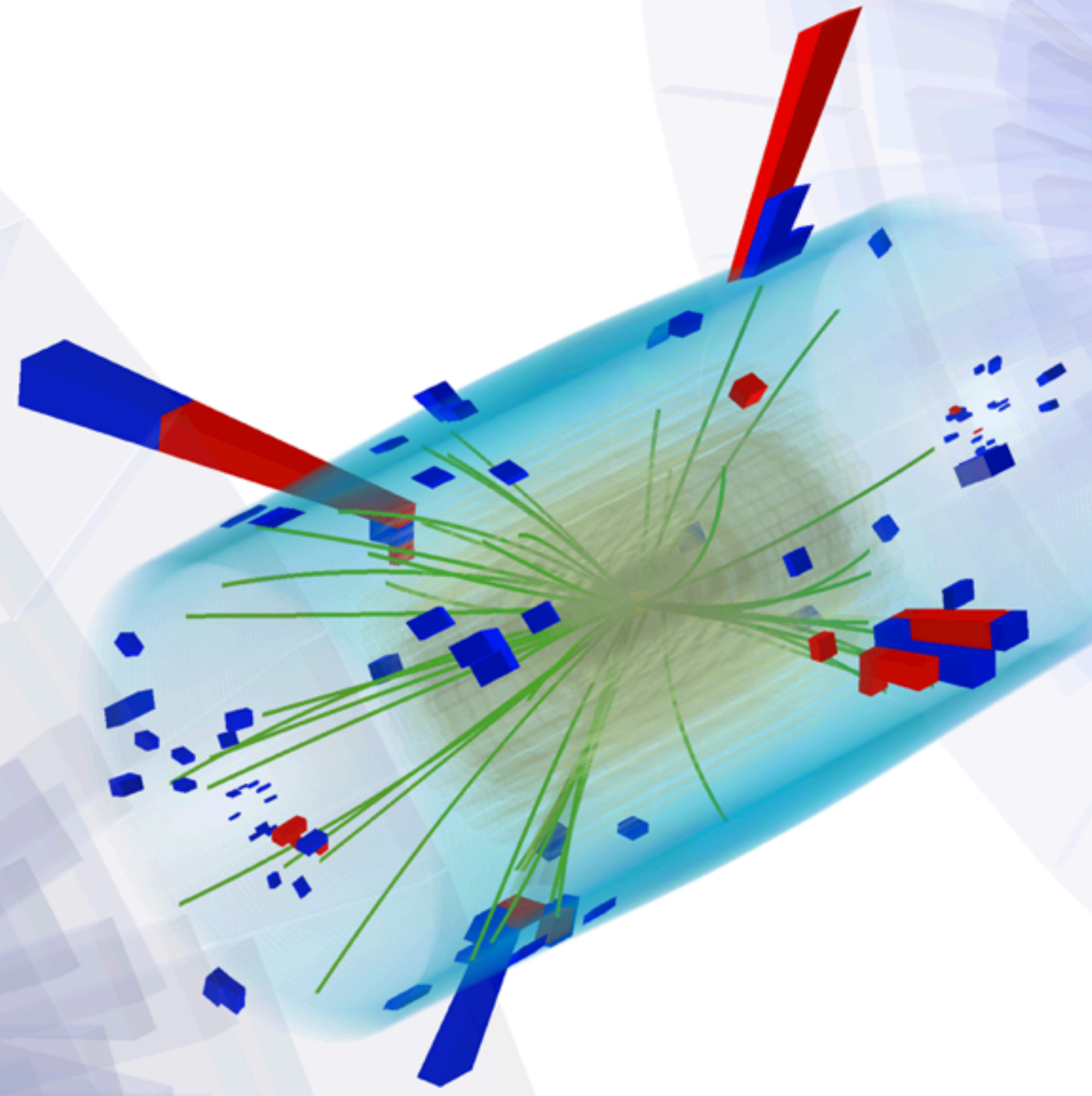
Double Higgs searches at CMS

G. Ortona,
for the CMS collaboration

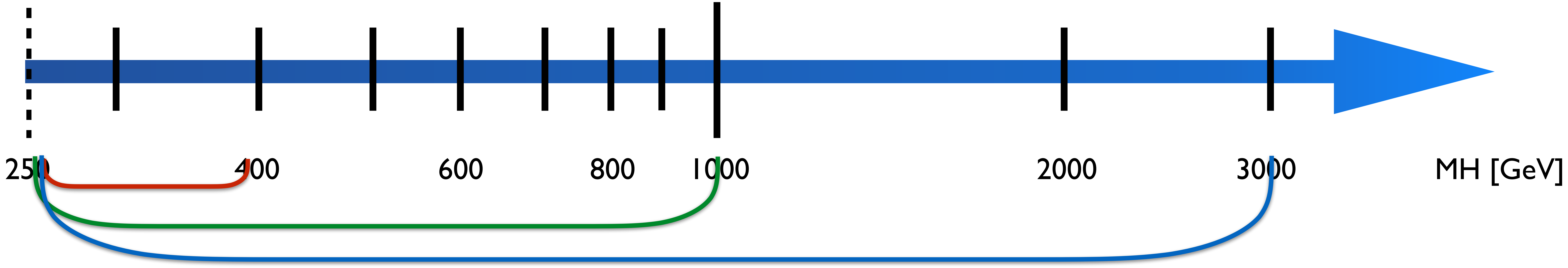
Co-funded by the Horizon 2020 Framework Programme of the European Union

Outline

1. Introduction
2. Double Higgs searches in CMS:
   A. $bb\gamma\gamma$
   B. bbbb
   C. bbWW
   D. $bb\tau\tau$
3. Results from LHC Run2
4. Future possibilities and projections



Motivations: Resonant searches



MSSM/2HDM: Additional Higgs doublet → CP-even scalar H.

- We can probe the low m_A/low tanβ region where BR(H → h(125)h(125)) is sizeable.

Singlet model: Additional Higgs singlet with an extra scalar H.

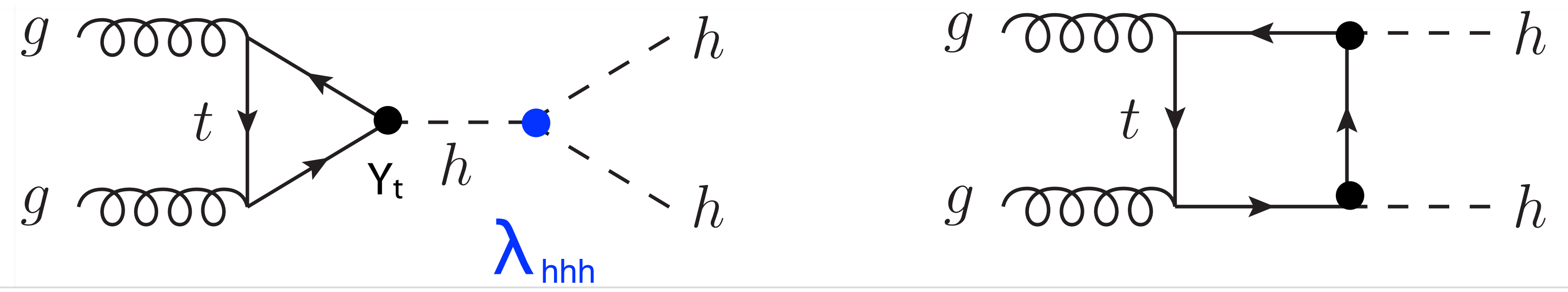
- Sizeable BR beyond 2xm_{top}, non negligible width at high m_H.

Warped Extra Dimensions:

spin-2 (KK-graviton) and spin-0 (radion) resonances.

- Different phenomenology if SM particles are allowed (bulk RS) or not (RSI model) in the extra dimensional bulk

Motivations: Non-resonant searches

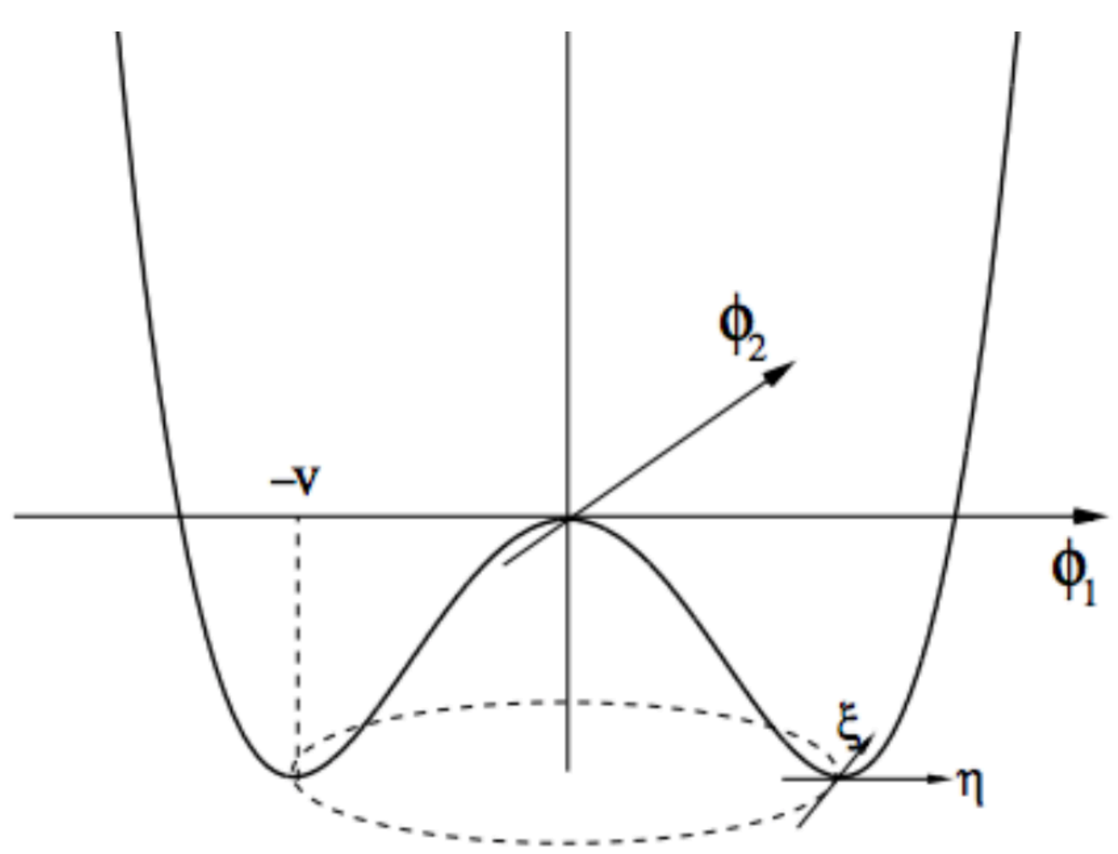


$\sigma^{SM}_{hh}(13TeV) = 33.45fb^{+4.3\%}_{-6.0\%}$(scale unc.) ±3.1%(PDF+$\alpha_S$ unc)[1]

The non-resonant double Higgs production allows to directly probe the Higgs trilinear coupling (λ_{hhh}).

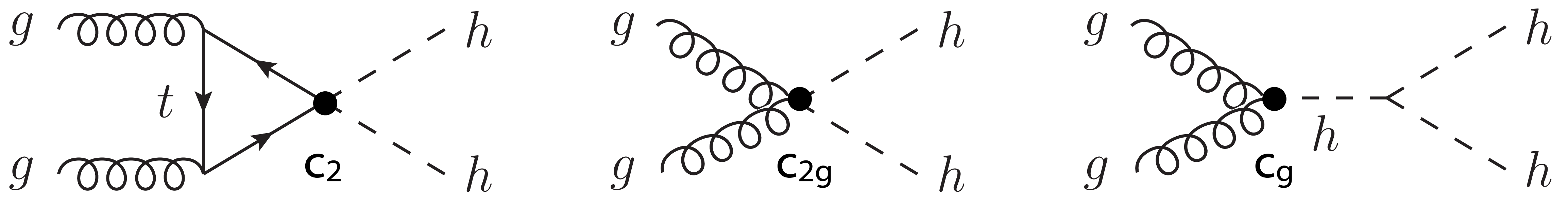
The shape of the Higgs potential is determined by the self coupling value

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$



Even if in Run2 we do not have full sensitivity to "measure" SM λ_{hhh} → The BSM physics can be modelled in EFT adding dim-6 operators[2] to the SM Lagrangian, and the physics can be described with 5 parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

- Non SM top Yukawa and λ_{hhh} couplings
- New diagrams and couplings in the game



[1] LHCHXSWG Yellow Report 4
[2] *Phys. Rev.* **D91** (2015), no. 11, 115008

CMS searches

4 main channels presented today:

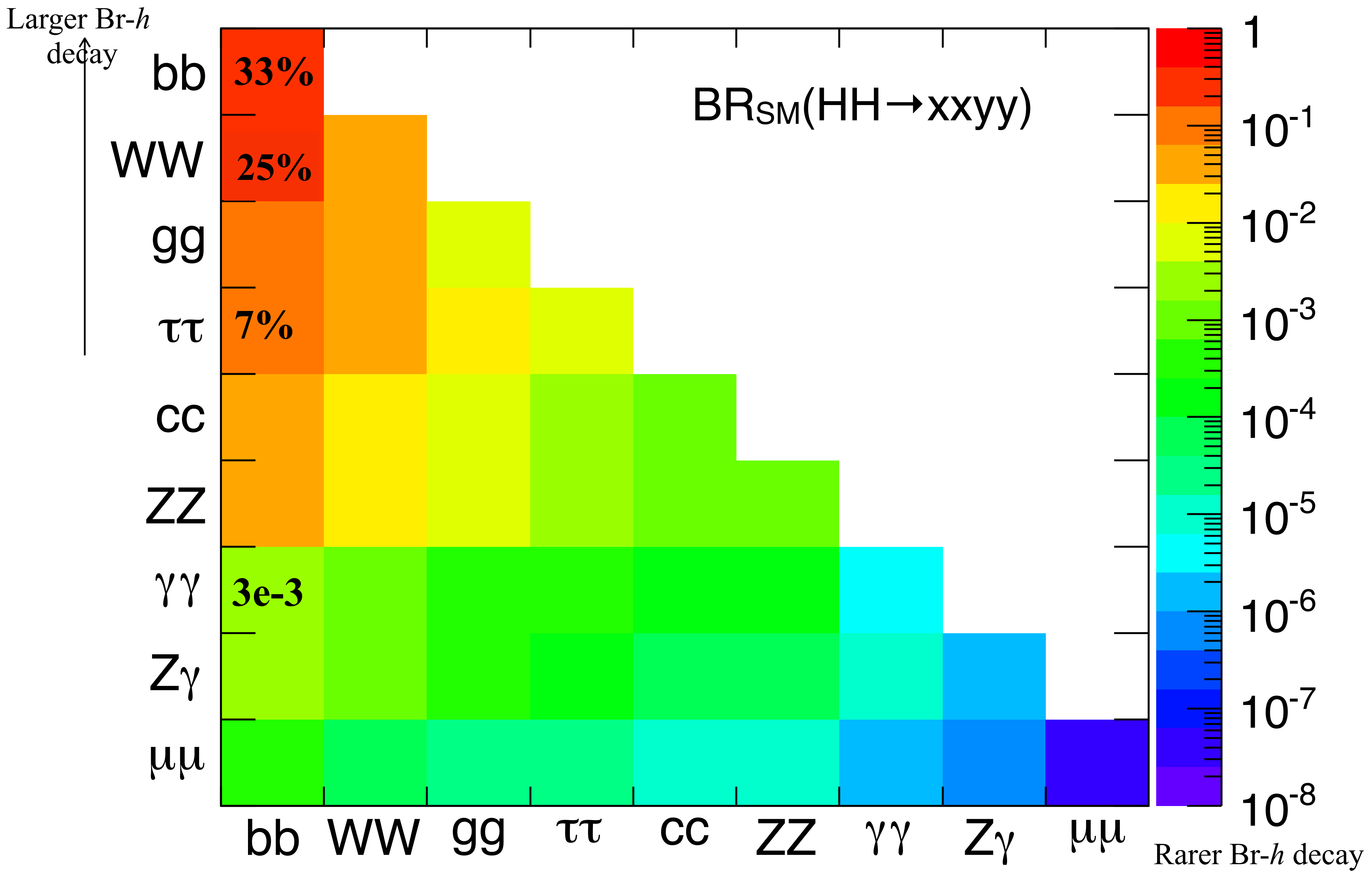
- bbbb, bbWW, bb$\tau\tau$, bb$\gamma\gamma$

At least one h→bb to have large enough BR

Rare processes, low σ, complex environment

Covering both resonant and non-resonant searches

- Run2:
  - bb$\tau\tau$ Resonant and non-resonant PLB 778 (2018) 101/PAS-B2G-17-006
  - bbWW Resonant and non-resonant JHEP01(2018)054
  - bb$\gamma\gamma$ Resonant and non-resonant PAS-HIG-17-008
  - bbbb Resonant PAS-HIG-17-009/arXiv:1710.04960 non-resonant PAS-HIG-16-026
- Run1:
  - bbbb Resonant: PLB 749 (2015) 560, arXiv:1602:08762
  - bb$\tau\tau$ Resonant: PLB 755 (2016) 217, PAS-EXO-15-008 Non-resonant PAS-HIG-15-013
  - bb$\gamma\gamma$ Resonant and Non-resonant: arxiv:1603.06896



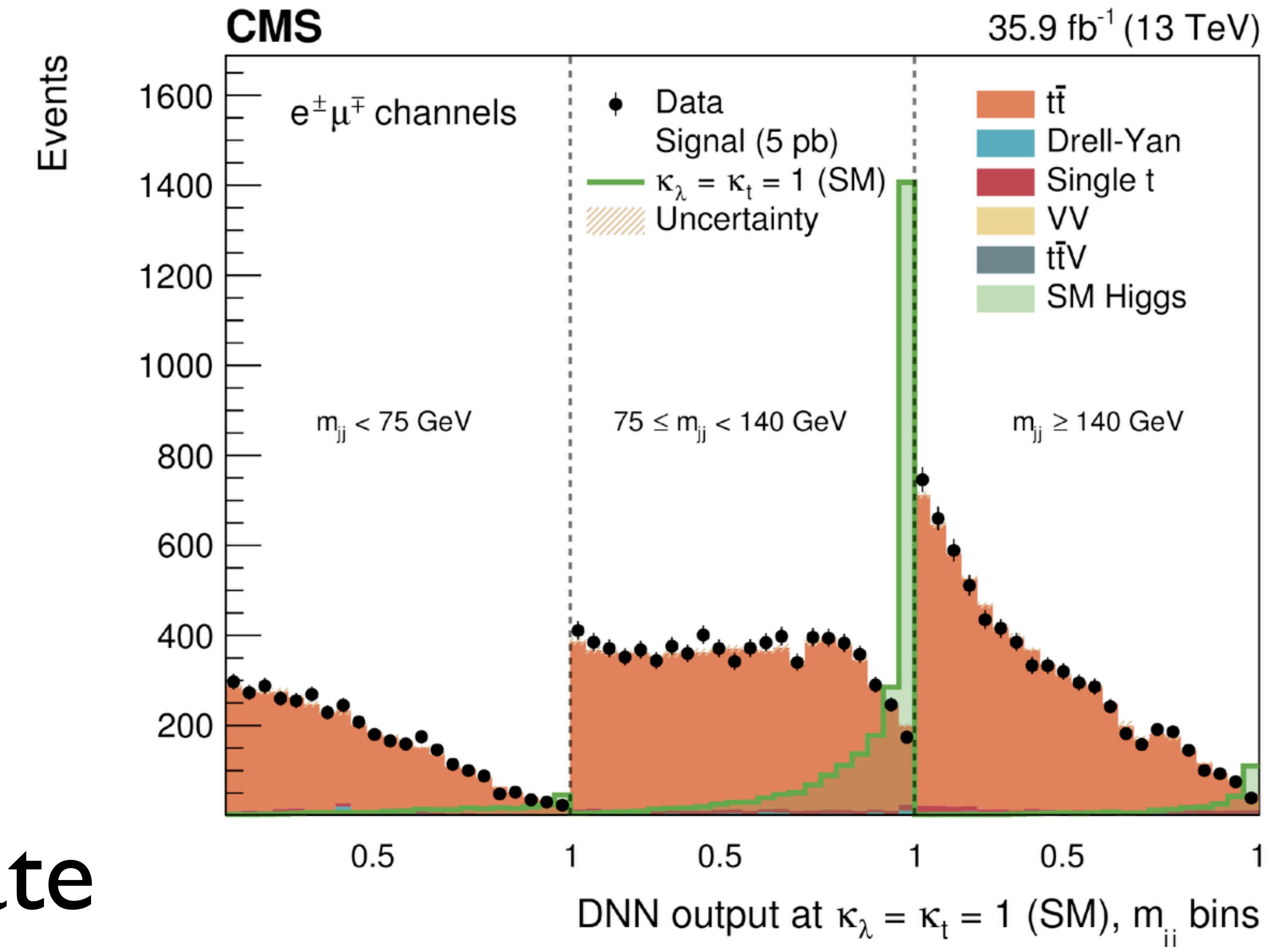
Trade-off between BR and contamination, complementarity among channels

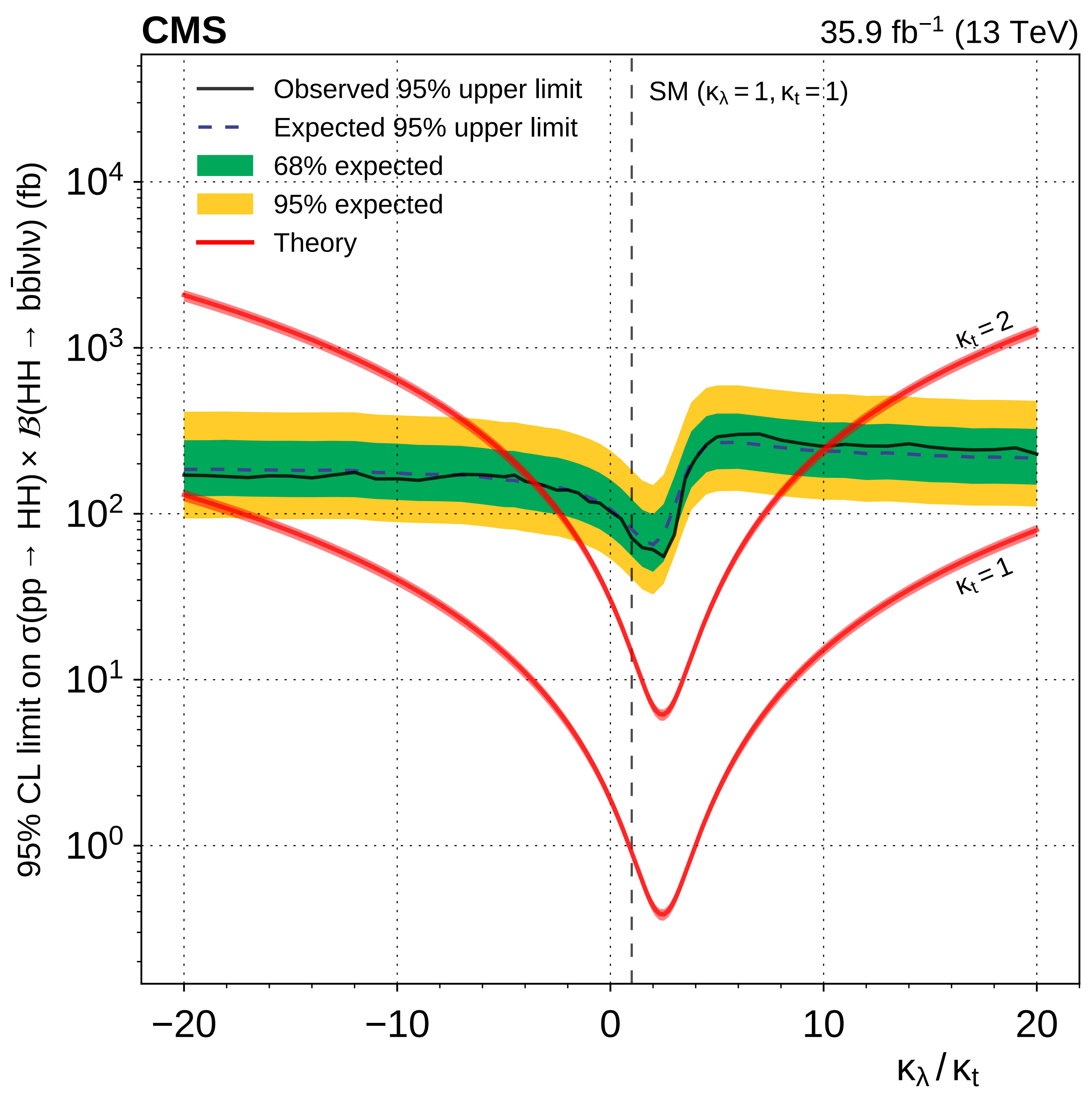
- bbbb: highest BR, high QCD/$t\bar{t}$ contamination
- bbWW: high BR, large irreducible $t\bar{t}$ background
- bb$\tau\tau$: relatively low background and BR
- bb$\gamma\gamma$: high purity, very low BR

bbVV(2l2ν)

35.9 fb^{-1} (2016). Low BR in the 2l2ν final state (2.72%)

- 2 OS leptons (ee, eμ, μe, μμ)
- Focus on the bbWW channel, Invariant mass cut to remove Z(ll) contributions
- Large background contamination from tt, Z+jets (from MC)



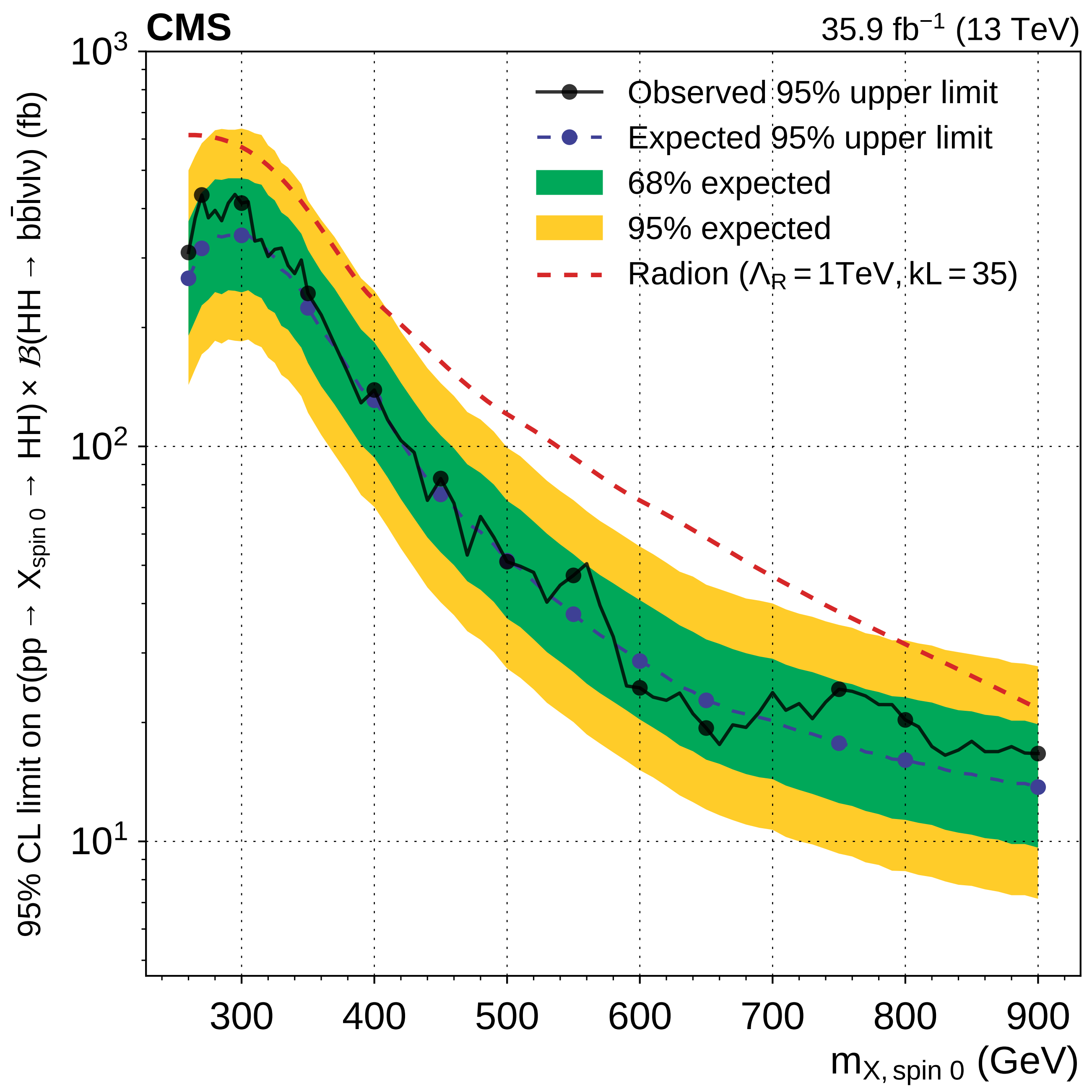


Parametrised DNNs used to discriminate against background

- Resonant: m_X, non-resonant k_t, $k\lambda$
- Limit extraction from DNN shape in 3 m_{jj} bins

Results

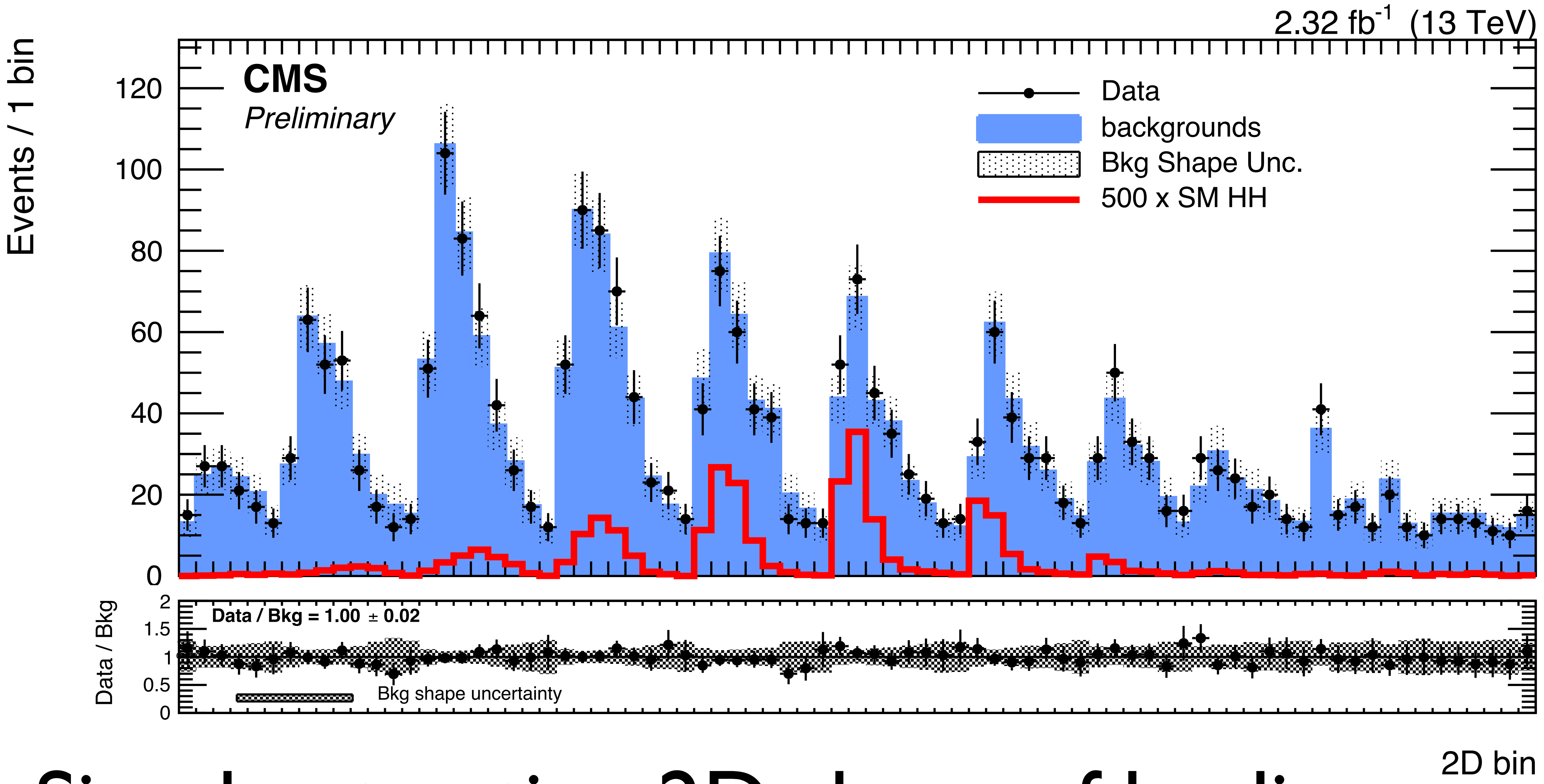
- SM σxBR<72fb
- Obs.(exp.): σ/σ_{SM}< 79 (89)



Non-resonant bbbb

2.3 fb^{-1} (2015)

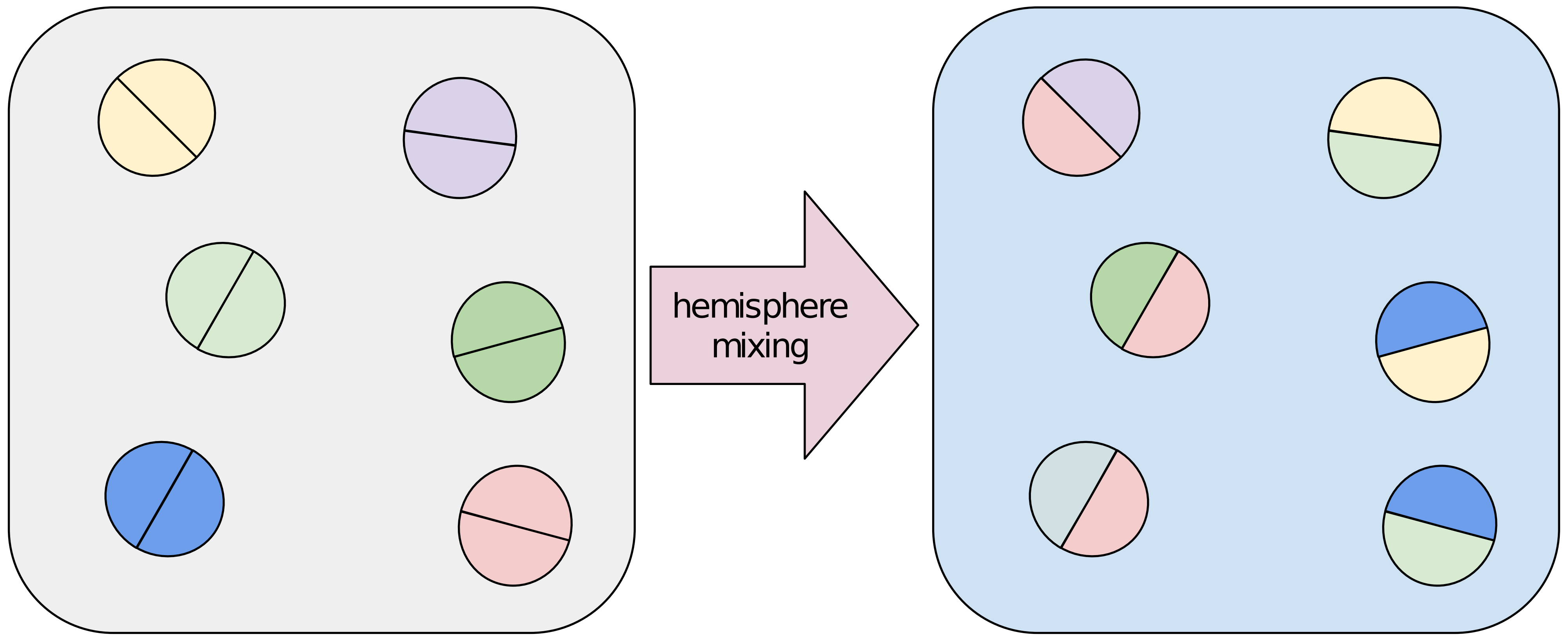
- Highest BR among HH searches
- 4 jets, 3/4 b-tagged jets
- Pairing: 2 pairs closest in mass



Signal extraction: 2D shape of leading vs. sub-leading m_{jj}

Large Multijet (and tt) backgrounds. We want reliable background estimation with large statistics → 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.
- Cut on BDT



Original dataset: bkgs and potentially a small signal fraction

Mixed dataset: new composed event that represent bkg-only

SMσxBR < 3.9 pb

Obs.(exp.): σ/σ_{SM} < 342 (308)

To be updated soon! Expect sensitivity close to bb$\tau\tau$

Resonant resolved bbbb

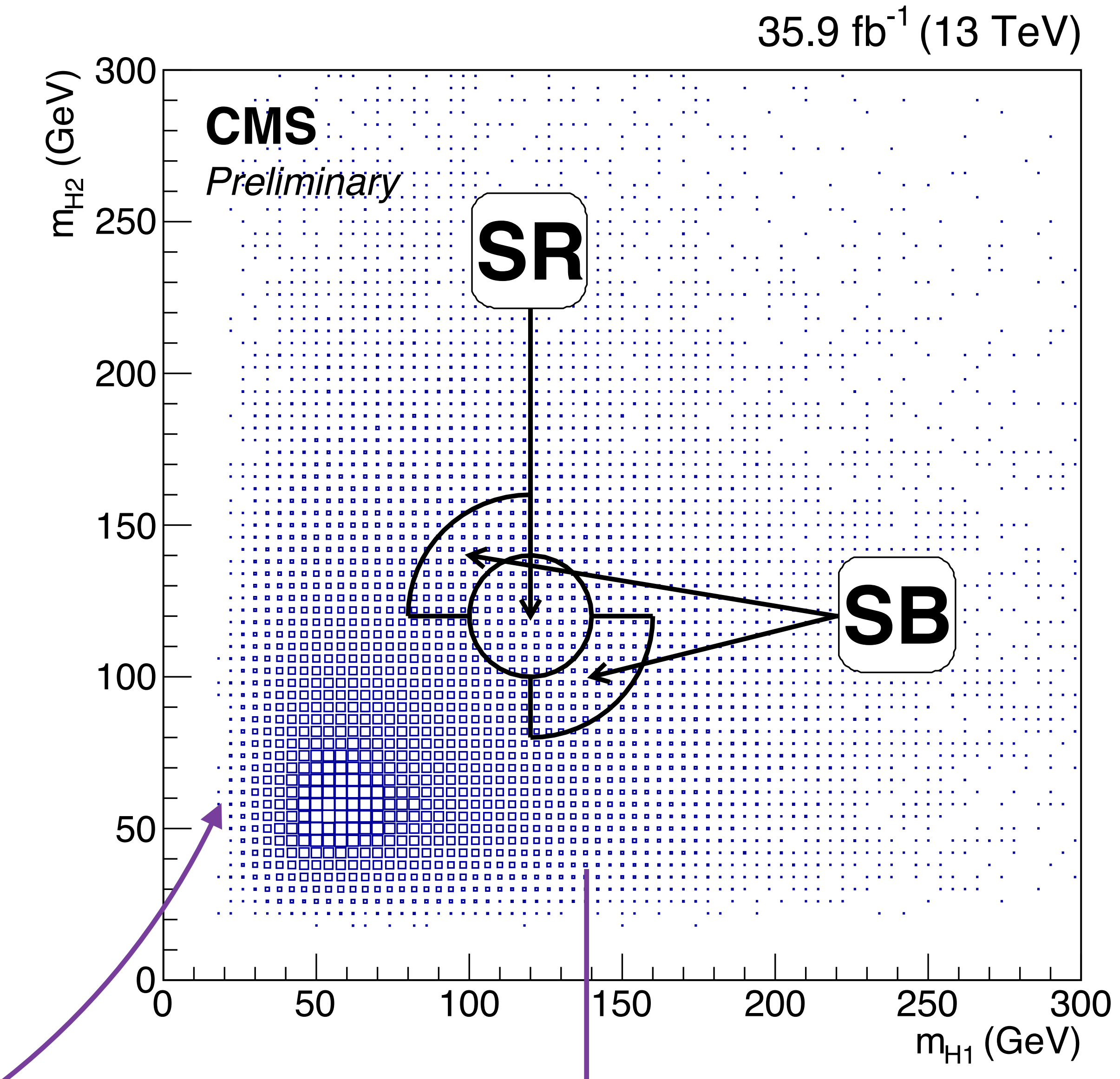
35.9 fb^{-1} (2016)

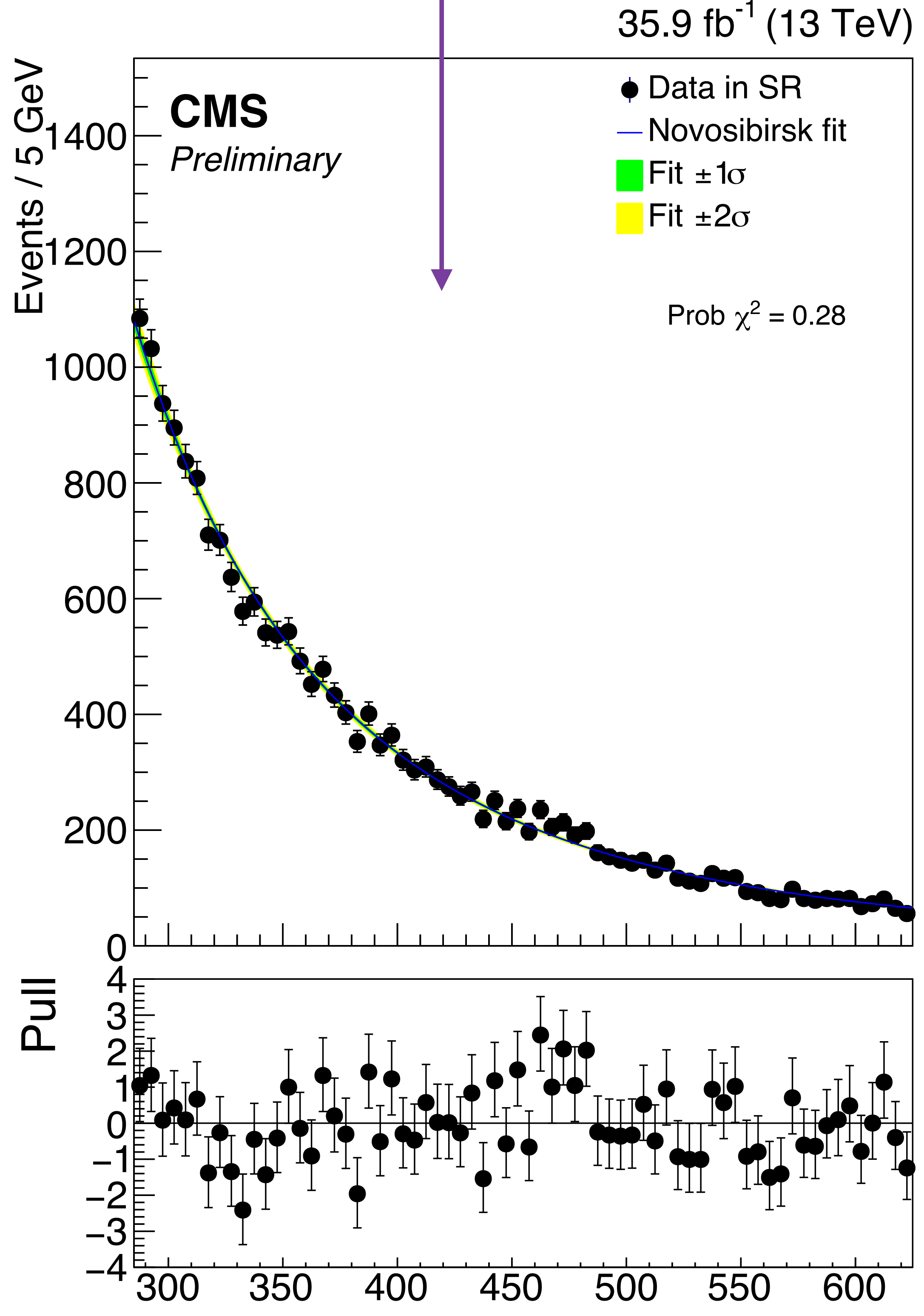
4 b-tagged jets, deepCSV algorithm

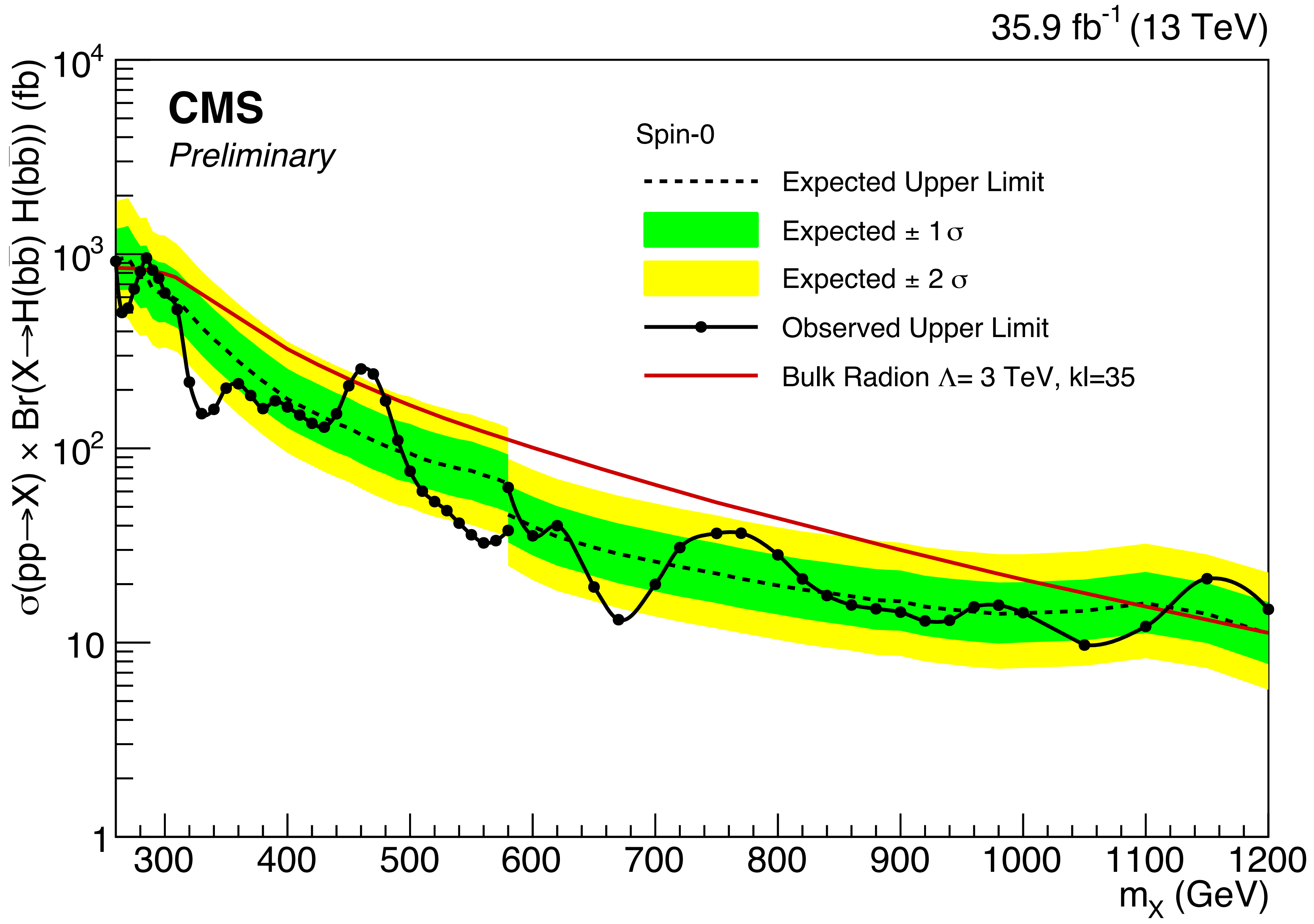
b-jet energy regression to improve resolution, Kinematic fit for m_{HH}

Low Mass Region (m_H<400) and High Mass Region (400<m_H<1200) studied separately to exploit kinematic properties of the signal

Background shape estimation from data in LMR, HMR







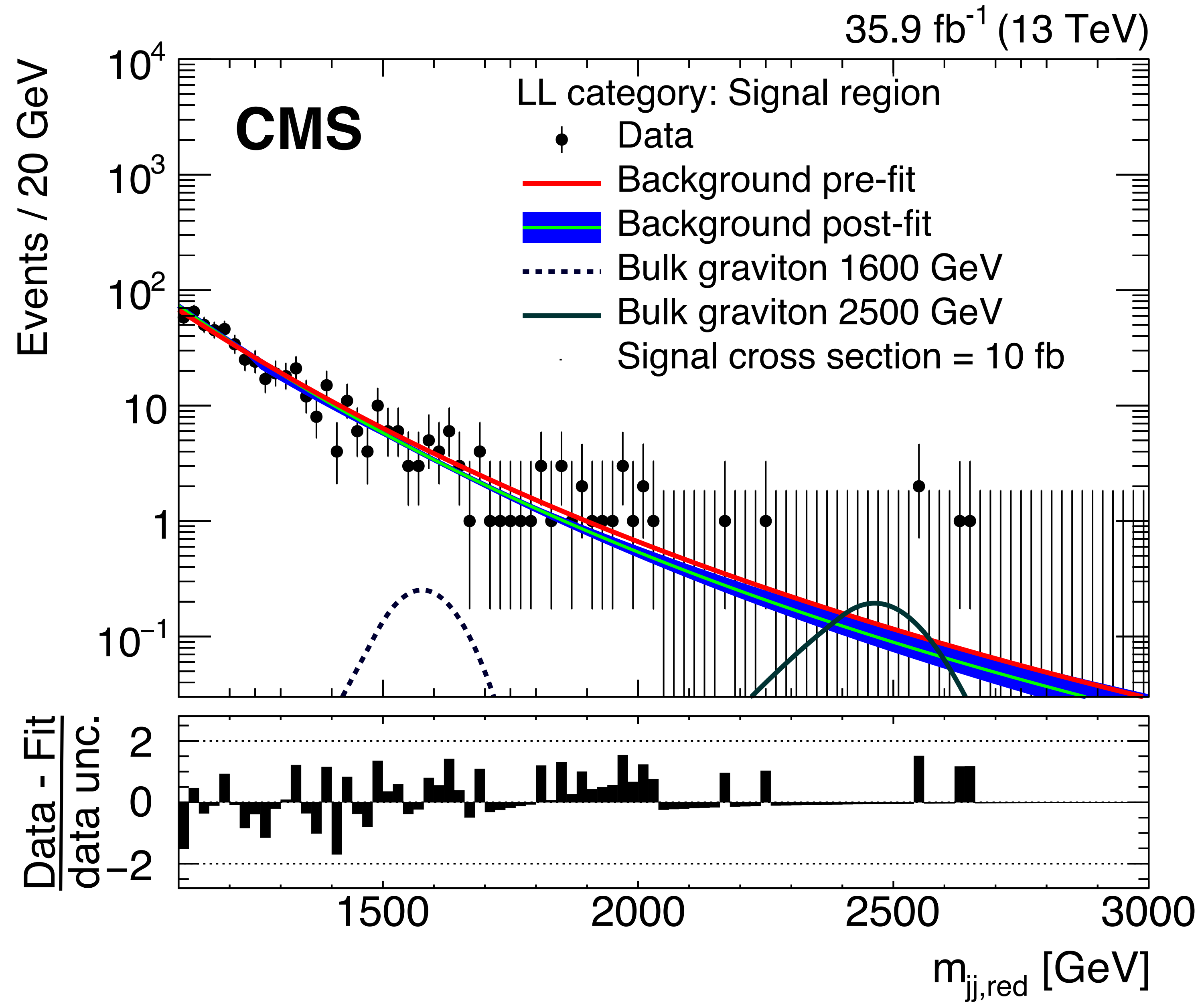
Background estimation cross-checked

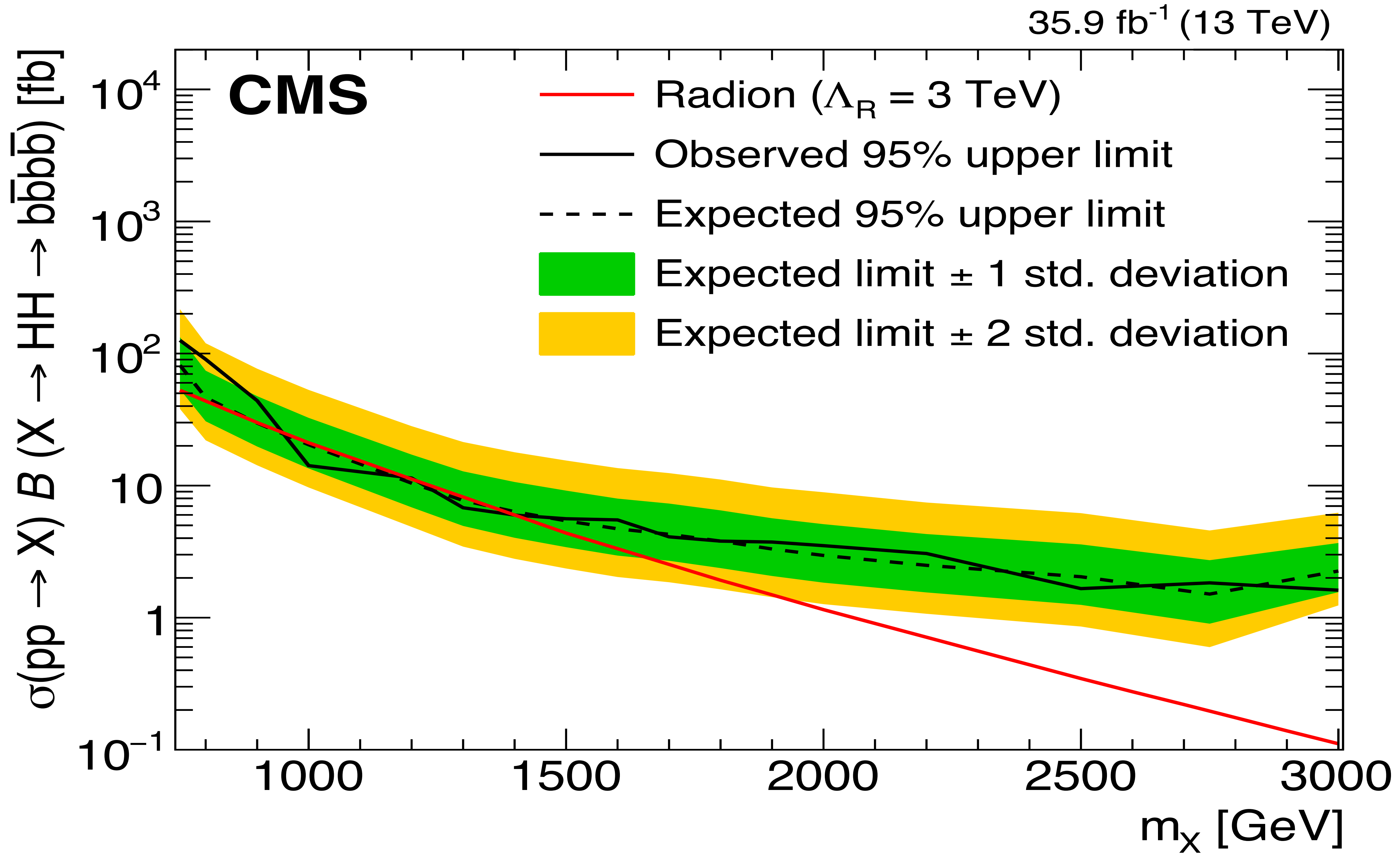
- In <4 b-tag side bands
- With alternate SR definitions

Resonant boosted bbbb

35.9 fb^{-1} (2016)

- Search for a heavy (MX>800GeV) resonance
- 2 "fat" jets (R=0.8), with double b-tagging
- B-tag based categories (LL, TT)
- Use constituent jets properties ("soft-drop" mass, N-subjettiness)
- Signal extraction → reduced mass: $M_{red}=m_{jj}-(m_{j1}-m_H)-(m_{j2}-m_H)$





Multijet background estimation

M_{red} < 1200 GeV: refined ABCD method

- m_{j1} and b-tag sidebands
- Interpolate dependence on m_{j1}

M_{red} > 1200 GeV:

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

$bb\tau\tau$

35.9 fb^{-1} (2016)

3 final states ($e\tau_H$, $\mu\tau_H$, $\tau_H\tau_H$), covering 88% of the BR

3rd lepton veto

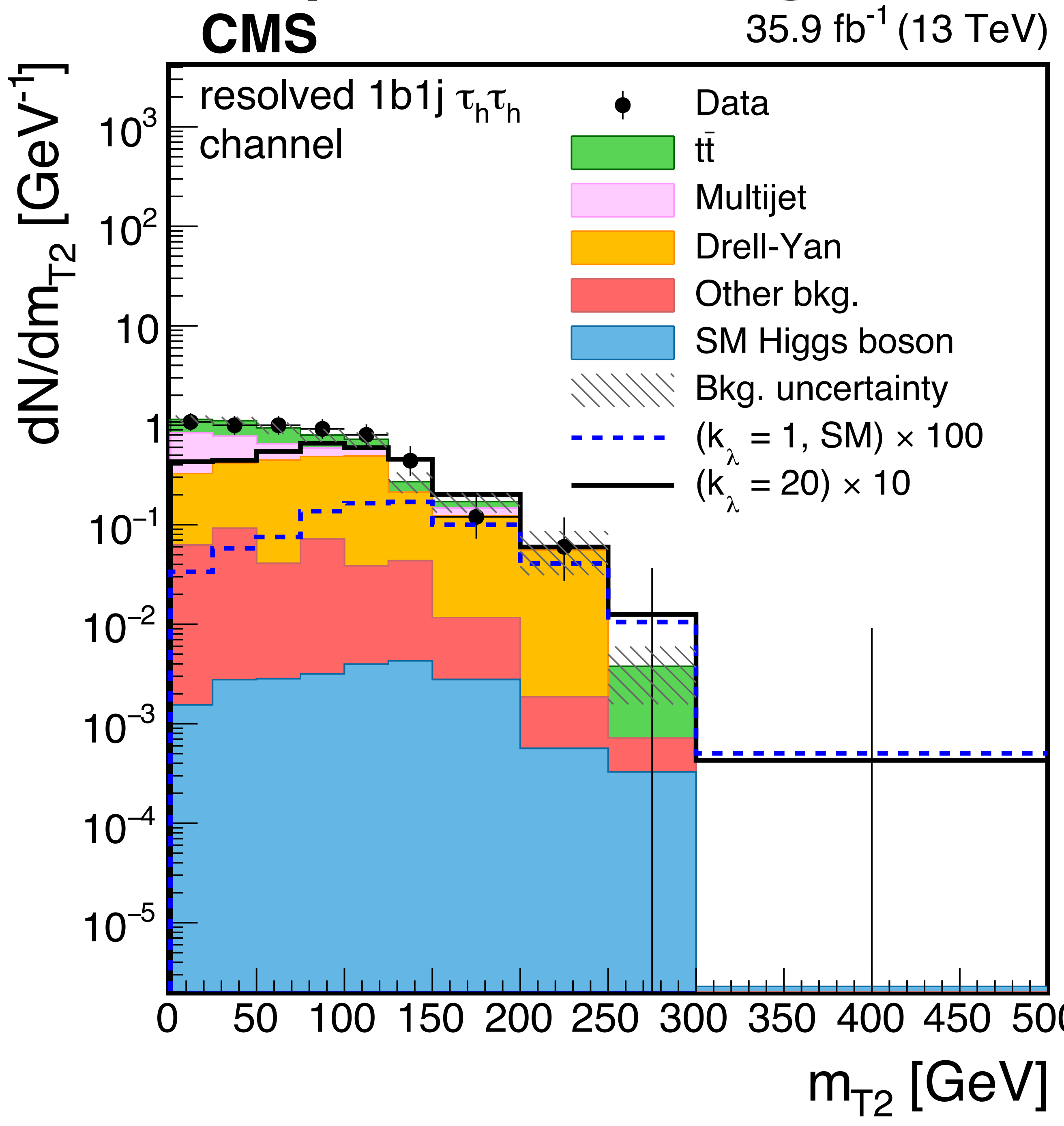
Kinematic fit (SVFit) to reconstruct m($\tau\tau$)

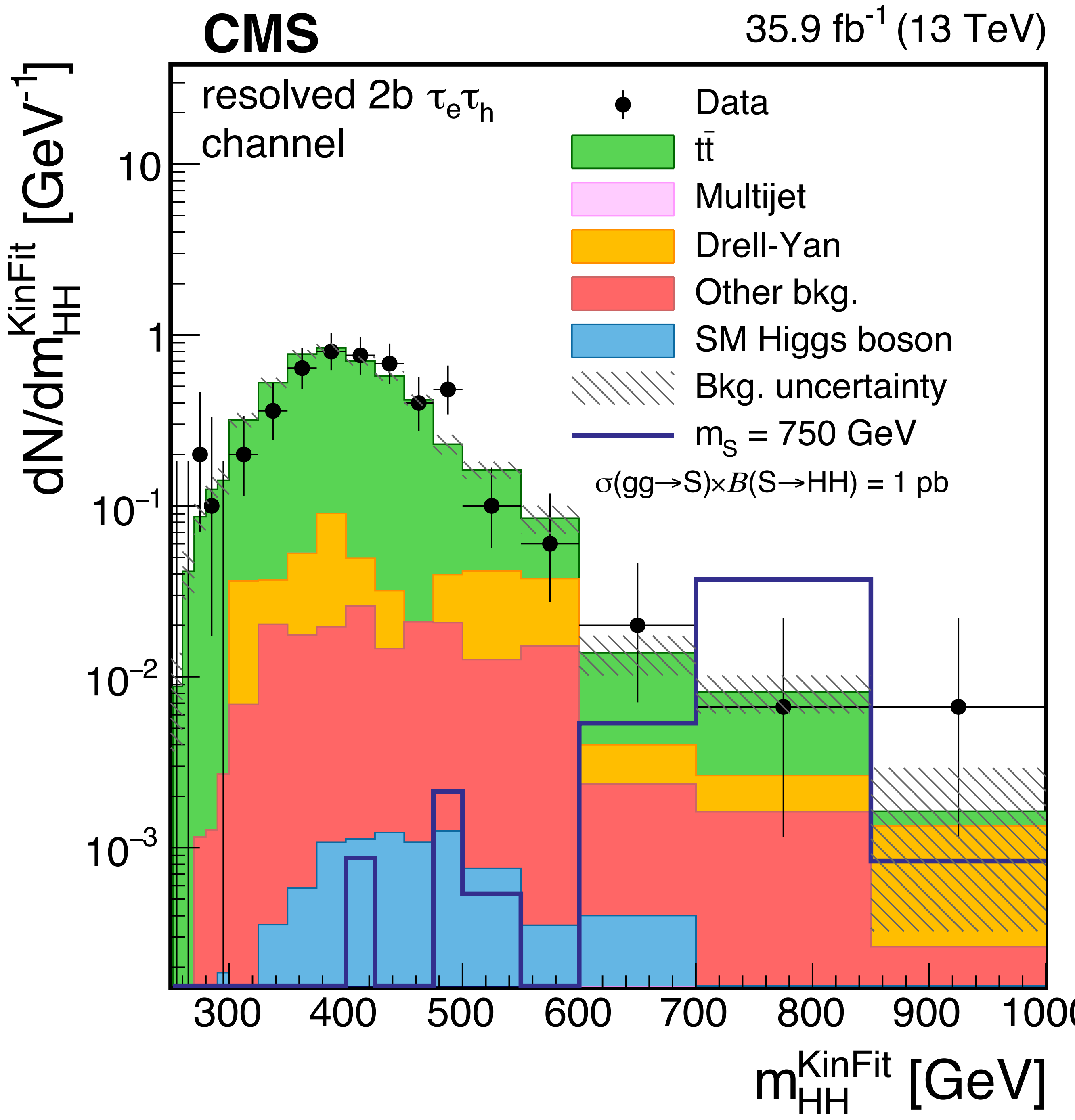
Discriminant variable:
- Non-resonant: Stransverse mass M_{T2}
- Resonant: Kinematic Fit of m($jj\tau\tau$)

Main backgrounds: tt, Z+jets (from MC) DY, multijet (from data)
- BDTs (low/high mass) to reject tt in semileptonic categories

Resolved analysis:
- 2 categories (1 or 2 b-jets)
- Elliptical cut in m($\tau\tau$),m(jj)

Boosted (bb) analysis
- 1 (R=0.8 jet), subjet b-tagging
- cut in m($\tau\tau$),m(j)





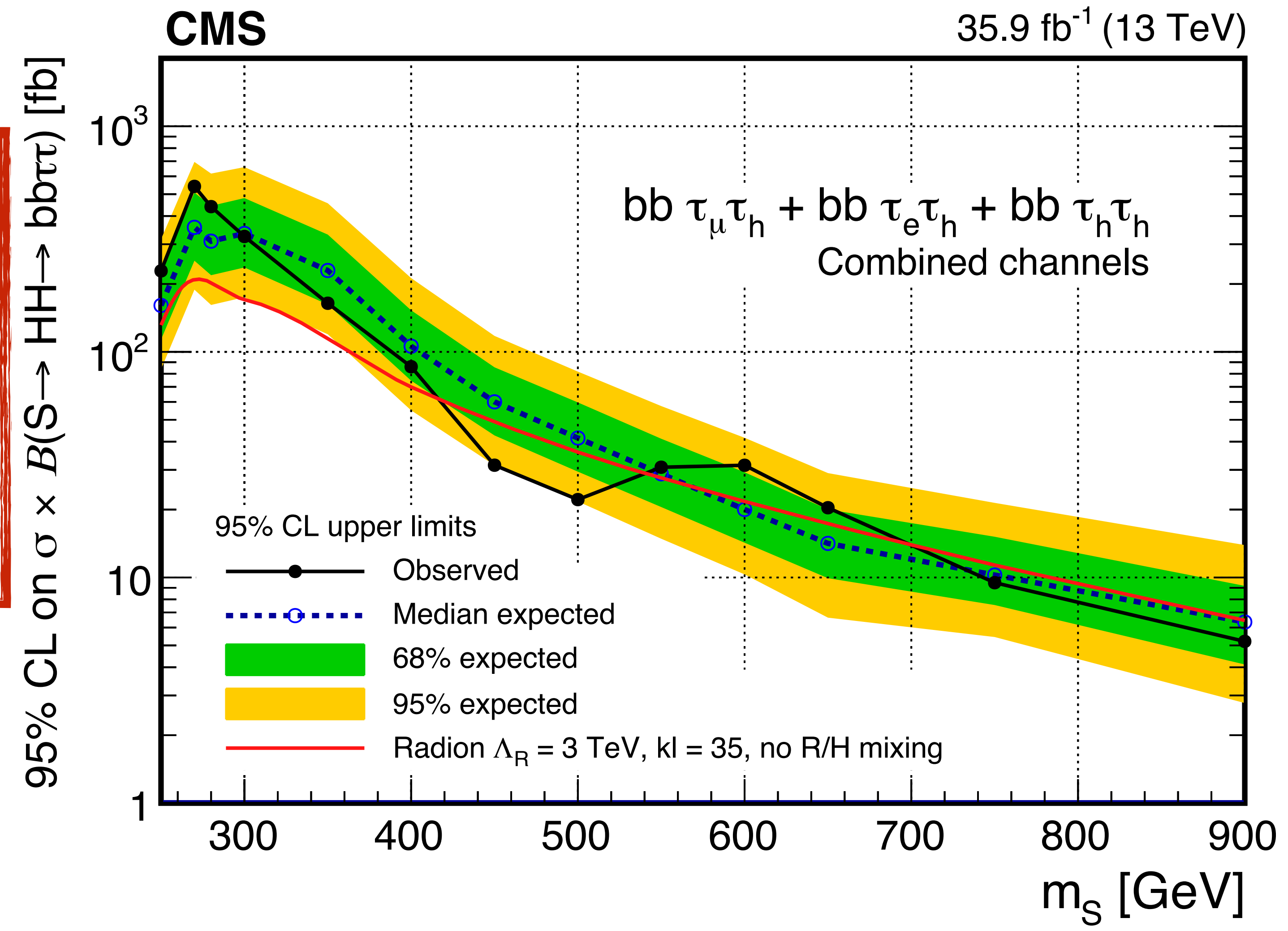
Phys. Lett. B 778 (2018) 101

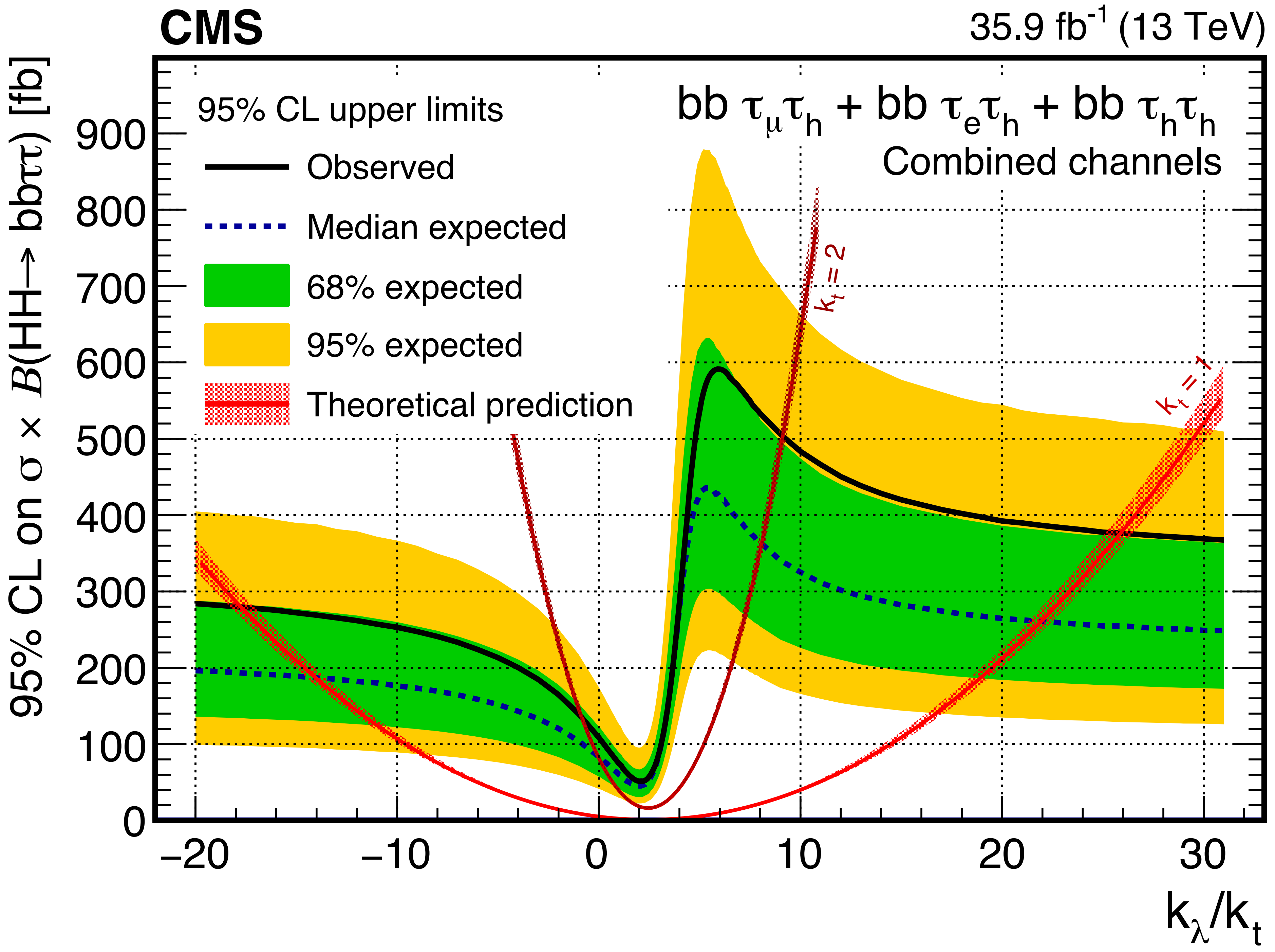
bbττ - Results

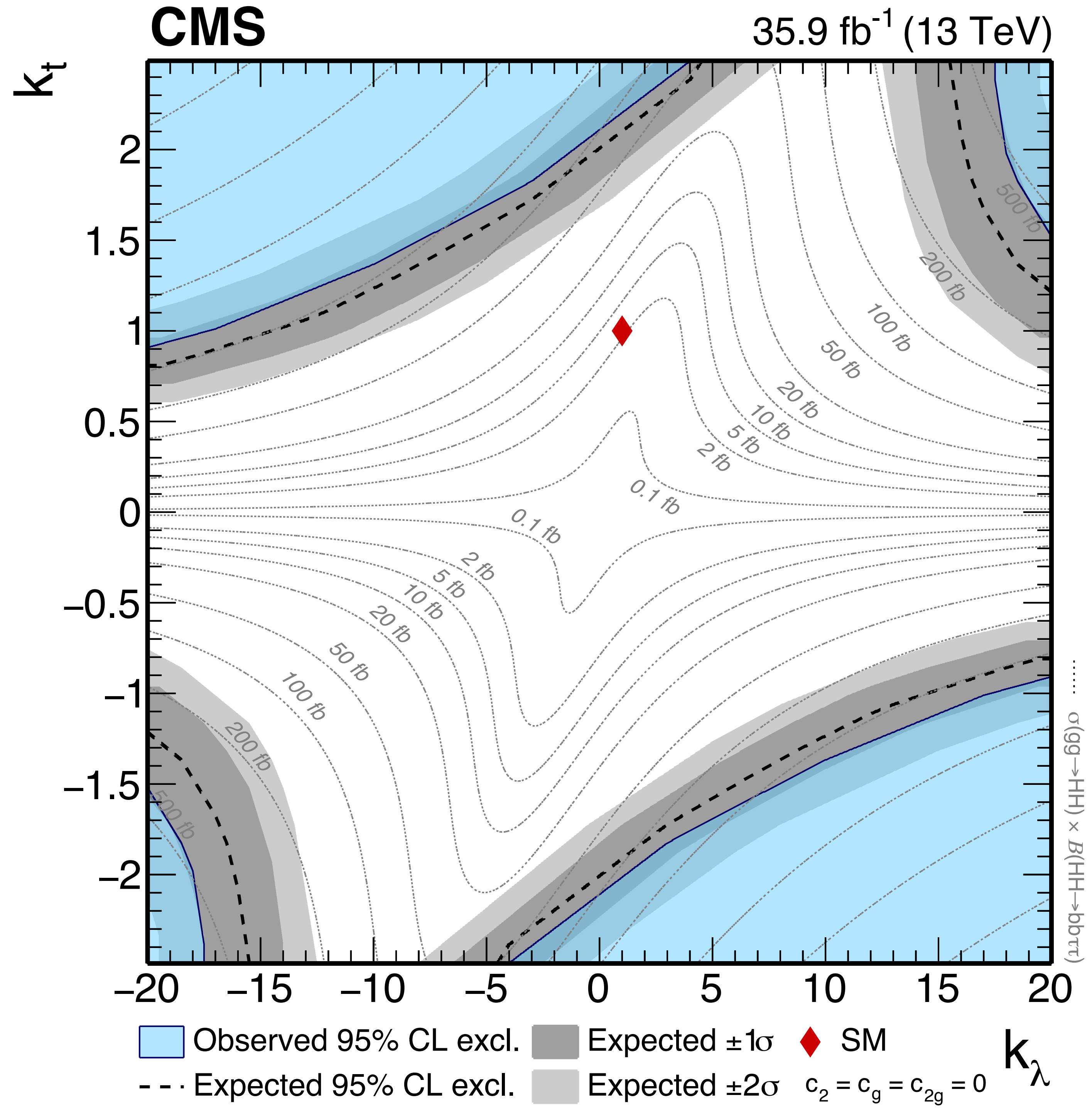
Non-resonant limits:

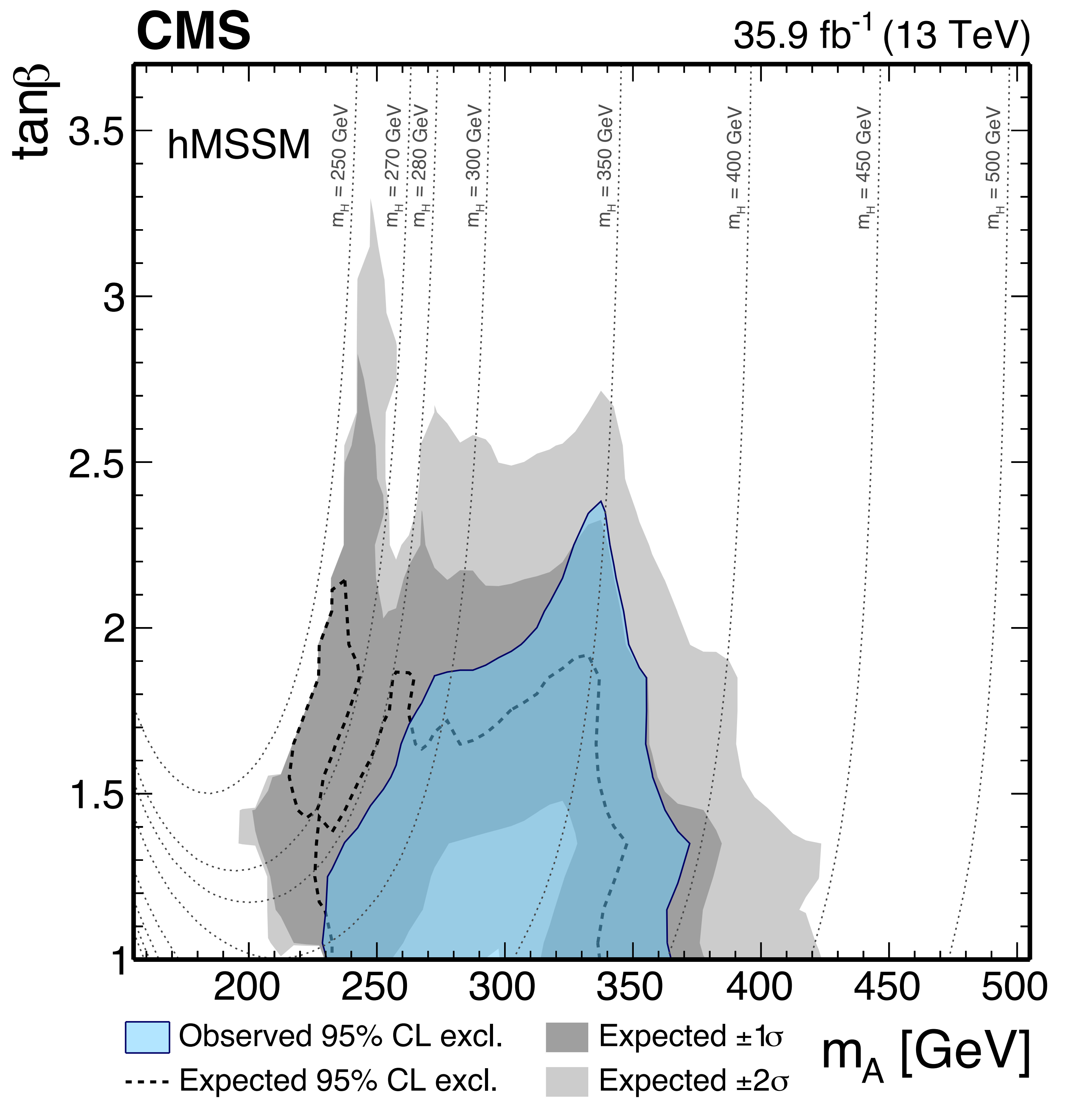
- SM σxBR<75.4fb
- Obs.(exp.): σ/σ_{SM}< 30 (25)

hMSSM interpretation on top of narrow width resonant searches









Resonant boosted bbττ

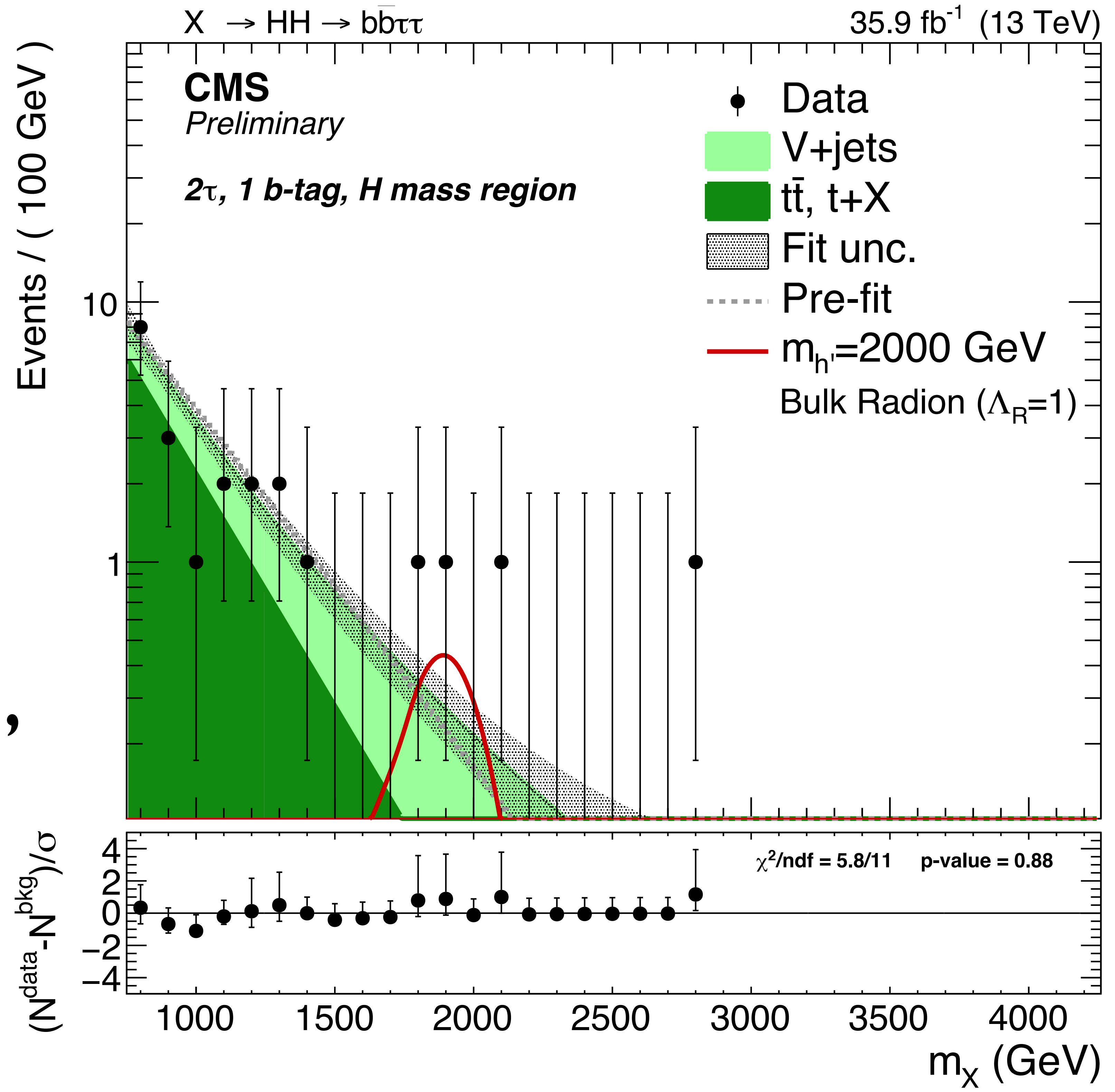
35.9 fb^{-1} (2016), search for heavy mass resonances

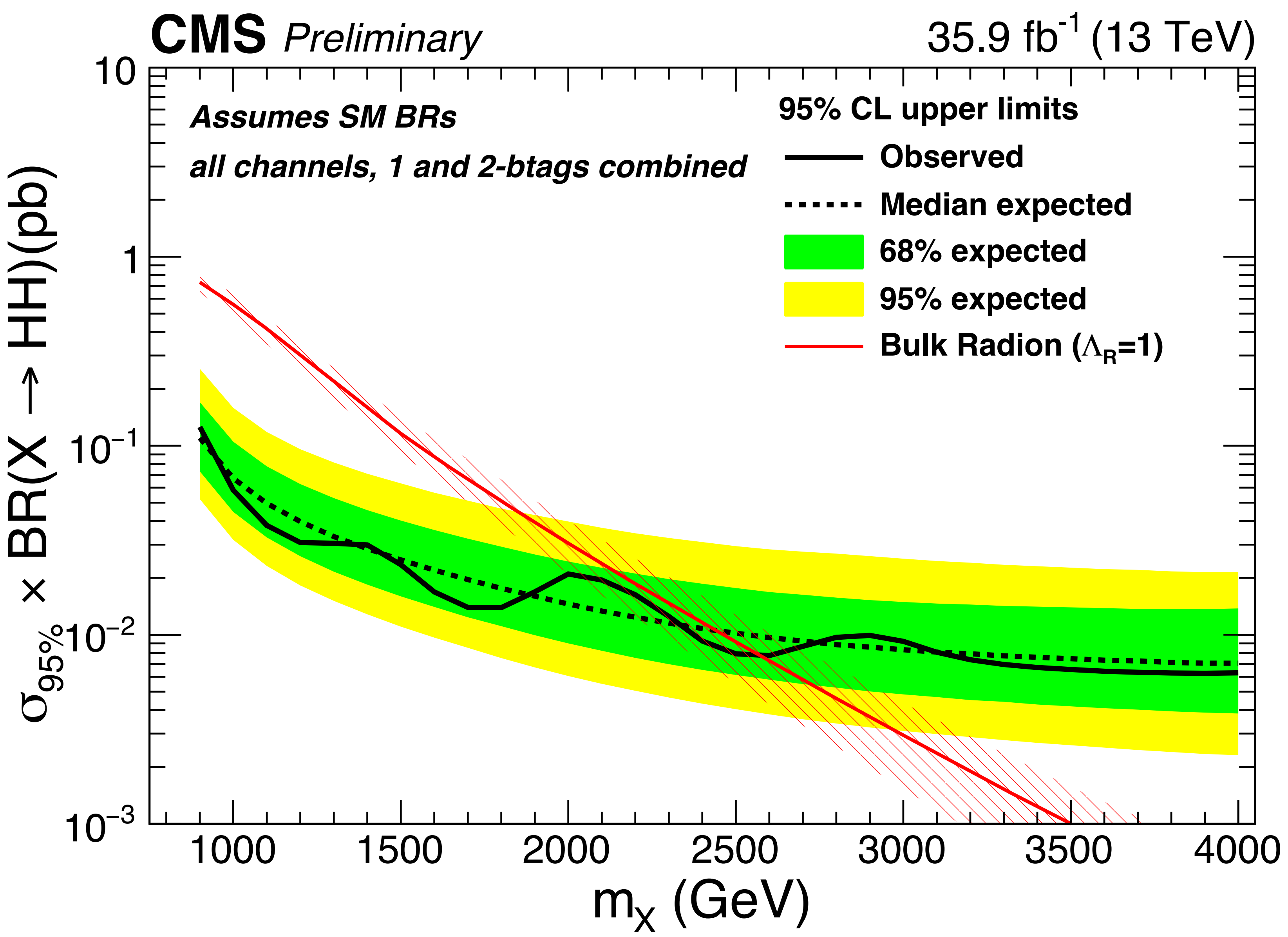
Boosted b-jet (anti-kT,R=0.8) and boosted **ττ** ($l\tau_H, \tau_H\tau_H$)

Kinematic fit to reconstruct $50 < m_{\tau\tau} < 150$GeV

>0 b-tagged sub-jet, $105 < m_j < 135$ GeV

Fit on the m_X distribution





Main backgrounds: tt, t+X, V+jets

- tt, t+X: Shape from MC simulation, normalisation from CR
- V+jets: from mj sidebands, shape corrected with simulation

Search performed up to 4TeV, excludes narrow width radion up to 2.5TeV

bbγγ

35.9 fb^{-1} (2016)

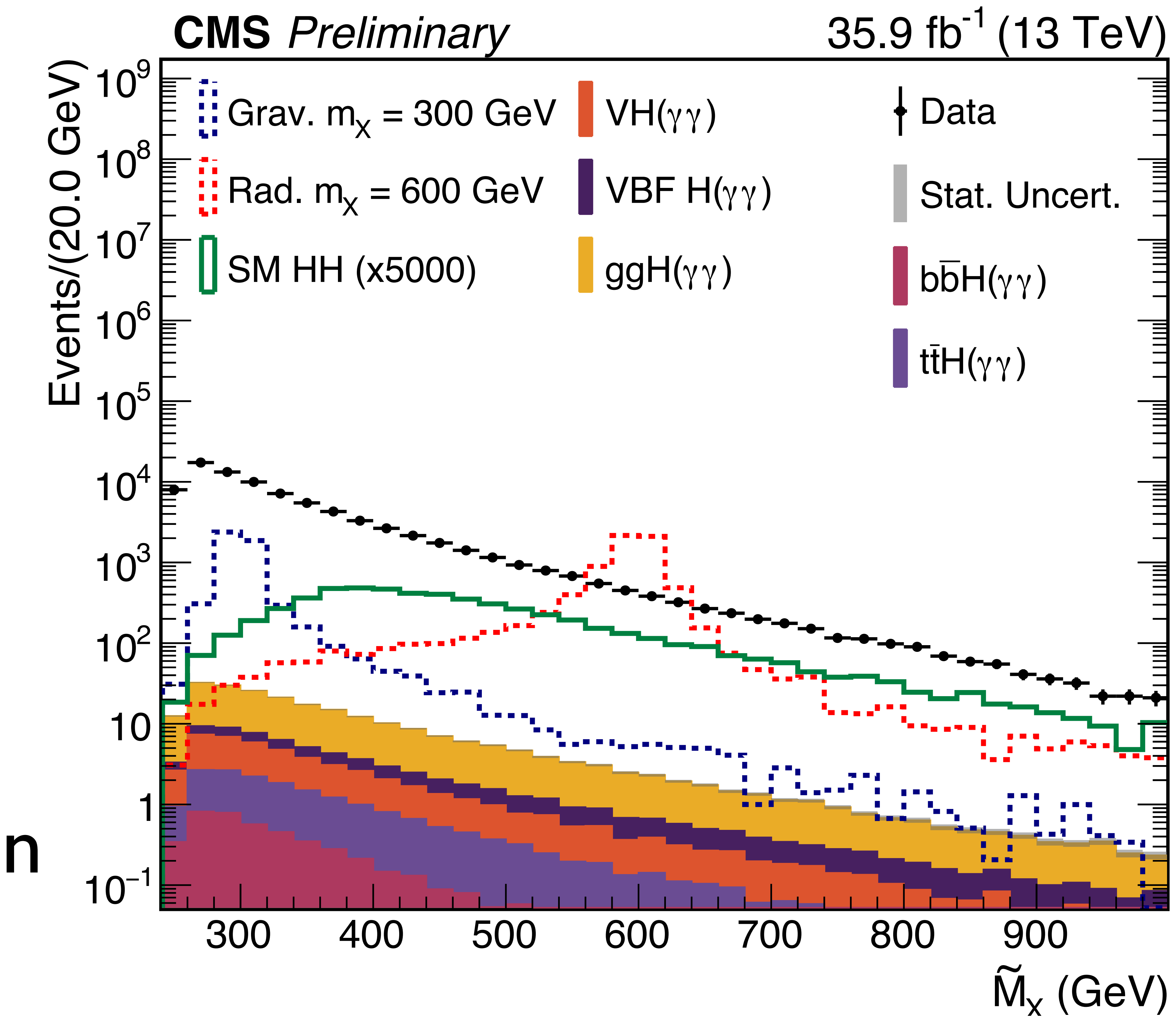
Low BR (0.26%), excellent resolution, clear signature

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

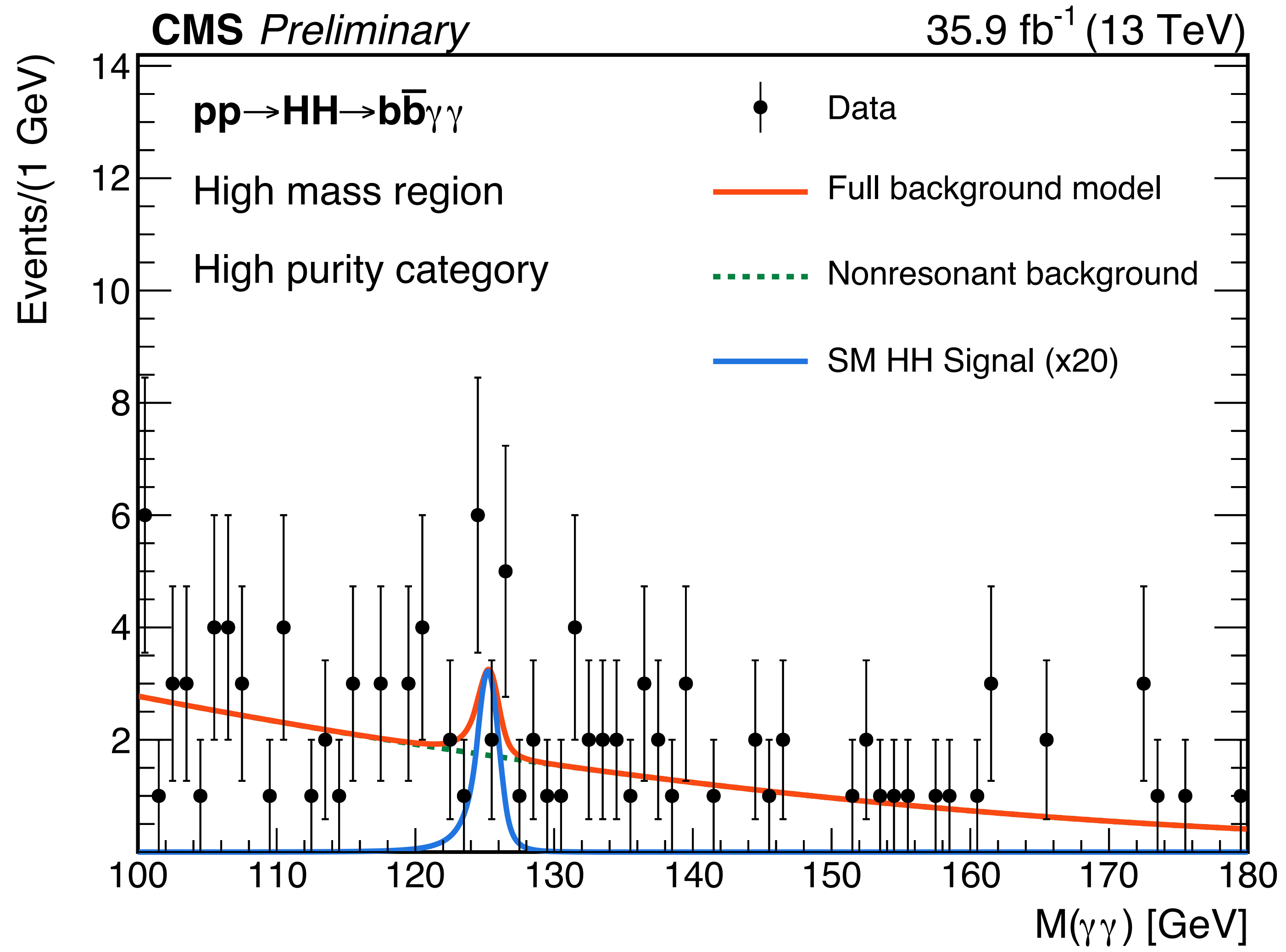
Reduced mass: $M_{\tilde{X}} = m_{jj\gamma\gamma} - m_{jj} - m_{\gamma\gamma} + 250$ GeV

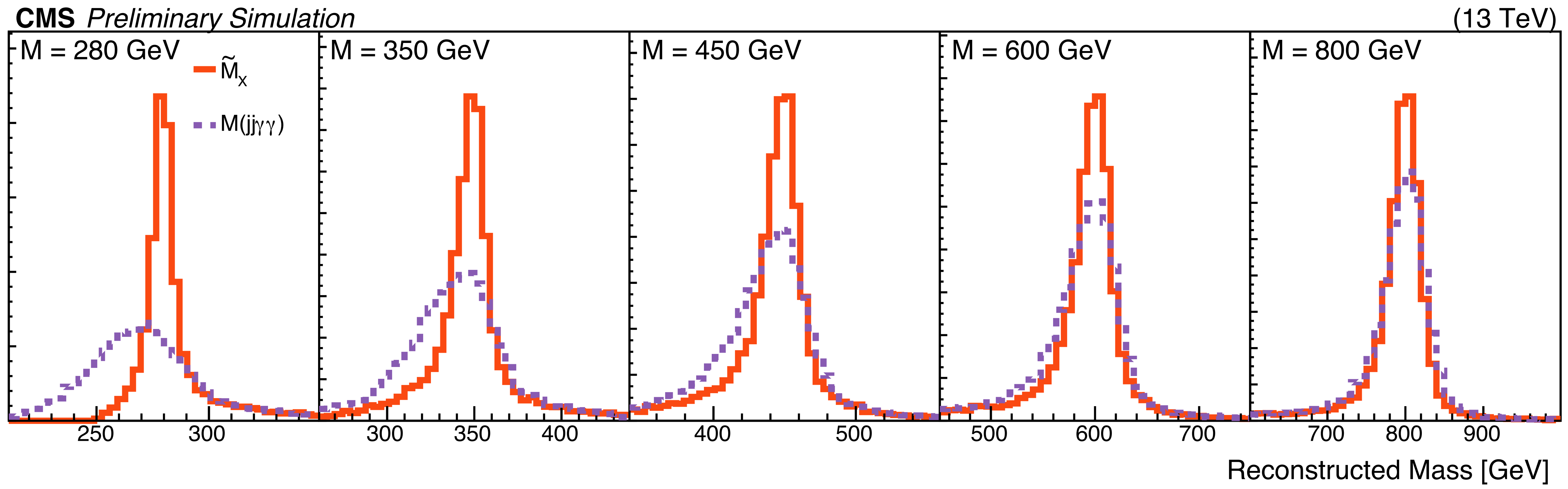
BDT x $M_{\tilde{X}}$ categorization: medium/high BDT purity and low/high reduced mass $M_{\tilde{X}}$<350GeV/$M_{\tilde{X}}$>350GeV)

Main backgrounds: multijet, fake photons, SM Higgs production

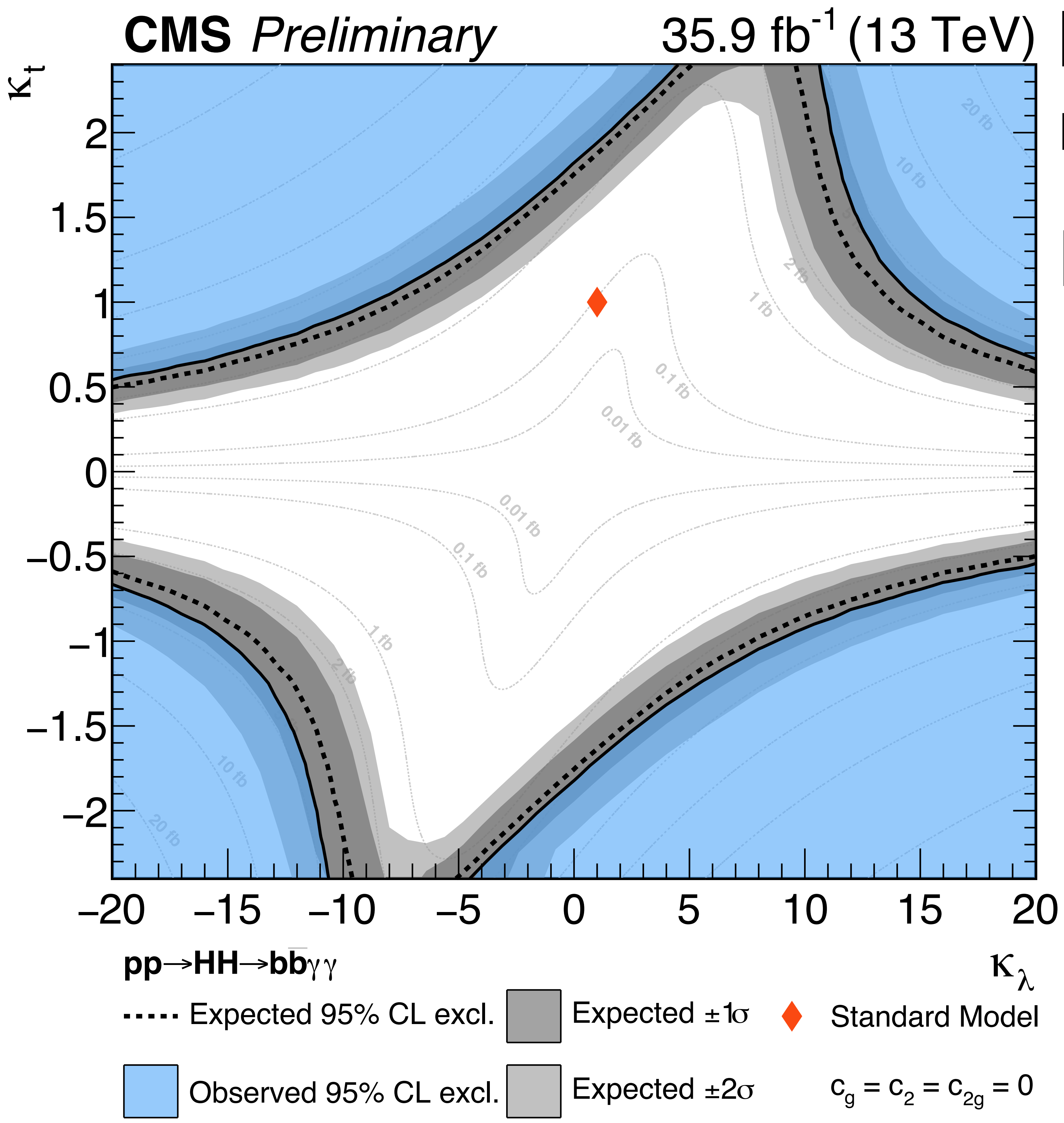


2D parametric fit in (m_{jj},$m_{\gamma\gamma}$) for signal extraction





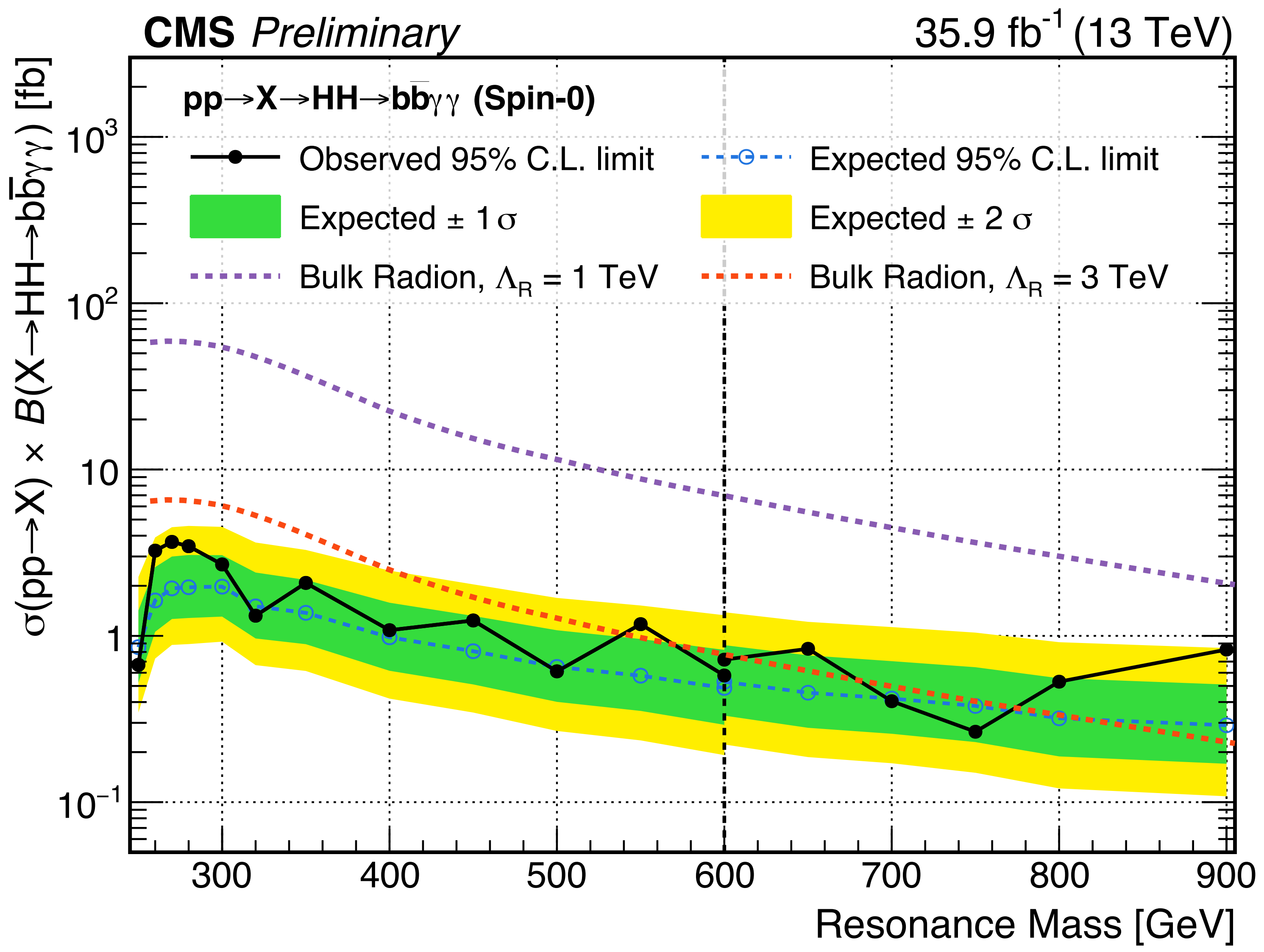
bbγγ - Results

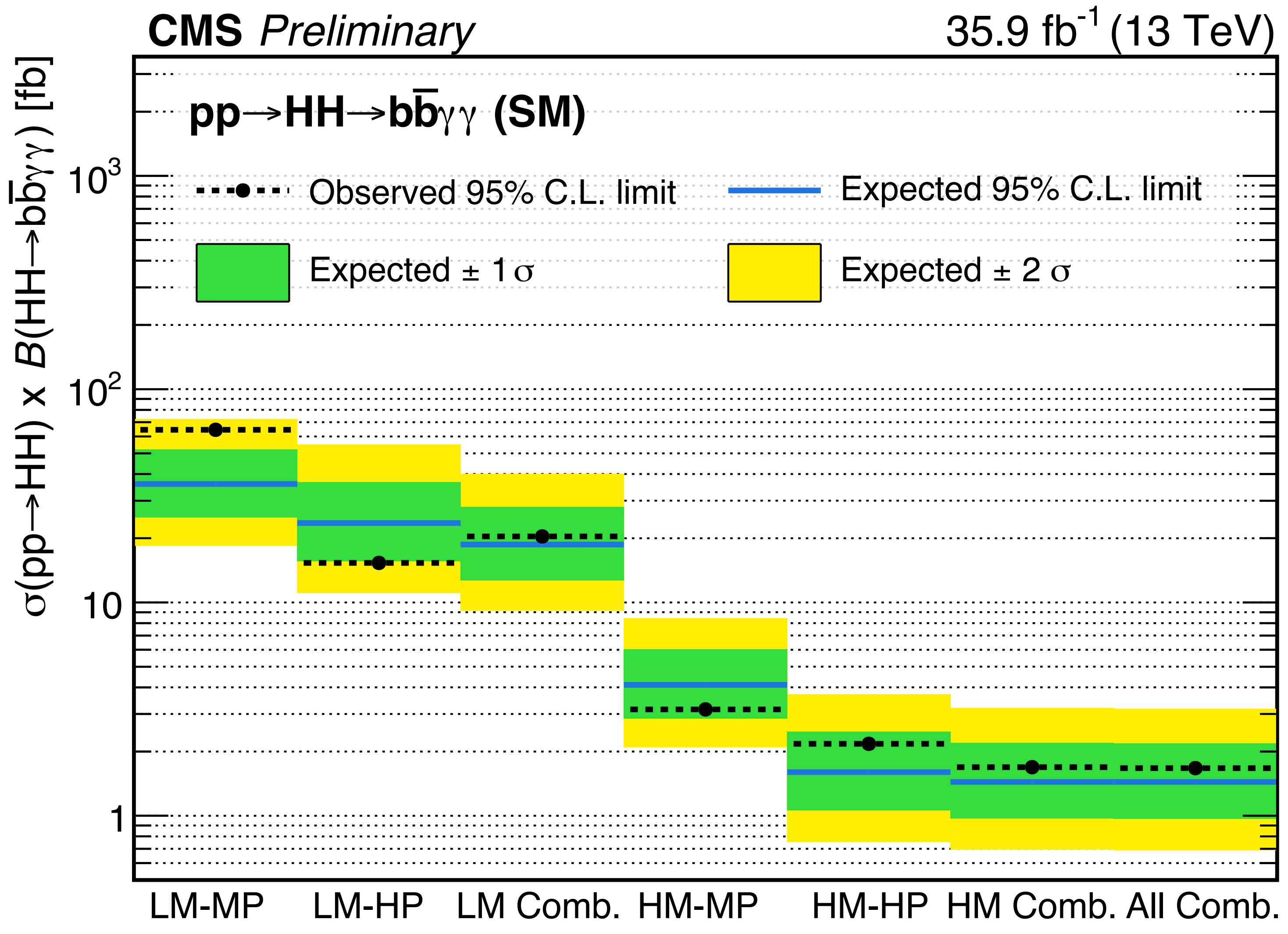


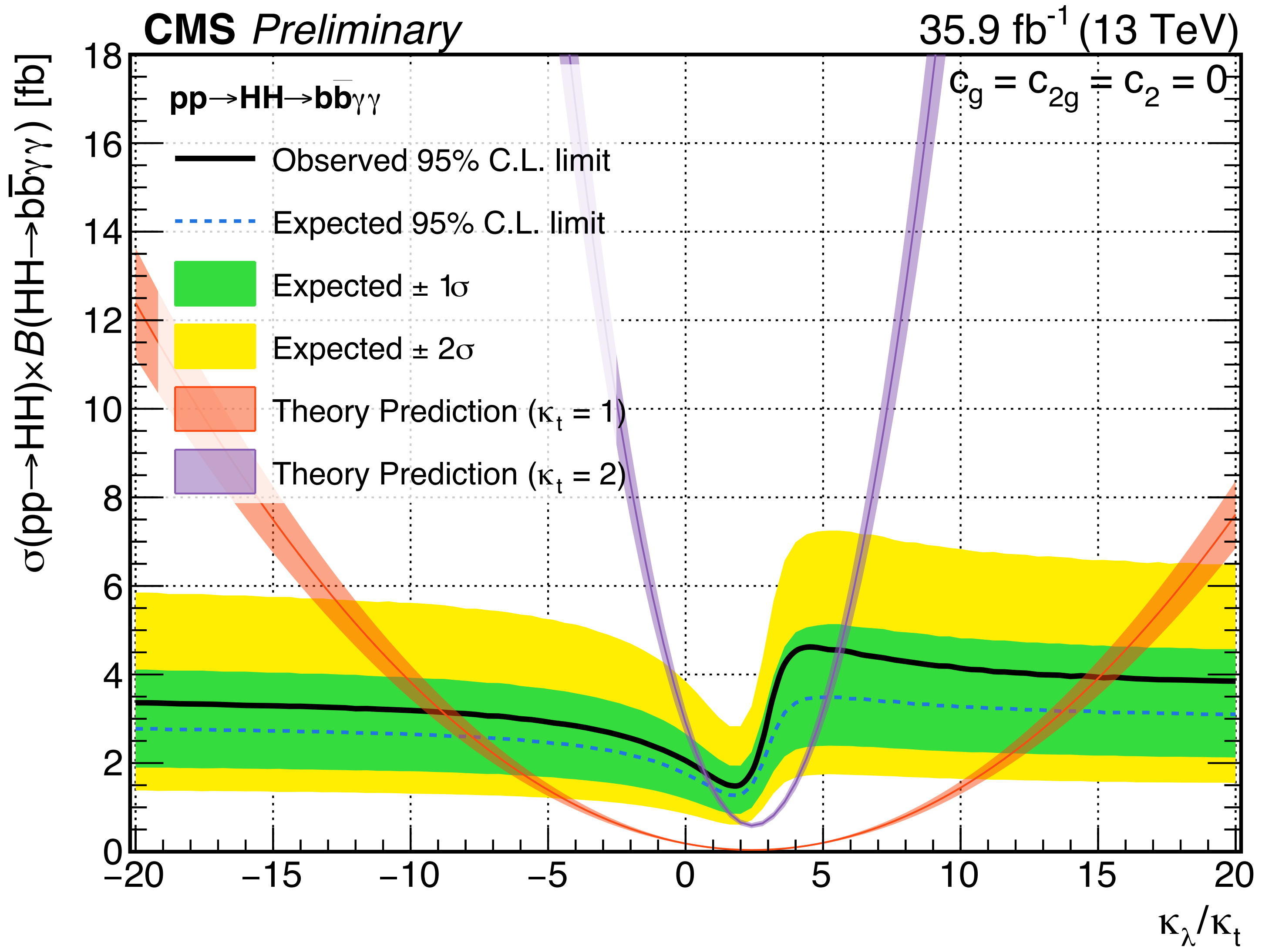
Sensitivity to non-resonant production dominated by the high mass/high purity category

Most performant CMS channel:

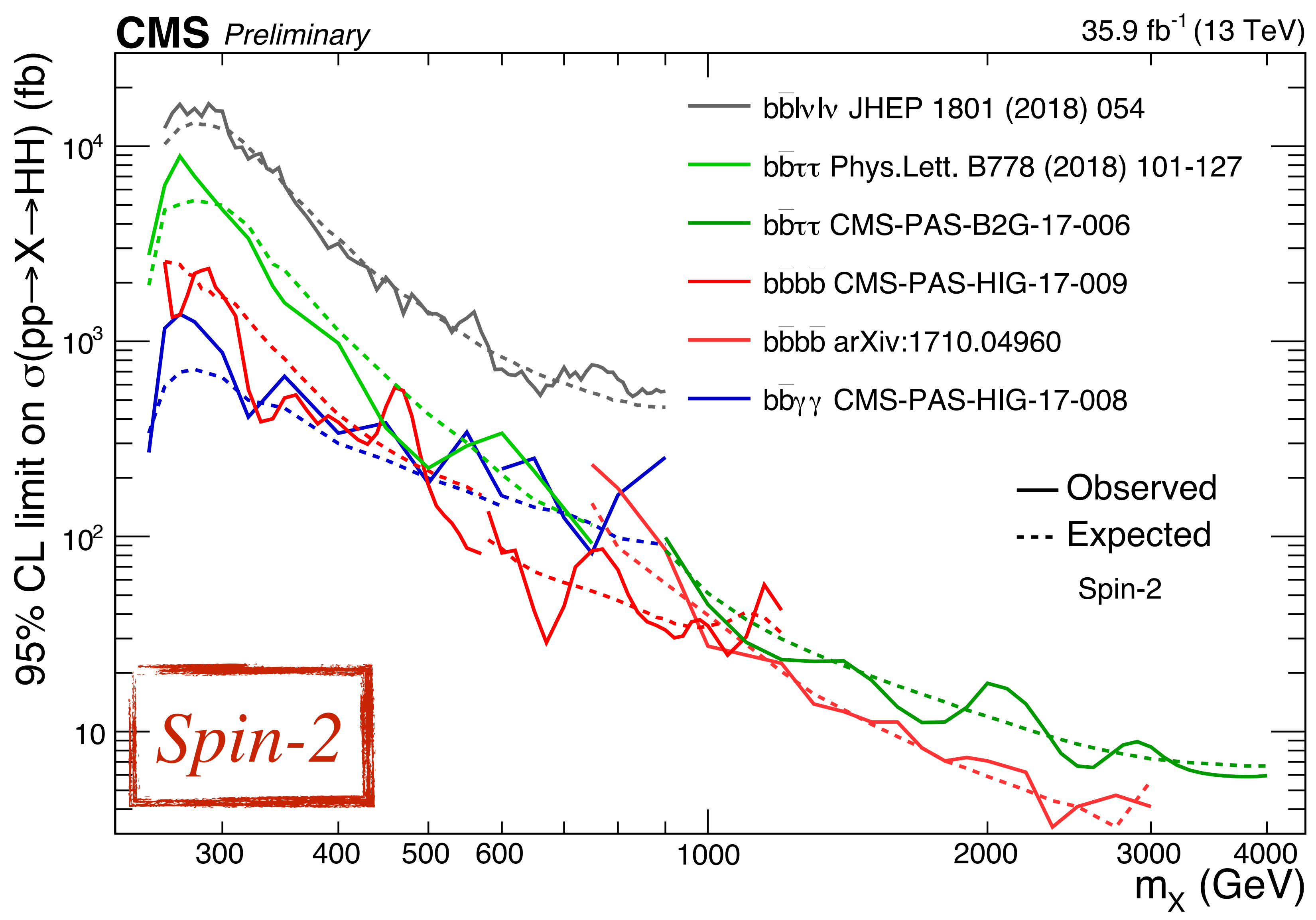
- SM σxBR<1.67 fb
- Obs.(exp.): σ/σ_{SM}< 19.2 (16.5)

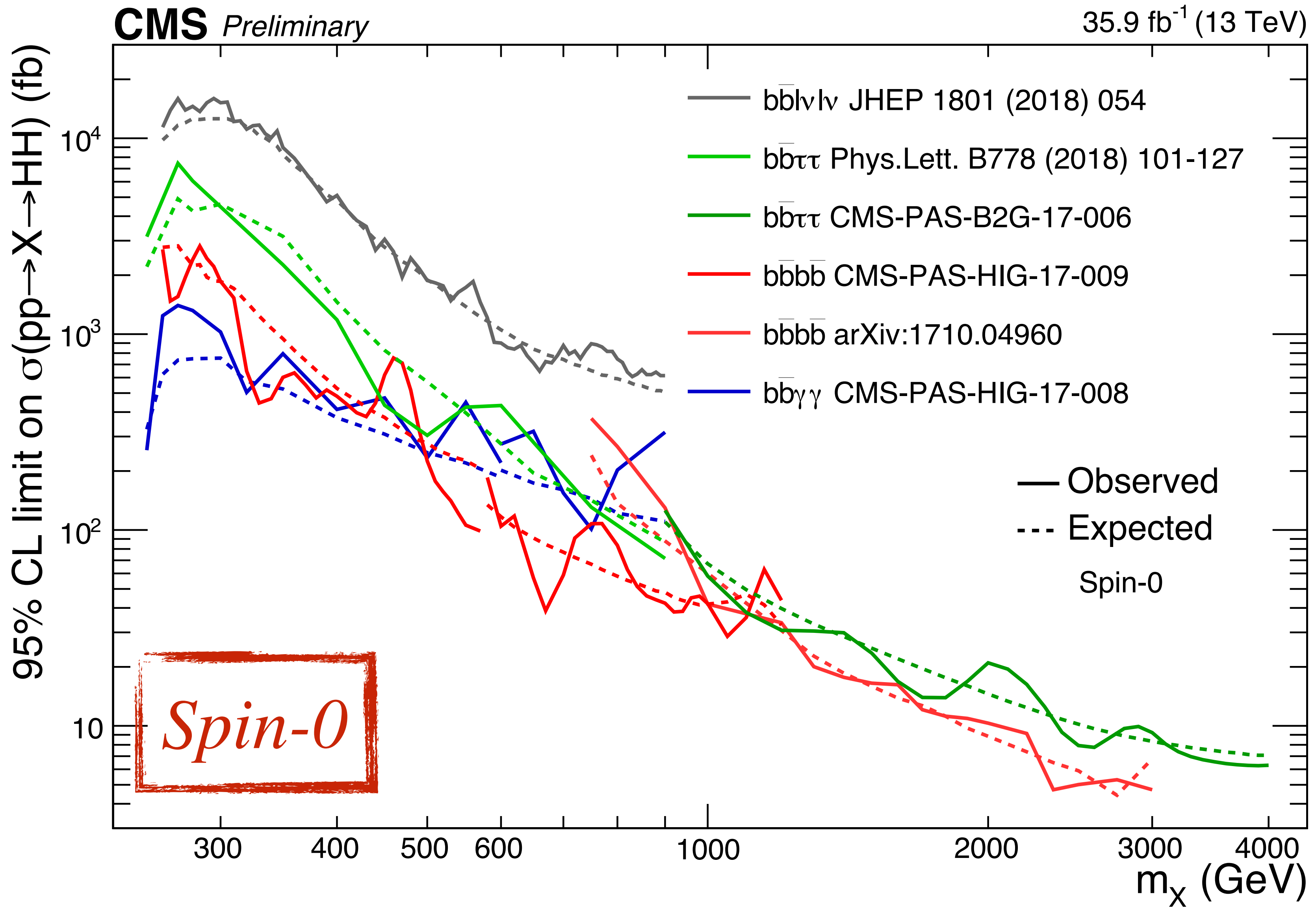






Summary





No evidence for either spin-0 or spin-2 resonance up to 4 TeV

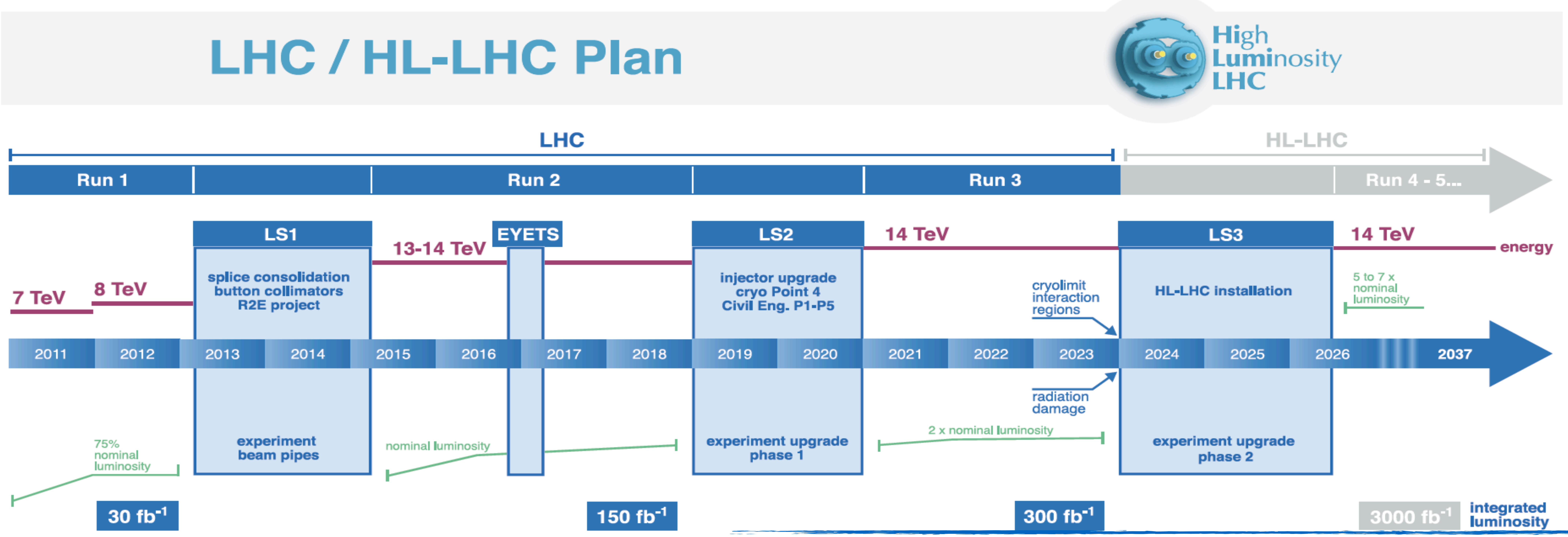
Excluded cross-section ranges from <1pb (300 GeV) to ~4 fb (3 TeV)

Sensitivity to non-resonant at ~20 times the SM expectation

Anomalous Higgs trilinear coupling constrained in the region $-8.8 < \lambda/\lambda_{SM} < 15$

Final state	Obs. (Exp.) limit on σ/σ_{SM}	
bbWW	79 (89)	35.9 fb^{-1}
bbbb	342 (308)	2.3 fb^{-1}
bbττ	30 (25)	35.9 fb^{-1}
bbγγ	19 (16)	35.9 fb^{-1}

Double Higgs at HL-LHC



Double Higgs searches are an important physics case for HL (and HE) LHC

CMS will undergo relevant upgrades for the HL-LHC phase.

New all-silicon tracker, $|\eta|<4$, track-trigger

Barrel calorimeters: new electronics

New endcap calorimeter (high granularity)

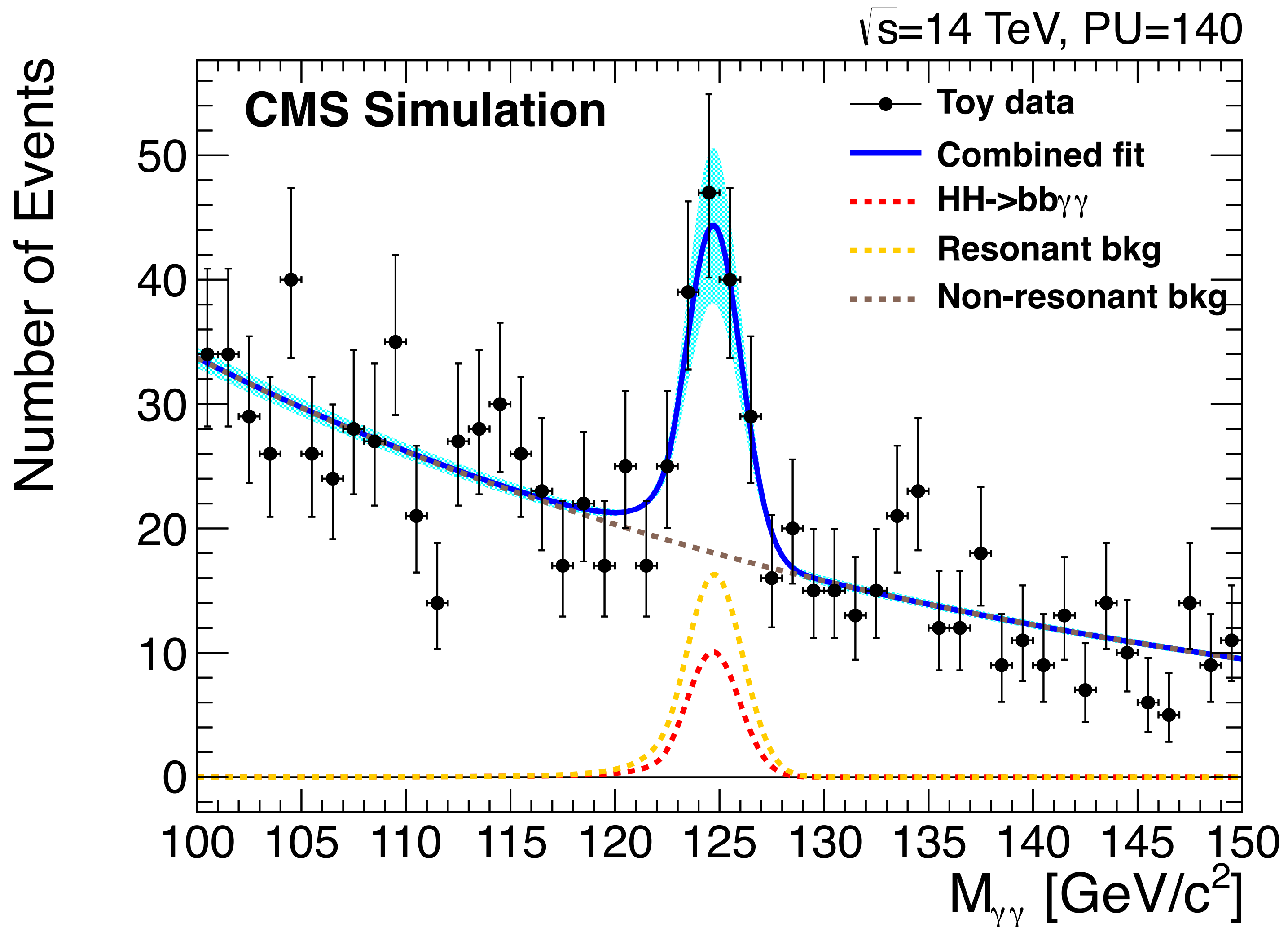
Muon detectors to $|\eta|<2.8$

Trigger: L1 @ 750 kHz, HLT @ 7.5 kHz

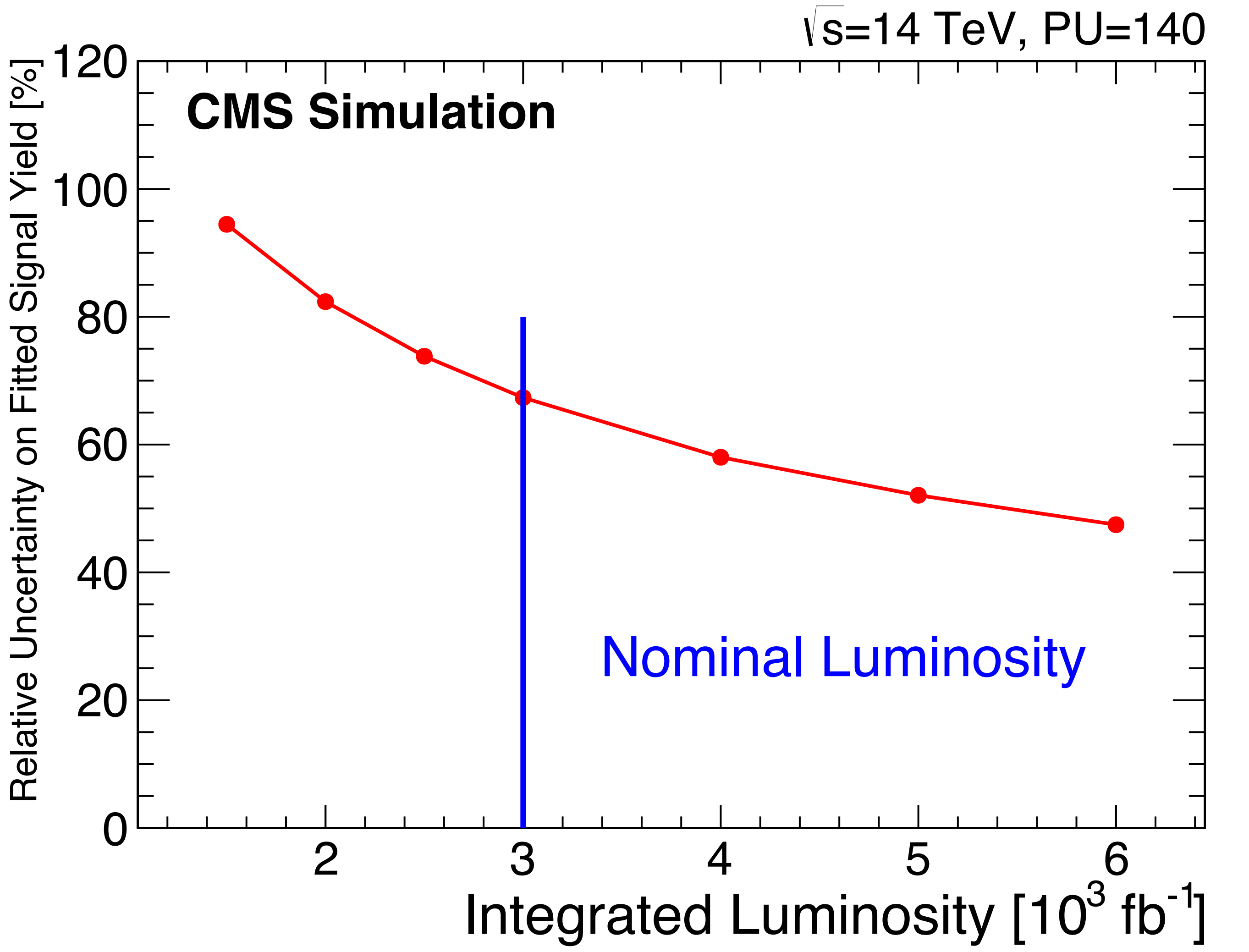
Double Higgs at HL-LHC, Projections

Dedicated studies: PAS-FTR-15-002

bbγγ, bbττ, bbVV(lνlν, lνjj) ~50% precision



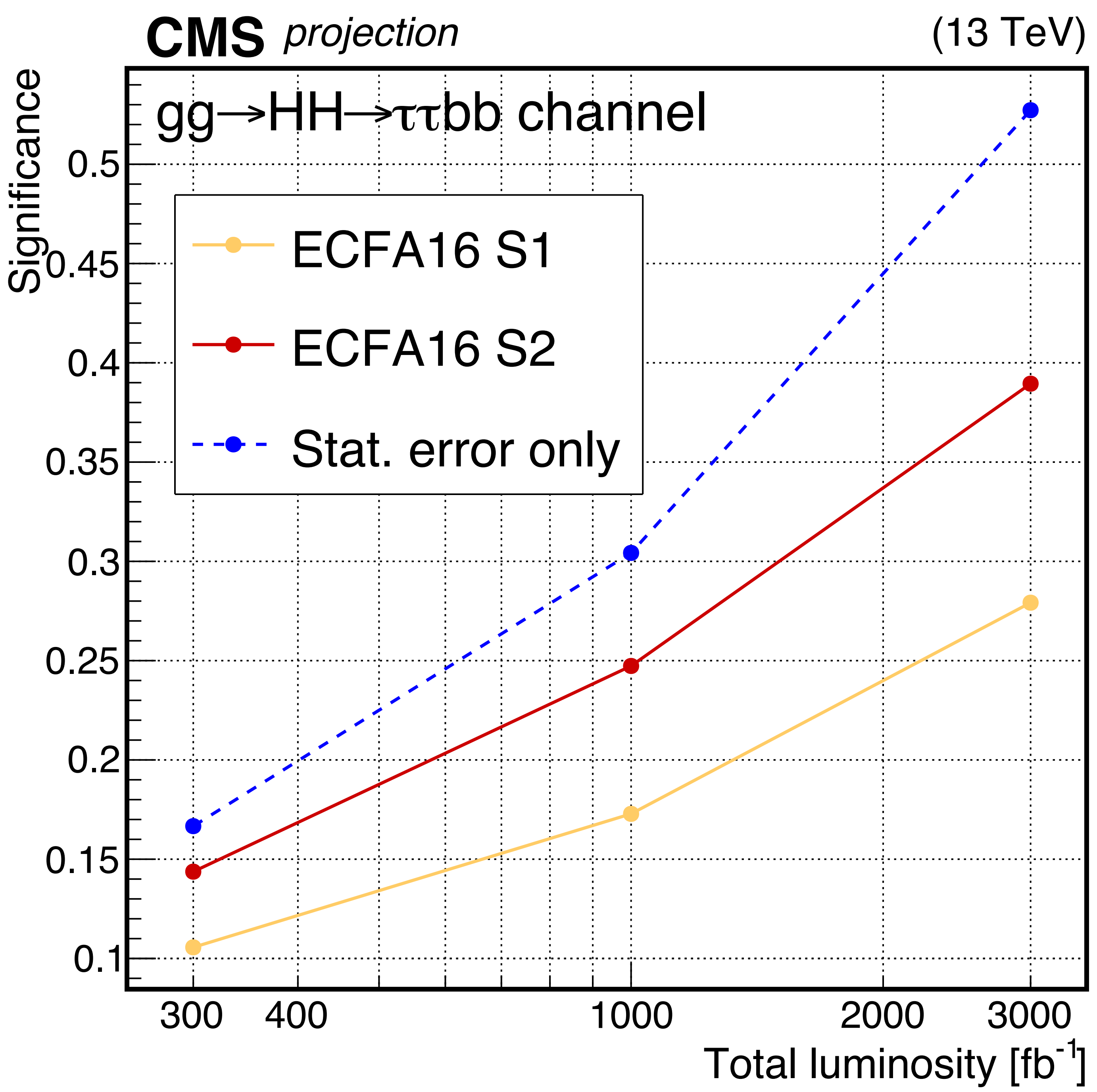
Significance: 1.9σ

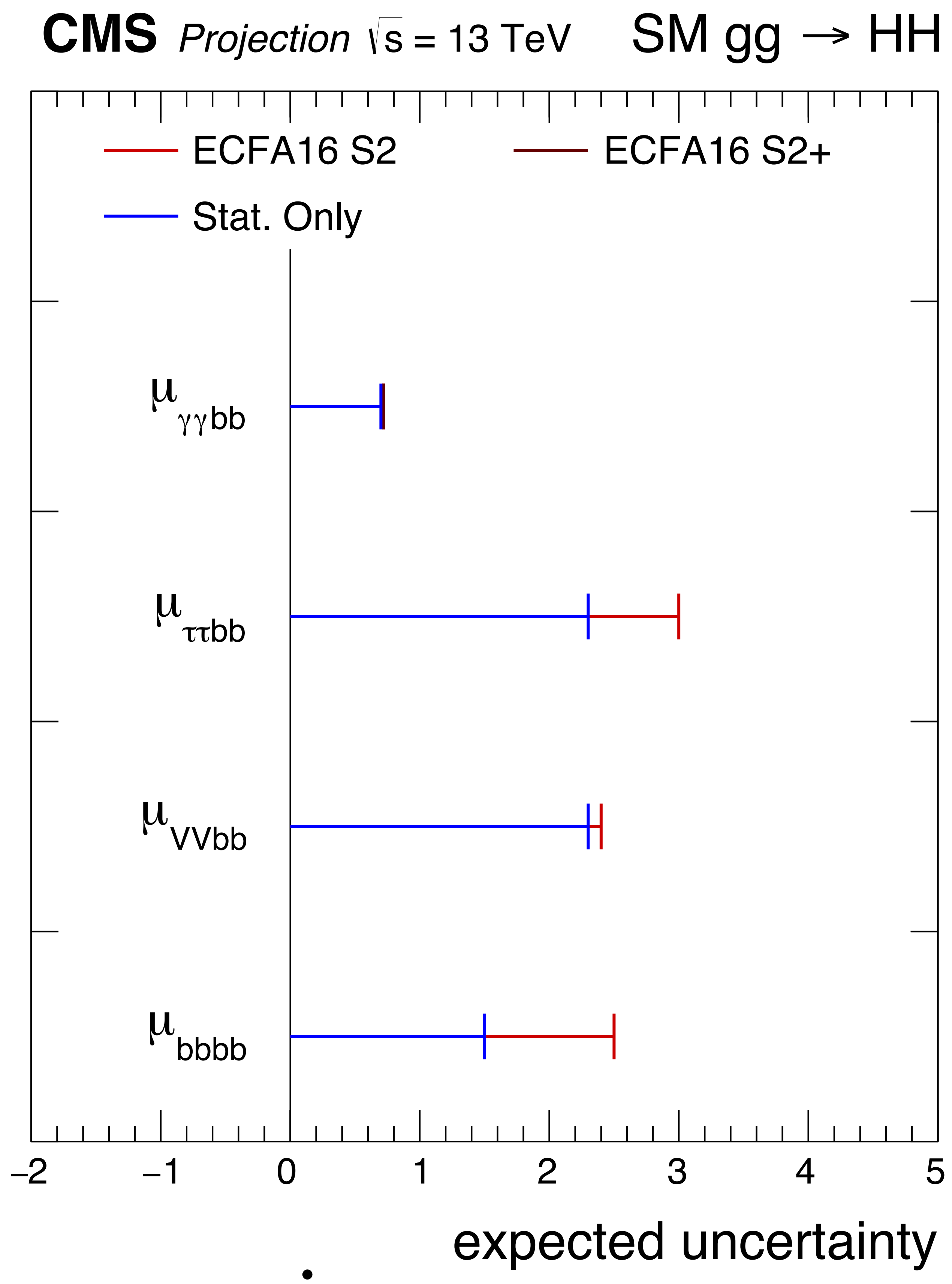


Extrapolations of 2015 analyses: PAS-FTR-16-002

bbγγ, bbττ, bbbb, bbVV(lνlν)

Poor stat. for projections





New studies with updated CMS simulations coming soon

Conclusions

Several competing analyses in different final states under study in CMS, providing excellent coverage in different decay modes.

Non resonant double Higgs production is the main way to measure Higgs self-coupling.

- At the moment, we can probe O(10-100xSM).
- More luminosity is needed to reach SM sensitivity, but we are starting to probe BSM and to constraint exotic BSM
- Outperforming Run1 (scaled) results and projections.

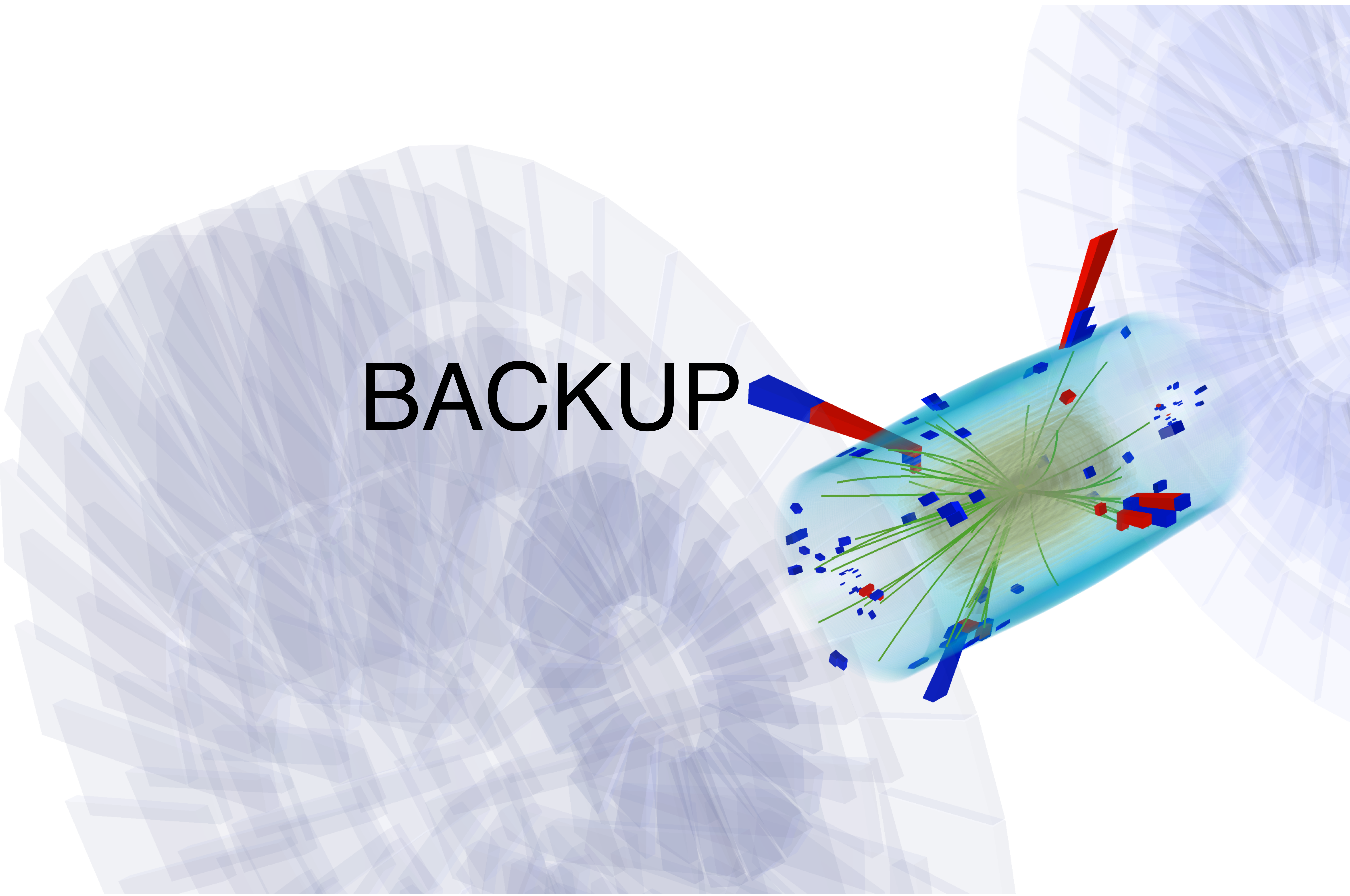
Resonant searches can already provide important constrain on BSM physics (MSSM, WED, heavy scalars).

- KK-graviton excluded below 800 GeV, Λ_R=1TeV Radion excluded below 2.5 TeV
- Boosted categories enhance sensitivity to high mass resonances

Further improvement awaited from the combination of the results among all channels

Exciting prospects for double Higgs searches

BACKUP

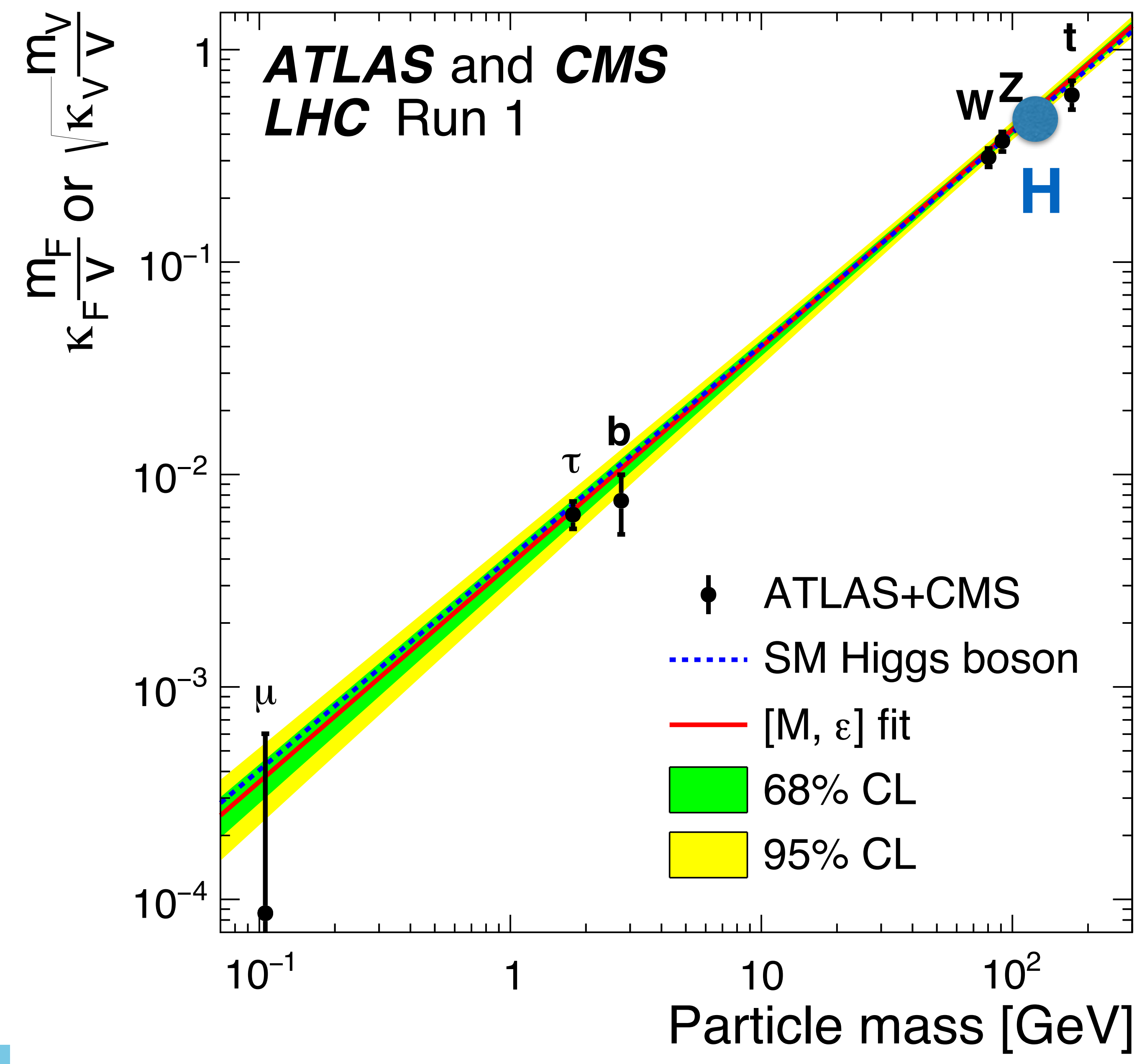


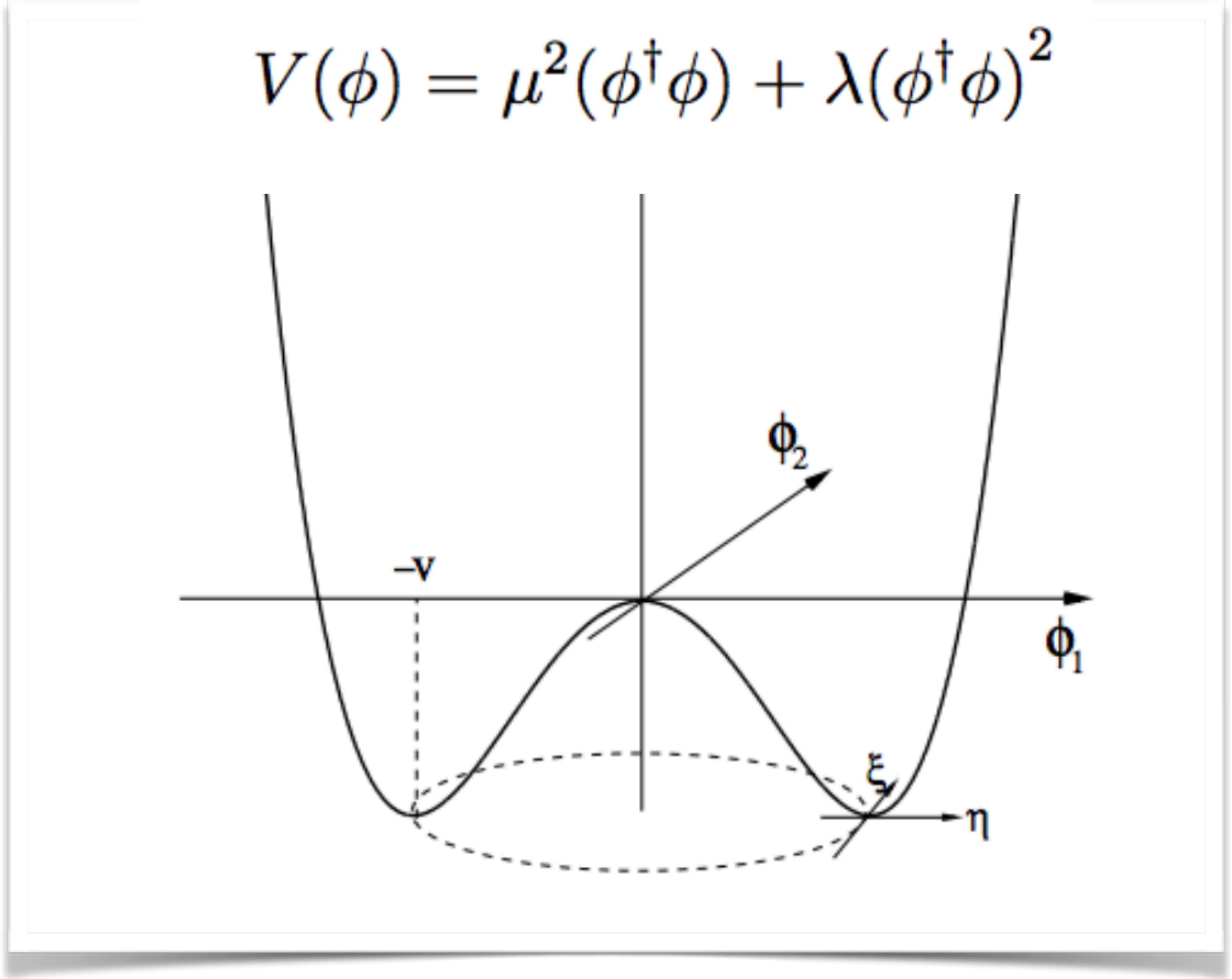
Why measure HH?

- Measurement of HH gives access to the magnitude of the **Higgs self-interaction**:

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

- Higgs trilinear coupling constant **λ** only depends on the Higgs field VEV and Higgs mass. Purely determined by EWSB (in the SM).
- Shape of the **Higgs potential** is determined by the self coupling value (EWPT)



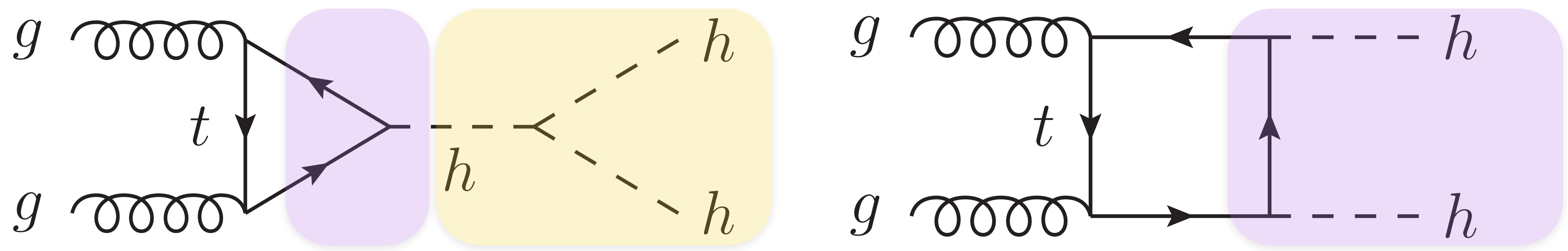


gg→hh parametrization

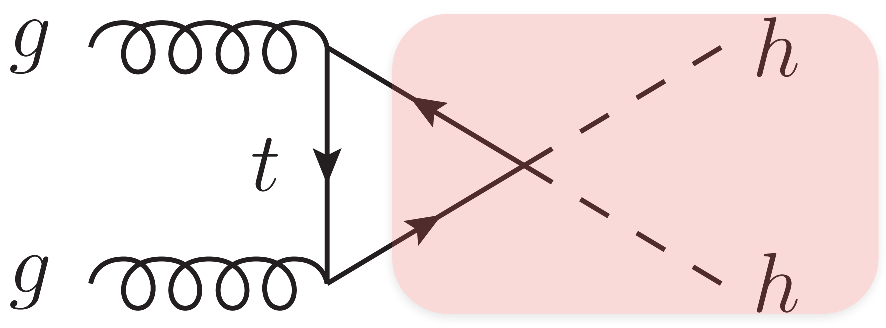
The relevant lagrangian terms of gg→HH production in D=6 EFT

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

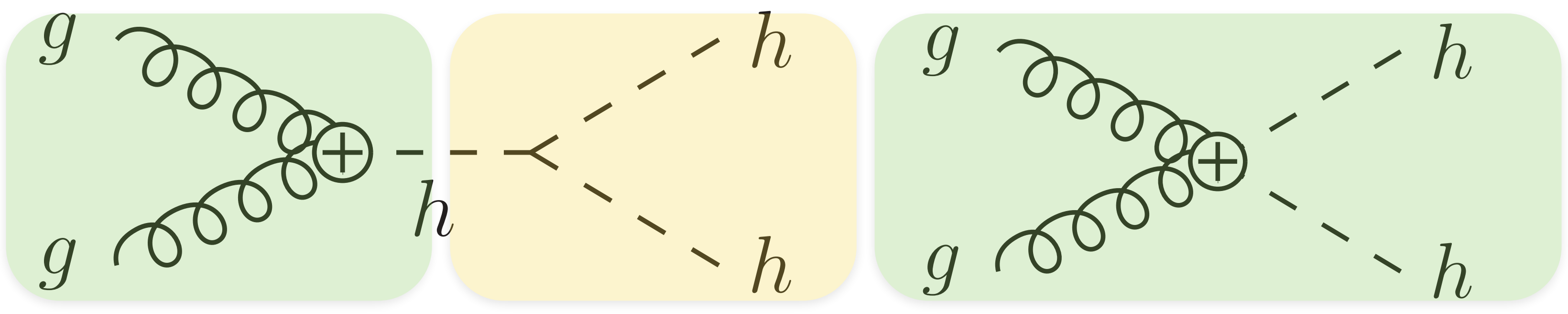
arXiv:1410.3471



SM diagrams



ttHH non-linear interaction



Higgs-gluon contact interactions

An EFT implementation for hh

The double Higgs production cross section can be written as a function of the 5 EFT parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

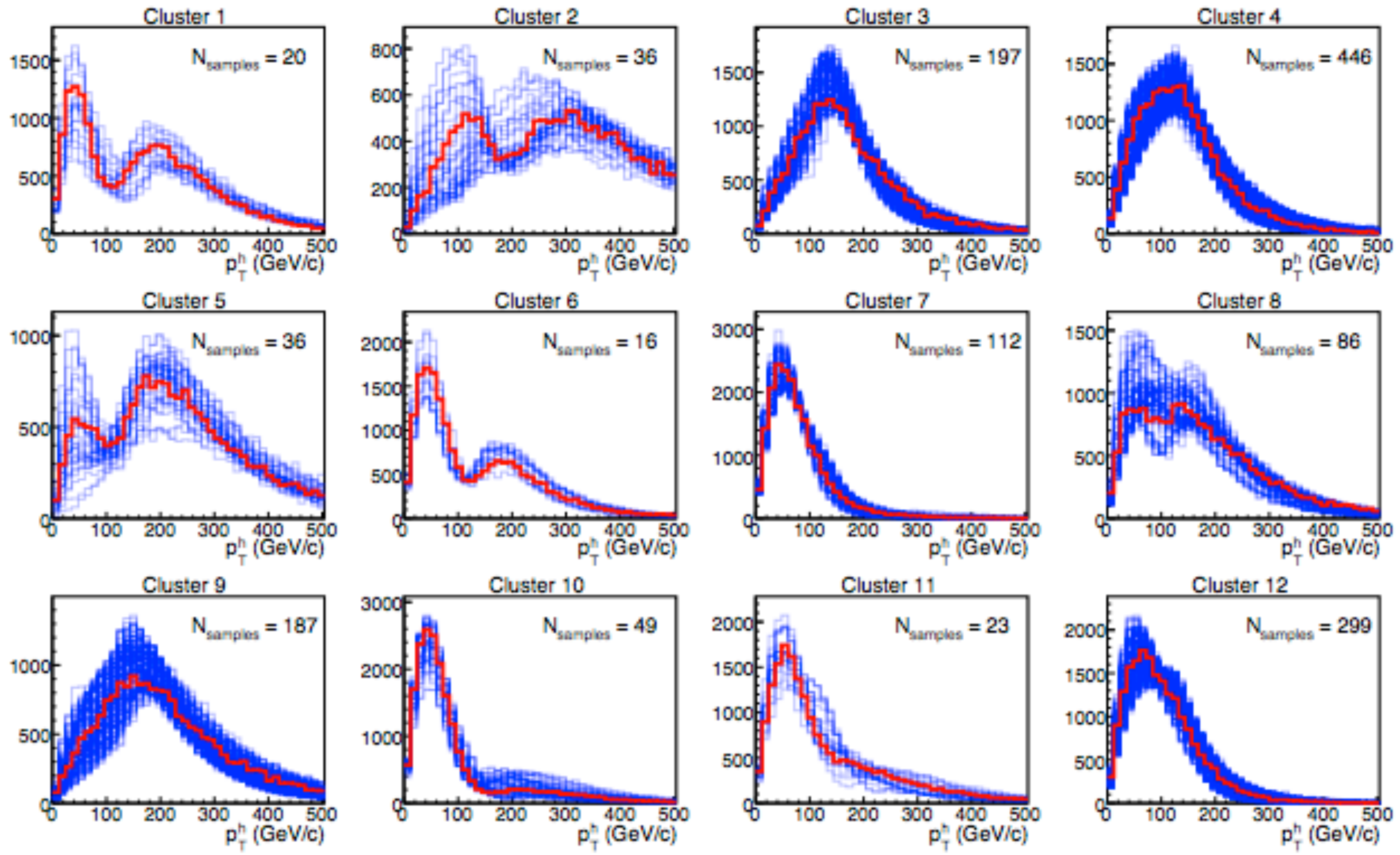
$$R_{hh} \equiv \frac{\sigma_{hh}}{\sigma_{hh}^{SM}} \stackrel{LO}{=} A_1\kappa_t^4 + A_2 c_2^2 + (A_3\kappa_t^2 + A_4 c_g^2)\kappa_\lambda^2 + A_5 c_{2g}^2 + (A_6 c_2 + A_7\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+(A_8\kappa_t\kappa_\lambda + A_9 c_g\kappa_\lambda)c_2 + A_{10}c_2 c_{2g} + (A_{11}c_g\kappa_\lambda + A_{12}c_{2g})\kappa_t^2$$
$$+(A_{13}\kappa_\lambda c_g + A_{14}c_{2g})\kappa_t\kappa_\lambda + A_{15}c_g c_{2g}\kappa_\lambda \, .$$

JHEP **04** (2016) 126

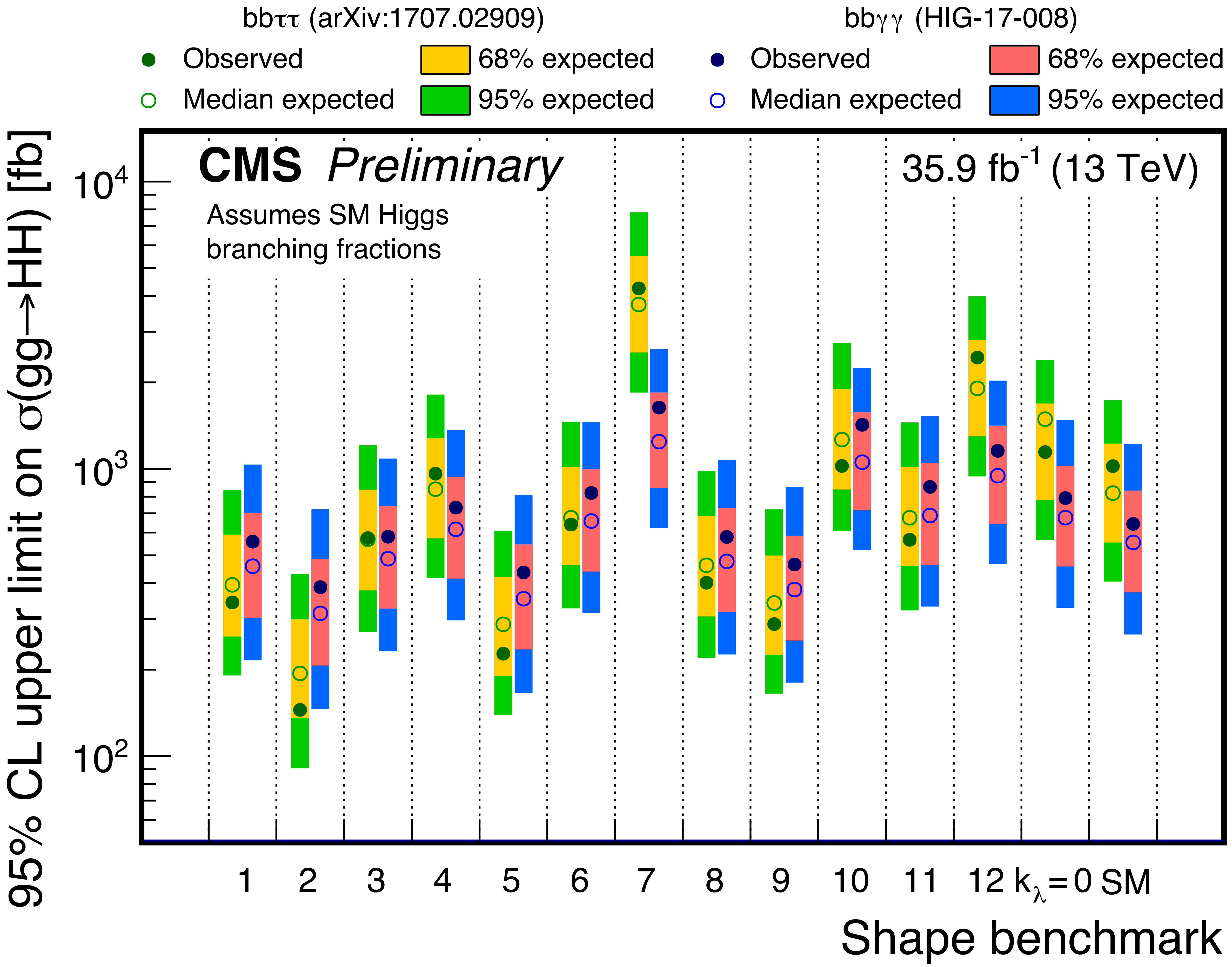
2D (M_{HH}, $\cos\vartheta^*$) signal shapes from different points in the 5D EFT phase space are clustered together.

12 clusters are identified according to there kinematical properties

Inside each cluster, a representative shape is identified, as the one with the minimum distance (in the test statistics) from all other shapes in the cluster

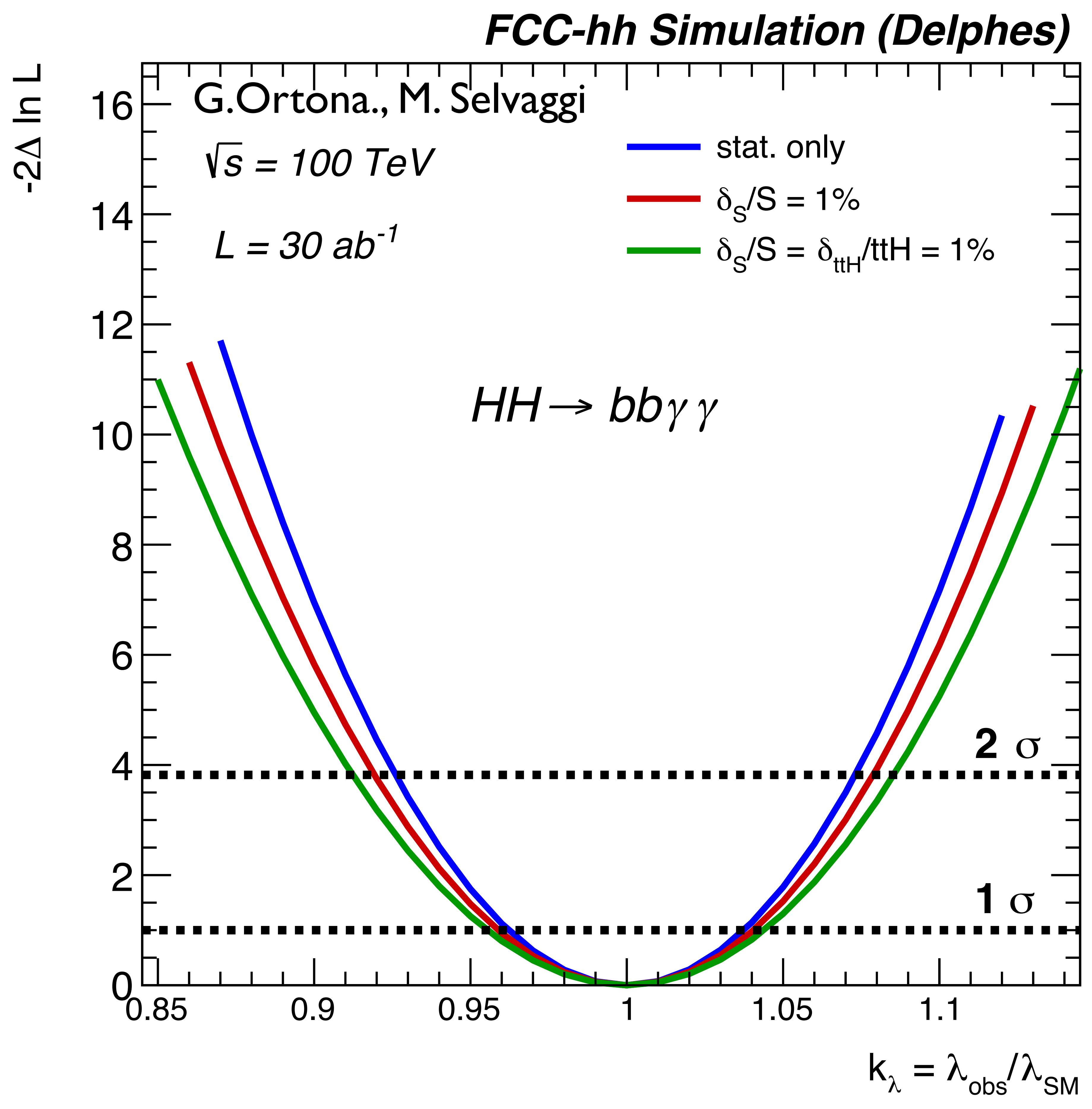


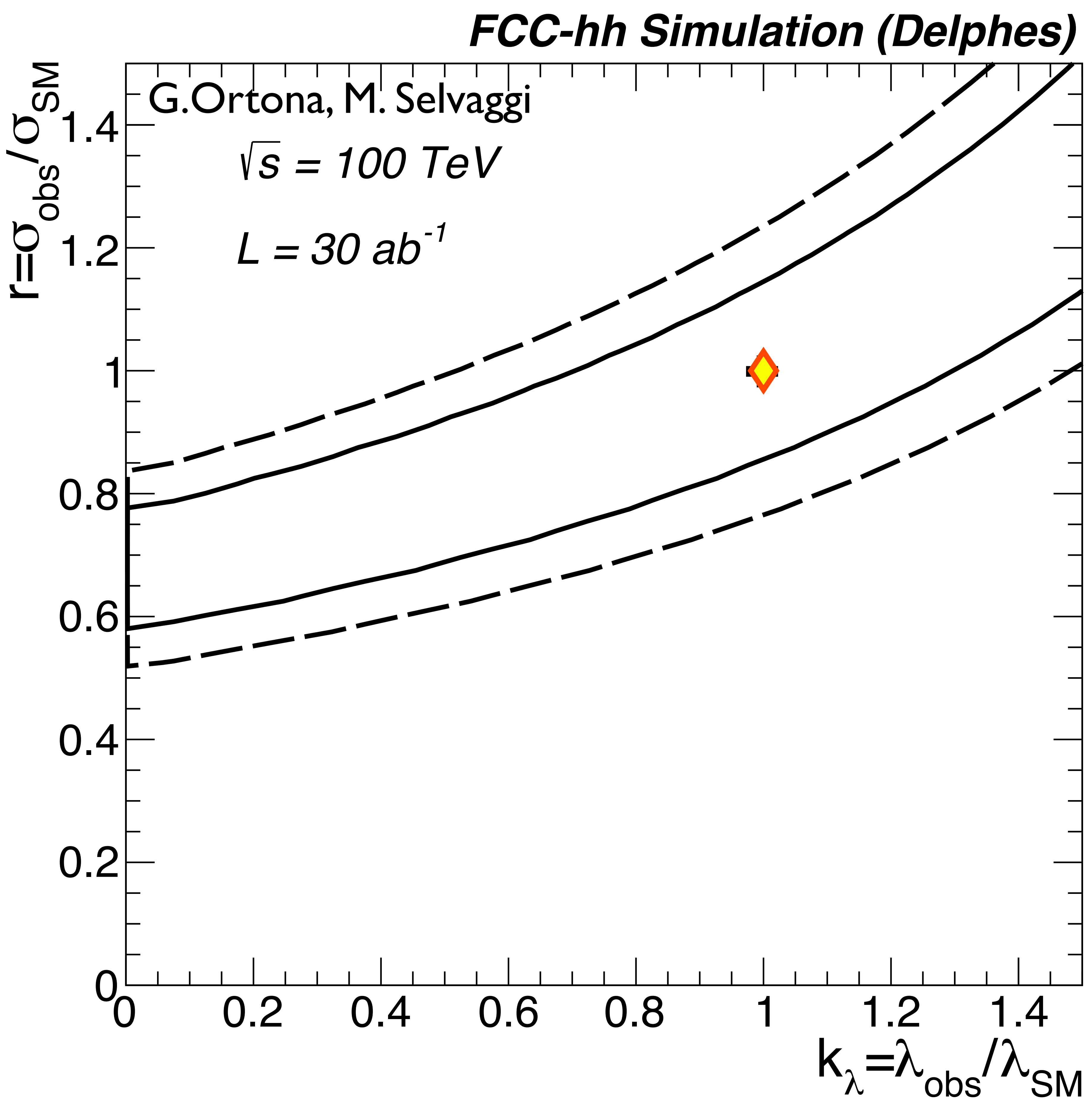
Each point of the phase space can be mapped by means of its cross-section and representative shape



bbττ (arXiv:1707.02909)
bbγγ (HIG-17-008)
Observed
Median expected
68% expected
95% expected
Observed
Median expected
68% expected
95% expected
CMS Preliminary
35.9 fb-1 (13 TeV)
Assumes SM Higgs
branching fractions
95% CL upper limit on σ(gg→HH) [fb]
10^4
10^3
10^2
1
2
3
4
5
6
7
8
9
10
11
12
kλ=0
SM
Shape benchmark

Beyond HL-LHC: HH@FCC-hh





Delphes based study for hypothetical FCC-hh detector. Not a CMS projection