Search for the resonant production of two Higgs bosons in the $\gamma\gamma b\bar{b}$ final state at CMS

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On behalf of the CMS Collaboration

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- The case for **DiHiggs production** with modest 2012 data can be motivated by
  - beyond the SM scenarios **WED, 2HDM, and (N)MSSM**
  - objective of **the Higgs self-coupling** measurement
- Models inspired by Warped Extra Dimensions (WED) predict new heavy resonances decayed to a pair of Higgs bosons: **Radion (spin-0), KK-graviton (spin-2)**
- **Radion** is a benchmark signal model
  - **couples** to gluons and Higgs
  - **production CS** depends on the scale Λ_R
  - **mass** depends on the stabilization mechanism of the ED
- KK-graviton interpretation as analysis is spin-independent
  - **RS1 model:** SM matter fields localized on the TeV brane
  - **bulk scenario:** SM matter fields localized on the ED bulk
- Public CMS document: **HIG-13-032**

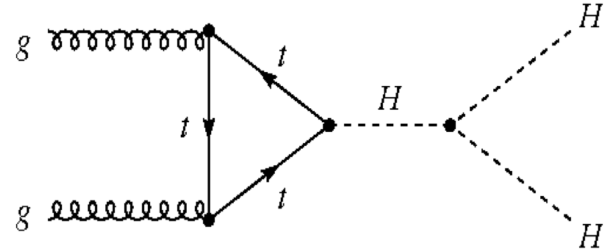
DiHiggs Production at LHC

Double Higgs production among the main objectives of HL-LHC, but this process is very challenging

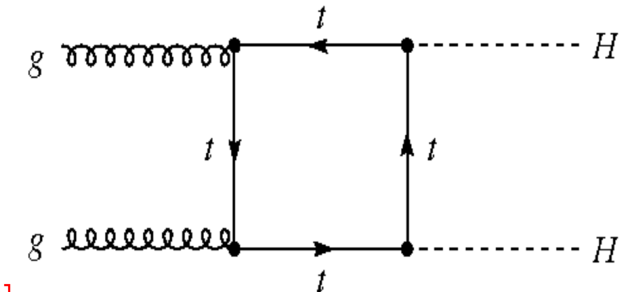
- Low rate makes high demands on detectors and integrated luminosity
  - tiny cross section $\sigma(\mathrm{HH}) = 40 \pm 3\,\mathrm{fb}$ (120K)
  - finding one requires at least 500K events
  - theoretical studies suggest possible: [arXiv:1309.6318]
- Self coupling diagrams **interferes destructively** with double Higgs processes
  - look for a deficiency in a small signal

Ongoing studies suggest some sensitivity

Higgs self coupling process

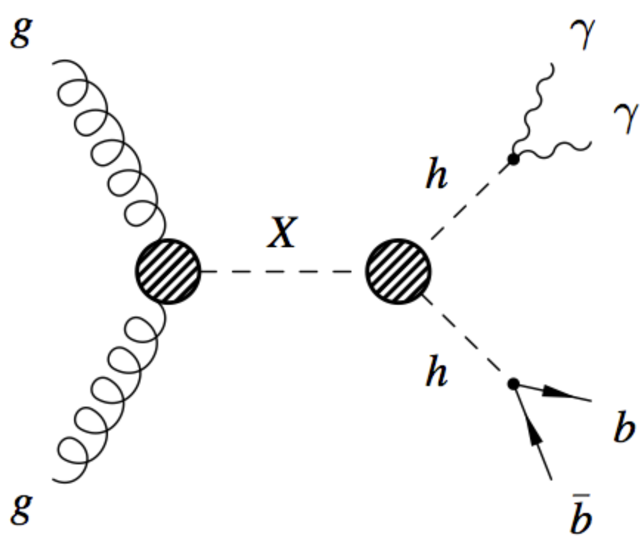


SM Double Higgs production



Produced Events at 3000 fb^{-1}

Mode	Yield
bbWW	30000
bb$\tau\tau$	9000
WWWW	6000
$\gamma\gamma$bb	320



Channel	Freq. (%)
H(bb,cc,gg)H(bb,cc,gg)	47.86
H (bb)H (bb)	33.30
H(bb,cc,gg)H(VV*)	33.40
H(bb,cc,gg)H($\tau\tau$)	8.77
H(bb)H($\tau\tau$)	7.29
H(VV*)H(VV*)	5.83
H(ll)H(VV*)	3.06
H($\tau\tau$)H($\tau\tau$)	0.40
H(bb,cc,gg)H($\gamma\gamma$)	0.32
H(bb)H($\gamma\gamma$)	**0.26**
H(bb,cc,gg)H($\mu\mu$)	0.03
H(ll)H($\gamma\gamma$)	0.03

☞ Search strategy

- **gluon fusion** is the dominant production mode for heavy resonance
- it decays into a **pair of SM Higgs**

One Higgs boson decays into two photons (high resolution) and the other into two b jets (highest $\mathcal{B}$)

- **Benchmark signal:** radion
  - no Higgs-Radion mixing
  - narrow width
  - $\Lambda_R = 1\text{TeV}, \ k_l = 35$
  - $\mathcal{B}(R \to HH) = 25\%$
- **Non-resonant** backgrounds:
  - QCD, γ+jets, $\gamma\gamma$+jets
  - DY, W$\gamma\gamma$, W/Z+$\gamma(\gamma)$
  - t$\gamma\gamma$, tt$\gamma\gamma$, tγjet
- **Resonant** backgrounds:
  - the SM Higgs samples: (ggH, VBF, VH, ttH)

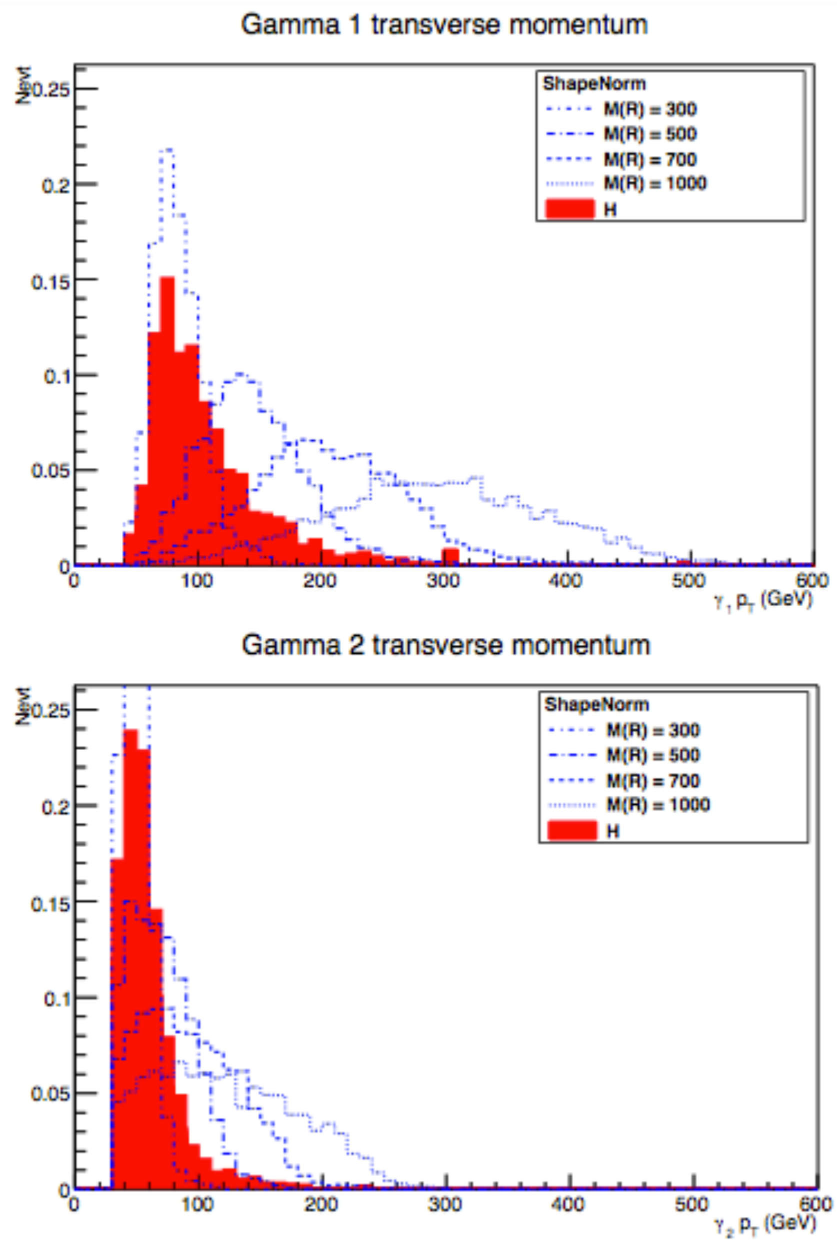
Production and Decay Rates $R \to H(\gamma\gamma)H(b\bar{b})$

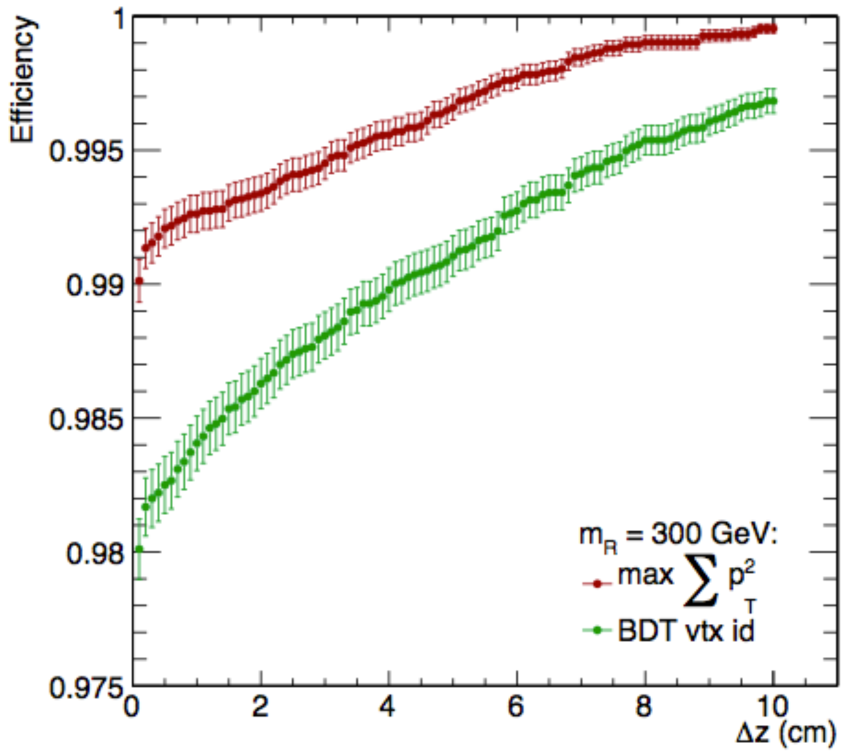
Mass (GeV)	σ (pb)	$N = \sigma \times \mathcal{B} \times \mathcal{L}$
300	20.6	263
350	13.0	166
400	7.5	95.6
500	3.8	49.3
900	0.62	7.9
1000	0.45	5.7

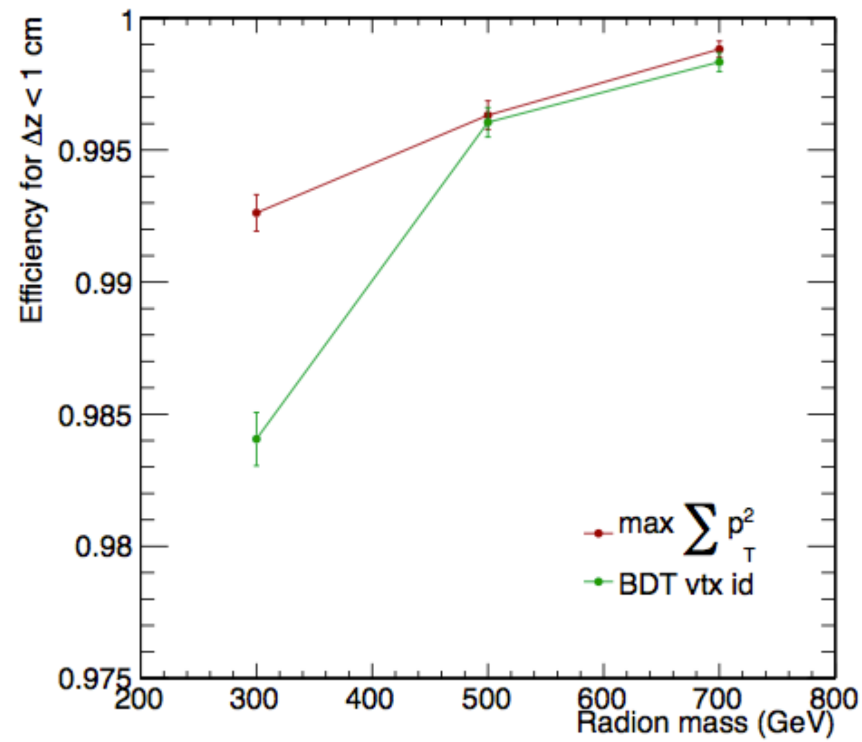
- **Data:** latest detector calibration
  - 19.7 fb^{-1}, $\sqrt{s} = 8$ TeV
  - DoublePhoton dataset
  - same trigger as $H \to \gamma\gamma$

Photon selection is based on CiC4PF
$H \to \gamma\gamma$ approach

- **Triggers**
  - $p_{T1(2)} > 26, 18$ GeV (loose shower shape and iso)
  - $p_{T1(2)} > 36, 22$ GeV (non converted)
- **Photon preselection** cuts
  - $p_{T1(2)} > \mathrm{M}_{\gamma\gamma}/3(4)$, $|\eta_\gamma| < 2.5$
  - 100 GeV $< \mathrm{M}_{\gamma\gamma} < 180$ GeV
- **SuperTight working point** from CiC analysis in $H \to \gamma\gamma$
- **Data/MC corrections**
  - trigger efficiency
  - photon ID efficiency
  - energy scale
  - energy resolution







- ☞ SM $\mathrm{H} \to \gamma\gamma$ has no tracks to LO:
  - ➠ vertex choice comes from a BDT
- ☞ Presence of tracks from the $\mathrm{H} \to \mathrm{b\bar{b}}$
  - ➠ vertex choice comes **from** $\Sigma\, \boldsymbol{p_T}^2$

For low M_X, $\Sigma\, p_T{}^2$ algorithm is more efficient

☞ **Preselection:**

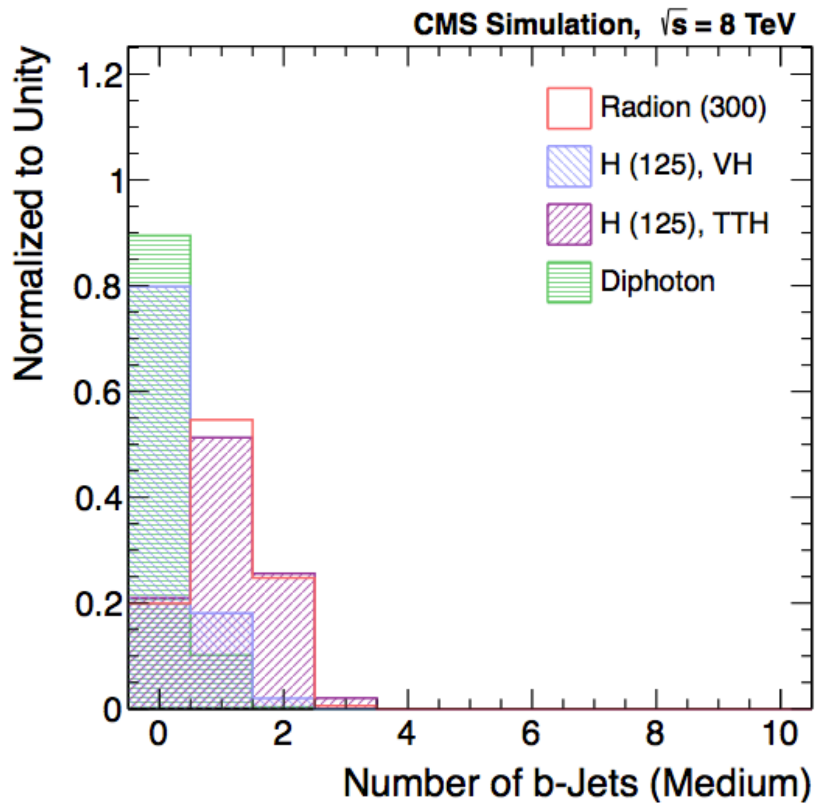
- anti-kT jets with R=0.5
- require at least two jets with
  - ➔ $p_T > 25$ GeV, $|\eta_j| < 2.5$
  - ➔ loose jet ID, pileup jet ID
  - ➔ $\Delta R > 0.5$ separation from each γ
- at least one loose CSV b-tagged jet

☞ **Data/MC corrections:**

- standard JEC
- b-tagging scale factors

☞ **Combinatorics:**

- select the pair with the highest $p_{T\,jj}$
- does not shape background



b-tagging:

☞ Use medium WP with CSV algorithm

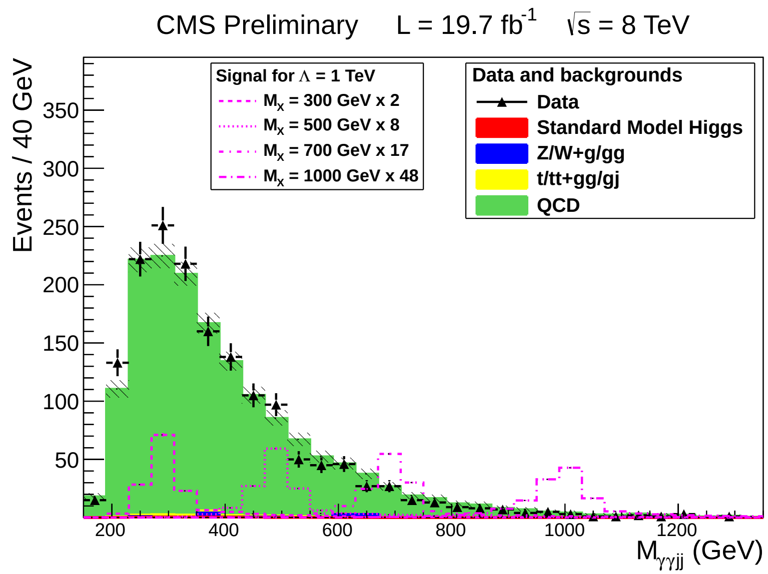
☞ Two mutual event categories:

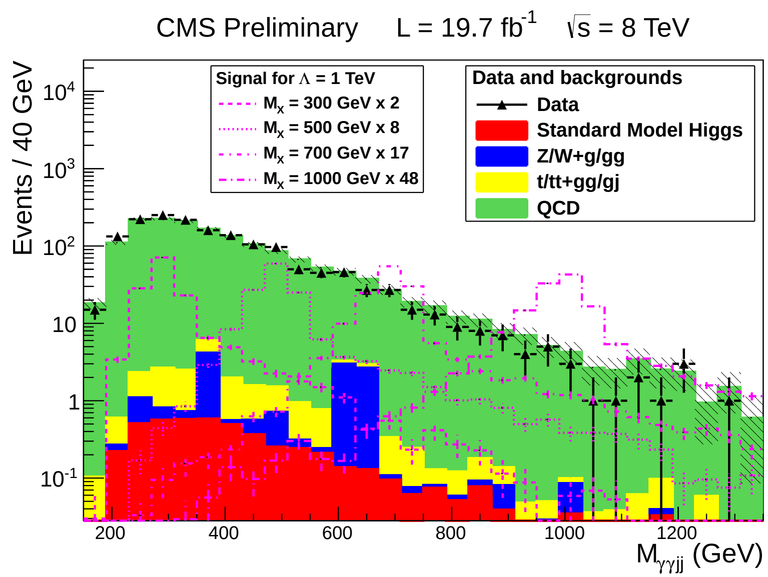
- high purity: $\geq$ **2 b-tagged** jets
- medium purity: $=$ **1 b-tagged** jet

A signal will appear as an excess in $\mathrm{M}_{\gamma\gamma}$, M_{bb}, $\mathrm{M}_{\gamma\gamma\mathrm{jj}}$ spectra

- $\mathrm{M}_{\gamma\gamma\mathrm{jj}}$ gives a natural handle on M_X
  - background peaking around 300 GeV
  - do not use to fit all M_X hypotheses
- Intermediate mass regime: **$\mathrm{M}_{\mathrm{x}} \geq$ 400GeV**
  - fit to $\mathrm{M}_{\gamma\gamma\mathrm{jj}}$ spectrum
  - $\mathrm{M}_{\gamma\gamma}$ and M_{jj} provide further discrimination
- Optimize mass window with **the control sample**

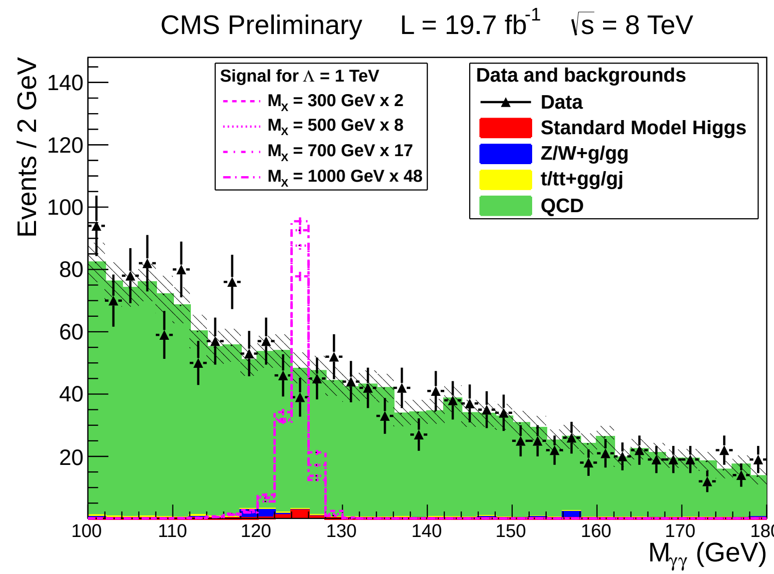
Spectrum	Window (GeV)
M_{jj}	[90,165]
$\mathrm{M}_{\gamma\gamma}$	[120,130]

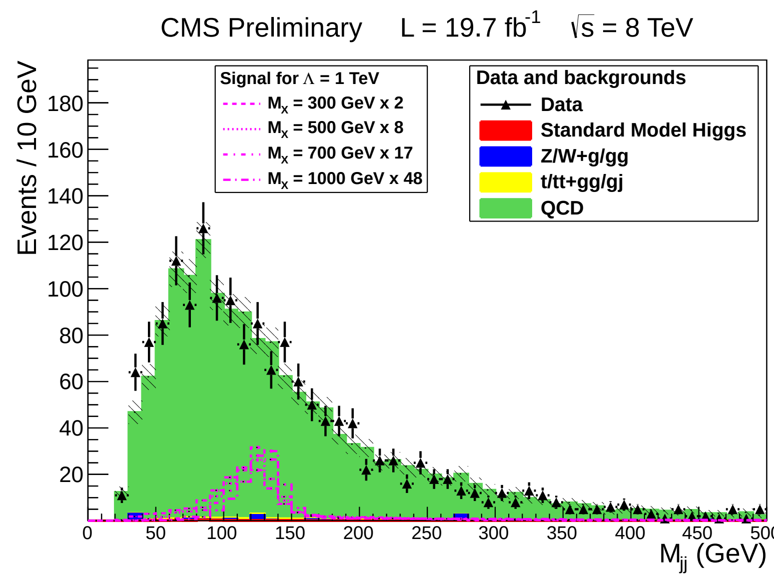




- $\mathrm{M}_{\gamma\gamma jj}$ becomes the discriminator for $M_X \sim 300$ GeV
- Low mass regime: $\mathbf{M_x < 400GeV}$
  - fit to $\mathrm{M}_{\gamma\gamma}$ spectrum
  - $\mathrm{M}_{\gamma\gamma jj}$ and M_{jj} provide further discrimination
- Optimize mass window for each mass hypothesis with **the control sample**

M_X (GeV)	$\mathrm{M}_{\gamma\gamma jj}$ window (GeV)
260	[225,280]
270	[225,295]
300	[255,335]
350	[310,395]
	M_{jj} window (GeV)
all masses	[85,155]



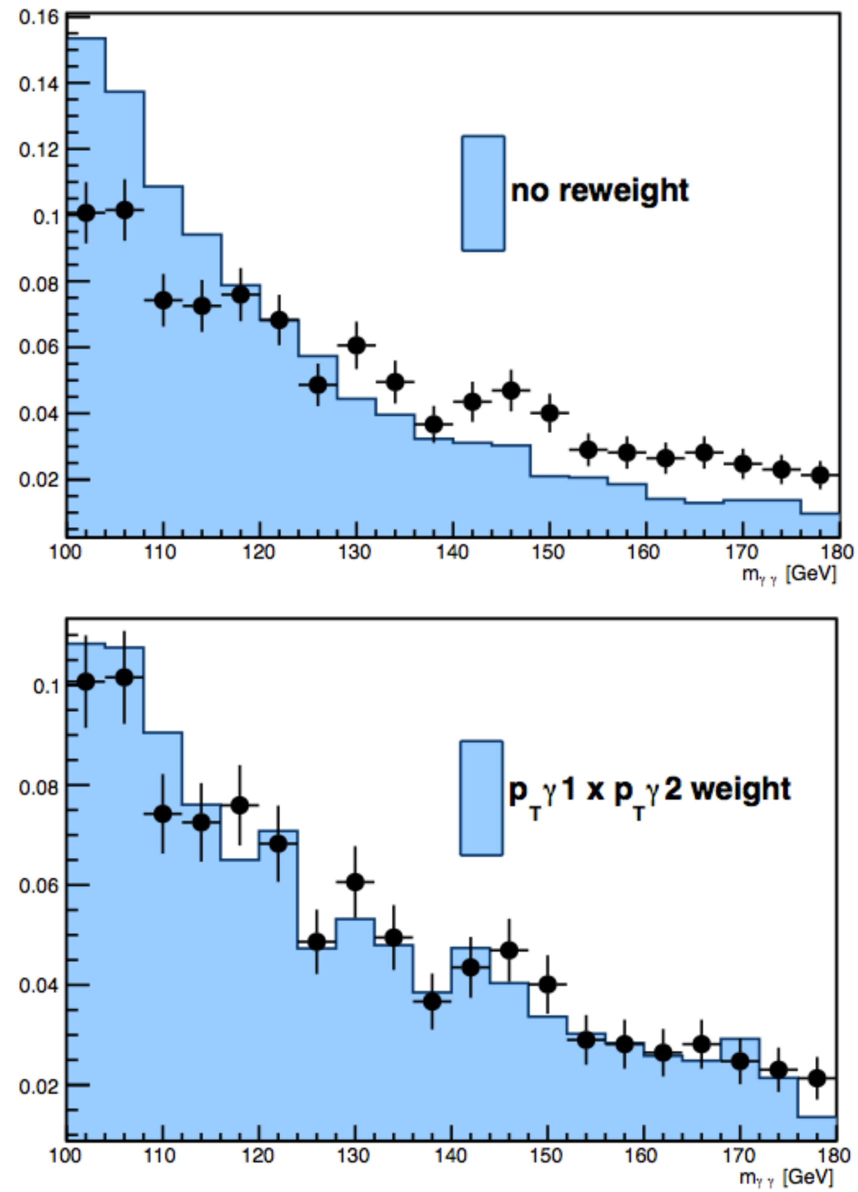


A control sample is constructed in data for optimization and background studies

☞ **Control sample (CS)**

- invert one photon CiC value (combines ID and isolation) to create a γjjj enriched data sample
- reweight to the blinded $\gamma\gamma$jj data sample with respect to $p_{T\gamma1} \times p_{T\gamma2}$

The reweighted control sample and data are in reasonable agreement

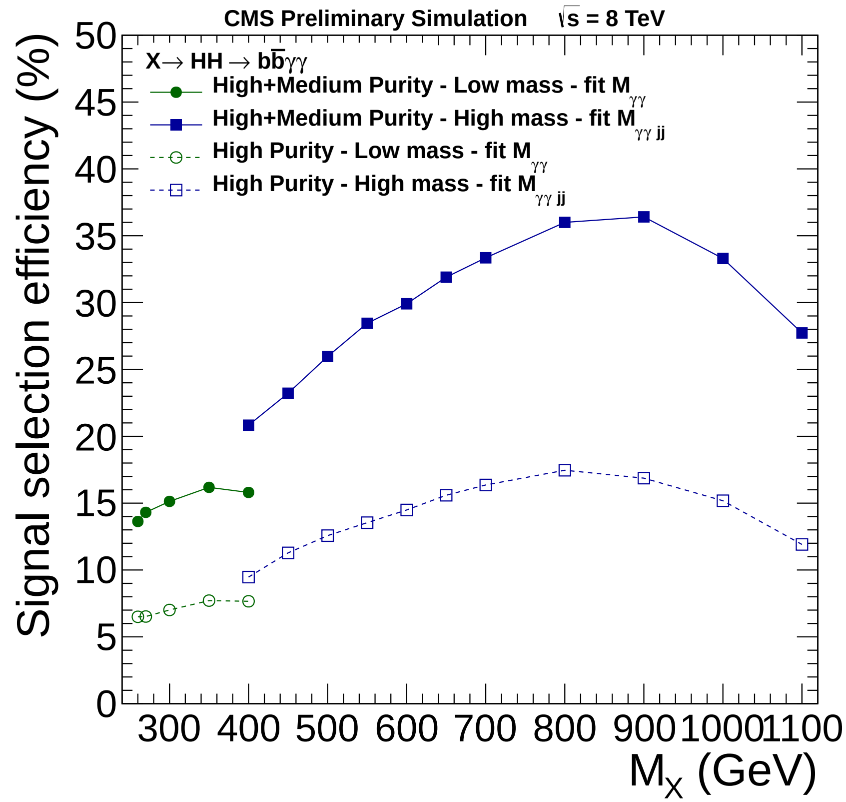


The CS in blue and data in black

- **The signal efficiency**
  - increases from 260 GeV to 900 GeV due to better photon and jet reconstruction efficiencies
  - drops after 900 GeV due to merging of b-quarks into a single jet

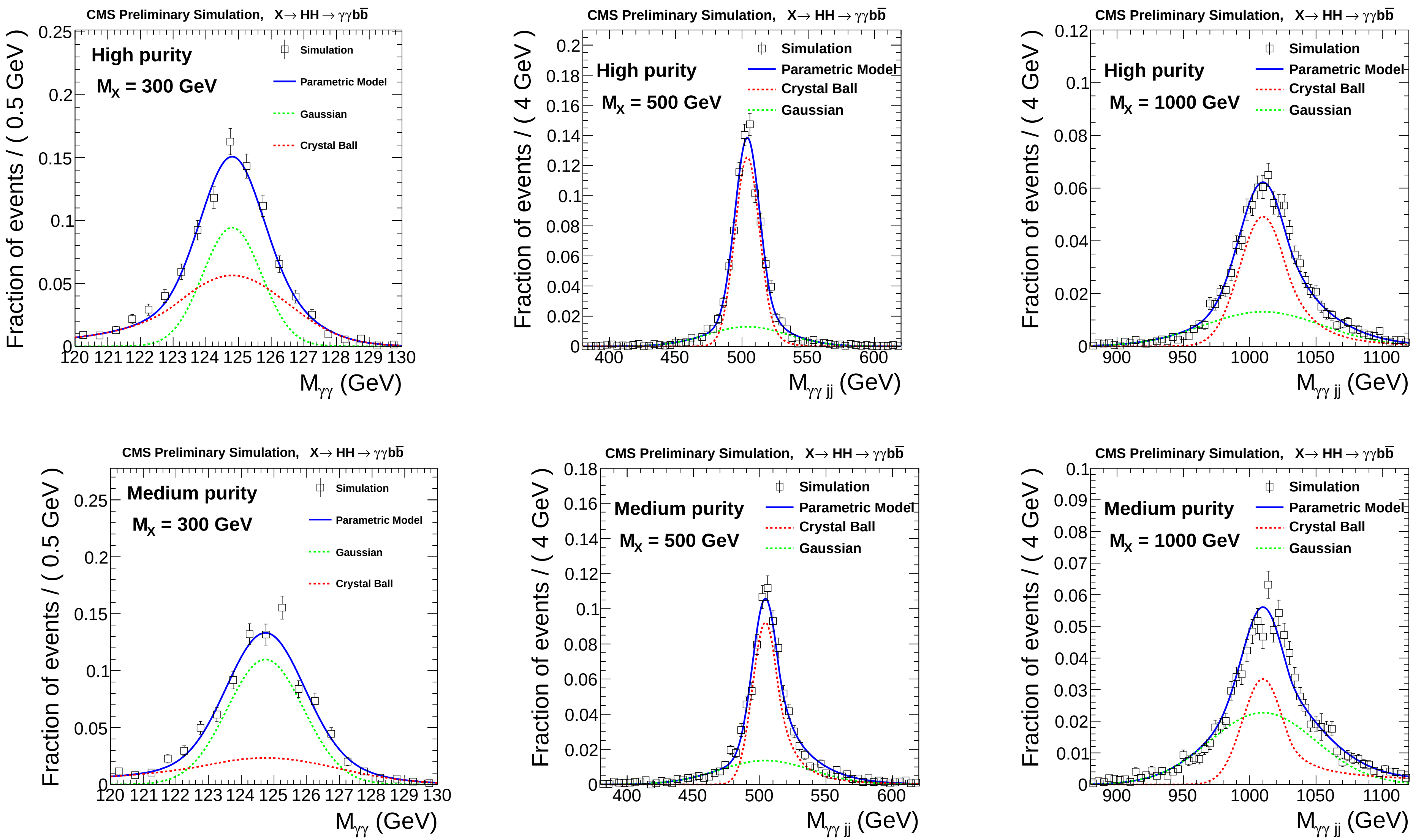
Event yields with the cuts finalized

Sample	1 b-tag	2-btag
R(300 GeV)	21.7	18.7
ggH ($\rightarrow \gamma\gamma$)	0.19	0.02
VBF (H$\rightarrow \gamma\gamma$)	0.04	-
WH ($\rightarrow \gamma\gamma$)	0.05	-
ZH ($\rightarrow \gamma\gamma$)	0.03	-
ttH ($\rightarrow \gamma\gamma$)	0.15	0.10
$\gamma\gamma$+jets	188	8.9
γ+jets	9.2	-
QCD	-	-
DY+Zγ+W$\gamma\gamma$	0.21	-
t$\gamma\gamma$+tt$\gamma\gamma$+ttγj	1.2	0.44
Data	230	21



Sample	1 b-tag	2-btag
R(500 GeV)	6.47	6.08
R(700 GeV)	3.03	2.92
R(1000 GeV)	1.12	0.94
$\gamma\gamma$+jets	70	3.0
γ+jets	3.0	-
QCD	-	-
DY+Zγ+W$\gamma\gamma$	0.08	-
t$\gamma\gamma$+tt$\gamma\gamma$+ttγj	0.55	0.15
Data	79	8

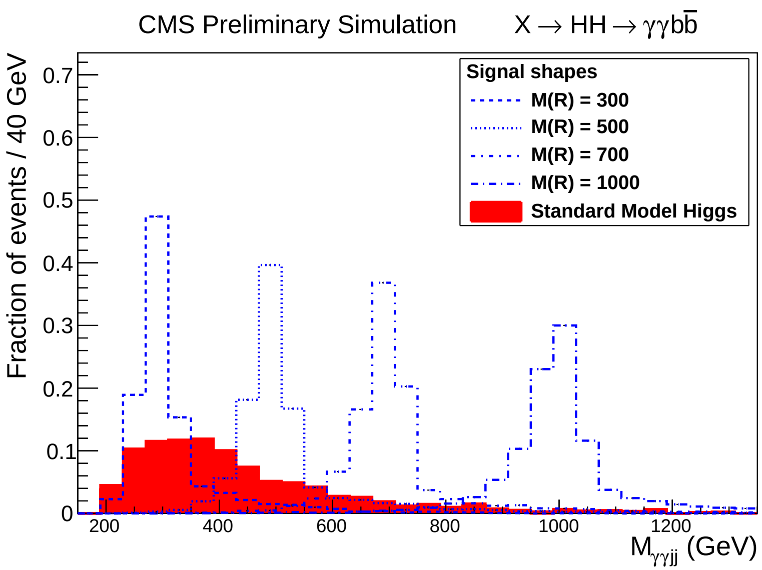
Model signal with Crystal Ball plus Gaussian lineshape

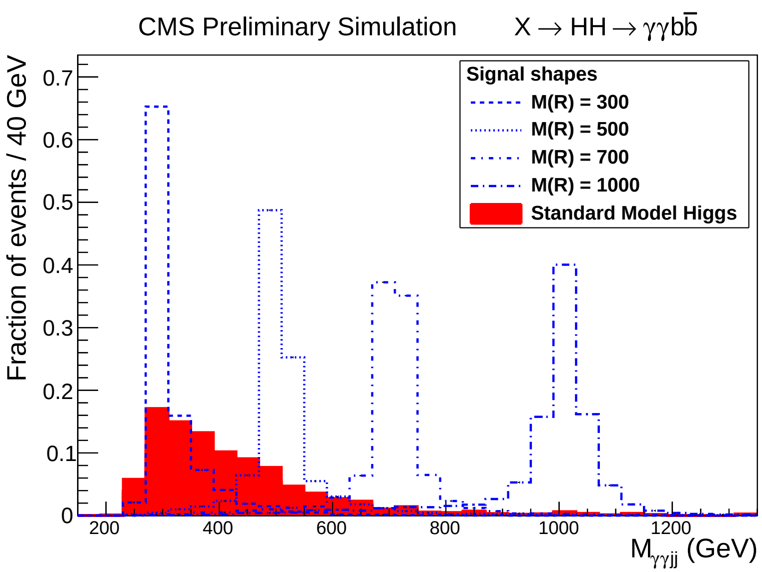


Perform Kinematic Fit to improve $M_{\gamma\gamma jj}$ mass resolution for intermediate mass resonance search

- After all cuts, an additional **constraint** M_{jj}**=125 GeV** is applied
  - the four-momentum of each jet in the dijet candidate is varied over its energy and position resolutions
  - the resonant and nonresonant backgrounds are shuffled around while the resolution of the signal is improved

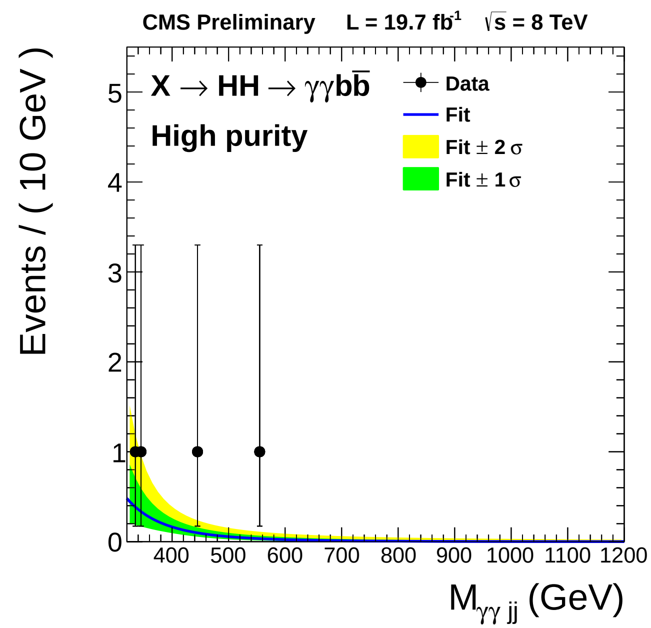
$M_{\gamma\gamma jj}$ background spectrum remains unbiased to a certain phase space

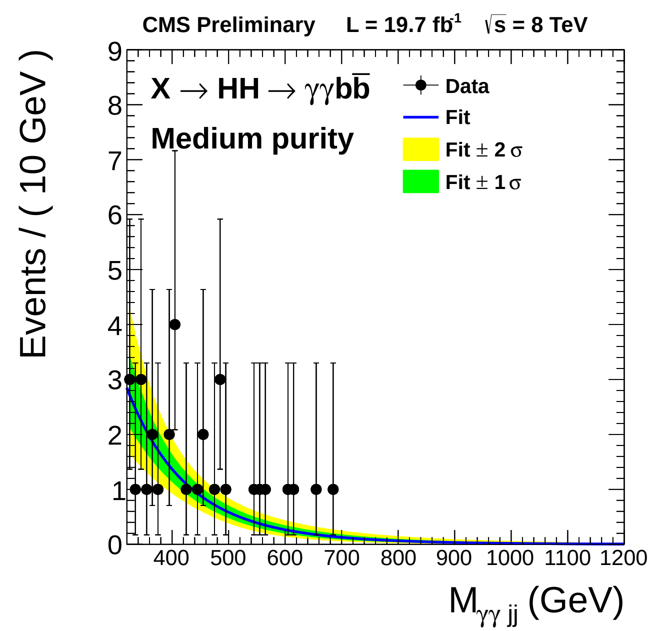


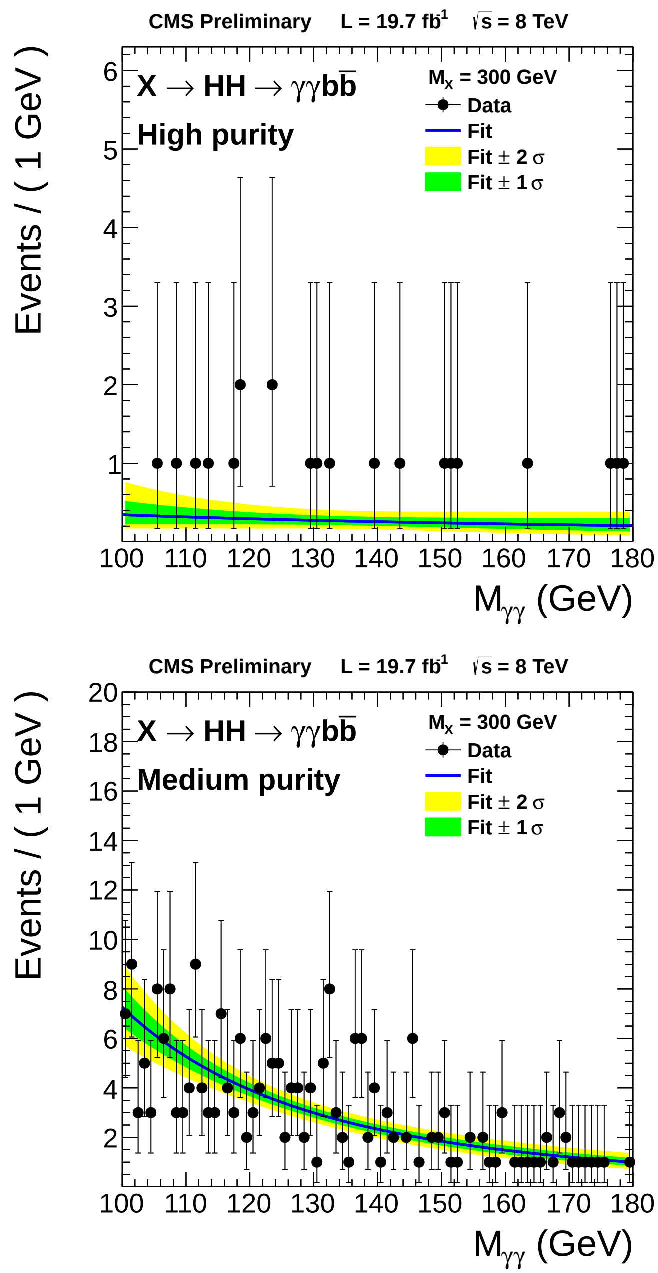


- Background model for $M_{\gamma\gamma jj} \in$[320,1200]:
  - medium purity category: $\frac{1}{(M^2_{\gamma\gamma jj}+b)^a}$
  - high purity category: $\frac{1}{(M_{\gamma\gamma jj})^{2a}}$
- **Bias studies:**
  - built truth models by fitting the control sample
  - candidate functions are fit to each toy
  - the pull is evaluated for signal regions about $M_{\gamma\gamma jj}$ =500, 700, 1000 GeV

$$\mathbf{bias} = \left| \mathbf{median} \left(\frac{N^{sig}_{gen} - N^{sig}_{fit}}{\sigma_{N^{sig}_{fit}}} \right) \right| < 0.14$$



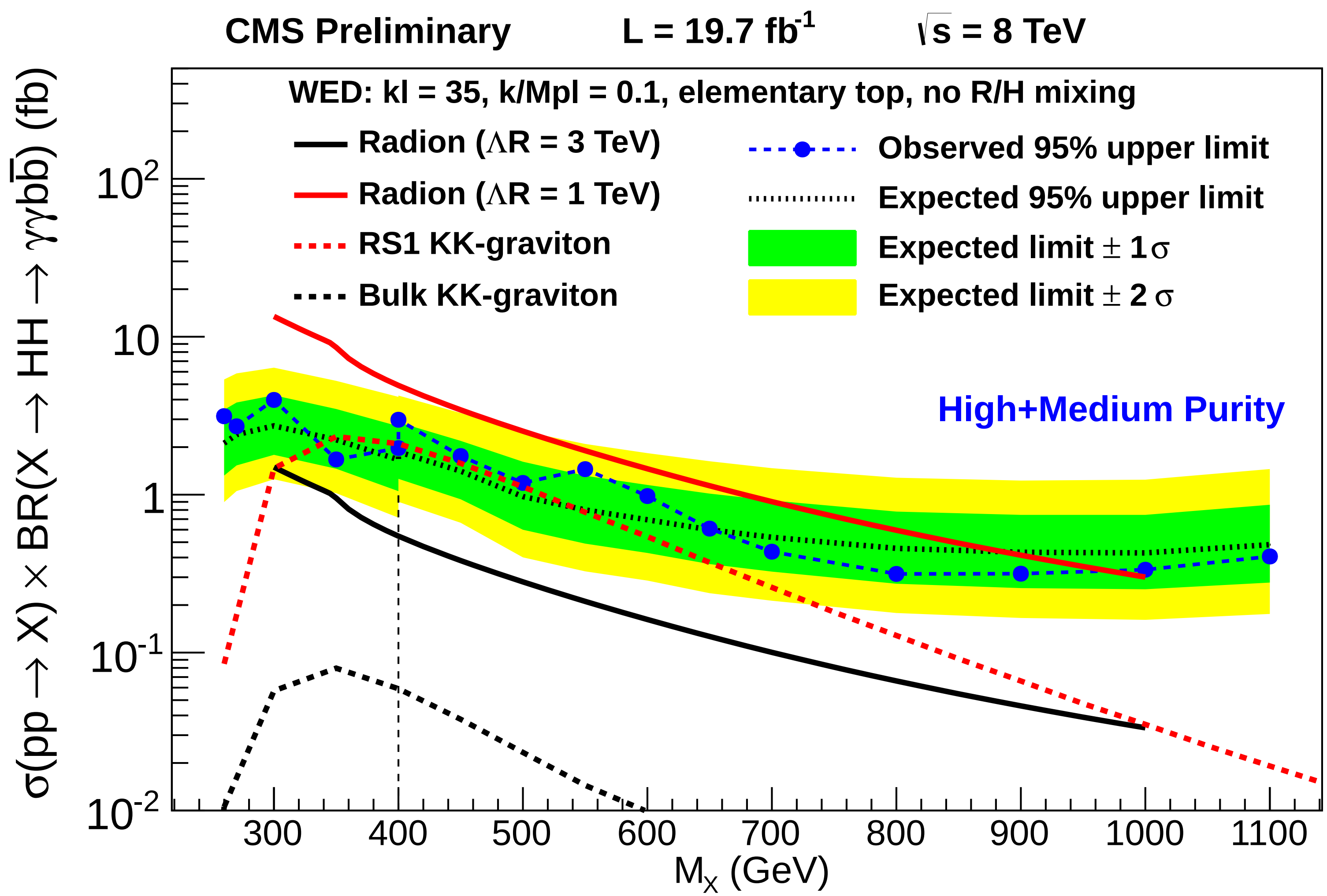




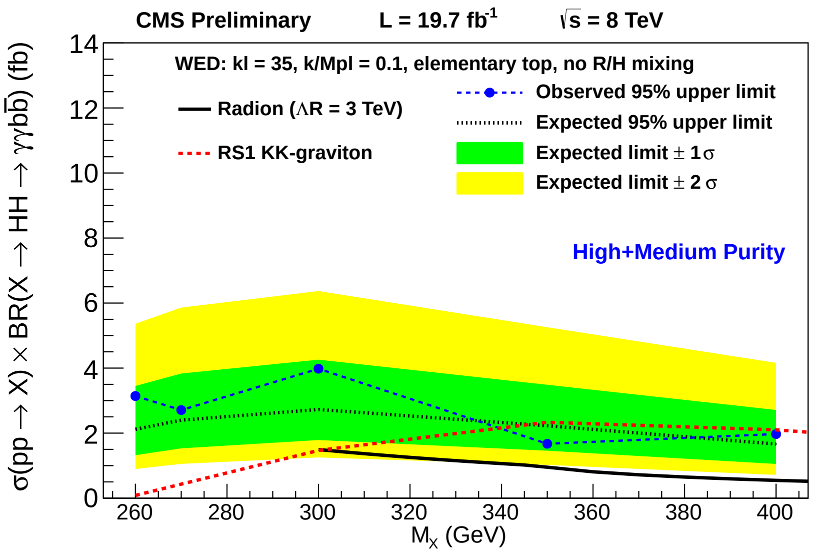
Model background with a power law

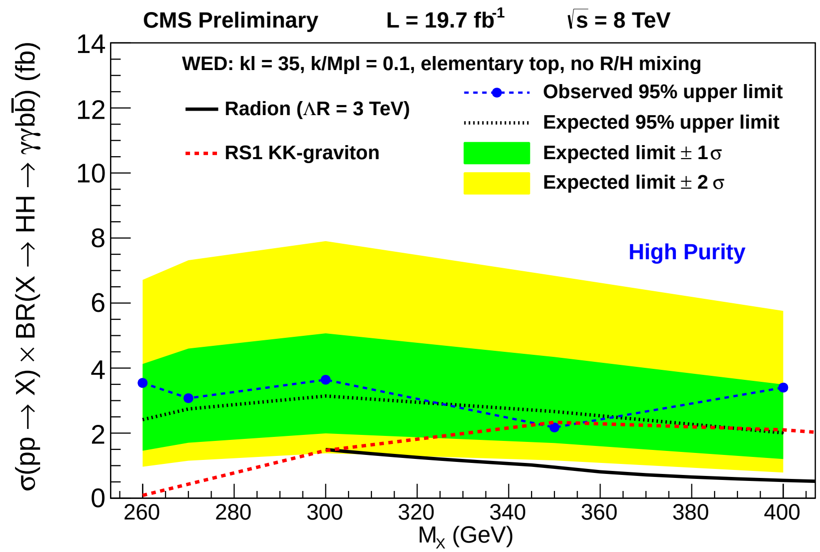
- **Bias studies:**
  - same idea as in the intermediate mass search
  - background plus signal are fit to each toy
  - the pull on signal yield is examined for M_H=120, 125, 130 GeV
- SM Higgs can contribute as signal in the $M_{\gamma\gamma}$ fit
  - contribute to 0.46 (0.13) events in the medium (high) purity category for M_X=300 GeV
  - theory uncertainty degrades the limit by ∼3%

Common normalization uncertainties	
Luminosity	2.6%
Diphoton trigger acceptance	1.0%
fit $M_{\gamma\gamma}$ - Background dominated	
Normalization uncertainties	
Photons selection acceptance	1.0%
"b-tag" eff. uncertainty 2 btag cat	4.6%
"b-tag" eff. uncertainty 1 btag cat	-1.2%
M_{jj} and $p_{T,j}$ cut acceptance (JES & JER)	1.5%
$M_{\gamma\gamma\mathrm{jj}}$ cut acceptance (PES $\oplus$ JES & PER $\oplus$ JER)	2%
Shape uncertainties	
Parametric scale shift (PES$\oplus$M(H) uncertainty)	$\frac{\Delta M_{\gamma\gamma}}{M_{\gamma\gamma}} = 0.45 \oplus 0.35\%$
Parametric resolution shift (RES)	$\frac{\Delta\sigma}{M_{\gamma\gamma}} = 0.25\%$ $\frac{\Delta\sigma}{\sigma_{\gamma\gamma}} = 22\%$
fit $M_{\gamma\gamma\mathrm{jj}}$ - Background dominated	
Normalization uncertainties	
Photons selection acceptance	1.0%
"b-tag" eff. uncertainty 2 btag cat	5.3%
"b-tag" eff. uncertainty 1 btag cat	-1.8%
M_{jj} and $p_{T,j}$ cut acceptance (JES & JER)	1.5%
$M_{\gamma\gamma}$ cut acceptance (PES & PER)	0.5%
Extra High pt norm. uncertainty	5.0%
Shape uncertainties	
Parametric abs. shift (PES $\oplus$ JES)	$\frac{\Delta M_{\gamma\gamma\mathrm{jj}}}{M_{\gamma\gamma\mathrm{jj}}} = 0.45 \oplus (0.8 \oplus 1.0) = 1.4\%$
Parametric shift (PER $\oplus$ JER)	$\frac{\Delta\sigma}{\sigma_{\gamma\gamma\mathrm{jj}}} = 10\%$



Radion with Λ_R=1 TeV is observed (expected) to be excluded for M_R <0.97(0.88) TeV at 95% CL





M_X	Observed limit (fb)	Expected limit (fb)	Observed limit (fb)	Expected limit (fb)
			High-purity category only	
260	3.14	2.12	3.54	2.41
270	2.70	2.40	3.07	2.74
300	3.98	2.73	3.64	3.14
350	1.67	2.23	2.17	2.66
400	1.97	1.66	3.40	2.01

The RS1 KK-graviton is excluded between 340 and 400 GeV at 95% CL

- A search for **diHiggs resonance** was performed in **the $\gamma\gamma bb$ final state** on the mass range $M_X \in$[260, 1100] GeV
  - two strategies for signal extraction were employed:
    - $M_{\gamma\gamma}$ fit for $M_X <$400 GeV
    - $M_{\gamma\gamma jj}$ fit for $M_X \geq$400 GeV
  - step toward most promising signature to measure **the Higgs self-coupling**
  - observations are compatible with expectations from Standard Model processes
  - analysis designed to minimize the sensitivity to spin hypothesis
- Three reference models based on gravity particles from **WED** were considered
  - **radion** with Λ_R=1 TeV is excluded for $M_R <$0.97 TeV at 95% CL
  - **RS1 KK-graviton** is excluded [340,400] GeV at 95% CL
  - **bulk KK-graviton** requires remarkable statistics

Backup

Background Model (Low Mass)