Lake Louise Winter Institute

February 19th, 2018 – Lake Louise, Canada

Search for double Higgs production with the CMS experiment

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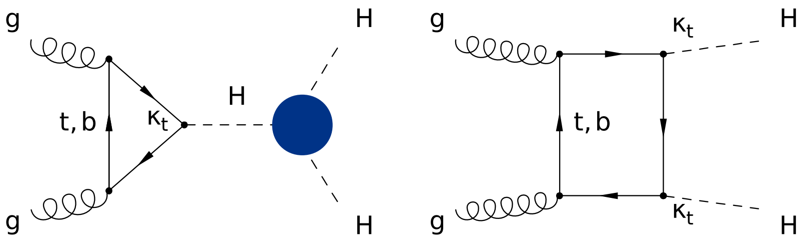
Université catholique de Louvain

Motivations

Nonresonant

- *Direct* access to Higgs self-coupling λ
- Probe shape of EWSB potential



- Destructive interference → small rate:
  - $\sigma_{HH,SM} = 33$ fb @ 13 TeV
- BSM effects → early discovery?
  - Higgs self-coupling: $\kappa_\lambda = \lambda/\lambda_{SM}$
  - Top Yukawa: $\kappa_t = y^t/y^t{}_{SM}$

  ↔ EFT parameterisation

→ strong effect on rates & kinematics

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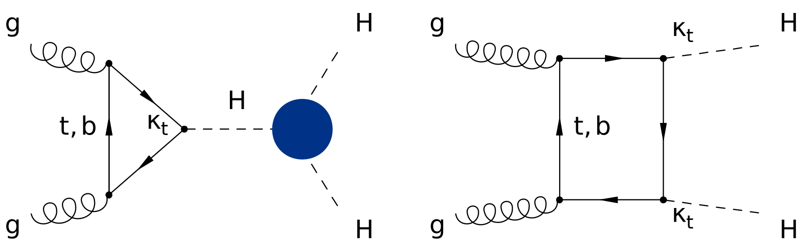

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  ↔ EFT parameterisation

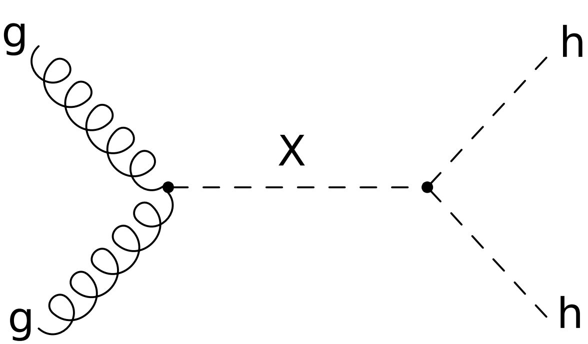
→ strong effect on rates & kinematics

Resonant

- MSSM/2HDM (extra doublet)
- Higgs portal (extra singlet)
- Warped extra dimensions
  - Radion
  - Graviton

…

- Searches assume **narrow width**
- Spin 0 & 2 benchmarks



Higgs pairs in practice

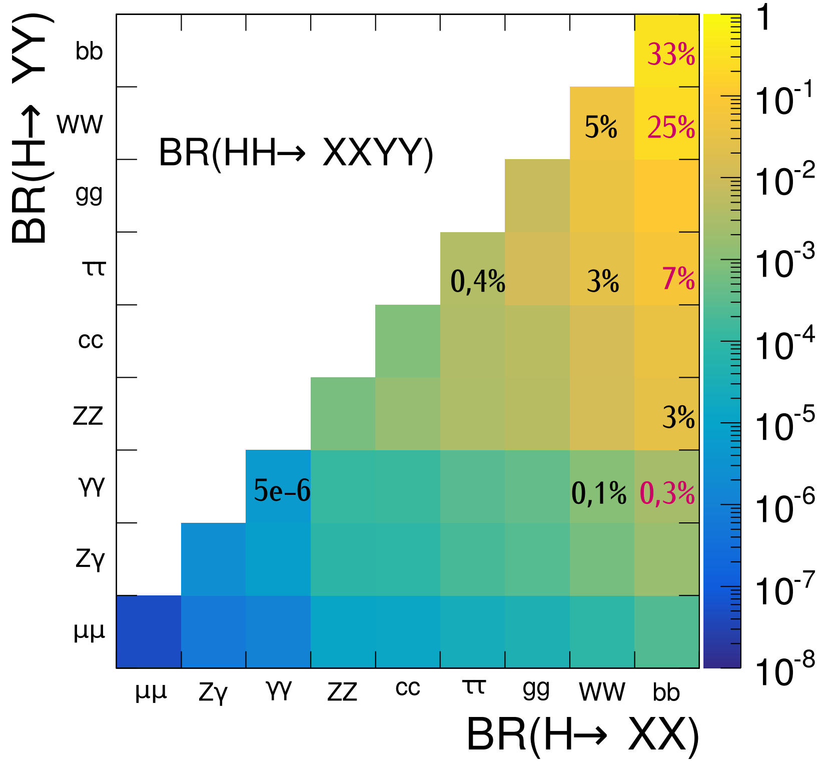
Variety of final states to look at! Rely on one H → b$\bar{b}$:

- **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

Best **Run I** results on **SM** HH:

Obs.(exp.) limit on σ_{HH}/σ_{SM}: **43 (47)**

PRD 96, 072004



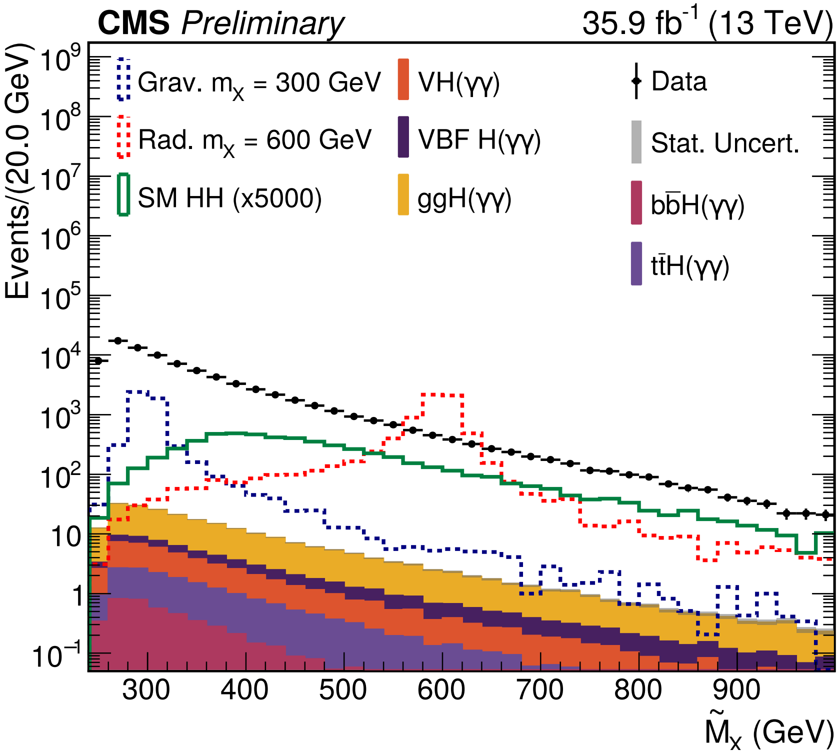
(Non)resonant $b\bar{b}\gamma\gamma$

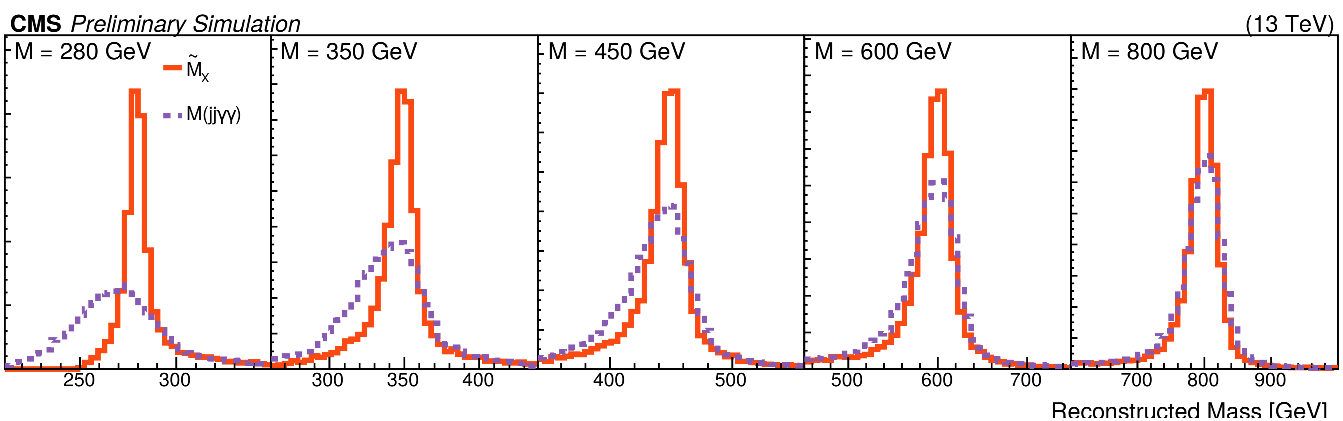
35.9 fb^{-1} (2016) PAS-HIG-17-008

- 2 photons, 2 b-tagged jets (R=0.4)
- **Reduced mass:**

  $M_x = m(jj\gamma\gamma) - m(jj) - m(\gamma\gamma) + 250$ GeV
- Categories from **BDT** & M_x windows
- Backgrounds:
  - Multijet + photons, fake photons
  - SM single Higgs (from MC)
- Signal extraction:

  2D parametric fit on $m(\gamma\gamma)$ vs. $m(jj)$

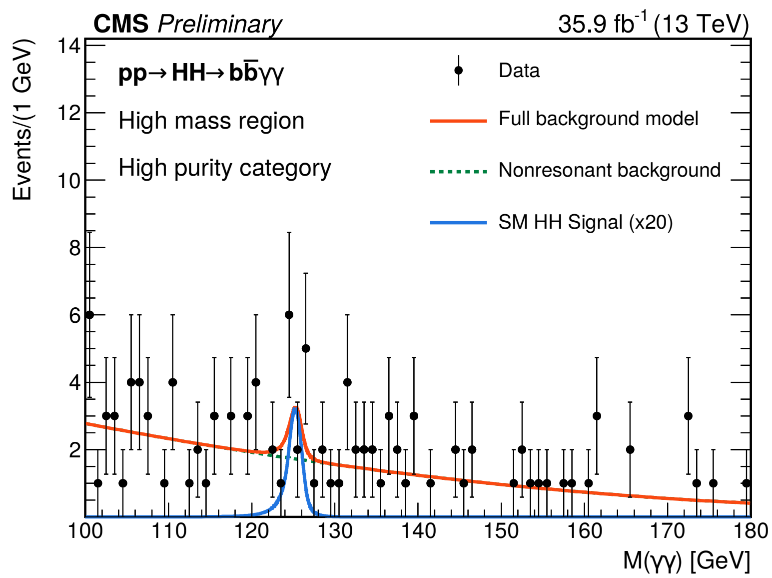


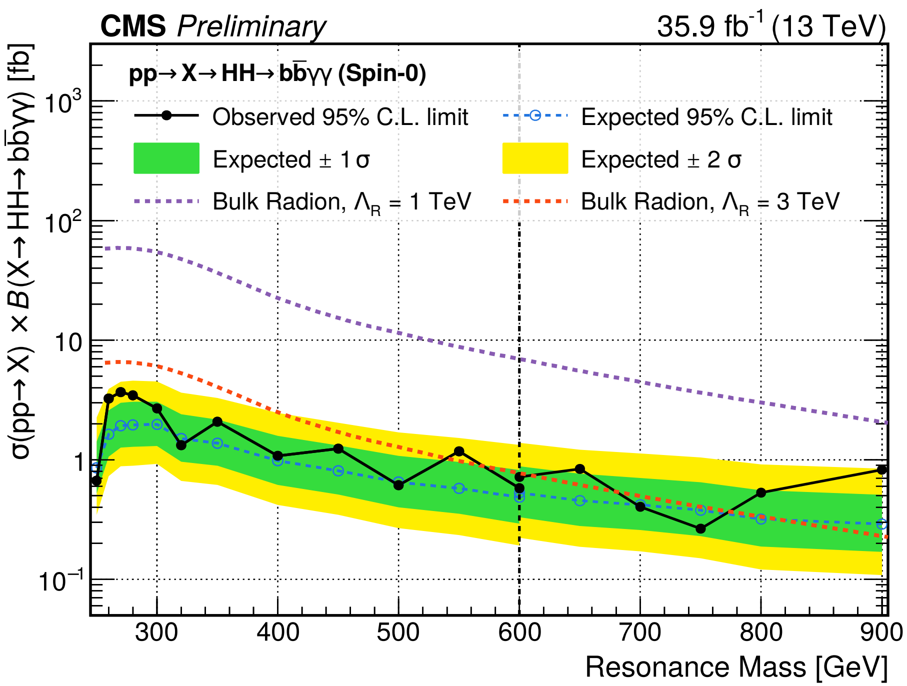


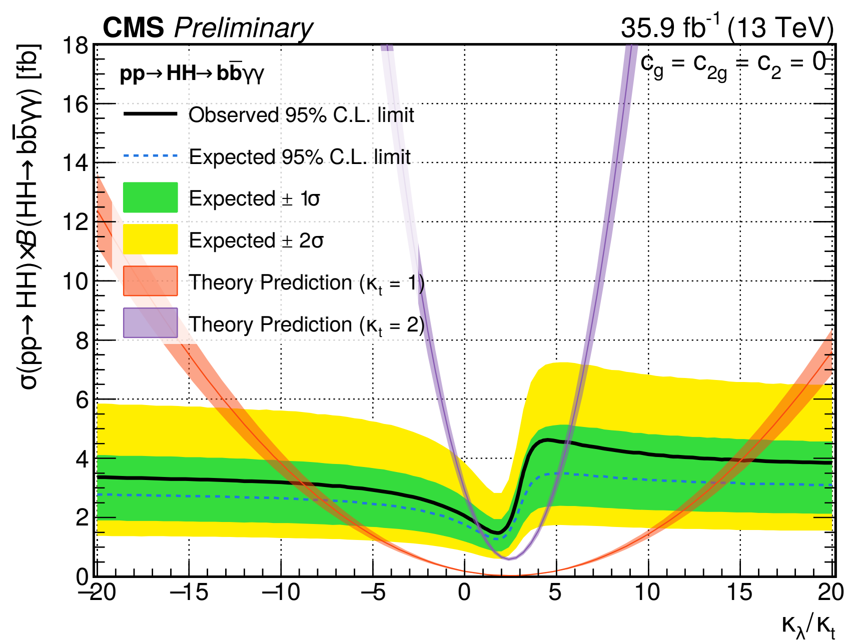
(Non)resonant $b\bar{b}\gamma\gamma$ results

<u>Nonresonant</u> results:

- SM σ x BR < 1.67 fb
- Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}}$ **< 19.2 (16.5)**







Resonant resolved $b\bar{b}b\bar{b}$

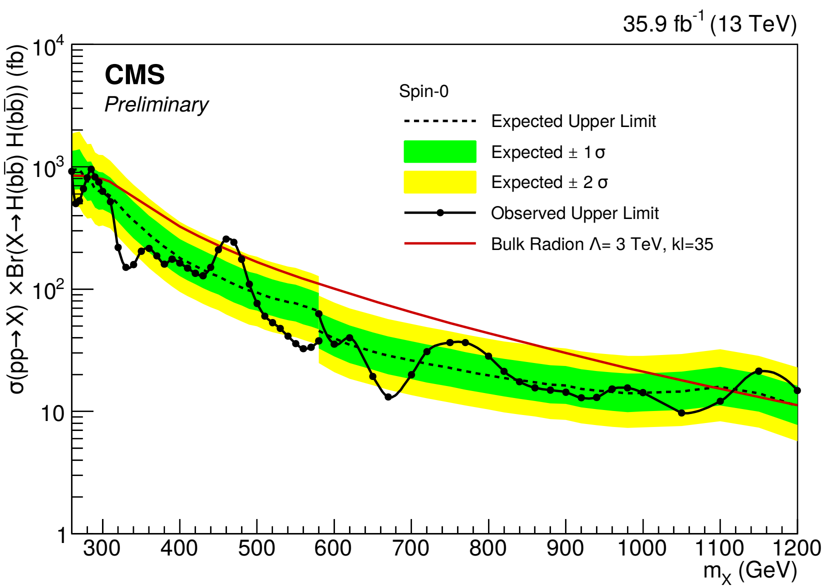
35.9 fb^{-1} (2016) PAS-HIG-17-009

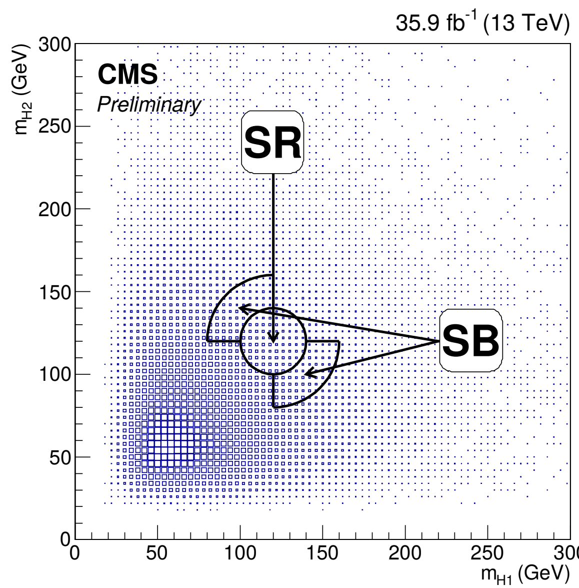
- 4 b-tagged jets
  - new **DeepCSV** algorithm
- B-jet energy regression
- Low & Medium Mass regions
  - Different jet pairing
- Kinematic fit → m(HH)

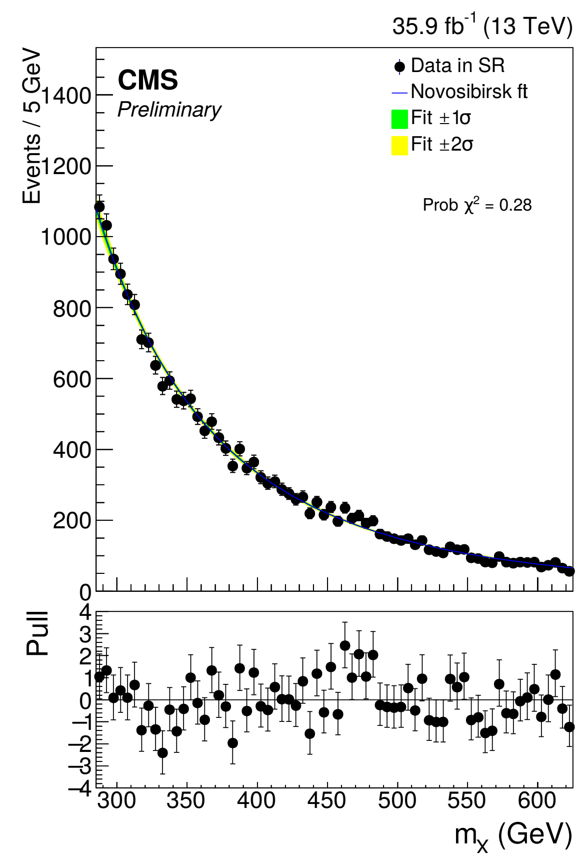
Backgrounds: multijet, $t\bar{t}$

- Parametric fits (3 mass ranges)
- Checks:
  - Mass sidebands, <4 b-tag
  - Alternate SR definition

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







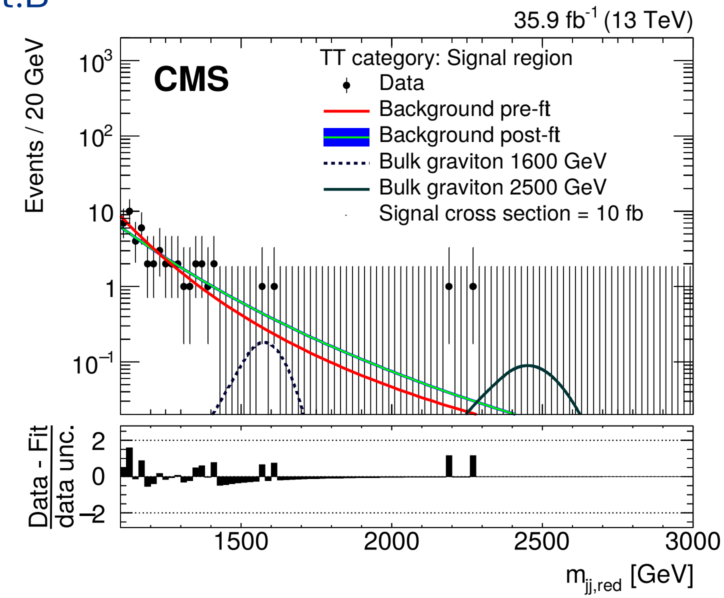
Resonant boosted $b\bar{b}b\bar{b}$

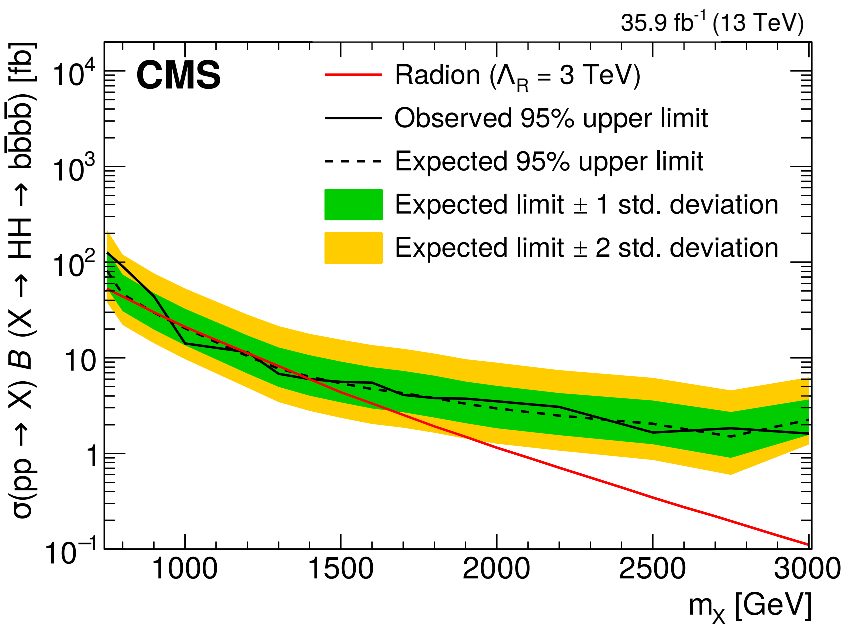
35.9 fb^{-1} (2016) B2G-16-026, submitted to Phys.Lett.B

Target m_X > 800 GeV

- 2 jets, R=0.8, "double-b" tagging
- Use "soft-dropped" m(J), N-subjettiness
- **Signal extraction → reduced mass:**

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





Multijet background estimation:

M_{red} < 1200 GeV: refined ABCD method

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

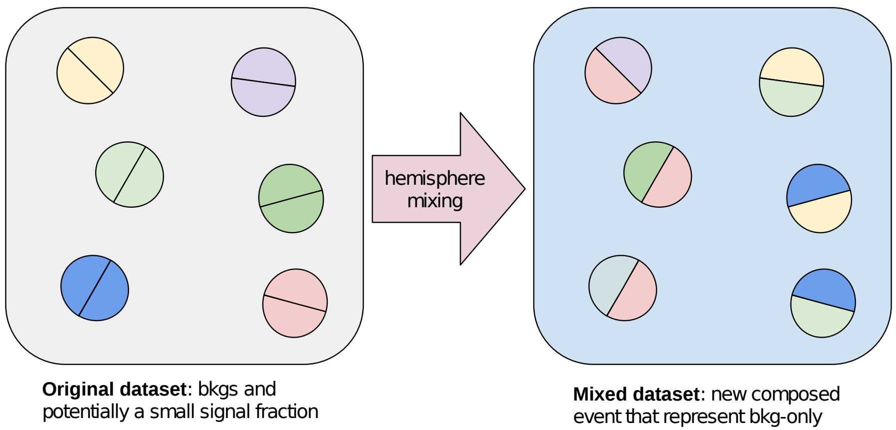
M_{red} > 1200 GeV:

- Parametric fit
- Same shape SB & SR, yields from ABCD

Nonresonant $b\bar{b}b\bar{b}$

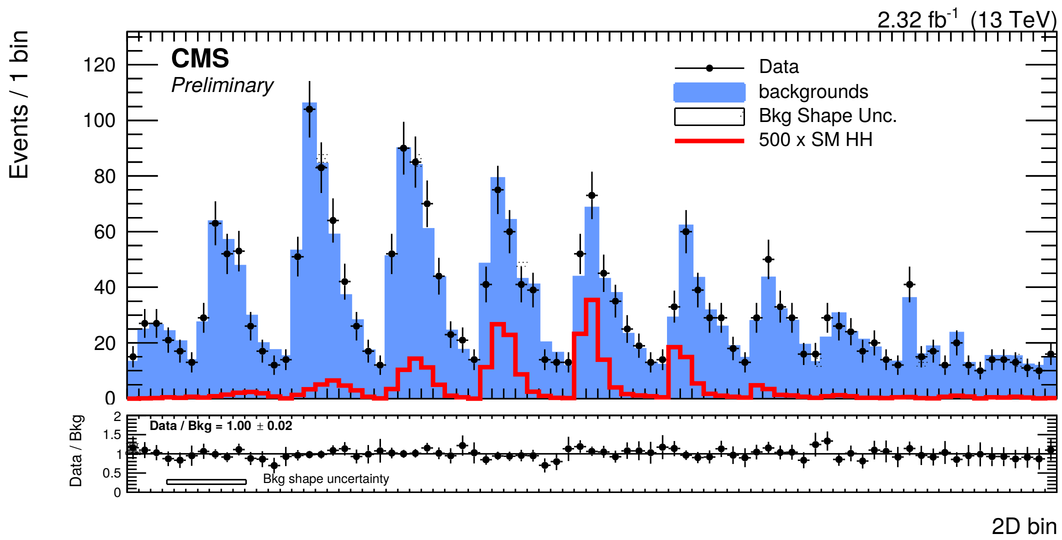
2.3 fb^{-1} (2015) PAS-HIG-16-026

- 4 jets (R=0.4), 3/4 b-tagged
- Jet pairing: closest to m_H



- Cut on **BDT**
- Signal extraction:

  2D shape of leading vs. sub-leading m(jj)



Multijet & $t\bar{t}$ background est. from data:

Hemisphere mixing:

- Data events cut in 2 hemispheres
- 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!

(Non)resonant $b\bar{b}\tau\tau$

35.9 fb^{-1} (2016) PLB778(2018)101

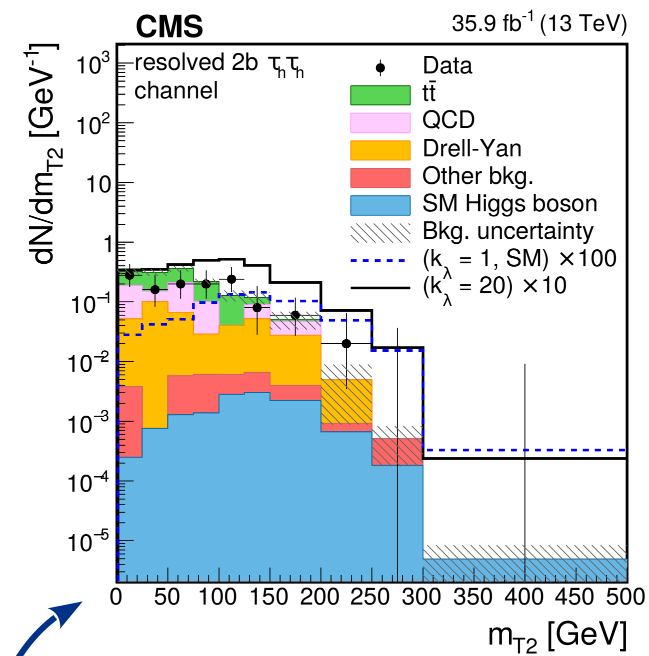
- 3 channels: $\tau_{had}\tau_{had}$, $\tau_{had}\tau_{\mu}$, $\tau_{had}\tau_{e}$ (88%)
- m($\tau\tau$) reconstruction from kinematic fit
- 2 jets (R=0.4)

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:

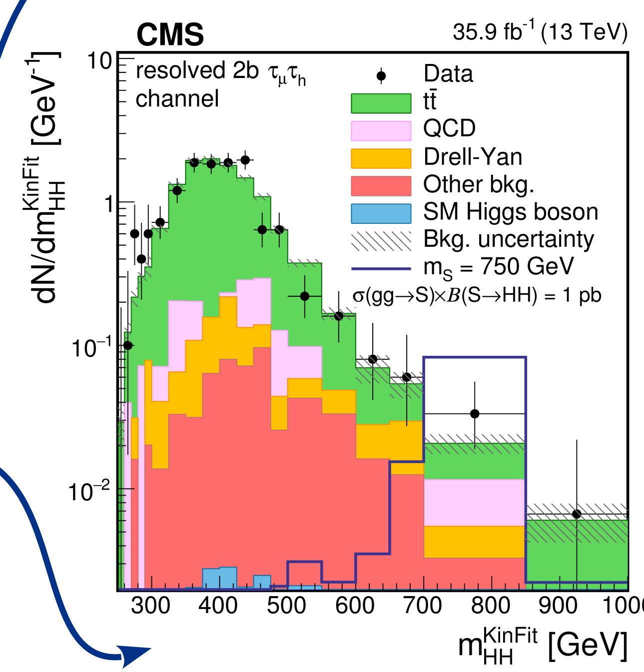
- $t\bar{t}$, Z+jets: MC
- QCD: data-driven

Nonresonant: "stransverse mass" M_{T2}

2 BDTs → categories

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

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



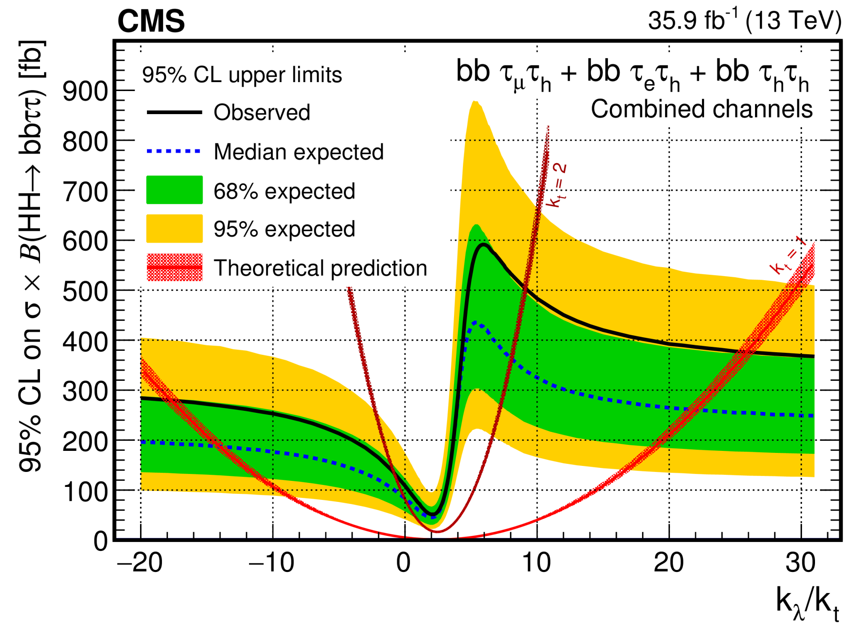
(Non)resonant $b\bar{b}\tau\tau$ results

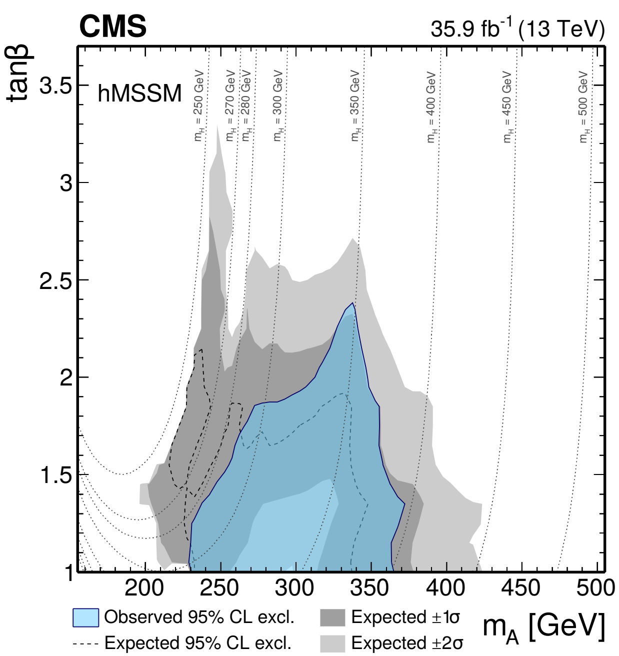
Nonresonant:

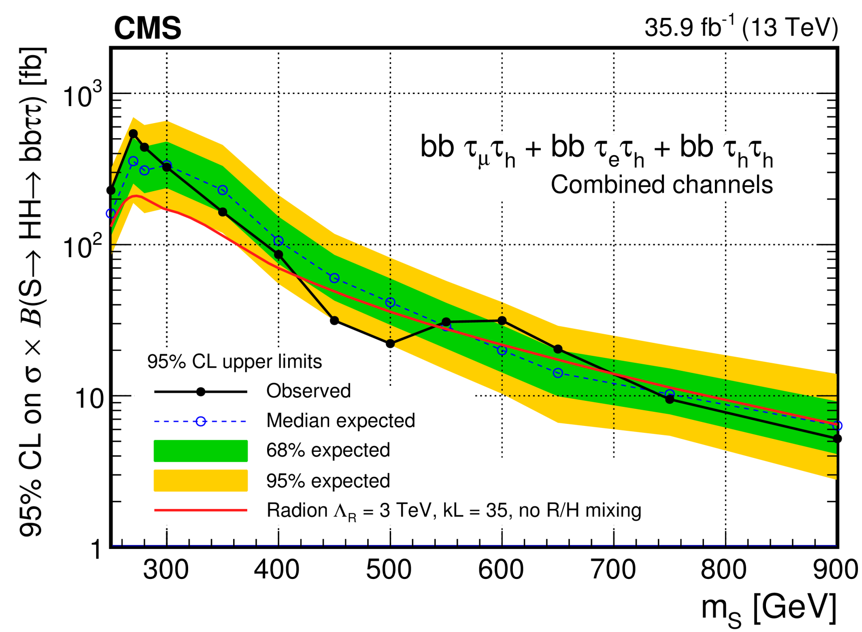
- SM σ x BR < 75.4 fb
- Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}} <$ **30 (25)**

Resonant:

- Interpretation in hMSSM







Resonant boosted $b\bar{b}\tau\tau$

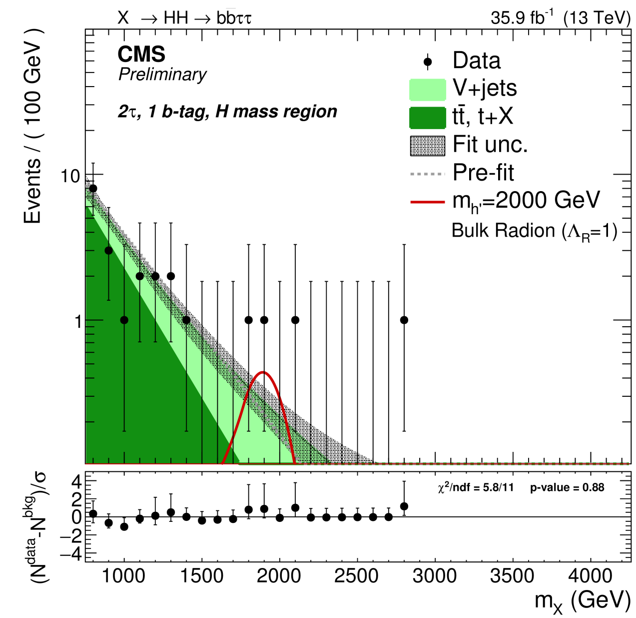
NEW!

35.9 fb^{-1} (2016) PAS-B2G-17-006

X → H($\tau\tau$) + H(bb)

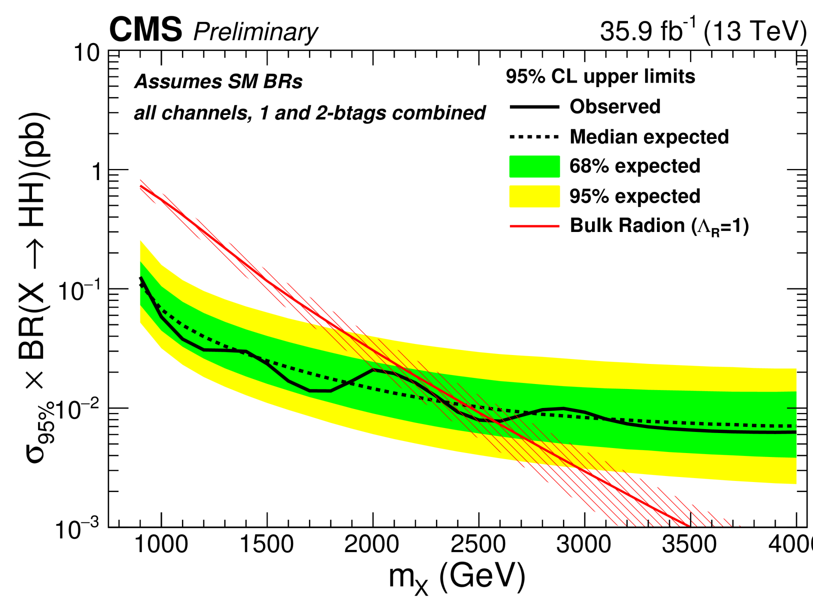
- CA jet (R=0.8)
- had/had or lep/had
- m($\tau\tau$) from kin. fit
- 50 < m($\tau\tau$) < 150 GeV

- AK jet (R=0.8)
- 1 or 2 sub-jets b-tagged
- 105 < m(J) < 135 GeV



Backgrounds:

	$t\bar{t}$, t+X	V+jets
Shape	Simulation	m(J) sidebands, corrected using simulation
Norm.	Control region	Fit to m(J) distribution



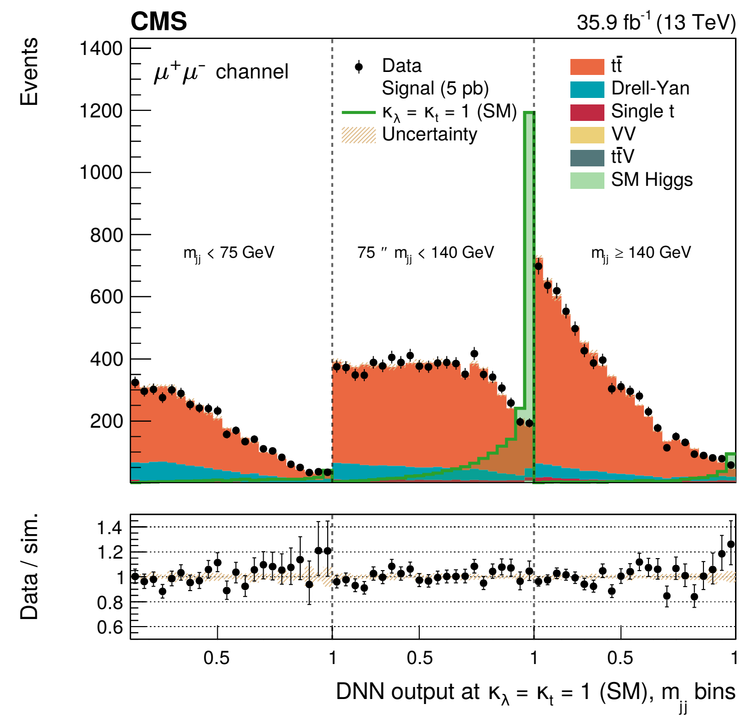
Signal extraction: parametric fit to m(HH)

→ Limits on spin 0 & 2 resonances

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

35.9 fb^{-1} (2016) JHEP01(2018)054

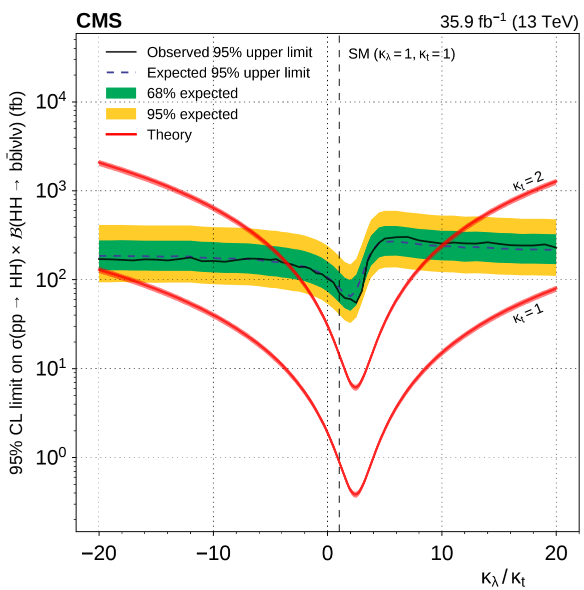
- 2 OS leptons → ee, $\mu\mu$, eμ+μe, 2 b-tagged jets
- Focus on WW* part – remove Z(ll) peak & tail
- Bkg.: $t\bar{t}$, Z+jets → simulation



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

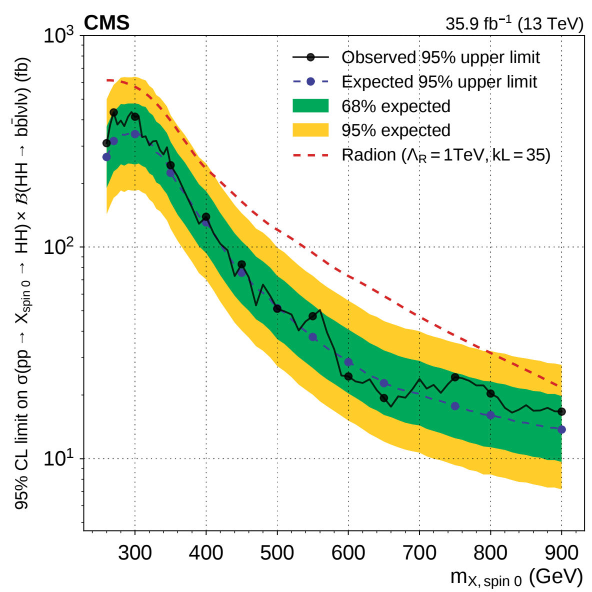
- Optimal sensitivity with single training
- Limit from DNN shape in 3 m(jj) bins

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



Nonresonant results:

- SM σ x BR < 72 fb
- Obs.(exp.): $\boldsymbol{\sigma/\sigma_{SM}}$ **< 79 (89)**



Results summary

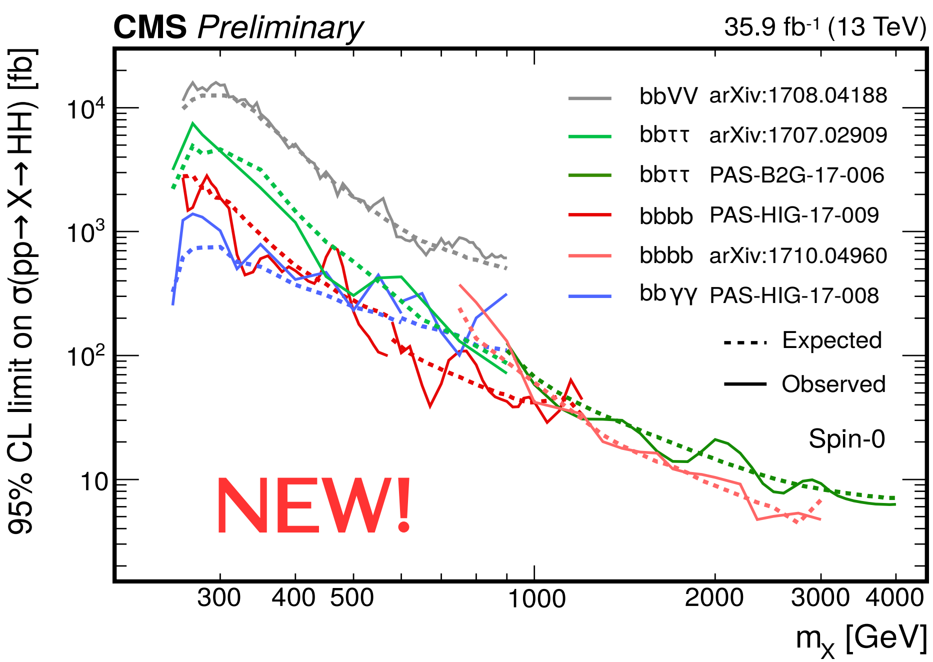
- Most stringent limit on Higgs self-coupling λ:

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

- Exclusions on resonances:

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

  4 fb (3 TeV)



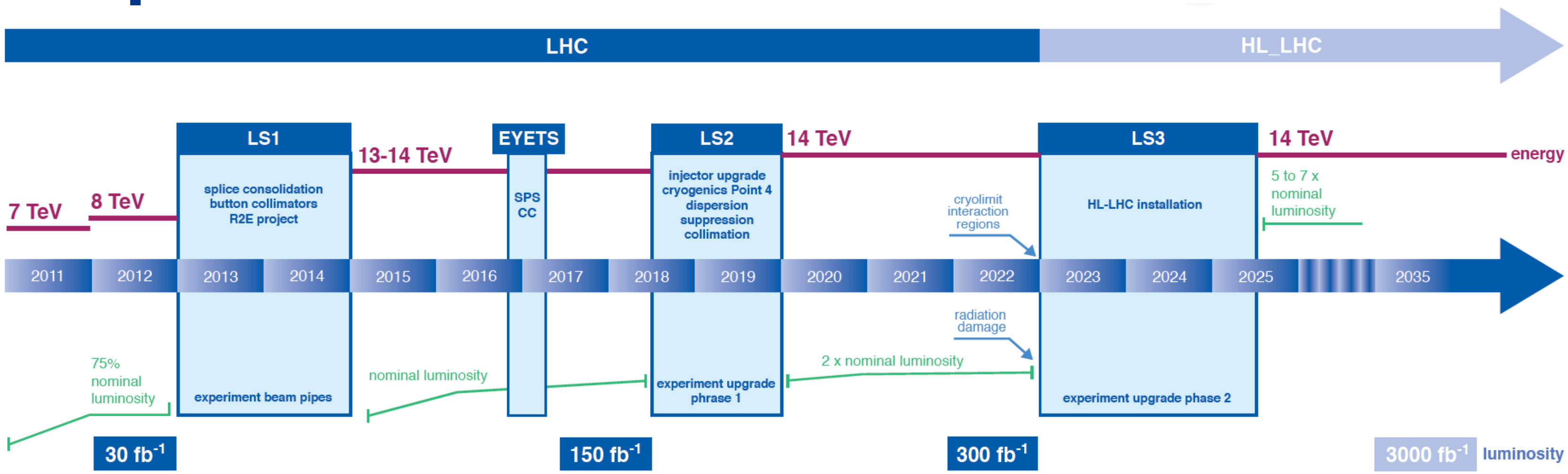
Limits on σ_{HH}/σ_{SM}:

Final state	Obs. (exp.)
$b\bar{b}\gamma\gamma$	19 (16)
$b\bar{b}\tau\tau$	30 (25)
$b\bar{b}b\bar{b}$	342 (308)
$b\bar{b}WW^*$	79 (89)

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

2016 (35.9 fb^{-1})

Prospects for HL-LHC



- LHC → $\sqrt{s}$ = 14 TeV → $\boldsymbol{\sigma}_{SM}$ +18%
- Ultimate L_{int} → 3000 fb^{-1} (2025 – 2035)
- L_{inst} → 5e34/cm²/s, average pileup → 200

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

- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}VV(l\nu l\nu, l\nu jj)$
- ~50% precision on σ_{SM}

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

- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$, $b\bar{b}VV(l\nu l\nu)$

Conclusions

- CMS: rich search program on double Higgs production
- Much more than SM!
  - Spin-0 and spin-2 (KK-Grav.) resonances
  - Nonresonant BSM effects
- **No excess** above SM expectations seen
- Long & exciting road ahead – crucial channel at HL-LHC

Stay tuned!

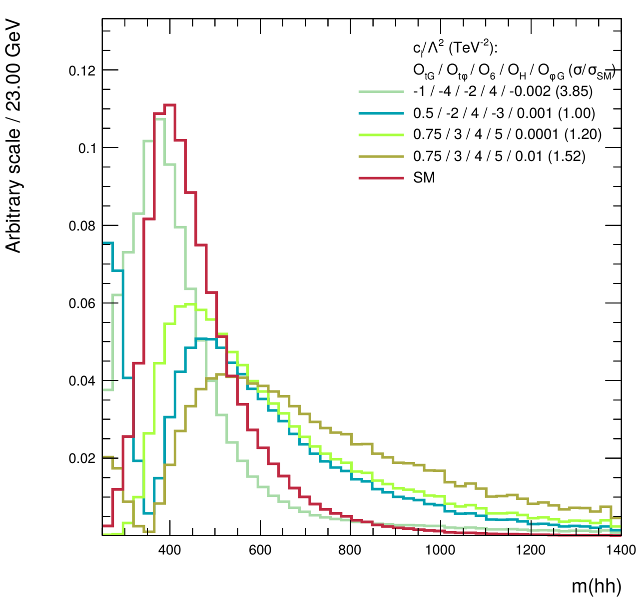
- Dataset updates coming soon
- Next milestone: full Run II analysis

Back-up

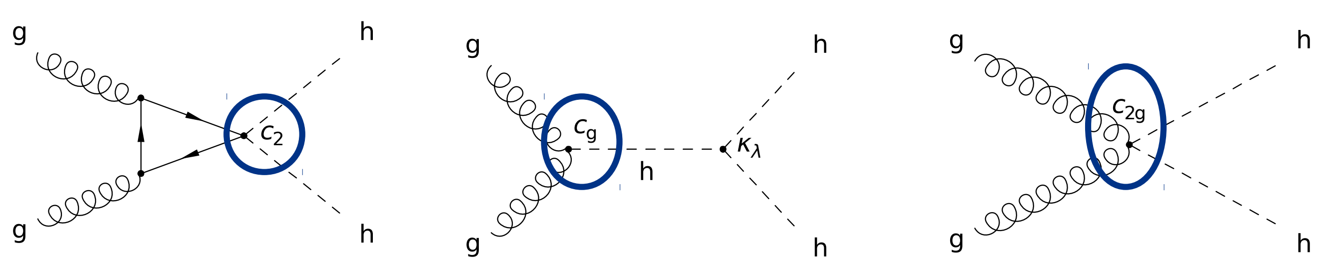
EFT and Higgs pairs

- 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)



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



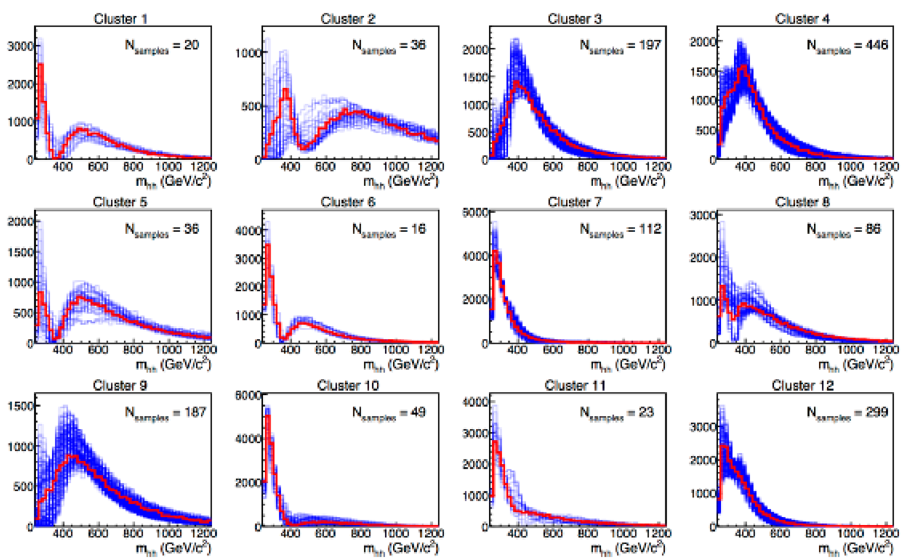
Nonresonant EFT results

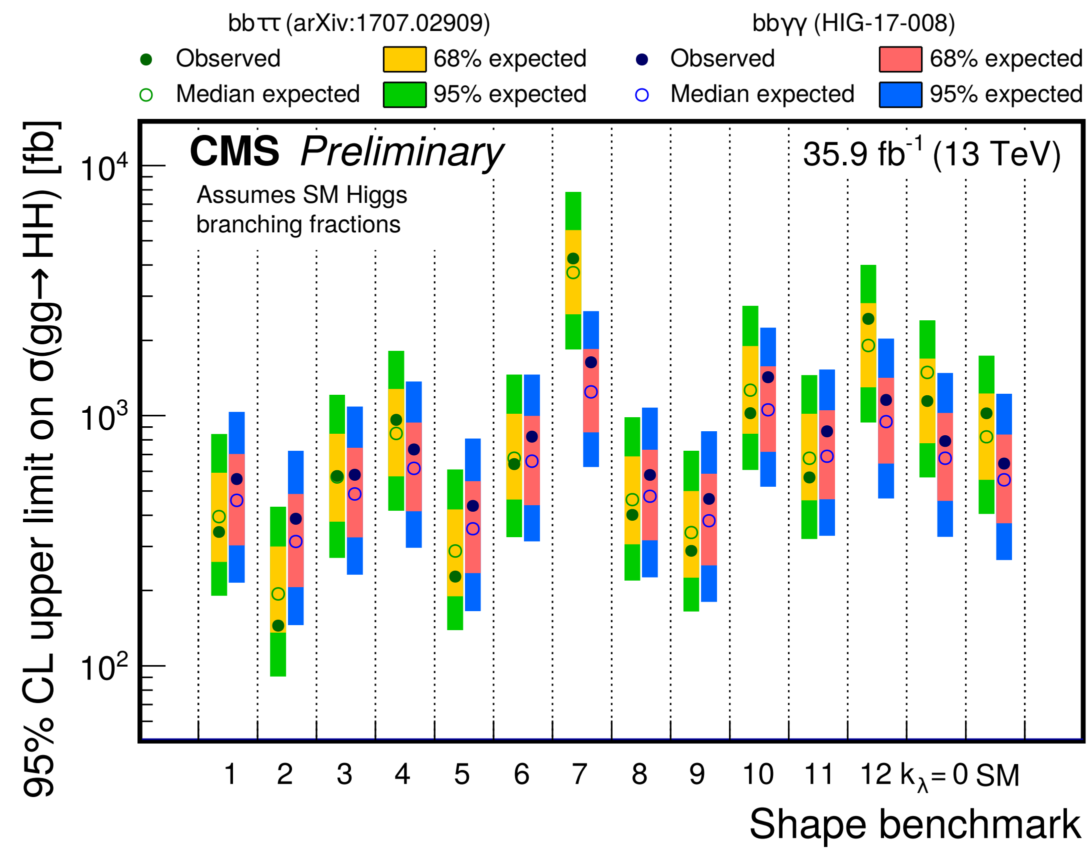
EFT: 5 parameters

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

Limits on shape „**benchmarks**":

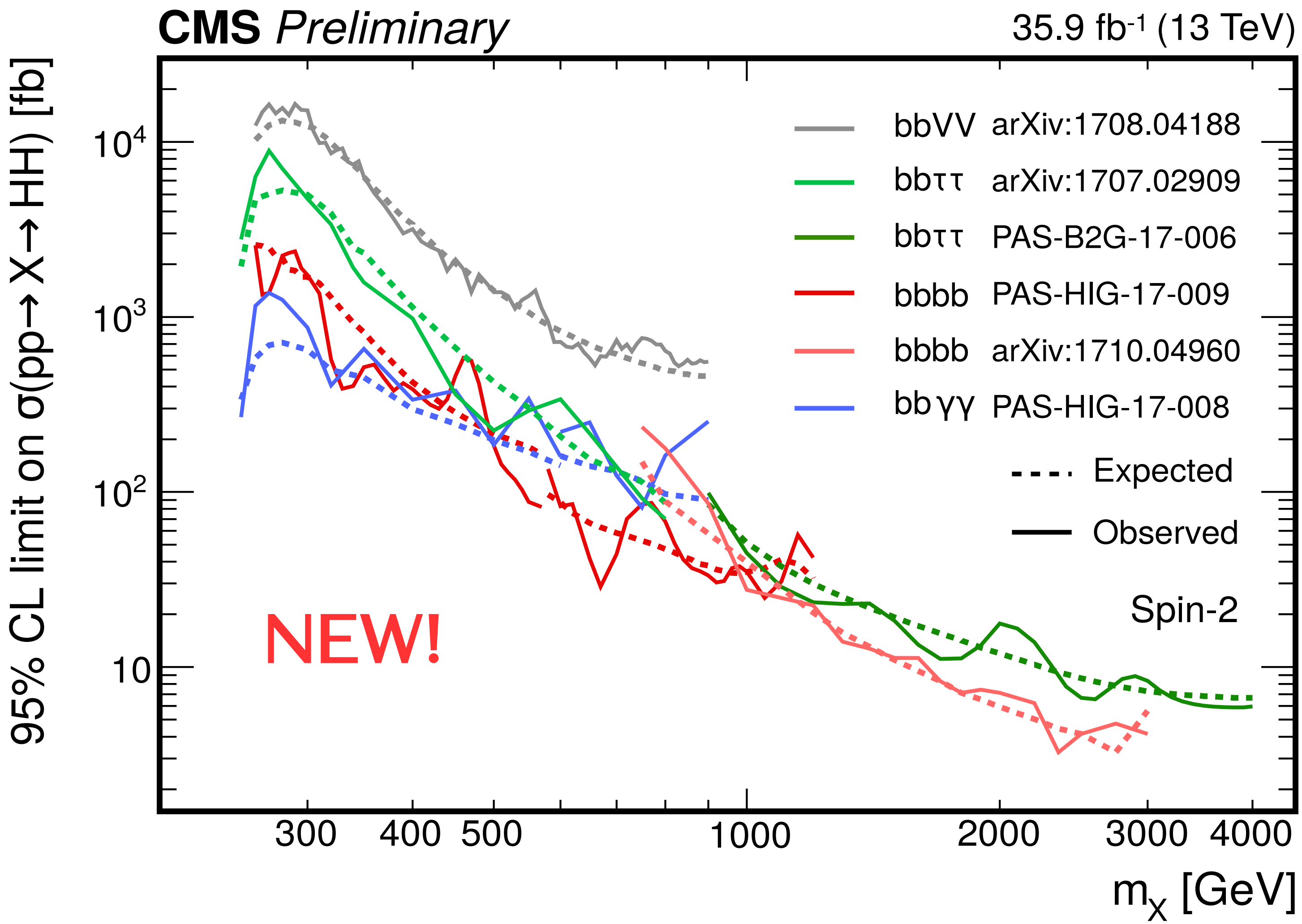
Channels have different sensitivity depending on kinematics!





Spin-2 resonances

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



HL-LHC upgrade studies

CMS upgrade:

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- Barrel calorimeters: new electronics
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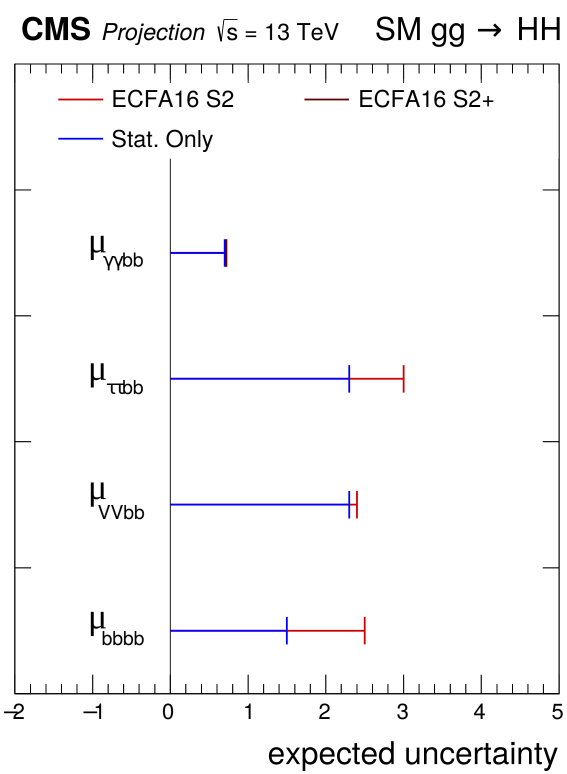
- Muon detectors to $|\eta|<2.8$
- Trigger: L1 @ 750 kHz, HLT @ 7.5 kHz

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

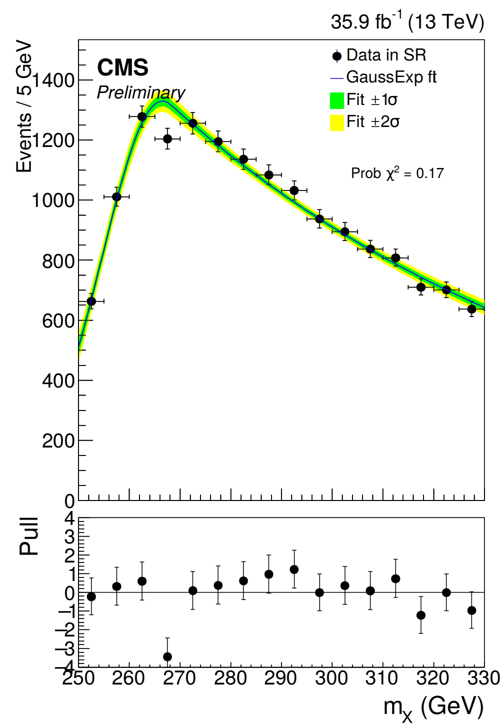
- **$b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$, $b\bar{b}VV(l\nu l\nu)$**
- Different scenarios:
  - No systematics ("stat. only")
  - Scenarios with reduced theory uncertainties & reduced systematics (≈ future detector performances)

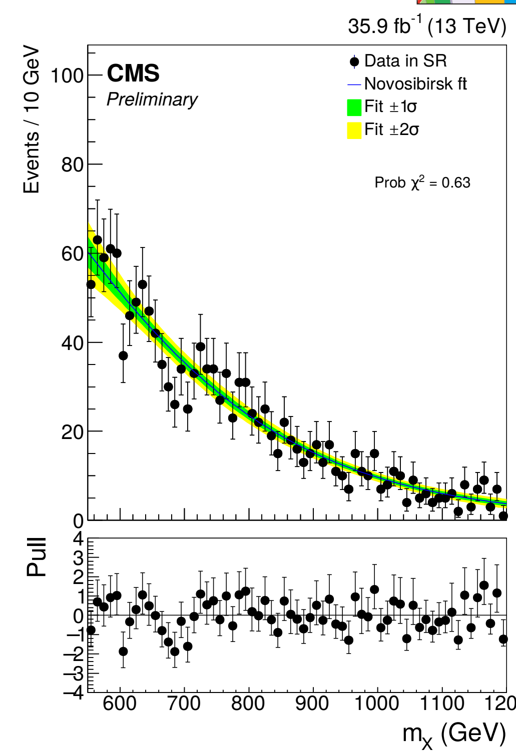
[1] JHEP02(2014)057

Resonant resolved $b\bar{b}b\bar{b}$

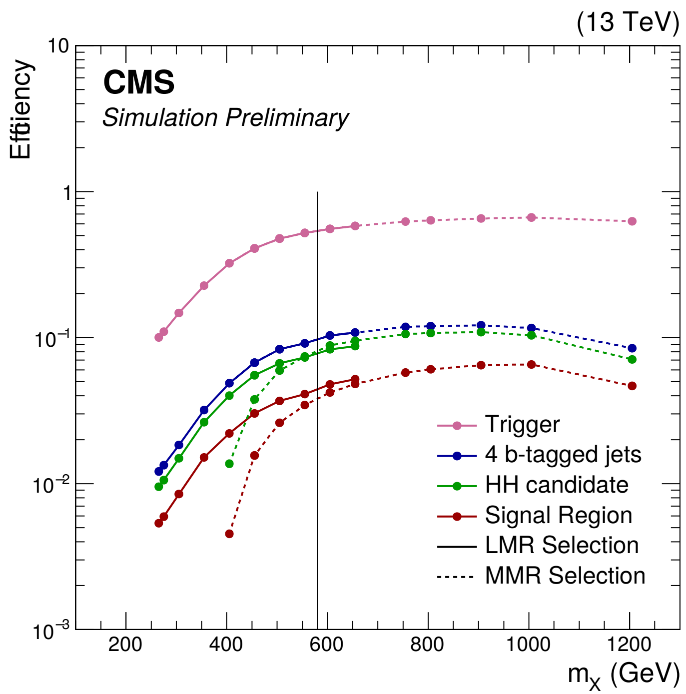
35.9 fb^{-1} (2016) PAS-HIG-17-009

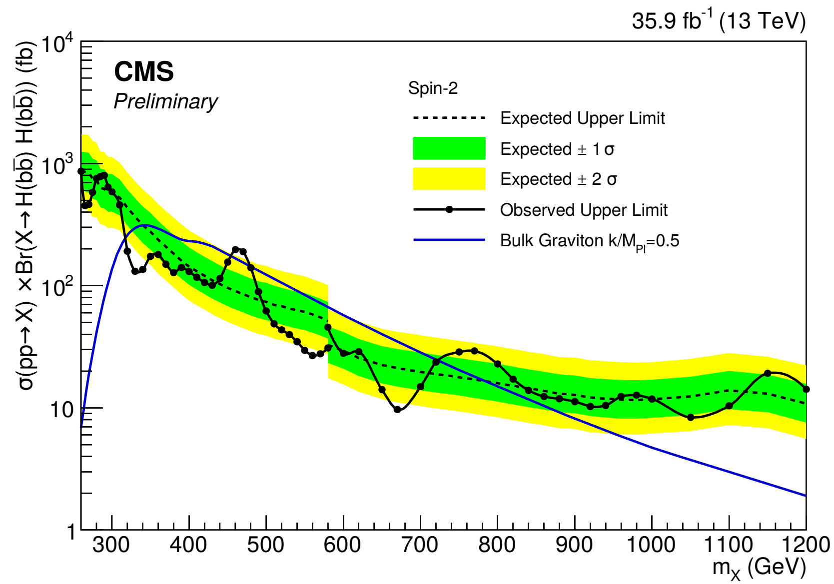
- LMR: |m(jj) -120| < 40
- MMR: ΔR(j,j) < 1.5 for each h cand.
- Ambiguities → minimise mass ChiSq
- Trigger: 4 jets, 3 b-tagged (CSVv2)





Efficiencies:



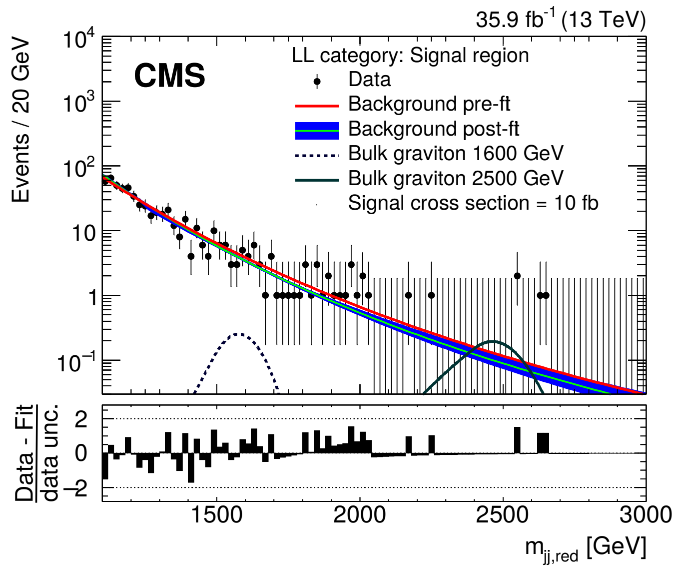


Resonant boosted $b\bar{b}b\bar{b}$

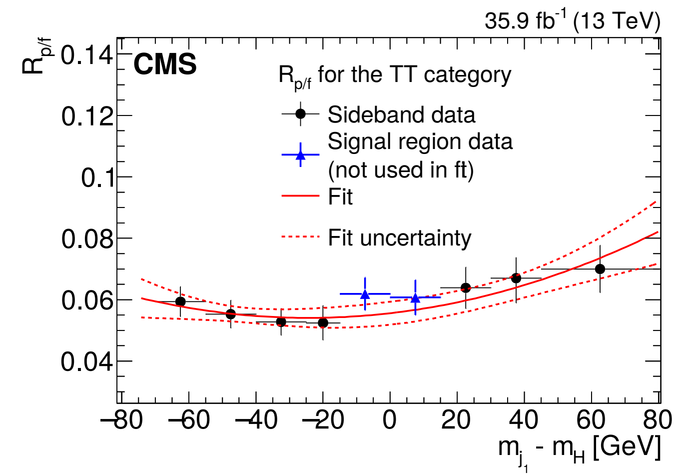
35.9 fb^{-1} (2016) B2G-16-026, submitted to Phys.Lett.B

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

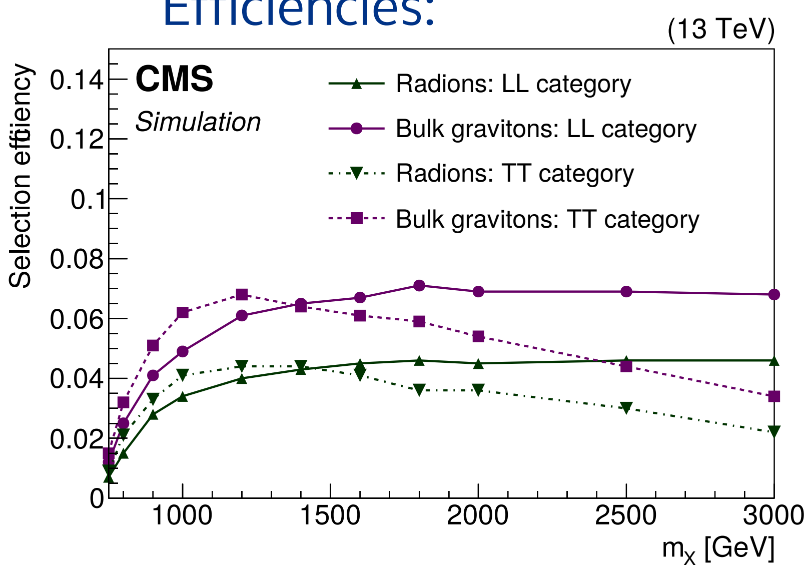
Fit in LL categ.:



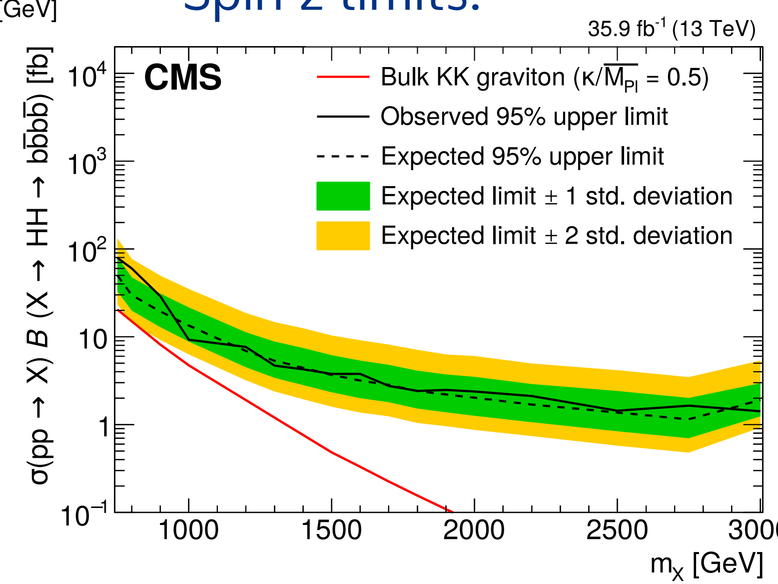
„alphabet" transfer factor:



Efficiencies:



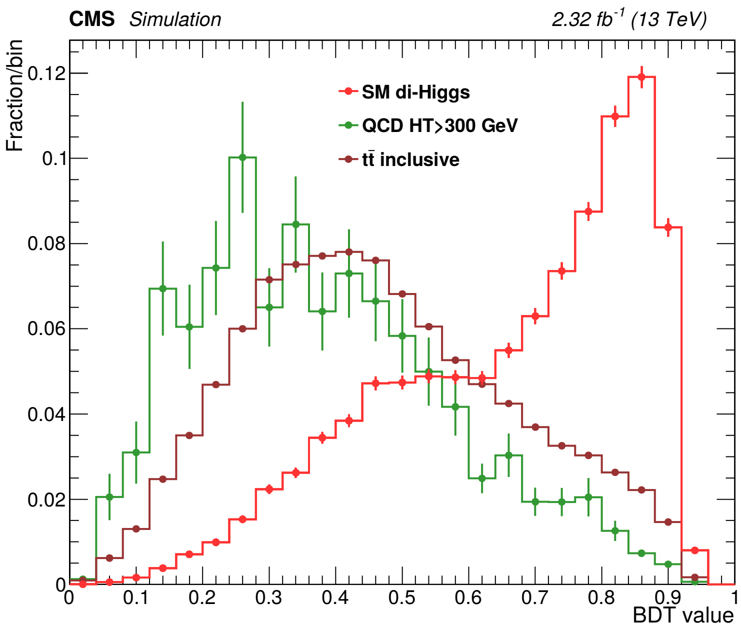
Spin 2 limits:



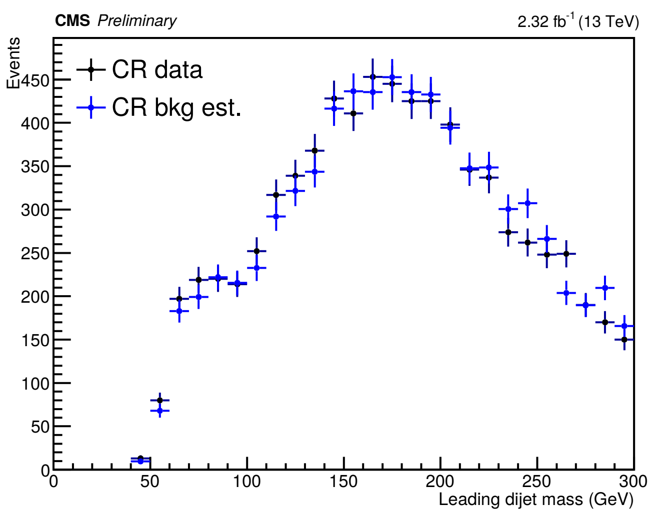
Nonresonant $b\bar{b}b\bar{b}$

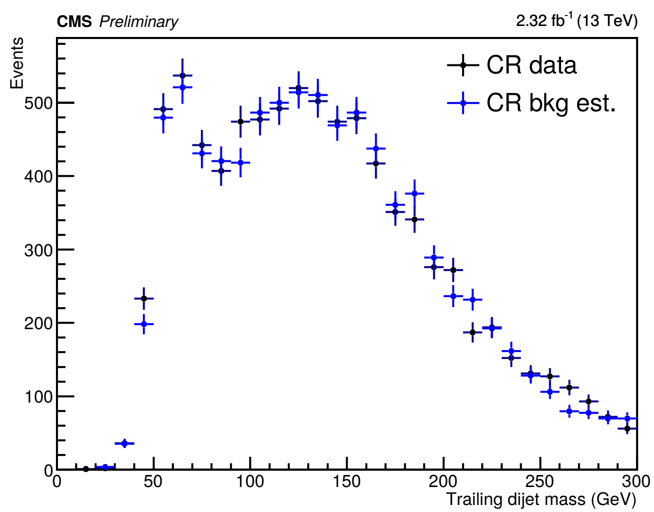
2.3 fb^{-1} (2015) PAS-HIG-16-026

- 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:

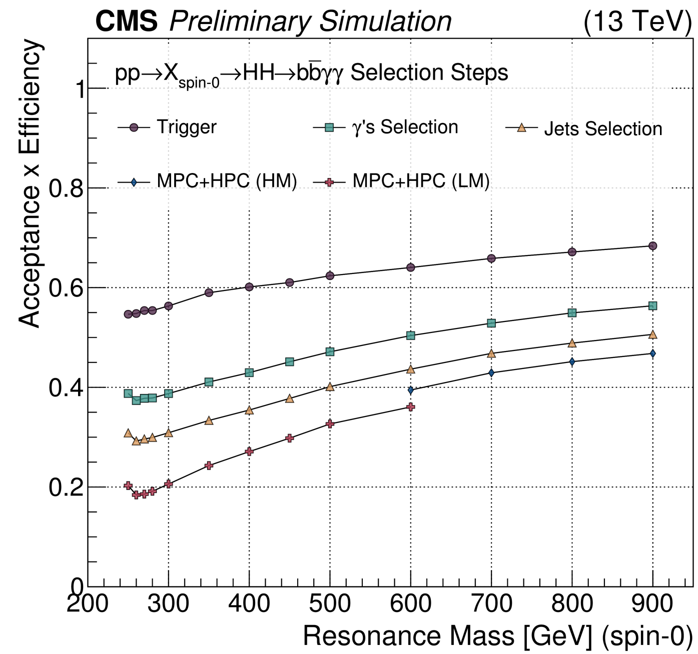


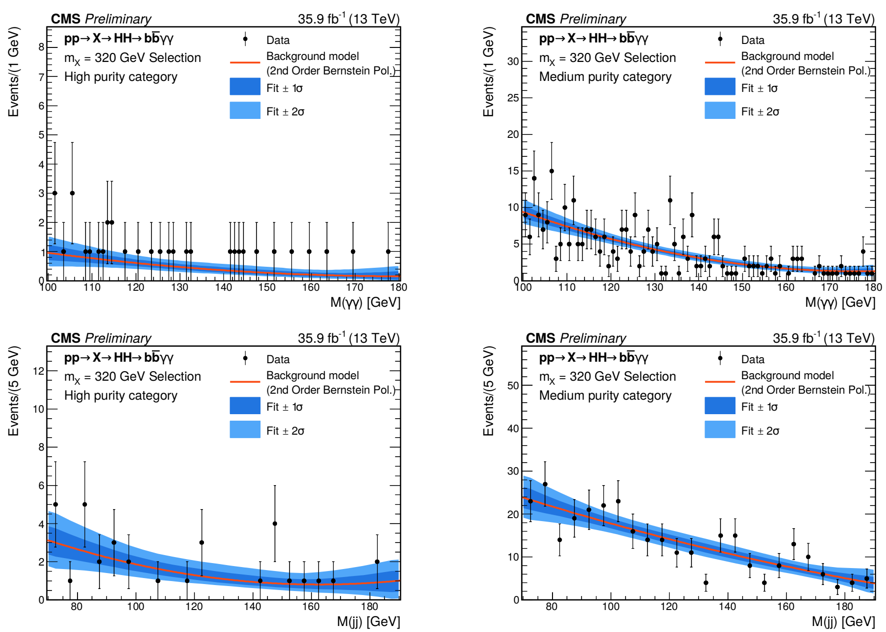


(Non)resonant $b\bar{b}\gamma\gamma$

$35.9\ fb^{-1}$ (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: highest b-tag score; energy regression
- BDT: b-tag scores, helicity angles (2→ 4 system), $p_T(\gamma\gamma)/m(jj\gamma\gamma)$, $p_T(jj)/m(jj\gamma\gamma)$
- 2 BDTs: res. + nonres. (all signals at once)



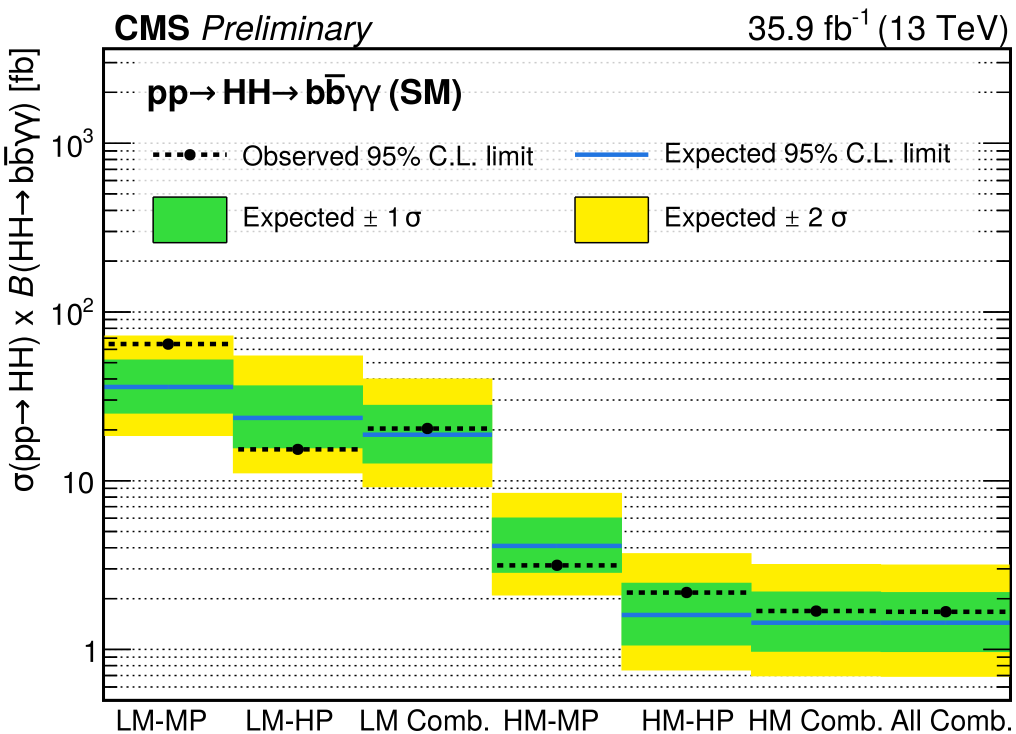


Analysis	Region	MVA Categorization	$\tilde{M}_X$
Nonresonant	High mass	HPC: MVA > 0.97 MPC: 0.6 < MVA < 0.97	$\tilde{M}_X$ > 350 GeV
	Low mass	HPC: MVA > 0.985 MPC: 0.6 < MVA < 0.985	$\tilde{M}_X$ < 350 GeV
Resonant	High mass	HPC: MVA > 0.5 MPC: 0 < MVA < 0.5	Mass window
	Low mass	HPC: MVA > 0.96 MPC: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

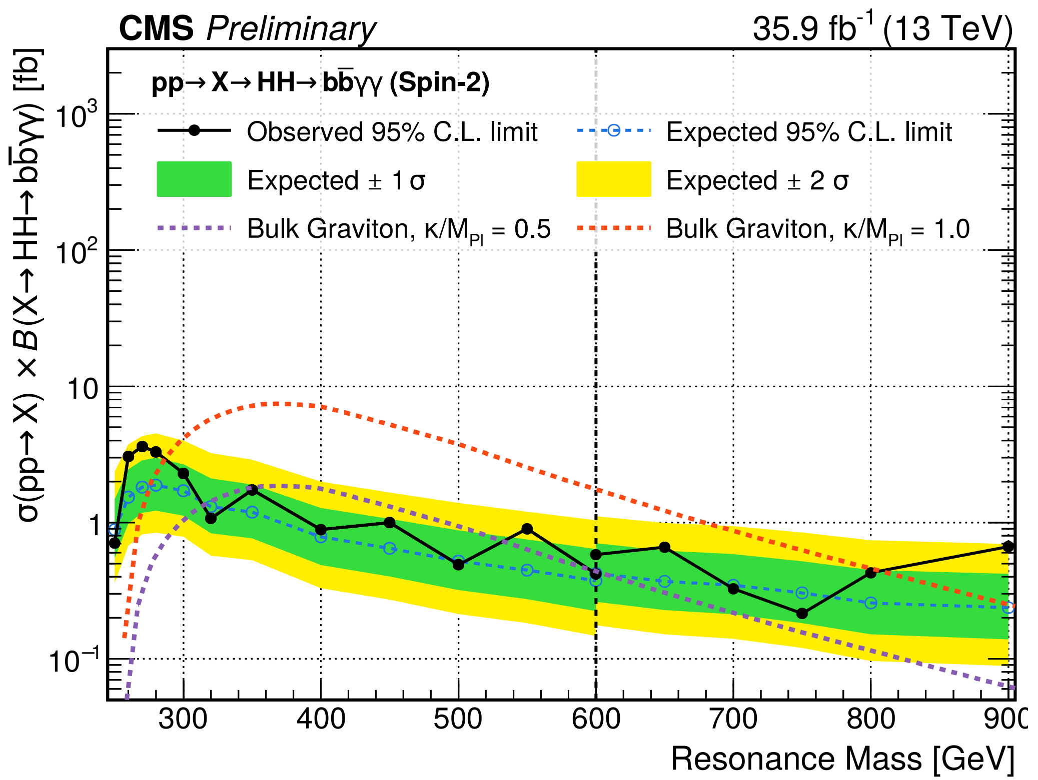
(Non)resonant $b\bar{b}\gamma\gamma$

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

Nonresonant categories:



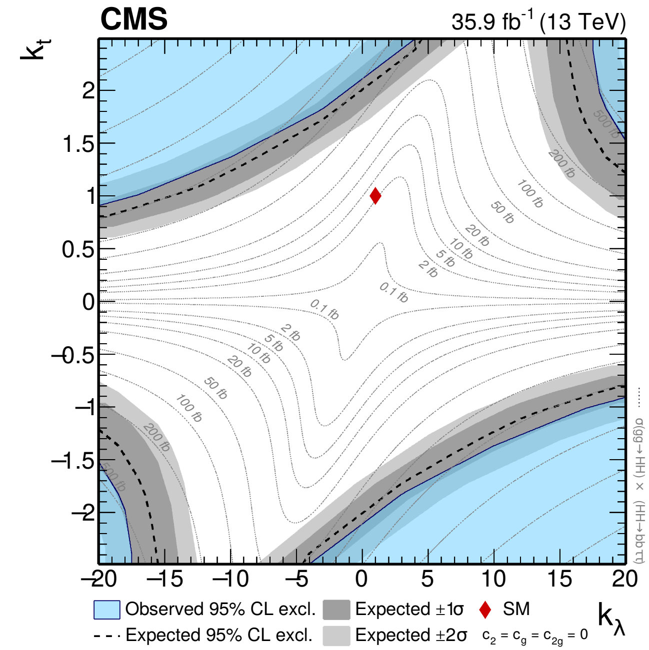
Spin-2 limits:



(Non)resonant $b\bar{b}\tau\tau$

35.9 fb^{-1} (2016) PLB778(2018)101

- 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}

→ PLB 728 (2014) 308

Largest mass for X in X(→ bW(→ $\tau \not{E}_T$)) X(→ bW(→ $\tau \not{E}_T$))

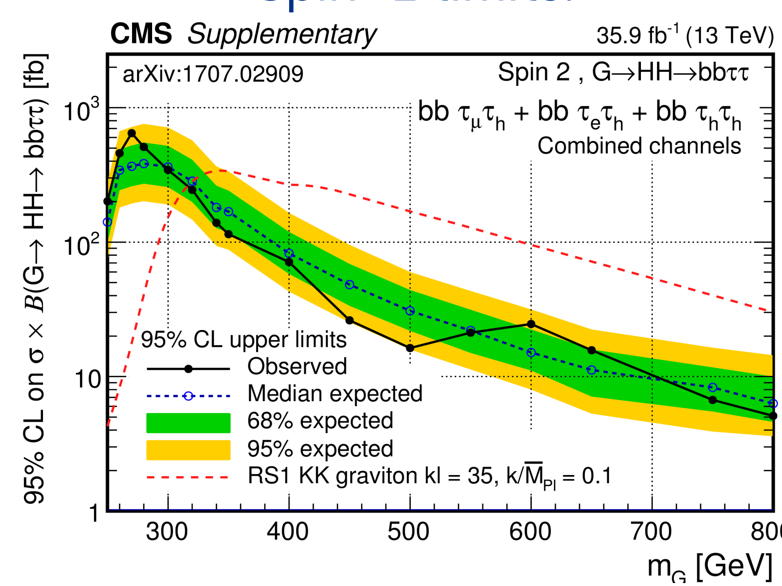
decay chain, given constraints

→ 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:



Resonant boosted $b\bar{b}\tau\tau$

NEW!

$35.9\ fb^{-1}$ (2016) PAS-B2G-17-006

Triggers:

- MET > 90 GeV + (jet or large H_T^{miss})

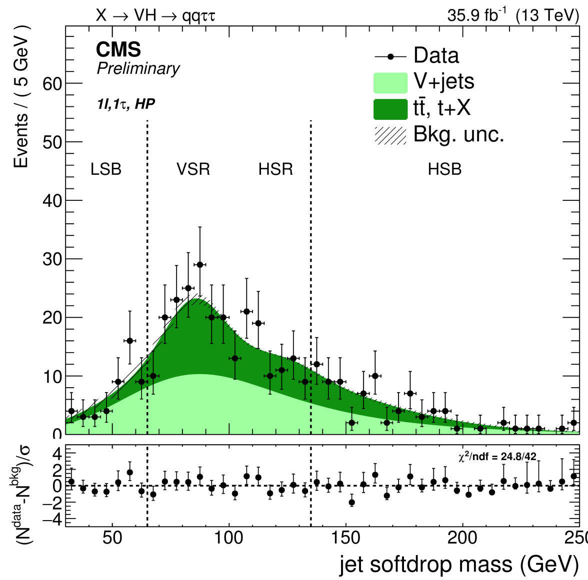
Taus:

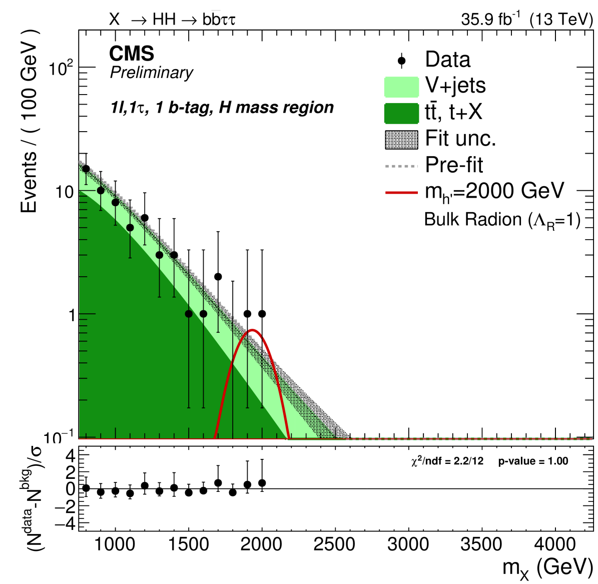
- 1 CA jet (R=0.8), p_T > 100 GeV
- 2 sub-jets → individual taus:
  - $\max(m_{subjet1}, m_{subjet2})$ / m(J) < 2/3, p_T > 10 GeV
  - τ_{had} reconstruction: „hadron plus strips", p_T > 20 GeV
  - MVA τ identification & isolation
  - 1.5 > $\Delta R(\tau,\tau)$ > 0.05 → remove QCD, W+jets

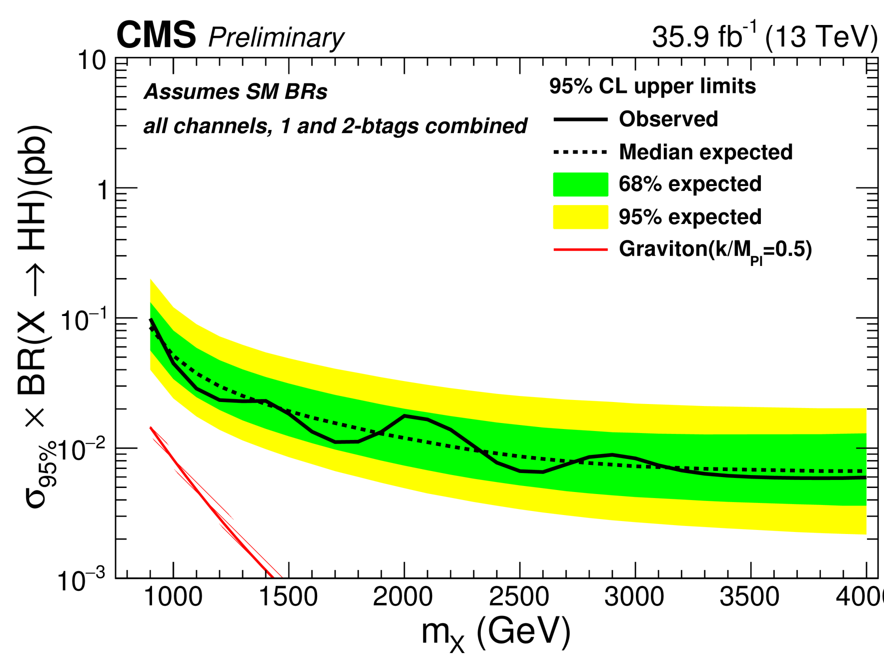
B-jets:

- anti-k_T jet (R=0.8), p_T > 200 GeV
- "Soft-drop" mass
- PUPPI pileup indentification
- Veto b-tagged R=0.4 jets → remove $t\bar{t}$
  - Inverted to define $t\bar{t}$ control region

Also require MET > 200 GeV → remove QCD







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

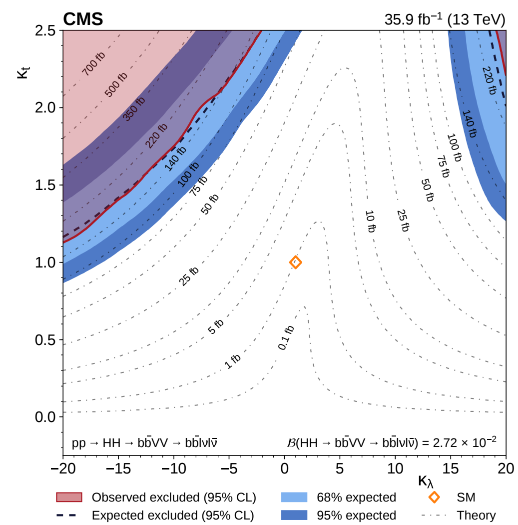
35.9 fb^{-1} (2016) JHEP01(2018)054

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

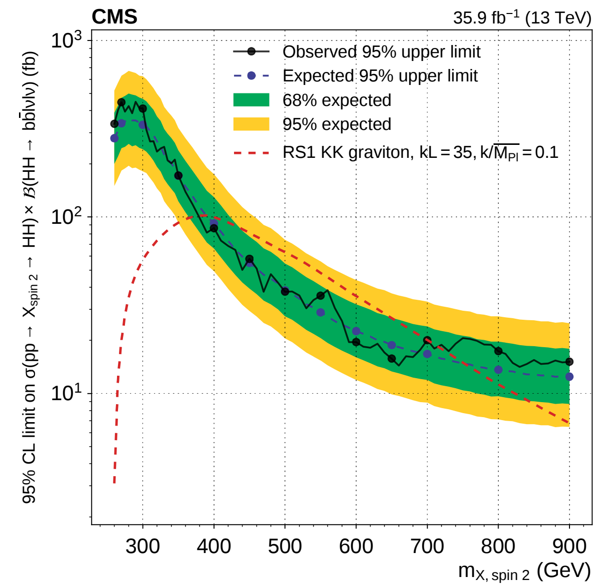
  + physics parameters

Single training, but:

→ smooth interpolation of performance as function of signal parameter



Spin 2 limits:



m_X →