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

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09.02.2016

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Je Me Présente

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 - Sept 2015

★ Post-Doctorate at CEA Saclay

- Diboson production for SM measurements and new physics searches at ATLAS

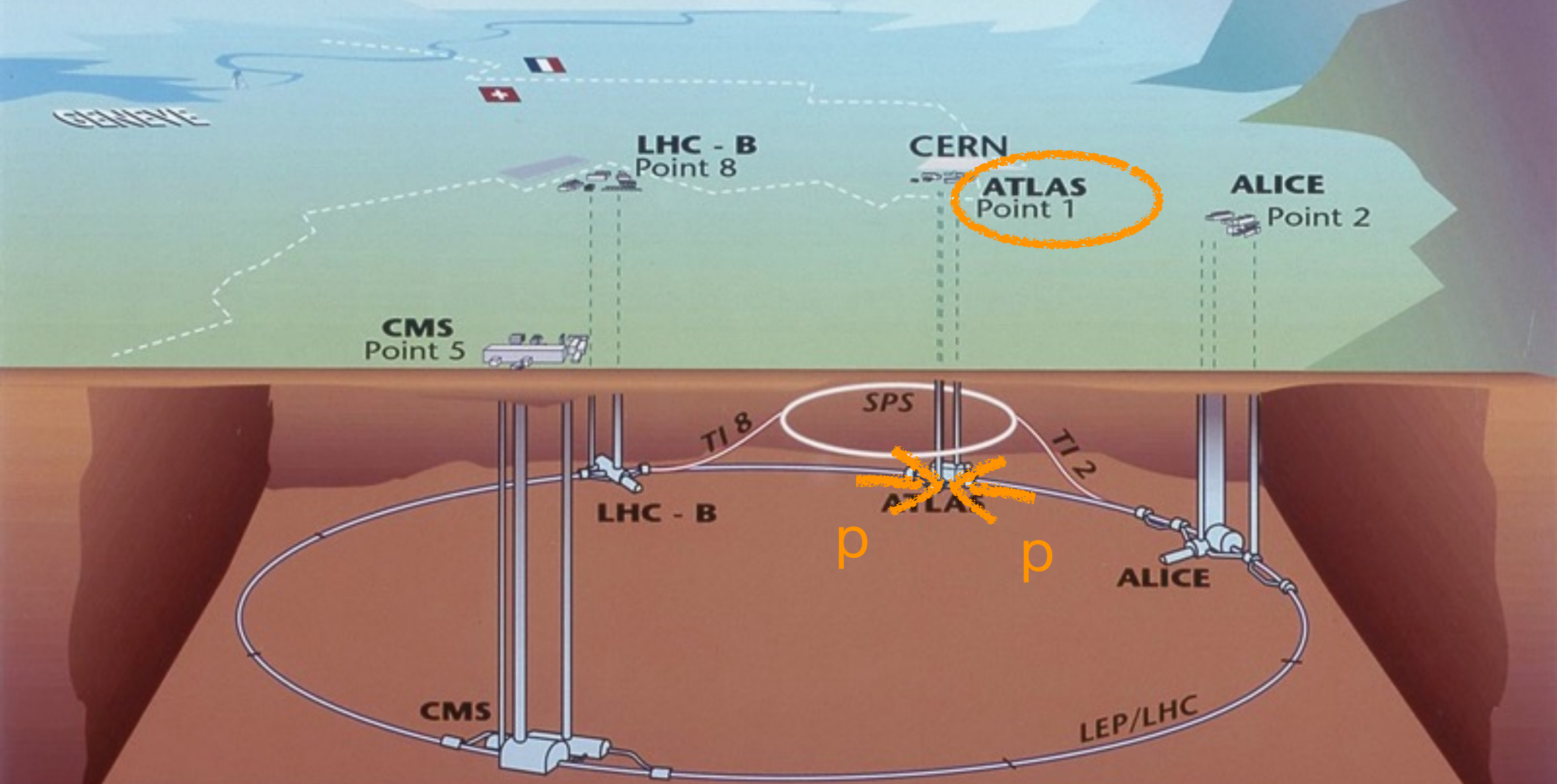
Oct 2015 - Sept 2017

★ Post-Doctorate at LAL Orsay

- Searches for Higgs and Higgs-like resonances decaying to $b\bar{b}$ pairs

Overall view of the LHC experiments.

- Proton-proton collider
- 27 Km of circumference
- Four experiments at the four interaction points



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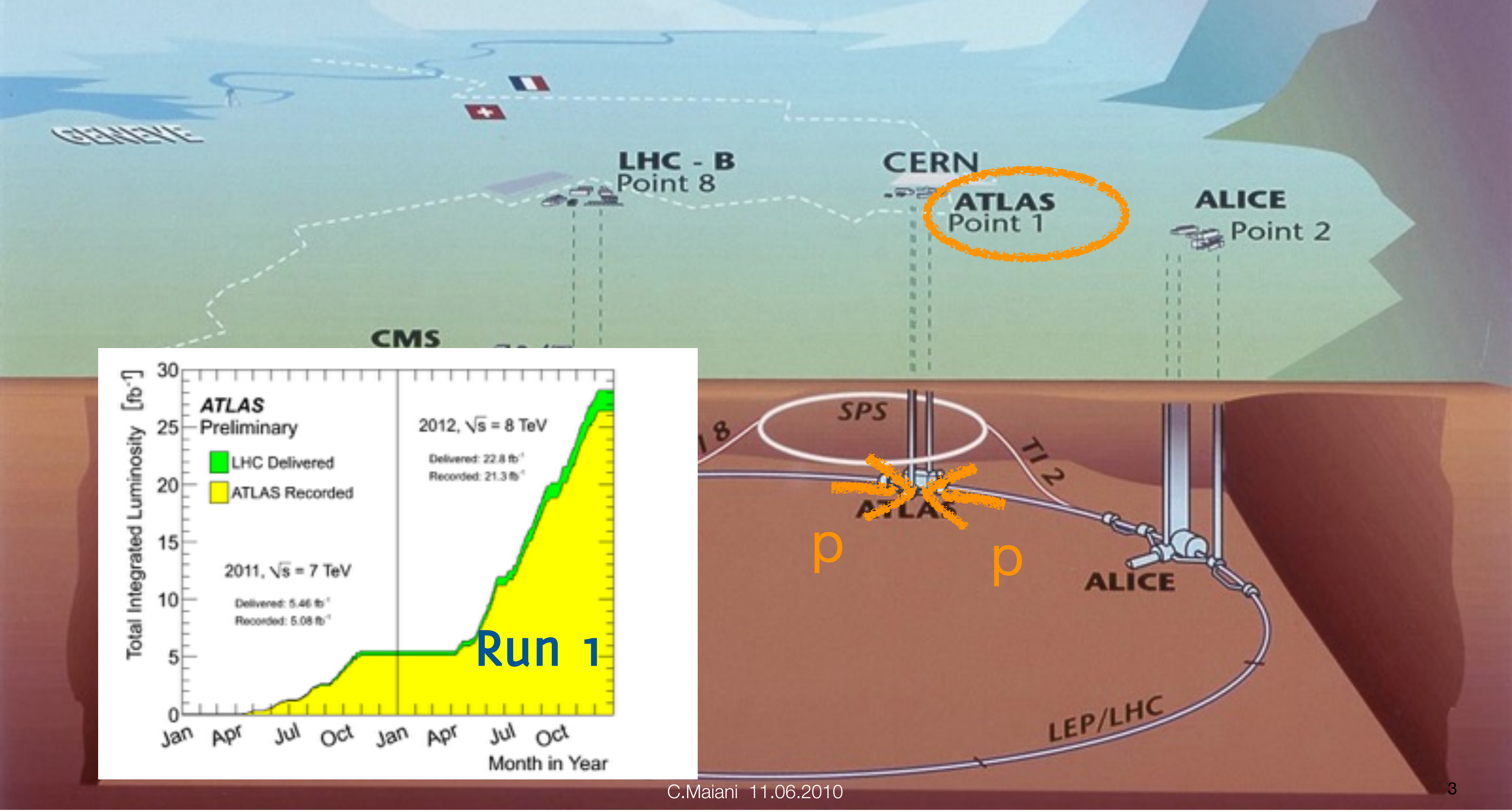

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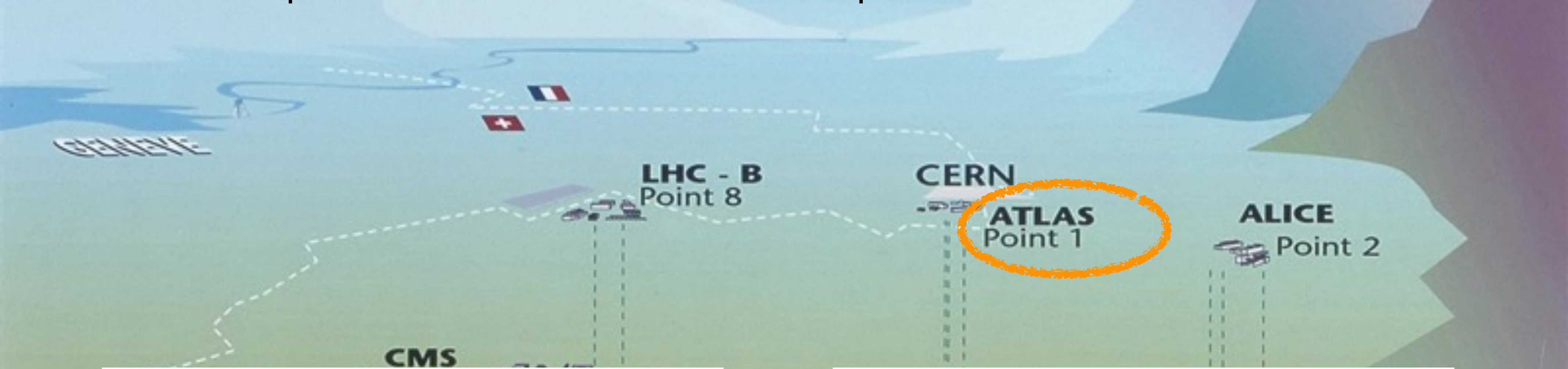
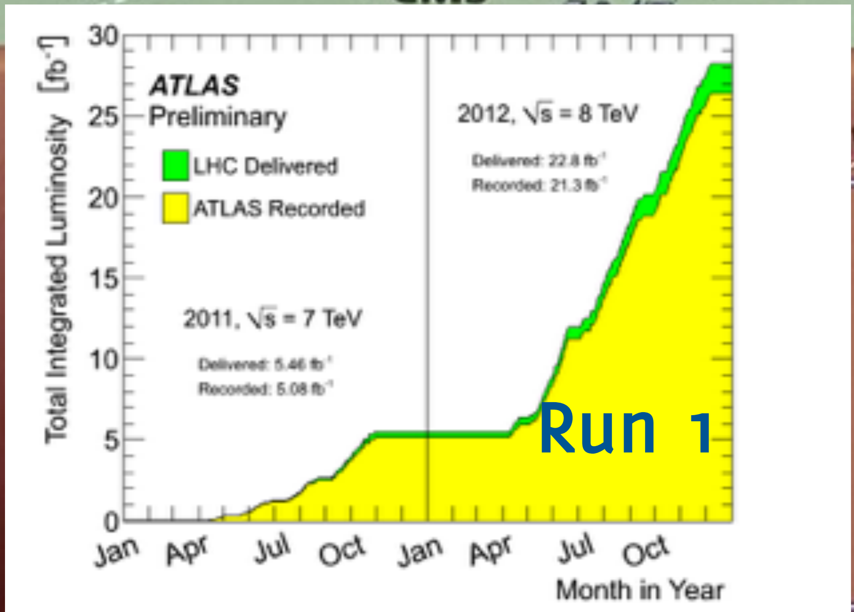
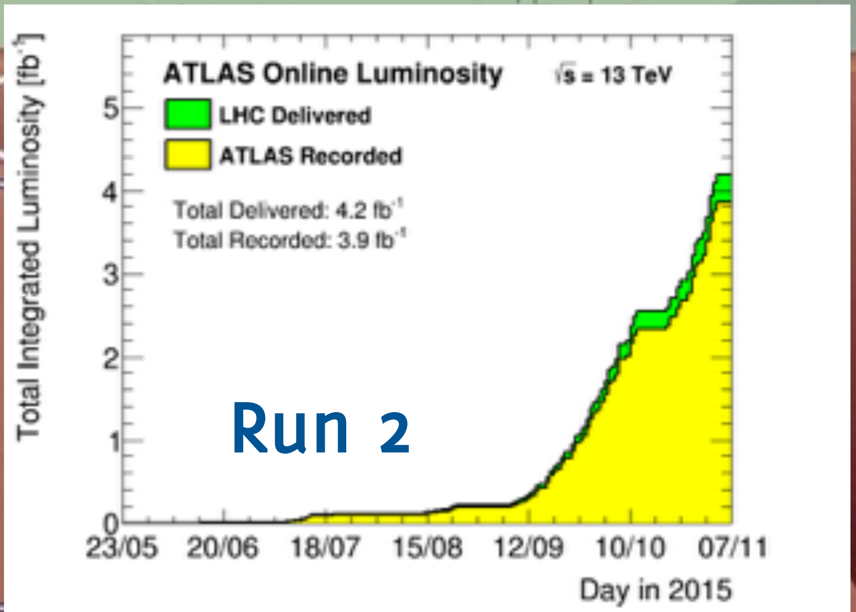
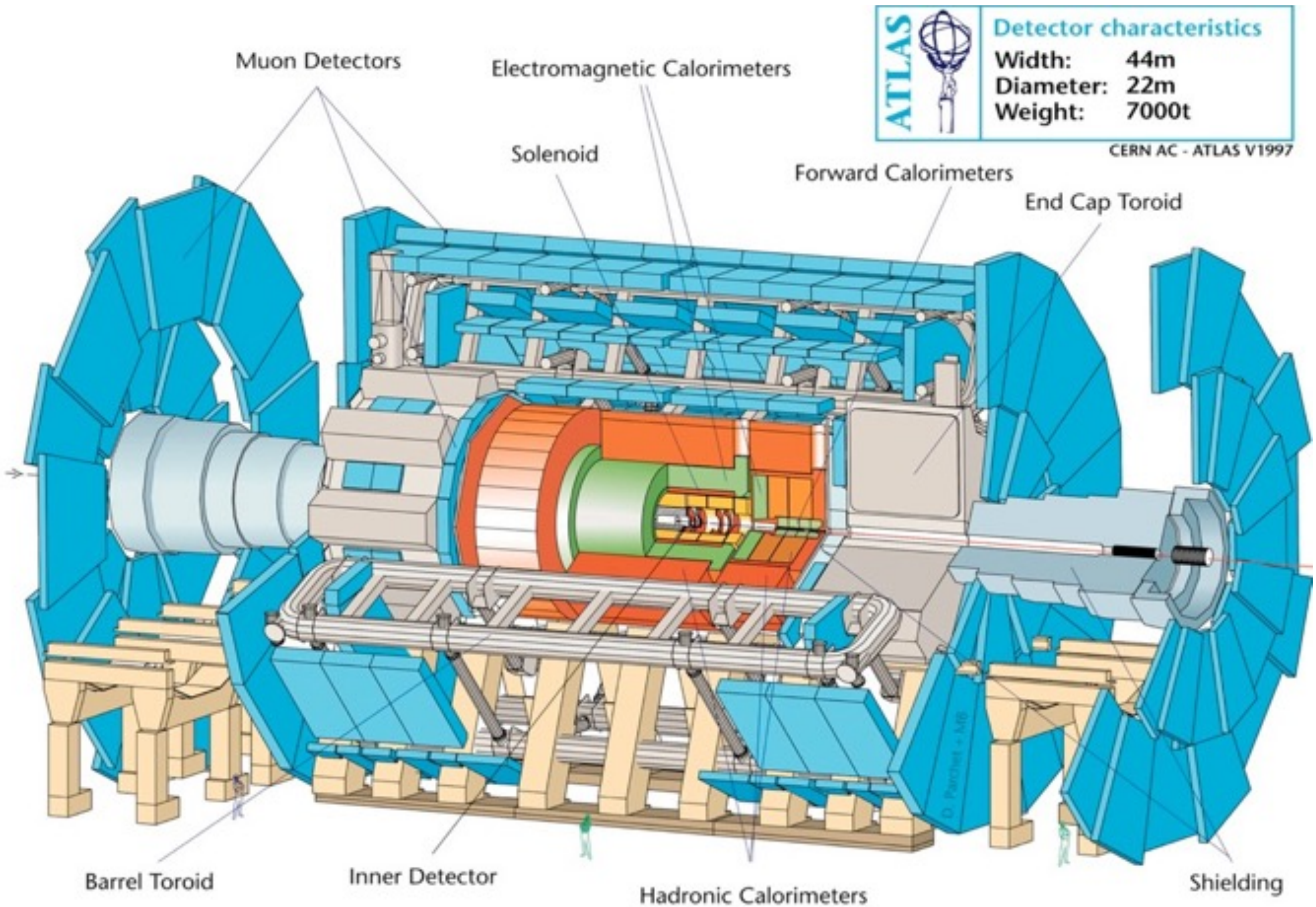


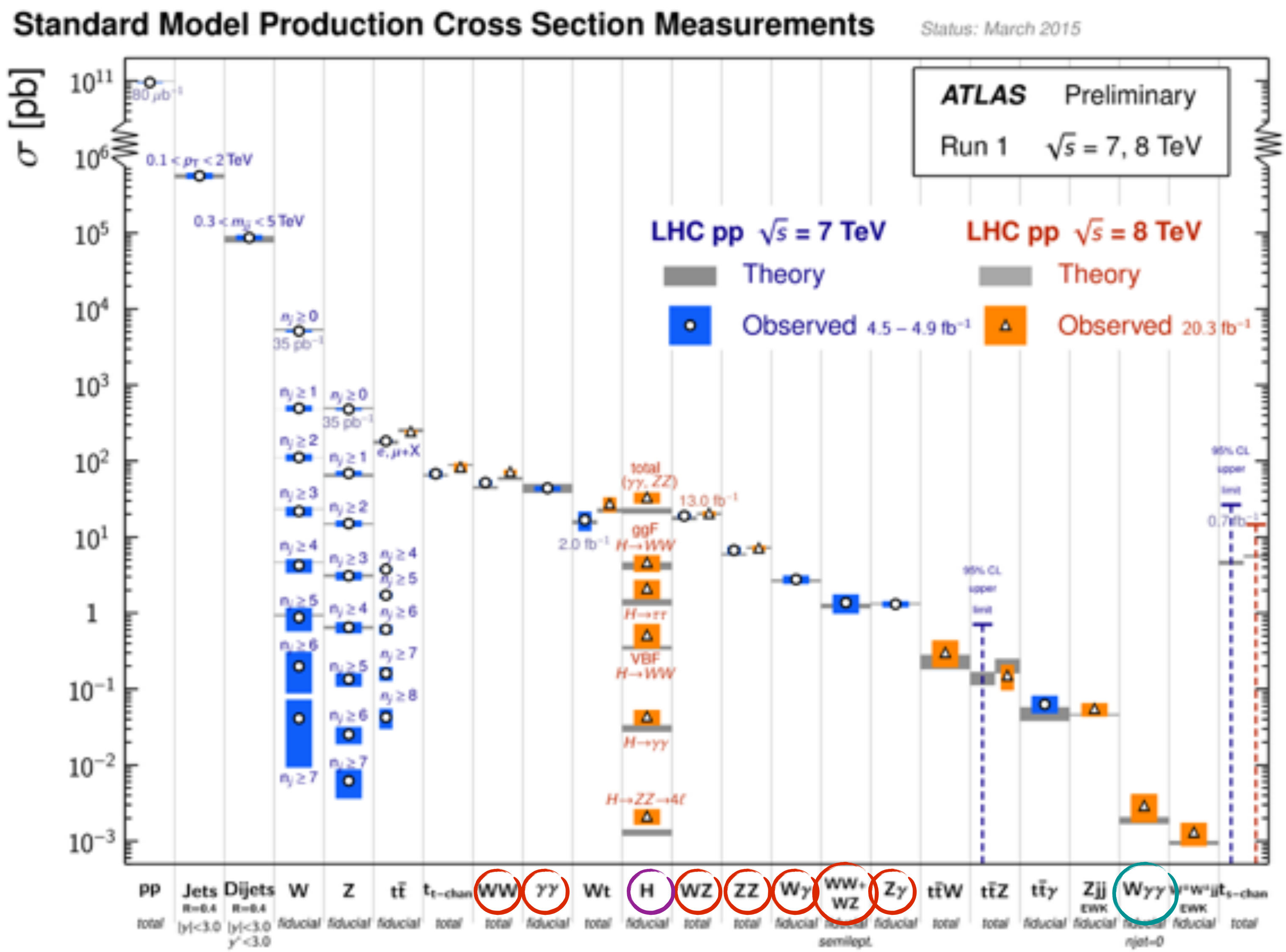




The ATLAS Experiment at LHC

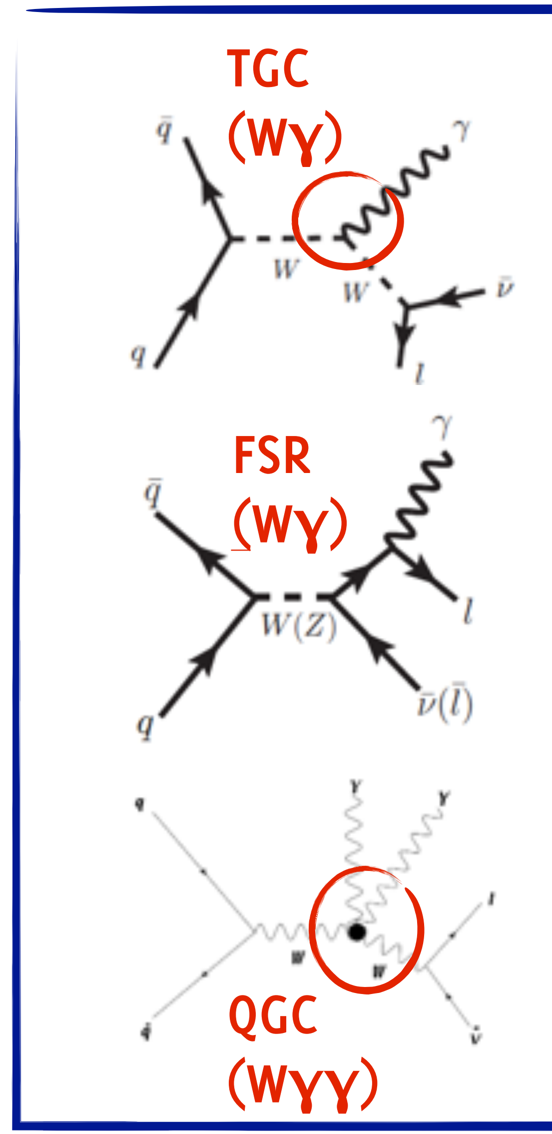


Physics Motivation: LHC Run 1 Legacy



Physics Motivation: Multi-Boson Measurements Allow for…

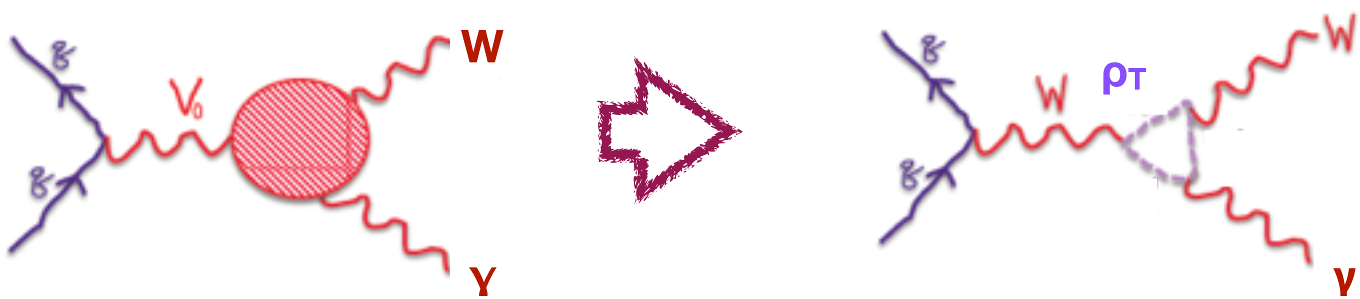
- ★ Precision tests of the Standard Model
  - cross-section measurement
    - → **Wγ final state**
- ★ **Indirect searches** for new physics
  - new physics → modifies Triple/Quartic Gauge Couplings (TGC, QGC)
    - → **Wγ and Wγγ final states**
- ★ **Direct searches** for new physics
  - resonances decaying to multiboson final states
    - → **X→W/Zγ , X→VH→ννb$\bar{\text{b}}$**
- ★ Higgs measurements
  - → **first spin-parity measurement with H→ZZ→4ℓ**



Chapter 1: Indirect Searches

Indirect Searches via Anomalous TGC measurement

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



parameters measurable in Wγ

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

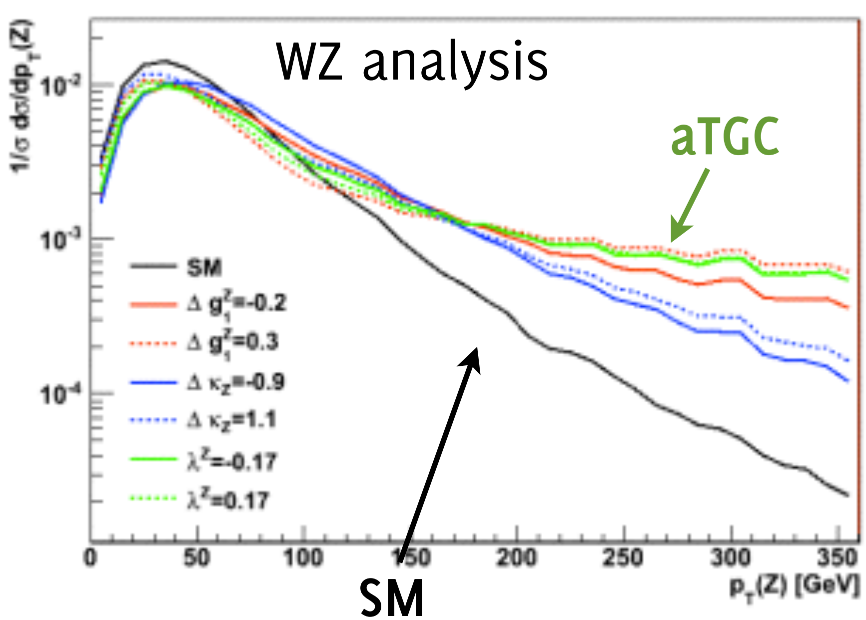
Deviations from the SM could:

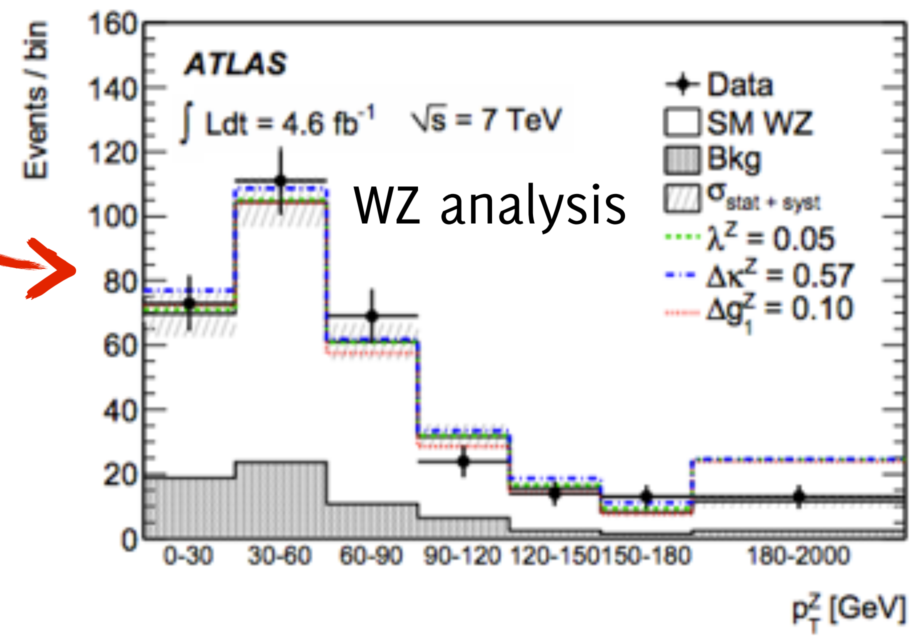
→ **modify** allowed triple gauge couplings

→ **introduce** new ones...

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

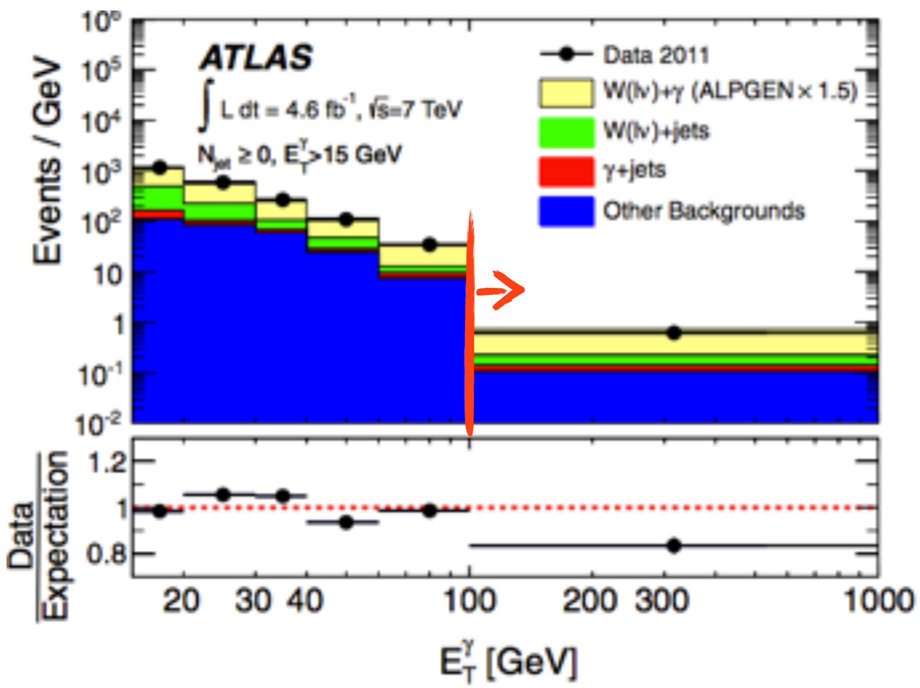




* Indirect searches
* Direct searches
* Other ways: using the Higgs

Wγ Analysis Overview

* Analyzing ATLAS 2011 dataset
* Signal:
  - $W\gamma \rightarrow \ell\nu\gamma$ (ℓ = e, μ)
* 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

Limits Extraction

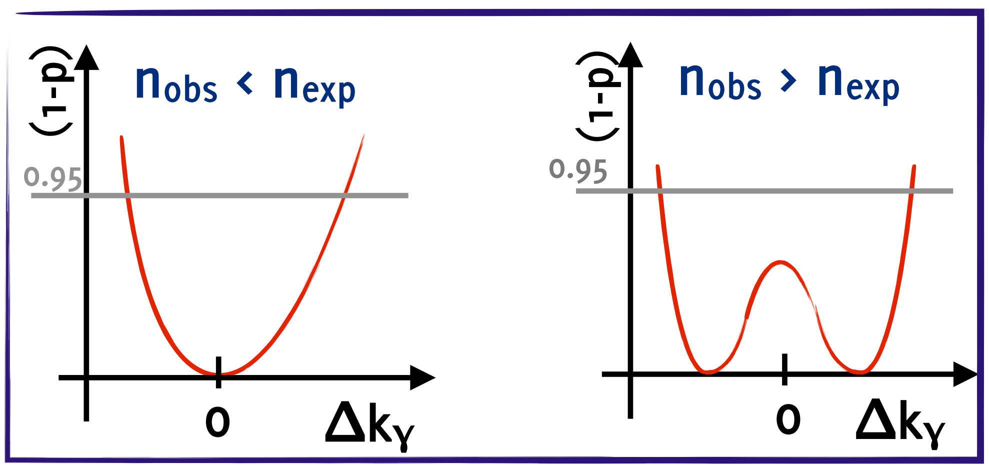
* The likelihood function is a Poissonian depending on **N**obs and **N**exp:

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

SM cross-sec

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

* TGC likelihood functions can have more than one minimum

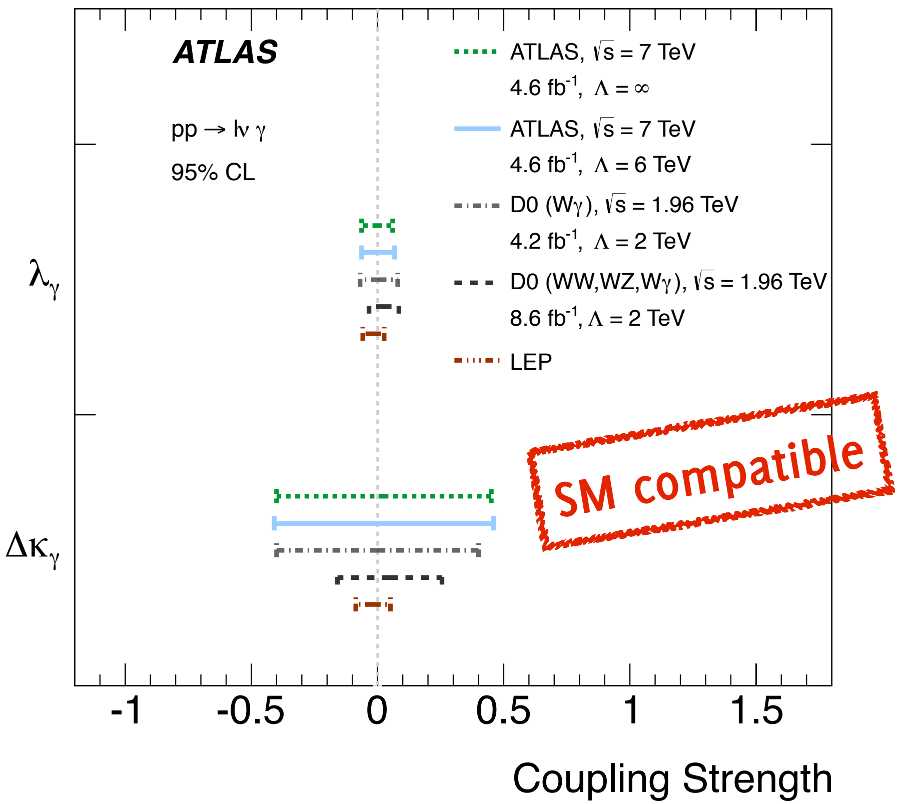


→ Maximizing the likelihood is not enough!

* Limits extraction
  * using negative log-likelihood ratio
  * applying frequentist procedure to look for 95% CLs interval

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

Wγ TGC Limits Extraction



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

★ **First measurement at such energies**
- Wγ → highest statistics channel
- sensitive to: λ_γ, Δk_γ
- still low sensitivity: the "interesting" range is a factor 10 away

→ $\Delta\kappa_\gamma \sim 0.01$ and $\lambda_\gamma \sim 0.001$

★ **Improvements**
- analysing full 2012 data sample
- combining channels sensitive to the same couplings
- run at 13 TeV and 100 fb^{-1} → 2-3 years of data taking

→ publications: Phys. Rev. D 87, 11 (2013)

Wγγ First Observation

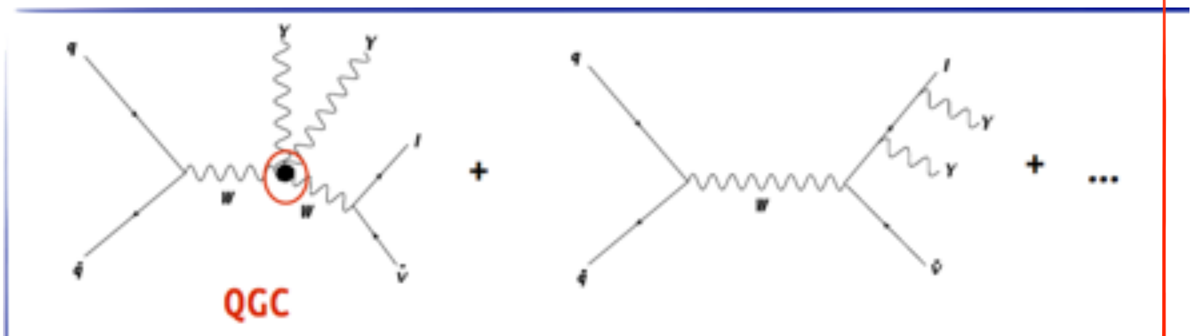
★ **Goal: First observation of triboson production**

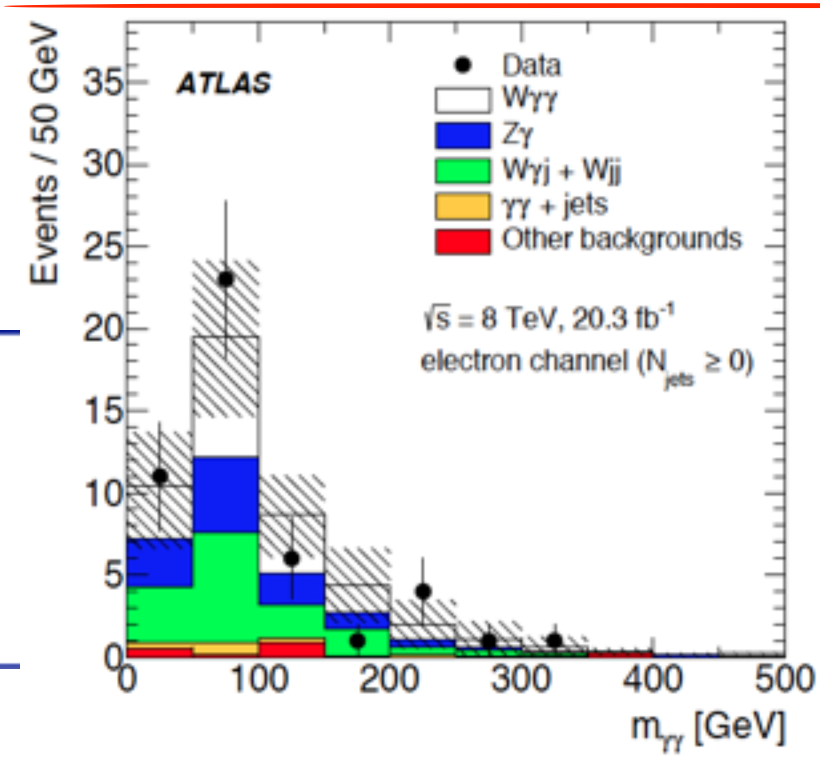
- Fiducial cross-section measurement
- Extraction of anomalous QGC limits

★ Using full 2012 ATLAS dataset, 20.3 fb^{-1} of p-p collisions data, $\sqrt{s}$ = 8 TeV

★ Main backgrounds:

- data driven: jets faking γ/leptons
- MC: Zγ, Dibosons, $t\bar{t}$





Wγγ Results

★ **Evidence** of Wγγ production at >3σ in the inclusive case ($N_{jet} \geq 0$)

★ Limits are set at 95% CL on aQGC parameters → **fully compatible with SM**

Cross-Section Measurement

	Cross-Section Measurement	MCFM@NLO
(Njet ≥ 0)	$\sigma^{\mathrm{fid}}(\ell\nu\gamma\gamma) = 6.1^{+1.1}_{-1.0}(\mathrm{stat.}) \pm 1.2(\mathrm{syst.}) \pm 0.2(\mathrm{lumi.})\mathrm{fb}$	2.9 ± 0.16
(Njet = 0)	$\sigma^{\mathrm{fid}}(\ell\nu\gamma\gamma) = 2.9^{+0.8}_{-0.7}(\mathrm{stat.})^{+1.0}_{-0.9}(\mathrm{syst.}) \pm 0.1(\mathrm{lumi.})\mathrm{fb}$	1.88 ± 0.20

★ **My role:**
- Cross-section extraction
- Responsible of the working team
- Editor of the publication

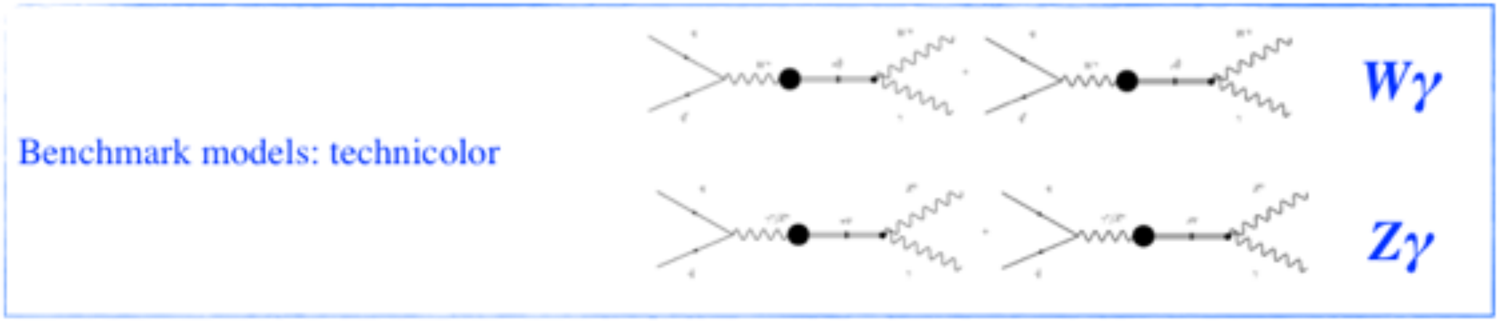
→ Phys. Rev. Lett. 115, 031802 (2015)

→ CERN courier article, last April issue

Chapter 2: Direct Searches

Direct Searches for Resonances Decaying To Wγ

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



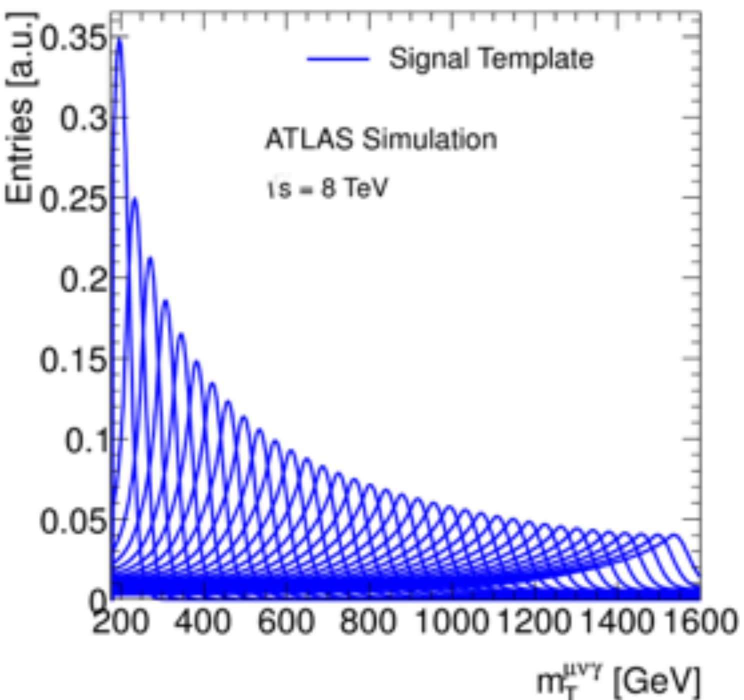
★ **Strategy:**

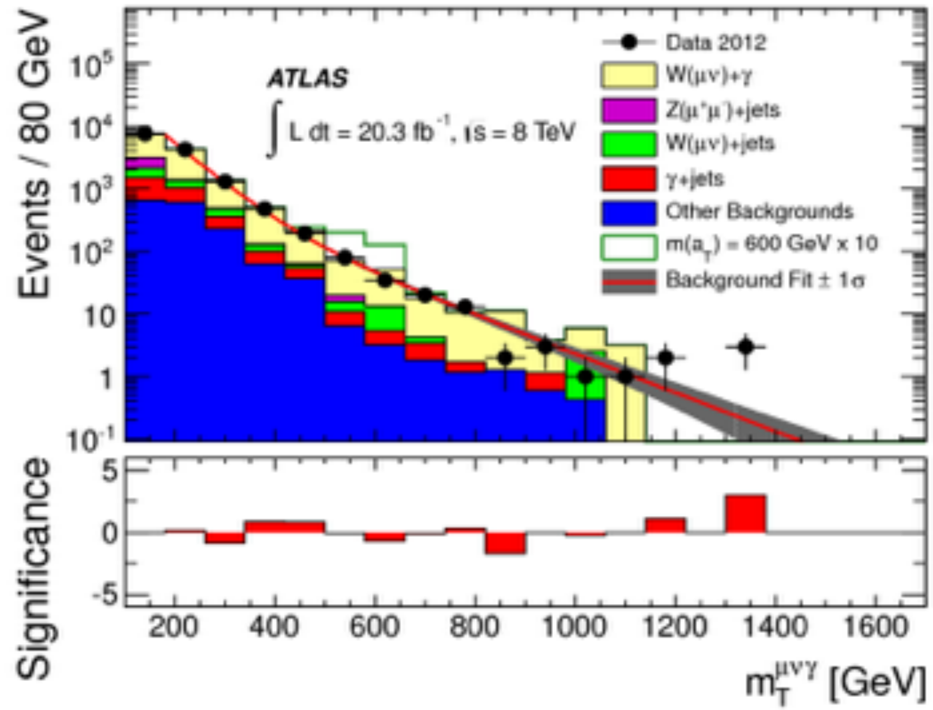
- Study background composition in “SM” dominated region
- Perform signal+background fit on $m_T(W\gamma)$ for different signal massese
- Extract exclusion/discovery limits by using ATLAS frequentist approach

★ **My role:**

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

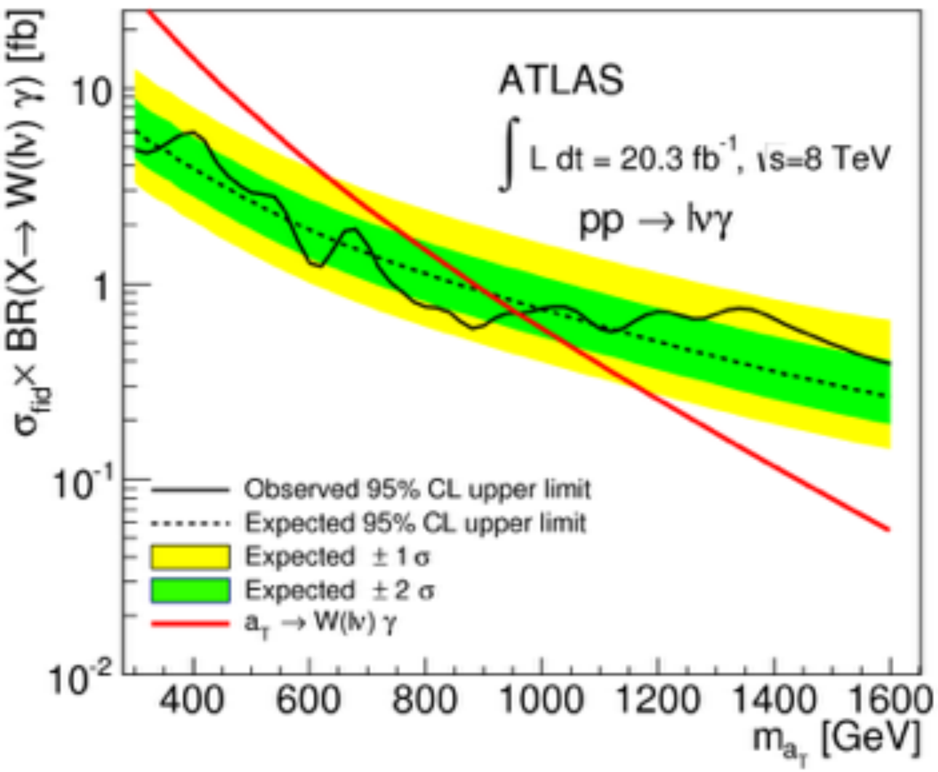
Signal and Background Modelling Overview

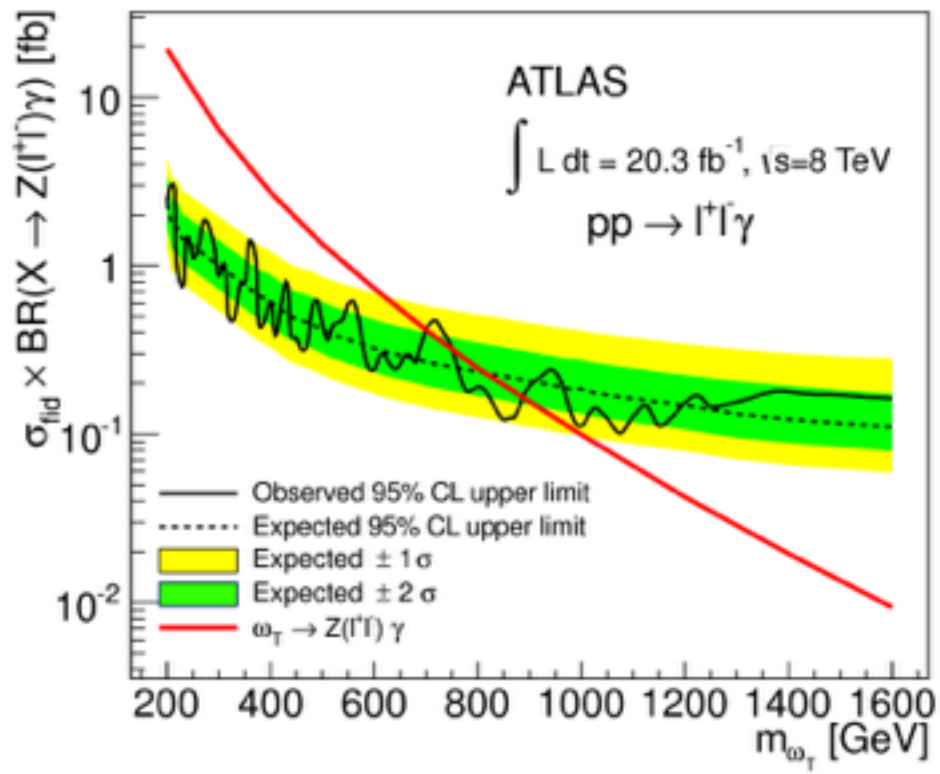




- **Wγ signal pdf:**
  - optimized on benchmark MC samples
- **Wγ background pdf:**
  - using background expectations (from MC and data driven estimates) to optimize the background shape
- **NB:** the parameters used in the final limits extraction are taken from a **direct fit on data**

Results





* **Extracting 95% CL limits**
  - exclusion for masses below 960 GeV in the Wγ analysis
  - exclusion for masses below about 900 GeV in the Zγ analysis

→Phys. Lett. B 738 (2014)

Chapter 3: Higgs Parameters Measurements

Higgs-Candidate as a Probe to Look for New Physics

In summer 2012 a new Higgs-like particle is found

- The discovery of the new Higgs-like particle prepares the path for a number of measurements
  - ★ significance, mass and couplings
  - ★ **spin-parity**
- These allow to test the nature of the new particle → is it a SM Higgs? Is it new physics? Does it point to new physics (CP violation terms, supersymmetric partners)?
- Diboson channels play an important role in the Higgs parameter measurements
  - ★ $H \to ZZ^{(*)} \to 4\ell$ is very clean, and the full decay kinematic is measured

Observables and Separation Power

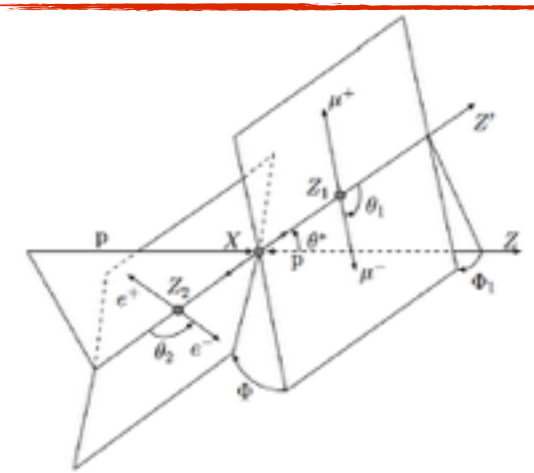
- A 1D discriminant is defined from all the observables sensitive to J^P:

$$m_1,\ m_2,\ \cos\theta^*,\ \phi_1,\ \cos\theta_1,\ \cos\theta_2,\ \phi$$

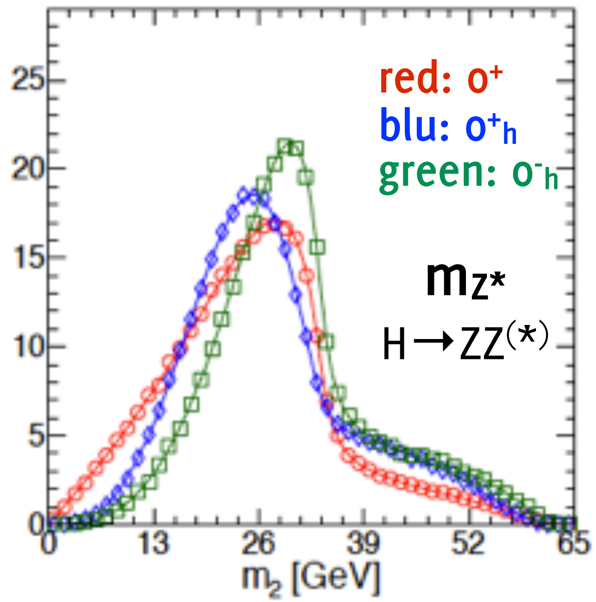
- In the Matrix Element approach (MELA):

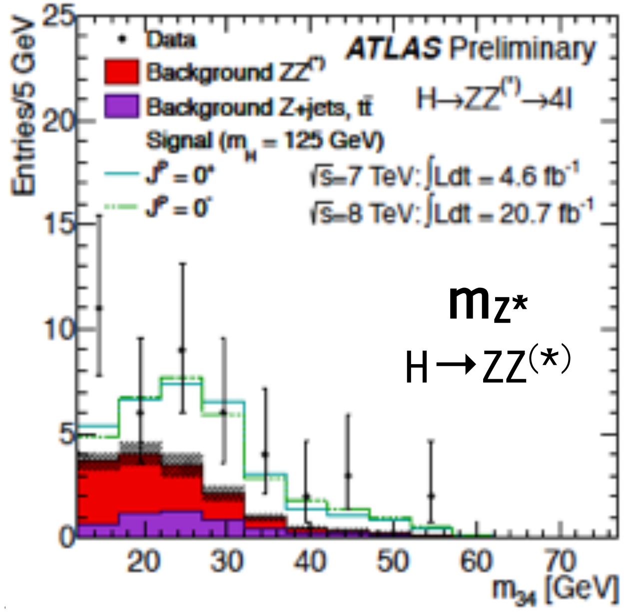
→ use **full theoretical description** of signal final states

→ include corrections for detector/selection effects



production and decay angles definition



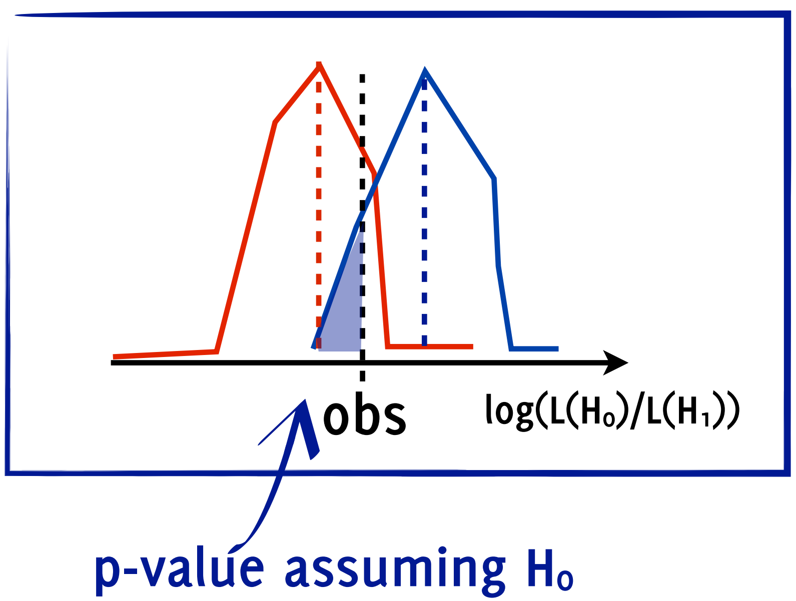


SEPARATIONS IN $H \to ZZ^{(*)} \to 4\ell$

- 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^-, $1^\pm$, $2_m^\pm$**



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

Higgs Spin CP Measurement

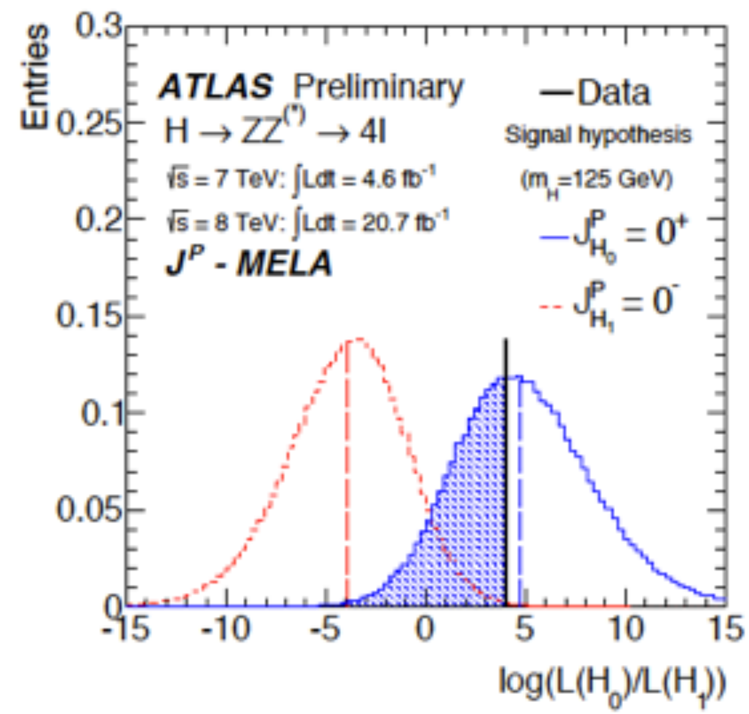
★ **Results:** excluding spin-parity 0^- and $1^\pm$ at CL > 95%

→ favouring SM Higgs boson

★ **My role:**

- development of the MELA framework
- understanding of detector acceptance and selection effects
- contribution to systematic uncertainties estimate
- extraction of signal/background hypotheses separations
- **editor** of the latest $H\rightarrow ZZ^{(*)}\rightarrow 4\ell$ spin-parity conference note

0^+ vs 0^-



→ publications: [ATLAS-CONF-2012-169](), [ATLAS-CONF-2013-013]()

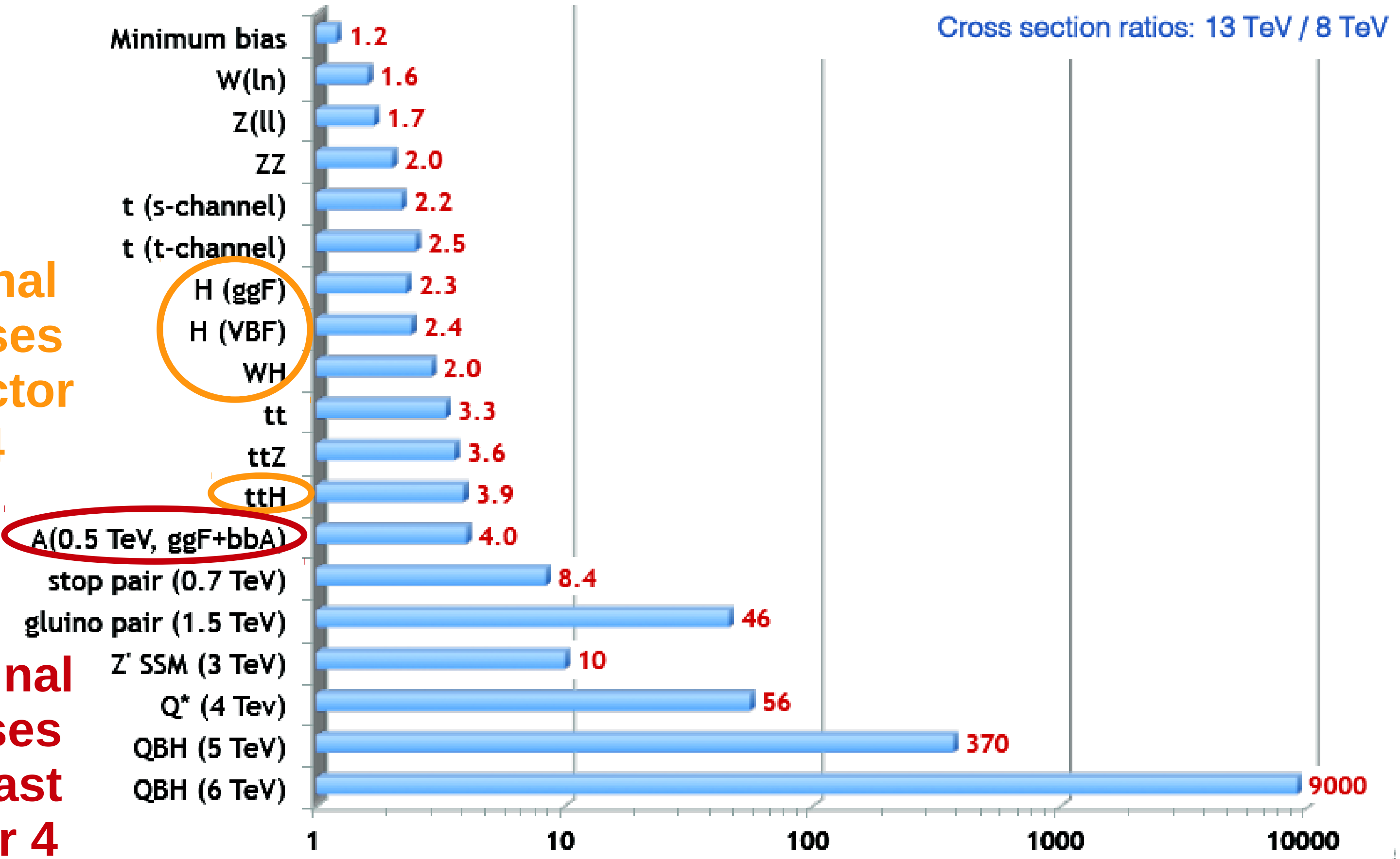
Chapter 4: LHC Run 2 and $VH\rightarrow \nu\bar{\nu}b\bar{b}$

New Beginning: LHC Run 2 Has Started

The LHC Run 2 started in the spring, at ATLAS we collected **3.2 fb^{-1}** of integrated luminosity at pp center-of-mass energy of **13 TeV**

SM signal increases by a factor 2 – 4

BSM signal increases by at least a factor 4 (mass-dependent)



[from J. Leveque talk at Higgs Hunting 2015]

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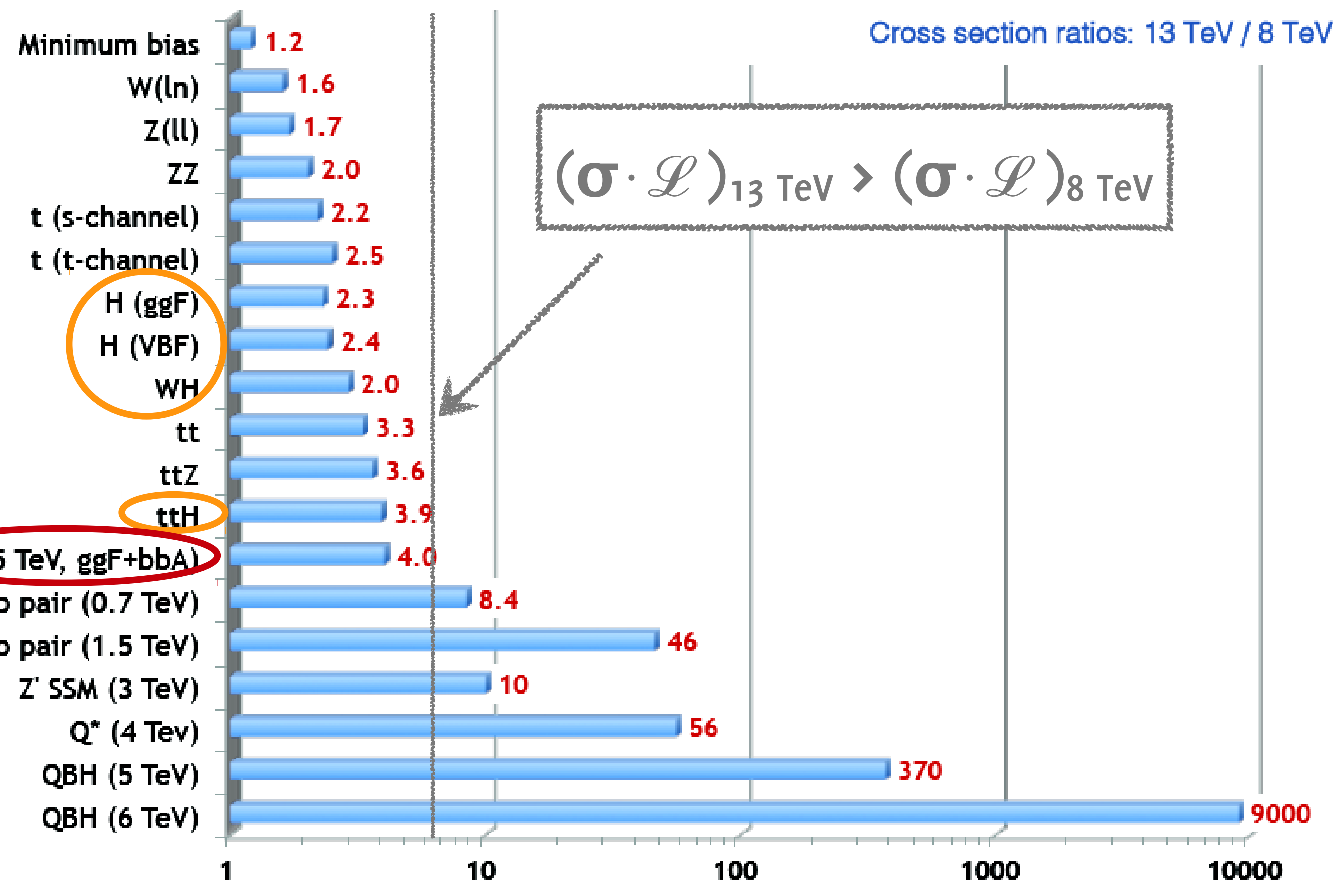
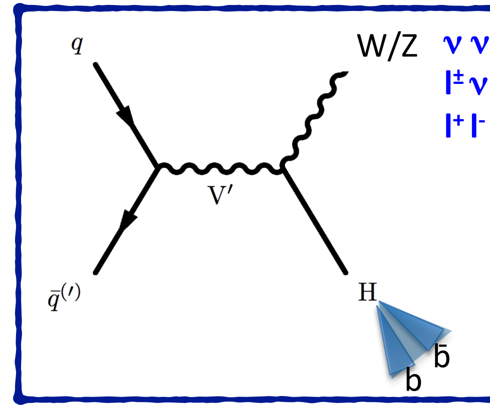
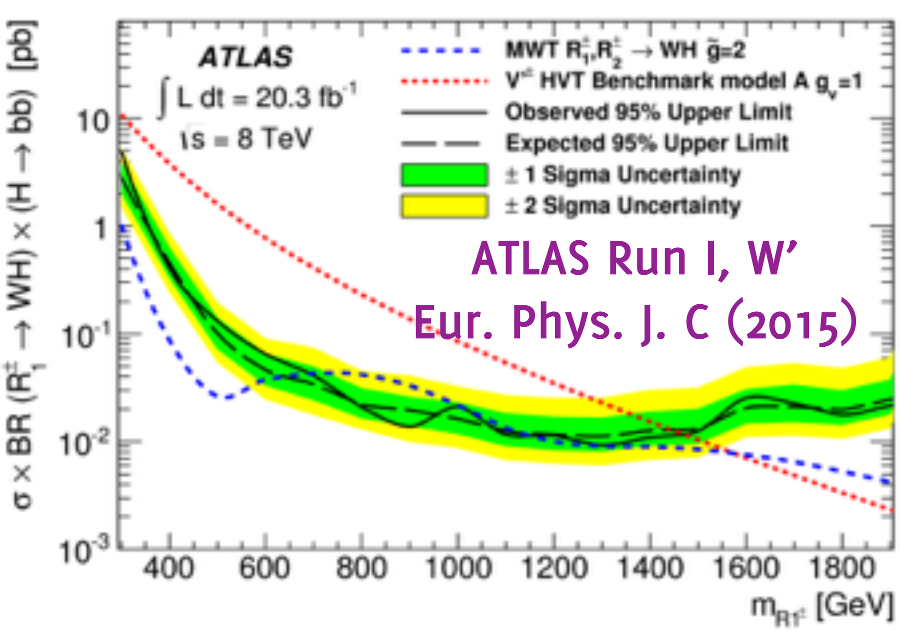


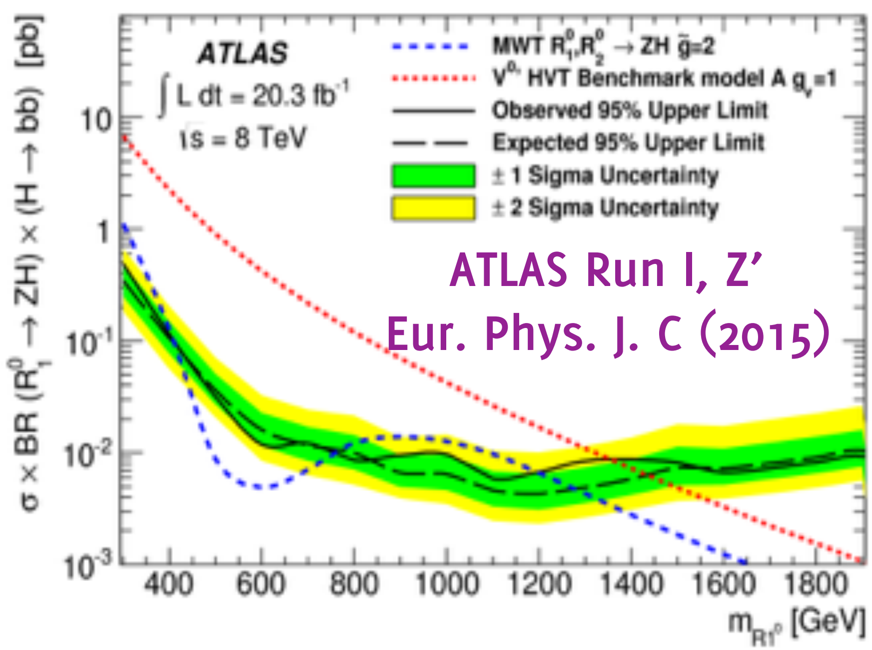
[from J. Leveque talk at Higgs Hunting 2015]

Physics Motivation and State-Of-The-Art



- Looking for narrow resonances decaying to VH(H→bb̄)
- Focusing on the **boosted regime**
  - Signal benchmarks: A→ZH, Heavy Vector Triplets (HVT) V'→VH
  - Relevant for m(VH) > 800 GeV, dominant above ~1.2 TeV





Analysis Strategy

- Channels considered:
  - $X \to ZH \to \ell\ell b\bar{b}$ (2-leptons)
  - $X \to WH \to \ell\nu b\bar{b}$ (1-lepton)
  - **$X \to ZH \to \nu\bar{\nu}b\bar{b}$ (0-leptons)**

→ here focusing on 0-lepton

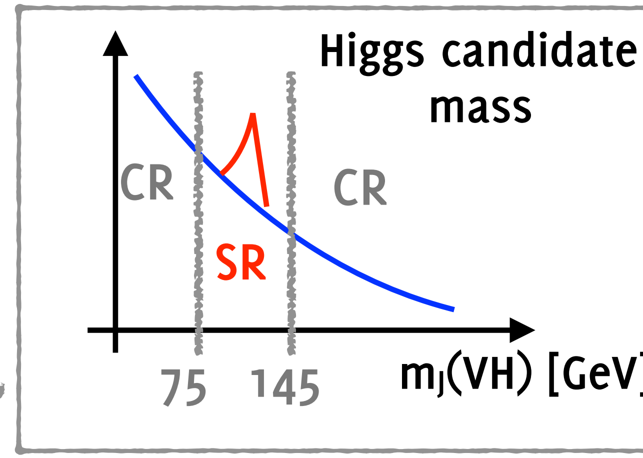
- **My role:**
  - work on the optimization of the analysis selection in the 0-lepton channel
  - study of the MC modelling of the expected background and production of the inputs for the fit in the signal and control regions

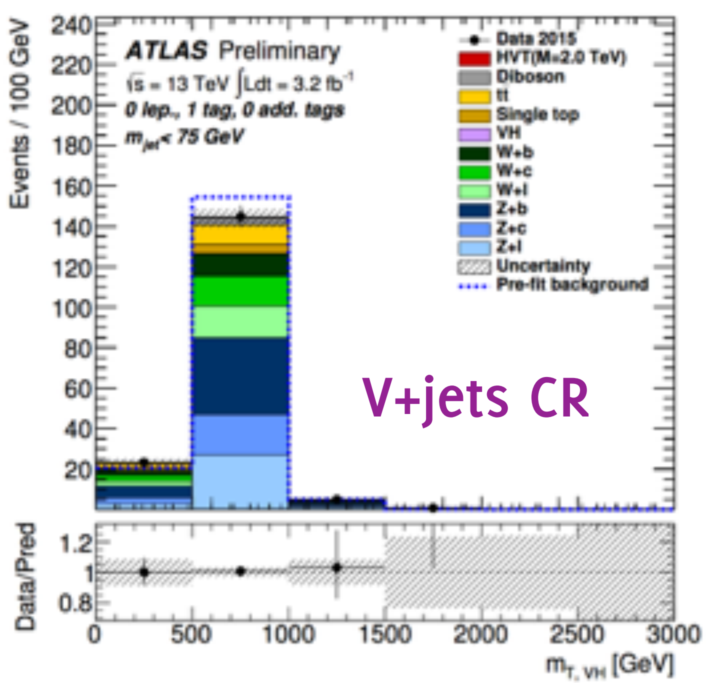
- Selecting events with
  - High transverse missing energy ($Z \to \nu\bar{\nu}$): MET > 200 GeV
  - One "fat" jet (R = 1) of high transverse momentum (H candidate): p_T > 250 GeV
  - B-tag at least once the highest p_T fat jet in the event
- Dominant backgrounds after selection
  - V+jets, ttbar (80-90% in the signal dominated regions)
  - single-top, diboson, SM Higgs

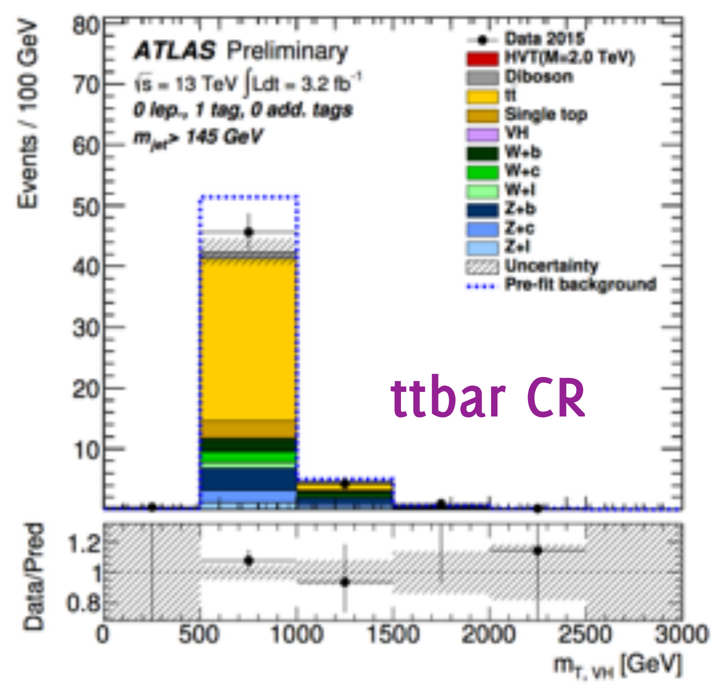
Statistical Procedure

★ **Looking for a bump in the m_T(VH) spectrum** by using a binned maximum likelihood fit

- the m_T shape is used to discriminate
- signal and background shapes from MC, background normalizations constrained using control regions

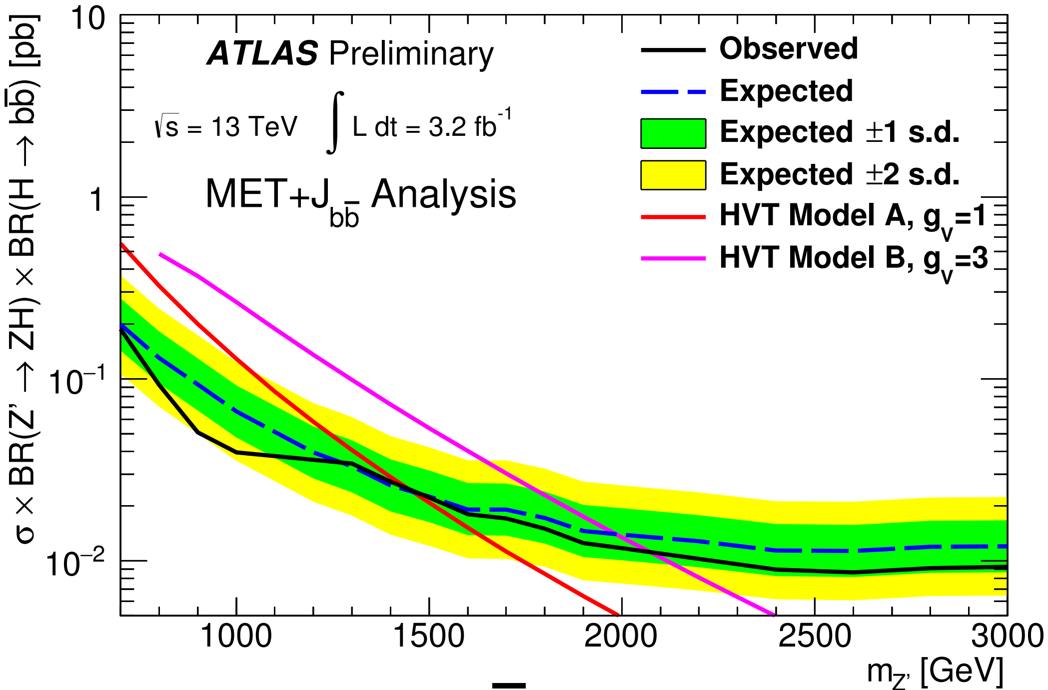




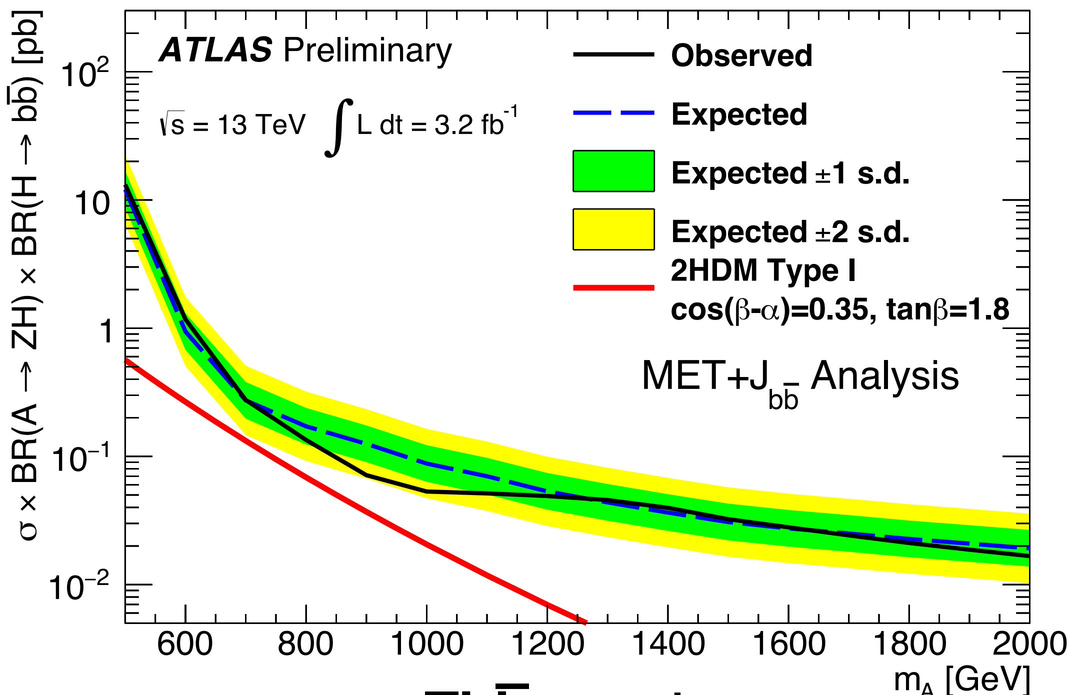


Results

No statistically relevant excess found…



$Z' \to ZH \to \nu\bar{\nu}b\bar{b}$ search



$A \to ZH \to \nu\bar{\nu}b\bar{b}$ search

- Exclusion for masses up to ~1500 (2000) GeV for HVT model A (B) in ννbb
- Run-I exclusion for V'→VH model A with the combination of 0, 1 and 2-lepton channels for masses up to 1500 GeV

→ publication: ATLAS-CONF-2015-074 (2015)

Conclusions

- Today I have shown you a small sample of searches for new physics brought on at ATLAS
  - ★ Using dibosons as a tool for testing the SM and uncovering new physics phenomena
- During the Run 2 phase, following this same path the focus will be, and is already, put on
  - ★ Searches for new physics at and above the TeV scale
  - ★ Precision measurements of the Higgs boson parameters

→ The VH->$\nu\bar{\nu}b\bar{b}$ final state is expected to play an important role for both purposes

Conclusions

- Overall the LHC results, from the SM precision measurements to direct searches for exotic particles, indicate that **the Standard Model stands his ground**
- The LHC Run 1 ended with:
  - ★ an extraordinary result ! The discovery of a new particle compatible with a SM Higgs boson
  - ★ no evidence of new physics…

    …yet ! We just reached the TeV scale, but haven't quite explored it !
- **There are many fundamental physics questions still open**
  - ★ dark matter: new matter? new force?
  - ★ naturalness and fine tuning problems → new physics at the TeV scale

    let's hope answers will be at reach during the LHC Run 2 !

Backup Slides