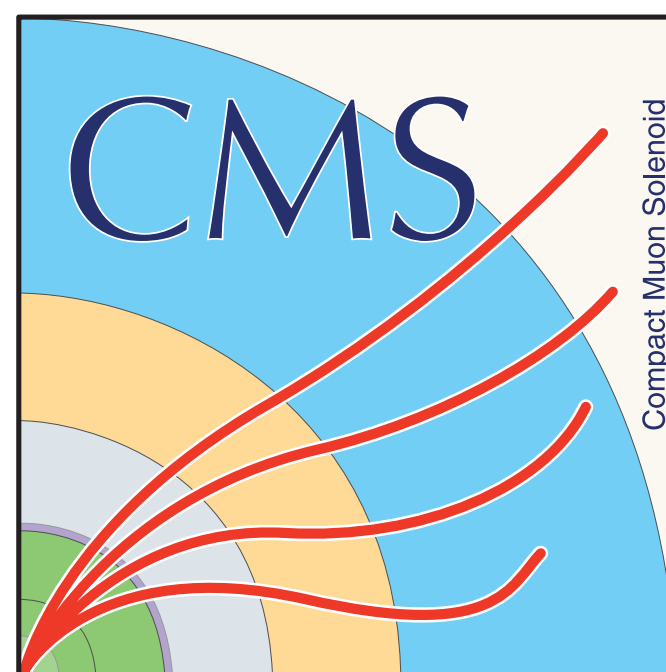


Observation of $WW\gamma$ production along with a search for the $H\gamma$ production by couplings of the Higgs boson to *light quarks*

Zhe Guan (关喆) on behalf of PKU $WW\gamma$ analysis team

第九届中国LHC物理年会 The 9th China LHC Physics Workshop (CLHCP2023)

2023/11/19



- Introduction
 - Physics motivation and public results review
- WW γ measurements
 - *Signal production*
 - *Selection/region definition*
 - *Background estimation*
 - *Results*
 - ✓ **WW γ signal significance**
 - ✓ **WW γ fiducial cross section**
- H γ production search
 - *H γ signal and background*
 - *Selection and results*
 - ✓ **H γ cross section upper limits and the interpreted Yukawa couplings results**

PAS

CMS-PAS-SMP-22-006



Observation of WW γ production and constraints on Higgs couplings to light quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration
23 March 2023

Abstract: The first observation of WW γ production with leptonic final states in proton-proton collisions at a center-of-mass energy of 13 TeV is presented. A data set corresponding to an integrated luminosity of 138 fb $^{-1}$ collected by the CMS experiment at the LHC in 2016-2018 is used. Events are selected by requiring exactly two leptons (one electron and one muon) of opposite charge, moderate missing transverse momentum, and a photon. The measured fiducial cross section for WW γ is $\sigma = 6.0 \pm 1.7$ fb, in good agreement with the next-to-leading order QCD prediction. The analysis is also extended to search for the associated production of a Higgs boson and a photon where the Higgs boson decays to W $^+W^-$, which is sensitive to the Higgs coupling to light quarks (the c, s, u, and d quarks), and limits on these couplings are reported at 95% confidence level.

Links: [CDS record \(PDF\)](#) ; [Physics Briefing](#) ; [CADI line](#) (restricted) ;

CMS news



Facebook



CMS Experiment at CERN

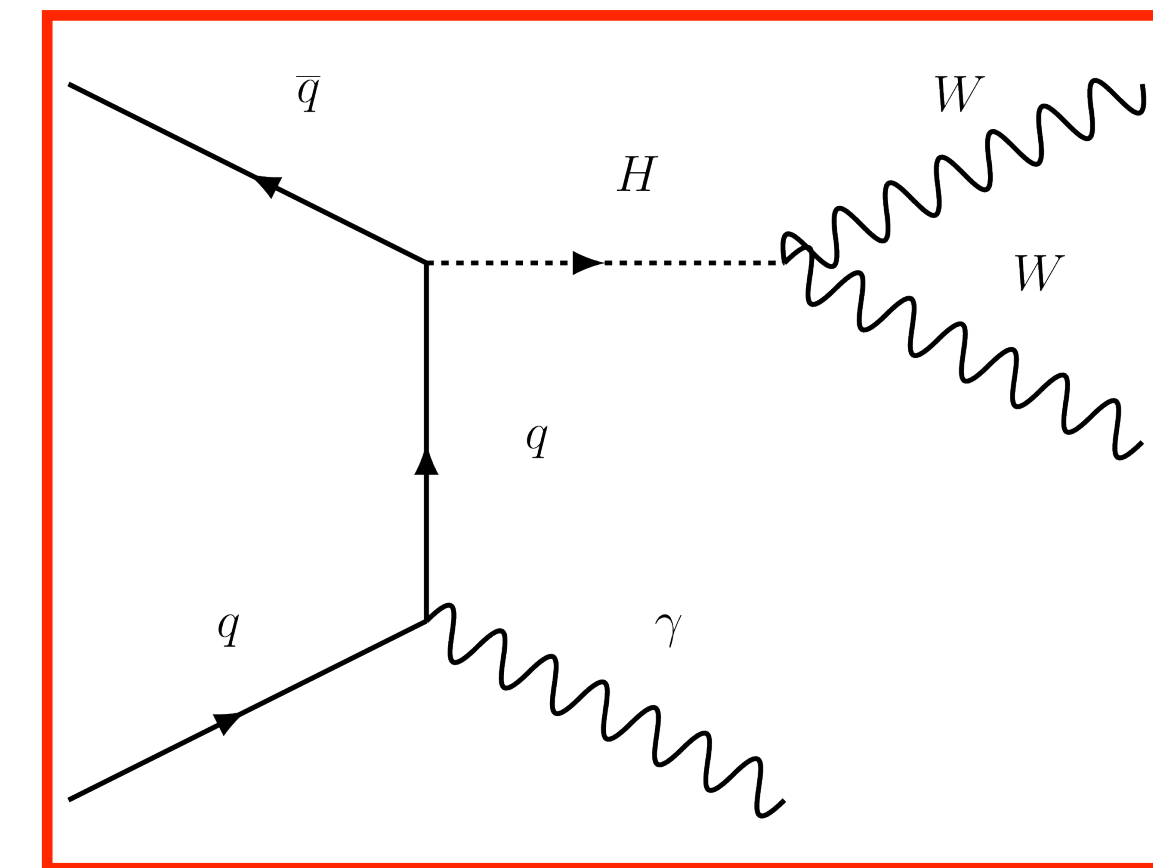
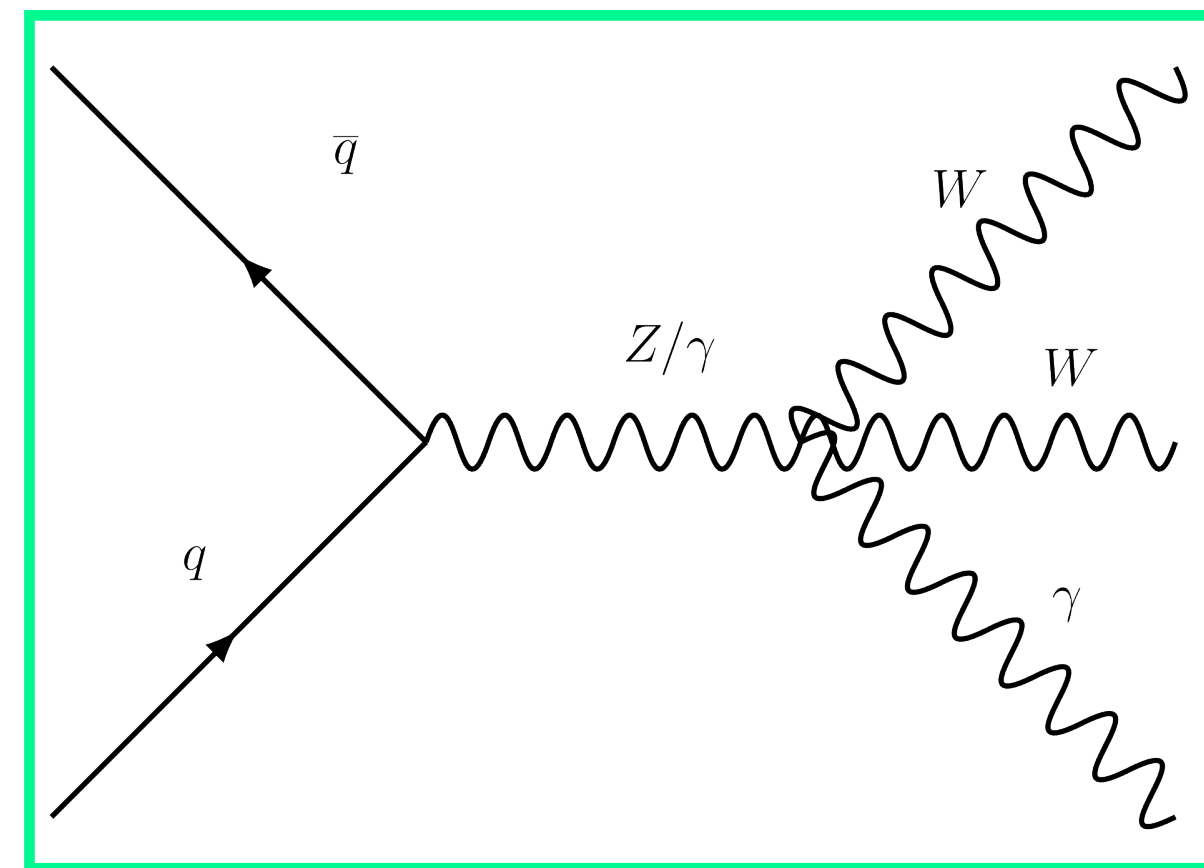
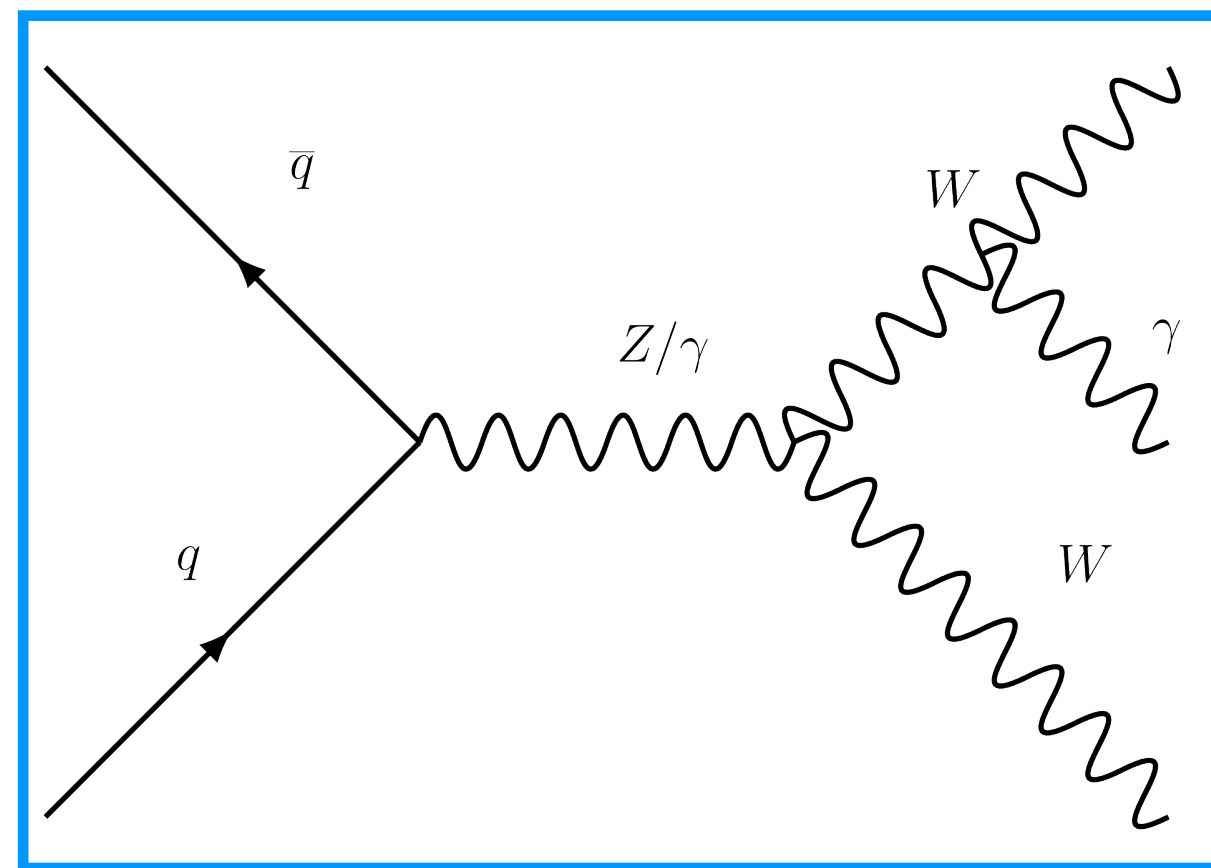
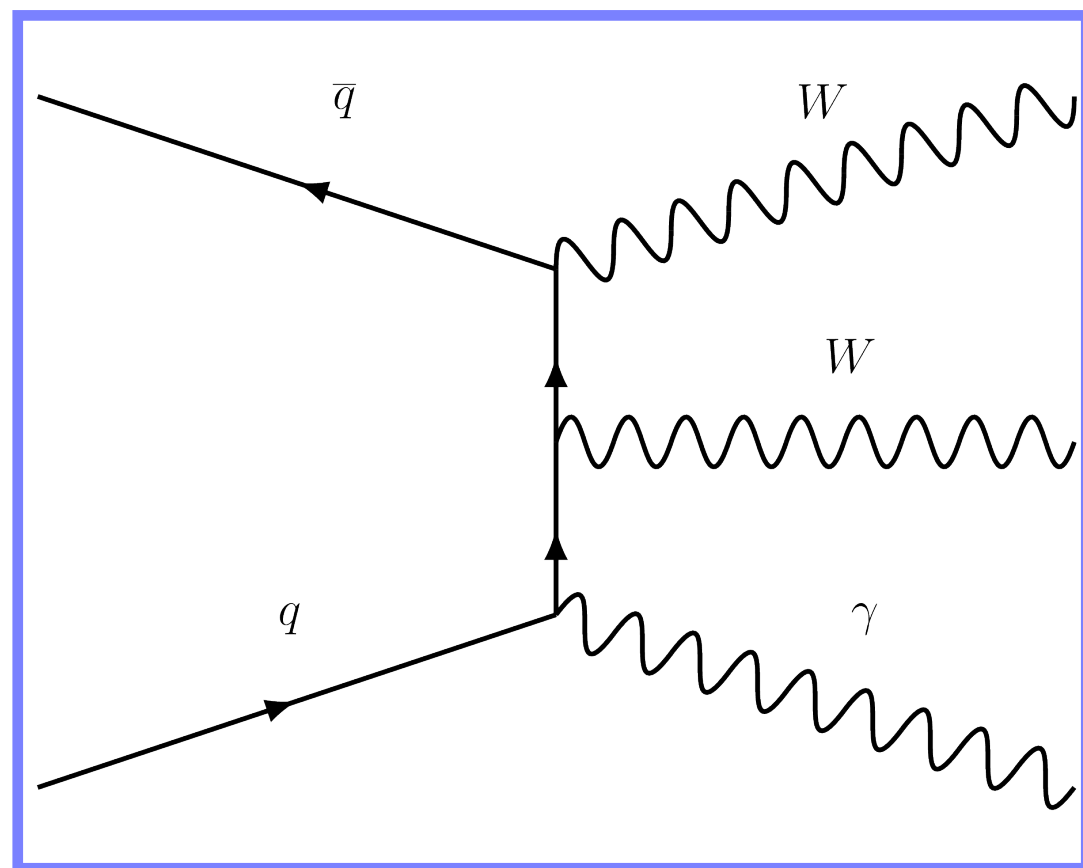
5月22日 · 🌐

CMS reports the first observation of the simultaneous production of two W bosons and a photon! 🎉 What a way to celebrate the 40th anniversary of the W boson discovery.

Read more here → <https://cms.cern/news/new-tri-boson-process-discovery>

CERN #CERN #CMSExperiment #physics

Introduction — Why triboson



- Large cross section compared with the full massive multiboson processes
- Include the multiboson couplings (QGC and TGC)
- Include the Higgs gauge couplings

Precise measurement for SM test

Platform to measure the anomalous coupling

Platform to search the Higgs to light quark Yukawa couplings

See talk: WZ γ observation at ATLAS from Prof. Ai

Introduction — $WW\gamma$

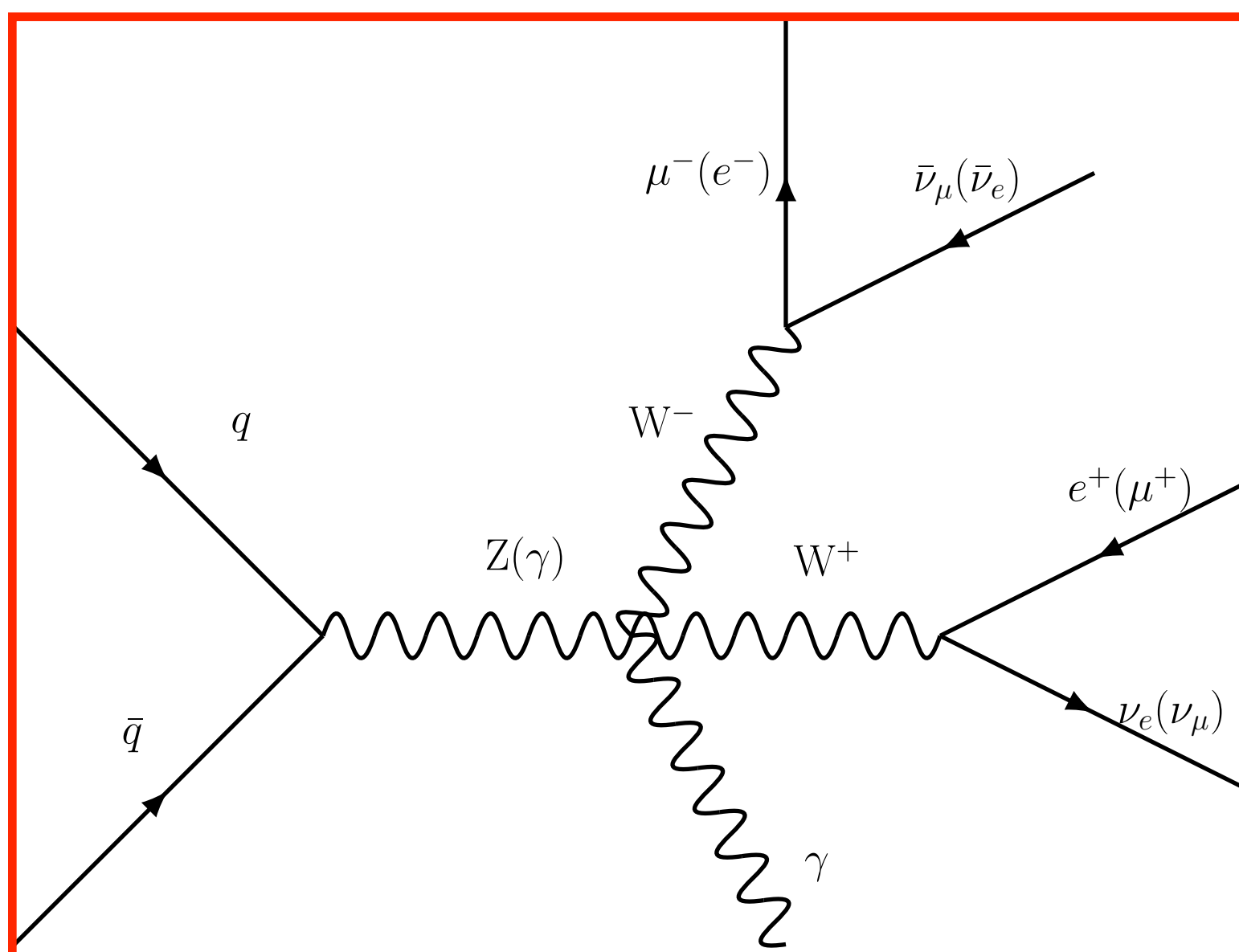
Experiment		CMS		ATLAS	
Triboson with γ	Final states	Journal	Lumi fb ⁻¹ / $\sqrt{s}$ TeV	Journal	Lumi fb ⁻¹ / $\sqrt{s}$ TeV
$WW\gamma$	$\ell\nu jj\gamma$	PRD 90 (2014) 032008	19.3/ 8	EPJC 77, 646 (2017)	20.2/ 8
$WW\gamma$	$e\mu\nu\nu\gamma$	SMP-22-006	138/ 13	—	138/ 13

CMS:

- Cross section limit of $WW\gamma$ ($\ell\nu jj\gamma$)
- Limits on dim-8 and dim-6 operators

ATLAS:

- Cross section limit of $WW\gamma$ ($e\mu\nu\nu\gamma$) and $WW\gamma$ ($\ell\nu jj\gamma$)
 - $\sigma_{\text{fid}}^{e\nu\mu\nu\gamma} = 1.5 \pm 0.9(\text{stat.}) \pm 0.5(\text{syst.}) \text{ fb } (N_{\text{jets}}=0)$
 - Observed (expected) 1.4σ (1.6σ)
- Limits on dim-8 operators



Full Run2 13 TeV data

$e^{\pm}\nu_e\mu^{\mp}\nu_{\mu}\gamma$ final states:

- Easy to generate the signal sample
- Clean signal signature
- Fewer kinds of backgrounds

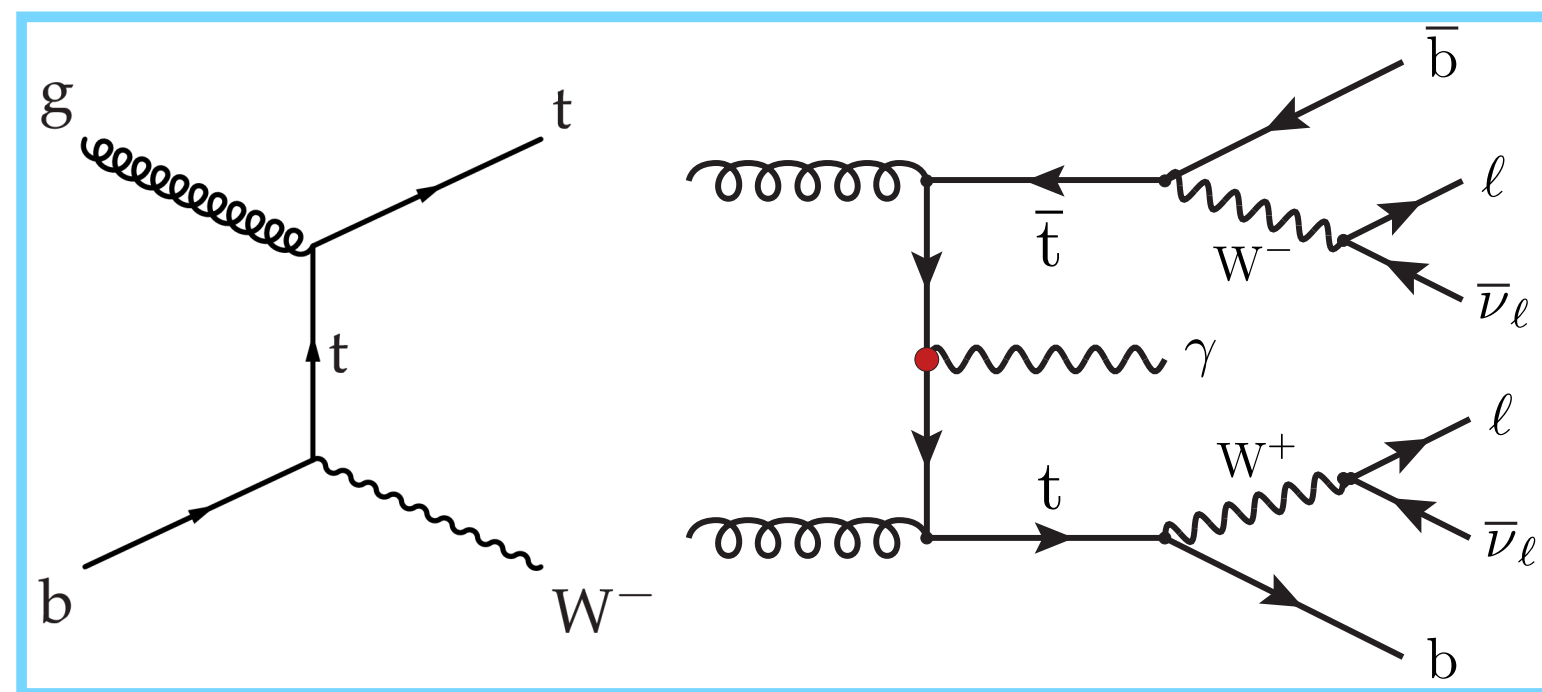
Signal production

Final state	Generator (MadGraph_aMC@NLO)	Lepton identification	Photon identification	Jet identification	MET
$e\mu\gamma E_T^{\text{miss}}$	process: $pp > e \nu_e \mu \nu_\mu \gamma$ [QCD] $p_T^\gamma > 10 \text{ GeV}$	MVA e ID($\approx 80\%$)	$\approx 80\%$	anti- k_T AK4CHS 98%-99%	PF
		MVA μ ID ($\geq 90\%$)			

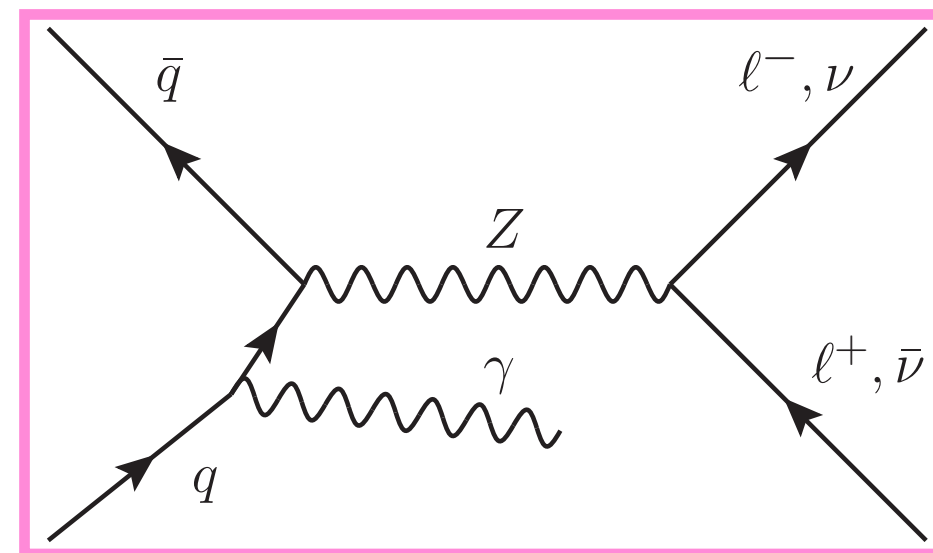
- Signal is produced by MadGraph at NLO in QCD accuracy showering by Pythia8 with NNLO PDF
 - ☑ FSR (final state radiation) photons are included
 - ☑ No EW or much higher QCD corrections
- MVA-based identifications are used for physics object **reconstruction**
 - ☑ Improve efficiency and sensitivity

Background estimation

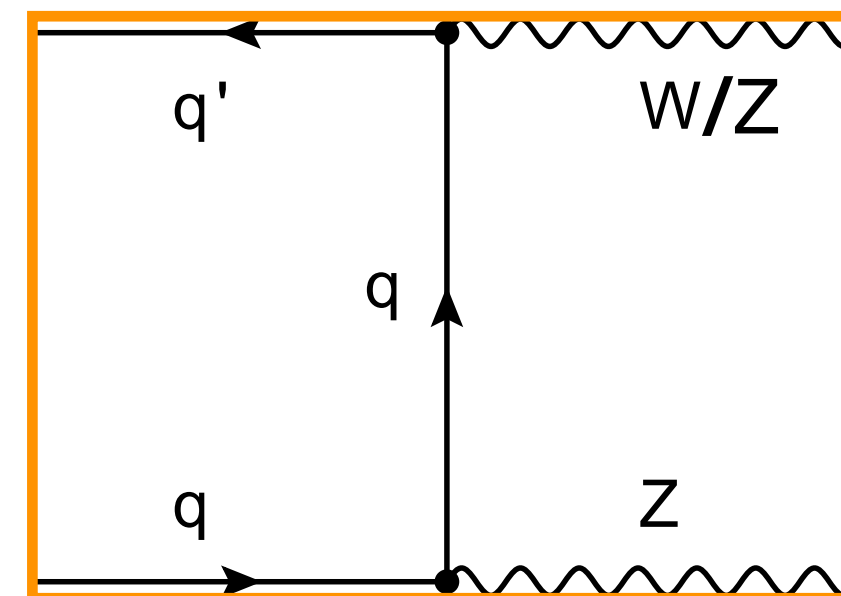
- $t\bar{t}\gamma$ and tW



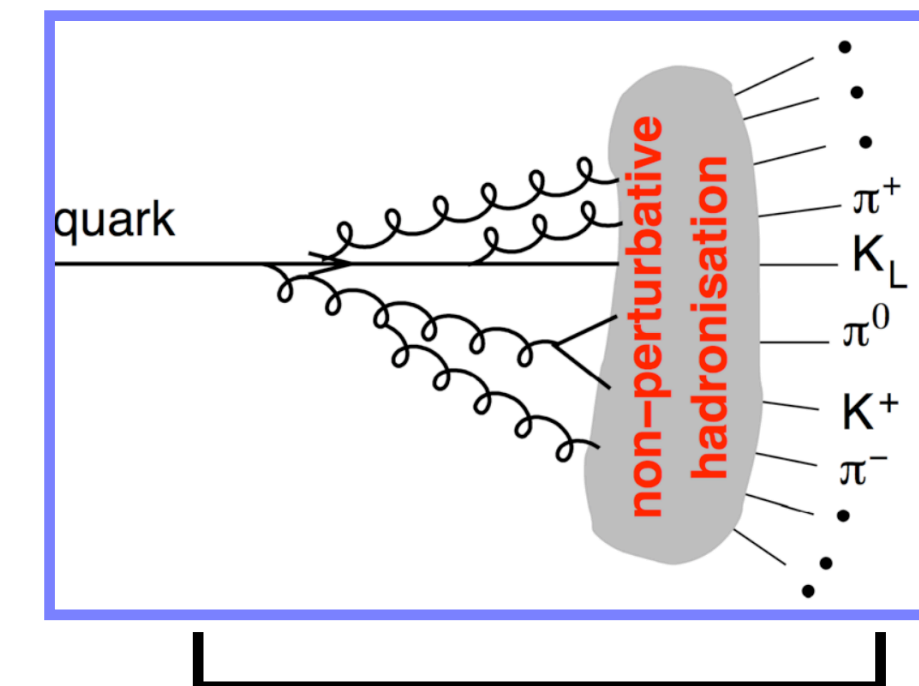
- $Z\gamma$ process



- Diboson



- Nonprompt ℓ from jet
- Nonprompt γ from jet



Estimated by normalizing MC to data

Estimated by data-driven method

- Top decays to b quark and W
- Suppressed by rejecting events containing b-jets

- Z to $\tau\tau^+$, and τ to e/ μ
- Suppressed by requirements of $p_T^{\ell\ell}$, $m_{\ell\ell}$, and E_T^{miss}

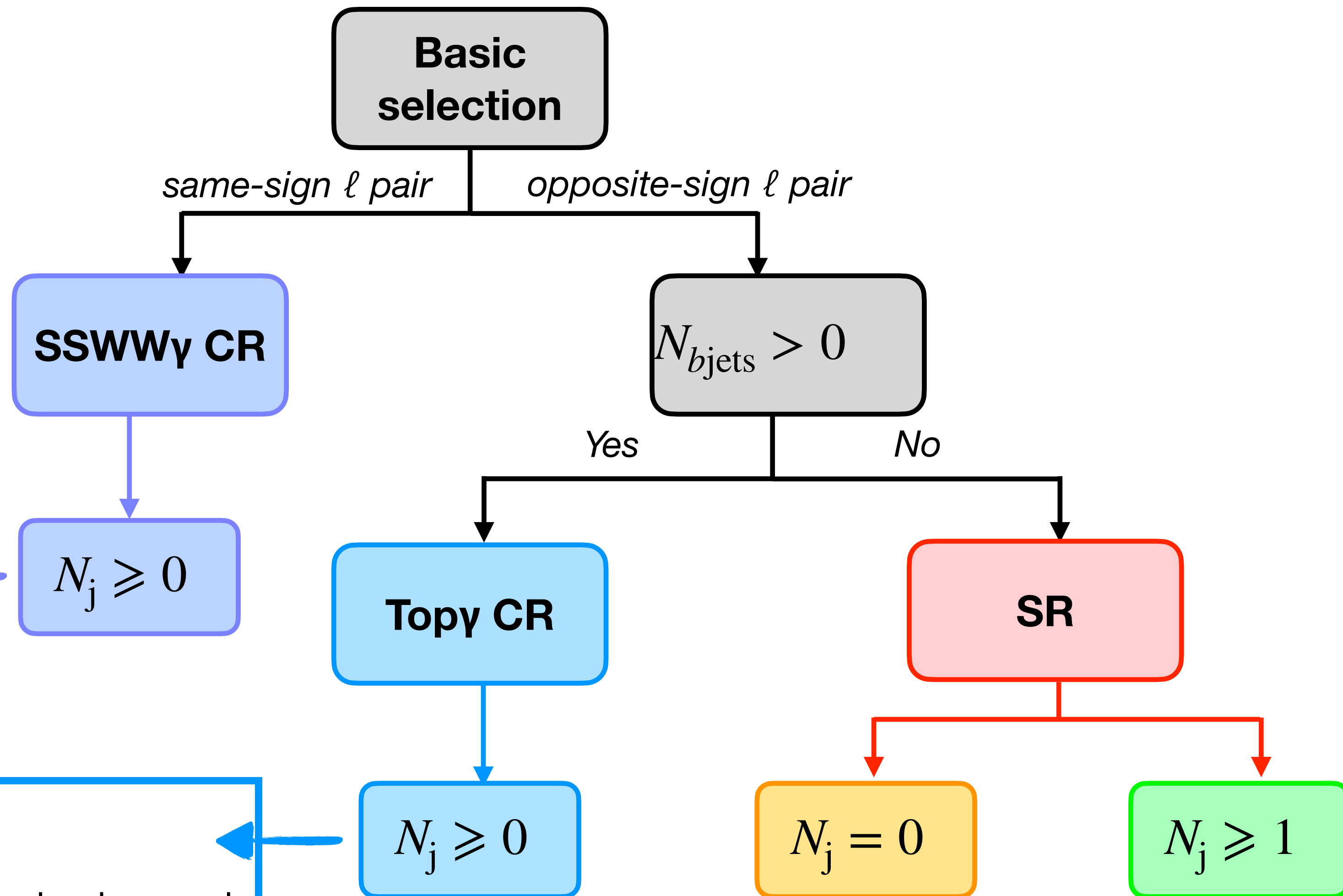
- W or Z decays to e/ μ / τ where one or two ℓ are not detected and γ from showering
- e misidentified as γ

- Jets misidentified as ℓ or γ

- Other backgrounds with ignorable contributions are $W\gamma$ +jets, tZq , etc
- All background simulation samples are generated at NLO (NNLO normalization factor considered if it exists)

Selection

Baseline selection	A. Two leptons with $p_{T^{\mu/e}} > 20$ (25) GeV, $\eta < 2.4$ (2.5) B. Pass HLT (μe) paths C. $m_{\ell\ell} > 10$ GeV and $p_{T^{\ell\ell}} > 15$ GeV D. $E_T^{\text{miss}}(\text{PF}) > 20$ GeV and $m_{T^{WW}} > 10$ GeV E. $p_{T^{\gamma}} > 20$ GeV in the barrel or endcap
--------------------	--



Nonprompt ℓ enriched region

- Validate the nonprompt ℓ background
- Constrain the nonprompt ℓ background by correlating the same systematic uncertainty in the SR

Top and nonprompt γ enriched region

- Validate the nonprompt γ background
- Constrain the top background by floating top background normalization
- Constrain the nonprompt γ background by correlating the same systematic uncertainty in the SR

Systematic uncertainties

Theoretical uncertainty

- Factorization and renormalization
- Parton shower
- PDF

- Correlated between years, categories, and regions
- Apply for processes of the signal, relevant top, and $V\gamma$ productions



Dominant in total syst. uncertainties (0.21)
Around 13% impact on the cross section

Experimental uncertainty

- Simulation and data-driven statistics

1. Correction and measurement

- Luminosity, pileup, L1prefiring
- Energy corrections for jet and MET
- Efficiencies

- Correlated between different categories and regions but correlated or uncorrelated between years.
- Apply for all simulation processes

2. Background modelling

- Nonprompt ℓ/γ uncertainty

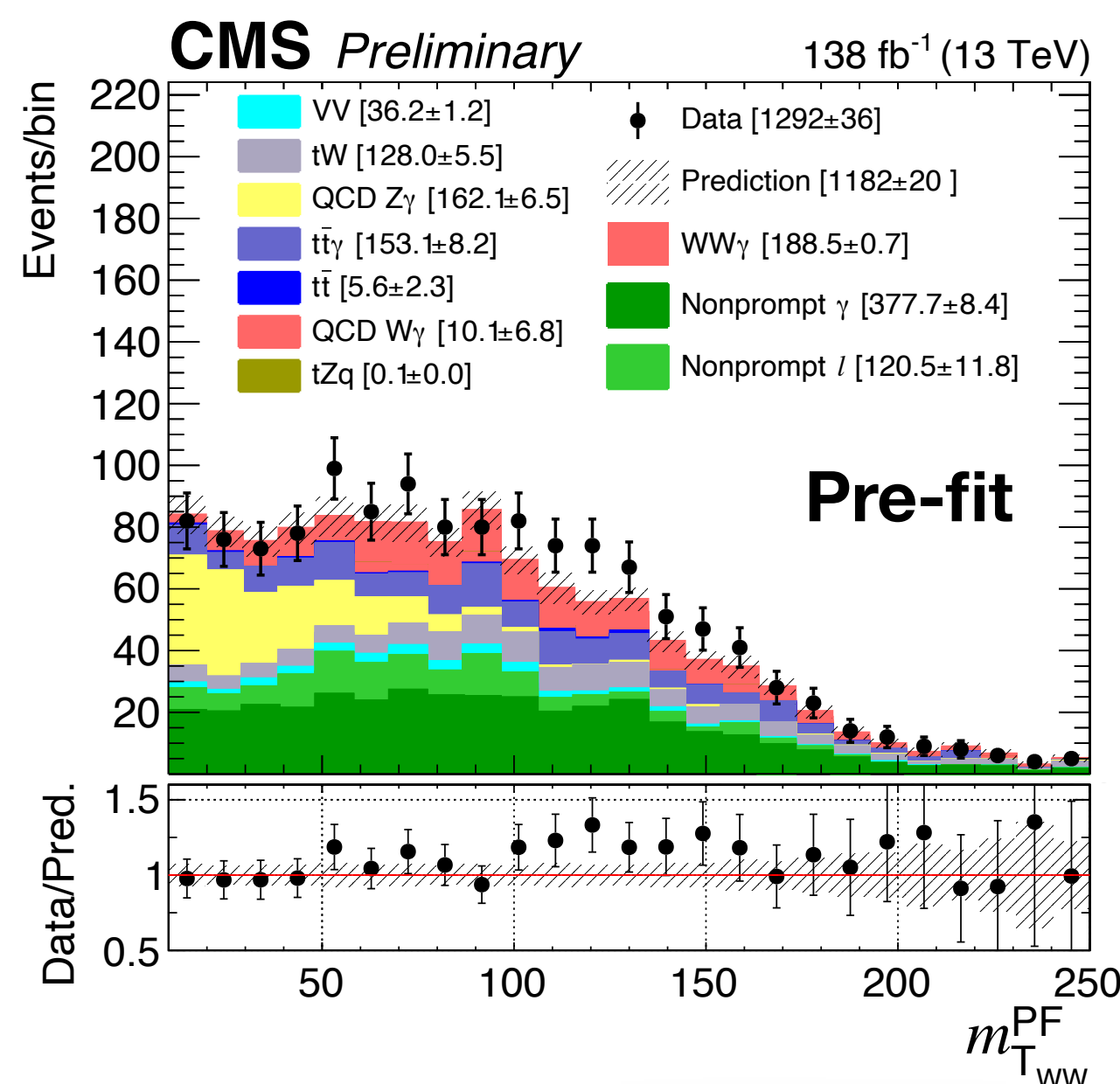
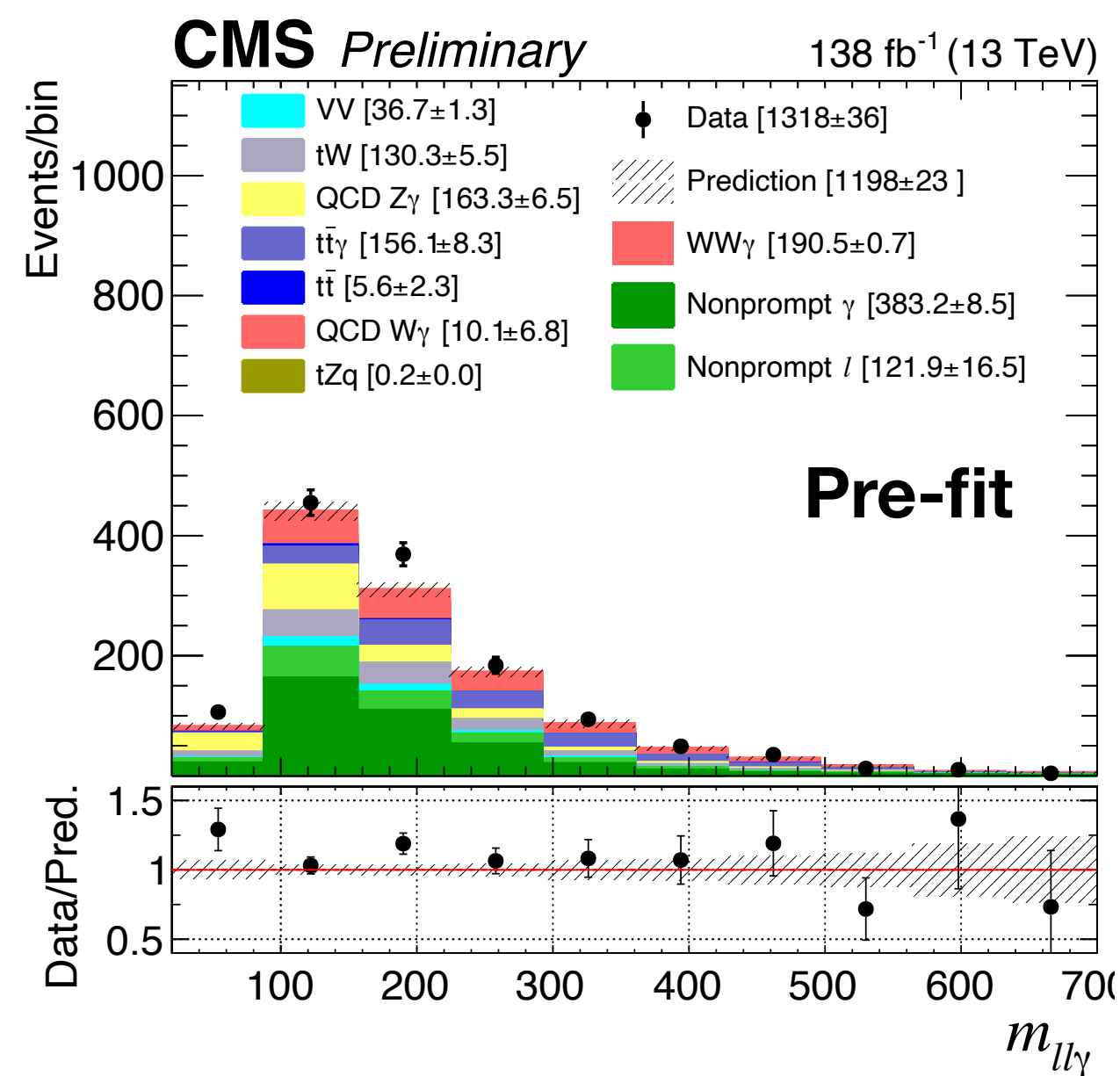
- Correlated between different categories and regions but uncorrelated between years
- Apply for corresponding data-driven process

Results — $WW\gamma$ significance

- Maximum likelihood fit for signal extraction

$$\mathcal{L}(\vec{\mu}; \vec{\theta}) = \prod_j \text{Poisson}(n_j | \mu \cdot s_j(\vec{\theta}) + b_j(\vec{\theta})) \cdot p(\vec{\theta})$$

- Simultaneous **fit with control regions**
- POI of the signal and normalization of the relevant top are float



SR

$$m_{T^{WW}}: [10, 40, 70, 110, \infty)$$

$$m_{\ell\ell\gamma}: [20, 150, 250, \infty)$$

Top γ CR

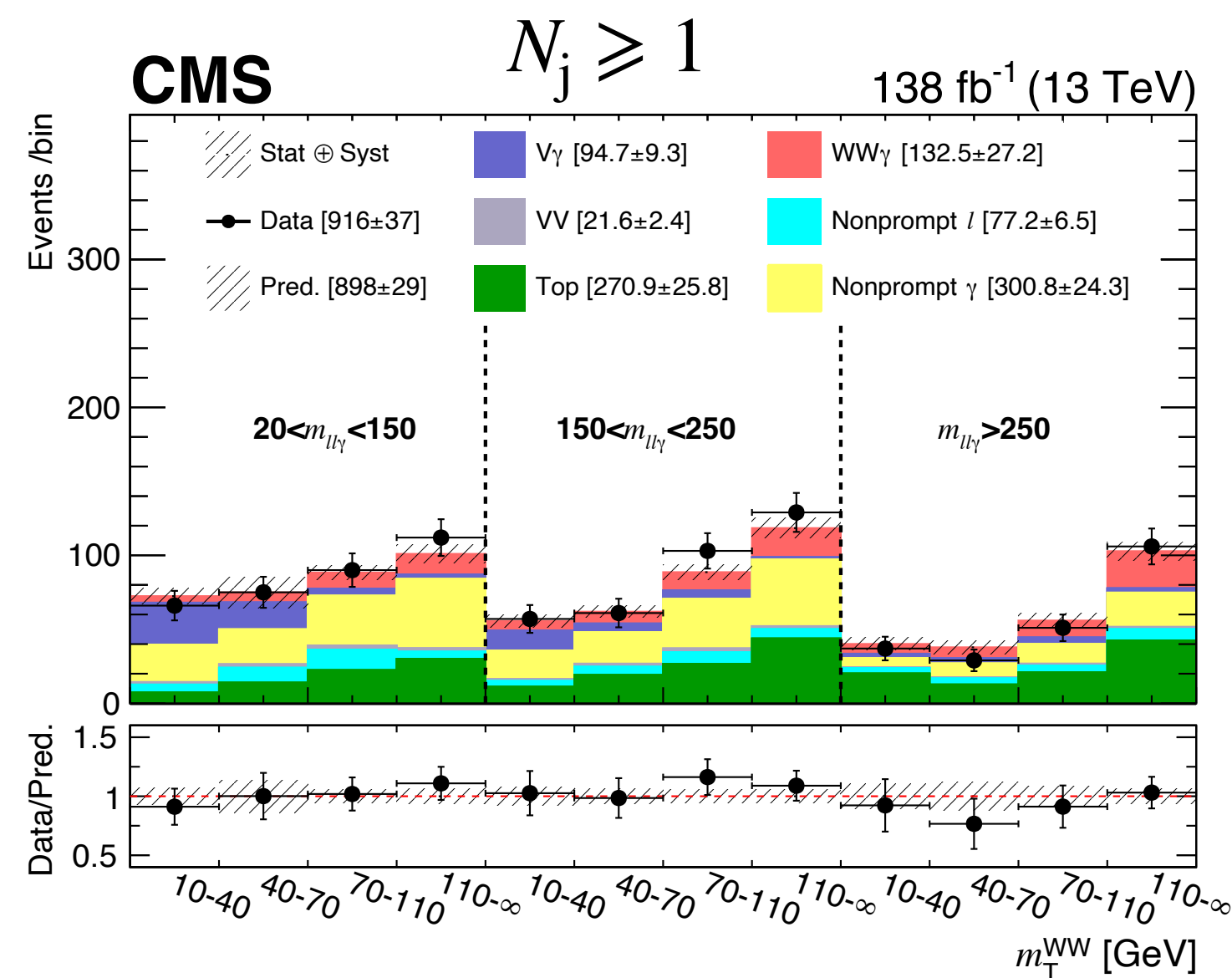
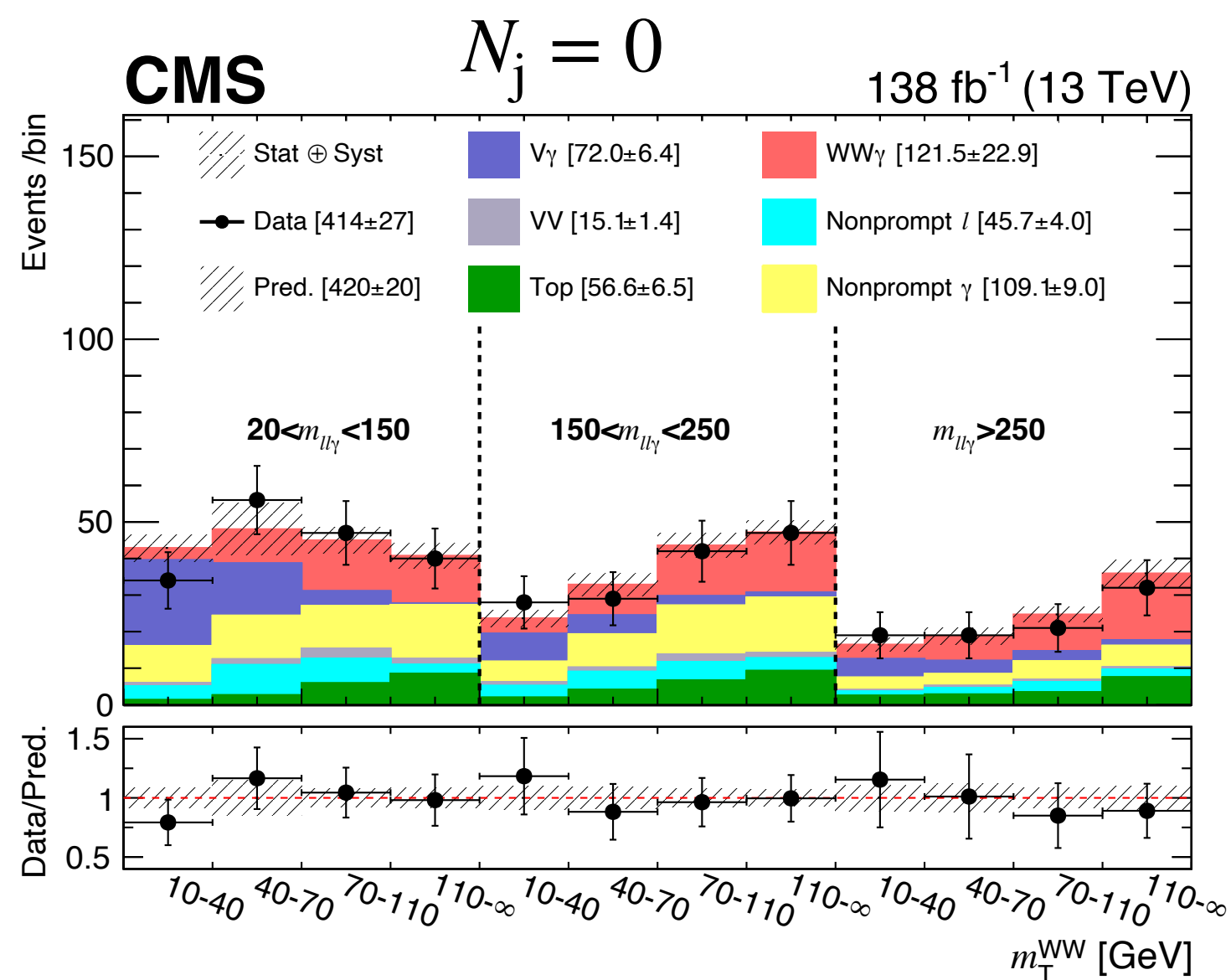
$$m_{T^{WW}}: [10, \infty)$$

SSWW γ CR

$$m_{T^{WW}}: [10, 40, 70, 110, \infty)$$

Reasonable agreement between data and predictions → Good background estimation

Results — $WW\gamma$ cross section



- Observed (Expected) significance is 5.6 (4.7) s.d.

The **first observation** of $WW\gamma$ process

Fiducial region definition

- $p_T^{e/\mu} > 25$ (20) GeV, $|\eta| < 2.4$ (2.5)
- $m_{\ell\ell} > 10$ GeV and $p_T^{\ell\ell} > 15$ GeV
- $p_T^\gamma > 20$ GeV in the barrel or endcap
- $\Delta R(\gamma/\ell, \ell) > 0.5$

- Cross section is measured in the fiducial region
- Theoretical cross section from MadGraph at NLO QCD accuracy is:

- $\sigma_{th} = 4.61 \pm 0.34$ (scale) ± 0.05 (PDF) fb

- Measured results are:

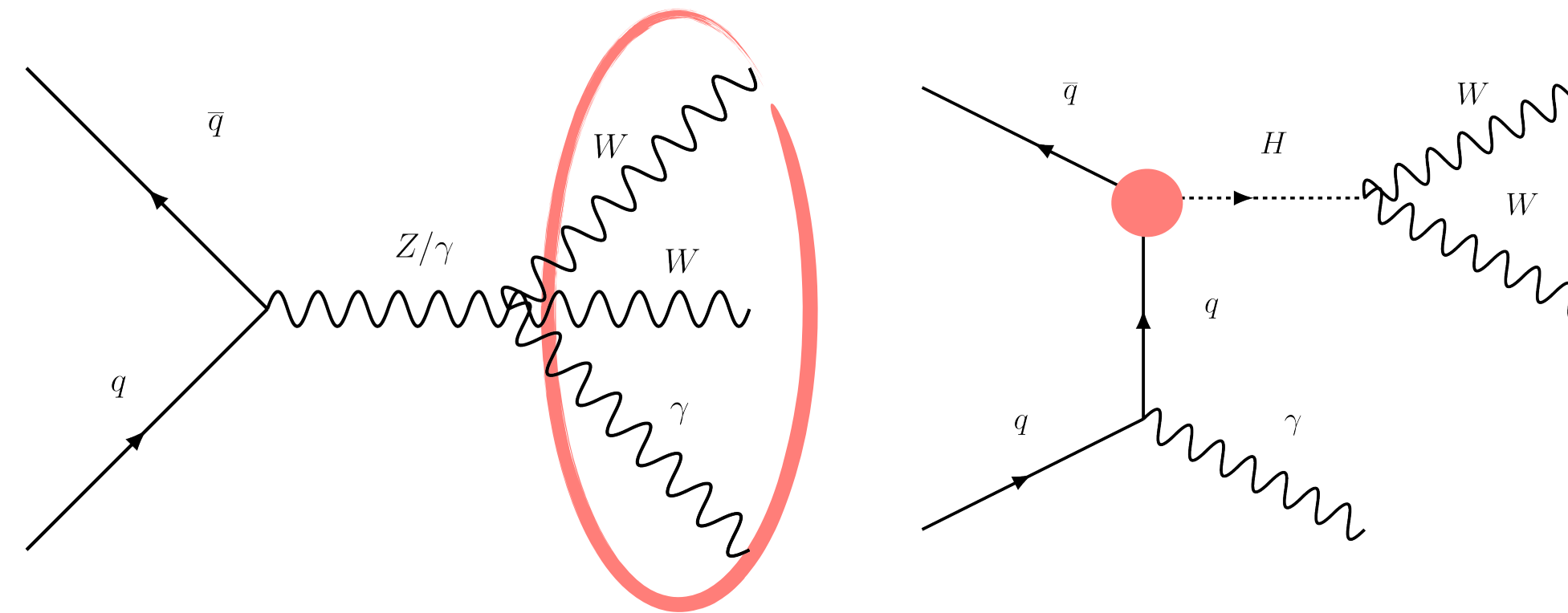
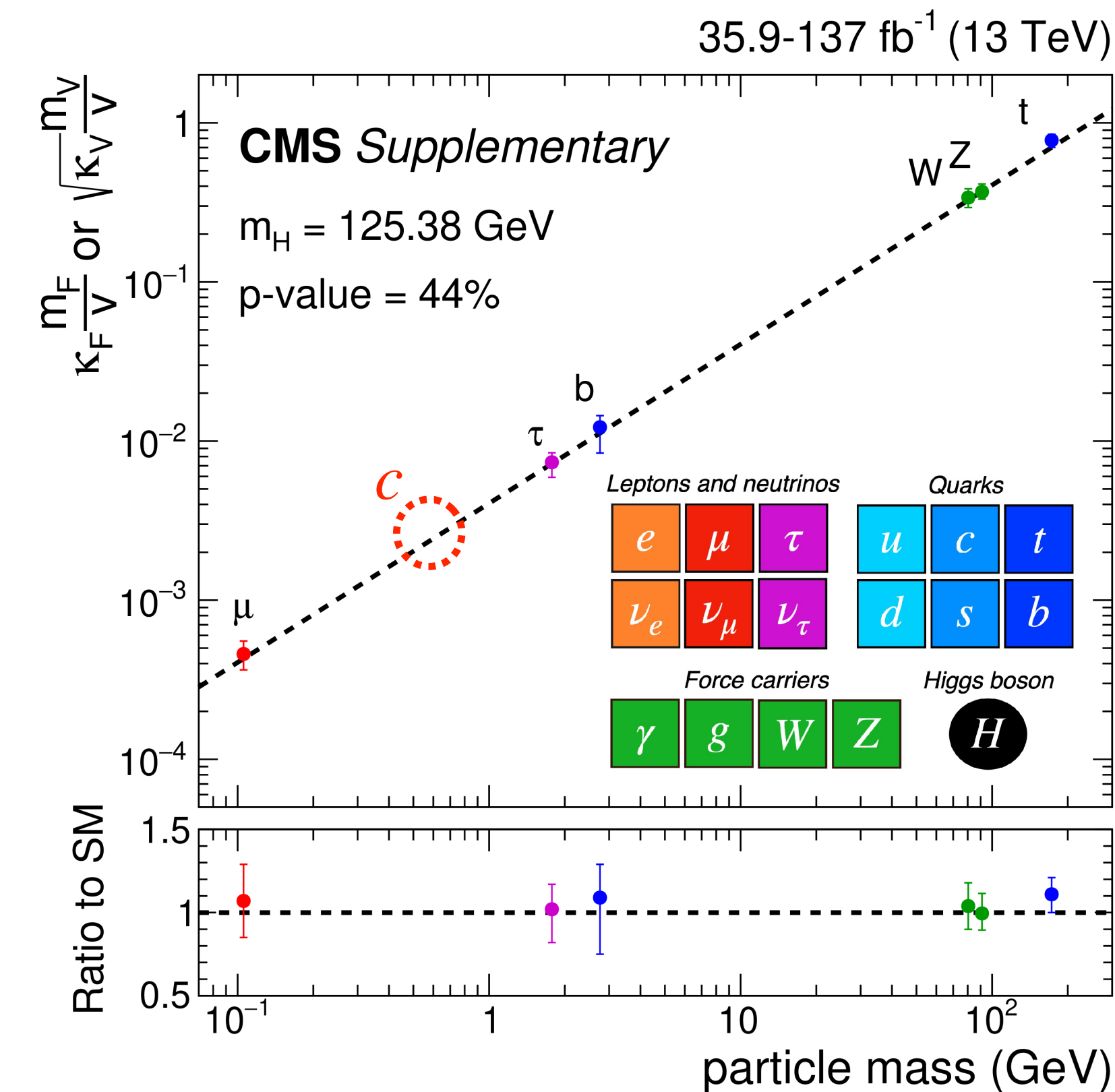
- $\mu_{comb} = 1.31 \pm 0.17$ (stat) ± 0.16 (syst) ± 0.13 (theo)

- $\sigma_{fid} = 6.0 \pm 0.8$ (stat) ± 0.7 (syst) ± 0.6 (theo) fb

- Main uncertainties** due to parton shower modelling calculations

Within uncertainties, measurements **agree** with the **SM** predictions

H($\rightarrow$ WW) γ — K_{2nd} quark review



- Possible to measure or constrain all light quarks Yukawa couplings

Higgs couplings with light fermions: next milestone @ LHC

Several channels to measure c-H coupling

- VH(cc): the most sensitive channel
- ggH(cc): the boosted region explored in CMS

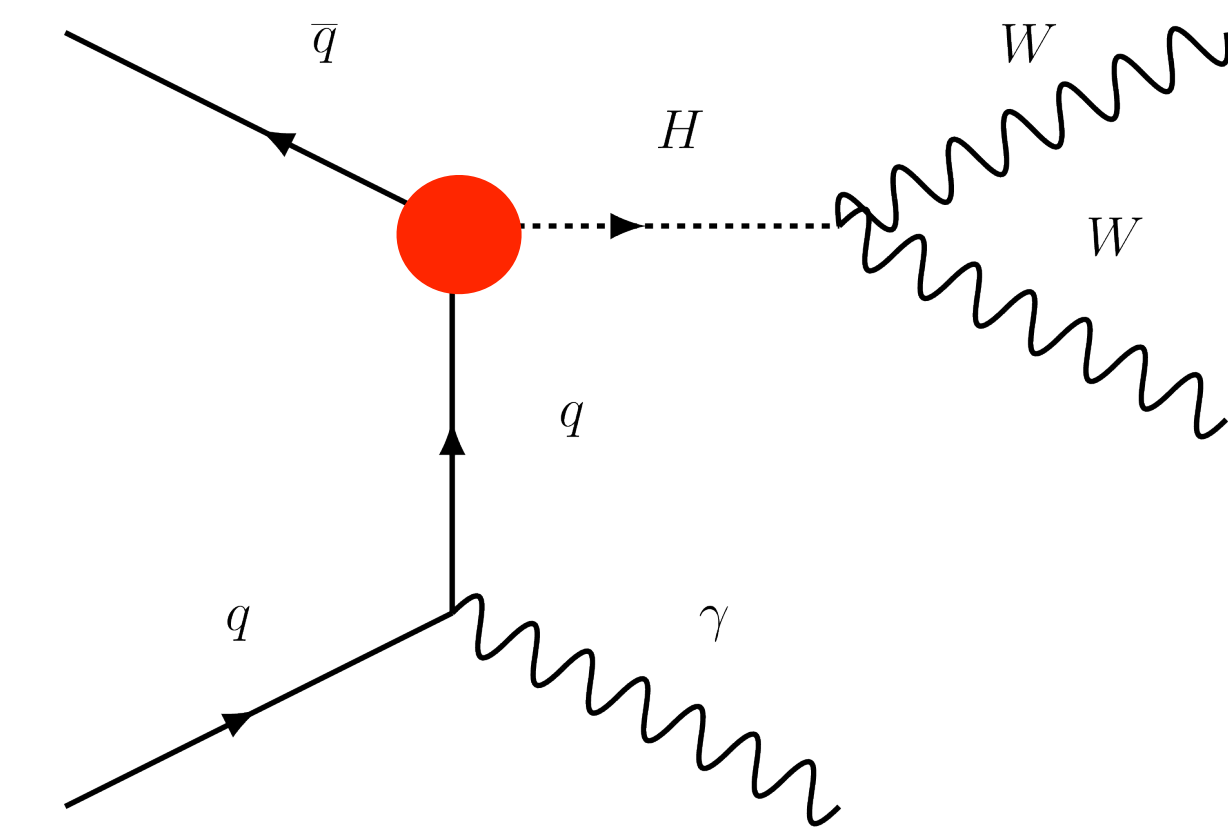
- H-s Yukawa coupling measurement is by $H \rightarrow \phi \gamma$ measurement [1]
- If translate the results [2] to κ_s , the $|\kappa_s| \approx 2.7 \times 10^4$

H-c coupling results	Exp. (Obs.) results
ATLAS VH(cc) ($Z \rightarrow \ell \ell, Z \rightarrow \nu \nu, W \rightarrow \ell \nu$) [EPJC 82 (2022) 717]	$ \kappa_c < 8.5$ (12.4)
CMS VH(cc) ($Z \rightarrow \ell \ell, Z \rightarrow \nu \nu, W \rightarrow \ell \nu$) [arXiv:2205.05550]	$1.1 < \kappa_c < 5.5$ ($\kappa_c < 3.4$)
CMS ggH(cc) [arXiv:2211.14181]	$\mu < 47$ (39)

[1] [https://doi.org/10.1007/JHEP07\(2018\)127](https://doi.org/10.1007/JHEP07(2018)127)

[2] <https://doi.org/10.1103/PhysRevD.101.115005>

H($\rightarrow$ WW) γ signal and background



For $q = u, d, s$

1. MadGraph

- Model “*Higgs effective Lagrangian*”
 - Current-quark masses in $\overline{\text{MS}}$ scheme from PDG are used
- Process: $q\bar{q} \rightarrow H\gamma$

2. JHU generator

- $H \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp \nu_e \bar{\nu}_\mu$

For $q = c$

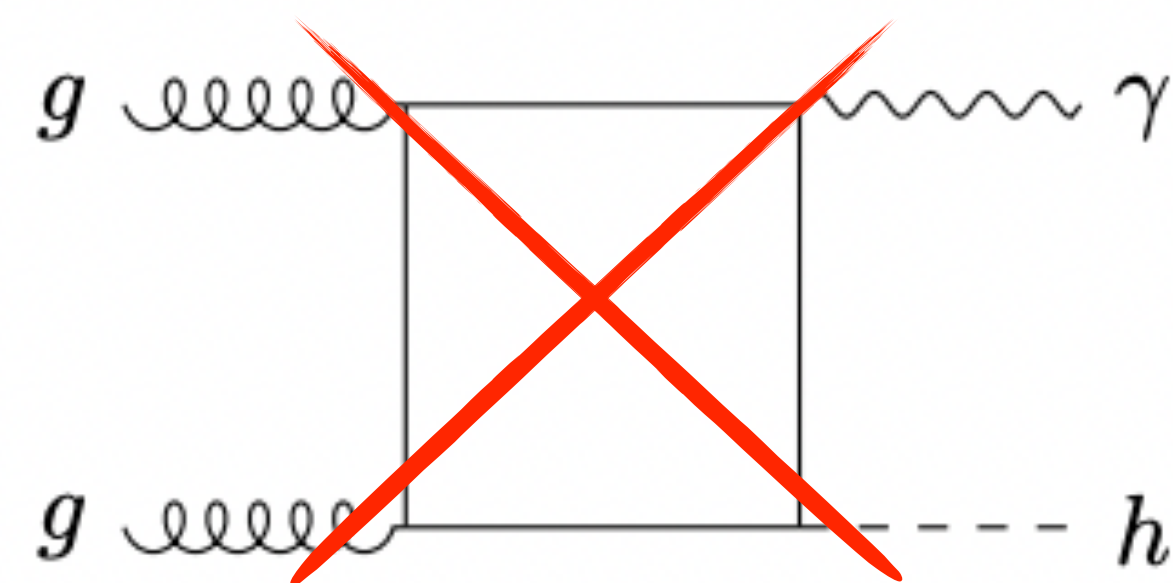
At NLO and considering the quark mass running effect

1. MadGraph

- **Model:** *loop_sm* UFO modified to have *ymc* in $\overline{\text{MS}}$ scheme
 - Closely following theory studies for bbH (1409.5301)
- Process: $q\bar{q} \rightarrow H\gamma$ [QCD]

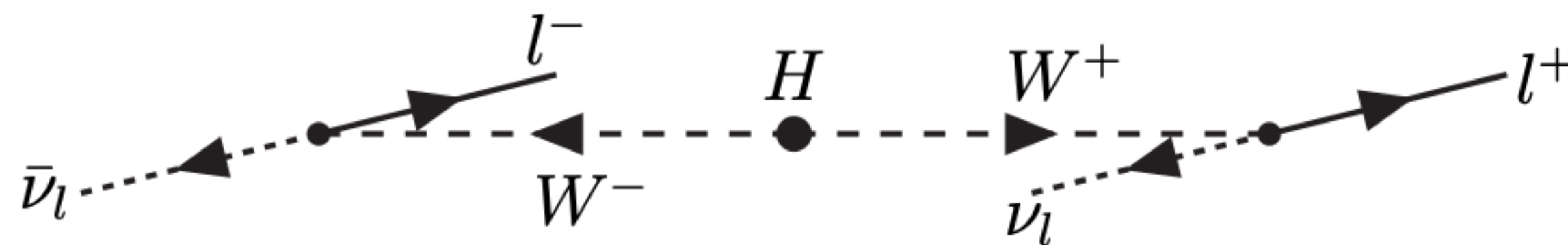
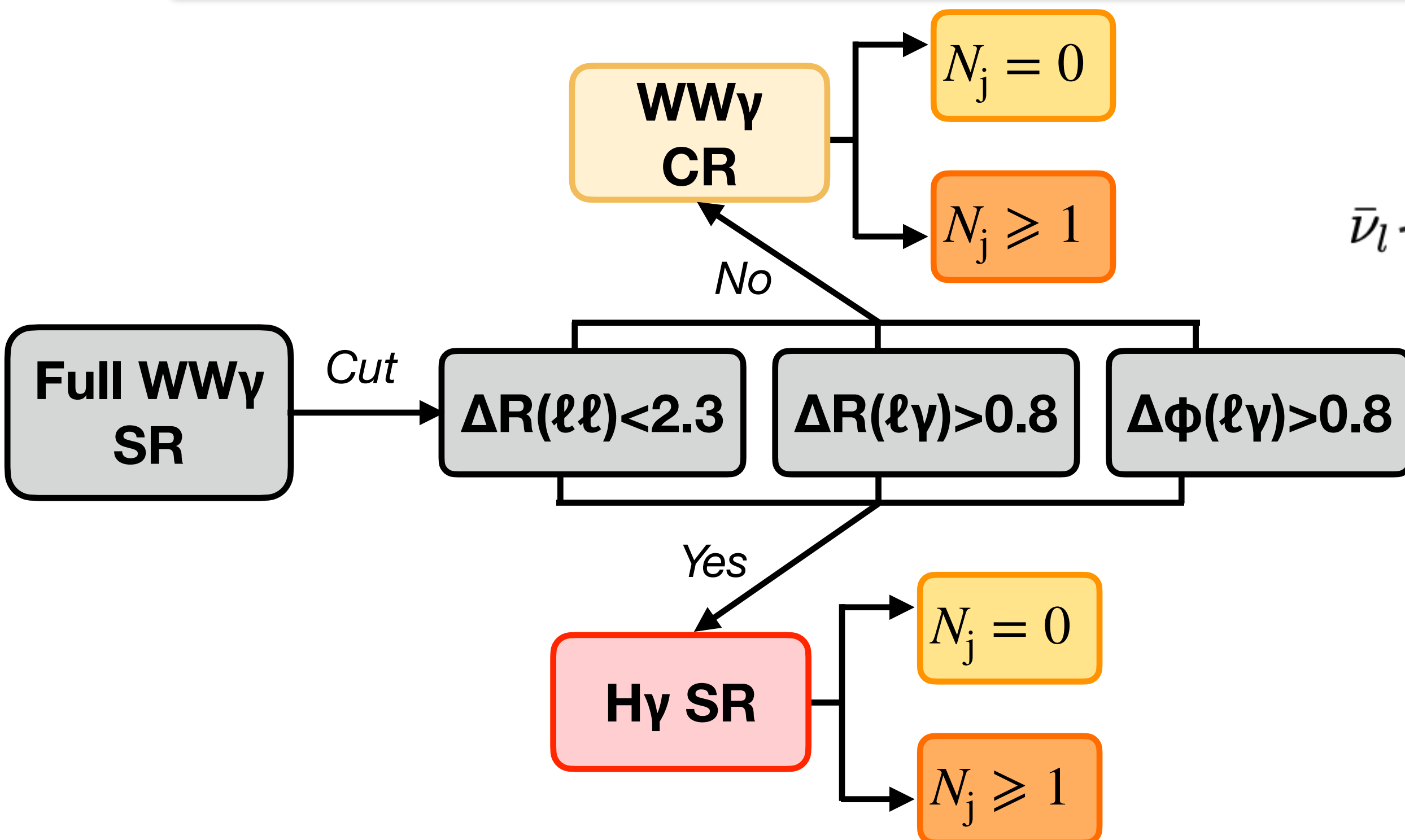
2. JHU generator

$$H \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp \nu_e \bar{\nu}_\mu$$



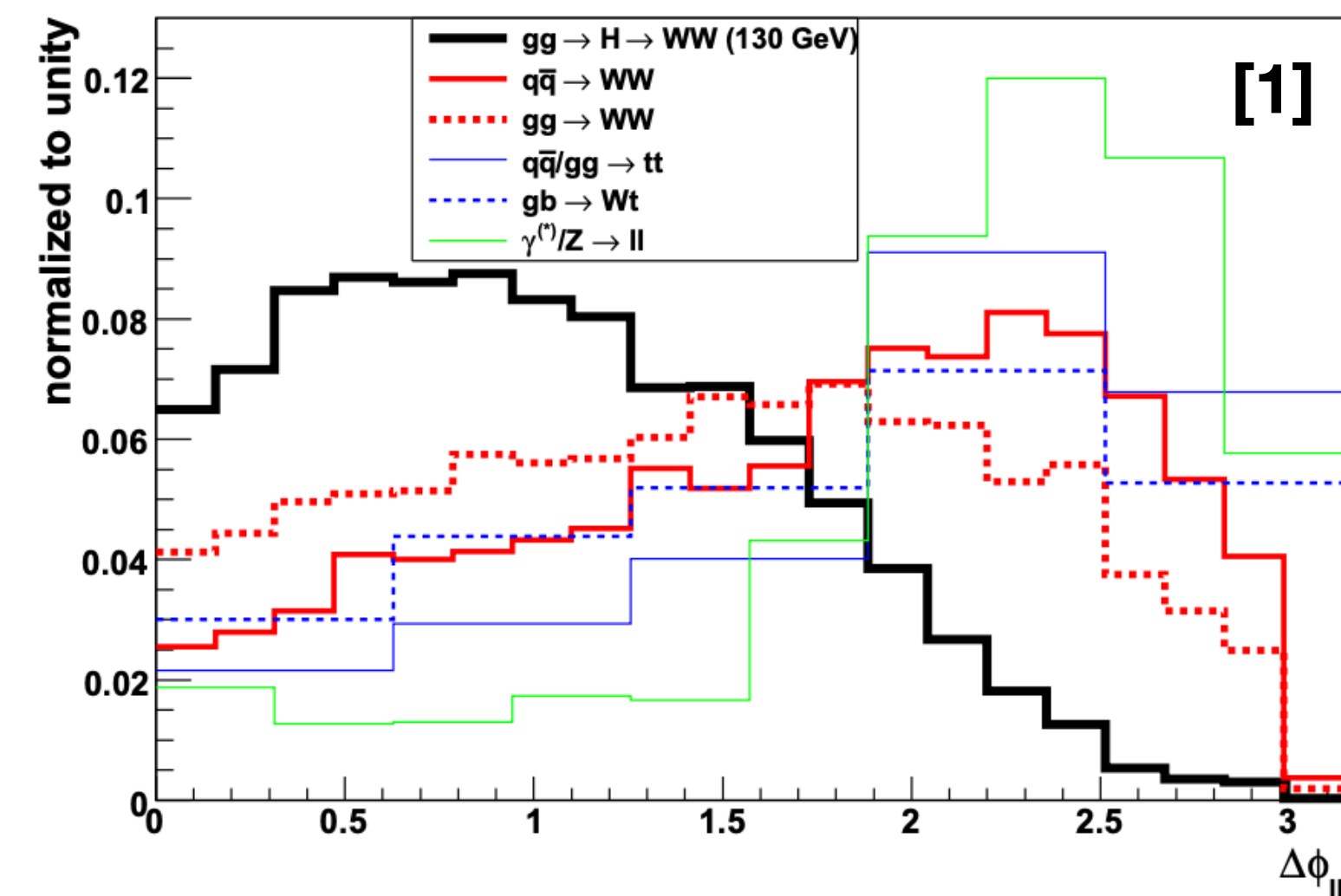
- Main background from gluon-initiated $H\gamma$ doesn't exist due to Furry's theorem [1]
- Backgrounds in $H\gamma$ are sum of signal and backgrounds in the $WW\gamma$ measurement
 - ggH , bbH are checked and can be neglected

$H(\rightarrow WW)\gamma$ selection



1. In the Higgs boson rest frame, the Higgs (spin 0) to two opposite-sign W bosons, traveling in opposite direction and with opposite relative spin orientation
2. The weak decay of the oppositely charged W bosons with opposite spin orientation results in two leptons that tend to travel in the same direction

- Maximum likelihood function for signal extraction
 - WWγ normalization is float
 - Fit for $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c} \rightarrow H\gamma$ separately
- Simultaneous fit of all regions (Hγ SR, WWγ CR, Topγ CR, and SSWWγ CR)
 - Hγ SR: 2D binning, $[10, 40, 70, 110, \infty)$ in m_T^{WW} and $[0.5, 1.0, 1.5, \infty)$ in $\Delta R_{\ell\ell}$
 - WWγ CR 1D binning, $[10, 40, 70, 110, \infty)$ in m_T^{WW}



H($\rightarrow$ WW) γ interpreted results

Cross section limits

Process	σ_{up} pb exp.(obs.)
$u\bar{u} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.085)
$d\bar{d} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.058 (0.072)
$s\bar{s} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.049 (0.068)
$c\bar{c} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.087)

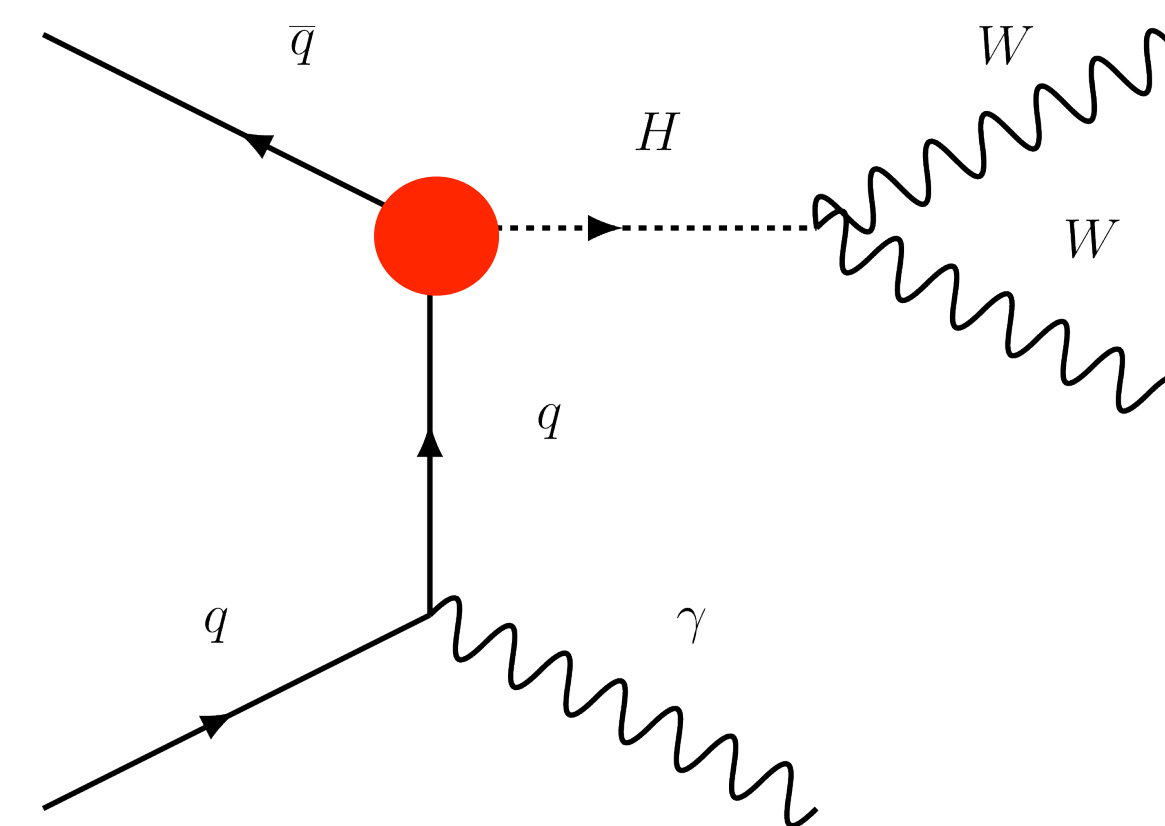
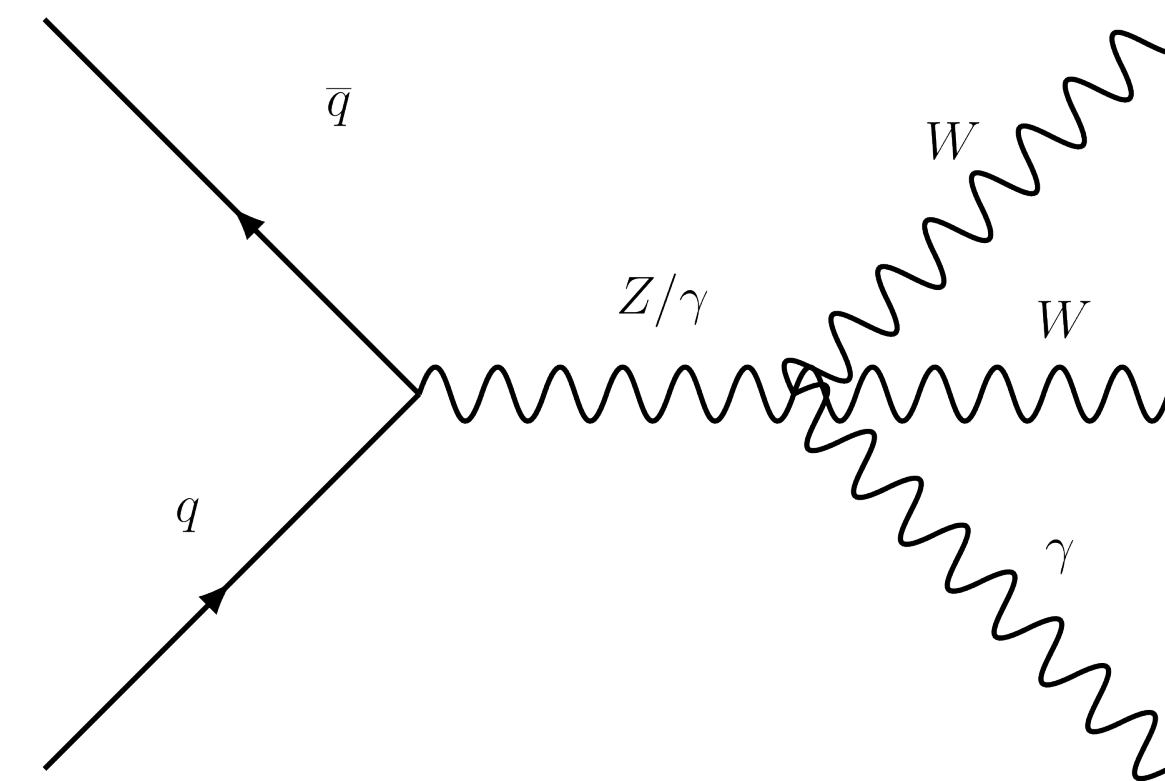
Flat direction: assuming all other SM κ scale as κ_H , which is constrained as a function of κ_q to give a signal strength of 1 for all other Higgs production decay processes [1]

$$\bullet \quad \kappa_H^2 \approx \frac{1 - Br_{q\bar{q}}^{\text{SM}}}{2} + \frac{\sqrt{(1 - Br_{q\bar{q}}^{\text{SM}})^2 + 4Br_{q\bar{q}}^{\text{SM}}\kappa_q^2}}{2}$$

$$\bullet \quad H\gamma \text{ rate can be scaled with } \kappa_q^2 \times \frac{\kappa_H^2}{(1 - Br_{q\bar{q}}^{\text{SM}})\kappa_H^2 + Br_{q\bar{q}}^{\text{SM}}\kappa_q^2}$$

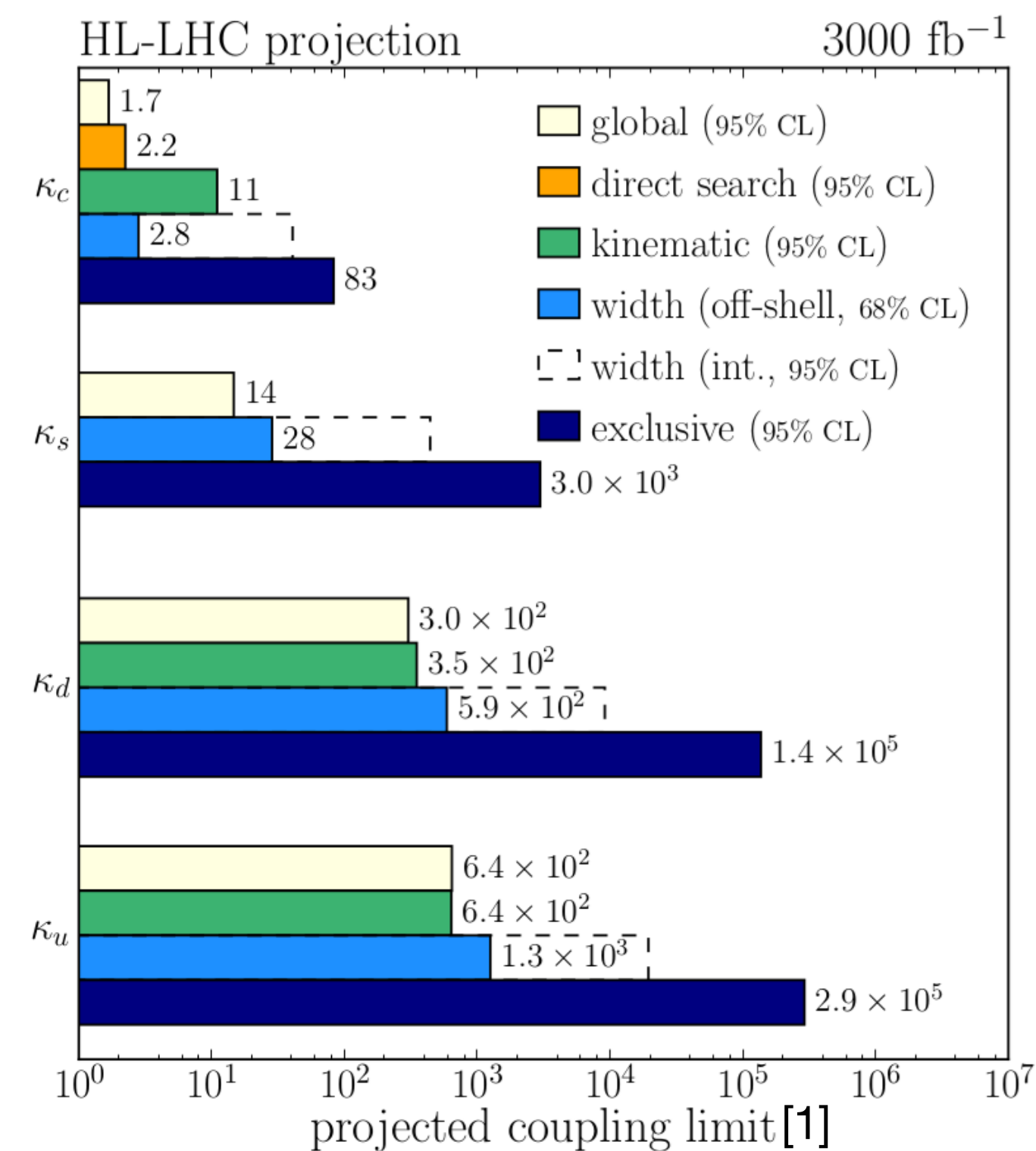
Yukawa couplings limits exp.(obs.)
$ \kappa_u \leq 13000$ (16000)
$ \kappa_d \leq 14000$ (17000)
$ \kappa_s \leq 1300$ (1700)
$ \kappa_c \leq 110$ (200)

- The first observation of $WW\gamma$ production with obs. (exp.)
 $5.6 (4.7) \sigma$
- Inclusive cross section in $e^{\pm}\nu_e\mu^{\mp}\nu_{\mu}\gamma$ final states and
 $WW\gamma$ signal fiducial region
- The cross section upper limits for $H\gamma$ production
- Yukawa coupling of κ_C , κ_S , κ_U , and κ_D interpreted results



Backup

H($\rightarrow$ WW) γ interpretation



Our results reach the HL-LHC exclusive level

Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.085)	$ \kappa_u \leq 13000$ (16000)
$d\bar{d} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.058 (0.072)	$ \kappa_d \leq 14000$ (17000)
$s\bar{s} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.049 (0.068)	$ \kappa_s \leq 1300$ (1700)
$c\bar{c} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.087)	$ \kappa_c \leq 110$ (200)

Branching ratio used in the interpretation results

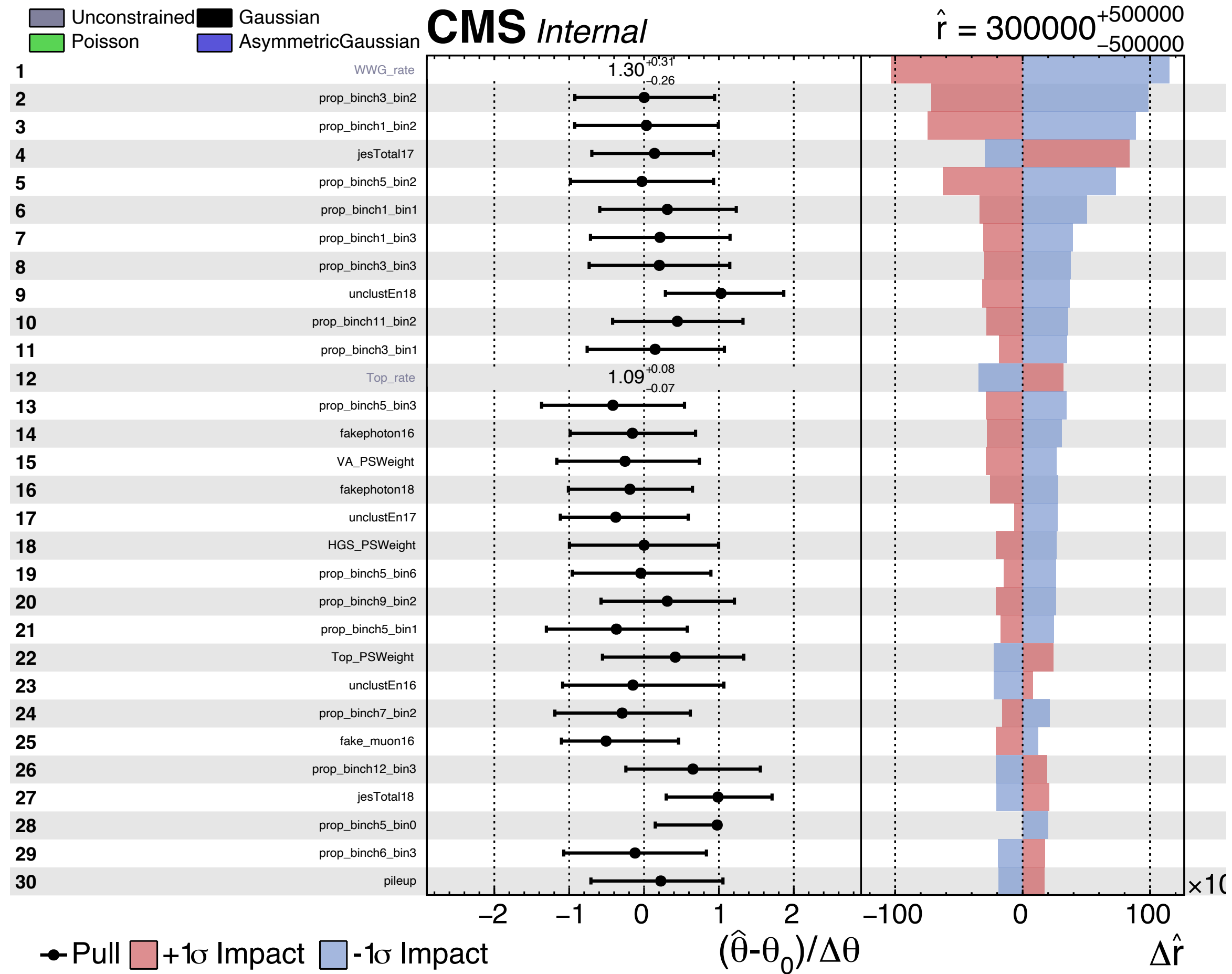
$$Br(H \rightarrow u\bar{u}) = 10^{-8};$$

$$Br(H \rightarrow d\bar{d}) = 10^{-8};$$

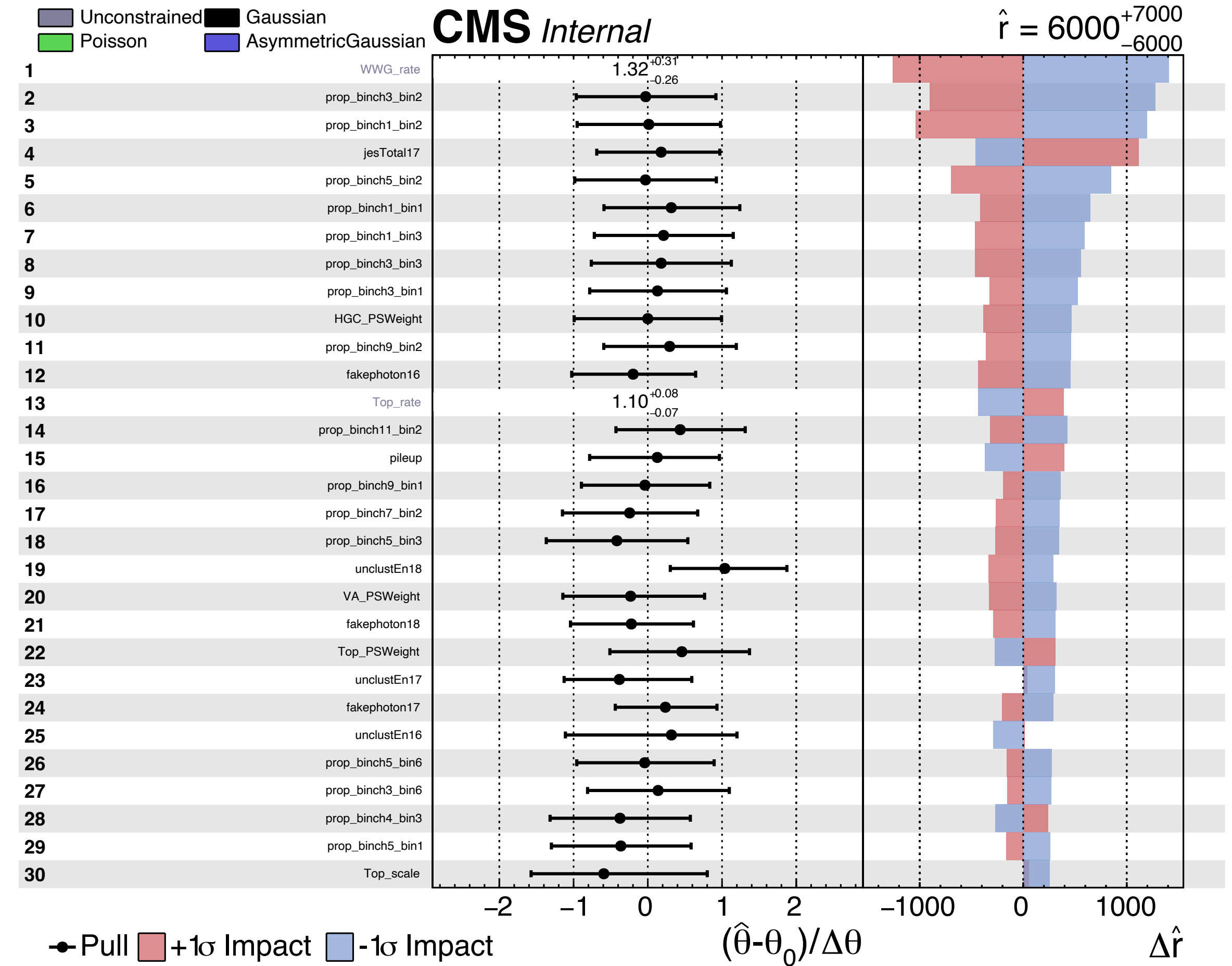
$$Br(H \rightarrow s\bar{s}) = 0.000246;$$

$$Br(H \rightarrow c\bar{c}) = 0.029.$$

Impact plot — H_γ



S process



C process

$H\gamma$ Assumption explanation

An assumption that as $k(u/d/c/s)$ is varied, all other SM k appas are universally rescaled in such a way that all other SM prod x decay processes retain their SM value

The effect of an enhanced Higgs Yukawa coupling k_q to a light quark (u, d, c, s) can be compensated by a related increase of the Higgs couplings to gauge bosons and third-generation fermions, leading to a “flat direction” in the fit along which the Higgs signal strengths remain unchanged

H γ Assumption explanation

1. Regarding the H $\rightarrow$ ss $\bar$ branching fraction, given the model assumptions, the enhancement is by a factor around 4000
2. kappa_s dependence for ggH has not been computed, estimate roughly under $m_b \approx 4\text{GeV}$ $m_c \approx 1\text{GeV}$ and $m_s \approx 0.1\text{GeV}$

$$\sigma/\sigma_{\text{SM}}(\text{ggH}) = 1.04 \cdot k_t^2 + 0.002 \cdot k_b^2 - 0.038 \cdot k_t \cdot k_b - 0.005 \cdot k_t \cdot k_c + 0.0004 \cdot k_b \cdot k_c + 0.00002 \cdot k_c^2$$

- K 2 item for b and c: $0.002/0.00002 = 100 \approx 5 \times (m_b/m_c)^2$
- K $_t$ item for b and c: $0.038/0.005 \approx 2 \times (m_b/m_c)$



$$-0.005 \cdot k_t \cdot k_c + 0.0004 \cdot k_b \cdot k_c + 0.00002 \cdot k_c^2$$



For $k_s = 1300$ (-1300)

$$-0.005/(2 \times m_c/m_s) \cdot k_t \cdot k_s + 0.0004 \cdot k_b \cdot k_c + 0.00002/(5 \times m_c/m_s \times m_c/m_s) \cdot k_s^2 \approx -0.26 \text{ (0.39)}$$

$$\sigma/\sigma_{\text{SM}}(\text{ggH}) = 1.04 + 0.002 - 0.038 + (-0.26) \text{ or } (0.39) \approx 0.75 \text{ (1.39)}$$

H γ Assumption explanation

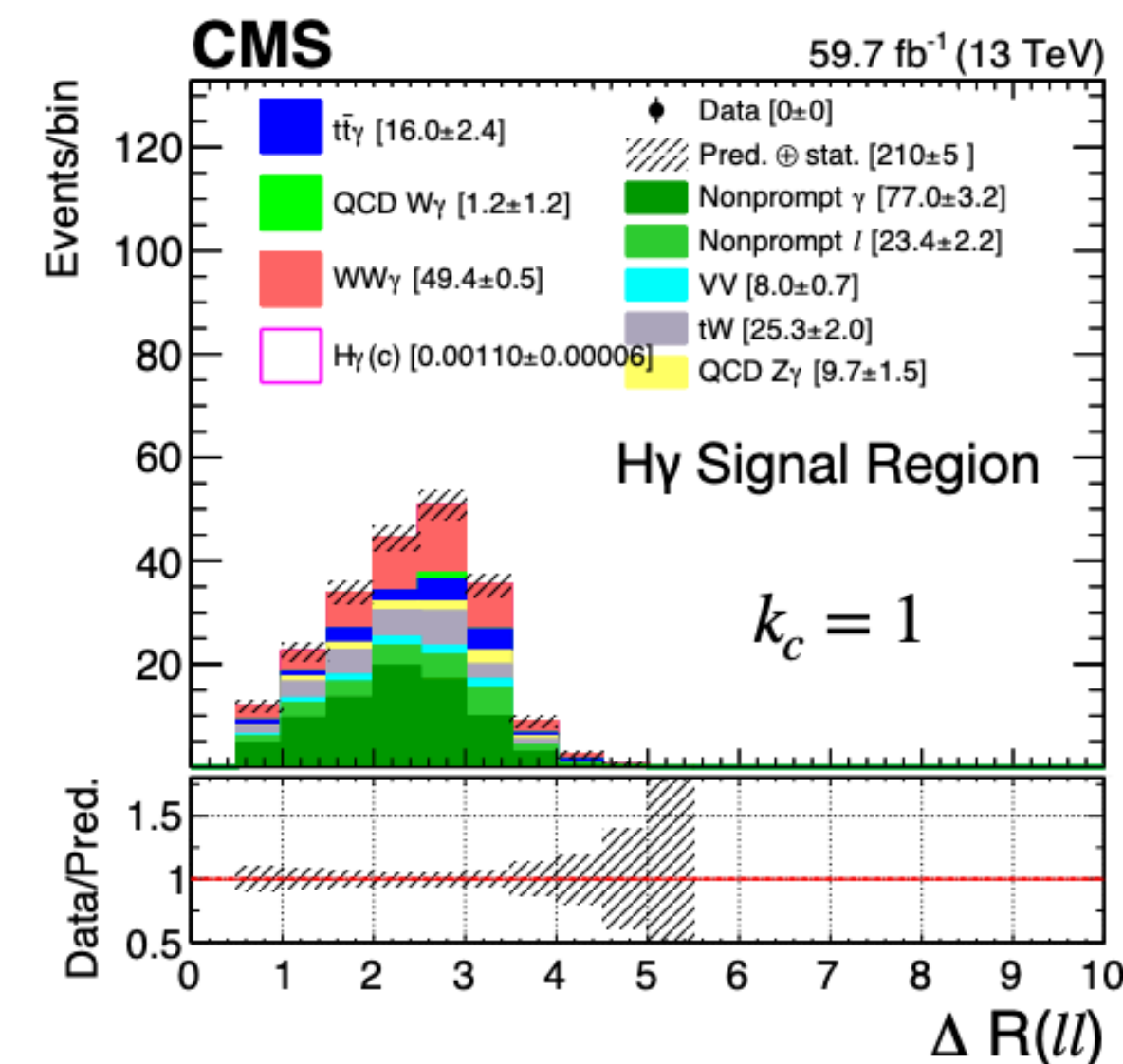
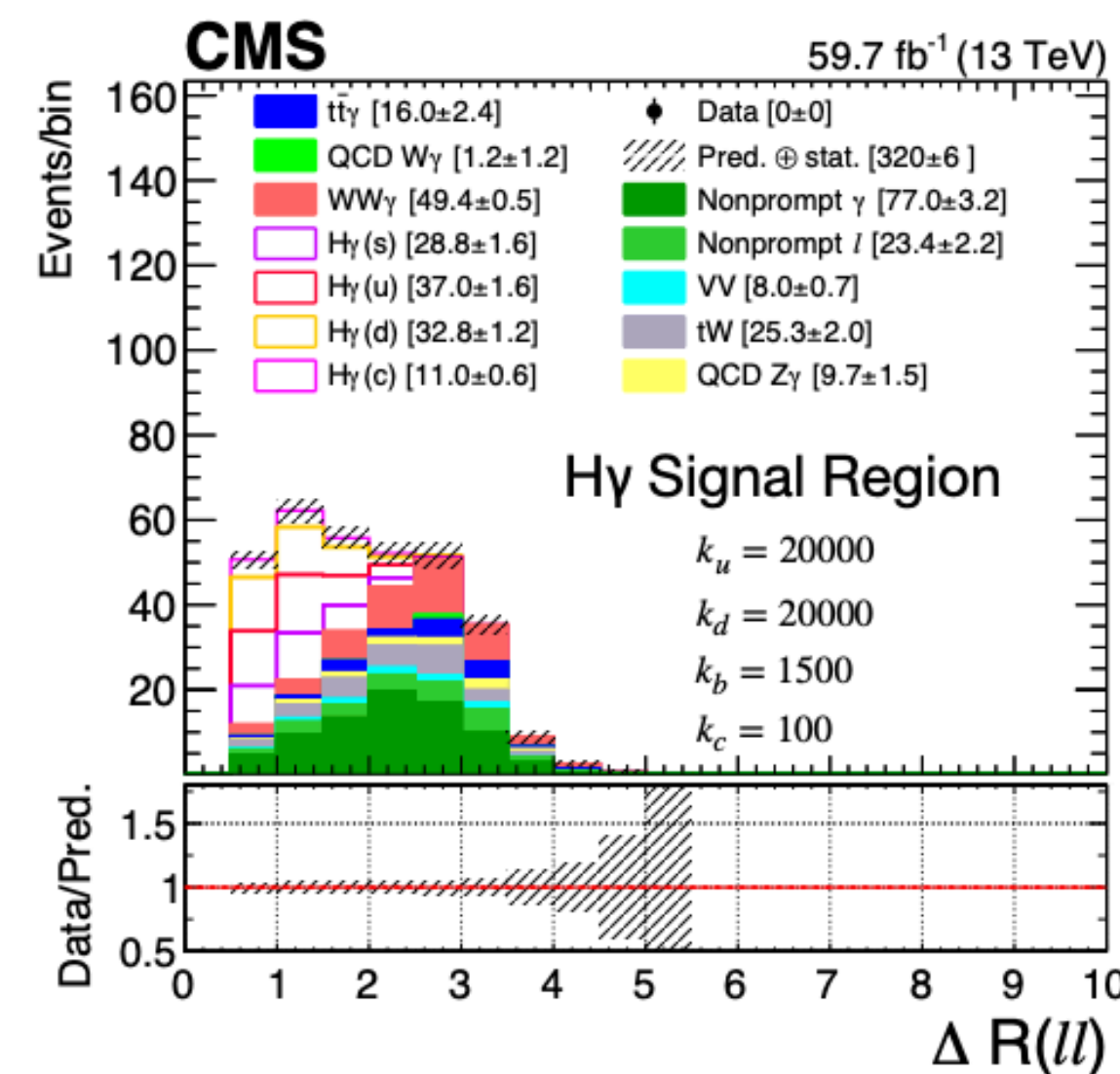
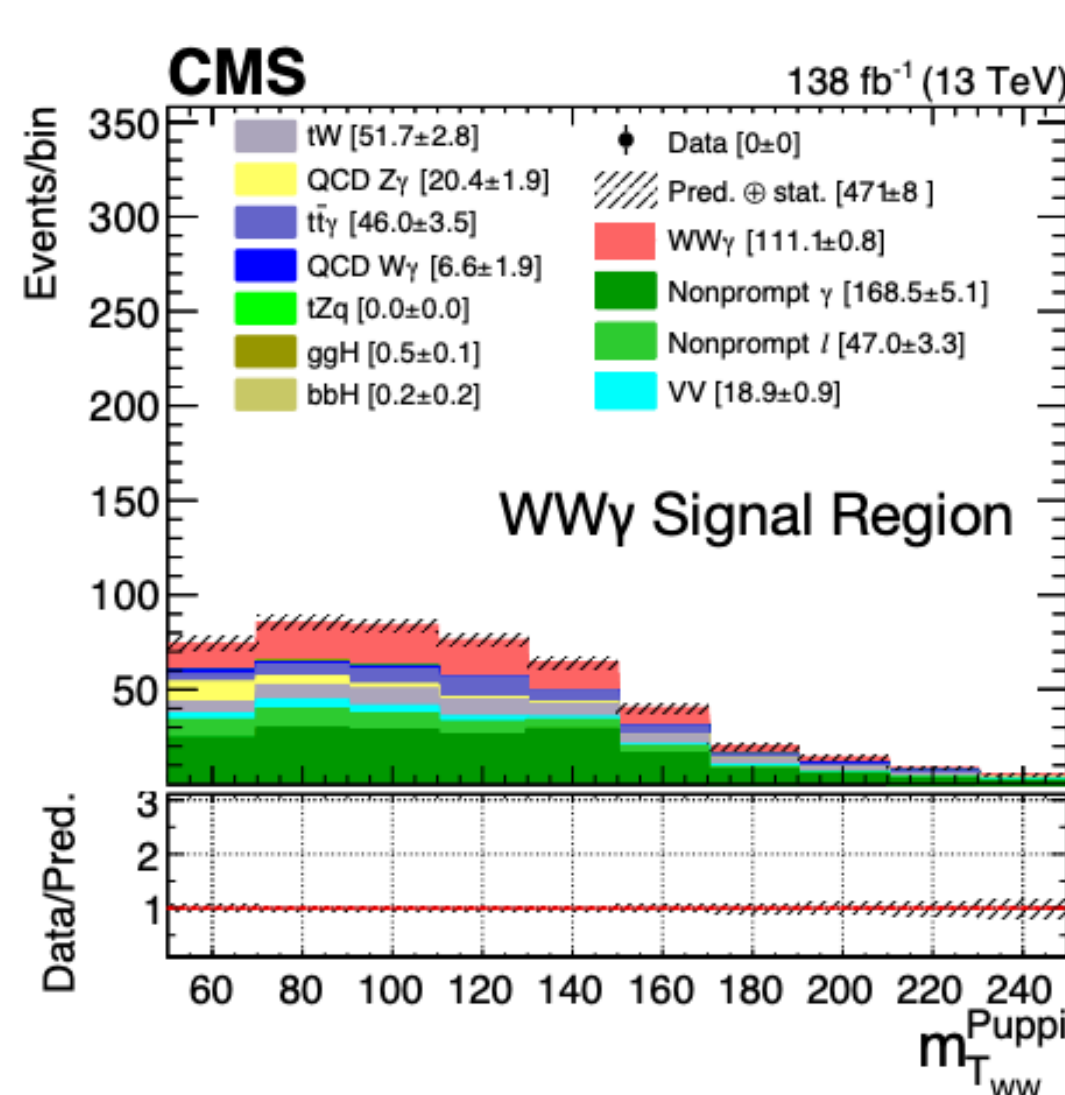
- Samples:

$\left\{ \begin{array}{l} \text{bbHToWWTo2L2Nu_M-125_4FS_yb2_TuneCP5_PSweights_13TeV_amcatnlo_pythia8} \\ \text{bbHToWWTo2L2Nu_M-125_4FS_ybyt_TuneCP5_PSweights_13TeV_amcatnlo_pythia8} \end{array} \right. \quad \text{Cross-section: 0.4027 (NanoAOD v7)}$
 $\left\{ \begin{array}{l} \text{GluGluHToWWTo2L2Nu_M125_TuneCP5_13TeV_powheg2_JHUGenV714_pythia8} \\ \text{ccToHyTo2L2Nu} \quad \text{Private Samples} \end{array} \right. \quad \text{Cross-section: 0.9913 (NanoAOD v9)}$
 Cross-section: $4.724 \text{ e-04} \times 0.01055$

branch ratio takes from [Link](#) with MH 125 GeV

$l = e \text{ or } \mu$

- The contribution in Signal and H γ Region



- ggH/bbH yields are small (about 0.2), can be ignored.
- H γ sensitive yields are about 10~100