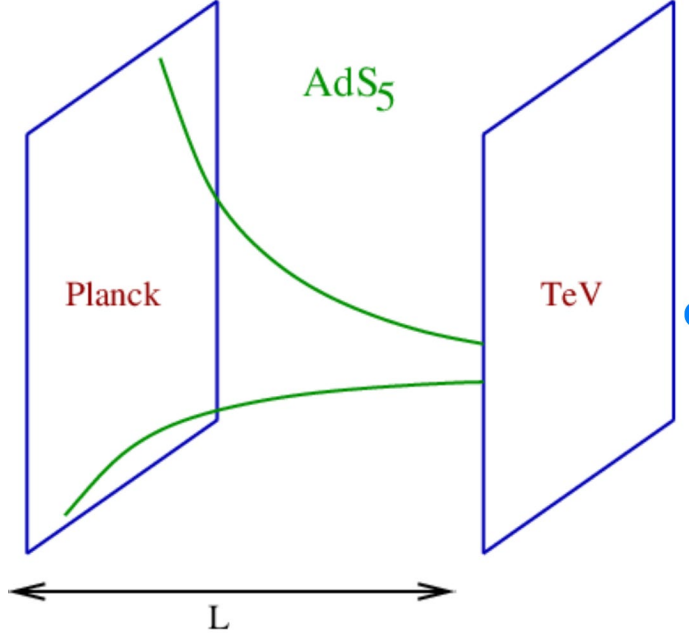
What is the 650 GeV resonance made of ?

INTRODUCTION

- For many years there has been growing evidence for indications around 650 GeV both in ATLAS and CMS
- Presently there are **9 such indications, each reaching ~3 sd**. When statistically combined they give a **global evidence ~6 sd** ! RUN3 should allow to reach individually 5 sd for some of them
- Coming after the 750 GeV episode, they provoke, at best, polite skepticism
- Today we come to the conclusion that the alleged 750 GeV in 2 photons first seen by ATLAS belongs to the same family, the shift in mass being presumably due to a **mis-calibrated detector + an initial positive fluctuation** in the ATLAS sample

What is it ?



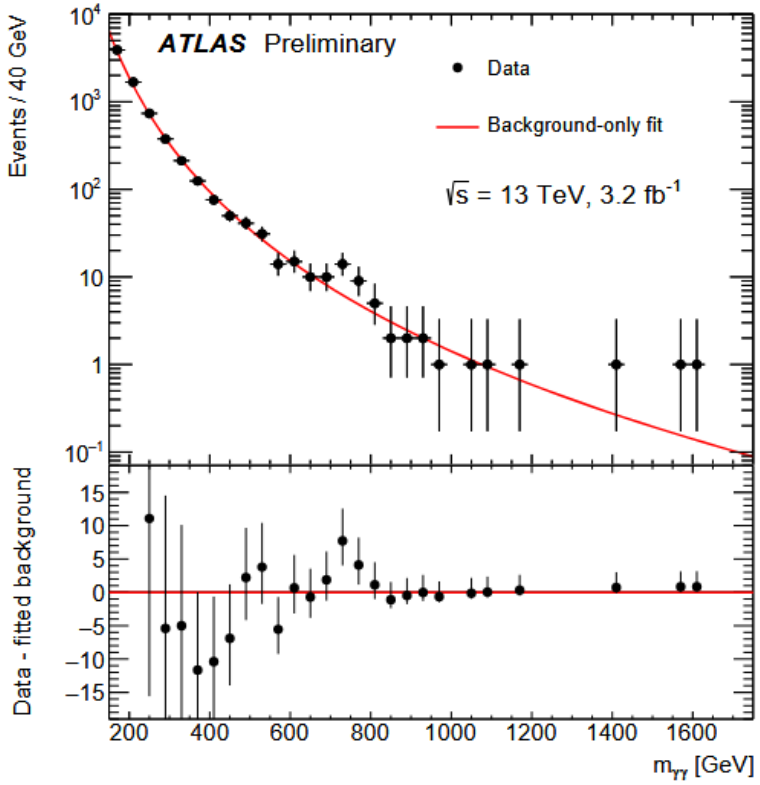
- Interpretations of this effect went through different phases but, at present, the best interpretation of these indications is given by the **Randall Sundrum** model
- However it is fair to add that various observations do not coincide with the strict predictions of this model, in particular the **absence of coupling to gluons** which considerably reduces the production rate for this resonance and explains that it takes so long to reach a full confirmation in spite of its low mass
- We understand the reason for this absence, invoking the classical **dual picture** where the RS 5D is dual to a 4D world where resonances are **composite objects**. In this picture the SM Higgs is itself made of **colorless/neutral preons** which therefore do not couple directly to **gluons** nor **photons**. The same would be true for KK gravitons which can only couple to gluons through top loops

References

[1]New resonances at LHC
Alain Le Yaouanc(IJCLab, Orsay), François Richard(IJCLab, Orsay) (Jun 11, 2025)
e-Print: 2506.09490
[2]X650->ZZ/WW/H125H95/A450Z -- scalar, tensor or both ?
Alain Le Yaouanc(IJCLab, Orsay), (IJCLab, Orsay), François Richard(IJCLab, Orsay(Aug 22, 2024
Contribution to: 3rd ECFA workshop on e+e- Higgs, Electroweak and Top Factories
e-Print: 2408.12178
[3]Triple Higgs coupling
Alain Le Yaouanc(IJCLab, Orsay), (IJCLab, Orsay), François Richard(IJCLab, Orsay)(Apr 15, 2024)
Contribution to LCWS24
e-Print: 2404.09827
[4]As a consequence of H(650)->W+W-/ZZ, one predicts H++->W+W+ and H+->ZW+, as indicated by LHC data
Alain Le Yaouanc(IJCLab, Orsay), François Richard(IJCLab, Orsay) (Aug 23, 2023)
Contribution to: 2nd ECFA Workshop on e+e- Higgs/EW/Top Factories
e-Print: 2308.12180
[5] Searches for scalars at LHC and interpretation of the findings Anirban Kundu (Calcutta U.),
Alain Le Yaouanc (IJCLab, Orsay), Poulami Mondal (Calcutta U.), François Richard (IJCLab, Orsay)
Contribution to 2022 ECFA Workshop on e+e- Higgs/EW/TOP factories
e-Print: 2211.11723

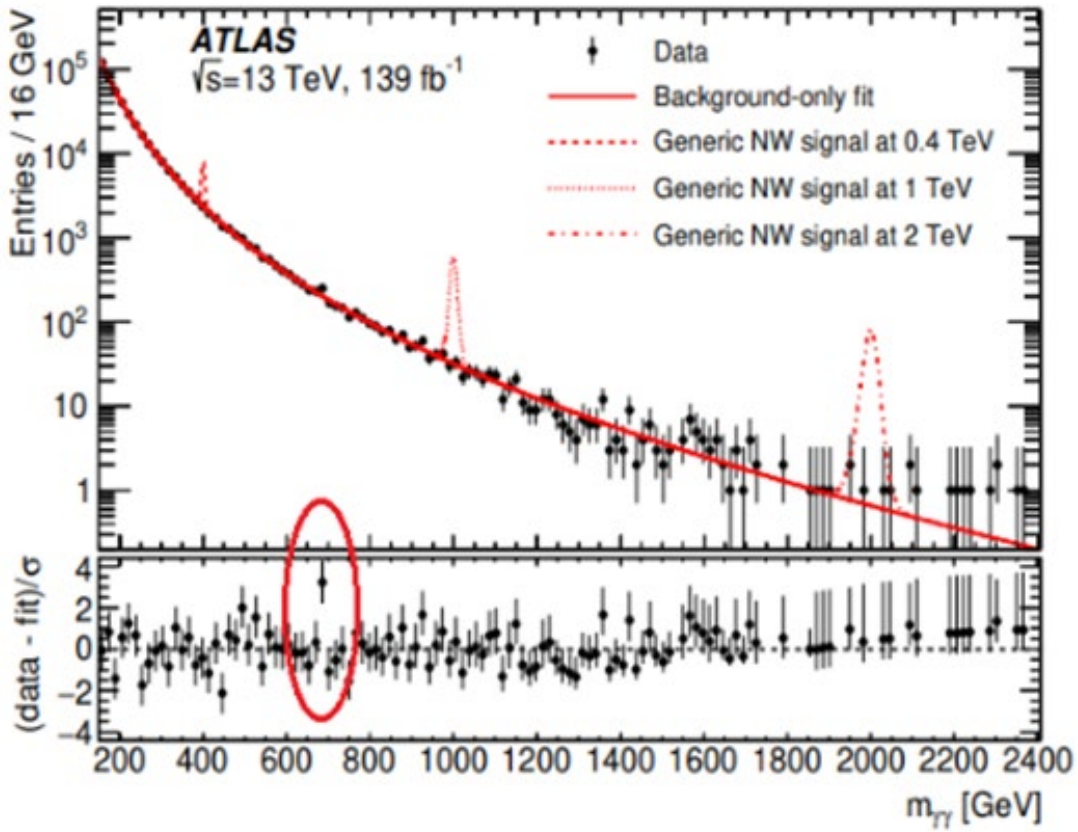
The two photon story

Yesterday: 750 GeV wide



ATLAS-CONF-2015-081

Today: 690 GeV narrow



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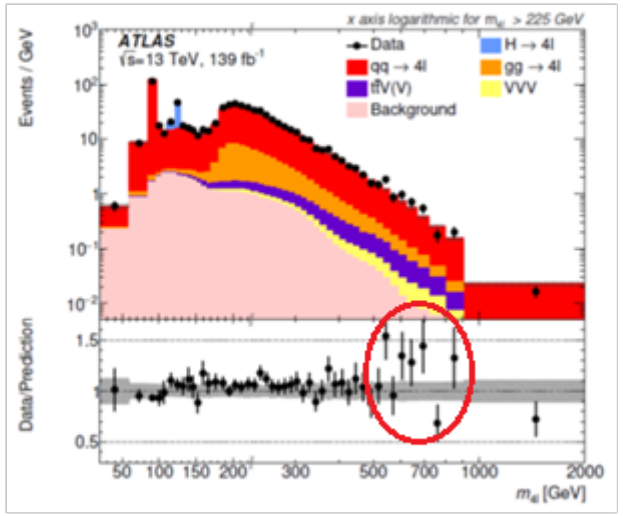
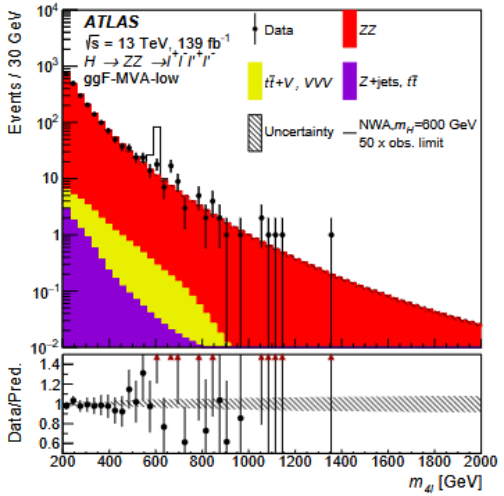
X650->ZZ-> $\ell^+\ell^-\ell'^+\ell'^-$ J=2 or J=0 ?

- Naive cut based analysis

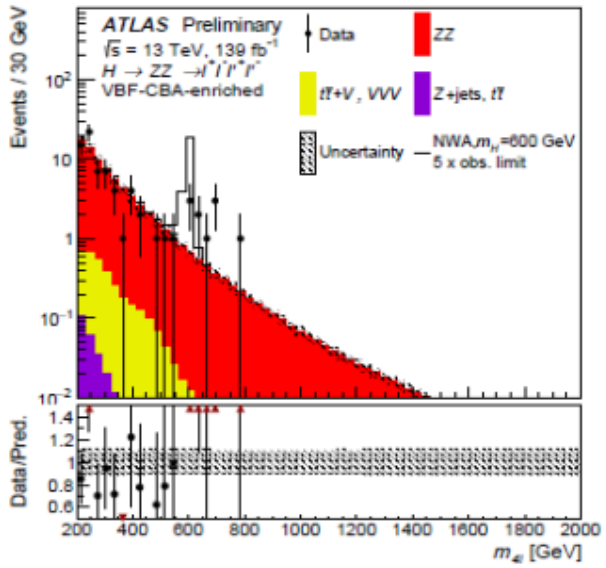


ggF+VBF

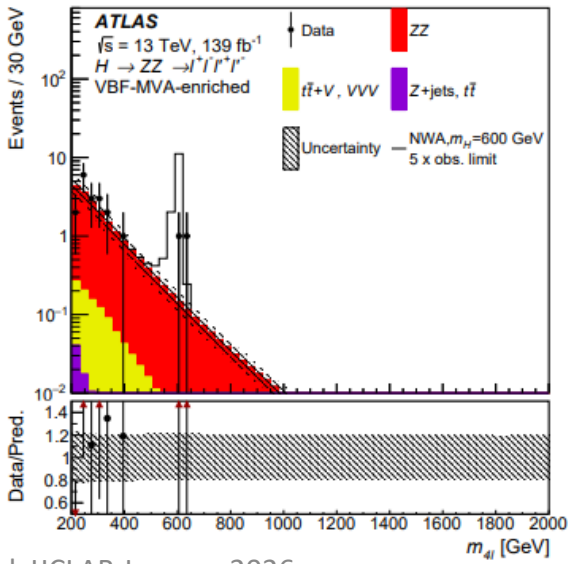
- Selecting a scalar against DY

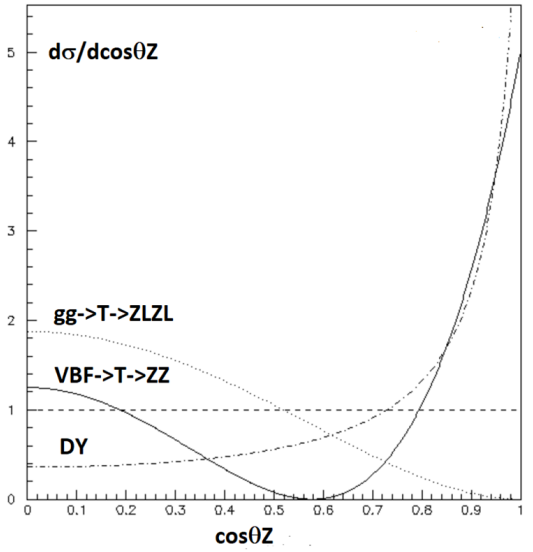


[2009.14791](2009.14791)



VBF

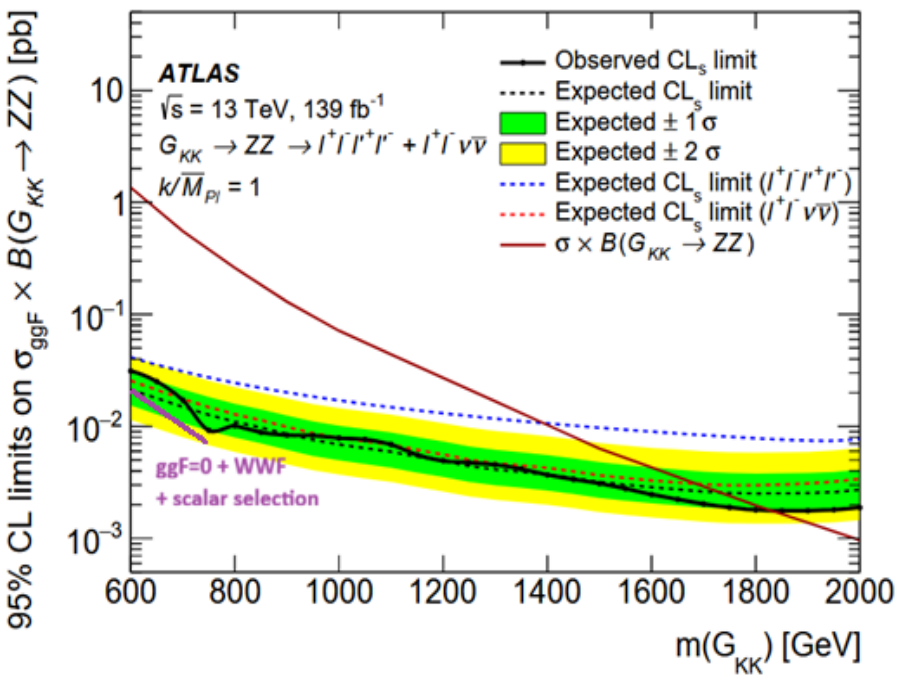




Only produced through VBF

- Both ATLAS and CMS loose the **ZZ channel** with scalar selections even w/o the VBF selection
- ggF should not suffer from a scalar selection !
- Same observation in the **WW channel** by CMS which concludes that this signal comes mainly from VBF and not from ggF
- Goes against RS standard predictions !
- Invalidates mass limit from ATLAS
- Explains why we need so much luminosity to observe a sub-TeV resonance

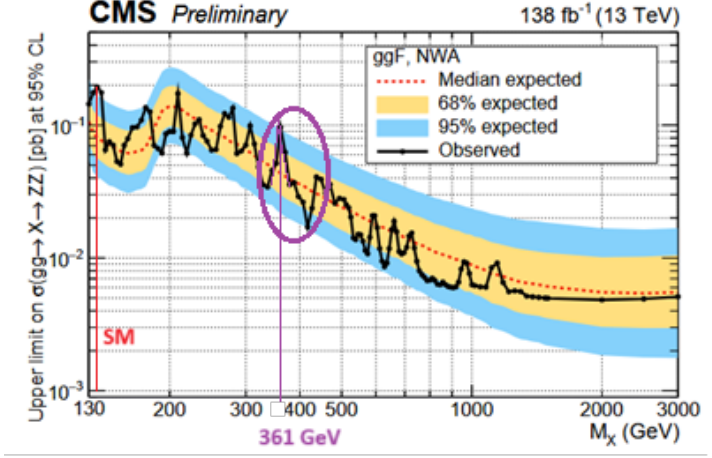
2009.14791

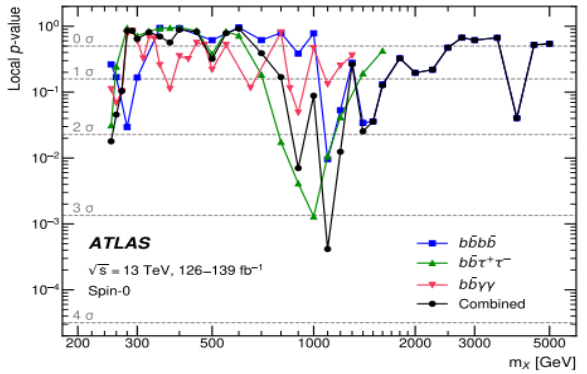


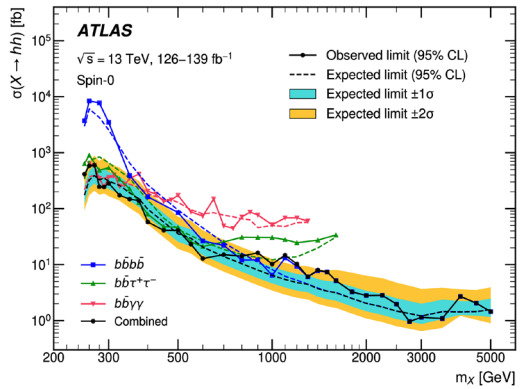
RS predictions

- RS predicts: **T376 T690 T1100 GeV** given by zeros of **Bessel function** (geometry)
- We have 5 indications compatible with T376 hence a significance of ~4 s.d.
- Explains the **width of T690 ~20 GeV** instead of ~3 GeV for T376
- Indication in **hh at 1000 GeV** from ATLAS
- **Perturbative unitarity** predicts that there could be **W^+W^+ and ZW** resonances to avoid early violation which seems true for the first sequence **T376**

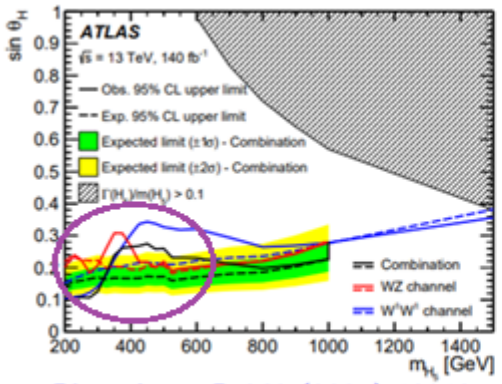
$$g^2(4m_W^2 - 3m_Z^2 c_W^2) \overset{\rho \simeq 1}{\simeq} g^2 m_W^2 = \sum_k g^2_{W^+W^-H_k^0} - \sum_l g^2_{W^+W^+H_l^{--}}$$







Phys. Rev. Lett. 132 (2024) 231801



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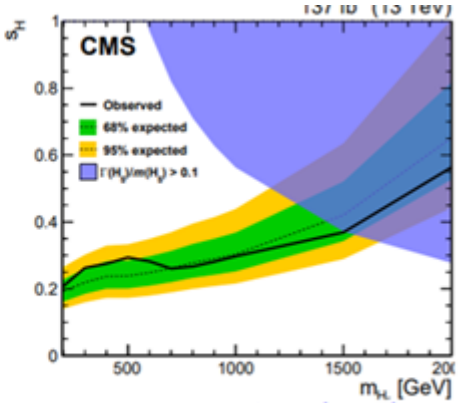
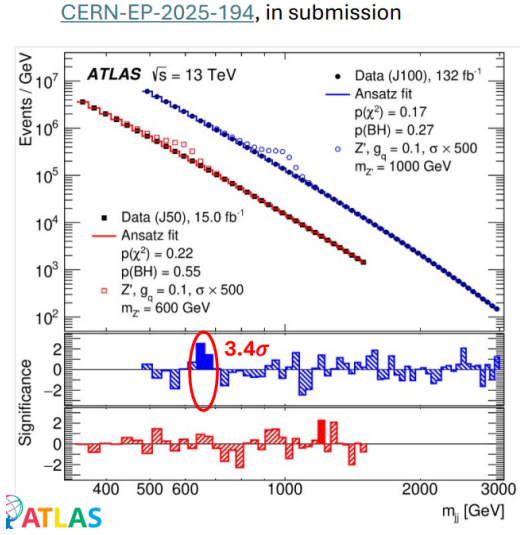


Eur. Phys. J. C 81 (2021) 723

Other evidences for 650 GeV

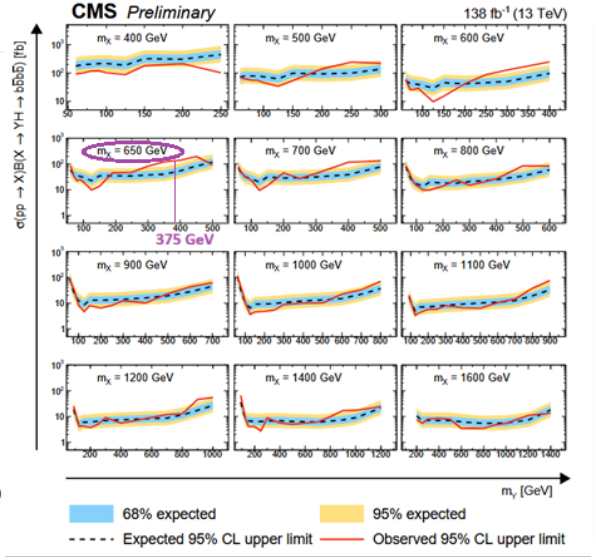
2509.01219

CERN-EP-2025-194, in submission



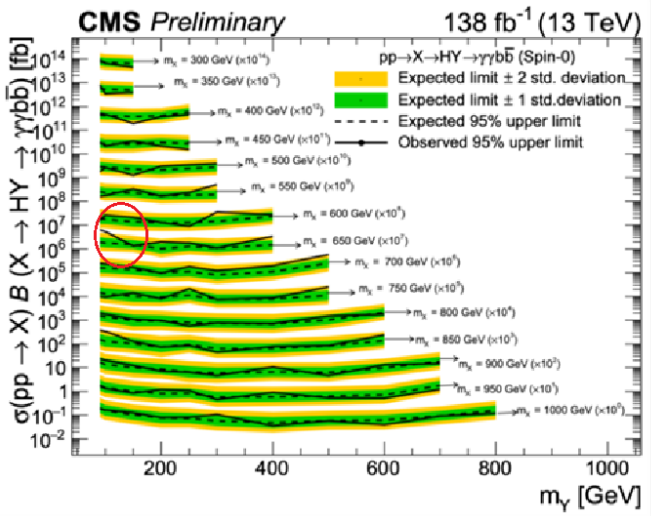
X650->2 Jets

CMS-PAS-HIG-20-012



X650->Y375+h125->bb+bb

2310.01643



X650-> h125h95 -> γγ +bb

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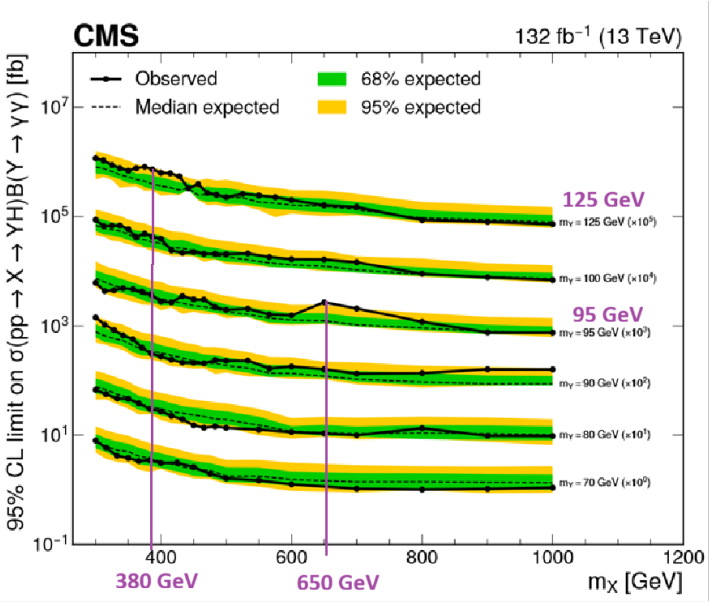
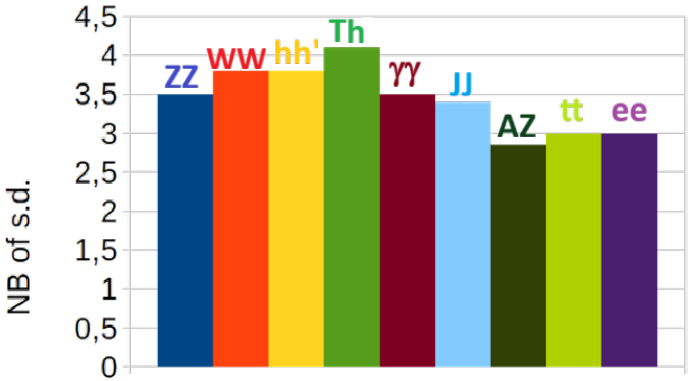


X650-> h125h95 -> γγ+ττ

T376-> h125h125->γγ+ττ



Open questions

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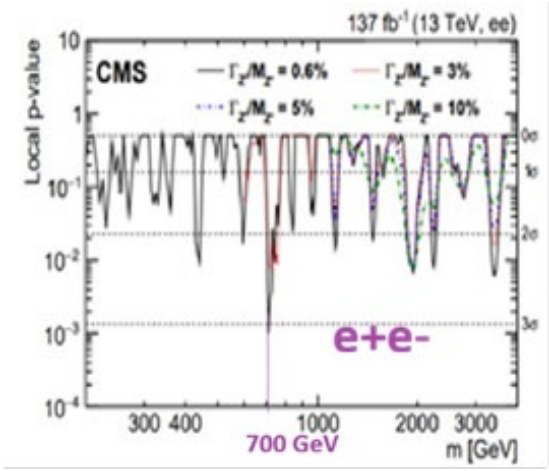
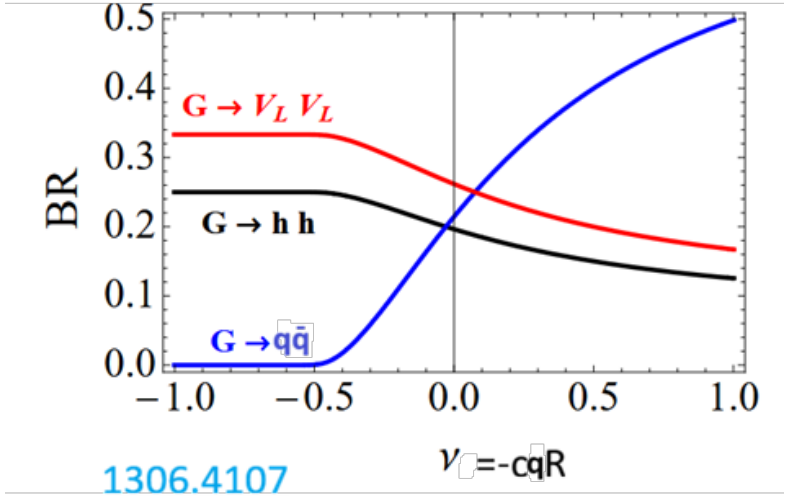


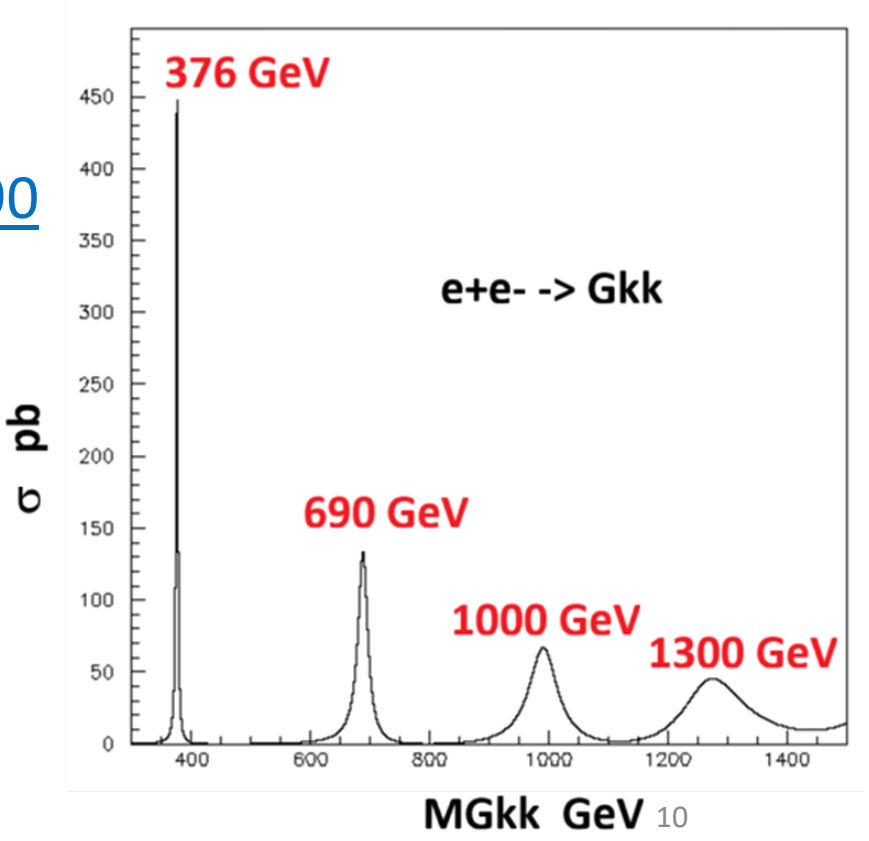


1306.4107

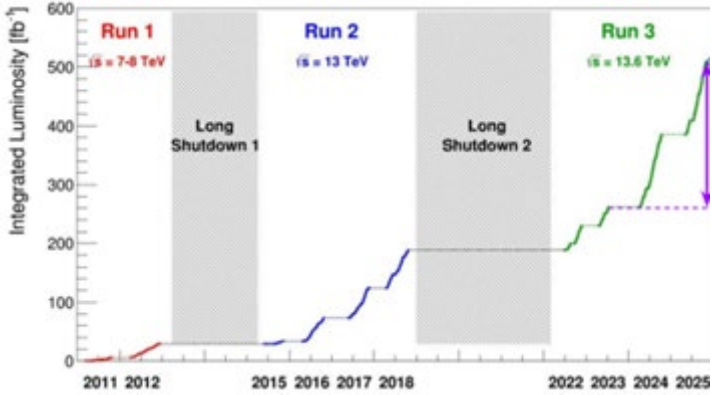
- Where are the other KK states like $\mathbf{Z_{KK}}$ etc… ?
- Two mechanisms are proposed to explain why

G_{KK} could be the lightest KK state 1603.06980 2506.09490

- Is it **coupled to e+e-** ? BR(G_{KK} ->ee)=0.25% from ATLAS/CMS is compatible with **$\sin^2\theta_{eff}$** from **LEP/SLD** if Z_{KK} is **much heavier than G_{KK}**
- Essential point: **BR(ee)~0.25%** would predict **Giga graviton factories** at e+e- colliders



SUMMARY



- '650' and '750' are probably not distinct !
- ZZ and WW suggest a **J=2 state** produced by **VBF** with seven more indications
- This resonance is accompanied by two other indications which suggest the **RS sequence T376 T690 T1000** which provides an explanation for the width and strengthen our interpretation
- Absence of coupling to **gluons** suggest G_{KK} is a **composite particle** made of **colorless partons** similarly to the Higgs boson
- T376, accompanied by T++ and T+, allows to push **perturbative unitarity limit > 29 TeV**
- To interpret LEP precision measurements and **BR(ee)~0.25%** KK gravitons should be much lighter than KK **Z**
- Implies **Gigafactories for e+e- colliders with ECM>400 GeV**
- **RUN2+RUN3** should provide enough data to confirm/reject this signal and its interpretations

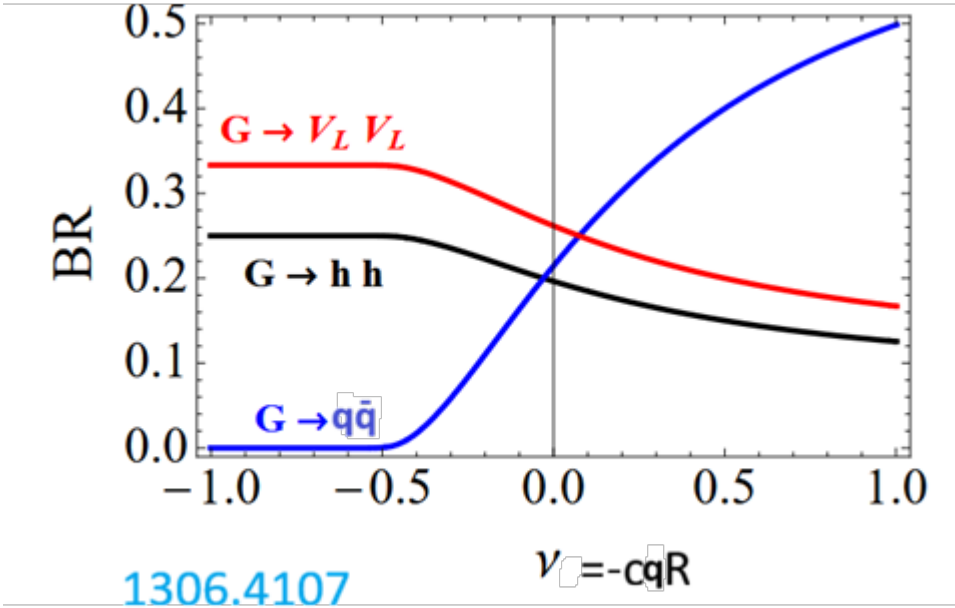
Acknowledgements

- Thanks to **Andreas Höcker** and **Gautier Hamel de Monchenault** for their encouragements in this task
- Useful and pleasant exchanges with **Abdelhak Djouadi**, **Ulrich Ellwanger**, **Adam Falkowski** and **Gilbert Moultaka** are gratefully acknowledged
- Thanks to **Roman Poeschl**, **Guillaume Unal** and **Louis Fayard** for useful exchanges
- Thanks to **Kaustub Agashe** and **Severin Lüst** experts on the RS model

Additional slides

LEP precision measurements

- In the RS model Z_{KK} can influence LEP PM
- AFBb, ALR show signs of deviations which can be fixed within a LR extension of the RS model
- So far a KK mass of **0.3TeV/sinθ'** was assumed, with sinθ'>0.1, see 0610173, hence **ceR=0.56** which gives a negligible BR(G_{KK}->ee)
- If this mass is of order 2.5TeV/sinθ', ALR implies that **ceR=0.45**
- This implies **BR(ee)~0.25%** compatible with ATLAS and CMS as suggested by the figure from 1306.4107



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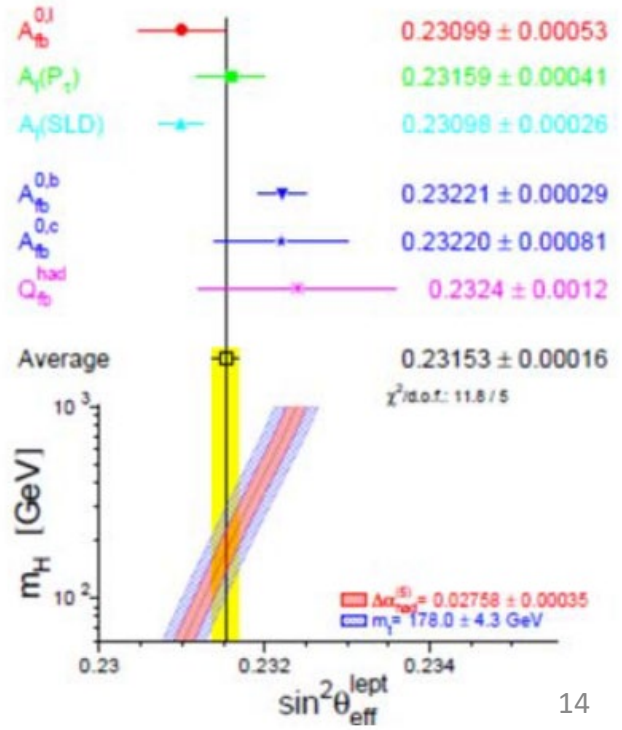
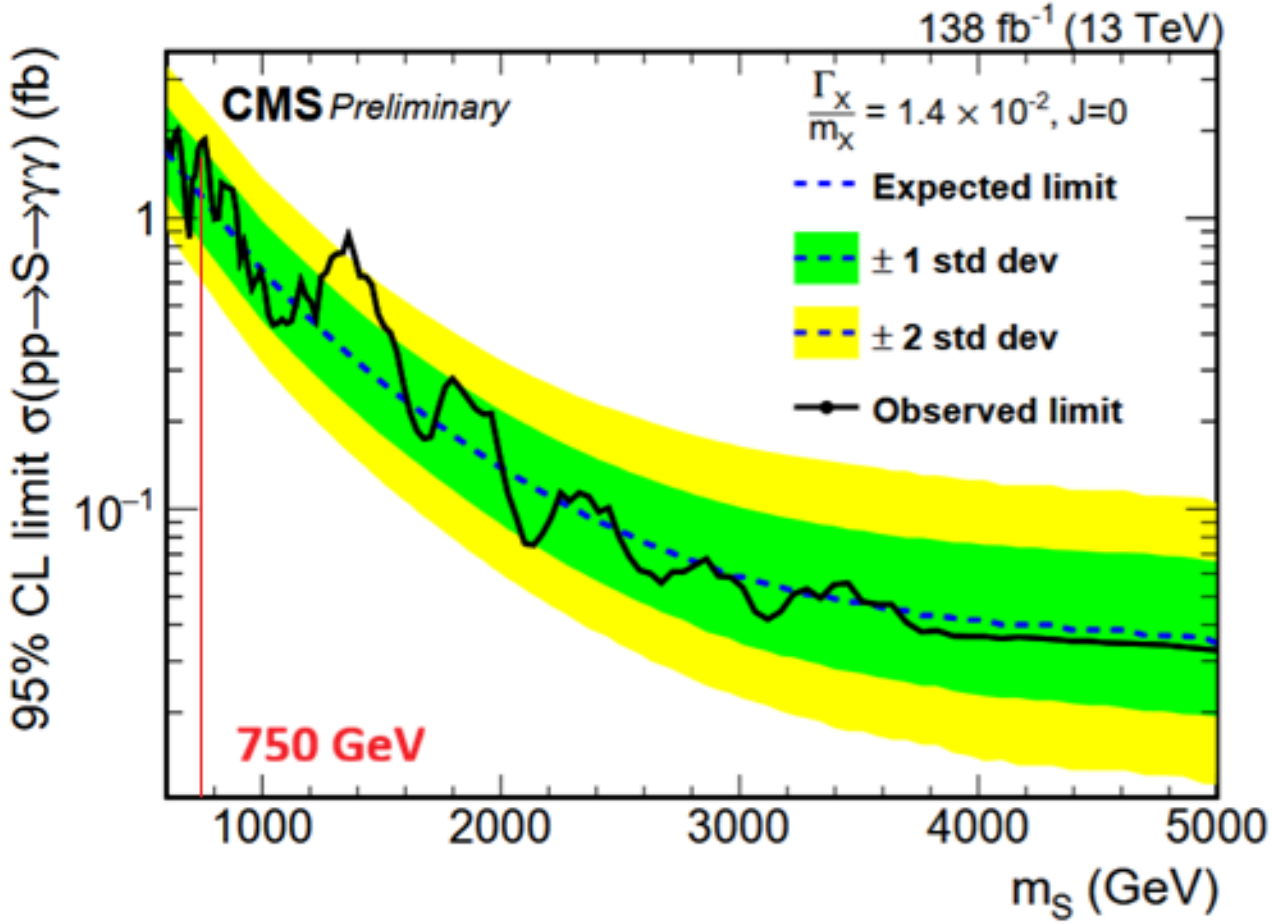


Why is G_{KK} much lighter than Z_{KK} ?

- In 1603.06980 a mechanism is recalled where bulk fields develop localized corrections to the **kinetic terms** which can modify the phenomenological predictions
- L**arge brane kinetic terms** allows to create a hierarchy between the diverse KK families
- A more radical way out is to invoke an **analogue of the Higgs mechanism.** As longitudinal degrees of freedom of Z and W come from the SM Higgs doublet, the additional degrees of freedom for the massive graviton KK modes (5 in the massive vs 2 in the massless case) would come from one vector and one scalar KK mode. Experimentally, these “eaten” vectors and scalar degrees of freedom are not visible as individual particles. The same thing could also happen for the fermionic KK modes in a SUSY theory. They can become the missing degrees of freedom of the massive gravitino KK modes.
- We are indebted towards Severin Lüst for suggesting this mechanism.

CMS on G_{KK}->2γ

- ATLAS has found a xsection of ~2 fb at ~700 GeV
- This result is not incompatible with the limit given by CMS in EXO-22-024



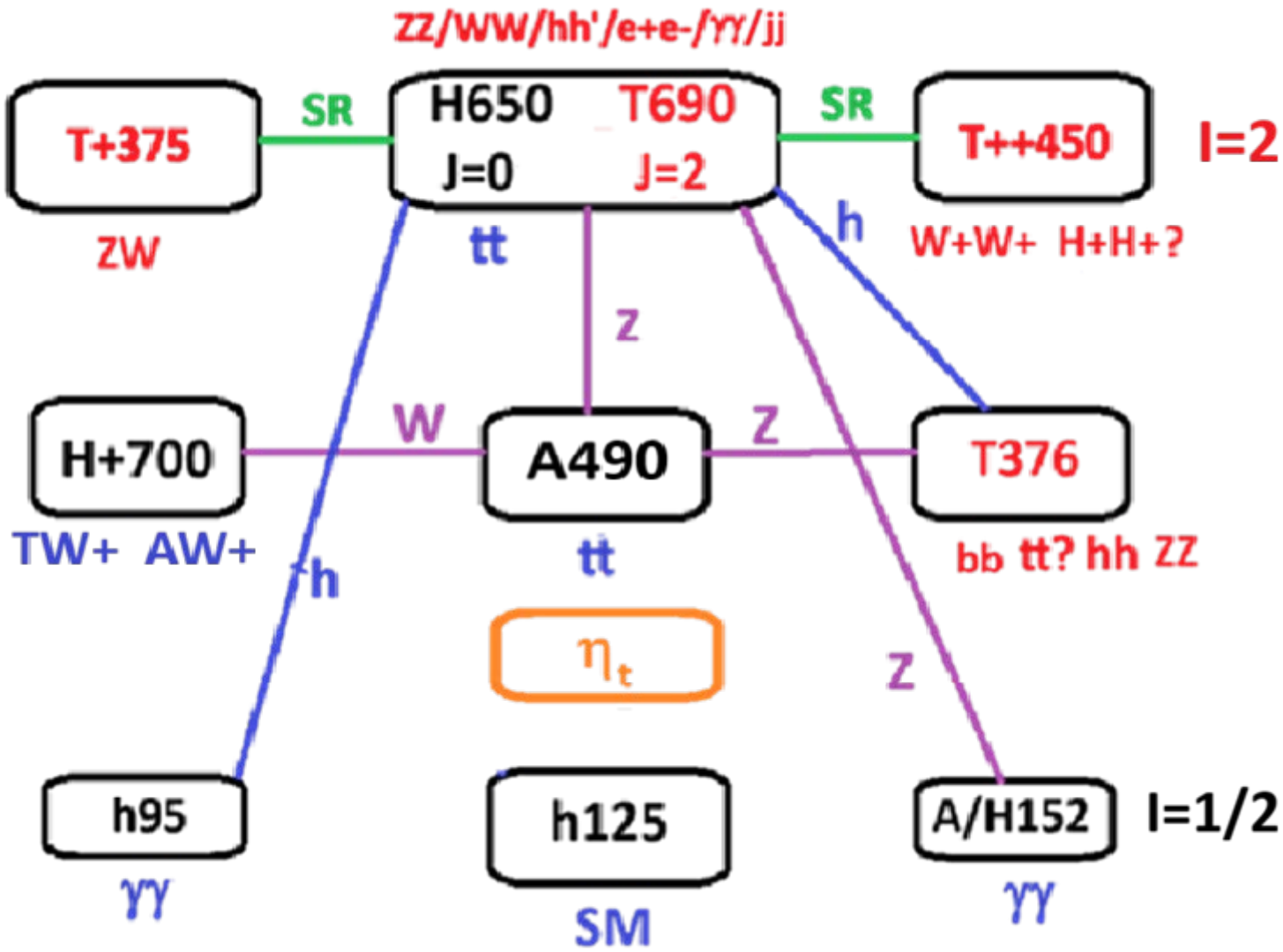
Sum Rules

- **Perturbative Unitarity** requirements predict sum rules for **scalar couplings**
- $\mathbf{W_L^+ W_L^- \rightarrow W_L^+ W_L^-}$ Haber et al. in *P.R.D* 43 (1991) 904-912
- They are satisfied by the SM and heavy scalar doublet (decoupling) contributions
- In the Georgi Machacek model one has compensation due to $\mathbf{H^{++}}$ (u exchange term)

$$g^2(4m_W^2 - 3m_Z^2 c_W^2) \overset{\rho \simeq 1}{\simeq} g^2 m_W^2 = \sum_k g^2_{W^+W^-H_k^0} - \sum_l g^2_{W^+W^+H_l^{--}}$$

- KK J=2 gravitons have a **different angular distribution** but could be compensated by doubly charged tensors $\mathbf{T^{++} \rightarrow W^+W^+}$ giving u exchange contributions
- In the same way ZZ->WW forces us to expect T->ZW
- They are indicated by LHC data for the first KK recurrence at 376 GeV
- They could also appear at 690 GeV for the second KK recurrence

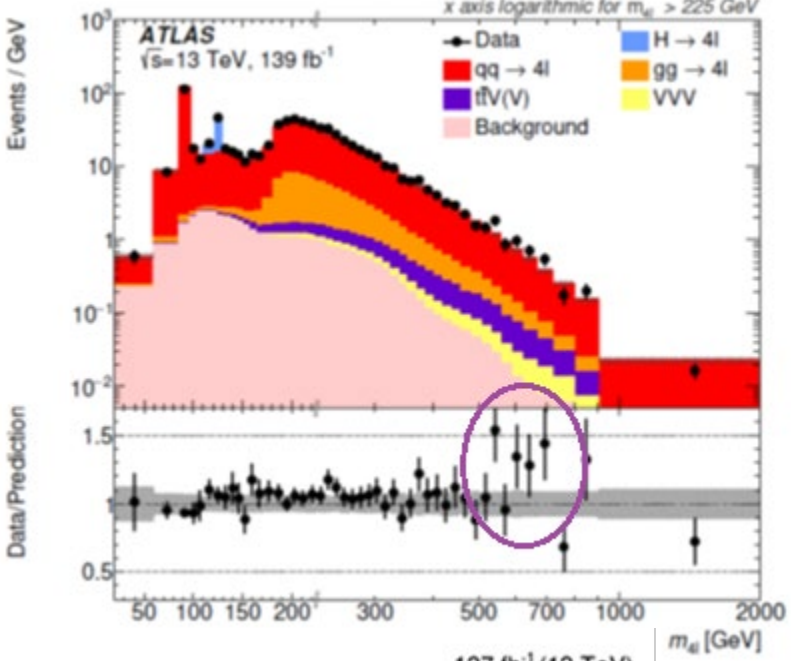
Summary diagram

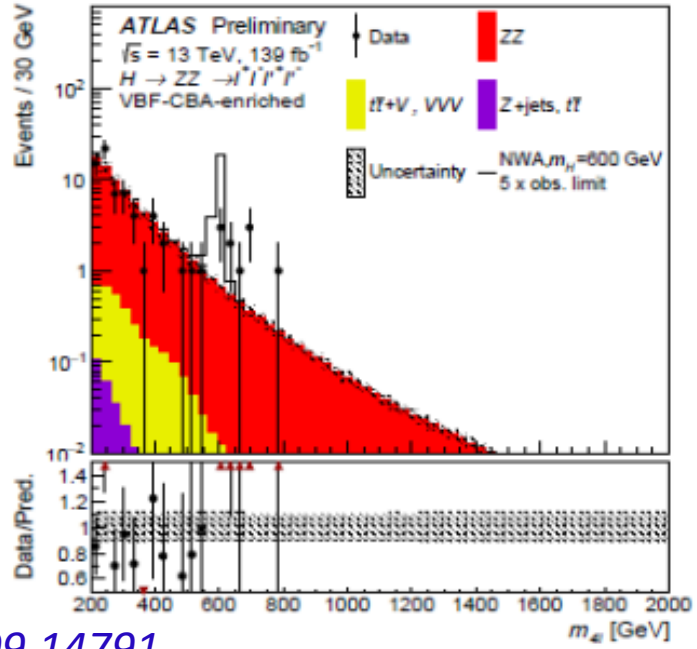


Evidences for ~650 GeV resonance(s)

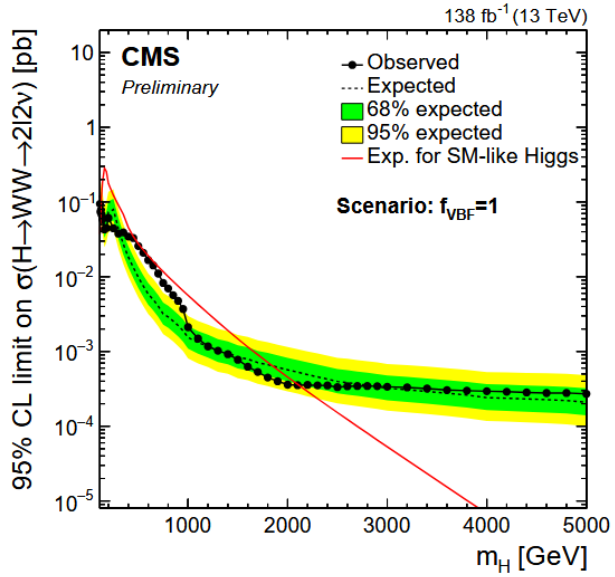
Channel	Significance s.d.	Reference
ZZ 4 leptons	3.8 ggF+VBF 2.8 VBF	ATLAS 2009.14791
WW 2leptons	3.8 VBF	CMS-PAS-HIG-20-016
h95h125 bb/ττ γγ	3.8	CMS 2310.01643 CMS 2506.23012
T376h125 bbbb	4.1	CMS-PAS-HIG-20-012
γγ	3.5	ATLAS 2102.13405
JJ	3.4	ATLAS 2509.01219
AZ tt 2leptons	2.85	ATLAS 2311
e+e-	3	ATLAS 1903.06248 CMS 2103.02708
tt	3	ATLAS 2404.18986 CMS 2507.05119

~ 6 sd global significance

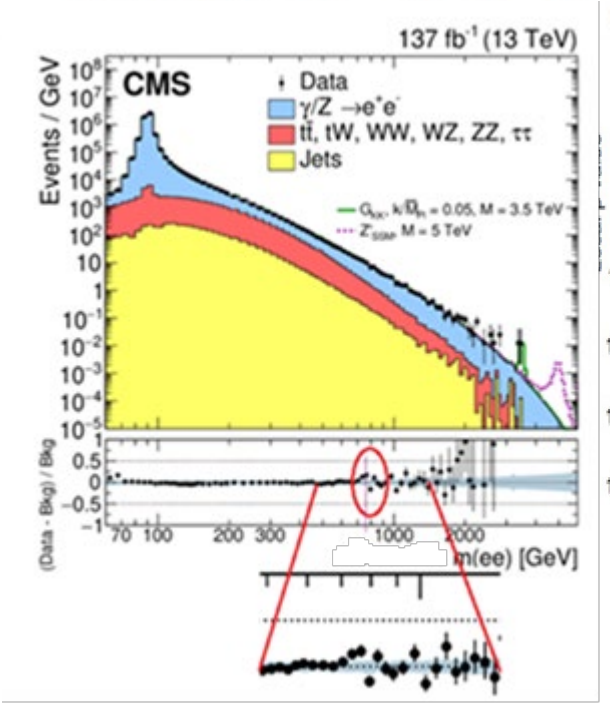


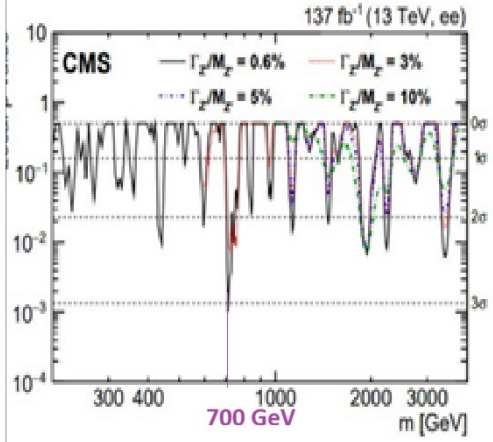


2009.14791



CMS-PAS-HIG-20-016





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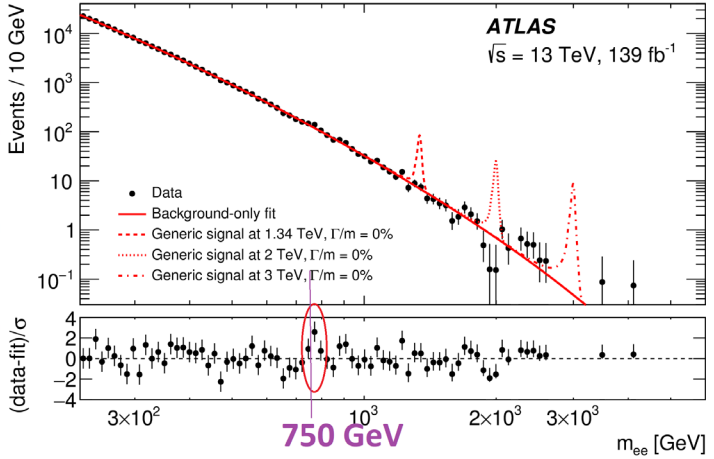

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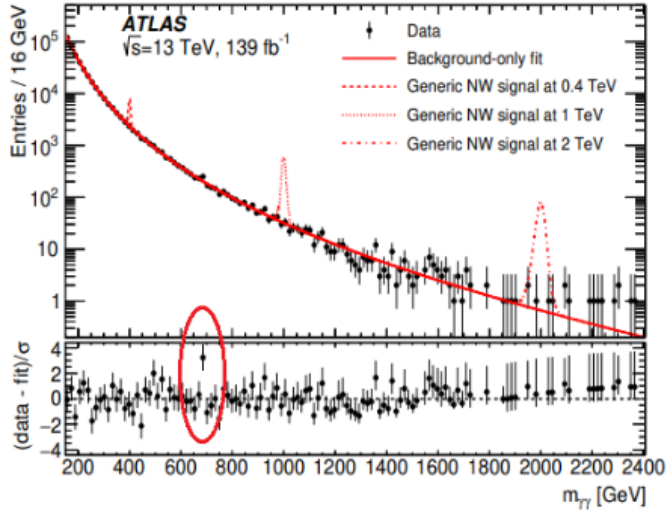

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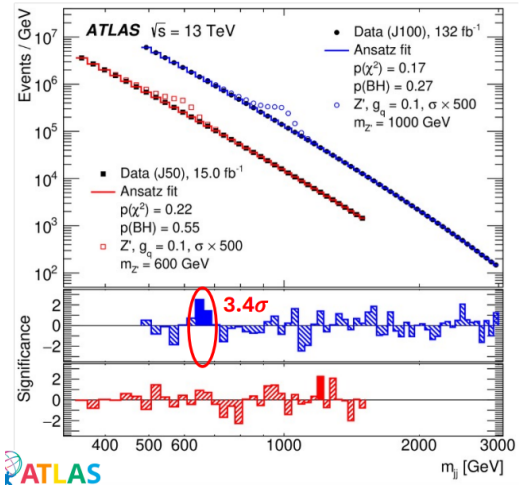
Complex modes

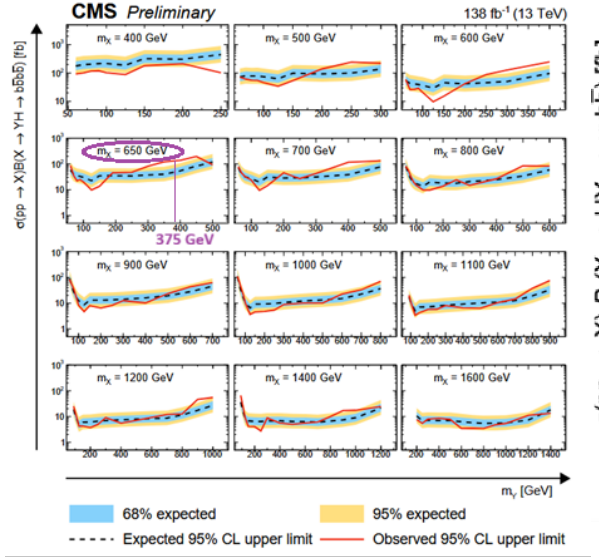
2509.01219

CERN-EP-2025-194, in submission



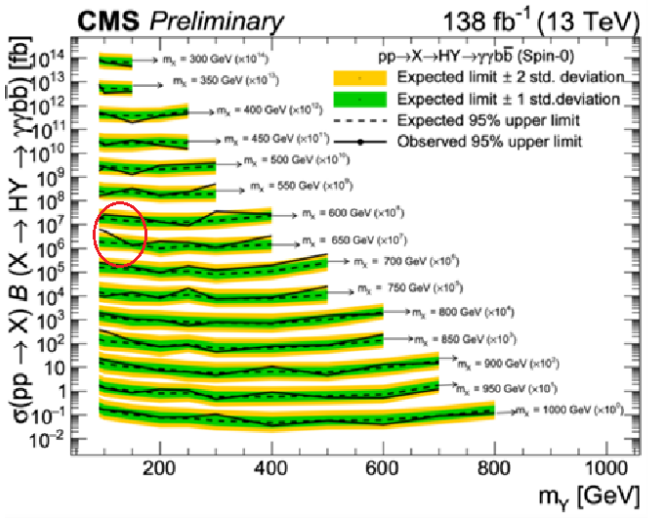
X650->2 Jets

CMS-PAS-HIG-20-012



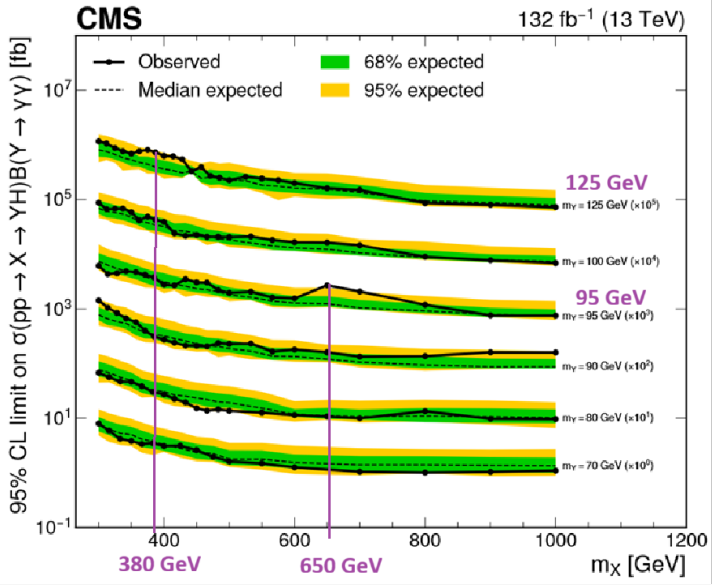
X650->Y375+h125->bb+bb

2310.01643



X650-> h125h95 -> γγ +bb

2505.23012

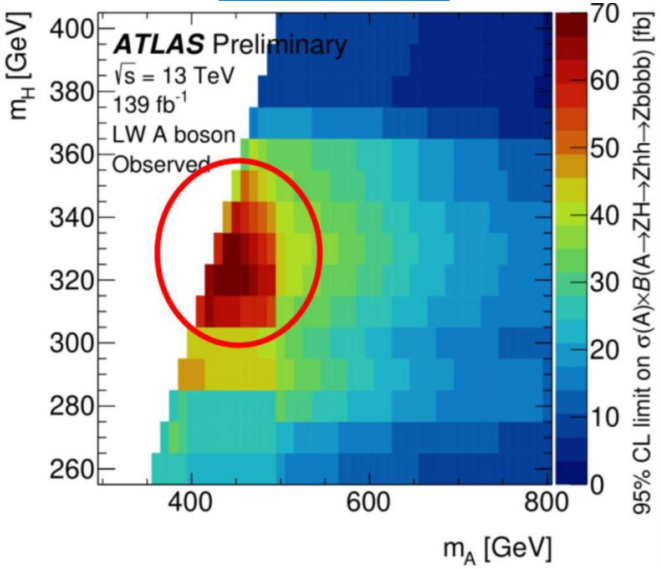


X650-> h125h95 -> γγ+ττ

T376-> h125h125->γγ+ττ

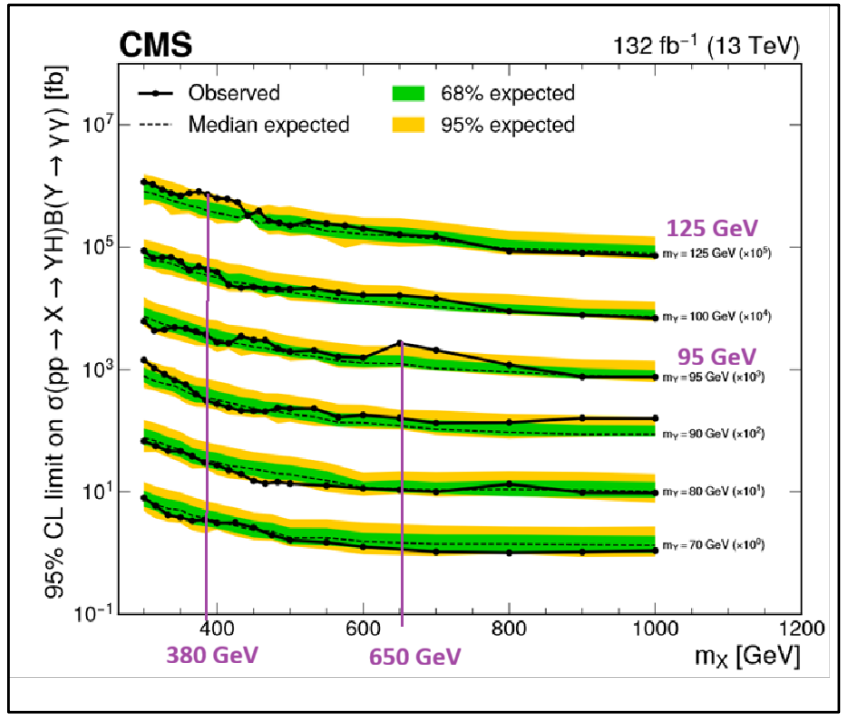
Next best candidate to T690 ?

2210.05415



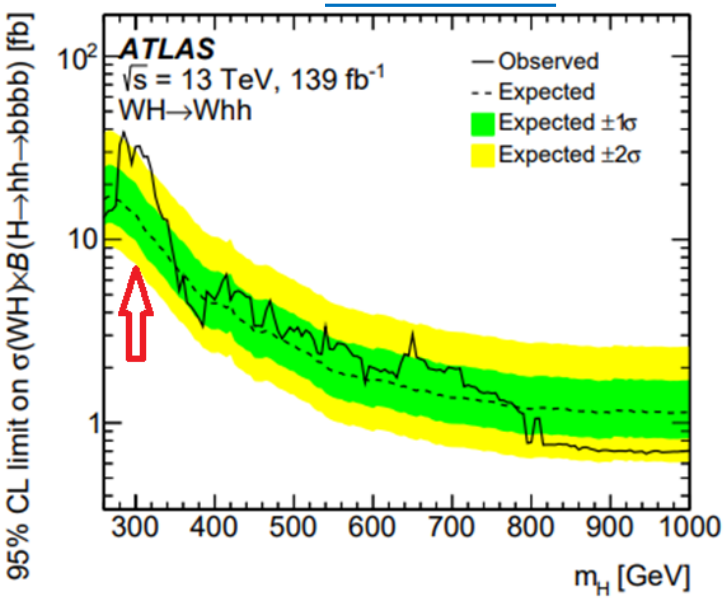
A490->T376Z->bbbbZ

CMS 2506.23012

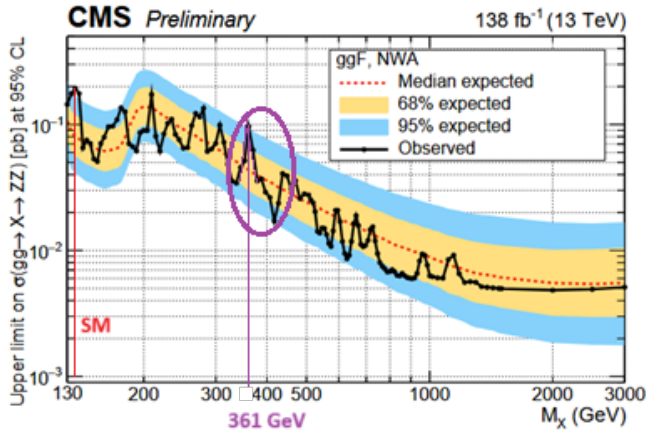


T376→ hh→ $\tau^+\tau^-$ +γγ

2210.05415



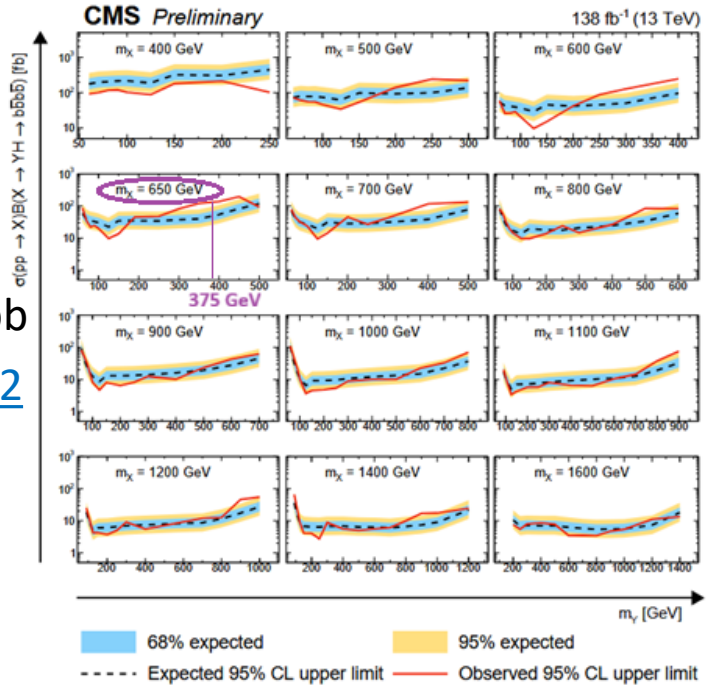
H+→T376+W→hh+W->bbbb+W



T376->ZZ->$\ell^+\ell^-\ \ell'^+\ell'^-$ CMS-PAS-HIG-24-002

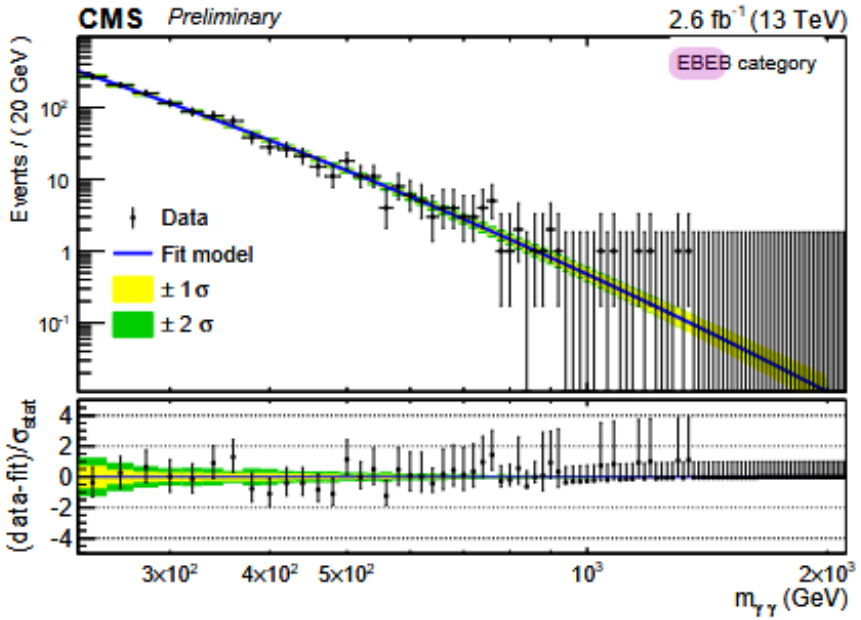
T690→ T375h → bb+bb

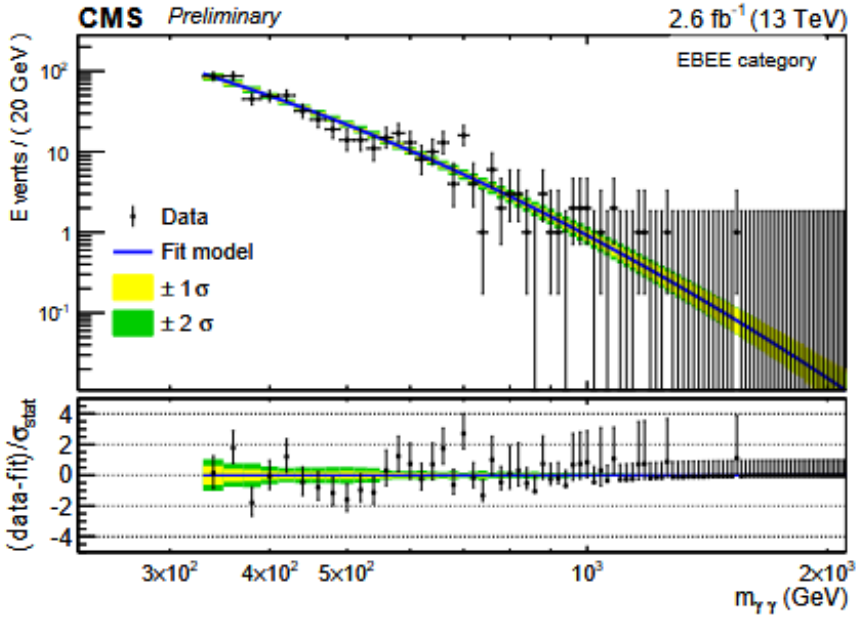
CMS-PAS-HIG-20-012

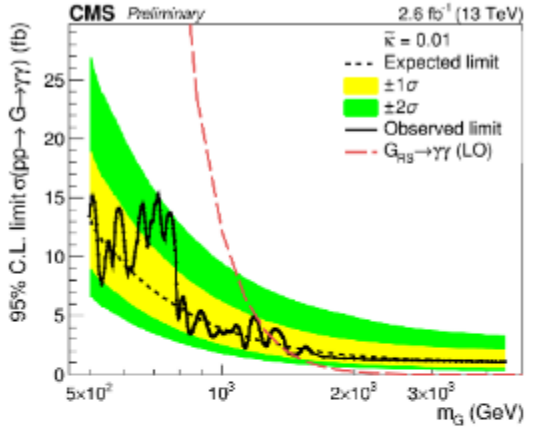


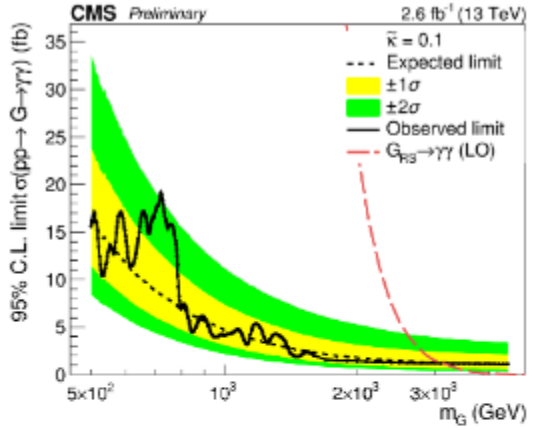
CMS results

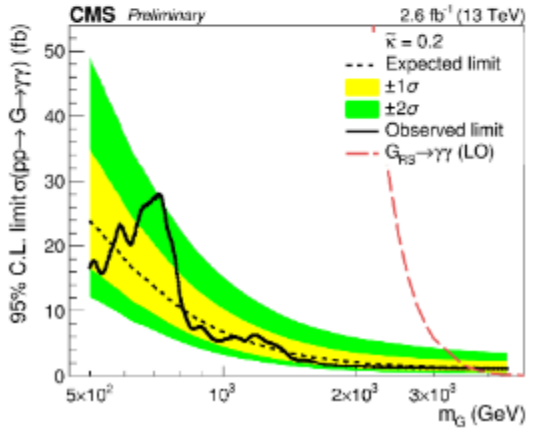
https://cds.cern.ch/record/2114808/files/EXO-15-004-pas.pdf





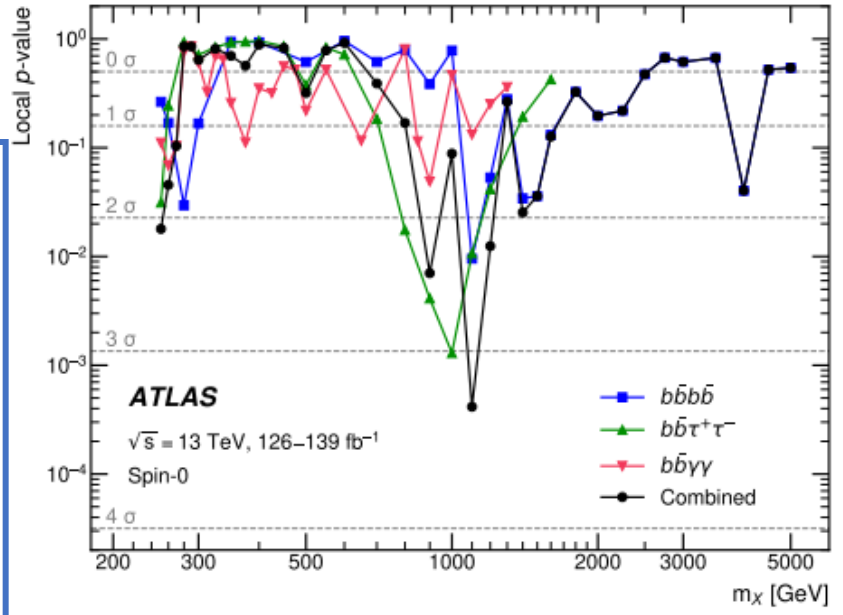




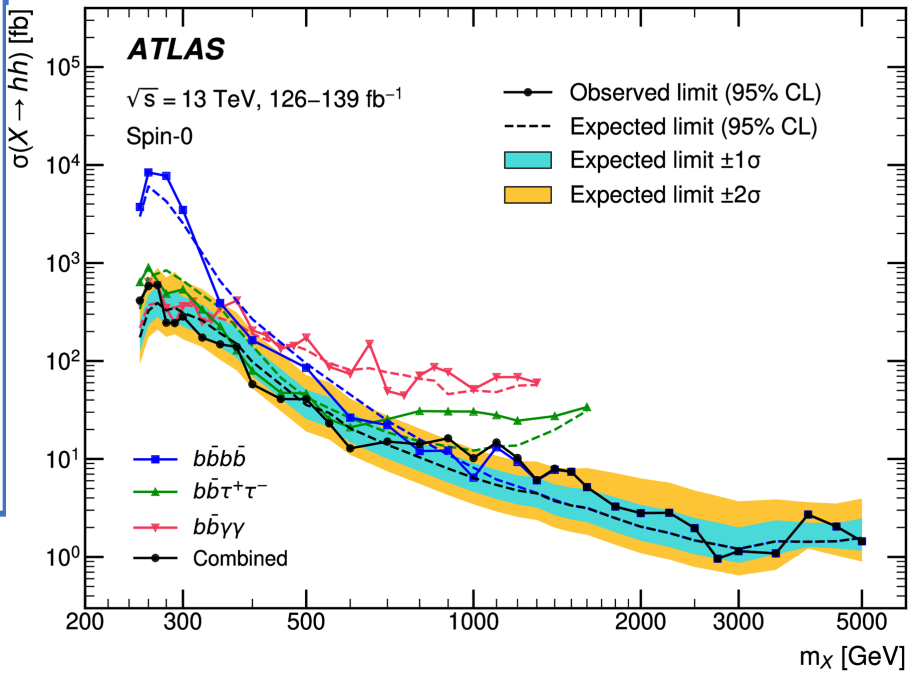


Graviton recurrences ?

- T690 seems a valid tensor candidate
- In the Randall Sundrum (RS) model, graviton KK resonances G_{iKK} have **masses** which go like **$m_i \sim 100 x^G_i$** in GeV, where x^G_i=3.8,7.0,10.2,13.3... and widths which go like $\Gamma \sim 0.06 (x^G_i)^3$
- These numbers which govern the RS model are of **geometric origin**, simply given by the zeros of the Bessel function $J_1(x)$
- Assuming that **T690 is the second KK resonance**, one predicts **T376** as the first one, as observed and the third one **T1000** , which seems indicated by ATLAS searches for h125h125
- The next one should be T1300



Phys. Rev. Lett. 132 (2024) 231801



A preliminary interpretation of these indications

J=0
I=1/2

J=2
I=2

HD1	**h125**→ SM	**WL**	**ZL**
HD2	**h95->**2γ	t→**H⁺130** b→bcb	**A152**→ 2γ+Z/W
HD3	**H650**->A490Z->ttZ	**H⁺700**→A490W⁺	**A490**→T376Z->hhZ
TQ1	**T⁺⁺450->**W⁺W⁺	**T⁺375**→ZW⁺	**T376**→hh,bb,tt
TQ2	**T690**→ZZ/WW/h125h95/tt/2γ/e+e-		
TQ3	**T1000**→ZZ/WW/h125h125		

Weinberg Model

Gauge Theory of CP violation, Phys. Rev. Lett, 37 (1976) 657.

Randall Sundrum

MTQ1=376

MTQ2=690

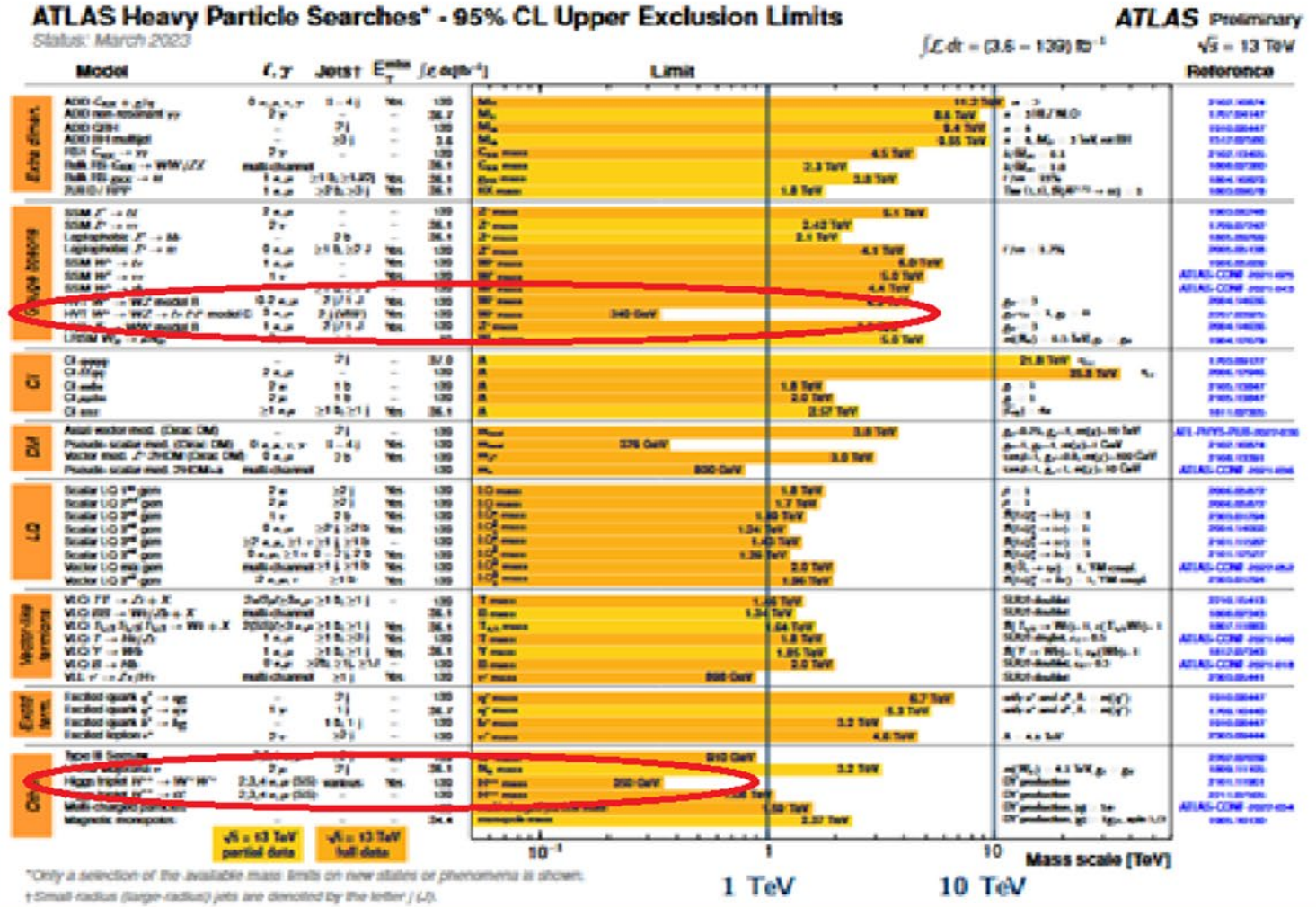
MTQ3=1000

Effective Field Theory: Why and why not?

- No signs for NP at LHC thus far
  - Most likely: $\Lambda_{NP} \gtrsim 1\,\text{TeV}$
  - Expansion in: $v^2/\Lambda_{NP}^2 \ll 1$
- **Effective Field Theory (EFT):**
  - Model independent
  - Valid at energies E below Λ_{NP}
- **But:**
  - How small does E/Λ_{NP} need to be? Validity for (non-)resonant processes?
  - Huge number of free parameters
    ⇒ Analysis with all couplings unfeasible
- ➡ **EFTs: powerful but complicated**

X->WZ

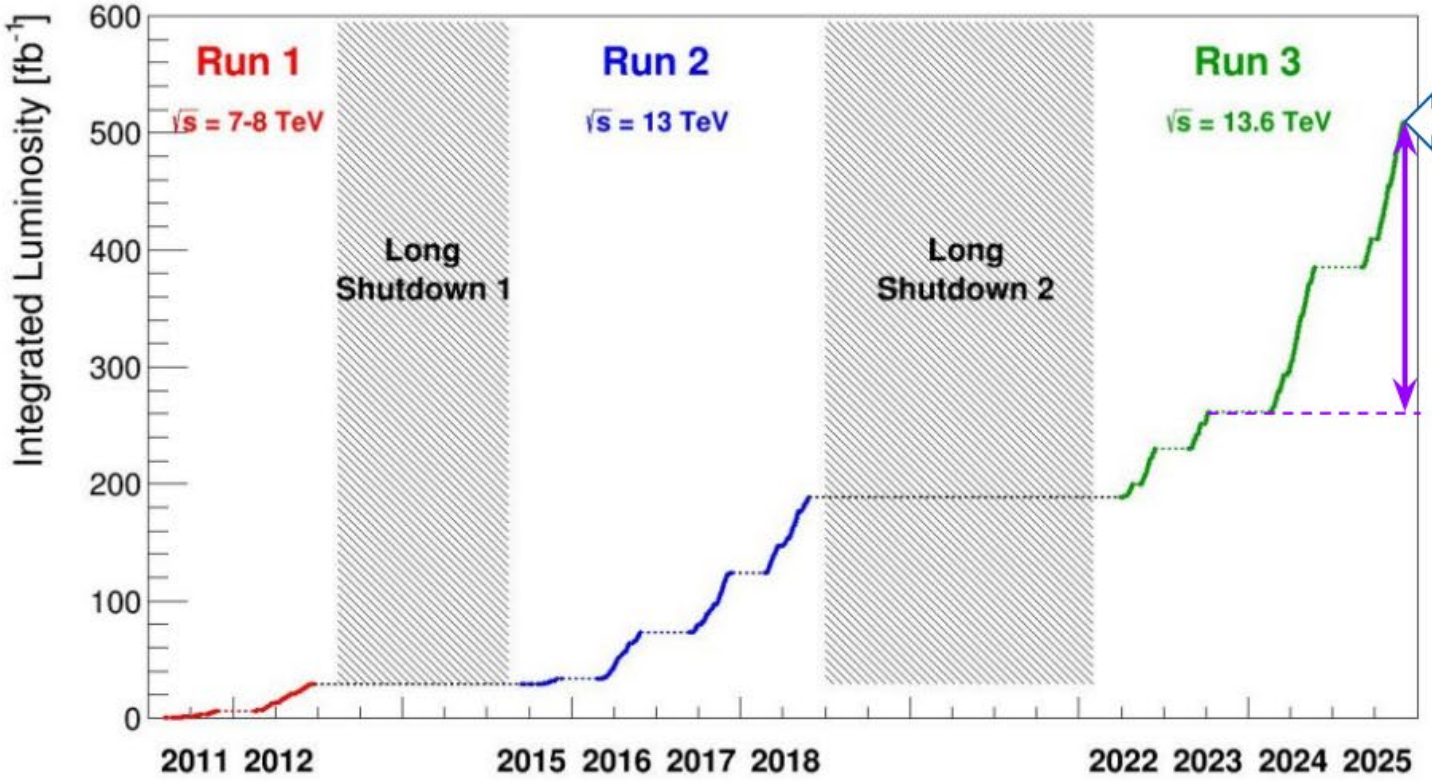
H++->W+W+



https://indico.ijclab.in2p3.fr/event/12138/contributions/39316/

entering the attobarn era

Michi Hostettler Moriond 2026



0.51 ab^{-1}
("x2" for ATLAS + CMS)

~50% of which delivered in the past 2 years…

+30 fb-1 in 2026