Laboratoire d'Annecy-le-Vieux de Physique des Particules

HH measurements in ATLAS and CMS

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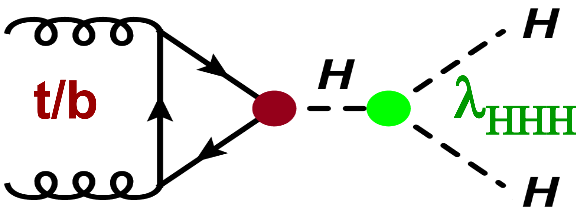
On behalf of the ATLAS and CMS collaborations

HL-LHC and HE-LHC workshop

CERN, 31st October 2017

Motivation for HH studies



Higgs self-coupling

- HH cross-section and differential distributions sensitive to

  the Higgs boson trilinear coupling (λ_{HHH})

  → Probe ElectroWeak Symetry Breaking

  → Measure the shape of Higgs potential

- Possible deviations or limits can be parametrised

  by low-energy effective Lagrangian (EFT)

Non-resonant double Higgs cross section

$\sigma^{SM}_{gg\rightarrow HH}$(14 TeV)=39.56 fb @ NNLO_NNLL with top mass effects, (arXiv.1610.07922)

with relative error in % : $^{+4.4}_{-6.0}$ (scale)±2.1 (PDF)±2.2(α_s)

→ *~120k events at HL-LHC*

$\sigma_{gg\rightarrow HH}$~33 fb @ 13 TeV → *O(1200) events in 2017 LHC data (40 fb^{-1})*

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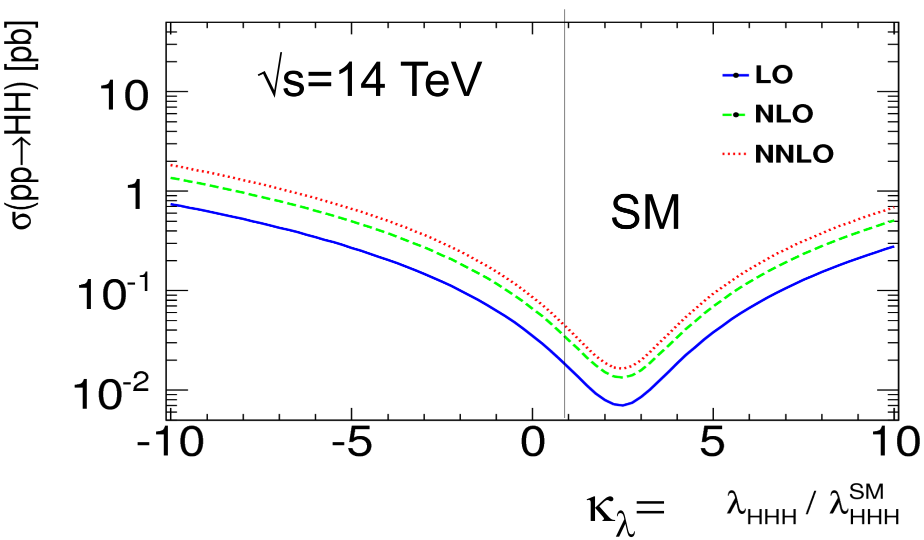
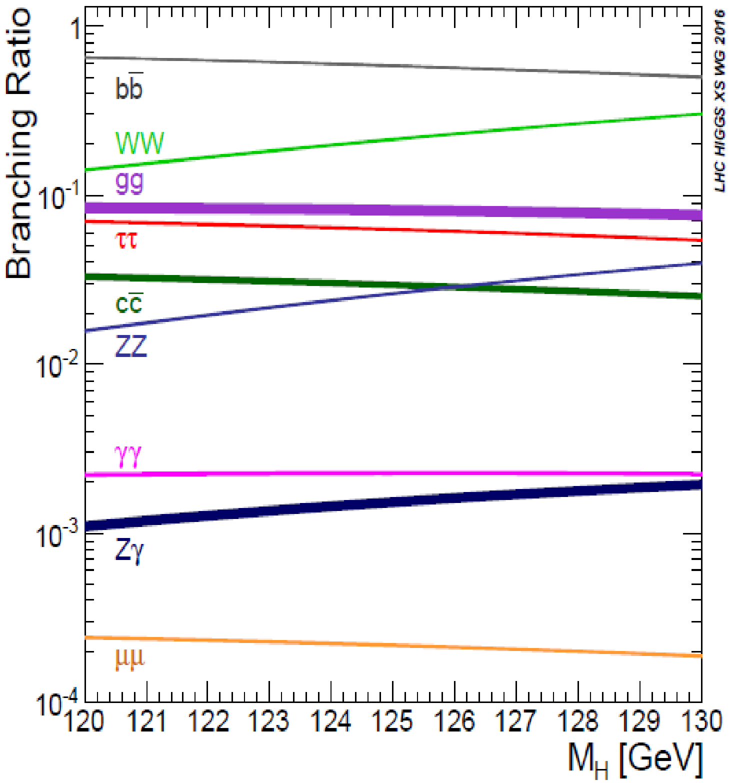
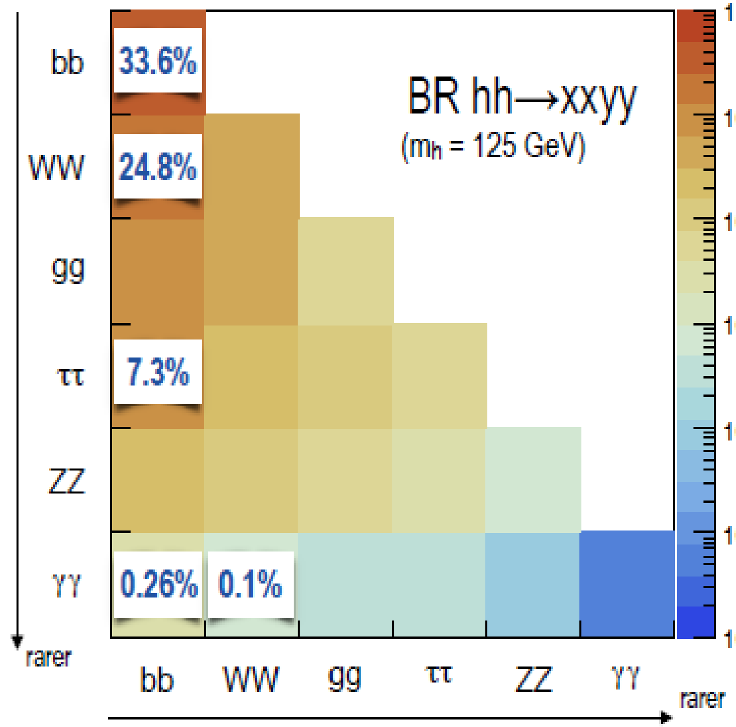


- LO→ NNLO_NNLL: Factor ~2
- Shape almost independant on √s

More in G. Heinrich talk

HH decay branching ratio



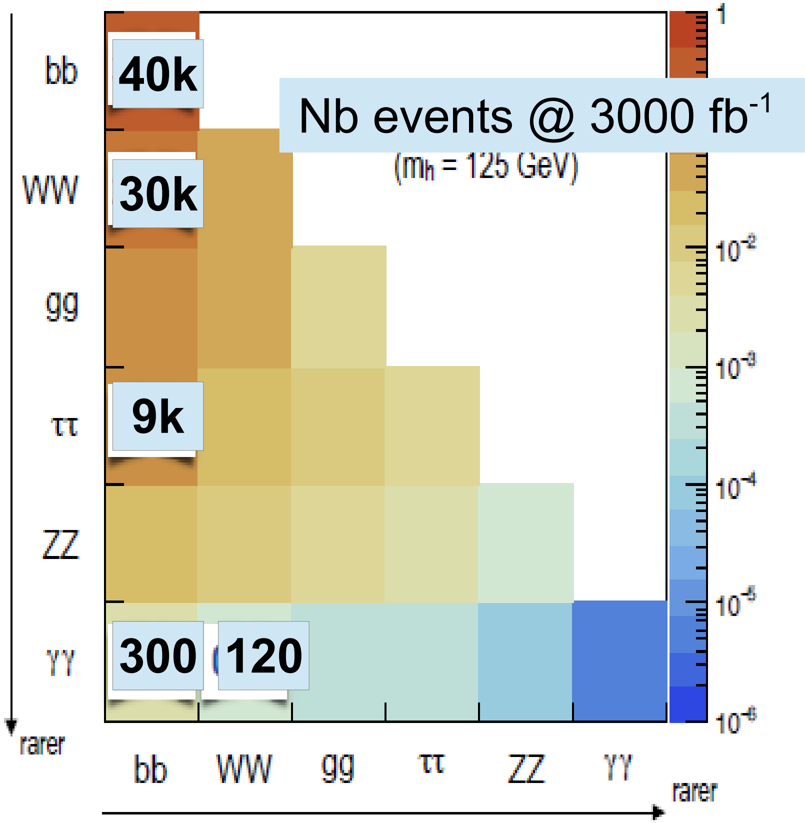


Final state particles mainly produced in the central part of the detectors

→ Within acceptance of current trackers

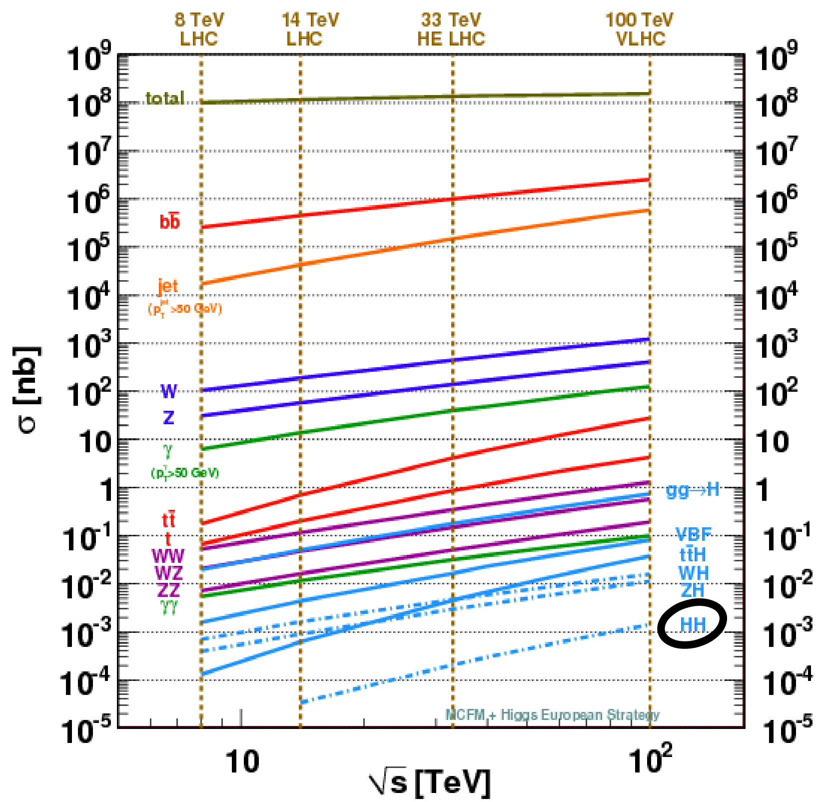
→ Direct extrapolation from Run2 to HL-LHC : Good first approximation

HH decay channels



- bbbb :
  - Large number of signal events
  - Large QCD and $t\bar{t}$ background
- bbWW :
  - Large number of signal events
  - Large $t\bar{t}$ background
- bb$\tau\tau$
  - Balance between purity and efficiency
- bb$\gamma\gamma$
  - Low number of signal events
  - Narrow H → $\gamma\gamma$ mass window with low background
- WW$\gamma\gamma$

Background contamination



Process	Generator	$\sigma \cdot BR$ [fb]	Order QCD	Equivalent Lumi. [fb^{-1}]
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 1$	MadGraph5/Pythia 8	0.11	NNLO	5.5×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 0$	MadGraph5/Pythia 8	0.23	NNLO	1.3×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 2$	MadGraph5/Pythia 8	0.05	NNLO	6.1×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 10$	MadGraph5/Pythia 8	1.81	NNLO	0.2×10^6
$ggF(\gamma\gamma)$	Powheg-Box/Pythia 6	1.2×10^2	NNNLO	8.1×10^3
$t\bar{t}H(\gamma\gamma)$	Pythia 8	1.40	NLO	7.1×10^4
$ZH(\gamma\gamma)$	Pythia 8	2.24	NLO	4.4×10^4
$b\bar{b}H(\gamma\gamma)$	Pythia 8	1.26	NLO	4.2×10^6
$b\bar{b}\gamma\gamma$	MadGraph5/Pythia 8	1.4×10^2	LO	1.8×10^4
$c\bar{c}\gamma\gamma$	MadGraph5/Pythia 8	1.1×10^3	LO	3070
$jj\gamma\gamma$	MadGraph5/Pythia 8	1.6×10^4	LO	2460
$b\bar{b}j\gamma$	MadGraph5/Pythia 8	3.8×10^5	LO	130
$c\bar{c}j\gamma$	MadGraph5/Pythia 8	1.1×10^6	LO	36
$b\bar{b}jj$	MadGraph5/Pythia 8	4.6×10^8	LO	0.005
$Z(\to b\bar{b})\gamma\gamma$	MadGraph5/Pythia 8	5.07	LO	2.0×10^4
$t\bar{t}(\geq 1\text{lepton})$	Powheg-Box/Pythia 6	5.3×10^5	NNLO	5.7×10^2
$t\bar{t}\gamma(\geq 1\text{lepton})$	MadGraph5/Pythia 8	5.0×10^3	NLO	2×10^3

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Example : HH → bbγγ

- Irreducible background (Cross-section : 1000 * signal)
- Single H (Cross-section : 10-1000 * signal)
- Reducible (Cross-section : Up to 10^9 * signal)

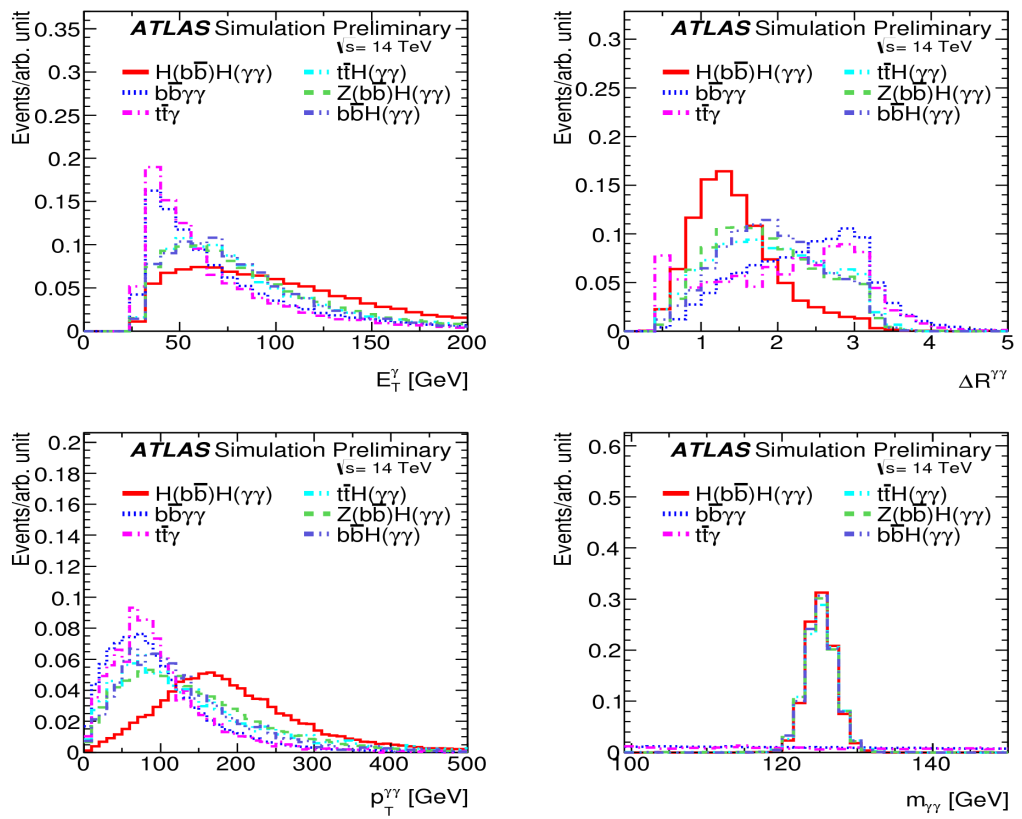
Can be worse for other HH decay channels

Analysis strategy

Main selection criteria

- Particle identification
- Single particle P_T / η acceptance
- Invariant mass
- Angles between particles

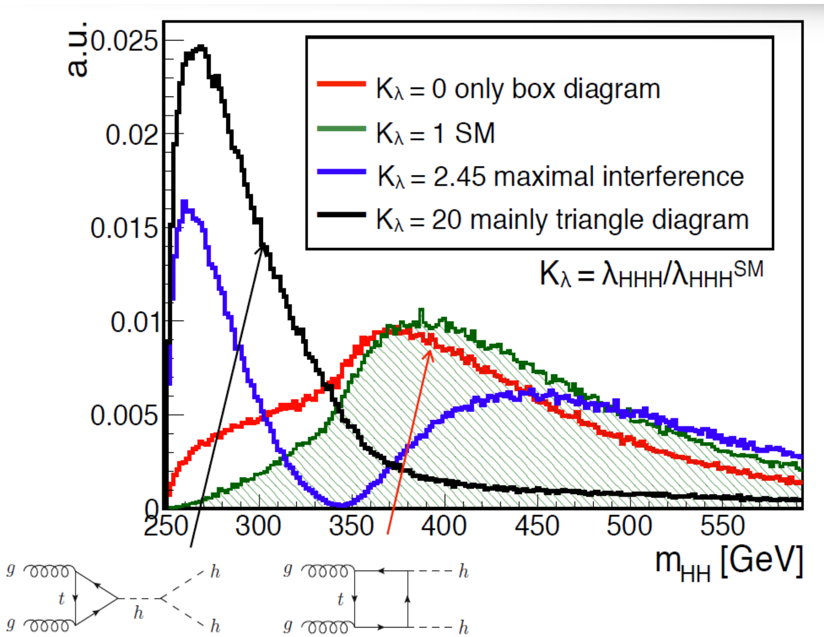
Cut flow vs MVA selection
+
Count vs fit methods



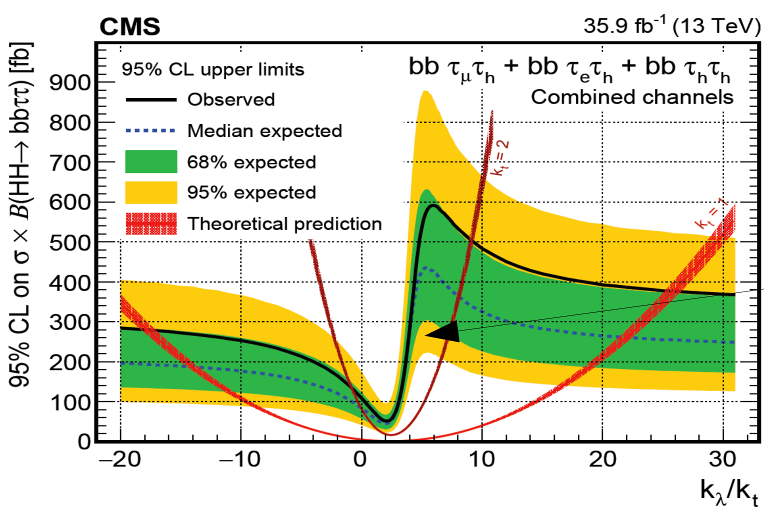
HH significance expected at HL-LHC

S/√B ~O(2-0.3) per channel

HH : self-coupling sensitivity



CMS-HIG-17-002



- Current analysis selection optimised to maximise significance for SM
- m_{HH}, Pt(H), ... distributions sensitive to coupling

  → Optimal selection cuts not identical to maximise significance versus minimise coupling limits

Selection efficiency depends on κ_λ

Technical challenges

- Detector operation in HL-LHC environment
  → Adressed now with detector optimisation and R&D

- Full simulation and reconstruction of signal/background not possible at HL-LHC scale (nb background events, CPU and memory consumption / event)

  - Solution 1 : Extrapolate from Run2 results
    - Issue : Estimation of pileup effect and performances of new detector

  - Solution 2 : Events described at particle level convoluted with parametrised detector response (efficiency, resolution, fake rate) : '*smearing function*'
    - Issue : Usually QCD background level/shapes not well modeled

- Large datasets → systematic uncertainty can become critical
  - How to estimate future systematics ?
    - Extrapolate from current Run-1/Run-2 systematics
    - Background control with data driven methods

Run1/2 results

- ATLAS : $\sigma/\sigma_{SM} < 48$ @ 95% C.L. CERN-PH-EP-2015-225
- CMS : $\sigma/\sigma_{SM} < 43$ @ 95% C.L. CMS-PAS-HIG-15-013

} Run-1

95 % C.L. limits on $\mu=\sigma/\sigma_{SM}$
Observed/(Expected)

Channel	**ATLAS**	**CMS**
bbbb	29 (38)	342 (308)
bbVV		79 (89)
$bb\tau\tau$		28 (25)
$bb\gamma\gamma$	117 (161)	19 (17)
$WW\gamma\gamma$	747 (386)	

green	3 fb^{-1}
red	13 fb^{-1}
blue	36 fb^{-1}

Run2

2015-2016 Run-2 data : Better limit than Run1

$HH \rightarrow bb\gamma\gamma$ (B.R. ~0.3%)

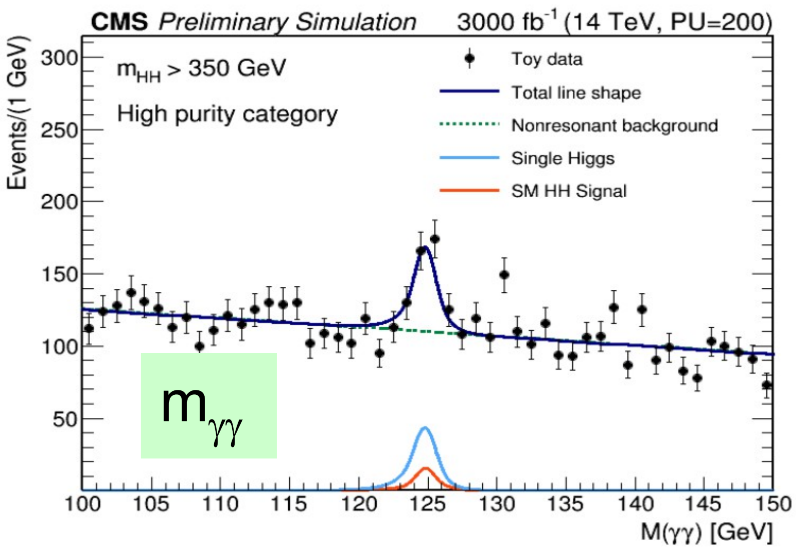
CMS-PAS-FTR-16-002

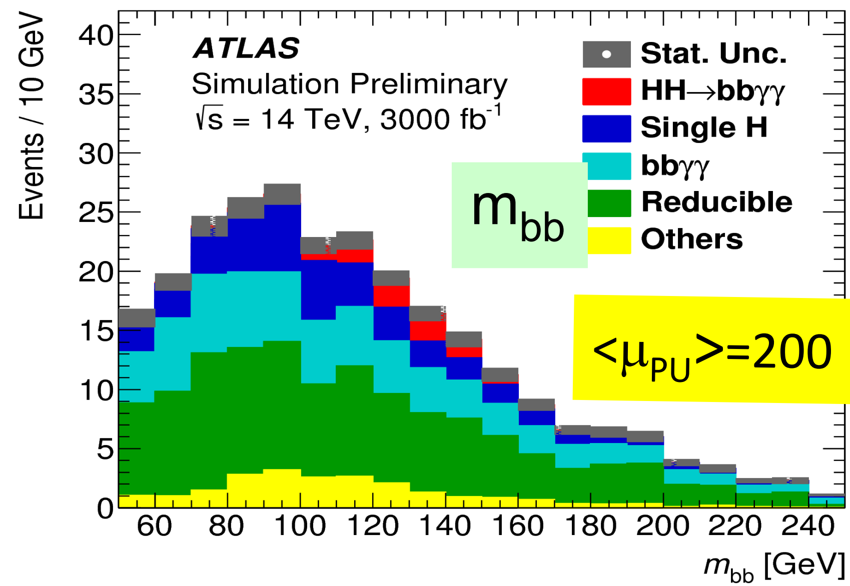
ATL-PHYS-PUB-2017-001

2 b-tagged jets + 2 photons :

Narrow γγ mass peak, m(bb), ΔR (γγ), ΔR(bb)

CMS-TDR-17-002





HH → bbγγ : Significance

Smearing function approach

- Cut and count method
- 2.9 % signal efficiency
- No syst. uncertainty

Channel	Nb events
Single H	15.8
Irreducible bbγγ	21.8
Reducible (bbjγ,…)	53.4
Signal	9.5

→ Significance : 1.05 σ

Extrapolation from Run2 analysis/data
(CMS-PAS-HIG-16-032)

- 2D fit of m(γγ) – m(bb) distributions
- **Syst. uncertainty:**S2+ scenario

→ Significance : 1.43 σ

HH → bbbb (B.R. ~33%)

CMS-PAS-FTR-16-002

ATL-PHYS-PUB-2016-024

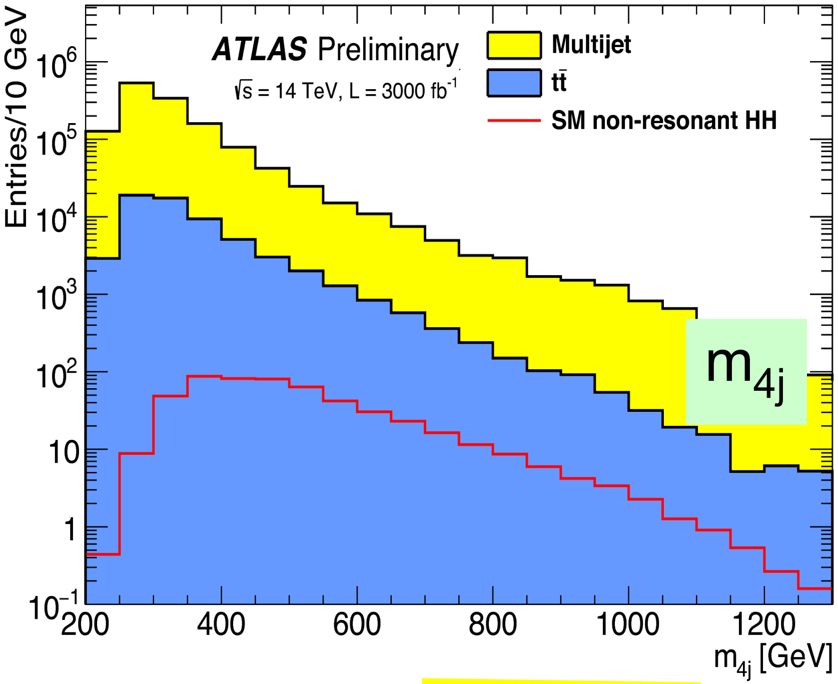
HH → bbbb : Selection

4 b-tagged jets :

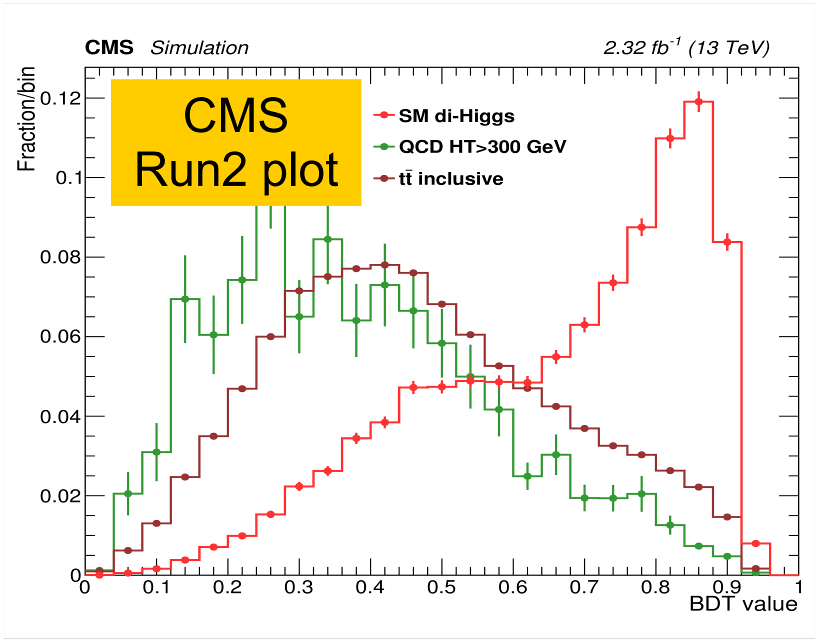
m(4 jets), b pairings matching m_H

Extrapolation from Run2 analysis/data (ATLAS+CMS)

Main background : multijet, $t\bar{t}$



$<\mu_{PU}>=200$

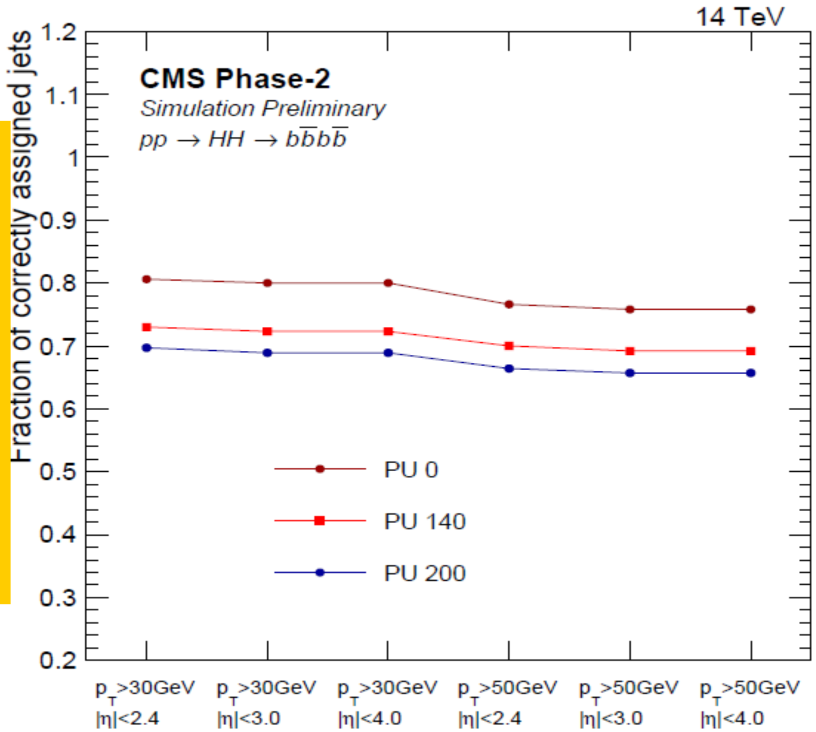


CMS-PAS-HIG-16-026

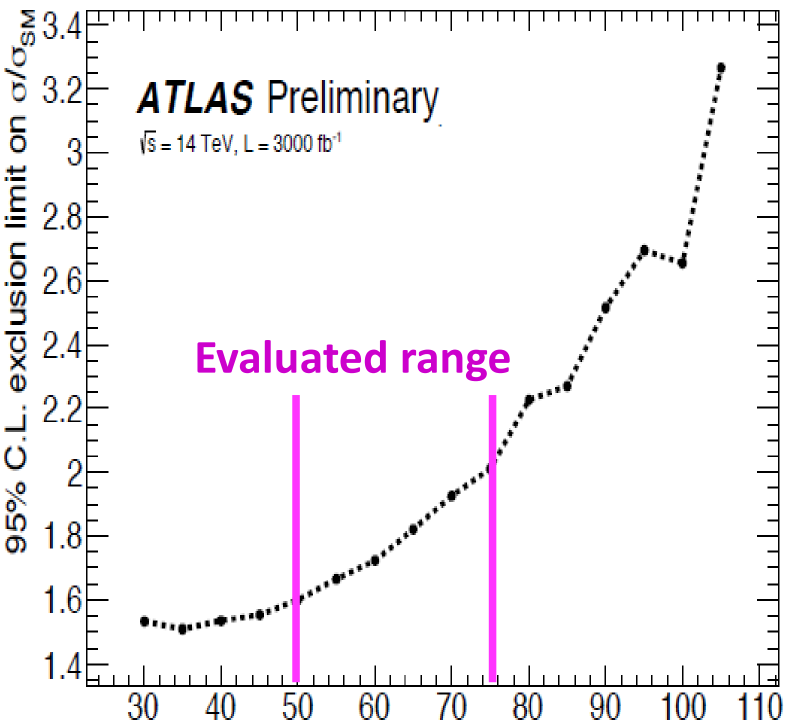
→ Significance : 0.39 σ

HH → bbbb : Significance degradation

CMS-TDR-17-001



Wrong/correct pairing assignment



4-jet trigger p_T threshold

- Run 2 : 30 GeV
- HL-LHC : 50-70 GeV

→ Up to 30% loss in sensitivity

HH → $bb\tau\tau$ (B.R. ~7.3%)

CMS-PAS-FTR-16-002

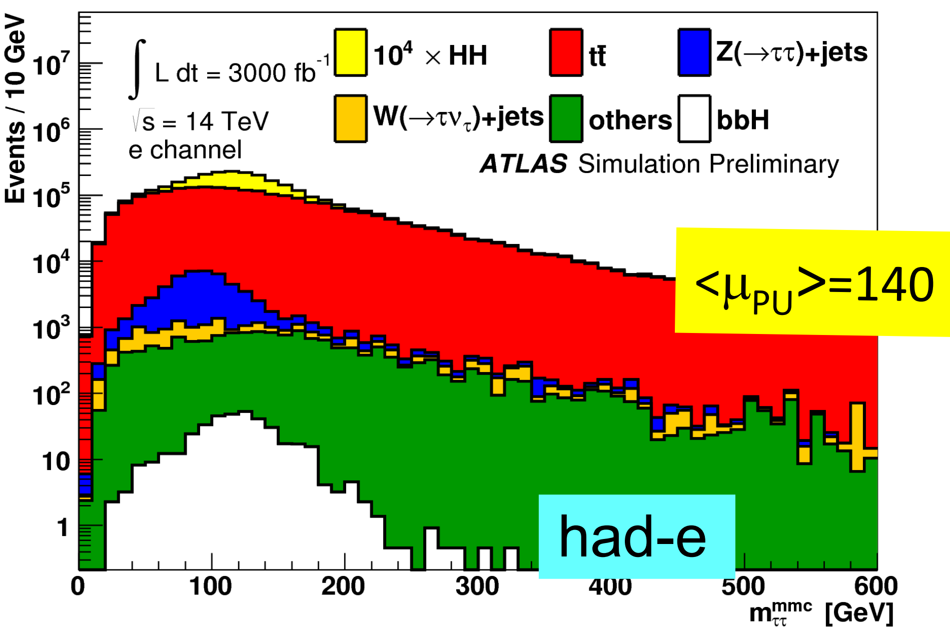
ATL-PHYS-PUB-2015-046

HH → bbττ : Selection

2 b-tagged jets + 2 τ (fully hadronic or semi-leptonic): m(bb), m(ττ)

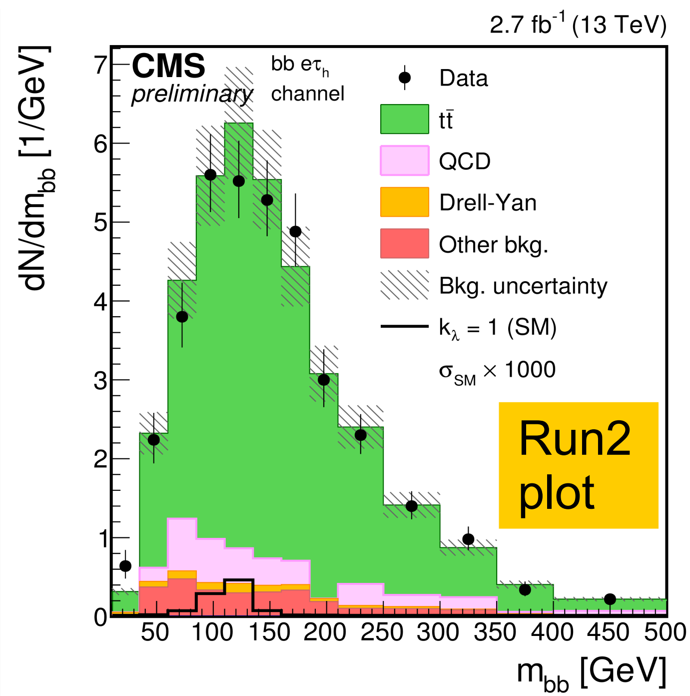
- Main backgrounds : had-e/μ : $t\bar{t}$
  had-had : Z→ττ + jets, $t\bar{t}$

Smearing function approach



$m_{\tau\tau}$

Extrapolation from Run2

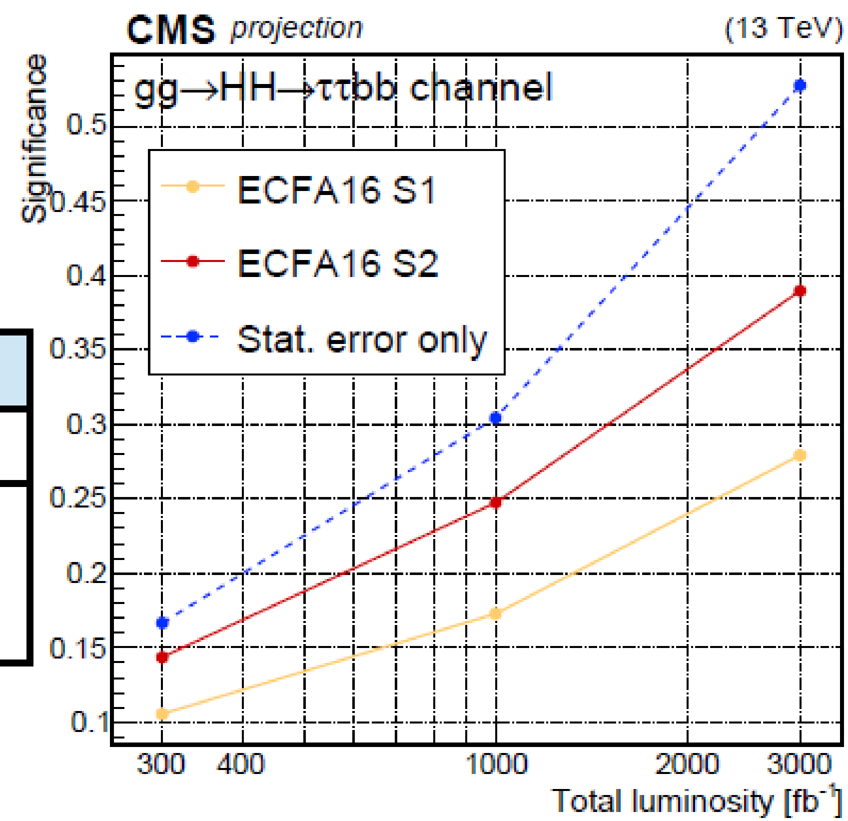


CMS-PAS-HIG-16-012

HH → bbττ : Significance

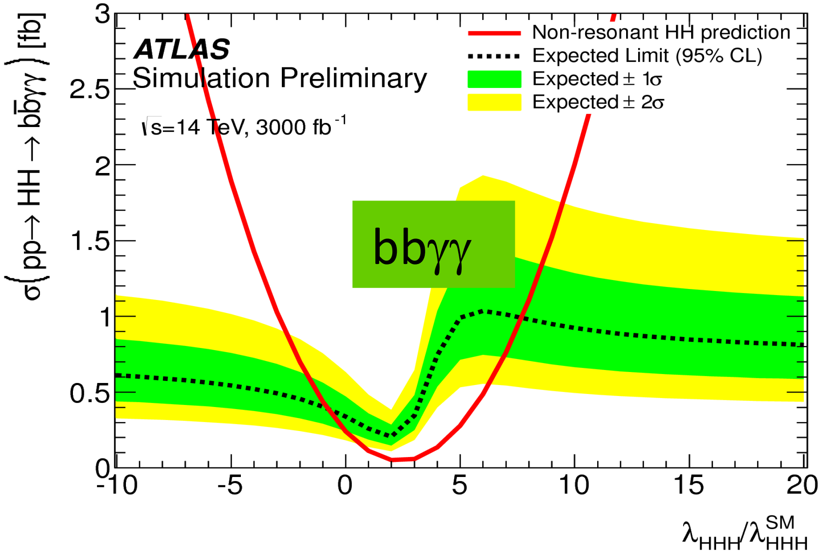
ATLAS Projection (3 ab^{-1})		
Channel	Significance	Combined
e/μ + jets	0.43	0.60
$\tau_{had}\tau_{had}$	0.41	

- **Syst. Uncertainty:** Run 1

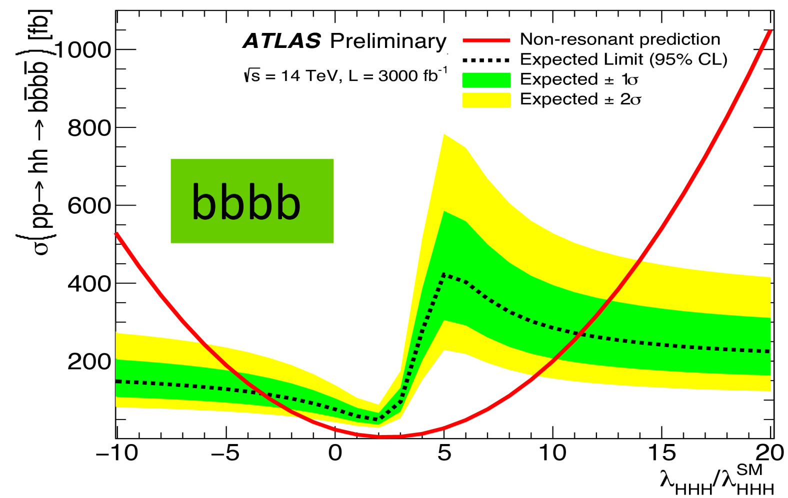


→ Significance : 0.39 σ

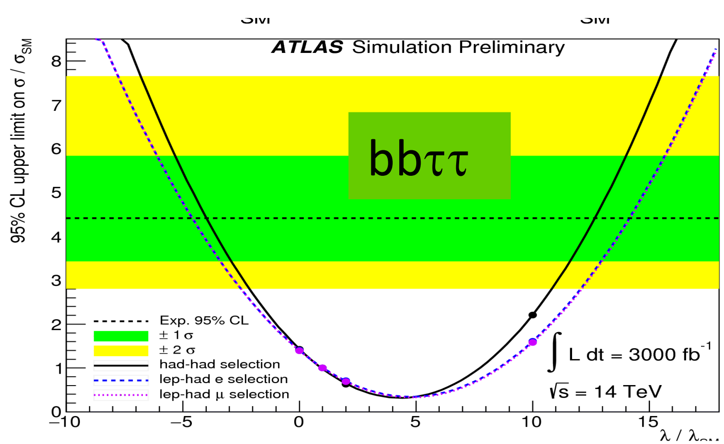
Coupling limits (@ 95% C.L.)



-0.8< $\lambda_{HHH}/\lambda_{SM}$<7.7 (no syst.)



-3.5< $\lambda_{HHH}/\lambda_{SM}$<11 (Run2 syst.)



-4< $\lambda_{HHH}/\lambda_{SM}$<12 (Run1 syst.)

ATLAS combination expected in 2018

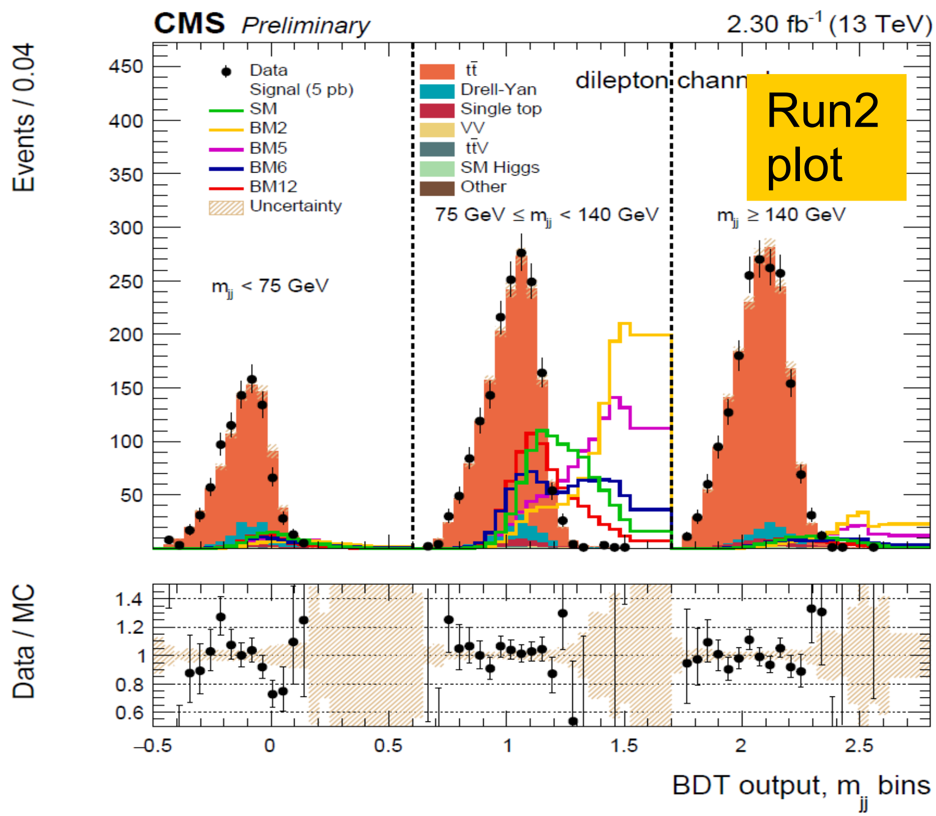
$HH \rightarrow bbVV \rightarrow bb\ell\nu\ell\nu$ (B.R. ~1.8%)

CMS-PAS-FTR-16-002

HH → bbVV → bbℓνℓν

2 b-tagged jets + 2 leptons + missing E_T

- Main background (estimated from data) : $t\bar{t}$, Drell-Yan



CMS-PAS-HIG-16-024

→ Significance : 0.45 σ

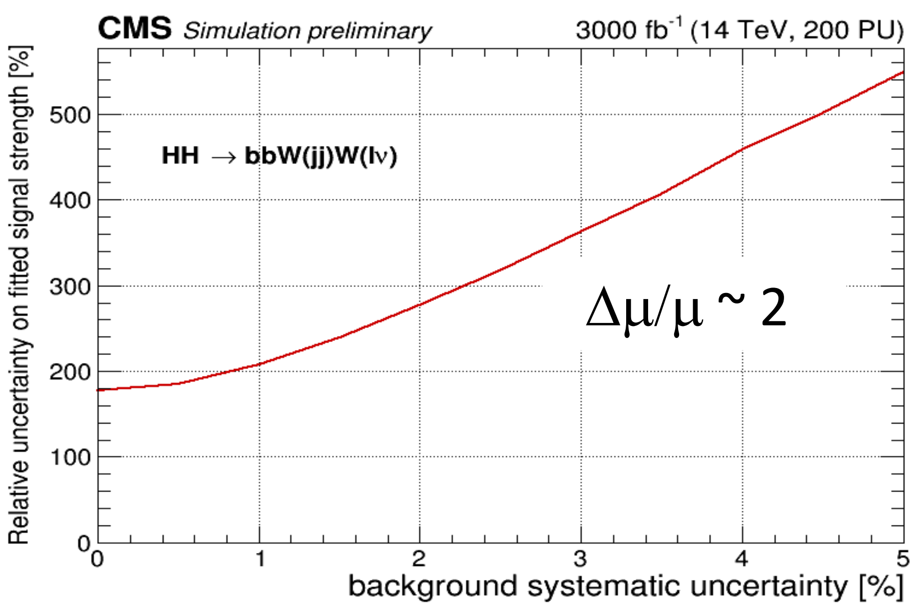
$HH \rightarrow bbWW \rightarrow bb\ell\nu qq$ (B.R. ~2.5%)

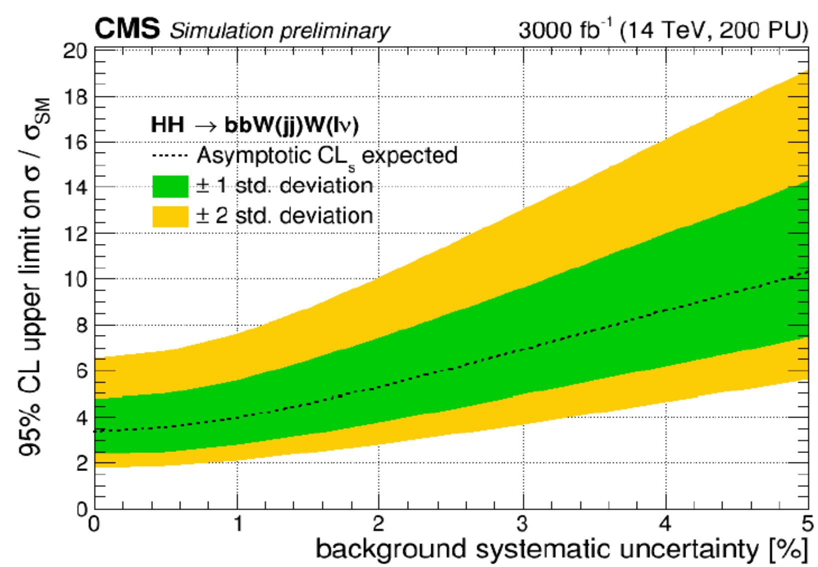
CMS-PAS-FTR-16-002

HH → bbWW → bblνqq

2 b-tagged jets + ≥ 2 jets + 1 e/μ + missing E_T

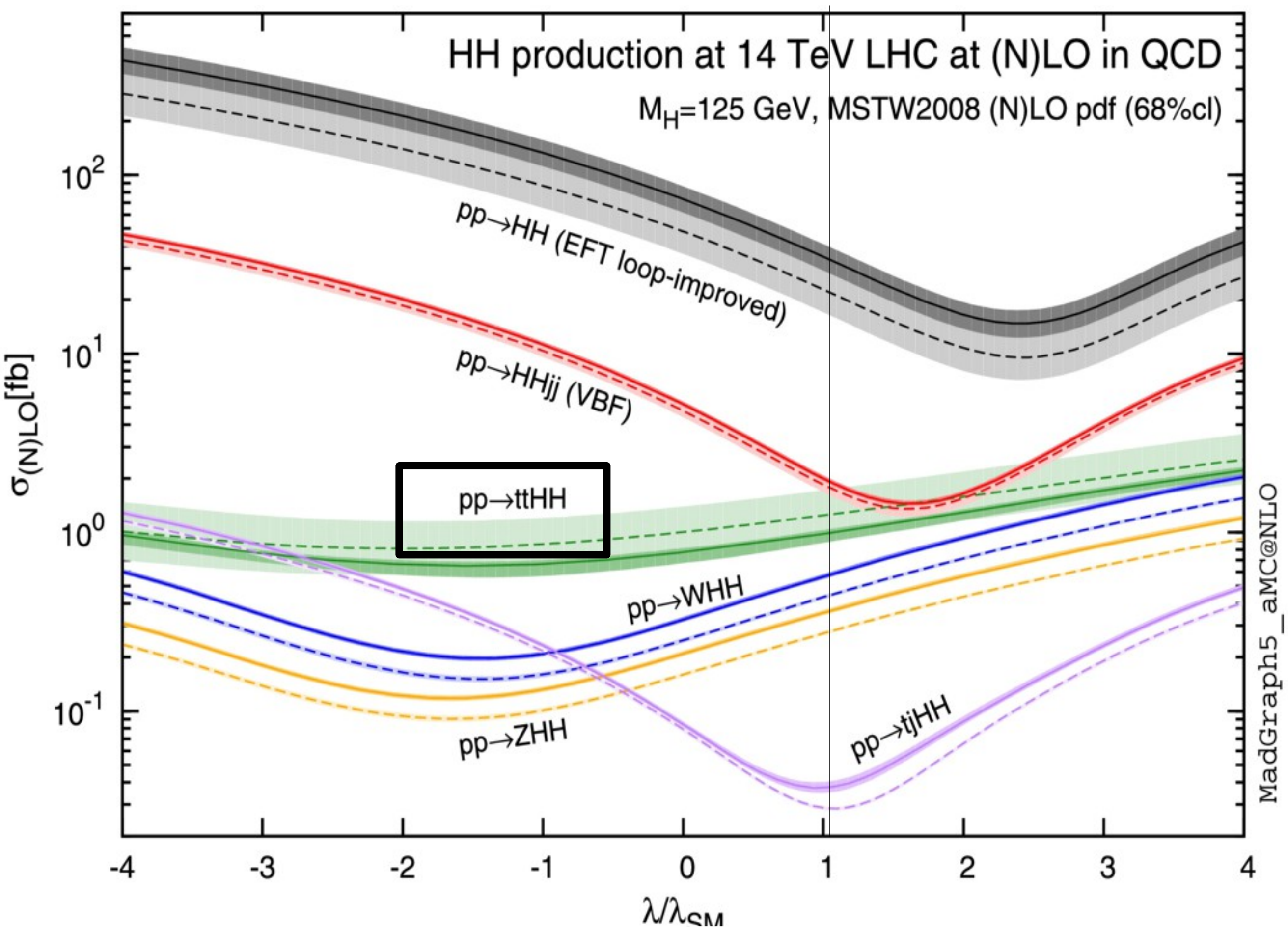
- Parametrised studies with fast simulation (DELPHES)
- √s=14 TeV with μ=200
- Main background : $t\bar{t}$ (cross section 10^5 higher than signal)
- Boosted Decision Tree (BDT) based on kinematic variables
  → 68 signal events for 8696 background ones





HH : Associated production

Phys. Lett. B732 (2014) 142-149



No destructive interference → σ_{ttHH}~1 fb

Lower cross sections than HH by at least factor 10

$t\bar{t}HH$, $HH \to b\bar{b}b\bar{b}$

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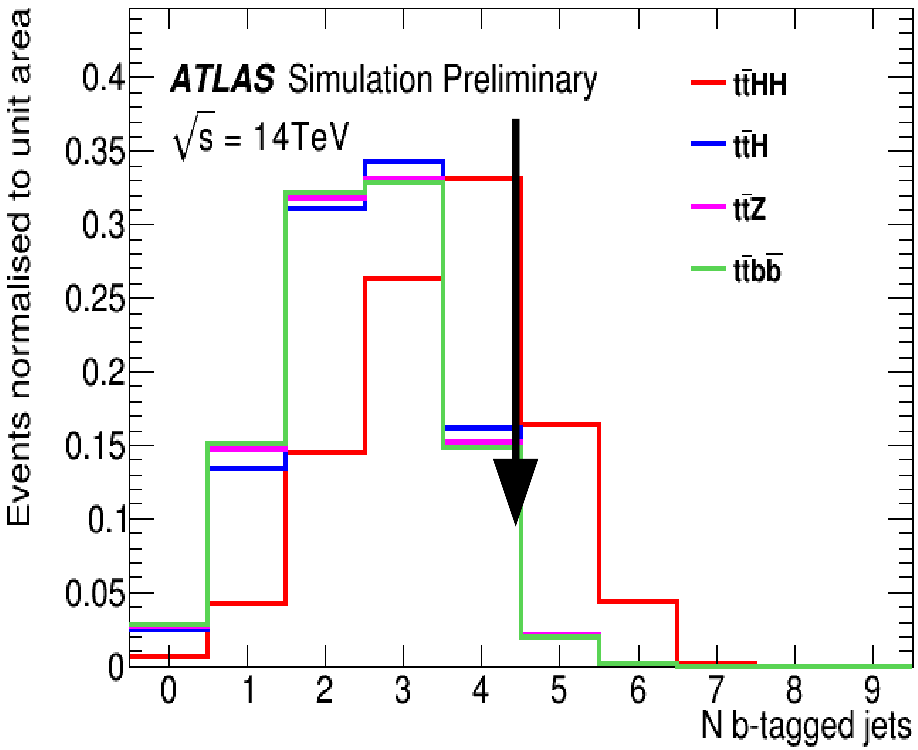
$<\mu_{PU}>=200$



- Final states :
  - $t\bar{t}$: semileptonic
  - HH → 4b
    - → 6 b-jets + 2 light jets
    - \+ e or μ + missing-E_T
- Cut based analysis:
  - Main variables : Nb b-tagged jets, angle between jets
  - For ≥5 b-tag jets : 25 signal events and 7100 background (mainly $t\bar{t}b\bar{b}$ + jets)

→ Significance : 0.35 σ

Expected HH results at HL-LHC

HH final state	ATLAS Significance Coupling limit (95 % C.L.)	CMS Significance
$HH \rightarrow b b \gamma\gamma$	1.05 σ $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$	1.43 σ
$HH \rightarrow b b \tau\tau$	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$	0.39 σ
$HH \rightarrow bbbb$	$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11.0$	0.39 σ
$HH \rightarrow bbVV$		0.45 σ
ttHH, HH-> bbbb	0.35 σ	

Improved results already in the pipeline (especially for HL-LHC TDRs)

Conclusion

HH physics is one of the benchmark channels for HL-LHC program

Current expected significance per experiment at the level of 0.5-1.5 σ

Improvement foreseen driven by :

- **Detector optimisation documented in the coming TDRs**
- **Analysis algorithms developed for Run2**
- **Combination of channels and experiments**
- **Optimisation of analysis for coupling limits**

Many improvements foreseen for the Yellow Report

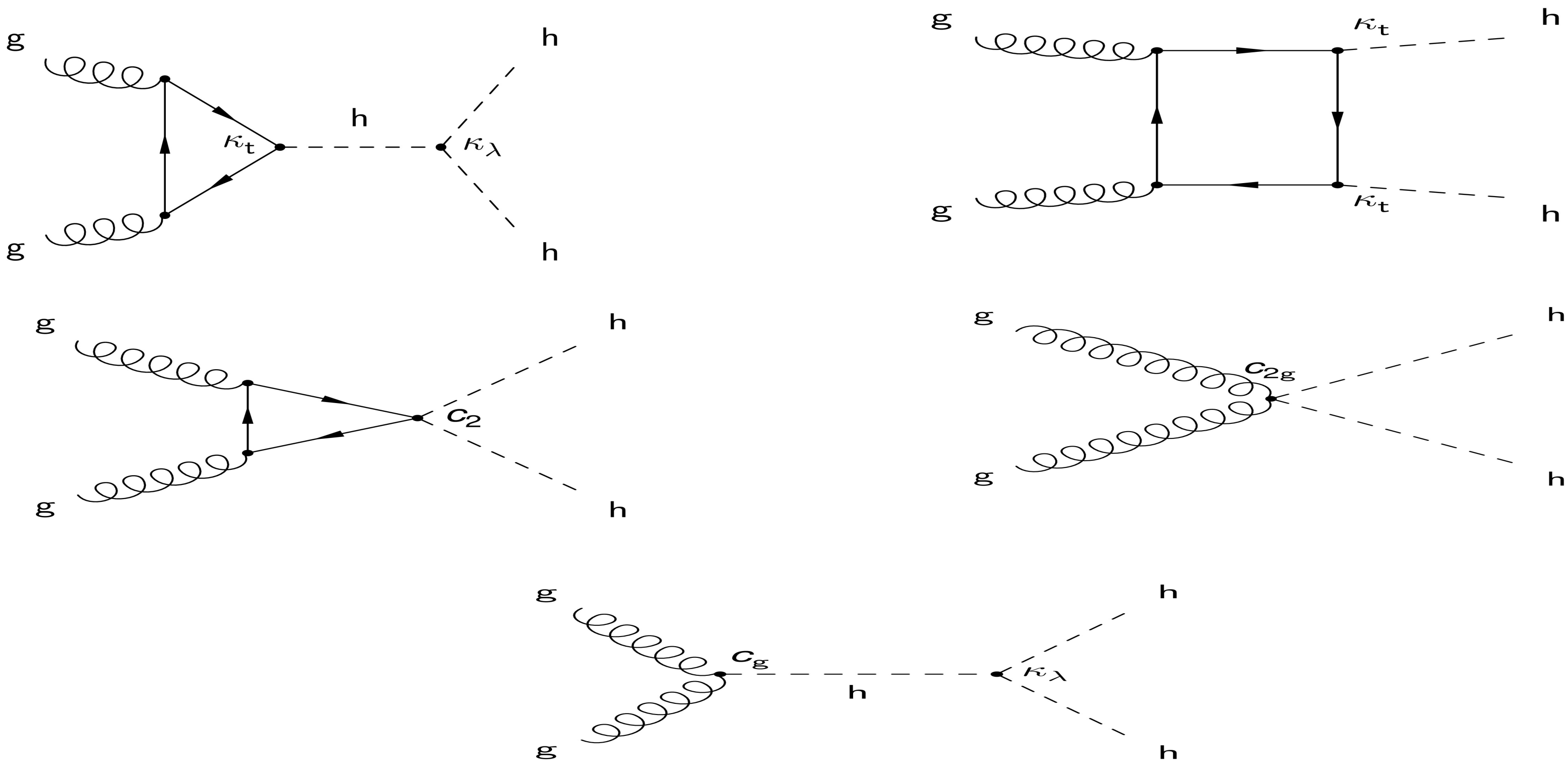
Posters

- **Prospects on HH production at the HL-LHC with the CMS experiment**
  S. Wertz

- **HH->bbyy and triple H coupling in ATLAS**
  D. Briglin

Backup slides

HH : Detailed production graphs



$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \, \lambda_{SM} v \, h^3 - \frac{m_t}{v}\left(v + \kappa_t \, h + \frac{c_2}{v} \, h \, h\right)\left(\bar{t_L} t_R + h.c.\right) + \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g \, h - \frac{c_{2g}}{2v} \, h \, h\right) G^{\mu\nu} G_{\mu\nu} \, .$$

ATLAS analysis strategy

- **Parametrised performances of upgraded detector layout**
  - Use fully simulated events with pile-up to parametrise efficiency/resolution for particle/object (e, γ, μ, τ, jet, missing-E_T)
  - Particles at event-generator level smeared according to these functions
  - Overlay with pile-up jets

- **Extrapolation from Run-2 results**
  - Assume similar detector performances and analysis approach as Run-2
  - Scale signal and background level to higher luminosity/CM

- **Theoretical systematics** : Implement the ones used for Run-2 publications (will have decreased by HL-LHC time)

- **Experimental systematics** : Scaled to best guess for ATLAS upgraded detector at HL-LHC

CMS analysis strategy

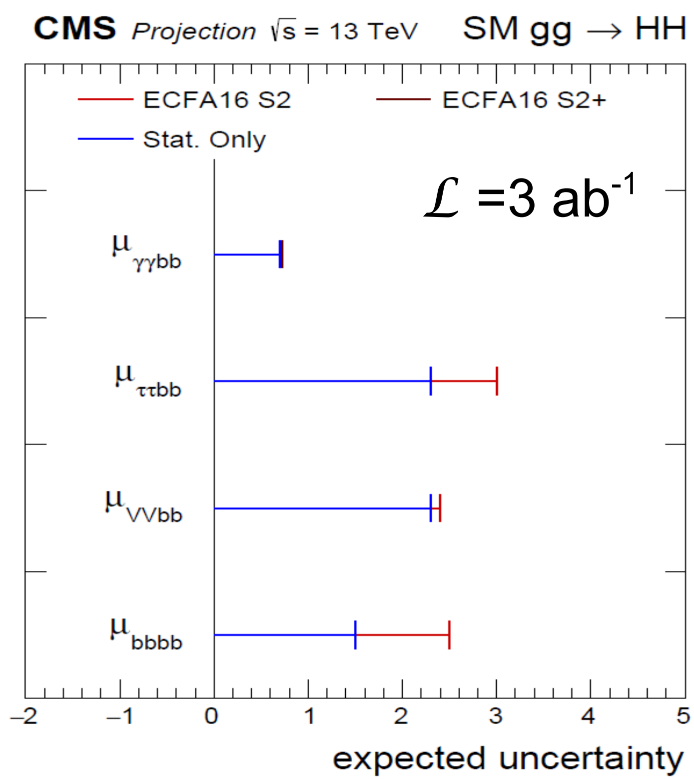
- Assuming $\sqrt{s}$=13 TeV and just extrapolate to HL-LHC luminosity
  → Underestimate significance by 15 %
- Data driven analysis from 2015 data (O(2 fb^{-1}))

- ECFA S1 :
  - Same CMS detector performance as in reference note
  - All systematic uncertainties kept constant with luminosity

- ECFA S2 :
  - Same CMS detector performances as in reference note
  - Theoretical uncertainties scaled down by factor 2
  - Experimental systematics scaling down with $\sqrt{\mathcal{L}}$ untill some limits

- ECFA S2+ :
  - Higher pileup and detector upgrades taken into account
  - Same treatment for systematic uncertainties as S2

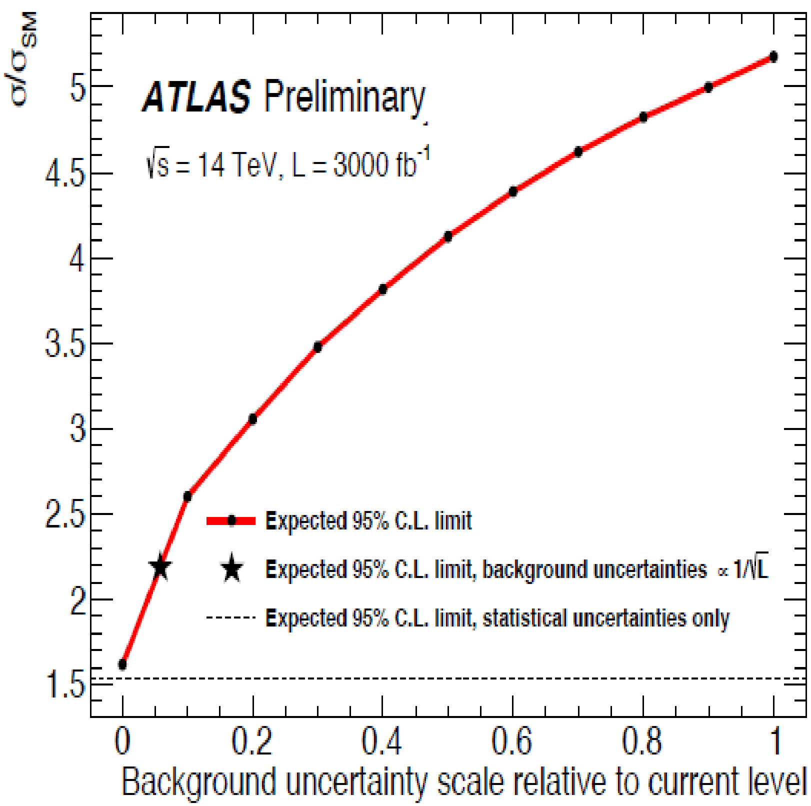
HH : CMS detailed numbers

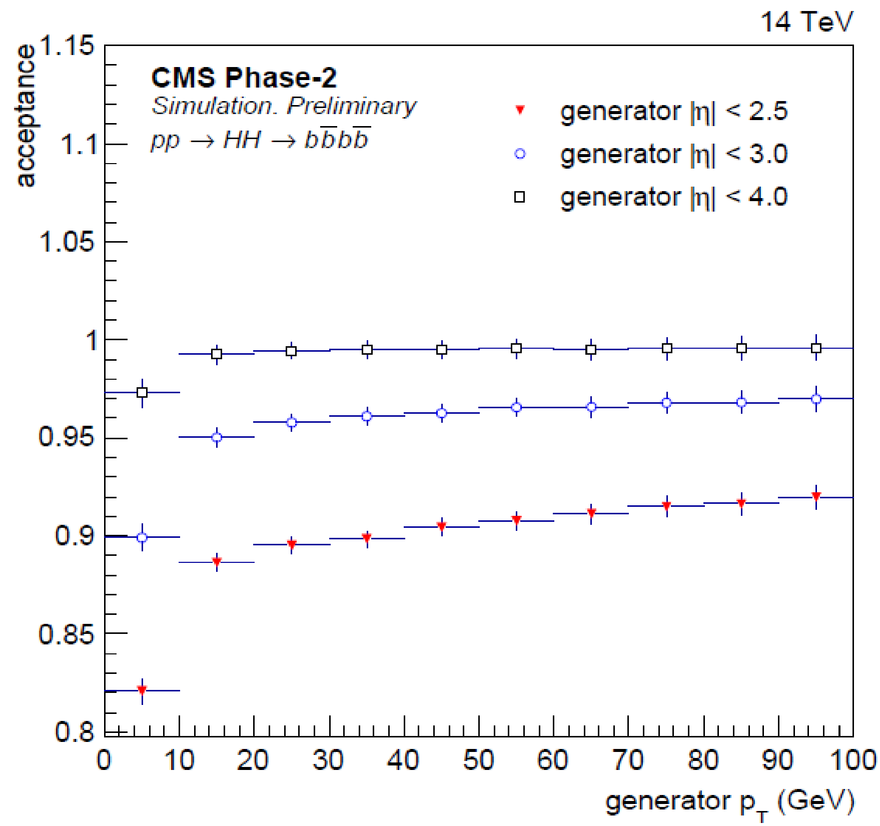


CMS-PAS-FTR-16-002

Channel	Median expected limits in μ_r		Z-value		Uncertainty as fraction of $\mu_r = 1$	
	ECFA16 S2	Stat. Only	ECFA16 S2	Stat. Only	ECFA16 S2	Stat. Only
$gg \to HH \to \gamma\gamma bb$ (S2+)	1.44	1.37	1.43	1.47	0.72	0.71
$gg \to HH \to \tau\tau bb$	5.2	3.9	0.39	0.53	2.6	1.9
$gg \to HH \to VVbb$	4.8	4.6	0.45	0.47	2.4	2.3
$gg \to HH \to bbbb$	7.0	2.9	0.39	0.67	2.5	1.5

HH → bbbb : Significance degradation)backup)





Systematic uncertainty
from Run2 data

Run1 results

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

ATLAS

Phys. Rev D 92, 09004 (2015)

CMS (CMS-HIG-15-013) : $\sigma/\sigma_{SM} < 43$ @ 95% C.L. ($bb\gamma\gamma + bb\tau\tau$)

HH → $b\bar{b}\gamma\gamma$: all mass distributions

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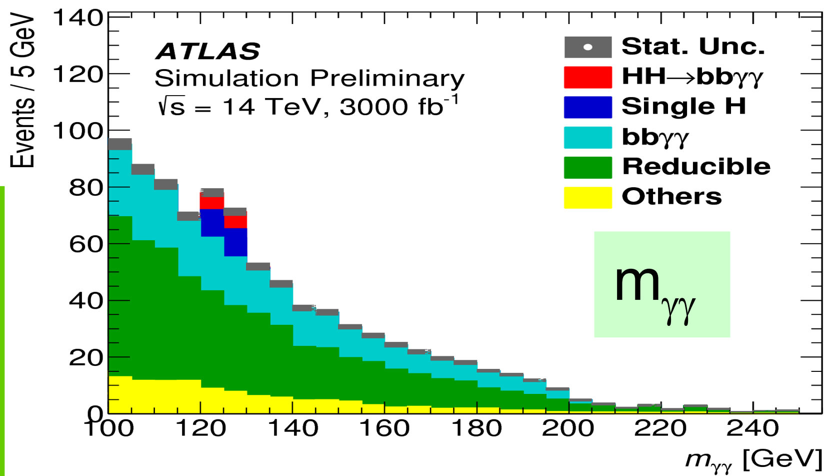
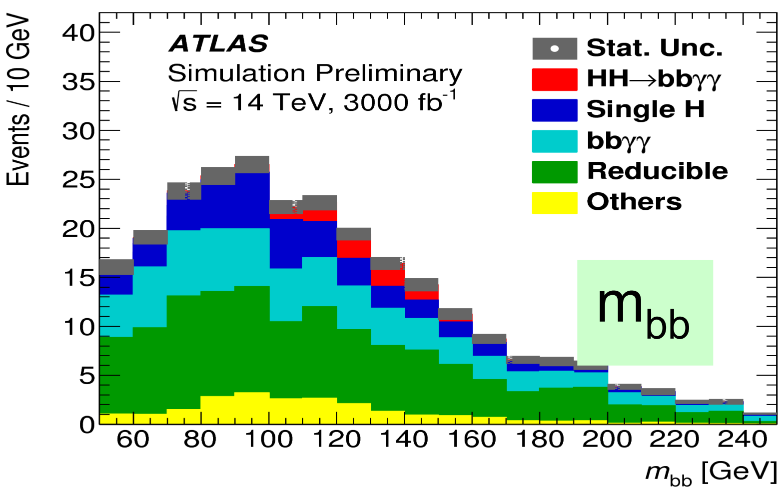
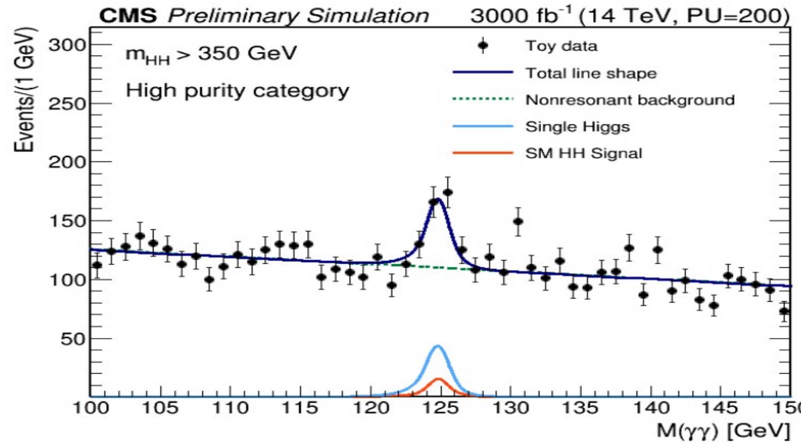
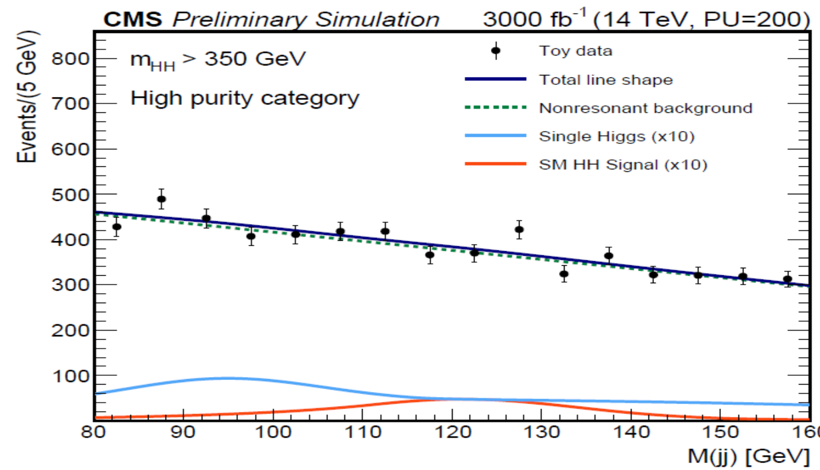




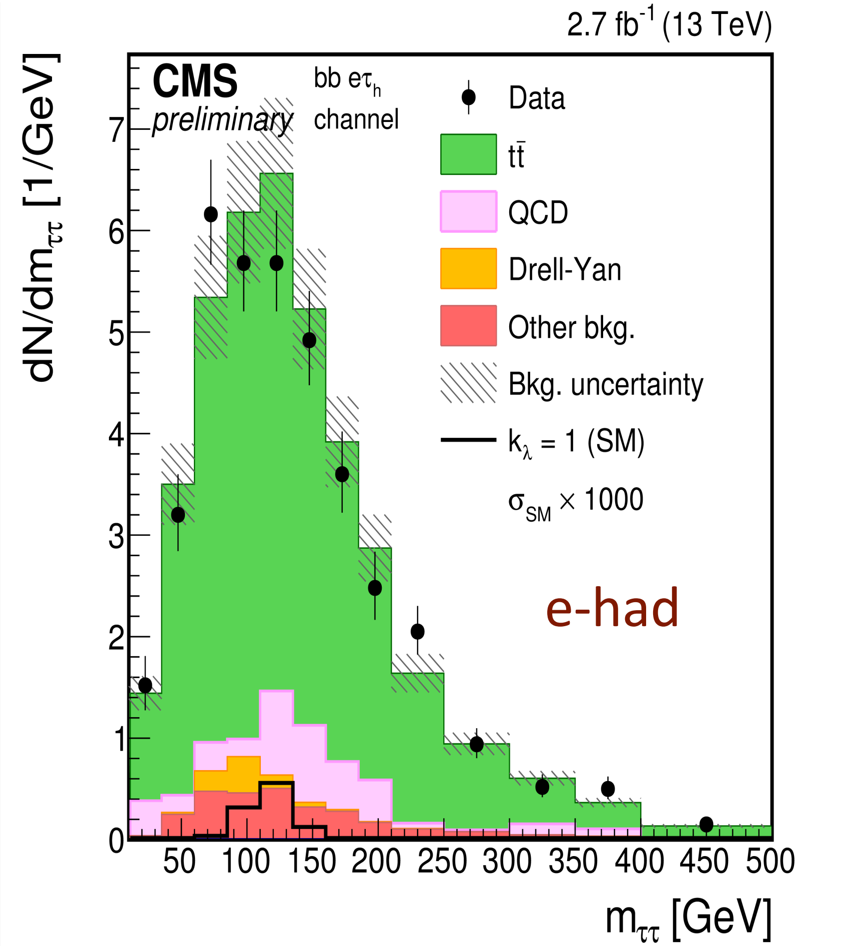


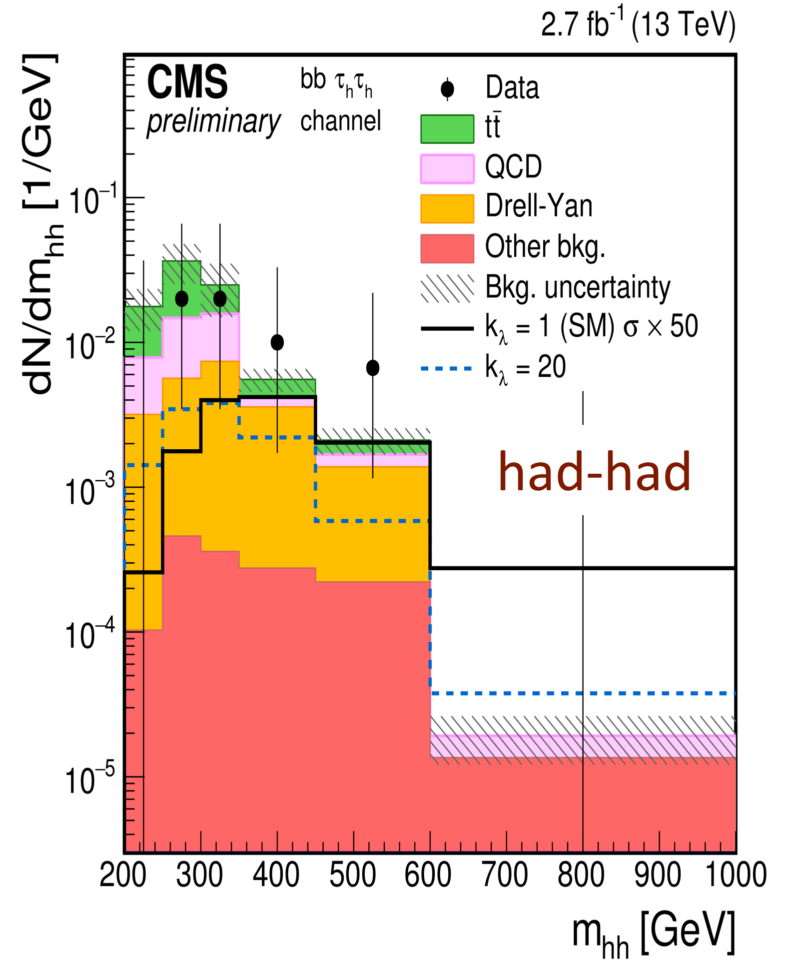


CMS-TDR-17-002

HH → bbττ : Selection (backup)

Run2 plots





HH → bbbb : coupling limits

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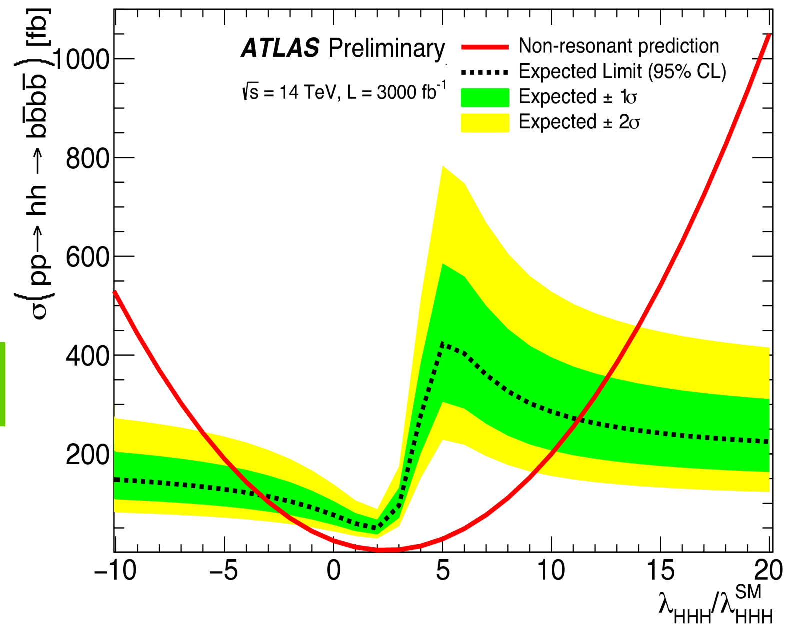
$<\mu_{PU}>=200$



$\lambda_{HHH}/\lambda_{SM}$

ATLAS : 95% C.L. limits :

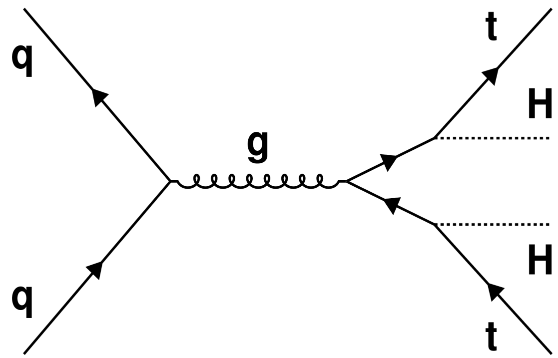
-0.2< $\lambda_{HHH}/\lambda_{SM}$<7 (negligible syst.)

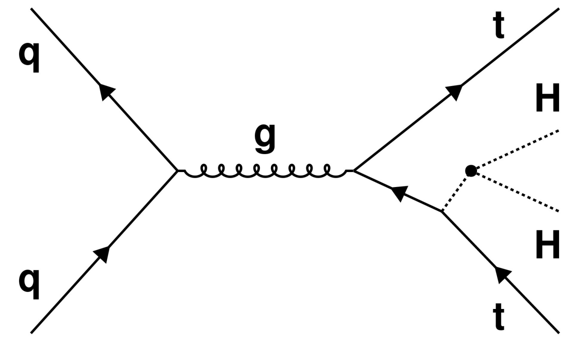
-3.5< $\lambda_{HHH}/\lambda_{SM}$<11 (current syst.)

-3.4< $\lambda_{HHH}/\lambda_{SM}$<12 (Trigger p_T > 75 GeV)

S. Jézéquel, DIS 2017

ttHH production





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