HH Production in the bbγγ Final State with 13 TeV data @ CMS

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HIGGS 2016 COUPLINGS

UNDERSTANDING THE STANDARD MODEL

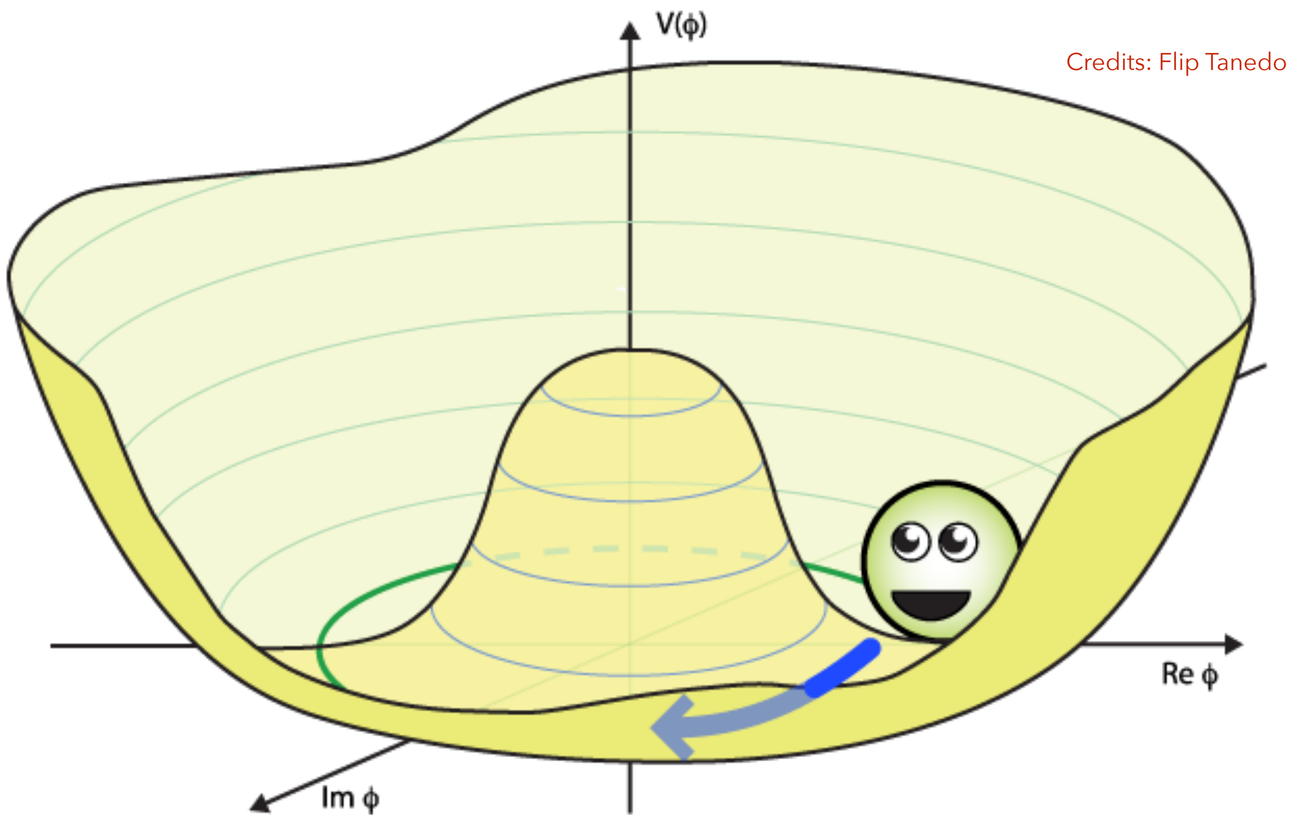
Probing the nature of the Electroweak Symmetry Breaking mechanism

What we know today:

- μ measured directly: $M_H = \sqrt{2}|\mu| = 125$ GeV
- λ measured indirectly: $\lambda = (\mu/v)^2 \sim 0.13$
  - v: electroweak vacuum expectation value = 246 GeV

What we want to know:

- Is the Higgs vacuum stable?
- Is the Higgs potential the one predicted by the SM?
- Are there more fields involved in the EWSB mechanism?



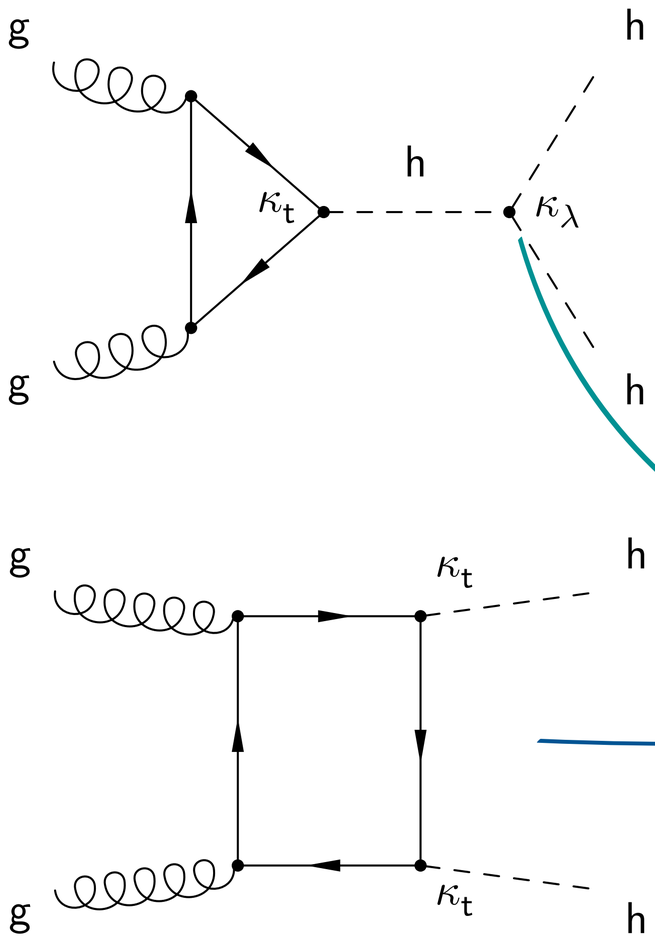
Credits: Flip Tanedo

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

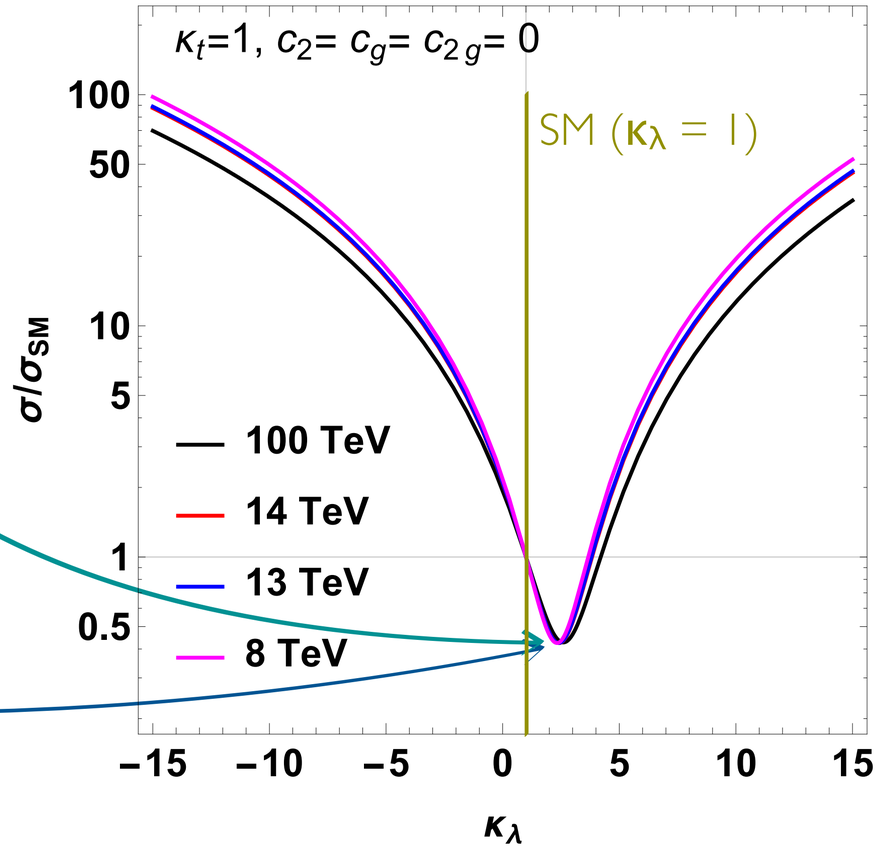
Higgs Mass

Higgs Self-Coupling

NONRESONANT HH



Carvalho et al, LHCHXSWG-2016-001



Destructive interference between diagrams almost maximal for SM

NNLL+NNLO (M_h = 125 GeV)	8 TeV	13 TeV	14 TeV
SM HH Cross Section	10.16 fb	33.45 fb	39.56 fb

LHCHXSWG Yellow Report 4

Not expected to be sensitive to SM HH @ LHC

But:

(1) BSM can increase σ(HH)

[κ_λ = 10 → σ_{BSM} = 10xσ_{SM}]

(2) Important to test the reach of current analysis for projecting HL-LHC sensitivity

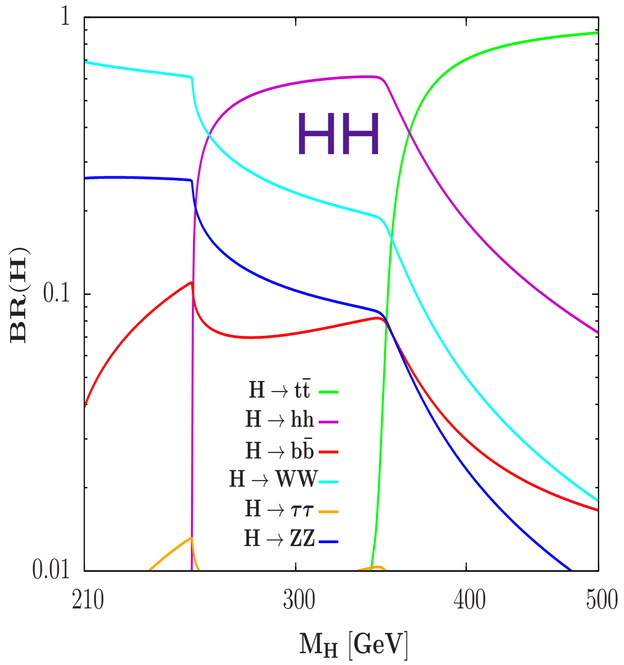
RESONANT HH

Many different BSM models predict HH resonances

Experimental solution: model independent results on narrow width resonances

Low tanβ MSSM

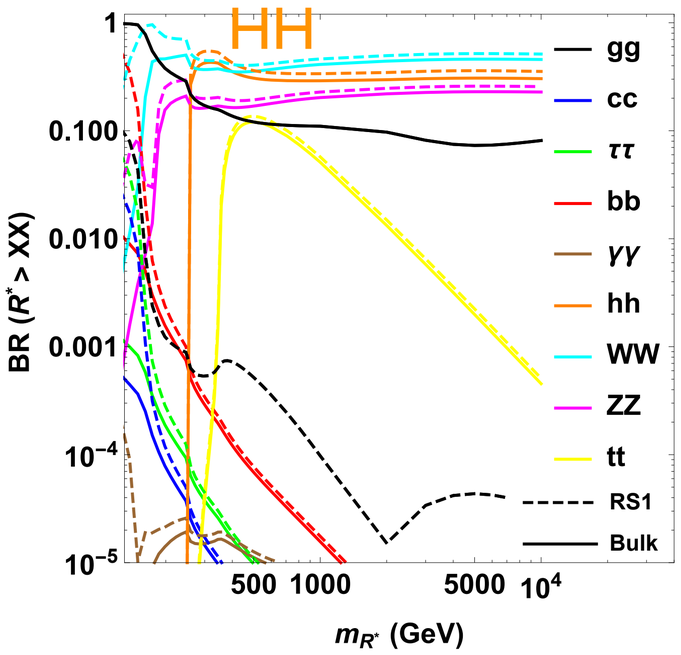
Djouadi & Quevillon, arXiv:1304.1787



Branching ratio of MSSM heavy H with tanβ = 2.5 and M_h = 126 GeV

Warped Extra Dimensions

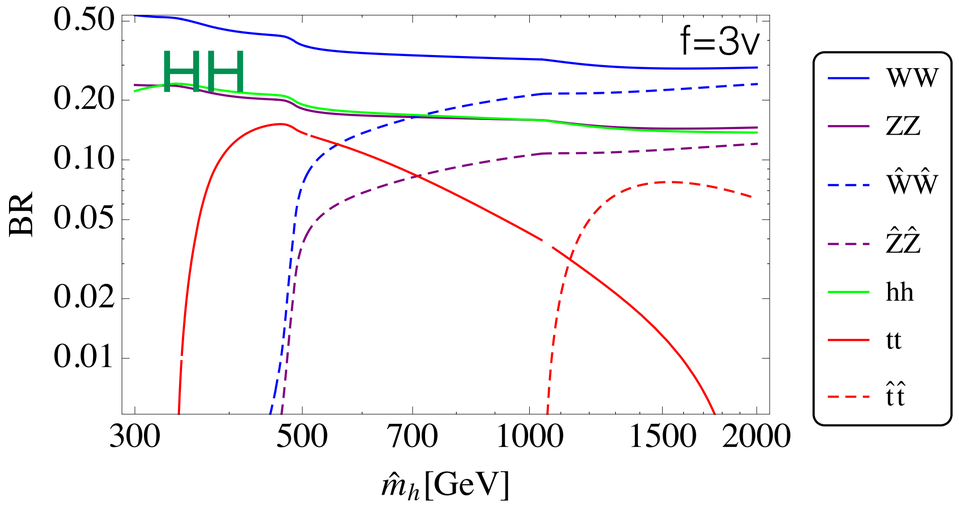
Carvalho, arXiv:1404.0102



Radion (spin-0) branching ratios on RS1 and Bulk scenarios

Neutral Naturalness

See N. Craig's talk on Wednesday



Heavy Twin Higgs decays to SM particles unconstrained

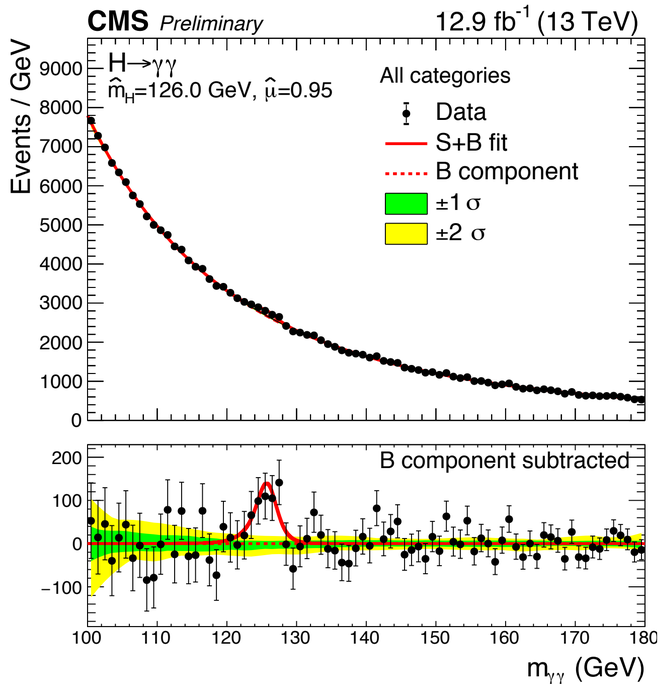
bbγγ FINAL STATE

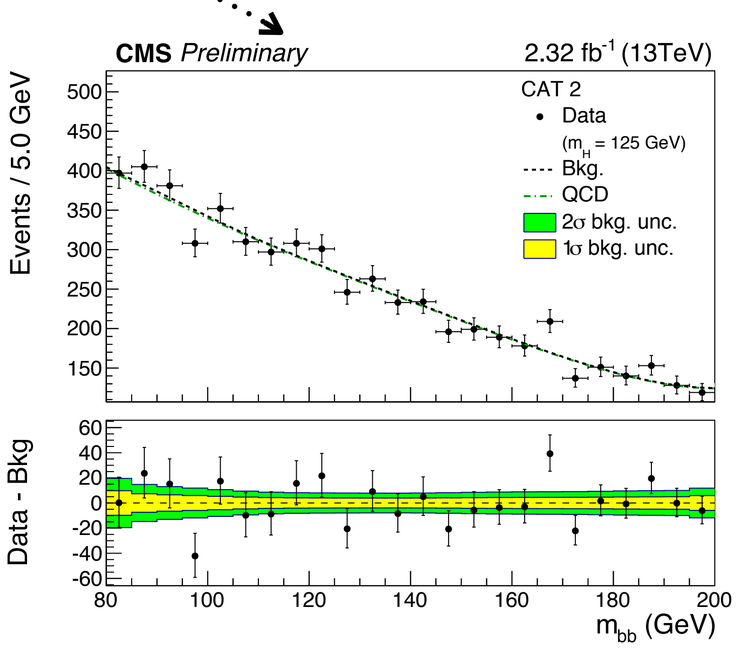
Br(HH→XXYY)

	$b\bar{b}$	WW	gg	ττ	$c\bar{c}$	ZZ	γγ	Zγ	$s\bar{s}$	μμ
μμ	2.5e-04	9.4e-05	3.8e-05	2.8e-05	1.3e-05	1.2e-05	1.0e-06	6.7e-07	1.1e-07	4.8e-08
$s\bar{s}$	2.8e-04	1.1e-04	4.2e-05	3.1e-05	1.4e-05	1.3e-05	1.1e-06	7.6e-07	6.1e-08	
Zγ	1.8e-03	6.6e-04	2.6e-04	1.9e-04	9.0e-05	8.1e-05	7.0e-06	2.4e-06		
γγ	2.6e-03	9.8e-04	3.9e-04	2.9e-04	1.3e-04	1.2e-04	5.2e-06			
ZZ	3.0e-02	1.1e-02	4.5e-03	3.3e-03	1.5e-03	7.0e-04				
$c\bar{c}$	3.4e-02	1.3e-02	5.0e-03	3.7e-03	8.5e-04					
ττ	7.3e-02	2.7e-02	1.1e-02	4.0e-03						
gg	9.9e-02	3.7e-02	7.3e-03							
WW	2.5e-01	4.6e-02								
$b\bar{b}$	3.3e-01									

Good mass resolution

High branching ratio





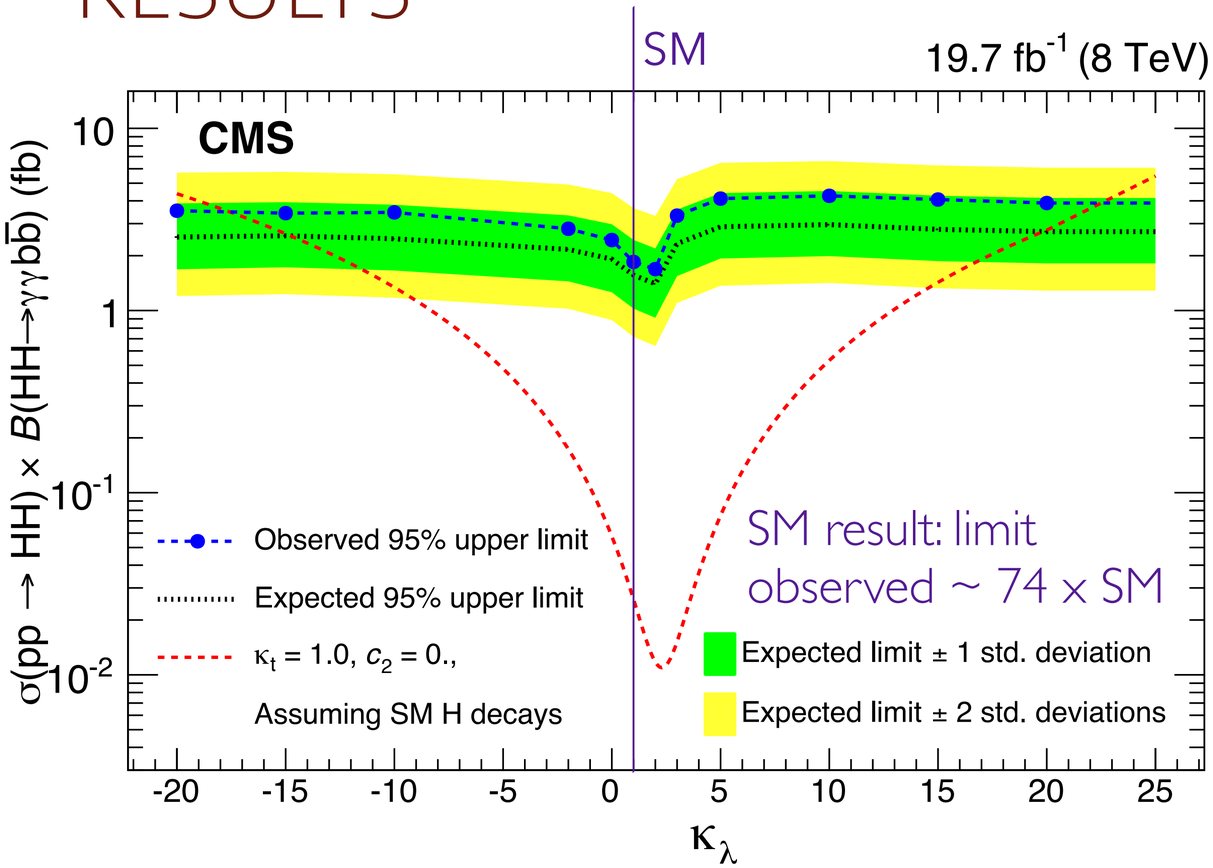
HH→bbγγ: Low background + All objects are reconstructed - Br(HH→bbγγ) = 0.26%

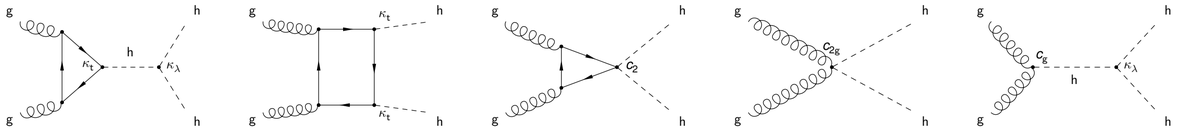
Expected to be the most sensitive channel to non-resonant SM HH production

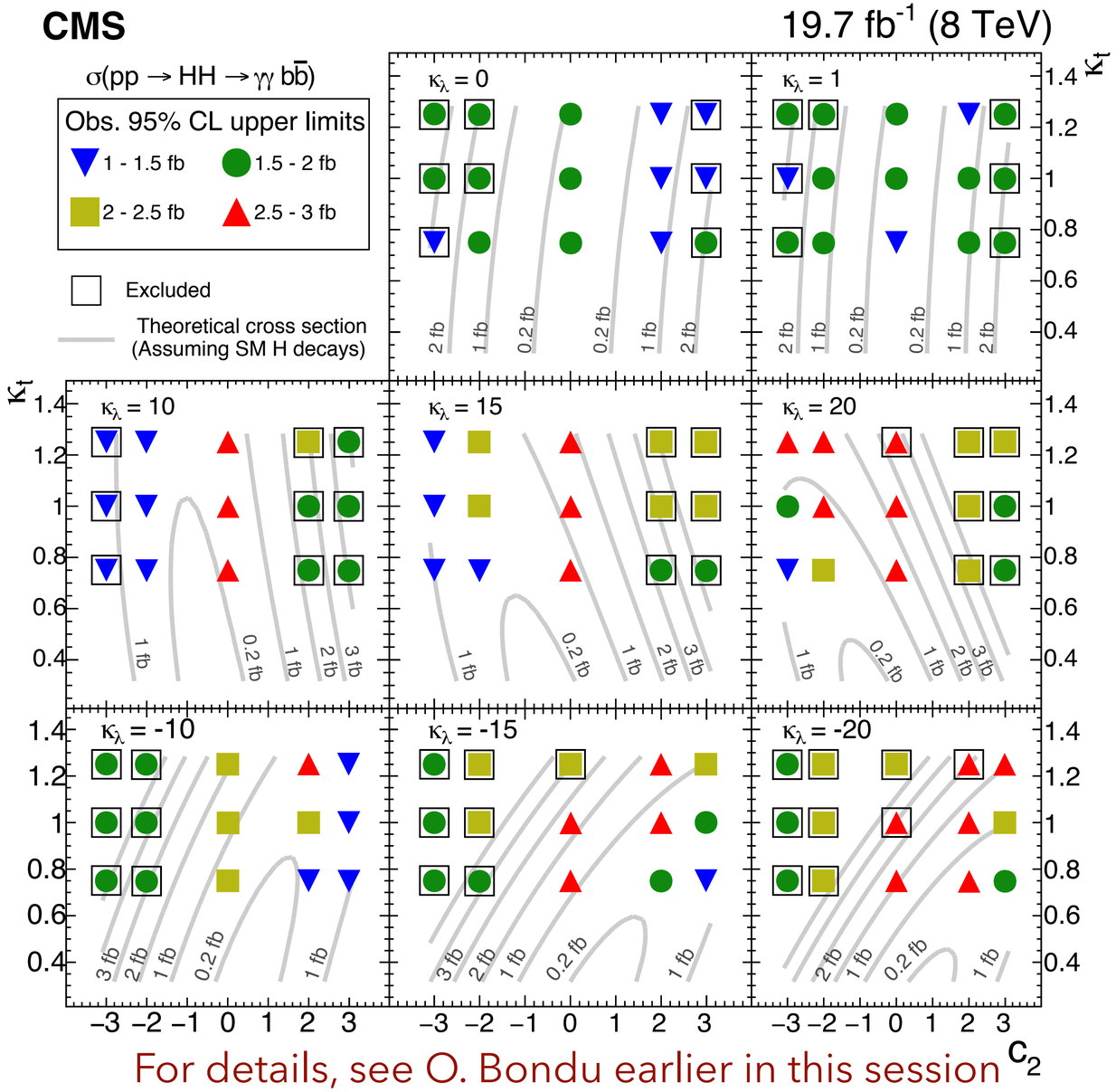
$\sigma(pp \to HH \to bb\gamma\gamma)_{NNLO+NNLL}$ = 0.087 fb @ 13 TeV

RUN I NONRESONANT RESULTS

Phys. Rev. D 94 (2016) 052012



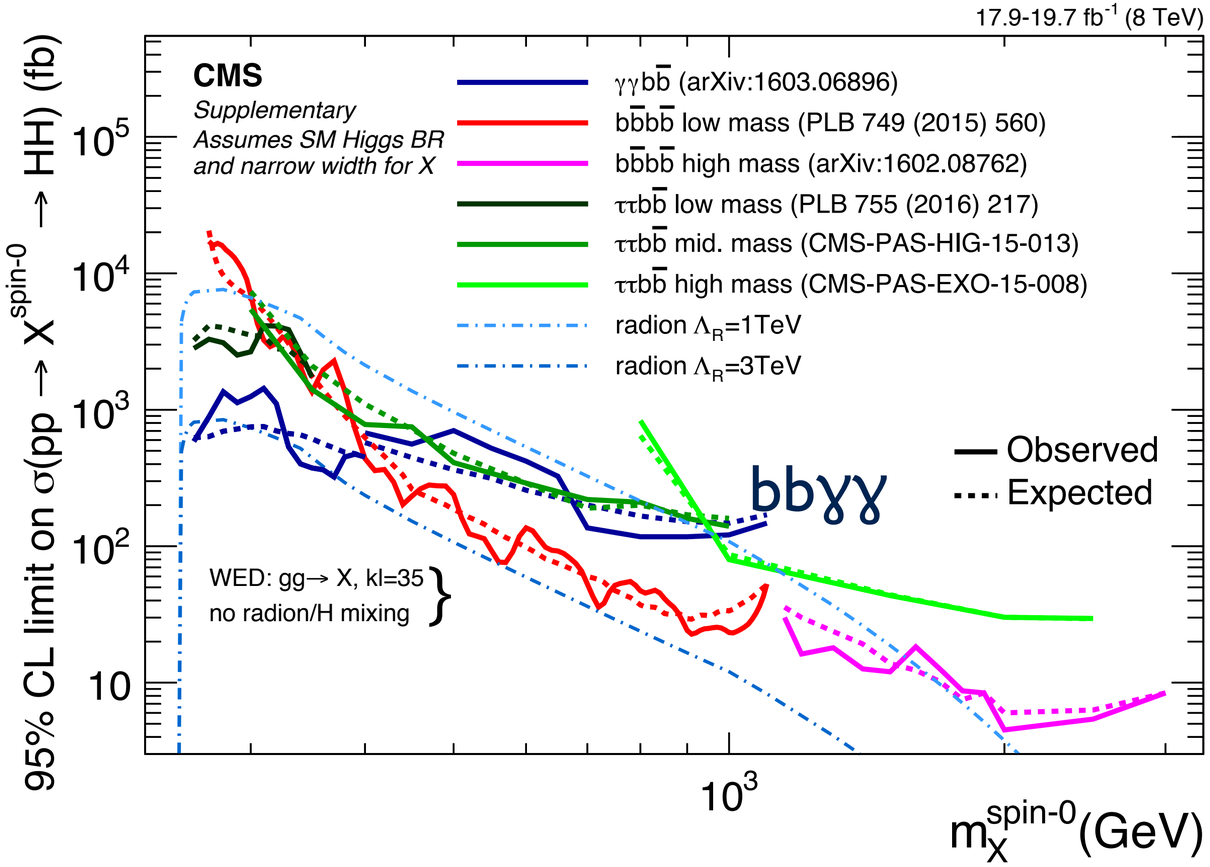


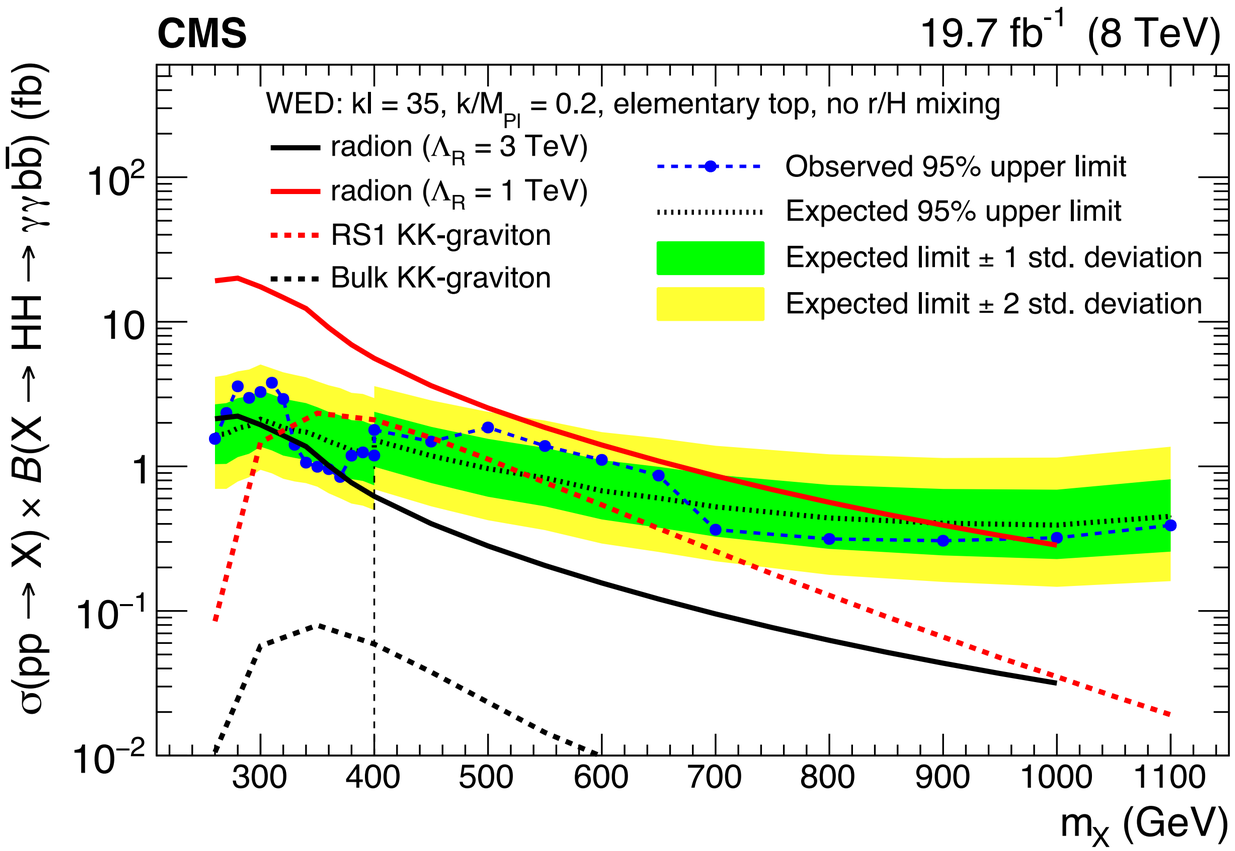


For details, see O. Bondu earlier in this session

RUN I RESONANT RESULTS

Phys. Rev. D 94 (2016) 052012





Most sensitive analysis in low mass region

RUN II ANALYSIS STRATEGIES

Resonant Low Mass Strategy [M_X < 500 GeV]

- According to signal hypothesis, select mass window in M(jjγγ) around resonance mass
- Two categories based on b-tagging

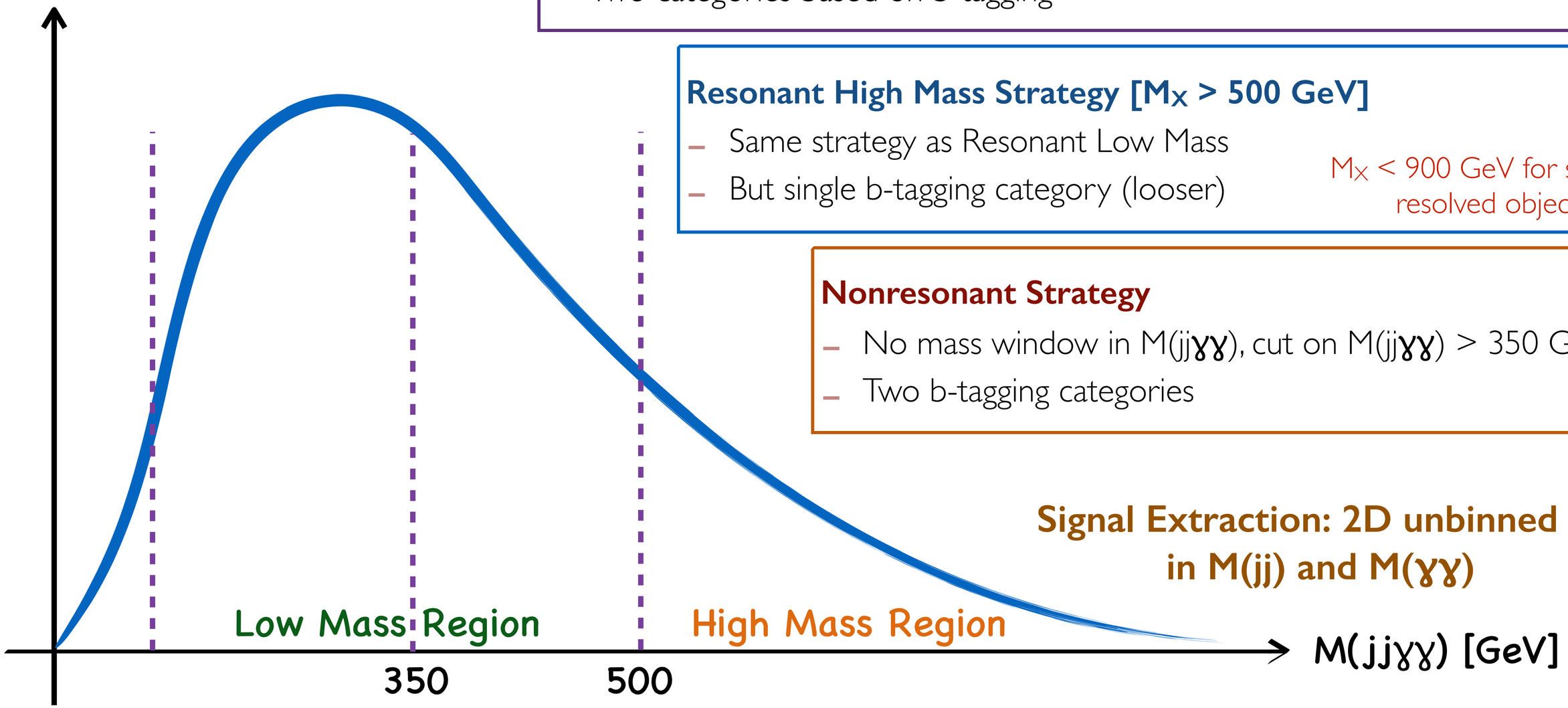
Resonant High Mass Strategy [M_X > 500 GeV]

- Same strategy as Resonant Low Mass
- But single b-tagging category (looser)

M_X < 900 GeV for spatially resolved objects

Nonresonant Strategy

- No mass window in M(jjγγ), cut on M(jjγγ) > 350 GeV
- Two b-tagging categories



Signal Extraction: 2D unbinned fit in M(jj) and M(γγ)

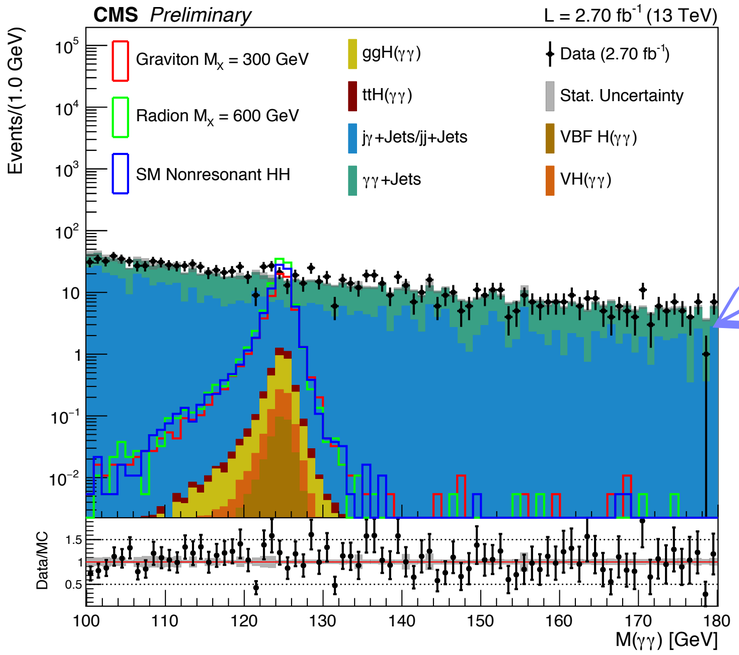
PHOTONS & JETS

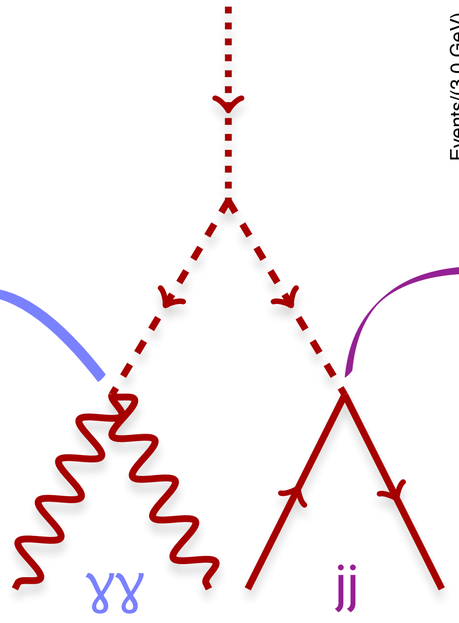
Photons selection ~ SM H→γγ

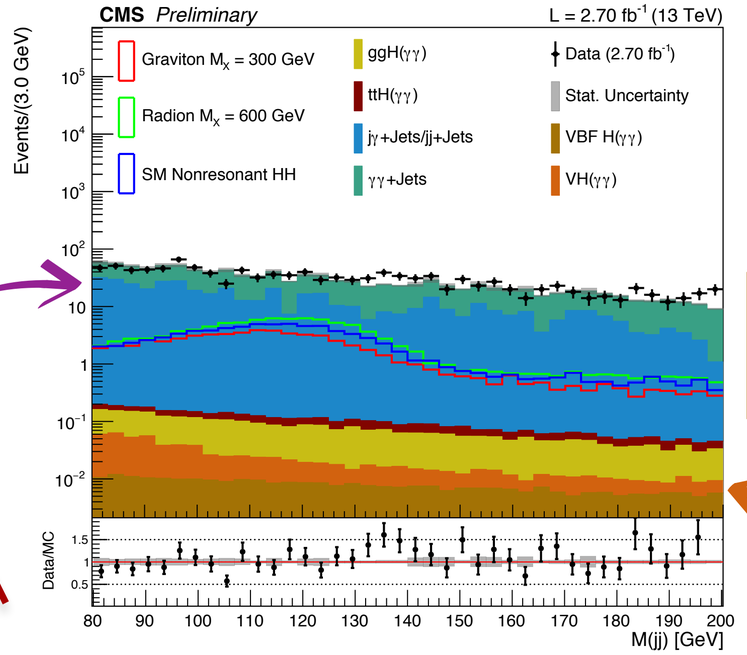
- Online: E_T, M(γγ), shower shape and isolation
- Offline:
  - E_T(γ1,2) > 30, 20 GeV and > M(γγ)/3, M(γγ)/4, |η(γ's)| < 2.5,
  - 100 < M(γγ) < 180 GeV
  - MVA Photon ID (~90% signal efficiency working point)

Jets selection

- ΔR(jet,γ's) > 0.4, p_T(jets) > 25 GeV, |η(jets)| < 2.4
- 80 < M(jj) < 200 GeV
- jj candidate: two jets with highest b-tagging score
  - b-tagging MVA (secondary vertex information) used for categorization
- Jet energy regression based on jets constituents developed to improve jet energy resolution and scale

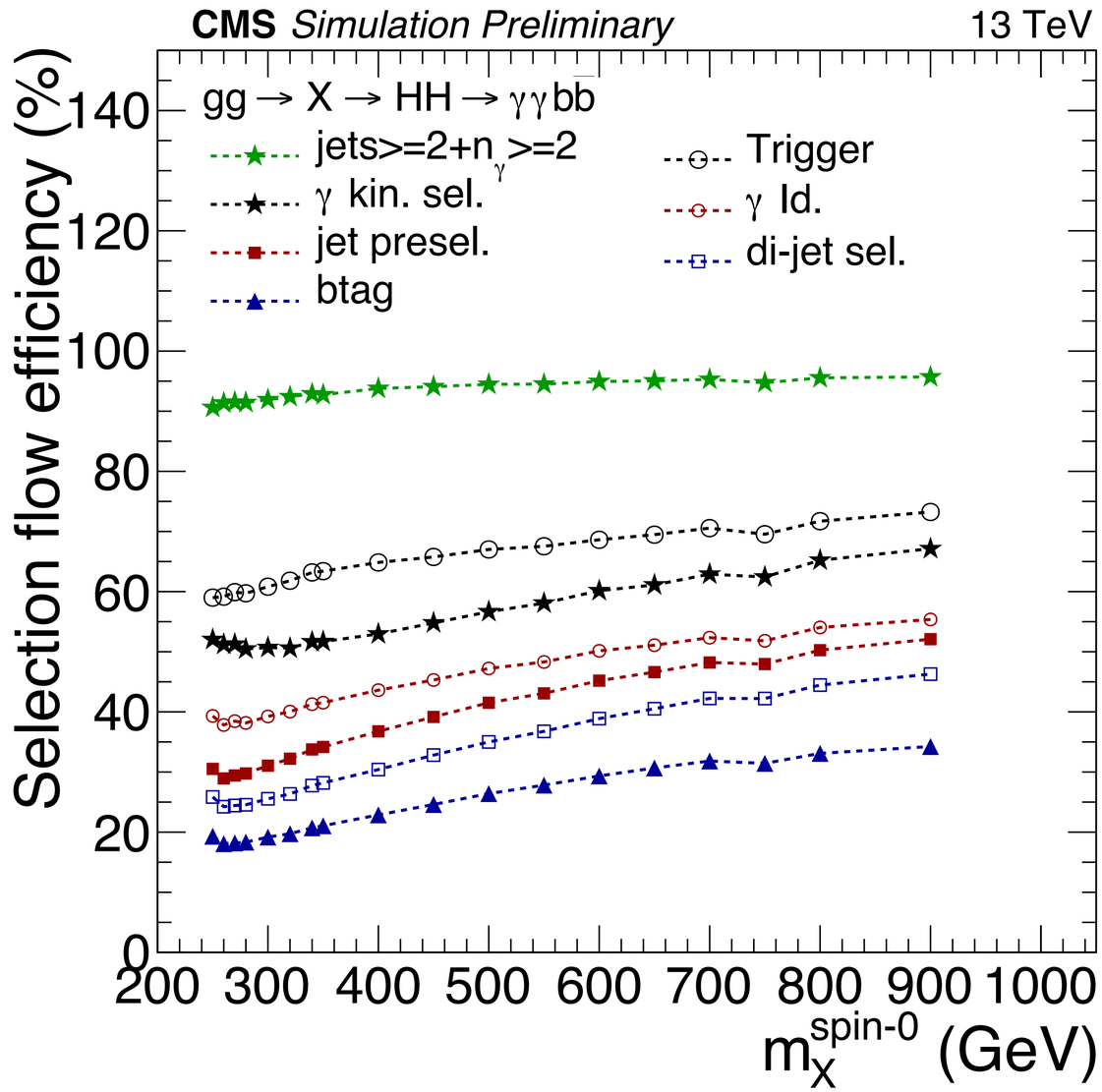


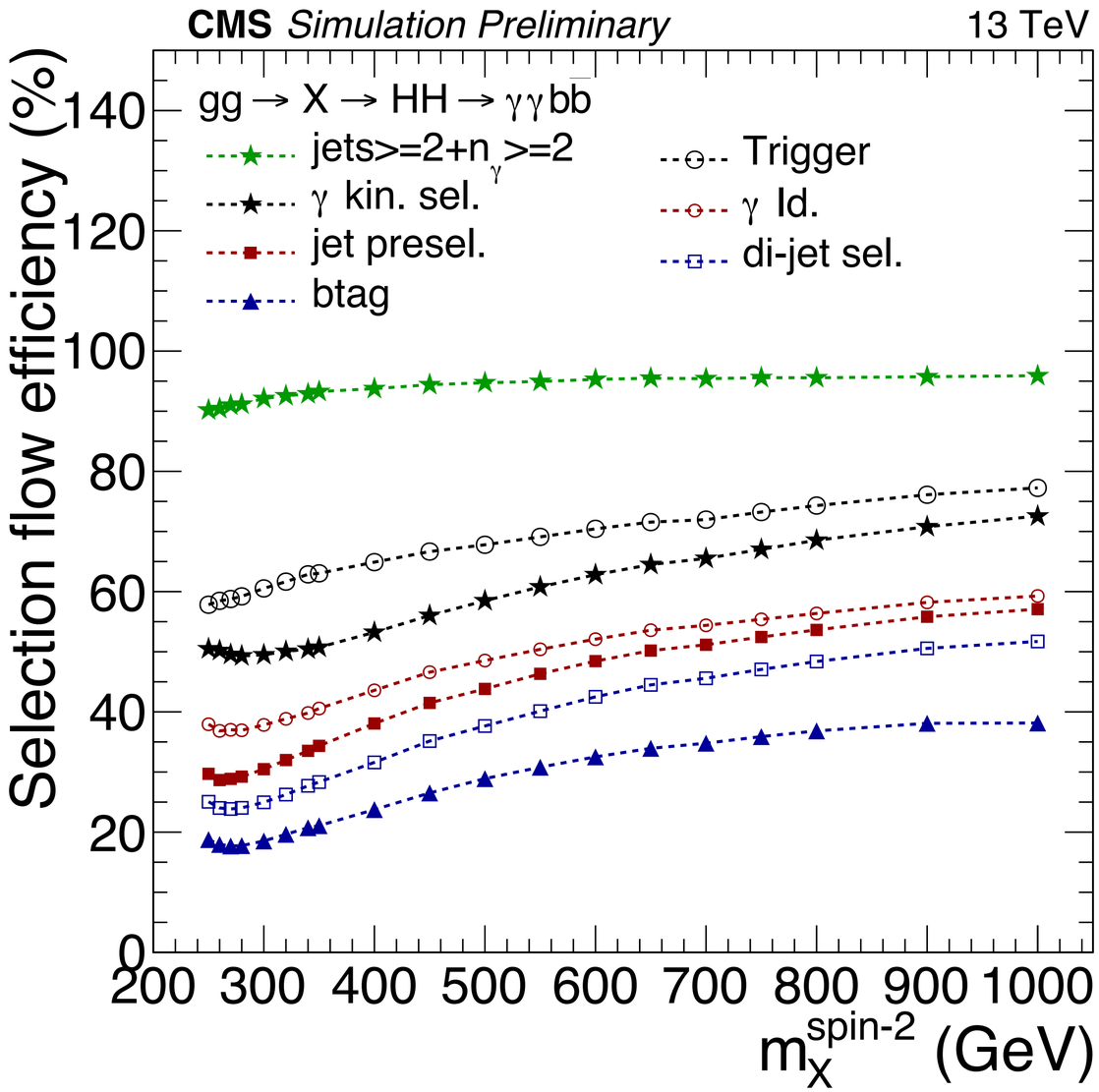




SM Higgs Contribution

EFFICIENCIES



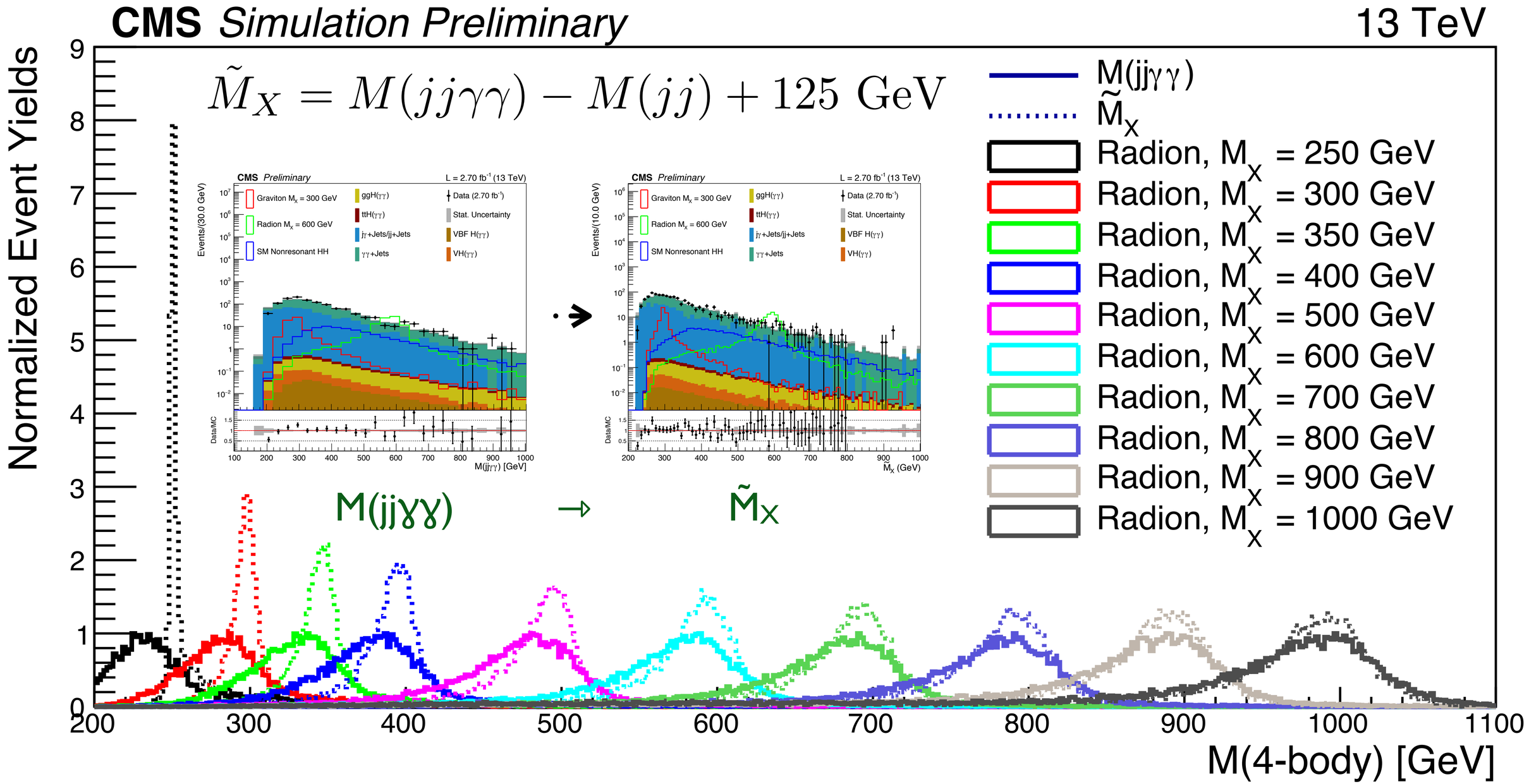


btag: efficiency of selecting at least one medium b-tagged jet

medium b-tagging working point ~ 80% efficiency

EFFECTIVE MASS

M(jjγγ) → $\tilde{M}_X$: resonance width improved



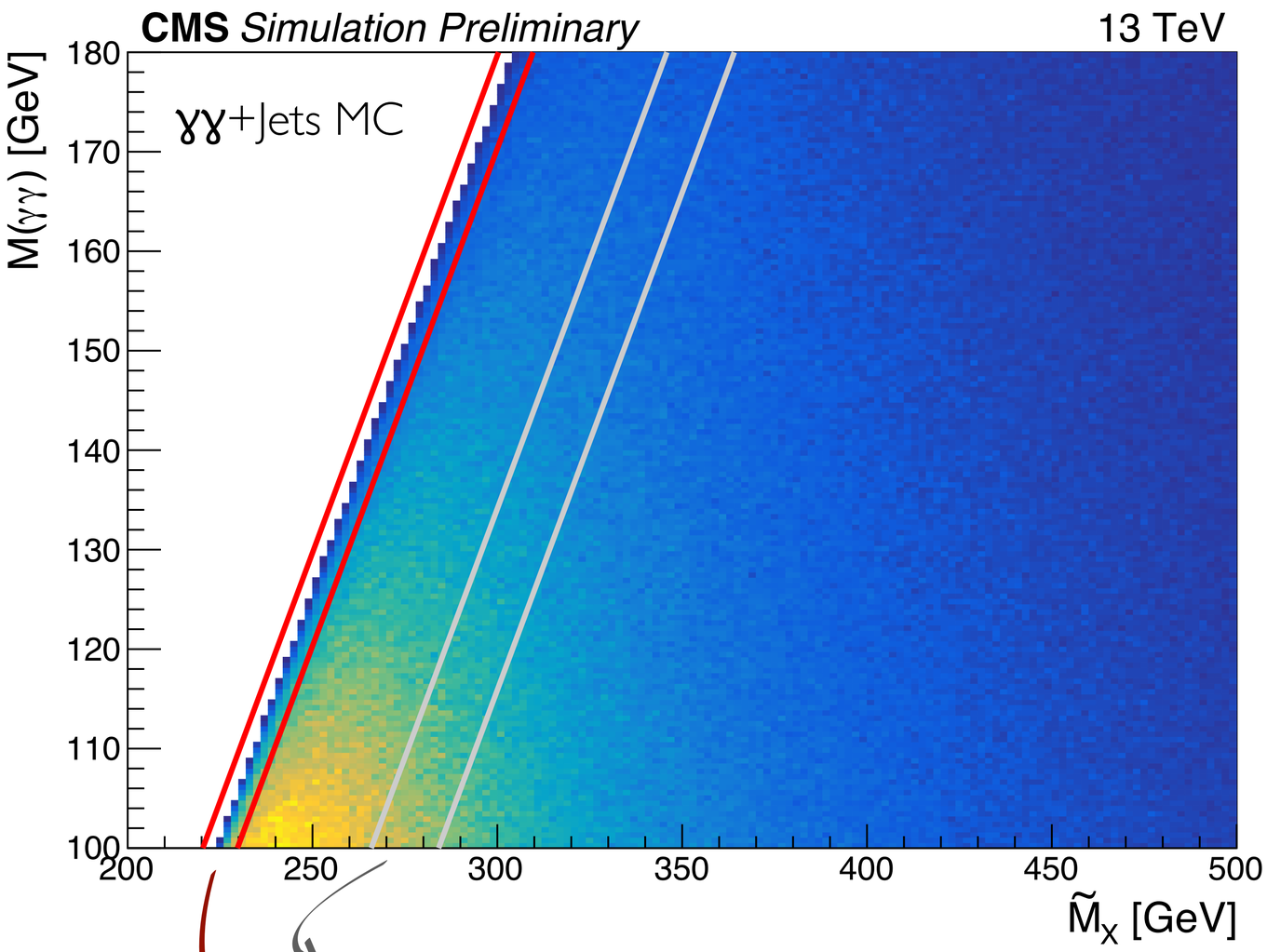
MASS WINDOW

In the resonant analysis, mass windows around the mass hypotheses are constructed in the M(γγ):$\tilde{M}_X$ plane

- Avoids performing the analysis in unphysical regions of kinematic phase space

$$\tilde{M}_X < M(\gamma\gamma) - 125\ \mathrm{GeV} + \Delta W/2,$$
$$\tilde{M}_X > M(\gamma\gamma) - 125\ \mathrm{GeV} - \Delta W/2$$

- ΔW/2 intervals defined ensuring 90% signal efficiency



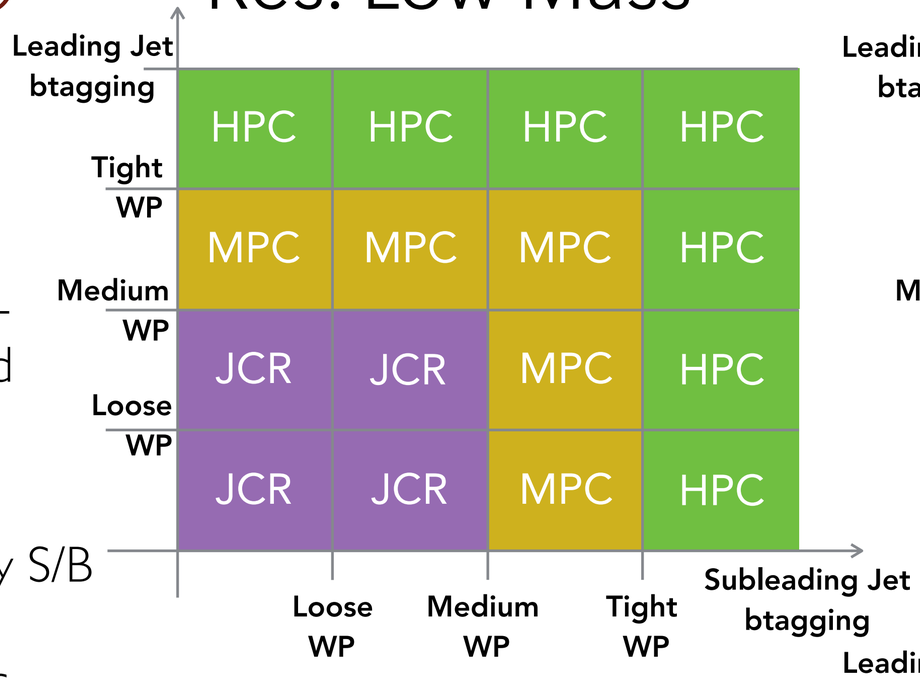
Mass window for Mx = 300 GeV mass hypothesis

Mass window for Mx = 250 GeV mass hypothesis

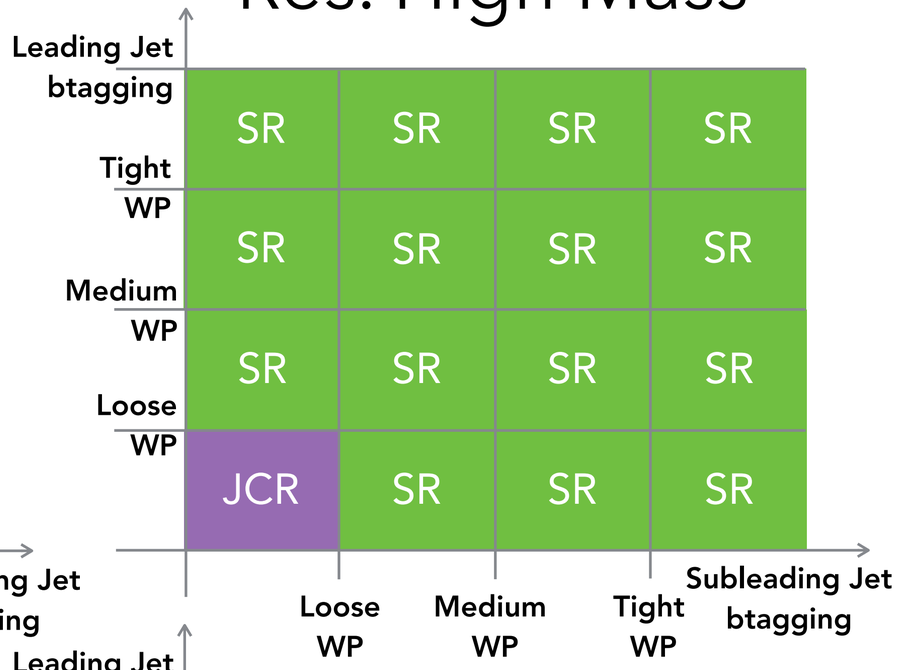
B-TAGGING BASED CATEGORIZATION

- B-tagging as a tool to create signal-enriched and background-enriched regions
- Categorization strategy dictated by S/B and by expected number of background events (for parametric background estimation)
- Tight: ~60% efficiency for signal jets
- Medium: ~80% efficiency for signal jets
- Loose: ~90% efficiency for signal jets

Res. Low Mass

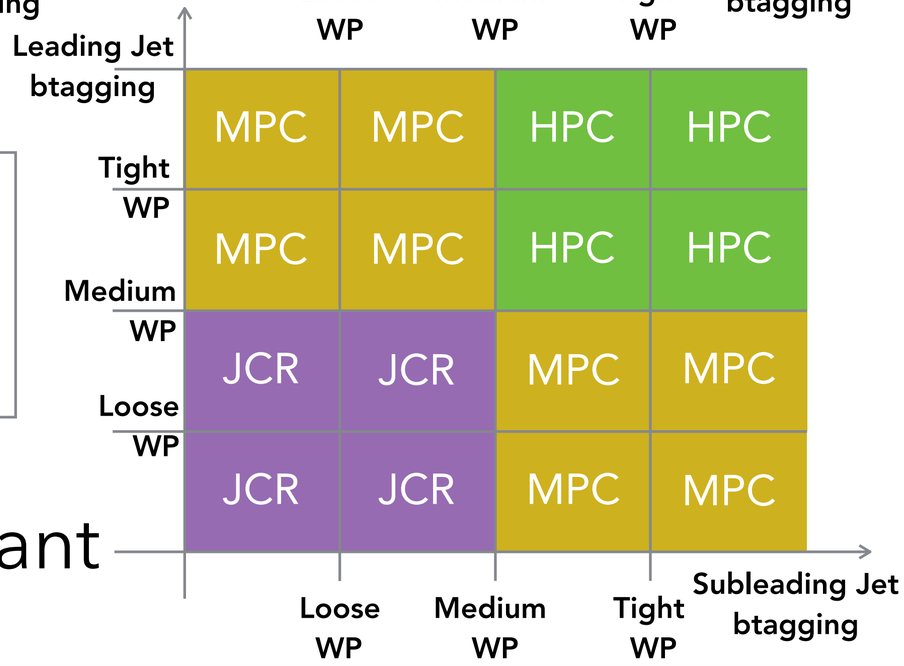


Res. High Mass



HPC: High purity category
MPC: Medium purity category
JCR: Light jets control region
SR: Signal Region

Nonresonant



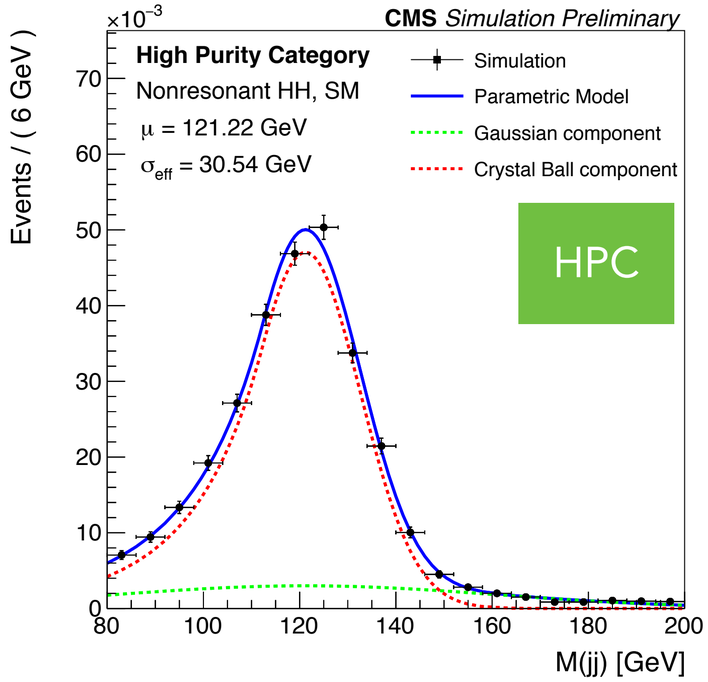
PARAMETRIZED SIGNAL

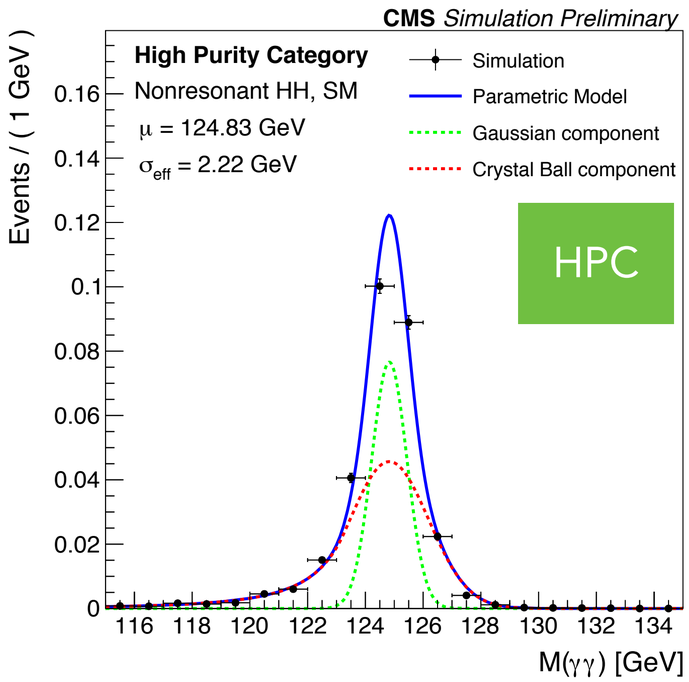
2D Signal shape: $f_{\gamma\gamma}[M(\gamma\gamma)] \times f_{jj}[M(jj)]$

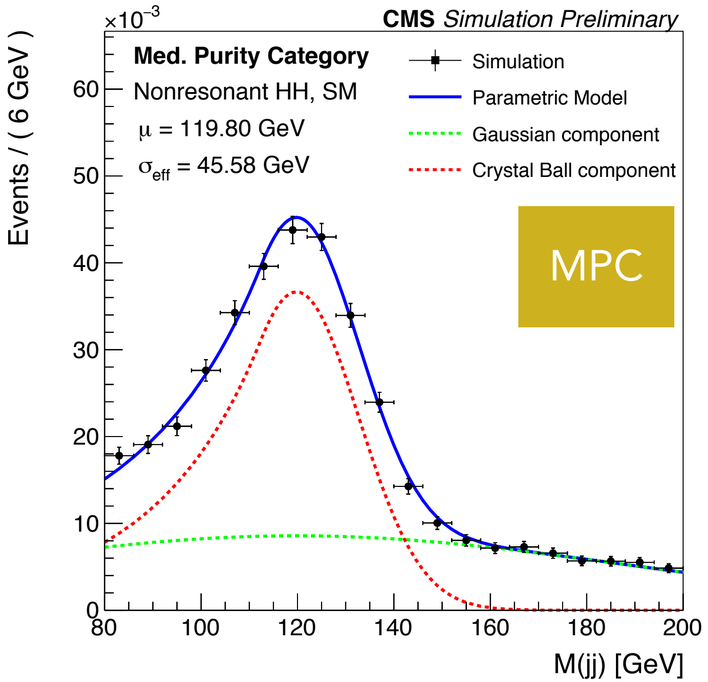
- $f_{\gamma\gamma}$ and f_{jj} are modeled as a sum of a gaussian and a Crystal-Ball function

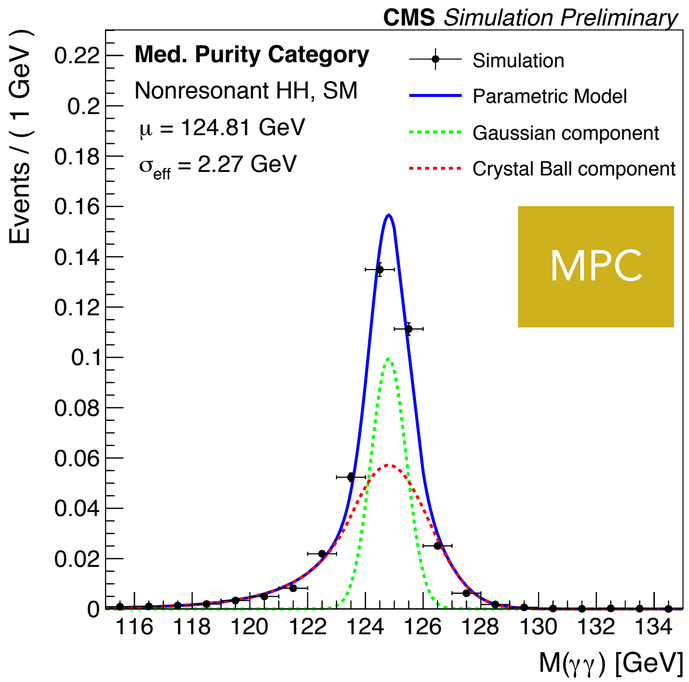
Signal shape is parametrized separately for each individual category and signal mass point

Example fits from the SM Nonresonant signal sample









PARAMETRIZED BACKGROUND

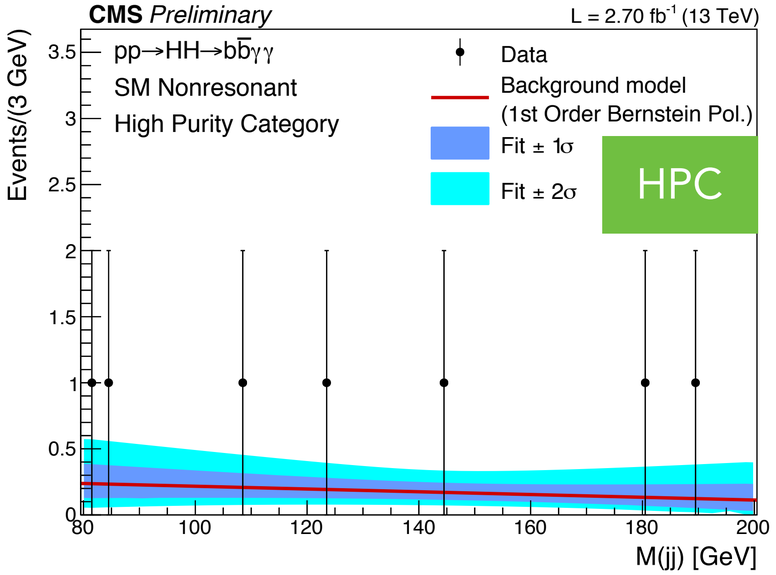
2D Background shape: $f_{\gamma\gamma}[M(\gamma\gamma)] \times f_{jj}[M(jj)]$

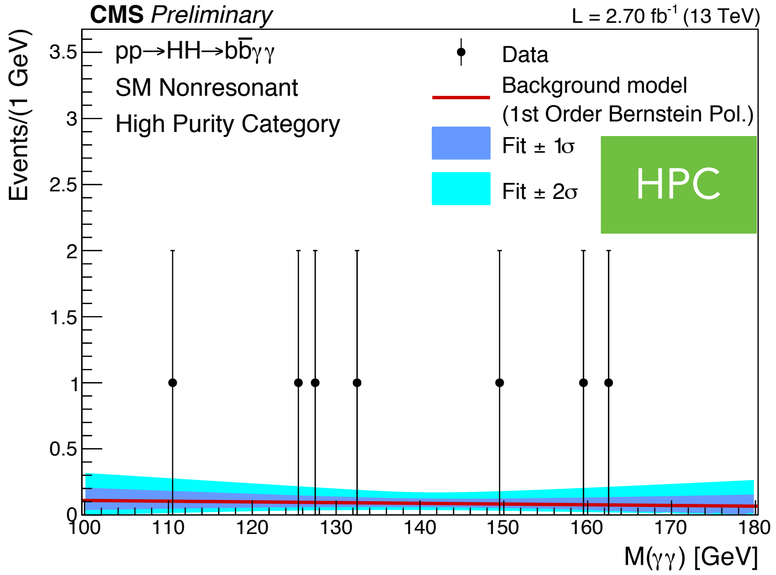
- $f_{\gamma\gamma}$ and f_{jj} are modeled as a **Bernstein polynomials** of order 2 if number of events in signal region > 10, or 1 otherwise

Cross checks performed on fake photon control region:

- Choice of PDF for **background modeling was found to be unbiased,** within statistical precision
- **Background correlation between M(γγ) and M(jj) was found statistically negligible** in data

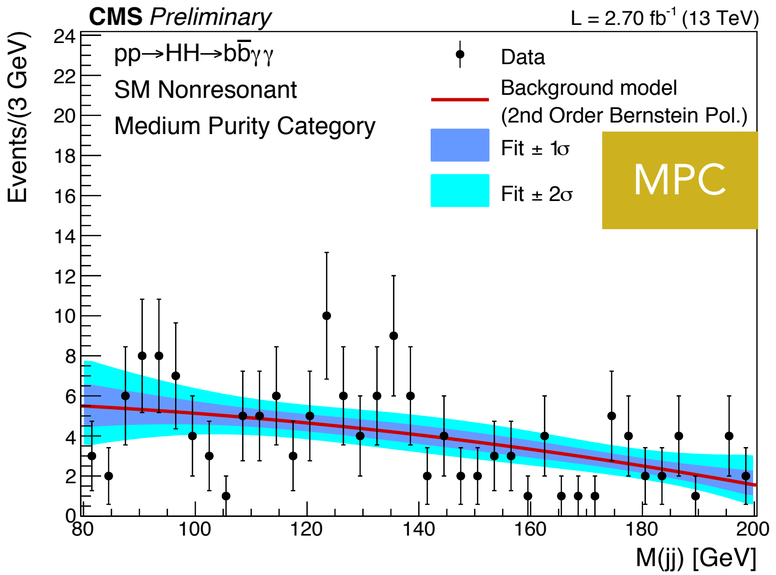
Example fits from the SM Nonresonant selection

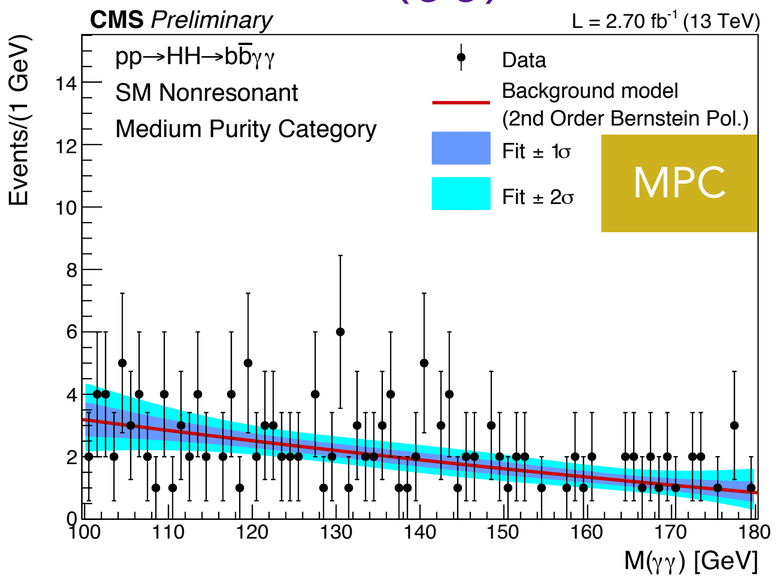




M(jj)

M(γγ)





RESULTS - NONRESONANT ANALYSIS

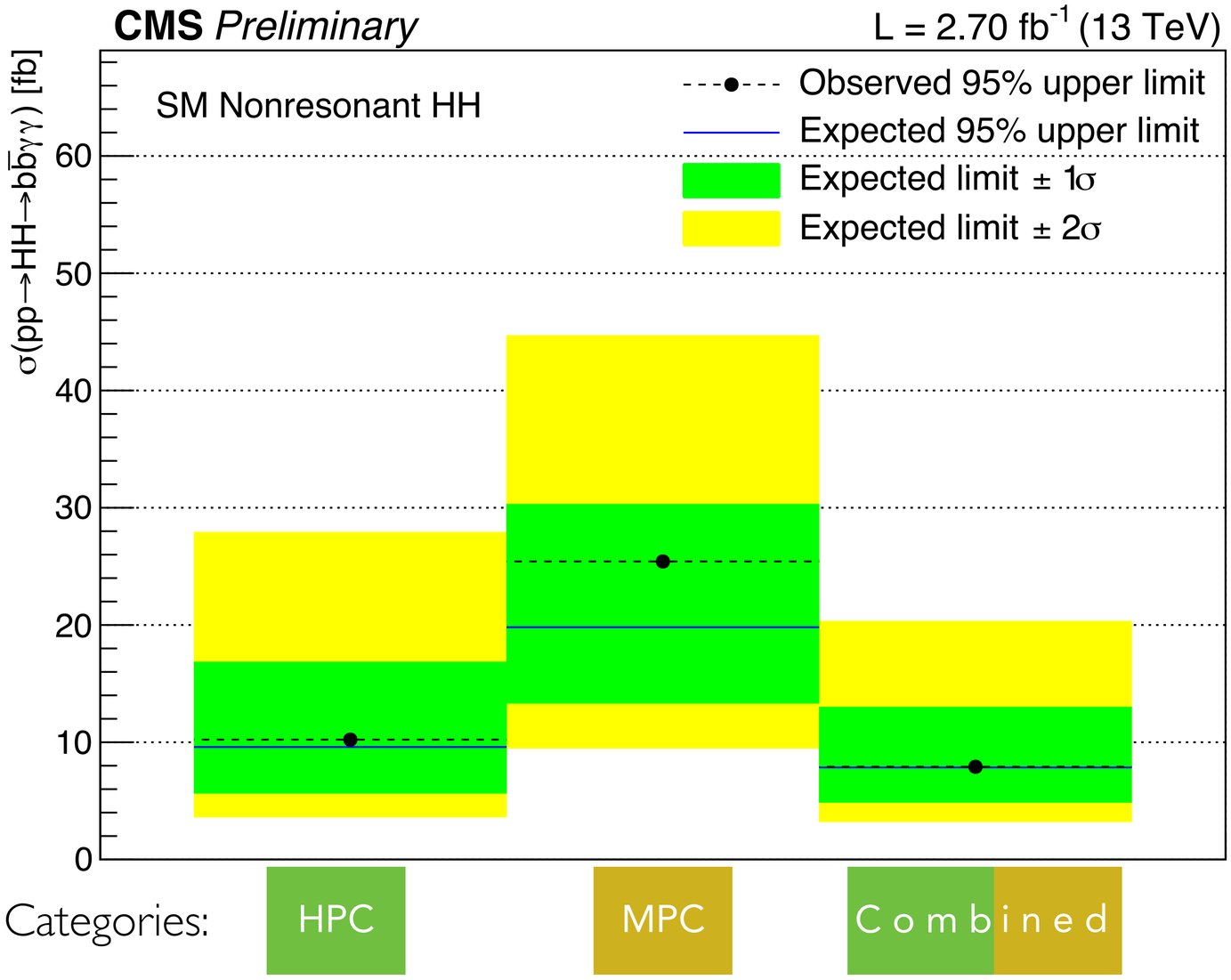
CMS PAS HIG-16-032

Analysis Uncertainties

- Largest analysis uncertainty is statistical - < 10% impact from systematical uncertainties
- Main systematical uncertainties coming from jet energy scale and resolution, and b-tagging

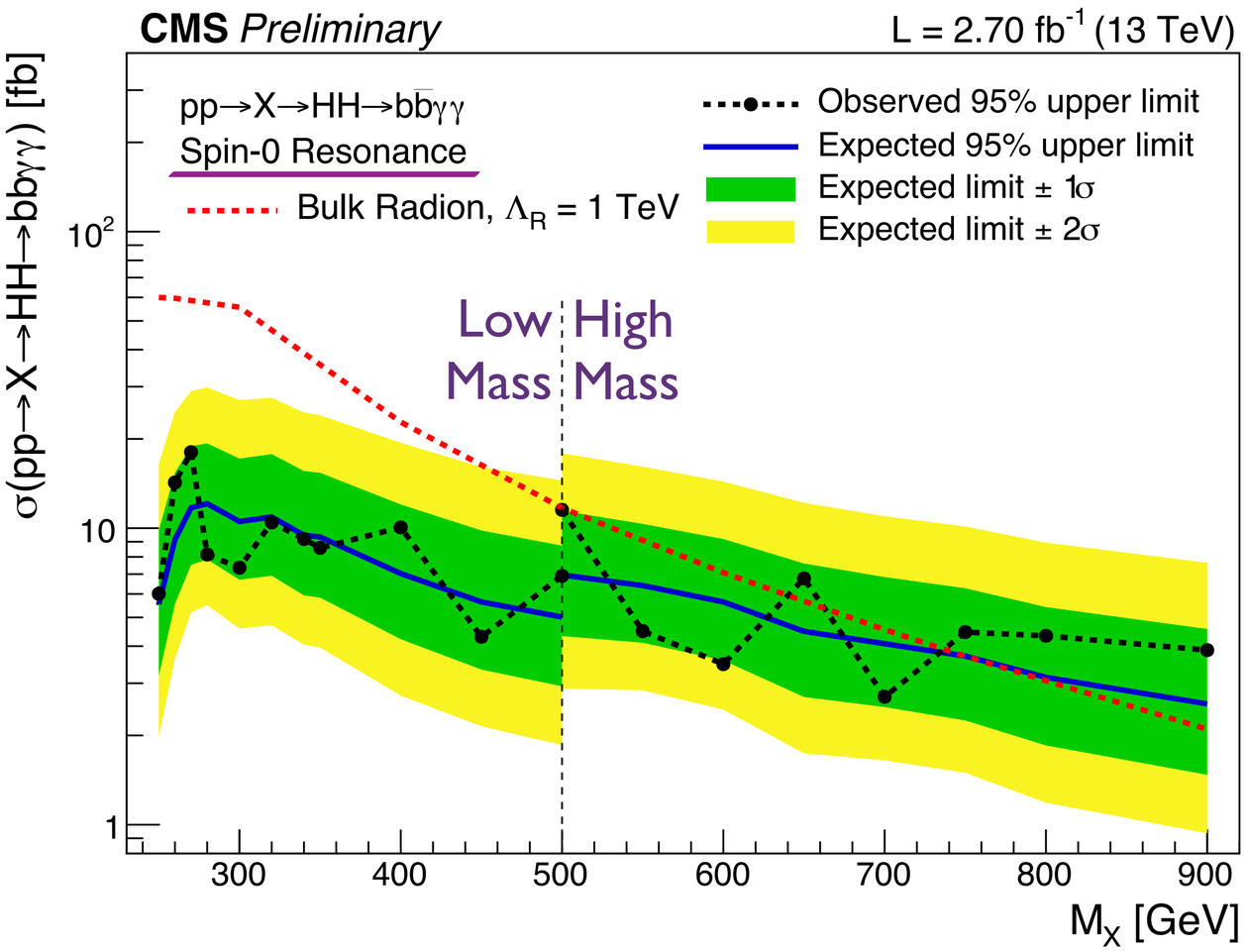
Nonresonant results:

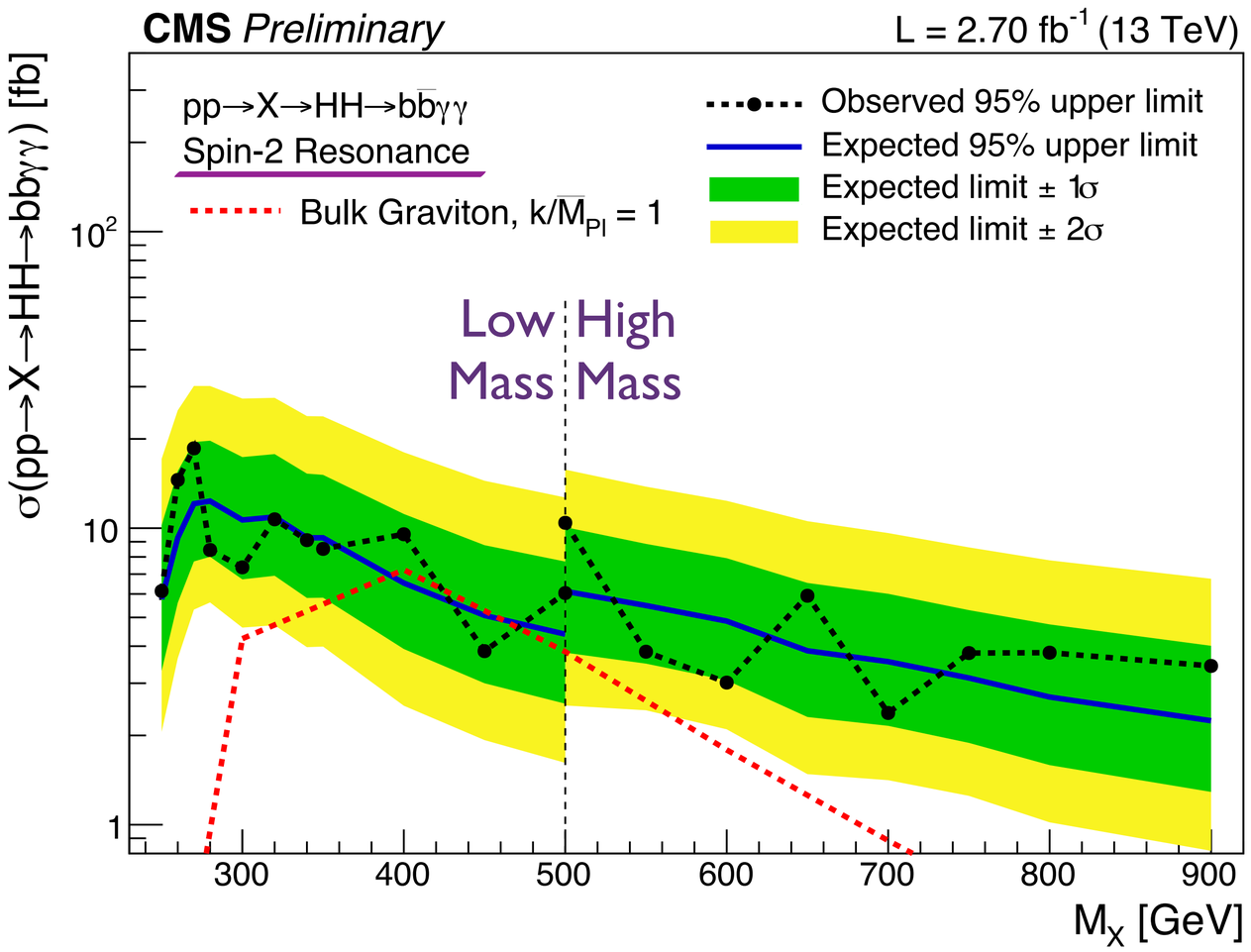
- $\sigma(pp \to HH \to bb\gamma\gamma)$ < 7.90 fb (7.85 fb expected) ~ 91 x SM



RESULTS - RESONANT ANALYSIS

CMS PAS HIG-16-032



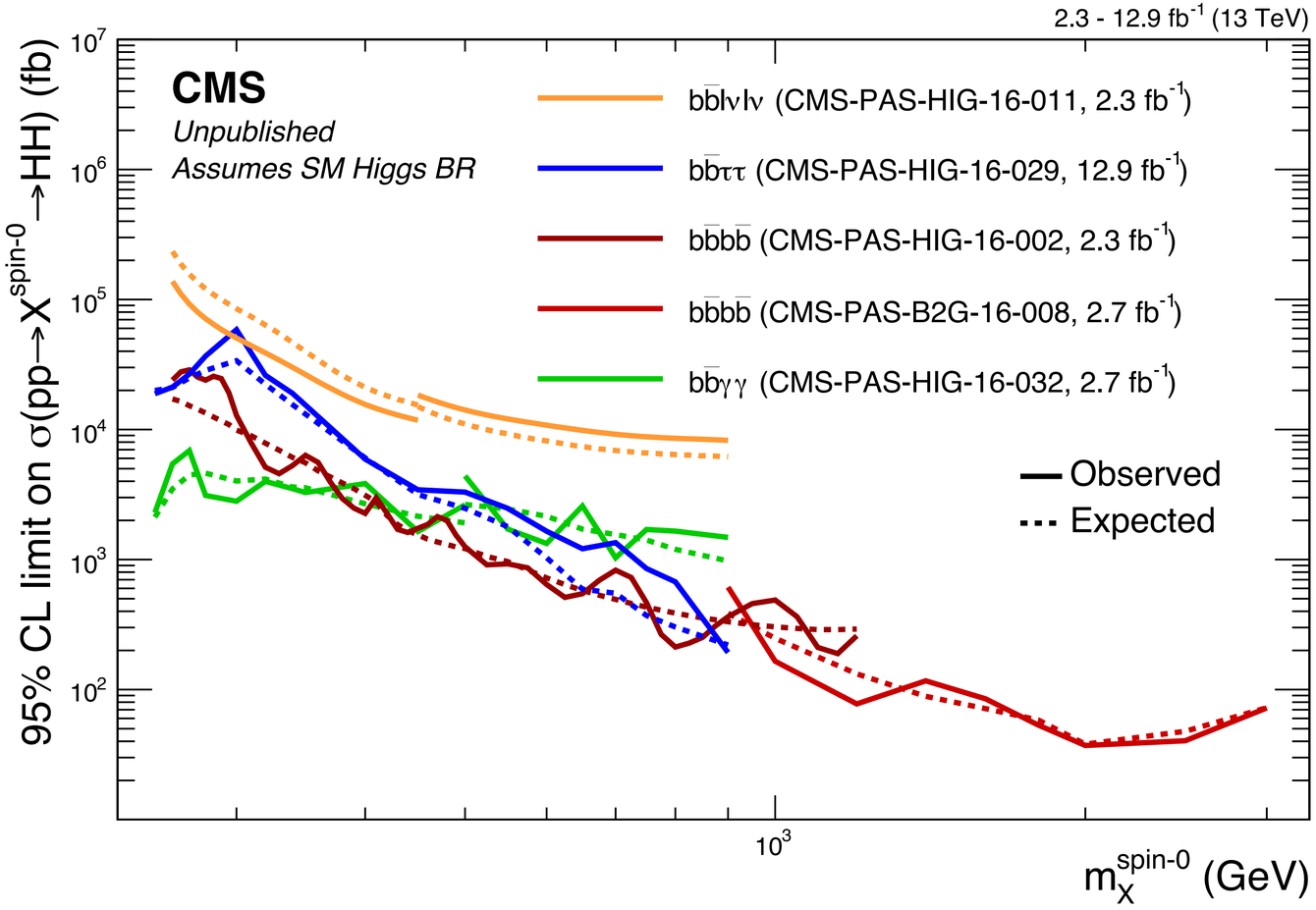


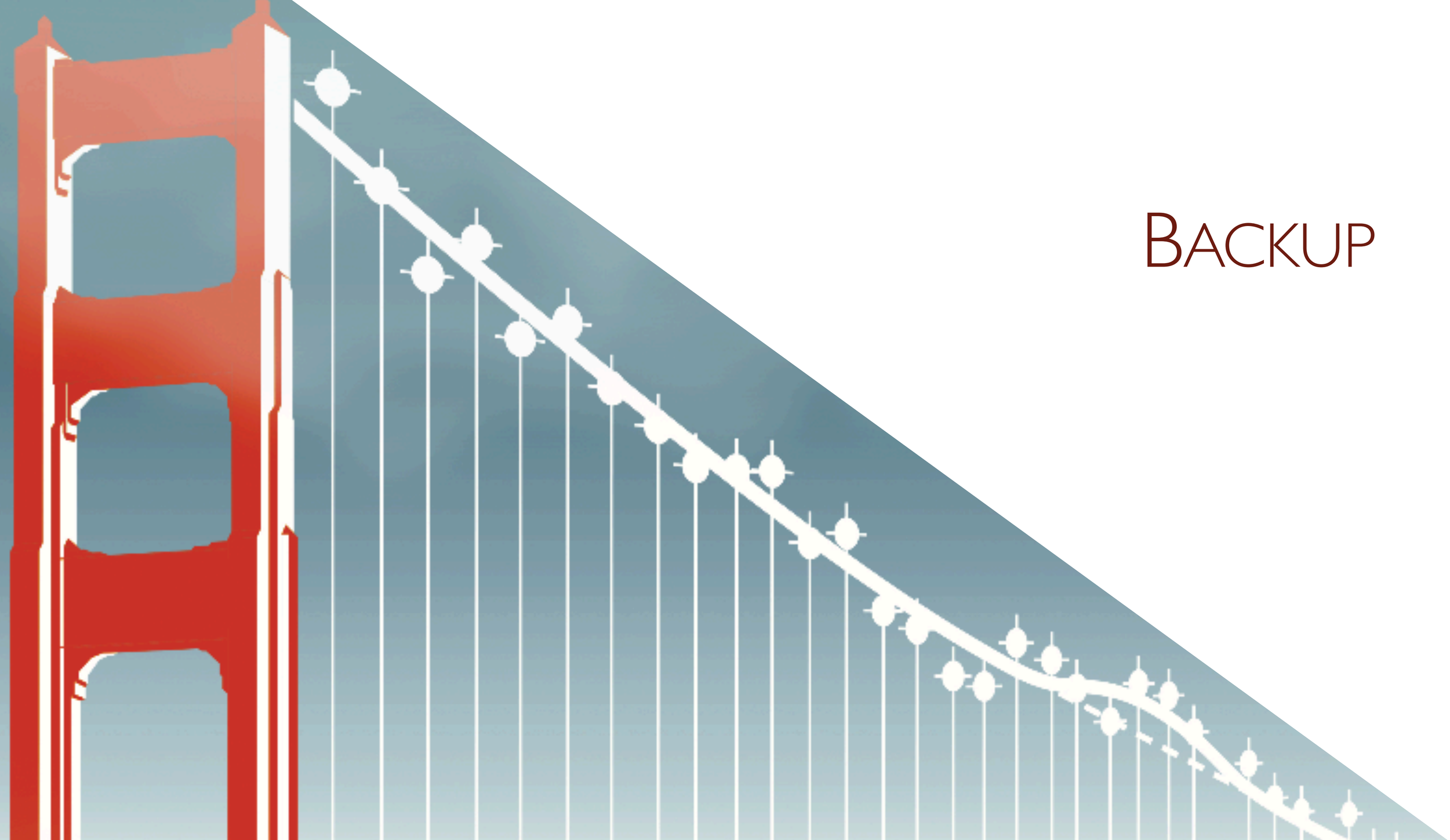
- Large fluctuations in expected and observed limits due to mass window requirement - limits are obtained in separate datasets

SUMMARY

For details, see S. Das earlier in this session

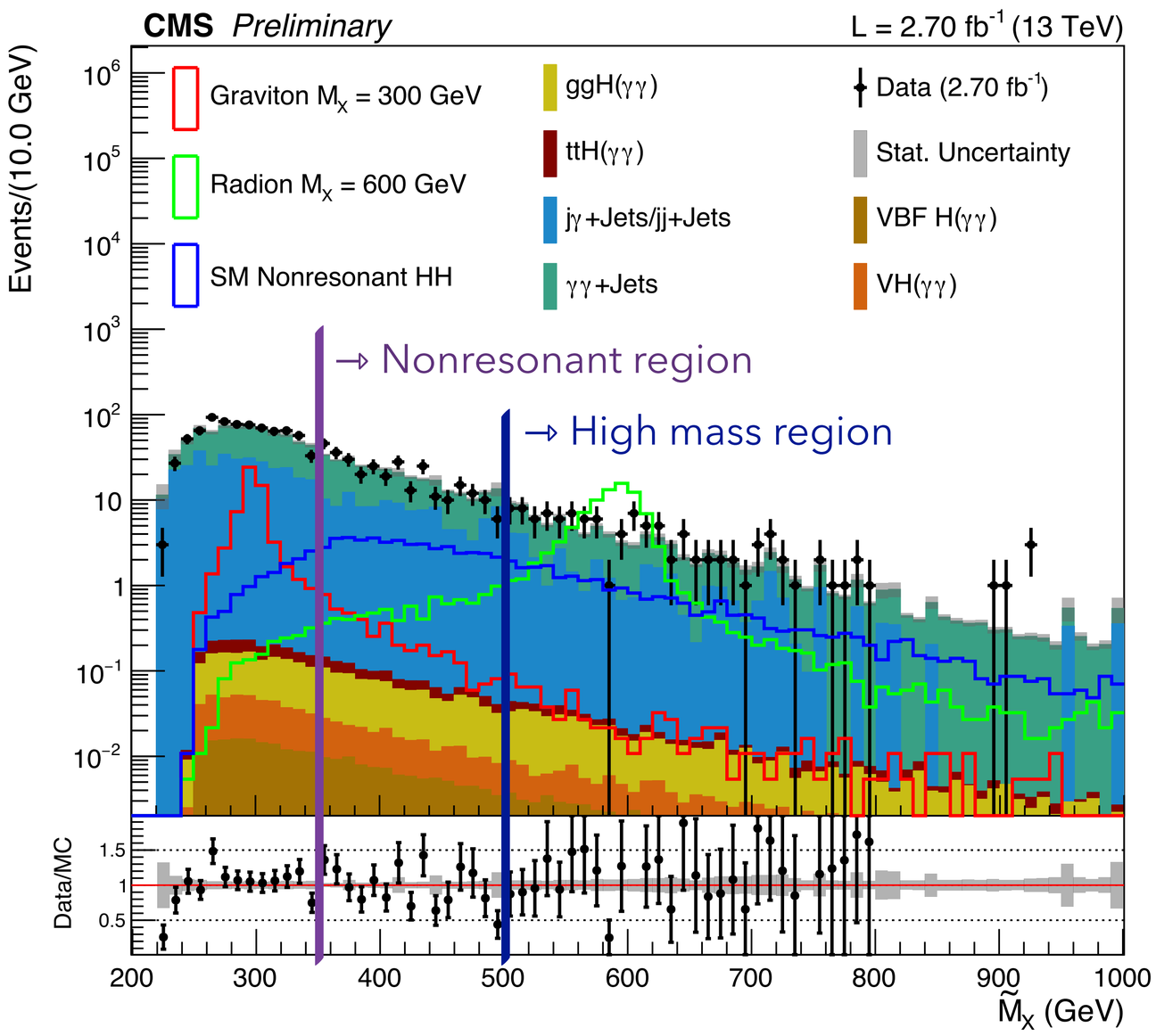
- HH→bbγγ searches performed with the 2015 dataset recorded by CMS at 13 TeV
- Observed **limits are consistent with the expected** by the null hypothesis
- HH→bbγγ is currently the **most sensitive final state to the SM nonresonant HH production at CMS**
- For resonant searches, it is the **most sensitive in the low mass region** (M_X < 400 GeV) and competitive up to 900 GeV





Backup

B-TAGGING CATEGORIES EXPLAINED



The b-tagging categorization ⟷ amount of background in individual analysis categories

- Goal: improve analysis sensitivity while maintaining enough events in individual categories for robust parametric background estimation
- Nonresonant analysis:
  - No mass window: b-tagging requirement tighter than in the other analysis categories.
- Resonant analyses:
  - Mass window (efficient at background mitigation) → b-tagging must be loose
  - Background(Low Mass) >> Background(High Mass) → b-tagging requirements must be looser at high mass. than in low mass