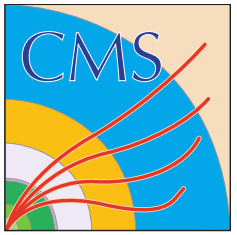


Higgs Couplings 2017

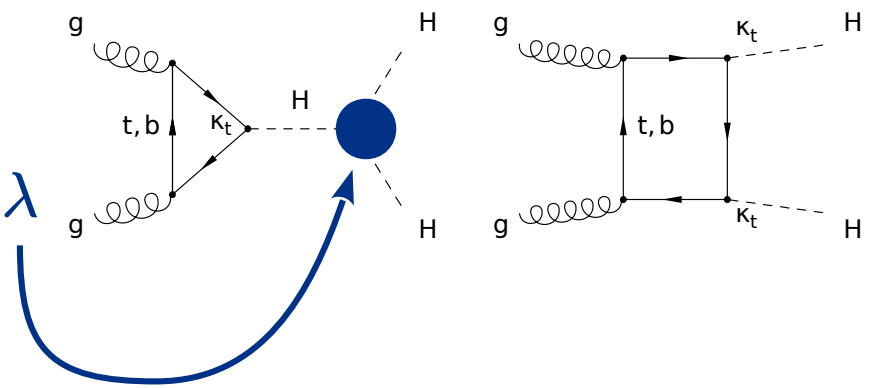
November 7th, 2017 – Heidelberg, Germany

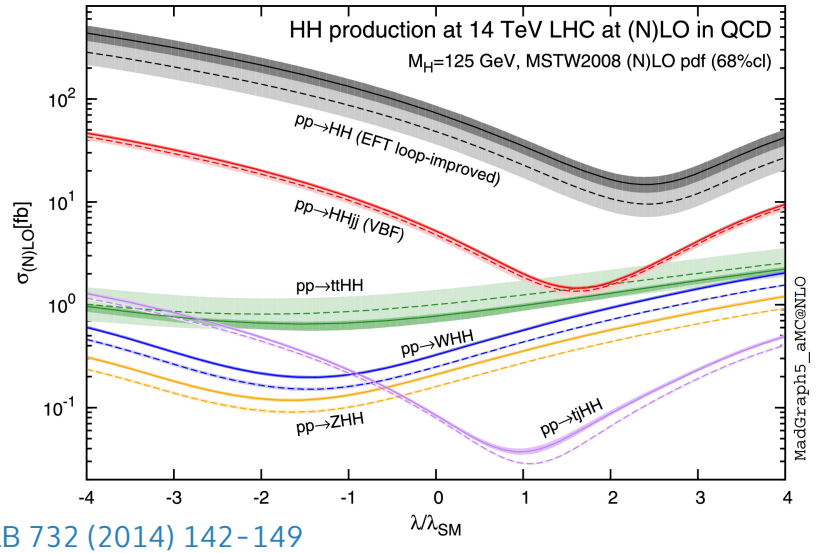
Search for double Higgs production with the ATLAS and CMS experiments

Sébastien Wertz, on behalf of the ATLAS and CMS collaborations

Motivations

- Key channel for SM study!
- Probe shape of EWSB potential
- *Direct** access to Higgs self-coupling λ
- SM prediction: $\lambda_{SM} = \frac{m_h^2}{2v^2} \approx 0.13$





PLB 732 (2014) 142-149

- Main production mode: gluon fusion
- Destructive interference → small rate:
  - σ_{SM} = 33,5 fb @ 13 TeV
  - NLO (m_t+PS), NNLO+NNLL ($m_t \to \infty$)
  - Rate & kinematics sensitive to λ

JHEP09(2016)151 JHEP10(2016)107
PRL117.012001 J.Nucl.Phys.B900(2015)412-430
1505.07122 PLB732(2014)142-149
JHEP08(2017)088, see also LHCHXSWG YR4

- Start to be sensitive to SM with 3 ab^{-1} (14 TeV)
- BSM effects → early discovery possible!

* See e.g. Thibaud's talk (open session)

Motivations: BSM reach

Resonant production of new states, for instance in:

- xMSSM/2HDM (extra doublet)

J.Phys.Rep.516(2012)1-102 JHEP09(2014)124
EPJC73(2013)2650 PhysRevD(69)053004

- Higgs portal (extra singlet)

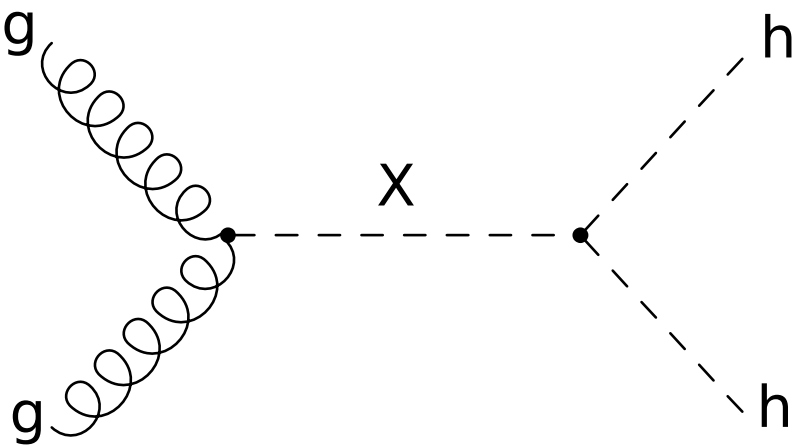
PhysRevD(72)093007 PhysRevD(89)095031
PhysRevD(91)035015 EPJC(2015)75:105

- Warped extra dimensions
  - Radion
  - KK-graviton (spin 2, gluon fusion)

PRL(83)3370 PhysRevD(76)036006 JHEP09(2007)013
PhysRevD(76)125015 NuclPhysB595:250-276

- Searches assume **narrow width**

Scalar resonances
→ **Model-independent** results!

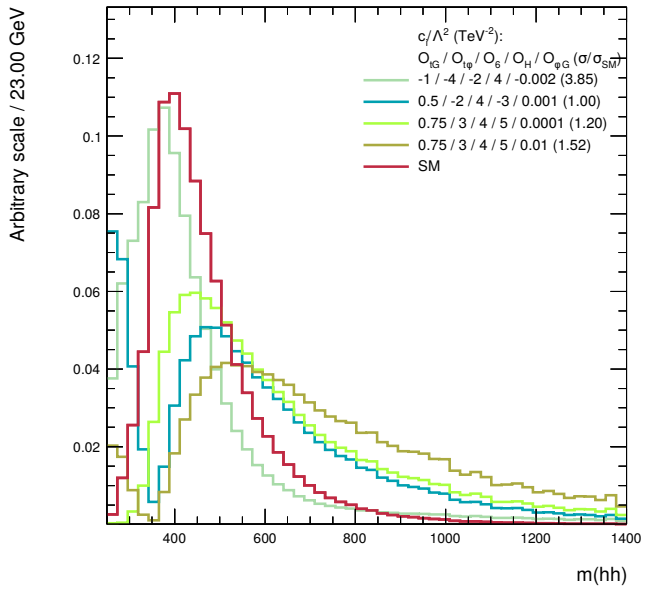


See also LHCHXSWG YR4

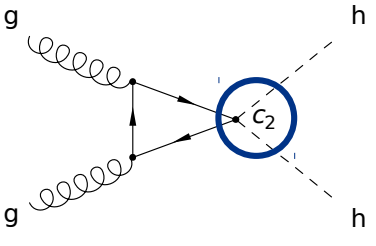
EFT and Higgs pairs

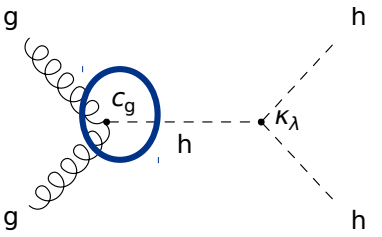
- New states out of reach → indirect effects: EFT parameterisation
- 5 dimension 6 operators contributing to double Higgs
- Modifications of:
  - Higgs self-coupling: $\kappa_\lambda = \lambda/\lambda_{SM}$
  - Top Yukawa: $\kappa_t = y^t/y^t_{SM}$
- New couplings → new diagrams
- Strong effect on rate & shapes – m(hh) sensitive at threshold

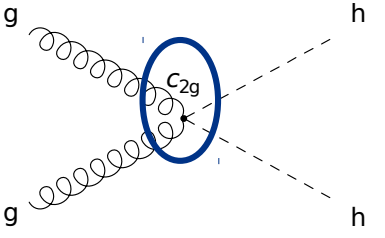
JHEP04(2015)167, 1704.05700, JHEP08(2012)154, PhysRevD.92.035001, JHEP09(2015)092, JHEP10(2016)123, see also LHCHXSWG YR4 (p.199)



$$L^{hh} = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{m_h^2}{2}h^2 - \kappa_\lambda \lambda_{SM} v h^3$$
$$- \frac{m_t}{v}\left(v + \kappa_t h + \frac{c_2}{v}hh\right)\left(\bar{t}_L t_R + h.c.\right) + \frac{\alpha_s}{12\pi v}\left(c_{1g}h - \frac{c_{2g}}{2v}hh\right)G^A_{\mu\nu}G^{A,\mu,\nu}$$



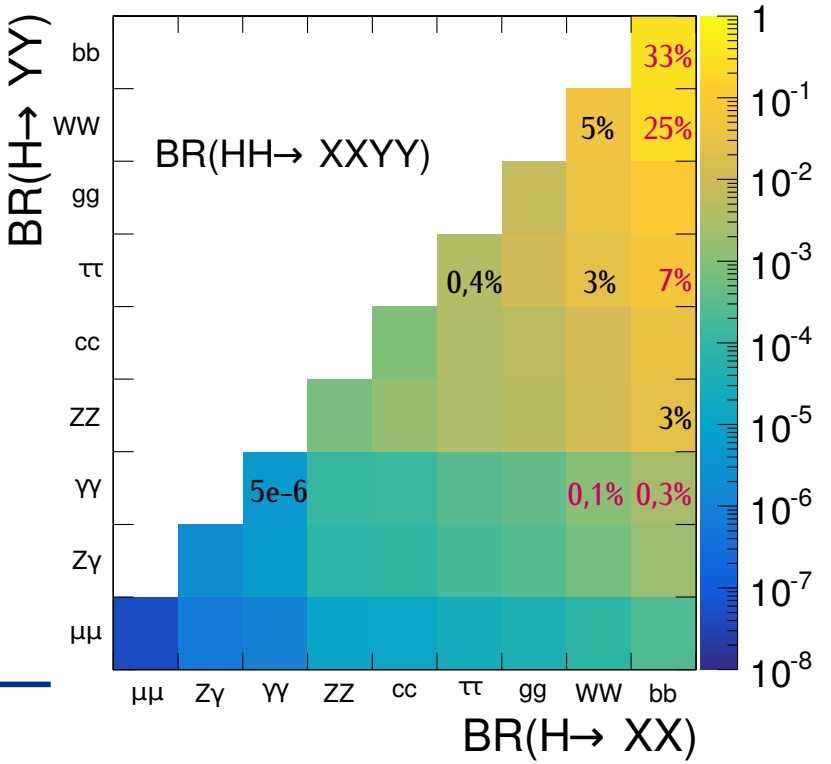




Higgs pairs in practice

Variety of final states to look at! Most rely on one h → $b\bar{b}$:

- $b\bar{b}b\bar{b}$: highest BR, high bkg. (multijet, $t\bar{t}$)
- $b\bar{b}\gamma\gamma$: very low BR, moderate bkg. (multijet+photons, single Higgs)
- $b\bar{b}\tau\tau$: compromise (moderate $t\bar{t}$ bkg.)
- $b\bar{b}$WW* : high BR, high $t\bar{t}$ bkg.
  - Loss from leptonic W decays
- $\gamma\gamma$WW* : very low BR, low bkg.



Best Run I results on SM hh:

Obs.(exp.) limit on σ_{hh}/σ_{SM}:	ATLAS	CMS
	70 (48)	**43 (47)**
	PRD 92, 092004	PRD 96, 072004

Searches in the $b\bar{b}b\bar{b}$ final state

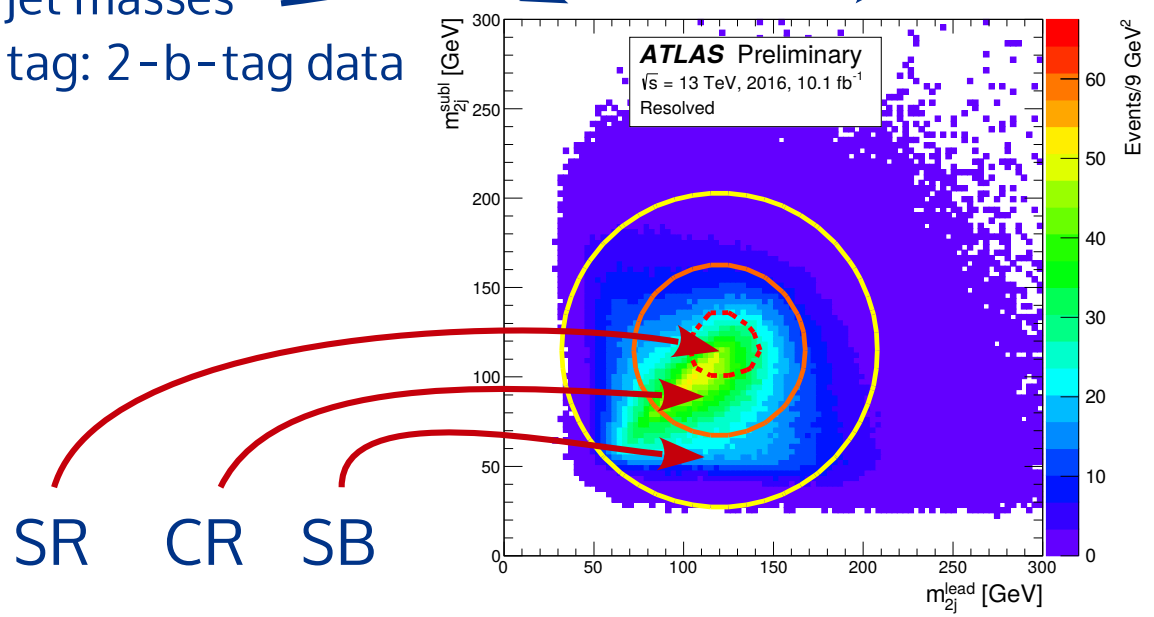
BR = 33,6%

ATLAS $b\bar{b}b\bar{b}$

13.3 fb^{-1} data (2015 & 2016) ATLAS-CONF-2016-049

Resolved: m_X < 1 TeV, SM

- $\geqslant$ 4 b-tagged jets (R=0.4)
- m(4j)-dependent jet selection & pairing
- Cut on $|\Delta\eta(h,h)|$; $\Delta R(h,h) > 1.5$
- 2 di-jet masses
- anti-tag: 2-b-tag data



Boosted: m_X > 1 TeV

- 2 b-tagged jets (R=1), 450/250 GeV
- Cut on $|\Delta\eta(h,h)| < 1.7$
- 2/3/4 associated b-tagged track jets
- 2 (trimmed) fat jet masses
  - anti-tag: 0-b-tag data

ATLAS $b\bar{b}b\bar{b}$

13.3 fb^{-1} data (2015 & 2016) ATLAS-CONF-2016-049

Resolved: m_X < 1 TeV, SM

- $\geqslant$ 4 b-tagged jets (R=0.4)
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- 2 di-jet masses
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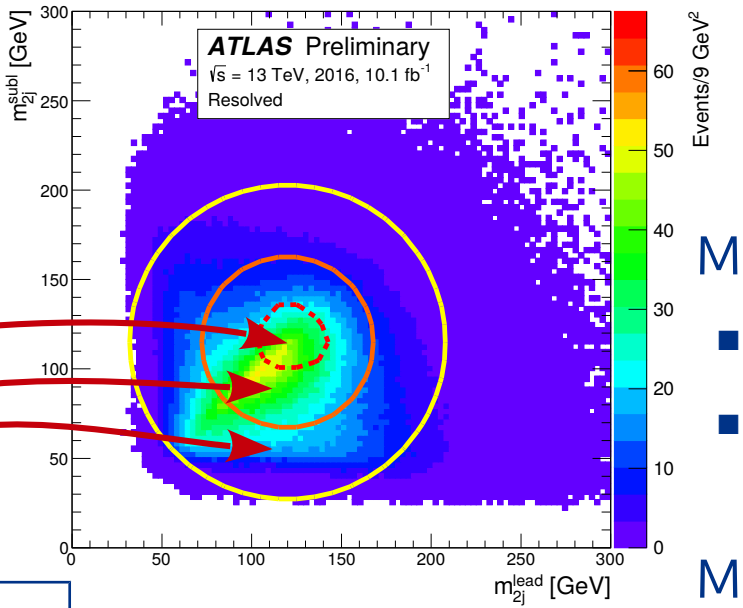


	SR	CR	SB
tag			N^{tag}
anti-tag			$N^{anti-tag}$

Boosted: m_X > 1 TeV

- 2 b-tagged jets (R=1), 450/250 GeV
- Cut on $|\Delta\eta(h,h)| < 1.7$
- 2/3/4 associated b-tagged track jets
- 2 (trimmed) fat jet masses
- anti-tag: 0-b-tag data

Multijet bkg. from data:

- Yields from $N^{tag}/N^{anti-tag}$ in SB
- Shape from anti-tag in SR:
  Kinematic re-weighting

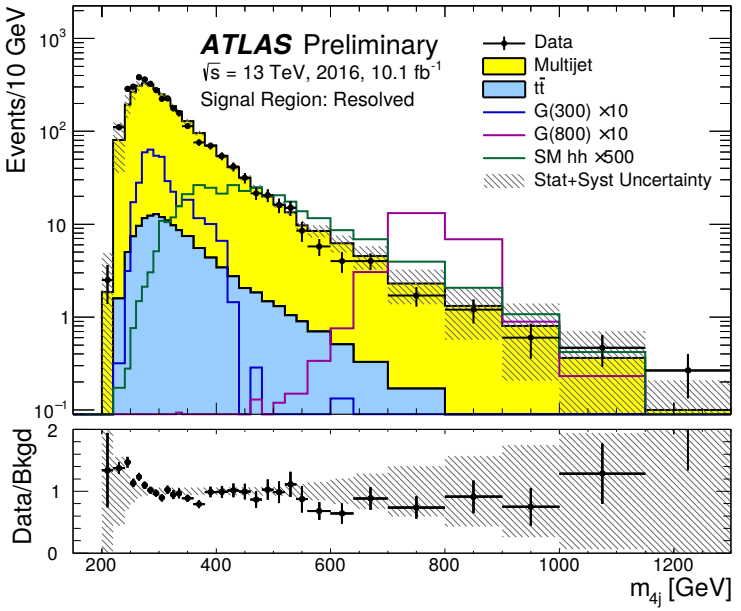
Method validated:

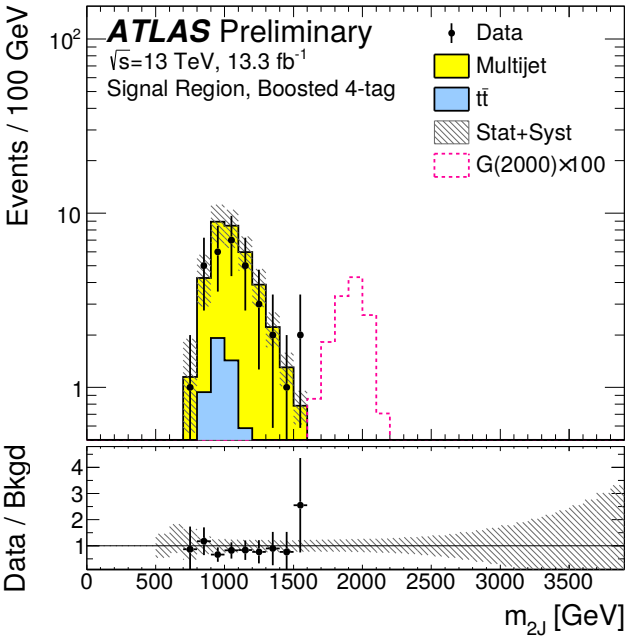
- in CR
- using alternate SR

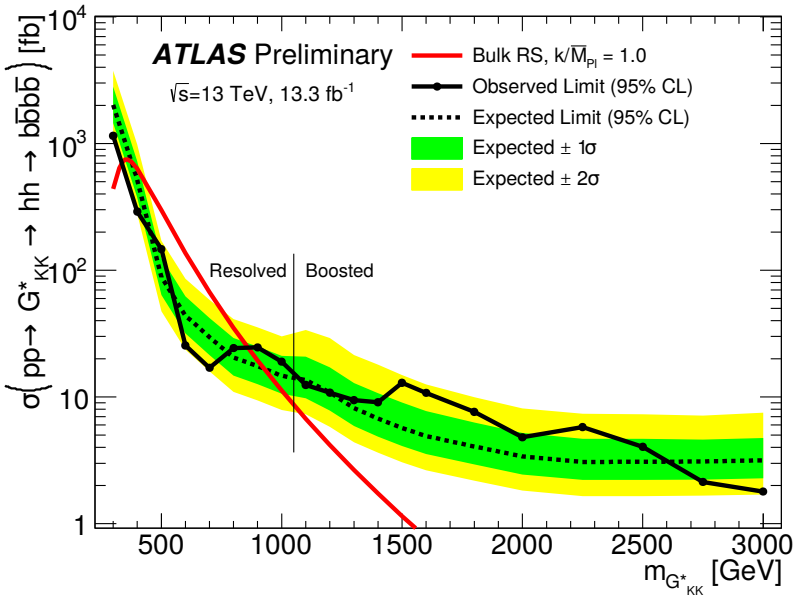
$t\bar{t}$ bkg. from MC

ATLAS $b\bar{b}b\bar{b}$ results

Signal extracted from m(4j)/m(2J) distributions:







Limits on **Bulk RS graviton** σ x BR

Non-resonant limit:

σ x BR < 330 fb

Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}}$ **< 29 (38)**

CMS resonant resolved $b\bar{b}b\bar{b}$

NEW!

35.9 fb^{-1} (2016) PAS-HIG-17-009

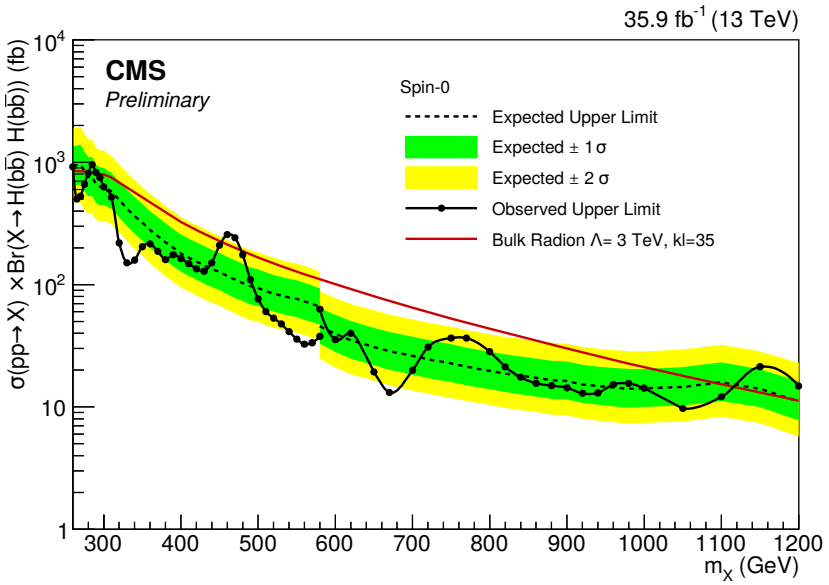
- 4 b-tagged jets
  - new **DeepCSV** algorithm
- B-jet energy regression
- Low & Medium Mass regions
  - Different jet pairing
- Kinematic fit → m(hh)

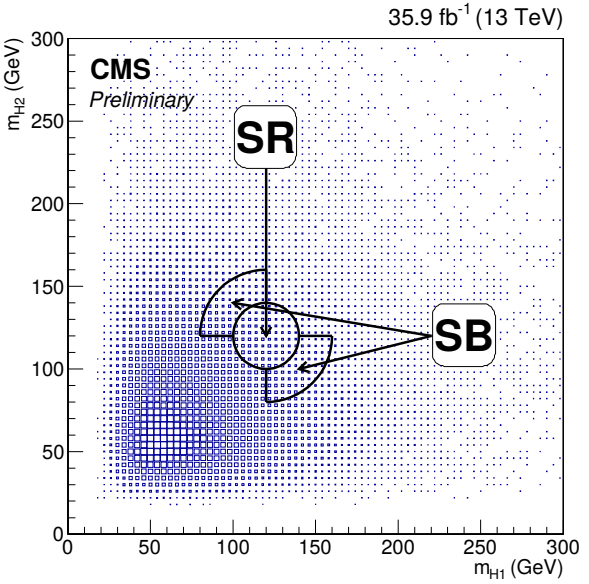
Multijet & $t\bar{t}$ bkg.: parametric fit

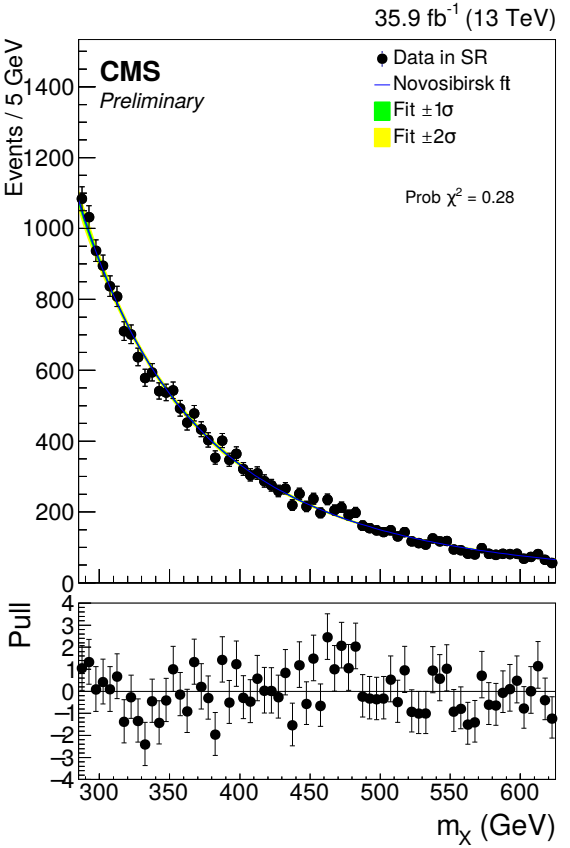
- 3 mass ranges → different functional forms
- ABCD method: mass sidebands, <4 b-tag
- Tested using alternate SR definition

Limits on spin 0 & spin 2 (KK-grav.) resonances

260 < m_X < 1200 GeV







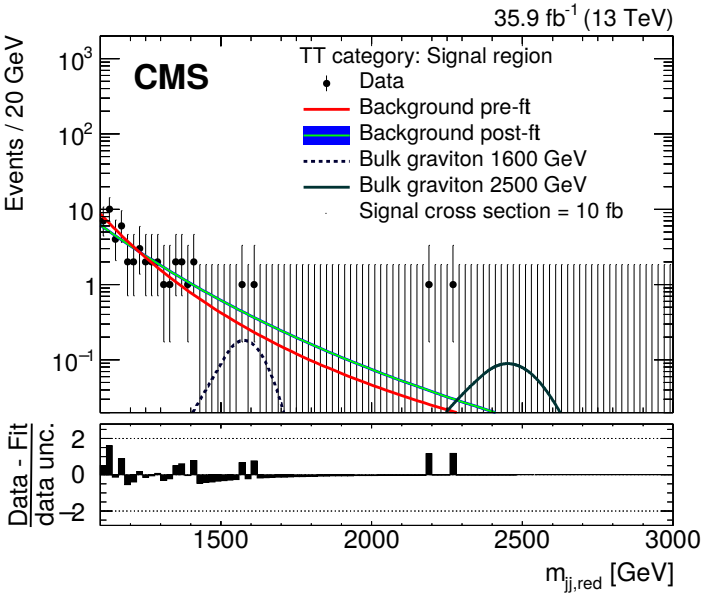
CMS resonant boosted $b\bar{b}b\bar{b}$

35.9 fb^{-1} (2016) B2G-16-026, submitted to Phys.Lett.B

Target m_X > 800 GeV

- 2 jets, R=0.8 → soft-dropped mass
- Cut on m(J), N-subjettiness, $|\Delta\eta(J,J)|<1.3$
- Veto additional leptons
- „Double-b" tagger
- Focus on „reduced" invariant mass:

$M_{red} = m(JJ) - (m(J_1) - m_h) - (m(J_2) - m_h)$



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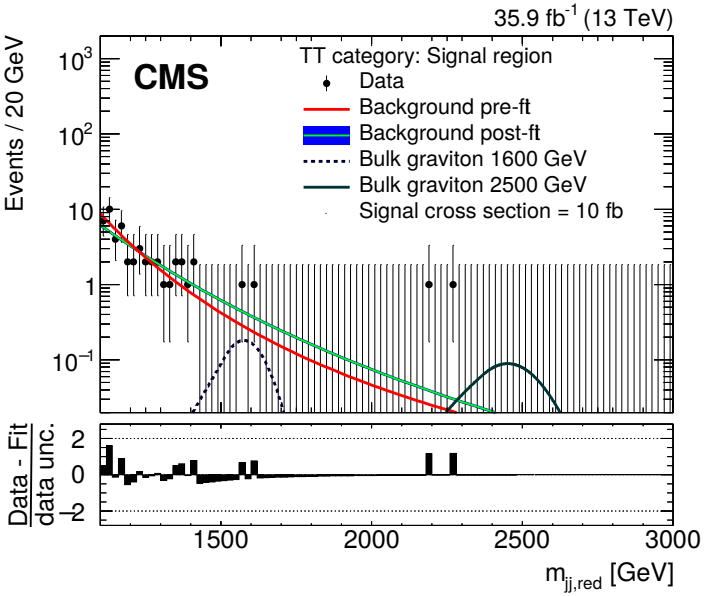
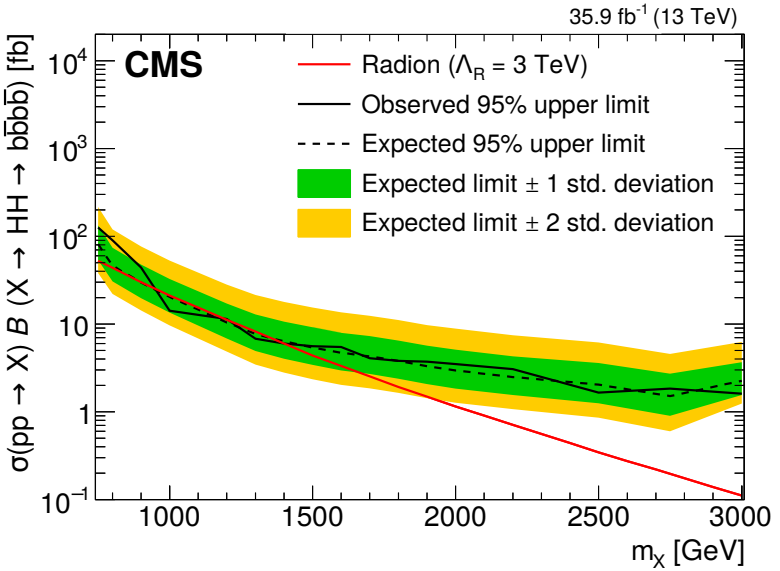




Multijet background estimation:

M_{red} < 1200 GeV: refined ABCD method

- $m(J_1)$ and b-tag sidebands
- Interpolate dependence on $m(J_1)$

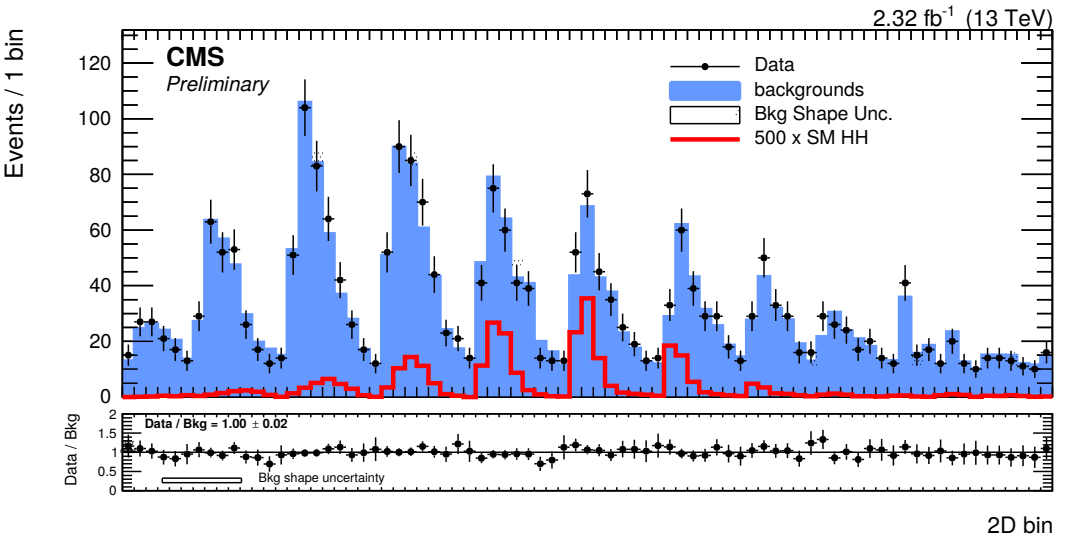
M_{red} > 1200 GeV:

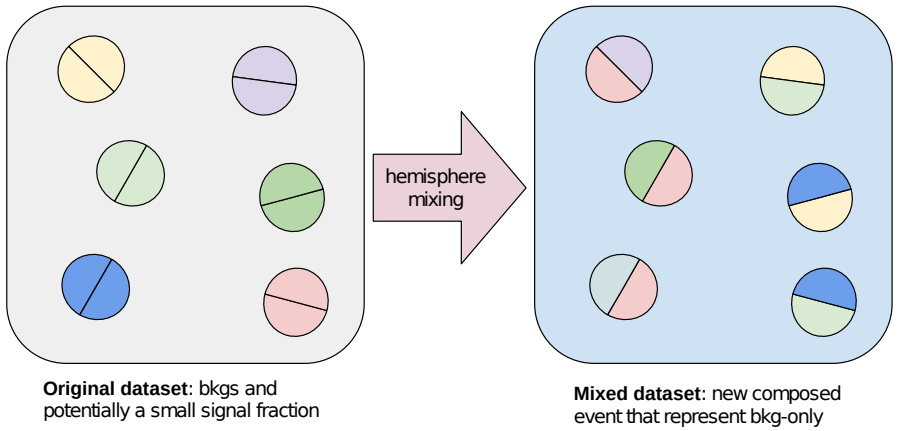
- Parametric fit (levelled exponential)
- Same shape SB & SR, yields from ABCD

CMS nonresonant $b\bar{b}b\bar{b}$

2.3 fb^{-1} (2015) PAS-HIG-16-026

- 4 jets (R=0.4), 3/4 b-tagged
- Jet pairing: closest to m_h
- BDT trained on QCD+$t\bar{t}$ MC
- Signal from 2D shape: leading vs. sub-leading m(jj) *after* cut on BDT





Bkg. template from data: **hemisphere mixing**

- Data events cut in 2 hemispheres:
  Cut ⊥ transverse thrust axis
- Hemisphere library → recreate events
- Pairing: nearest neighbour (kinematics)
- Validated in BDT sideband
  - Small bias → systematic on bkg.

Result: SM σ x BR < 3.9 pb

Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}}$ **< 342 (308)**

To be updated soon!

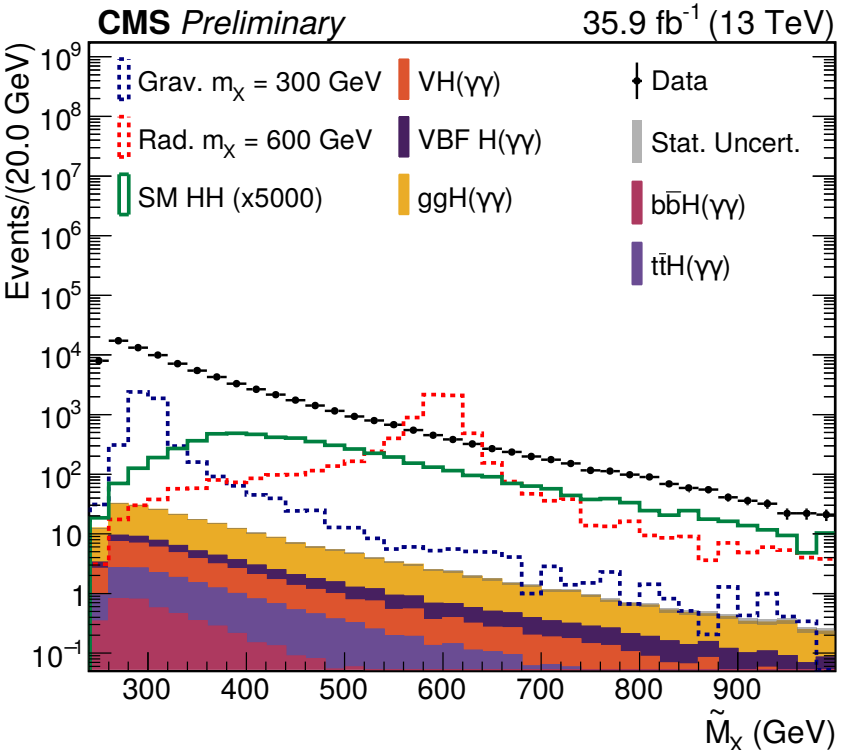
Searches in the $b\bar{b}\gamma\gamma$ final state

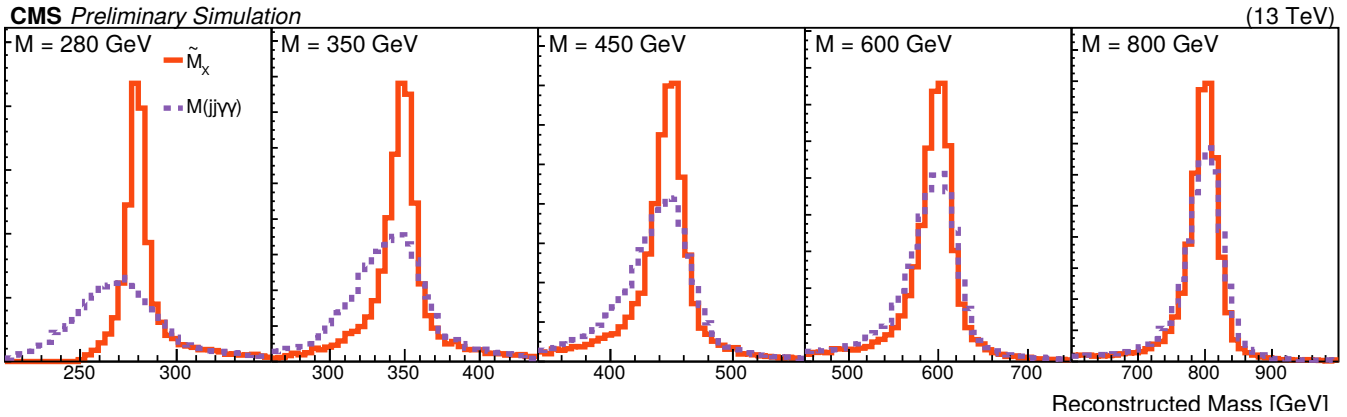
BR = 0.26%

CMS $b\bar{b}\gamma\gamma$

35.9 fb^{-1} (2016) PAS-HIG-17-008

- 2 photons, 2 b-tagged jets (R=0.4)
- b-jet energy regression
- Cut on $E_T(\gamma)$, $E_T(\gamma)/m(\gamma\gamma)$, $m(\gamma\gamma)$, $\Delta R(j,\gamma)$, $m(jj)$
- $M_x = m(jj\gamma\gamma) - m(jj) - m(\gamma\gamma) + 250$ GeV
- Categories using BDT & M_x windows
  - optimised separately for resonant & non-resonant searches
- Search: 2D parametric fit on $m(\gamma\gamma)$ vs. $m(jj)$
  - 2D PDF = product of 1D densities (Bernstein)
- SM single Higgs background from MC



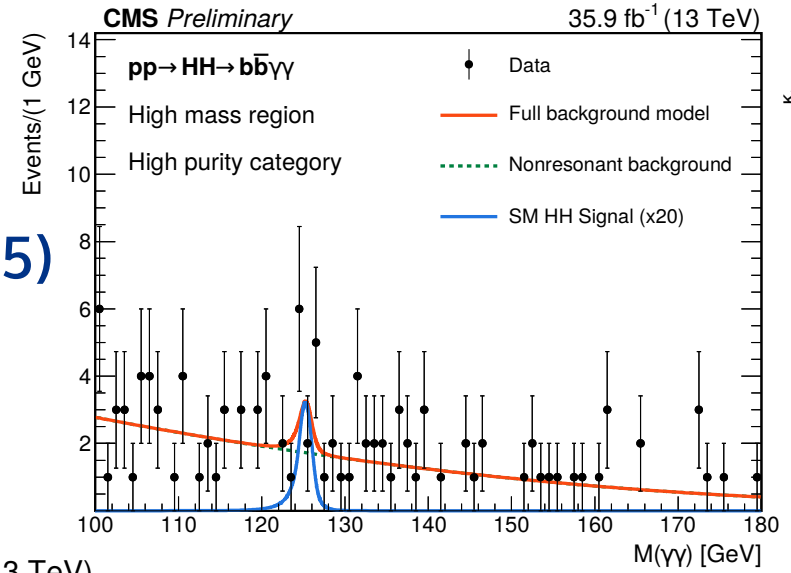


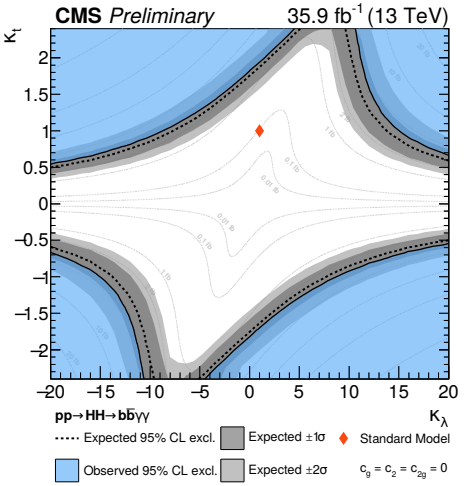
CMS $b\bar{b}\gamma\gamma$ results

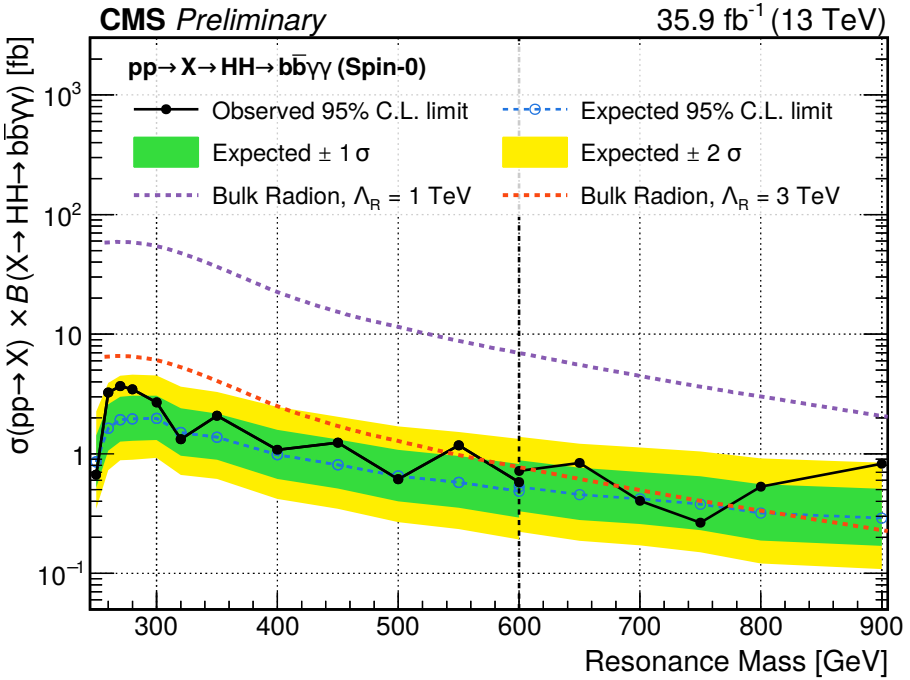
Resonant: spin 0 & spin 2 (KK-grav.)

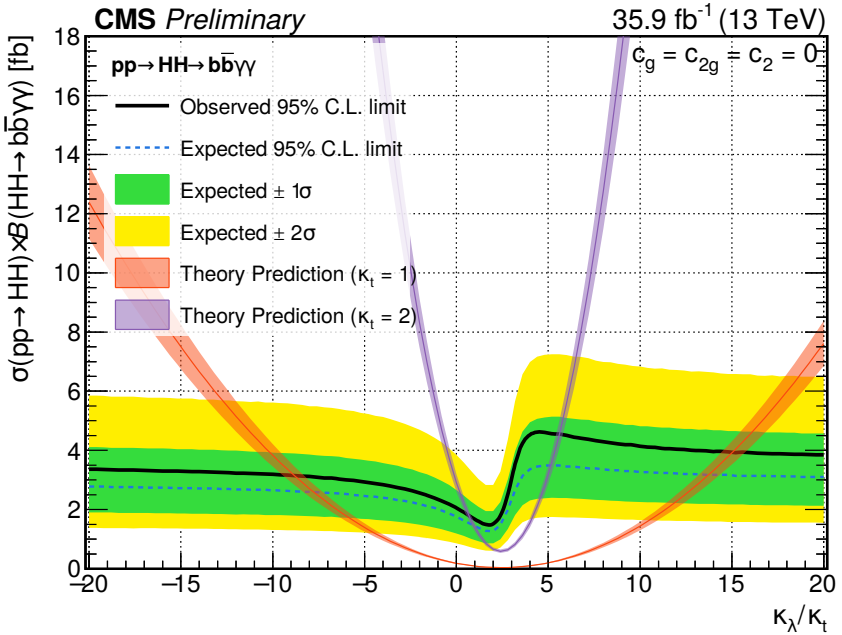
Nonresonant results:

- SM σ x BR < 1.67 fb
- Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}}$ **< 19.2 (16.5)**
- Limits as a function of κ_λ/κ_t
- Constrain the κ_t vs. κ_λ plane









ATLAS $b\bar{b}\gamma\gamma$

3.2 fb^{-1} (2015) ATLAS-CONF-2016-004

- 2 photons, 2 b-tagged jets (R=0.4)
- di-jet momentum scaled by $m_h/m(jj)$
- Cut on $E_T(\gamma)/m(\gamma\gamma)$; $m(\gamma\gamma)$ & m(jj) windows
- Use 0-b-tag region → data-driven bkg.
- Single Higgs bkg. from MC

ATLAS $b\bar{b}\gamma\gamma$

3.2 fb^{-1} (2015) ATLAS-CONF-2016-004

- 2 photons, 2 b-tagged jets (R=0.4)
- di-jet momentum scaled by $m_h/m(jj)$
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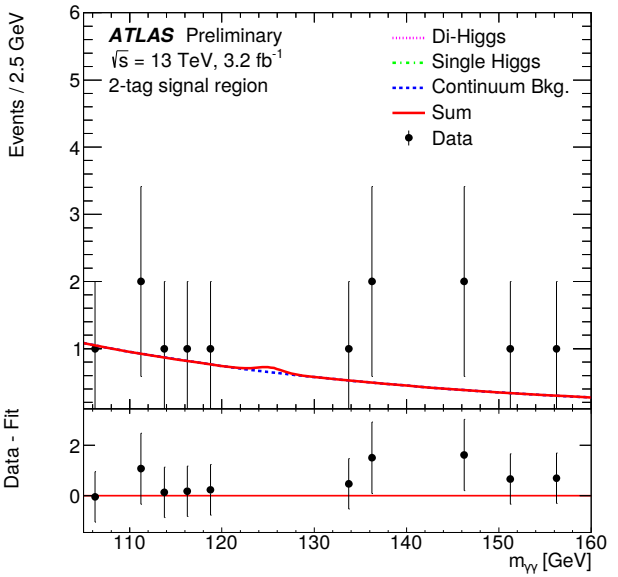

Nonresonant:

- Parametric fit of $m(\gamma\gamma)$ – excluding $m_h \pm 2\sigma_m$
- Same shape in 0-tag and 2-tag, norm. free

Result: $\sigma_{hh} < 3.9$ pb

Exp./obs.: $\boldsymbol{\sigma/\sigma_{SM} < 162/177}$

ATLAS $b\bar{b}\gamma\gamma$

3.2 fb^{-1} (2015) ATLAS-CONF-2016-004

- 2 photons, 2 b-tagged jets (R=0.4)
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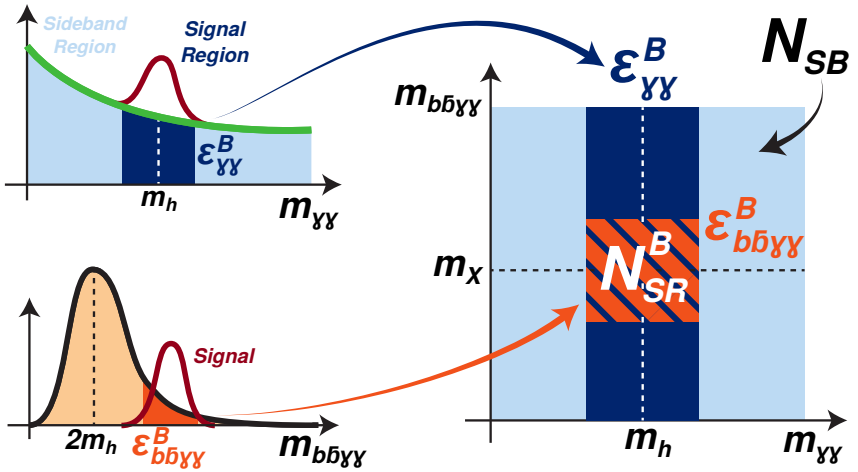
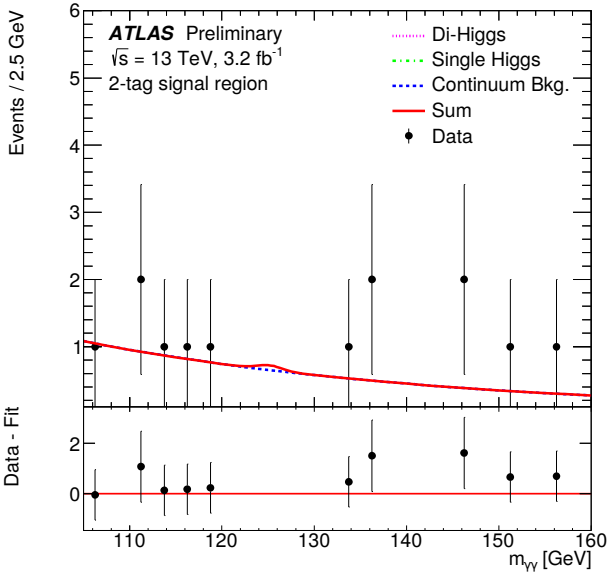
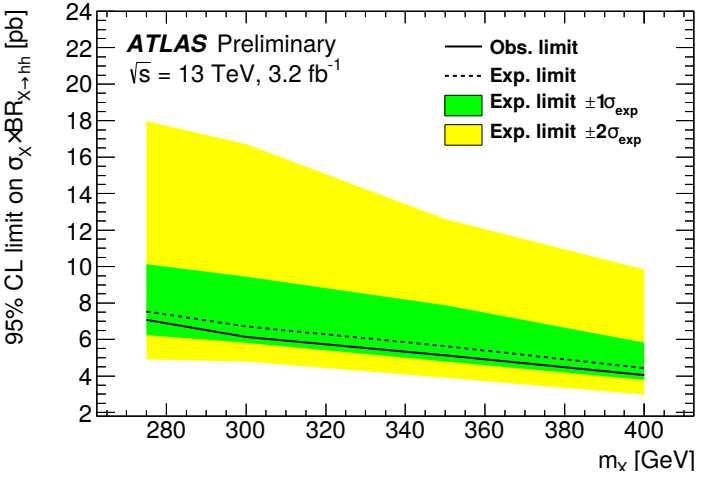




Resonant:

- Yield in SR from sidebands in $m(\gamma\gamma)$ and $m(jj\gamma\gamma)$
- Window size ↔ resolution at m_X
- Cut efficiencies from fits in 0-tag region



Nonresonant:

- Parametric fit of $m(\gamma\gamma)$ – excluding $m_h \pm 2\sigma_m$
- Same shape in 0-tag and 2-tag, norm. free

Result: σ_{hh} < 3.9 pb

Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}}$ **< 177 (162)**

Other final states

CMS $b\bar{b}\tau\tau$ – BR = 7.3%

35.9 fb^{-1} (2016) HIG-17-002, submitted to Phys.Lett.B

- 2 OS taus, 3 channels: $\tau_{had}\tau_{had}$, $\tau_{had}\tau_{\mu}$, $\tau_{had}\tau_{e}$ (88%)
- Veto extra leptons
- m($\tau\tau$) reconstruction from kinematic fit
- 2 jets (R=0.4)

Resolved:

- b-tag: 2b, 1b1j
- Elliptical m($\tau\tau$) vs. m(jj) window

Boosted:

- 1 jet (R=0.8) matched to the 2 jets
- Subjet b-tagging
- Rectangular m($\tau\tau$) vs. m(J) cut

Backgrounds:

- $t\bar{t}$, Z+jets: MC
- QCD: from data

2 BDTs → categories

- Low-mass + nonresonant
- High-mass (> 350 GeV)

CMS $b\bar{b}\tau\tau$ – BR = 7.3%

35.9 fb^{-1} (2016) HIG-17-002, submitted to Phys.Lett.B

- 2 OS taus, 3 channels: $\tau_{had}\tau_{had}$, $\tau_{had}\tau_{\mu}$, $\tau_{had}\tau_{e}$ (88%)
- Veto extra leptons
- m($\tau\tau$) reconstruction from kinematic fit
- 2 jets (R=0.4)

Resolved:

- b-tag: 2b, 1b1j
- Elliptical m($\tau\tau$) vs. m(jj) window

Boosted:

- 1 jet (R=0.8) matched to the 2 jets
- Subjet b-tagging
- Rectangular m($\tau\tau$) vs. m(J) cut

Backgrounds:

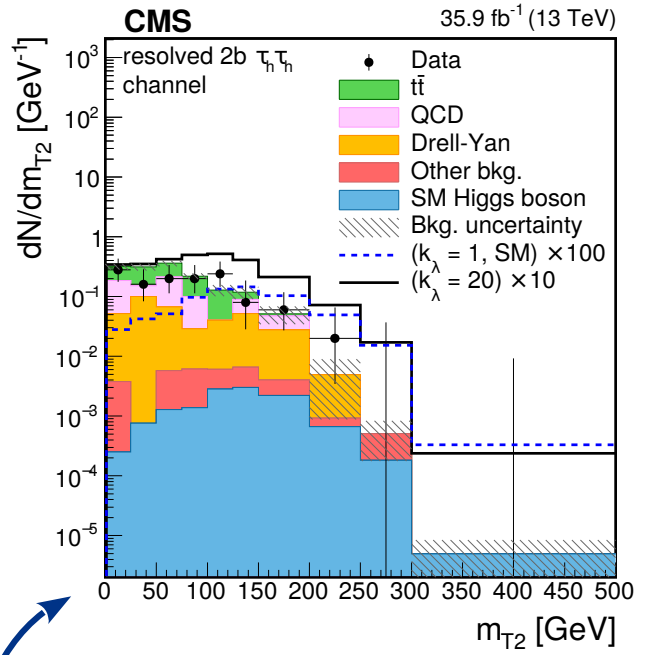
- $t\bar{t}$, Z+jets: MC
- QCD: from data

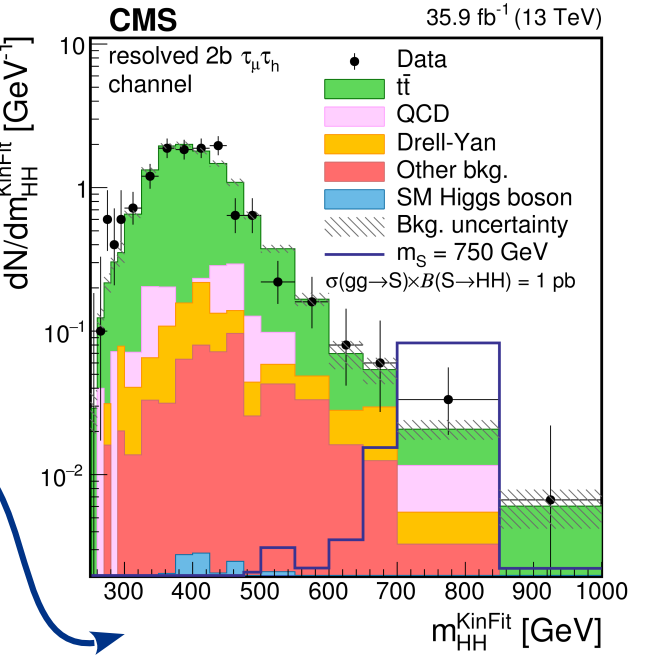
2 BDTs → categories

- Low-mass + nonresonant
- High-mass (> 350 GeV)

Nonresonant: "stransverse mass" M_{T2}

Resonant: m(jj$\tau\tau$) + kin. fit





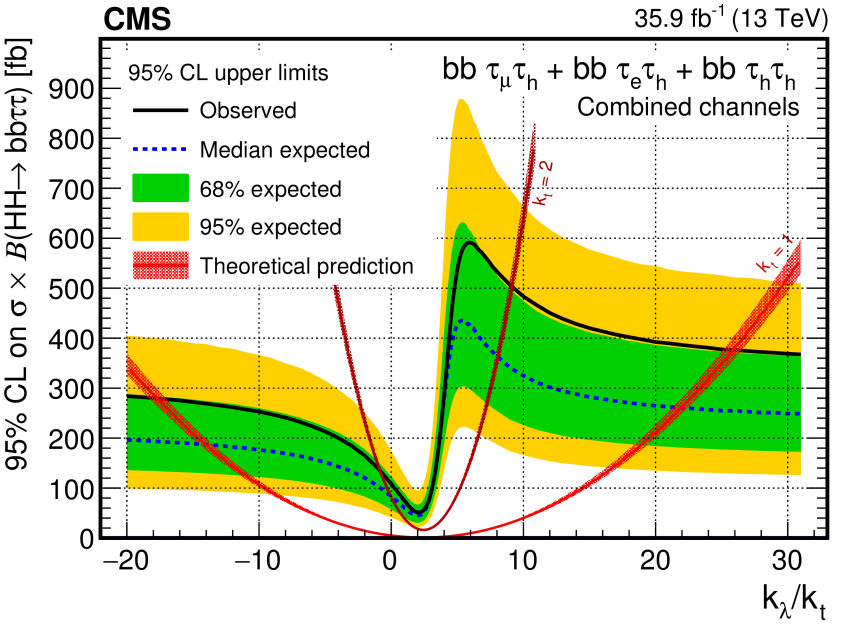
CMS $b\bar{b}\tau\tau$ results

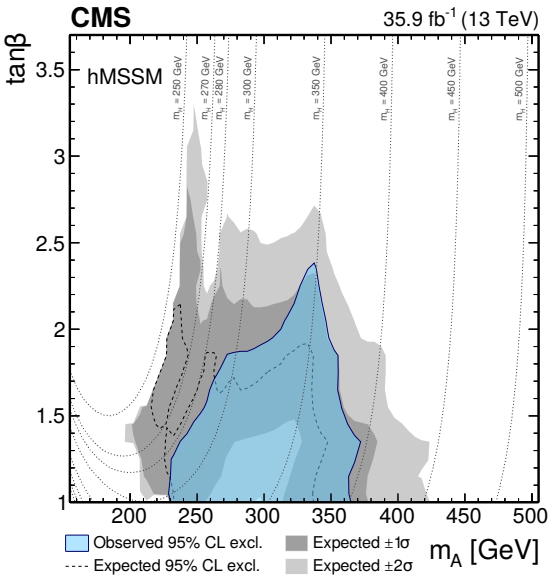
Nonresonant:

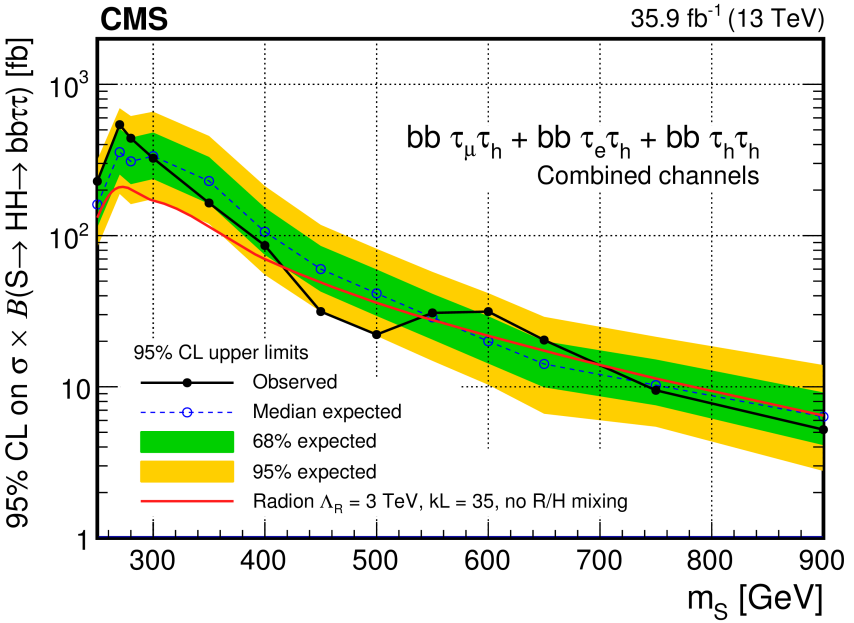
- SM σ x BR < 75.4 fb
- Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}}$ **< 30 (25)**
- Limits as a function of κ_λ/κ_t
- Constrain the κ_t vs. κ_λ plane

Resonant: spin 0 & spin 2

- Interpretation in hMSSM



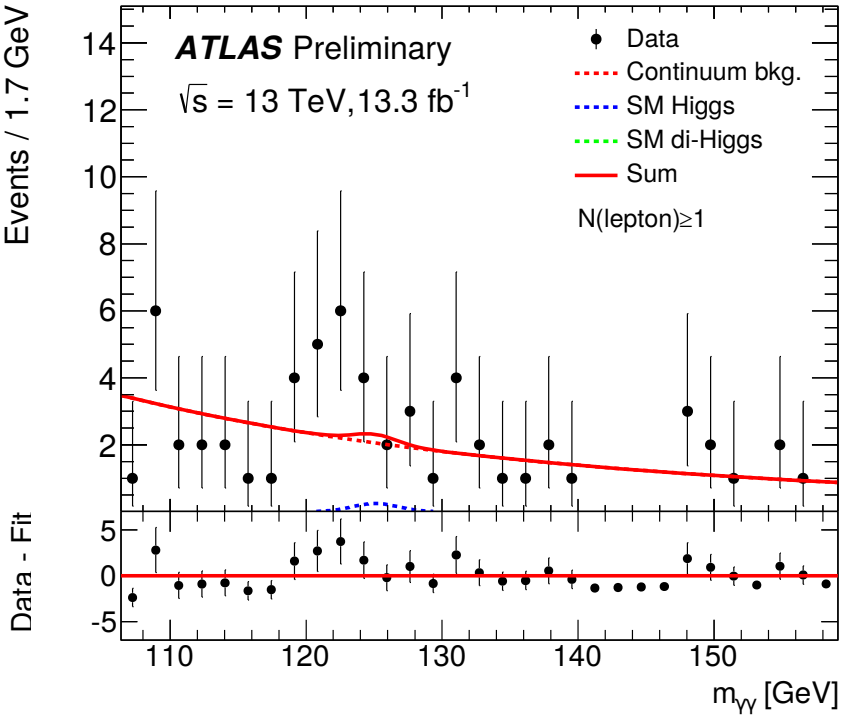


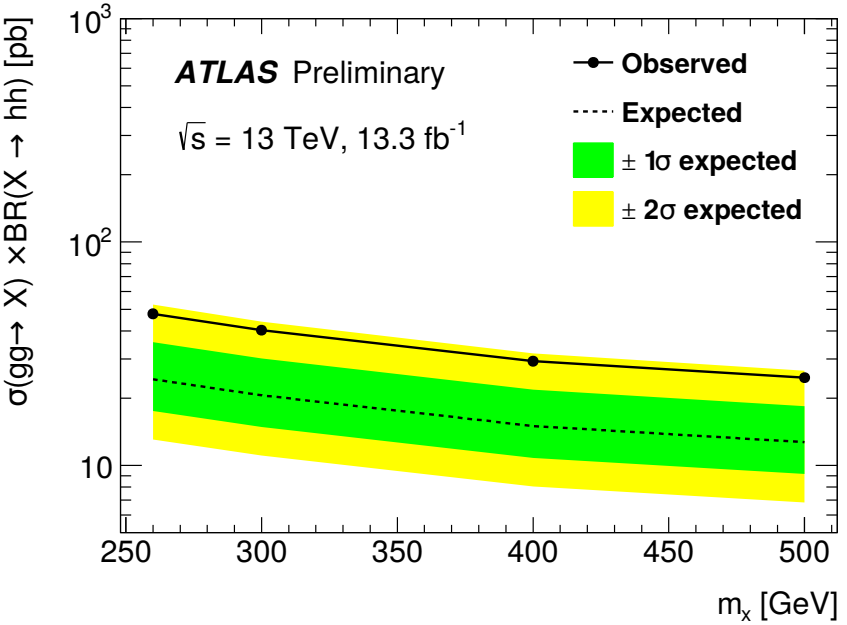


ATLAS $\gamma\gamma$WW* – BR = 0.1%

13.3 fb^{-1} (2015 & 2016) ATLAS-CONF-2016-071

- 2 photons, cut on $E_T(\gamma)/m(\gamma\gamma)$; $m(\gamma\gamma)$ window
- **W(lν)W(jj)** → 2 jets (b-tag veto) & 1 lepton (e/μ)
- Signal region/sideband: $m(\gamma\gamma)$ in/out $m_h \pm 2\sigma_m$
- Control region: 0 leptons
- Single Higgs bkg. from simulation





Continuum bkg. from data:

- Yield from SR/SB ratio (on/off peak)
- On/off ratio obtained in CR: parametric fit of $m(\gamma\gamma)$ (2nd order exponential)

Nonresonant result: σ_{hh} < 25 pb

Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}}$ **< 750 (386)**

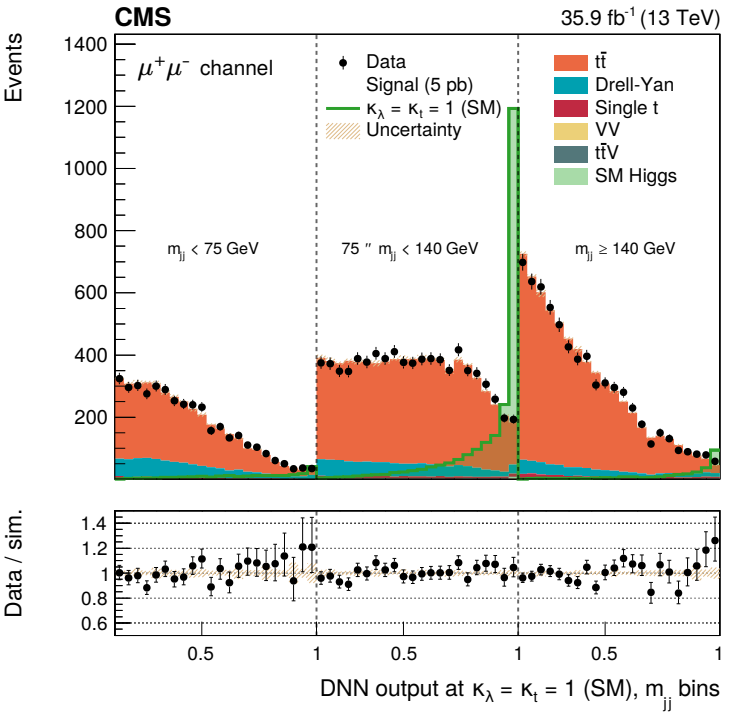
CMS $b\bar{b}VV^*(l\nu l\nu)$ – BR = 2.7%

35.9 fb^{-1} (2016) HIG-17-006, submitted to JHEP

- 2 OS leptons → 3 categs.: ee, $\mu\mu$, eμ+μe
- Focus on WW* part – remove Z(ll) peak & tail
- 2 b-jets (cMVAv2 tagger), ΔR(j,l) > 0.3
- $t\bar{t}$ & small bkg. from MC
- Z+jets: from data, reweighted ($\geq$0 b-jets)

Parameterised DNNs[1]: input m_X or κ_t and κ_λ

- Optimal sensitivity with single training
- Limit from DNN shape in 3 m(jj) bins



[1] Phys.J.C 76:235 (2016)

CMS $b\bar{b}VV^*(l\nu l\nu)$ – BR = 2.7%

35.9 fb^{-1} (2016) HIG-17-006, submitted to JHEP

- 2 OS leptons → 3 categs.: ee, $\mu\mu$, eμ+μe
- Focus on WW* part – remove Z(ll) peak & tail
- 2 b-jets (cMVAv2 tagger), ΔR(j,l) > 0.3
- $t\bar{t}$ & small bkg. from MC
- Z+jets: from data, reweighted ($\geq$0 b-jets)

Parameterised DNNs[1]: input m_X or κ_t and κ_λ

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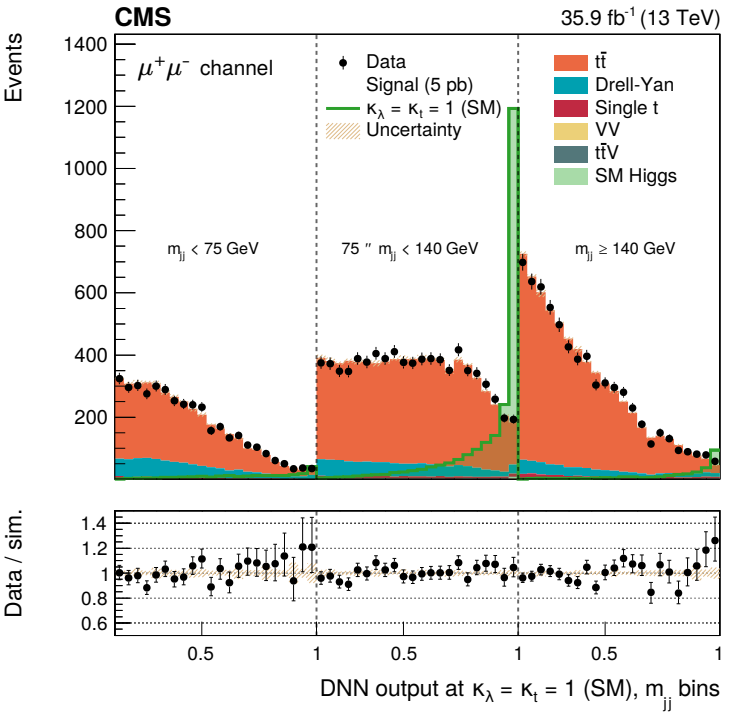
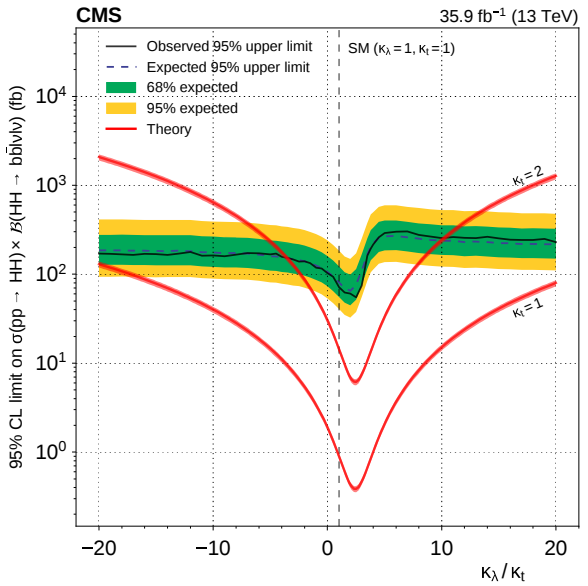


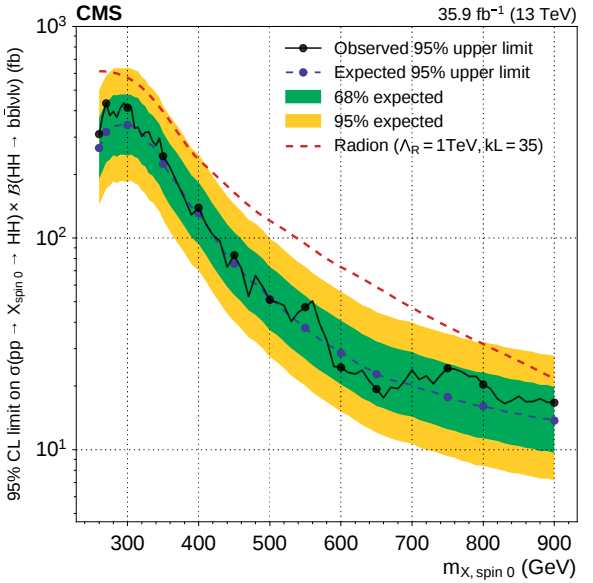
[1] Phys.J.C 76:235 (2016)



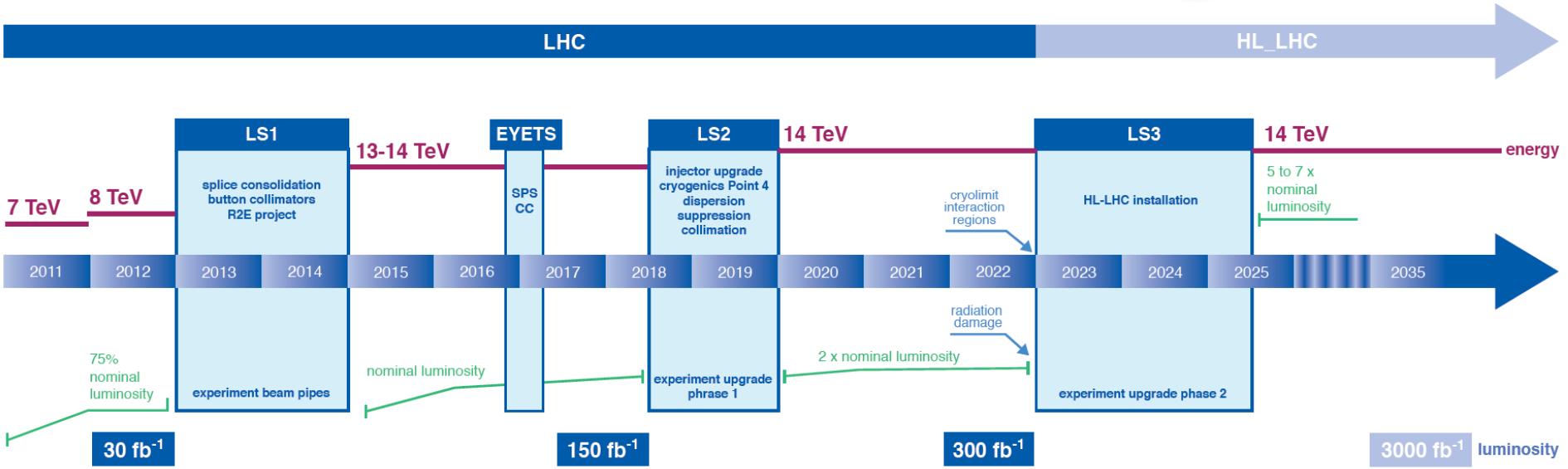
Resonant: spin 0 & 2 (KK-grav.)

Nonresonant:

- SM σ x BR < 72 fb
- Obs.(exp.): σ/σ_{SM} < **79 (89)**
- Limits as a function of κ_λ/κ_t
- Constrain the κ_t vs. κ_λ plane



LHC / HL-LHC Plan



Prospects for HL-LHC

- LHC → $\sqrt{s}$ = 14 TeV → σ_{SM} +18%
- Ultimate L_{int} → 3000 fb^{-1} (2025 – 2035)
- L_{inst} → 5e34/cm^2/s, average pileup → 200

ATLAS upgrade studies

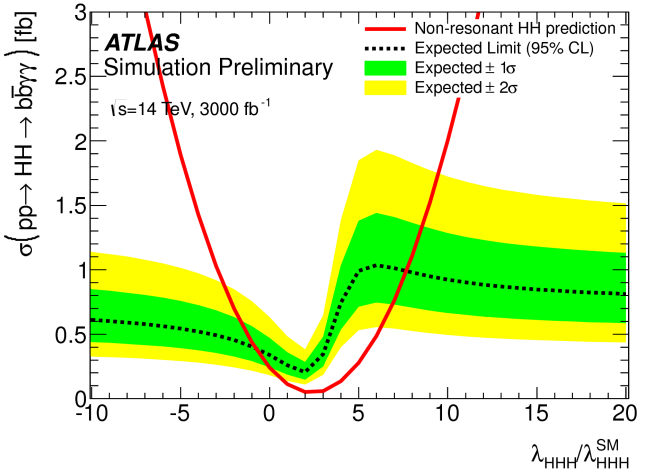
ATLAS upgrade:

- New all-silicon inner tracker, $|\eta|<4$
- Barrel calorimeters: new electronics
- New endcap calo. (high granularity)
- Muon tagging to $|\eta|<4$
- Trigger: L1 @ 0.4-1 MHz, HLT @ 10 kHz

$b\bar{b}\gamma\gamma$: ATL-PHYS-PUB-2017-001

- Gen-level MC smeared
- Without systematics:

  SM: $\mathbf{1.05\sigma}$, $\mathbf{-0.8 < \kappa_\lambda < 7.7}$



$b\bar{b}b\bar{b}$: ATL-PHYS-PUB-2016-024

- Extrapolated from 2016 analysis
- With systematics:

  $\boldsymbol{\sigma/\sigma_{SM} < 5.2, -3.5 < \kappa_\lambda < 11}$

- Sensitivity on jet p_T thresholds

$b\bar{b}\tau\tau$: ATL-PHYS-PUB-2015-046

- Gen-level MC smeared
- With systematics:

  SM: $\mathbf{0.6\sigma}$, $\boldsymbol{\sigma/\sigma_{SM} < 4.3}$

$t\bar{t}hh(b\bar{b}b\bar{b})$: ATL-PHYS-PUB-2016-023

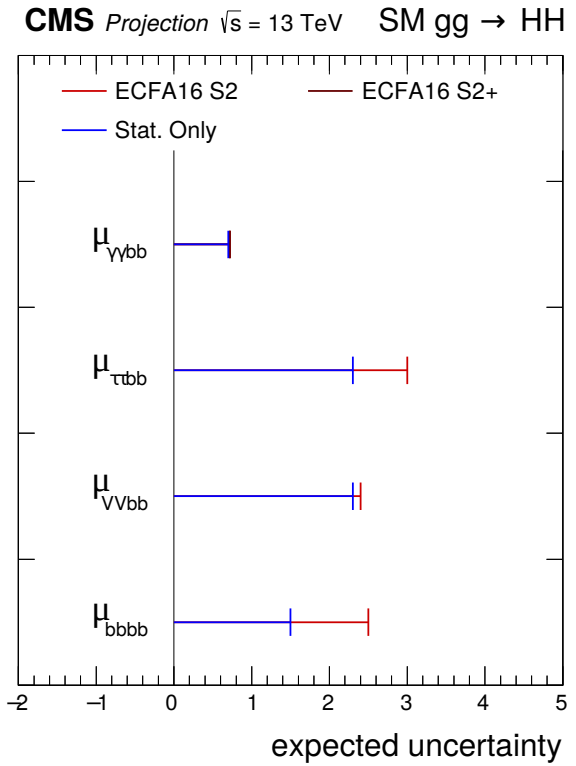
- Gen-level MC smeared
- Without systematics:

  SM: $\mathbf{0.35\sigma}$

CMS upgrade studies

CMS upgrade:

- New all-silicon tracker, $|\eta|<4$, track-trigger
- Barrel calorimeters: new electronics
- New endcap calo. (high granularity)
- Muon detectors to $|\eta|<2.8$
- Trigger: L1 @ 750 kHz, HLT @ 7.5 kHz



Dedicated studies: PAS-FTR-15-002

- DELPHES[1] fast parametric simulation
- Gen-level MC smeared
- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}VV(l\nu l\nu, l\nu jj)$

Combined, with systematics:

SM: **1.9σ, 54% precision on σ_{SM}**

Extrapolations of 2015 analyses: PAS-FTR-16-002

- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$, $b\bar{b}VV(l\nu l\nu)$
- Different scenarios:
  - No systematics ("stat. only")
  - Scenarios with reduced theory uncertainties & reduced systematics (≈ future detector performances)

[1] JHEP02(2014)057

Summary & conclusion

Results summary

Current status:

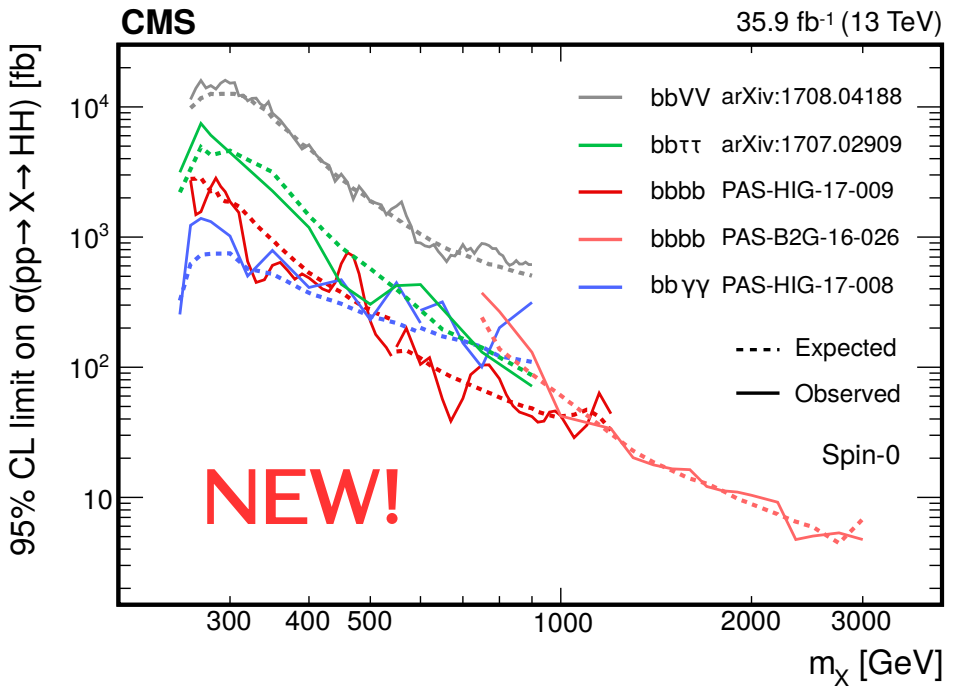
- Most stringent limit on λ:

  $-8.8 < \lambda/\lambda_{SM} < 15$

- Exclusions on resonances:

$\sigma_{gg\to X} \times BR_{X\to hh} <$ 1 pb (300 GeV)

4 fb (3 TeV)



Obs.(exp.) limit on σ_{hh}/σ_{SM}:

Final state	ATLAS	CMS
$b\bar{b}\gamma\gamma$	177 (162)	19 (16)
$b\bar{b}\tau\tau$		30 (25)
$b\bar{b}b\bar{b}$	29 (38)	342 (308)
$b\bar{b}WW^*$		79 (89)
$\gamma\gamma WW^*$	750 (386)	

2015 (2.3-3.2 fb^{-1})

2015+2016 (13.3 fb^{-1})

2016 (35.9 fb^{-1})

Conclusions

- CMS & ATLAS: rich search program on double Higgs production
- Variety of final states probed
- **No excess** above SM expectations seen
- Limits on spin-0 and spin-2 (KK-Grav.) resonances
- Limits on nonresonant SM & BSM process – Run I limits already x ½ !
- Future prospects: start closing in on SM at HL-LHC

Stay tuned!

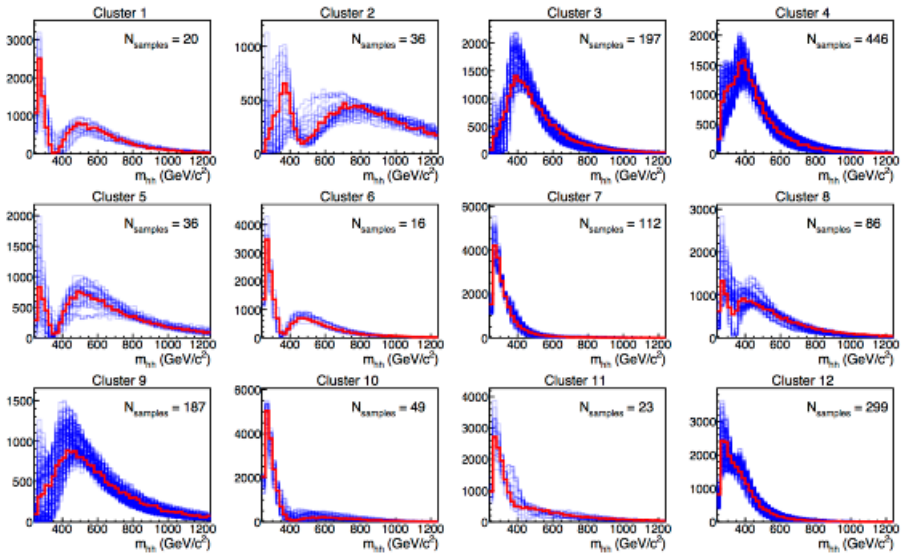
- Updates with 2016 dataset coming soon
- Combination of final states' results
- Next milestone: full Run II analysis

Back-up

CMS nonresonant EFT results

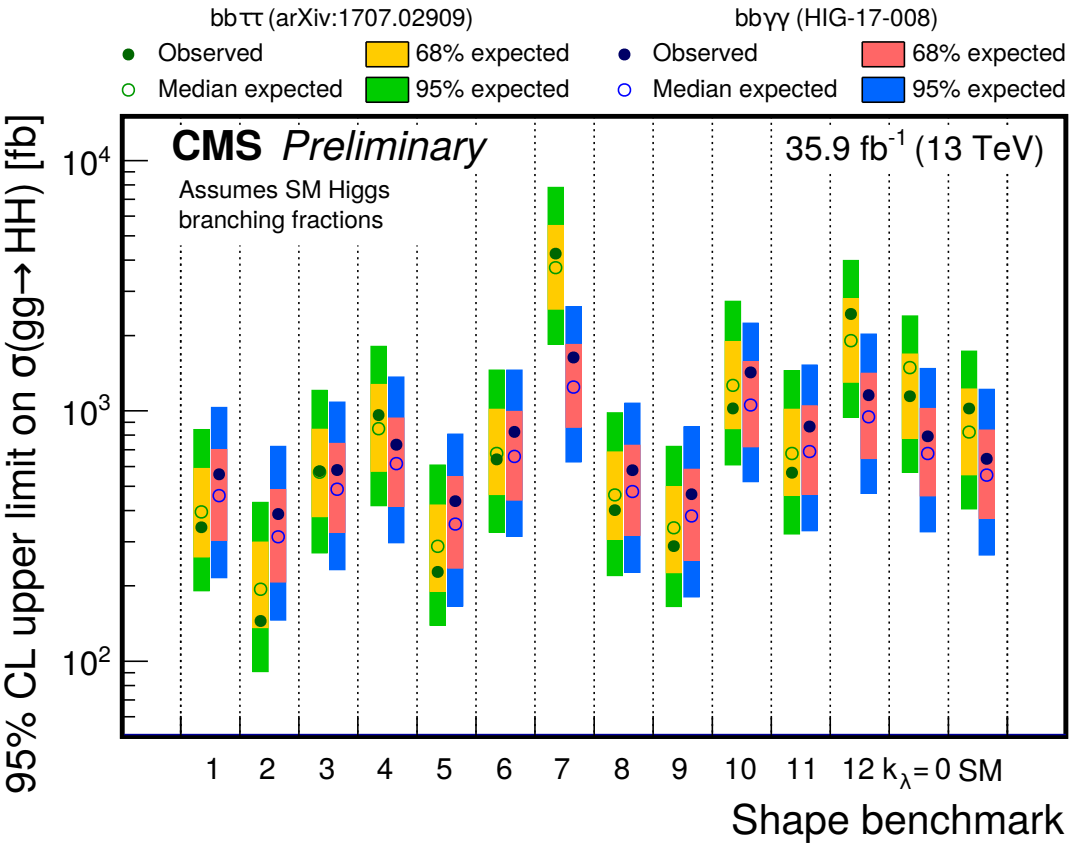
EFT: 5 parameters (see slide 4)

- **Clustering** procedure → representative points
  JHEP 04 (2016) 126
- Highly varying kinematics probed
- Basis for event re-weighting
- **Re-casting** possibilities 1710.08261



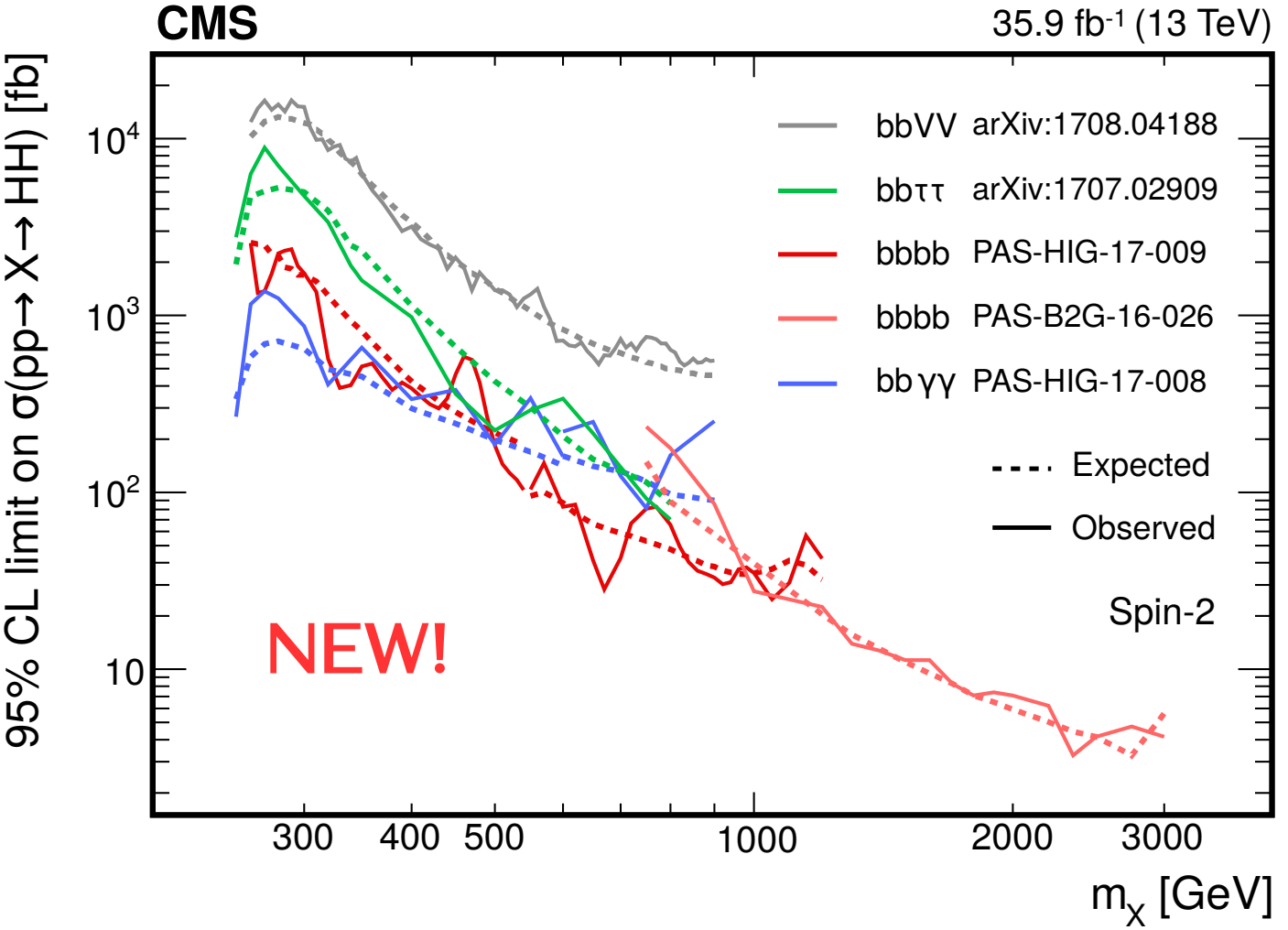
CMS limits on shape „**benchmarks**":

Channels have different sensitivity depending on kinematics!



CMS spin-2 resonances

Results summary on spin-2 narrow-width resonances produced in gluon fusion (KK-Gravitons):



ATLAS $b\bar{b}b\bar{b}$

13.3 fb^{-1} data (2015 & 2016) ATLAS-CONF-2016-049

Resolved:

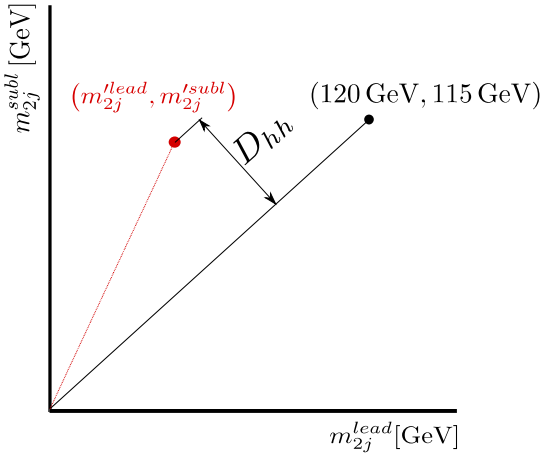
- All combinations passing
- Choose pairs minimizing D_{hh}
- Additional cuts on h cand.
- Trigger: 1/2 b-tagged jets [extra jets]

+ quality & kinematical requirements

$$\left.\begin{aligned} \frac{360}{m_{4j}} - 0.5 < \Delta R_{jj,\text{lead}} < \frac{655}{m_{4j}} + 0.475 \\ \frac{235}{m_{4j}} < \Delta R_{jj,\text{subl}} < \frac{875}{m_{4j}} + 0.35 \end{aligned}\right\} \text{if } m_{4j} < 1250 \text{ GeV}$$

$$\left.\begin{aligned} 0 < \Delta R_{jj,\text{lead}} < 1 \\ 0 < \Delta R_{jj,\text{subl}} < 1 \end{aligned}\right\} \text{if } m_{4j} > 1250 \text{ GeV}$$

$$D_{hh} = \sqrt{\left(m_{2j}^{\text{lead}}\right)^2 + \left(m_{2j}^{\text{subl}}\right)^2} \left| \sin\left(\tan^{-1}\left(\frac{m_{2j}^{\text{subl}}}{m_{2j}^{\text{lead}}}\right) - \tan^{-1}\left(\frac{115}{120}\right)\right)\right|$$

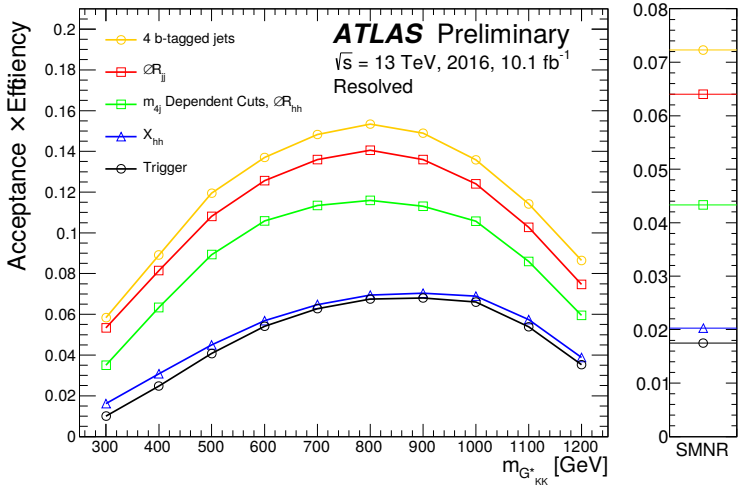


$$p_{\text{T}}^{\text{lead}} > 0.5 m_{4j} - 90 \text{ GeV}$$

$$p_{\text{T}}^{\text{subl}} > 0.33 m_{4j} - 70 \text{ GeV}$$

$$|\Delta\eta_{hh}| < \begin{cases} 1.1 & \text{if } m_{4j} < 850 \text{ GeV} \\ 2 \times 10^{-3} m_{4j} - 0.6 & \text{if } m_{4j} > 850 \text{ GeV} \end{cases}$$

Efficiencies:



Signal region definition:

$$X_{hh} = \sqrt{\left(\frac{m_{2j}^{\text{lead}} - 120 \text{ GeV}}{0.1 m_{2j}^{\text{lead}}}\right)^2 + \left(\frac{m_{2j}^{\text{subl}} - 115 \text{ GeV}}{0.1 m_{2j}^{\text{subl}}}\right)^2} < 1.6$$

ATLAS $b\bar{b}b\bar{b}$

13.3 fb^{-1} data (2015 & 2016) ATLAS-CONF-2016-049

Boosted:

- 2 highest p_T jets, $|\eta|<2$
- B-tagging:
  - ≥ 1 b-tagged R=0.2 track-jet matched to fat jet
- Trigger: 1 fat jet (p_T > 360/420)

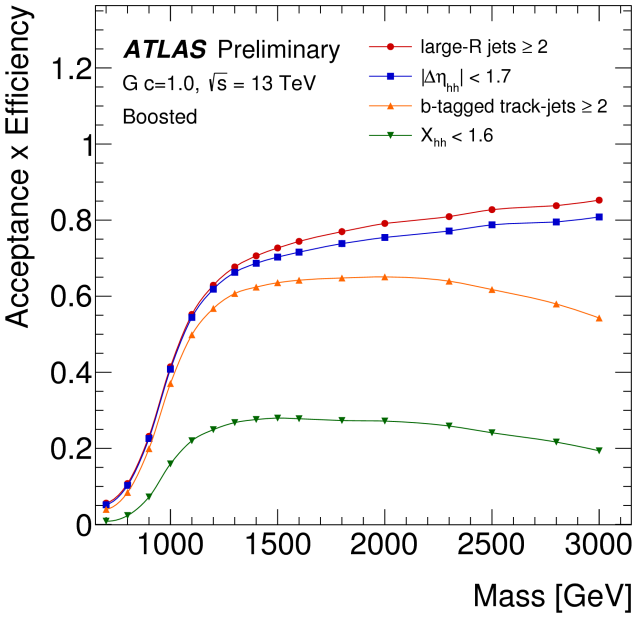
Signal region definition:

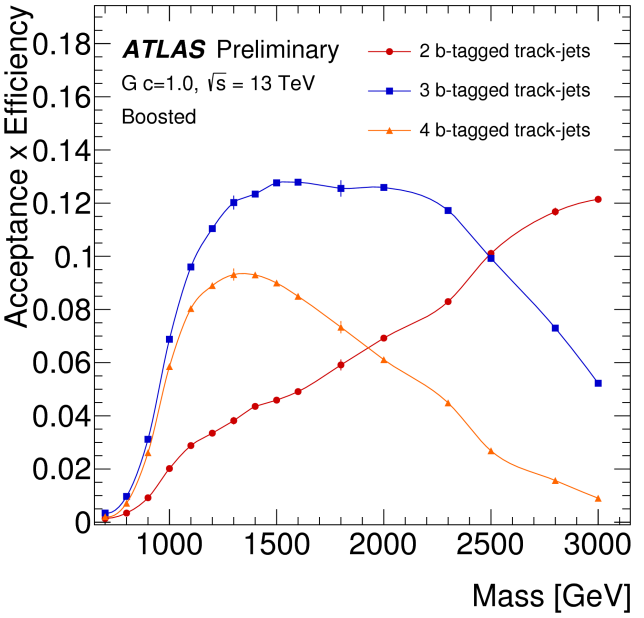
$$X_{hh} = \sqrt{\left(\frac{m_J^{lead} - 124\ GeV}{0.1 m_J^{lead}}\right)^2 + \left(\frac{m_J^{subl} - 115\ GeV}{0.1 m_J^{subl}}\right)^2} < 1.6$$

Sideband definition:

$$36\ GeV < \sqrt{(m_J^{lead} - 124\ GeV)^2 + (m_J^{subl} - 115\ GeV)^2} < 63\ GeV$$

Efficiencies:



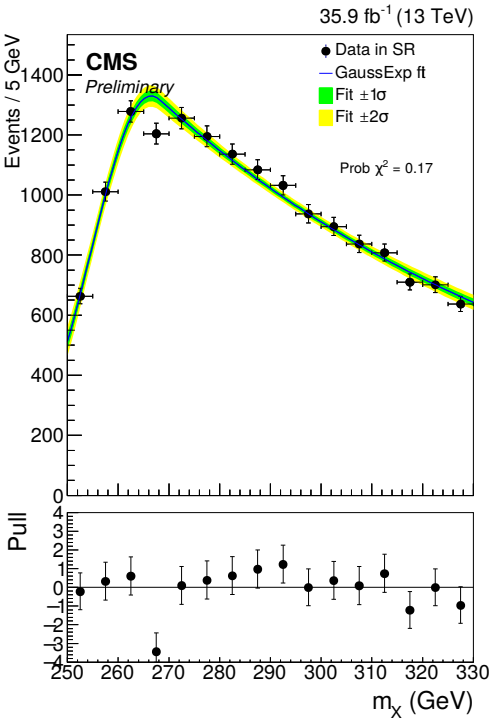


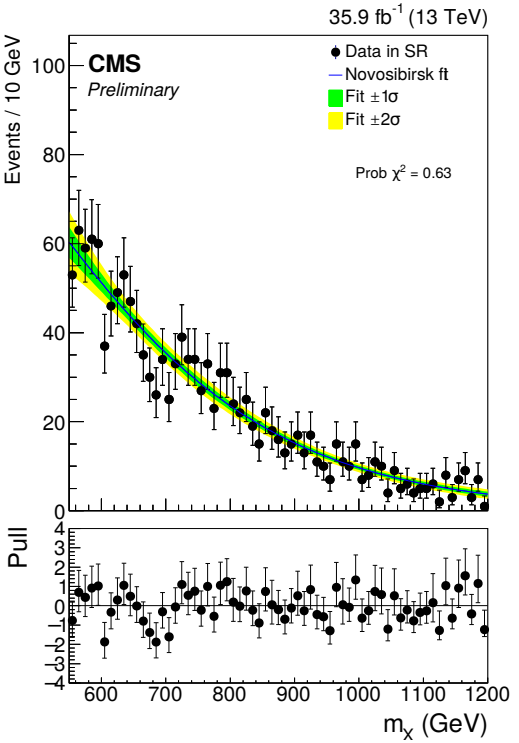
CMS resonant resolved $b\bar{b}b\bar{b}$

NEW!

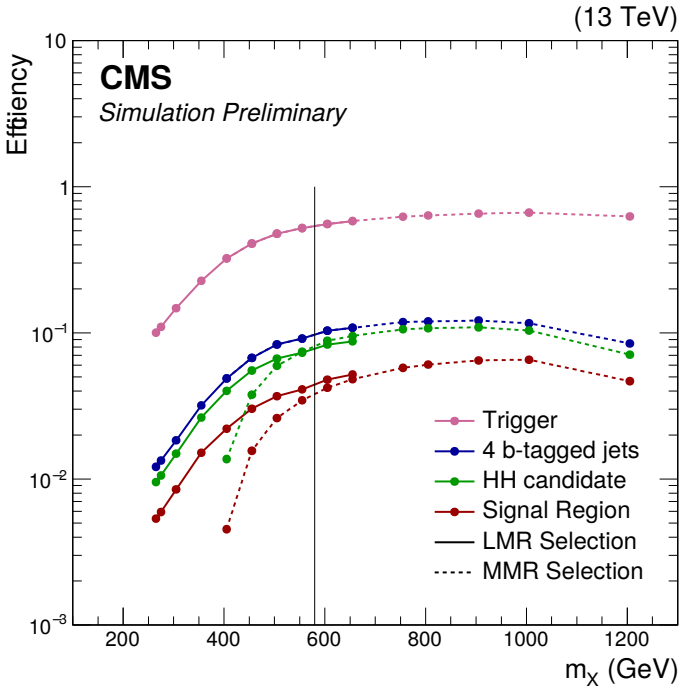
35.9 fb^{-1} (2016) PAS-HIG-17-009

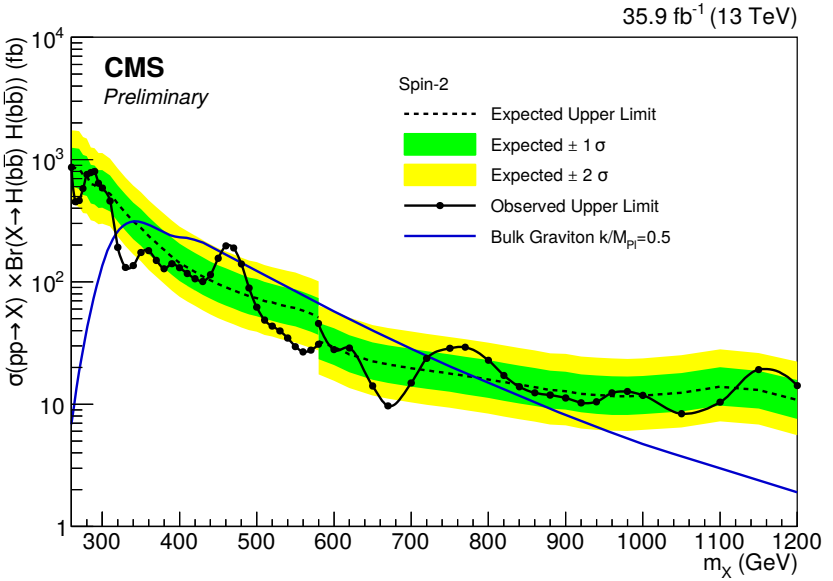
- LMR: |m(jj) -120| < 40
- MMR: ΔR(j,j) < 1.5 for each h cand.
- Ambiguities → minimise mass ChiSq
- Trigger: 4 jets, 3 b-tagged (CSVv2)





Efficiencies:



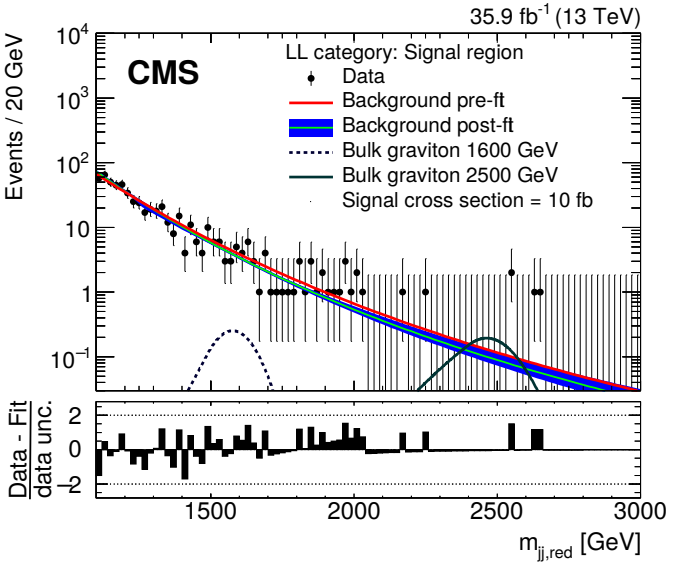


CMS resonant boosted $b\bar{b}b\bar{b}$

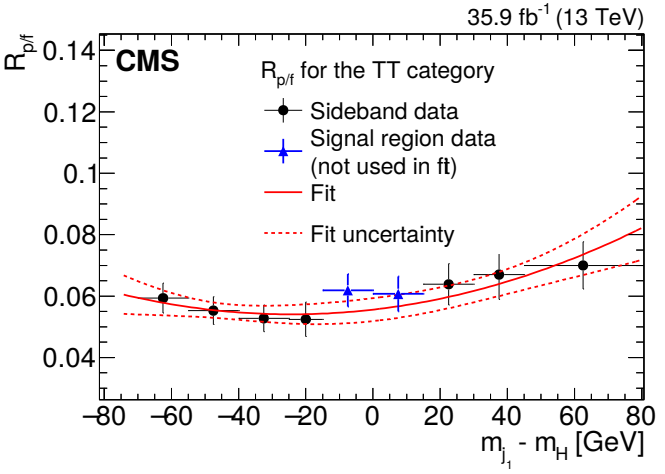
35.9 fb^{-1} (2016) B2G-16-026, submitted to Phys.Lett.B

- Triggers: jets, H_T cuts, $|\Delta\eta(J,J)|$
- 2 highest pT jets, $p_T > 300$, $|\eta|<2.4$
- LL & TT b-tag categs.
- $105 < m(J) < 135$, $\tau_{21} < 0.55$, $|\Delta\eta(J,J)|<1.3$

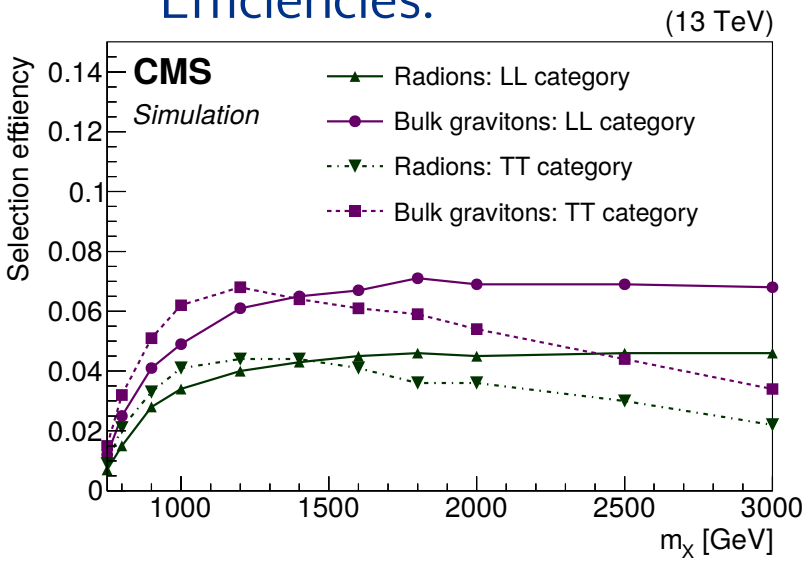
Fit in LL categ.:



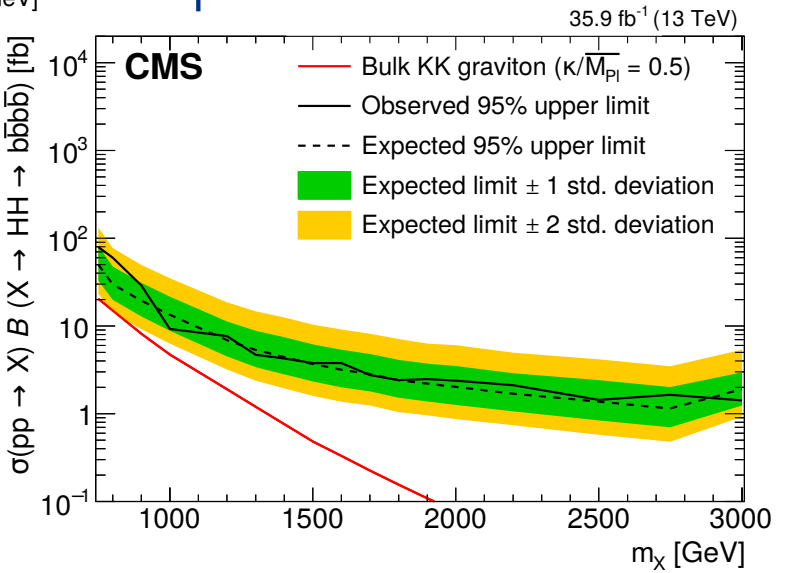
„alphabet" transfer factor:



Efficiencies:



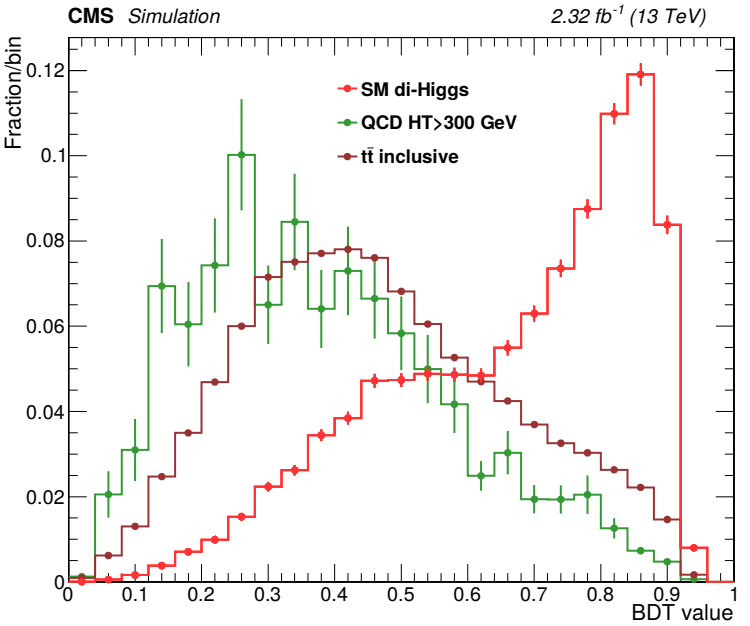
Spin 2 limits:



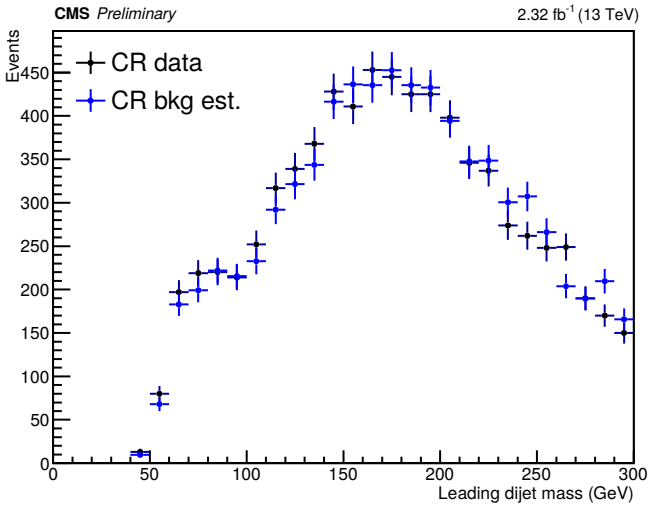
CMS nonresonant $b\bar{b}b\bar{b}$

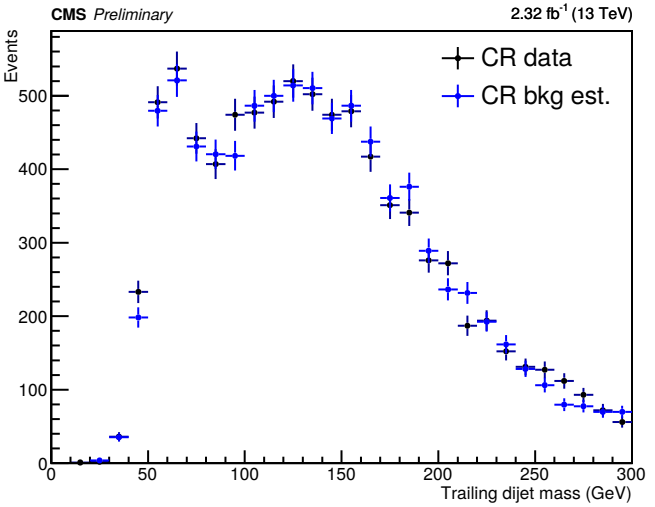
2.3 fb^{-1} (2015) PAS-HIG-16-026

- Trigger: 4 jets, 3 b-tagged
  - $p_T > 45$ || p_T>30/30/90/90
- BDT: $p_T(jj_1)$, $p_T(jj_2)$, $\Delta\eta(jj, jj)$, $\Delta\phi(jj,jj)$
  - Cut: 65% signal eff.



Validation of hemisphere mixing technique in Control Region:

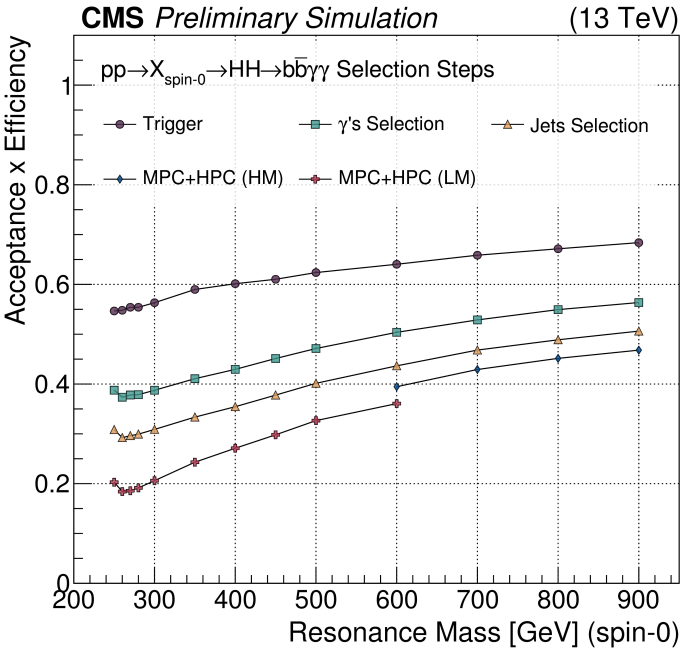


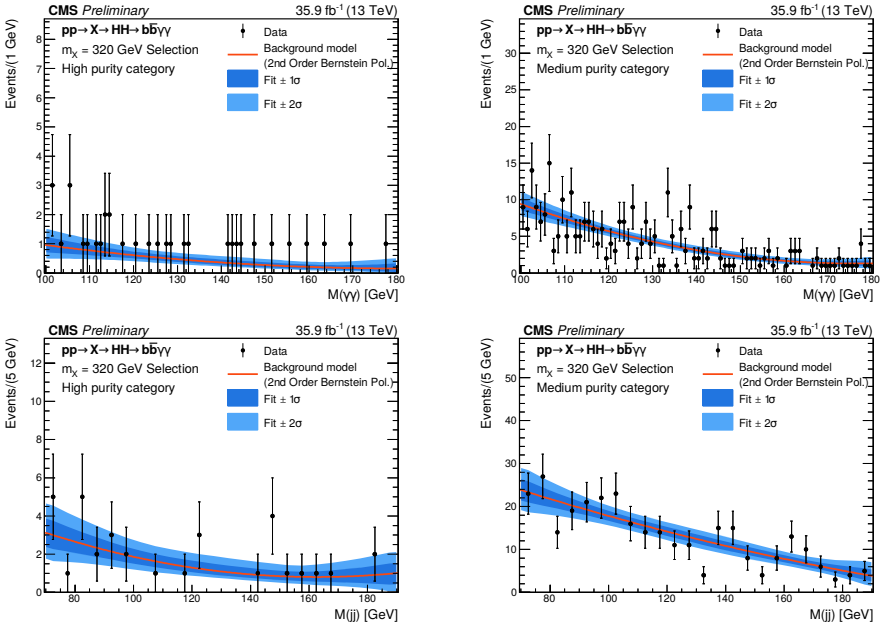


CMS $b\bar{b}\gamma\gamma$

35.9 fb^{-1} (2016) PAS-HIG-17-008

- Trigger: di-photon E_T>30/18
- $E_T(\gamma)/m(\gamma\gamma) > 1/3$ & $1/4$, $100 < m(\gamma\gamma) < 180$
- $\Delta R(j,\gamma) > 0.4$, $70 < m(jj) < 190$
- Jets with highest b-tag score
- BDT: b-tag scores, helicity angles ($2\rightarrow 4$ system), $p_T(\gamma\gamma)/m(jj\gamma\gamma)$, $p_T(jj)/m(jj\gamma\gamma)$
- 2 trainings: res. & nonres., all signals together



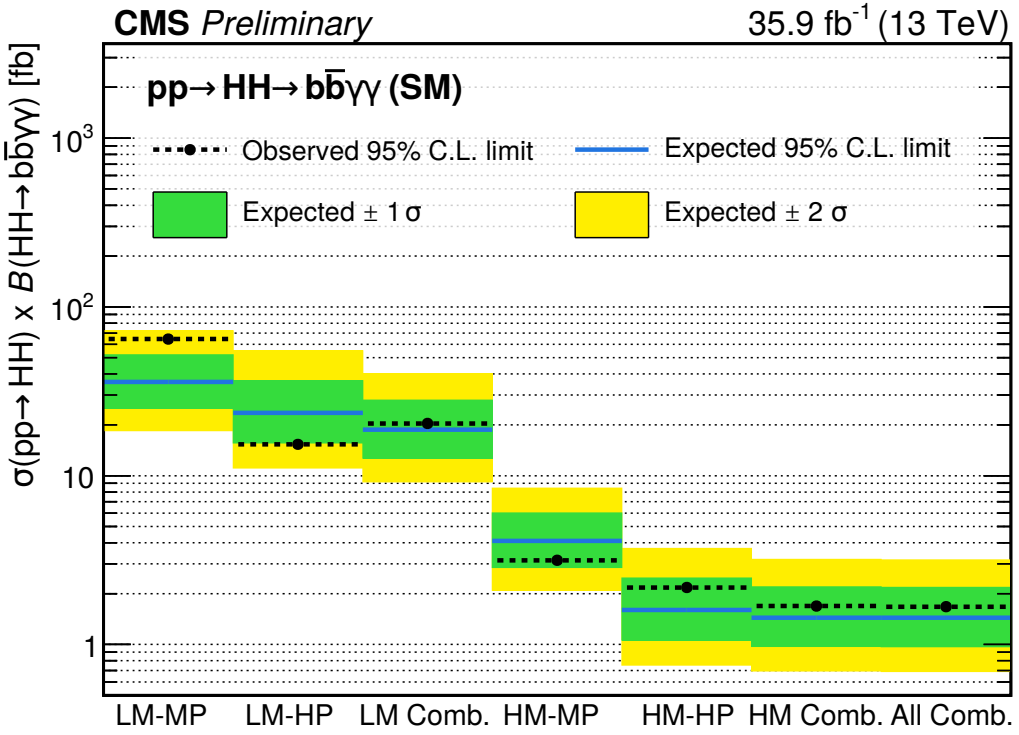


Analysis	Region	MVA Categorization	$\tilde{M}_X$
Nonresonant	High mass	HPC: MVA > 0.97 MPC: 0.6 < MVA < 0.97	$\tilde{M}_X > 350$ GeV
	Low mass	HPC: MVA > 0.985 MPC: 0.6 < MVA < 0.985	$\tilde{M}_X < 350$ GeV
Resonant	High mass	HPC: MVA > 0.5 MPC: 0 < MVA < 0.5	Mass window
	Low mass	HPC: MVA > 0.96 MPC: 0.7 < MVA < 0.96	Mass window

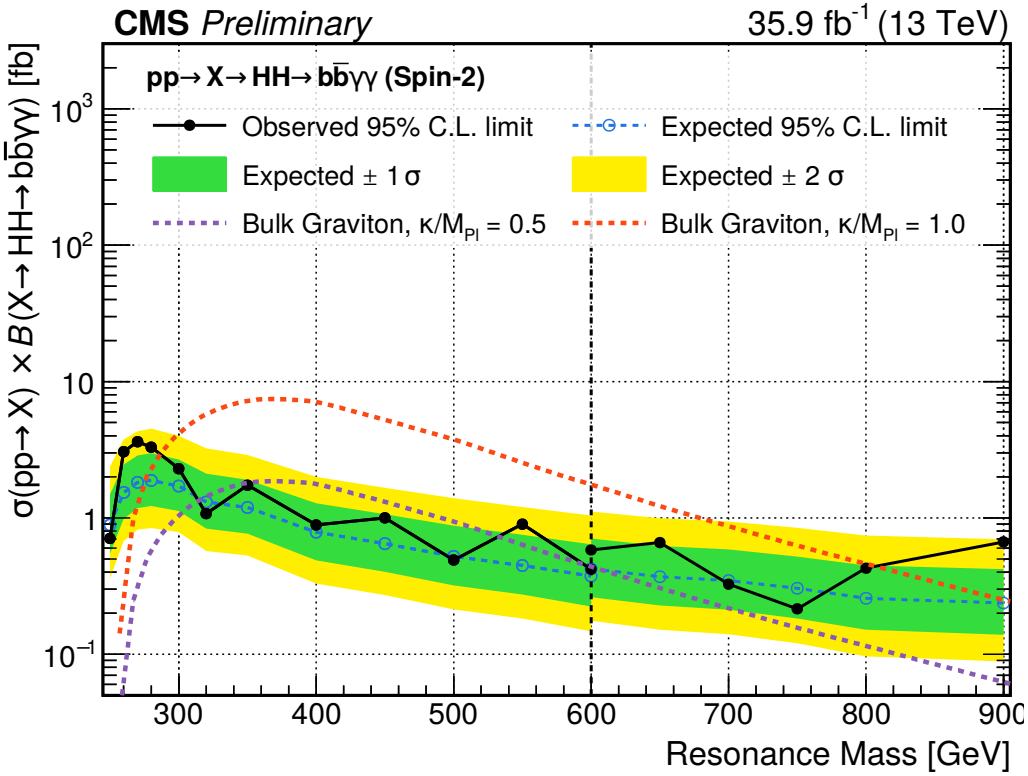
CMS $b\bar{b}\gamma\gamma$

35.9 fb^{-1} (2016) PAS-HIG-17-008

Nonresonant categories:



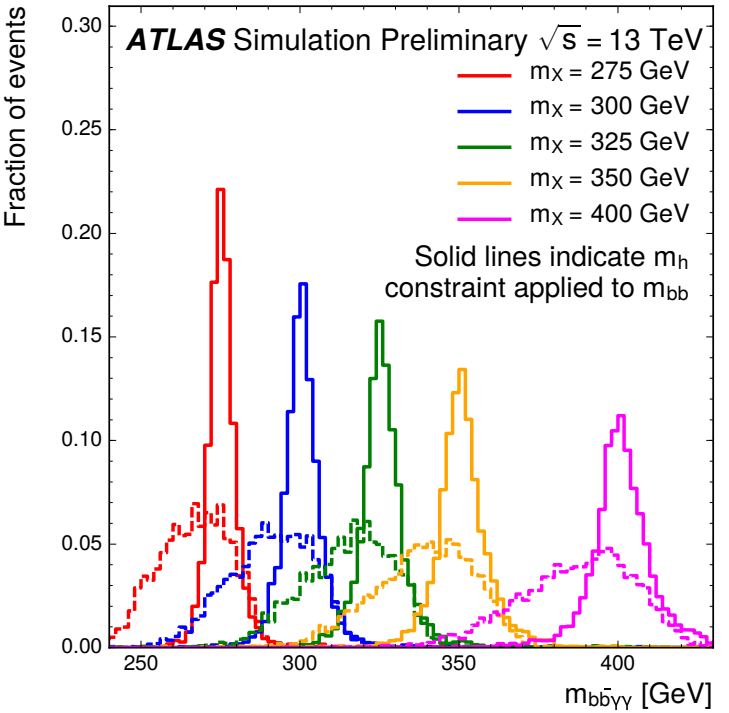
Spin-2 limits:

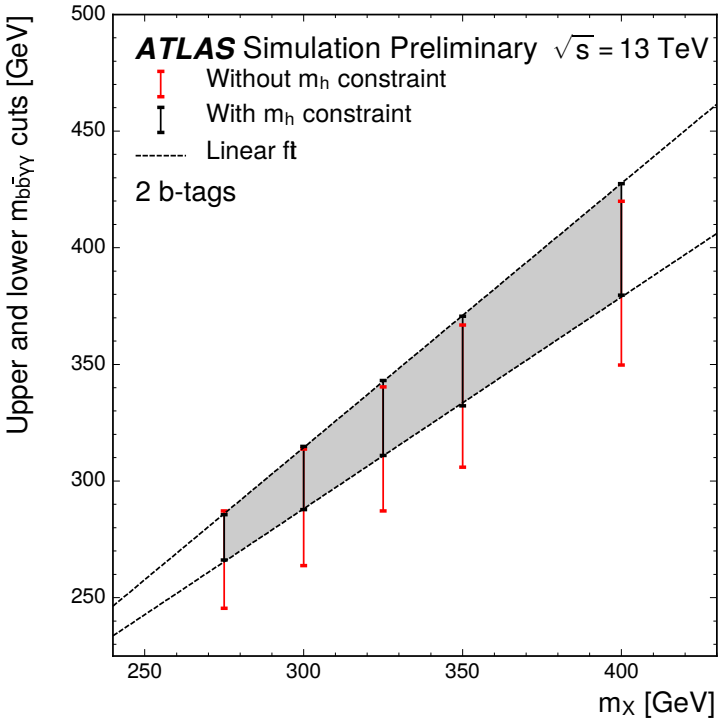


ATLAS $b\bar{b}\gamma\gamma$

3.2 fb^{-1} (2015) ATLAS-CONF-2016-004

- Trigger: di-photon E_T > 35/25
- $E_T(\gamma)/m(\gamma\gamma)$ > 0.35/0.25, 105 < $m(\gamma\gamma)$ < 160
- Primary vertex consistent with di-photon
- Jets p_T > 55/35, 95 < m(jj) < 135, =2 b-tags
- Sliding window in $m(jj\gamma\gamma)$ → 95% signal eff.





$$N_{SR}^{B} = N_{SB}\frac{\varepsilon_{m_{\gamma\gamma}}^{B}}{1-\varepsilon_{m_{\gamma\gamma}}^{B}}\varepsilon_{m_{b\bar{b}\gamma\gamma}}^{B}$$

CMS $b\bar{b}\tau\tau$

35.9 fb^{-1} (2016) HIG-17-002, submitted to Phys.Lett.B

- Triggers: 1 x lepton or 2 x τ_{had}
- τ_{had} reconstruction: „hadron plus strips"

Resolved:

$$\frac{(m_{\tau\tau} - 116\,\text{GeV})^2}{(35\,\text{GeV})^2} + \frac{(m_{bb} - 111\,\text{GeV})^2}{(45\,\text{GeV})^2} < 1$$

Boosted:

$80 < m(\tau\tau) < 160$,

$90 < m(jj) < 160$

Nonresonant:

„stransverse mass" M_{T2}

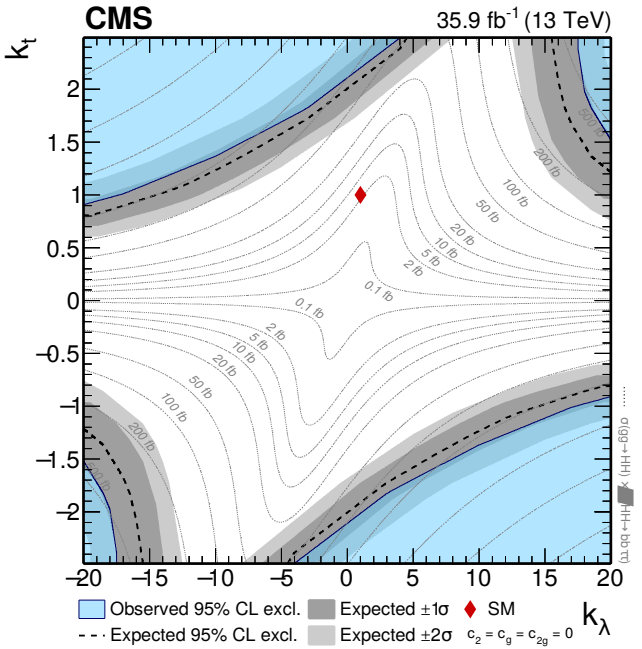
→ Phys. Lett. B 728 (2014) 308-313

Largest mass for X in X(→ bW(→ $\tau\not{E}_T$)) X(→ bW(→ $\tau\not{E}_T$)) decay chain, given constraints

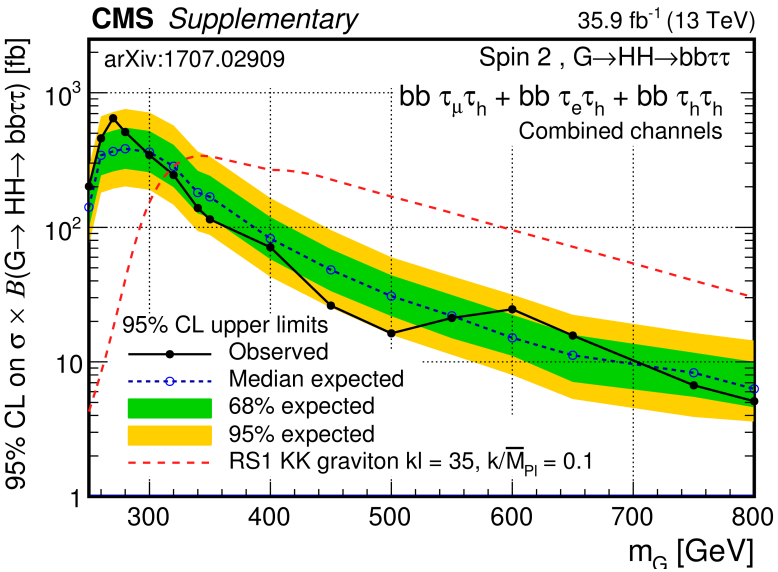
→ boundary at m(t) for $t\bar{t}$

$$m_{T2}\left(m_b, m_{b'}, \vec{b}_T, \vec{b}'_T, \vec{p}_T^{\,\Sigma}, m_c, m_{c'}\right) = \min_{\vec{c}_T + \vec{c}_T{}' = \vec{p}_T^{\,\Sigma}} \left\{\max\left(m_T, m'_T\right)\right\}$$

$$m_T\left(\vec{b}_T, \vec{c}_T, m_b, m_c\right) = \sqrt{m_b^2 + m_c^2 + 2\left(e_b e_c - \vec{b}_T \cdot \vec{c}_T\right)}$$



Spin-2 limits:



CMS $b\bar{b}VV^*(l\nu l\nu)$

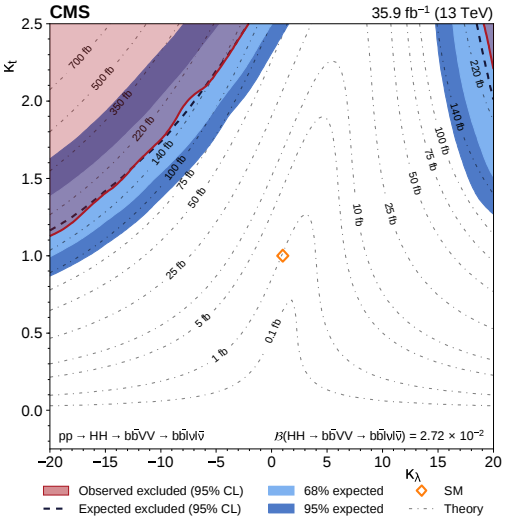
35.9 fb^{-1} (2016) HIG-17-006, submitted to JHEP

- Triggers: 2 leptons (p_T > 10/20 → 15/25)
- 12 < m(ll) < 76
- m(jj) bins: 0 ↔ 76 ↔ 140 →
- Neural network: 8 variables

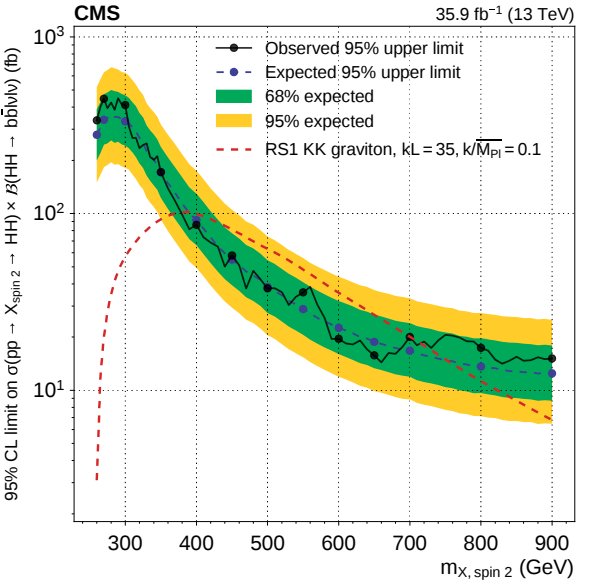
+ physics parameters

Single training, but:

→ smooth interpolation of performance as function of signal parameter



Spin 2 limits:



m_X →