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Combination of Run-1 Exotic Searches in Diboson Final States at the LHC

CERN reinterpretation workshop

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1) How did it get started

- If you remember in June 2015, ATLAS X → VV paper generated lots of interest and "first day publications" (202 citations up to today):

[20] Georges Aad et al. "Search for high-mass diboson resonances with boson-tagged jets in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector". In: (2015). arXiv:1506.00962 [hep-ex] (cit. on pp. 2, 5, 8, 25, 31, 32).

- In fact it came as the last paper of a long session of 5 other paper:
  - CMS: X → WV + ZV – 1405.3447, X → VV – 1405.1994.
  - ATLAS: X → ZV – 1409.6190, X → WV – 1503.04677.

- Here some of the titles:
  - 2 TeV Walking Technirho at LHC?
  - Interpretations of the ATLAS Diboson Anomaly
  - W′ Boson near 2 TeV: Predictions for Run 2 of the LHC
  - Composite Heavy Vector Triplet in the ATLAS Diboson Excess

Notations:
X – heavy resonance
V – W or Z decaying hadronically.
W – W decaying to lν leptonically.
Z – Z decaying to ll.

- At the title level we can see that we have sometimes an "upper fluctuation bias" that may lead some mis-interpretations of the experimental results. So we decided to help our theorists friends and provide them "model independent and statistically kosher combination".

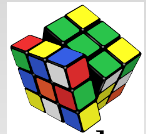
2) The combination philosophy

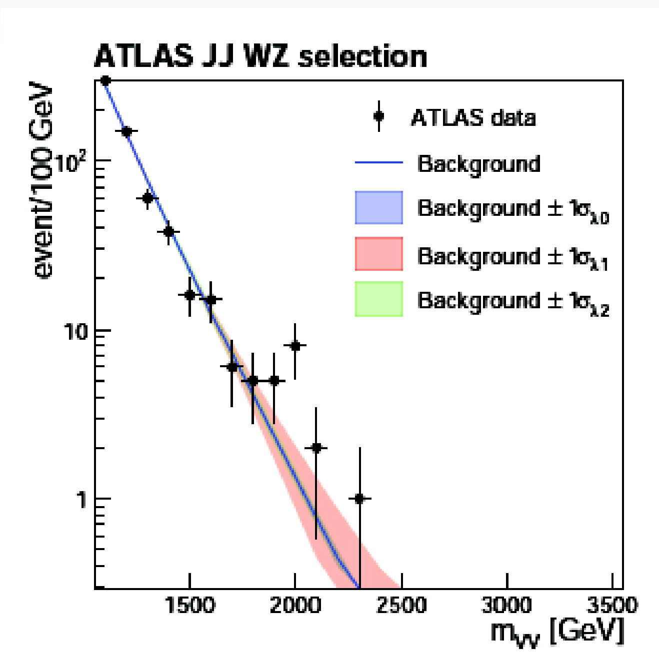
- Normally this kind of combinations shall be done by the experiments themselves. But in 2015 experiments was busy with new data. We had a green light to do it ourselves.

- The way that the information are extracted is provided in the table:
  - All the data have to be published. They are all available on HEPDATA.
  - The background and signal is a more complicated deal.

Experiment	Channel	Background modelling	Background uncertainties	Signal modelling	Signal efficiency	Fudge factor
ATLAS	JJ [20]	Fit	Fit	Paper & extrap.	Public plots	Yes
	$\ell\nu$J [79]	HEPDATA	HEPDATA	Gauss. approx.	Public plots	Yes
	$\ell\ell$J [80]	Fit	HEPDATA	Gauss. approx.	Public plots	Yes
CMS	JJ [22]	HEPDATA	HEPDATA	HEPDATA	HEPDATA	No
	$\ell\nu$J [21]	Fit	Fit	MC	Public plots & MC	Yes
	$\ell\ell$J [21]	Fit	Fit	MC	Public plots & MC	Yes

3) Background extraction

- This is the most tricky thing.  Experiments are very scarce on the background information.
  - Best: background and correlated bin-by-bin uncertainties are provided.
    - We just use it (CMS X → VV, ATLAS X → WV).
  - Standard: background provided but not uncertainty.
    - We obtain the relative correlated uncertainties from a fit to data.
    - Check that our fit match the public background.
    - Assign our uncertainties to the public background.



Blue line: official ATLAS background
Colored bands: uncertainties band from our background fit.

Our fit matches ATLAS one within 10%.

$$f(m_{\rm JJ}) = p_0(1 - m_{\rm VV})^{p_1 - \xi p_2} m_{\rm VV}^{p_2}$$

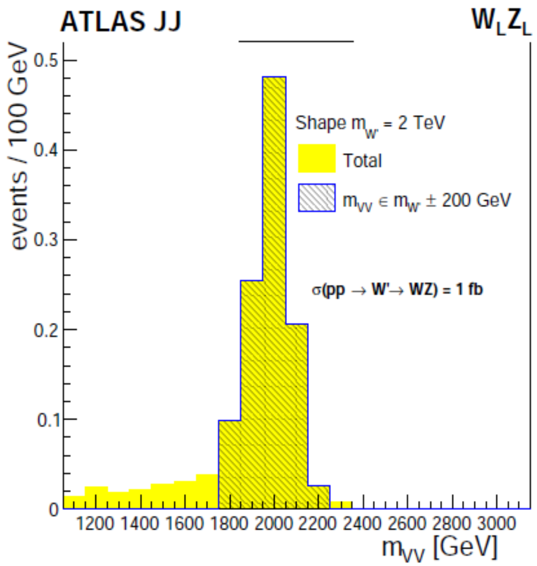
4) Signal and systematics

- The signal shape is:
  - Usually extracted from figures.
  - If we are lucky there is a root file provided in HEPDATA.
  - If we know it is Gaussian we emulate the signal using resolution information.
- Need to be sure we combine signal with same properties:
  - Need to recast also finite-width results (ATLAS) into narrow-width results (CMS) for combination.
  - Luckily both experiments have a same spin (Spin-2), same production mechanism (gluon-gluon fusion), same polarity of decays ($V_L V_L$) model: bulk graviton.

- The signal efficiency is usually provided in a table in the paper, or in the text or in a figure.

- The systematics are taken form the paper and emulated in the likelihood.

We consider inter-channel correlations:
  - Jet/muon/electron/MET scales, resolutions.
  - Lumi.
  - Acceptance.

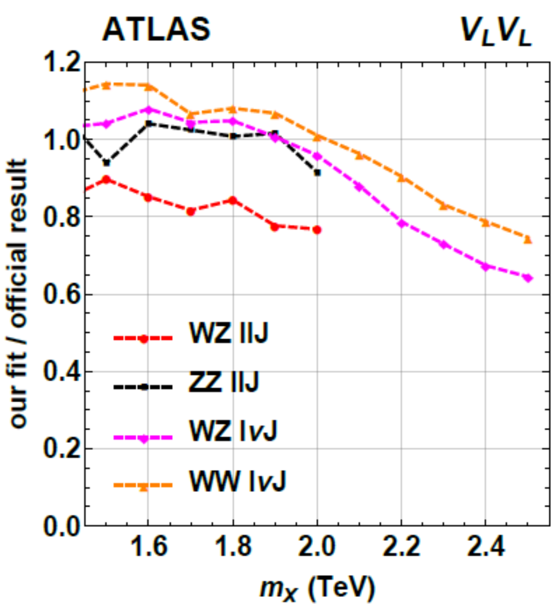


5) Statistical procedure and fudge factor

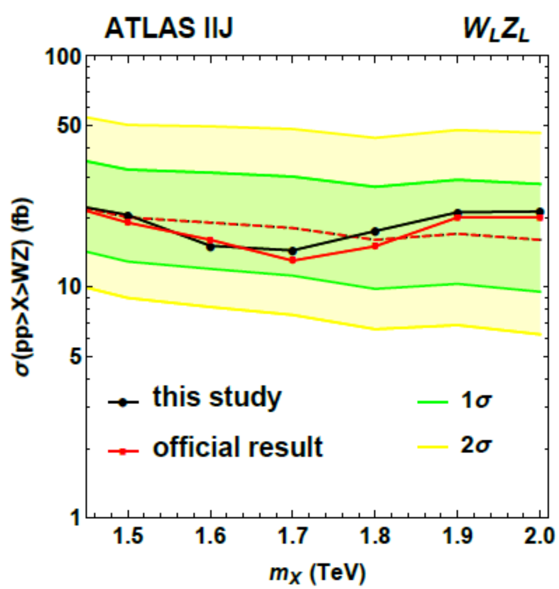
- We decided to use THETA, a public (mainly frequentist) statistical tool. Well known in CMS.
- We build a binned likelihood and extract the limits / p-values / significances (Z-values).
- First compare channel by channel what we obtain with public results.

We rescale our limits by a “Fudge factor” to match expected public limits. They cover a lack of documentation by the experiments:

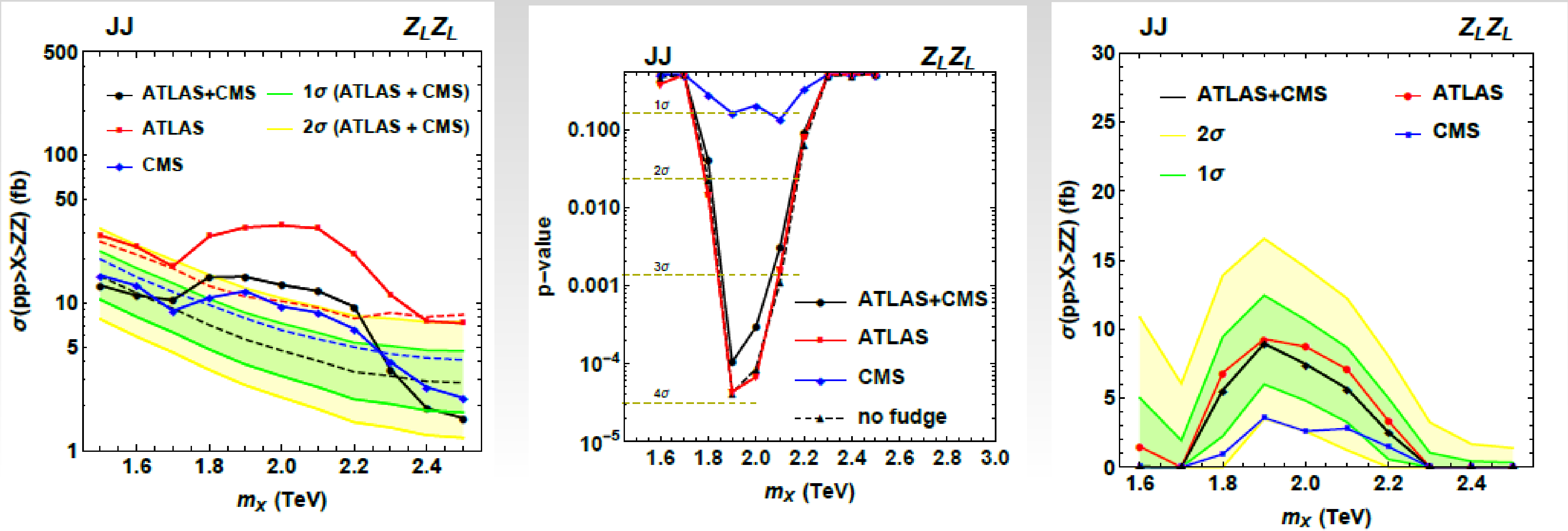
- 0.8-1.2 for X → WV, X → ZV.
- 1.0 for CMS X → VV.
- 0.5-0.6 for ATLAS X → VV.



Fudge →

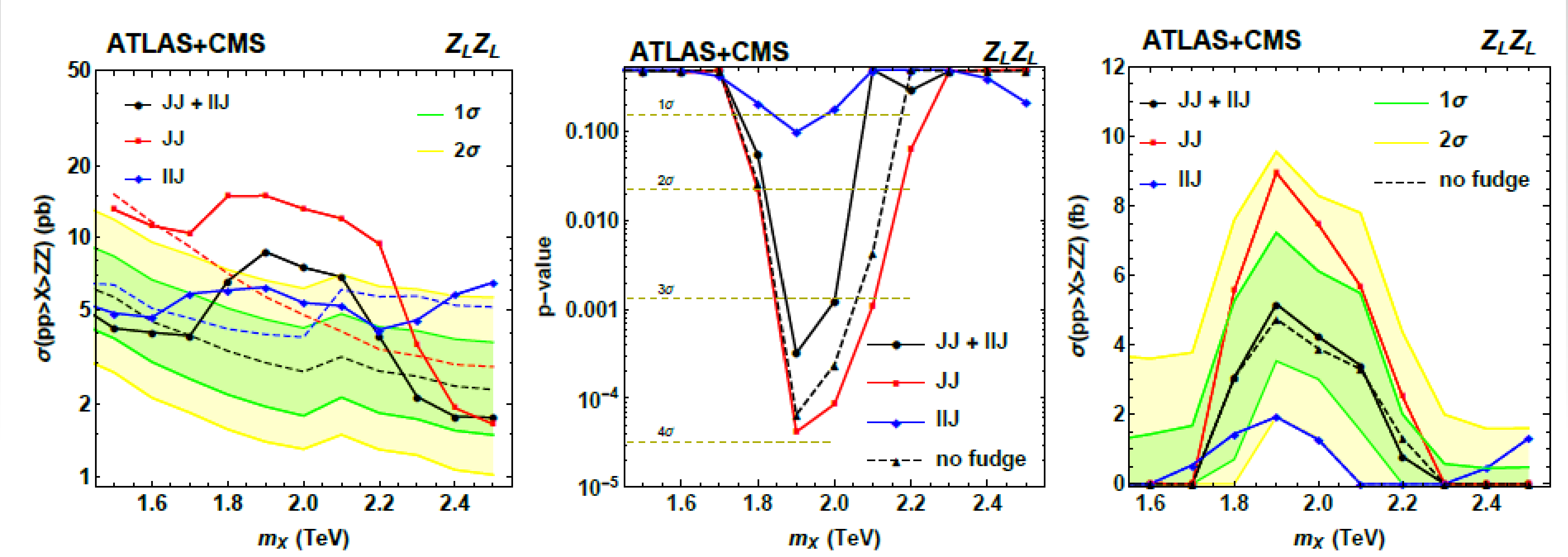


6) Results 1: Channel-by-channe ATLAS/CMS



- Example of fully hadronic combination with ZZ hypothesis (WW, WZ also availables)

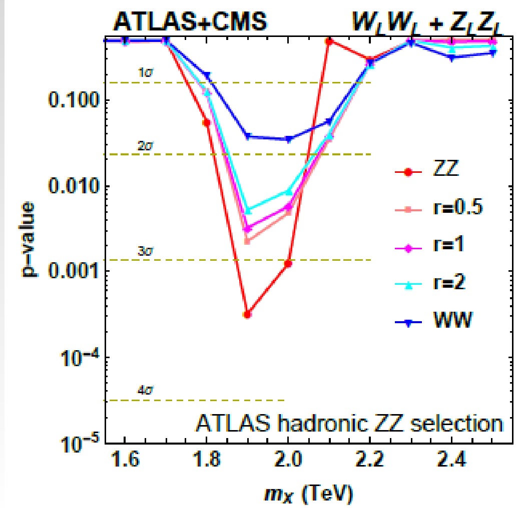
6) Results 2: global combination



- Example of fully hadronic combination with ZZ hypothesis (WW, WZ also availables)

6) Results 3: interpretation and conclusion

Signal hypothesis	m_X (TeV)	Significance	p-value	Best-fit cross section (fb)	
$W' \to W_L Z_L$	1.9	2.5 (3.1)	6.5 (1.0) $\times 10^{-3}$	$5.3^{+2.3}_{-2.0}$	$(5.5^{+2.0}_{-1.6})$
	2.0	2.5 (3.2)	7.0 (0.8) $\times 10^{-3}$	$4.3^{+2.1}_{-1.5}$	$(4.7^{+1.8}_{-1.3})$
$G_{bulk} \to W_L W_L$	1.9	0.49 (0.83)	0.30 (0.20)	$0.75^{+1.67}_{-0.75}$	$(1.4^{+1.7}_{-1.4})$
	2.0	0.88 (1.33)	0.20 (0.092)	$1.1^{+1.4}_{-1.1}$	$(1.8^{+1.8}_{-1.4})$
$G_{bulk} \to Z_L Z_L$	1.9	3.4 (3.8)	3.2 (0.65) $\times 10^{-4}$	$5.2^{+2.1}_{-1.6}$	$(4.7^{+1.8}_{-1.2})$
	2.0	3.0 (3.5)	1.2 (0.24) $\times 10^{-3}$	$4.2^{+1.9}_{-1.2}$	$(3.9^{+1.6}_{-1.0})$
G_{bulk} (r=2)	1.9	2.6 (3.4)	5.2 (0.40) $\times 10^{-3}$	$3.9^{+2.4}_{-1.5}$	$(4.9^{+2.0}_{-1.7})$
	2.0	2.4 (3.1)	8.8 (0.89) $\times 10^{-3}$	$3.1^{+1.8}_{-1.3}$	$(3.9^{+1.6}_{-1.4})$



- We have shown the consistency between both experiments.
- We suggest to use the output of this analysis for interpretation by theorists. In particular we provide the preferred cross section, better than a “by eye” extraction.

- Whatever would happen we think that this is a stress test of the “reproduc -hunts” at the LHC. It is not easy but possible. Definitively there is a way to improve:
  - Provide shapes; bin-by-bin uncertainties on the background; more clear instructions how the systematics enters the likelihood.
- To go further we need the experiments:
  - Provide interpretations width different final-width same for both experiments.
  - Provide interpretation for different spin-parity X and different production mechanisms, DY and gluon-gluon fusion.