Observation of WWγ** production* along with a search for the **Hγ production** *by couplings of the Higgs boson to **light quarks

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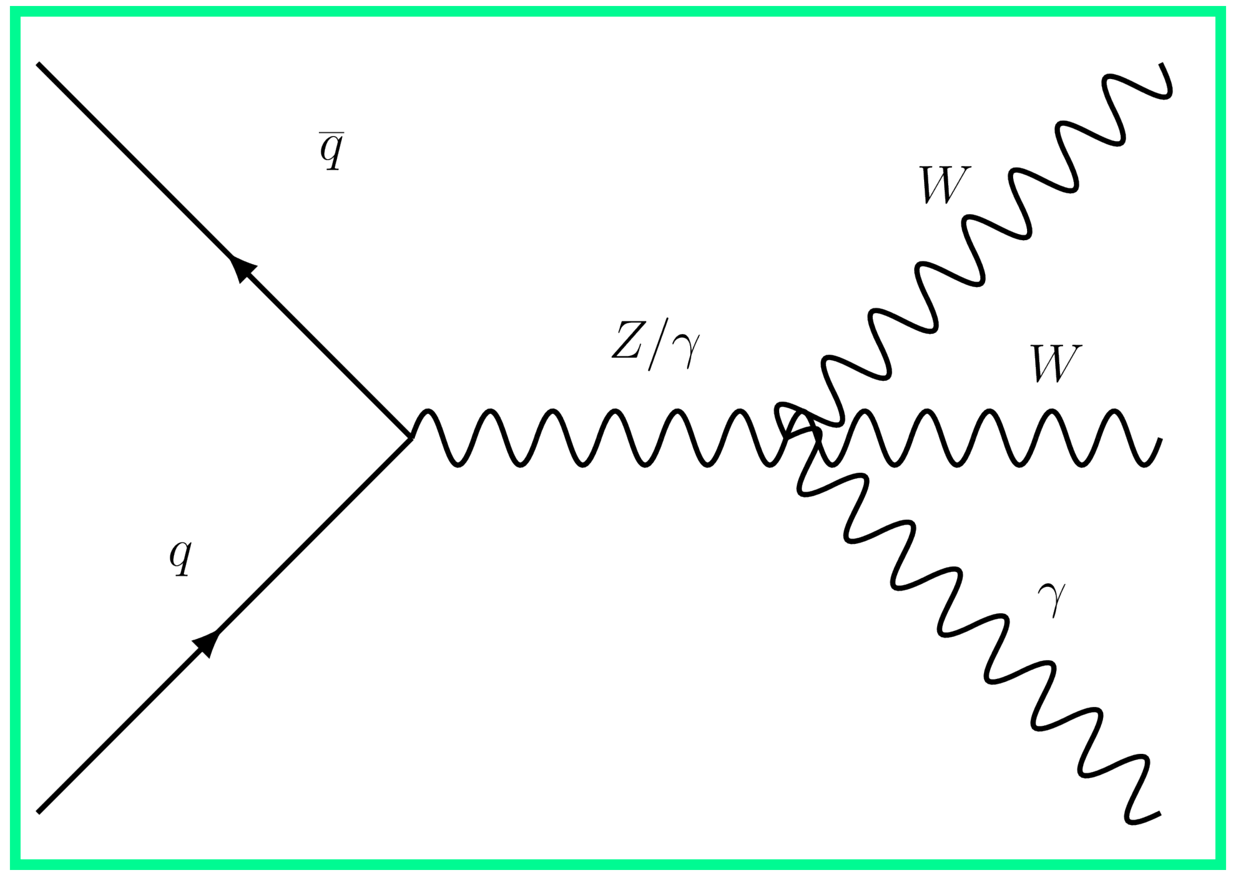
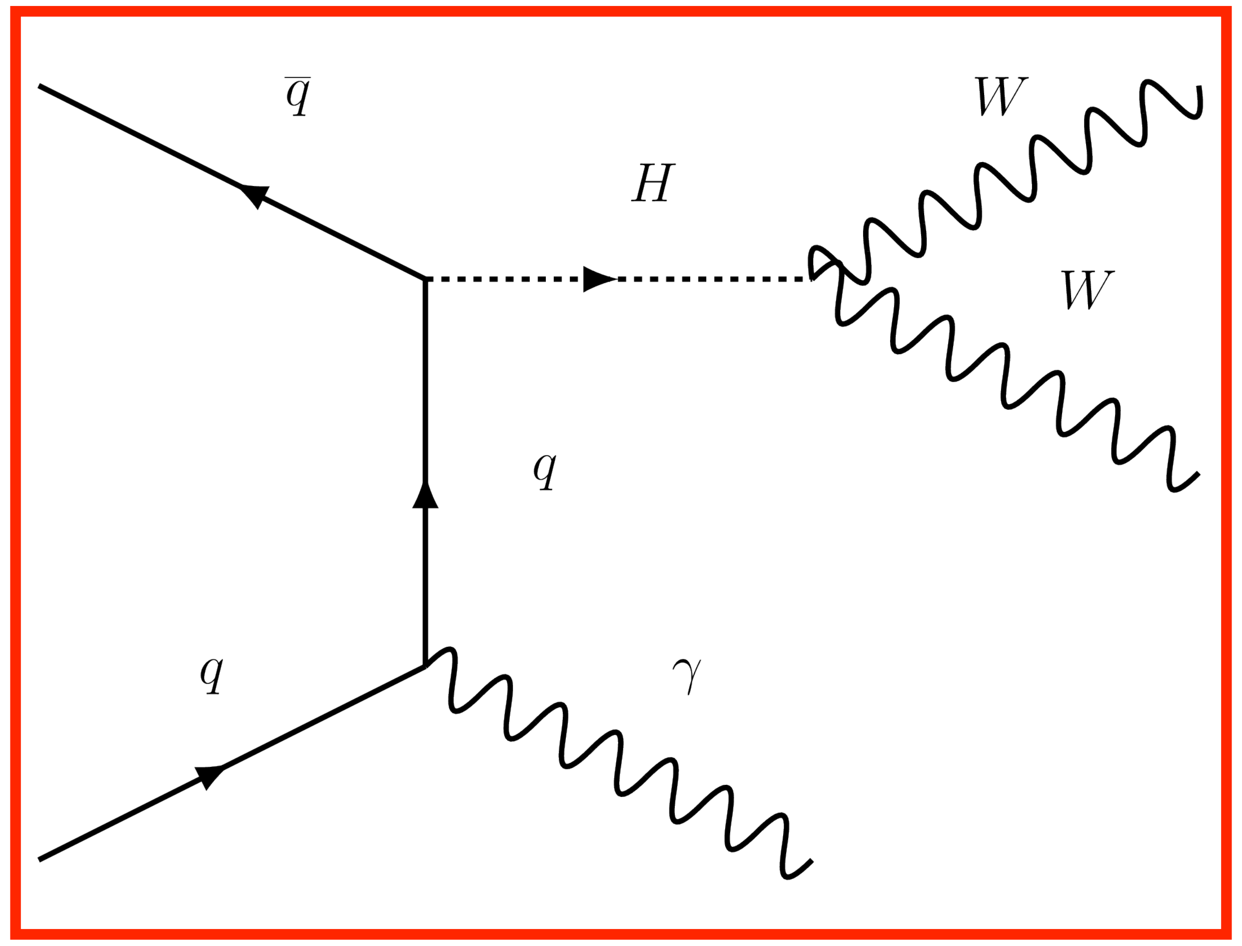
LHC EW WG MB 07/06/2023

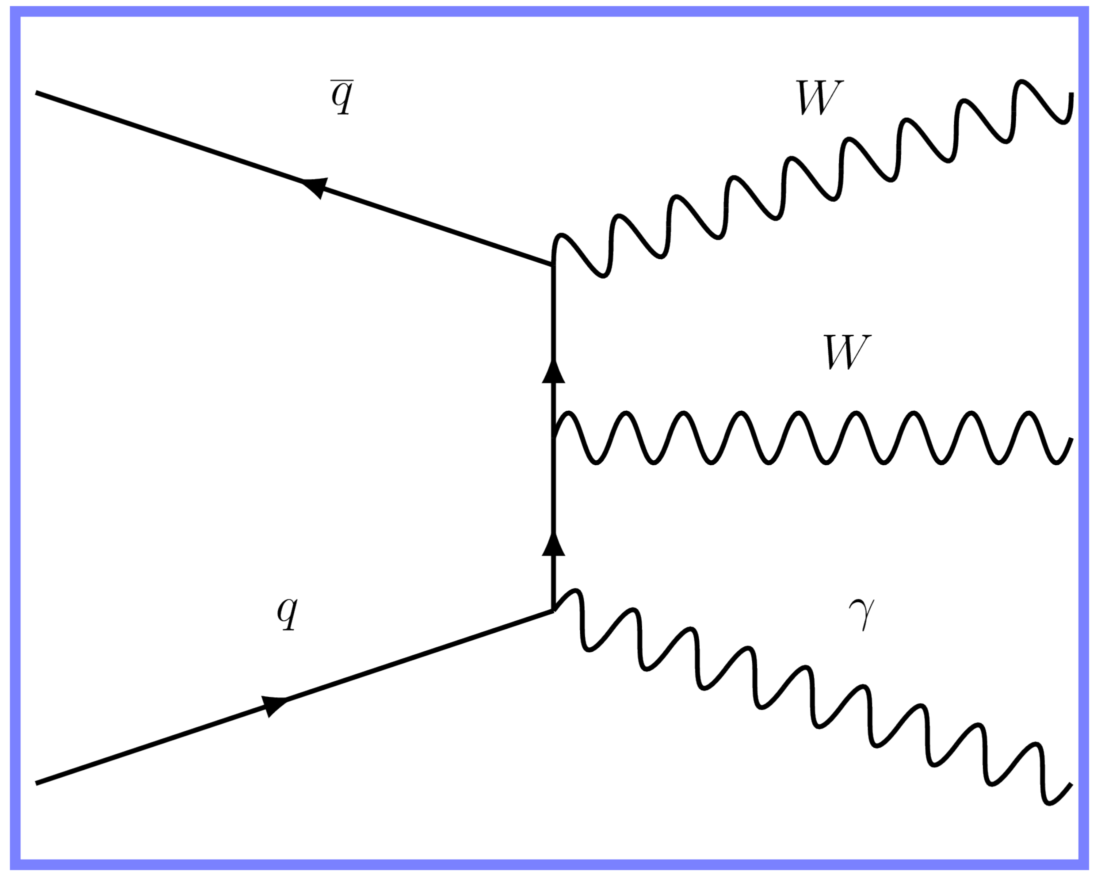
Outline

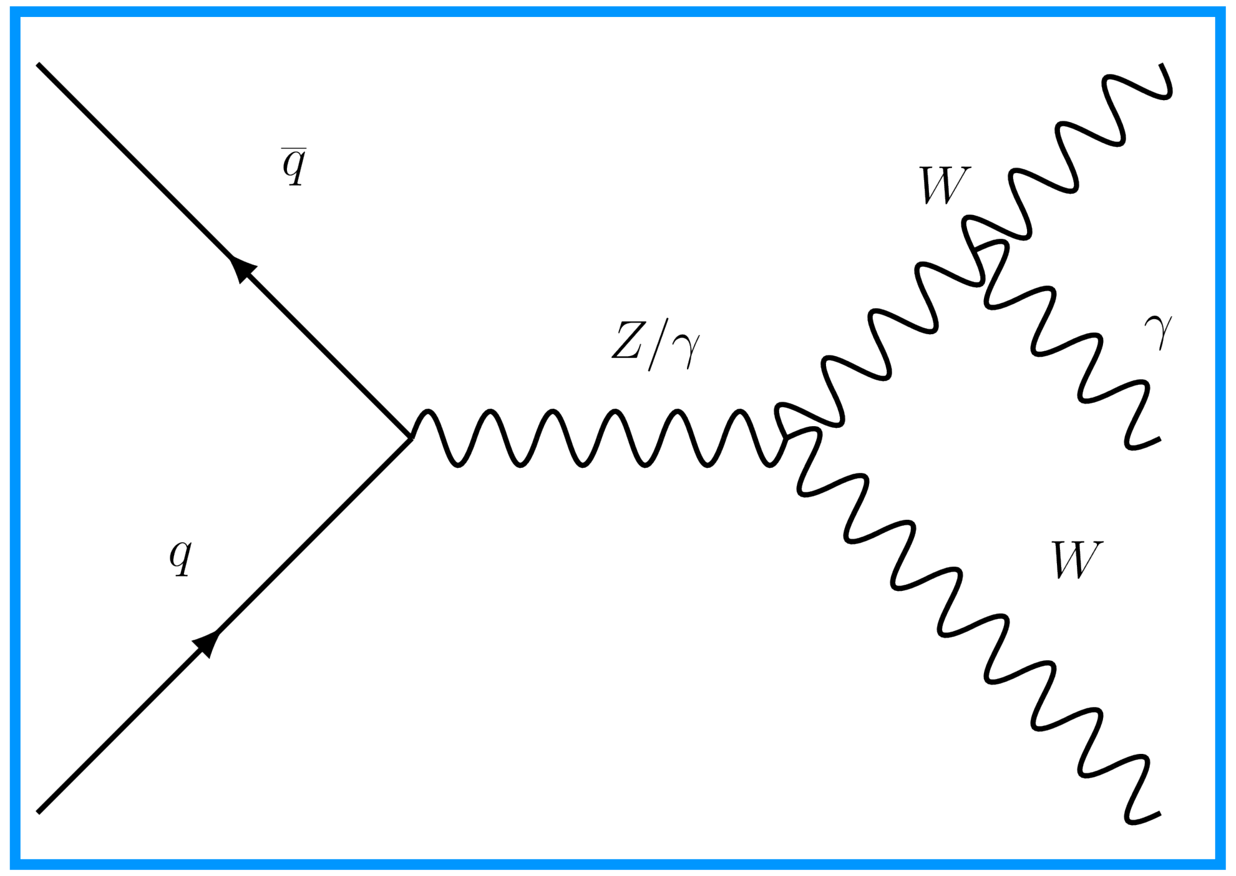
- Introduction
  - Physics motivation and public results review
- WWγ measurements
  - *Signal production*
  - *Selection/region definition*
  - *Background estimation*
  - *Results*
    - ☑ **WWγ signal significance**
    - ☑ **WWγ inclusive cross section**
- Hγ production search
  - *Hγ signal and background*
  - *Selection and results*
  - ☑ **Hγ cross section upper limits** and **the interpreted Yukawa couplings results**

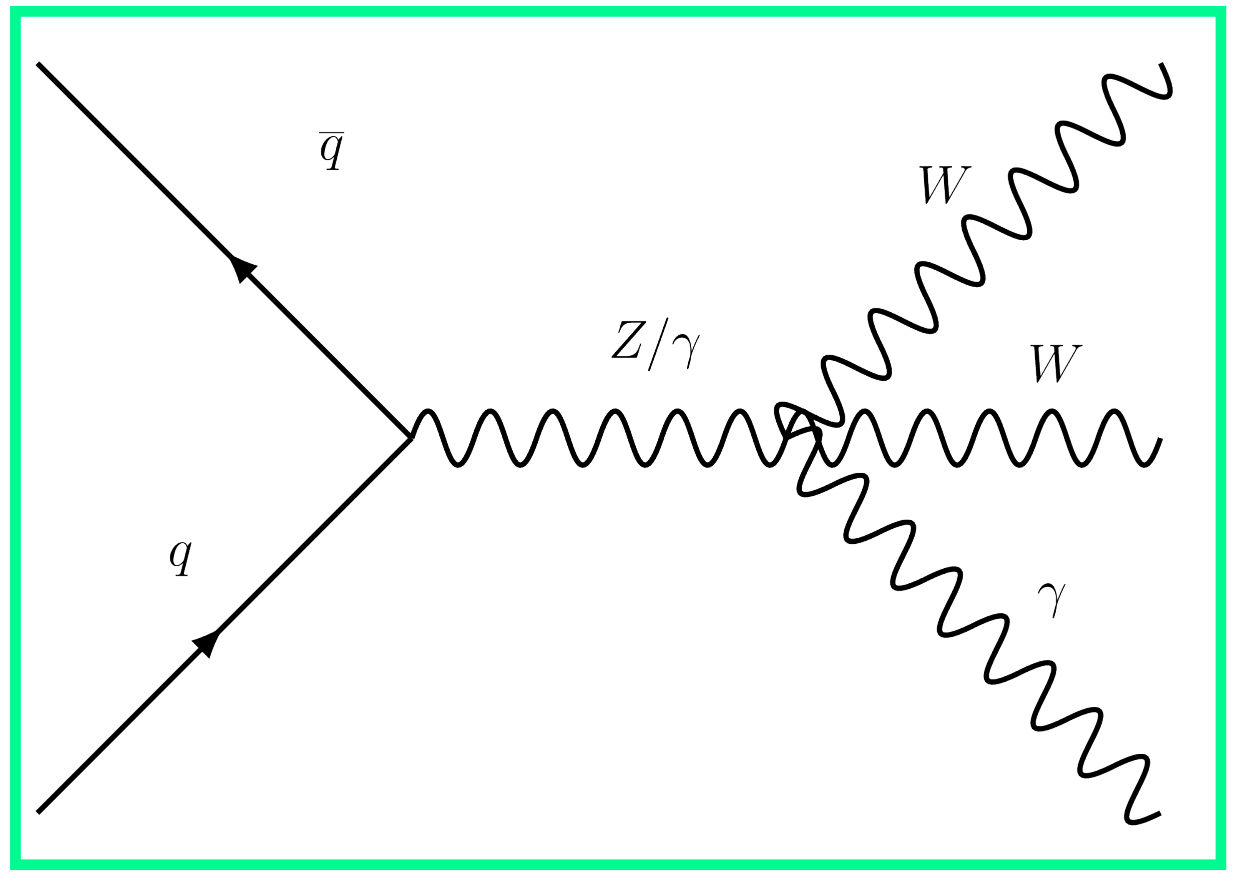


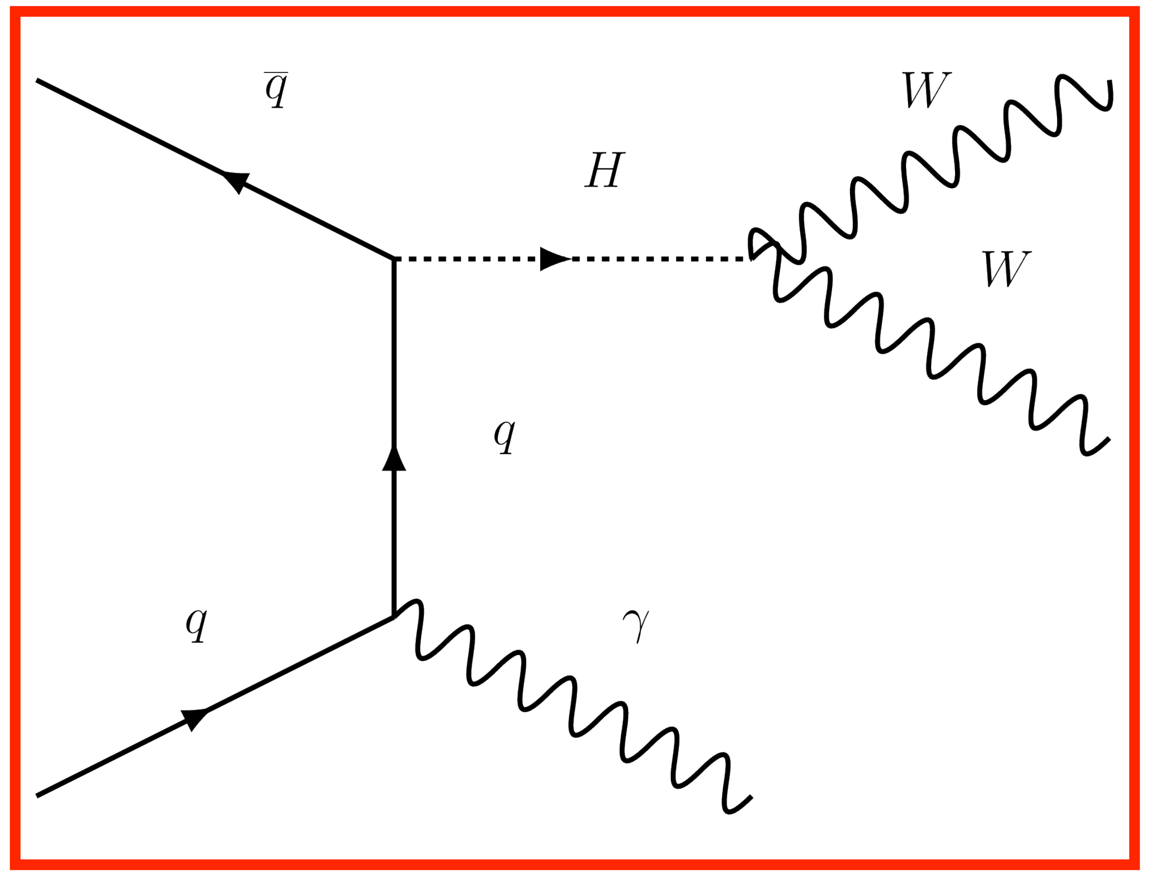


Introduction — Why triboson









- 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

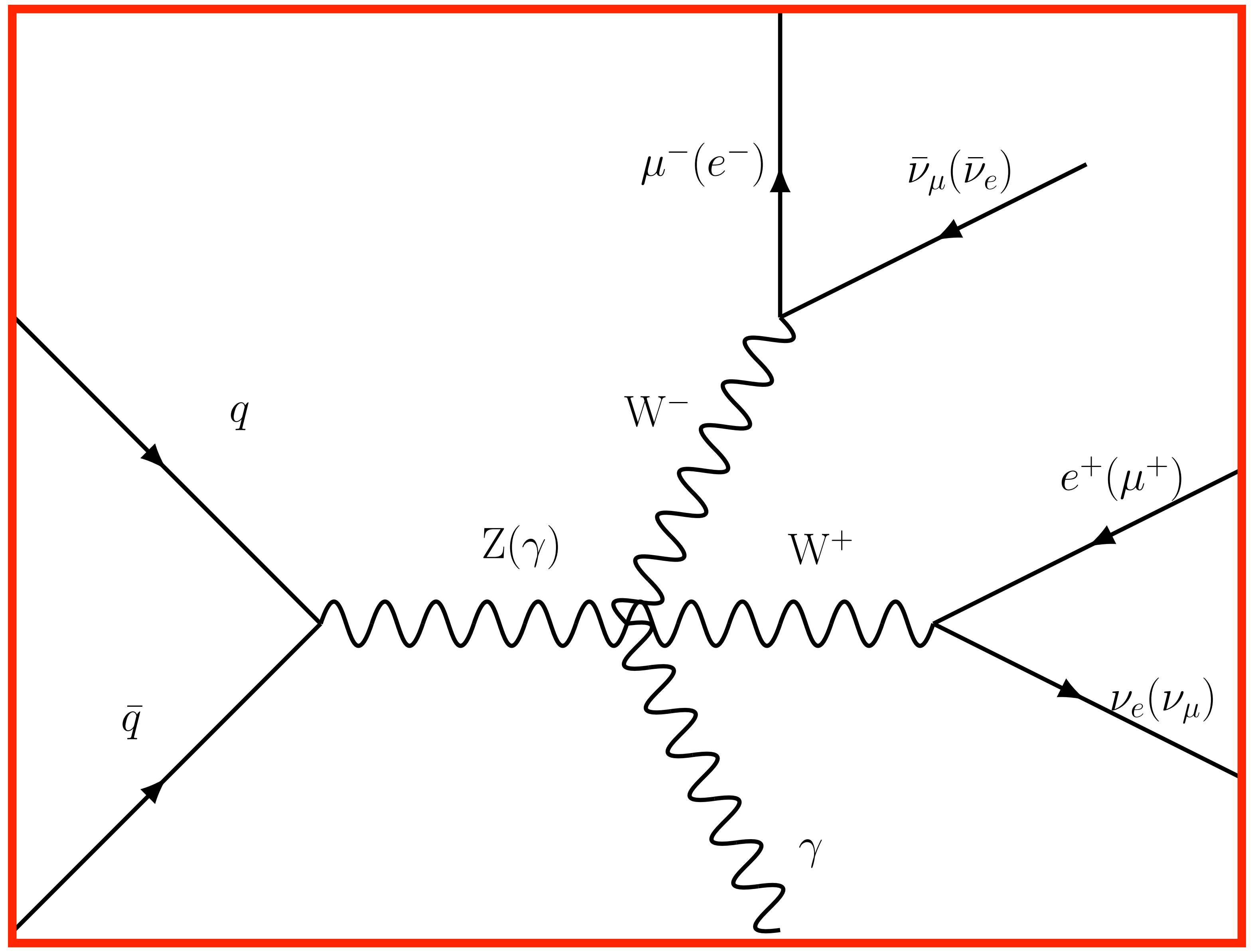
Platform to search the Higgs to light quark Yukawa couplings

Introduction — WWγ

Experiment		CMS		ATLAS	
Triboson with γ	Final states	Journal	Lumi fb^{-1} /√s TeV	Journal	Lumi fb^{-1}/ √s TeV
WVγ	ℓvjjγ	PRD 90 (2014) 032008	19.3/ 8	EPJC 77, 646 (2017)	20.2/ 8
WWγ	eμvvγ	**SMP-22-006**	138/ 13	—	20.2/ 8

CMS:
- Cross section limit of WVγ (ℓvjjγ)
- Limits on dim-8 and dim-6 operators

ATLAS:
- Cross section limit of WWγ (eμvvγ) and WVγ (ℓvjjγ)
  - $\sigma_{\text{fid}}^{e\nu\mu\nu\gamma} = 1.5 \pm 0.9(\text{stat.}) \pm 0.5(\text{syst.})$ fb (N_{jets}=0)
  - Observed (expected) 1.4 σ (1.6 σ)
- 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

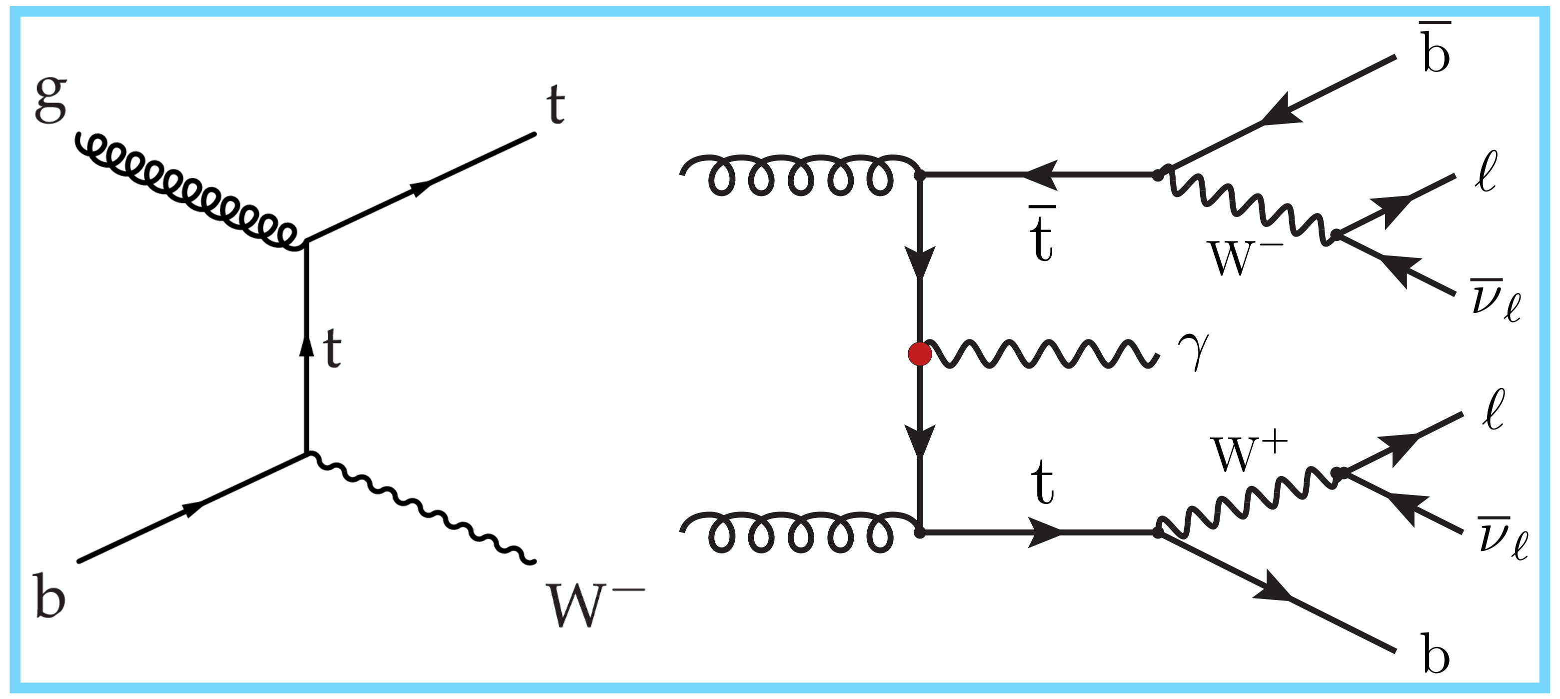
Signal production

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

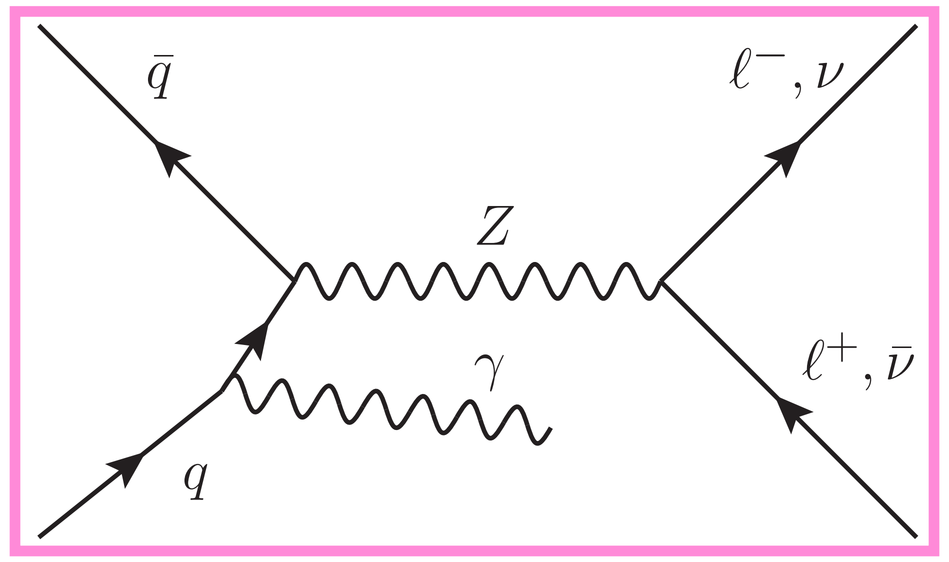
- Signal is produced by MadGraph at NLO in QCD accuracy showering by Pythia8 with NNLO PDF
  - ☑ FSR (final state radiation) photons are included
  - ☑ No EW or much higher QCD corrections
- MVA-based identifications are used for physics object **reconstruction**
  - ☑ Improve efficiency and sensitivity

Background estimation

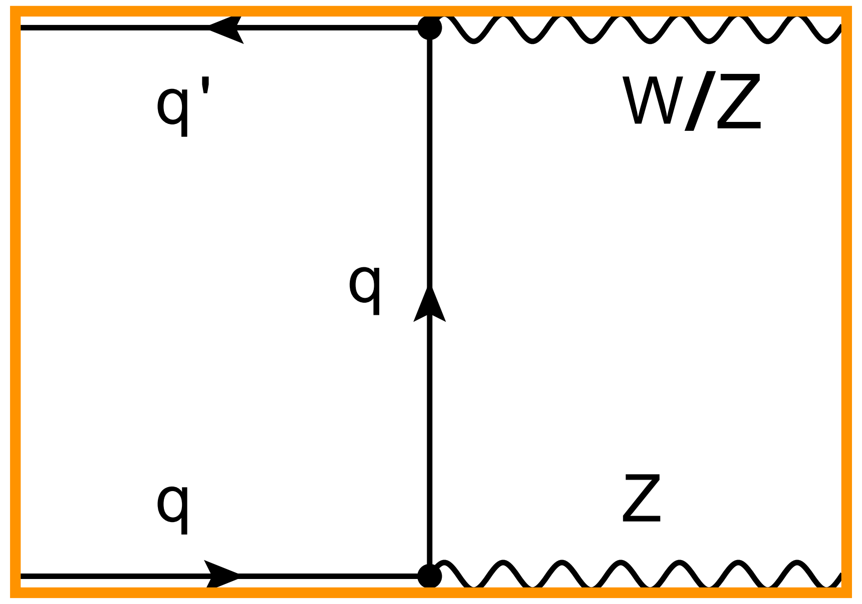
- $t\bar{t}\gamma$ and tW



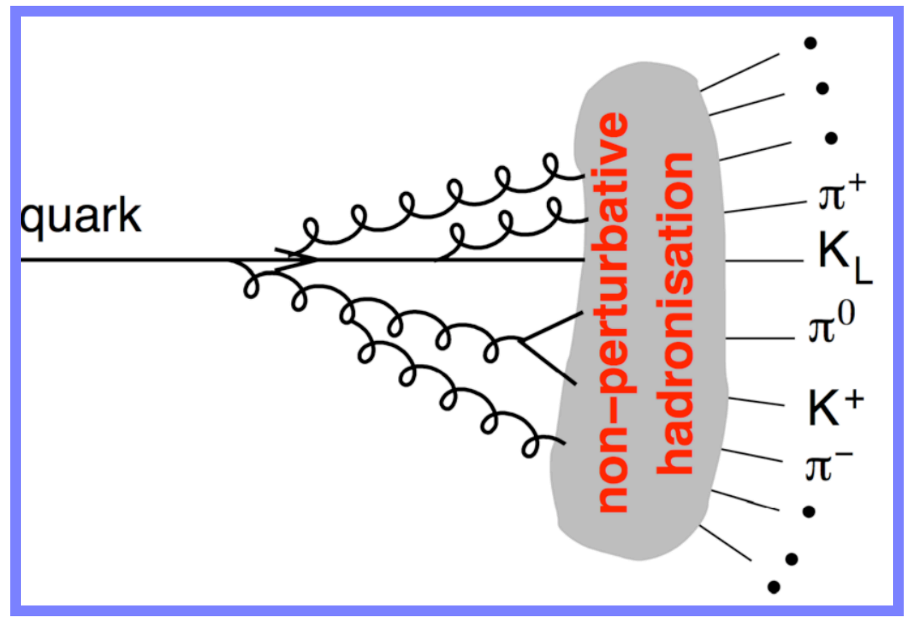
- Zγ process



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

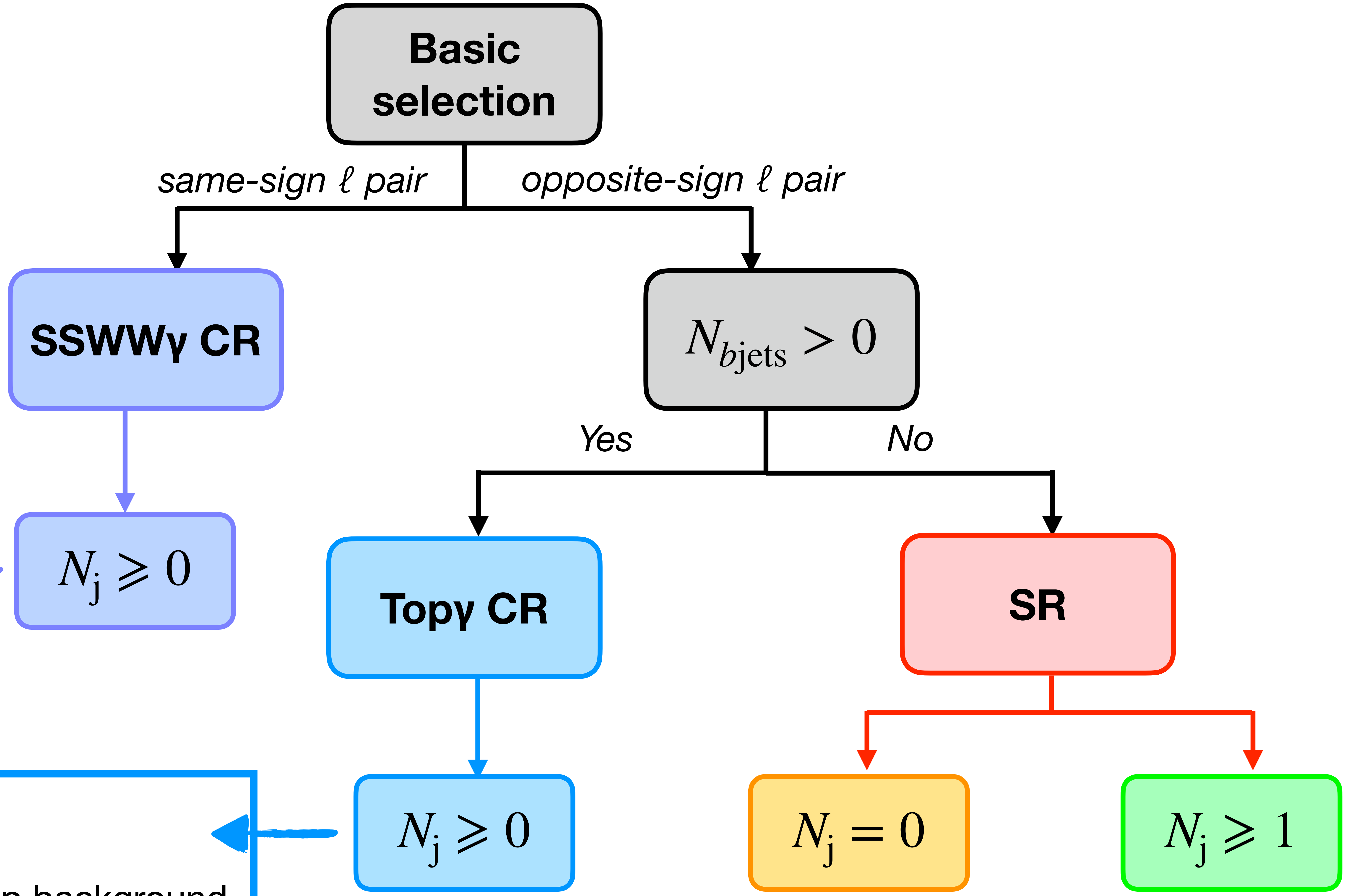
- W or Z decays to e/μ/τ where one or two ℓ are not detected and γ from showering
- e misidentified as γ

- Jets misidentified as ℓ or γ

- Other backgrounds with ignorable contributions are Wγ+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, $\lvert\eta\rvert$ < 2.4 (2.5) B. Pass HLT (μe) paths C. m_{ll} > 10 GeV and p_T^{ll} > 15 GeV D. E_T^{miss}(PF) > 20 GeV and m_T^{WW} > 10 GeV E. p_T^{γ} > 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 Vγ 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

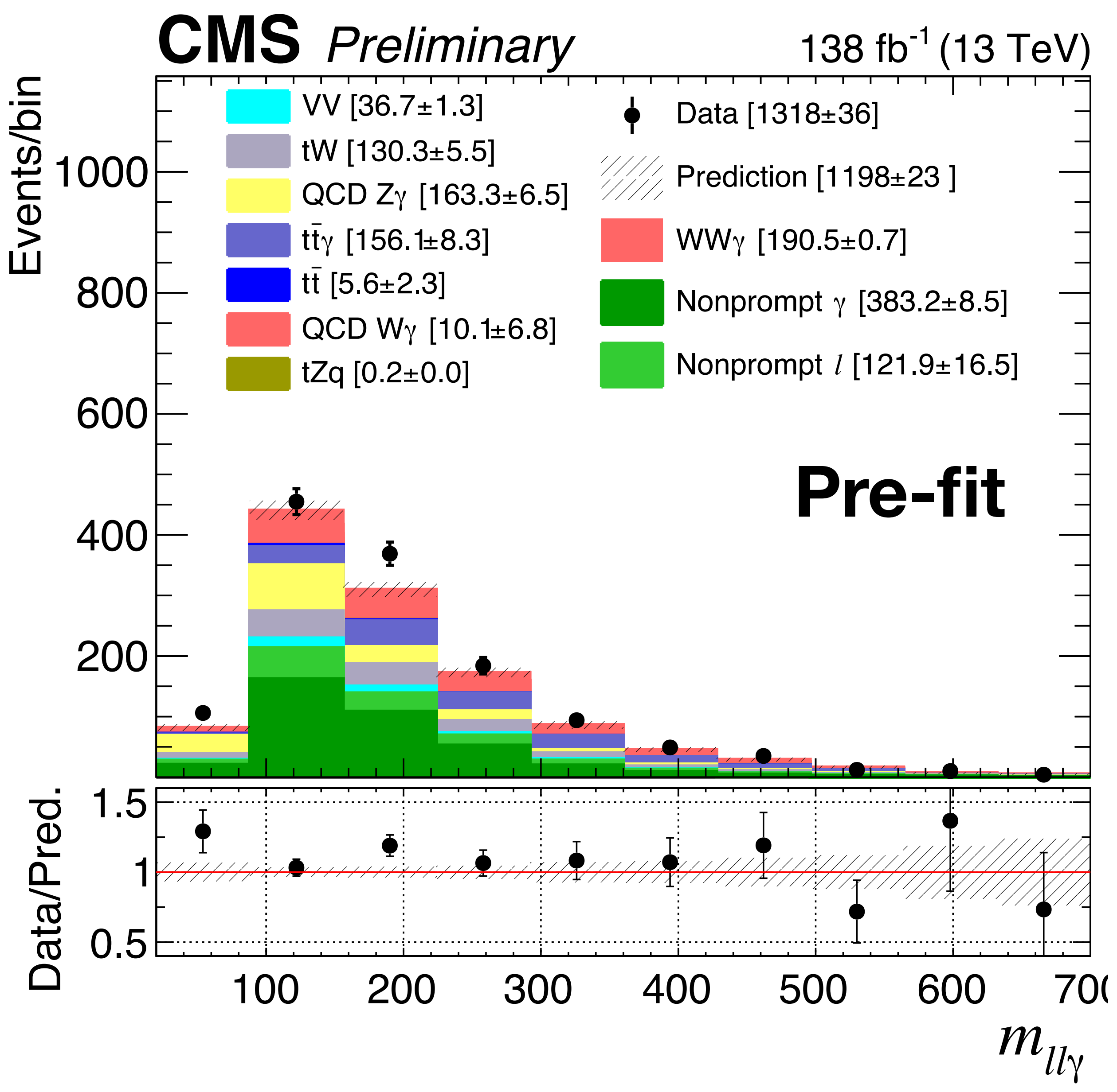
2. **Background modelling**
   - Nonprompt ℓ/γ uncertainty

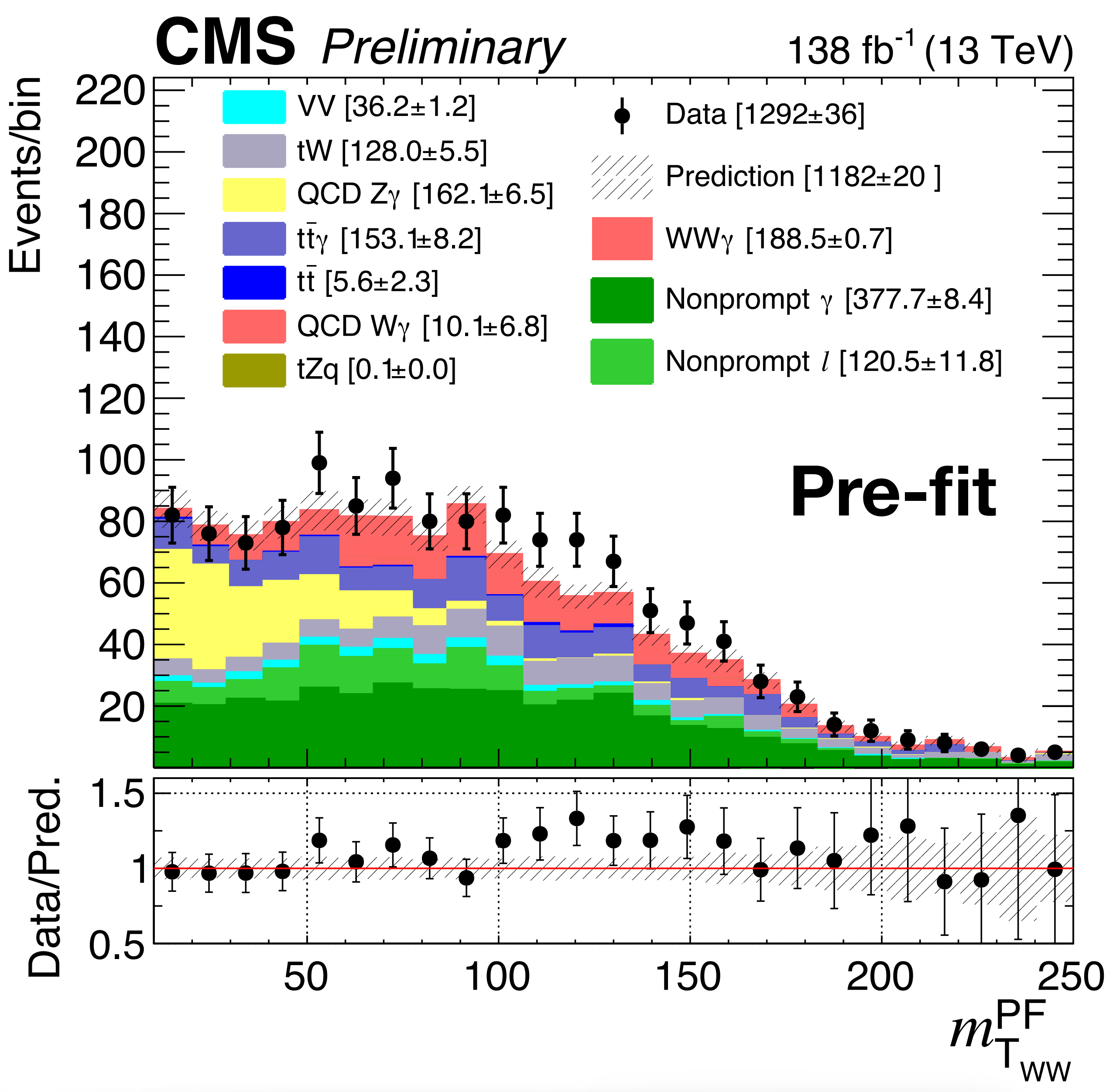
- Correlated between different categories and regions but uncorrelated between years
- Apply for corresponding data-driven process

Results — WWγ significance

- Maximum likelihood fit for signal extraction
  - $\mathscr{L}(\vec{\mu};\vec{\theta}) = \prod_j \text{Poisson}(n_j \,|\, \mu \cdot s_j(\vec{\theta}) + b_j(\vec{\theta})) \cdot p(\vec{\theta})$

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

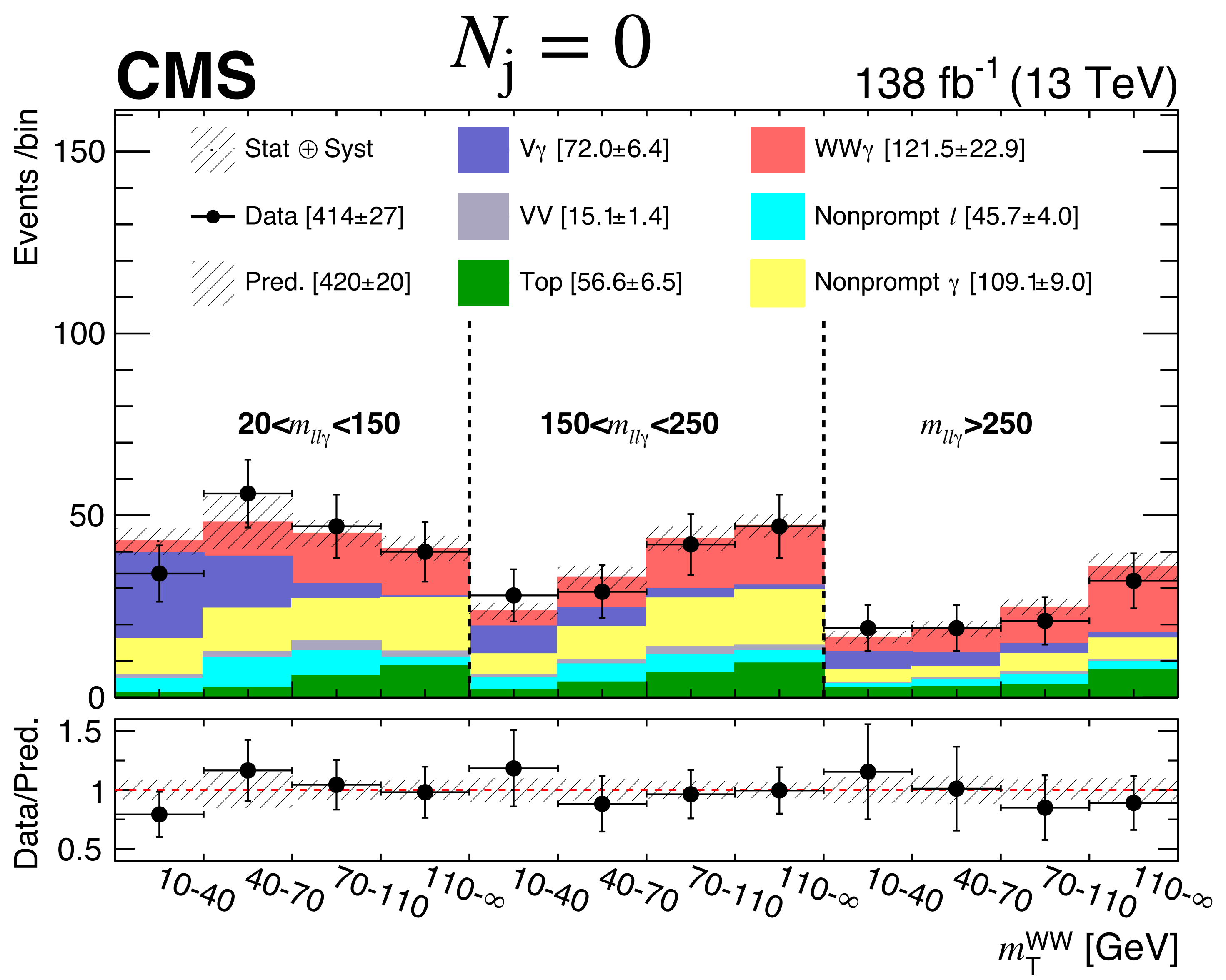


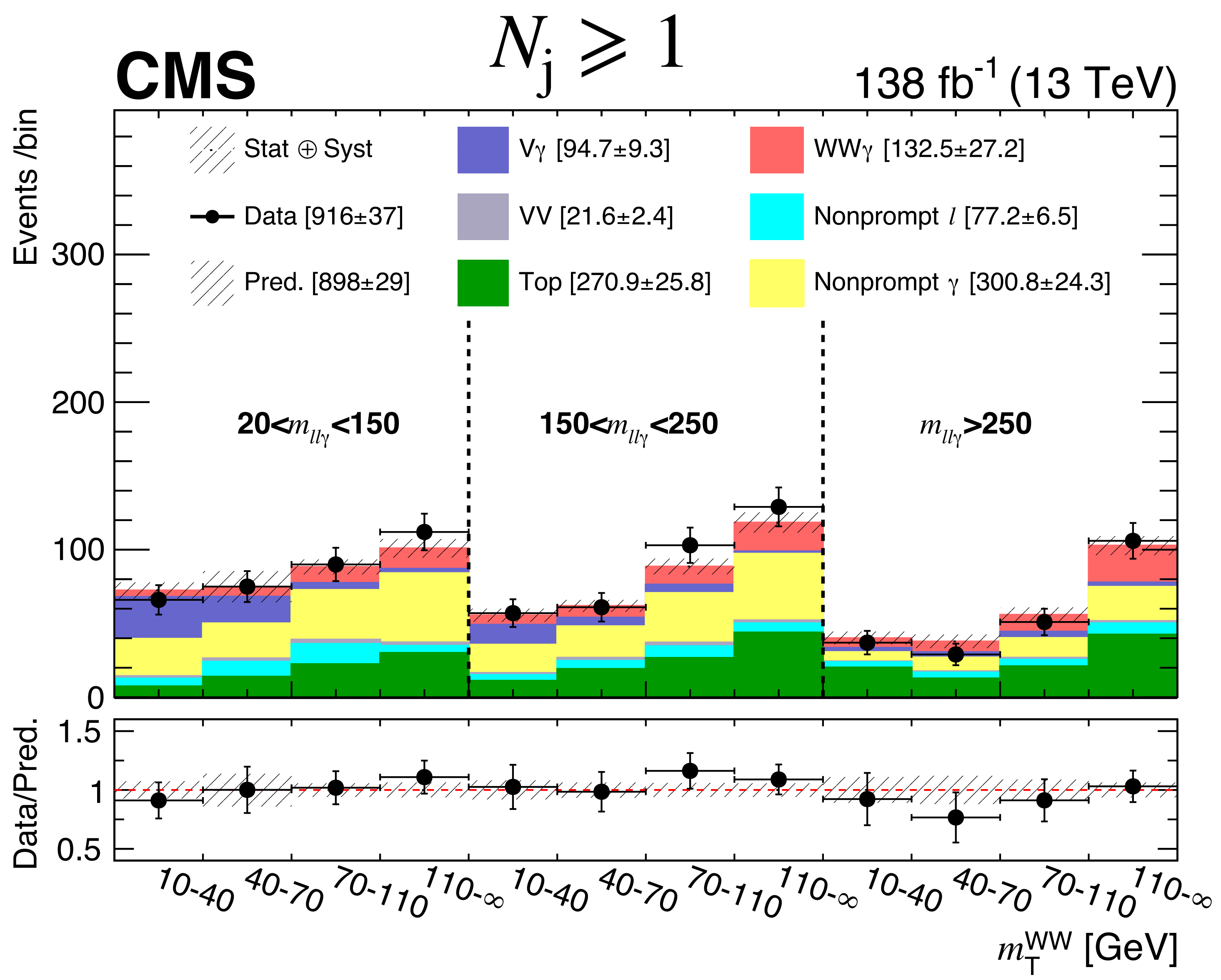


Reasonable agreement between data and predictions → Good background estimation

SR	m_T^{WW}: [10, 40, 70, 110, ∞) $m_{\ell\ell\gamma}$: [20, 150, 250, ∞)
Topγ CR	m_T^{WW}: [10, ∞)
SSWWγ CR	m_T^{WW}: [10, 40, 70, 110, ∞)

Results — WWγ cross section





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

The **first observation** of WWγ process

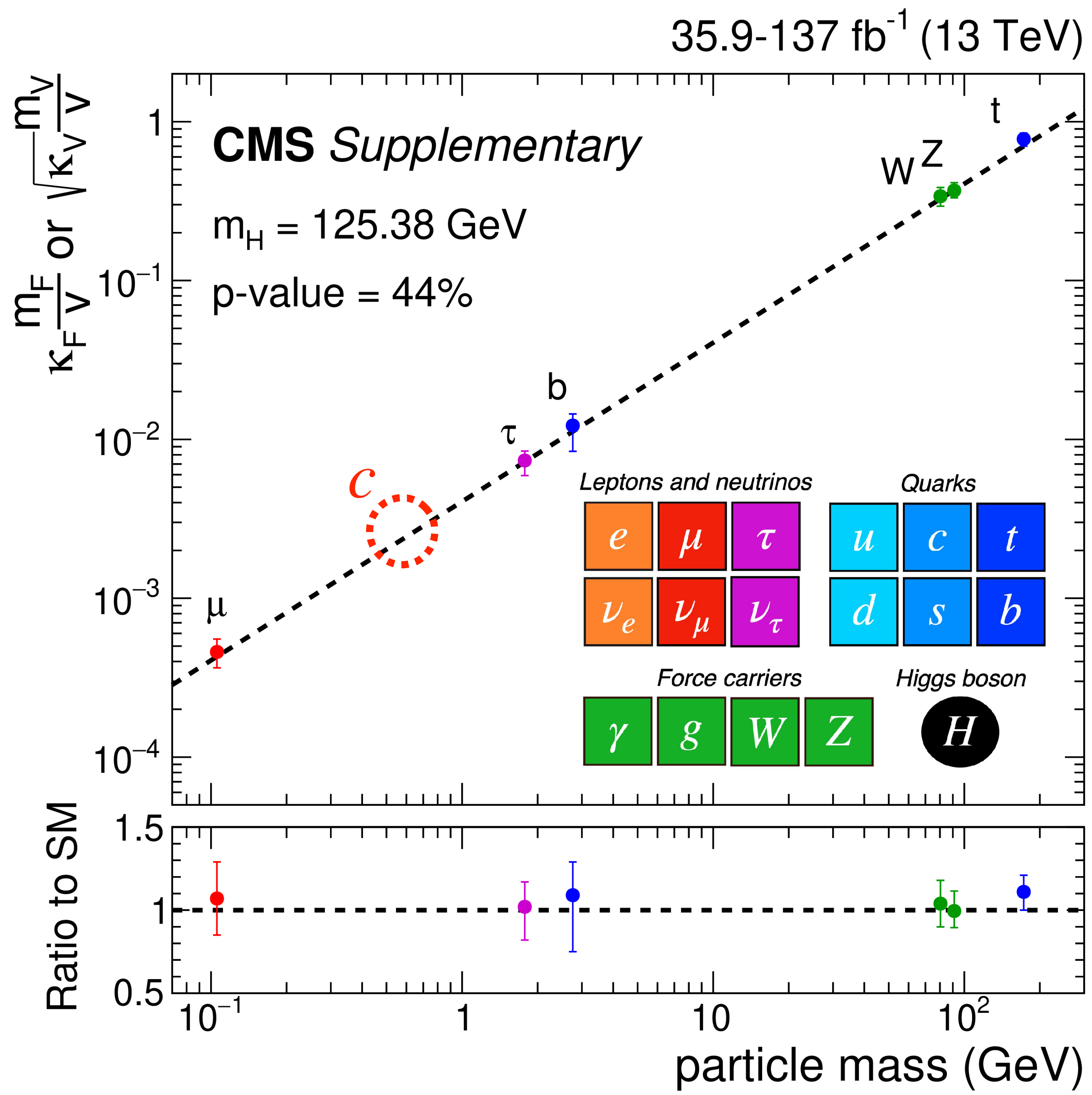
Fiducial region definition

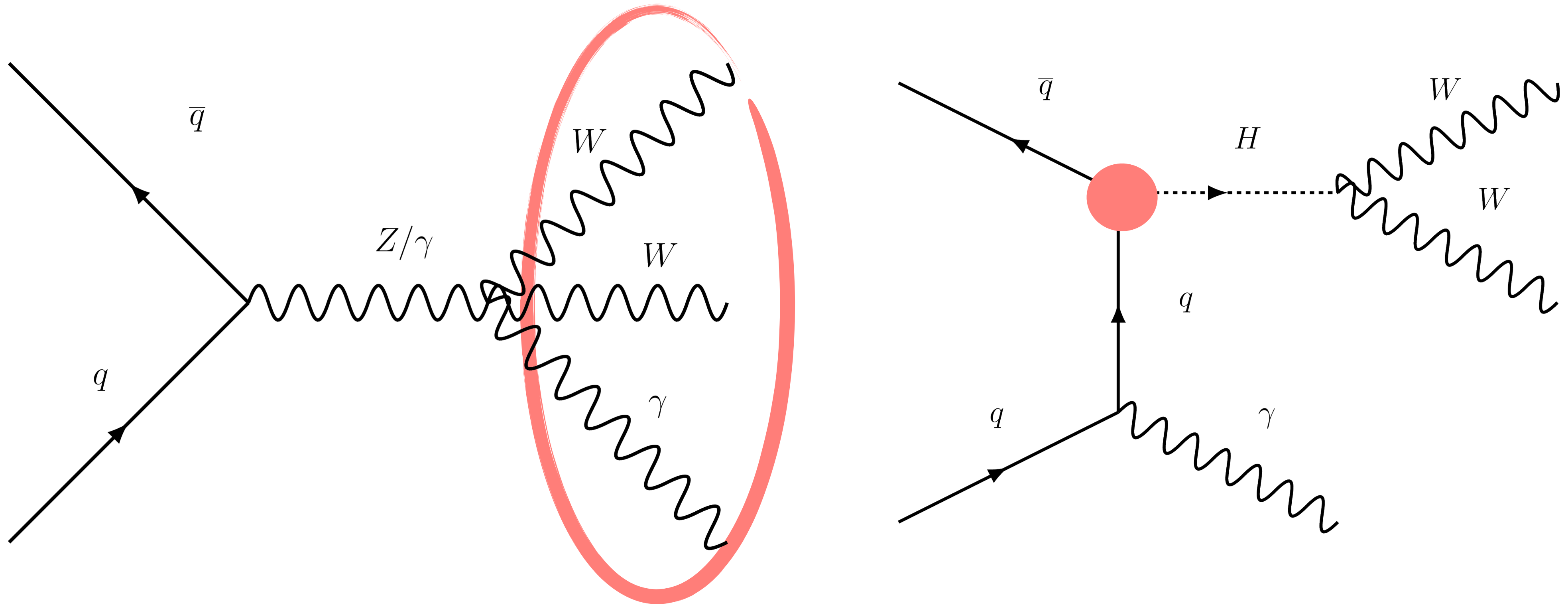
A. $p_T^{e/\mu} > 25$ (20) GeV, $|\eta| < 2.4$ (2.5)
B. $m_{\ell\ell} > 10$ GeV and $p_T^{\ell\ell} > 15$ GeV
C. $p_T^{\gamma} > 20$ GeV in the barrel or endcap
D. $\Delta R(\gamma/\ell,\ell) > 0.5$

- Cross section is measured in the fiducial region
- Theoretical cross section from MadGraph at NLO QCD accuracy is:
  - $\sigma_{\text{th}} = 4.61 \pm 0.34\,(\text{scale}) \pm 0.05\,(\text{PDF})$ fb
- Measured results are:
  - $\mu_{\text{comb}} = 1.31 \pm 0.17\,(\text{stat}) \pm 0.16\,(\text{syst}) \pm 0.13\,(\text{theo})$
  - $\sigma_{\text{fid}} = 6.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.6\,(\text{theo})$ fb
- **Main uncertainties** due to parton shower modelling calculations

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

H(→WW)γ — κ_{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

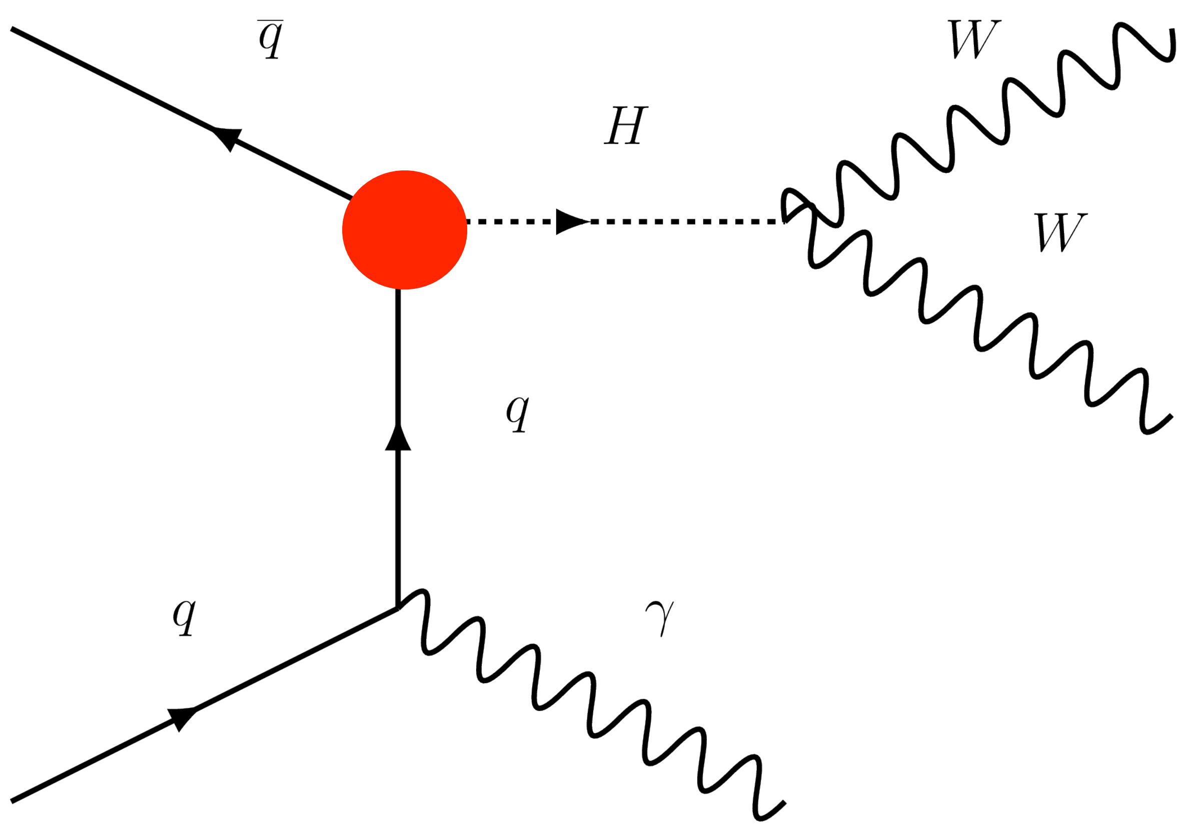
- VH(cc): the most sensitive channel
- ggH(cc): the boosted region explored in CMS

- H-s Yukawa coupling measurement is by H→ϕγ 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→ℓℓ, Z→νν, W→ℓν) [EPJC 82 (2022) 717]	$|\kappa_c| < 8.5$ (12.4)
CMS VH(cc) (Z→ℓℓ, Z→νν, W→ℓν) [arXiv:2205.05550]	**1.1 < $|\kappa_c|$ < 5.5 ($|\kappa_c|$ < 3.4)**
CMS ggH(cc) [arXiv:2211.14181]	μ < 47 (39)

[1] https://doi.org/10.1007/JHEP07(2018)127
[2] https://doi.org/10.1103/PhysRevD.101.115005

H(→WW)γ signal and background



For $q = u, d, s$

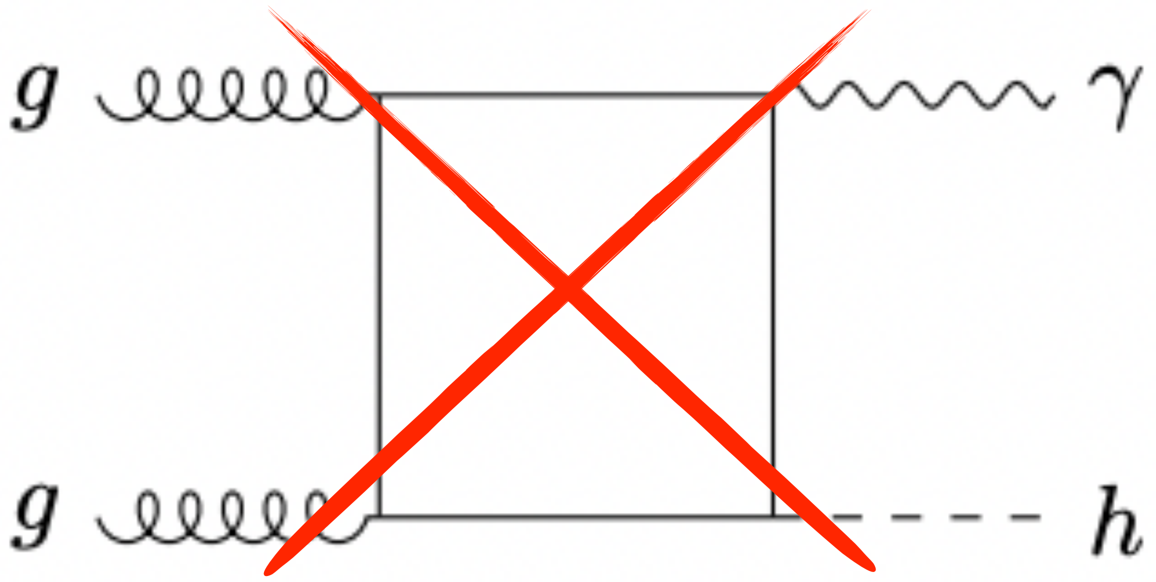
1. **MadGraph**
    - Model "*Higgs effective Lagrangian*"
        - Current-quark masses in $\overline{\text{MS}}$ scheme from PDG are used
    - Process: $q\bar{q} \to \text{H}\gamma$
2. **JHU generator**
    - $\text{H} \to \text{W}^+\text{W}^- \to e^{\pm}\mu^{\mp}\nu_e\bar{\nu}_\mu$

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: $q\bar{q} \to \text{H}\gamma$ [QCD]
2. **JHU generator**

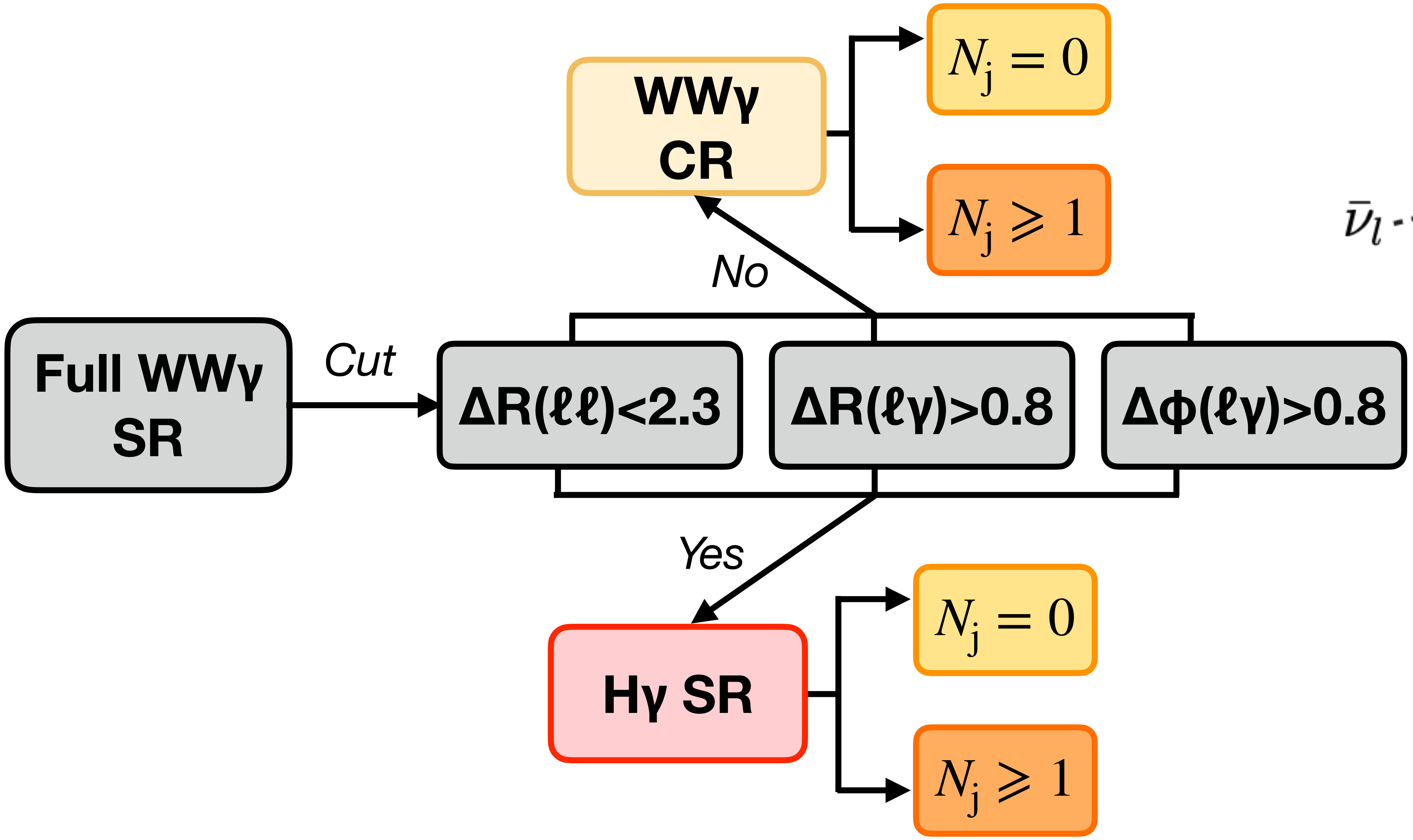
$\text{H} \to \text{W}^+\text{W}^- \to e^{\pm}\mu^{\mp}\nu_e\bar{\nu}_\mu$

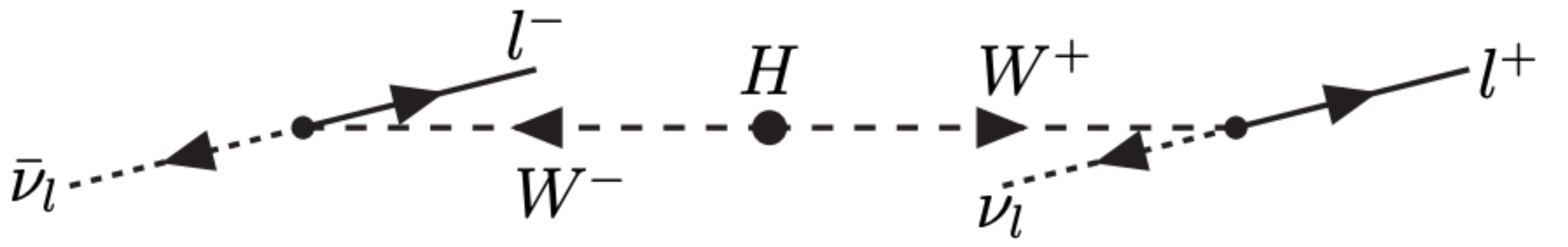


- Main background from gluon-initiated Hγ doesn't exist at LO due to Furry's theorem [1]
- Backgrounds in Hγ are sum of signal and backgrounds in the WWγ measurement
    - ggH, bbH are checked and can be neglected

[1] https://journals.aps.org/pr/abstract/10.1103/PhysRev.51.125

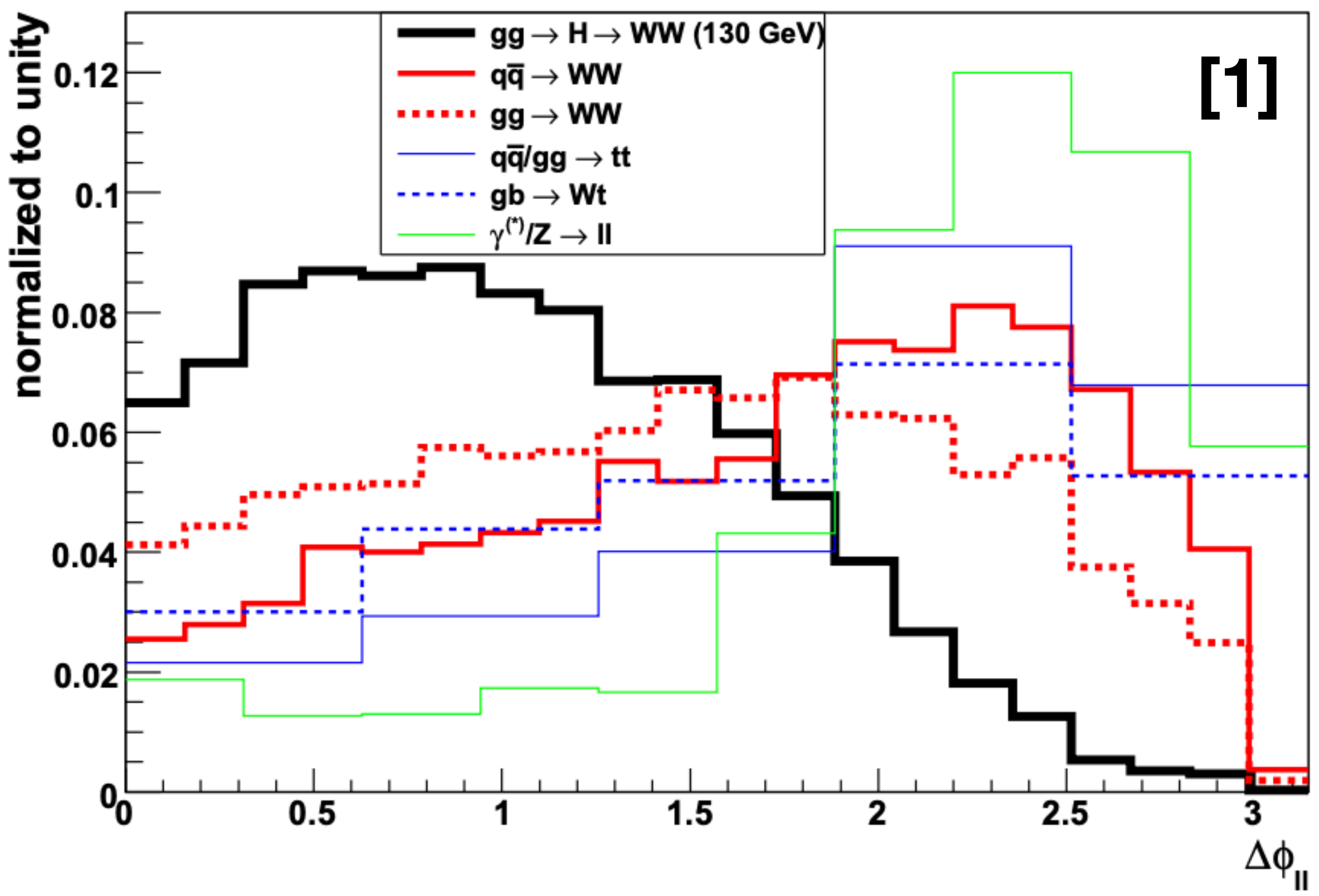
H(→WW)γ selection





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 $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ → Hγ separately
- Simultaneous fit of all regions (Hγ SR, WWγ CR, Topγ CR, and SSWWγ CR)
  - Hγ SR: 2D binning, [10, 40, 70, 110, ∞) in m_T^{WW} and [0.5,1.0,1.5,∞) in $\Delta R_{\ell\ell}$
  - WWγ CR 1D binning, [10, 40, 70, 110, ∞) in m_T^{WW}



[1] https://cds.cern.ch/record/1261372/files/CERN-THESIS-2010-061.pdf

H(→WW)γ interpreted results

Cross section limits

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

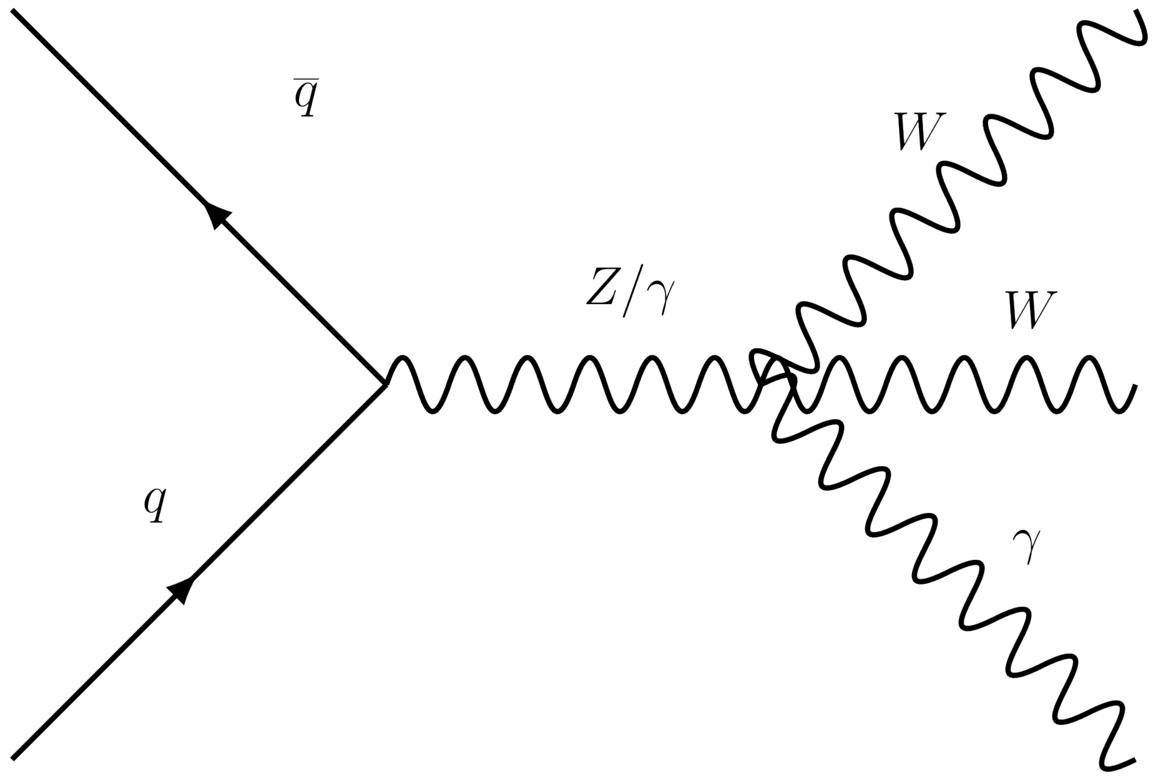
- $$\kappa_H^2 \approx \frac{1 - Br_{q\bar{q}}^{SM}}{2} + \frac{\sqrt{(1 - Br_{q\bar{q}}^{SM})^2 + 4Br_{q\bar{q}}^{SM}\kappa_q^2}}{2}$$
- Hγ rate can be scaled with $\kappa_q^2 \times \dfrac{\kappa_H^2}{(1 - Br_{q\bar{q}}^{SM})\kappa_H^2 + Br_{q\bar{q}}^{SM}\kappa_q^2}$

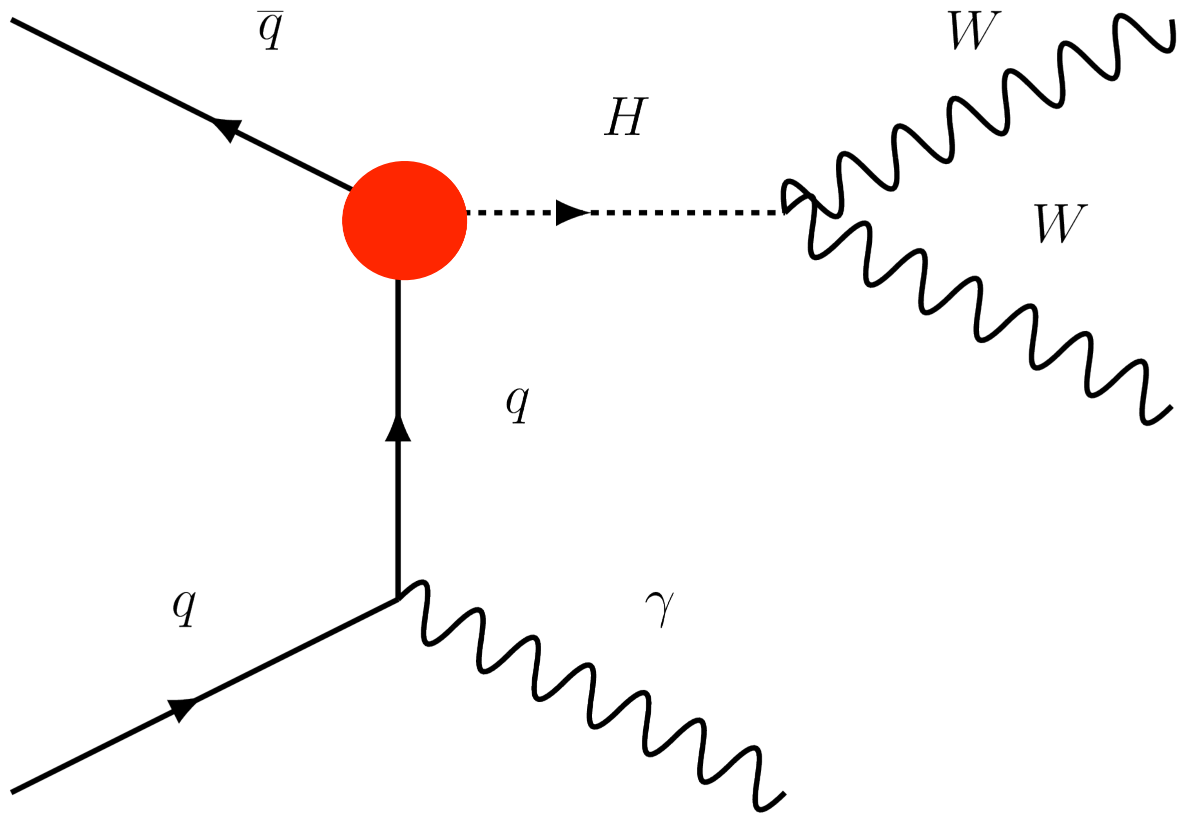
Yukawa couplings limits exp.(obs.)
$\lvert\kappa_u\rvert \leq 13000$ (16000)
$\lvert\kappa_d\rvert \leq 14000$ (17000)
$\lvert\kappa_s\rvert \leq 1300$ (1700)
$\lvert\kappa_c\rvert \leq 110(200)$

[1] https://journals.aps.org/prd/pdf/10.1103/PhysRevD.100.073013

Summary

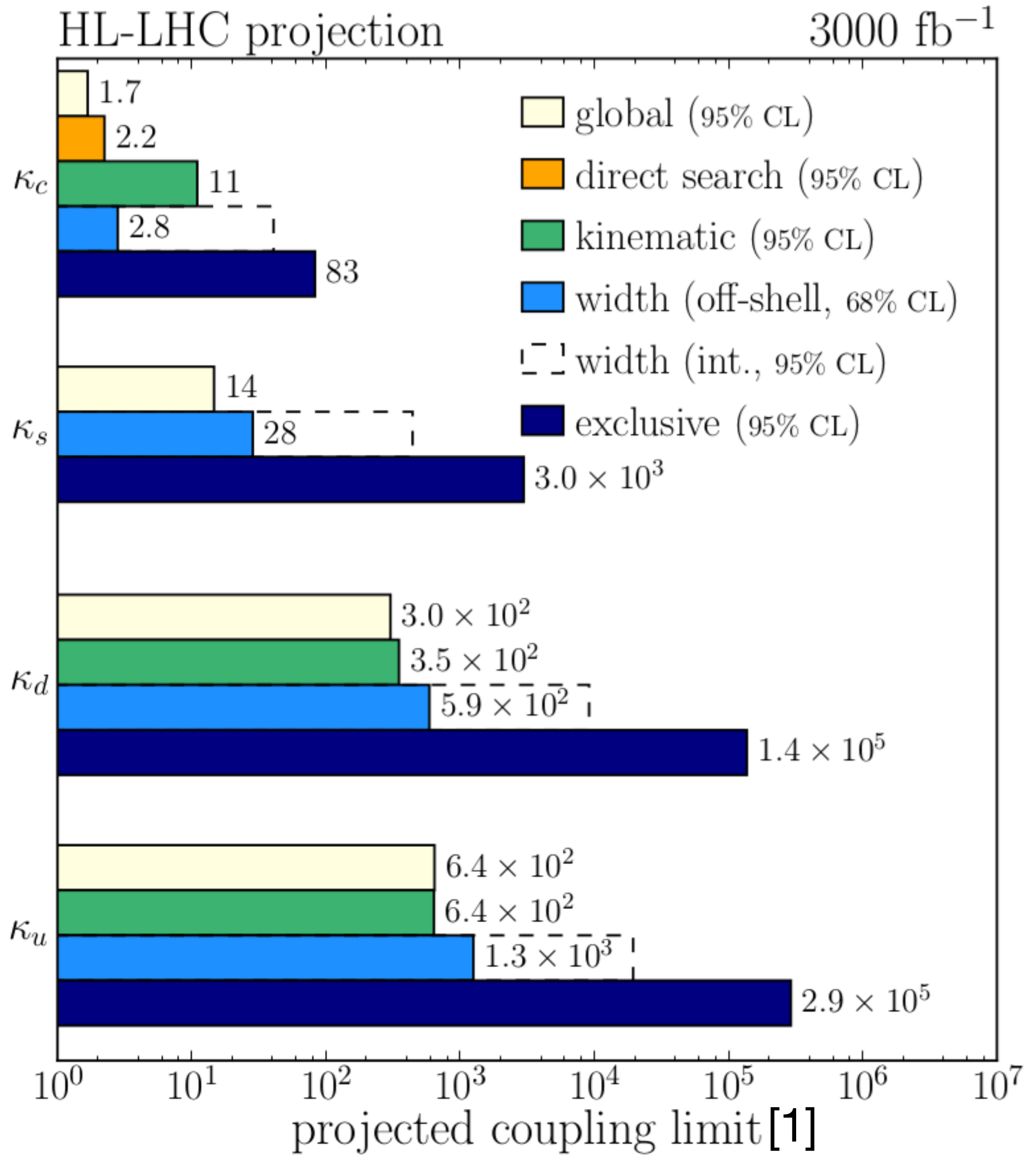
- The first observation of WWγ production with obs. (exp.) 5.6 (4.7) σ
- Inclusive cross section in $e^{\pm}\nu_e\mu^{\mp}\nu_\mu\gamma$ final states and WWγ signal fiducial region
- The cross section upper limits for Hγ production
- Yukawa coupling of κ_c, κ_s, κ_u, and κ_d interpreted results





Backup

H(→WW)γ interpretation



Our results reach the HL-LHC exclusive level

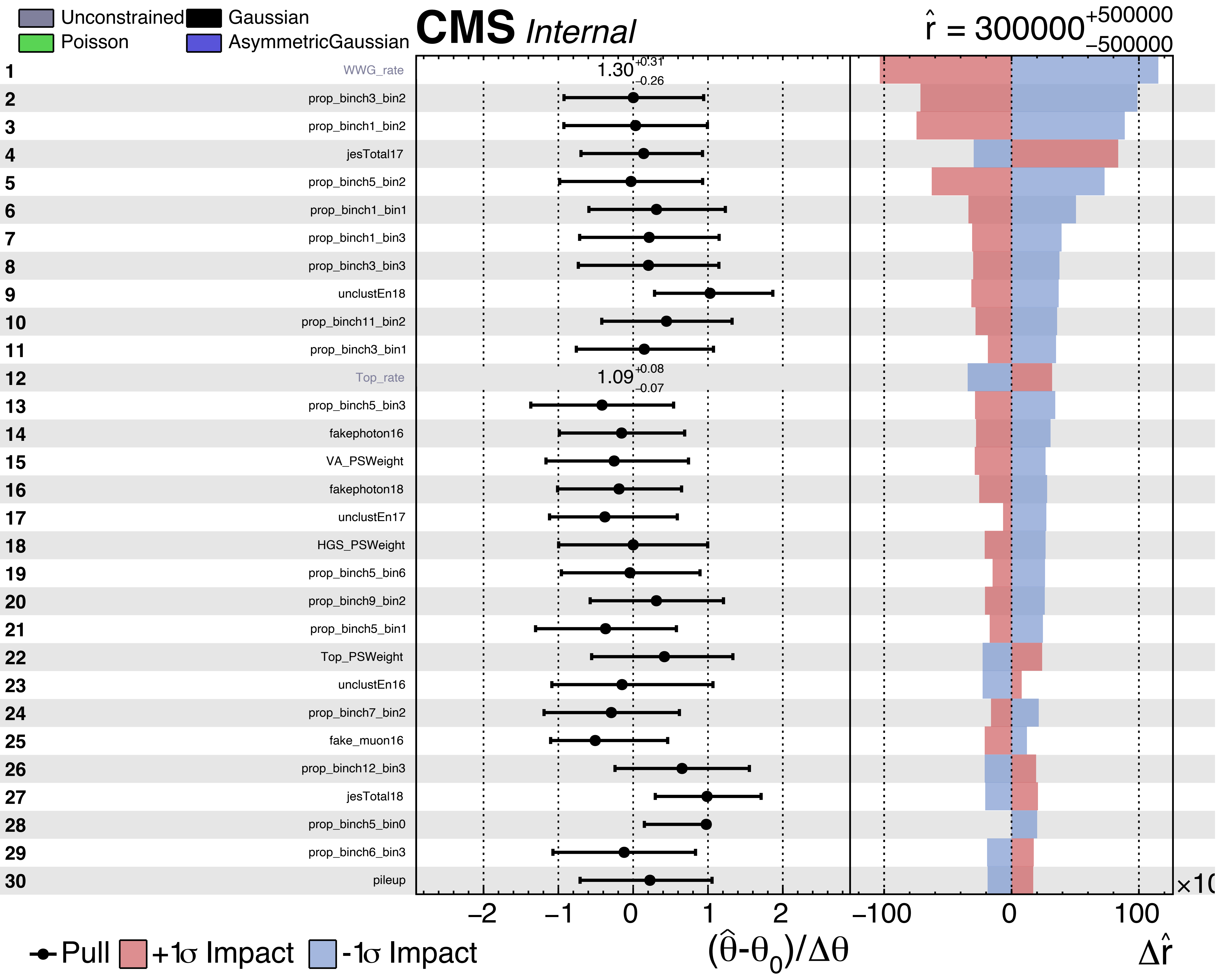
Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq 13000$ (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq 14000$ (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049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

Branching ratio used in the interpretation results

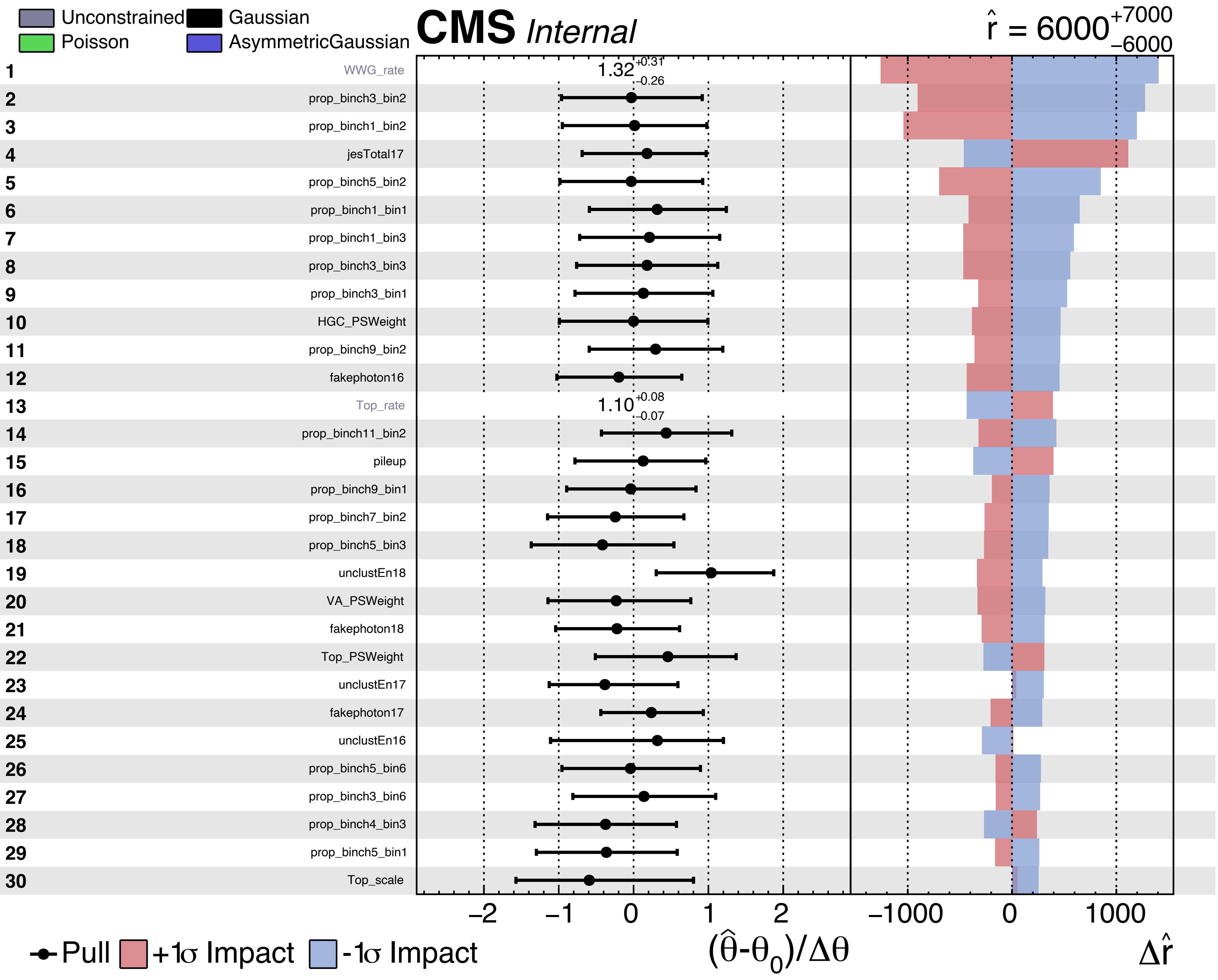
$$Br(H \to u\bar{u}) = 10^{-8};$$
$$Br(H \to d\bar{d}) = 10^{-8};$$
$$Br(H \to s\bar{s}) = 0.000246;$$
$$Br(H \to c\bar{c}) = 0.029.$$

[1] https://twiki.cern.ch/twiki/pub/LHCPhysics/HLHELHCWorkshop/report.pdf

Impact plot — Hγ



S process



C process

Hγ Assumption explanation

An assumption that as k(u/d/c/s) is varied, all other SM kappas 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

Hγ Assumption explanation

1. Regarding the H->ssbar 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 $m_b \approx 4$GeV $m_c \approx 1$GeV and $m_s \approx 0.1$GeV

sigma/sigma_SM(ggH) = 1.04*kt2 + **0.002***kb2 -0.038*kt*kb -0.005*kt*kc + 0.0004*kb*kc + **0.00002** * kc2

- 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*kt*kc + 0.0004*kb*kc + **0.00002** * kc2

For ks = **1300 (-1300)**

$-0.005/(2\times m_c/m_s)$*kt*ks + ~~0.0004*kb*kc~~ + $0.00002/(5\times m_c/m_s \times m_c/m_s)$ * ks2 ≈ **-0.26 (0.39)**

sigma/sigma_SM(ggH) = 1.04 + 0.002 - 0.038 + (-0.26) or (0.39) ≈ **0.75 (1.39)**

[1] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG2KAPPA?redirectedfrom=LHCPhysics.LHCHXSWG2KAPPA#1_gluon_gluon_Fusion_Process

Hγ Assumption explanation

- Samples:

bbHToWWTo2L2Nu_M-125_4FS_yb2_TuneCP5_PSweights_13TeV_amcatnlo_pythia8 Cross-section:0.4027 (NanoAOD v7)
bbHToWWTo2L2Nu_M-125_4FS_ybyt_TuneCP5_PSweights_13TeV_amcatnlo_pythia8

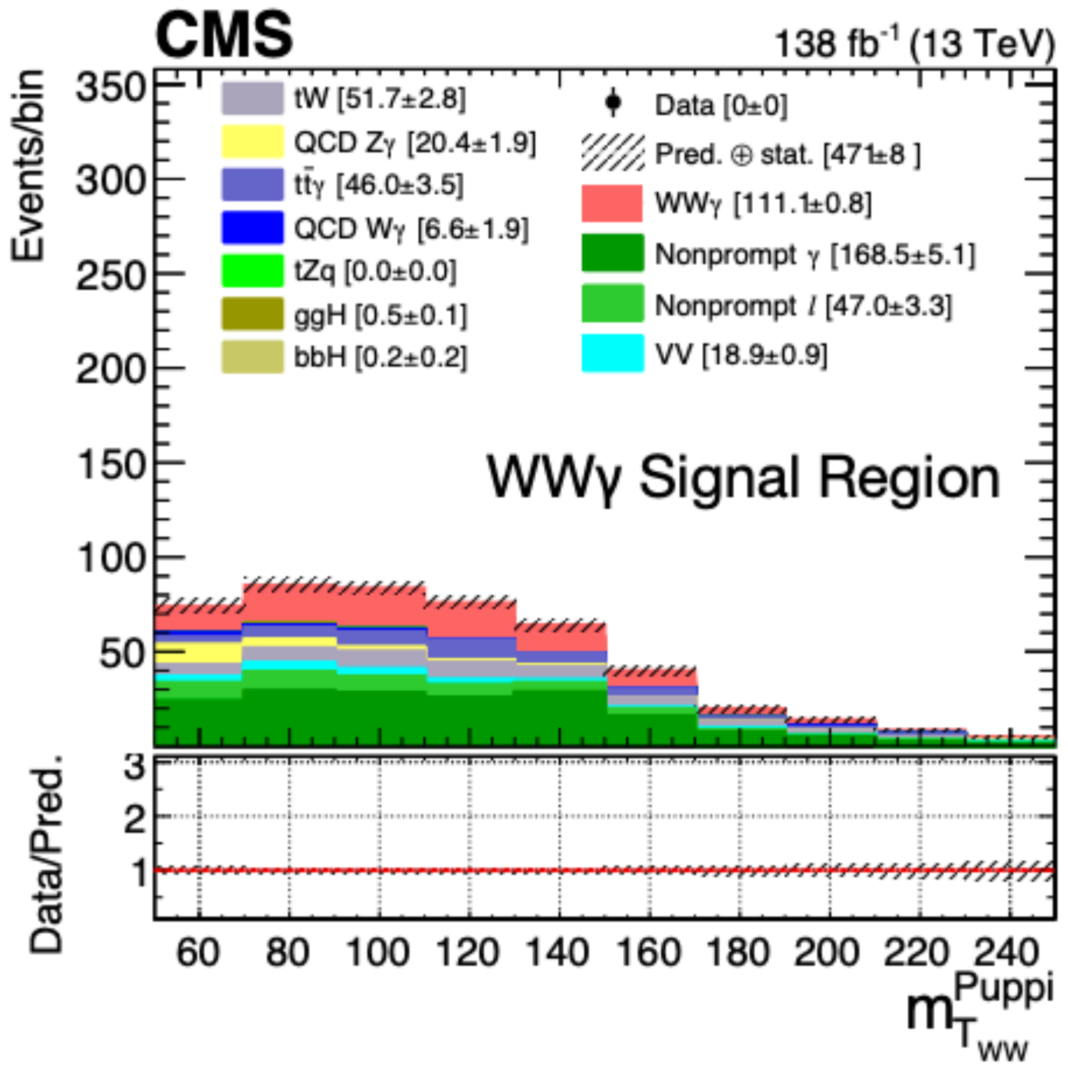
GluGluHToWWTo2L2Nu_M125_TuneCP5_13TeV_powheg2_JHUGenV714_pythia8 Cross-section:0.9913 (NanoAOD v9)

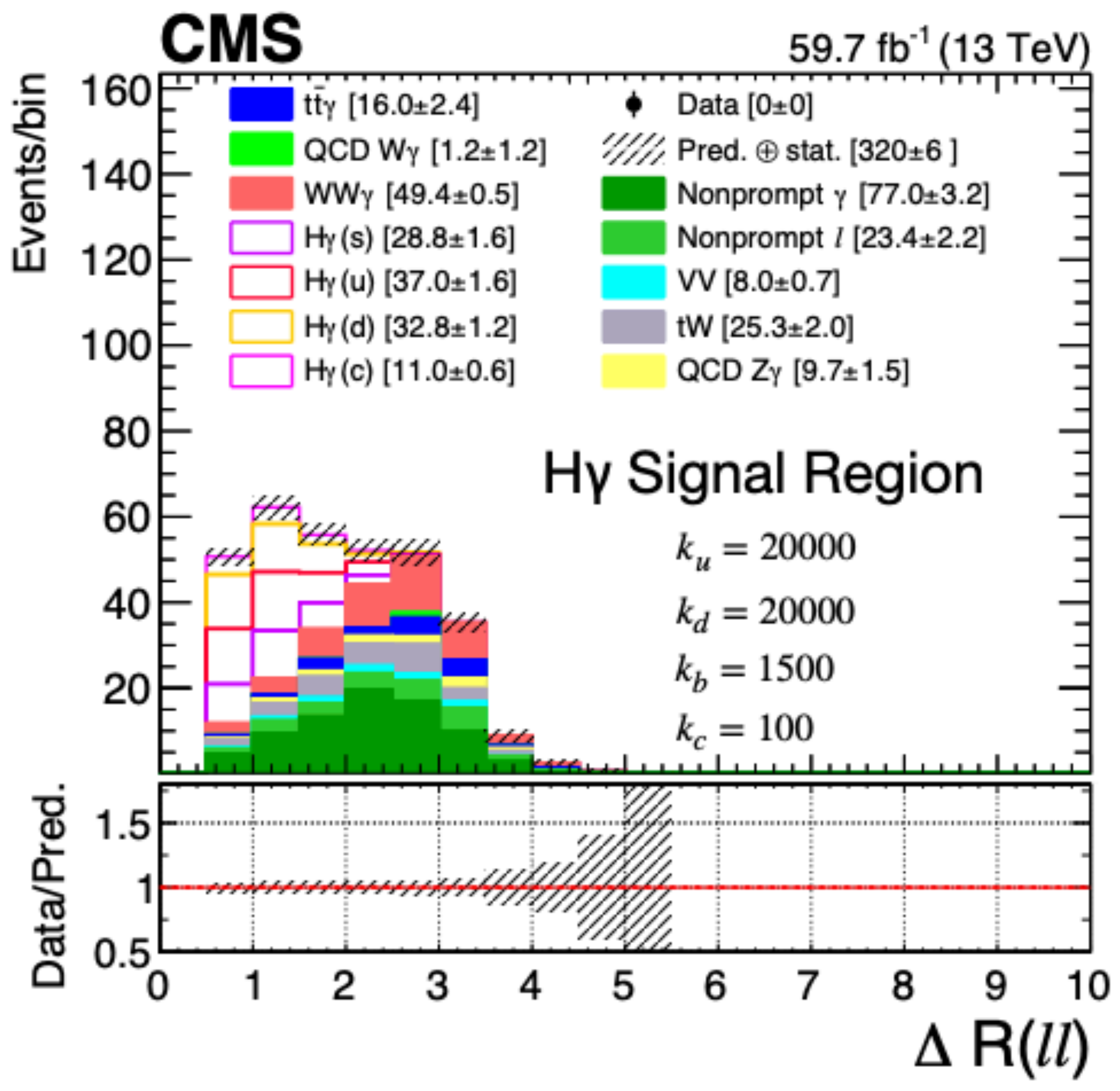
ccToHγTo2L2Nuγ Private Samples Cross-section: 4.724 e-04 × 0.01055

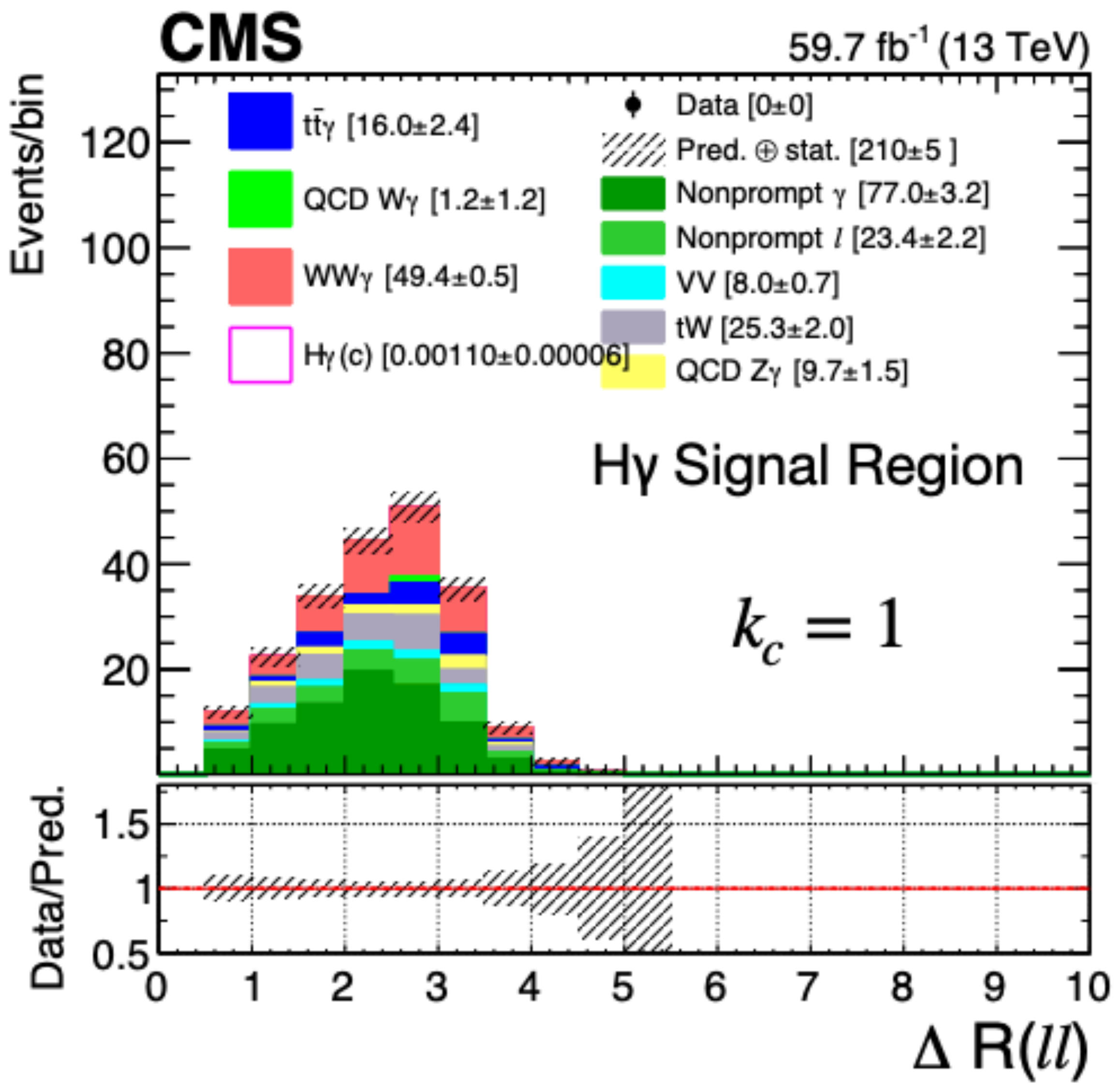
branch ratio takes from Link with MH 125 GeV

l= e or μ

- The contribution in Signal and Hγ Region







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