Search for heavy resonance in boosted jet plus MET final state in CMS

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on behalf of the CMS collaboration

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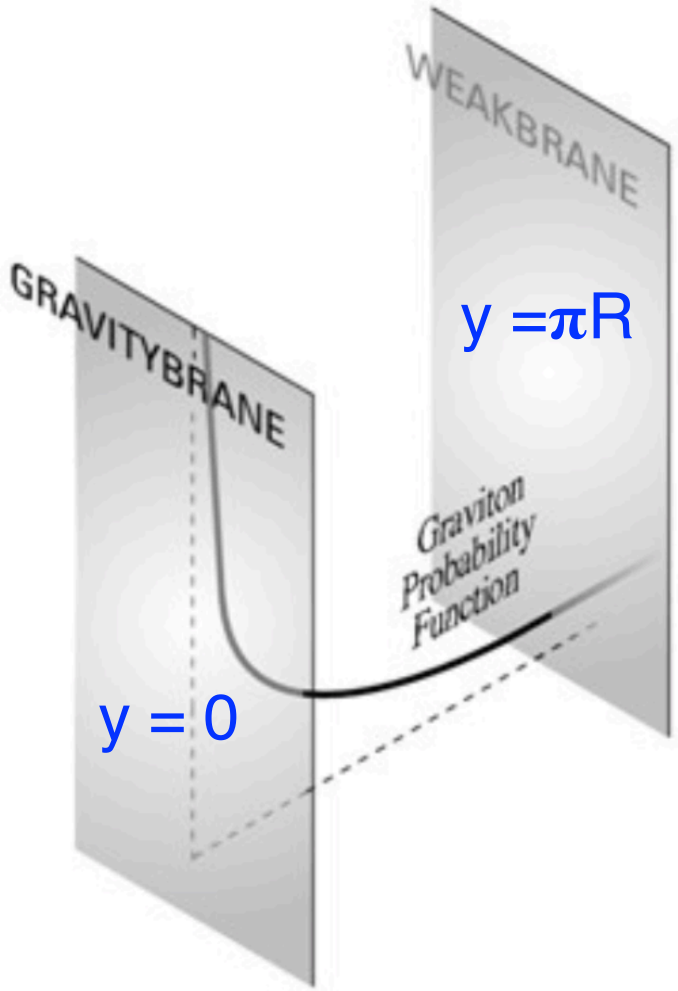
Introduction

- **Beyond Standard Model theory (Extra dimension):**

  Extra dimensional models can potentially explain the large hierarchy between electroweak energy scale and the energy scale of gravity.

- **Randall-Sundrum (RS) model:**
  - One additional dimension (y) that extends between the Planck/gravity scale and the Weak (SM) scale in the form of "warp" geometry.
  - Resonance
    - Graviton: Kaluza-Klein modes (heavy particles of O(TeV))
    - Radions: Scalar fields for the stabilization

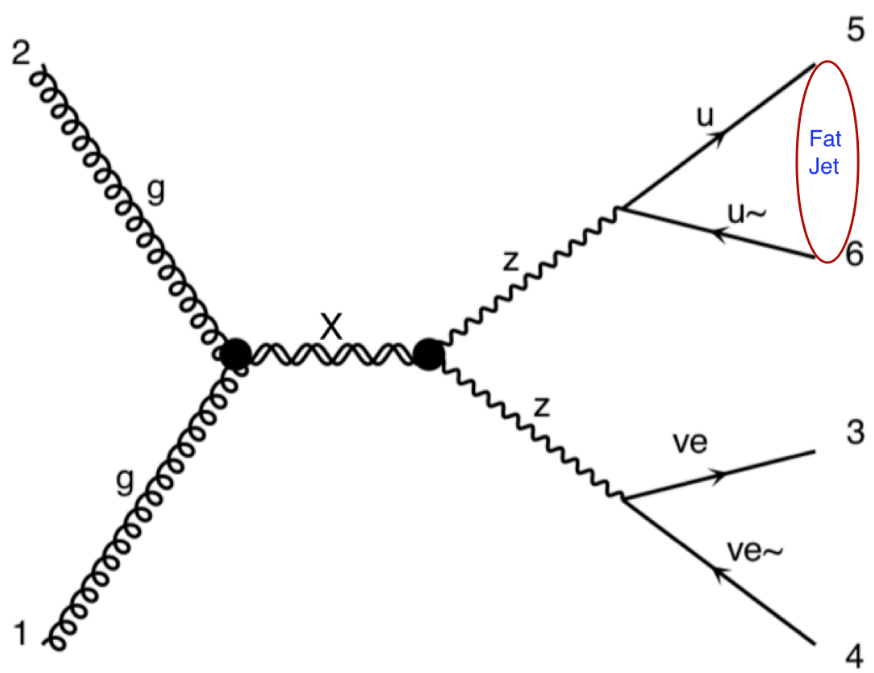


- **Heavy vector triplet (HVT) method:**
  - To bridge between the experimental data and many theoretical methods.
  - Proposes the heavy resonance in the form of a vector triplet (3 spin-1 weak vector bosons).

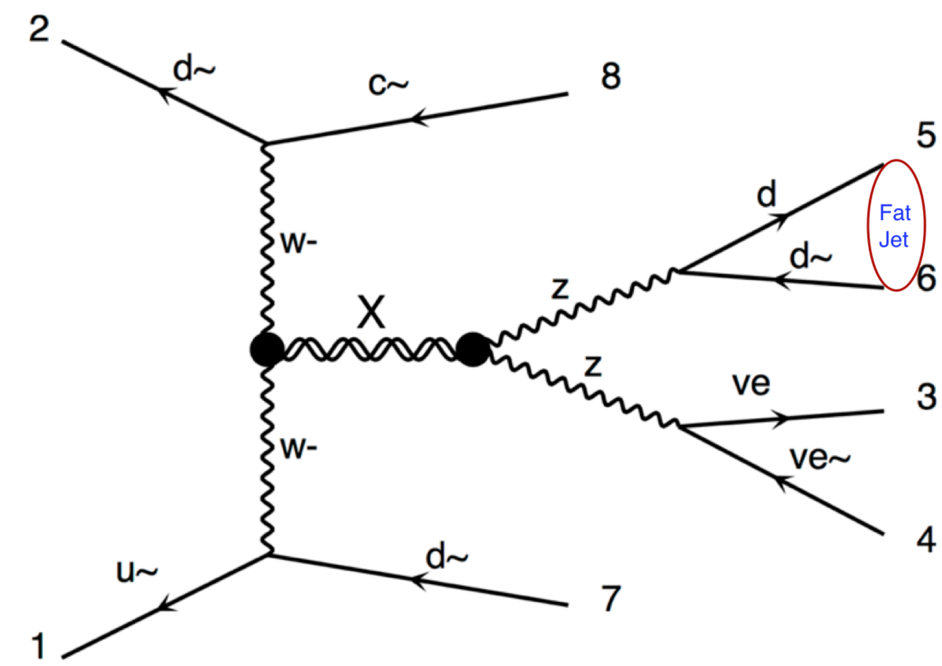
- **We are looking for the following resonances:**
  - Spin 0: Radion (Bulk scenario)
  - Spin 1: W' (HVT model B (DY production), model C (VBF production only))
  - Spin 2: Graviton (Bulk scenario)

Search channel

gluon-gluon fusion (ggF)



Vector boson fusion (VBF)



X:

spin 0: Radion → ZZ

spin 1: W' → WZ

spin 2: Graviton → ZZ

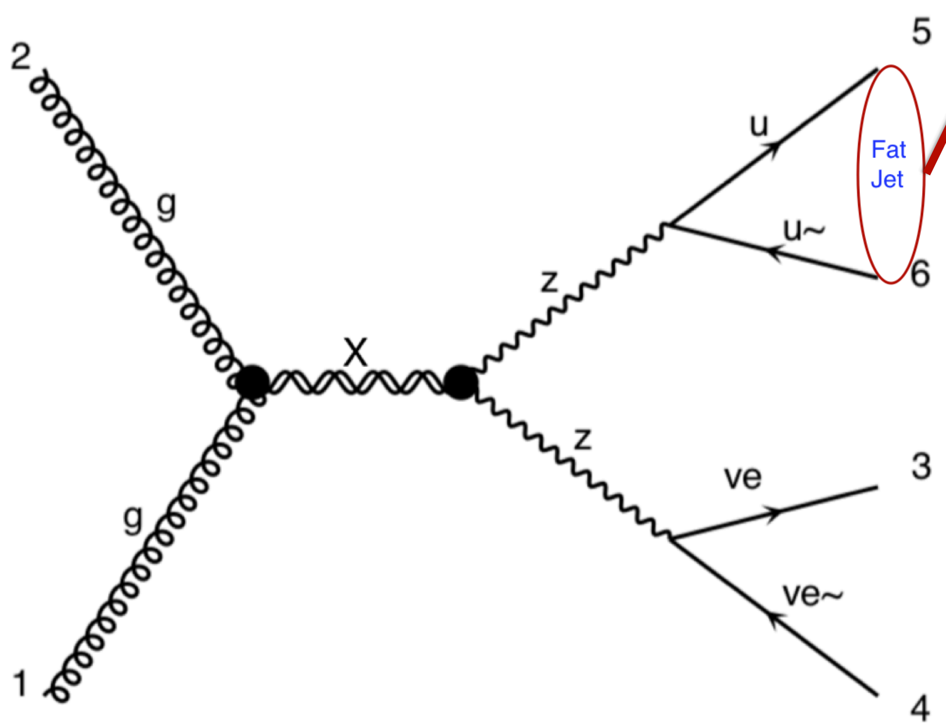
** For W':

(ggf → DY process)

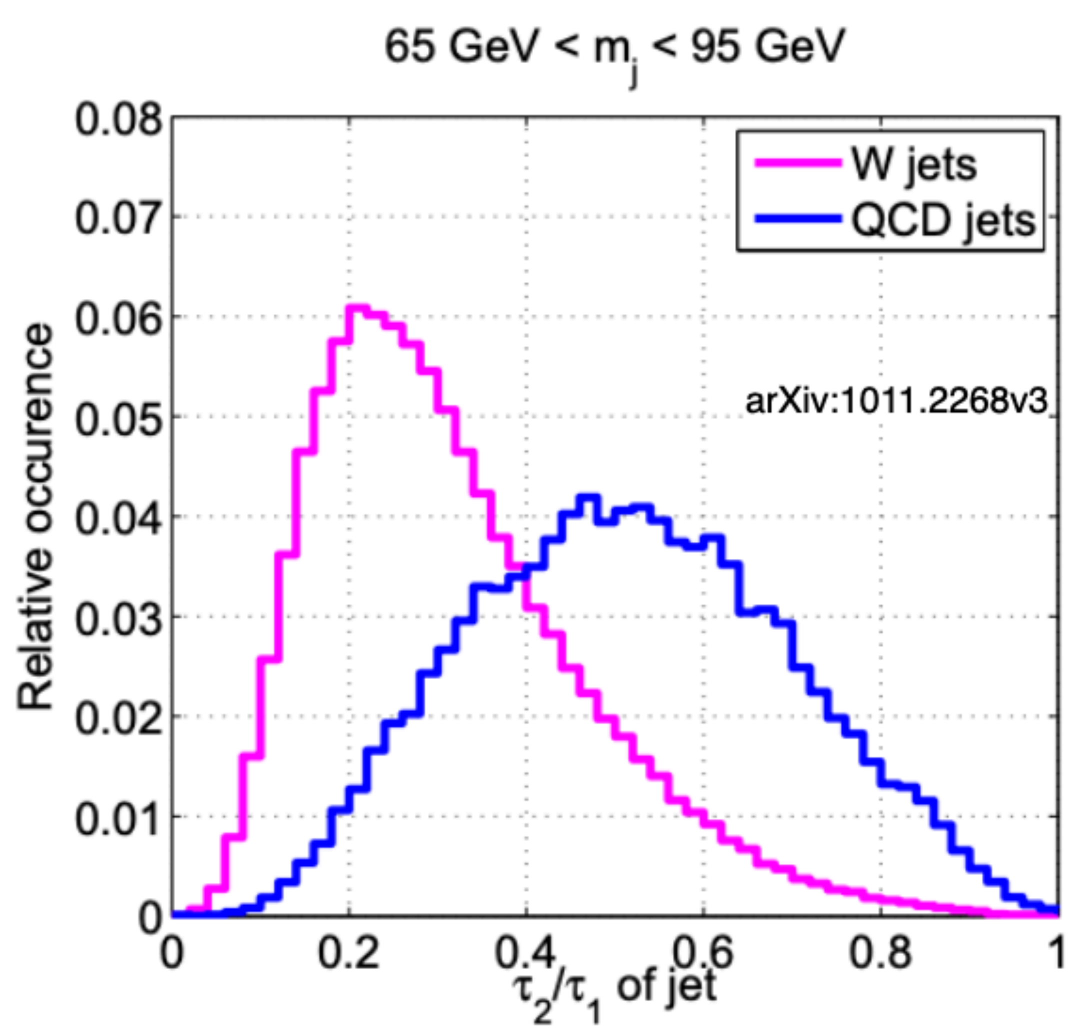
- ggF:
  - Signature: boosted jet
  - Previously done (spin 1 & 2) with 2016 data: JHEP 07 (2018) 075
  - Performed with full Run 2 data (137 fb^{-1}) and also adding spin-0 interpretation.
- VBF:
  - Signature: forward jets and boosted jet.
  - New particles may predominantly couple to heavy bosons.
  - All 3 spin interpretations are new additions.

Objects and event selections

- **Invisible Z selection:**
  - Missing energy (MET) > 200 GeV
- **Jets:**
  - AK4 and AK8 (fat) in terms of cone size
  - AK4: $p_T > 30$ GeV
  - AK8 leading jet: $p_T > 200$ GeV, $|\eta| < 2.5$
- **Veto:**
  - electrons, muons, taus
  - photons ($p_T > 100$ GeV)
  - b-jet
- **Angular cut:**
  - $\Delta\phi$ (MET, AK4 jet) > 0.5

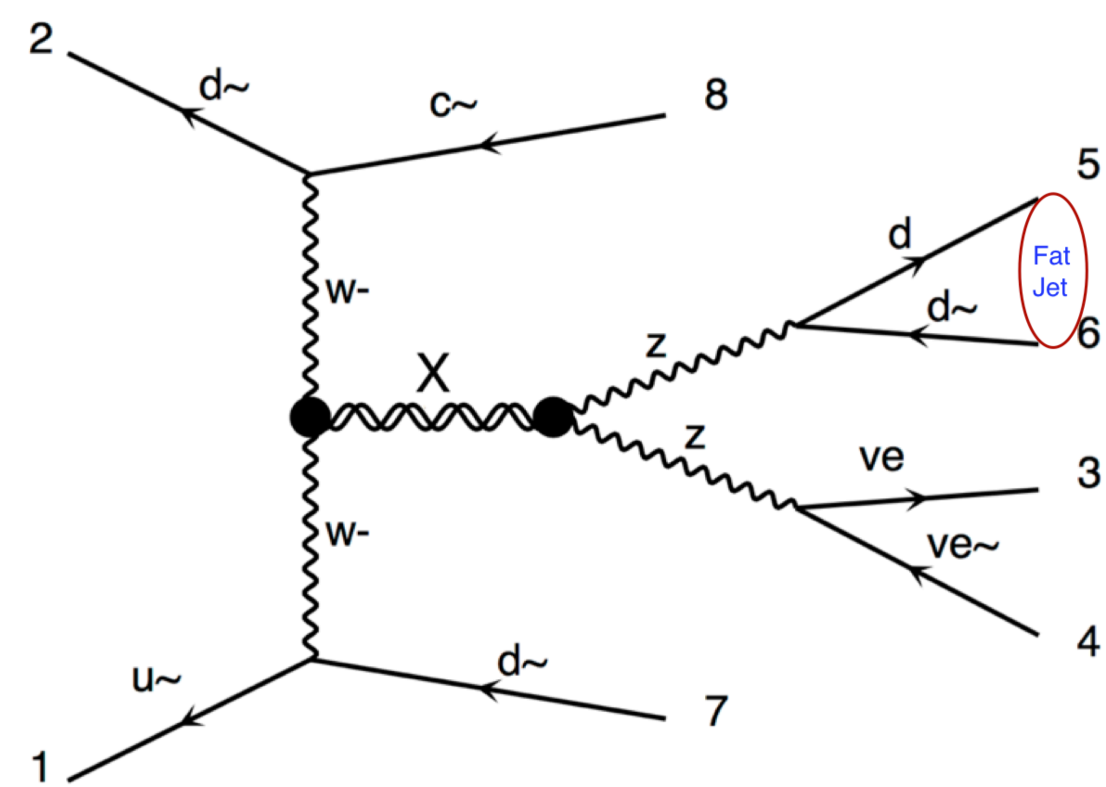


- **Z/W (hadronic) tagging:**
  - AK8 leading jet soft-drop mass:
    - Signal Region (SR): 65-105 GeV
    - Sideband (SB): 30-65 & 135-300 GeV
  - N-subjettiness ratio (τ_{21}):
    - < 0.35 (high purity (HP))
    - $0.35 < \tau_{21} < 0.75$ (low purity (LP)).



Objects and event selections

- **VBF selection: forward jets**
  - 2 AK4 jets with $p_T > 30$ GeV
  - Skip W/Z events by removing the overlap with leading AK8 jet.
  - di-jet mass (m_{jj}) > 500 GeV
  - $|\Delta\eta| > 4.0$
  - $\eta_{j1} \times \eta_{j2} < 0$ (opposite hemisphere)
  - if more than one candidate pair, choose the one with the larger m_{jj}.



- **Heavy resonance mass:**
  - Estimated by calculating the transverse mass (m_T) of the hadronic W/Z and the invisible Z:

$$m_T = \sqrt{2 p_T^J p_T^{miss}[1 - cos\Delta\phi]}$$

Categorization

AK8 leading jet mass	Sideband (SB)	Signal Region (SR)
τ_{21}	High purity (HP)	Low purity (LP)
forward jets	VBF pass (VBF)	ggF/DY

Kinematics: ggF vs VBF production mode

- Transverse mass (m_T) distribution for ggF/DY (left) and VBF (middle) production modes.
- Significantly different shape in VBF production mode: polarization effect.
- Decay angle of SM vector bosons in the rest frame of their parent particle (bottom right).
- Complicated signal shapes make a binned fit a far simpler approach for our statistical interpretations.

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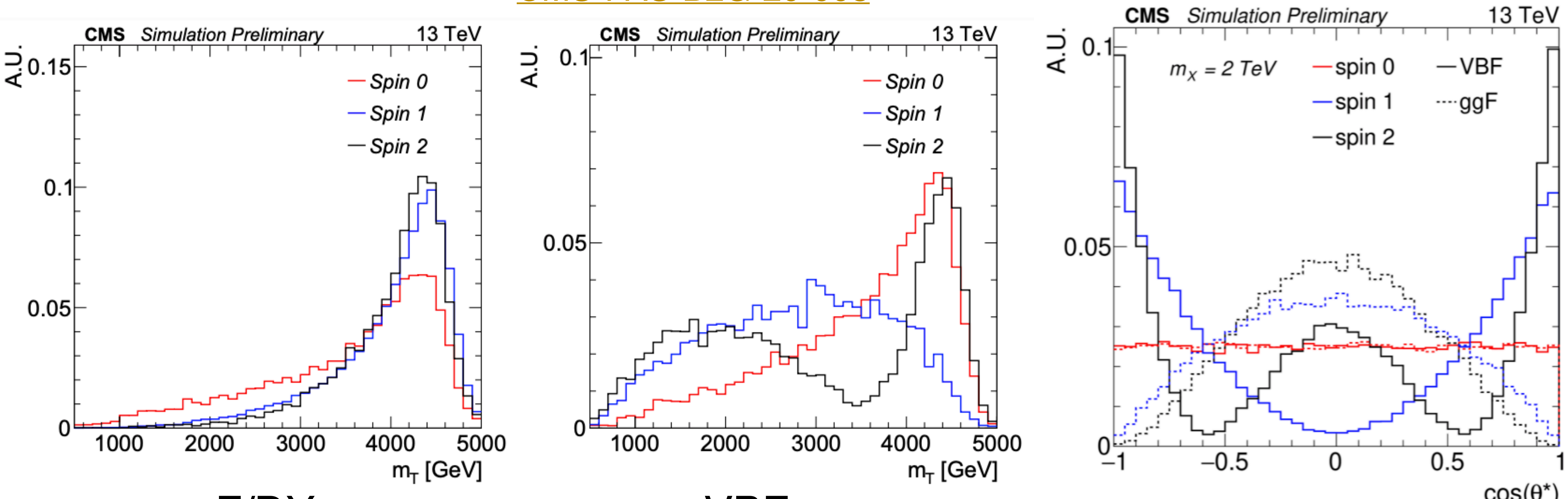
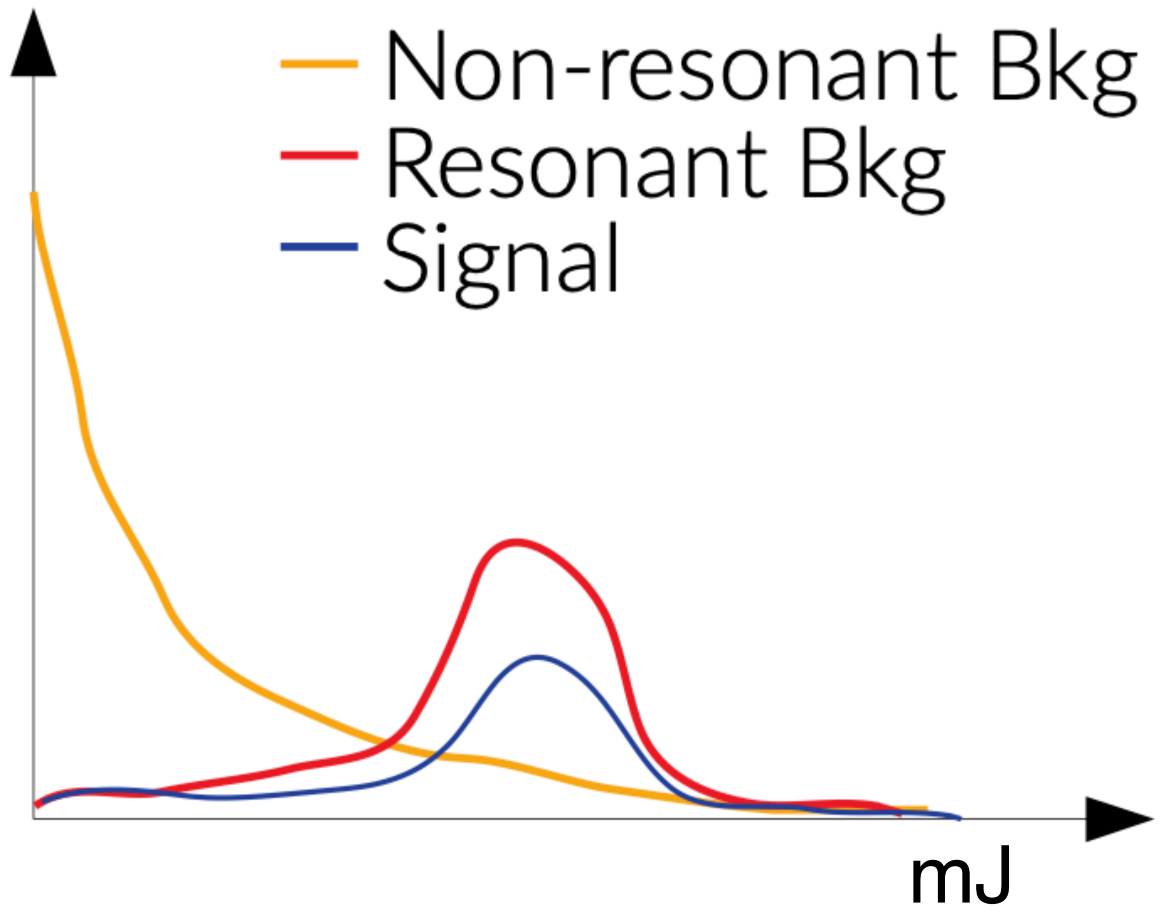


ggF/DY VBF

Samples

- Data: 2016–2018 (137 fb^{-1})
  - MET dataset
- Dominant background:
  - Non-resonant (Z+jets and W+jets)
- Rare background:
  - Resonant (TTbar, Single top, and Other)



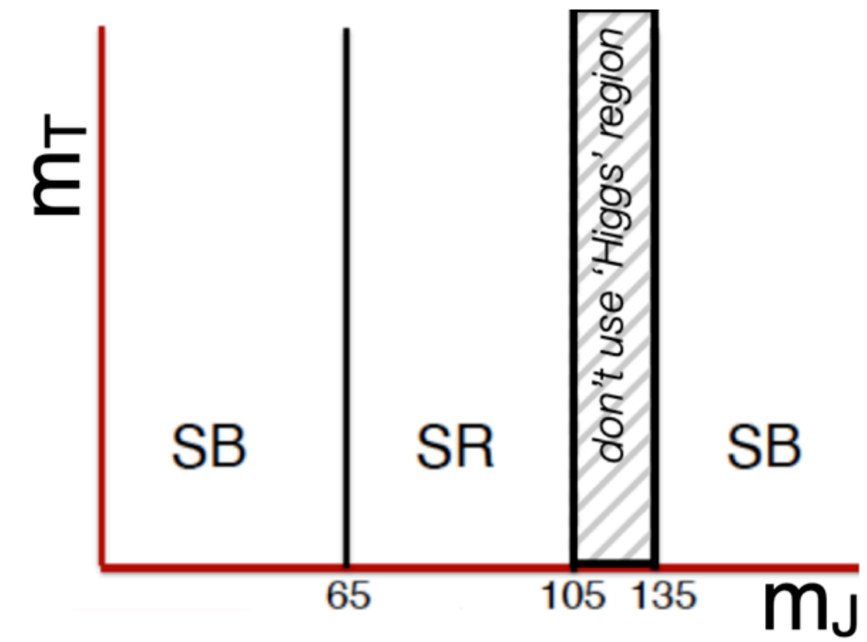
- Signal samples:
  - VBF_RadionToZZ_narrow_M-*
  - VBF_WprimeToWZ_narrow_M-*
  - VBF_BulkGravToZZ_narrow_M-*

  - RadionToZZ_narrow_M-*
  - WprimeToWZ_narrow_M-*
  - BulkGravToZZ_narrow_M-*

M = [1000 - 4500] GeV

Background estimation strategy

- We use the leading pT AK8 jet mass (m_J) to define the signal and control regions.
  - Analysis can be thought of as 2D (m_T vs m_J).
- Two types of backgrounds:
  - Resonant bkg: taken from the MC.
  - Non-resonant bkg: mostly data-driven
    - the m_J sideband (SB) is used to predict the m_T shape & normalization in the signal region (SR).
    - We define a transfer factor (α) that depends on m_T for each category:
      - Computed with MC using only Z and W+jets (V_{jet}).
      - Many systematics cancel in the ratio.
    - Observed distribution in SB is corrected with α after accounting for resonant backgrounds (as predicted from MC).

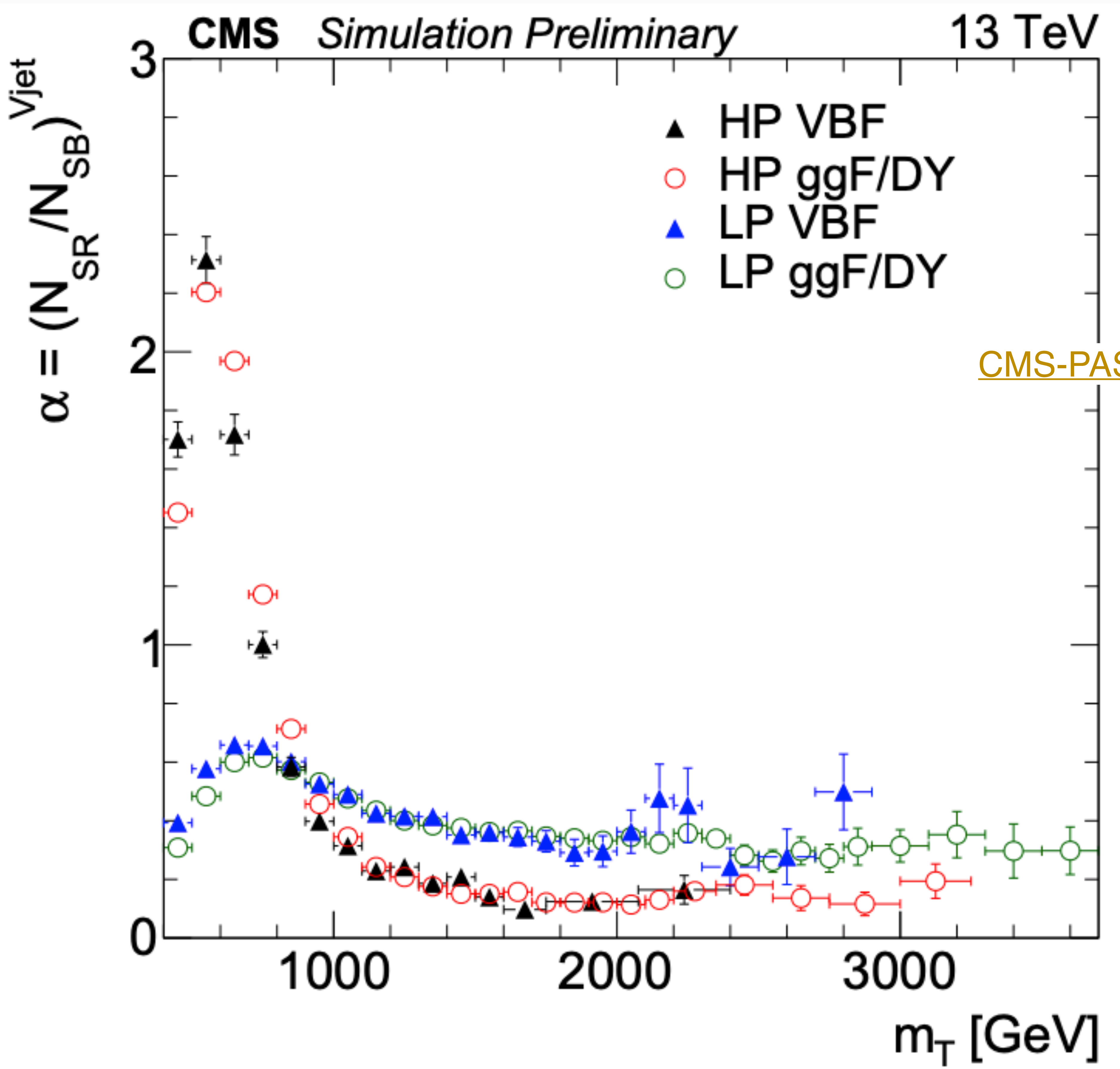


$$\alpha(m_T) = \left(\frac{N_{SR}}{N_{SB}}\right)_{MC,V_{jet}}$$

$$N_{SR}^{predicted}(m_T) = [N_{SB}^{data} - N_{SB}^{MC,Top+VV}] \times \alpha(m_T) + N_{SR}^{MC,Top+VV}$$

Non-resonant prediction

$\alpha(m_T)$ plot



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$$\alpha(m_T) = \left(\frac{N_{SR}}{N_{SB}}\right)_{MC,V_{jet}}$$

Post fit predictions (SR HP): ggF/DY vs VBF

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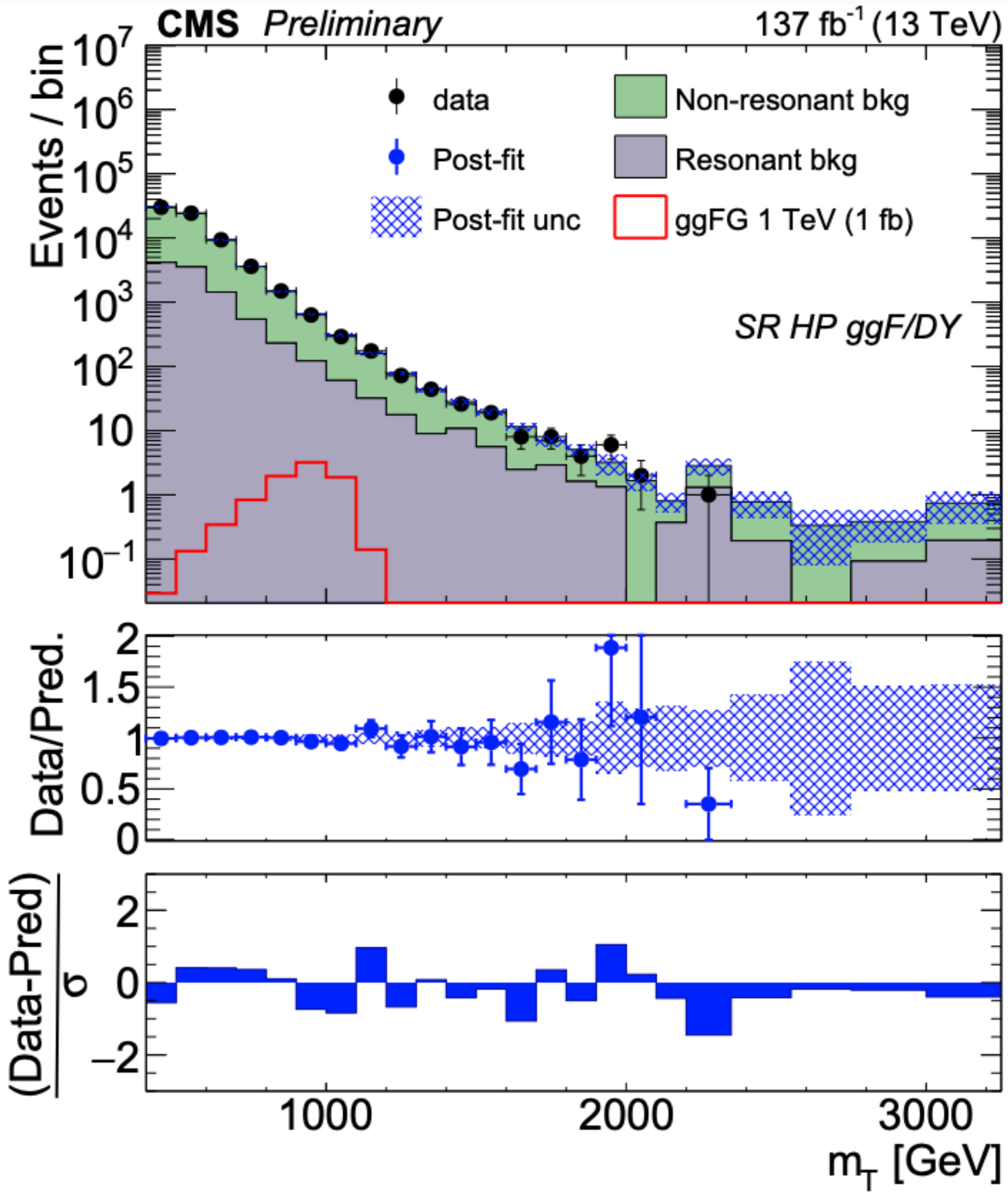
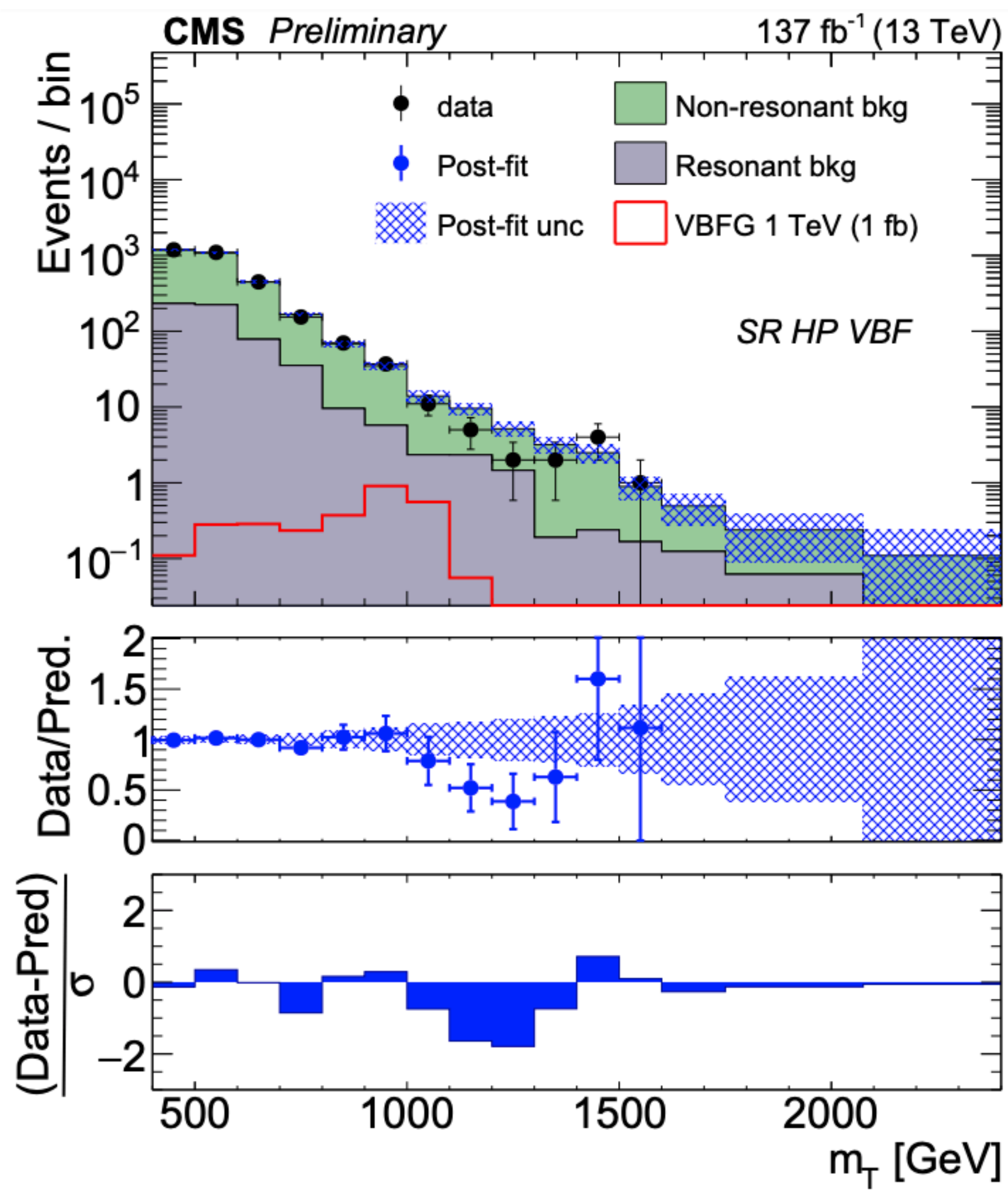




post fit

Data/post-fit

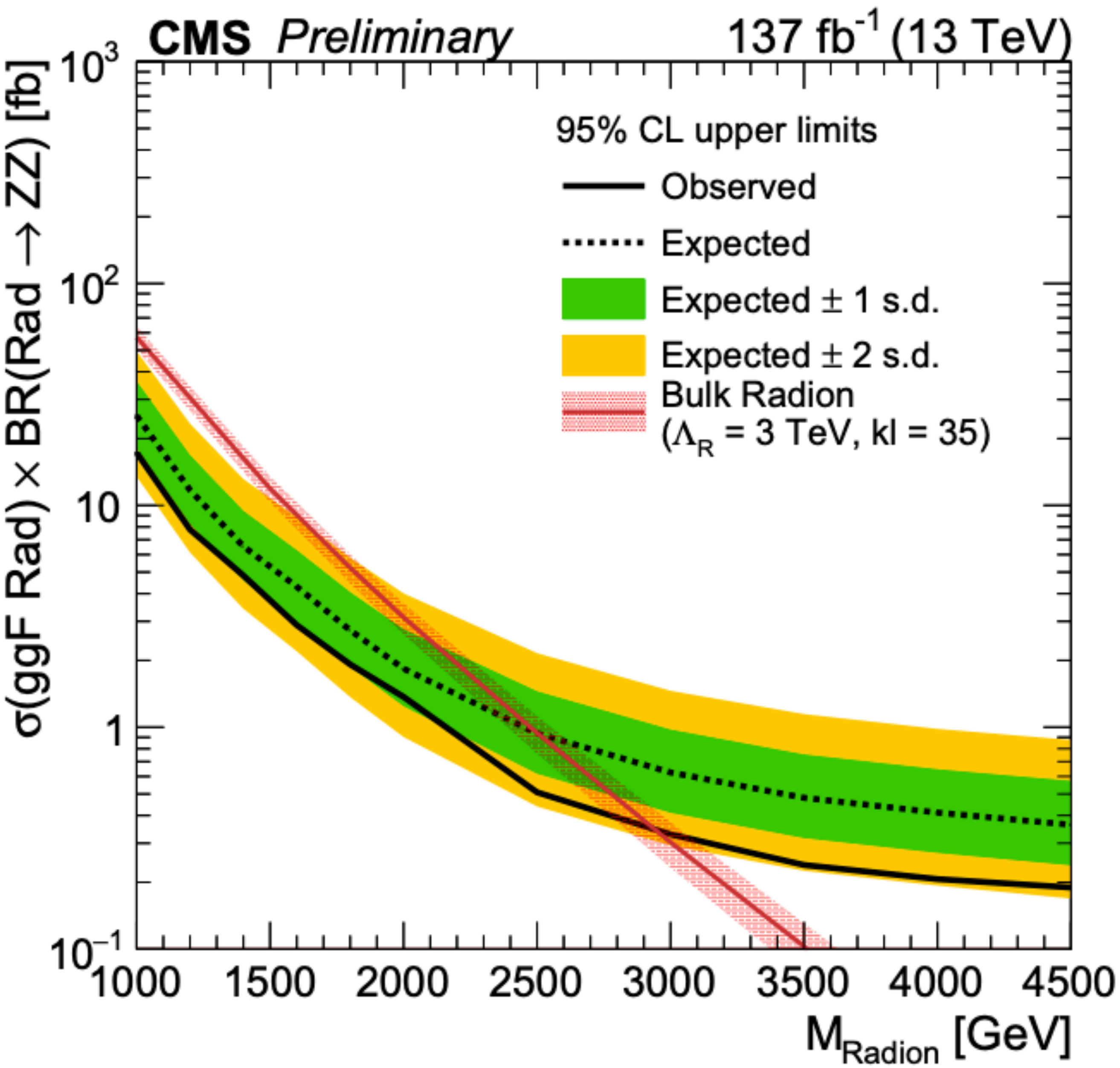
post-fit pulls

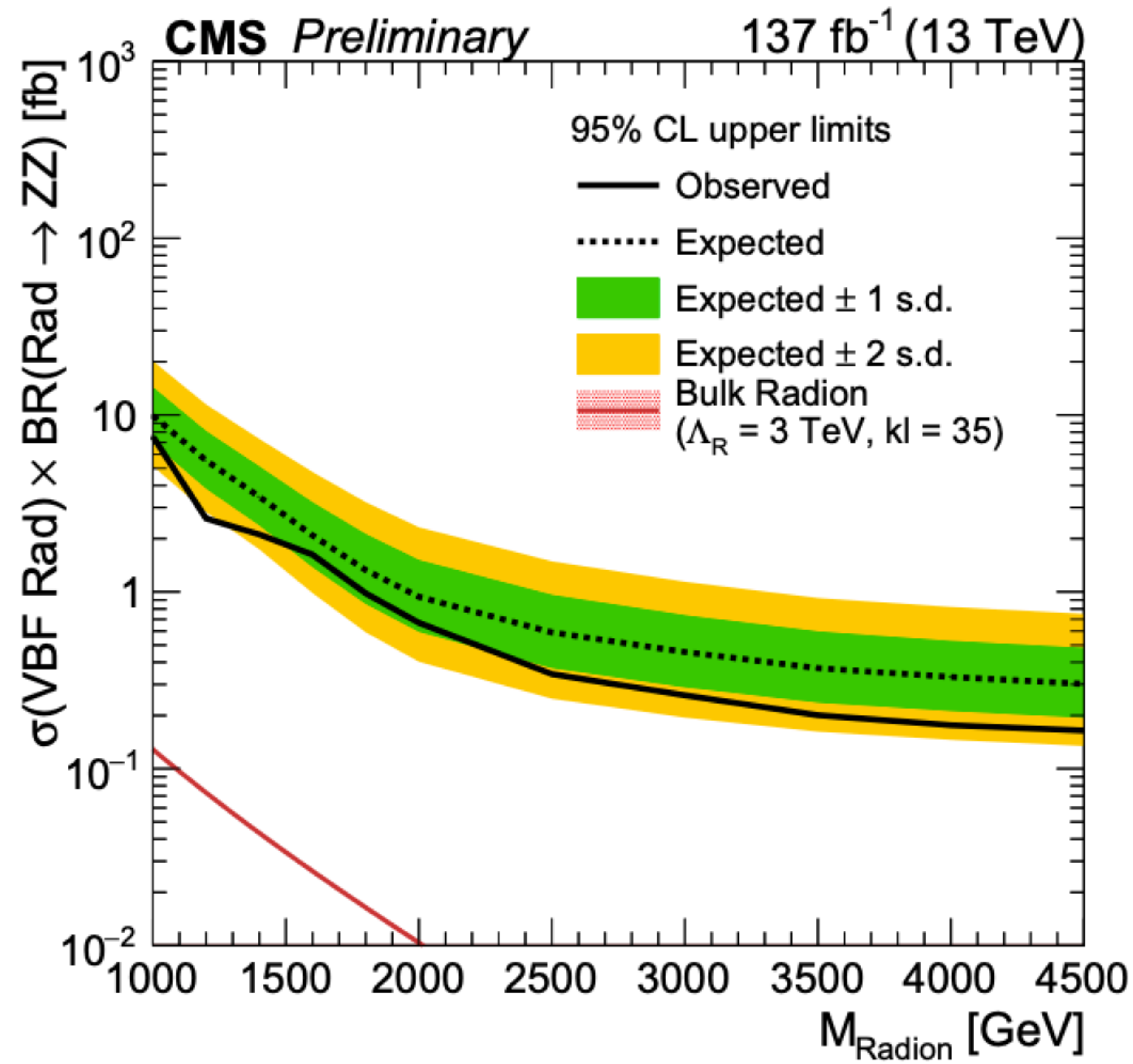
- Left: ggF/DY, right: VBF
- No excess in data is observed.
- Pulls shows up to ~2σ under-prediction.
- Low purity plots are in backup.

Exclusion limits: Radion (spin-0)

- Results after combining all categories (high-purity, low-purity, vbf, and ggF/DY) using the ggF (left) and VBF (right) produced samples.

[CMS-PAS-B2G-20-008]





- New in this channel.
- Mass exclusion (non-VBF):
  - 3.0 TeV (observed)
  - 2.5 TeV (expected)

- VBF: New in this channel.
- Xsec*BR exclusion: 0.2 - 8 fb

Exclusion limits: W' (spin-1)

- Results after combining all categories (high-purity, low-purity, vbf, and DY) using the DY (left) and VBF (right) produced samples.

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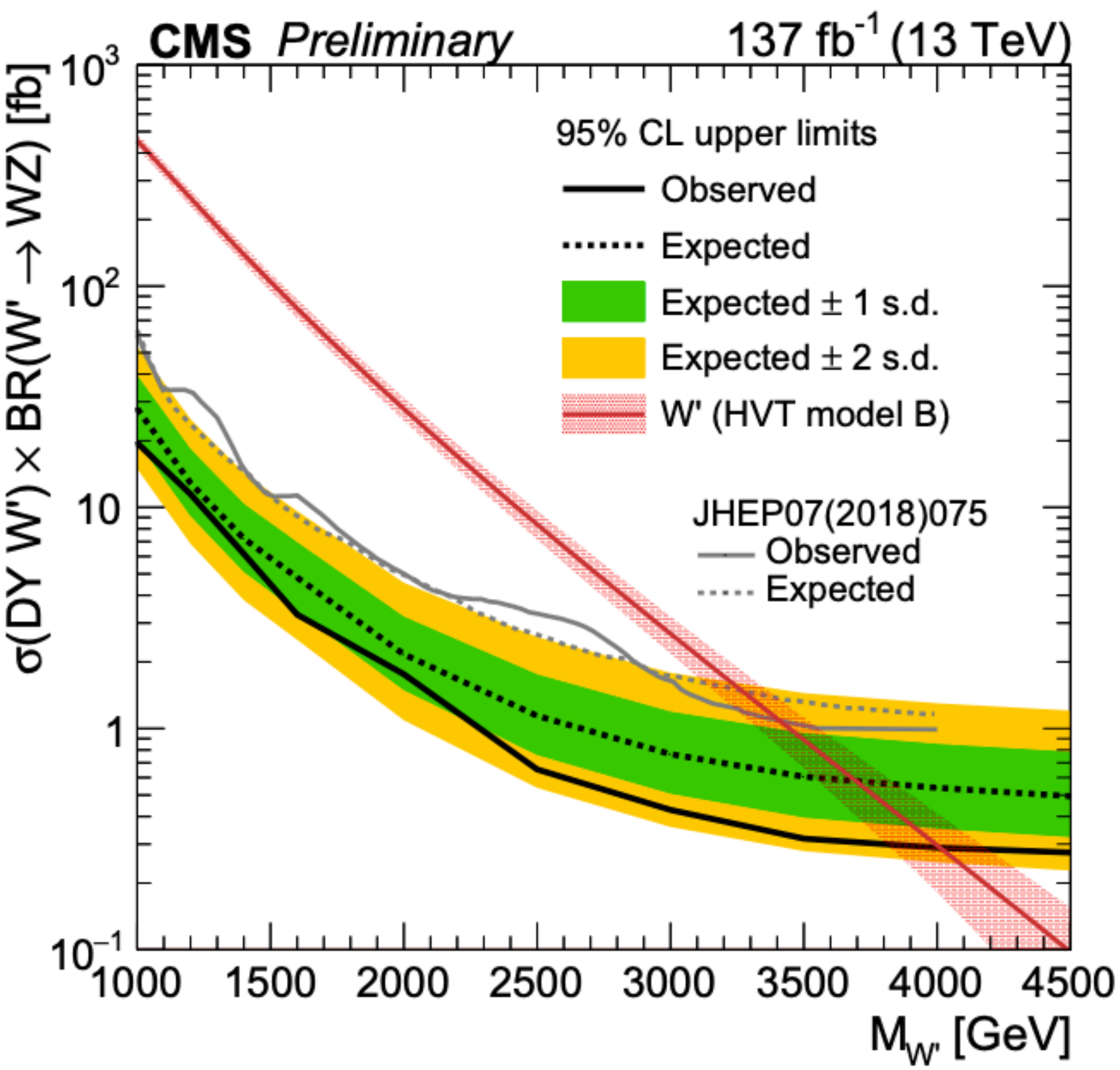
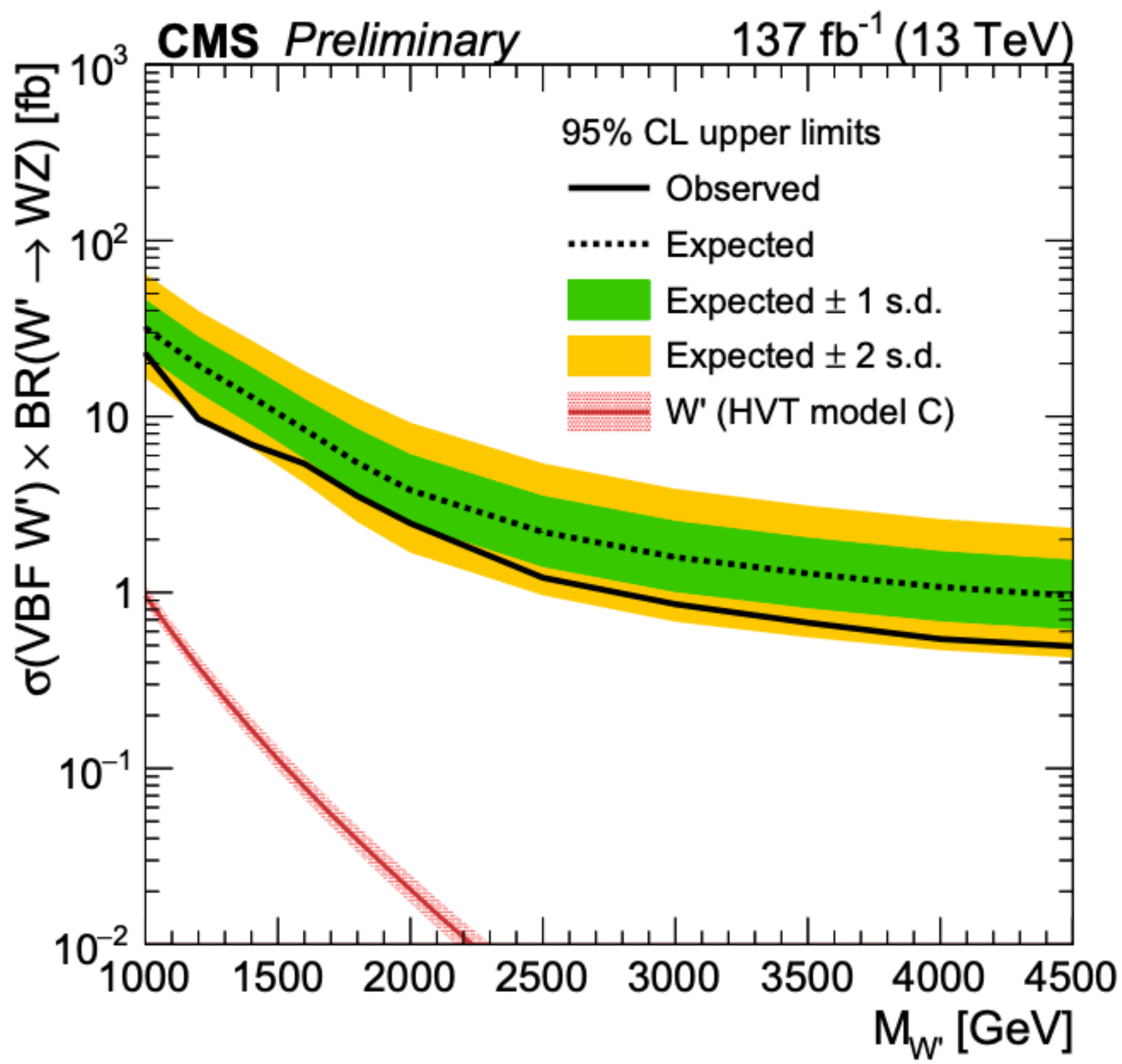


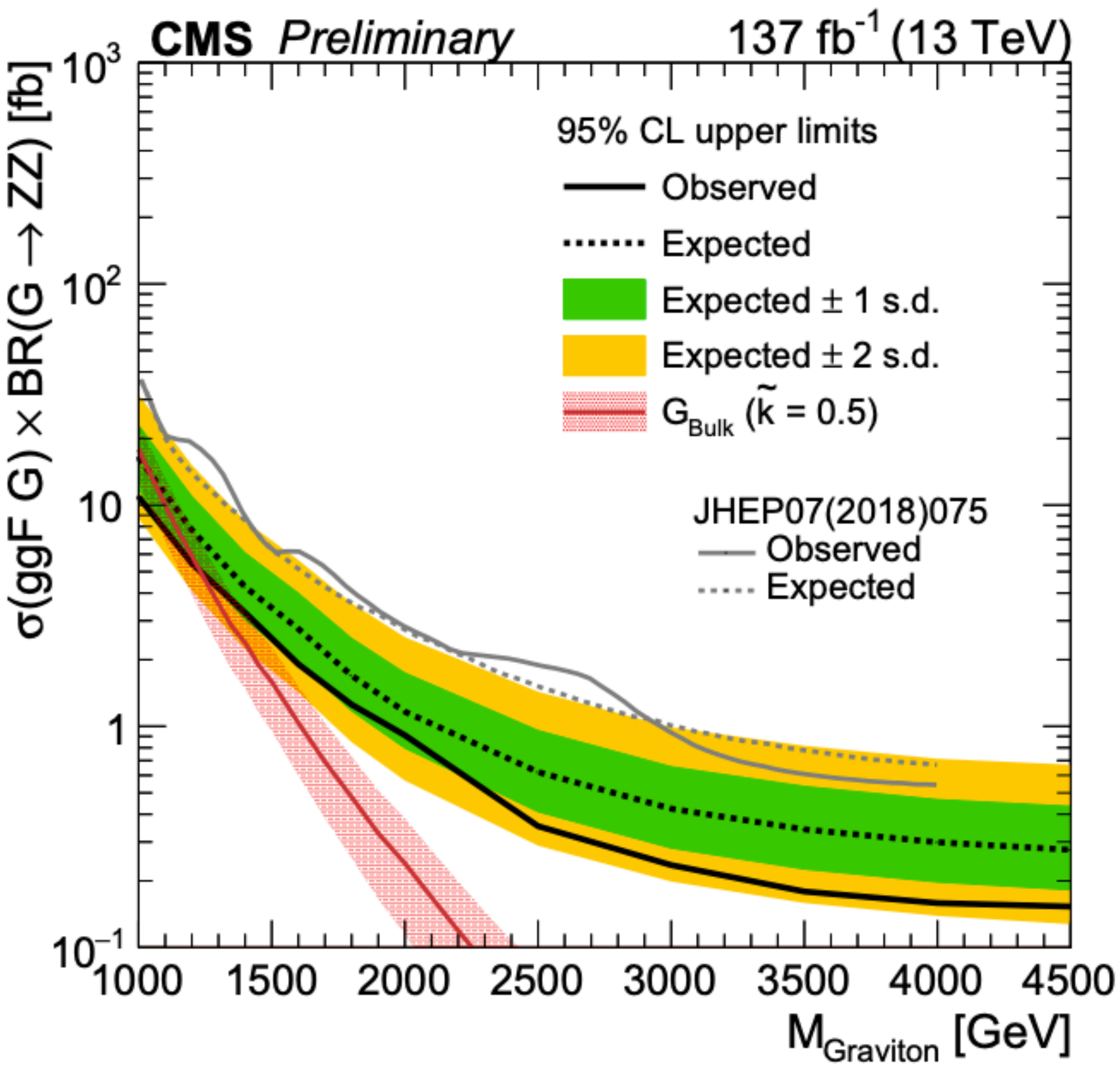


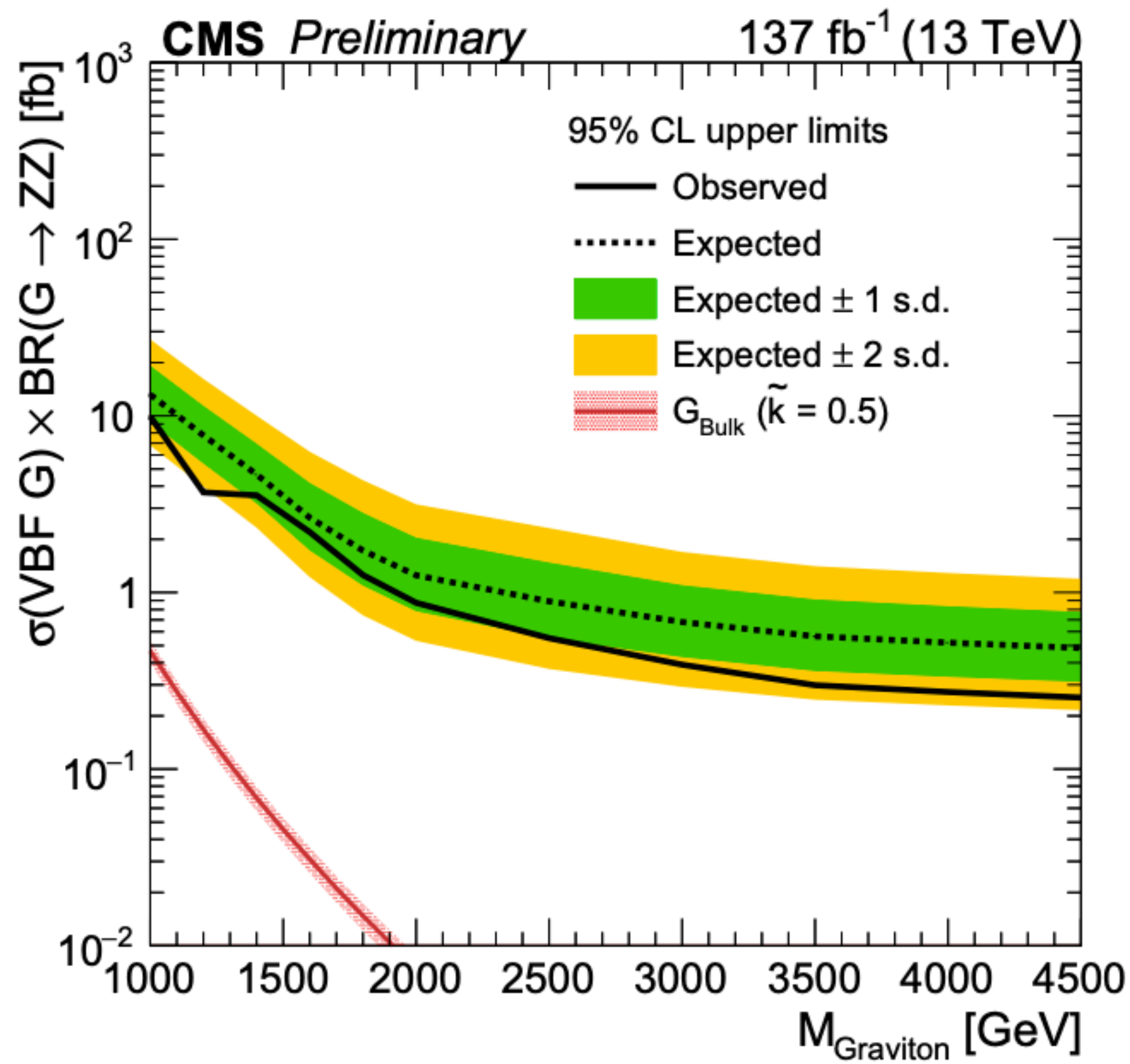
- Mass exclusion (non-VBF):
  - 4.0 TeV (observed)
  - 3.7 TeV (expected)
  - from 2016: 3.4 TeV (observed)
    3.2 TeV (expected)

- VBF: New in this channel.
- Xsec*BR exclusion: 0.5 - 20 fb

Exclusion limits: Graviton (spin-2)

- Results after combining all categories (high-purity, low-purity, vbf, and ggF/DY) using the ggF (left) and VBF (right) produced samples. CMS-PAS-B2G-20-008



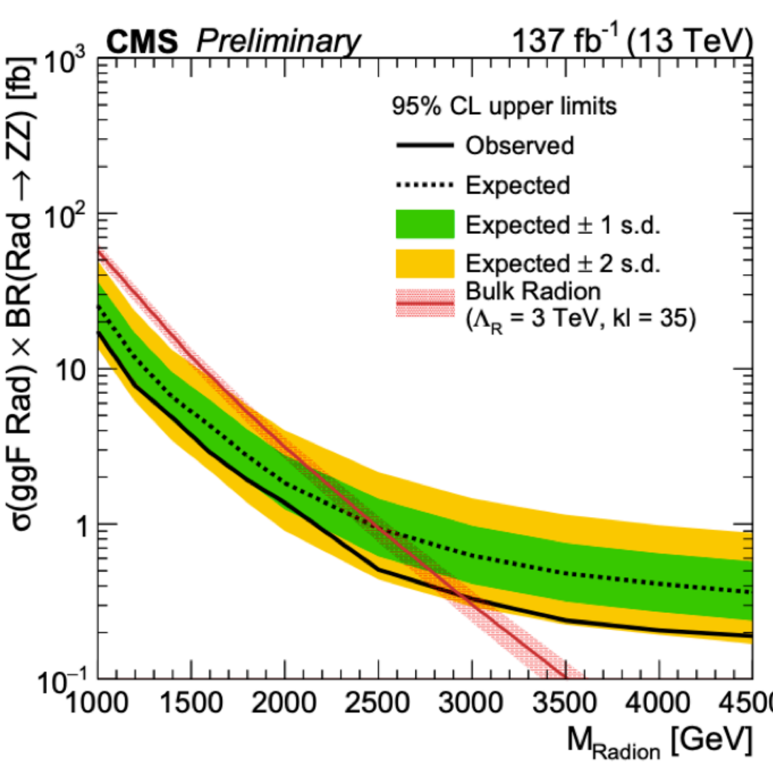


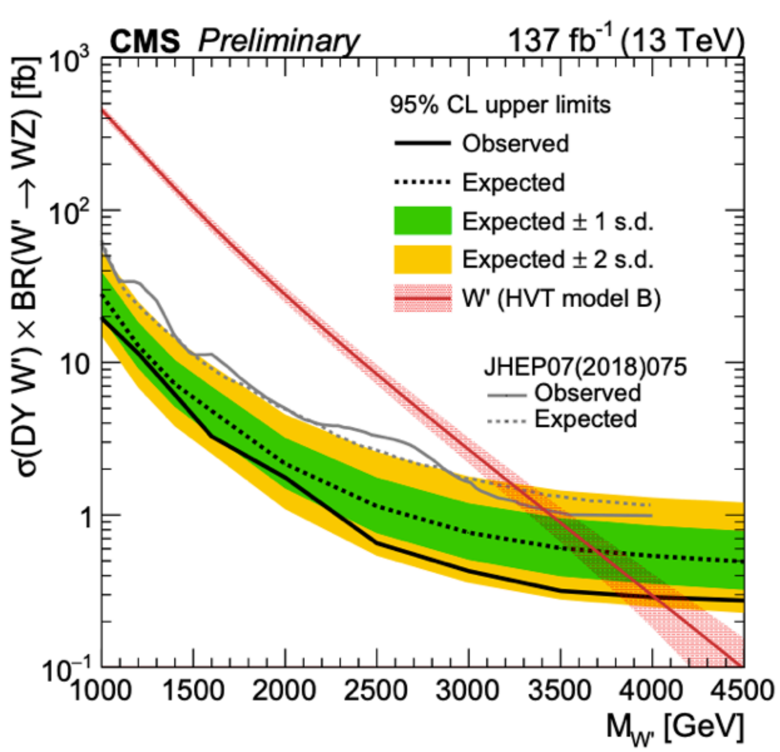
- Mass exclusion (non-VBF):
  - 1.3 TeV (observed)
  - 1.1 TeV (expected)
  - from 2016: —

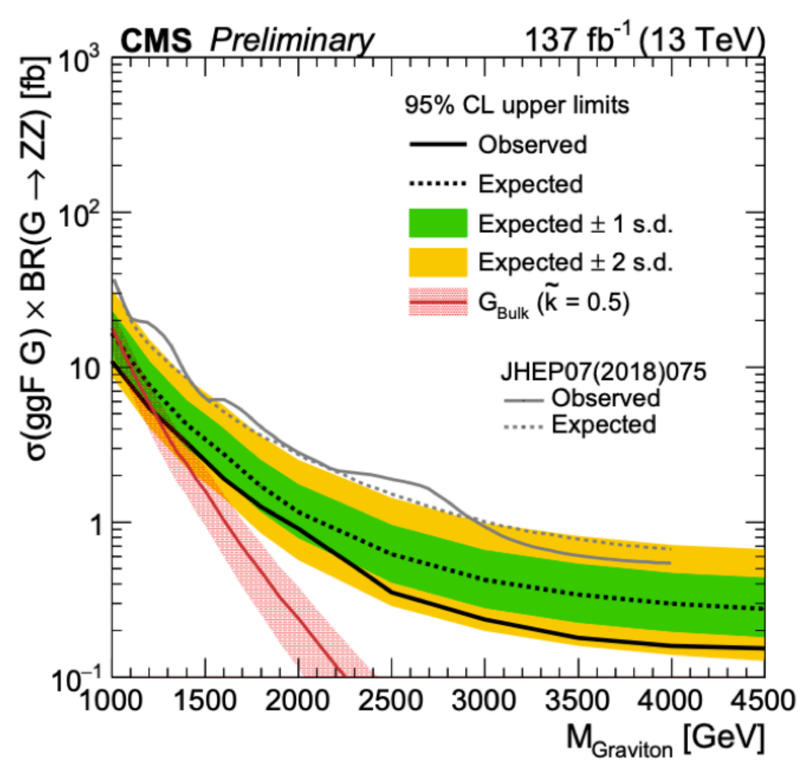
- VBF: New in this channel.
- Xsec*BR exclusion: 0.3 - 8 fb

Summary

- A search for a heavy resonance in boosted jet plus MET final state in both VBF and ggF/DY production mode is presented.
- The polarization effect in the VBF production mode for different spins is explored.
- Jet substructure and forward jet tagging were utilized for the object tagging.
- VBF production of all spins (0, 1, and 2) and ggF production of spin-0 is new in this channel.
- Exclusion limits:
  - ggF/DY: 3.0 TeV (Radion), 4.0 TeV (W'), and 1.3 TeV (Graviton)
  - VBF: 0.2 - 8 fb (Radion), 0.5 - 20 fb (W'), and 0.3 - 8 fb (Graviton)
- More details can be found on [CMS-PAS-B2G-20-008]
- CMS results from other channels are presented in next talk.
  "Searches for heavy resonances decaying into Z, W, and Higgs bosons at CMS"

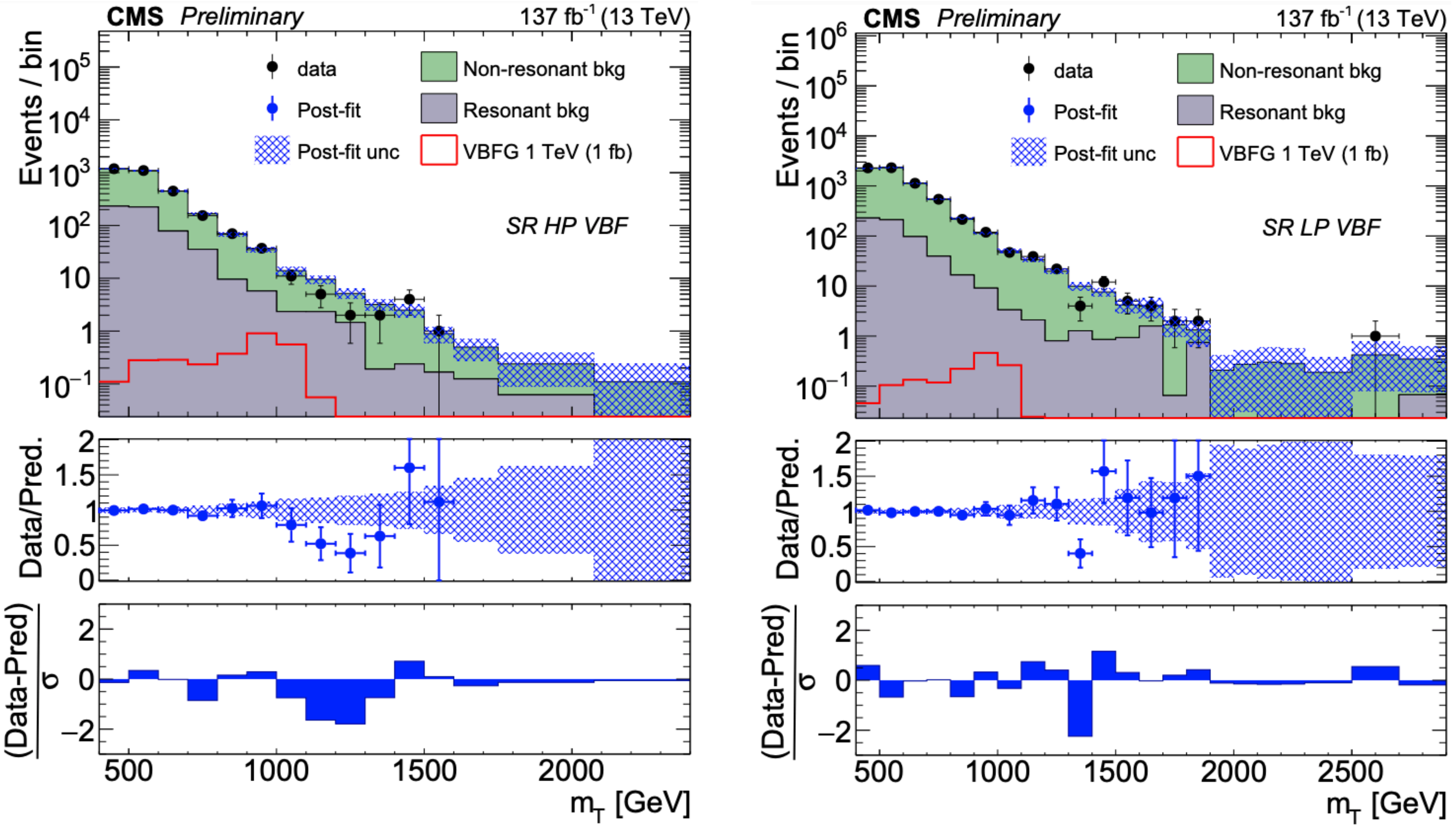






Backup

Post fit predictions: VBF-pass



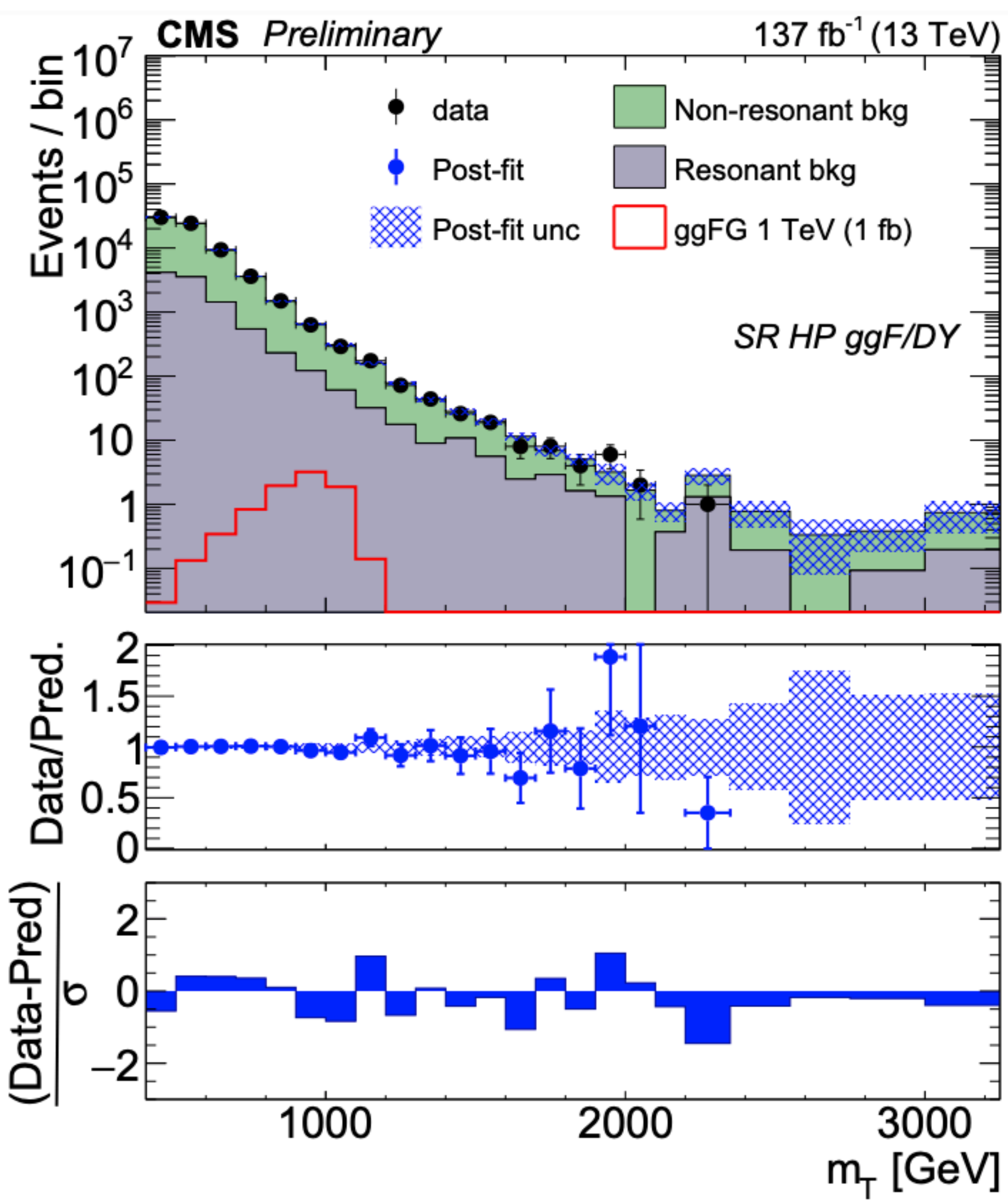
post fit

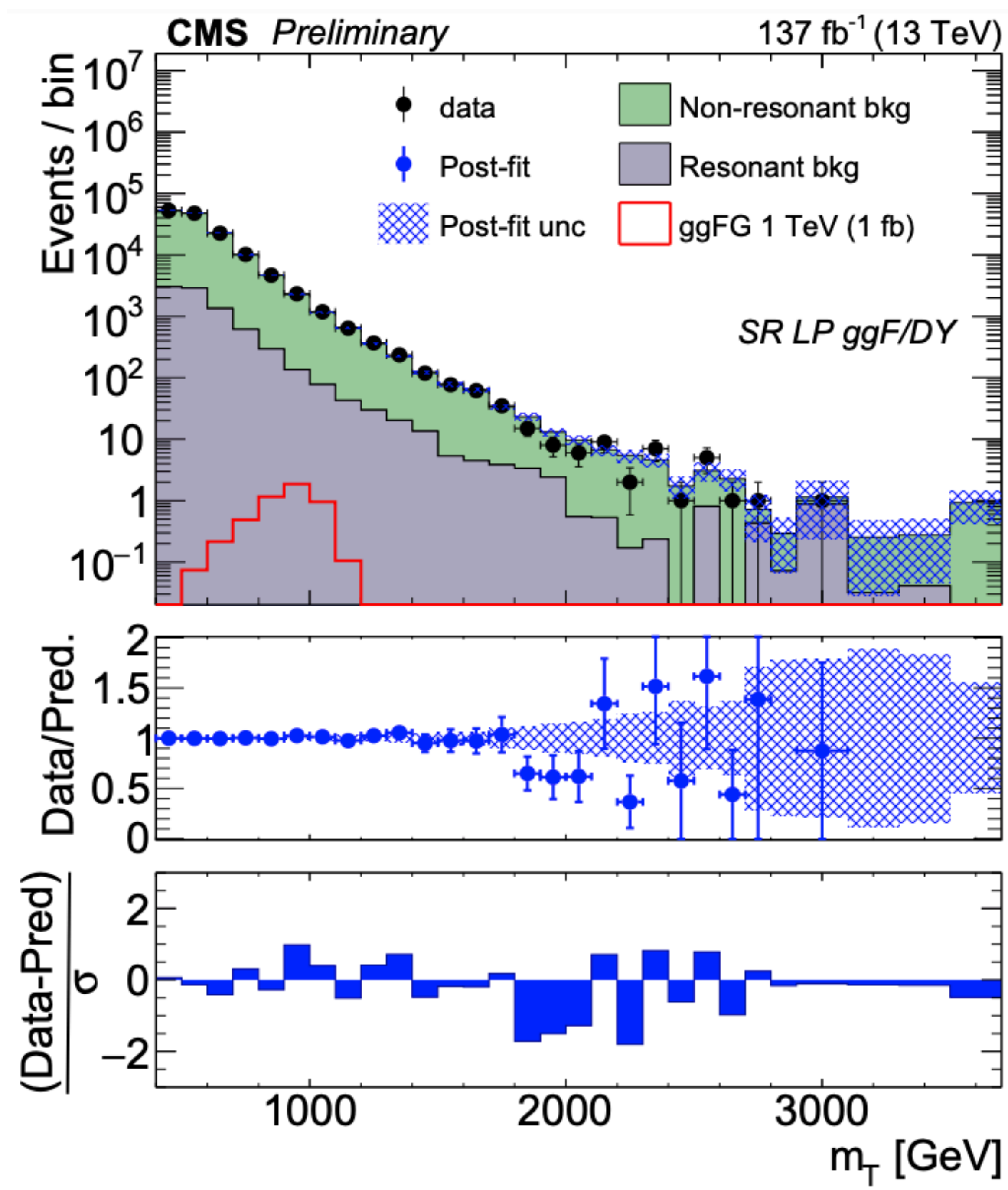
Data/post-fit

post-fit pulls

- Pulls shows up to ~2σ under-prediction.
- No excess in data.

Post fit predictions: ggF/DY





post fit

Data/post-fit

post-fit pulls

- Pulls shows up to ~2σ under-prediction.
- No excess in data.

Systematics

CMS-PAS-B2G-20-008

Non-resonant | Resonant

Systematics	α_{VBF}	$\alpha_{\mathrm{ggF/DY}}$	VBF SR	VBF CR	ggF/DY SR	ggF/DY CR
Luminosity	-	-	2.4	2.4	2.4	2.4
τ_{21} SF (HP)	-	-	7.3	7.3	7.3	7.3
τ_{21} SF (LP)			17.0	17.0	17.0	17.0
Pileup (HP)	-	-	3.9	2.0	1.0	1.7
Pileup (LP)	-	-	3.9	3.7	0.8	0.9
b jet veto (HP)	-	-	2.4	3.5	1.8	2.8
b jet veto (LP)	-	-	2.9	3.2	2.2	2.6
Prefiring (HP)	-	-	0.7	0.8	0.3	0.4
Prefiring (LP)	-	-	0.6	0.7	0.2	0.3
Unclust. Energy (HP)	-	-	2.4	1.8	1.8	1.6
Unclust. Energy (LP)	-	-	1.6	1.4	1.3	1.5
JMR (HP)	-	-	1.2	5.9	1.7	7.1
JMR (LP)	-	-	1.6	0.7	1.01	0.96
τ_{21} p_T extrap. (HP)	-	-	2 - 18	2 - 18	2 - 18	2 - 18
τ_{21} p_T extrap. (LP)	-	-	1 - 10	1 - 10	1 - 10	1 - 10
JMS Up (HP)	-	-	0.3	1.8	0.3	1.6
JMS Down (HP)	-	-	0.5	0.9	0.3	1.2
JMS Up (LP)	-	-	0.4	0.5	0.2	0.4
JMS Down (LP)	-	-	0.4	0.5	0.3	0.4
Trigger Up (HP)	-	-	1.0	0.8	1.1	0.9
Trigger Down (HP)	-	-	1.4	1.4	1.4	1.4
Trigger Up (LP)	-	-	1.0	0.9	1.0	0.9
Trigger Down (LP)	-	-	1.4	1.4	1.4	1.4
JEC	3.0	1 - 2	40 - 13	40 - 13	4.0	4.0
JER	3.0	1.5	35 - 13	35 - 13	2.0	2.0
PDF normalization	-	-	5.0	5.0	2.0	2.0
PDF shape	3.0	1.5	0.5 - 4	0.5 - 4	0.5 - 4	0.5 - 4
μ_R, μ_F scale normalization	-	-	15	15	11	12
μ_R, μ_F scale shape	1 - 2	1 - 2	1 - 10	2 - 4	3 - 8	3 - 4
Non-closure	7 - 40%	7 - 40%	-	-	-	-

Signal

Systematics	VBF SR	VBF CR	ggF/DY SR	ggF/DY CR
Luminosity	2.4	2.4	2.4	2.4
τ_{21} SF (HP)	7.3	7.3	7.3	7.3
τ_{21} SF (LP)	17.0	17.0	17.0	17.0
Pileup (HP)	0.2	0.7	1.1	1.1
Pileup (LP)	0.5	1.0	0.9	0.6
b jet veto (HP)	1.3	1.4	1.3	1.3
b jet veto (LP)	1.4	1.6	1.4	1.5
Prefiring (HP)	1.0	1.0	0.6	0.6
Prefiring (LP)	0.9	1.0	0.5	0.5
Unclust. Energy (HP)	0.1	0.1	0.1	0.1
Unclust. Energy (LP)	0.1	0.1	0.1	0.1
JMR (HP)	3.2	6.9	3.3	7.5
JMR (LP)	2.8	4.0	2.4	3.4
τ_{21} p_T extrap. (HP)	2 - 18	2 - 18	2 - 18	2 - 18
τ_{21} p_T extrap. (LP)	1 - 10	1 - 10	1 - 10	1 - 10
JMS Up (HP)	0.9	2.4	0.7	2.0
JMS Down (HP)	0.7	2.6	0.7	2.4
JMS Up (LP)	0.3	1.6	0.3	1.2
JMS Down (LP)	0.2	1.9	0.2	1.5
Trigger Up (HP)	0.8	0.8	0.8	0.8
Trigger Down (HP)	1.4	1.4	1.4	1.4
Trigger Up (LP)	0.8	0.8	0.8	0.8
Trigger Down (LP)	1.4	1.5	1.6	1.5
JEC	5 - 11	4 - 14	1 - 7	1 - 5
JER	2 - 3	6 - 7	1 - 7	1 - 5

- Largest systematics:
  - τ_{21} scale factors and pT extrapolation, JEC/R (VBF) for resonant bkg & signal.

Polarization in ggF vs VBF for G → ZZ

Additional peak for VBF process:

- *G has stronger coupling to longitudinal component of vector boson.*

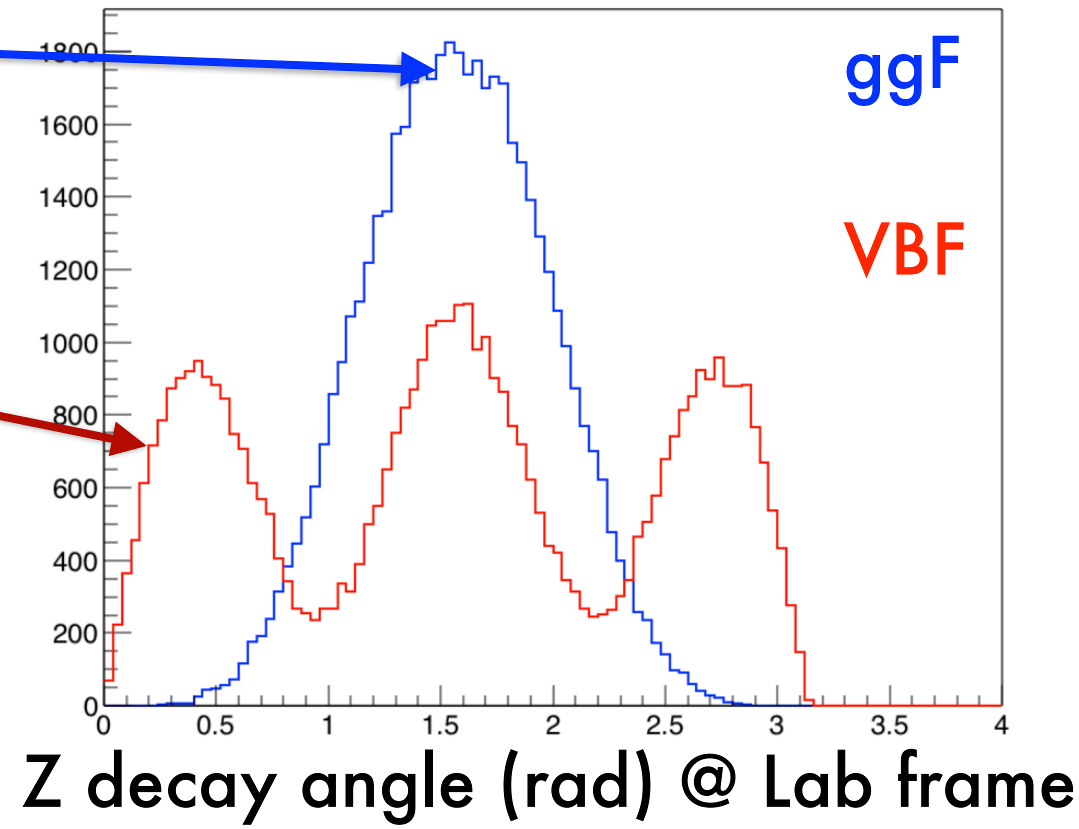
$$ggF \rightarrow \frac{d\sigma}{d\theta} \sim sin^5\theta \qquad A_{\pm\mp00} \sim sin^2\theta$$
ggZZ

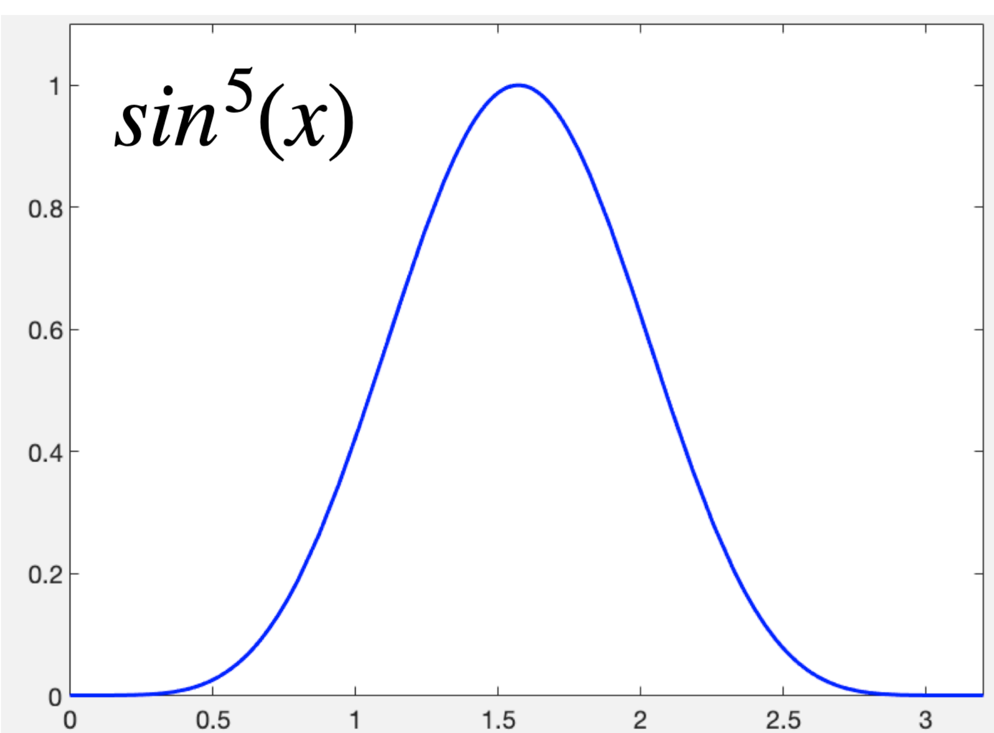
$$VBF \rightarrow \frac{d\sigma}{d\theta} \sim sin\theta \times (\frac{2}{3} - sin^2\theta)^2$$

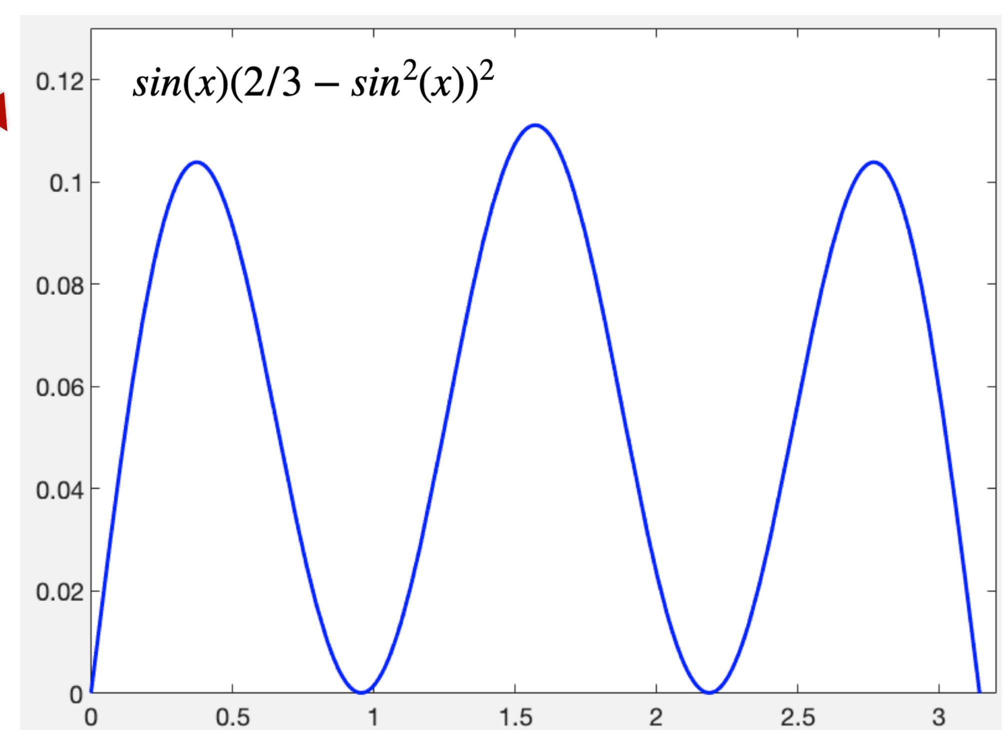
$$A_{0000} \sim (\frac{2}{3} - sin^2\theta)$$
VVZZ

arXiv:hep-ph/0701186

Equation 13 and 18 in this paper supports this observation.







Angular distribution and the spin