Maxime Gouzevitch

Experimental challenges at the LHC in HH final state

Mainz HH workshop

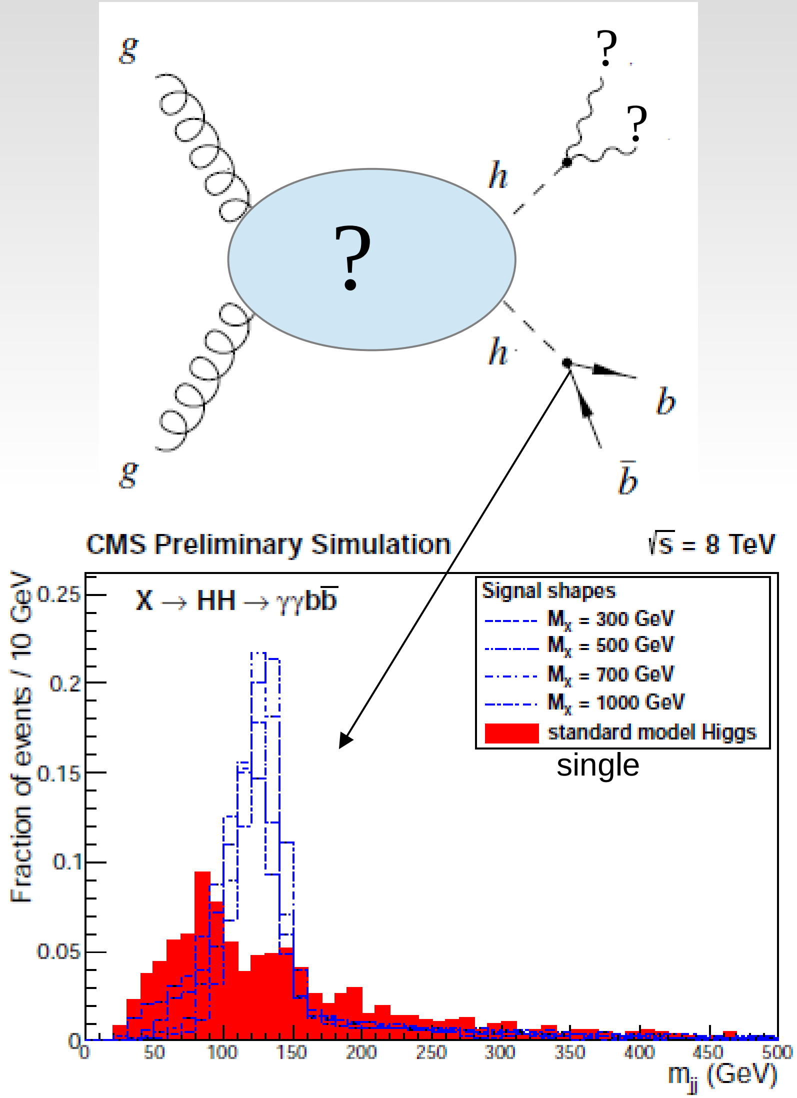
Material and help from:
HH HXSWG, A. Oliveira, O. Bondu, R. Salerno, L. Cadamuro

30/03/2015

1.1) HH production final states

Channel	BR[%]	Expected Events 8 TeV 20 fb-1	Expected Events 14 TeV 3 ab-1
bbbb	33	66	~40000
bbττ	7.3	15	~9000
bbγγ	0.26	0.52	317
bbWW→bblνjj	7.3	15	~9000
bbWW→bblνlν	1.2	2.4	~1500
bbZZ→bblljj	0.29	0.58	354
bbZZ→bbllll	0.014	0.027	17

- One leg is usually H→bb:
  - good MH resolution (10-15%); best BF.
  - No serious argument till now for any other solution.
- Second leg “golden/silver” discovery channel on single H production.
- Efficiencies would divide the number of expected events at least by 10.



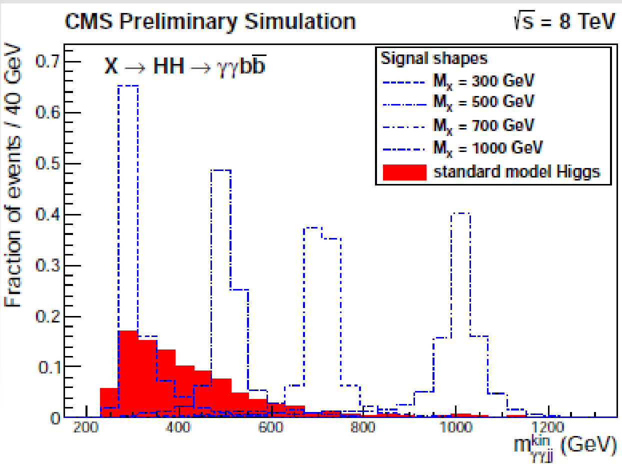
1.2) HH production BSM

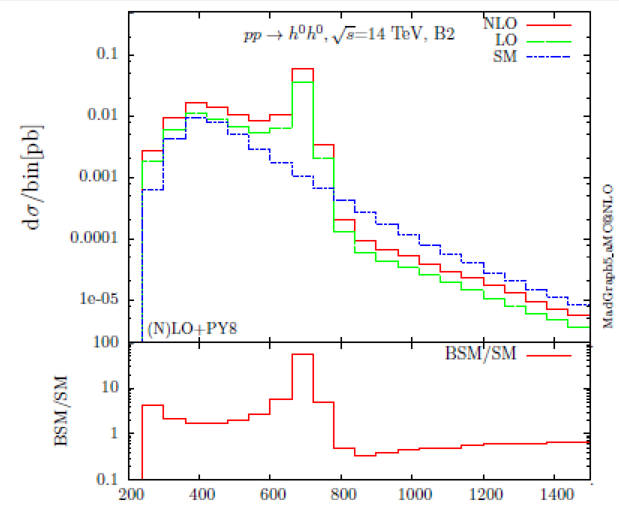
- We can classify the modifications of the HH production rate wrt to SM (references are given as example)

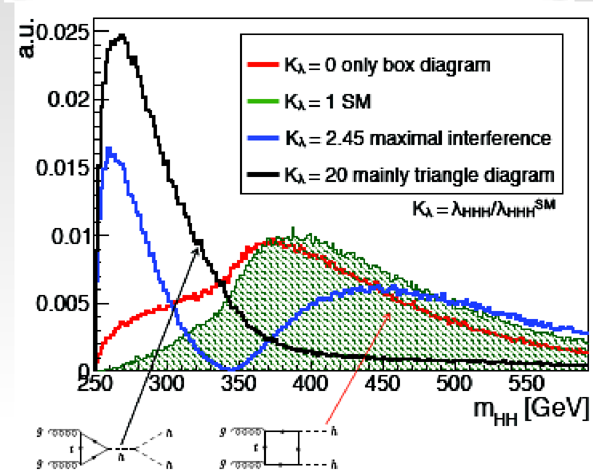
Maximum deviation in (plausible) BSM for which there are not another EWSB states accessible at LHC

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^{a}$ $-15\,\%^{b}$
NMSSM	$-25\,\%$

arXiv:1305.6397







Models with extra particles coupling to HH: resonant contribution to M_{HH}.

http://arxiv.org/abs/1404.0102

- WED, SUSY, 2HDM, etc...
- Generic formalism: single resonance with a given width.

Models with both effects:

http://arxiv.org/pdf/1407.0281v2.pdf

- 2HDM, WED, SUSY

Models with loop effects: non-resonant contribution to M_{HH}.

http://arxiv.org/pdf/1502.00539.pdf

- Top composite models, Higgs portal etc...
- Formalism: EFT

1.3) How woud I proceed

- I would present 3 channels considered by the experiments/pheno:
$\gamma\gamma$bb, 4b, $\tau\tau$bb and WWbb.

- For each channel I would say what we learned from Run I/HL-LHC predictions : the analysis procedure, the important backgrounds, what can be improved in selections.

- Compare channels based on existing experimental results for resonant searches and extrapolate to non-resonant searches.

$HH \to \gamma\gamma bb$

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$bb\tau\tau$	7.3	15	~9000
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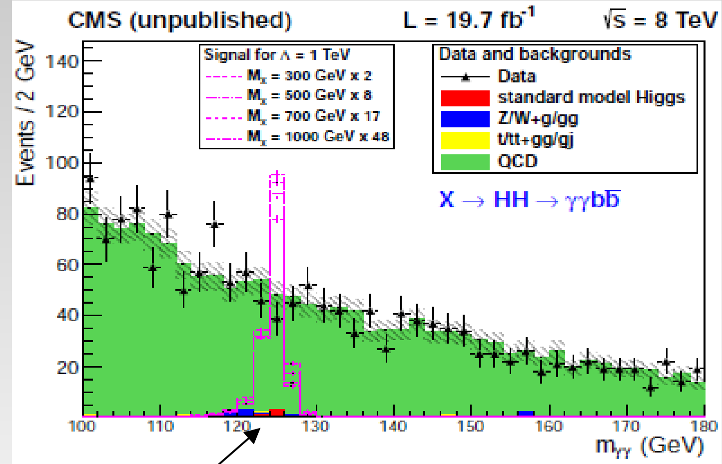
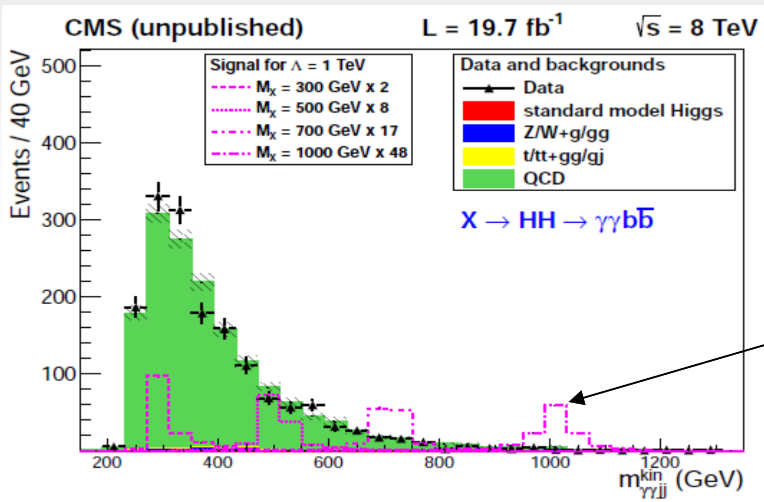
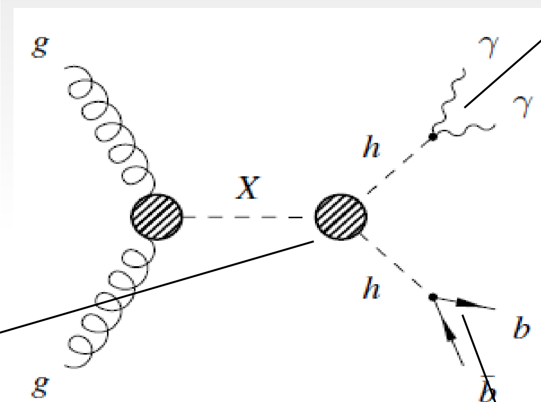
2.1) General properties

- fully reconstructible final state.
- but small BF: 0.26%

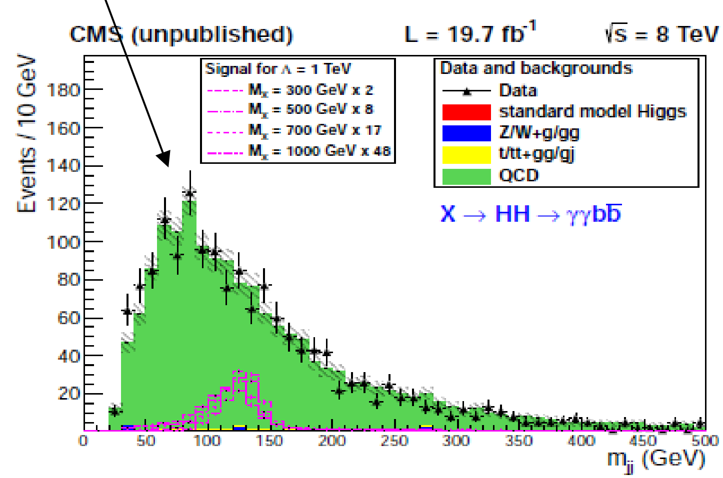






CMS-PAS-HIG-13-032

ATLAS,
Phys. Rev. Lett. 114,
081802 (2015)



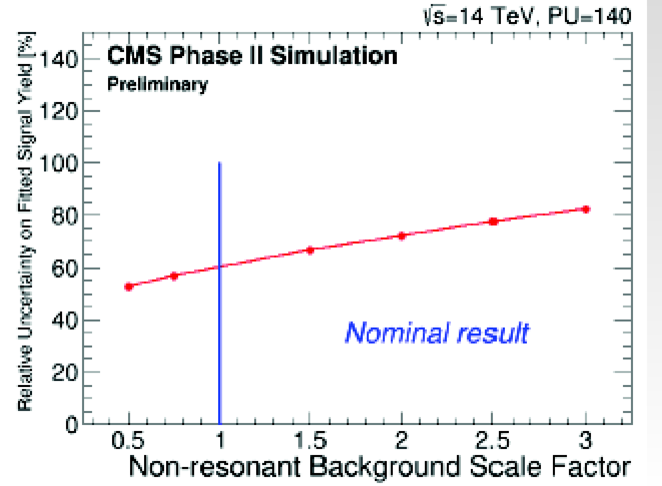
2.1) General properties

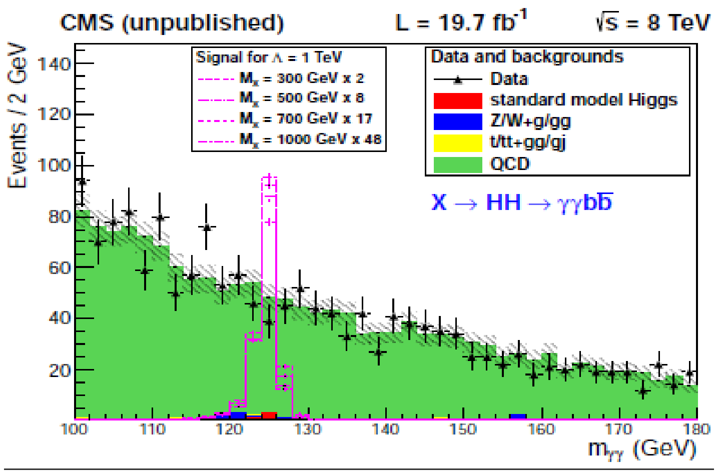
Channel	M_{H1}	M_{H2}	M_{HH}
H1(γγ)H2(bb) CMS low mass resonant (M_X < 400 GeV)	Fit	Cut	Cut
H1(γγ)H2(bb) CMS high mass resonant (M_X > 400 GeV)	Fit	Cut	Cut
H1(γγ)H2(bb) ATLAS resonant (M_X < 500 GeV)	Cut	Cut	Count
H1(γγ)H2(bb) ATLAS non-resonant	Count	Cut	Not-used

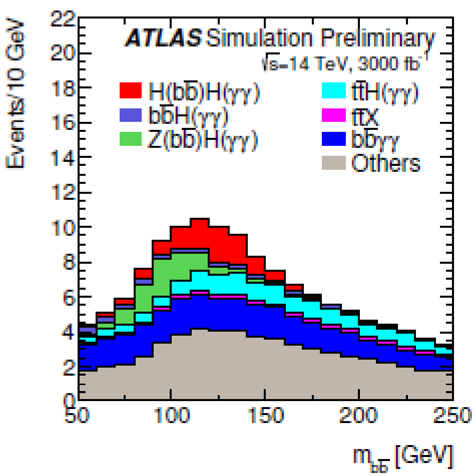
2.2) QCD Backgrounds

Main backgrounds (labelled QCD on the figure):
- Non-resonant QCD with real photons = γγjj (>80%):
  - Tree and box diagram (do not forget!)
  - SHERPA (Multileg LO MEPS) seems to provide a good description within 20%
- Non-resonant QCD with fake photons = γjbb+jjbb (<20%).
  - σ(Large)*Eff(small)
  - Significant uncertainties with high PU
  - Hard to simulate due to small efficiency.
- Experimentally a smooth background fit is performed.

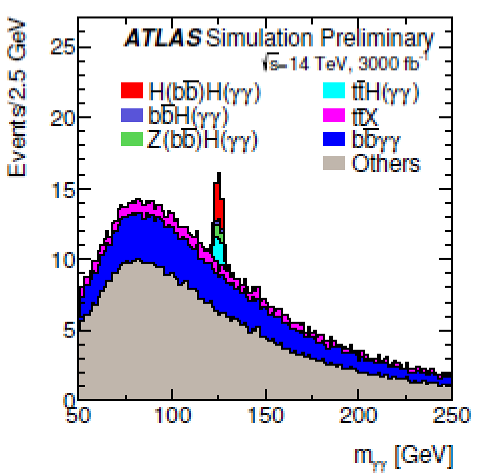
« not an issue » for the analysis itself,
but an issue for the sensitivity estimates!!!







(a) $m_{b\bar{b}}$

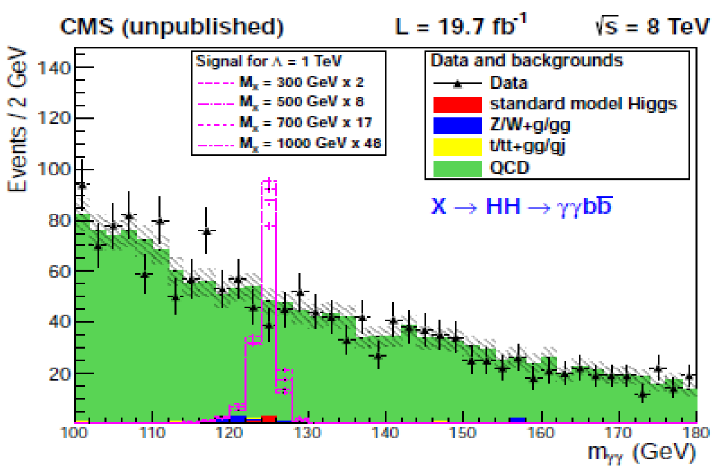


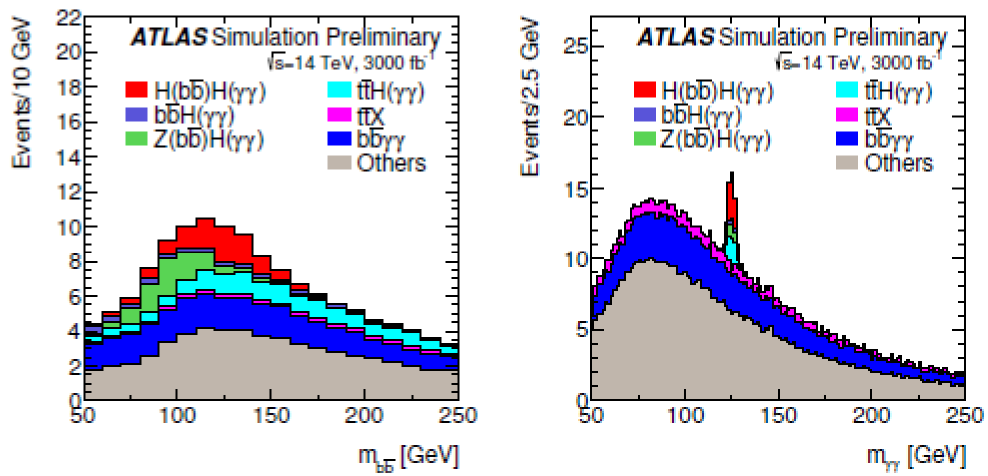
(b) $m_{\gamma\gamma}$

2.3) Rare backgrounds

Other minor backgrounds:

- Resonant: SM H production
    - less than 1 event in final selection at 8 TeV. But comparable or larger than the signal!
    - Need a deep measurement program of associated production H+jets.
    - V(→bb/cc/cs)H may be distinguished looking on bb spectrum.
- Non resonant: hopefully could be absorbed in bkg smooth fit
    - Irreducible: Z(→bb)+γγ or t/ttbar + jets → expect to be studies for ttH
    - Reducible: Z/W + γγ, γj, jj

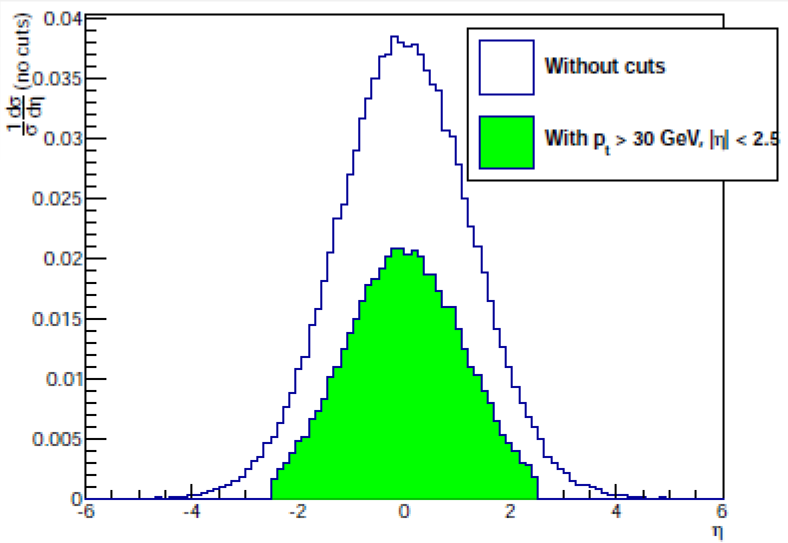


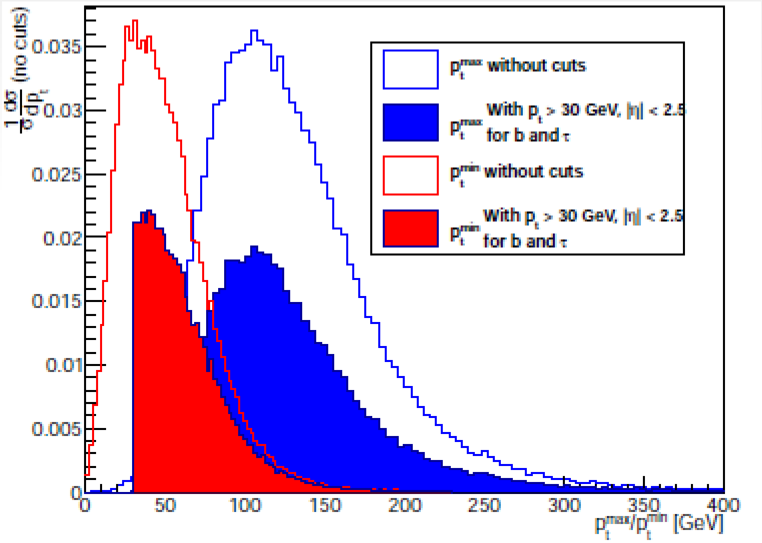


(a) $m_{b\bar{b}}$ (b) $m_{\gamma\gamma}$

2.4) Kinematics: photons p_T and acceptance

- Photons selections: same constraints than $H \rightarrow \gamma\gamma$ search
- $p_{T,\gamma 1} > M_{\gamma\gamma}/3$, $P_{T,\gamma 2} > M_{\gamma\gamma}/4$
  - Trigger limited. Some improvements could come from online conditions on jets.
  - Especially important for second photon and second jet.
  - Especially important for « threshold analysis »
- $|\eta| < 2.5$: defined by tracker acceptance; barrel photons matters more than end-cap ones.



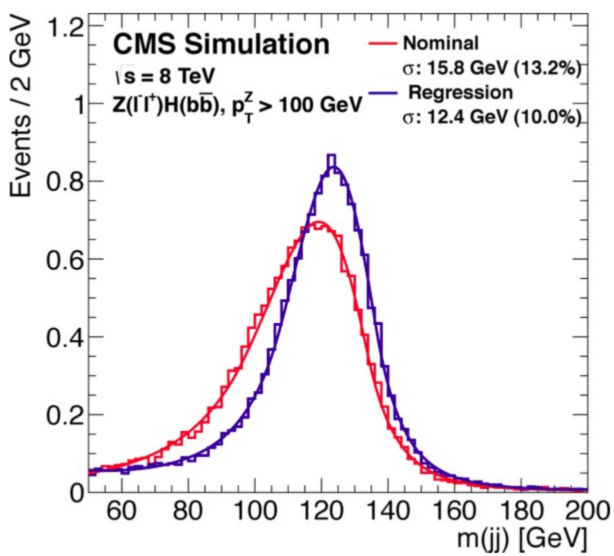


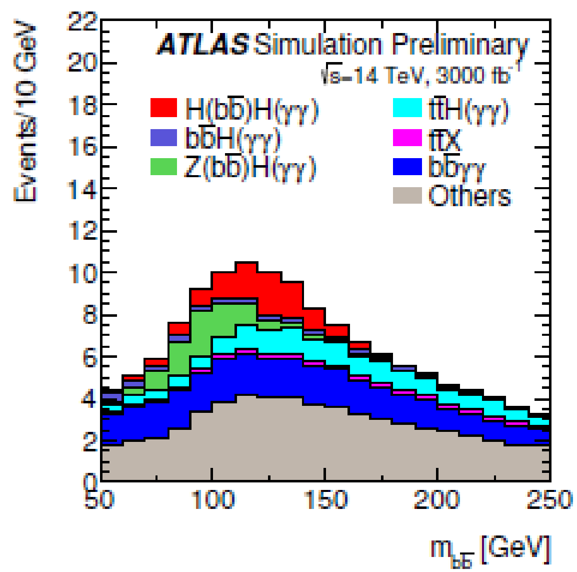
$$\frac{G_F^2\alpha_s^2}{512(2\pi)^3}\left[\left|\frac{3m_h^2}{\hat{s}-m_h^2}F_\triangle + F_\Box\right|^2 + |G_\Box|^2\right]$$

Plots done for bb by L. Cadmuro but perfectly valid for discussion here

2.5) Kinematics: jets p_T and acceptance

- It worth to push jets theresholds close to photon ones: need « tracker » or PFlow jets
  - CMS uses: 25 GeV PFlow jets
  - Atlas: 55, 35 GeV calo jets
- B-tagging: need as pure as possible to kill QCD background (large part of the grey band).
- Jet energy regression: like in Hbb search helps to reduce b-jets resolution;
  - Better QCD/HH/VH separation
  - Expected to be efficient since no genuine MET. But there are challenges: regression works well for arrow region in $p_{T,H}$, large pT,H spread like in non-resonant HH is challenging.

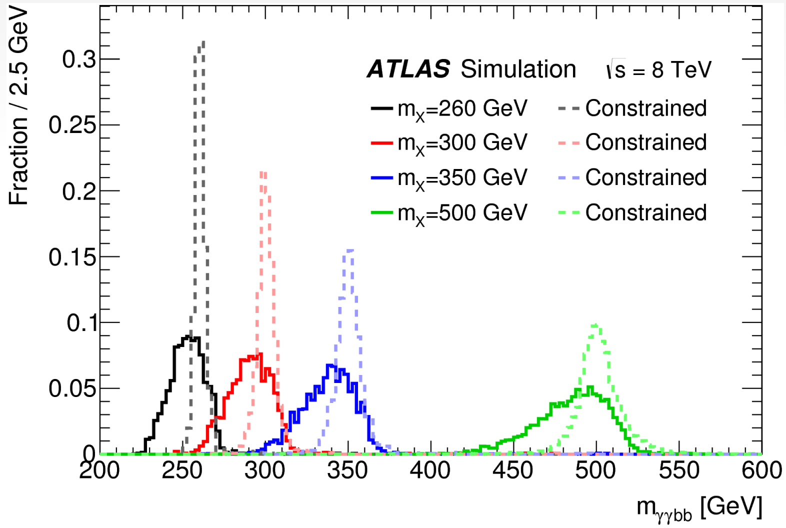




(a) $m_{b\bar{b}}$

2.6) HH Kinematics: 3 masses

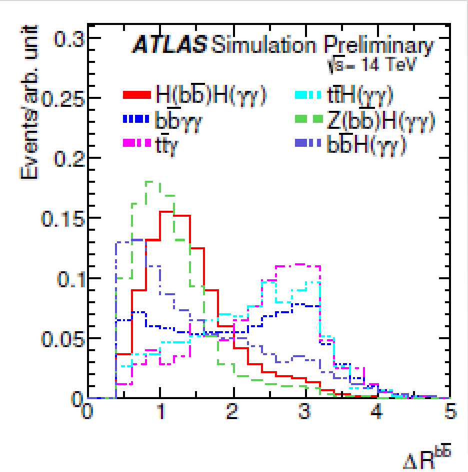
- For the signal they are « a priori » uncorrelated, except due to b-jets resolution M_{bb}
  - Regression reduces the b-resolution correlation.
  - Technique of Kinematic fit of M_{bb} consist in forcing $M_{bb} = M_H$ assuming that that the difference comes from jets resolution.
    - Improves significantly $M_{\gamma\gamma bb}$ for resonant signal.
    - Decorrelates M_{bb} and $M_{\gamma\gamma bb}$.
- For the background Kinematic fit « reshuffle » $M_{\gamma\gamma bb}$ but do not creates « fake peaks ».
- To be confirmed: after this « diagonalisation » in the « vicinity of the Higgs mass », ($100 < M_{bb}, M_{\gamma\gamma} < 200$) the 3 masses are nearly uncorreleated!
  - It is possible to cut or do shape analysis in any combination of them and this would perform as well as a BDT.

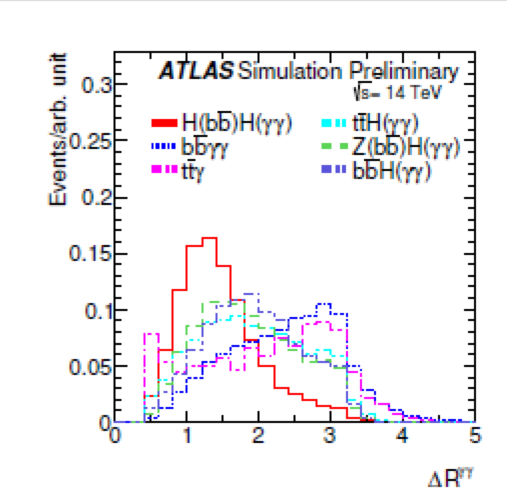


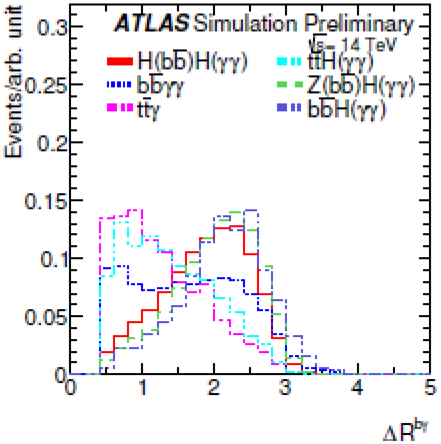
2.7) HH Kinematics: decay product angles

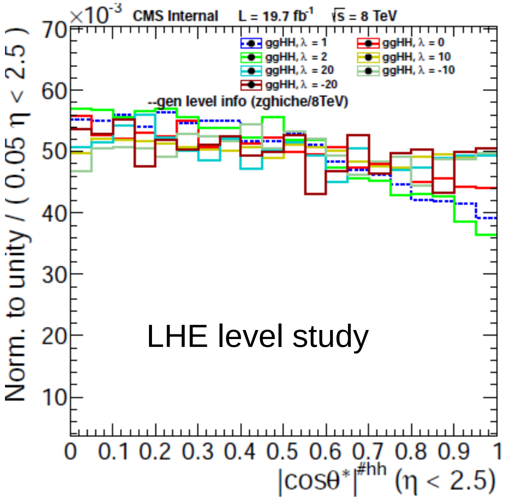
- ΔR_{bb} and $\Delta R_{\gamma\gamma}$: Are strongly correlated with $p_{T,H}$ and M_{HH}. Better use $\cos\theta^*_H$.
- $\Delta R_{b\gamma}^{min}$: interesting variable. Not so correlated to $p_{T,H}$ and M_{HH}. Kills probably fragmentation photons in QCD (my hypothesis would be interesting to test).
- $\Delta\eta_{HH} \sim \cos(\theta^*_{HH})$ – flat since process dominated by s-wave.
- $\Delta\phi_{HH}$: quite dangerous since very sensitive to ISR.

- Idea: on top of shape cut analysis in masses one may do a BDT analysis of the angles: since s-wave dominates all the angles are fixed for non-resonant or spin 0 resonant.

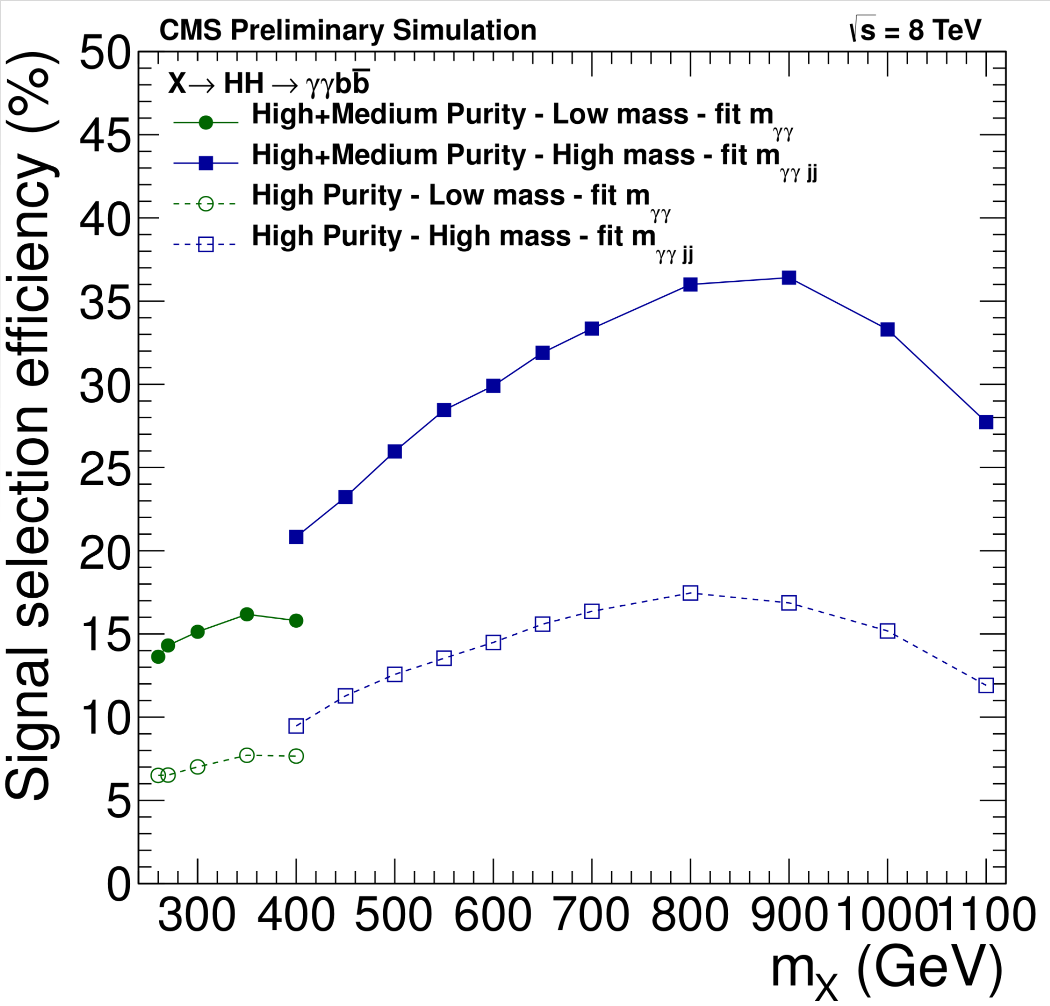








2.9) Efficiency



High purity: 2 b-tag
Low purity: 1 b-tag

ATLAS:
Acceptance x Efficiency: only High purity category used
4% (260 GeV) to 8% (500 GeV).

2.12) Conclusion: independent information

- What I think would be an analysis using maximal information in a maximally comprehensive way:
  - Push p_T of the second jet and photon as low as possible.
  - Do 2D shape analysis in $M_{\gamma\gamma}$, M_{bb} in bins of $M_{\gamma\gamma bb}$ after kinematic fit (or 3D if you are bold). All those masses are (probably) quite uncorrelated in signal and background.
  - Add a cut based or BDT analysis in angles. Be careful for correlation with masses.
- By how much could you improve the sensitivity?
  - Need to test :)

HH→4b

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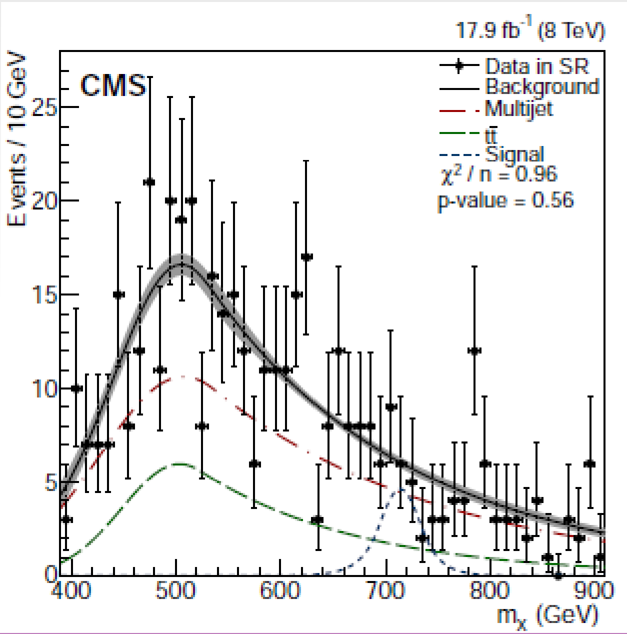
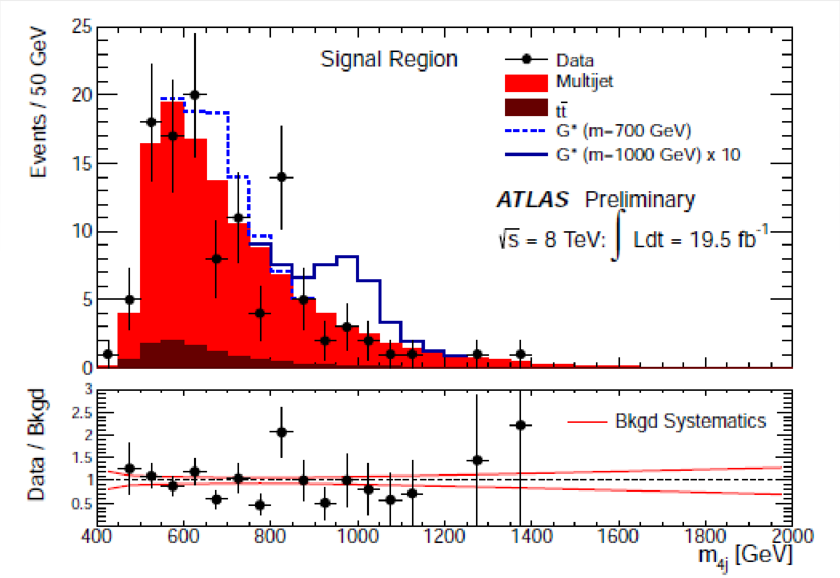
3.1) Backgrounds

- Background: multi-jet (80-90%); ttbar fully hadronic (10%).
  - ATLAS removes ttbar by applying mass selections.
- Background shape validated in side bands.



CMS http://arxiv.org/abs/1503.04114



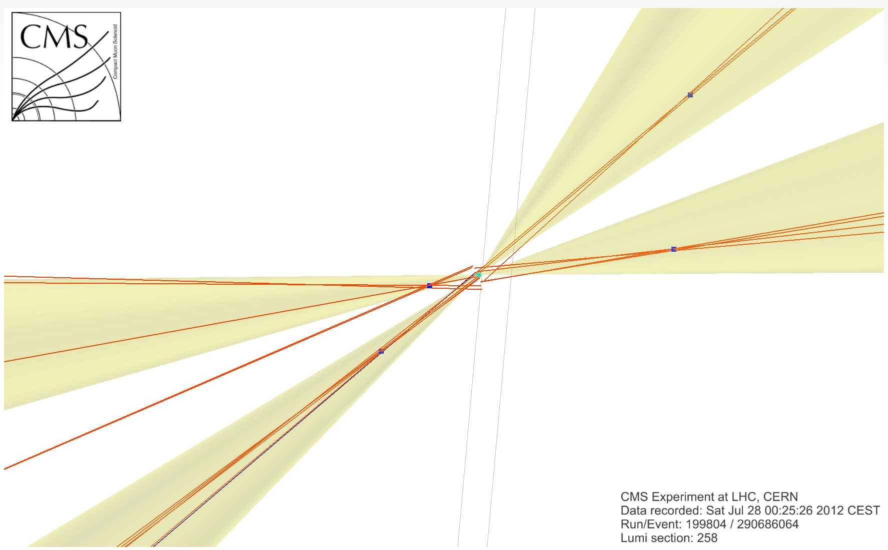
ATLAS-CONF-2014-005

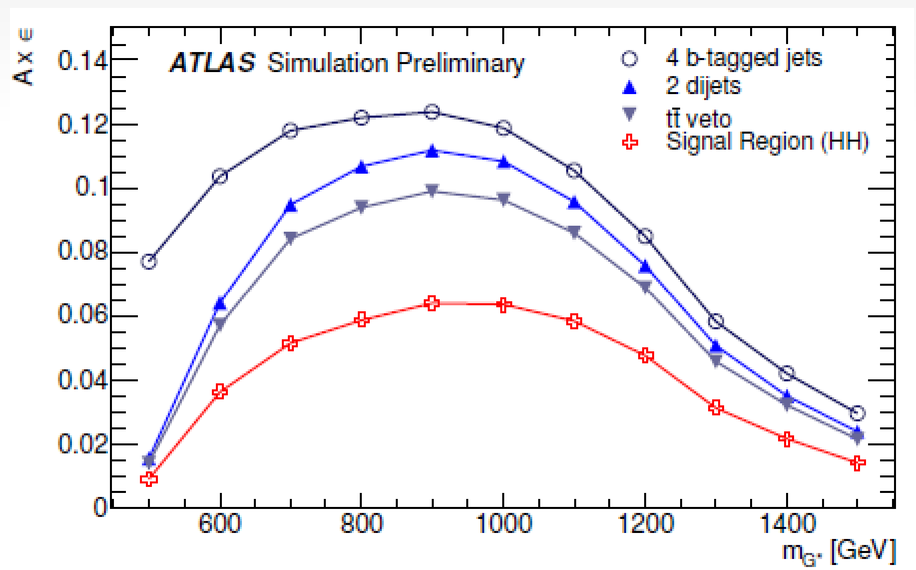
3.2) Jets selection and pairing

- Selections: 4 b-tagged jets with p_T > 40 GeV.
  - Theresholds limited by the trigger.
  - Complex trigger strategy requires online b-tagging (3-4 btags).
  - Very efficient b-tagging is compulsory for analysis success.
- Complex pairing strategy (much easier in $\gamma\gamma$bb). Typically pairs of b-quarks are done to be the closest possible to M_H.
  - Different pairing and selections criteria in boosted and unboosted regimes (see also for more details M. Gouzevitch @ al: http://arxiv.org/abs/1303.6636).

3.3) Efficiency

- Efficiencies typically: below 1% below 500 GeV for CMS; 1-6% above 500 GeV for CMS and ATLAS.
- Analysis severely limited for M_{4b} below 400 GeV.





HH→ττbb

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4.1) Backgrounds

- Complex background cocktail with different relative contributions according to the τ final state:
  - Irreducible bakground: tt, Z+jets, H+jets.
  - Reducible backgrounds with fake τ: V+jets, QCD.
- Interesting feature per channel:
  - tt is important in 2-btag category. In fact 1-btag in this analyis is even more important than in γγbb.
  - tt is at least 3 times less important in τhτh than in eτ/μτ.
  - ee/μμ channels overwhelmed by DY.
- In this channel backgrounds more comlex than in 4b and γγbb but in some sense « better known ».

4.2) Selections

- The $\tau\tau$ leg:

  - fully leptonc and semi-letonic channel uses double-lepton trigger or lepton+tau triggers. Can go lower than $\gamma\gamma$ triggers.

  - fully hadronic channel uses tau-tau trigger with typically higher threshold like $p_T \sim 40$ GeV.

- The bb leg have the same properties than in $\gamma\gamma$.

- The τ are boosted, ie decay products collinear A kinematic fit is usually used to reconstruct $M_{\tau\tau} \sim M_{bb} \sim M_H$. It provides optimal resolution on $M_{\tau\tau bb}$ especially for resonant signal.

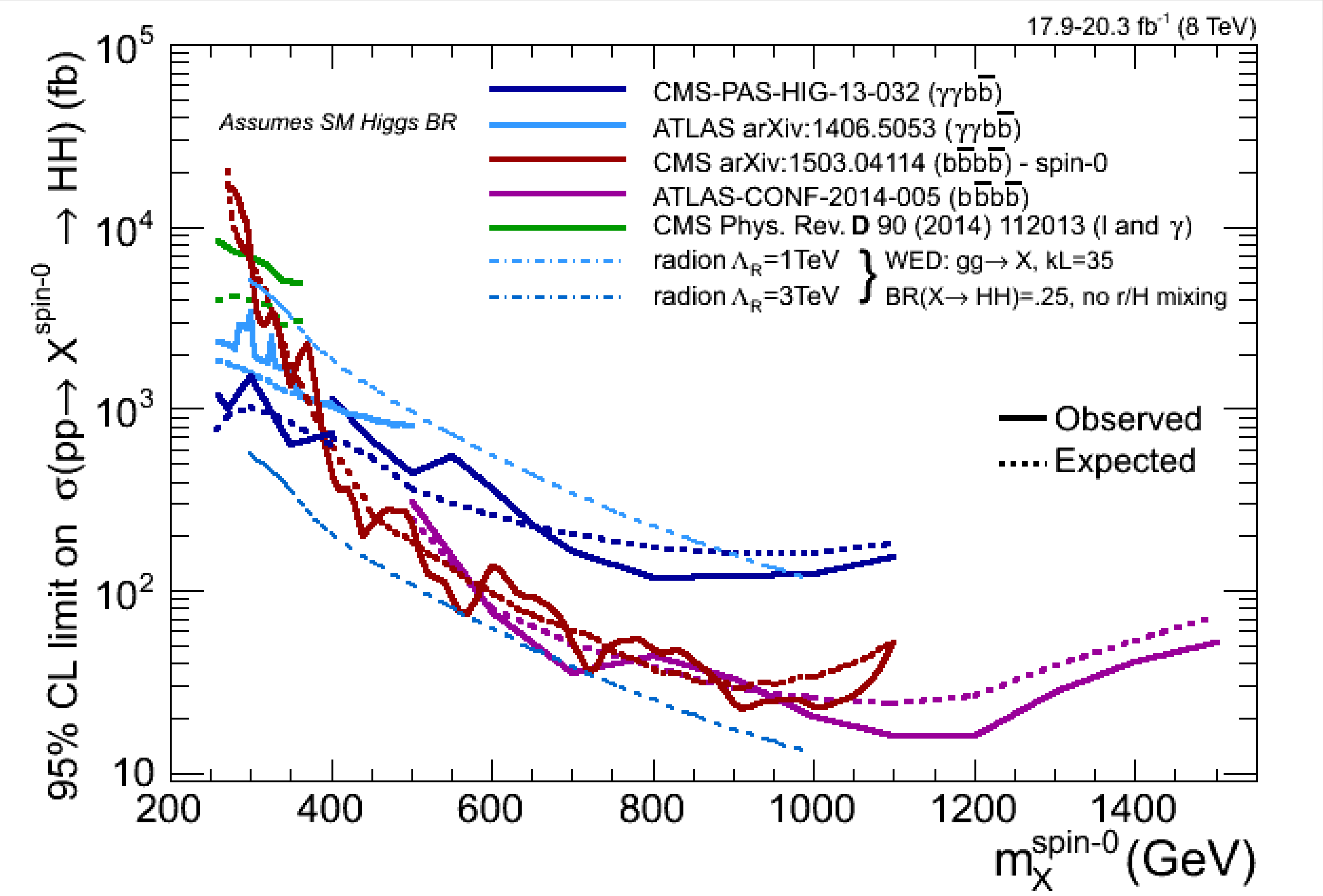
- In semi-leptonc analysis one need to reduce the W+jets and tt contributions by applying MT or MT2 cuts.

Methodology comparison

5.1) Methodology comparison

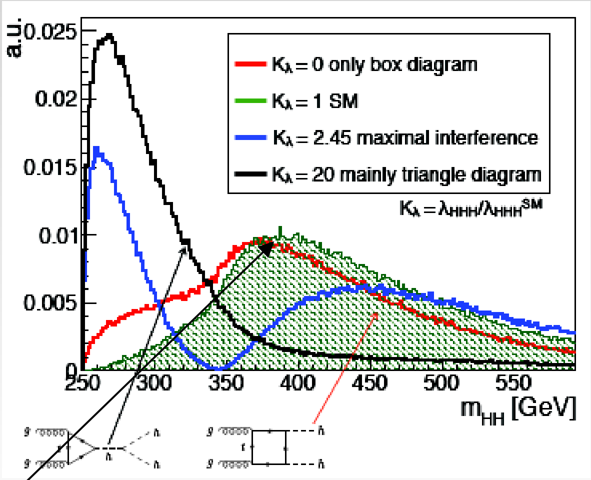
Channel	M_{H1}	M_{H2}	M_{HH}
H1(γγ)H2(bb) CMS low mass resonant (M_X < 400 GeV)	Fit	Cut	Cut
H1(γγ)H2(bb) CMS high mass resonant (M_X > 400 GeV)	Fit	Cut	Cut
H1(γγ)H2(bb) ATLAS resonant (M_X < 500 GeV)	Cut	Cut	Count
H1(γγ)H2(bb) ATLAS non-resonant	Count	Cut	Not-used
4b resonant ATLAS MX > 500 GeV CMS MX > 260 GeV	Cut	Cut	Fit

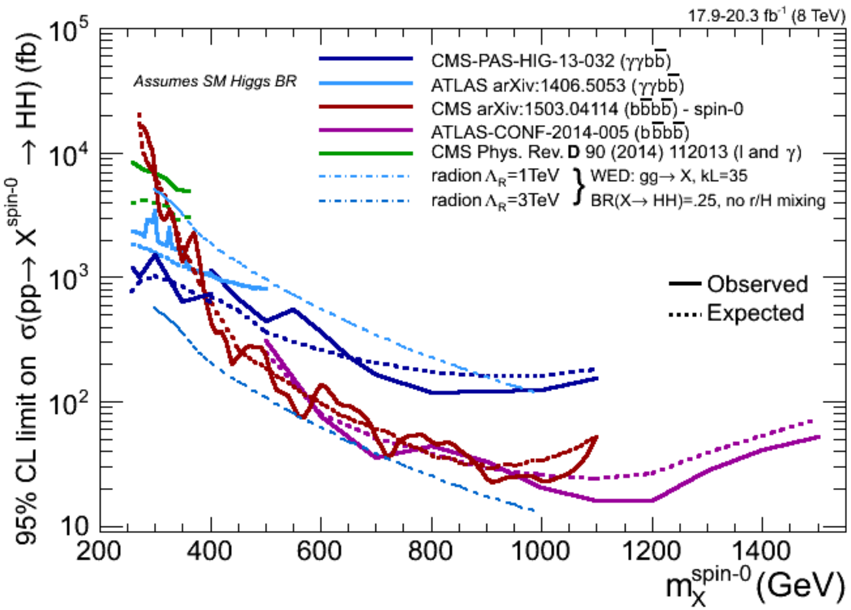
5.2) Results comparison



- The 4b channel is limited below 400 GeV by trigger efficiency and background turn on in M_{4b} method.
- The 2γ2b channel is limited above 400 GeV by low BF.

5.3) What about non-resonant search



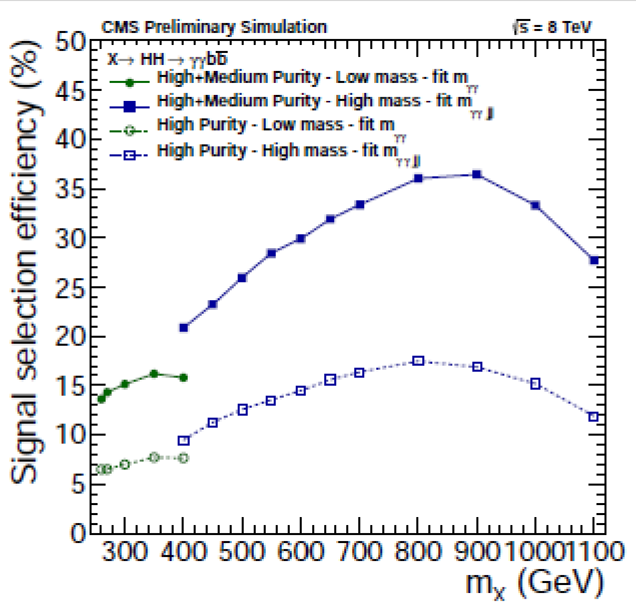


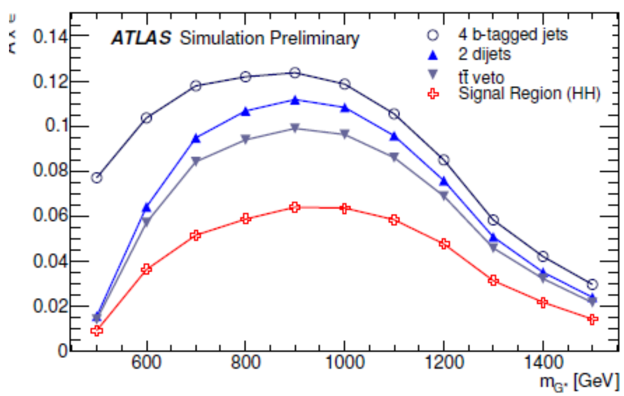
- The peak in SM HH spectrum is at 400 GeV.

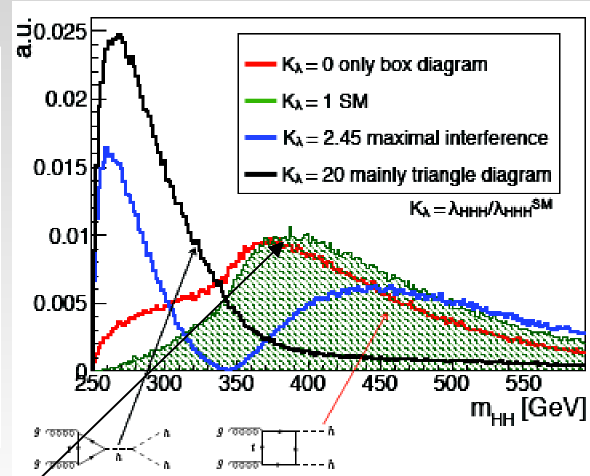
Extrapolation from resonant analysis:

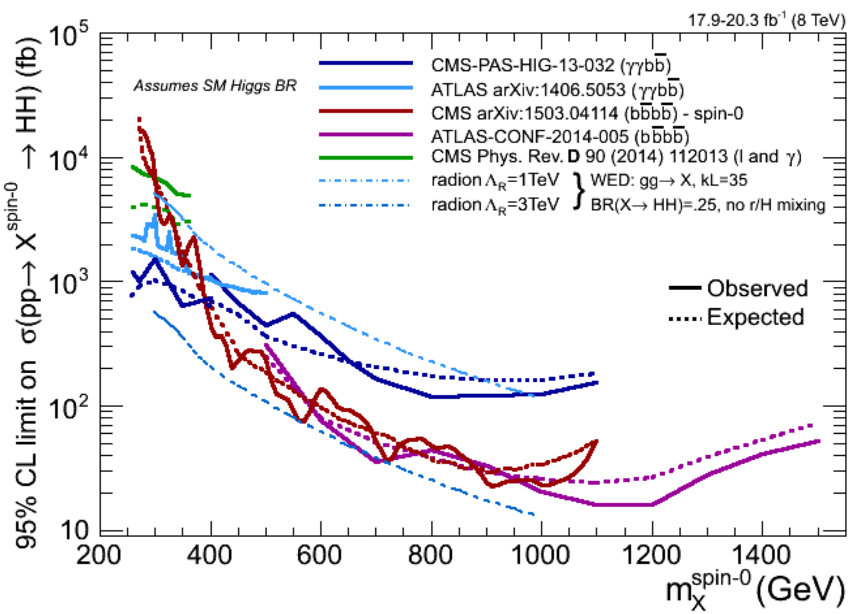
$2\gamma 2b$ and 4b shall have the same sensitivity.

5.3) What about non-resonant search



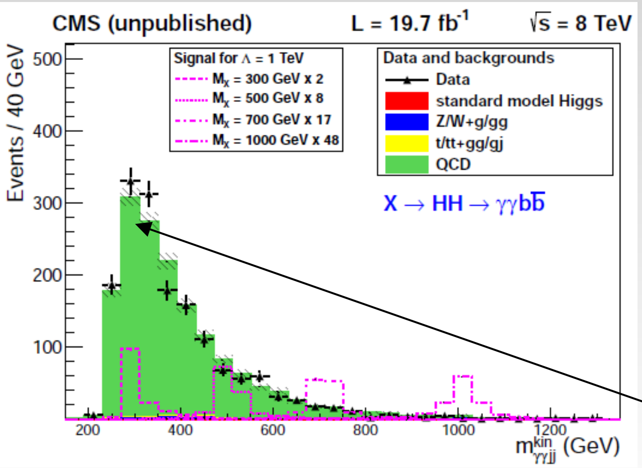


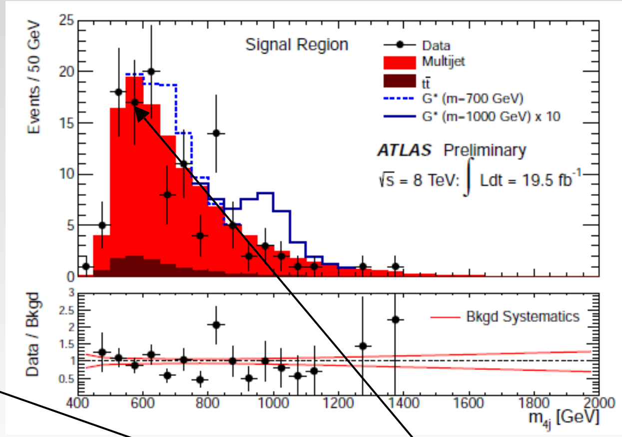


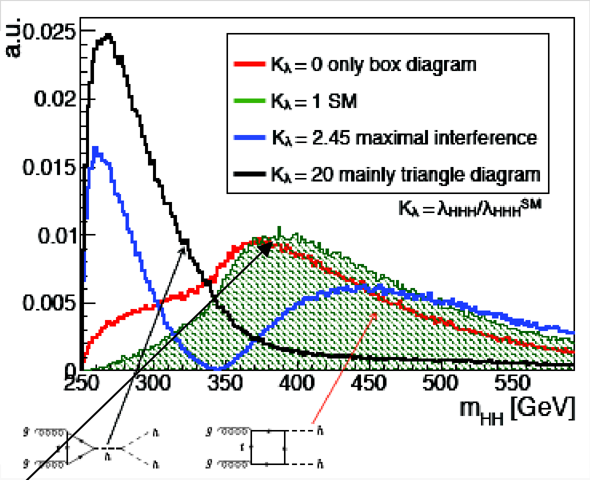


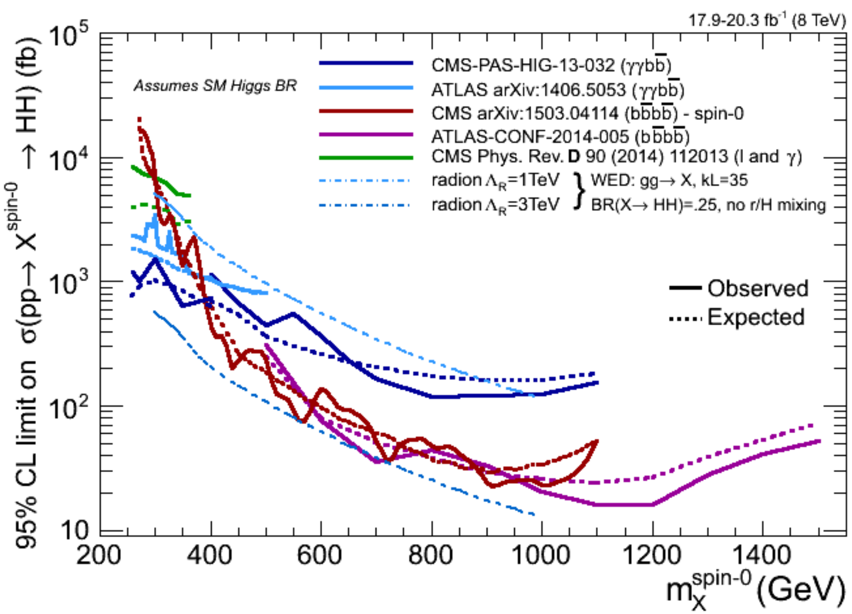
- The peak in SM HH spectrum is at 400 GeV. Extrapolation from resonant analysis: $2\gamma 2b$ and 4b shall have the same sensitivity.
- But 4b efficiency is vanishing below 400 GeV while $2\gamma 2b$ stays relatively stable.

5.3) What about non-resonant search





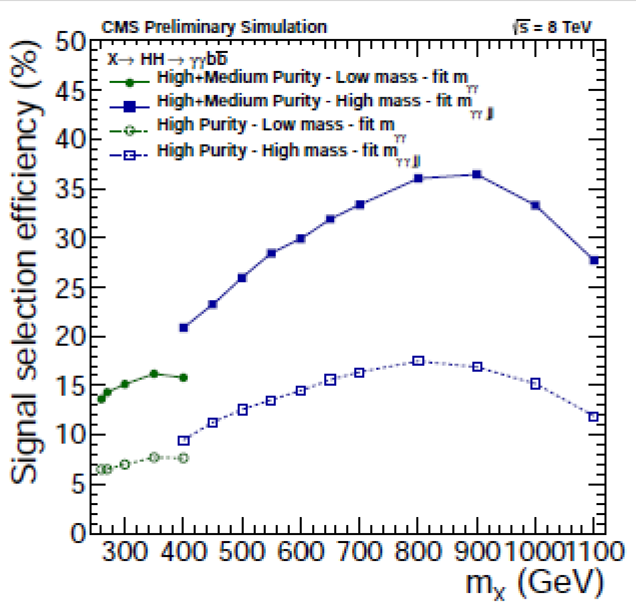


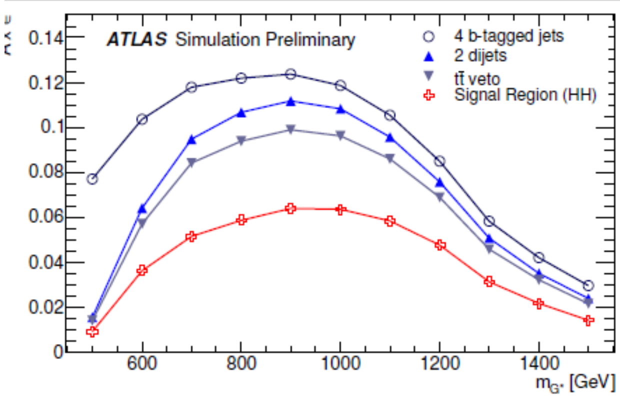


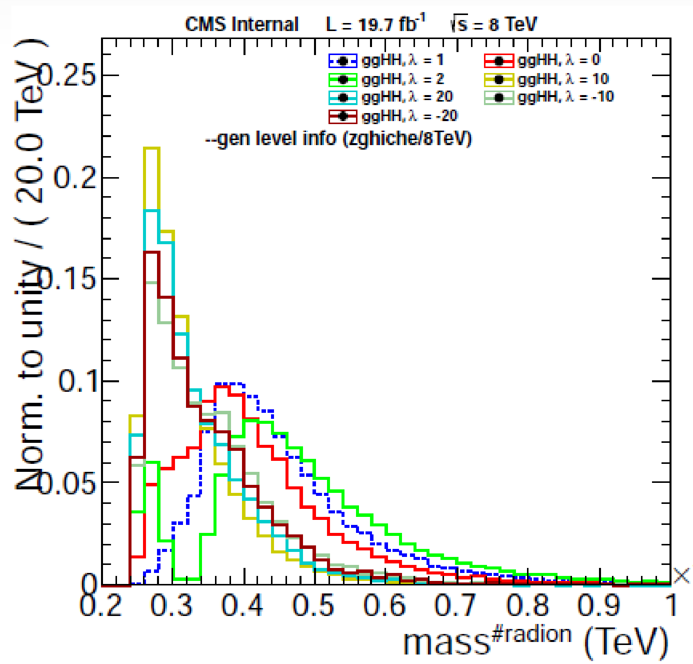
- The peak in SM HH spectrum is at 400 GeV. Extrapolation from resonant analysis: 2γ2b and 4b shall have the same sensitivity.
- But 4b efficiency is vanishing below 400 GeV while 2γ2b stays relatively stable.
- Consequently 4b background nearly like SM background! No discrimination power!!!

So using 4b for non-resonant search requires to rethink completely the analysis, while 2γ2b is easy to adapt.

5.4) Sensitivity to cluster analysis







- The efficiency pattern, background spectra, resolution and analysis strategy would sculpt the sensitivity to the MHH details (and to BSM operators):
  - 4b insensitive to threshold effects and λ.
  - 2γ2b very adaptable due to the flat efficiency.
  - 2τ2b would be probably intermediate.

A LITTLE BIT PROVOCATIVE CONCLUSION

1) Till 2013 the experimental field was driven by the phenomenologist. Great job. Exeriments slowly take over the pheno on prospects/usage of 4 golden channels and benefit from their experience (augM2ed is a good example).

- Except if you have a very clever idea how to improve an analysis I think one shall let them do and spend time for new things :)
- Which? For example explore new channels and say if they are or not useful. Exploration is much more « easy » for you than for experiments.

A LITTLE BIT PROVOCATIVE CONCLUSION

2) How? Here are my personal and biased recommendations:

- Be very careful with experimental assumptions. Better consult a specialist in « SOS experimental hotline ».
- If you use a « golden » channel to assess the sensitivity to your preferred new physics model verify that you are consistent with what experiments observe/predict at 8 TeV/HL-LHC and Run II: backgrounds, uncertainties etc...
- Be VERY careful with MVAs. Typical questions I ask myself for an MVA:
  - If you have a fully reconstructed final state do you really need an MVA?
  - Did you checks that you use the minimal reasonable set of variables.
  - Don't you use 2 times the same information (pTH1 and pTH2 with a LO MC without extra hard jets for example).
  - If you see a huge improvement wrt to a cut based, may be the cut based is severely sub-optimal?
- Do no assume: “this background would be perfectly known by that time ». It is very background depedent: ttbar is not the same than QCD with fake photons ...

BACKUP

Search for TeV-scale X→HH→bbbb

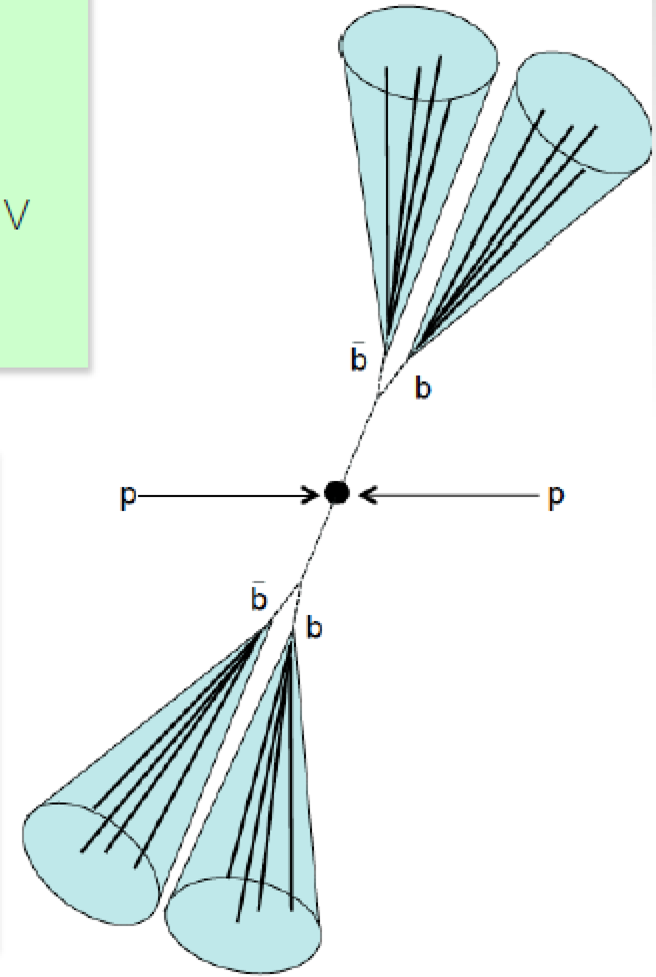
X→HH→bbbb candidate preselection:

- Trigger: 5 jet triggers with online b-tagging
  - Trigger efficiency >99.5%
- 4 b-tagged anti-k_t R=0.4 jets with $|\eta|<2.5$, $p_T>40$GeV
- Two dijets with ΔR(jet,jet)<1.5, pT>200GeV

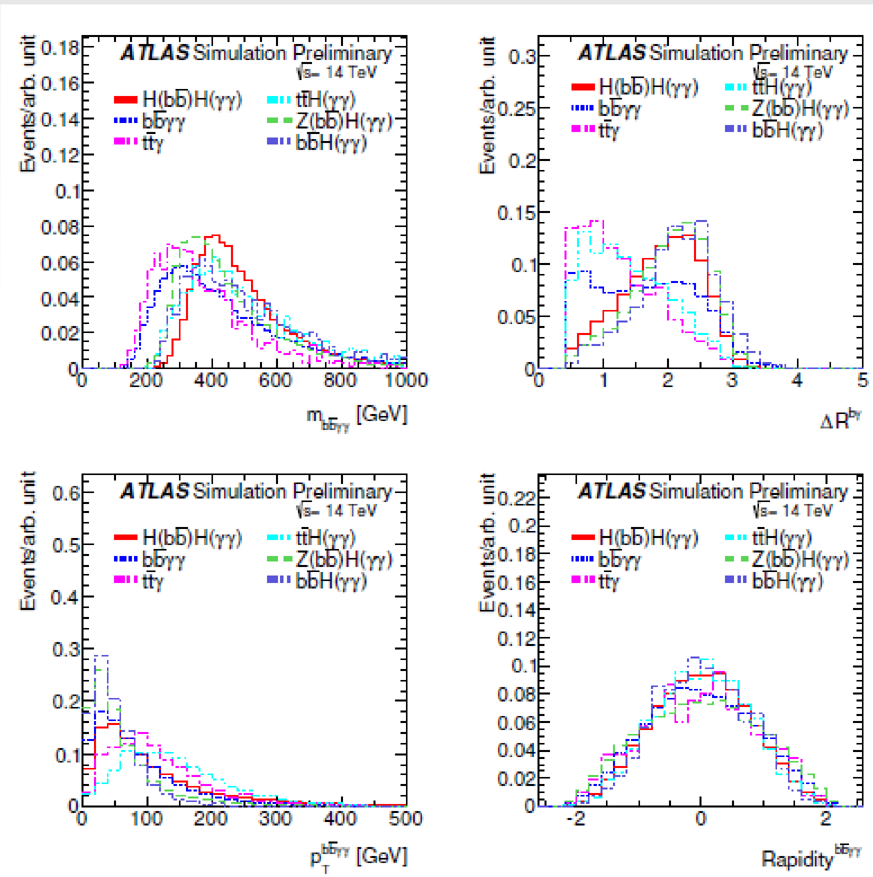
In addition:

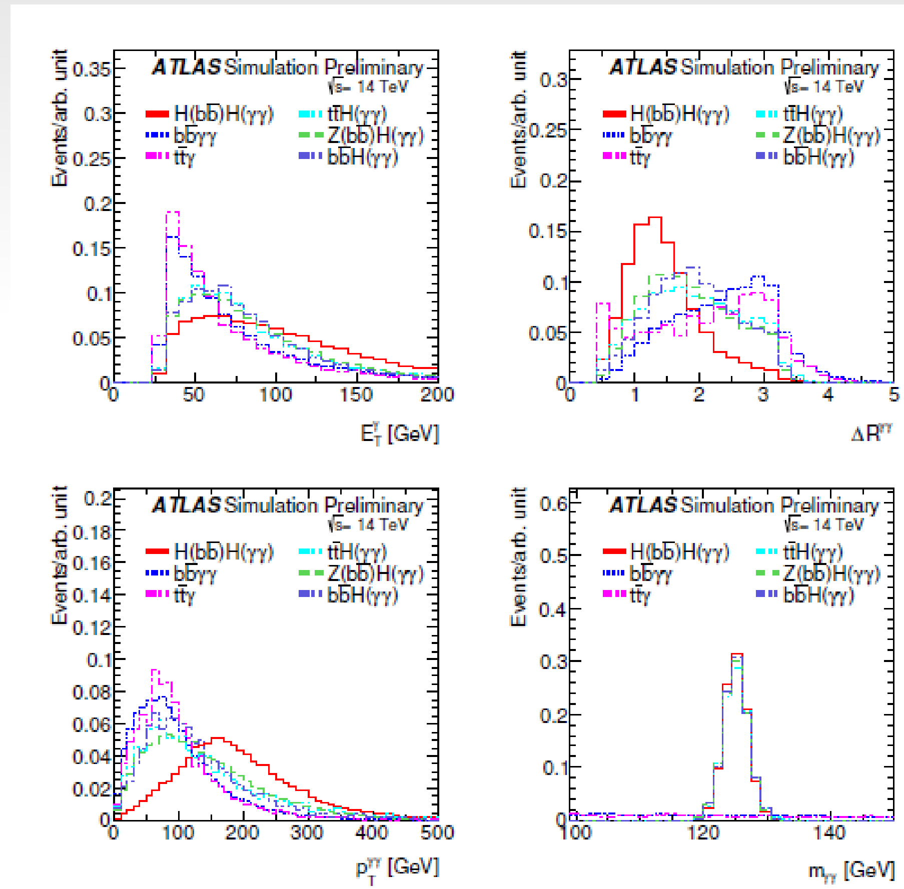
- ttbar veto: $X_{tt} = \sqrt{\left(\frac{m_W - 80.4}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5}{0.1 m_t}\right)^2} > 3.2$
- HH signal region: $X_{HH} = \sqrt{\left(\frac{m_1 - 124}{0.1 m_1}\right)^2 + \left(\frac{m_2 - 115}{0.1 m_2}\right)^2} < 1.6$

Background: QCD multijets (~90%) and tt (~10%)



Event Selection Criteria
$\geq$ 2 isolated photons, with p_T > 30 GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$
$\geq$ 2 jets identified as b-jets with leading/subleading p_T > 40/25 GeV, $\|\eta\| < 2.5$
No isolated leptons with p_T > 25 GeV, $\|\eta\| < 2.5$
< 6 jets with p_T > 25 GeV, $\|\eta\| < 2.5$
$0.4 < \Delta R^{b\bar{b}} < 2.0$, $0.4 < \Delta R^{\gamma\gamma} < 2.0$, $\Delta R^{\gamma b} > 0.4$
$100 < m_{b\bar{b}} < 150$ GeV, $123 < m_{\gamma\gamma} < 128$ GeV
$p_T^{\gamma\gamma}$, $p_T^{b\bar{b}}$ > 110 GeV





HH → bbγγ Analysis Description

- Search for non-resonant HH->bbγγ
  - Cross section at √s=14 TeV is 40.2 fb [NNLO]
- Event selection
  - 2 photons: p_T>40GeV and p_T>20GeV, |η|<2.5
  - 2 b-tagged jets, CSV medium WP, p_T>30GeV, |η|<2.4
- Kinematic selection
  - Additional lepton veto
  - Less than 4 jets with |η|<2.4 and p_T>30GeV
  - ΔR_{bb} and $\Delta R_{\gamma\gamma}$ less than 2.0, min of $\Delta R_{\gamma b}$>1.5
- Two categories considered
  - Both photons in barrel
  - At least one photon in endcap
- Likelihood fit signal extraction
  - 2D fit of M_{bb} and $M_{\gamma\gamma}$
  - Mass fit window of 100GeV<$M_{\gamma\gamma}$<150GeV and 70GeV<M_{bb}<200GeV is used
- Parameterized object performance tuned to Phase II detector
  - Preliminary tune as the final tuning need to be obtained from final Phase II samples

$HH \rightarrow bbWW$: Analysis Description

Search for $HH \rightarrow b\bar{b}WW \rightarrow b\bar{b}l\nu l\nu$

Event preselection:

- 2 b-jets Medium WP, $pT > 30$ GeV
  2 leptons, muons: $pT > 20$ GeV, electrons: $pT > 25$ GeV
- MET >20GeV
  Clean up cuts (mjj , mll , ΔRjj , ΔRll , $\Delta\phi jj,ll$)

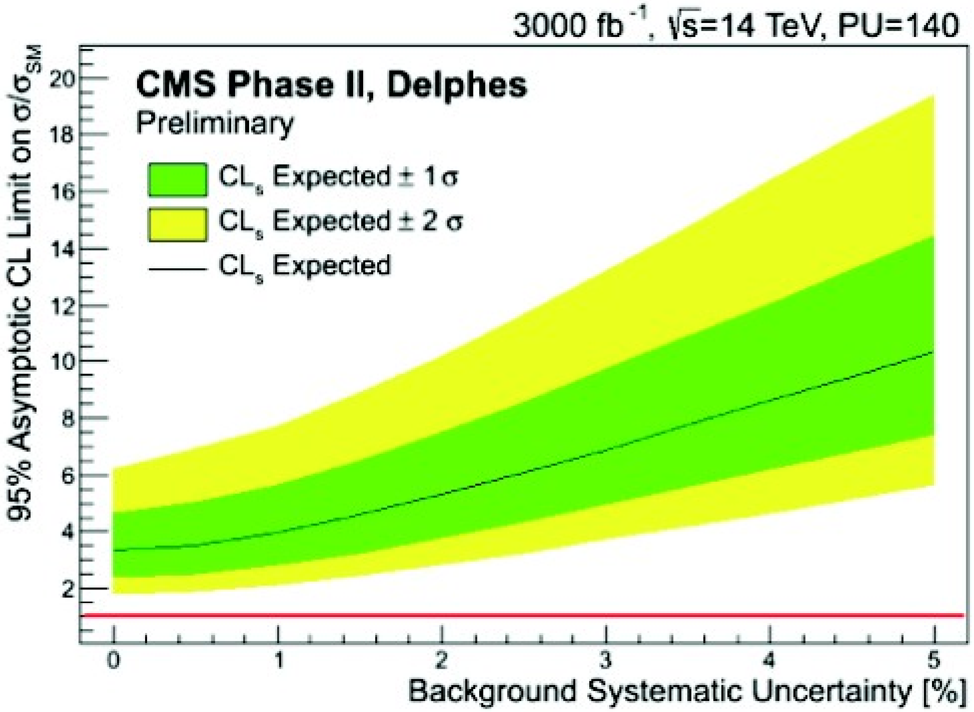
Analysis Optimization:

- Neural network discriminant from kinematic variables
- Variables: Mll, Mjj, ΔRll, ΔRjj, ΔRjl, MET, $\Delta\phi ll,jj$, pjj , and MT

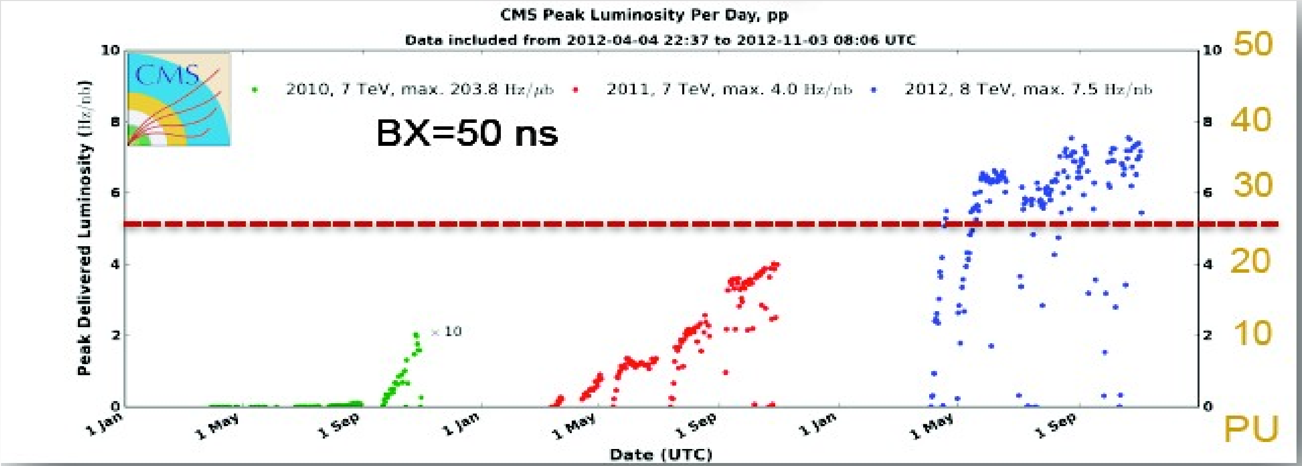
Analysis Setup:

- Phase II scenario Assuming 3000 / fb
- Based on Delphes reconstruction
- Considering only the main background: $t\bar{t}$
- The rest of the SM processes are negligible

HH → bbWW: 95% CL Limits

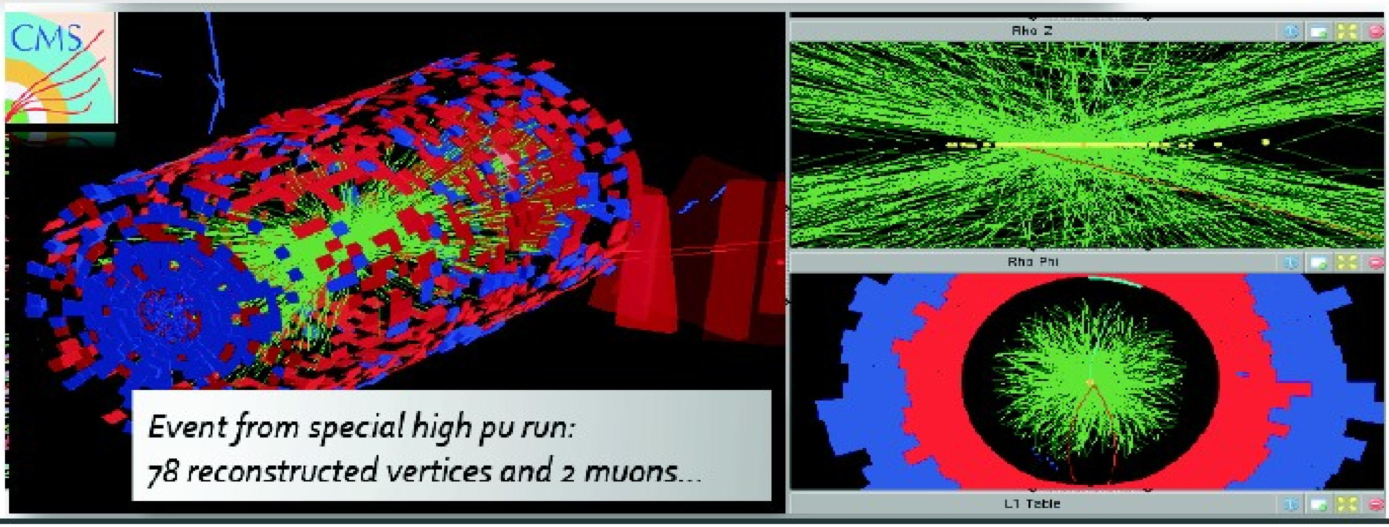


PU

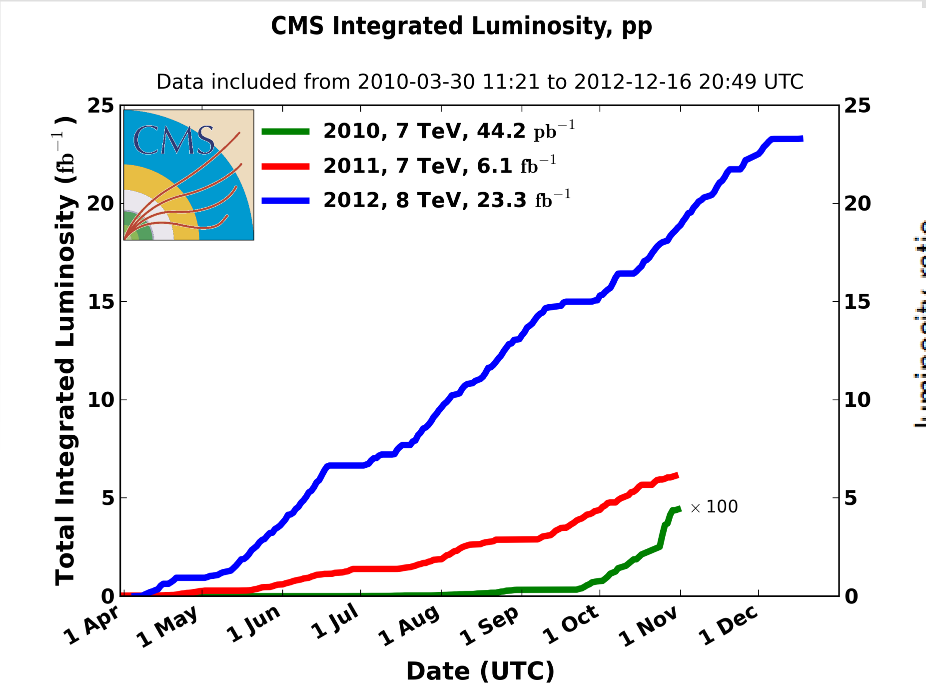


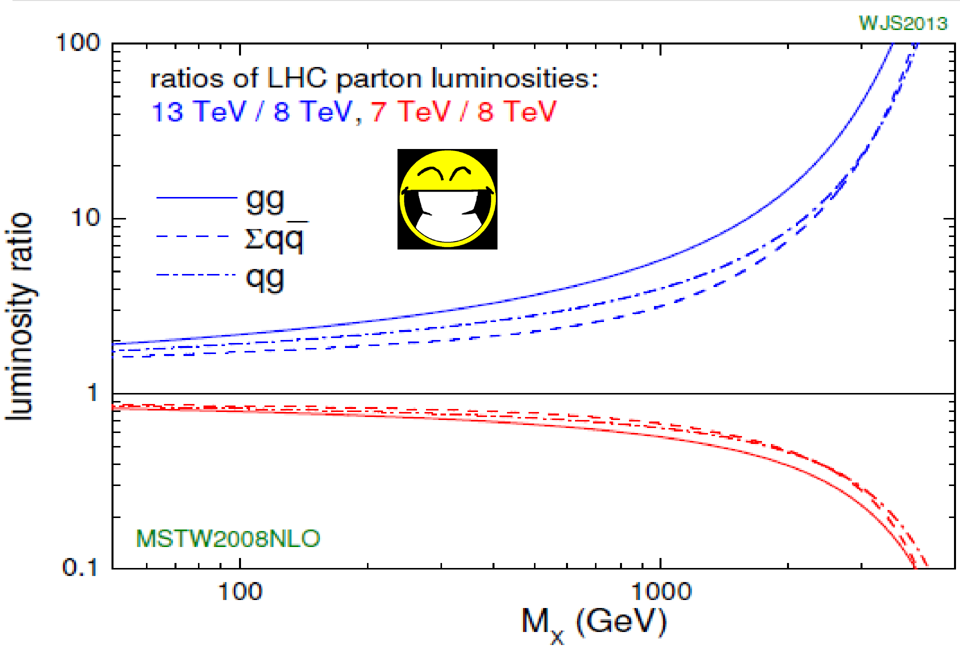
Peak: 37 pileup events

Design value
25 pileup events
(L=10^{34}, BX=25 ns)



Luminosity





- Produced Higgs bosons: 25 fb-1 * 2 experiments * 20 000 fb ~ 1 million!
- LHC project costed : 5 billion dollars

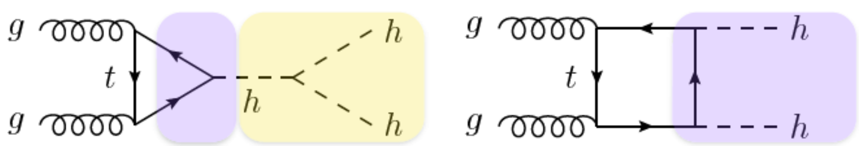
3.1) Non-resonant HH production: EFT and BSM

The relevant lagrangian terms of gg→HH production in D=6 EFT

$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H + c_6\right)h^3 + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a - \left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \mathrm{h.c.}\right] - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \mathrm{h.c.}\right]$$

arXiv:1410.3471

Non SM Yukawa coupling is not considered

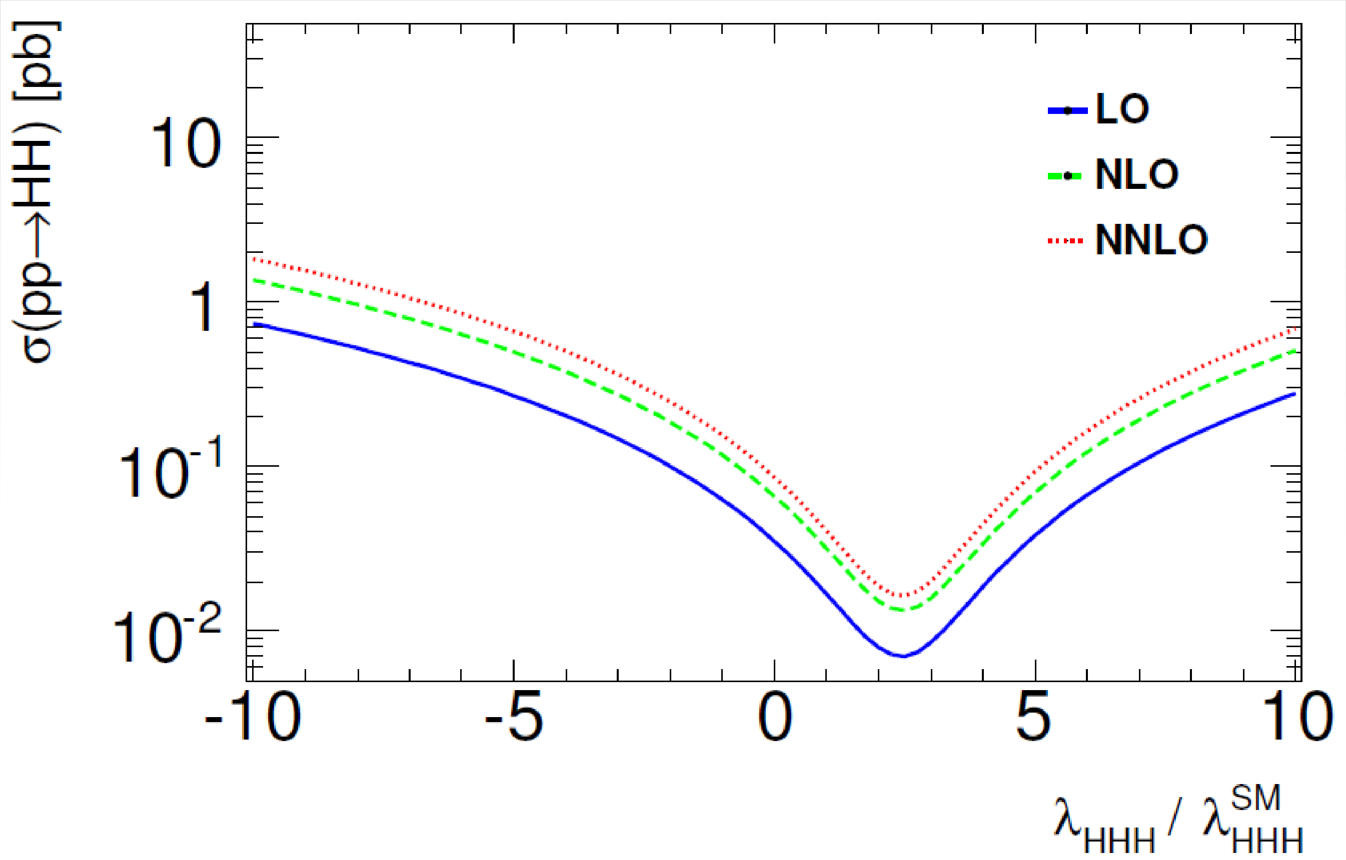


SM diagrams

ttHH non-linear interaction **Higgs-gluon contact interactions**

- Five relevant operators for HH sector. Differs mainly by MHH kinematics.
- Within some approximation (top loop predominant contribution) k = NNLO/LO is same than for SM.
- S-wave dominated: no significant difference in cos(θ^*_{HH}) between operators.

3.1) Non-resonant HH production: EFT and BSM



- Five relevant operators for HH sector. Differs mainly by MHH kinematics.
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