Double Higgs Production at Colliders Workshop

4-9 September 2018
Fermilab
Europe/Rome timezone

Experimental summary

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How (and why) this workshop was organized

- the workshop idea started at spring last year, when the hh domain contacts (me and John Allison at that time) were contacted by CMS equivalents (Olivier Bondu and Giacomo Ortona) in order to help with the ATLAS contributions to an *hh* workshop, to be hosted at Mainz, mainly theory driven as it was done in 2015:

Higgs Pair Production at Colliders

27-30 April 2015
Mainz Institute for Theoretical Physics
Johannes Gutenberg University
Europe/Berlin timezone

- discussing with CMS, and observing the different sensitivity of similar analyses, we thought that would have been better to have a workshop experimentalist driven, in order to compare and discuss different techniques and add theoreticians to help experimental choices: MC generators, result interpretation in complete models and analysis techniques

- call for proposals to the theory, ATLAS and CMS communities to host the workshop, among 8 proposals FNAL was chosen (first workshop in US, good facilities to handle the workshop organization)

Targets of the workshop

1. bring the ATLAS and CMS analyzers together, to share ideas and to profit of each other experience to improve the analyses (SM hh production sensitivity still far, many relevant differences between ATLAS and CMS analyses)

2. define a common basis of signal MC generators to have a consistent signal definition among experiments

3. define a set of benchmarks models used to interpret data

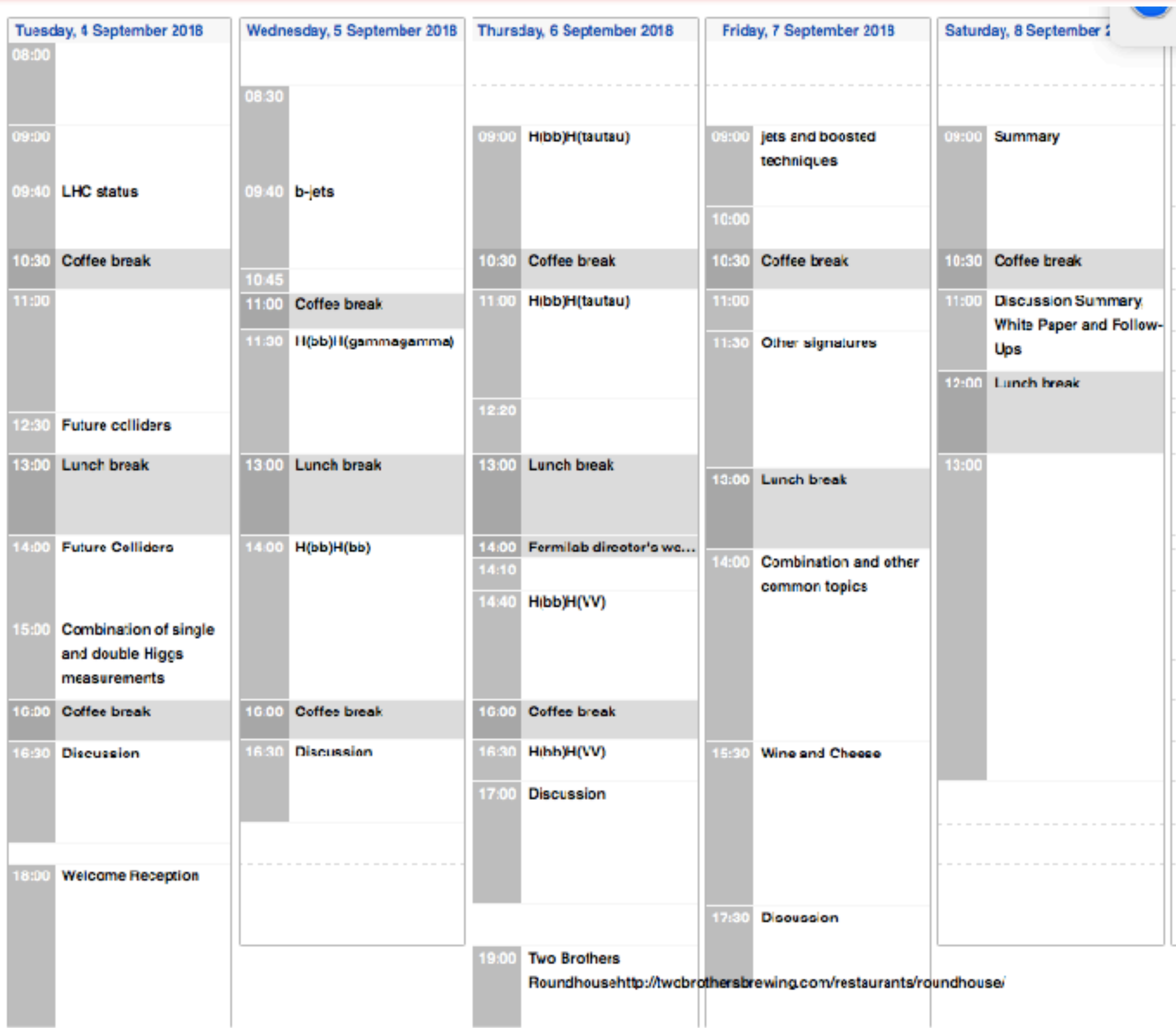
4. given the low sensitivity to SM hh production, start the effort for an ATLAS/CMS combination at the end of Run-2

5. (unexpected target) set a new deadline to push out new results on combination and other channels [ATLAS showed 3 new results: combination, WWbb and WWWW final states]

6. try to make the point on the current interest for hh production search

Workshop timetable

- first day dedicated to general talks on ATLAS/CMS results, show projections at Future Colliders and HL-LHC projections
- following days: signature specific sessions: bbbb, bbVV, bbττ, bbγγ, others (4W's, WWγγ, ττττ), 2 performance sessions: b-jets and JET/MET, boosted techniques
- 1h discussion session for each day (up to 3 parallel discussion sessions)
- discussion sessions were freely organized, the first day there was a general discussion on the topics, the following days those topics were developed in specific sessions



HL-LHC projections

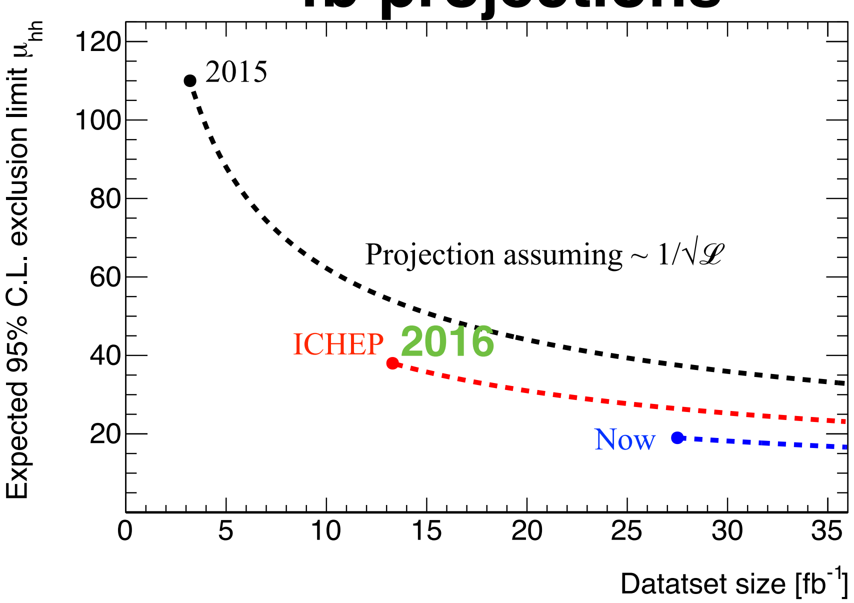
Channel	CMS	ATLAS
HH→ bbbb	$Z(\sigma_{HH}(SM))=0.39\ \sigma$ CMS PAS FTR-16-002	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L. ATLAS-TDR-030
HH→ $bb\tau\tau$	1.6 xSM CMS-TDR-019	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L. ATL-PHYS-PUB-2015-046
HH→ $bb\gamma\gamma$	1.43 σ CMS PAS FTR-16-002	1.5 σ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only) ATLAS-TDR-030
HH→ WWbb	0.45 σ CMS PAS FTR-16-002	
tt(HH→ bbbb)		0.35 σ ATL-PHYS-PUB-2016-023

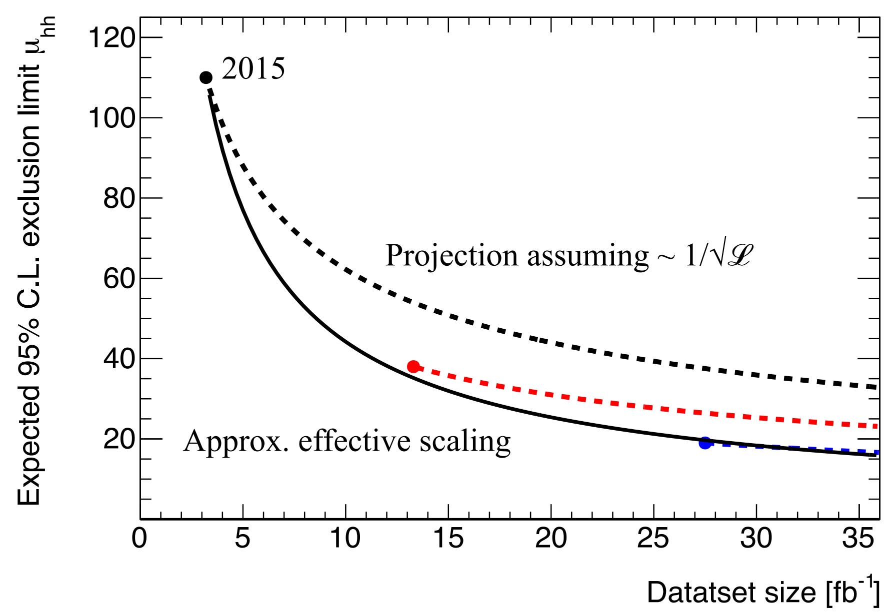
S. Gori

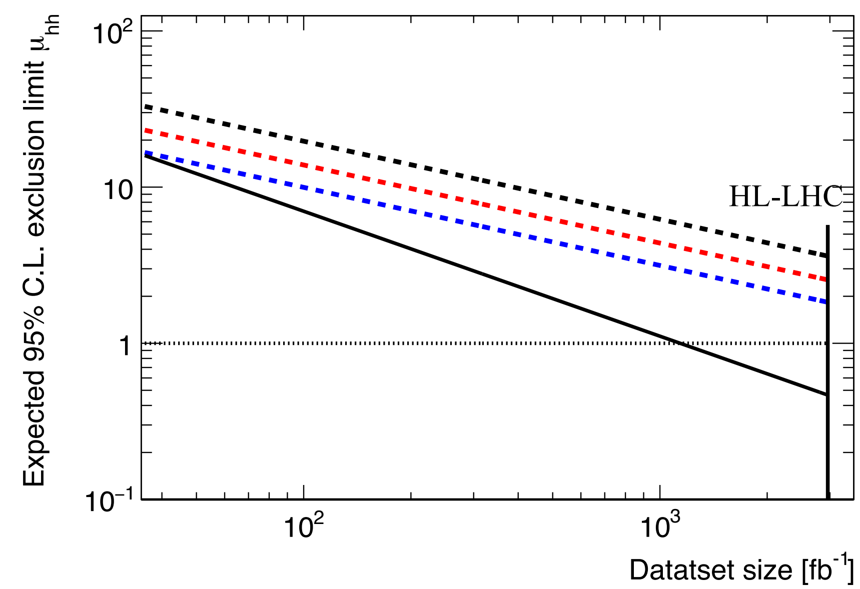
Most likely pessimistic giving that we have with 27 fb^{-1} 4b: $-12 < \kappa_\lambda < 19$, with a factor 100 less luminosity

J. Alison

4b projections

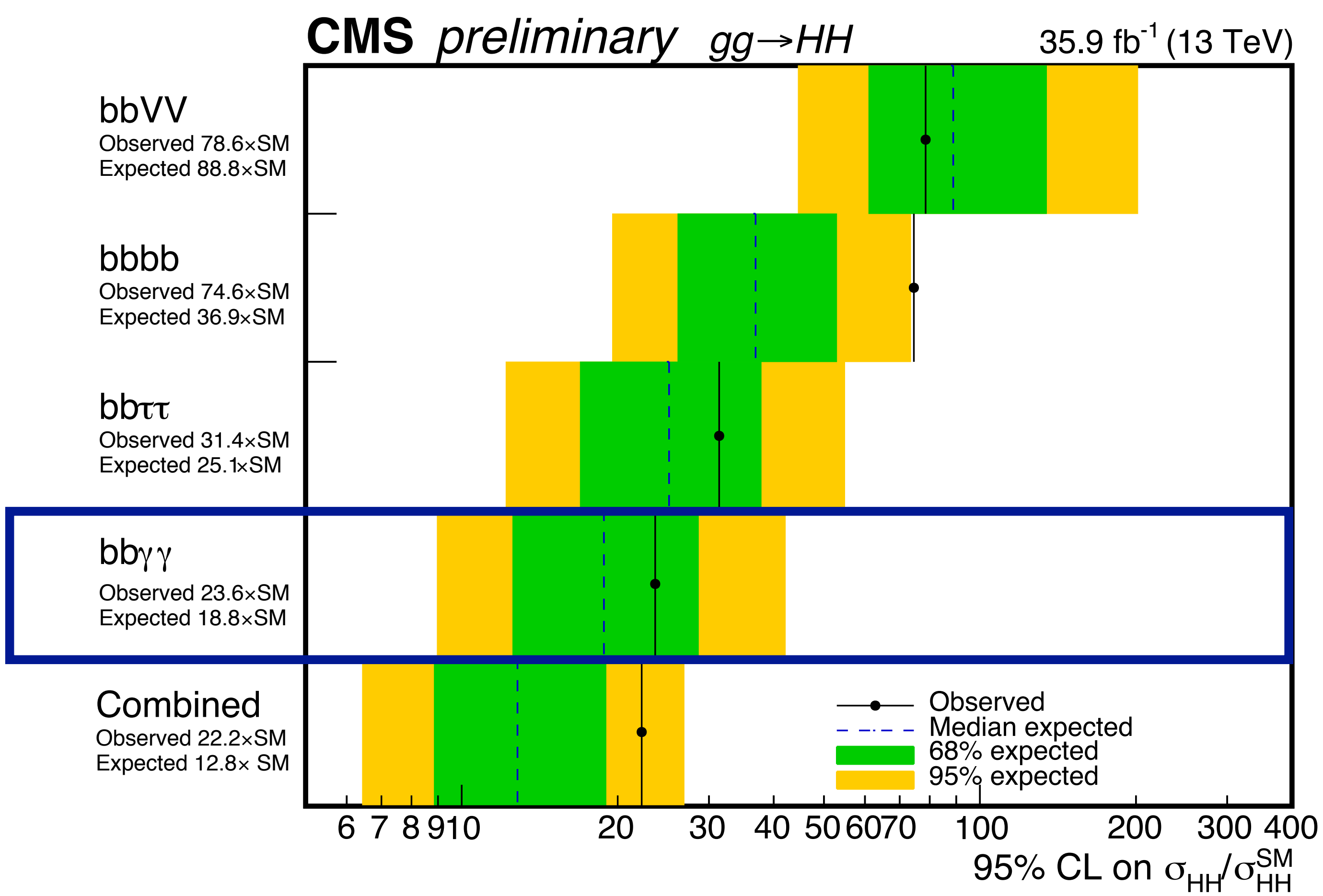


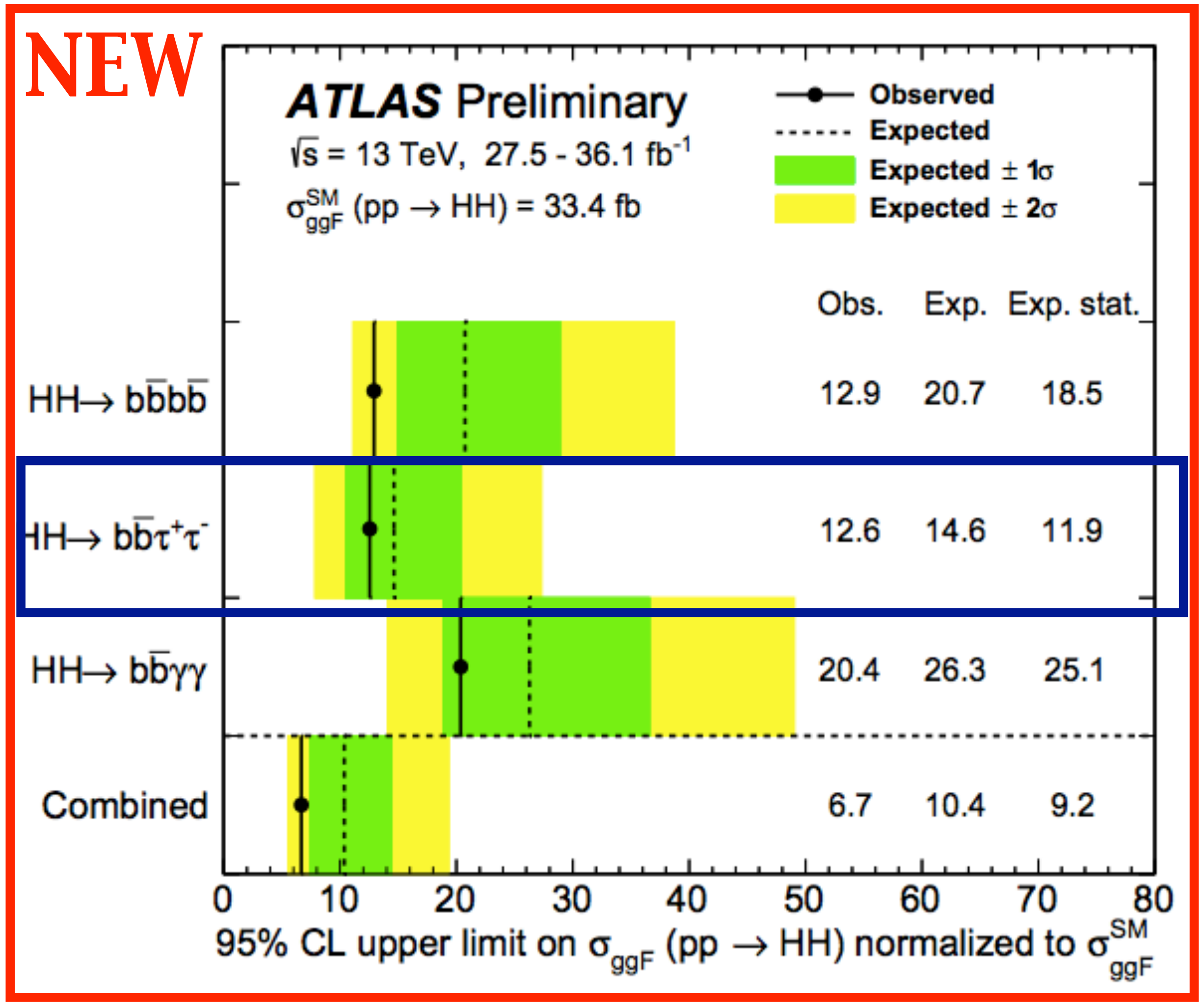




analysis improvements push sensitivities quickly faster than luminosity increasing

Upper limits on σ(pp→HH)





best limit from bbγγ in CMS

bbττ in ATLAS

4b ~2 worse in CMS

theoretical xs error:
~8% not included in ATLAS result

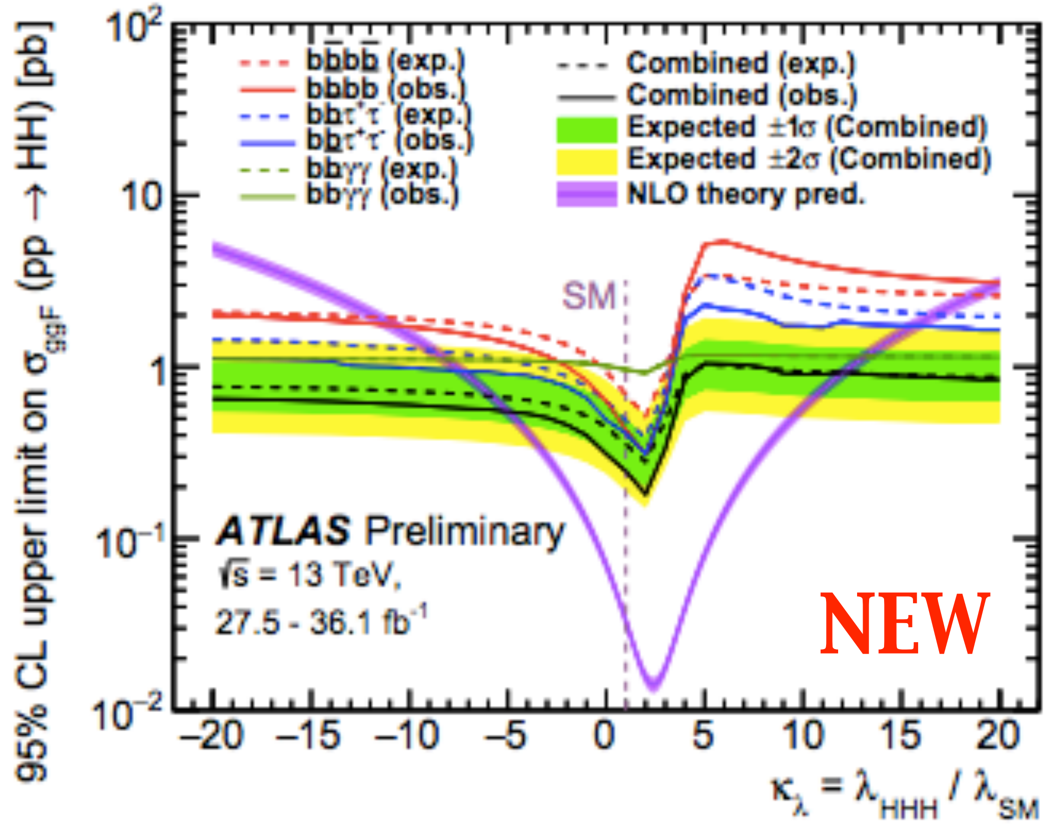
Present limits on κλ

Limits on the cross-section as a function of κ_λ

4b
$bb\tau\tau$
$bb\gamma\gamma$
combination

dashed: expected

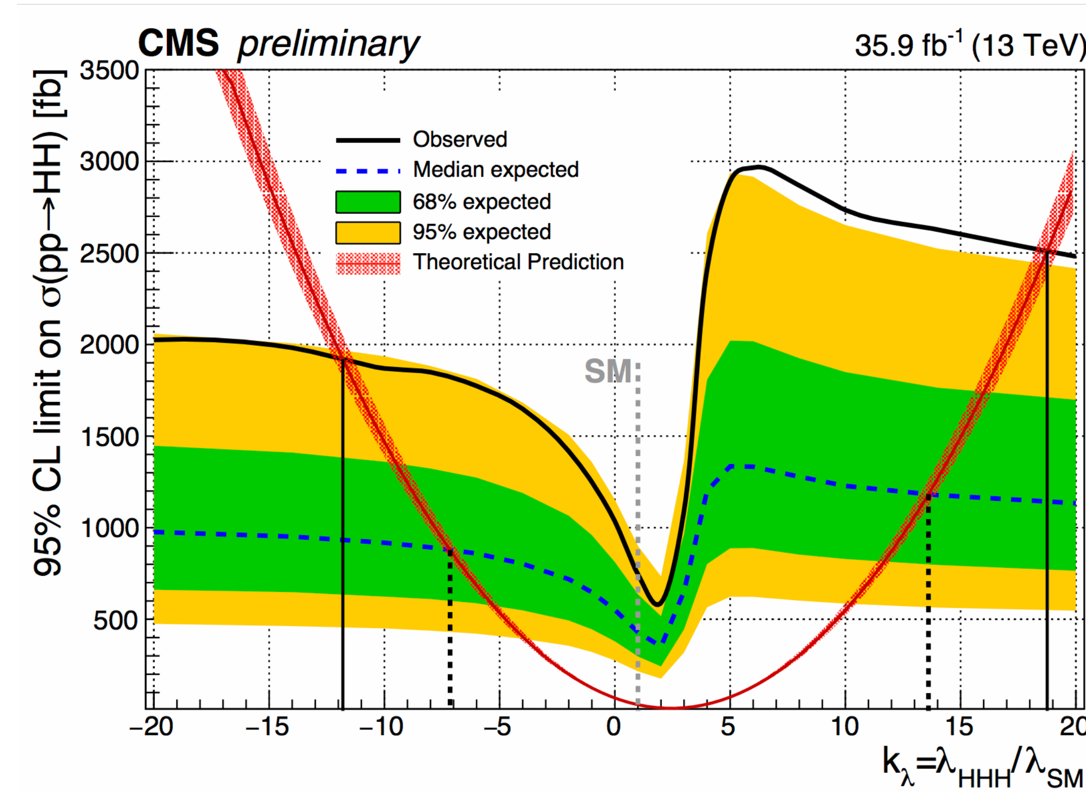
solid: observed



The scale factor κ_λ is observed (expected) to be constrained in the range:

$-5.0 < \kappa_\lambda < 12.1$ $(-5.8 < \kappa_\lambda < 12.0)$

14/19



κλ ∈[-11.8, 18.8] assuming SM top-H coupling
[-7.1, 13.6] expected

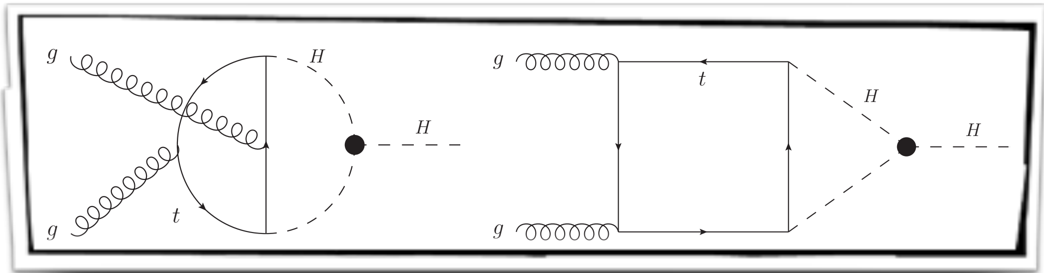
ATLAS has presented 3 new results at the workshop:
bbbb, bbττ, bbγγ combination, 4W's and WWbb results

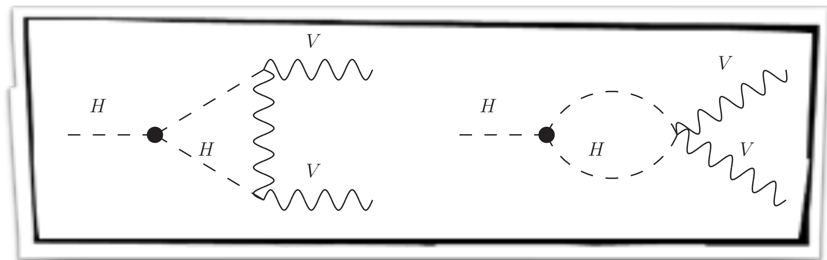
limits are far from SM sensitivity, main interest is to look if there is room for NP to cime in

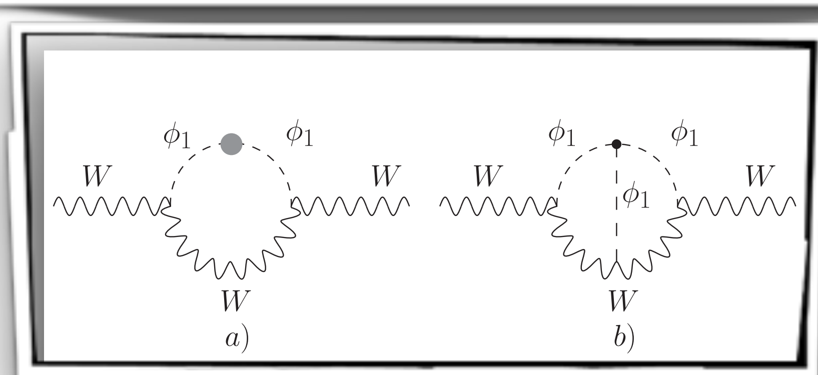
Room left from New Physics in k_λ

indirect constraints from experimental measurements G. Degrassi et al.

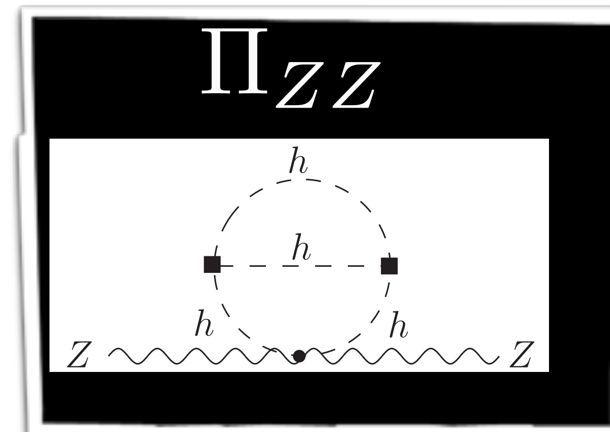
Higgs boson production and decay







$$m_W + \sin^2\theta_{\rm eff}^{\rm lep}$$



S&T relation in Vacuum Polarisation (global EWK fit)

R. Groeber et al.

constraints from unitarity requirements

S-wave hh ↔hh scattering unitarity constraints

$$a^0_{hh\to hh} = -\frac{1}{2}\frac{\sqrt{s(s-4m_h^2)}}{16\pi s}\left[\lambda^2_{hhh}\left(\frac{1}{s-m_h^2} - 2\frac{\log\frac{s-3m_h^2}{m_h^2}}{s-4m_h^2}\right) + \lambda_{hhhh}\right]$$

$$\left|{\rm Re}\,a^0_{hh\to hh}\right| < \frac{1}{2}$$

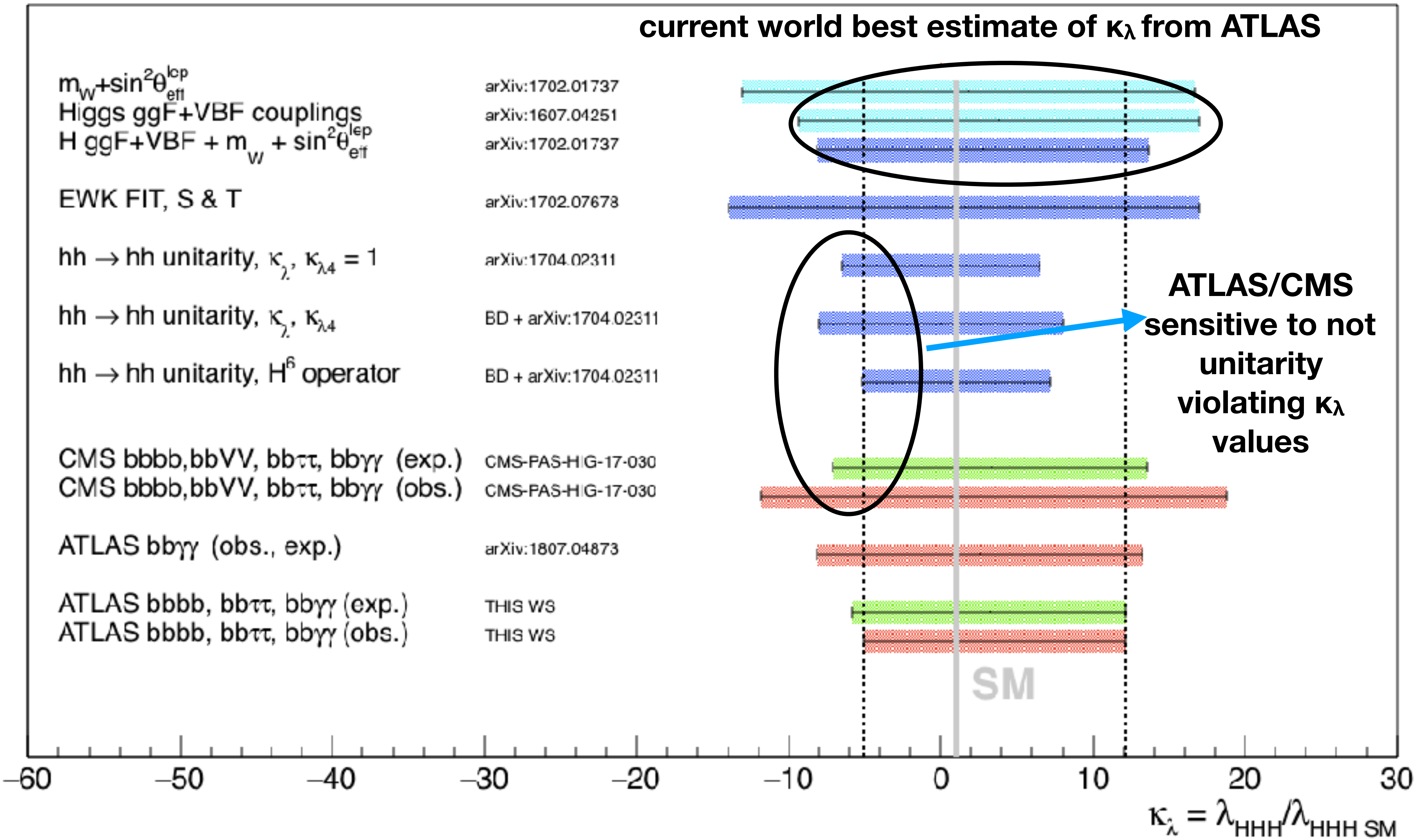
constraint involving both the hhh and the hhhh coupling

$$V^{(6)}(H) = -\mu^2|H|^2 + \lambda|H|^4 + \frac{c_6}{v^2}|H|^6$$

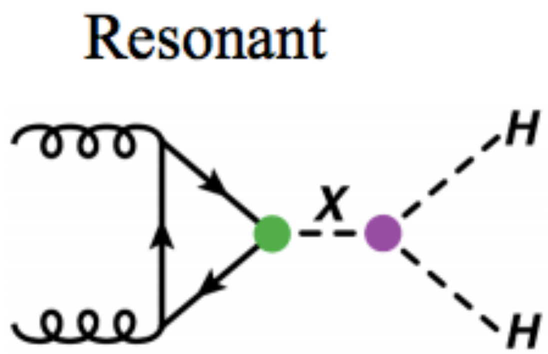
1) can probe arbitrary variations
2) variations correlated by the O^6 operators

$$\kappa_\lambda = 1 + 7.8c_6 \quad \kappa_{\lambda 4} = 1 + 47c_6$$

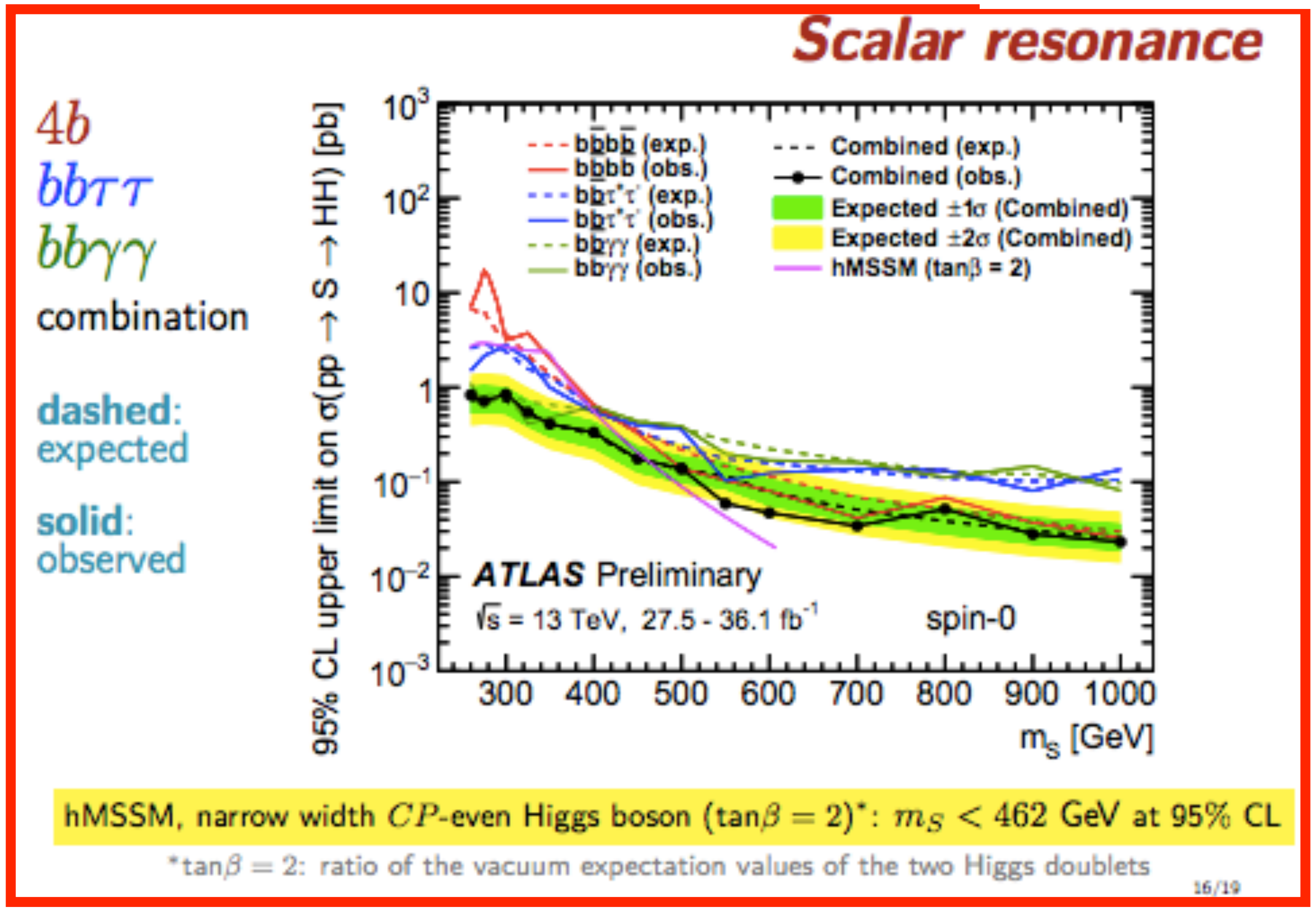
Present status of κ_λ determination

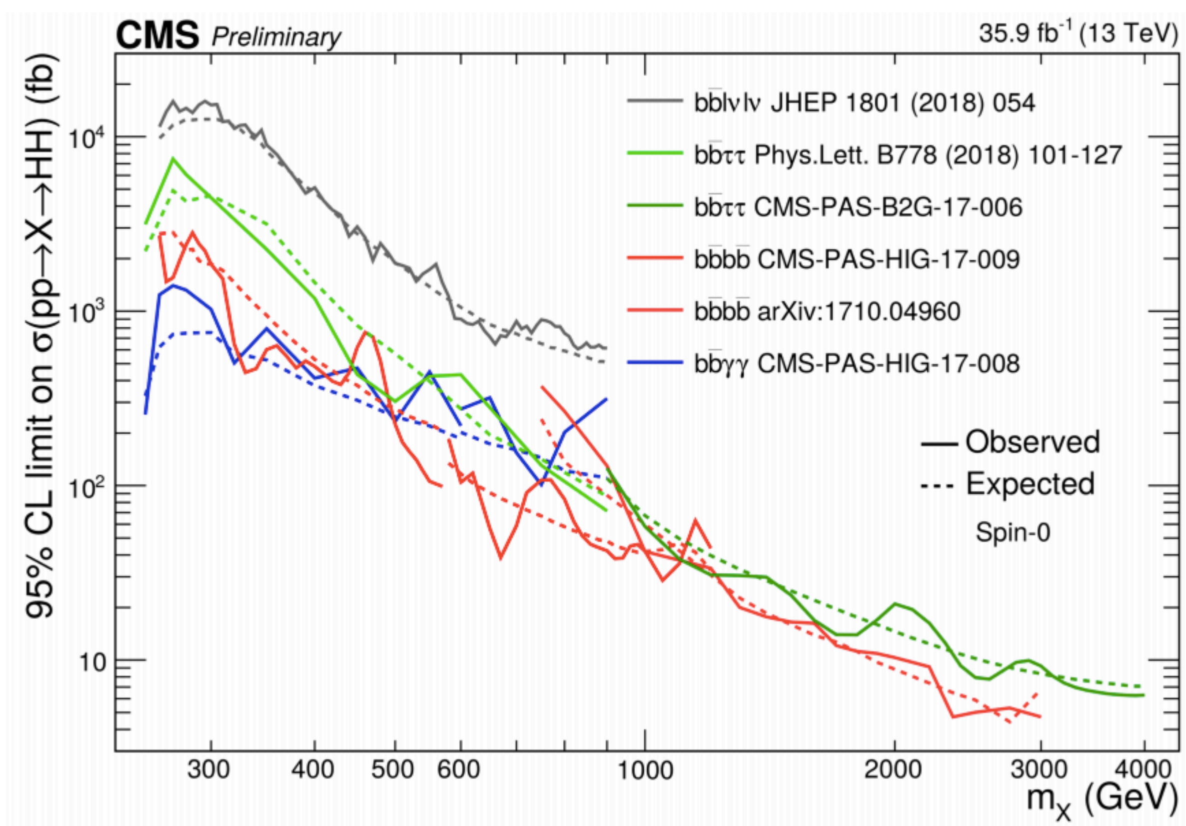


Resonant hh

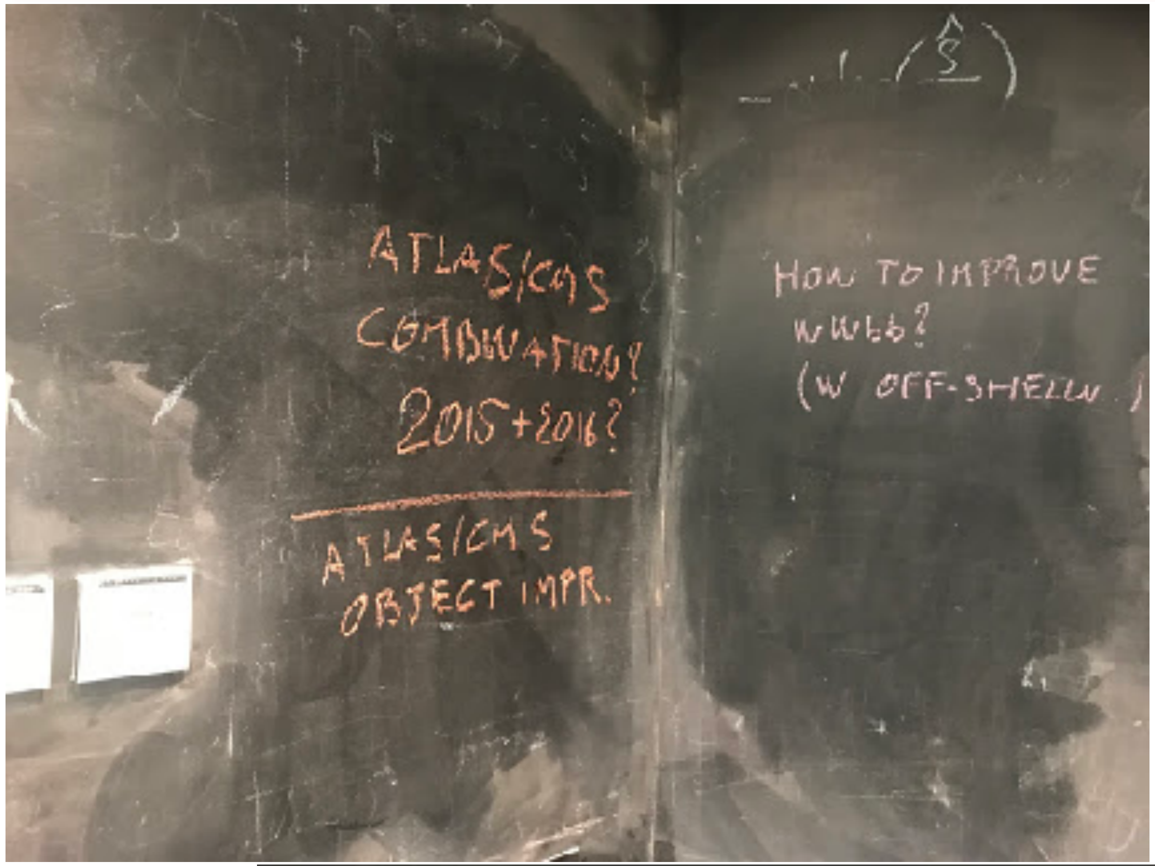


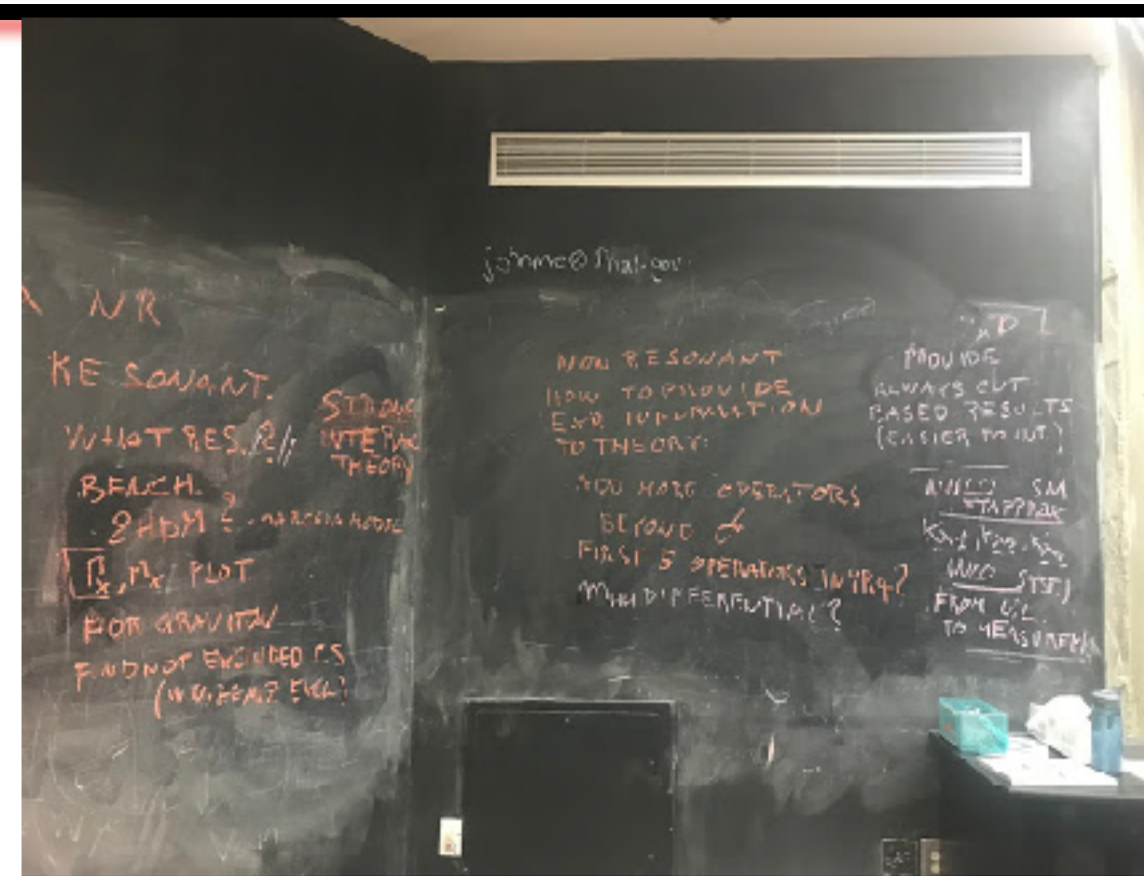
NEW

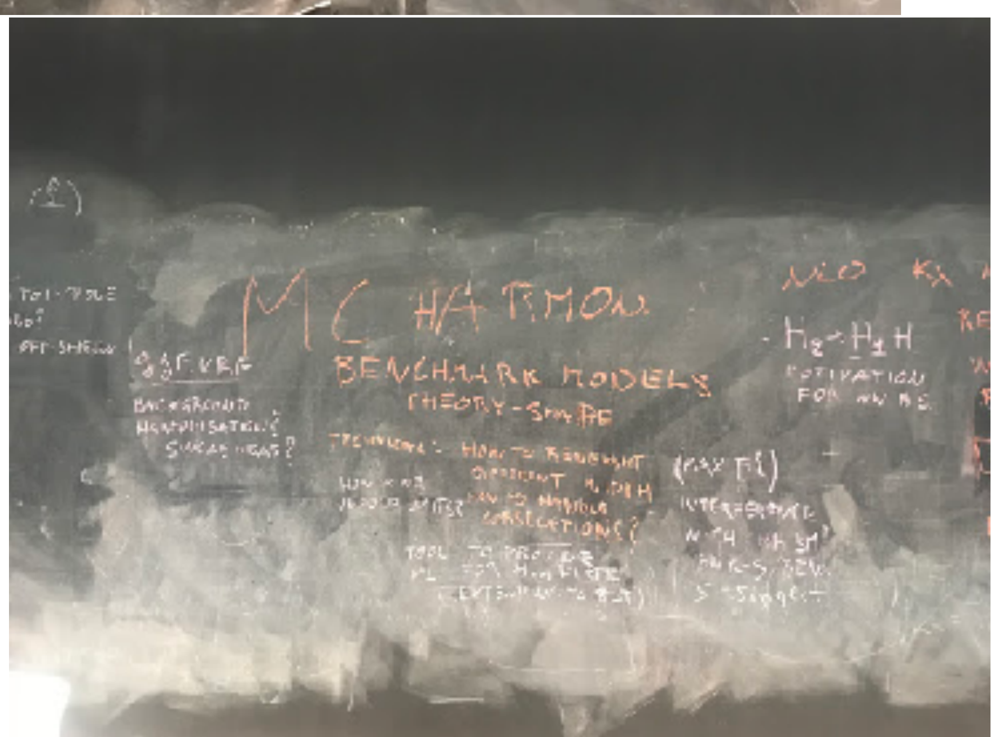




Discussion sessions







Started the first day, with blackboard notes taken writing down ideas and arguments to discuss

Ideas developed in the following days

Discussion session arguments

1. ATLAS+CMS combination (Luca C., David W., Javier M., B. Di Micco) - Wednesday Room Ramsey
   - based on 2015+2016 in preparation of the Run-2 legacy
   - MC settings (NLO vs LO)
   - Single H+HH combination
   - Total cross section vs k_lambda + uncertainties

2) How to make results public (J. Allison, Max S., K. Leney) - Friday 1W (17:30 - 18:30)

- Tools to provide unfolded UL
  - How to handle bbb correlations?
- Resonant: Gamma vs Mx plot?
  - How to reweight different widths?
- cut based results
- differential results in m_HH (truth vs. reco)
- Special care for BDT-based results

3) EFT (S. Di Vita, M. Gouzevitch, J. Robinson) [17:30 - 18:30] 11th floor ROC

- Which framework? More operators beyond O6
- How to make EFT useful for model testing?
- Which inputs from H and HH?
- Which topology? ggF/VBF single H background?
- Usage of shape benchmarks

4) BSM (M. Carena, K. Tschann-Grimm, Ian Lewis, Lian-Tao Wang, X. Carvalho) We

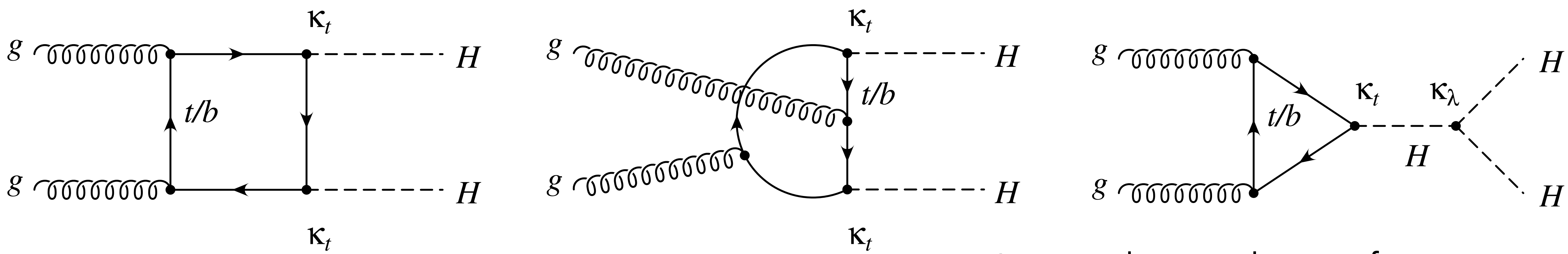
- Benchmark models : which one ?
  - Resonant: Is graviton still a good benchmark?
  - Interplay with VV
- Motivations for H1->H2 h
- Interference with SM HH (EWK-S, 2HDM) benchmark

5) ATLAS/CMS objects/analysis strategies (M.Kagan, F. Micheli, C.Vernieri) [Thursday 1W

- Trigger strategies
- B-tagging and b-jets (regression)
- MET

6) How to improve WWbb (W off-shell) [S. Shrestha, N. De Filippis - Thursday 11 ROC]

Interplay between single H and HH measurements



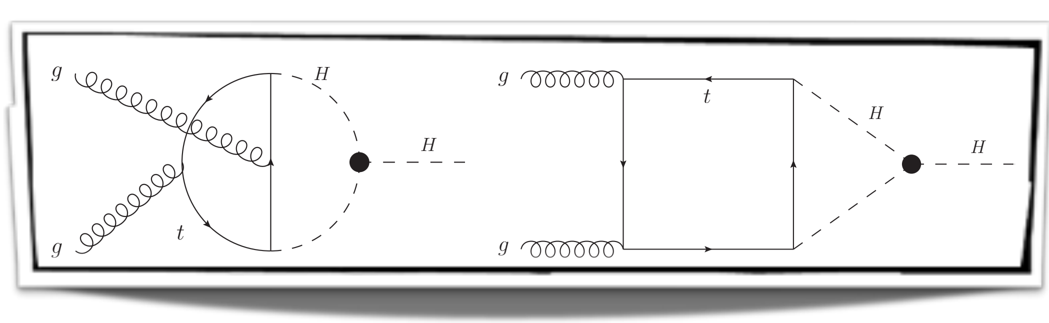
$$\sigma(pp \to HH) \sim k_t^4 \left[|B|^2 + \frac{k_\lambda}{k_t}(B^*T + TB^*) + \left(\frac{k_\lambda}{k_t}\right)^2 |T|^2 \right]$$

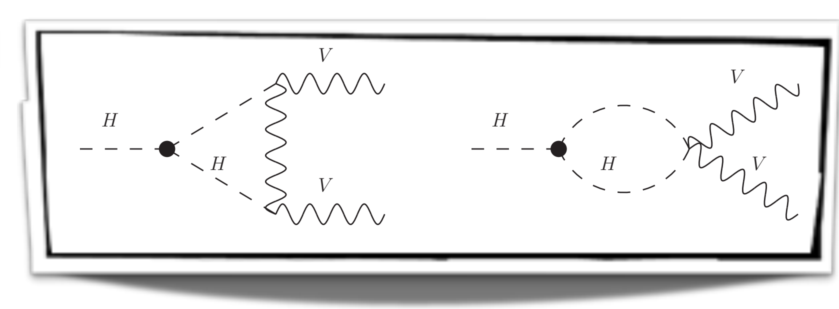
strong dependence from κ_t
assuming that NP affects only κ_λ (κ_t = 1) looks a strong assumption

leaving κ_t fully floating would probe parameter space regions already excluded by single Higgs measurements

Need to fit all together but:

1) κ_λ appears in single Higgs measurements at NLO-EWK (need to move to an NLO k-framework)





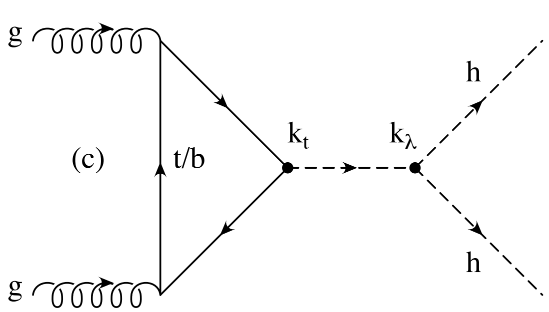
2) κ_t affects the ggF and ttH single-Higgs background to HH production (need to take it into account)

Toward an ATLAS/CMS combination (MC choice)

1) each collaboration has ~4 times more data on disk;
2) SM sensitivity still far, it makes sense to combine ATLAS/CMS at the end of RUN-2
3) we need to make uniform decision about MC signal model

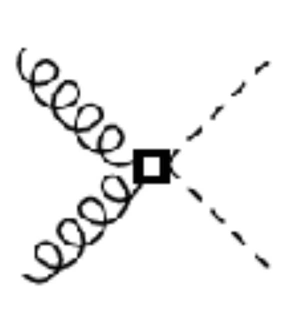
ATLAS

LO MC, finite m_t

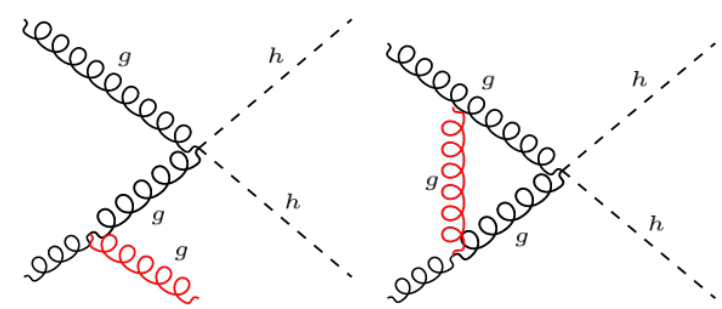


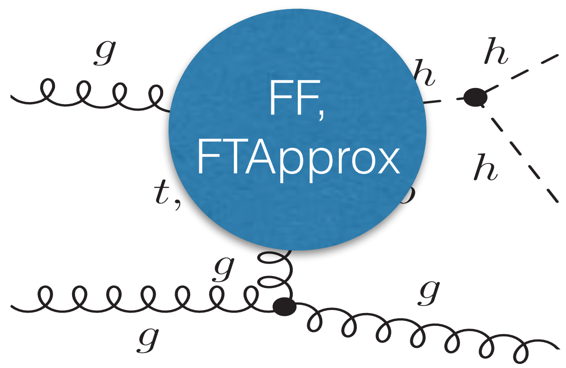
CMS

LO MC $m_t \rightarrow \infty$



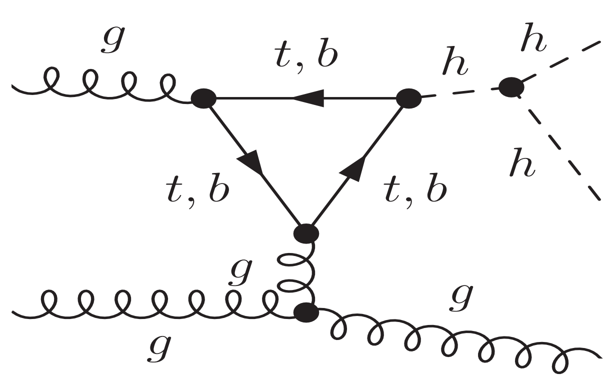
NLO MC $m_t \rightarrow \infty$





NLO MC FTApprox
including form factors to take into account finite m_t

now available:
Full NLO with finite m_t



to set as default for end of Run-2
validation on going in both Powheg and MG5_aMC@NLO
with Pythia8 and Herwig7 P.S.

Result interpretation in BSM models (from discussion minutes)

Simple models that could be included in searches:

1. S-channel resonances: spin-0, spin-2
2. higgsino→ hh+MET or higgsino→ hh+jets
3. X→Sh where one h is 125 GeV and S is NOT 125 GeV, also X→ V(W,Z)S where S is not 125 GeV

We should move away from graviton-RS models, which were firstly introduced to have sizable cross sections to be probed…

- on the other side, models where hh is a leading channel are difficult to find, unless tuned like the EWK singlet model; one could build up simplified models. Simplified models, like in DM searches, that gradually develops when analyses become more accurate

AGREEMENT TO SETUP A SIMPLIFIED MODEL AS REFERENCE

- details of the model still to be discussed
- in addition X→Sh, with $m_S > 2m_W$ is interesting for analyses looking at a WW final state

Result presentation for all models

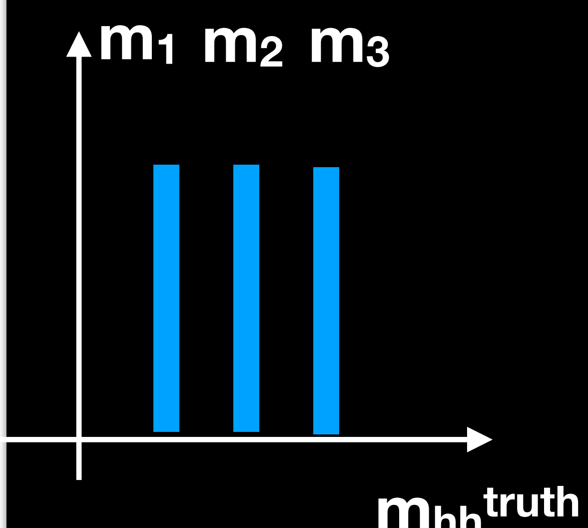
1) theoreticians ask to have the differential m_{hh} distribution in order to fit their preferred model

2) we cannot provide it, because (unless we discover something, and in that case we would be very happy to do it) we don't have any hh pair in our dataset, but only misidentified hh pairs

3) limits as a function of m_{hh}^{truth} would be misleading, because bin by bin correlation would not be taken into account (how to integrate a broad signal?)

The idea is to provide an mass interpolate likelihood

signal generated with flat m_{hh}, or a discrete set of masses



build one likelihood for each $m_{1,2,3...}$

$$\mathcal{L}(x_i, \theta_j, \mu, m_1) \quad \mathcal{L}(x_i, \theta_j, \mu, m_2) \quad \mathcal{L}(x_i, \theta_j, \mu, m_3)$$

Use RooMorph to interpolate the signal template $\mathcal{L}(x_i, \theta_j, \mu, m)$

The theoretician provides $\frac{dP}{dm}(m)$

We compute:

$$\int \mathcal{L}(x_i, \theta_j, \mu, m) \frac{dP}{dm} dm = \mathcal{L}_{int}(x_i, \theta_j, \mu)$$

compute CLs upper limit on cross section

Conclusions

1)interesting and fruitful workshop, many exchanges of ideas with CMS colleagues and theoriticians, will allow to improve analyses of both collaborations

2) starting to think to common MC signal, model interpretation, presentation of analysis results (it is just the start of a common effort through a hh combination)

3) starting to setup common reference cross sections and uncertainties

4) white/paper as an outcome of the workshop, to be reviewed inside the Higgs XS WG, with all the workshop outcomes and agreed procedures (open to new contributions from Higgs XS WG)

5) we are already setting interesting constraint on κ_λ, but we still need to improve sensitivity beyond simple luminosity scaling (new ideas and new channels are mandatory)

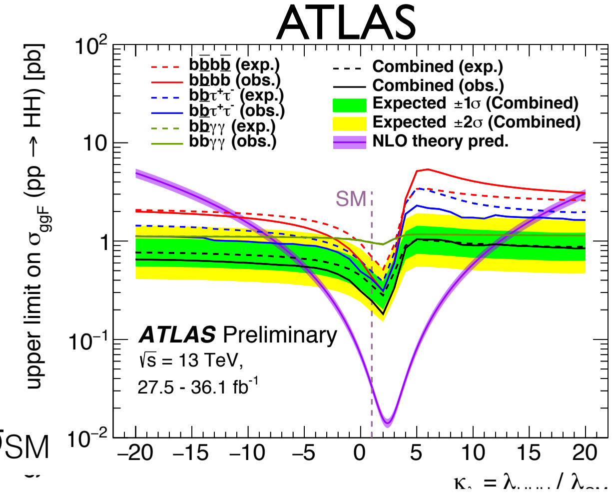
backup

4b results

Data-driven background estimates : bump-hunt, anti-tag reweighting, hemisphere mixing
With more data, **systematics uncertainties** related to the data-driven backgrounds will become more dominant
Can we get a better simulation for this?

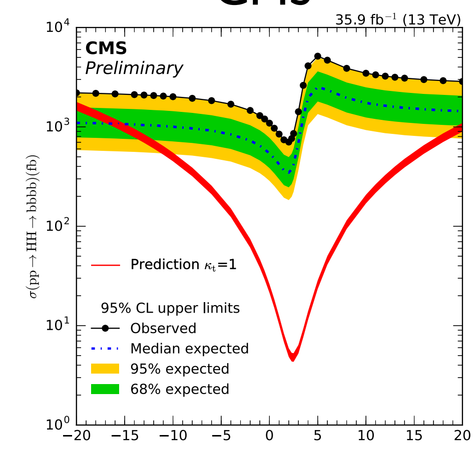
Non-resonant Results (Jana Schaarschmidt, Andres Tiko)

ATLAS



Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

CMS

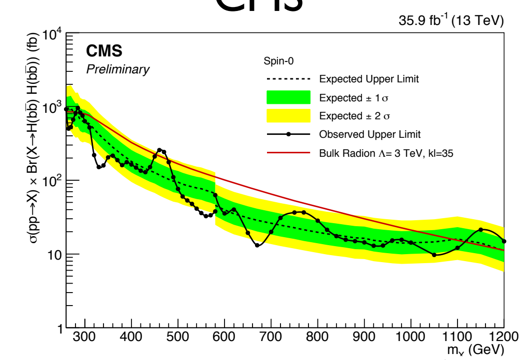


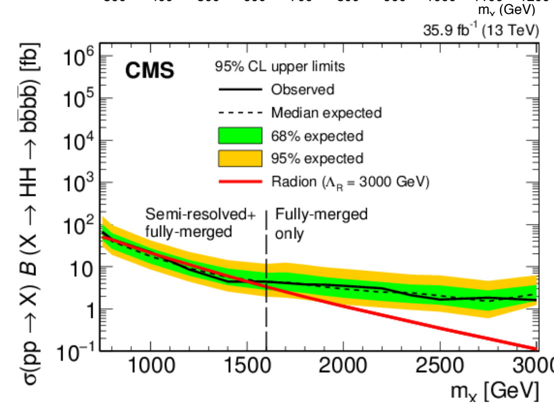
Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
74.5	19.5	26.2	36.9	52.9	73.4

ATLAS sensitivity ~2× than CMS analysis

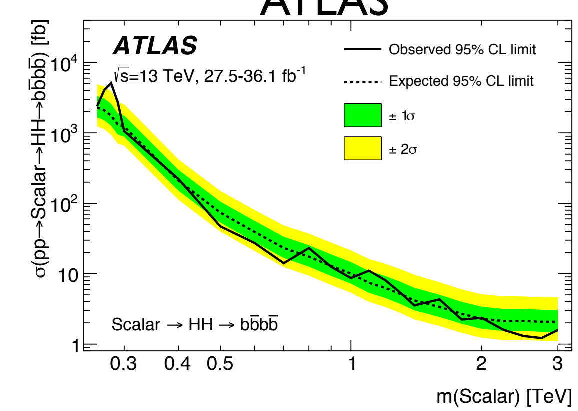
Resonant Results (Jana Schaarschmidt, Andres Tiko)

CMS





ATLAS



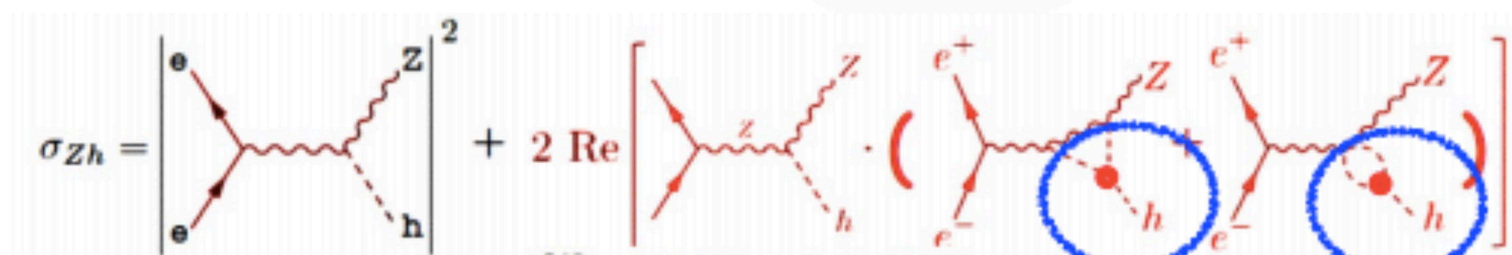
Resonant results are broadly comparable

Future colliders expectations 1/2

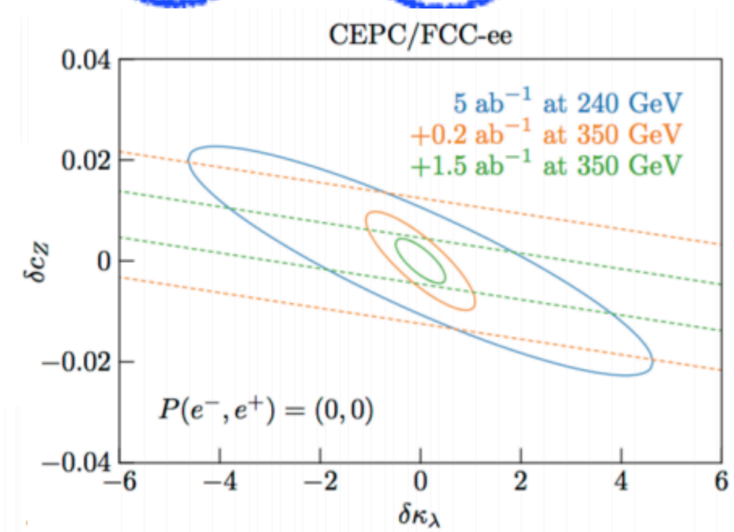
FCC/ee

A. Canepa

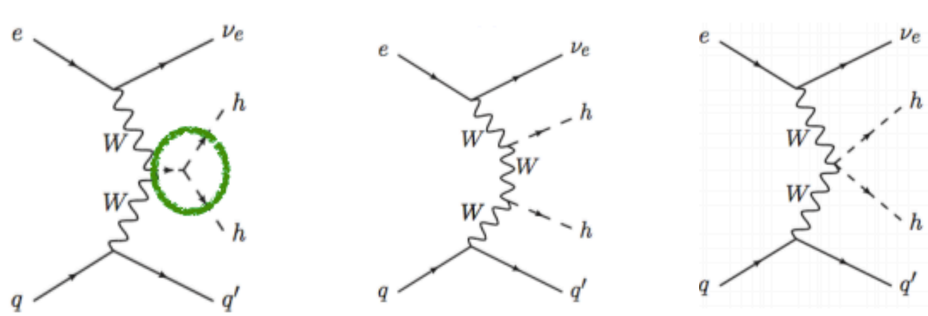
- At FCC-ee, Higgs trilinear indirectly constrained through loop corrections to σ(H+Z)

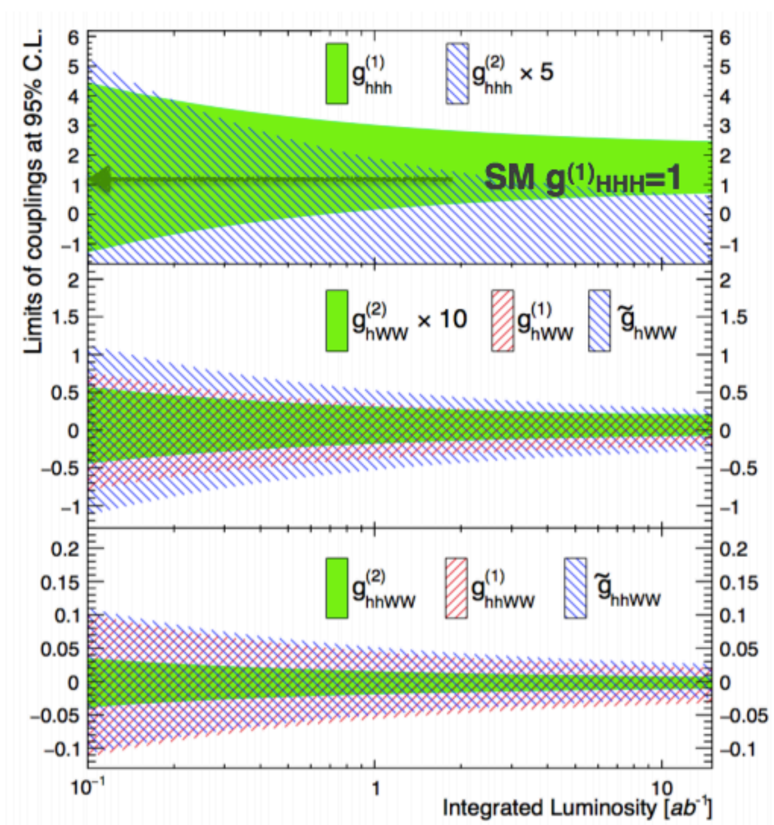


- Testing possible only thanks to excellent precision on the ZH cross-section measurement
- ~40% precision on trilinear coupling from global fit and combination of 240 and 350 GeV datasets



FCC/eh





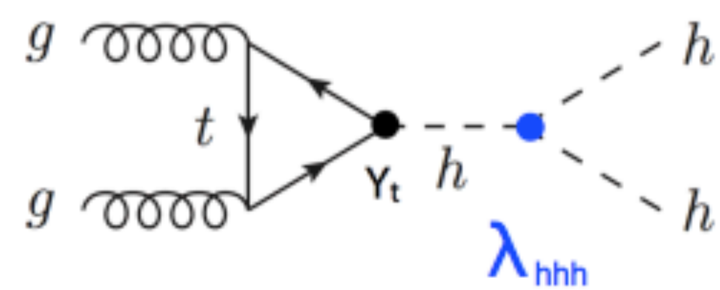
- Precision on the trilinear coupling is determined for two electron energy hypotheses, 60 and 120 GeV:

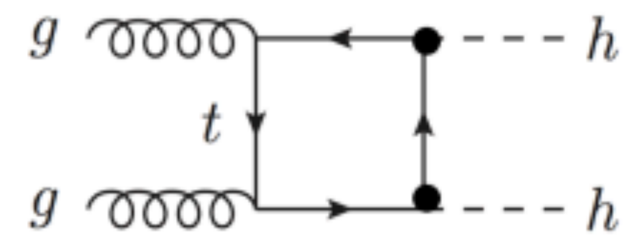
$$g^{(1)}_{hhh} = 1.00^{+0.24(0.14)}_{-0.17(0.12)}$$

10 ab^{-1} $\sqrt{s}$ =3.5 (5.0) TeV

Future colliders expectations 2/2

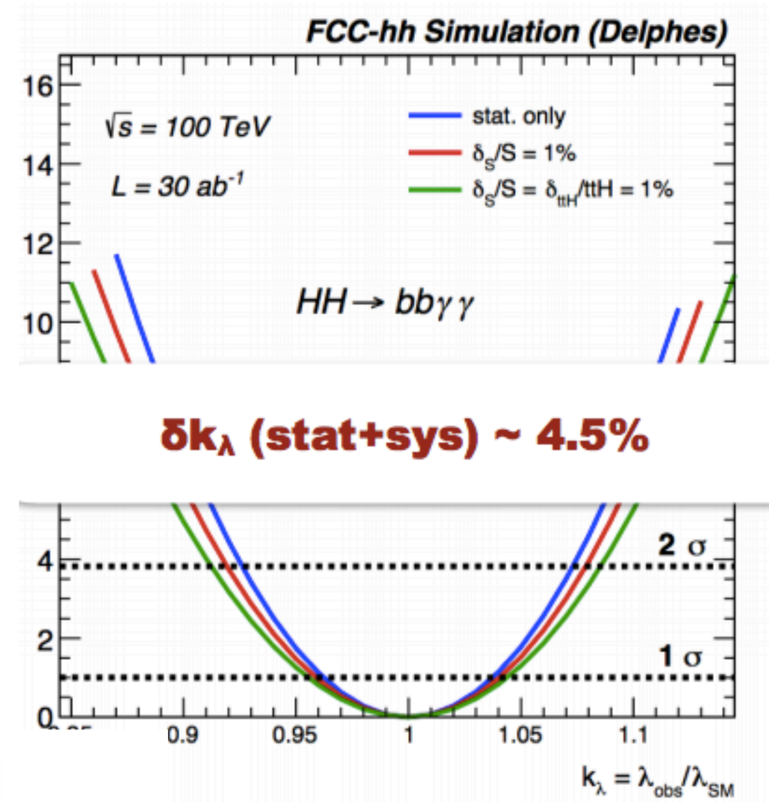
FCC/hh





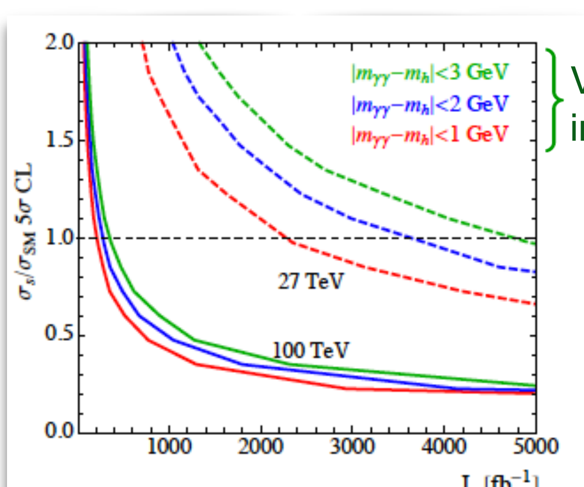
A. Canepa

With a cross-section ~ 30x HL-LHC and 7x larger dataset, FCC-hh unique opportunity complete the exploration of the SM Higgs sector **~5% uncertainty on κ_λ**



δk$_\lambda$ (stat+sys) ~ 4.5%

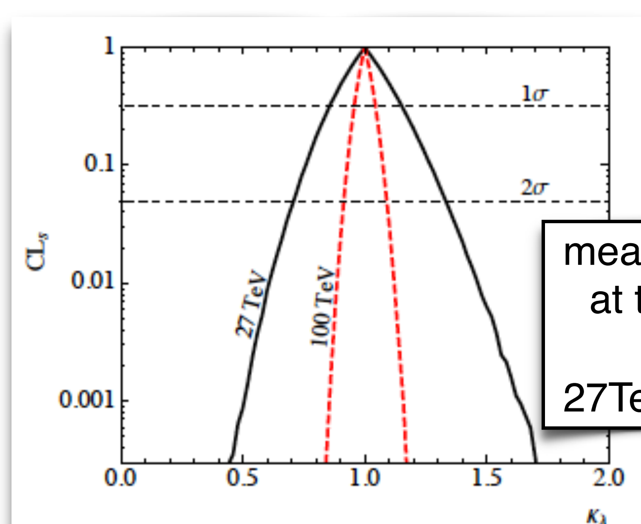
HE-LHC (27 TeV, 15 ab^{-1})



Very large impact

Resolution used for this study:

$|m_{bb} - m_h| < 25$ GeV,

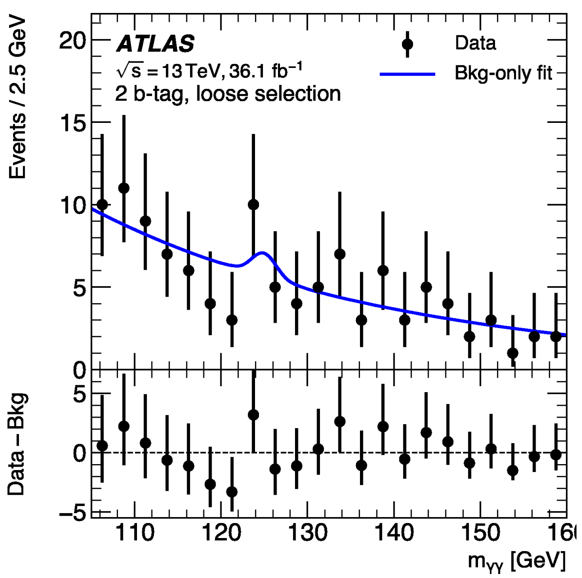


measurement at the 30% level 27TeV, 15ab^{-1}

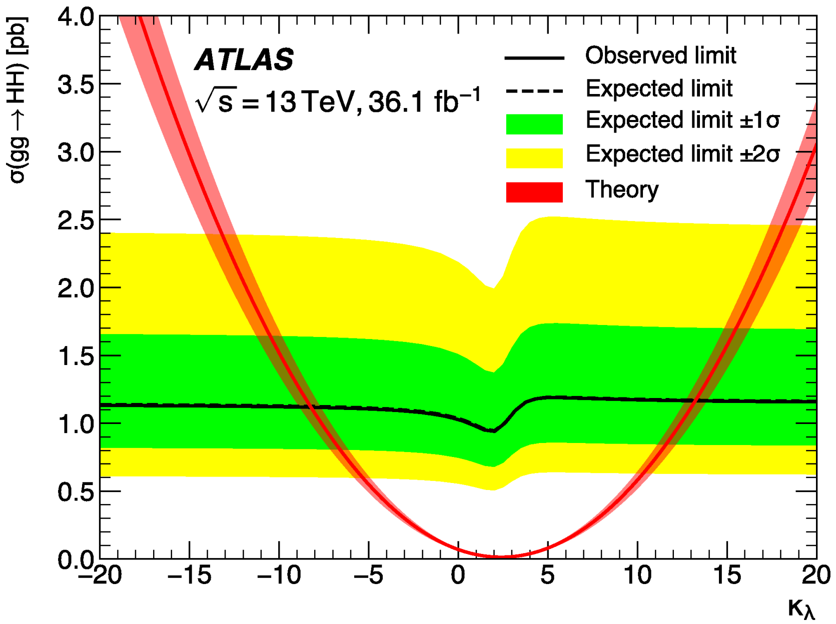
γγbb non resonant

ATLAS

- Fit $m_{\gamma\gamma}$: resonant signal on top of continuum background
- SM γγ+jets: MC re-weighted to data (shape + normalization) in 0-tag CR.
- Jets faking photons from fully data-driven 2x2D method



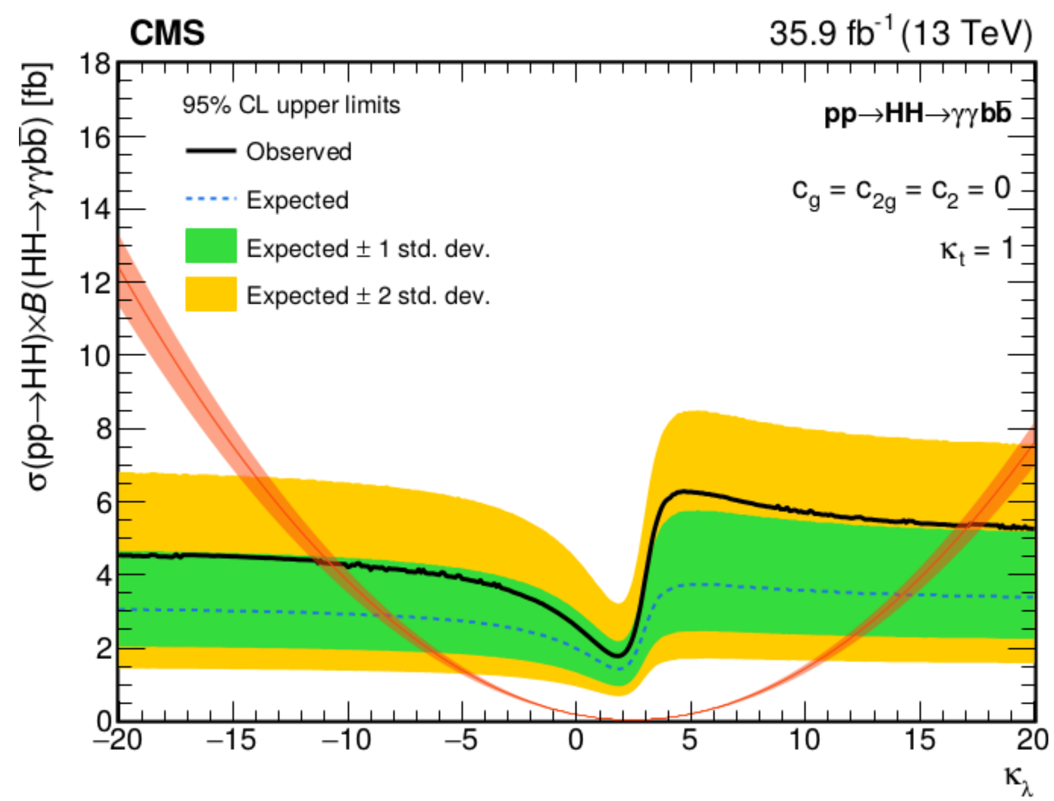
most sensitive to κλ



follow up

CMS

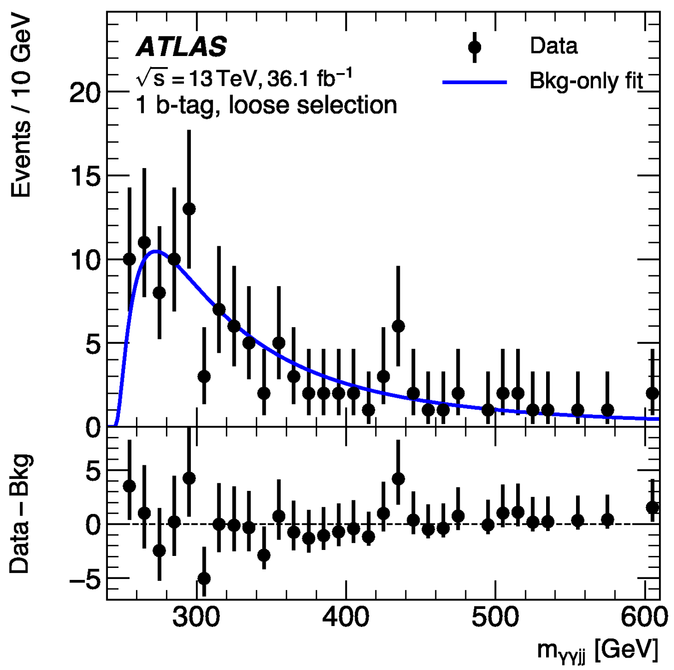
- Tight object selection to reduce background from fakes:
  - Photon selection similar to H(γγ), regression for b-jets to improve m_{bb} resolution
- **MVA classification** using kinematic variables:
  - Resonant/nonResonant, low/High mass optimized separately
- **2D fit** to $\mathbf{m_{\gamma\gamma}}$ and $\mathbf{m_{bb}}$ to derive limits

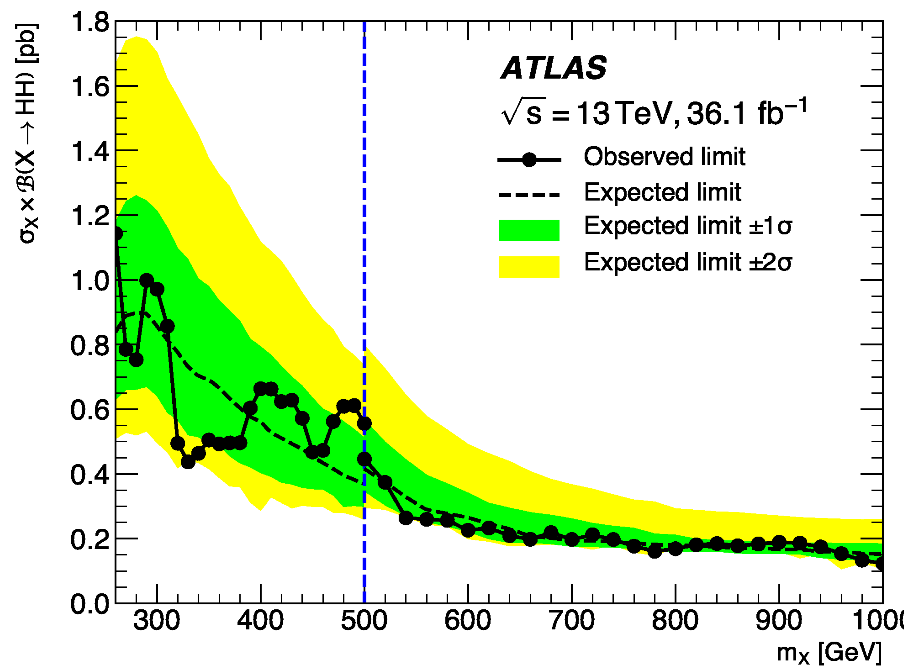


γγbb resonant

Fit $m_{\gamma\gamma jj}$ constructed after scaling jj 4-vector to have $m_{jj} = m_H$

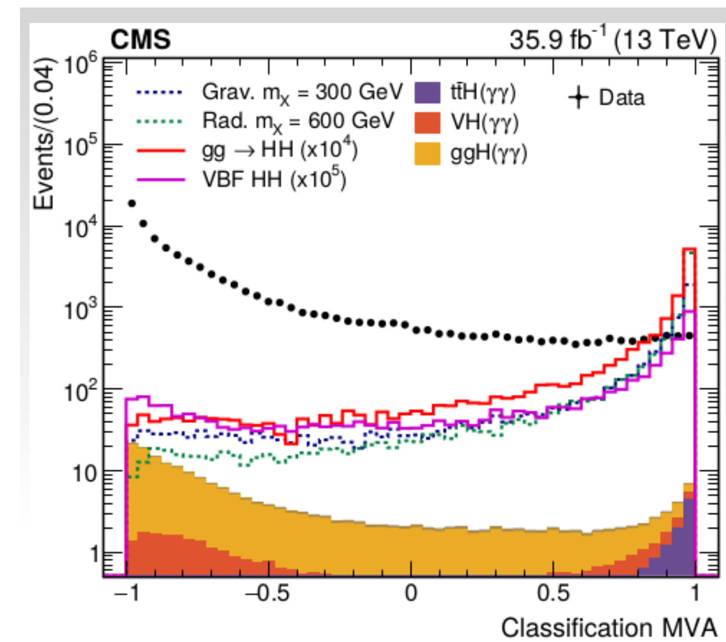
Interference between BSM HH and SM HH considered to be negligible and **ignored**



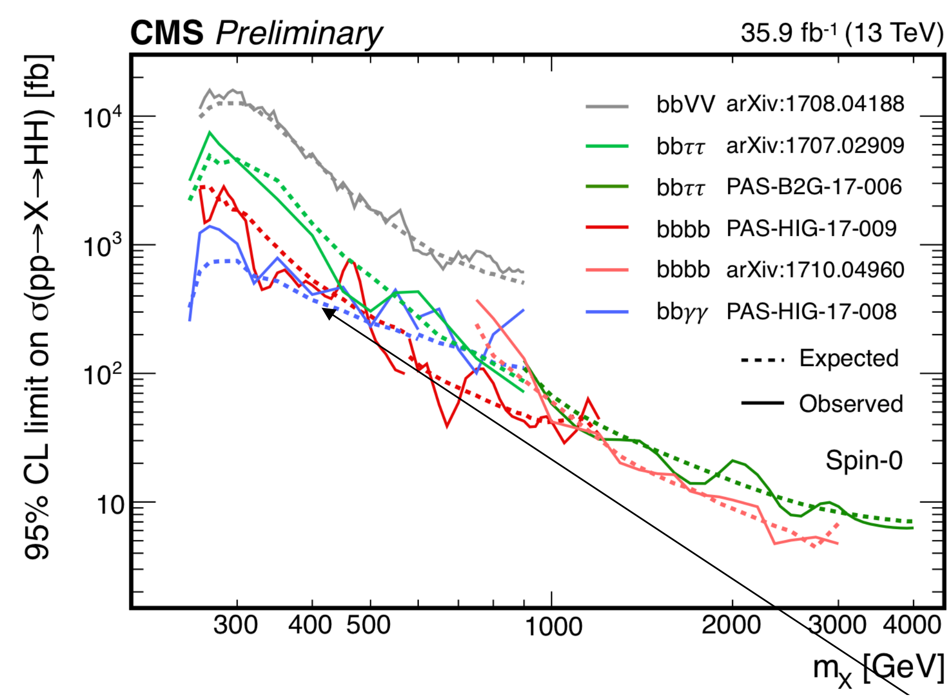


CMS resonant

MVA based analysis



- **More general approach**:
  - For this channel, **relax the mass window on bb pair** (~60-250 GeV) to test exotic models (X→h(125)Y) could be doable without huge effort
    - ML approach for bump hunting could help
  - Better integration with **single Higgs** measurements and wider interpretations
- Improvements on **b-jet reconstruction** are foreseen
- **Updates on projections** will come soon:
  - Photon resolution to be treated carefully in these estimates

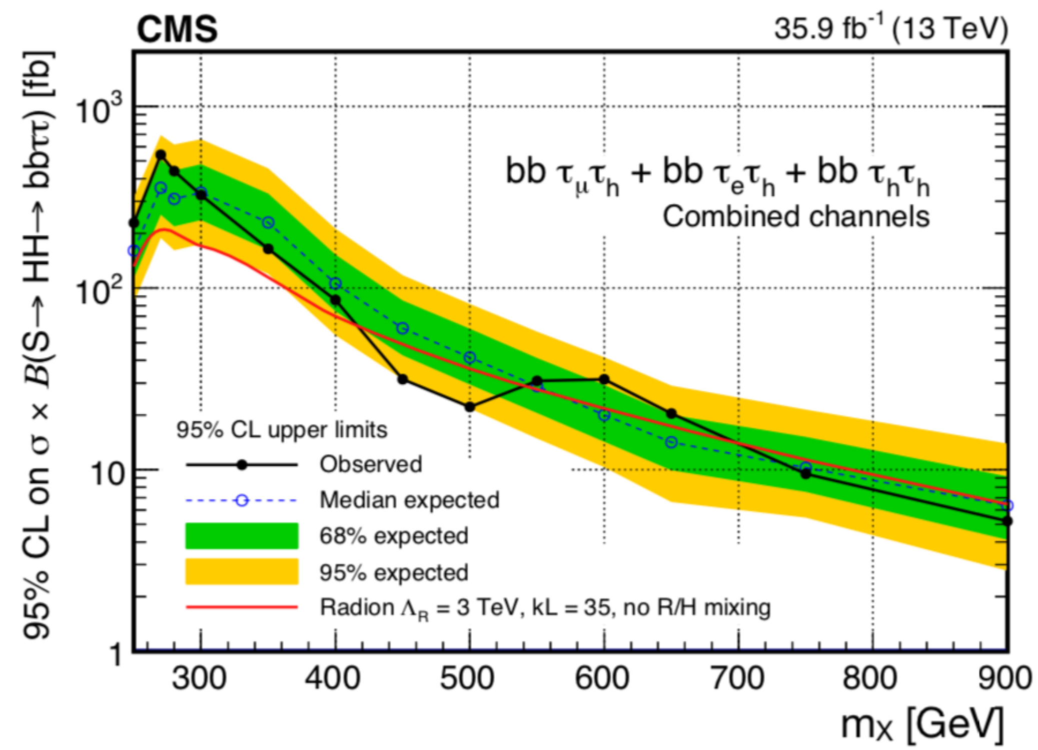


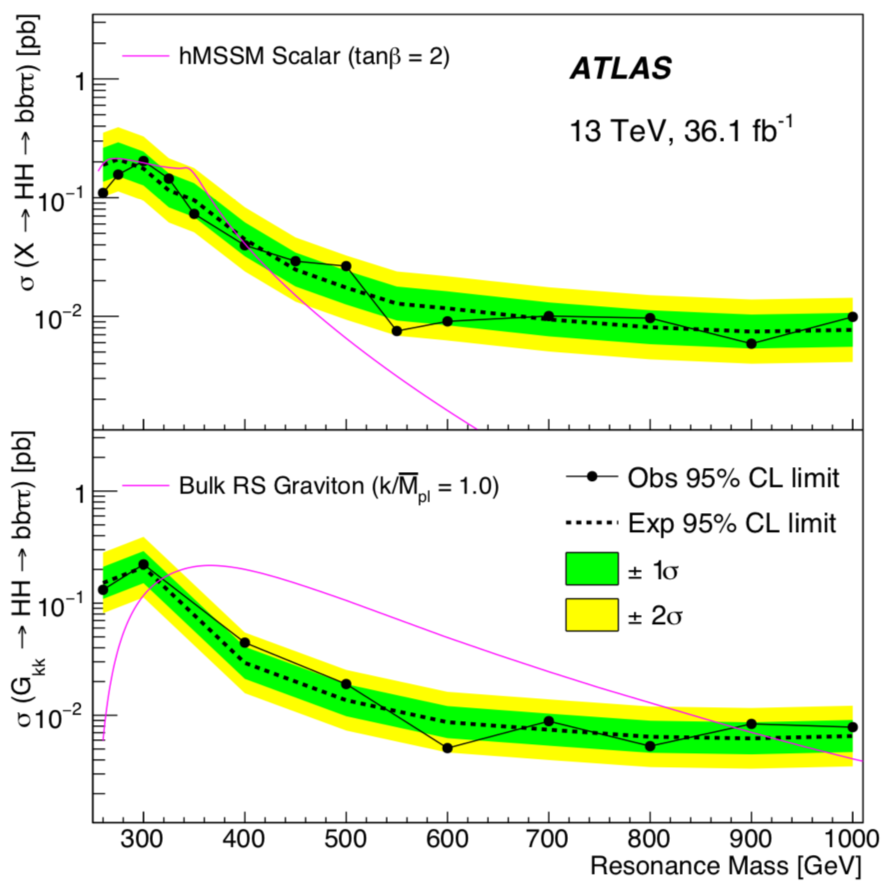
bbττ

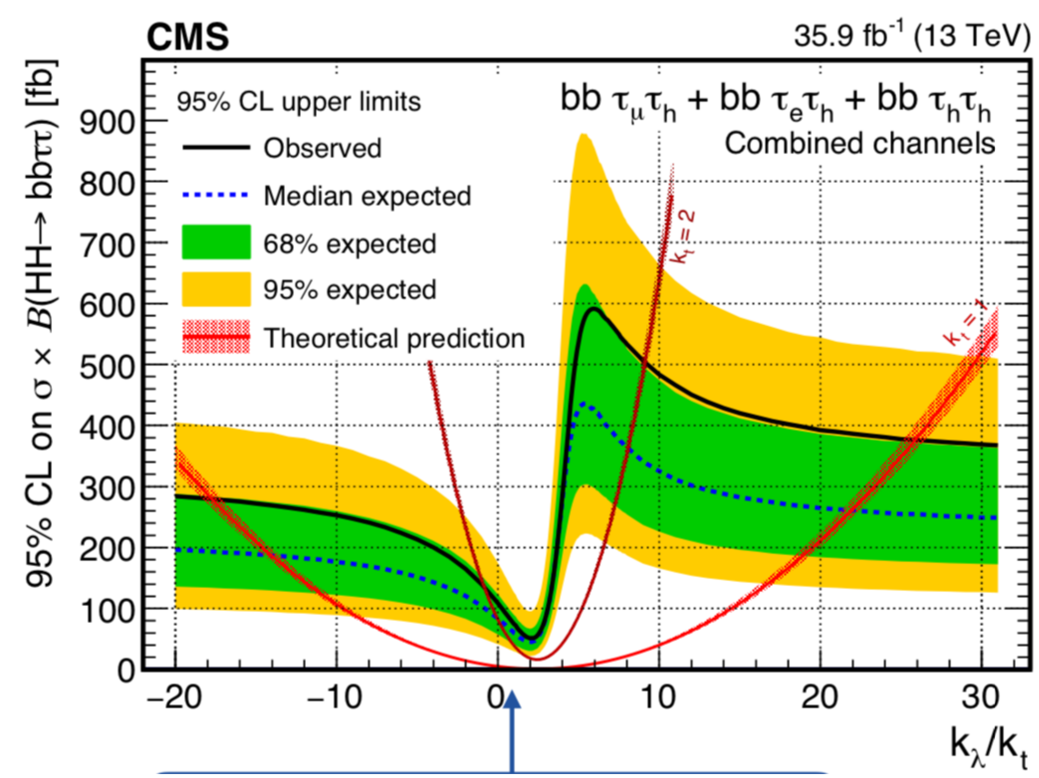
Results

σ/σSM

	Expected	Observed
ATLAS	14.8	12.7
CMS	25	30







bbττ

Analysis Strategies

CMS uses also **boosted** events (and semi-resolved events) to improve sensitivity (for non-resonant too)

1 b-tag category adds 10% to sensitivity in CMS.

Multivariate techniques help but require attention:

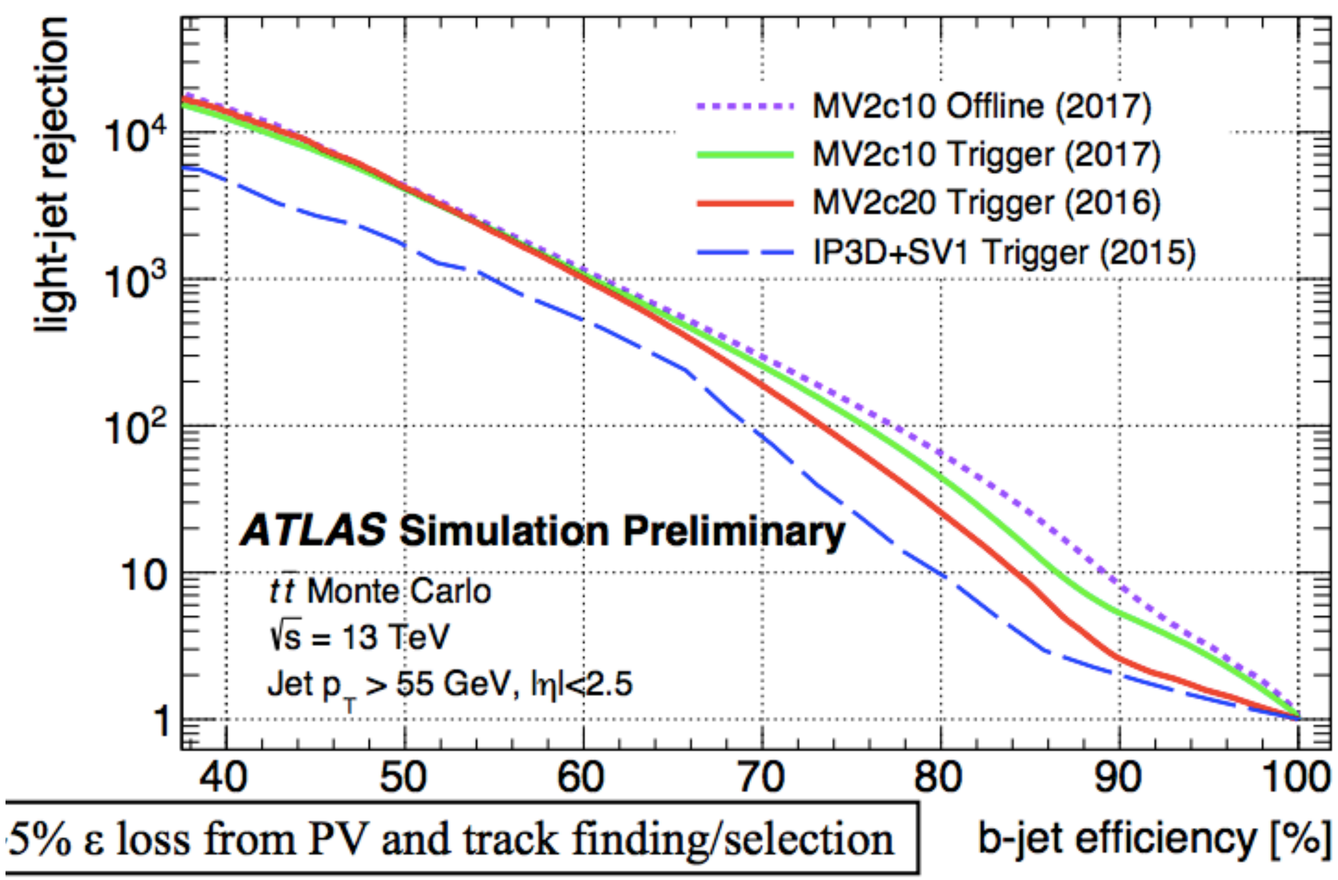
- How can we be sure that backgrounds are well modelled in high BDT region.
- Training lots of different BDTs for different scenarios is computational expensive.
- Parameterized NN's should be investigated by both experiments.
- Re-weighting BDT inputs is possible means you need to validate everything again (more work), and leads to more fluctuations.
- Interesting to open up the BDTs to see what cuts are being applied.

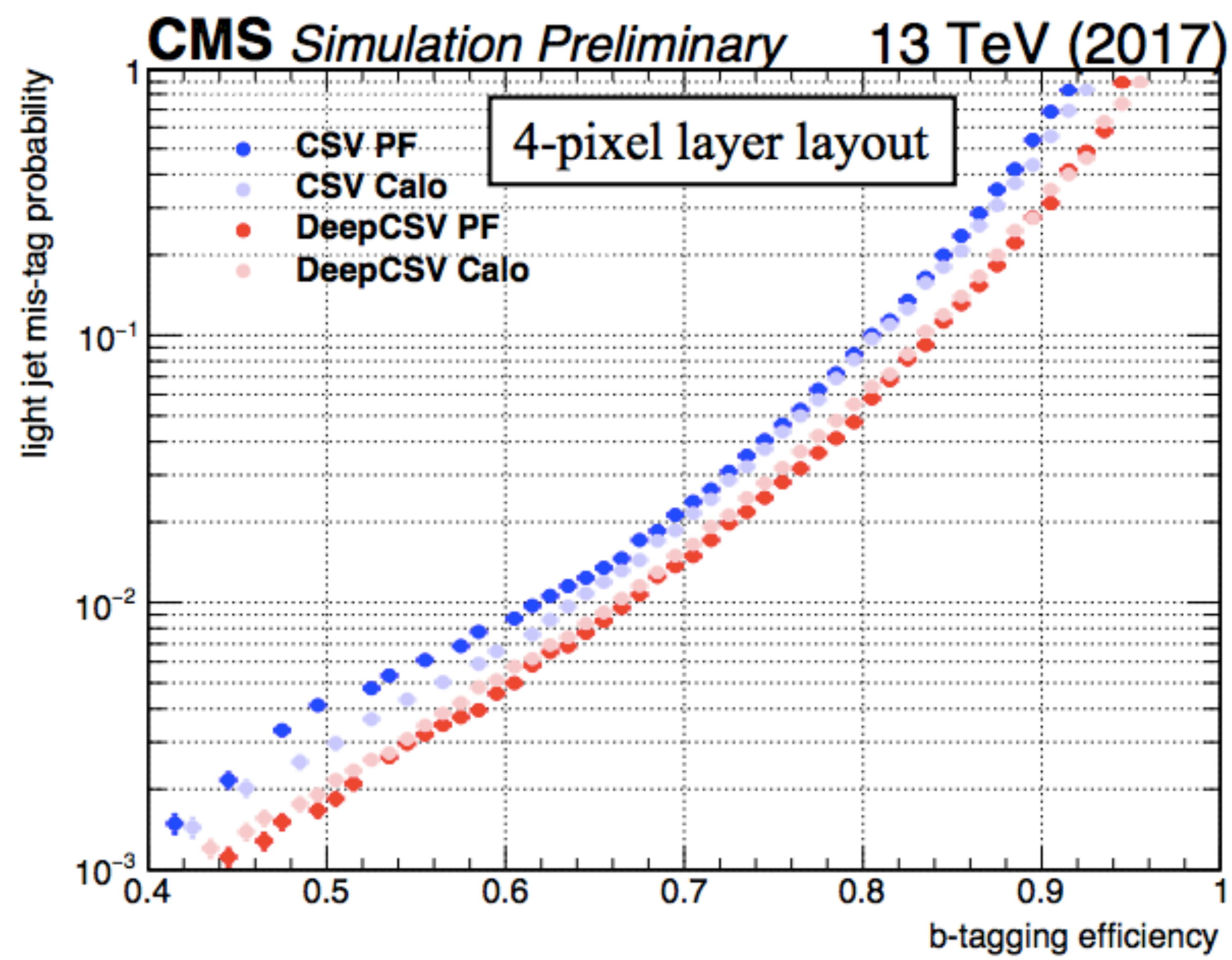
Both experiments confirm each others results when comparing cut-based and MVA analyses.

Using multivariate discriminants as final fitted value give optimal analysis sensitivity.

4b channel, trigger performance

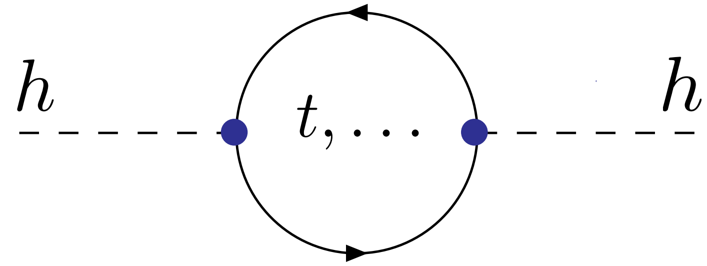
Main issue: b-jet triggers, ATLAS 2 b-jet trigger allows low uncertainty QCD estimation
CMS 3 b-jet trigger, it needs hemisphere decomposition at low m_{HH} for non resonant

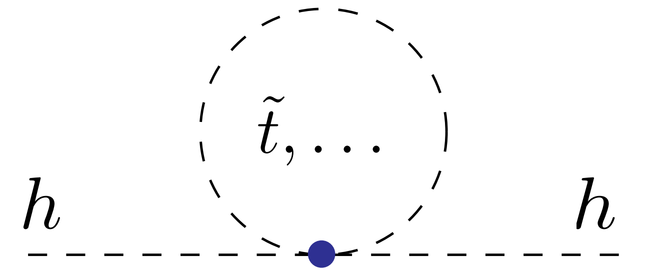




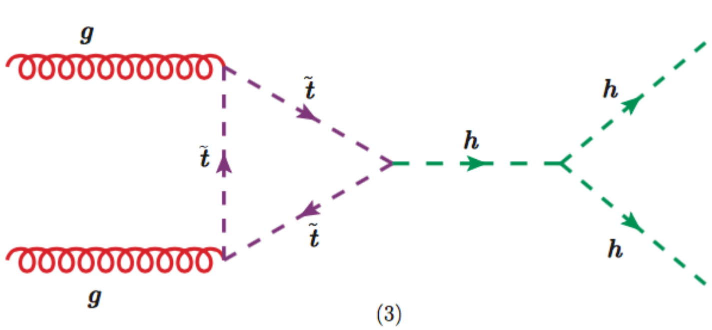
Possible model implementation

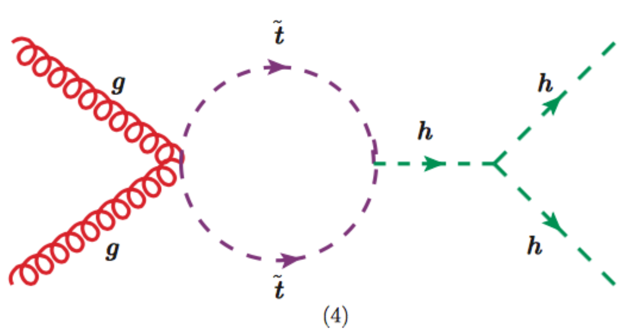
e.g., stops in SUSY stabilize Higgs mass

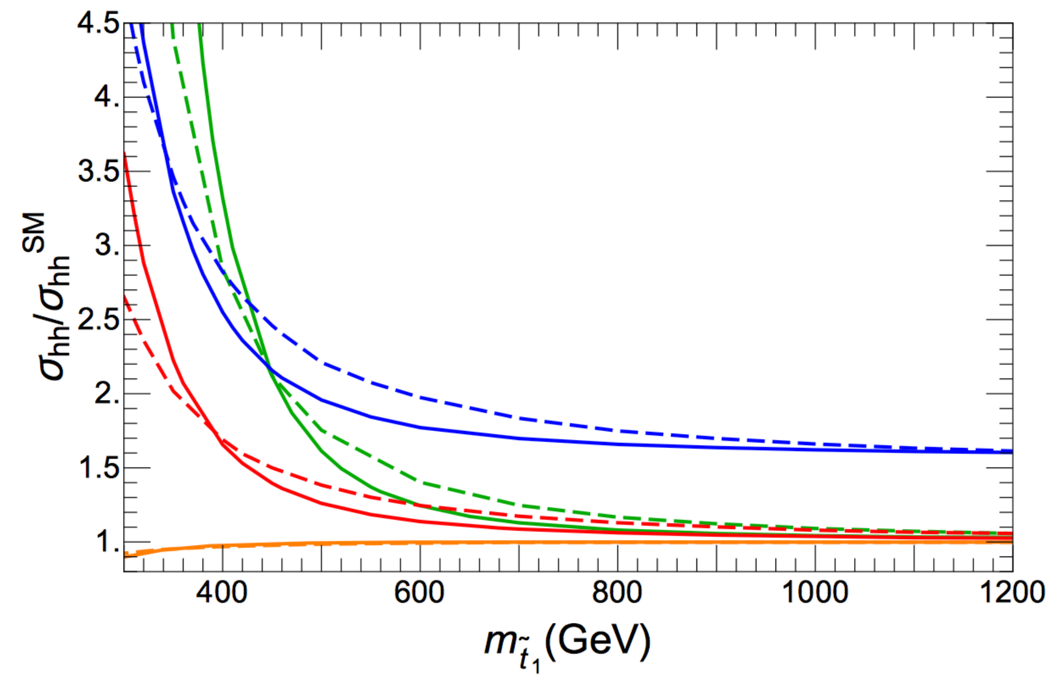




Stops are colored, couple strongly to Higgs, and thus can provide an important contribution to Higgs pair production

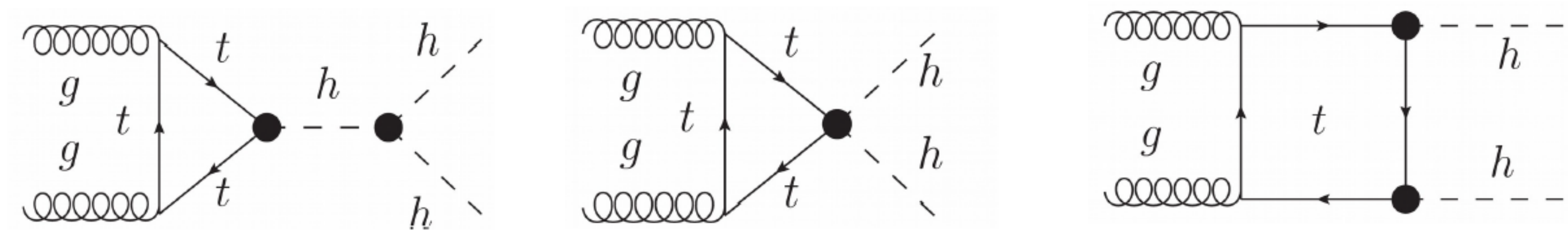




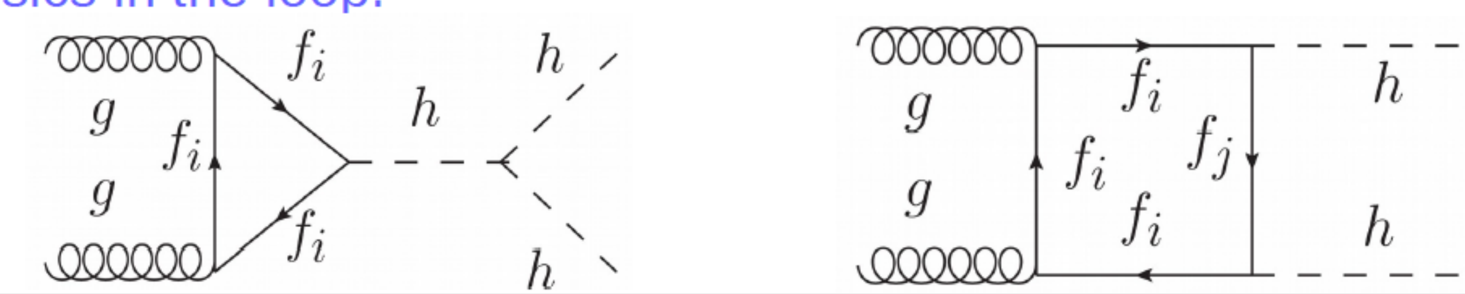


BSM enhanced hh production

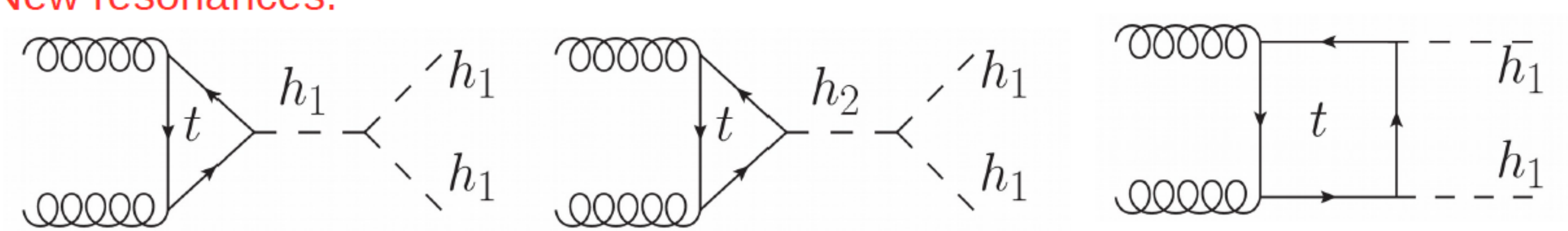
- Couplings different from the SM+EFT



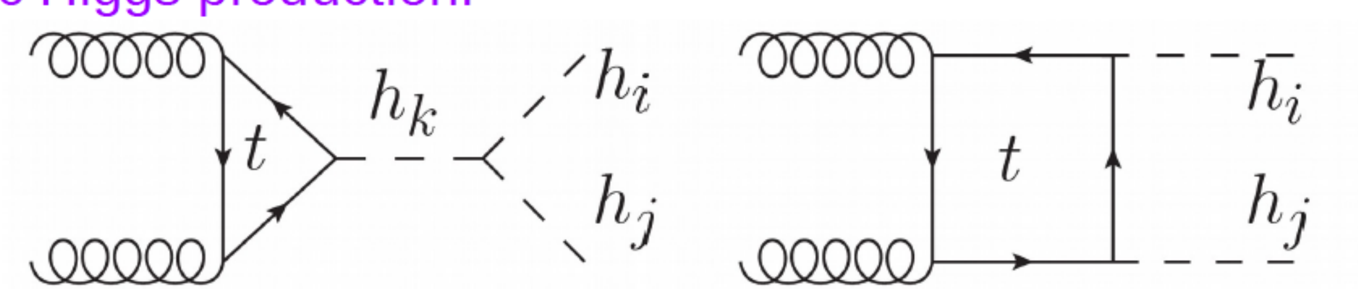
- New physics in the loop.



- New resonances.



- Double exotic Higgs production.



Sept. 6, 2018

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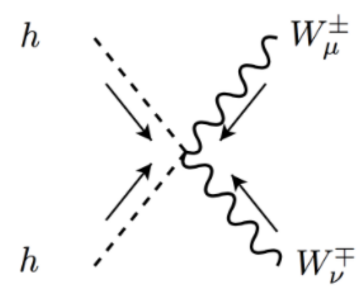
VBF di-Higgs production

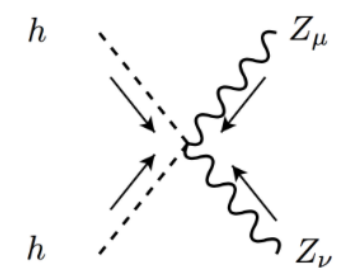
In my view, one class of couplings that has not received enough attention is the HHVV coupling:

Talk by Ian Low

$$D_\mu H^\dagger D^\mu H \;\supset\; g^2 h^2 V_\mu V^\mu$$

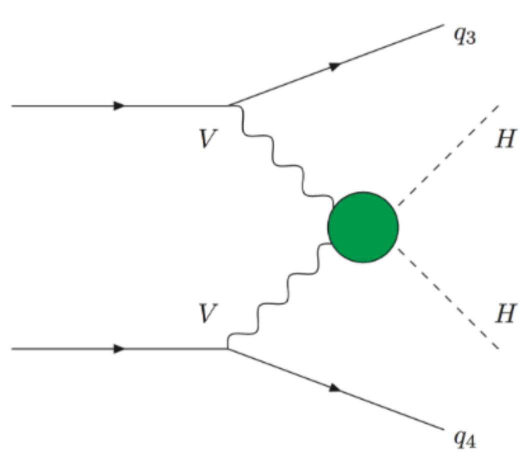


$$\frac{i}{2} g^2 g_{\mu\nu}$$



$$\frac{i}{2} \frac{g^2}{\cos^2\theta_W} g_{\mu\nu}$$

This coupling can be probed by double Higgs production in the VBF channel!



- Simultaneous measurements of HVV, HHVV and TGCs provide a unique window into the pNGB nature of the 125 GeV Higgs.

Expected deviation on κ_λ from NP

B. Batell (theory summary talk)

How well do we need to measure the self-coupling?

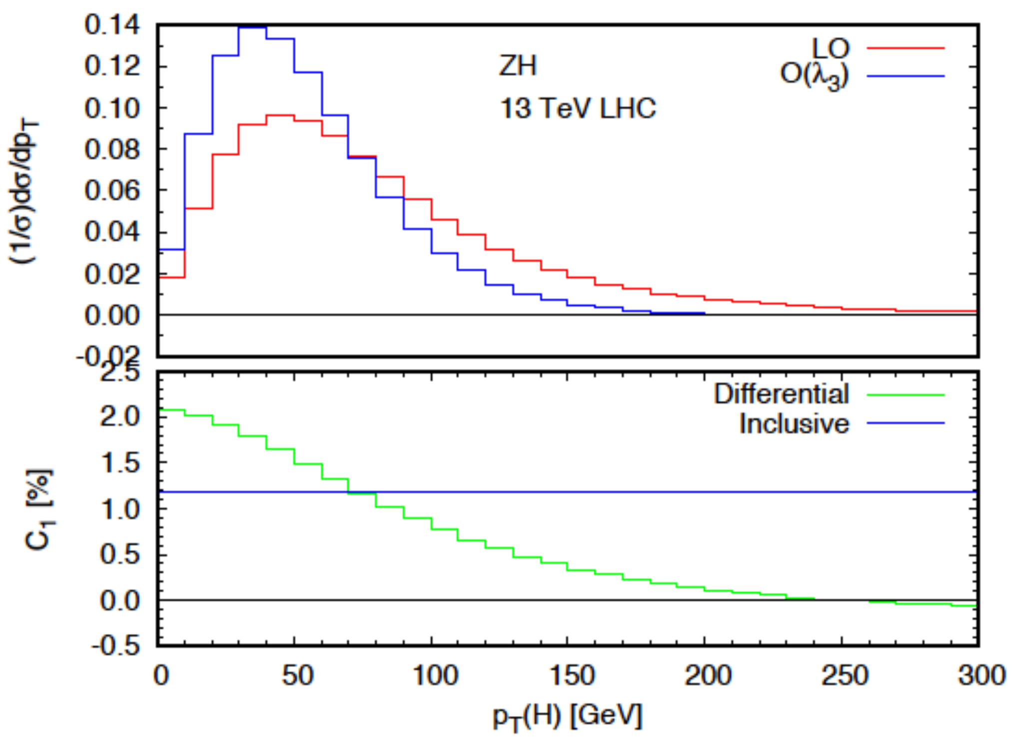
- Answer 1: As precisely as we can!
- Answer 2: If no new state associated with EWSB is found a the LHC, then one can potentially still expect deviations on the order of 20%

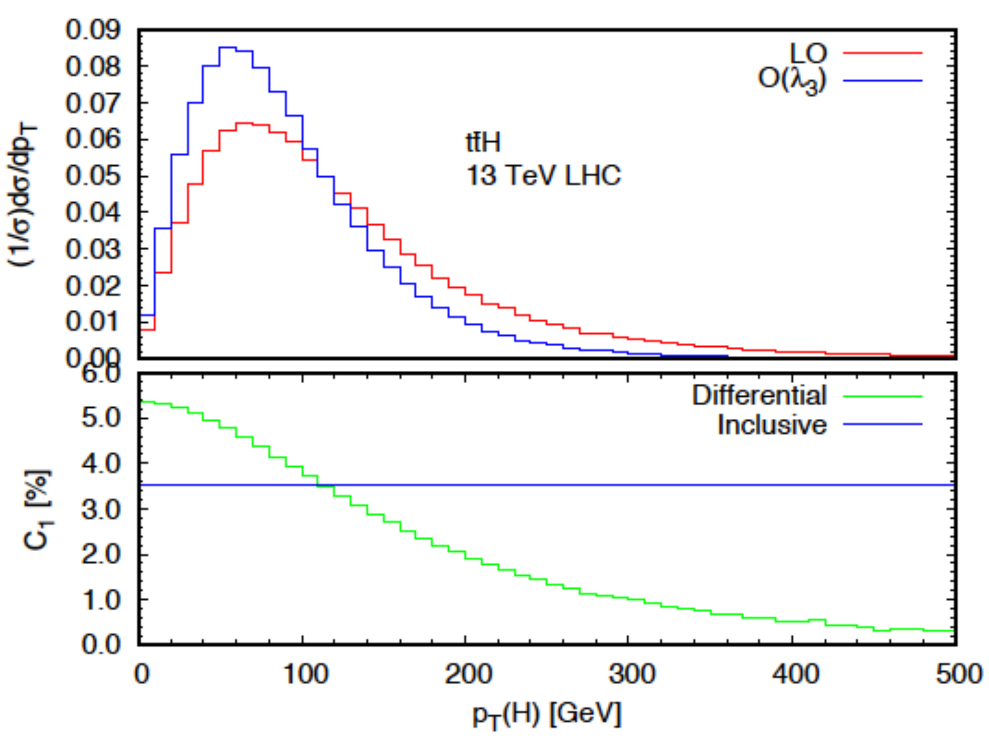
Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$
LHC 3 ab^{-1} [36]	$[-20\,\%, +30\,\%]$

[Gupta, Rzehak, Wells]

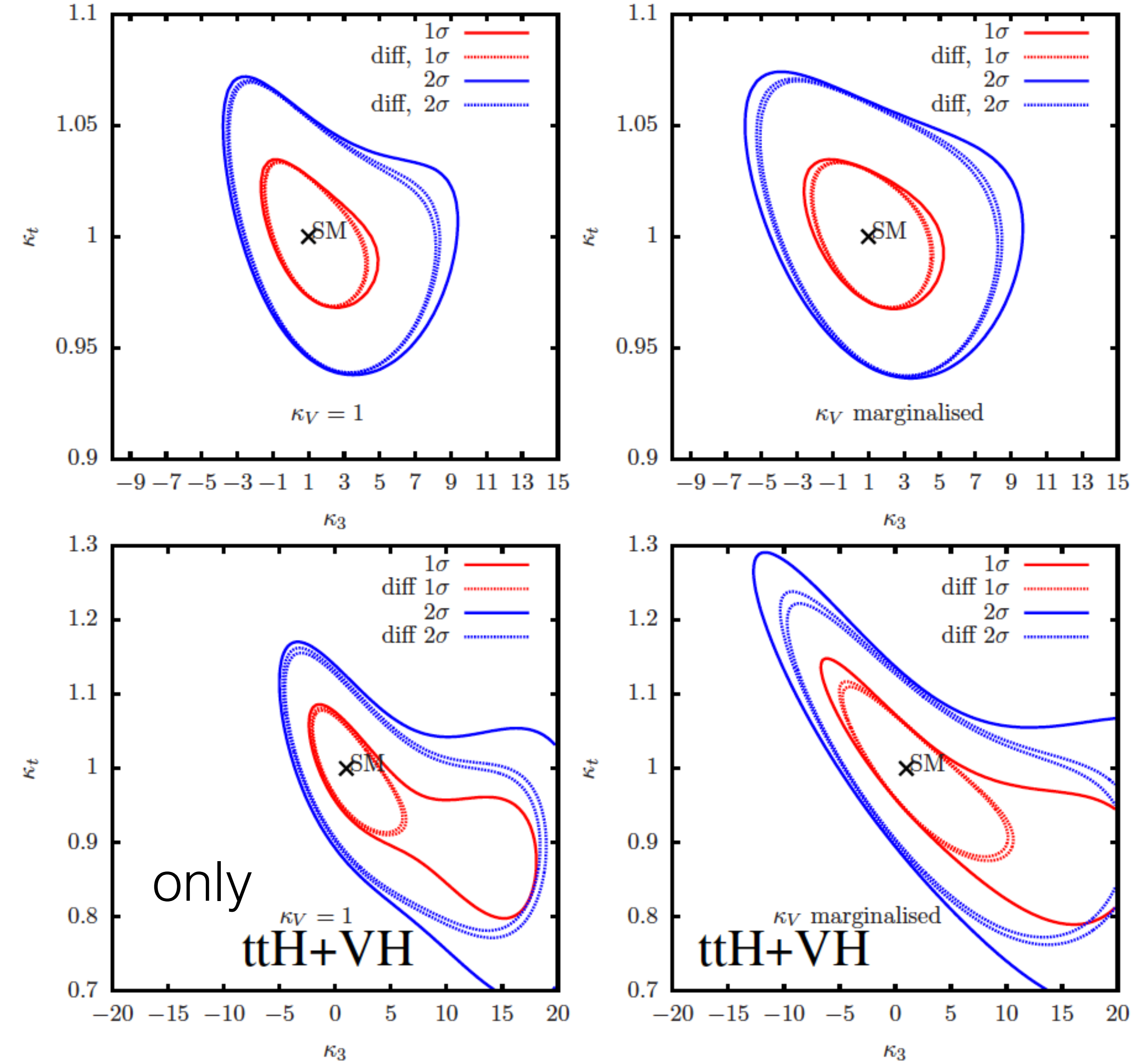
If we find large deviations on κ_λ from 1, they would be associated to NP show up at LHC

VH, ttH κλ impact on differential observables





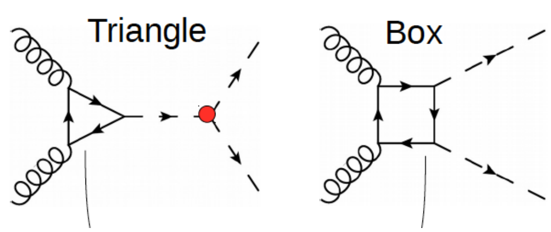
all modes



1) differential informations can be used to probe κλ
2) κλ impact on single-Higgs bkg acceptance needs to be taken into account (need NLO-EWK generators)

Toward an ATLAS/CMS combination (total cross section)

- **Leading Order: loop-induced**
  Eboli, Marques, Novaes, Natale 87; Glover, Van Der Bij 88, Dicus, Kao, Willenbrock 88; Plehn, Spira, Zerwas 96



- **Next-to-Leading Order approximations**
  - NLO in the Born-improved heavy m_t limit (HTL) **+90%**
    Dawson, Dittmaier, Spira 98
  - FTapprox: full m_t dependence in real radiation **-10%**
    Maltoni, Vryonidou, Zaro 14
  - $1/m_t$ expansion in virtual corrections **±10%**
    Grigo, Hoff, Melnikov, Steinhauser 13; Grigo, Hoff, Steinhauser 15

- **Full NLO corrections** **-15% w.r.t. B-i NLO**
  Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 16; Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke 16
  - Two-loop corrections computed numerically using sector decomposition
  - Grid+interpolation for fast numerical evaluation

  New independent calculation, see Julien Baglio's talk

- **More results including full NLO m_t dependence**
  - NLO matched to parton shower using MC@NLO and POWHEG frameworks → Sherpa (Jones, Kuttimalai 17), Pythia (Heinrich, Jones, Kerner, Luisoni, Vryonidou 17)
    Dedicated talk by Eleni Vryonidou
  - NLL transverse momentum resummation → reasonable agreement with NLO+PS
    Ferrera, Pires 16
  - **NEW!** Full NLO including BSM dimension 6 operators
    Buchalla, Capozi, Celis, Heinrich, Scyboz 18
  - **NEW!** NLL threshold resummation with full m_t dependence **+4% w.r.t. NLO**
    de Florian, JM 18

- **Beyond NLO**
  - Born improved HTL at NNLO **+20% w.r.t. NLO**
    de Florian, JM 13; Grigo, Melnikov, Steinhauser 14
  - NNLL threshold resummation in the HTL
    Shao, Li, Li, Wang 13; de Florian, JM 15
  - NNLO including finite m_t effects (FTapprox) **+12% w.r.t. NLO** ← Current HXSWG recommendation for total XS (8% smaller than YR4)
    Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, JM 18
  - **NEW!** NNLL+NNLO threshold resummation in the FTapprox
    de Florian, JM 18

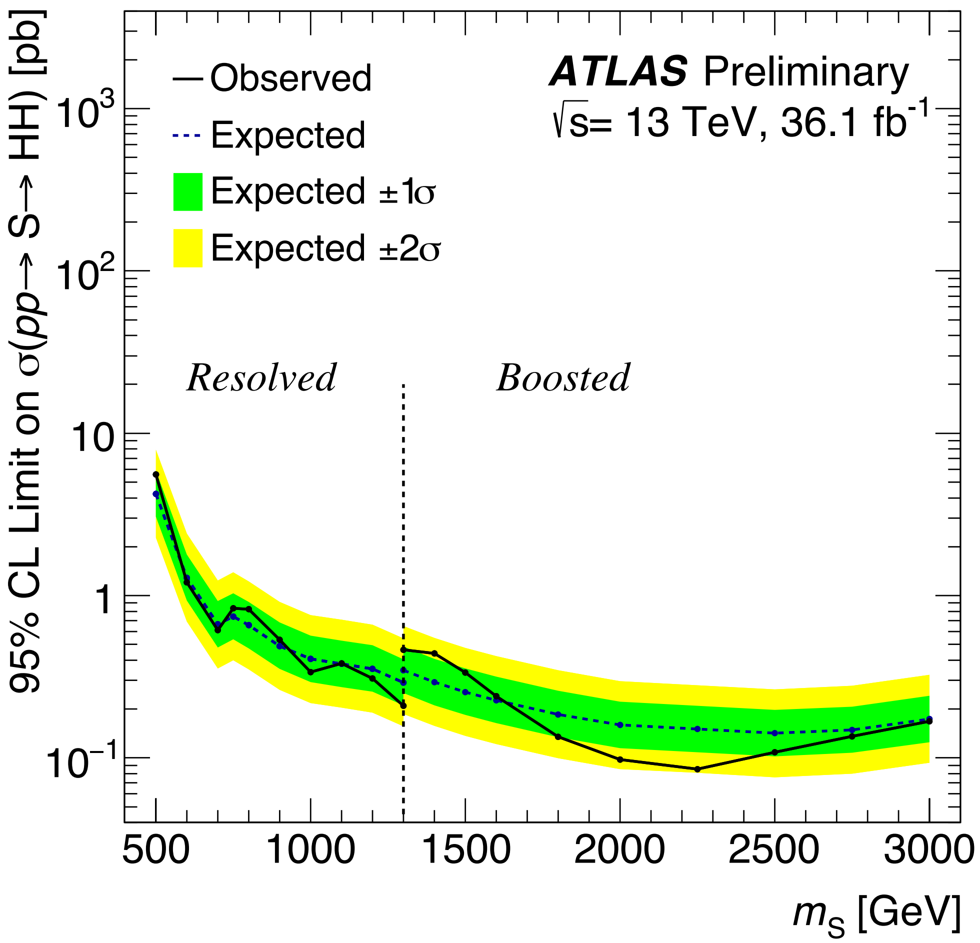
26 in

our present estimate

1. move to the new reference when full uncertainty will be available;
2. use the same accuracy for κ_λ dependent reference cross section (at the moment scaling NNLO SM with κ_λ dependent correction factors at LO)

WWbb results

ATLAS new, 1 lepton channel



Non-resonant production

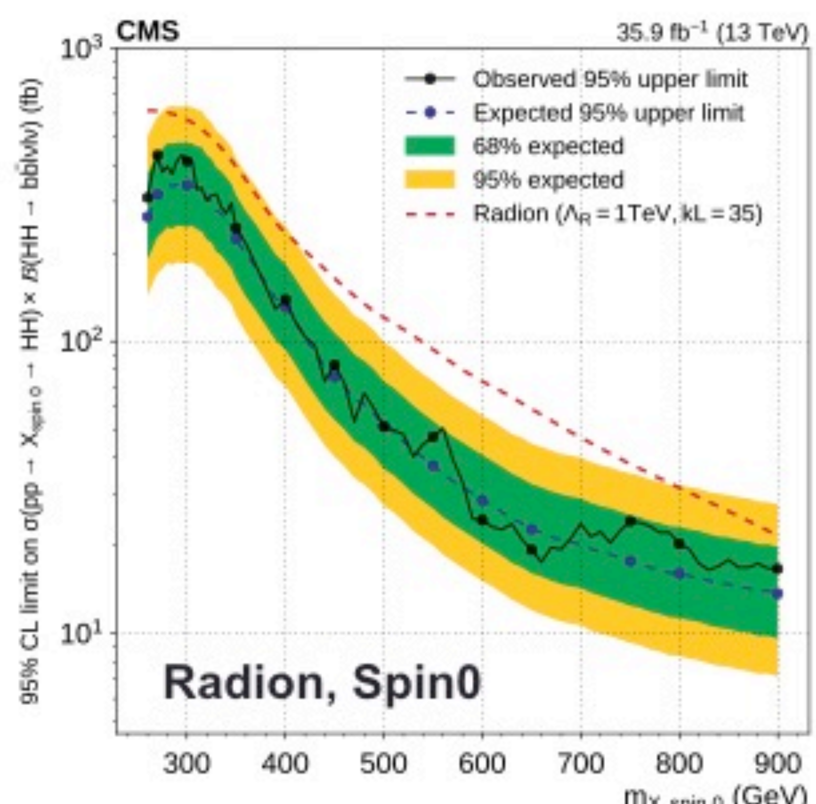
$$\sigma(pp \to HH) < 10 \left(10^{+4.1}_{-2.8}\right) \text{ pb at } 95\% \quad \text{CL}$$

- Current non-resonant di-Higgs production limit is ~300 x σ_{SM}

CMS 2 leptons

95% C.L. upper limit on signal strength σ/σ_{SM} : Observed = 79 and Expected $= 89^{+46}_{-28}$

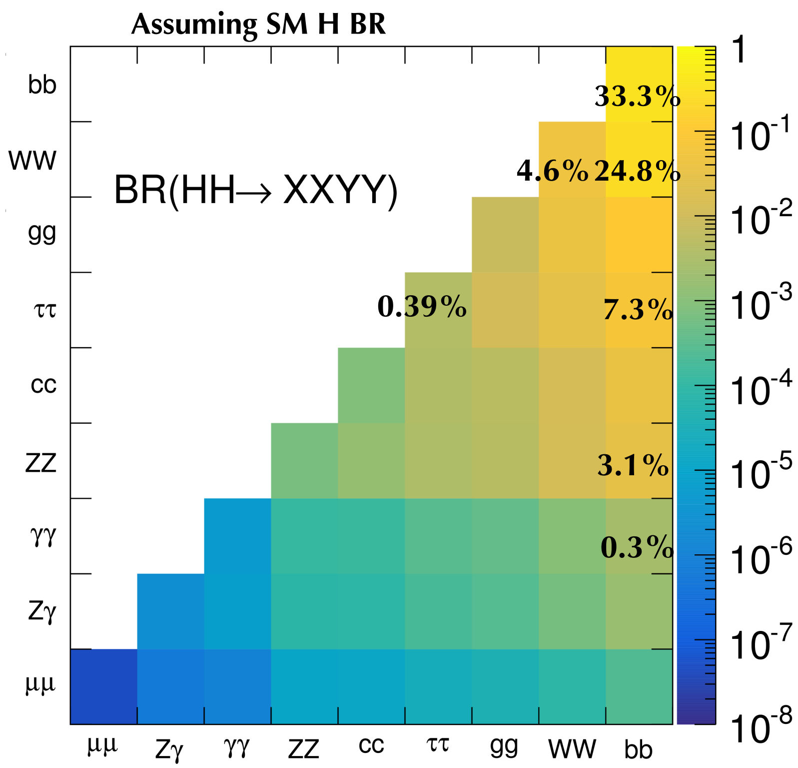
Stringent limits could be expected by combing other channels



CMS resonant almost same sensitivity than ATLAS
CMS non-resonant x3 better than ATLAS

There is room for improvement, need to push analysis sensitivity at the extreme (need to add full had and 2 leptons channels on ATLAS side too)

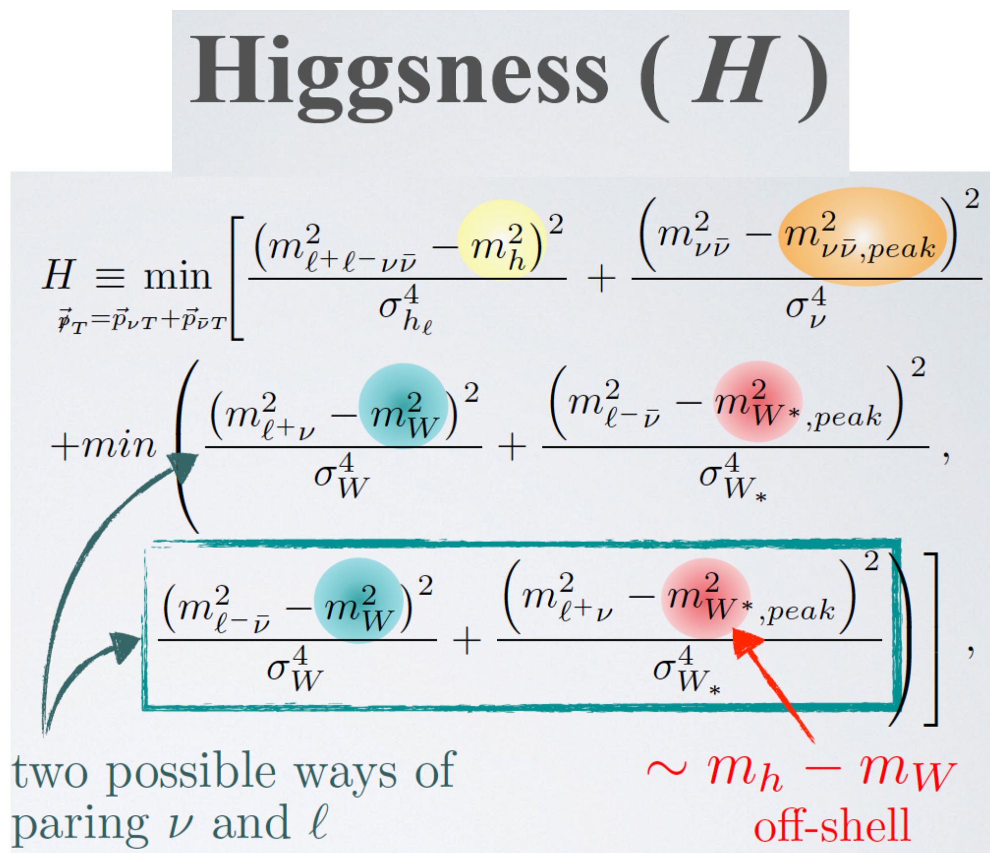
Pheno work on WWbb analysis improvement

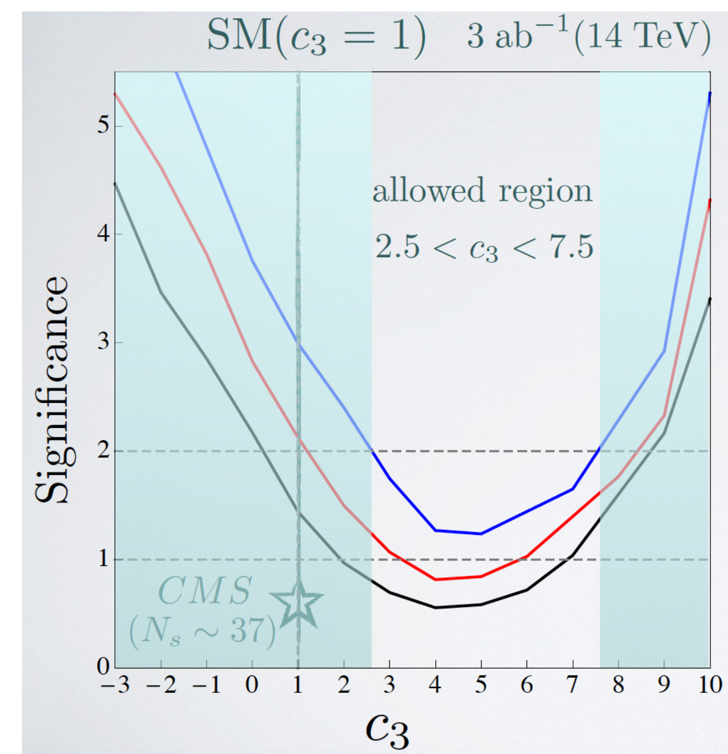


- Br to WWbb quite large, analysis improvement can be tried developing techniques to suppress top background (therefore big interest from pheno community)

proposed variable from phenomenologists

minimised respect to neutrino p_z





can be used also for the 1 lepton channel

bbττ

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Multivariate techniques help but require attention:

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Both experiments confirm each others results when comparing cut-based and MVA analyses.

Using multivariate discriminants as final fitted value give optimal analysis sensitivity.

it allows to define at low BDT a CR to constraint ttbar systematics

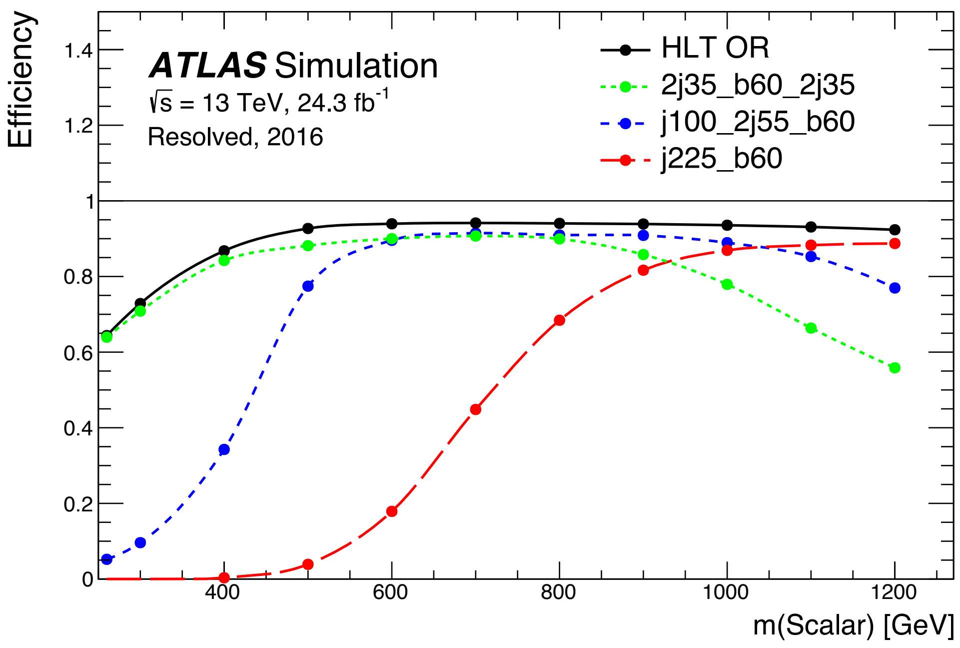
Online b-tagging (John Alison)

b-jet triggers are most complicated LHC trigger paths

- Need jet reconstruction, vertexing, tracking, b-tagging

Acceptance × efficiency constrained by:

- L1 rate: (only calorimeter info for decision)
- CPU resources available in HLT (and output rate)



Trigger places limits on HH→bbbb analysis in both ATLAS and CMS

- Limitations even more serious at HL-LHC

ATLAS has 2 b-jet trigger paths for improved low m_{HH} sensitivity

- Enables background model with normalisation from 2-tag control sample

CMS requires at least 3 b-jets to pass trigger

- Reduces efficiency, motivates hemisphere background model

David Wardrope 2

CMS experimental summary

- Tight object selection to reduce background from fakes:
  - Photon selection similar to H(γγ), regression for b-jets to improve m_{bb} resolution
- **MVA classification** using kinematic variables:
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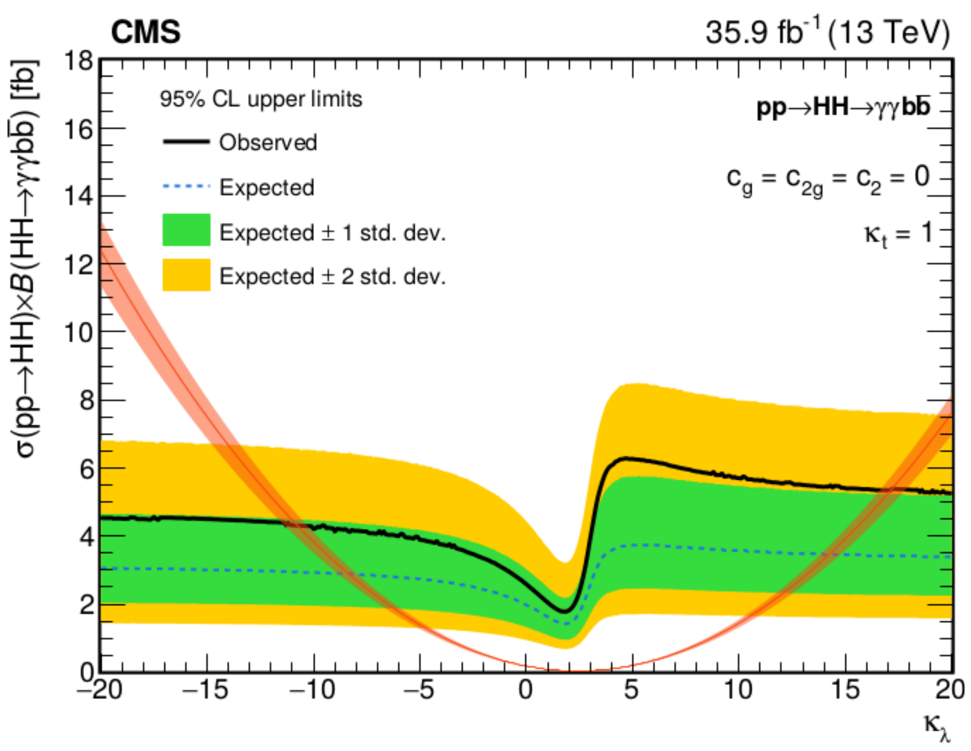

Most sensitive channel:

Dominating $\boldsymbol{\kappa_\lambda}$ scan

Dominant channel for resonant at low mass