The 2013 CERN-Latin-American School of High-Energy Physics

Arequipa, Peru (6–19 March 2013)

LHC Results Highlights

(Lecture III: Results on Higgs and New Physics Searches)

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Outline of Lecture III

(Results on Higgs and New Physics Searches)

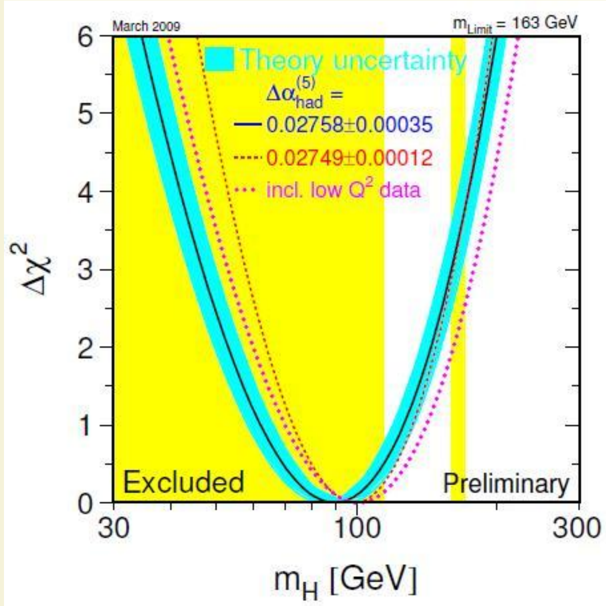
- **The SM Higgs boson**
  - ⇒ The search of the boson: the last two years
  - ⇒ The Higgs discovery
  - ⇒ Measure as many channels as posssible
  - ⇒ Measuring its properties: Is the 125-GeV boson the Higgs?
  - ⇒ Other searches for Higgs-like particles
- **Searches of other SM-like Higgs bosons**
- **Searches of New Physics** (SUSY covered in Lecture II)
  - ⇒ Mostly an overview. . . too much to cover, no obvious hint to follow
  - ⇒ Inclusive searches: resonances, tails, . . .
  - ⇒ Common models: extradimensions, leptoquarks, . . .
  - ⇒ Searches motivated by “Natural Higgs”
- **Upgrades and plans for the “Run 2” (2015 and beyond)**

The SM-Higgs Search

Where should the Higgs be? (before Dec 2011)

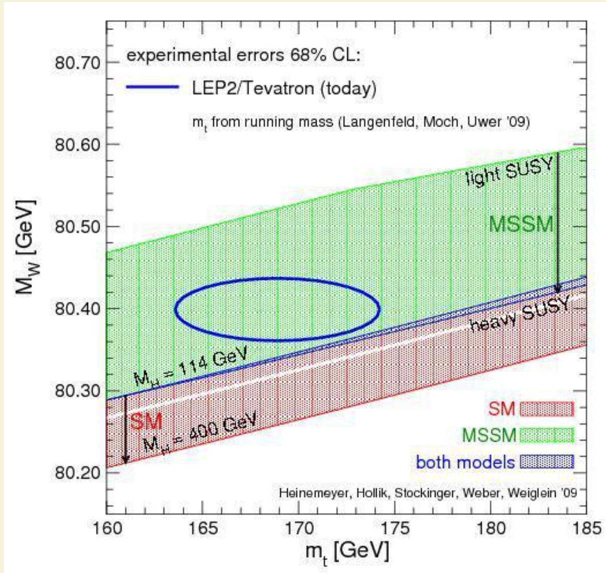
The Higgs is the missing keystone of the Standard Model. Its existance is strongly motivated by the success of the model but there is nothing proving it.

The EWK constraints from pre-LHC colliders indicated a mass around 100 GeV.



There are also theoretical considerations that motivates a light Higgs. The idea is that SM-related parameters that are sensitive to the Higgs mass allows to make estimations of preferred values.

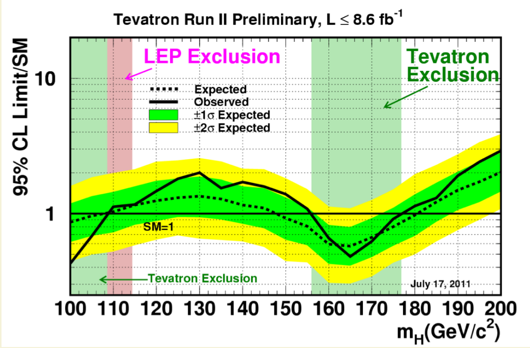
Even with the addition of new physics (e.g. Supersymmetry) the bounds were close to what the EWK fits suggested.



On the other hand, most of these assume the Higgs sector is as the SM indicated.

Nature might not be as predictable as we think

The search at the LHC experiments was performed assuming a SM-Higgs-like boson at any not-excluded (by Tevatron or LEP) mass.



For low masses (115-135 GeV)

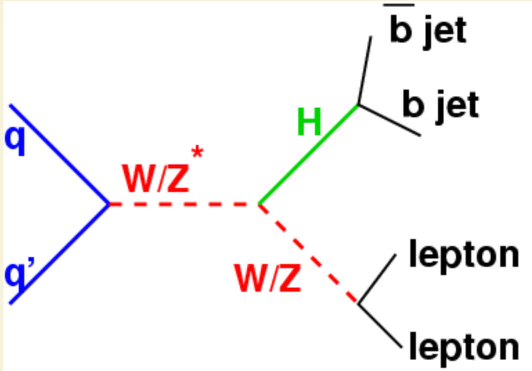
$\Rightarrow$ $H \rightarrow bb$ is the dominant decay channel

Impossible to detect the direct production channel ($pp \rightarrow H$)

Associated production with a weak vector

$\Rightarrow$ others: $\gamma\gamma$, $\tau\tau$

Branching ratios are small, but the LHC produces many Higgses

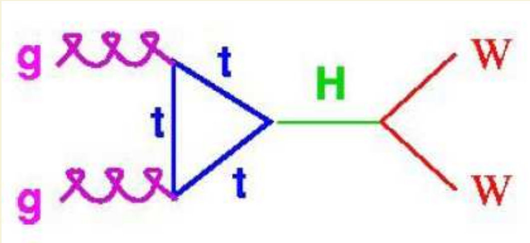


For medium masses (135-200 GeV)

$\Rightarrow$ Main channel is $H \rightarrow WW$ so use direct production

$\Rightarrow$ Need of leptons prevents full decay reconstruction

$\Rightarrow$ Associated channels helped on this, but smaller yield.



Masses higher than 200 were not reachable at Tevatron, but the LHC opened them:

$\Rightarrow$ Specifically the "Golden channel" $H \rightarrow ZZ \rightarrow ll l' l'$

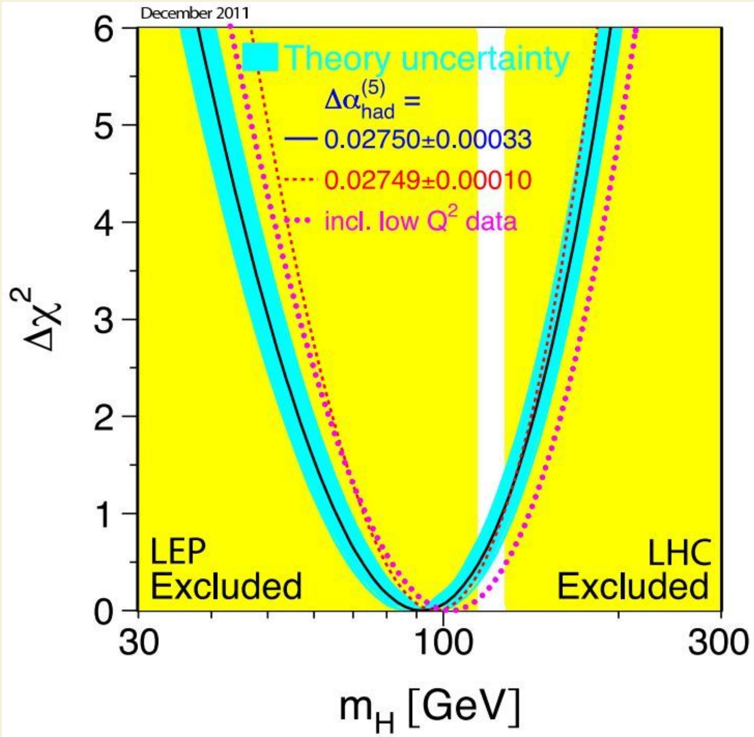
This simple structure was "violated" since using off-shell bosons the different channels contributed beyond their optimal regions.

December 2011

On December 13 of 2011, ATLAS and CMS presented at CERN the status of the SM Higgs searches and for the first time hints of a particle with mass close to 125 GeV.

Signal was not completely significant, but excesses appeared in several channels and seemed consistent with a reasonance in that area decaying to several final states.

In addition, the analyses performed were able to exclude all the medium masses, allowing only the region of the excesses to be reasonable compatible with the EWK fits.



Due to its theoretical motivation within the SM, the Higgs boson becomes the first candidate to be the particle causing the excess.

So all the focus was in searching for a possible SM-like Higgs boson with a mass around 125 GeV.

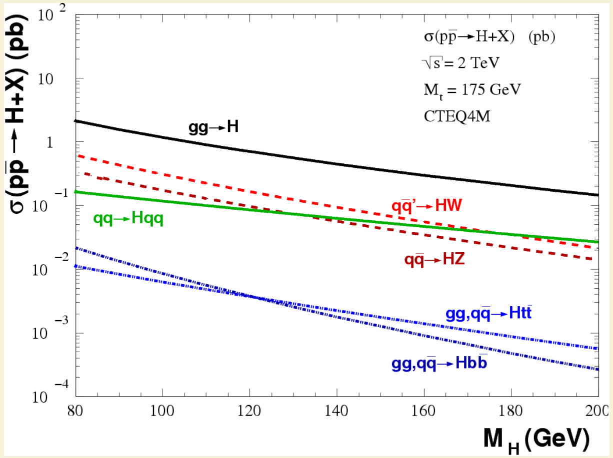
And we enter in 2012, the year of the 8 TeV and the Higgs search. . .

The search of the 125-GeV Higgs: strategy

After the “December 2011 event” the plan was to confirm the presence of a signal (and also reach the “discovery”, 5σ level) using the new data collected from April.

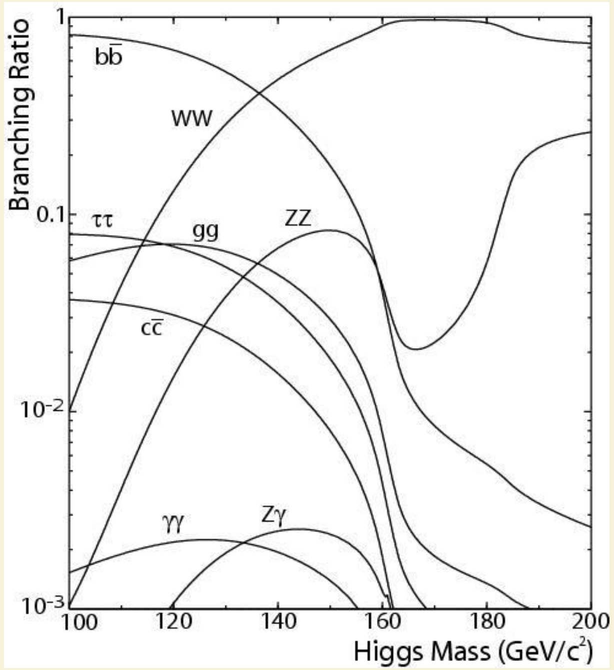
- **LHC energy raised to 8 TeV to increase yield.**
- **Efforts focusing on most sensitive channels:**

$$H \to \gamma\gamma$$
$$H \to ZZ^* \to lll'l'$$



These also provide the cleanest channels to **measure the properties since we reconstruct the full decay.**

They are also complementary: **one with reasonable yield but high background and the other with small yield but very low background.**



- **Of course, secondary channels also very relevant**

$$H \to \tau\tau$$
$$H \to WW^* \to l\nu l'\nu$$
$$H \to bb \text{ (associated production)}$$

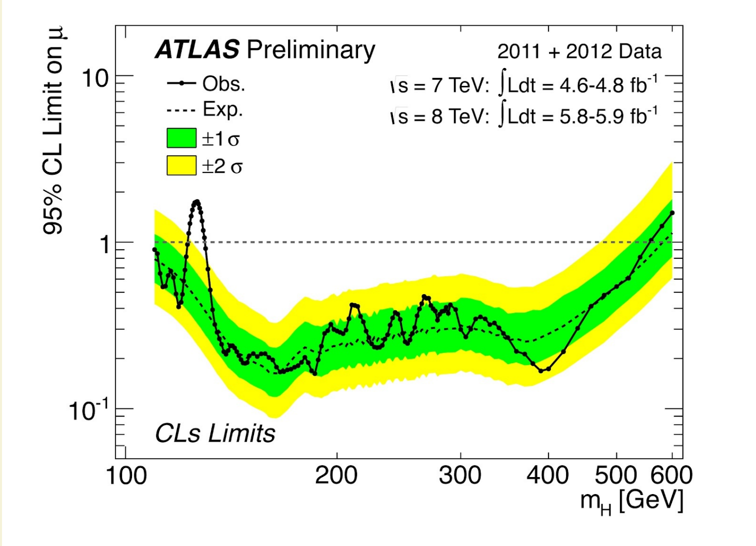
because they provide further sensitivity (but low-significant signal)

and because they provide additional information (additional couplings to the boson)

Higgs Search: update for ICHEP-2012

For ICHEP-2012 the size of the available dataset was ~ 5.5 fb^{-1} of 8 TeV collisions

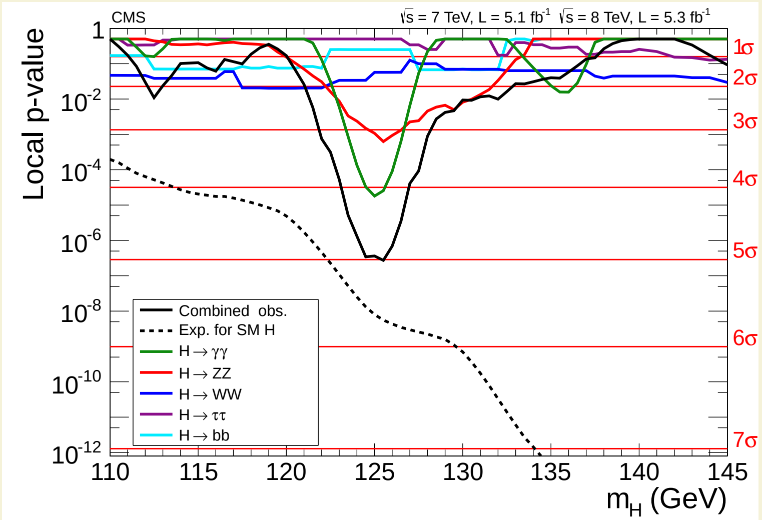
Higher available energy but tougher conditions (pile-up, triggering) led to a comparable sensitivity (a bit better) with respect to the 7-TeV sample.



Analysis focused to the observed excesses appearing in the region that is not excluded.

$\Rightarrow$ ATLAS presented the results for the most sensitive channels ($\gamma\gamma$ and $lll'l'$) leading the quest.

It provided a clean result for the discovery of a new boson.



$\Rightarrow$ CMS used the five channels that has reasonable sensitivity.

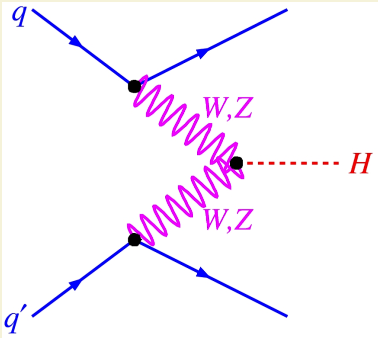
More prone to fluctuation in less sensitive channels, but it provided a more general picture about the boson.

It is worth it to discuss the details of the current results involving this boson: several updates after ICHEP!

A new boson at 125 GeV: CMS Results (I)

- The CMS $H \rightarrow \gamma\gamma$ (CMS-PAS-HIG-12-016) is performed by using several categories of diphoton (for inclusive production mode) and two categories for tagging Vector-Boson Fusion processes.

- For Higgs, VBF process is very important since it is sizable (LO $gg \rightarrow H$ process is via loops) and involve very different couplings



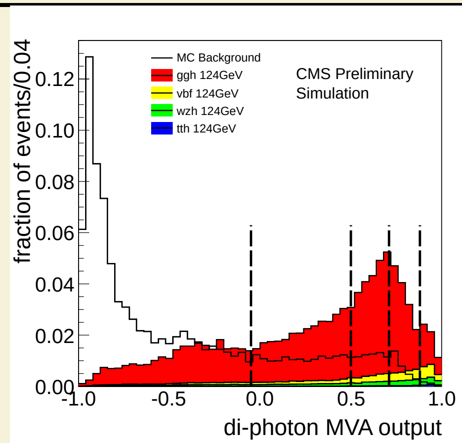
$\rightarrow$ Specially atractive for fermiophobic Higgss

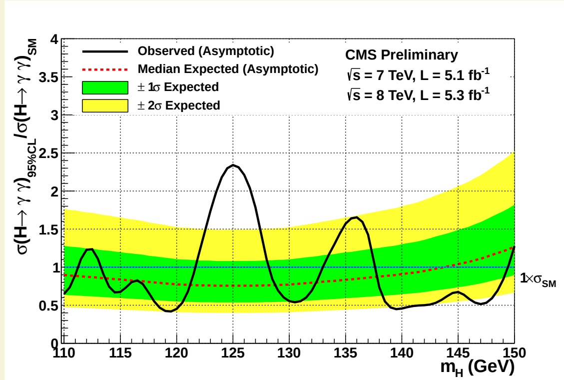
$\rightarrow$ Tagged with forward jets.

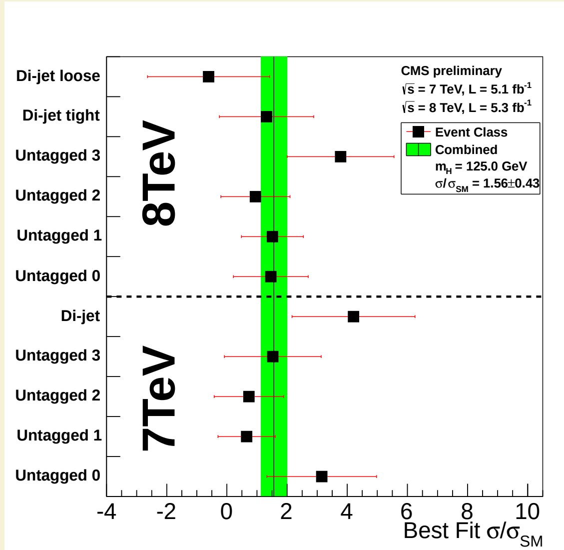
- Analysis with MVA cross-checked with cut-based analysis: comparable result.

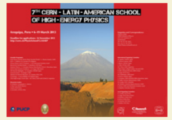
- Local significance: 4.1σ,a bit higher yield than expected.

- Updated result expected during the Conferences at Moriond...



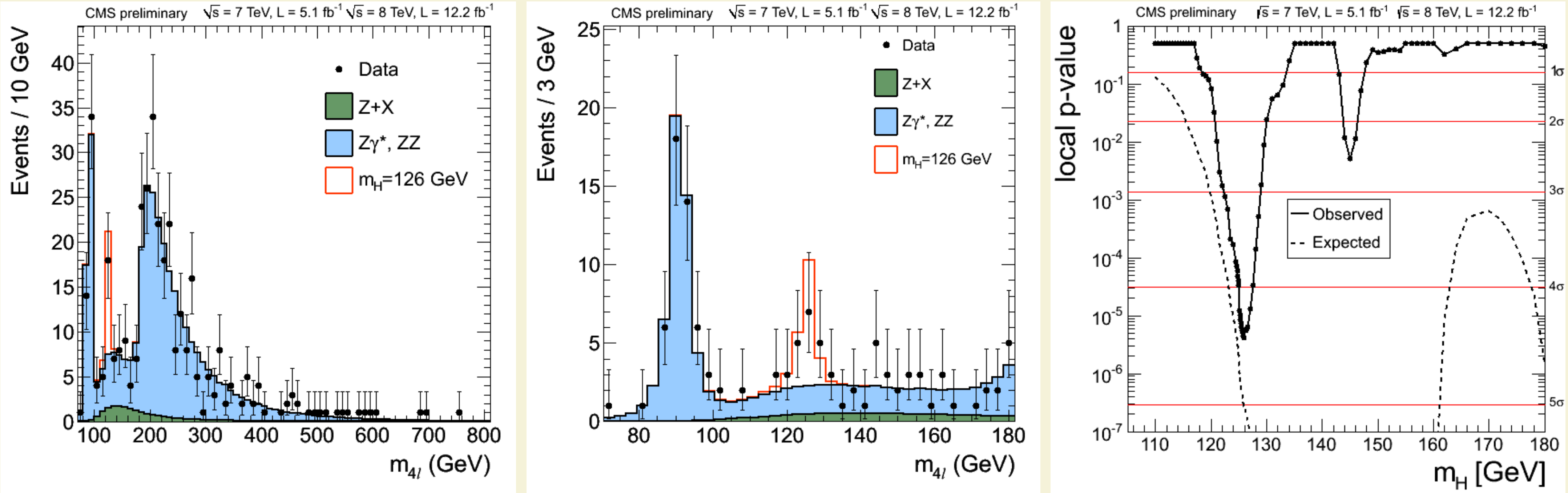






A new boson at 125 GeV: CMS Results (II)

- The $H \to 4l$ analysis by CMS (CMS-PAS-HIG-12-041) has been updated several times since July.
- Also expected new results for Moriond, but mostly focused on properties since signal is well established.



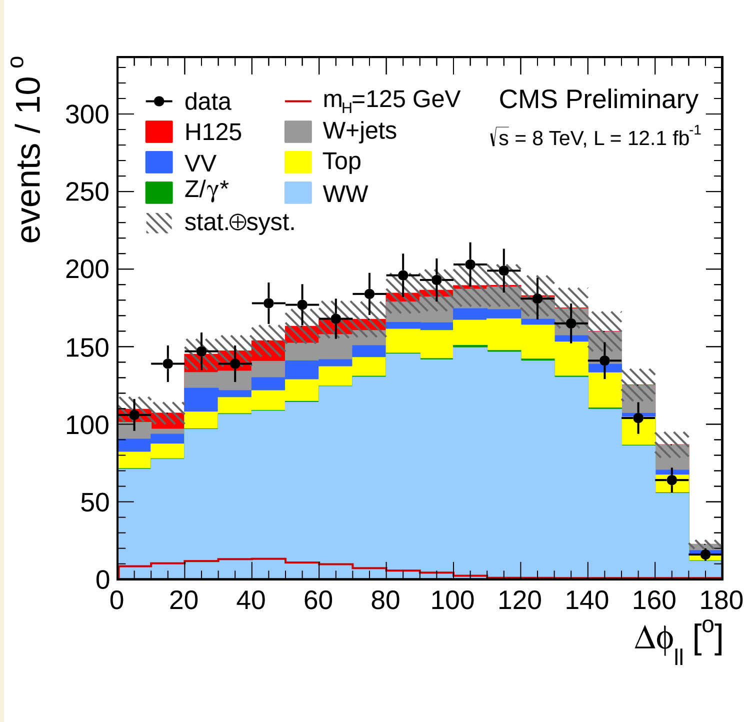
- Using a kinematic discriminant based on the masses of the reconstructed Z and angular correlations (which are based on the scalar nature of the boson).
- The yield is a bit lower, but still in agreement with SM: $\mu = 0.80^{+0.35}_{-0.28}$
- This analysis is the central reference for properties of the boson (see later).

A new boson at 125 GeV: CMS Results (III)

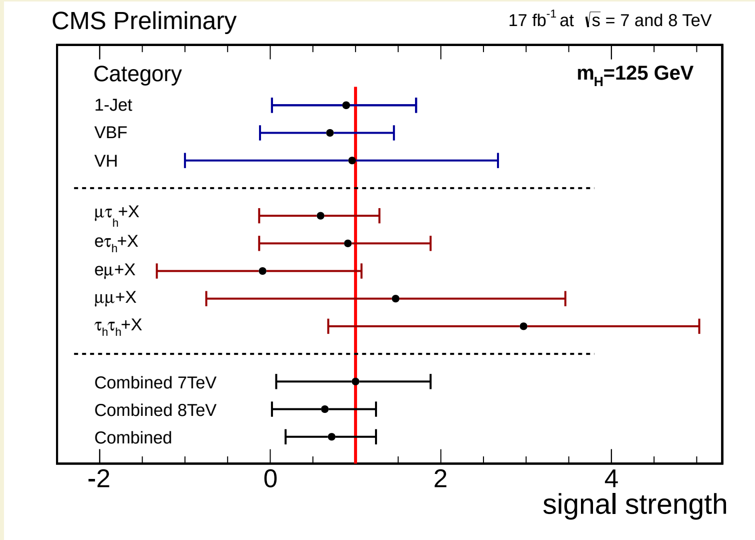
- After the two most sensitive analysis, CMS has produced many others that are informative about the presence of the boson.

- $H \rightarrow WW^*$ (**CMS-PAS-HIG-12-042**) provide an important yield, but sensitivity is reduced since the requirement of leptonic decays prevents the reconstruction of the full mass.
- Still results are compatible with a SM boson, with a large uncertainty:

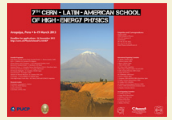
$$\mu = 0.74 \pm 0.25$$



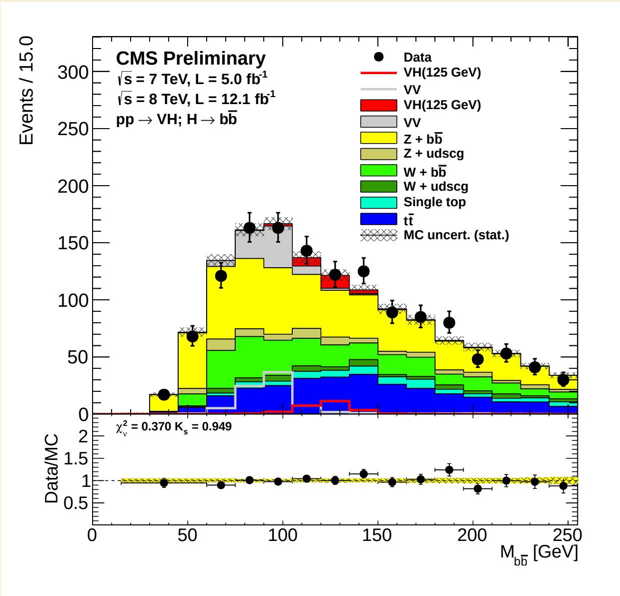
- The $H \rightarrow \tau\tau$ analysis (**CMS-PAS-HIG-12-043**) is the most sensitive channel with a direct decay to fermions.
- Large uncertainty for now, so more data is welcome.
- μ in agreement with SM-Higgs hypothesis.
- and with a branching ratio ~ 0.

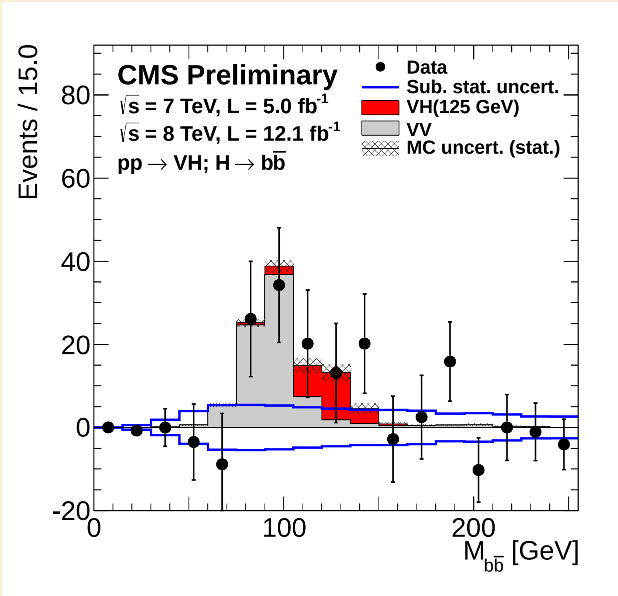


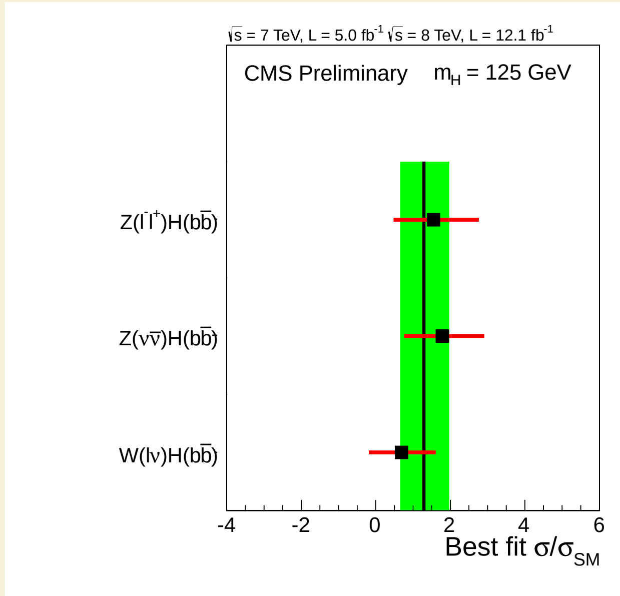
A new boson at 125 GeV: CMS Results (IV)



- Many other analyses in the pipeline. As the previous, they do not have a lot of sensitivity with the current sample, but still important.
- In addition, studies are trying to include as many as possible channels and exclusive identification of final states (e.g. VBF or associated production (VH)) to gather as much information as possible about the boson.
- Among them, the most important are those having a Higgs decaying into $b\bar{b}$, in VH channels (CMS-PAS-HIG-12-044).



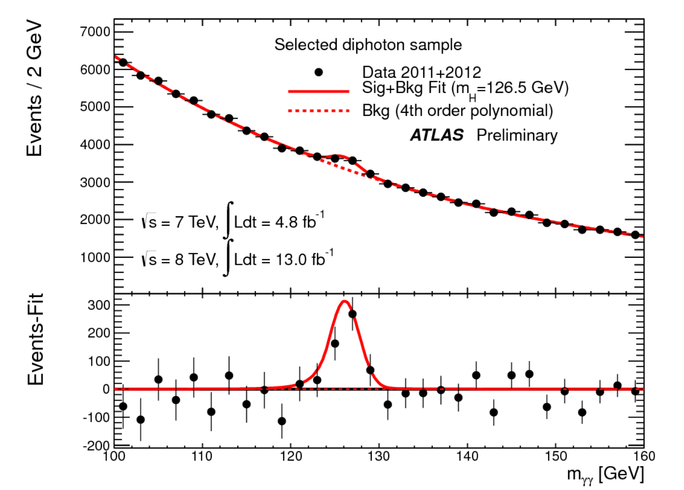


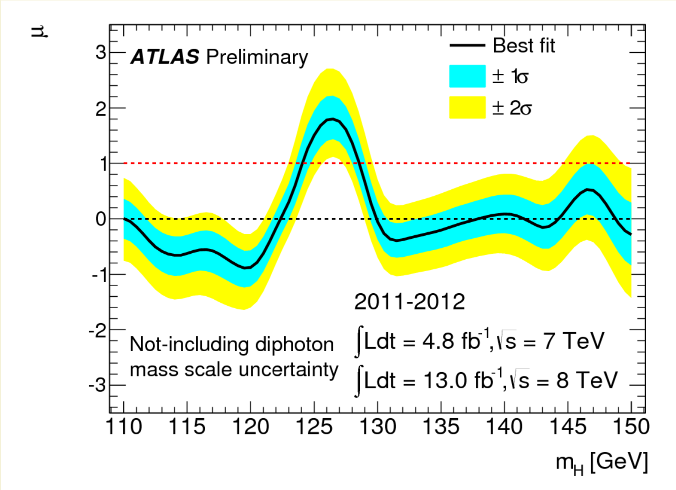


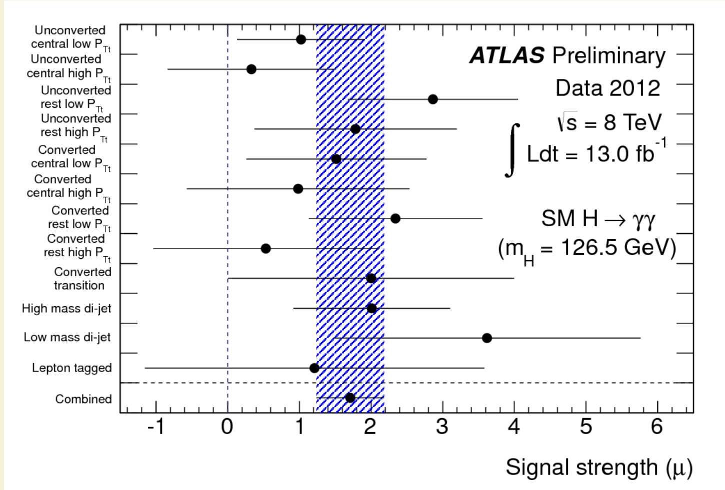
- Again, with large uncertainties, compatible with SM-Higgs hypothesis.
- For $H \rightarrow b\bar{b}$, the "channel of the future" is that of production associated with $t\bar{t}$: interesting to have a complete understanding on how the Higgs couples to b and t.

A new boson at 125 GeV: ATLAS Results (I)

- **ATLAS made a major update after ICHEP by the end of the year.**
- **The update on the diphoton decay (ATLAS-CONF-2012-168) was very relevant. Specially since CMS did not update it since July.**
- **Similarly to CMS, the sample is divided into 12 categories, in this case having 9 for inclusive production, 1 for VBF and 2 which were intended to get signal from VH channels.**



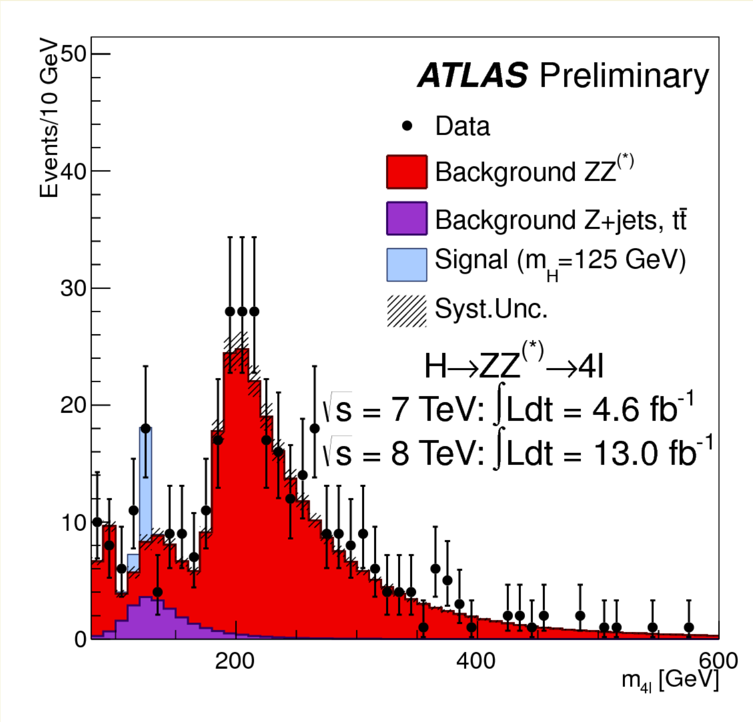


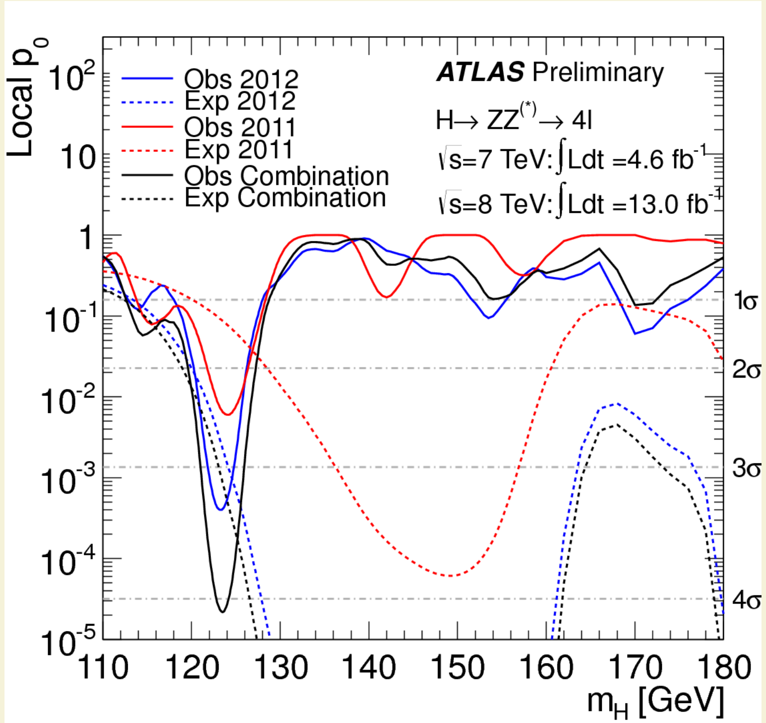


- $\mu = 1.80 \pm 0.30(\text{stat})^{+0.21}_{-0.15}(\text{syst})^{+0.20}_{-0.14}(\text{th})$ **is coming a bit high.**
- **Per-channel μ does not indicate anything striking, but more data needed.**

A new boson at 125 GeV: ATLAS Results (II)

- The updated $4l$ analysis (ATLAS-CONF-2012-169) increased the luminosity on the 8 TeV sample with respect to July.
- As CMS, some sensitivity is gained by exploting the spin characteristics of the signal.





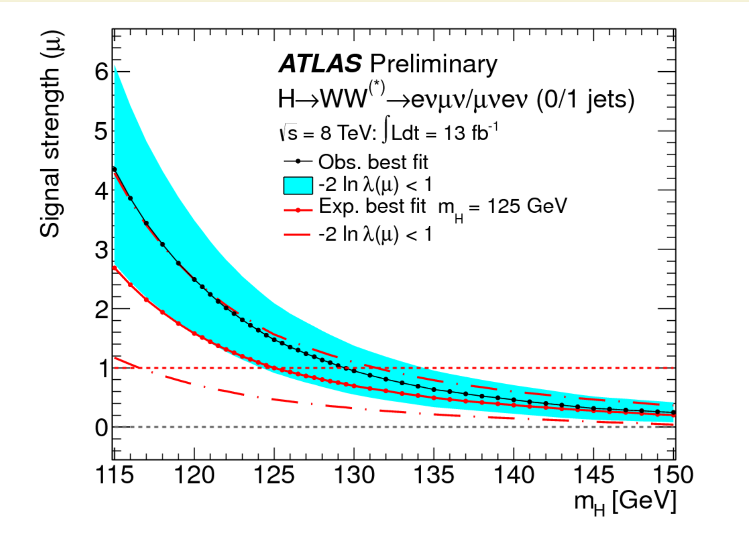
- Yield a bit higher, and the peak of excess it is at 123.5 GeV.
- The signal strength is $\mu = 1.30^{+0.5}_{-0.4}$

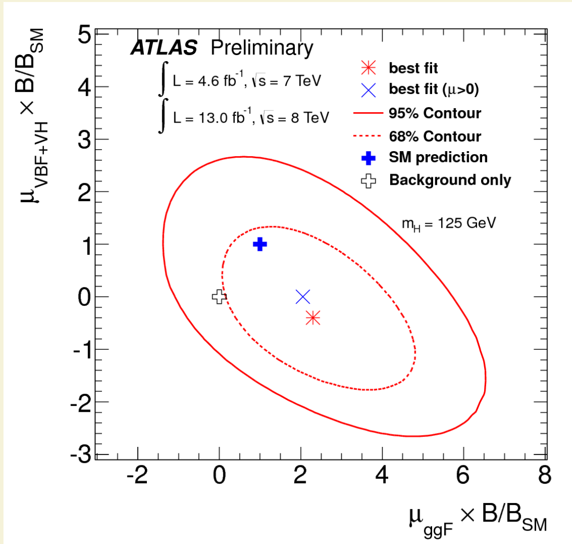
As in the case of CMS, this is the central channel to perform the measurements of the properties of the new particle.

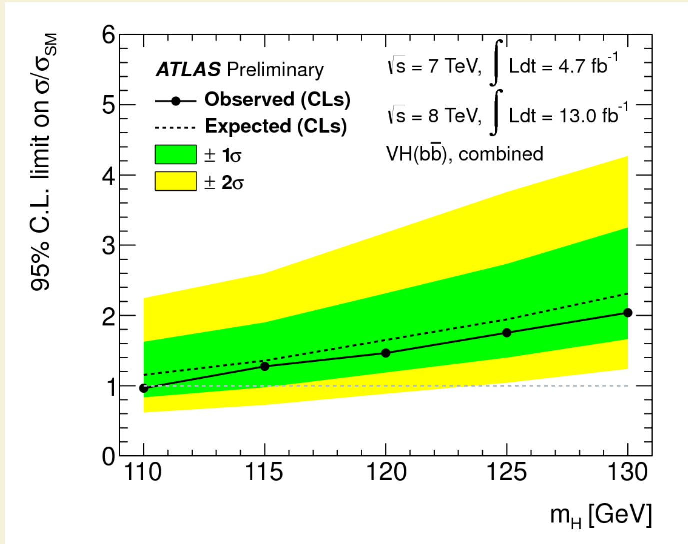
A new boson at 125 GeV: ATLAS Results (III)

- The secondary channels were also updated by ATLAS.
- Great effort with a lot of detailed studies regarding signal strength and measurements of coupling-related quantities.

$H \to WW^*$	$H \to \tau\tau$	$H \to b\bar{b}$
ATLAS-CONF-2012-158	**ATLAS-CONF-2012-160**	**ATLAS-CONF-2012-161**





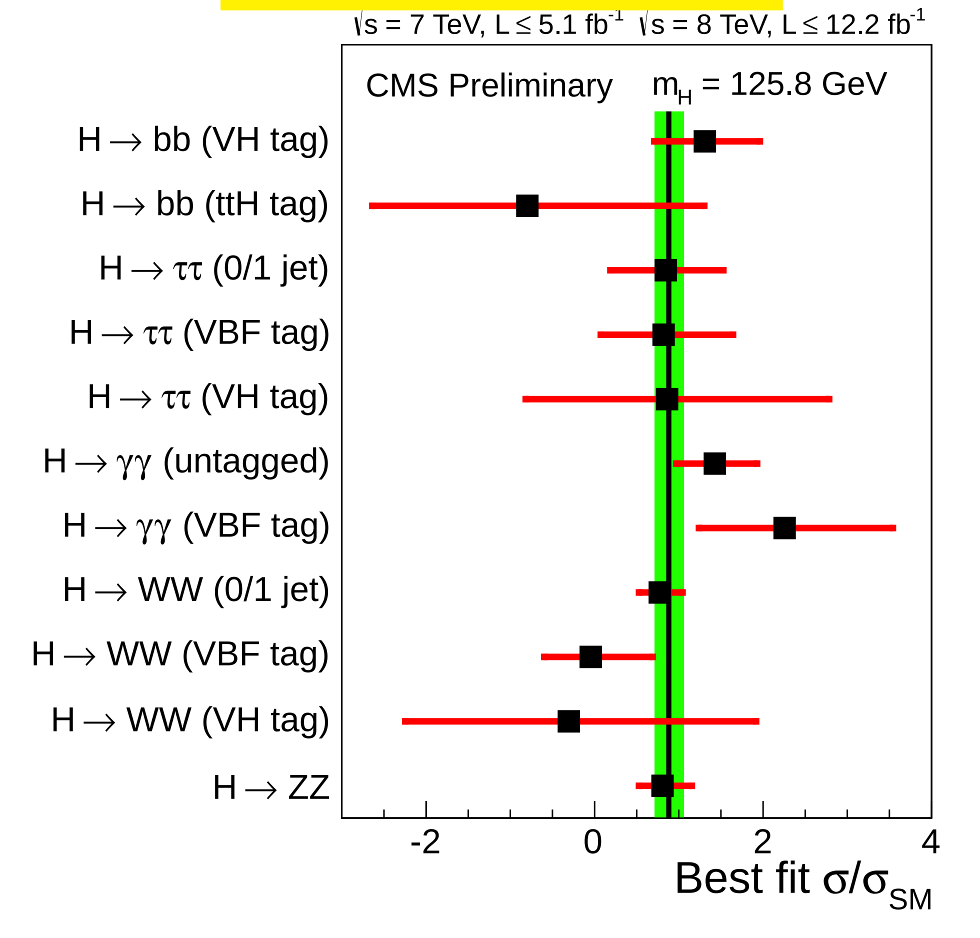


- Signal strength a bit high for WW^* and $\tau\tau$ (in $gg \to H$)
- $H \to \tau\tau$ a bit low in VBF+VH.
- Probably too early to start worrying: SM withing 1σ.
- $H \to b\bar{b}$ does not seem to have SM strength (not yet excluded though).

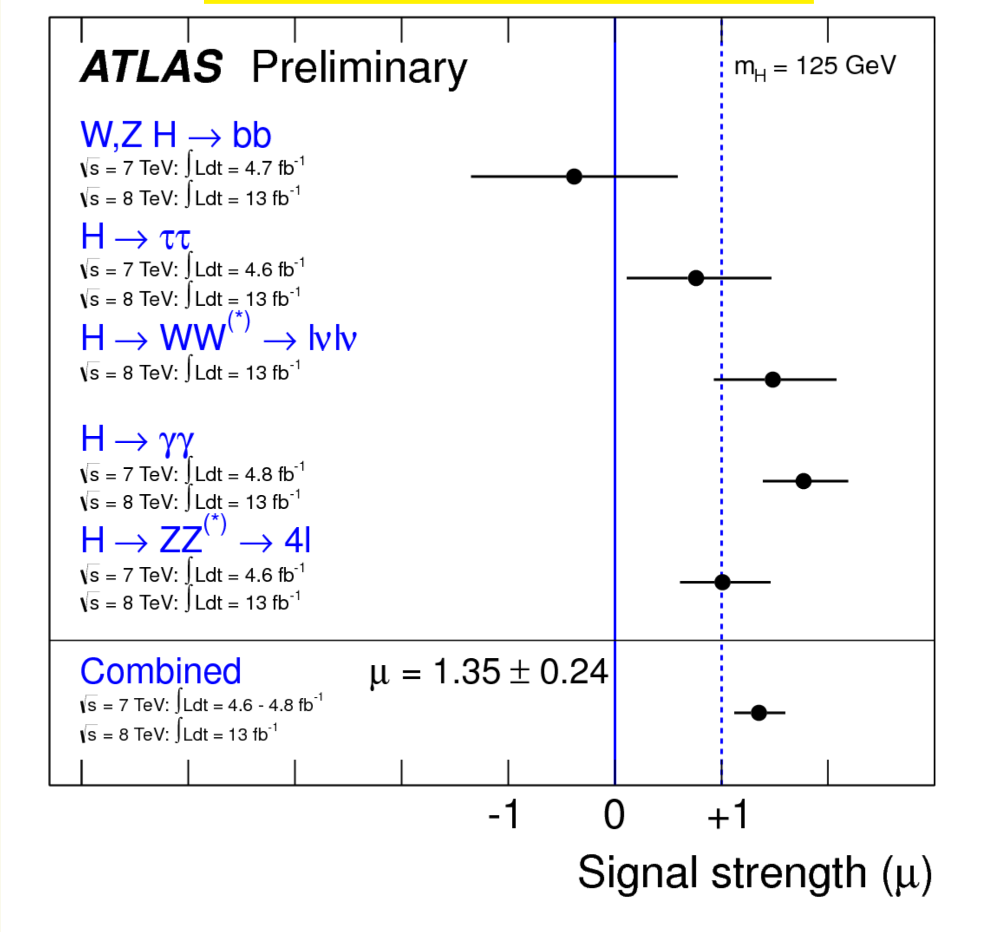
A new boson at 125 GeV: Summaries

- **After the big news on July, more data analyzed by the two experiments.**
- **The picture is getting more complete... but not much more clear.**

CMS-PAS-HIG-12-045



ATLAS-CONF-2012-170



But be tuned about the results presented at Moriond:

Results with the whole data are being presented these days!

Moving towards the post-discovery sample

- The results at ICHEP were very clear regarding the questions about the existence of the boson around the EWK scale.

- But it also keeps several questions unanswered.

Not only that... some of them are even more interesting than before, now that the boson was there:

⇒ Which are the couplings to the bosons?

⇒ Which are the couplings to the fermions? Do they scale with the mass?

⇒ Is it really a scalar 0^+ particle?

⇒ Is it the responsible object to give mass to the particles?

⇒ Does it couple to itself?

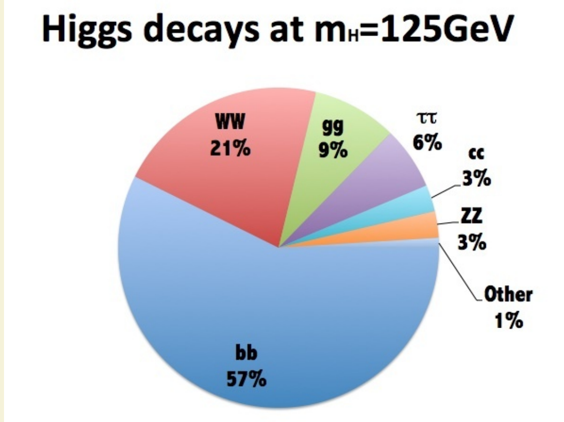
⇒ Is it directly related to the field producing the EWK symmetry breaking?

⇒ ... (choose your favorite)

So, in one sentence:

Is this the SM boson?

Providing answers



The steps are obvious, but it may require time/more data:

⇒ **Precision measurement of the mass (almost there!) and the width (tough!)**

⇒ **Measure the Spin and the Parity**

⇒ **Measure signal strength in as many channels as possible**

(Nature was kind: Higgs decays are reasonably varied so many channels are accessible)

⇒ **We need to explicitly obtain couplings (or coupling ratios) of the Higgs to all massive particles (or as many as possible).**

Need to include Higgs-strahlung for top (likely the most interesting one)

⇒ **We need to measure the self-couplings of the particle**

Again, very specific predictions from SM, but directly sensitive to New Physics, especially the structure of the Higgs sector.

Possible at the LHC? Linear-Collider or anything else?

From a practical point of view:

Identify and study ALL possible events which (may) include the new boson

Properties of the boson at CMS

- With the current datasample and available information from relevant channels (some with little significances/precision), the properties accessible are the mass, the spin/parity and the signal strength for fermions and bosons.
- The last precise study is based on the $4l$ analysis.

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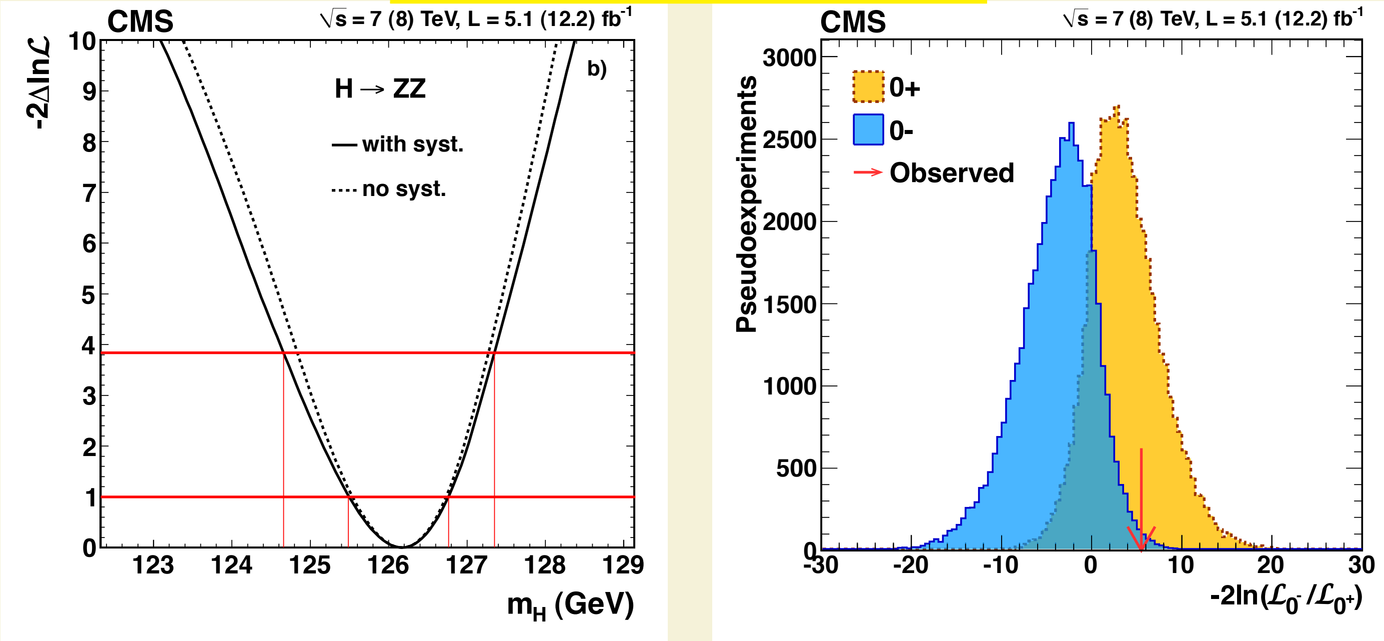
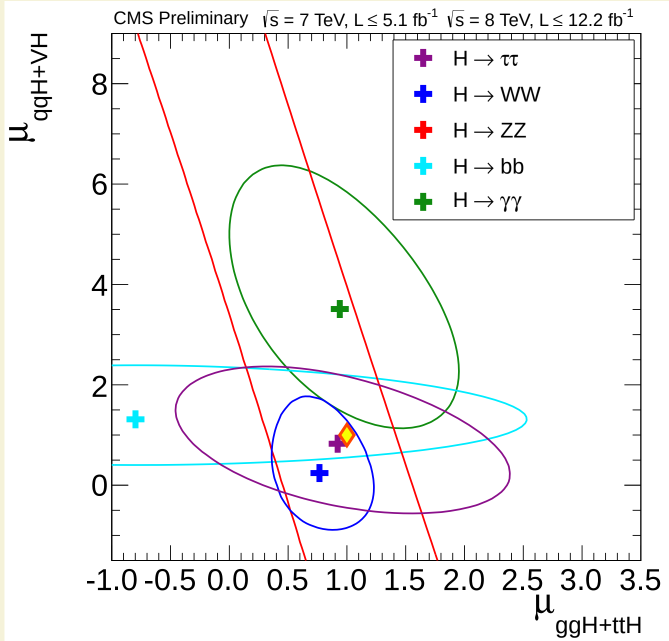


CMS-PAS-HIG-12-045



- Best mass: $m(H) = 126.2 \pm 0.6$(stat) ± 0.2(syst) GeV
- Data clearly favours a pure scalar (0^+) against a pseudoscalar (0^-) hypothesis.
- More data is needed to distiguish 0^+ from 2^+.
- Couplings are compatible with the SM values.

Properties of the boson at ATLAS

- The last results (ATLAS-CONF-2012-170) presented yielded some tension between the masses as extracted from the $4l$ and the $\gamma\gamma$ analyses:

$$m(H) = 123.5 \pm 0.9(\text{stat}) \pm 0.3(\text{syst})\ \text{GeV} \quad (H \to 4l)$$

$$m(H) = 126.6 \pm 0.3(\text{stat}) \pm 0.7(\text{syst})\ \text{GeV} \quad (H \to \gamma\gamma)$$

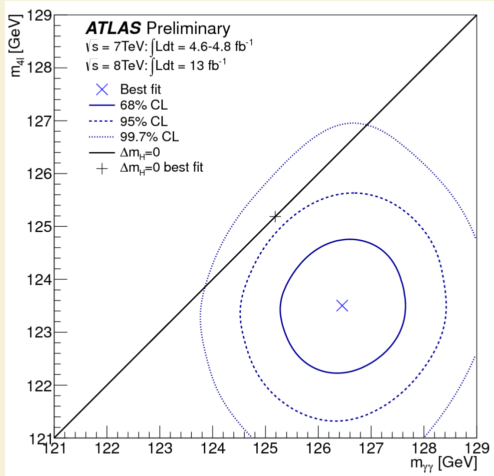
- Investigation ongoing... answer at Moriond Conferences?

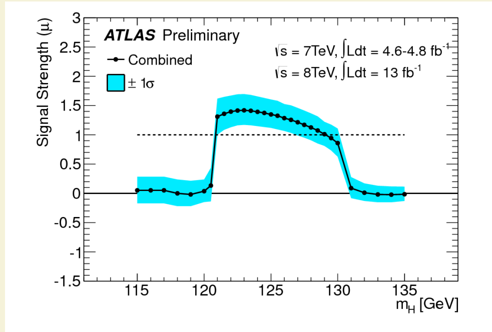
- The signal strength, measured with the sensitive channels, returns a bit higher value than the expected from the SM.

- Some work to try to confirm this. More data available (not all 8 TeV data used).

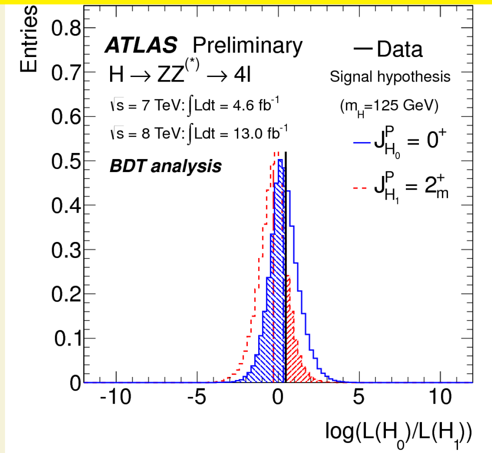
- In the meanwhile, spin/parity properties measured from the $4l$ analysis, which is the most sensitive one.

- Similar conclusions as the CMS analysis: data clearly favours 0^+ against 0^- and not enough distinction power with respect to 2^+.





ATLAS-CONF-2012-169



Other SM-like Higgs searches at ATLAS

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- **If the boson at 125 GeV were not the SM-Higgs boson, one may think that the original one (or another similar object) is still hiding somewhere.**

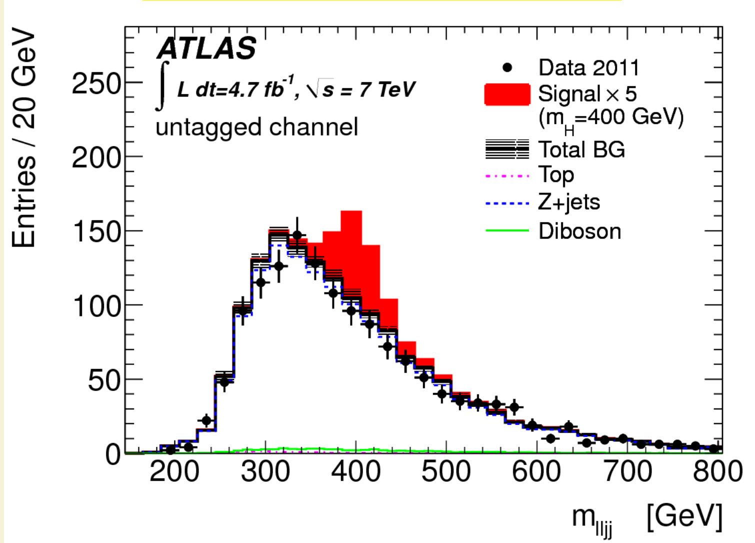
- **Limits may not apply since cross section may be affected by the 125 GeV boson.**

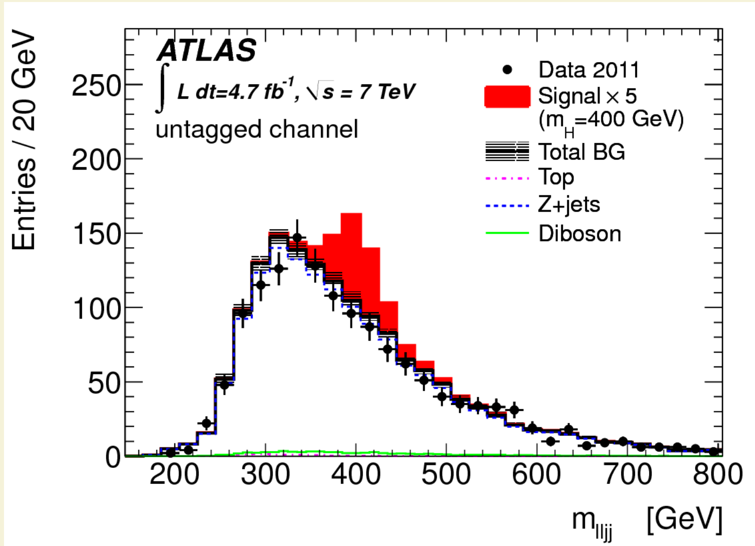
⇒ Basically all the channels used to study the Higgs at low mass (~ 125 GeV) are used to go higher in mass.

⇒ Since SM-like decays are assumed, the most relevant are those based on ZZ and WW once we are above 200 GeV.

⇒ The semileptonic $H \to ZZ \to llqq$ has better reach at high masses where the branching ratio reduces the $4l$ signal.

⇒ Need of kinematic constraints, but very competitive limit.

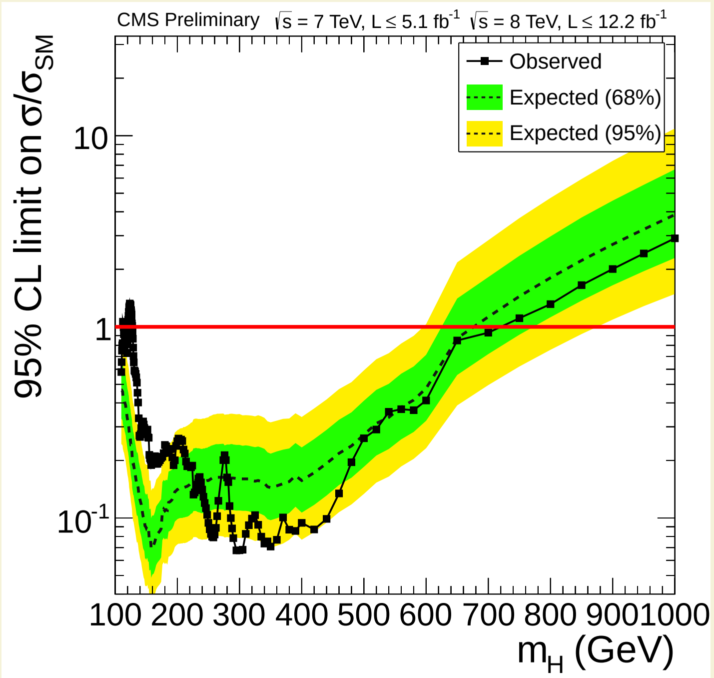


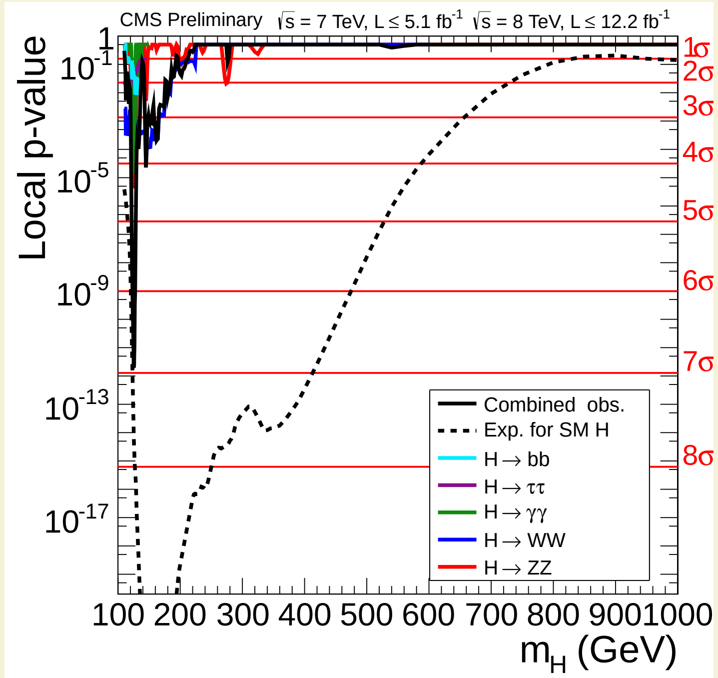


- **No significant discrepancy found in any of the channels.**

Other SM-like Higgs searches at CMS

- Similar approach in CMS, doing a combination of the relevant analyses (CMS-HIG-12-045) and obtaining a limit over the full range.





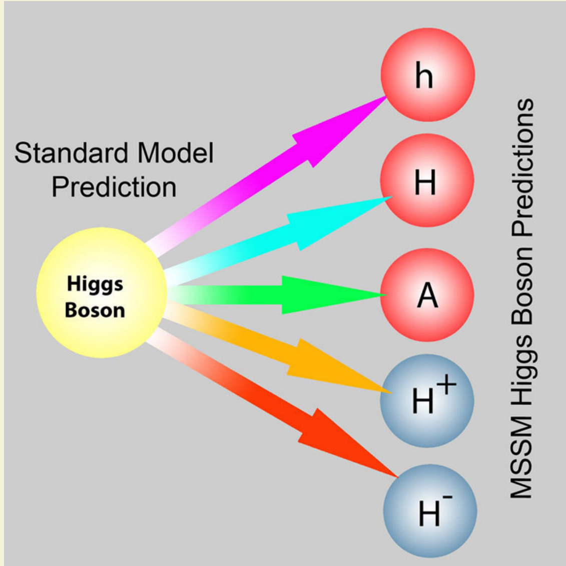
- At high masses the relevant channels ($H \rightarrow ZZ \rightarrow llqq$, $H \rightarrow ZZ \rightarrow ll\nu\nu$, $H \rightarrow WW \rightarrow l\nu qq$,...) do not provide good mass resolution.

- But not that relevant since Higgs is very broad at large masses.
- In any case, all these searches will soon become more general, with signal not exactly SM-Higgs-like.

- No hint of Higgses beyond the 125 GeV candidate. Too much SM-like Nature?

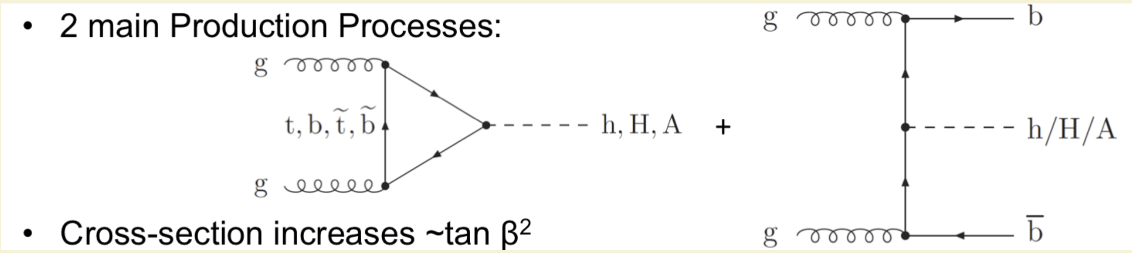
SUSY Higgs searches at the LHC

- Even with a 125 GeV boson looking like the SM Higgs, other searches are attactive since several extension of the SM would predict a SM-like Higgs.
- Probably the best example is, as always, SUSY models, in which it is not possible to have just a single (SM-like) Higgs
- Already in the simpler SUSY models (MSSM) there are characteristics in the Higgs sector that motivates specific searches:



$\Rightarrow$ Enhacements at large $\tan\beta$ of the coupling to the b and τ

The dominant production processes now involve b-jets in the final state



The increase in the cross section motivates a specific search

$\Rightarrow$ Presence of charged Higgses

Appearing in top quark decays, motivating the study of the τ decay channel

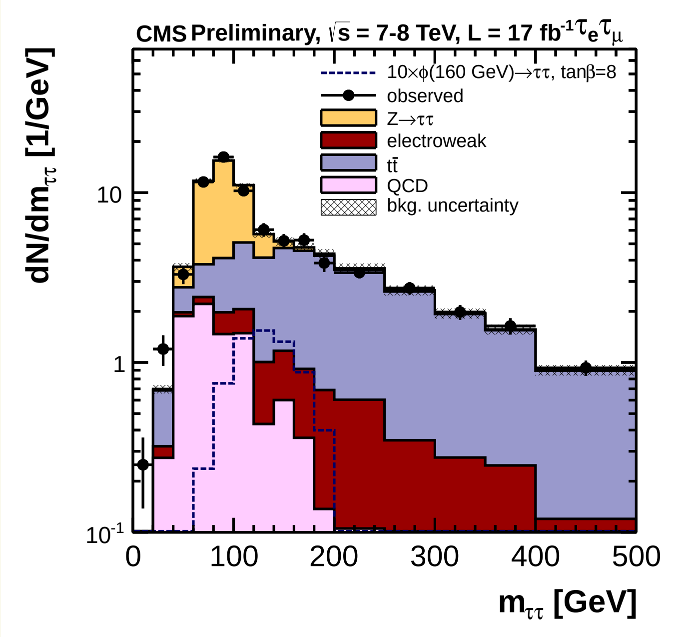
However, for low $\tan\beta$ the decay $H^{\pm} \rightarrow cs$ becomes important

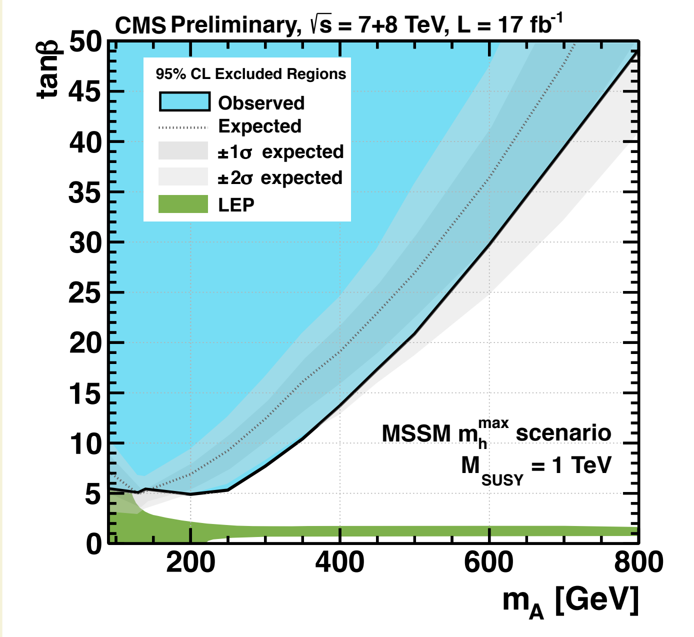
SUSY Higgs: searches for neutral Higgs

- Both collaborations looking for $\phi \to \tau\tau$ produced in association of b-jets.

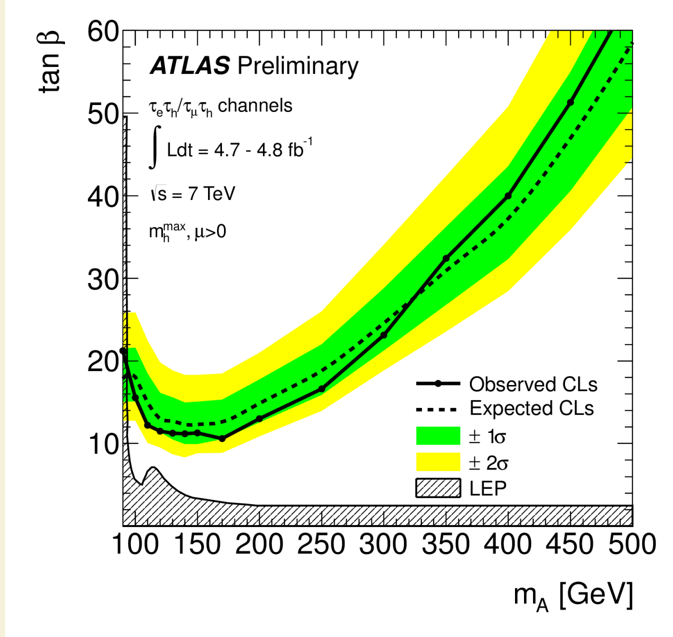
- Specially sensitive to the **reconstruction of the hadronic τ, although leptonic τ decays are also used.**

CMS-PAS-HIG-12-050





ATLAS-CONF-2012-094



- Nice agreement with the SM predictions (dominado by $Z \to \tau\tau$)

- Results are interpreted in terms of cMSSM parameters. **Usually $\tan\beta$ and m_A that are the ones with larger influence in this search.**

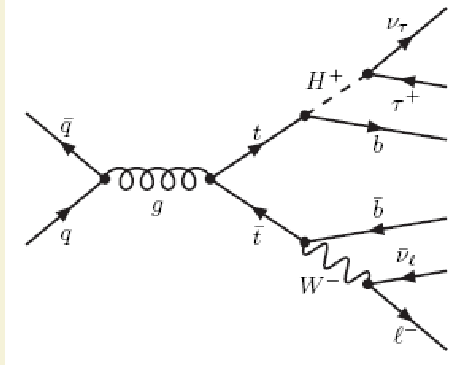
SUSY gets more constrained. Now from the Higgs sector!

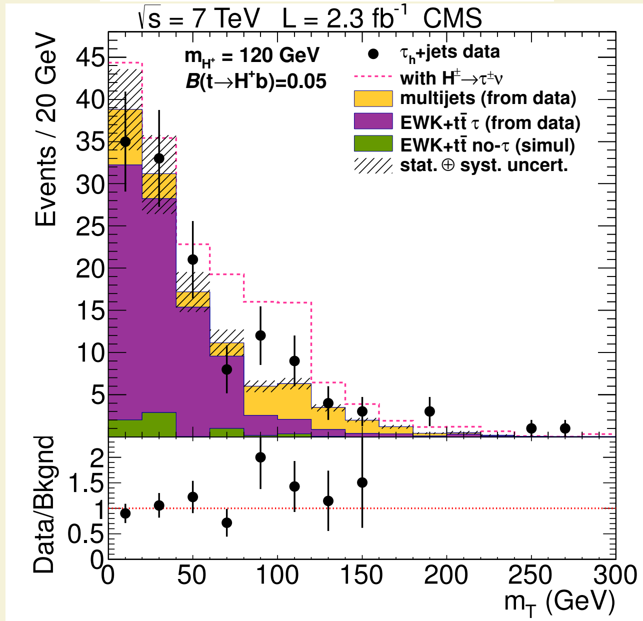
SUSY Higgs: searches for charged Higgs

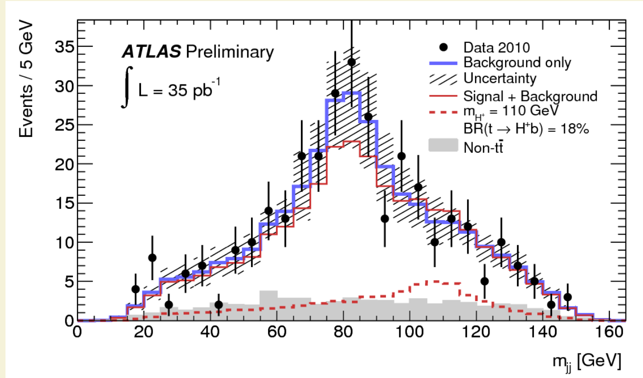
- **Both possible decays of $H^{\pm}$ has been performed, always in top decays.**

- **For $H^{\pm} \to \tau\nu$ at CMS (JHEP 07 (2012) 143):**
  - $\longrightarrow$ Several channels considered, including τ_h+jets.
  - $\longrightarrow$ No significant discrepancy found.
  - $\longrightarrow$ ATLAS produced a similar analysis.
  - $\longrightarrow$ Limits on production cross section and models.

- **For $H^{\pm} \to cs$ at ATLAS (ATLAS-CONF-2011-094):**
  - $\longrightarrow$ Looking for dijet mass not peaking at the W.
  - $\longrightarrow$ Decrease due to full hadronic: $t\bar{t} \to H^{+}bH^{-}\bar{b}$.
  - $\longrightarrow$ Good agrement with the background expectation.
  - $\longrightarrow$ Setting upper limit on branching ratio.
  - $\longrightarrow$ Soon: Update of the analyses on the topic.







Other Higgs searches at the LHC

- **Aside from SUSY, other extensions of the SM incorporates new Higgses or modify the SM one.**

⇒ Models like SM4 or Fermiophobic Higgs are now treated as part of the 125 GeV boson properties.

Other models have different properties/implications

⇒ nMSSM Models predicting light bosons decaying into muons.

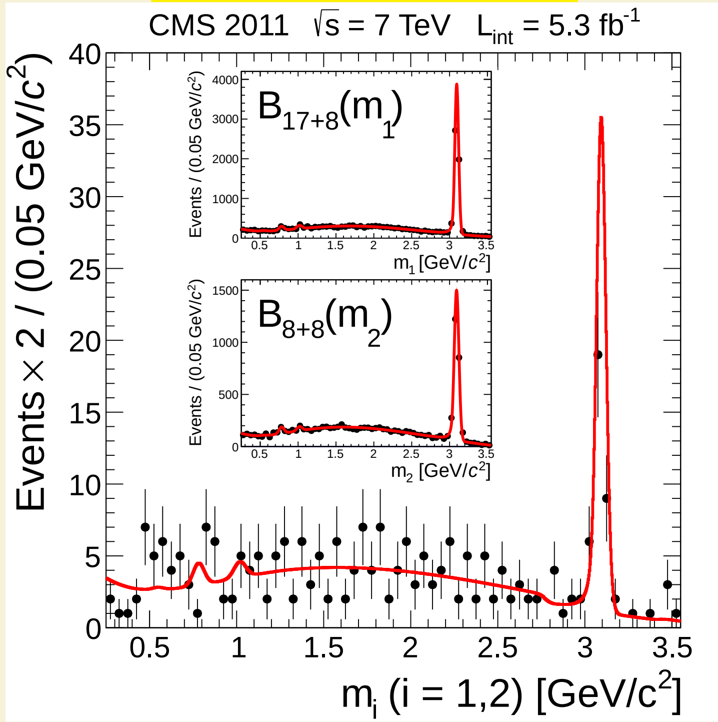
- **– Signal is 4 muons in final state**
- **– Also Dark-SUSY Models**
- **– Need to understand low-mass resonances.**
- **– No significant excess. Limits set.**

⇒ Models with doubly-charged Higgses:

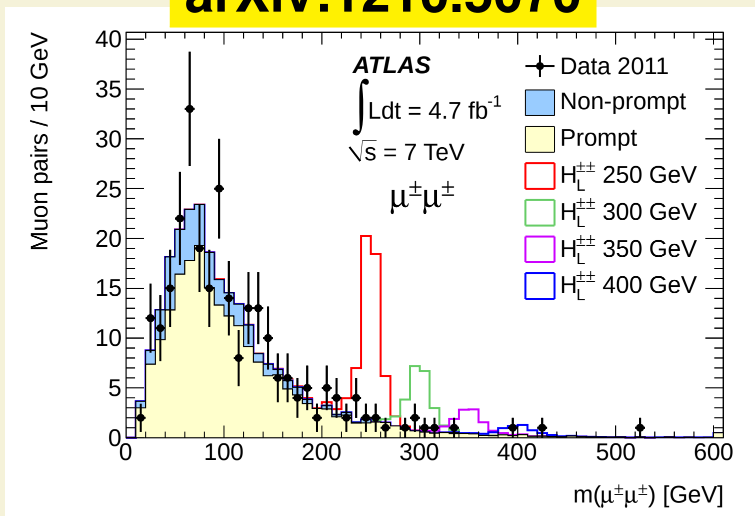
- **– Looking in same-sign dilepton resonance.**
- **– No significant escess found.**
- **– Limits in several models.**

- **Nothing found (yet?) so the SM-like Higgs (if it is the 125 GeV boson) seems to be unique.**

arXiv:1210.7619



arXiv:1210.5070



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Current status and future perspectives

- A new particle has been found with mass ~ 125 GeV that is compatible with the long-sought Higgs boson of the SM.

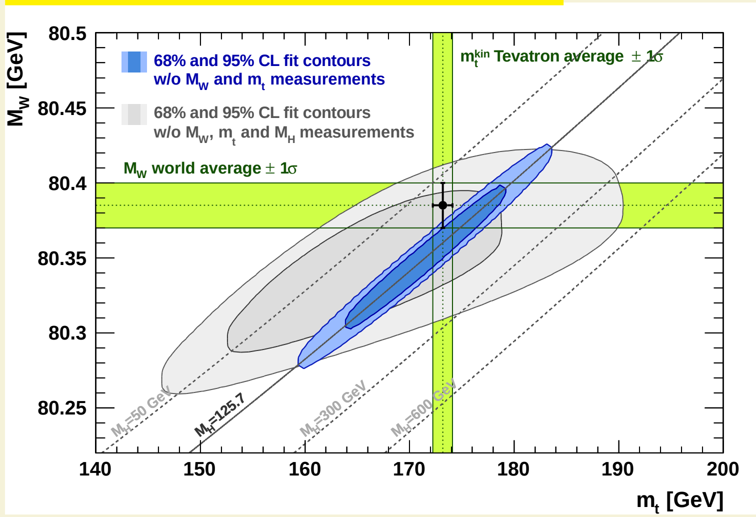
- Apart from this: Nothing similar (or plausible alternative) found, so it really points to *The* SM Higgs boson.

- Precision measurements are also available. SM seems consistent with overconstrained data, but some tensions here and there.

But we do know the SM cannot be the last word!

If the "125 GeV boson" is the SM Higgs the standard model is complete as defined… but not the end of the story. Many questions unanswered.

M. Baak et al., arXiv:1209.2716



The discovery of the Higgs not only confirms the SM, also its limitations… so the next steps are:

$\Rightarrow$ Study the Higgs properties in detail (as mentioned before)

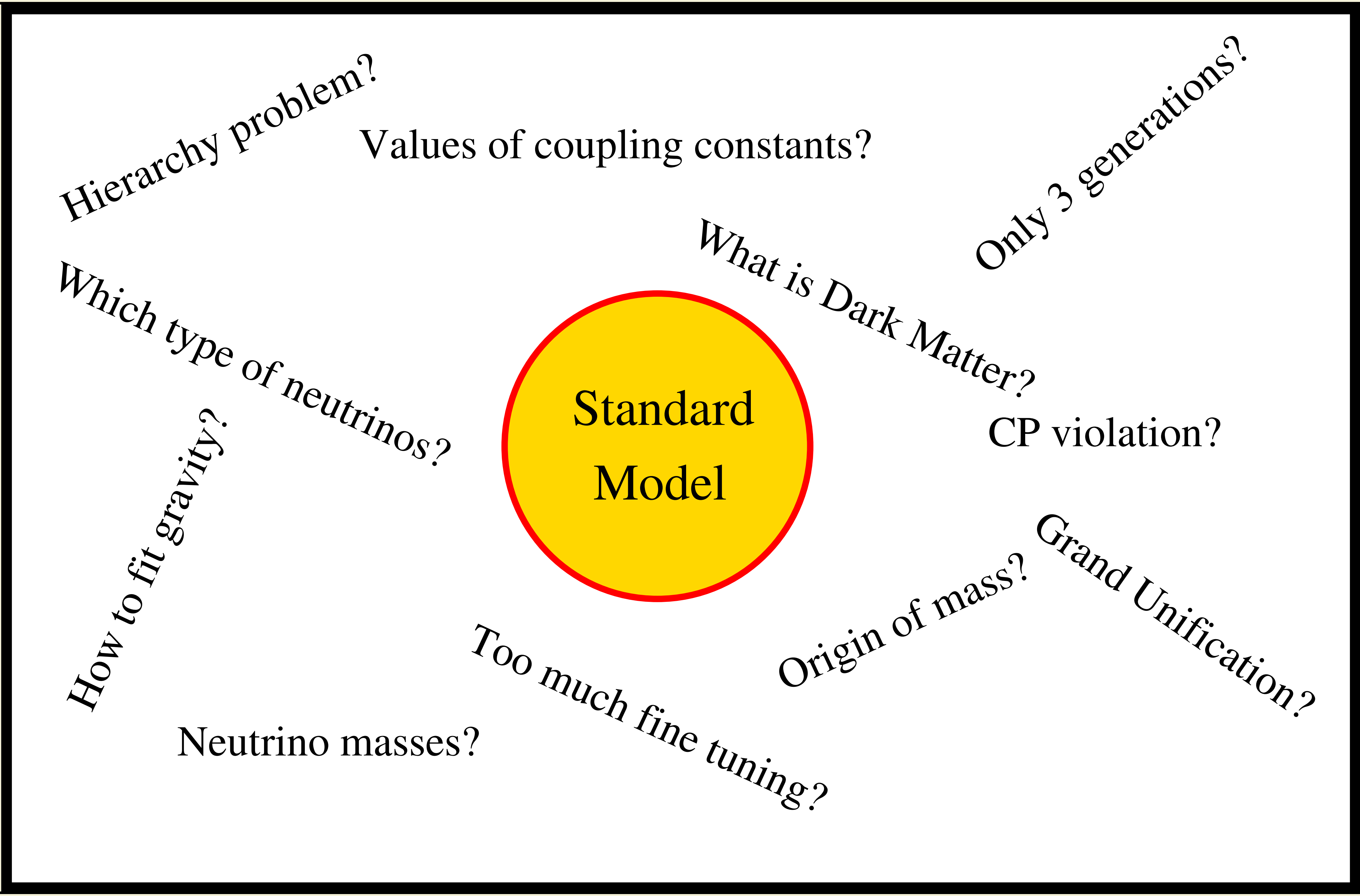
$\Rightarrow$ Measurements to look for discrepancies (more data needed)

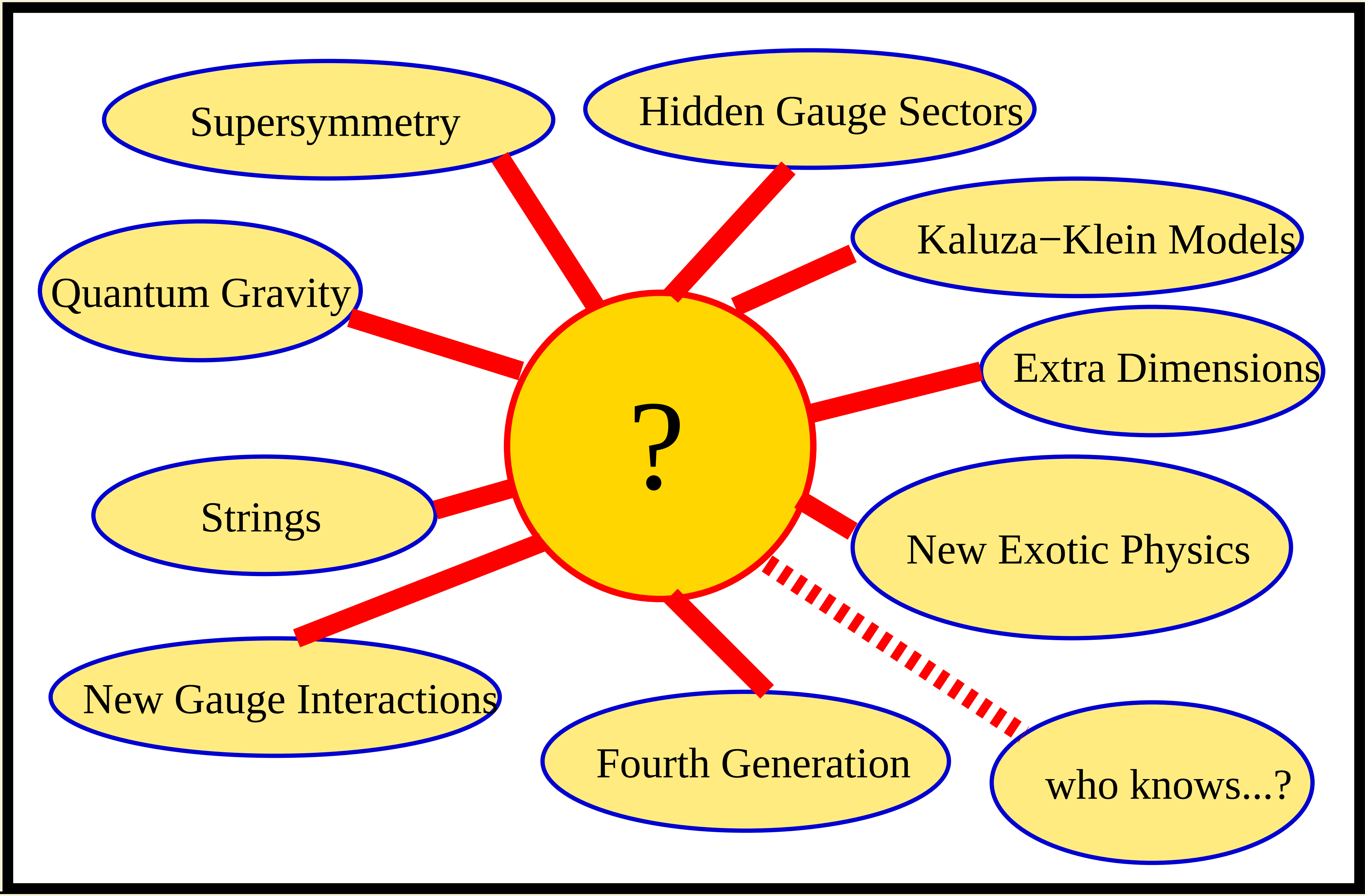
$\Rightarrow$ And specially:

Move the focus to New Physics to complement the Higgs discovery

Searches of New Physics at the LHC Experiments

The big picture



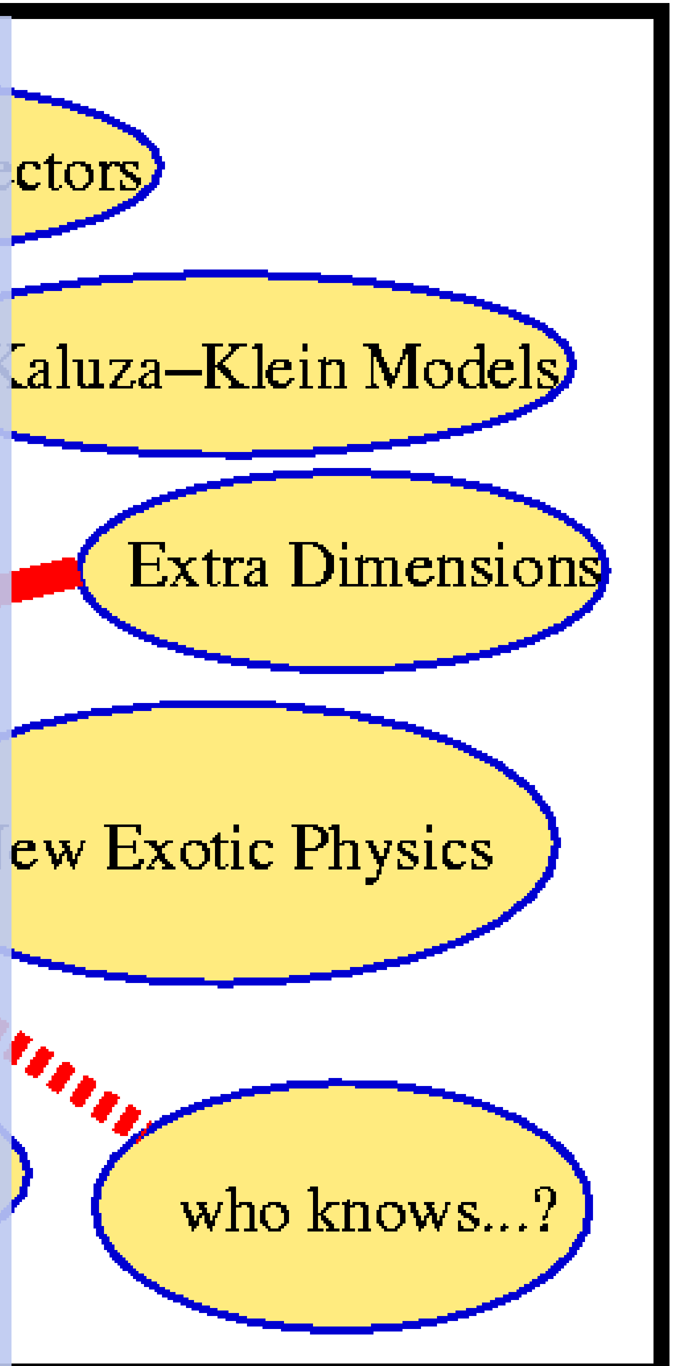

Supersymmetry
Hidden Gauge Sectors
Kaluza−Klein Models
Quantum Gravity
Extra Dimensions
?
Strings
New Exotic Physics
New Gauge Interactions
Fourth Generation
who knows...?

Outline of topics

- Supersymmetric particles: covered in second lecture.
- New resonances:
  - ⇒ Dileptons, diphotons, multijets.
  - ⇒ Also decaying into dibosons
- Excited states of particles and internal structure
- Leptoquarks
- Extradimensions: monophoton and monojet
- Top sector and a fourth generation
- More exotic searches:
  - ⇒ Microscopic blackholes
  - ⇒ Long-lived particles
  - ⇒ RP violating Supersymmetry

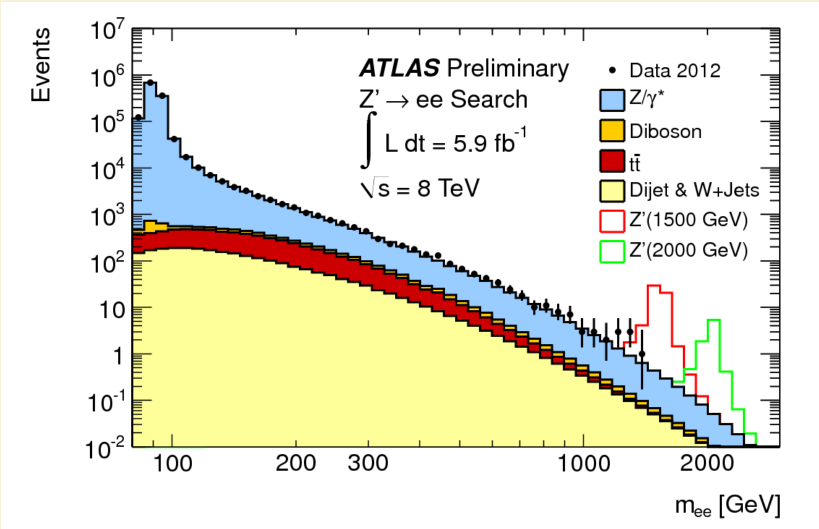
This contains a general overview of the searches performed at the experiments (CMS and ATLAS mainly), to give an idea of the status and reaches for several topologies.

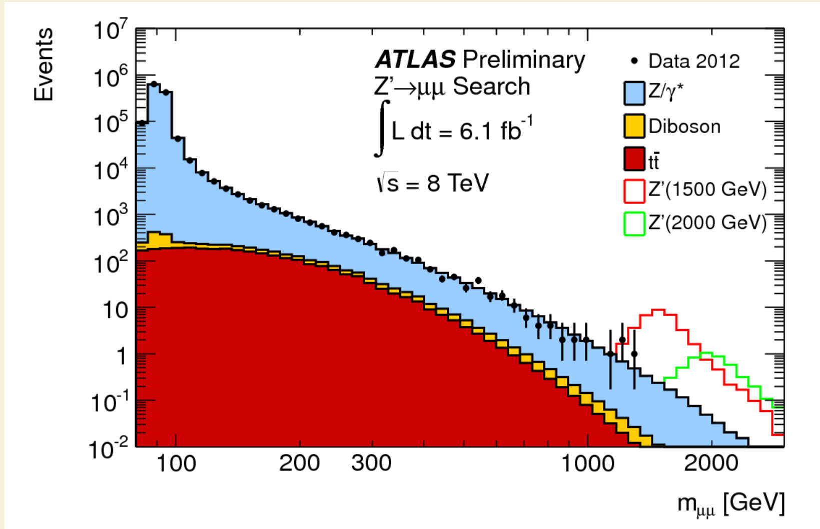
Not meant to be complete... each may be a seminar by itself!



New dilepton resonances: ATLAS

- The first obvious thing to look at are new resonances decaying into pairs of detectable particles: leptons, jets, photons.
- Predicted in extensions of the SM seeking for unification, e.g. broken E6 group.
- Using as a reference the Sequential SM, where Z' behaves like a massive Z.

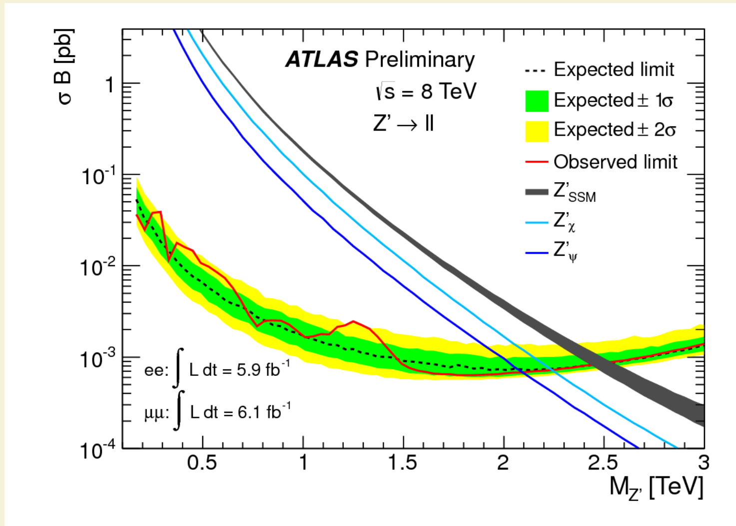




- Documented in **ATLAS-CONF-2012-129**
- Combining the ee and $\mu\mu$ channels:

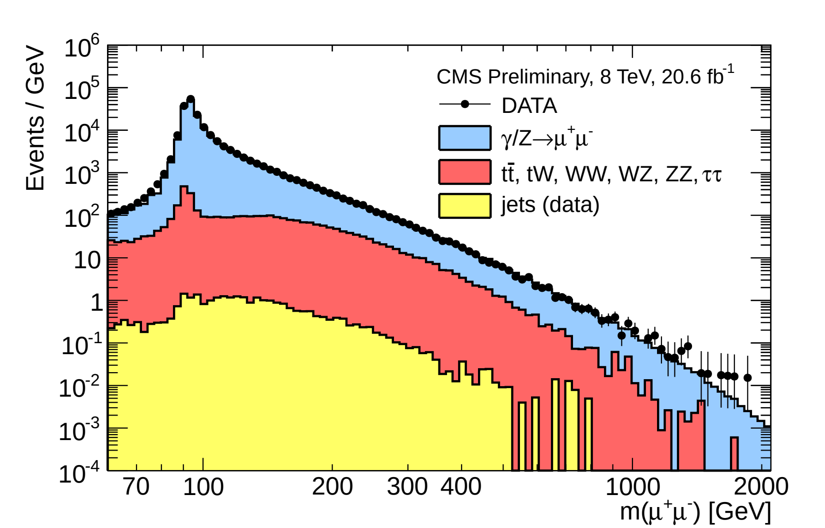
$m(Z') < 2.49$ **TeV** **[SSM]**

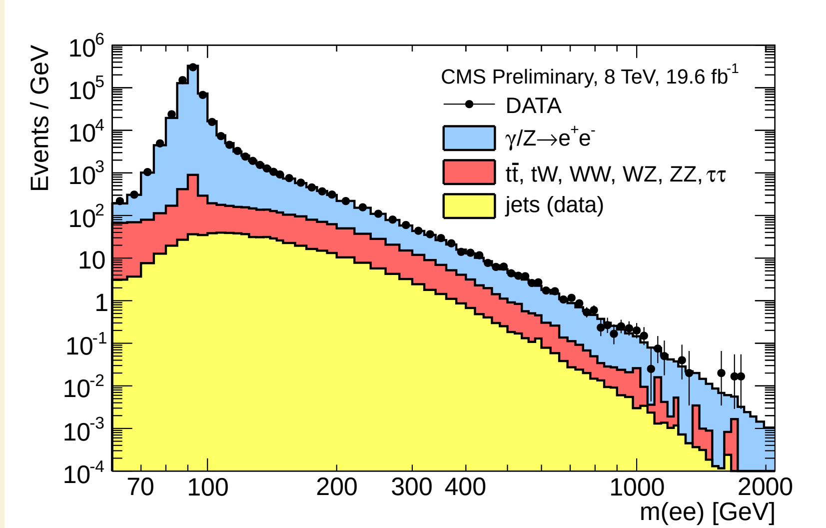
$m(Z') < 2.09 - 2.24$ **TeV** **[E6 models]**



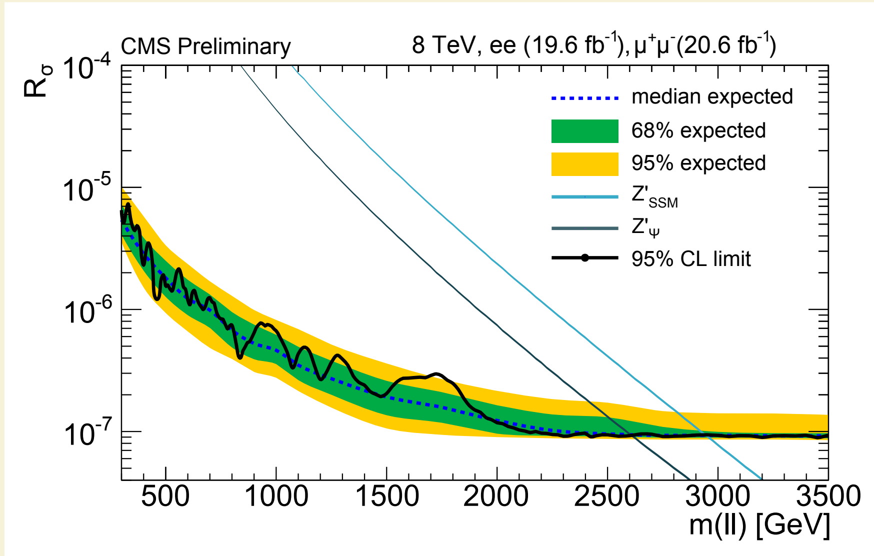
New dilepton resonances: CMS

- **Similar outcome from the CMS analyses.**
- **Splitting the electrons in barrel-barrel (both electron in central rapidity) and barrel-endcap (one is not central).**





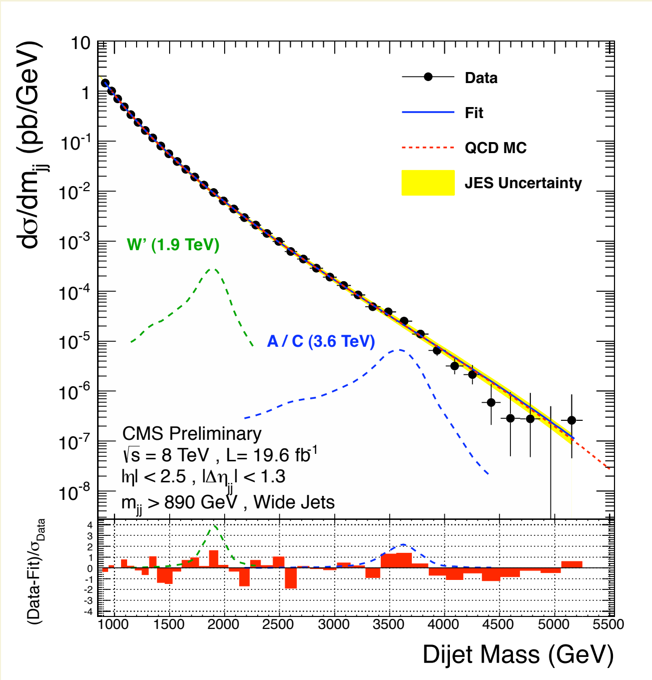
- **As in the case of ATLAS: great agreement over several orders of magnitude.**
- **Documented in CMS-PAS-EXO-12-061**
- **Combining the ee and $\mu\mu$ channels:**
  - $m(Z') < 2.96$ **TeV [SSM]**
  - $m(Z') < 2.6$ **TeV [ψ, Superstring E6 inspired]**

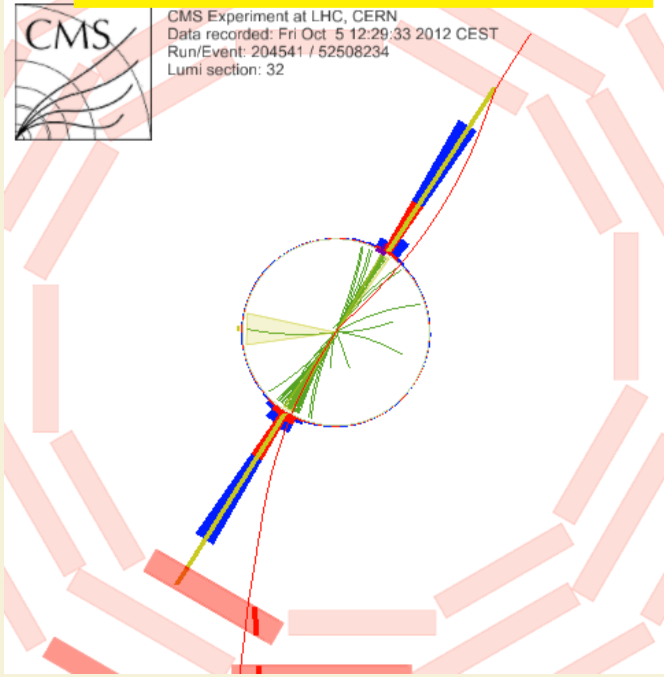


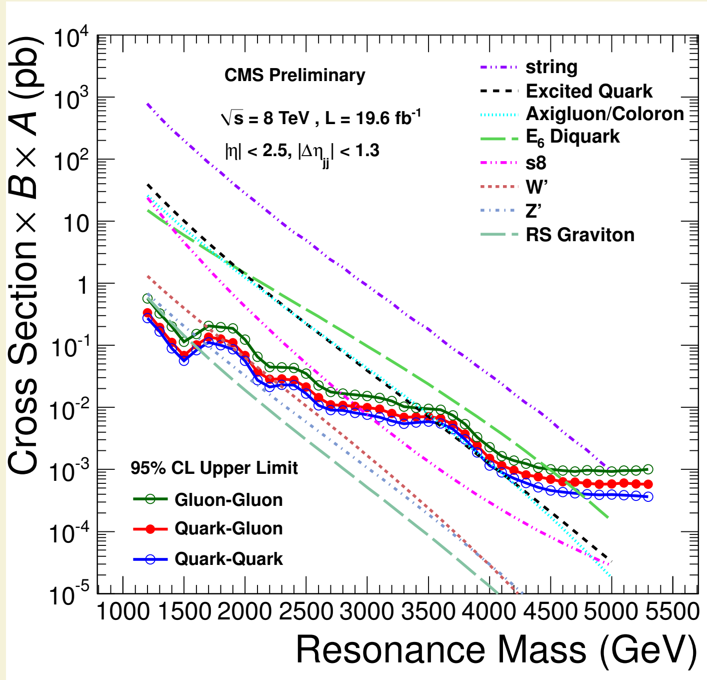
Search of dijet resonances

- A resonance decaying into quarks and/or gluons may appear as a bump on top of the dijet mass spectrum.

CMS-PAS-EXO-12-059







⇒ Impressive event with $m_{jj} = 5.15$ TeV

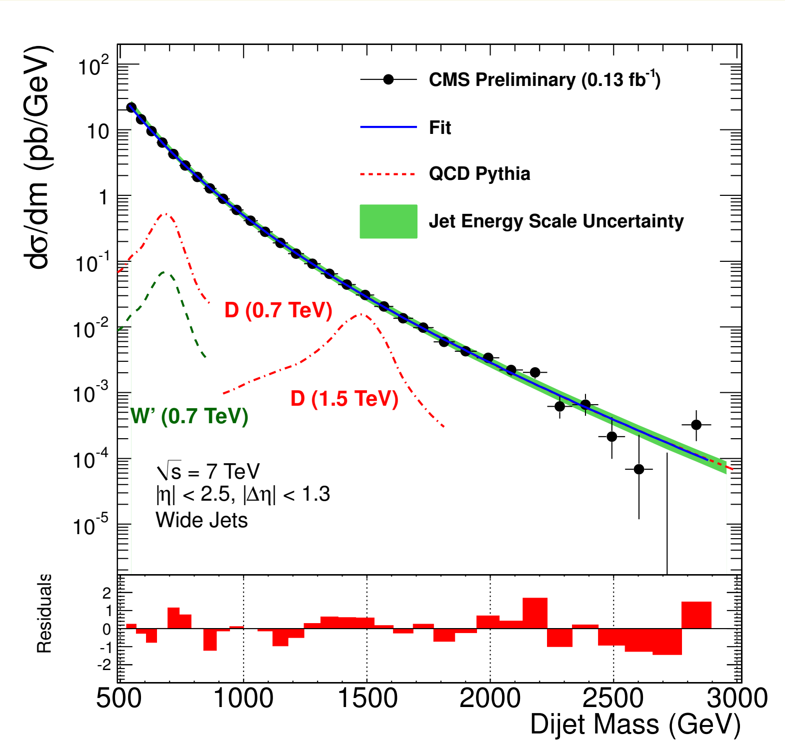
⇒ Good description by 4-pars function (and QCD MC) over 7 orders of magnitude

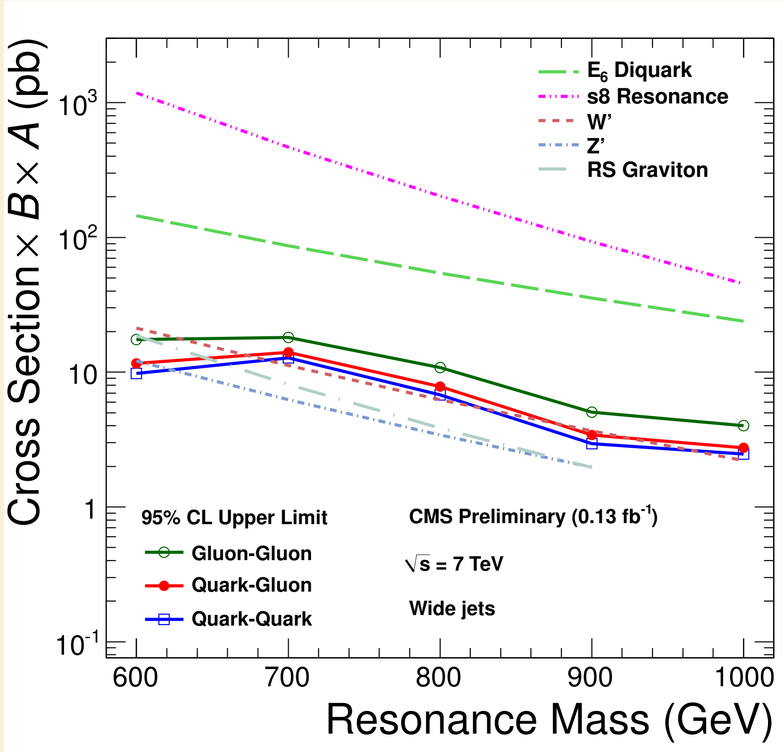
⇒ Limit set as function of the types of dijets

- A specific search for dijet resonances in $b\bar{b}$ does not find any significant discrepancy either.

Low-mass dijet resonances: Data scouting

- The previous search was started at $m_{jj} \sim 1$ TeV due to the trigger thresholds, that are high due to the great performance of the LHC.
- Could we be missing some low-cross section resonance below 1 TeV?
- This is the perfect place to make use of the data scouting: 130 pb^{-1} at 7 TeV.





⇒ Again, impressive agreement… and now limits below 1 TeV.

⇒ Data from the "scouting" understood and able to provide physics output!

⇒ Unfortunately, it confirms the SM predictions.

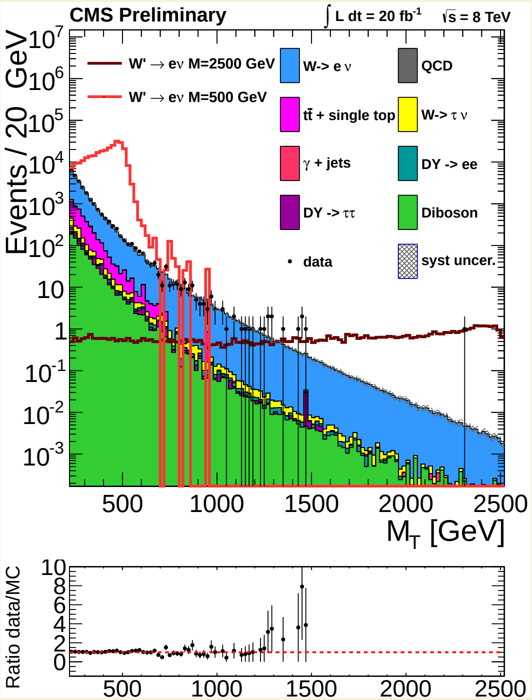
Search for W'-like resonances (I)

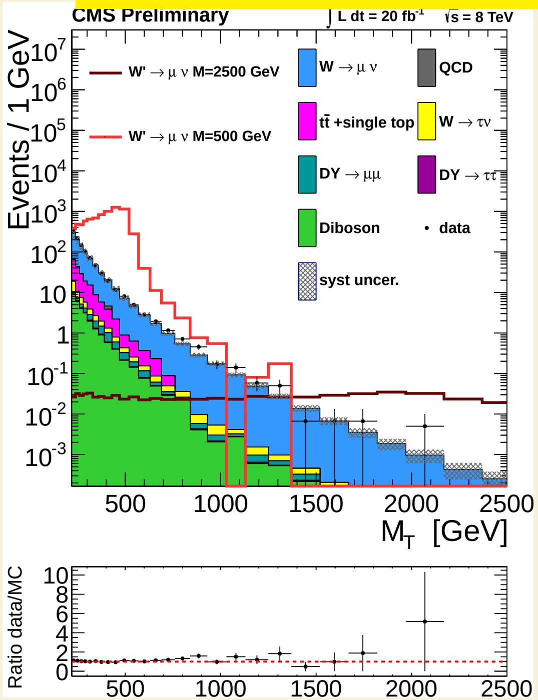
- **Similarly, another resonance into leptons, but we cannot reconstruct the full invariant mass, so using the transverse mass:**

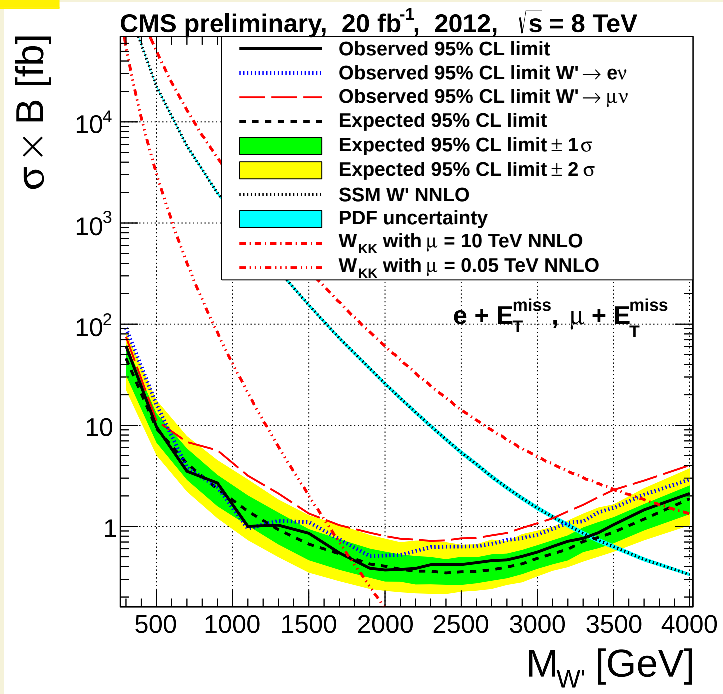
$$M_T = \sqrt{2 \cdot p_{T,\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

- **That shows a Jacobian peak at the mass of the relevant particle.**

CMS-PAS-EXO-12-060







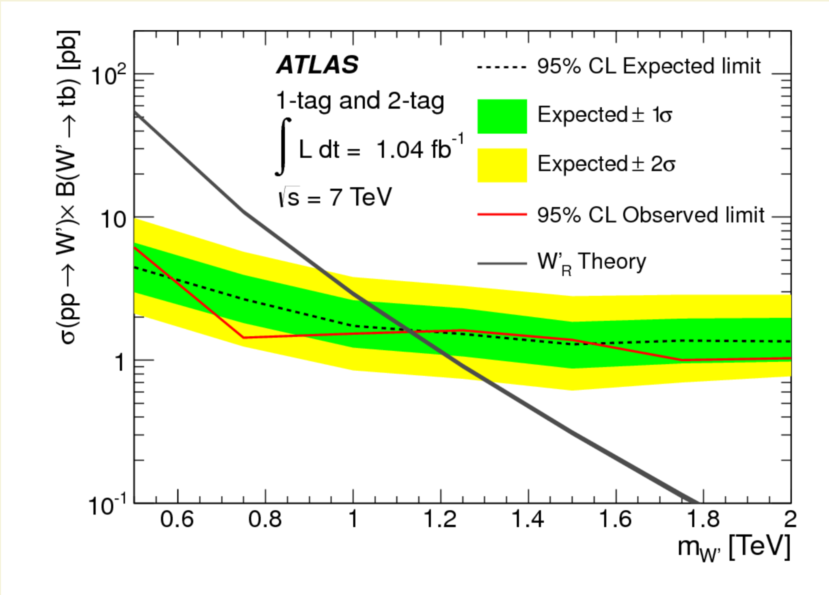
⇒ **Data well described by the SM predictions over several orders of magnitude.**

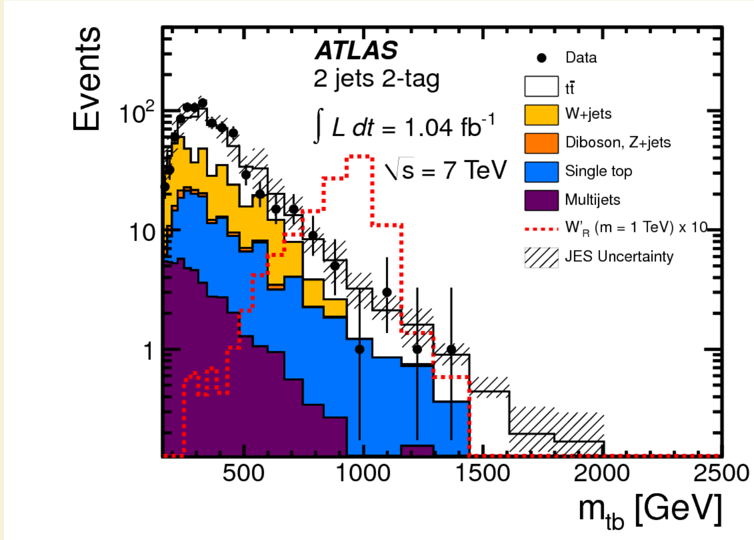
⇒ **Limits for W'_{SSM}, taking into account decay on tb (lowers the BR to leptons).**

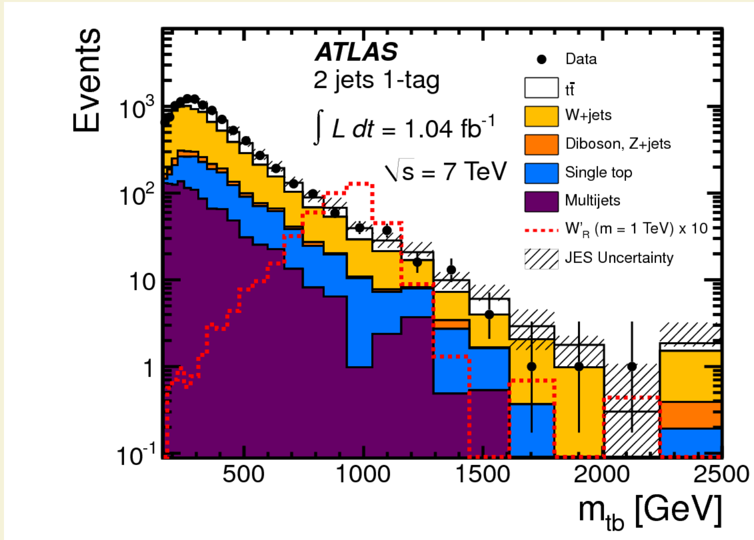
⇒ **Assuming no interference with SM W boson.**

Search for W'-like resonances (II)

- For very massive W', decay to tb is open.
- Not as simple as with leptons, but needs to explore that possibility since W' might be leptophobic (what do we expect for a W coupling to right-handed neutrinos?).
- Clean resonant channel: nothing in the SM decays in top (since it is the most massive)
- Documented in **PRL 109 (2012) 081801**







⇒ No sign of an excess looking as a resonance.

⇒ Indepedently of the number of required tags.

Resonances decaying to weak diboson

- Several extensions of the SM predict the presence of new particles decaying into pairs of weak dibosons.

e.g. technicolor particles decaying the WZ.

- Search by ATLAS in the very clean 3-lepton+MET channel.

- In order to gain sensitivity to new resonances, is preferred to consider the semileptonic or full hadronic models

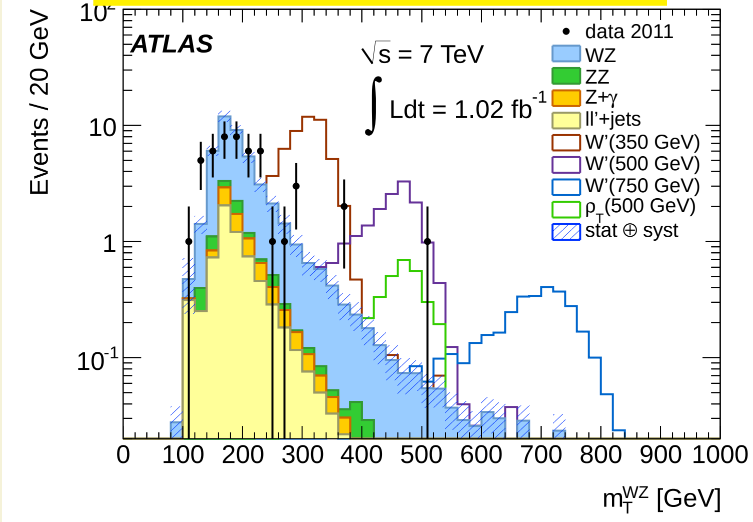
- Main disadvantage is that for very massive objects, the EWK bosons are very boosted and the two quarks are reconstructed as a single (fat) jet.

- However, CMS has turned this into a benefit to enhance signal: dijet events where jet(s) are W/Z-tagged.

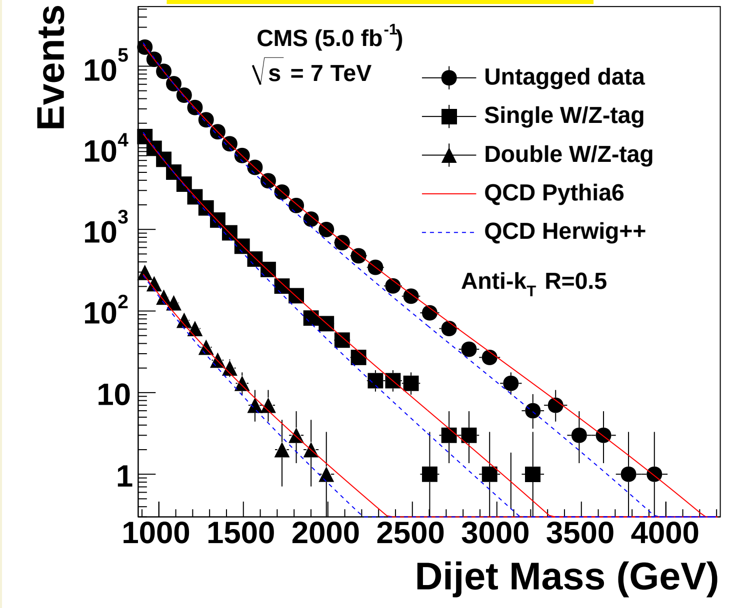
$\Rightarrow$ Taking nice advantage of the development of boosted-jet tools.

$\Rightarrow$ Good description of the data from the expected background.

PRD 85 (2012) 112012



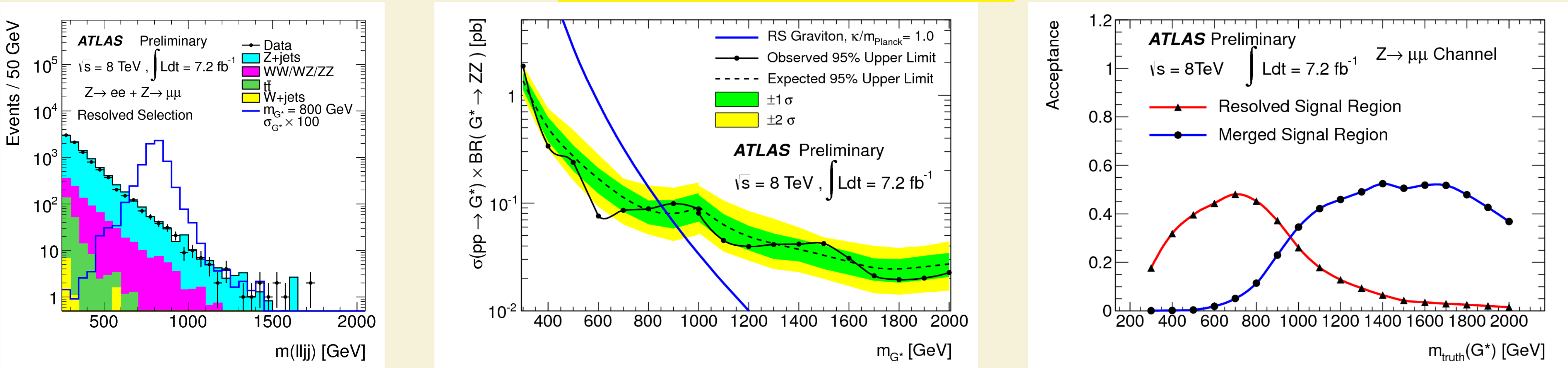
arXiv:1212.1910



Resonances in semileptonic ZZ

- The boosted-jet topologies are becoming more and more relevant as we increase the energy scales under test.
- The search of more massive objects implies this difficulty.
- A good example is ATLAS $X \rightarrow ZZ$ in the semileptonic channel.

ATLAS-CONF-2012-150



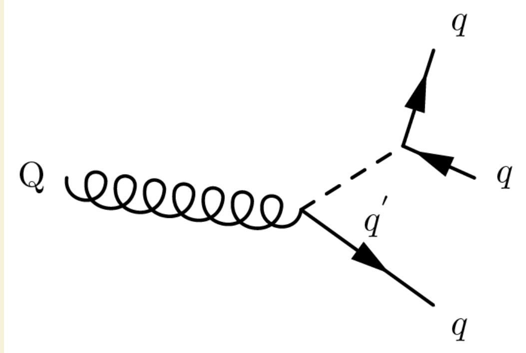
⇒ Parallel analyses: dijet and merged-jet topologies! Kinematic separation

⇒ Clearly the merged-jet topology is able to recover acceptance at higher masses.

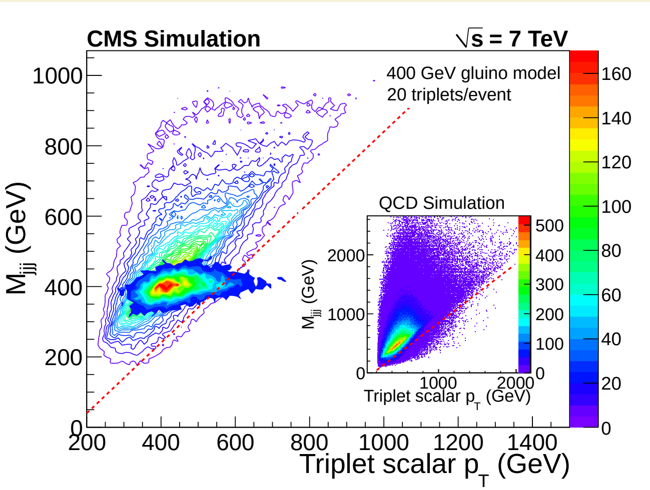
⇒ This kind of analysis (specially with specific W/Z-tags) will be fundamental at higher LHC energies.

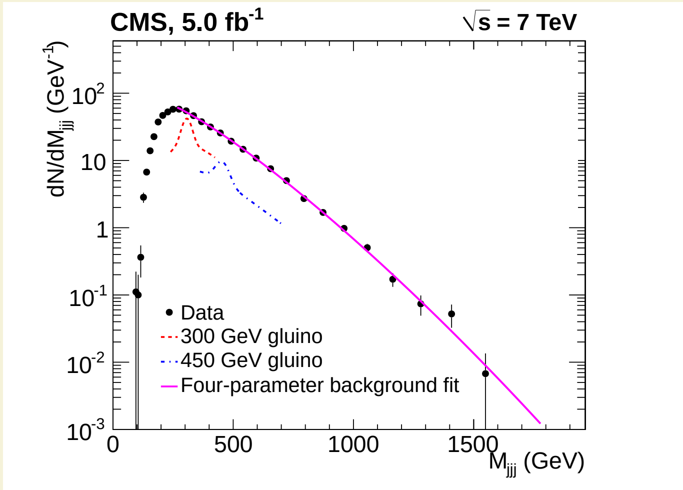
Three-jet resonances

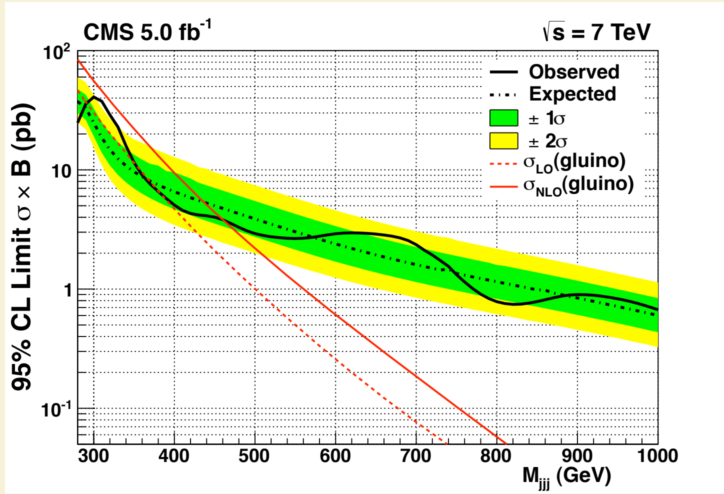
- Certain models predict the existence of particles decaying into three jets (e.g. RPV gluinos).
- If pair produced, we expect 6 or more jets on which some triplets of jet peak at the mass of the resonance.



PLB 718 (2012) 329







⇒ Using the jet-ensemble technique: triplets in inclusive 6-jet events

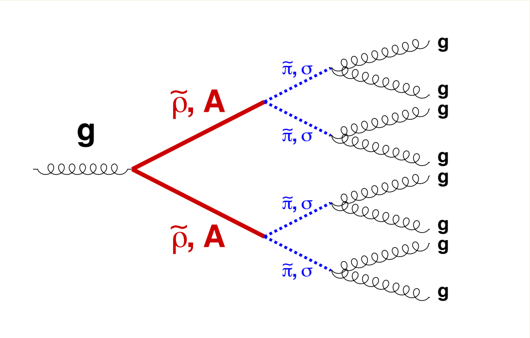
⇒ Combinatorial background (even from signal events)

⇒ In boosted events, p_T vs m of the triplet discriminate signal and background.

⇒ Technique may be extrapolated to other searches.

Multijet resonances in 8-jet events

- Other possible approach is to identify cascade decays bringing to multijet final states by intermediate resonances.
- Hard to handle due to combinatorics: sensitivity degraded!
- But it may be simplified if at some point a state is identified.



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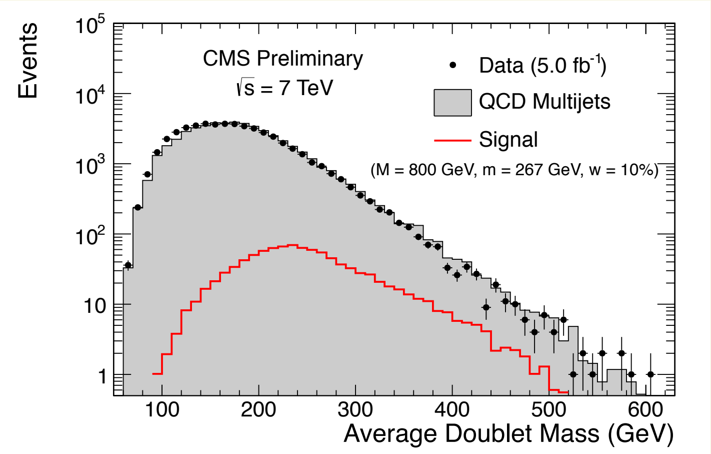
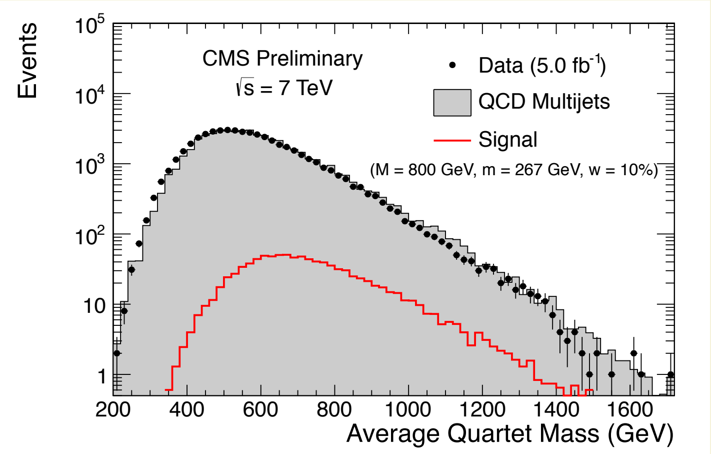
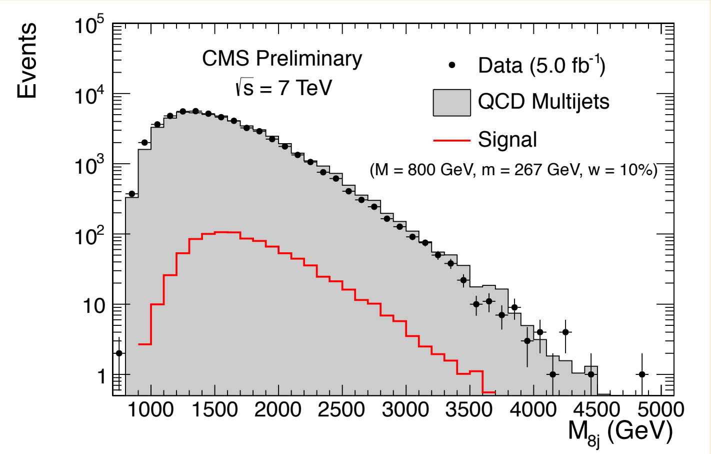






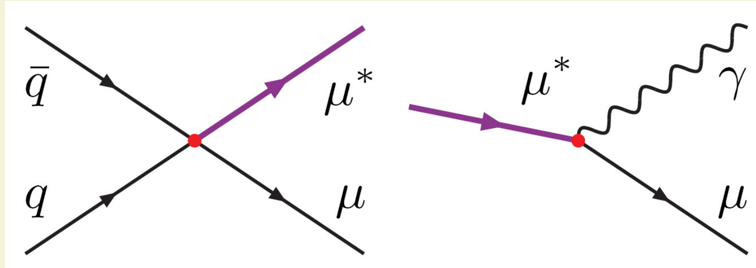
⇒ Artificial NN used to enhance signal-like topologies.

⇒ Good agreement with background expectation.

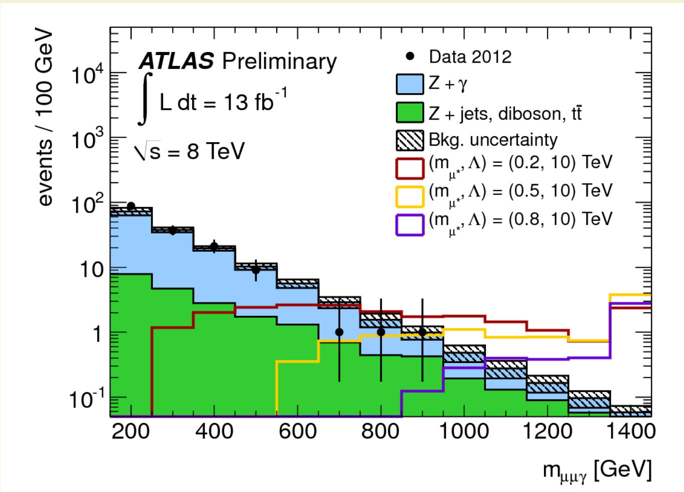
⇒ Limits set in models related to this kind of processes

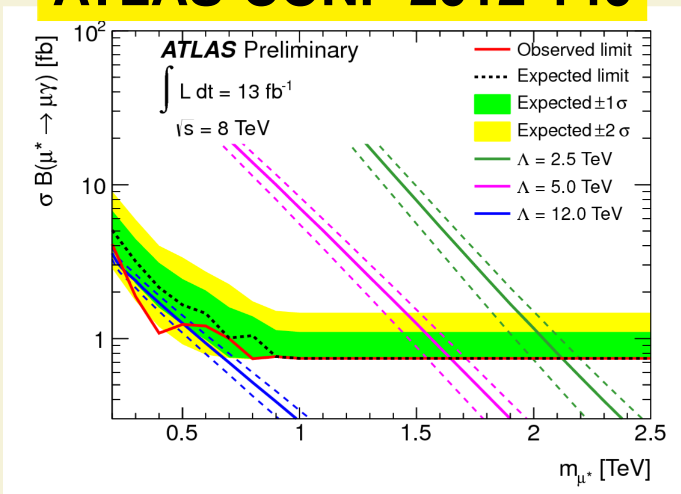
Excited leptons: $\mu^* \to \mu\gamma$

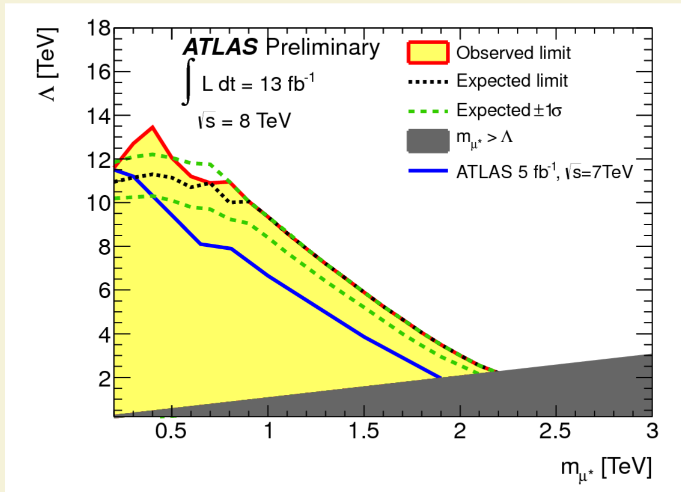
- Excited muons may be detected in Drell-Yan production.
- Decay into **a muon and a photon in addition to the partner muon provide the signature.**
- Selection done by requiring large invariant masses, excluding the $Z \to \mu\mu$ resonance.



ATLAS-CONF-2012-146







⇒ Good agreement with SM predictions.

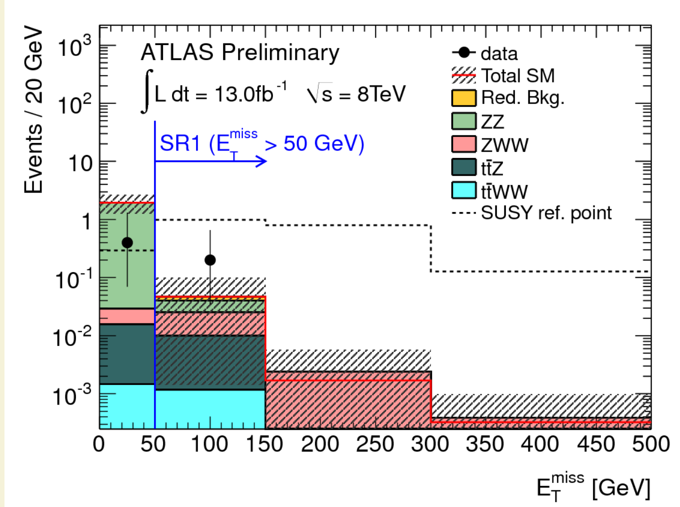
⇒ The same analysis includes an identical study for excited electrons.

⇒ Same conclusions and similar exclusions.

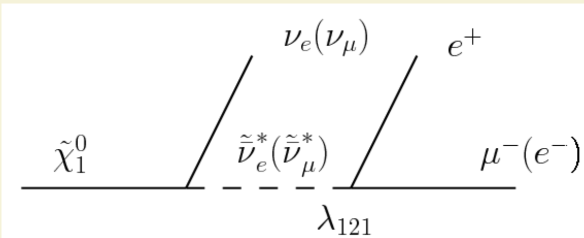
RPV Supersymmetry

- Since SUSY is such a great idea, it is worth it to explore all possibilities.
- One possibility is that R-Parity is not conserved, what makes SUSY not being the source of Dark Matter.

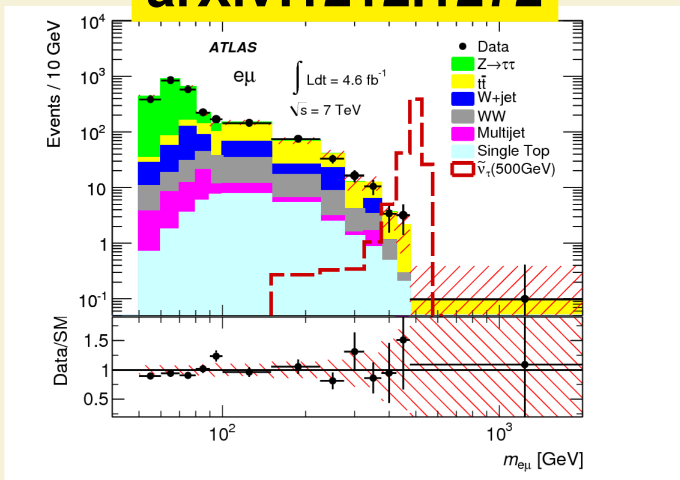
ATLAS-CONF-2012-153



- But allows to avoid the most stringent limits, based on MET-related topologies.
- Characteristics of RPV SUSY:
  - ⇒ LSP could be any particle (unstable).
  - ⇒ Dominant terms may prefer pair production.
  - ⇒ Everything decays: high multiplicities
  - ⇒ Many types of particles in final states.



arXiv:1212.1272

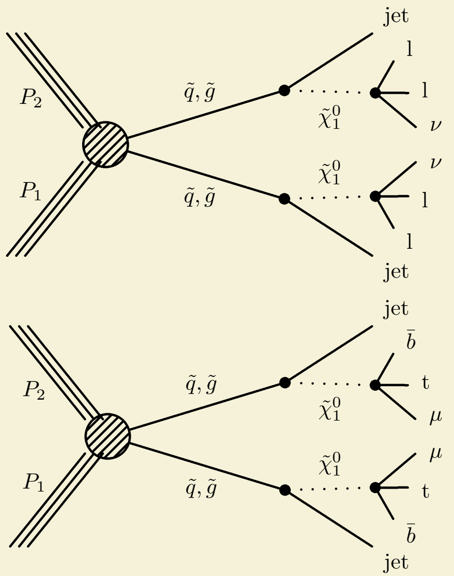


- ⇒ Also exotic resonances: $\tilde{\nu}_\tau \to e\mu$

- Basically every final state is possible if choosing the right phenomenology.
- No hint for discrepancies in RPV-based final states.

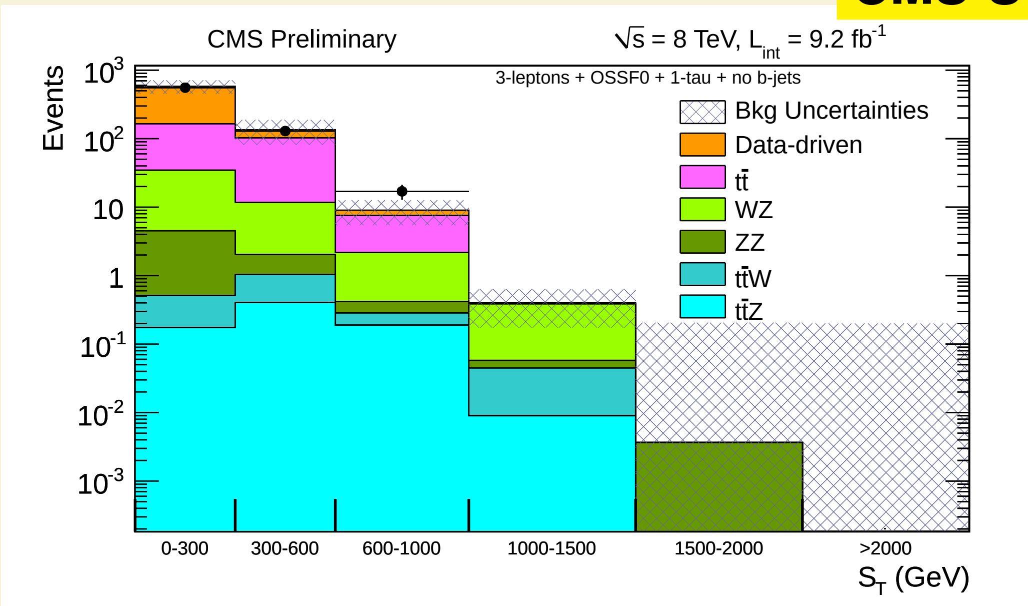
(But limits usually have little implications due to large set os possibilities)

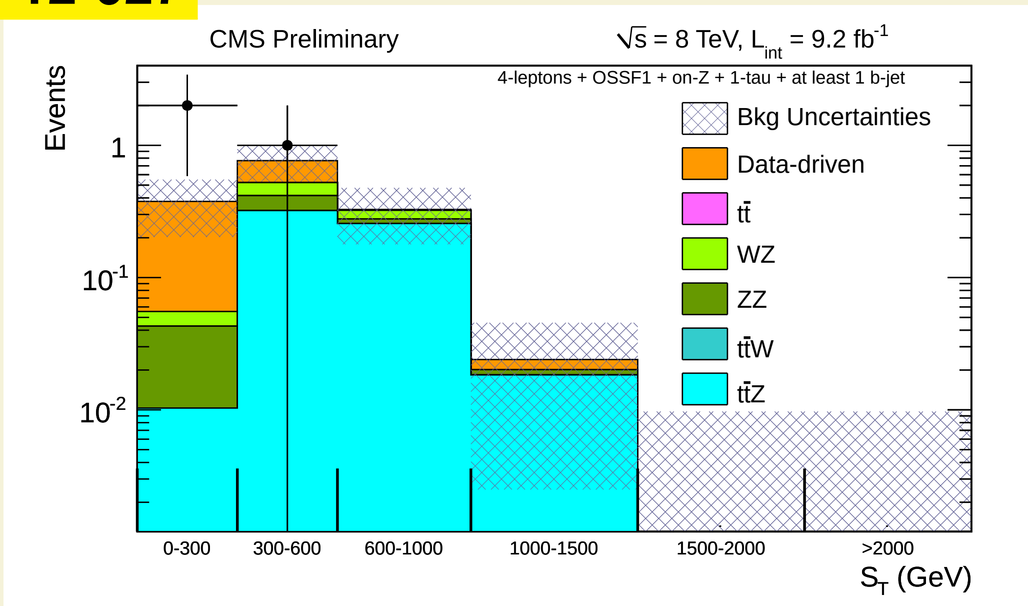
RPV Supersymmetry: multileptons y (b-)jets



- An example of possible "crazy" final state: multileptons+b-jet.
- Backgrounds reduced requiring 3 or more leptons (also τ).
- Scalar sum of p_T used as key discriminating variable.
- **High multiplicities implies high complexity in reconstruction and interpretation.**

CMS-SUS-12-027



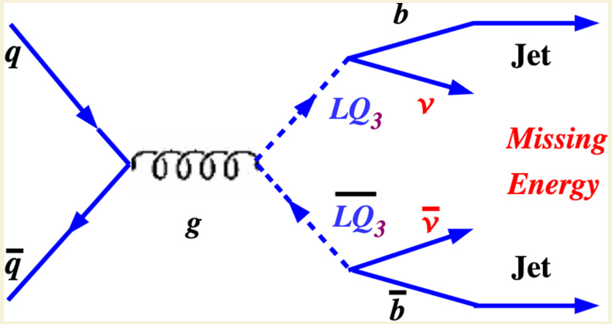


$\Rightarrow$ **One interesting thing: sensitivity to very rare SM processes.**

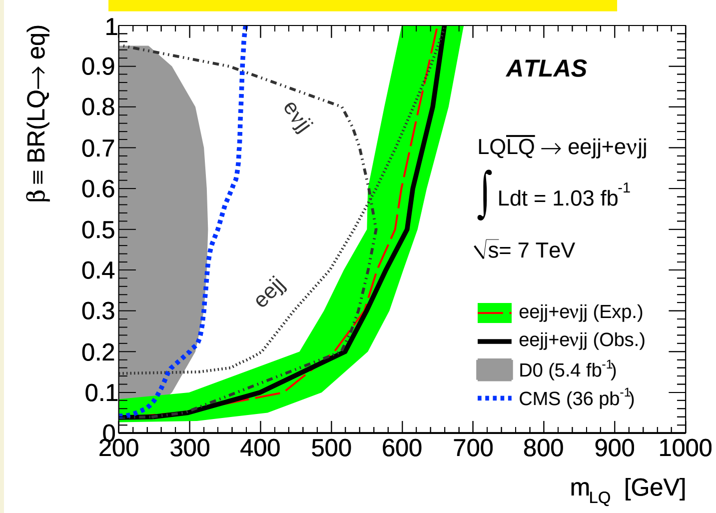
$\Rightarrow$ **Observation of those as interesting as New Physics…**

Leptoquarks (I)

- Several unification models predict the existence of particles having both lepton and baryon numbers: leptoquarks (LQ).
- They are strongly produced, and decay in a quark and a lepton.

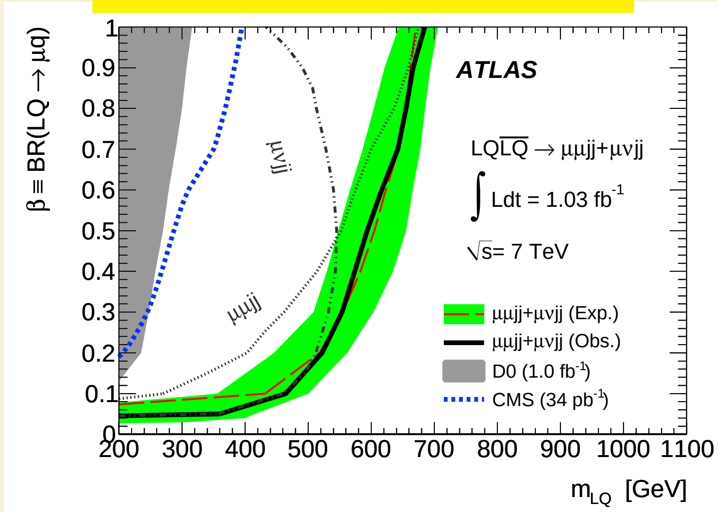


PLB 709 (2012) 158



- Rich phenomenology, depending on many parameteres and classes of leptoquarks.
- Analyses with leptons (and/or MET) and jets.
- Usually assumed that LQ are also structured in families, and normally they do not mix fermions from different families.
- Analysis inclusive for the first two LQ generations: the lepton type determines selection class.
- Good agreement observed.

EPJC 72 (2012) 2151

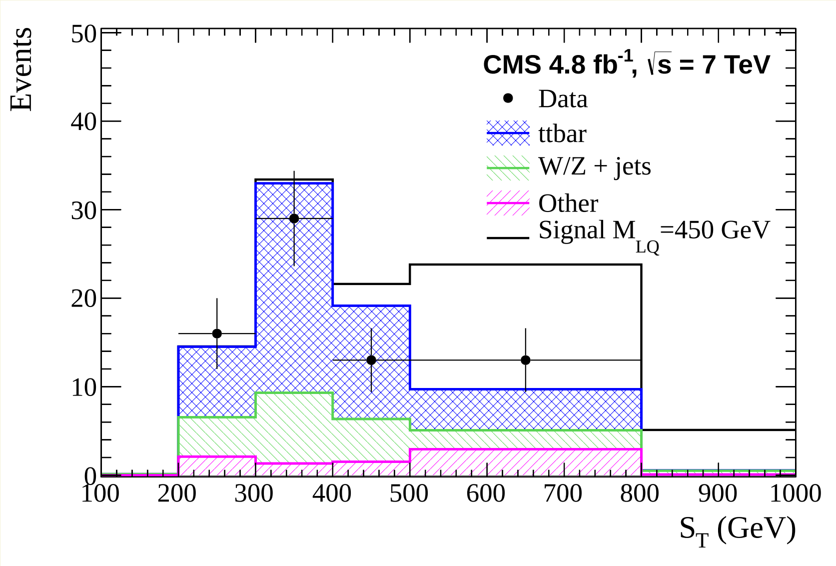


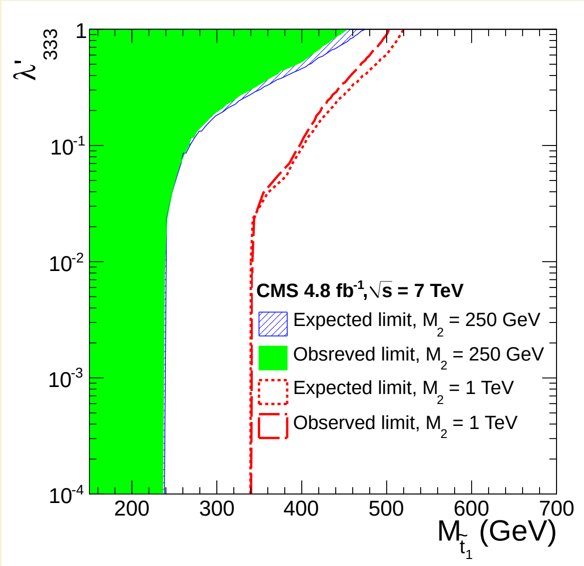
- Limits on leptoquarks set: LHC going beyond previously explored areas.

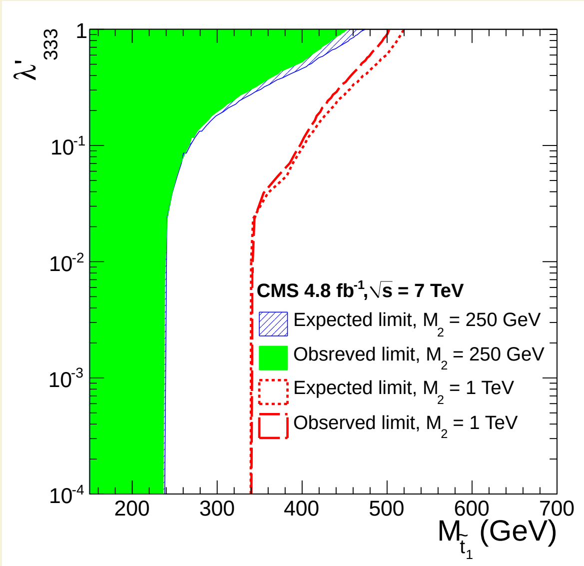
Leptoquarks (II)

- Due to the importance of the third generation in the limitations of the SM, specific studies for them are encouraged.
- As described in several analysis, the presence of b-jets allows the enhancement of the sensitivity to signal by using b-tagging.
- Investigated decay: $b\tau$ for the corresponding final state.
- Discriminating with S_T, the scalar sum of the p_T of the decay products.

PRL 110 (2013) 081801







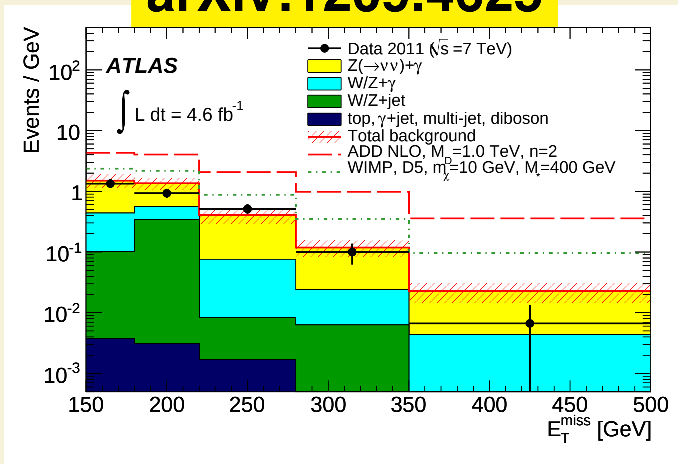
⇒ Analysis also sensitive to stops in R-Parity violating modes.

⇒ No significant discrepancy wrt SM expectations.

Extradimensions: photon-based searches

- Several kind of models predict the existence of additional dimensions, which would be microscopic.

arXiv:1209.4625

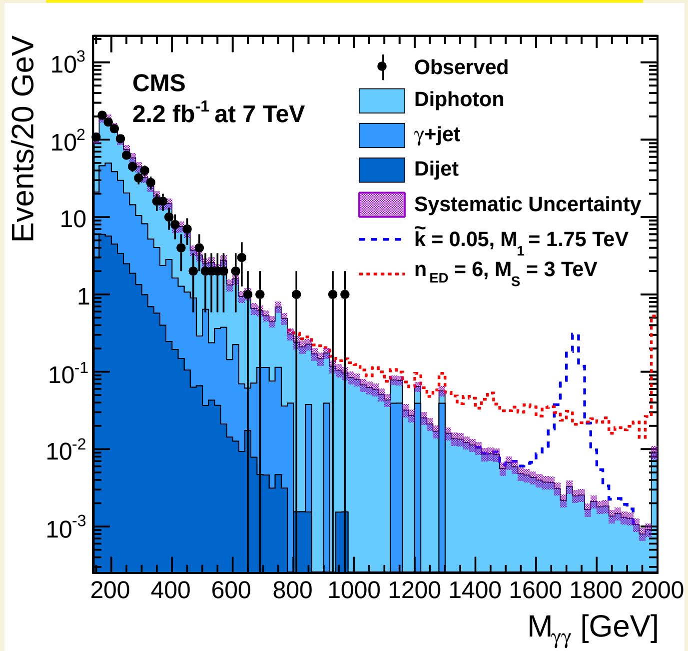


- Useful to explain the large scale difference between EWK and Gravitation.
- The SM is constrained to 3+1 dimensions. However, gravitational/related interaction might be able to test the additional extra dimensions.
- Production of gravitons (that scape detection) may be accompanied of SM particles.
- **Striking signatures: γ+MET or jet+MET**
- For very high p_T the backgrounds are small.

  $\Rightarrow$ Z/W whose decay not detected ($Z \to \nu\nu$)

  $\Rightarrow$ Detector effects.

PRL 108 (2012) 111801

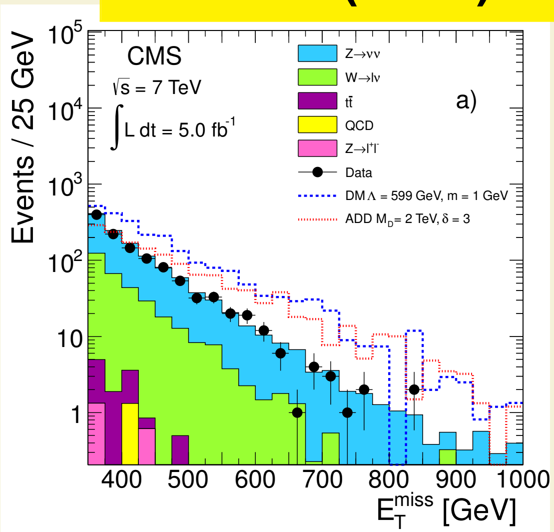


- Another possibility (from Randall-Sundrum Models) is that the graviton decays into SM particles.
- Many possibilities. One is diphoton resonances.
- Good signature: issue is large background.

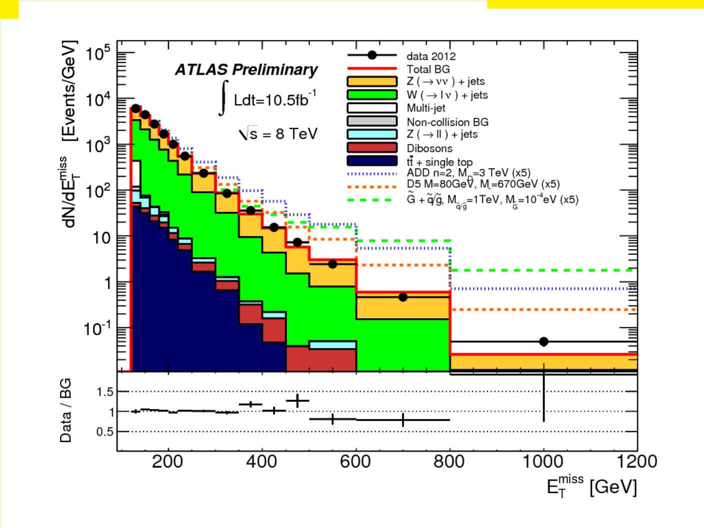
Extradimension: monojet searches

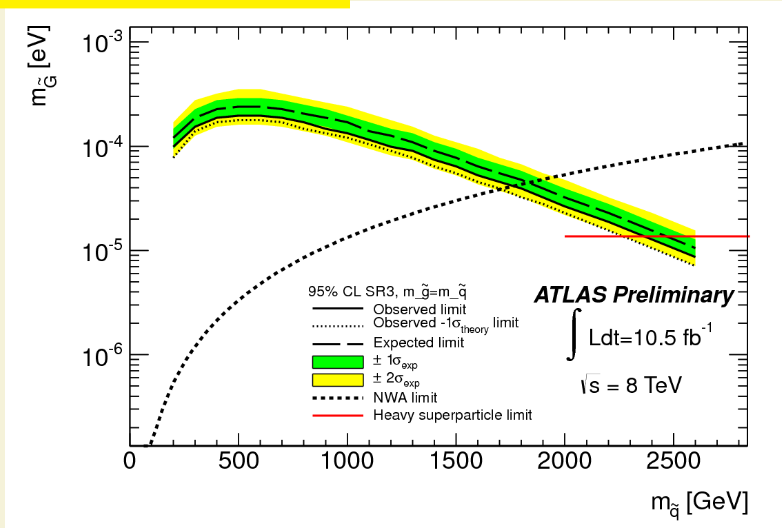
- In a hadron collider, the presence of coloured particles always is a motivation for a high-rate final state.
- Looking for the presence of a single unbalanced high-p_T jet.
- The rest may be taken by the escaping graviton... or other possible particle in several models.
- This signature has become very popular to look for inclusive production of invisible particles (Dark Matter!) in which the jet is initial-state radiation boosting to the undetectable object.

JHEP 09 (2012) 094



ATLAS-CONF-2012-147





⇒ **Many models tested:** ATLAS even sets limits on gravitino for squark/gluino production.

⇒ LHC results on extradimensions are already better than Tevatron and LEP.

New Physics in the top-quark sector

● Although most of the previous ("more traditional") models were trying to solve very deep issues of the SM, the lack of hints about the New Physics has lead to alternative approaches.

● The most common one is just to focus on the fine-tuning needed for the Higgs Mass, concretely the need of a "partner" for the top quark to reduce the radiative corrections.

● So focusing on the top-quark sector... or the presence of a new (more massive) generation, closely related to top and bottom:

⇒ They are the most suitable candidate to guide us to New Physics.

⇒ Mass of the top quark makes it very special.

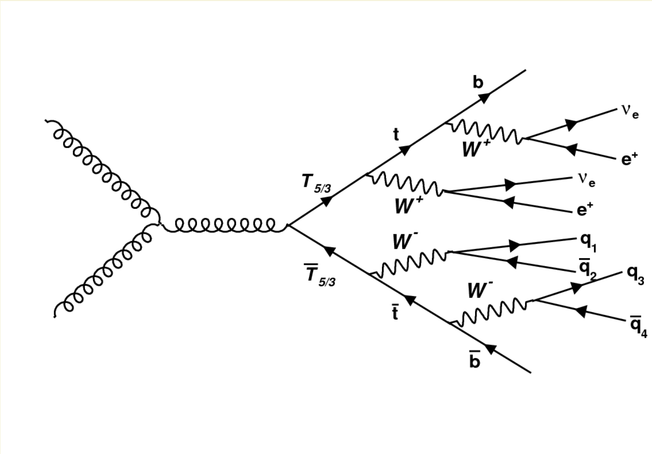
⇒ Lack of measurements (or reached precision not being enough) motivates pointing to top.

⇒ Bottom and charm physics do not seem to match perfectly.

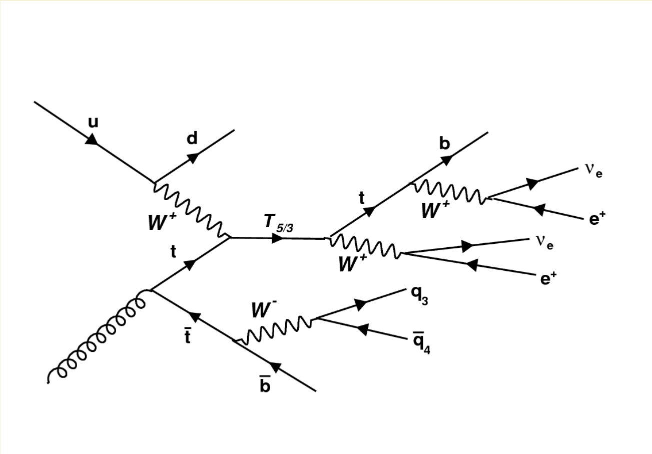
● Motivation similar to stop in "Natural SUSY" (discussed in Lecture II).

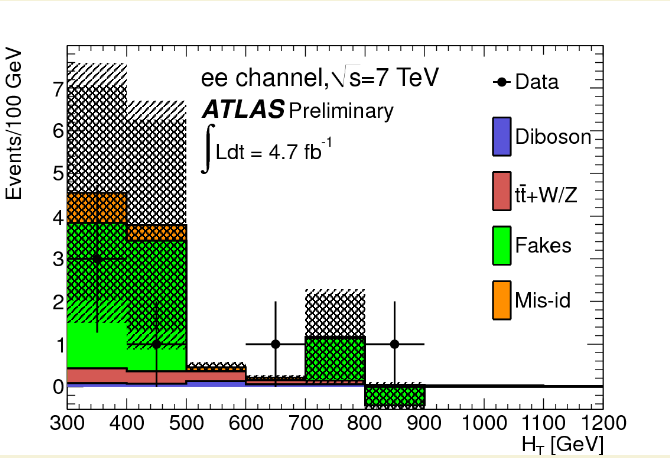
● The idea is always that New Physics may show up in the top-quark sector, but perhaps not as straightforward as though (however, FB assymmetry at Tevatron may indicate the opposite).

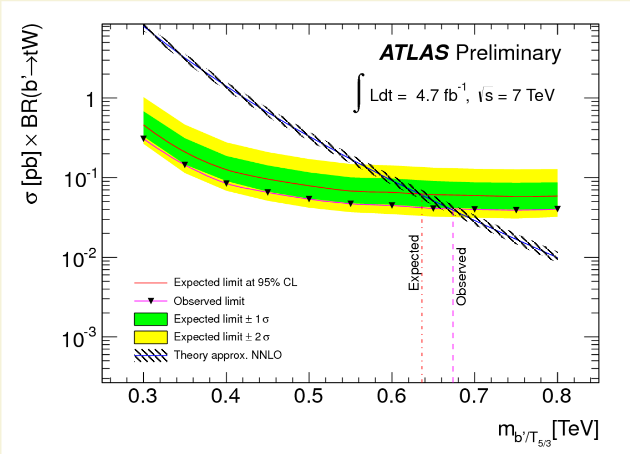
Search for a $T_{5/3}$ top partner



- A possible partner of the top with $Q = 5/3$ ($T_{5/3}$) has been proposed in several models.
- Even in single production, topology is full of particles that detectors are able to reconstruct.
- ATLAS has searched (ATLAS-CONF-2012-130) for this as part of more general set of searches based on same-sign dileptons: b'







⇒ H_T is a good discriminating variable for these busy topologies.

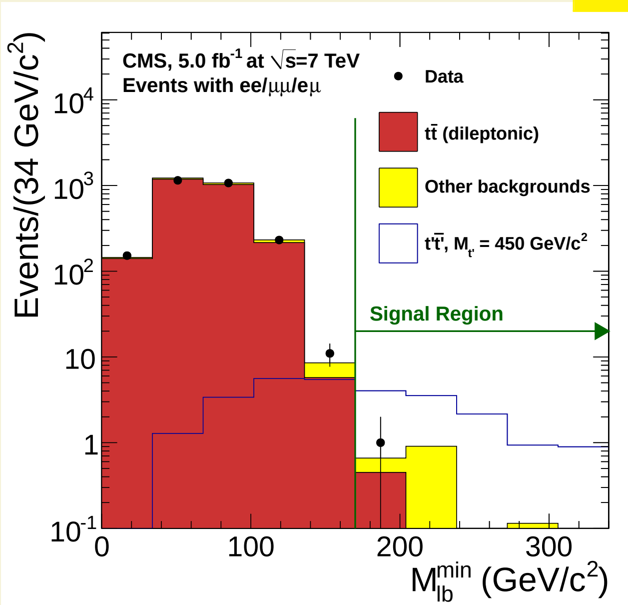
⇒ Good agreement: no striking discrepancy observed.

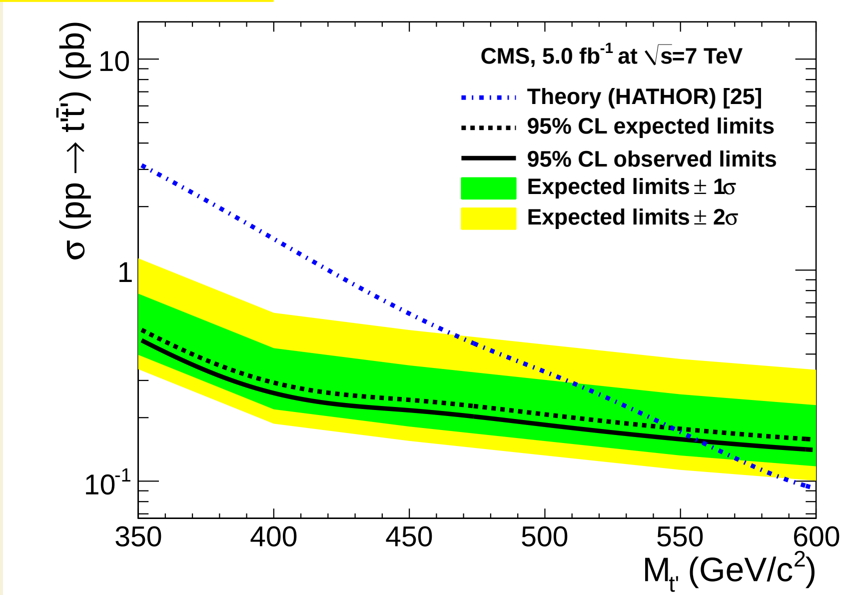
Search for a 4th generation (I)

- The existence of an additional generation is coming as a solution to the question on why 3 generations... easy answer (but not discarded).
- Although not a single hint to support it (in fact, all possible places where it could appear shows strong support for 3 generations), attractive final states.
- High multiplicites, high variety of objects...

e.g. a possible t' with a decay similar to the top quark (Wb): its pair production would lead to events with 2 W and 4 b-jets.

PLB 716 (2012) 103





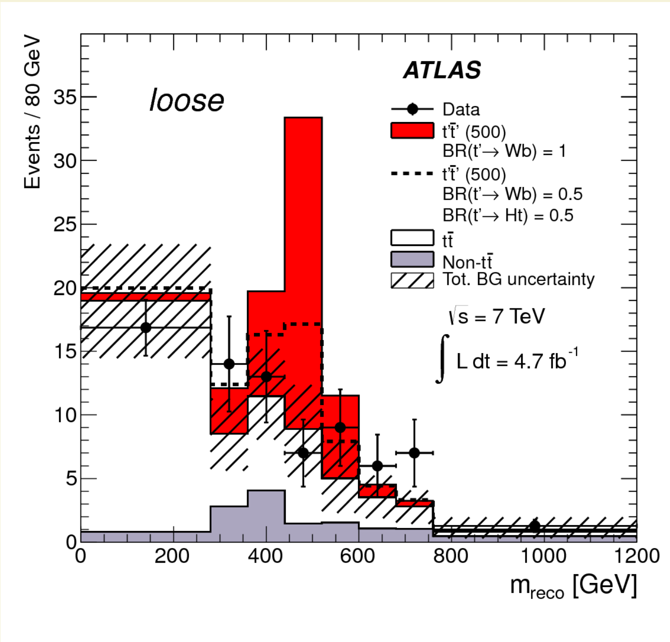
⇒ Looking for it in 2l+b-jets: bump in the $m(lb)$ distribution.

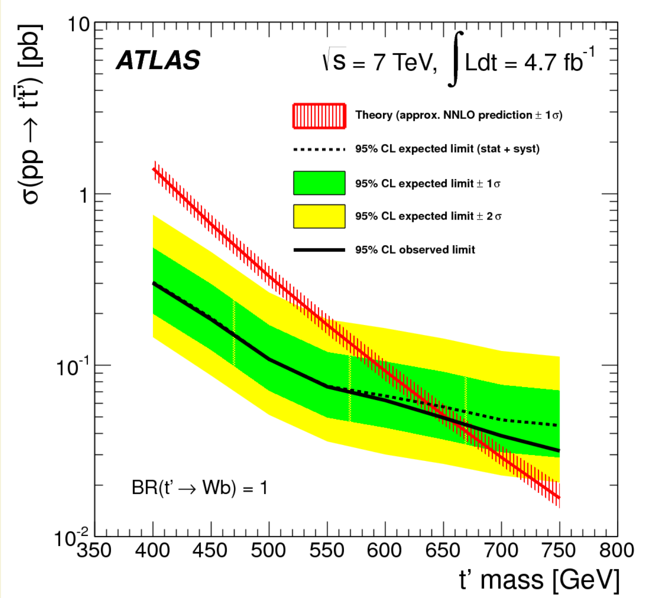
⇒ Very sensitive: Exclusion limit beyond the naturalness region for top partners.

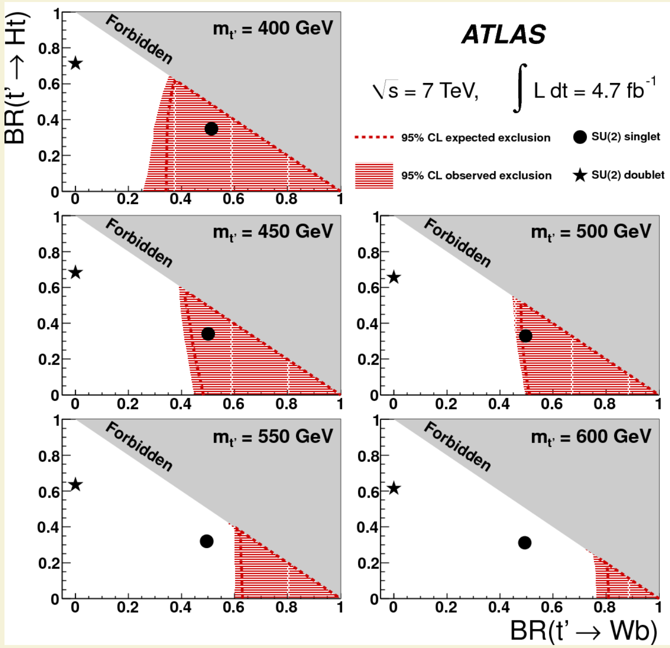
Search for a 4th generation (II)

- Search in the same topology ($t'\bar{t}' \to WbWb$ is performed in other possible channel combinations.
- Remember: models are just for getting topologies, things may be different.
- Reducing top background by relying on significant $W(jj)$ boost: $H_T > 750$ GeV.

PLB 718 (2013) 1284







$\Rightarrow$ Good agreement with ths SM predictions (dominated by $t\bar{t}$.

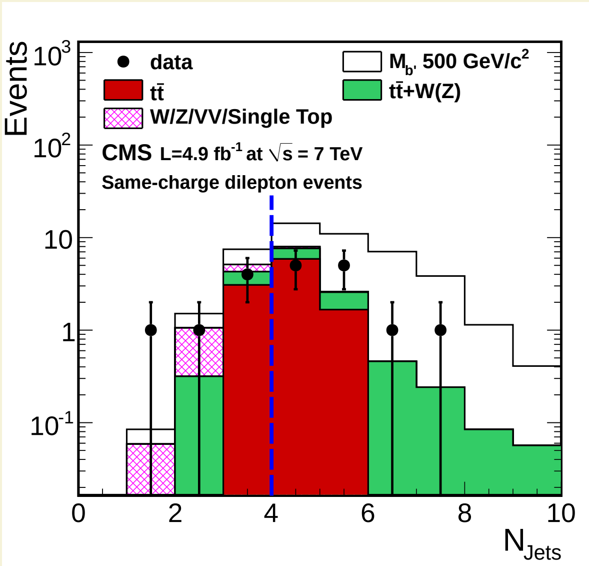
$\Rightarrow$ Limits sets: – in the mass

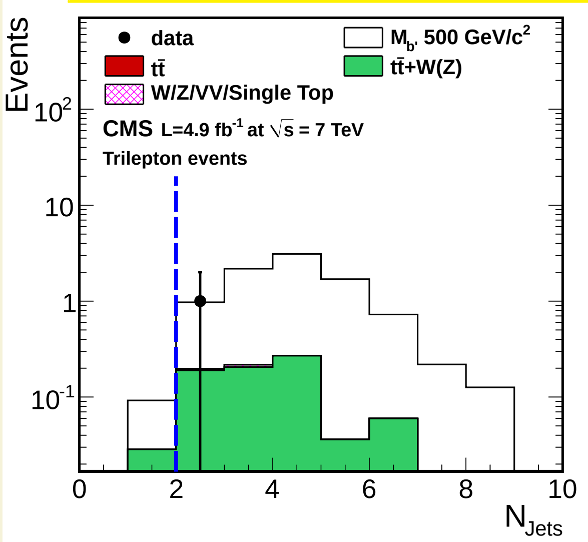
– in the Branching Ratios to W and non-W (Higgs-like, Z)

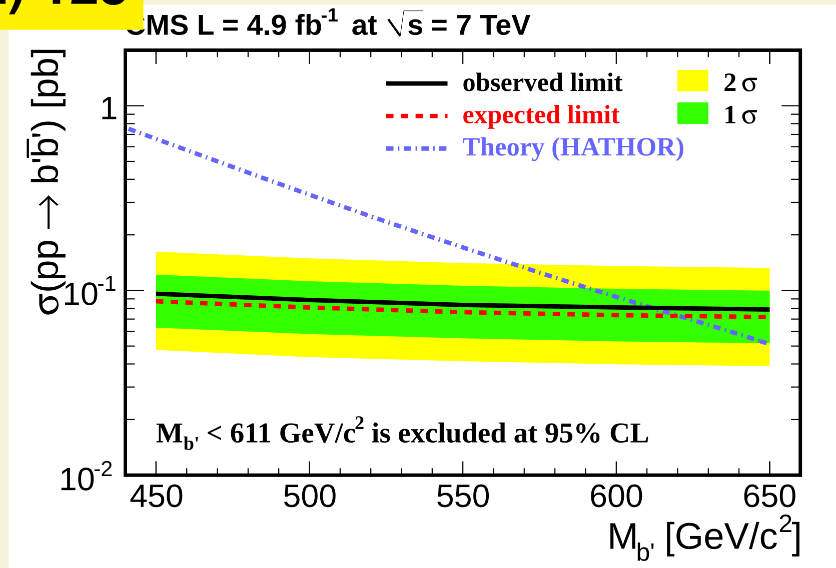
Search for a 4^{th} generation (III)

- Symmetric to the previous signature: a b' may decay to Wt, giving rise to a rich topology: 4 W bosons and 2 b-jets.
- It may show up basically in every top-like or multiobject analysis.
- CMS has exploited the same-sign dilepton and trilpeton signatures with the requirement of a b-jet.

CMS JHEP 1205 (2012) 123







⇒ Very low backgrounds for reasonable expected signals.

⇒ Data compatible with SM predictions.

⇒ The global conclusion is that there no hints for a 4^{th} generation.

⇒ Nor anything that may look like it regarding rich topologies.

Even more exotic searches

- No sign of New Physics in the most obvious extensions of the SM.
- Even for things we were "100% sure" will show up at the first LHC run.

But nobody was assuming Nature would practice "Fair Play"

- So we should not give up or think something is wrong... just misleading.
- So we start thinking on where New Physics could have escaped our limits:

  ⇒ Long-lived particles: no trigger, misreconstruction,...

  ⇒ Confusing signatures: many objects, no clear cascade decays

  ⇒ No beam crossing-correlated signals.

  ⇒ Something we did not think about?

- Other approach is to move to more fundamental levels:

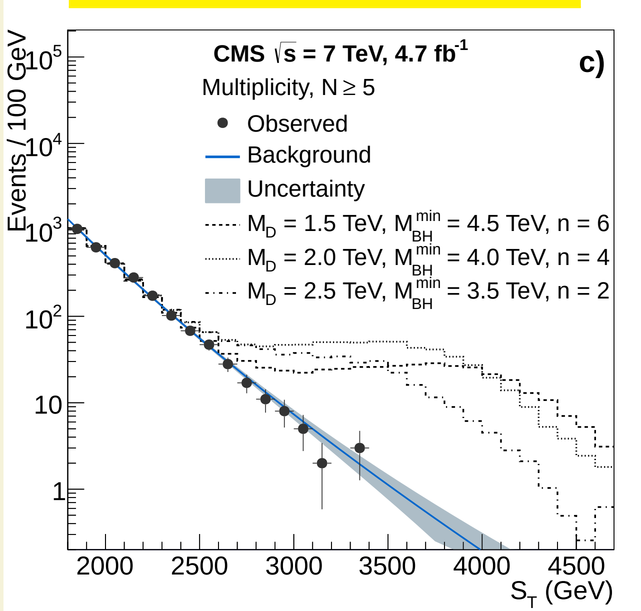
  ⇒ Dark Matter: Are we sure of its existence? Is it a WIMP?
  (It would probably show up in any of the MET-based signatures)

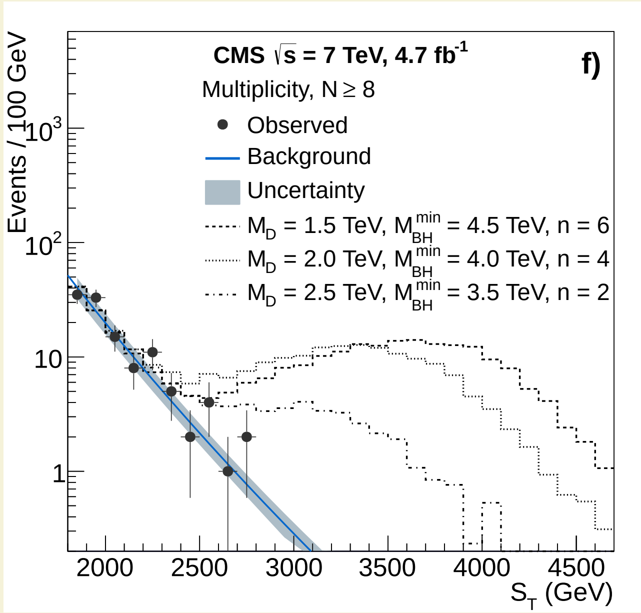
  ⇒ Magnetic monopoles: Very motivated, but LHC detectors may not be optimal.

Microscopic black-holes

JHEP 04 (2012) 061

- **Quantum-Gravity models predict the production of microscopic black holes at the LHC.**
- **Theories usually related to extradimensions, but we now focus on the production of these anomalous objects:**
  - ⇒ **Fast evaporation**
  - ⇒ **Decay in multiparticle final-state**
  - ⇒ **Pretty democratic treatment of objects.**
- **Analysis strategy based on the properties of the final state:**
  - ⇒ **Low multiplicity events used to parameterize background**
  - ⇒ **S_T (scalar sum of E_T) shape does not depend on multiplicity for background.**
  - ⇒ **Well tested in data and in MC predictions.**
- **Good greement at all multiplicities (up to $N \geqslant 8$)**
- **New model-independent limit in the result**





Long-lived exotics particles (I)

- One way new particles may avoid the current limits if by being long-lived: assumed decay products escape selection or trigger windows.

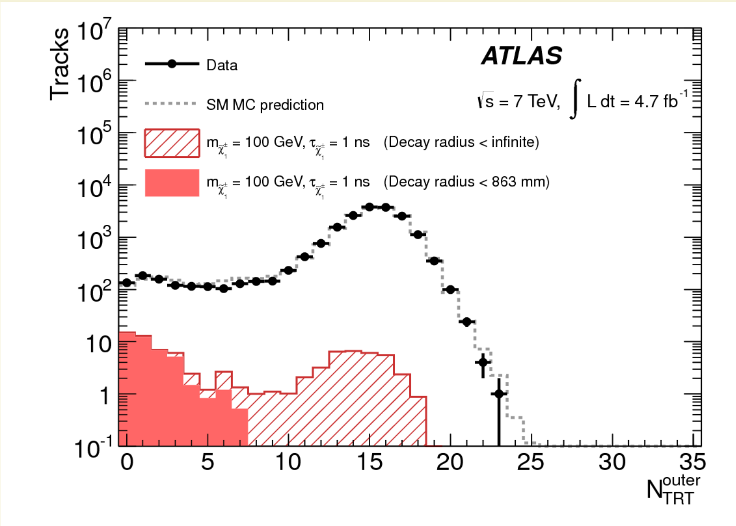
- SUSY theories may allow long-lived particles by several cases:

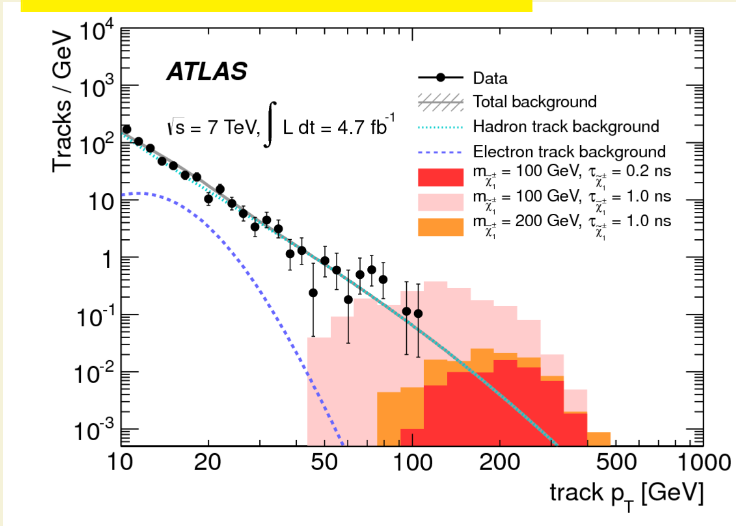
  $\Rightarrow$ R-Parity almost conserved: LSP may be long-lived.

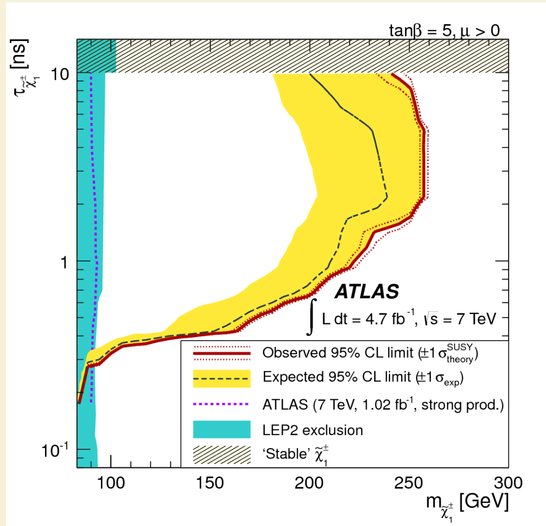
  $\Rightarrow$ NLSP-LSP mass difference very small: decay slowed by phase space.

- ATLAS performed a search of long-lived chargino ($c\tau \sim 10$ cm) by exploiting lack of hits in the outer tracker (disappearing track).

JHEP 01 (2013) 131







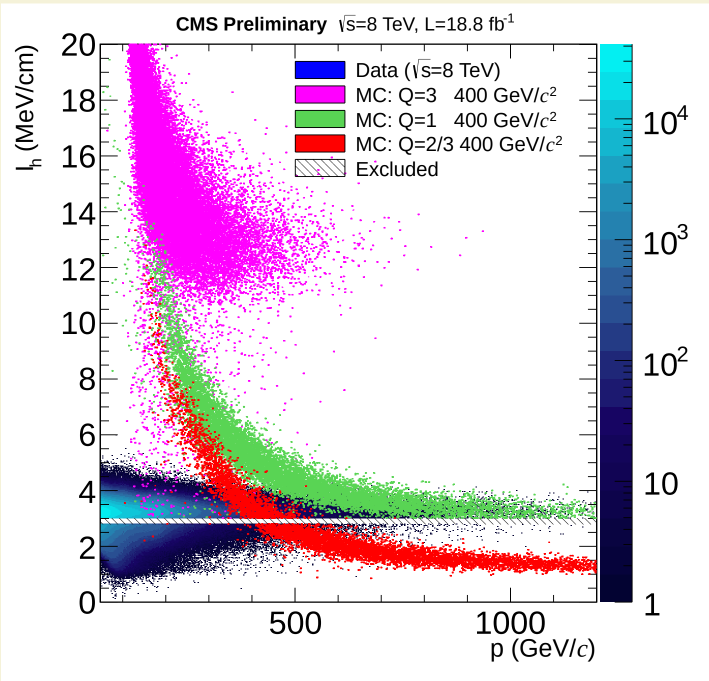
$\Rightarrow$ Long-lived state due to degeneracy with neutralino (LSP).

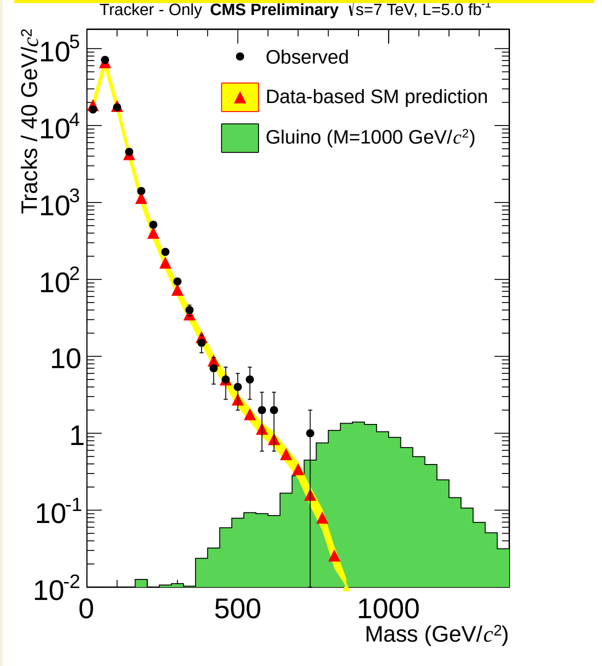
$\Rightarrow$ Data well reproduce by expectations.

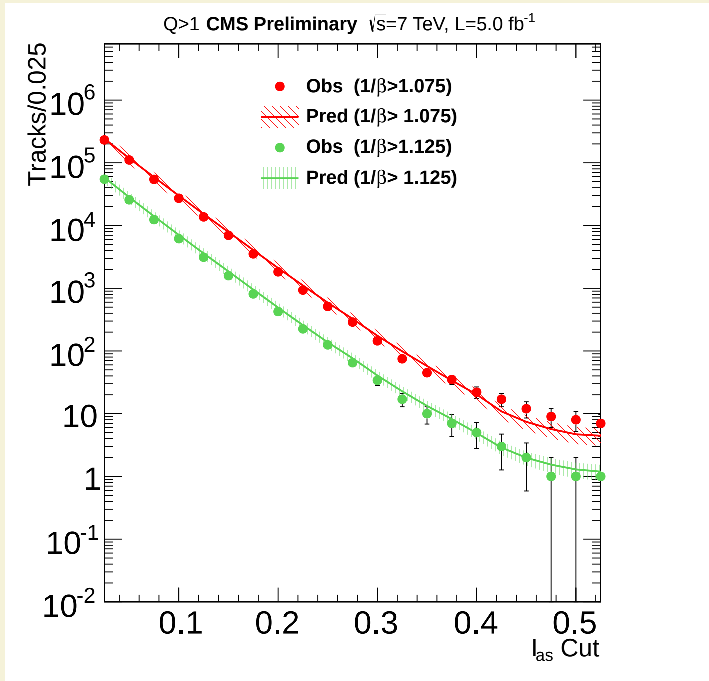
Long-lived exotic particles (II)

- Other possibility is that the LHC produced charged massive particles (CHAMPs) that escape the selection because they are slow-moving.
- May be lost in standard reconstruction assuming charged particles propagate at the speed of light: use MET and muon-only trigger.
- Requires very specific identification of slow-moving tracks: ionization, time-of-flight,...

CMS-PAS-EXO-12-026







⇒ Several types of particles: $\tilde{\tau}, \tilde{g}, \ldots$

⇒ Results are in agreement with the expectations: limits on CHAMP production.

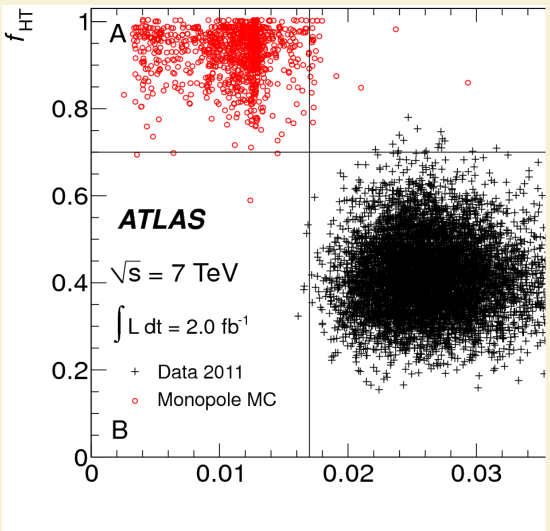
Magnetic Monopoles

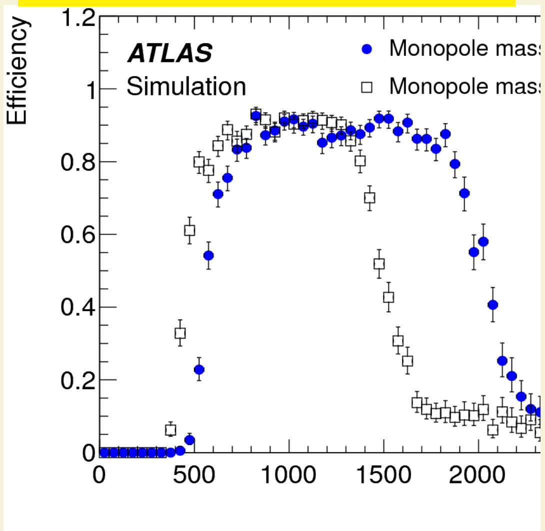
- Magnetic monopoles has been **predicted theoretically as part of the electromagnetic unification.**
- Its existence is enough to have electric charge quantization:

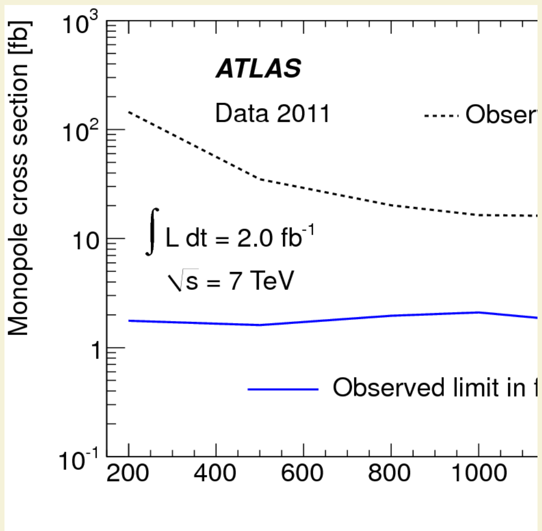
does the opposite holds?

- May be missing even if produced copiously because they are not electric charges.
- Again, they require some specific reconstruction and identification: **narrow EM calorimeter deposit and high ionization energy in ATLAS TRT.**

JHEP11 (2012) 138



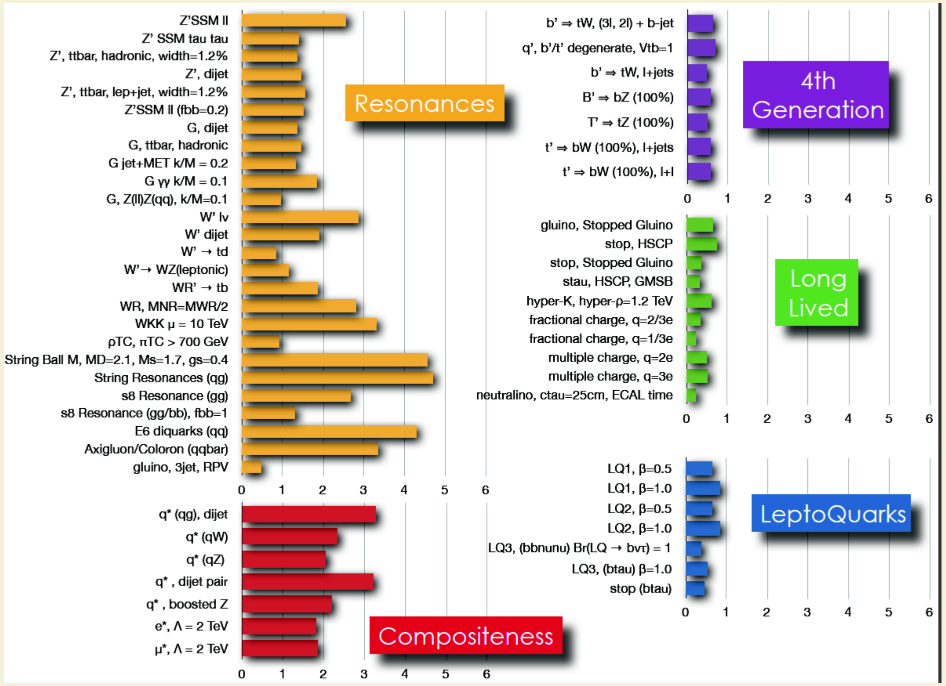


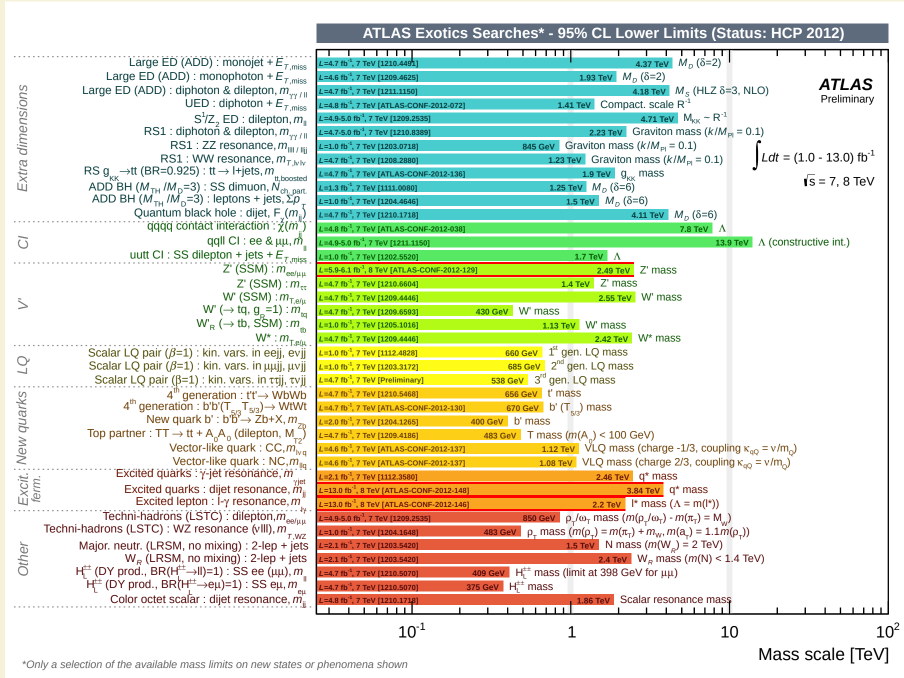


⇒ **No signal observed.**

Summary of mass limits for BSM particles

- Many more searches and analyses could not be included due to time constraints.
- The collaborations have put summaries to give an indication on where we are in the search of New Physics.





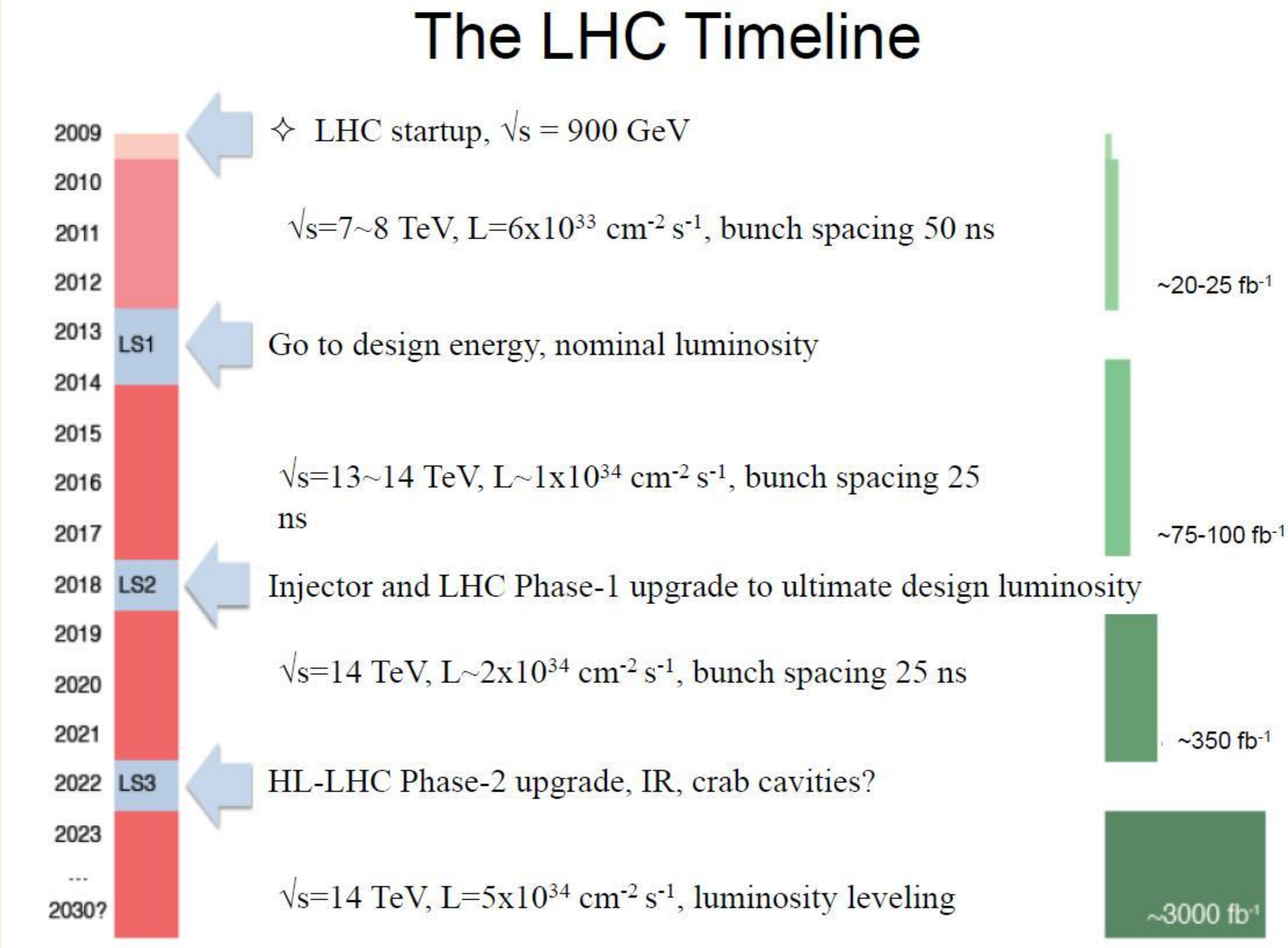
- Some of the recent results not included in these figures, but the conclusions are:
  - ⇒ The LHC has significantly extended the explored area (as expected)
  - ⇒ No significant excesses has been seen that could be a hint of New Physics.

The Standard Model is doing as good as always... for how long?

Upgrades and plans for the future running

LHC Schedule and running plans

- Currently the LHC is in shutdown for some maintenance work.
- Also for fixing the issues that prevent to reach the nominal energy.



Expecting 25-30 fb^{-1} in the first year of running at 13 TeV.

It may require some luminosity-leveling to allow the experiments to collect data efficienctly specially if running with 25 ns buch-spacing).

Goals of the several run periods

- In the next two years: shutdown for reaching nominal energy (LS1)

- After the LS1: 2015-2017

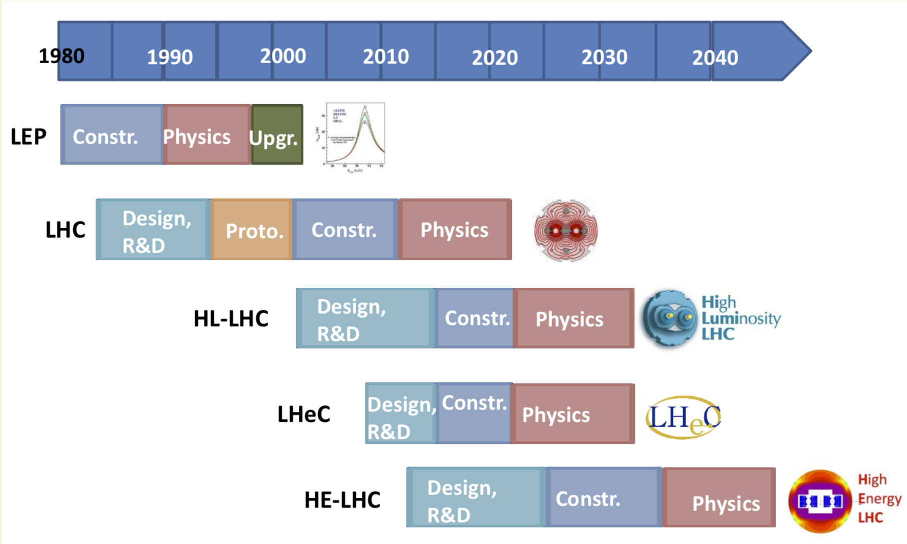
  Reach the nominal instantaneous luminosity (10^{34} cm^{-2}/s).

  Collect 100 fb^{-1} at 13-14 TeV.

- After the LS2: 2018-2022

  Twice the instantaneous luminosity.

  Collect additional 300 fb^{-1} at 14 TeV.



- Afterwards. . .

Present Triplet magnets at the end of their useful life. Also luminosity collection may not be that effective (too long doubling time).

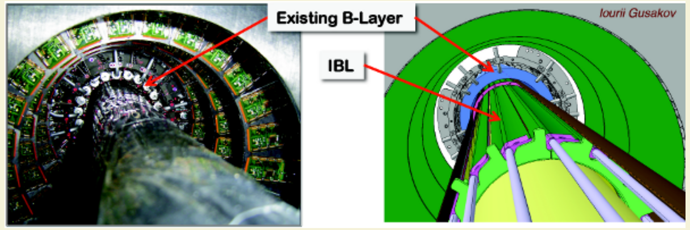
Time to go for an improved machine

Perhaps a HL-LHC to collect ~ 3000 fb^{-1} at 14 TeV for high precision studies

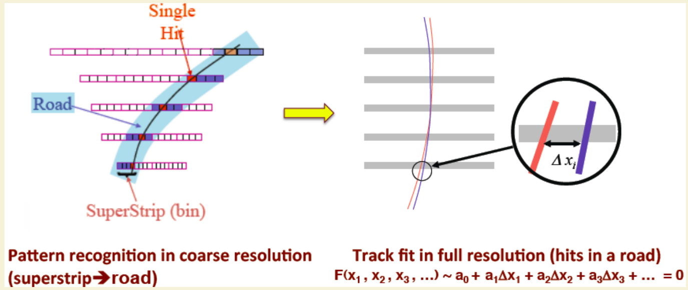
Or move towards higher energies to reach a new energy regime.

Upgrades and future plans for ATLAS

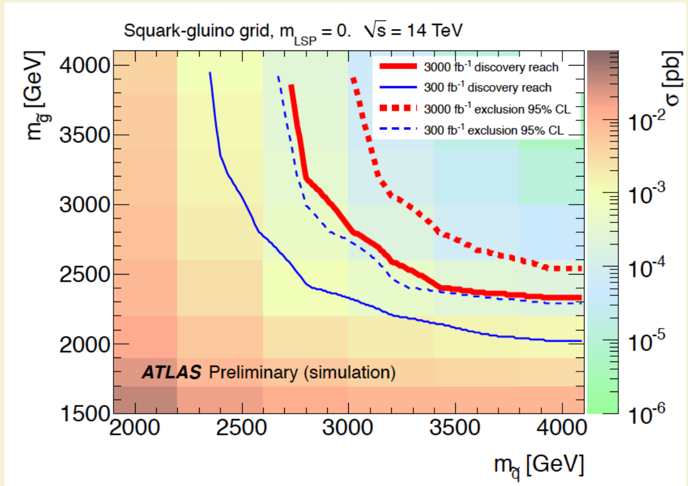
- **For LS1:**
  - Consolidation and getting ready for future: new Al beam pipe
  - Additional neutron shielding in endcap toroid
  - New Insertable B-layer (4th) of pixel
  - Close to the beam pipe



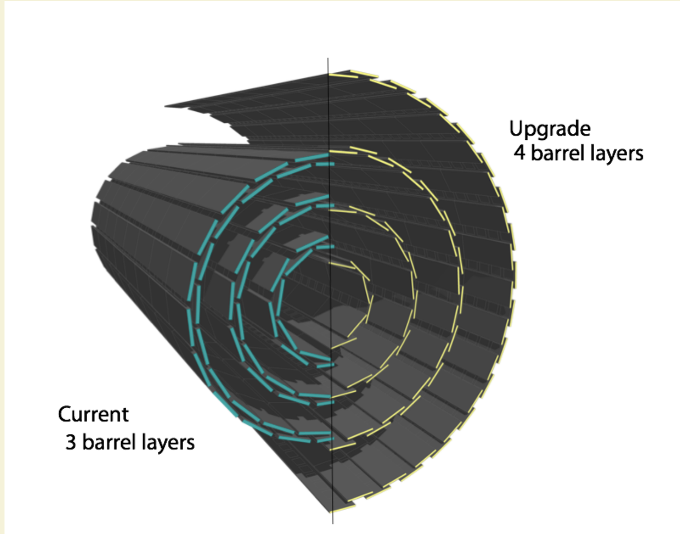
- **For LS2:**
  - Finer granularity of the calorimeter triggers
  - Fast track trigger
  - Other trigger/DAQ upgrades, to satisfy the needs for the third running period.
  - Possibility of topological triggers at Level 1
  - Detector for forward physics



- **Getting ready for HL-LHC**
  - New detectors to replace aged ones (as silicon inner tracker)
  - Improved trigger/DAQ layout
  - The goal: improve the detector to exploit the possibilities of the HL-LHC dataset in measurements (Higgs properties) and reach for New Physics.



Upgrades and future plans for CMS



- **For LS1:**

  Complete muon coverage and improve muon triggers

  Replace forward calorimeter PMT (HCAL) and use of additional segmentation

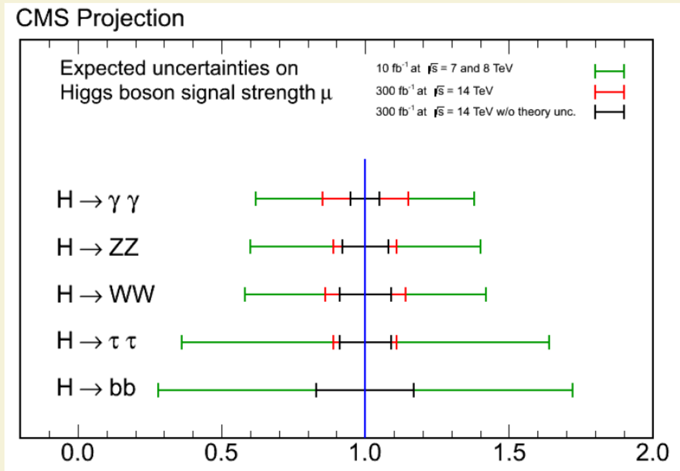
- **For LS2:**

  New Pixel detector.

  Improved HCAL electronics and L1 trigger.

  Require some preparatory work during LS1: the future starts today.

  (New Beampipe, test slices of future systems)



- **Getting ready for HL-LHC**

  Scope still to be defined: expected Technical proposal in 2014

  Replace tracker, forward calorimetry and muon detectors

  The running conditions will require track trigger.

In addition, all experiments are involved in activities on alternative/later projects (HE-LHC?) and help in producing the long-term plan.

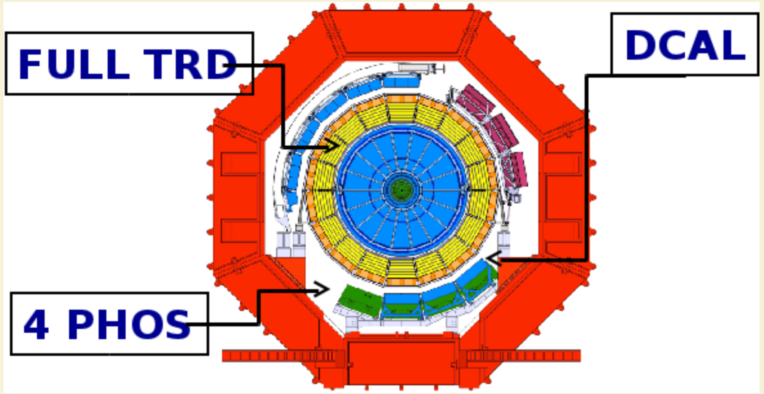
Upgrades and future plans for ALICE

The long-term goals of the Heavy-Ion program is to

⇒ Understand the Quark-Gluon Plasma with unprecedent accuracy.

⇒ Precision studies of heavy-flavour and EWK-boson production.

⇒ Specially interesting the (difficult) low-p_T region



- **During LS1:**

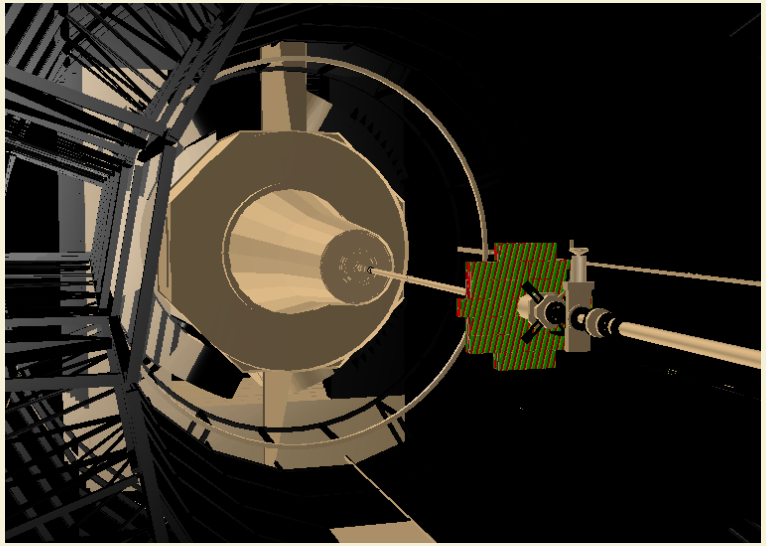
  Completion of ALICE and upgrades (PHOS and DCAL)

- **During LS2:** Major upgrades to reach new frontiers

  Improved inner tracking system

  New TPC for high-rate readout in high luminosity regime

  Forward EM calorimeter (FOCAL). improved muon reconstruction (MFT), and others...

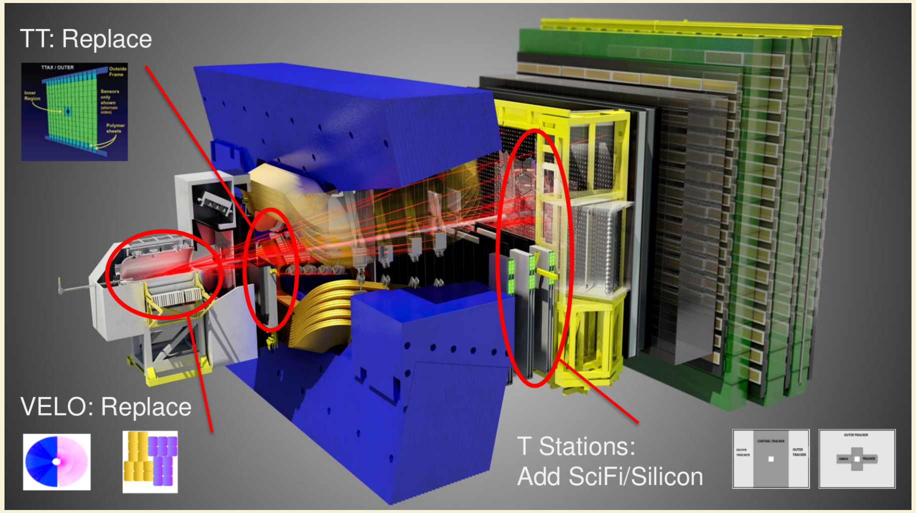


- Still unclear whether ALICE will have a presence in the future HL-LHC since the interest will depend on the findings after the current shutdown.

- LS2-Upgraded detector should be able to make it until mid 2020's, taking advantage of the Heavy-Ion run in the period, with several ion species.

Upgrades and future plans for LHCb

- **The plan is to collect 1 fb^{-1} per year during 5 years.**
- **Upgrade the detector (during LS2) to collect 50 fb^{-1}.**
  - $\Rightarrow$ Improve statistics in rare processes (specially observed in the 5 fb^{-1} for the first time).
  - $\Rightarrow$ Reach higher experimental precision ($\sim$ theoretical one) in key observables.
- **Major upgrade of the detector and readout system:**
  - $\Rightarrow$ 40 MHz readout for all detectors and the full DAQ system
  - $\Rightarrow$ Implies also a huge effort/improvement to process the data output.
  - $\Rightarrow$ Allowance for instantaneous luminosity of $2 \cdot 10^{33}$ cm^{-2}/s
  - $\Rightarrow$ New RICH photon detectors and Tracking detectors, with a radiation-hard Vertex Locator



- **As ALICE, it is not yet defined the rôle of LHCb in the possible projects after the basic LHC program is done: HL-LHC, HE-LHC?**

Overview and Conclusions

- The LHC experiments have made the first discovery: a boson at ~ 125 GeV
  - Signal showing up in several channels.
  - Already measuring the properties.
  - Compatible with the Higgs predicted by the SM.
- Searches of Physics beyond SM
  - No hint of New Physics found.
  - Even in the most exotic signatures.
  - The SM still alive and stronger than ever.

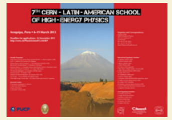
Current results of the LHC and those coming right after the current shutdown will be fundamental for the future of particle physics:

$\Rightarrow$ Requests to future accelerators

$\Rightarrow$ Information needed from complementary (low-energy) experiments

$\Rightarrow$ Understand theoretical and cosmological implications

We are (and going to be) in a very interesting time for particle physics, dictated by what is found and not found at the LHC within 2-5 years.



Closing remarks

- Results already achieved at LHC are of the highest level.
- Need to wait for more collisions, but before we expect (even at Moriond!):
  - ⇒ More results to come with the current data samples.
  - ⇒ Studies on the SM particles (now a Higgs candidate also).
  - ⇒ Precision physics along the program with complete datasets.
  - ⇒ Searches and studies about New Physics.
- But if you cannot wait for the news, you may entertain yourselves with the already published results, not mentioned (nor covered in detail) due to time constraints.
- Available at the web pages of the experiments:

  http://aliceinfo.cern.ch/ArtSubmission/publications

  https://twiki.cern.ch/twiki/bin/view/AtlasPublic

  http://cms.web.cern.ch/news/cms-physics-results

  http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/index.php

Thanks for your attention!