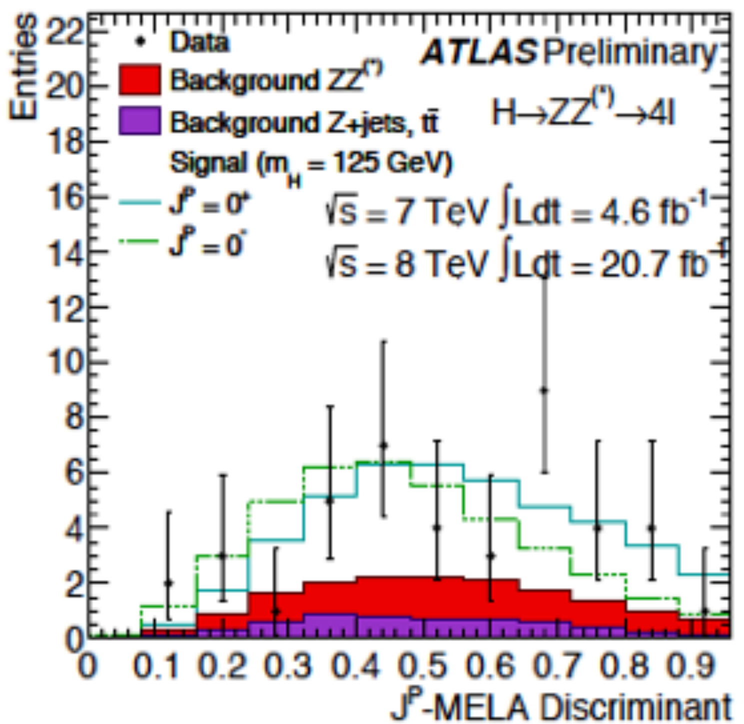
- J^P-MELA discriminant:

$$J^P\text{-MELA} = \frac{P(H_0)}{P(H_0) + P(H_1)}$$

- Test **one hypothesis (H_0) against another one (H_1)**
  - ★ assuming that the spin-parity is **0^+**
  - ★ testing against non-SM hypotheses: **0^-, $1^\pm$, $2m^\pm$**
  - ★ spin-2: varying ggF/$q\bar{q}$ production fraction



0⁺ vs 0⁻



SEPARATIONS IN $H\rightarrow ZZ^{(*)}\rightarrow 4\ell$

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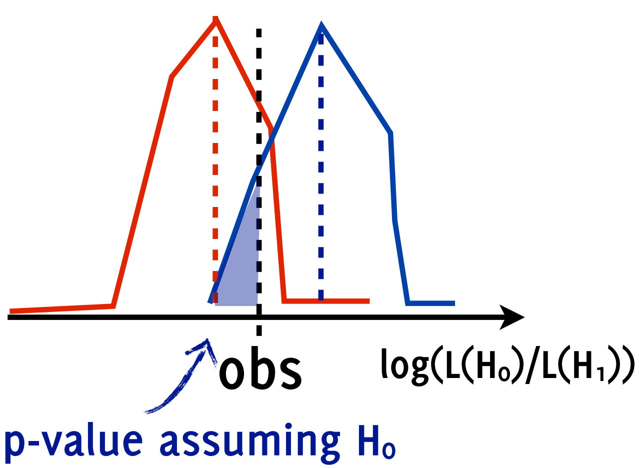
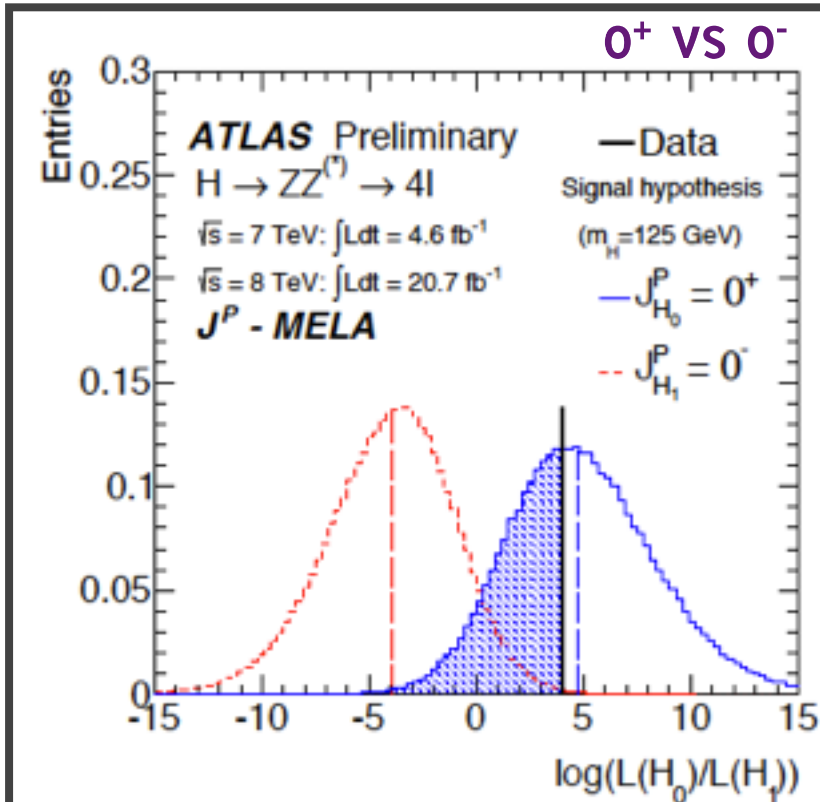




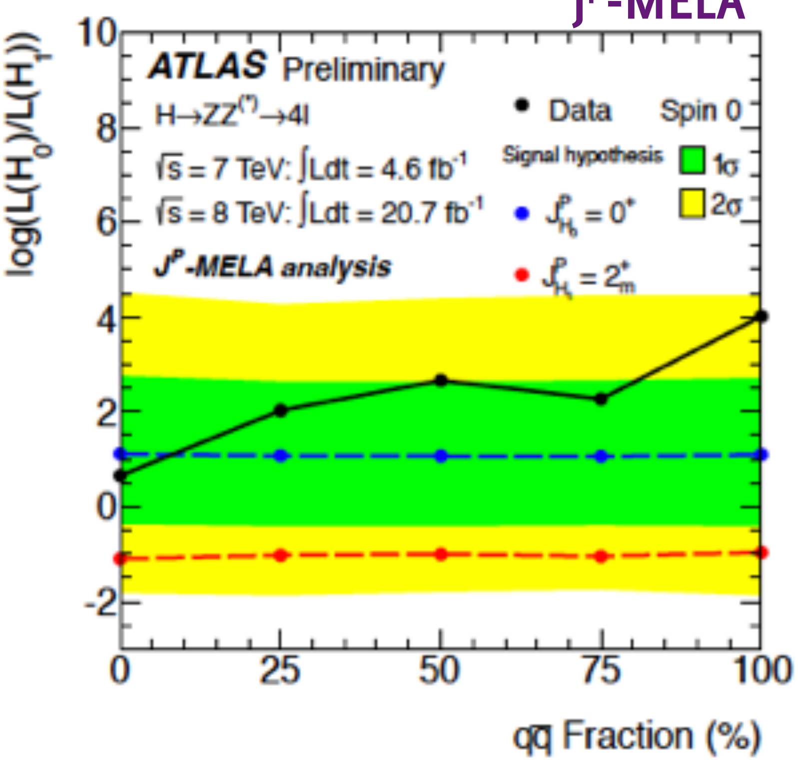
→ excluding 0^-, 1^+, 1^- at > 95% CL
→ data prefers the SM Higgs hypothesis

Study of Spin-2 Admixtures

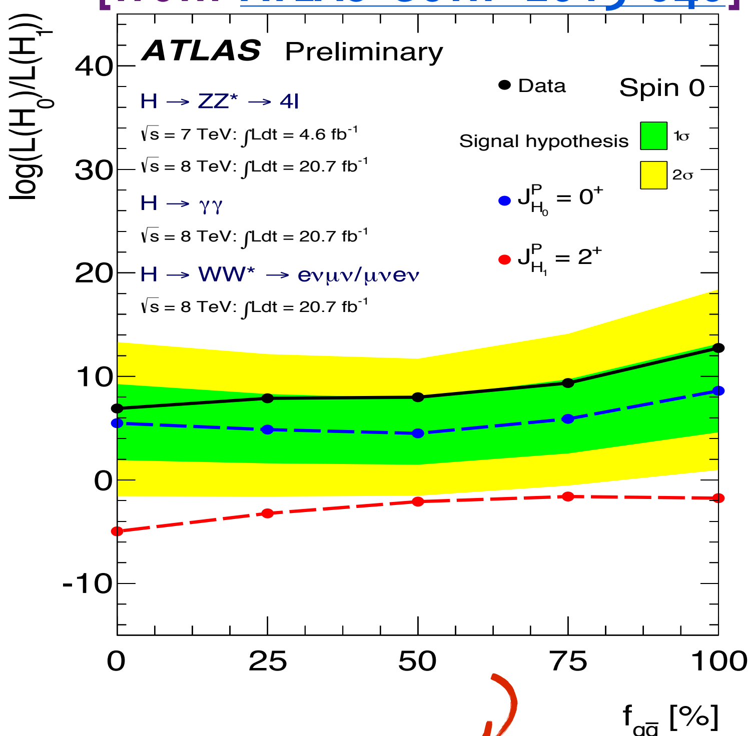
★ for spin-2: gluon-gluon fusion, $q\bar{q}$ production mechanisms or an admixture of the two are allowed

★ testing different spin-2 production mechanisms, $f_{q\bar{q}}$ **= 0, 25, 50, 75, 100%**

J^P-MELA



[from ATLAS-CONF-2013-040]



combining with γγ and WW excluding graviton-inspired spin-2^+ model at 99.9%

Conclusions and Plans

- **All these results (plus the huge work done on SUSY, exotics, SM precision measurements) indicate that the Standard Model stands his ground**
  - ★ no indications of new physics
  - ★ extraordinary result: discovery of new Higgs-like particle!
- **There are open issues still**
  - ★ dark matter: new matter? new force?
  - ★ naturalness and fine tuning problems → new physics at the TeV scale

    we just reached the TeV scale, but haven't quite explored it yet
- **My plans for the near future**
  - ★ pursue searches for new physics in preparation of the 13 TeV data
  - ★ participate to the ATLAS trigger upgrade: plans to join the Saclay effort on the New Small Wheels in the spring