9TH Higgs Hunting

Di-Higgs production in CMS

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on behalf of the CMS Collaboration

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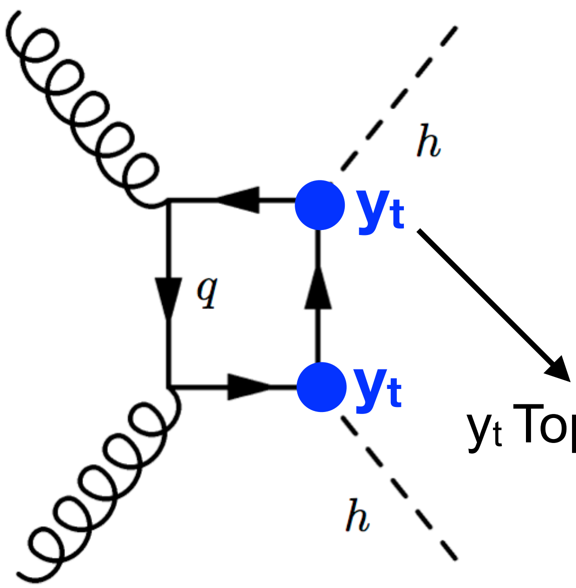
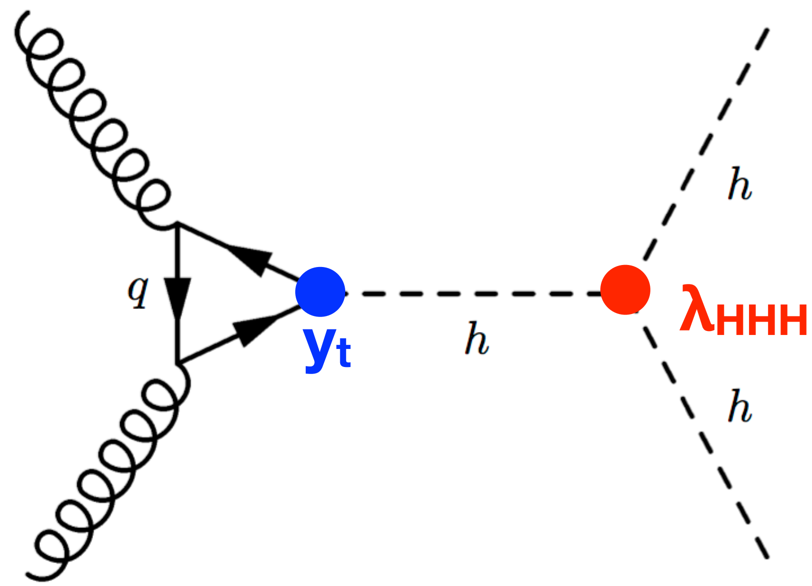
Di-Higgs in SM

CERN-2017-002-M

- Di-Higgs production cross-section measurement probes the trilinear self-coupling λ_{HHH}
- Main production mode: gluon-gluon fusion



y_t Top Yukawa coupling



$$\lambda_{\mathrm{HHH}} = \frac{\mathrm{m}_{\mathrm{H}}^2}{2\mathrm{v}^2} = 0.13$$

- Destructive interference ⇒ small cross section

$$\sigma(gg \to \mathrm{HH})_{\mathrm{SM}} = 33.5\ \mathrm{fb}^{+4.3\%}_{-6.0\%}\ (\mathrm{scale})\ \pm 5.9\ \%\ (\mathrm{PDF})$$

$$\sigma(\mathrm{VBF\ HH})_{\mathrm{SM}} = 1.64^{+0.05}_{-0.06}\ \mathrm{fb}$$

@ 13 TeV (NNLO+NNLL w/ finite top quark mass effects)

- BSM contributions could enhance the HH production cross-section

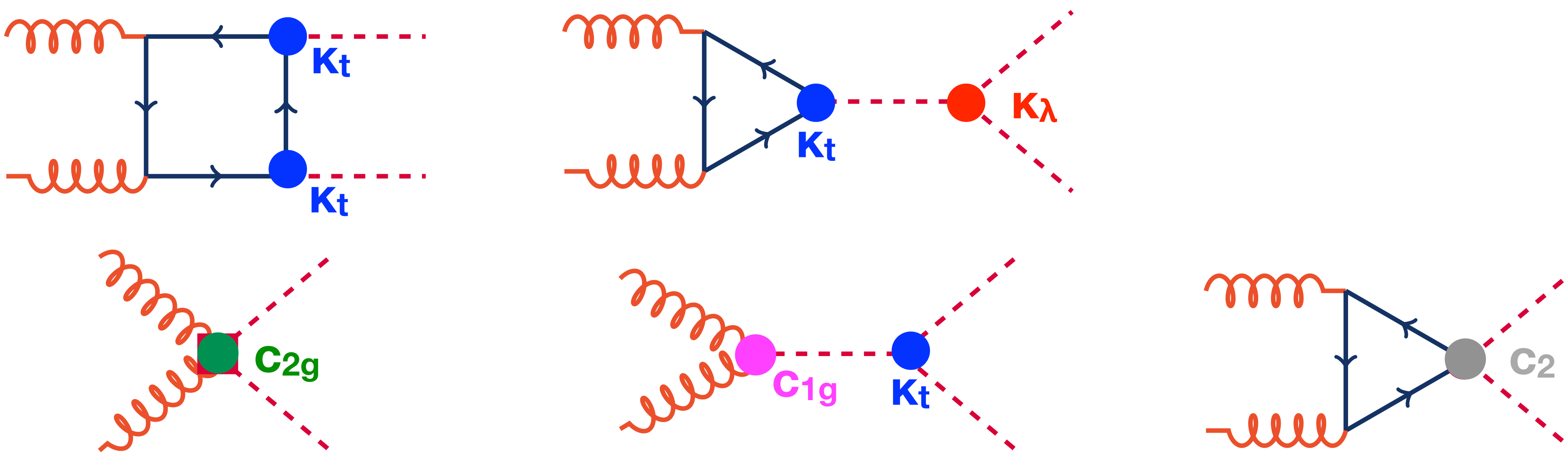
Di-Higgs in BSM

Non-resonant

- EFT approach using higher dimension operators
  - modified kinematics

$$\kappa_t = \frac{y_t}{y_{t,SM}}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH,SM}}$$



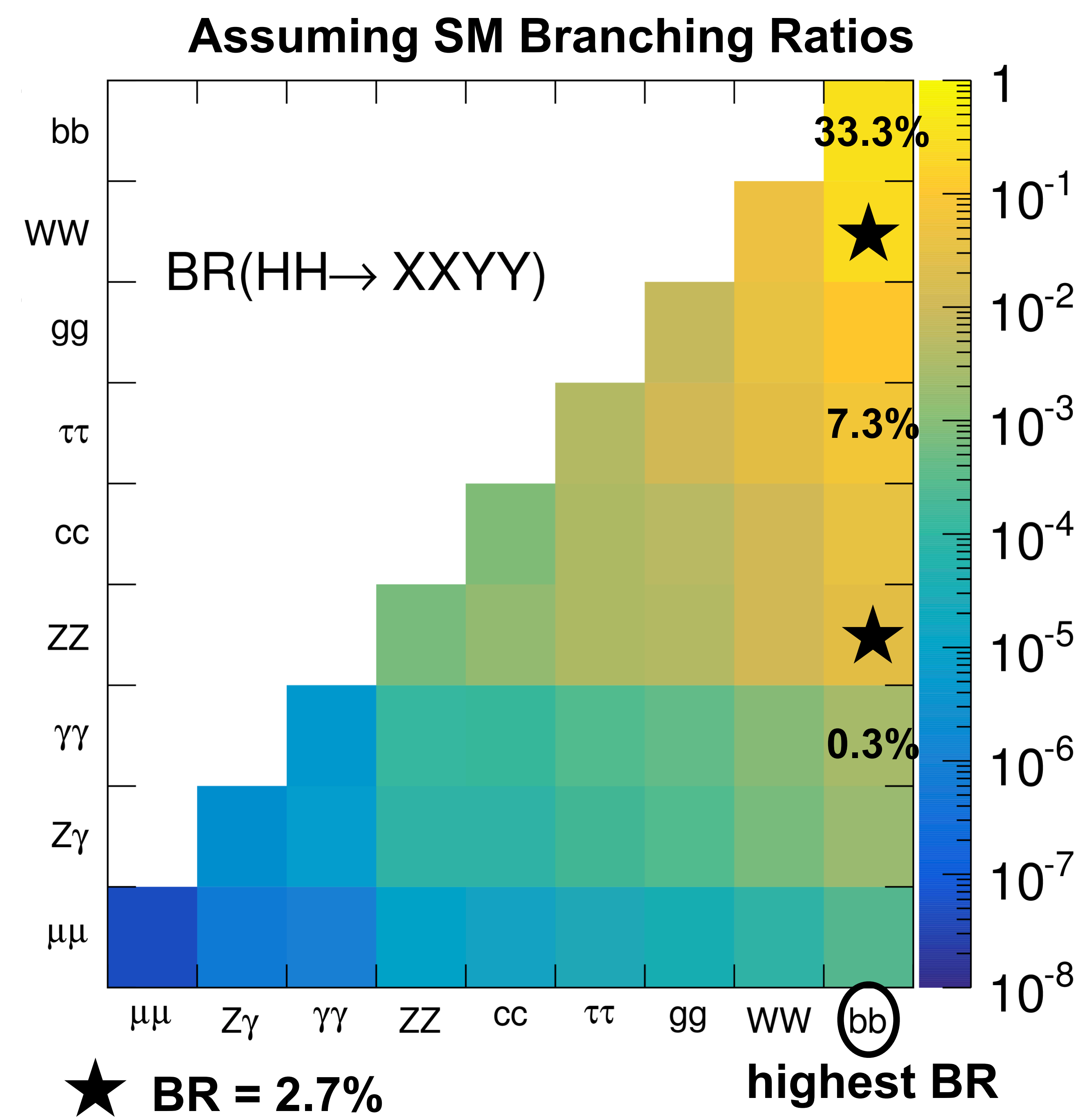
Resonant

- The reach for BSM physics is very large
- e.g. narrow-width resonance decaying into HH: **spin-0 radion** (two-Higgs-doublet model), **spin-2 KK graviton** (bulk Randall-Sundrum model) …

Di-Higgs decay channels

Resonant
+
Non Resonant

- **bbbb**
  - Resolved
  - Semi-resolved
  - Boosted (fully-merged)
- **bbττ**
  - Resolved
  - Boosted
- **bbVV*($\ell^+\ell^-\nu\nu$)**
- **bbγγ**
- **COMBINATION of all analyses** to achieve best signal sensitivity



ALL ANALYSES: $\sqrt{s}$ = 13 TeV (2016)
L_{int} = 35.9 fb^{-1}

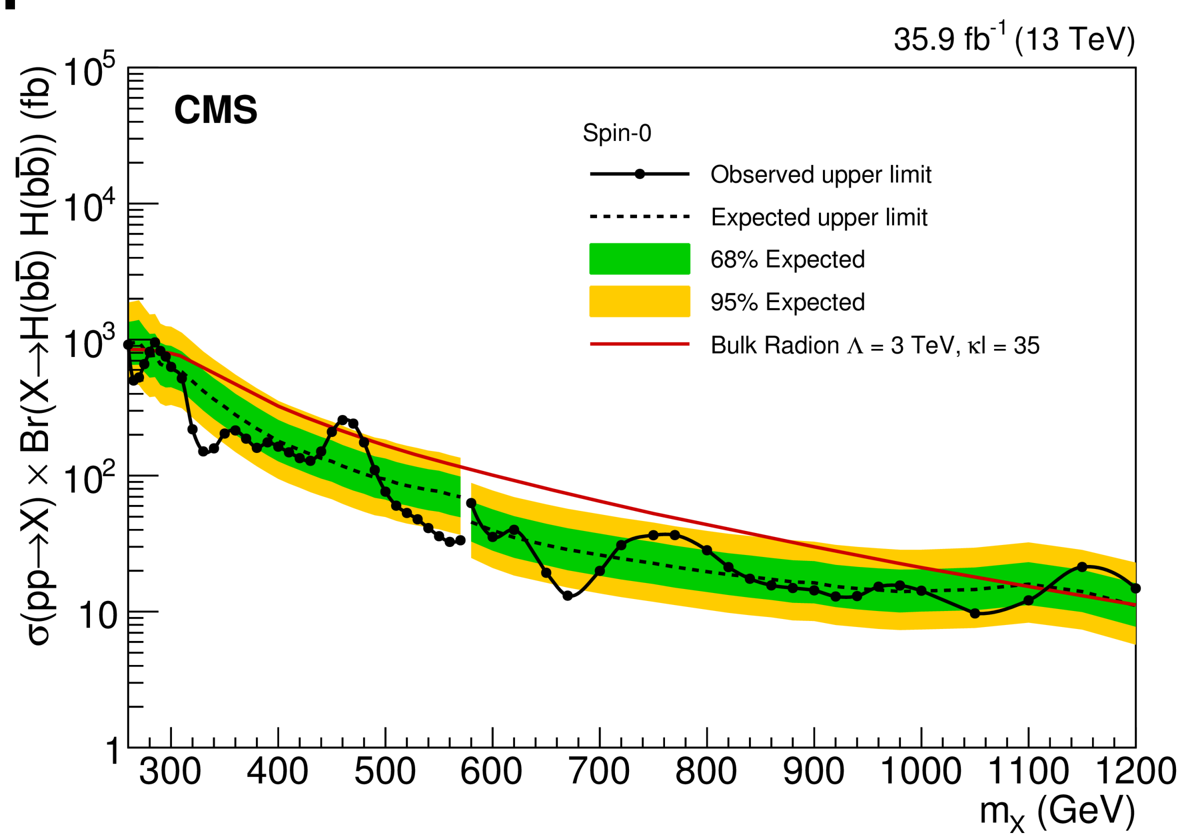
bbbb - resonant

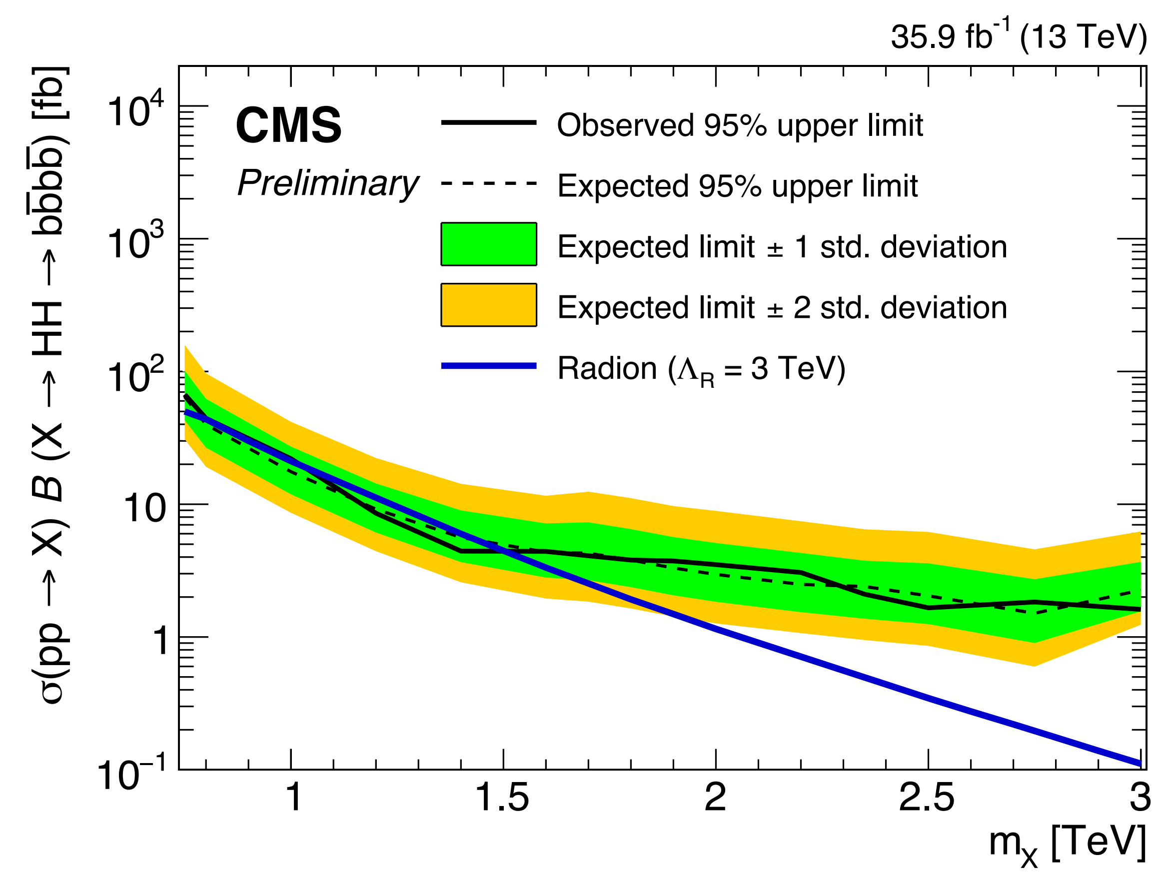
CMS PAS HIG-17-009
CMS PAS B2G-16-026
PLB 781 (2018) 244
CMS PAS B2G-17-019

- Resolved → low mass: 260 ÷ 1200 GeV
  4 b-jets
- Boosted → high mass: 750 ÷ 3000 GeV
  2 large-area jets
- Semi-resolved combined with boosted
  1 large-area jet + 2 b-jets ⇒ improvement: 55÷8% for radion, 18÷7% for graviton

- Background (main: multi-jet QCD) modeled from data (sidebands of H boson mass distribution)

spin-0 radion **Resolved** **Combined boosted + semi-resolved**



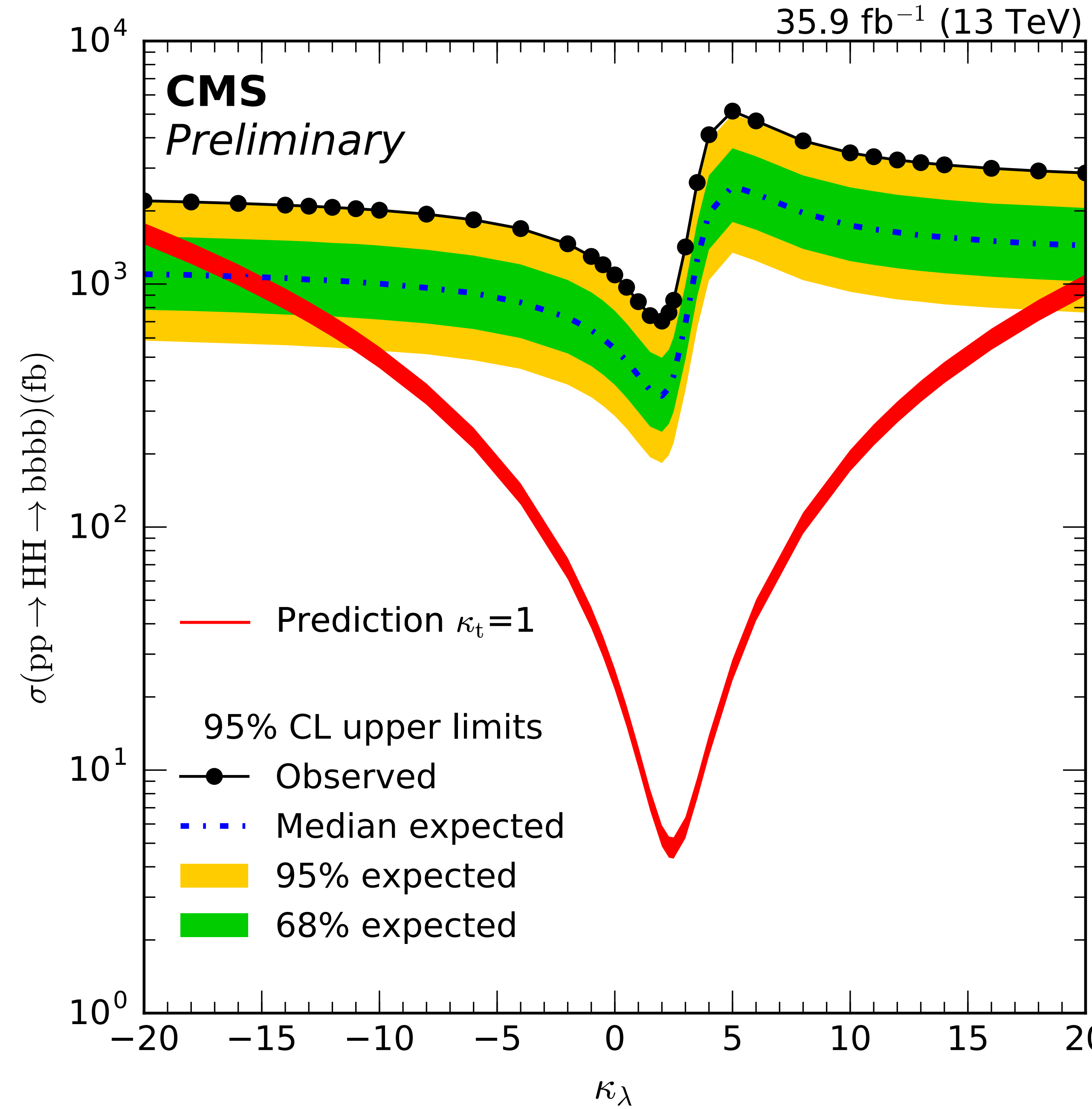


bbbb - non resonant

CMS PAS HIG-17-017

SM + 12 BSM benchmarks + null self-coupling

- 4 b-jets
- Analysis optimized for SM signal
- BDT for signal/background separation (modelling checked with sidebands)
- Background modelling: hemisphere mixing technique to (i) provide input for BDT training (ii) predict the BDT background shape



κ_λ scan
assuming κ_t = 1

bbττ

CMS PAS HIG-17-002
PLB 788 (2018) 101
CMS PAS B2G-17-006

Resonant & Non Resonant

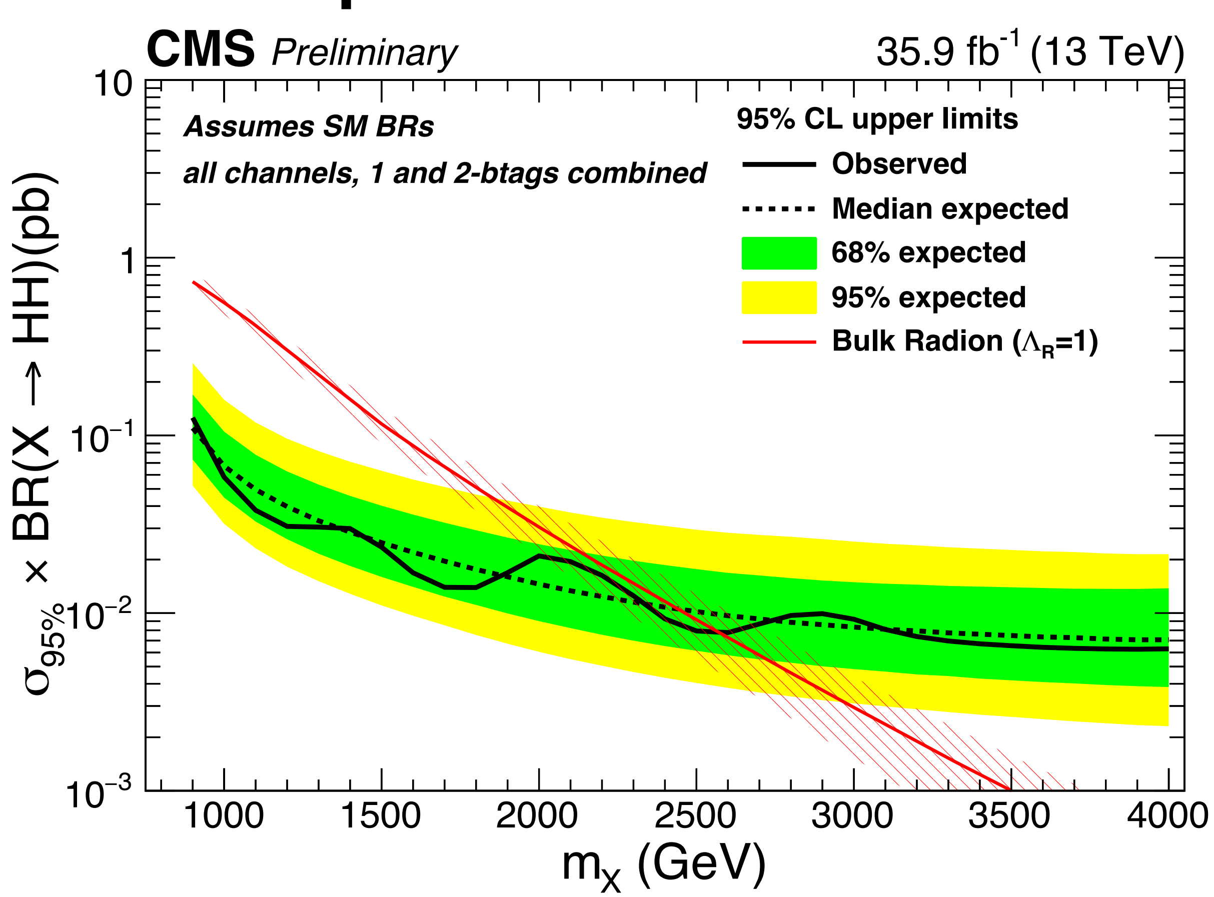
- low - high mass resonance (<1000 GeV, 900 ÷ 4000 GeV)
- 2 b-jets (resolved) or 1 large-area jets (boosted)
- 2 $\tau \Rightarrow \tau_h\tau_h + \tau_h\tau_e + \tau_h\tau_\mu$ (88%)

- Backgrounds:

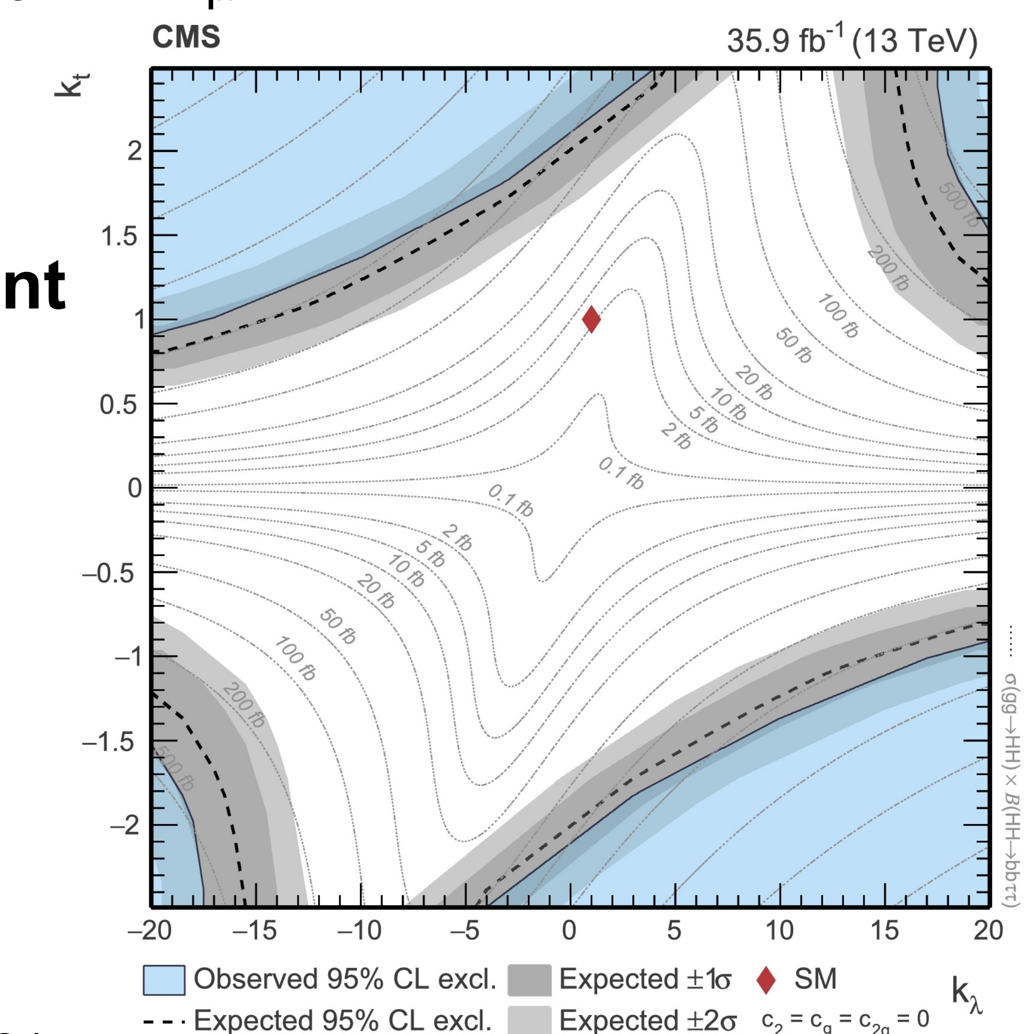
Z/γ+jets, single top, tt, SM H from MC
multi-jet from data

- BDT to reject top background in $\tau_h\tau_e + \tau_h\tau_\mu$ events

Resonant: spin-0 radion



Non Resonant



bbVV(ℓνℓν)

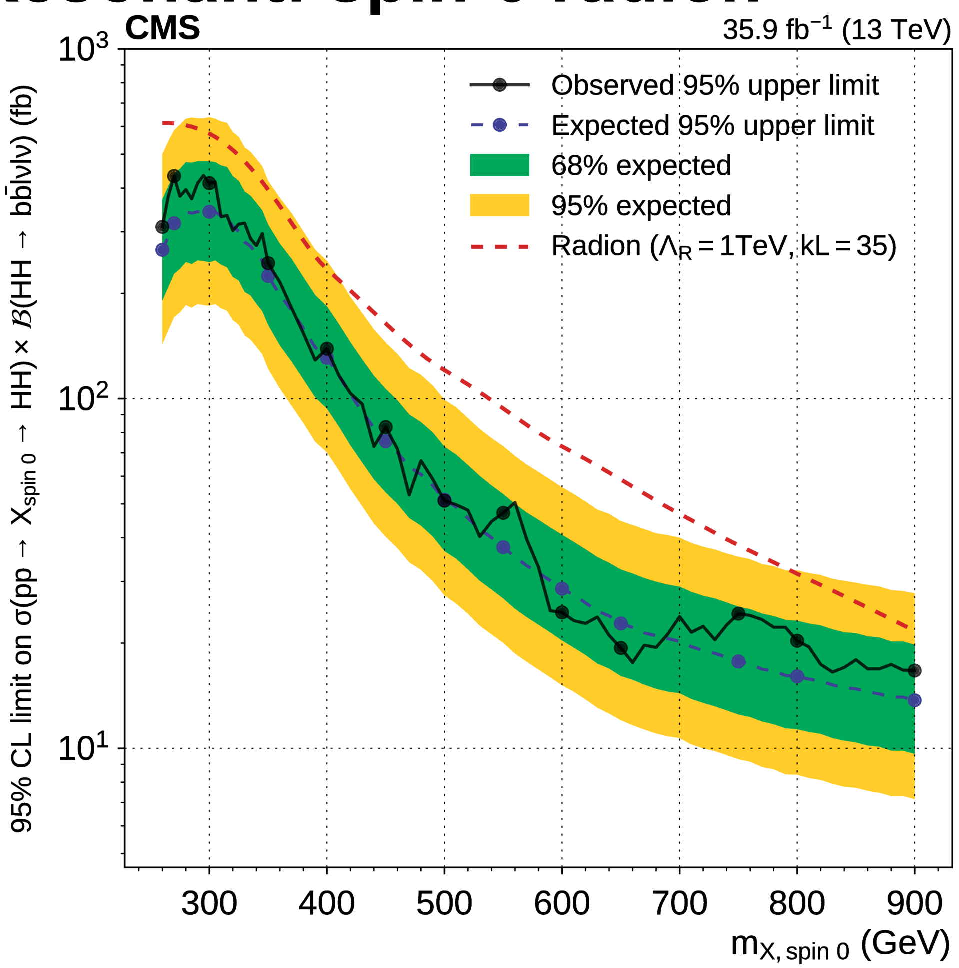
CMS PAS HIG-17-006
JHEP 01 (2018) 054

Resonant & Non Resonant

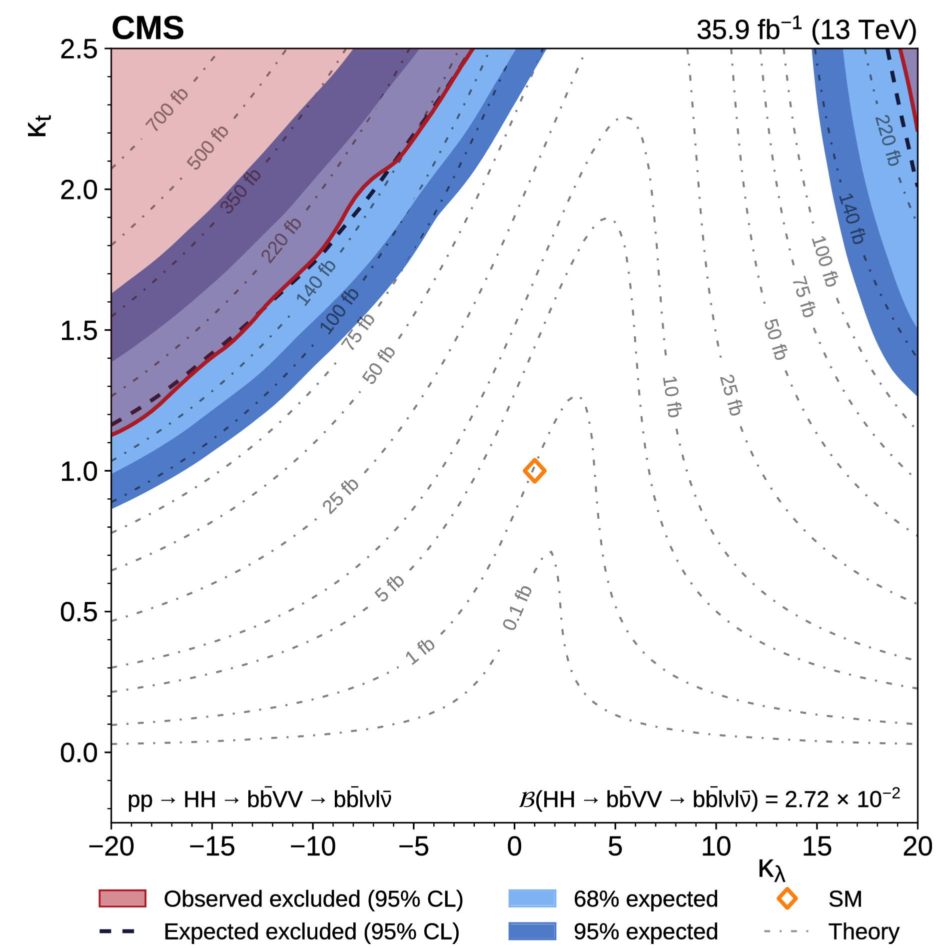
- mass range: 260-900 GeV
- 2 b-jets + Z(ℓℓ)Z(νν)
  OR W(ℓν) W(ℓν)
  where ℓ = e, μ, τ ⇒ BR = 2.7%

- Main backgrounds: tt + single top (modeled from MC) and DY (from data)
- Deep NN uses a parametrized ML technique to improve signal-to-background separation (exploits event kinematics)

Resonant: spin-0 radion



Non Resonant



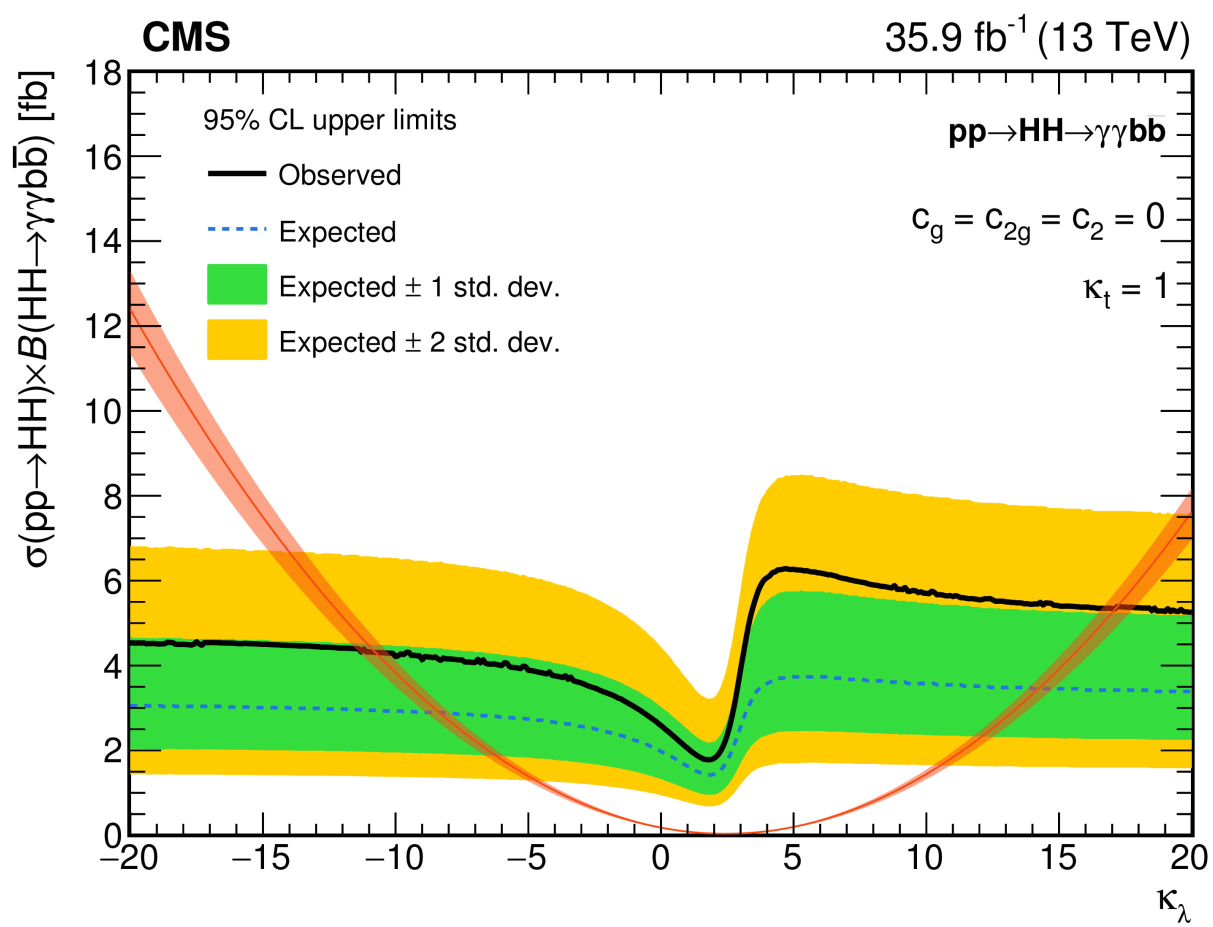
bbγγ

CMS PAS HIG-17-008
submitted to PLB

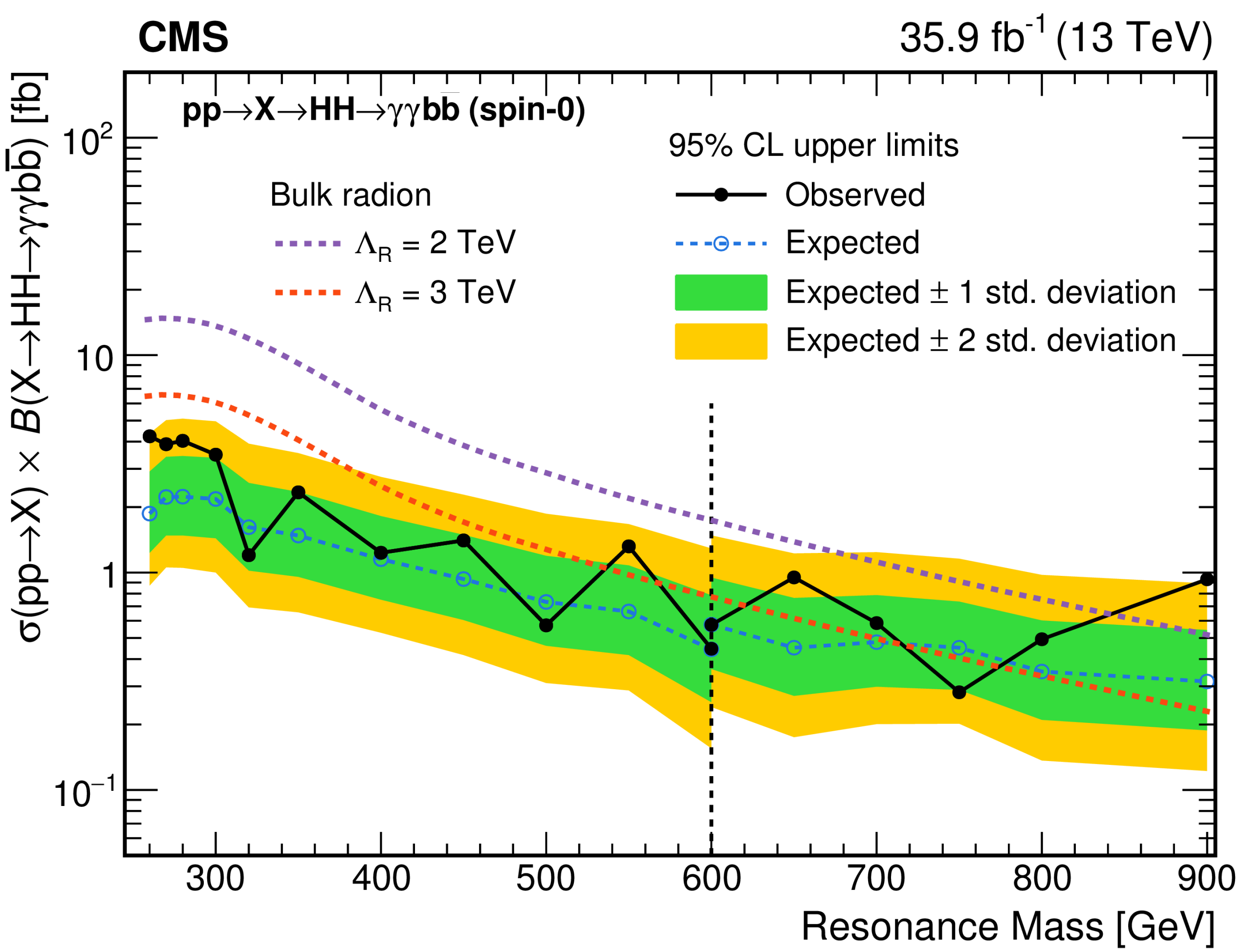
Resonant & Non Resonant

- mass range: 260-900 GeV
- 2 photons + 2 b-jets
- small BR but clean signature
- Main backgrounds: *n*γ + jets, VH, ttH, ggH
- MVA to categorize events

Non Resonant



Resonant: spin-0 radion



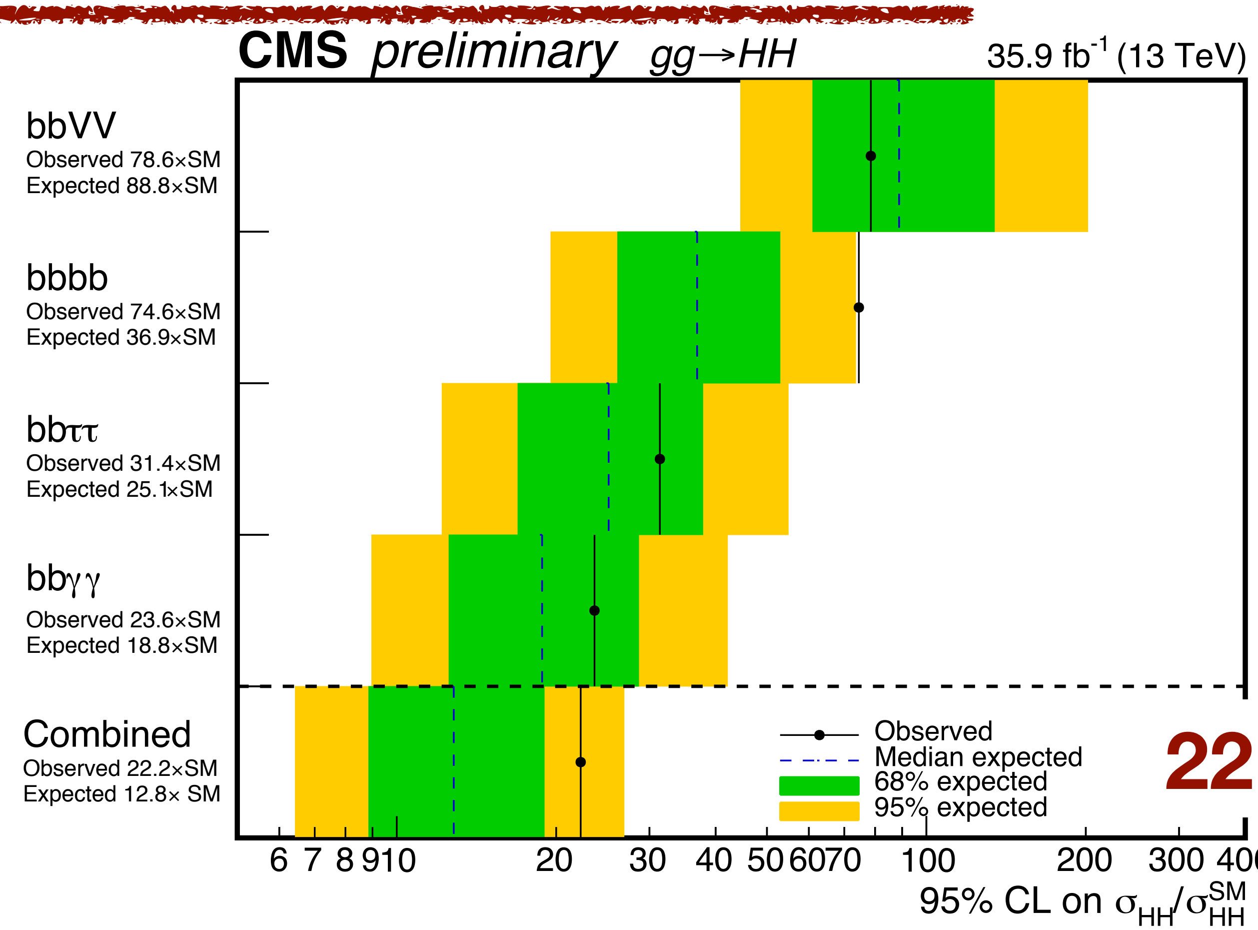
- **Most sensitive channel to SM HH**
- VBF HH considered: 1.3% increase in sensitivity

Combination

CMS PAS HIG-17-030

more on Chiara's talk on Wed

- Four HH channels: bbbb, bbττ, bbℓνℓν, bbγγ
- Resonant and non-resonant
- Results compatible with expected SM background



79 (89)

75 (37)

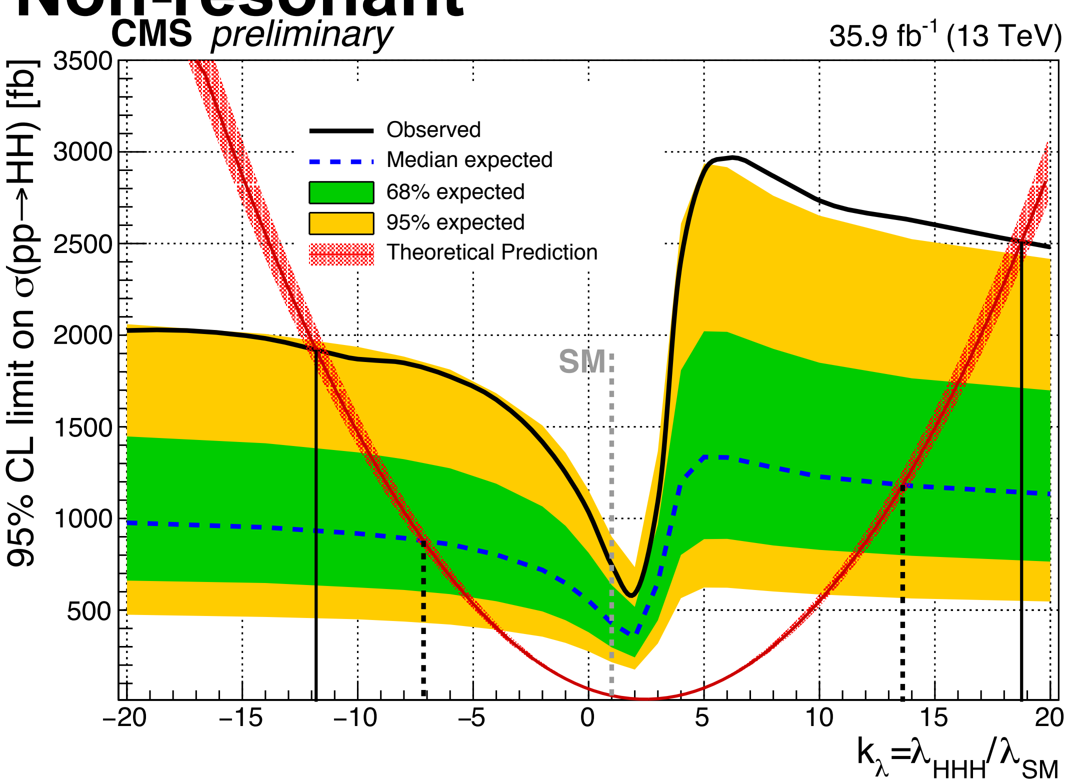
31 (25)

24 (19)

22.2 (12.8)

most sensitive result up to now!

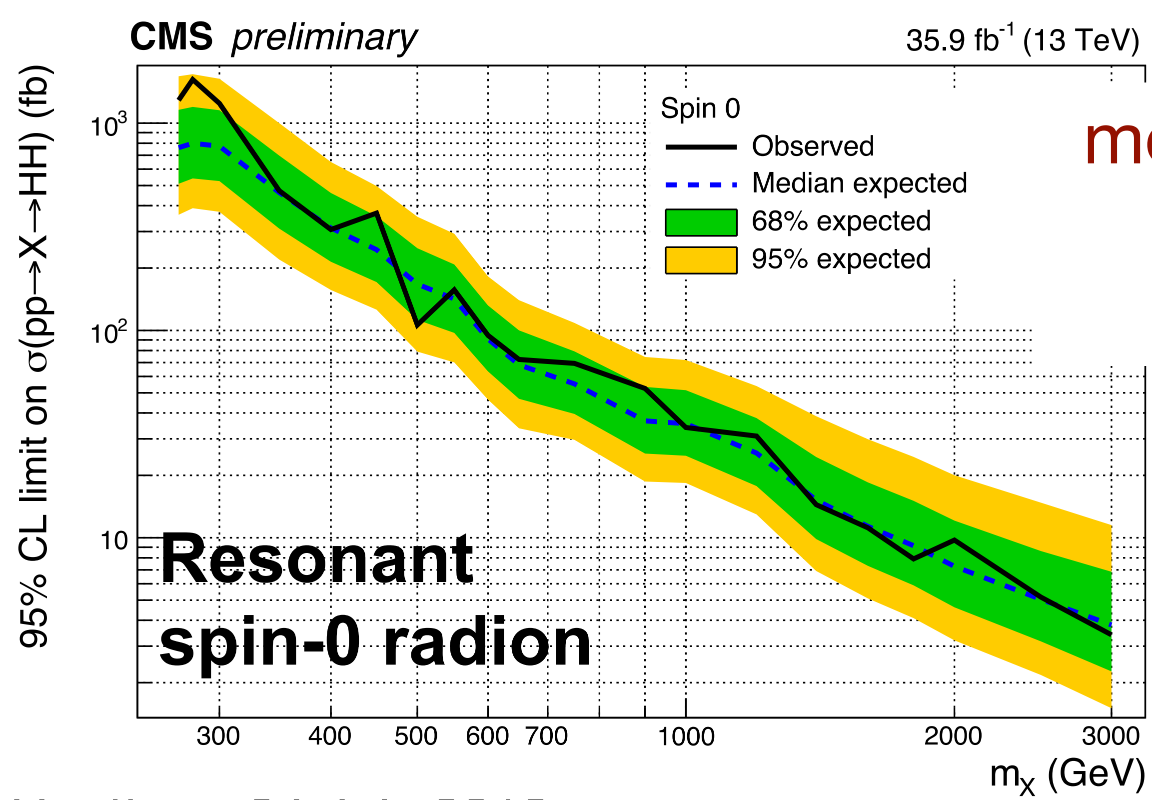
Non-resonant



Limit for κ_λ ($\kappa_t = 1$):

$-11.8 < \kappa_\lambda < 18.8$ (obs)

$-7.1 < \kappa_\lambda < 13.6$ (exp)

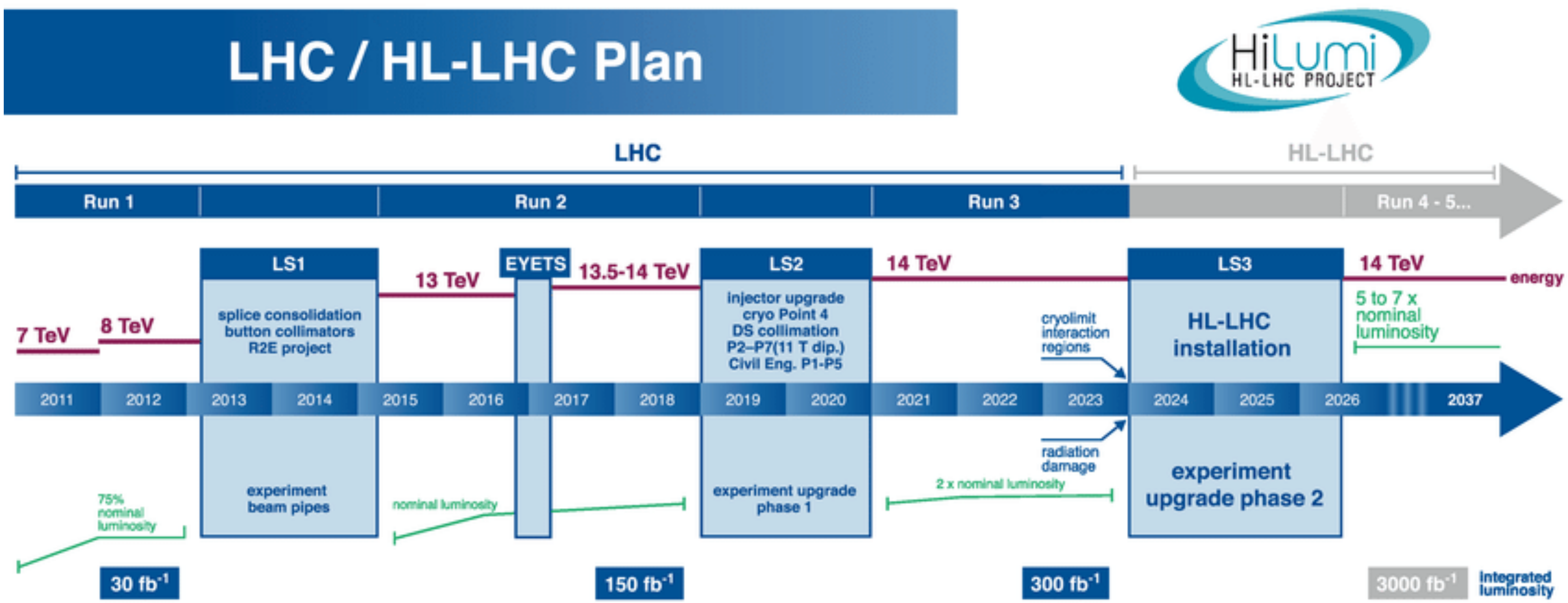


Resonant spin-0 radion

High Luminosity LHC

- Challenging conditions: $\mathcal{L}$ = 5x10^{34} cm^{-2}s^{-1}, PU: 140 → 200
- $\sqrt{s}$ = 14 TeV → σ_{HH} ≈ 40 fb (18% increase)
- L_{int} = 3000 fb^{-1}
- Major upgrade of the CMS detector → improve object reconstruction

- HL-LHC will enable precision measurements in the Higgs sector

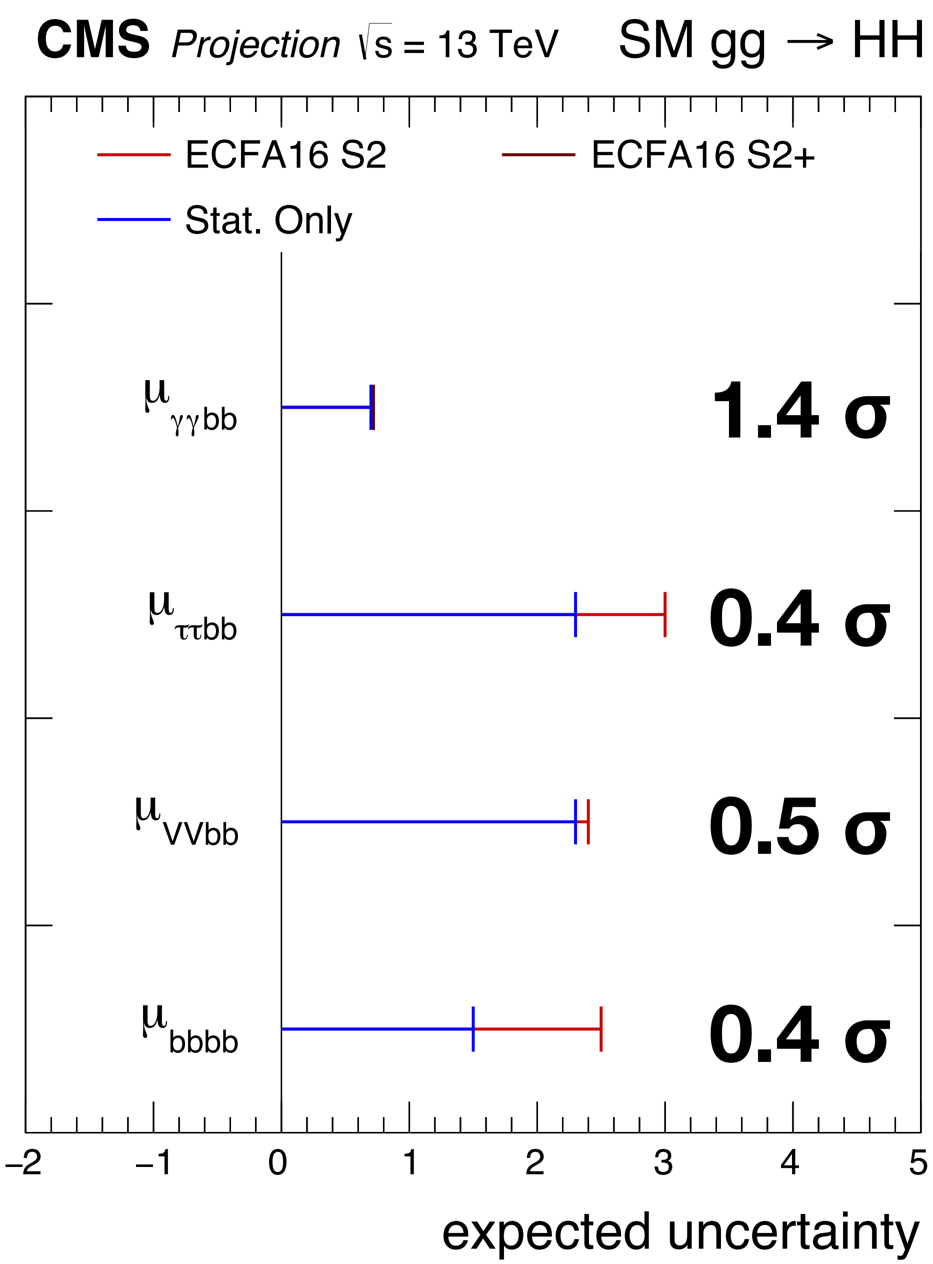


Di-Higgs @ HL-LHC

Existing extrapolations

CMS PAS FTR-16-002
CMS-TDR-019

- From Run 2 data (2015 data: 2.3 - 2.7 fb^{-1} only)
- 3 different scenarios studied:
  - no systematics
  - ECFA16 S2 (reduces uncertainties)
  - ECFA16 S2+ (including future detector performance)
- $\sqrt{s}$ = 13 TeV
- These projections are too conservative!
  in bb$\tau\tau$ achieved with 2016 data (35.9 fb^{-1}) the same sensitivity that we projected for 100 fb^{-1}



Di-Higgs @ HL-LHC

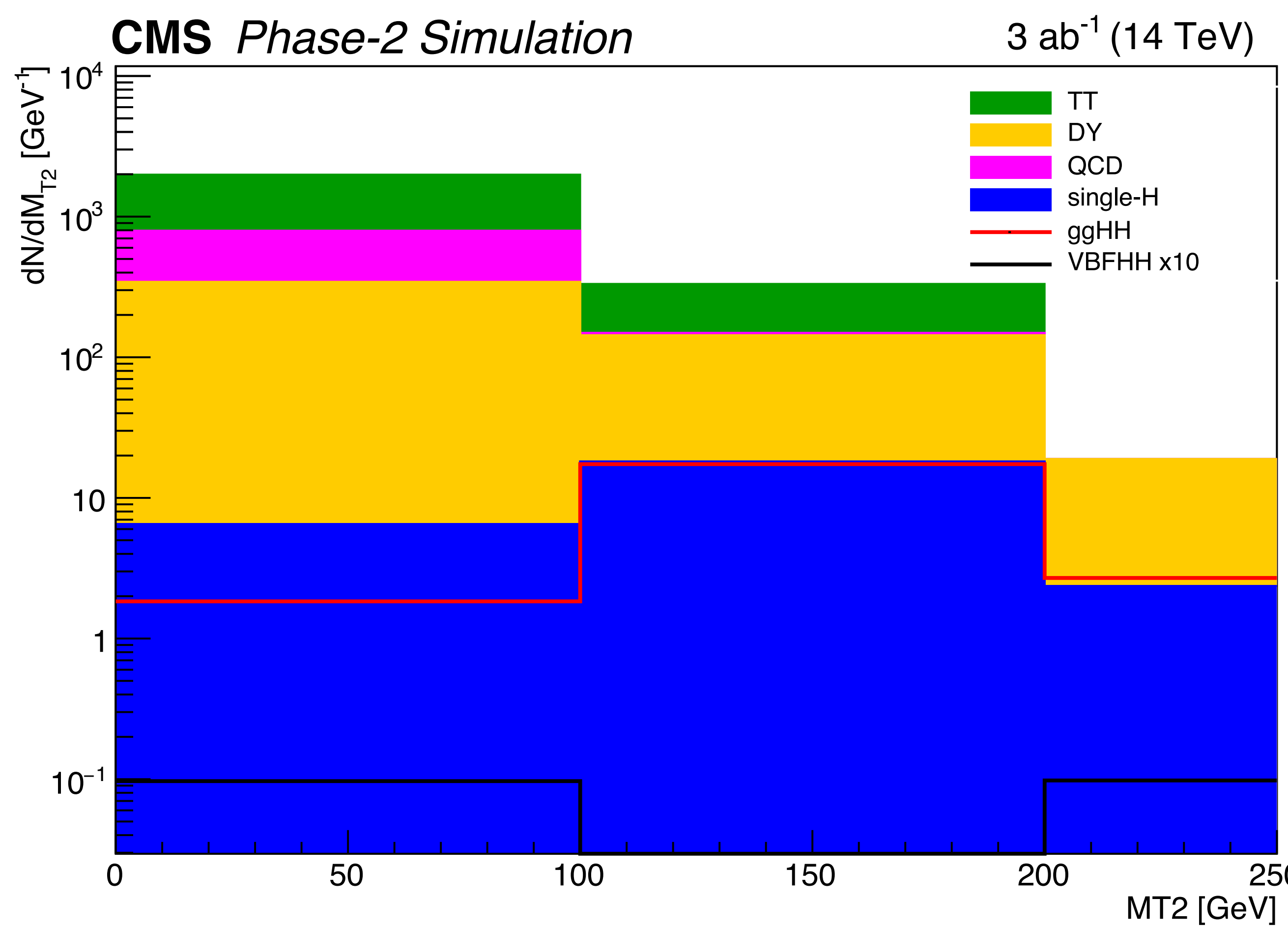
Updating projections for YR

CMS PAS FTR-16-002
CMS-TDR-019

- Ongoing effort to update projections (2018 CERN Yellow Report)

- **Example: bbττ**

- Update projection exploiting analysis improvements
- ggF + VBF considered



Upper limits (95% CL):

$1.7 \times \sigma_{ggH}$

$51 \times \sigma_{VBF}$

$\rightarrow 1.6 \times \sigma_{SMH}$

- Combine all results to obtain the best sensitivity

Conclusions

- Di-Higgs searches based on 2016 data (35.9 fb^{-1})
- 4 final states: bbbb, bbττ, bbVV, bbγγ
- Resonant and non-resonant studies, low and high mass ranges covered

- Results are compatible with expectation of SM background
- Combination of all analyses:
  - 95% CL limit on σ_{HH}/σ_{SM}: 22 (obs) 13 (exp)
  - Limits set on the resonant production of HH from spin-0 radion and spin-2 graviton

- Di-Higgs prospects for HL:
  - challenging
  - existent extrapolation from 2015 data are conservative
  - big effort ongoing to update projection (Yellow Report)

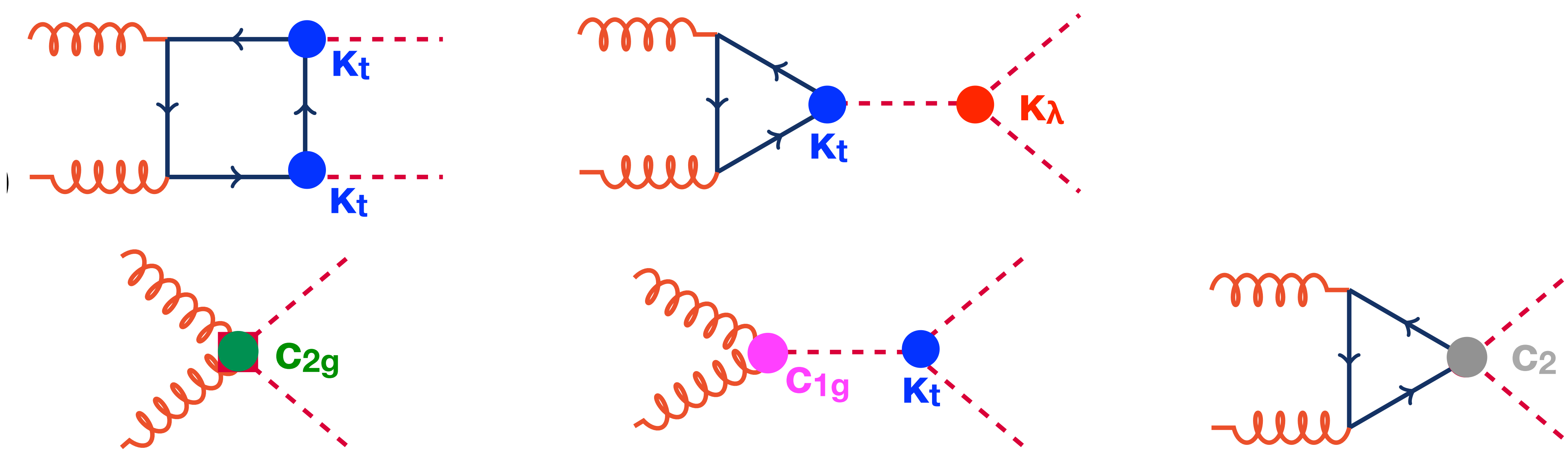
Backup

Di-Higgs in BSM

Non-resonant

- EFT approach using higher dimension operators
  - modified kinematics

$$L_{hh} = \frac{1}{2}\partial_\mu\partial^\mu h - \frac{1}{2}m_h^2h^2 - \kappa_\lambda\lambda_{SM}vh^3 - \frac{m_t}{v}\left(v + \kappa_t h + \frac{c_2}{v}hh\right)(t_L tR + h.c.) + \frac{\alpha_S}{12}\left(c_{1g}h - \frac{c_{2g}}{2v}hh\right)G^A_{\mu\nu}G^{A\mu\nu}$$



$$\kappa_t = \frac{y_t}{y_{T,SM}}$$

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

12 BMS benchmarks

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

+ k_λ = 0

Systematic uncertainties

bbbb - resolved - resonant

Source of systematic uncertainty	Impact in LMR (%) Signal	Impact in MMR (%) Signal
Luminosity	2.5	2.5
Jet energy scale	0.2–1.8	0.9–2.9
Jet energy resolution	0.9–2.1	1.0–1.5
b tagging scale factor	6.5–6.9	6.9–8.6
Trigger efficiency	6.4–9.0	5.3–7.0
PDF	1.5–2.2	2.1–3.5

bbbb - boosted - resonant

Source	Uncertainty (%)
Signal yield	
Trigger efficiency	1–15
H jet energy scale and resolution	1
H jet mass scale and resolution	2
H jet τ_{21} selection	$+30\,/-26$
H-tagging correction factor	7–20
Double-b tagger discriminator	2–5
Pileup modelling	2
PDF and scales	0.1-2
Luminosity	2.5
Background yield	
$R_{p/f}$ fit	2.6 (LL category) 6.8 (TT category)

Systematic uncertainties

bbbb - semi-resolved & boosted - resonant

Source	Uncertainty (%)
Signal yield	
Trigger efficiency	1–15
H jet energy scale and resolution	1–3
H jet mass scale and resolution	2
H jet τ_{21} selection	14–30
H tagging correction factor	5–20
b tagging selection	2–9
Pileup modelling	1–2
PDF and scales	0.1–3
Luminosity	2.5
Background yield	
QCD background $R_{p/f}$ fit	2–10
$t\bar{t}$ +jets cross section	5

Source	Affects	Exp. limit (50%) variation
Bkg shape	bkg	29.53%
Bkg norm.	bkg	8.60%
B-tagging eff.	sig	2.79%
Luminosity	sig	<0.01%
JES	sig	<0.01%
Trigger eff.	sig	<0.01%
PDF unc.	sig	<0.01%
Pileup	sig	<0.01%
JER	sig	<0.01%
QCD scale	sig	<0.01%

bbbb - non resonant

Systematic uncertainties

bbττ

Systematic uncertainty	Value	Processes
Luminosity	2.5%	all but multijet, $Z/\gamma^* \to \ell\ell$
Lepton trigger and reconstruction	2–6%	all but multijet
τ energy scale	3–10%	all but multijet
Jet energy scale	2–4%	all but multijet
b tag efficiency	2–6%	all but multijet
Background cross section	1–10%	all but multijet, $Z/\gamma^* \to \ell\ell$
$Z/\gamma^* \to \ell\ell$ SF uncertainty	0.1–2.5%	$Z/\gamma^* \to \ell\ell$
Multijet normalization	5–30%	multijet
Scale unc.	+4.3%/−6.0%	signals
Theory unc.	5.9%	signals

Systematic uncertainties

bb$\ell\nu\ell\nu$

Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.0–3.2%	1.9–2.9%
Jet b tagging (heavy-flavour jets)	2.5%	2.5–2.7%
Integrated luminosity	2.5%	2.5%
Trigger efficiency	0.5–1.4%	0.4–1.4%
Pileup	0.3–1.4%	0.3–1.5%
Muon identification	0.4–0.8%	0.4–0.7%
PDFs	0.6–0.7%	1.0–1.4%
Jet b tagging (light-flavour jets)	0.3%	0.3–0.4%
Muon isolation	0.2–0.3%	0.1–0.2%
Jet energy scale	<0.1–0.3%	0.7–1.0%
Jet energy resolution	0.1%	<0.1%
Affecting only $t\bar{t}$ (85.1–95.7% of the total bkg.)		
μ_R and μ_F scales	12.8–12.9%	
$t\bar{t}$ cross section	5.2%	
Simulated sample size	<0.1%	
Affecting only DY in $e^{\pm}\mu^{\mp}$ channel (0.9% of the total bkg.)		
μ_R and μ_F scales	24.6–24.7%	
Simulated sample size	7.7–11.6%	
DY cross section	4.9%	
Affecting only DY estimate from data in same-flavour events (7.1–10.7% of the total bkg.)		
Simulated sample size	18.8–19.0%	
Normalisation	5.0%	
Affecting only single top quark (2.5–2.9% of the total bkg.)		
Single t cross section	7.0%	
Simulated sample size	<0.1–1.0%	
μ_R and μ_F scales	<0.1–0.2%	
Affecting only signal	SM signal	$m_X = 400$ GeV
μ_R and μ_F scales	24.2%	4.6–4.7%
Simulated sample size	<0.1%	<0.1%

Systematic uncertainties

bbγγ

Sources of systematic uncertainties	Type	Value (%)
Integrated luminosity	Normalization	2.5
Photon related uncertainties		
Diphoton selection (with trigger uncertainties and PES)	Normalization	2.0
Photon identification	Normalization	1.0
PES ($\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}}$)	Shape	0.5
PER ($\frac{\Delta \sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	Shape	5.0
Jet related uncertainties		
Dijet selection (JES+JER)	Normalization	0.5
JES ($\frac{\Delta m_{jj}}{m_{jj}}$)	Shape	1.0
JER ($\frac{\Delta \sigma_{jj}}{\sigma_{jj}}$)	Shape	5.0
Resonant analysis specific uncertainties		
Mass window selection (JES+JER)	Normalization	3.0
Classification MVA (HPC)	Normalization	11–19
Classification MVA (MPC)	Normalization	3–9
Nonresonant analysis specific uncertainties		
$\widetilde{M}_X$ Classification	Normalization	0.5
Classification MVA (HPC)	Normalization	11–19
Classification MVA (MPC)	Normalization	3–9
Theoretical uncertainties in the SM single-Higgs boson production		
QCD missing orders (ggH, VBF H , VH, $t\bar{t}$H)	Normalization	0.4–5.8
PDF and α_S uncertainties (ggH, VBF H , VH, $t\bar{t}$H)	Normalization	1.6–3.6
Theoretical uncertainty $b\bar{b}$H	Normalization	20
Theoretical uncertainties in the SM HH boson production		
QCD missing orders	Normalization	4.3–6
PDF and α_S uncertainties	Normalization	3.1
m_t effects	Normalization	5