Recent di-boson and tri-boson measurements at CMS

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2023 July

Outline

Hot off the news!

☑ Di/Tri boson measurement status at CMS

PAS is public!!!

☑ measurement of ZZ production

CMS news

- Differential cross-section measurement

☑ measurement of WWγ production

CMS news

- WWγ signal significance
- WWγ inclusive cross section
- Hγ cross section upper limits and the interpreted Yukawa couplings results

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.

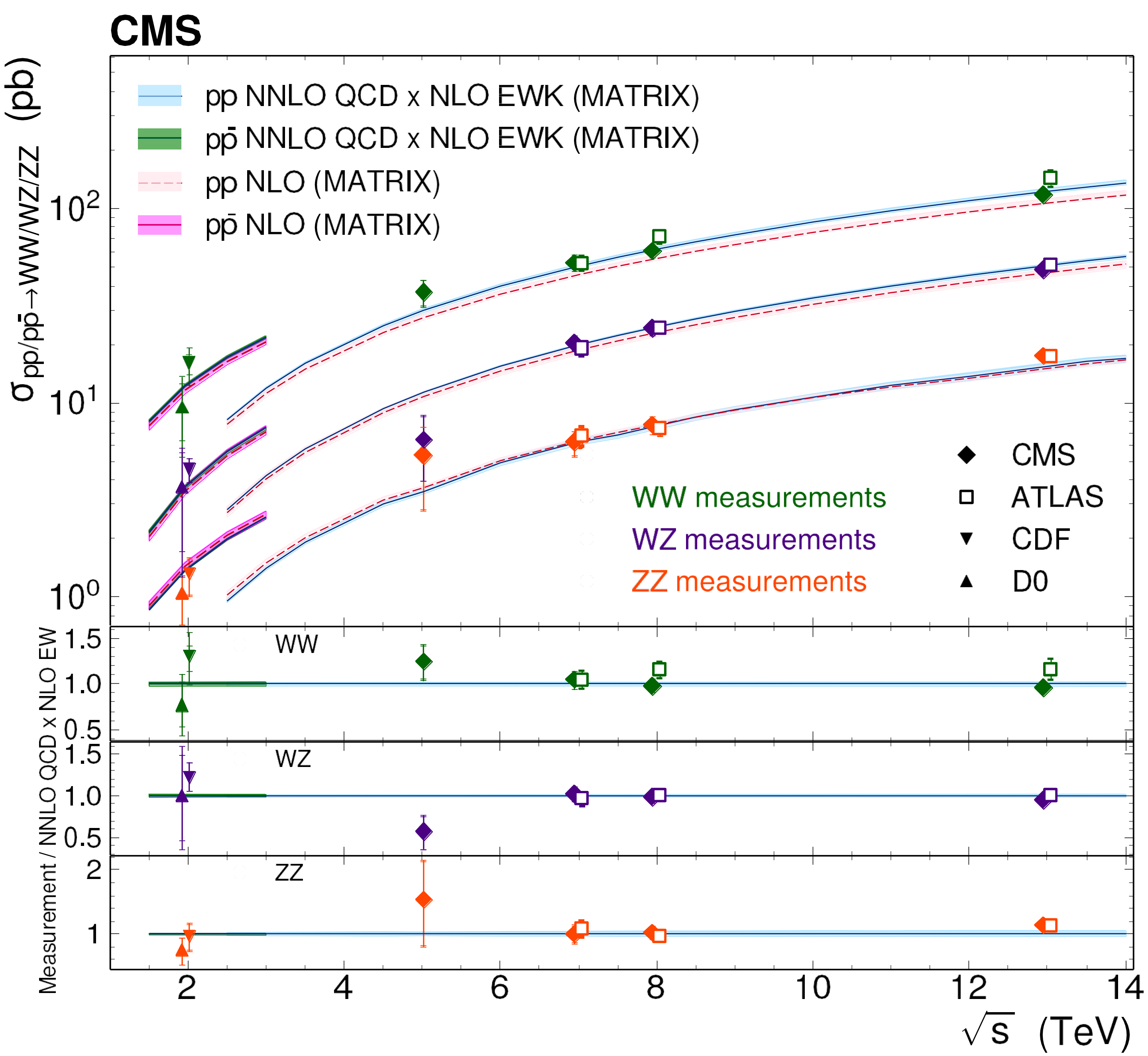
Read more here → https://cms.cern/news/new-tri-boson-process-discovery

CERN #CERN #CMSExperiment #physics

Why study Di/Tri-boson processes?

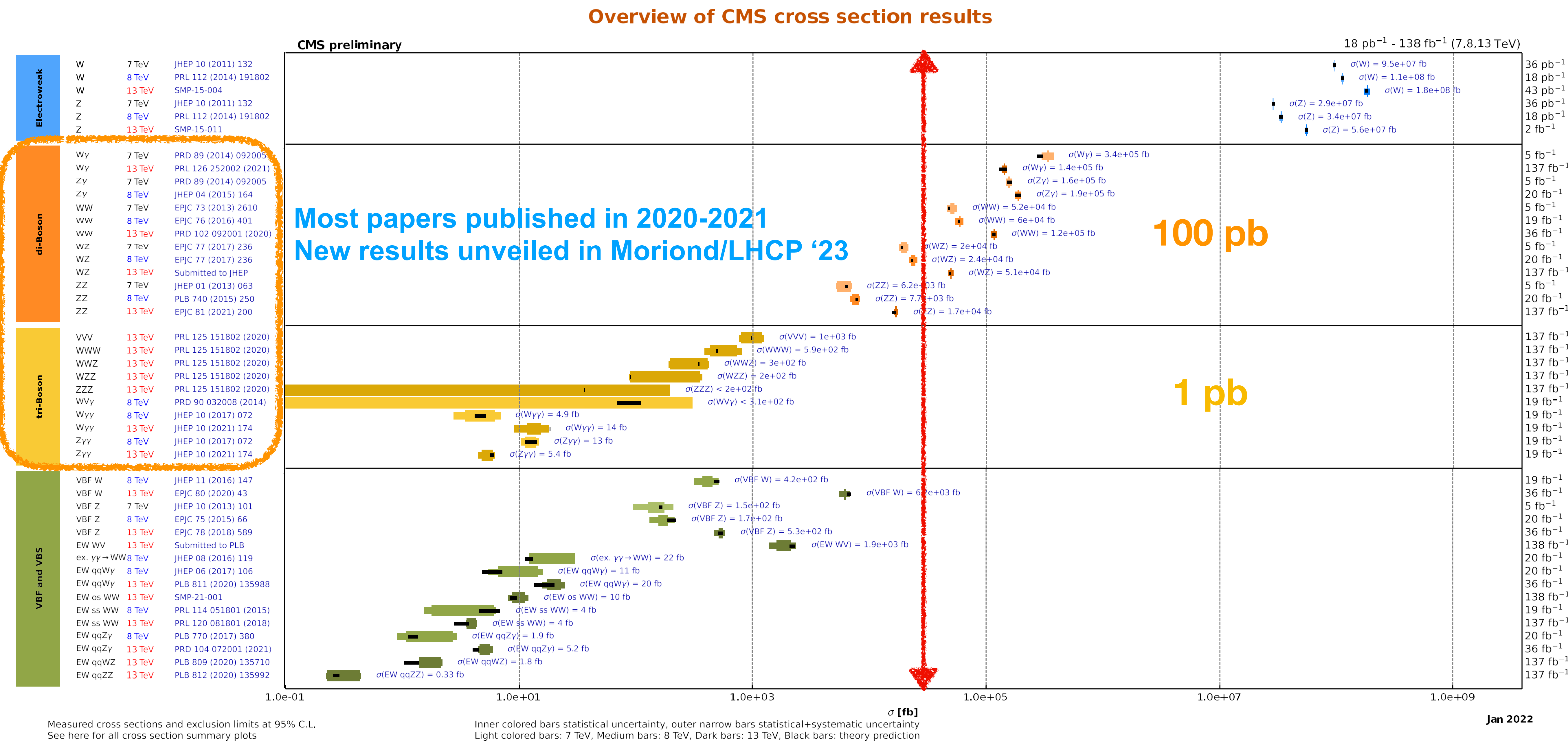
- Stringent test of the standard model (SM)
  - Precise measurement for SM test
    - help to constrain SM contribution (background) in searches of many new physics models and Higgs analysis.
- Search for new physics at the TeV scale.
  - Platform to measure the anomalous coupling
  - Platform to search the Higgs to light quark Yukawa couplings

Di-boson cross section measurements at several center of mass energies



- Many multi-boson processes are currently accessible only at the CERN LHC given the energies and integrated luminosities required to observe them.

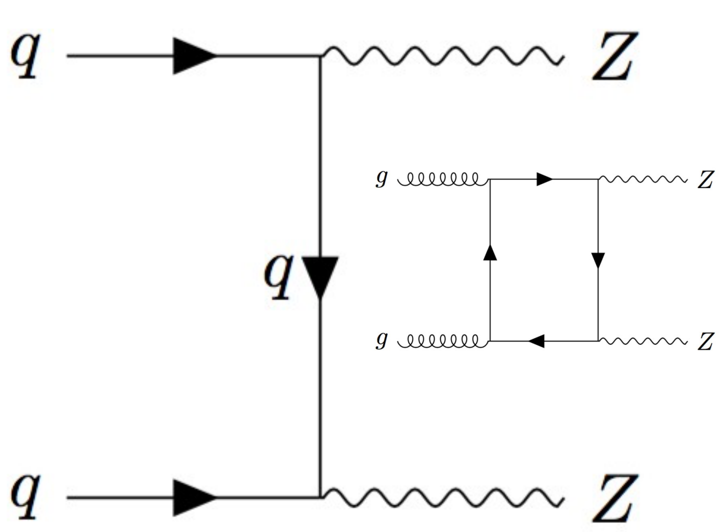
Di/Tri-boson overview at CMS

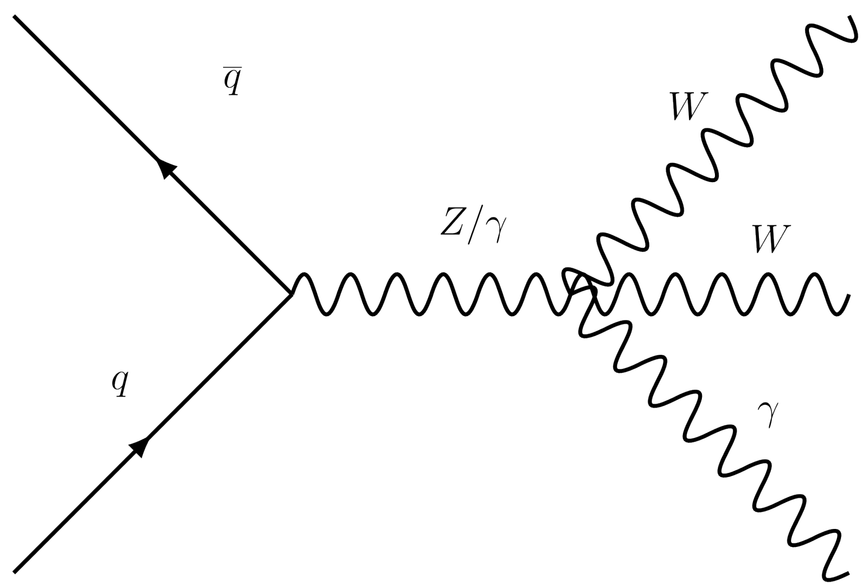


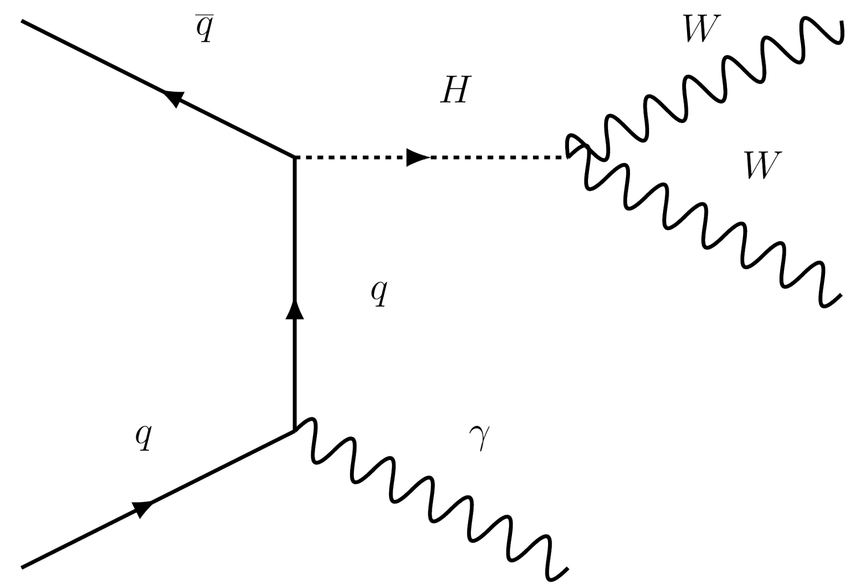
Span several orders of magnitude!

[1] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

Hot off the news!







At CMS, recent public analyses:

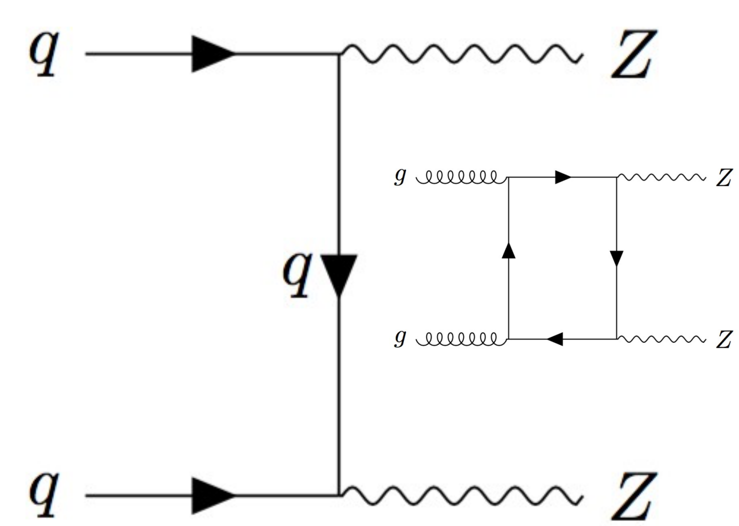
SMP-22-001: Measurement of the ZZ(4ℓ)+jets production **Public on LHCP!!!**

SMP-22-006: Measurement of the WWγ production **Public on Moriond QCD!!!**

Measurement of ZZ production Introduction

LINK

Channel: 4 lepton final state (ZZ->4ℓ)
Loop effects: up to 10% contribution



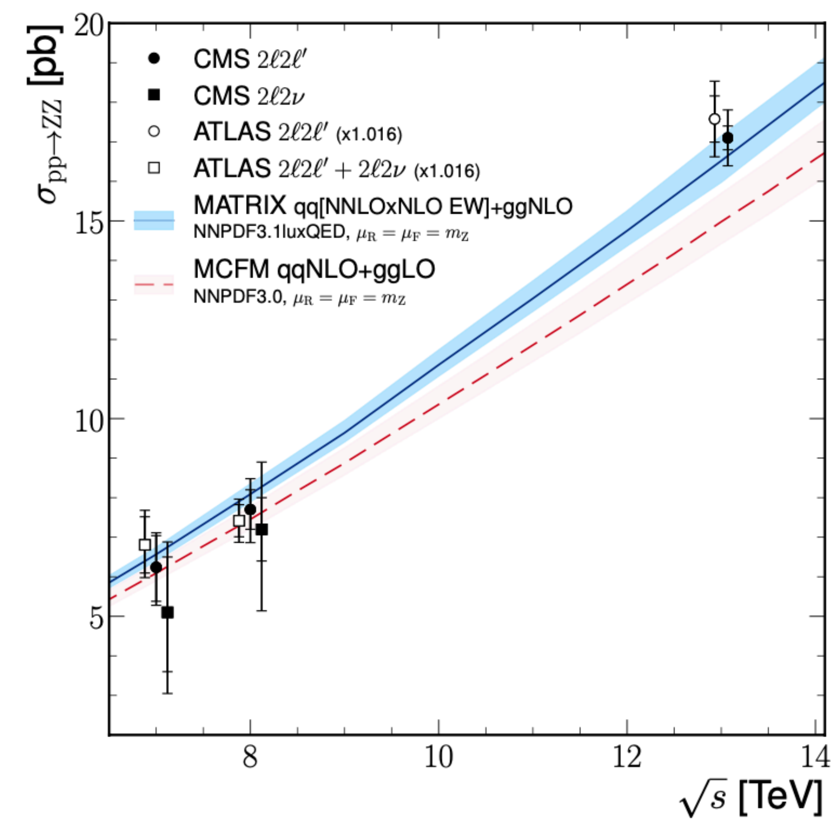
- **First differential cross sections measured** as a function of:

☑ number of jets and properties of the jets

☑ m_{4l} as a function of different jet multiplicities

☑ invariant mass of the highest p_T jet and the second highest p_T jet

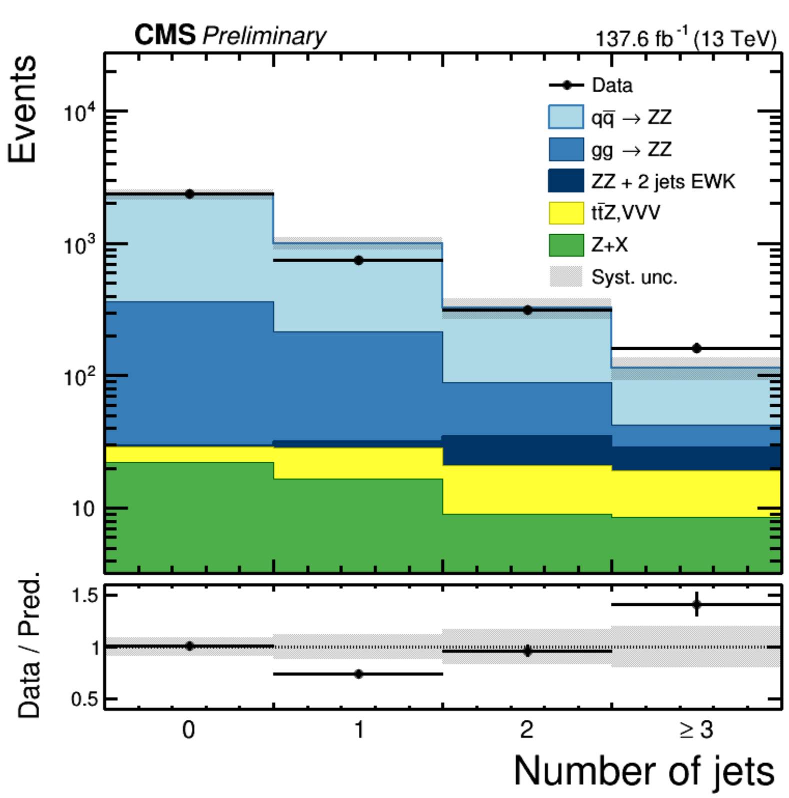
☑ Δη of the highest p_T and the second highest p_T jets

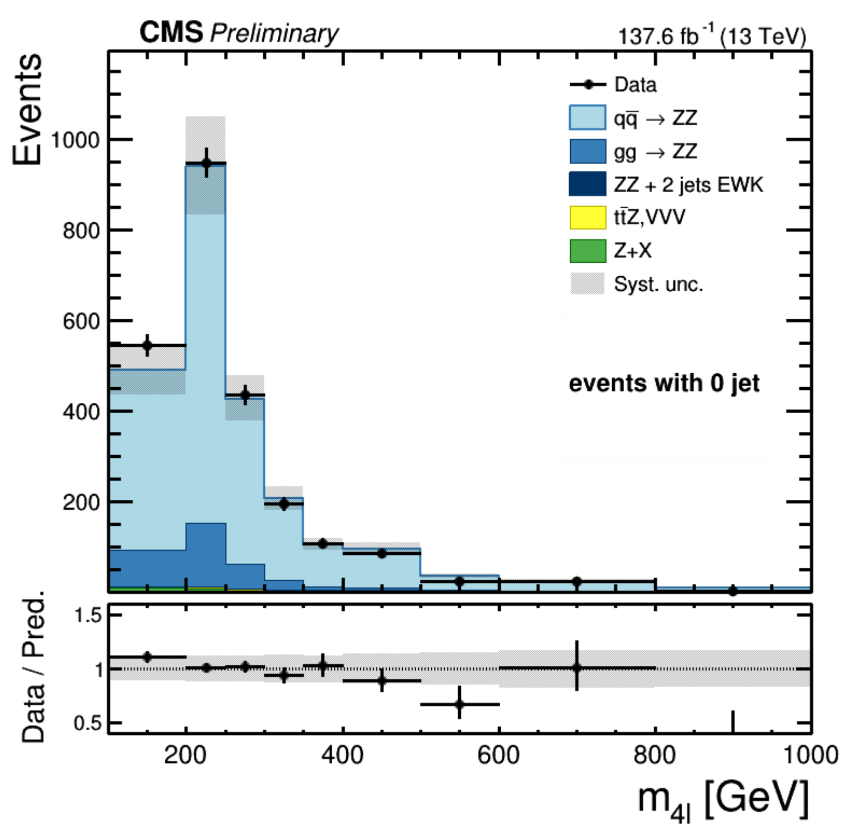


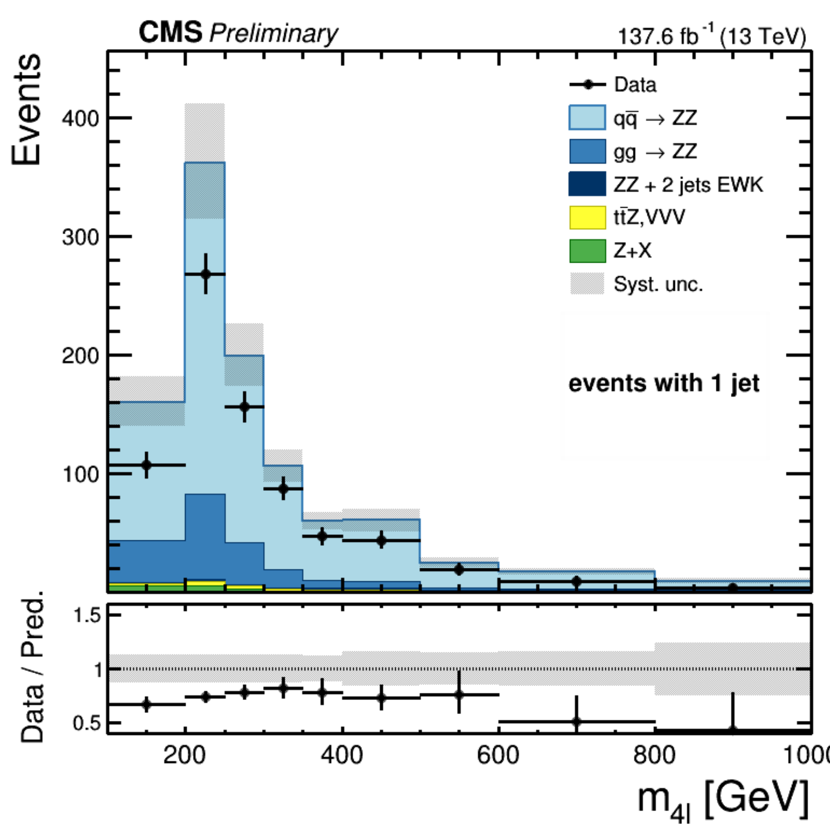
New results compared with the state-of-the-art next-to-next- to-leading order (NNLO) and parton shower (PS) predictions using MiNNLOPS

Measurement of ZZ production

- Shape of distributions described well by predictions → normalization is not
- Predictions over-estimate data → largest discrepancy for highest p_T jet with $p_T < 100$ GeV
  - Large uncertainty from MC modeling like QCD scale







Differential cross sections of ZZ production

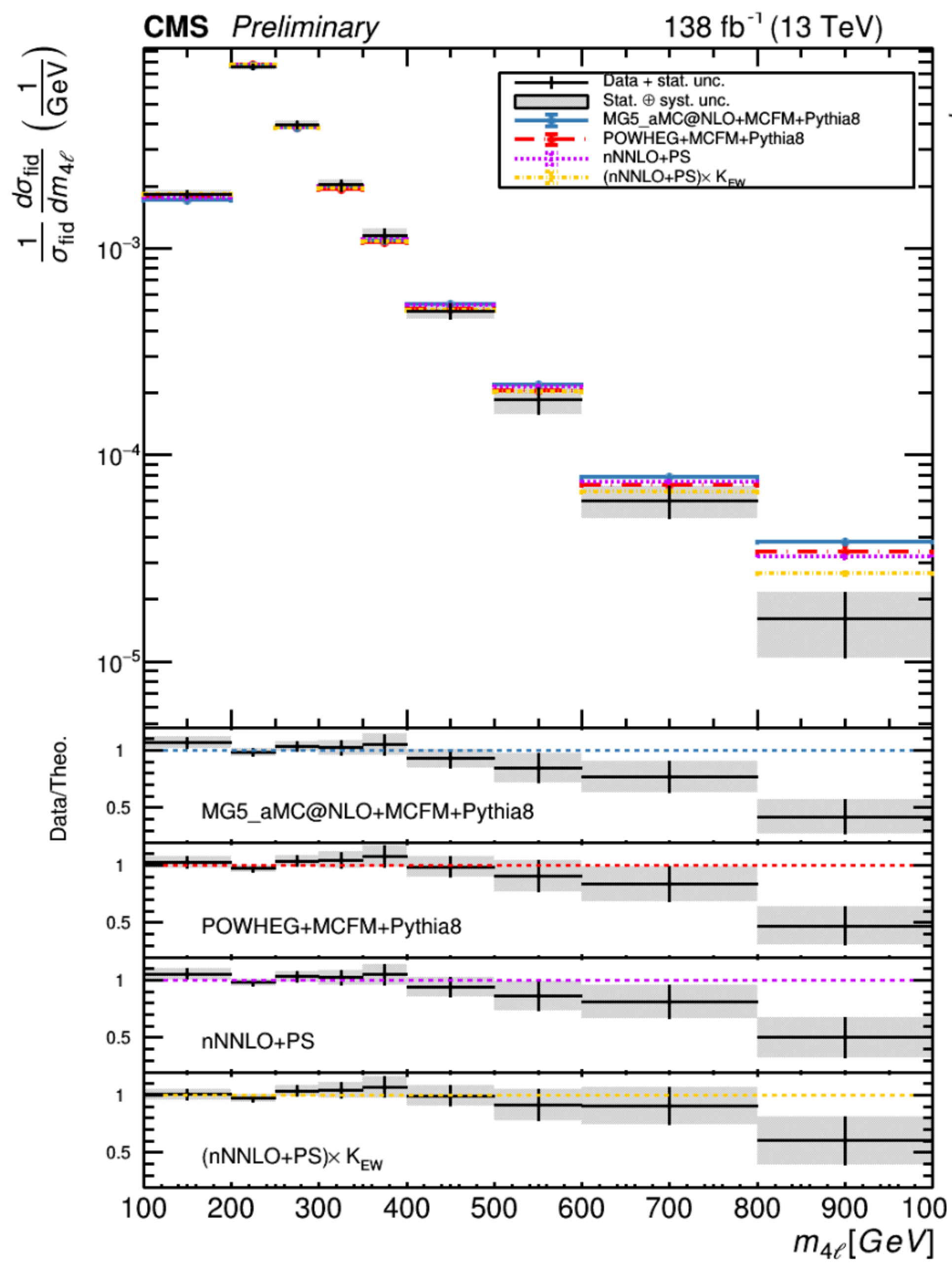
- ☑ Differential cross sections normalized to the fiducial cross sections
- ☑ On-shell Z-boson requirement applied ($60 < m_{Z1,Z2} < 120$)

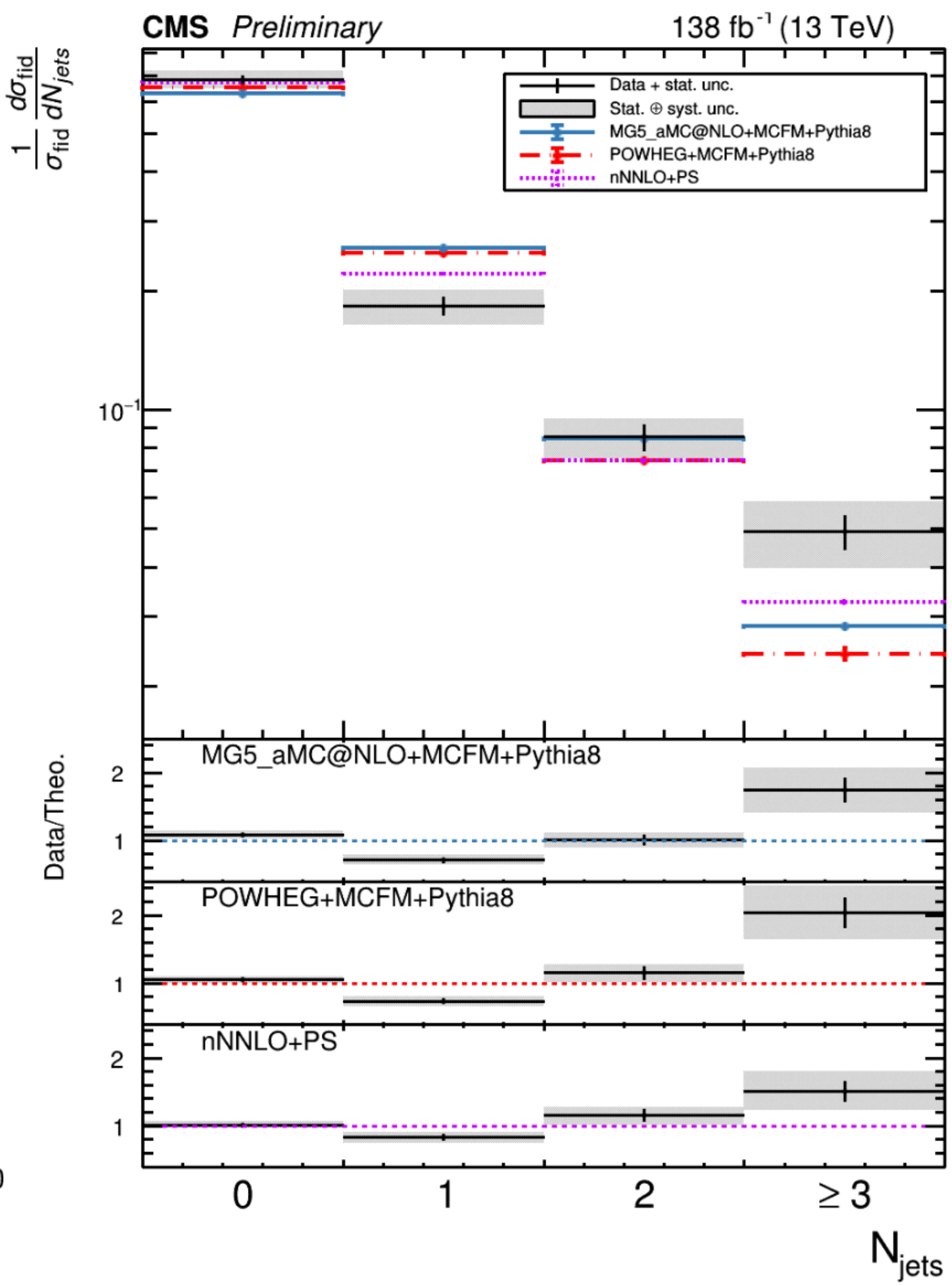
Comparisons with:

- Madgraph5_aMC@NLO
  +MCFM (gg → ZZ)
  +POWHEG (H → ZZ)
- POWHEG ($q\bar{q} \to ZZ$)
  +MCFM ($gg \to ZZ$)
  +POWHEG ($H \to ZZ$)

(Both predictions include Madgraph electro-weak corrections)

- NNLO+PS
- NNLO+PS with electroweak corrections





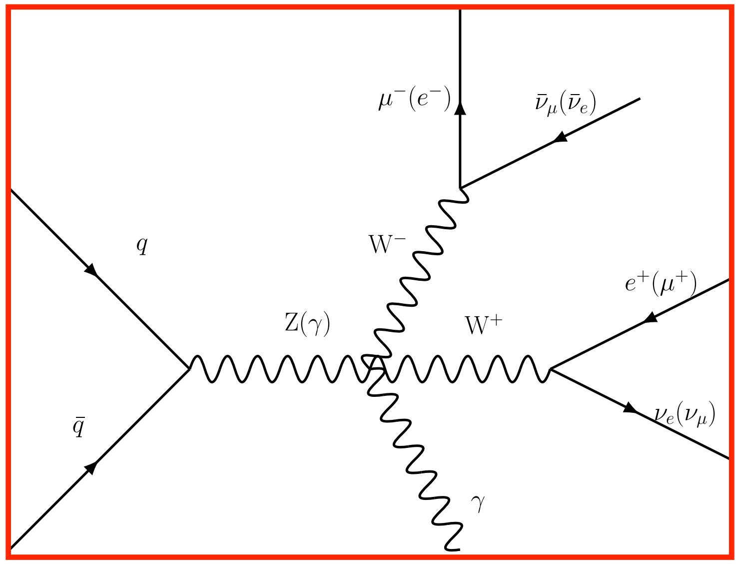
WWγ production introduction

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	eμννγ	**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 (eμννγ) 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$_{\text{jets}}$=0)
  - Observed (expected) 1.4 σ (1.6 σ)
- Limits on dim-8 operators

SMP-22-006



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

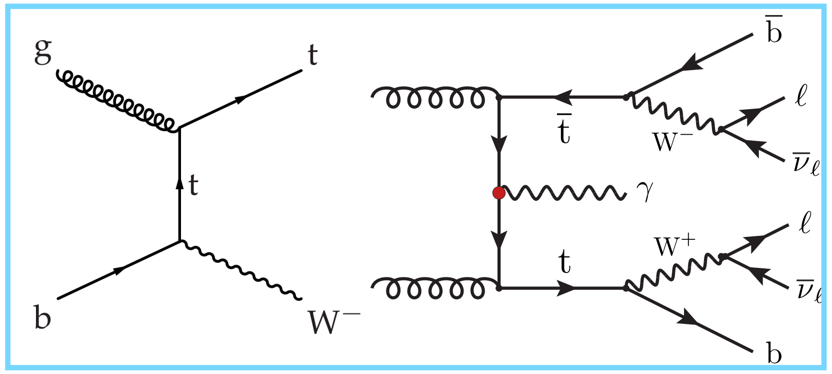
Signal production

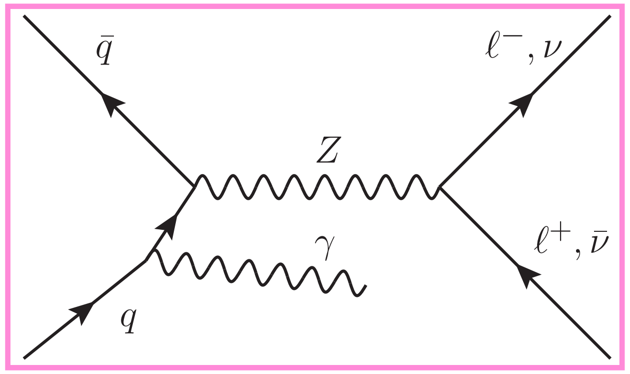
Final state	Generator (MadGraph_aMC@NLO)	Lepton identification	Photon identification	Jet identification	MET
$e\mu\gamma E_T^{miss}$	process: pp > e ν_e μ ν_μ γ [QCD] $p_T^\gamma > 10$ GeV	MVA e ID(≈80%) MVA μ ID (≥90%)	≈80%	anti-k_T AK4CHS 98%-99%	PF

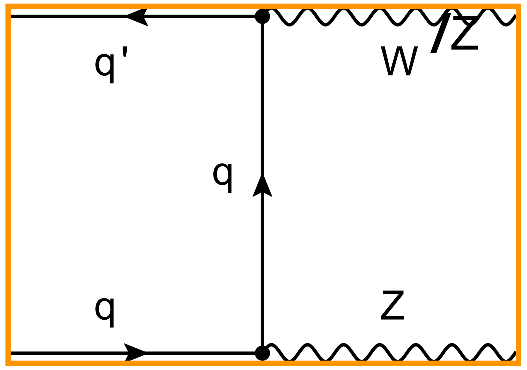
- Signal is produced by MadGraph at NLO in QCD accuracy showering by Pythia8 with NNLO PDF
  - ☑ FSR (final state radiation) photons are included
  - ☑ No EW or much higher QCD corrections
- MVA-based identifications are used for physics object **reconstruction**
  - ☑ Improve efficiency and sensitivity

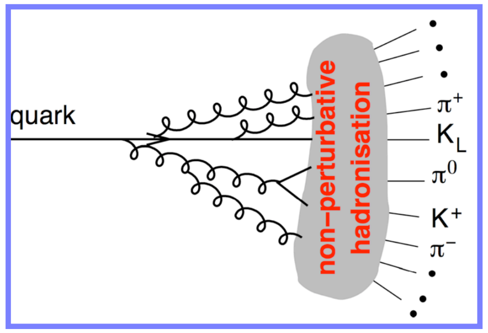
WWγ production backgrounds

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

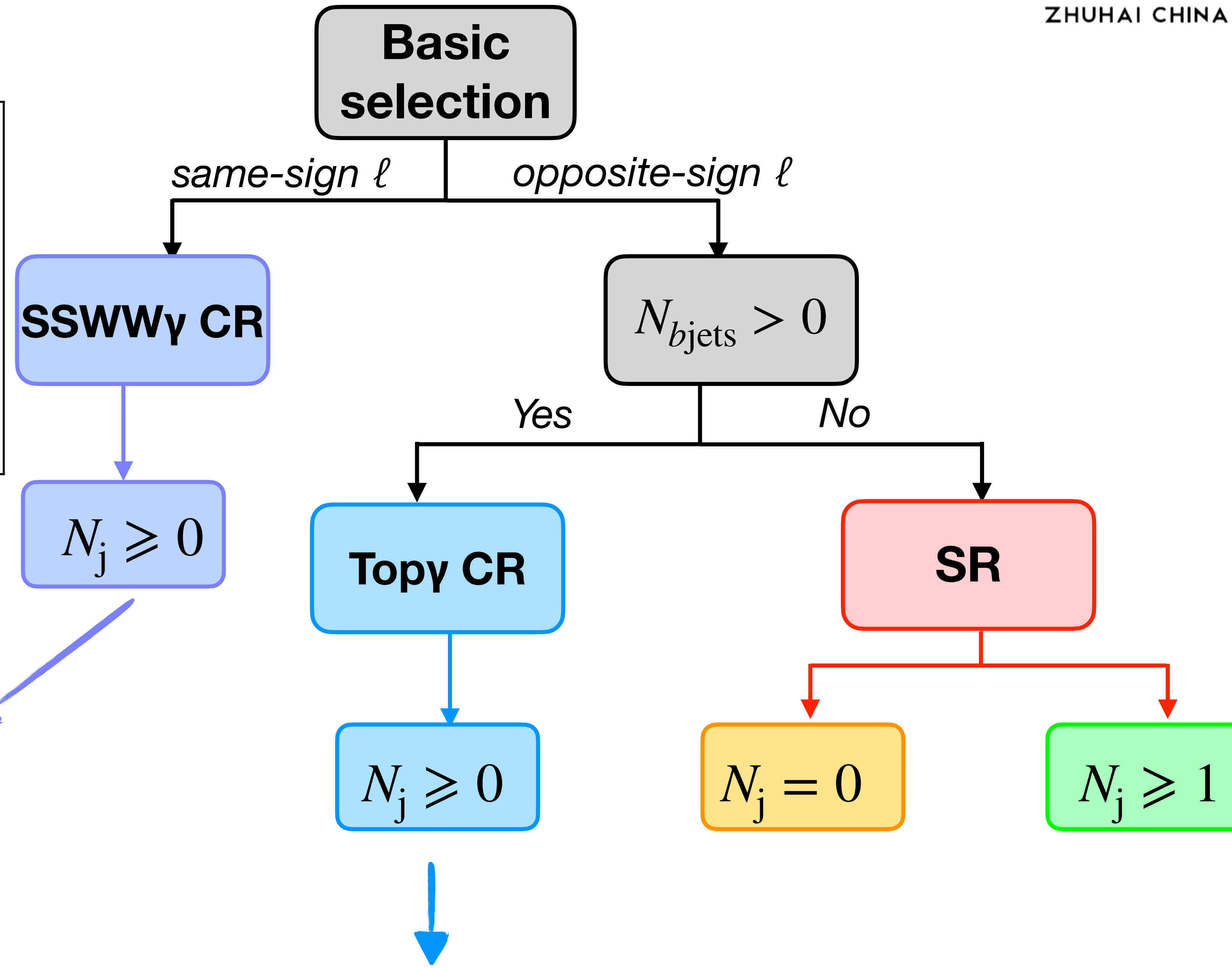
- W or Z decays to e/μ/τ where one or two ℓ are not detected and γ from showering
- e misidentified as γ

- 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)

Selections

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. $m_{\ell\ell}$> 10 GeV and $p_T^{\ell\ell}$ > 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



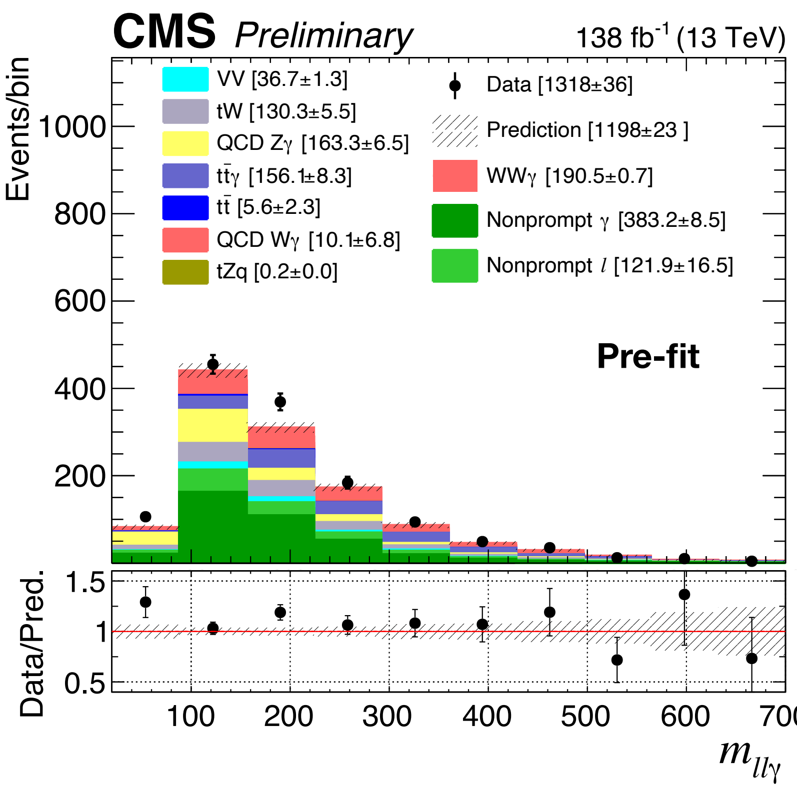
Nonprompt ℓ enriched region

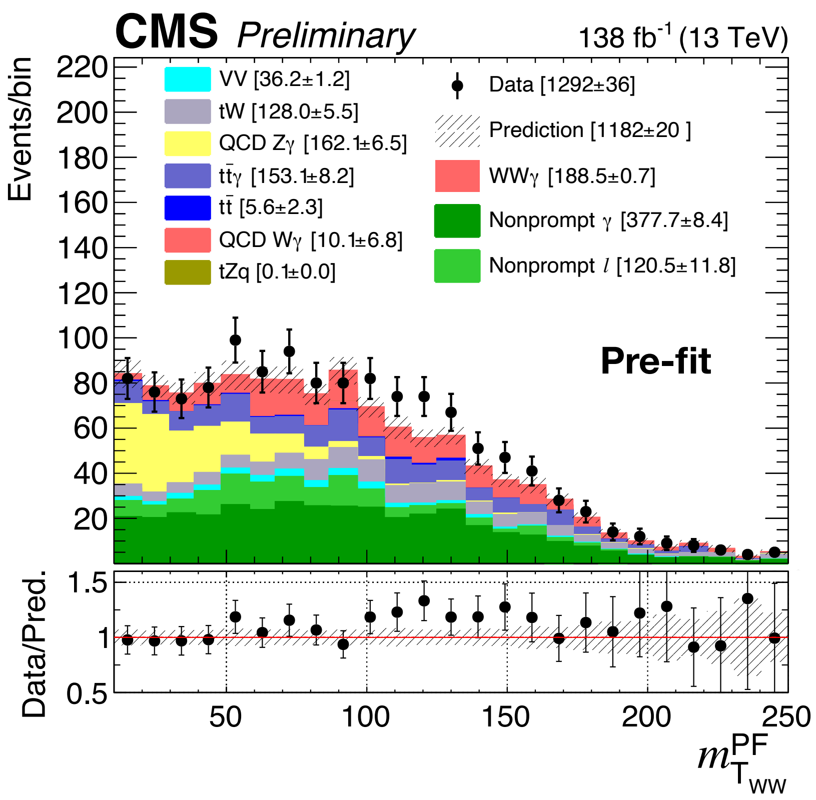
- Validate the nonprompt ℓ background
- Constrain the nonprompt ℓ background by correlating the same systematic uncertainty in the SR

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

Measurement of WWγ production





Reasonable agreement between data and predictions → Good background estimation

- 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

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, ∞)

Measurement of WWγ production

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

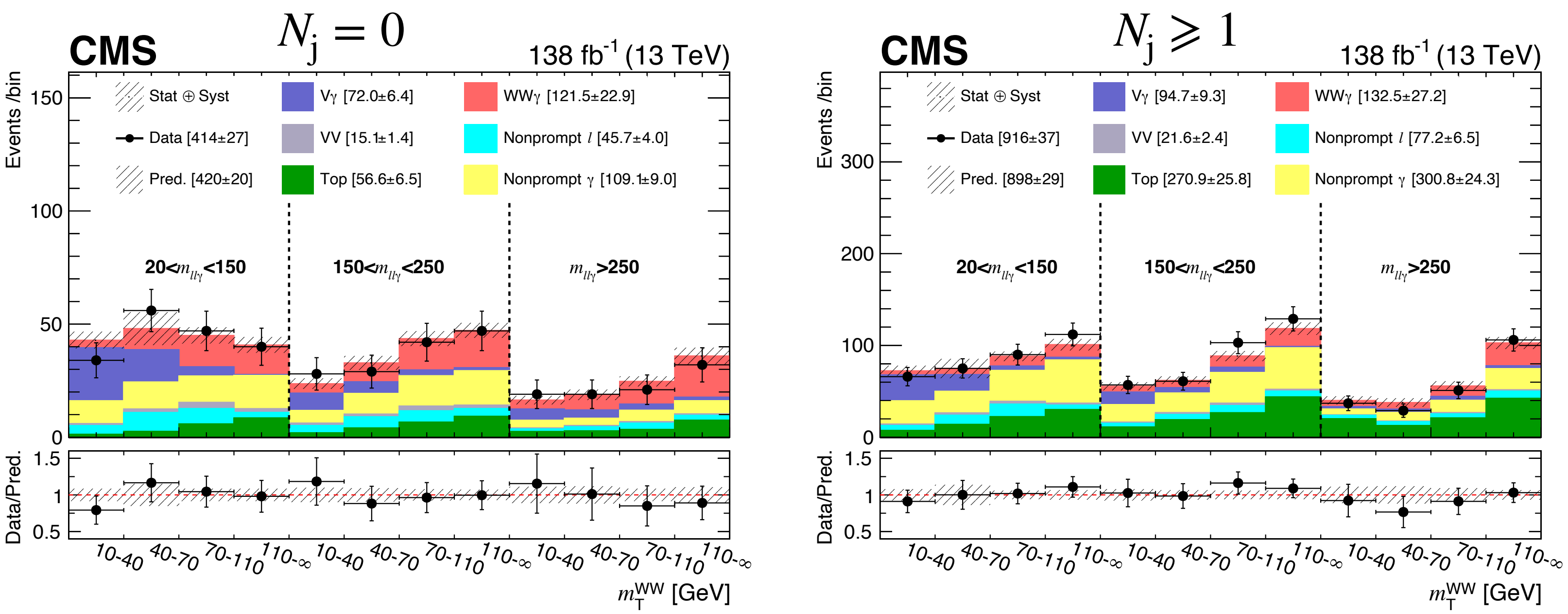
- Correlated between different categories and regions but correlated or uncorrelated between years.
- Apply for all simulation processes

2. Background modelling

- Nonprompt ℓ/γ uncertainty

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

Measurement of WWγ production



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

The **first observation** of WWγ process

Fiducial region definition

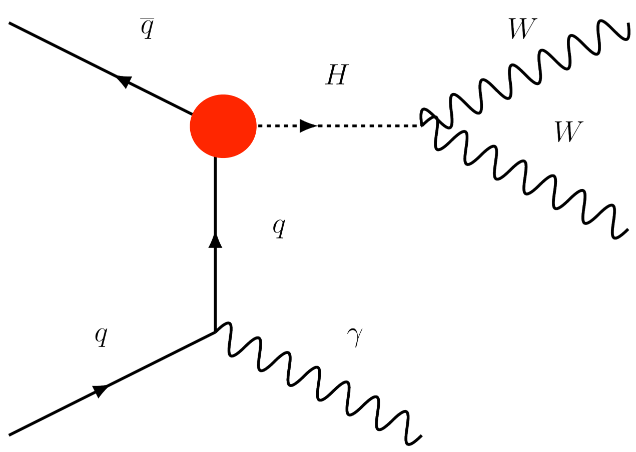
A. $p_T^{e/\mu}$> 25 (20) GeV, |η| < 2.4 (2.5)
B. $m_{\ell\ell}$> 10 GeV and $p_T^{\ell\ell}$ > 15 GeV
C. p_T^{γ}> 20 GeV in the barrel or endcap
D. ΔR(γ/ℓ,ℓ) > 0.5

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

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

Measurement of Hγ production

At NLO and considering the quark mass running effect

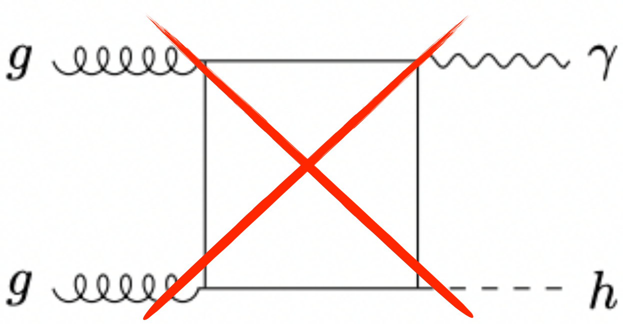


For $q = u, d, s$

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

For $q = c$

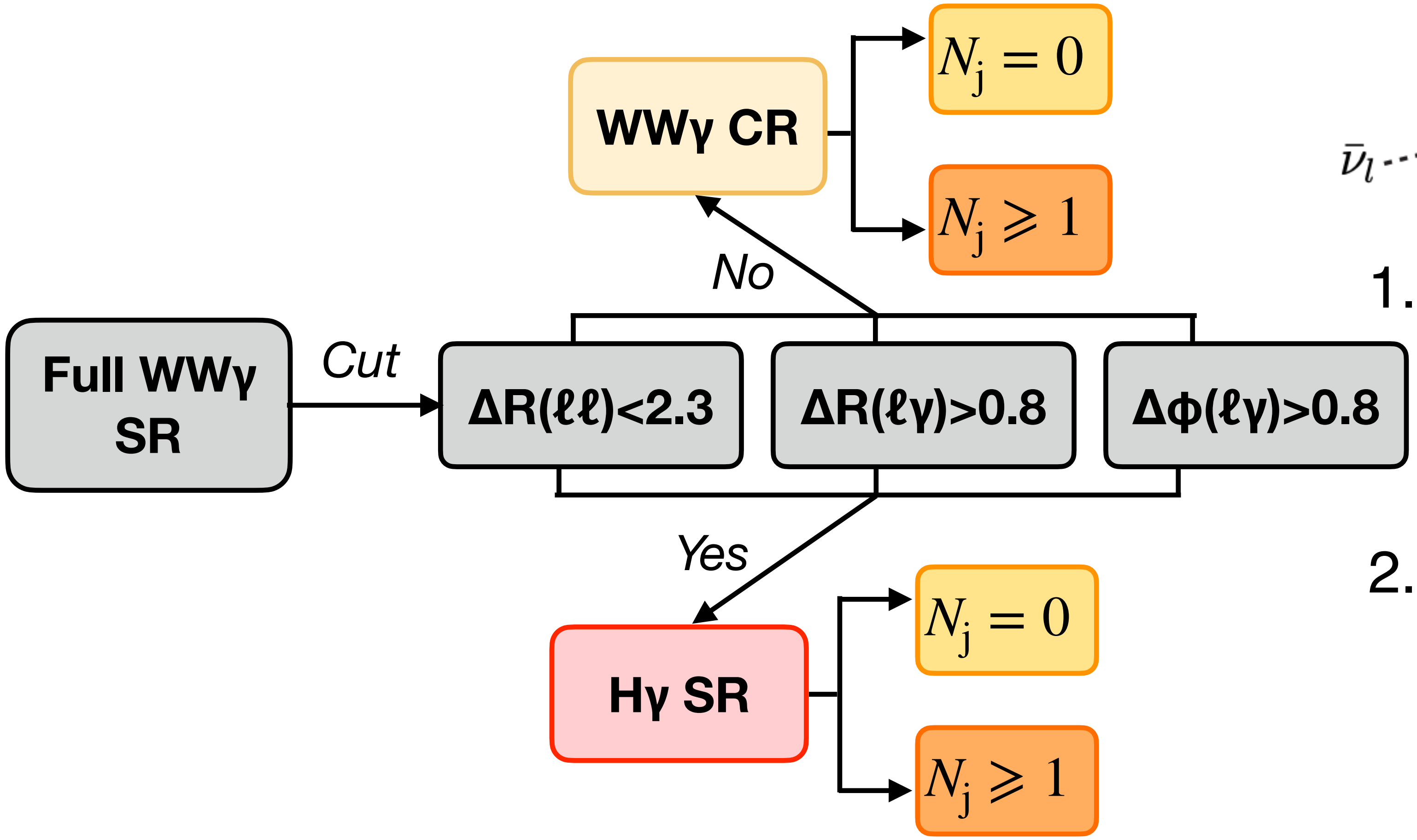
1. **MadGraph**
   - Model: *loop_sm* UFO modified to have *ymc* in $\overline{\mathrm{MS}}$ scheme
     - Closely following theory studies for bbH (1409.5301)
   - Process: $q\bar{q} \rightarrow \mathrm{H}\gamma$ [QCD]
2. **JHU generator**
   $\mathrm{H} \rightarrow \mathrm{W}^{+}\mathrm{W}^{-} \rightarrow e^{\pm}\mu^{\mp}\nu_{e}\bar{\nu}_{\mu}$

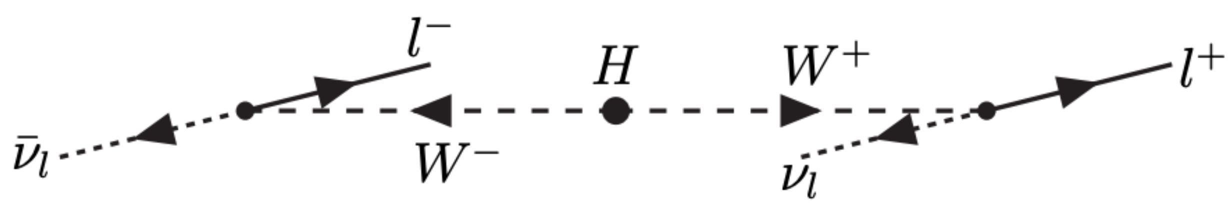


- Main background from gluon-initiated Hγ doesn't exist due to Furry's theorem [1]
- Backgrounds in Hγ are sum of signal and backgrounds in the WWγ measurement
  - ggH, bbH are checked and can be neglected

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

Measurement of WWγ production

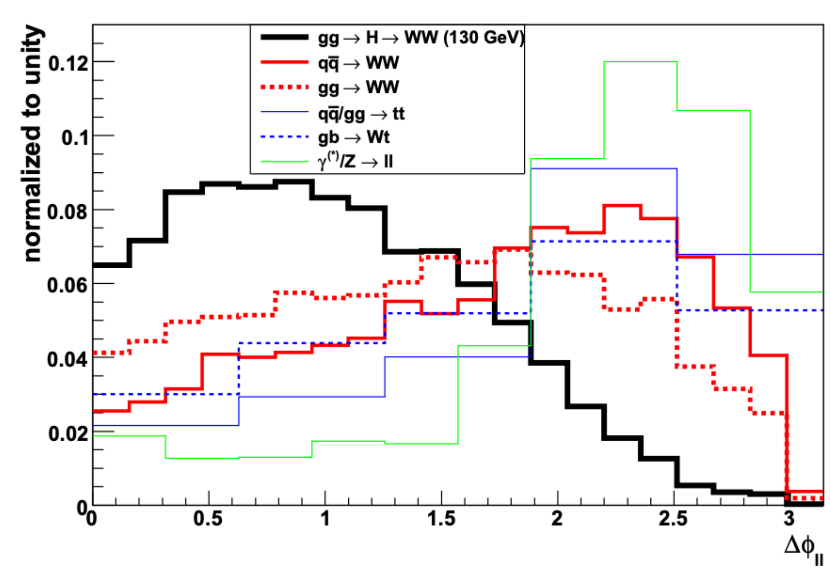




1. In the Higgs boson rest frame, the Higgs (spin 0) to two opposite-sign W bosons, traveling in opposite direction and with opposite relative spin orientation
2. The weak decay of the oppositely charged W bosons with opposite spin orientation results in two leptons that tend to travel in the same direction

[1]

- 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
  - 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

Measurement of WWγ production

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

- Differential Cross-section from ZZ production (to be submitted to ***JHEP***)
- Observation of WWγ production (to be submitted to ***PRL***)
  - ★ Significance and Inclusive cross section in $e^{\pm}\nu_e\mu^{\mp}\nu_\mu\gamma$ final states
  - ★ The cross section upper limits for Hγ production, and Yukawa coupling of κ_c, κ_s, κ_u, and κ_d interpreted results
- In 1983, We found the W/Z boson at CERN. Now, Run-3 Ongoing:

More surprise expected!

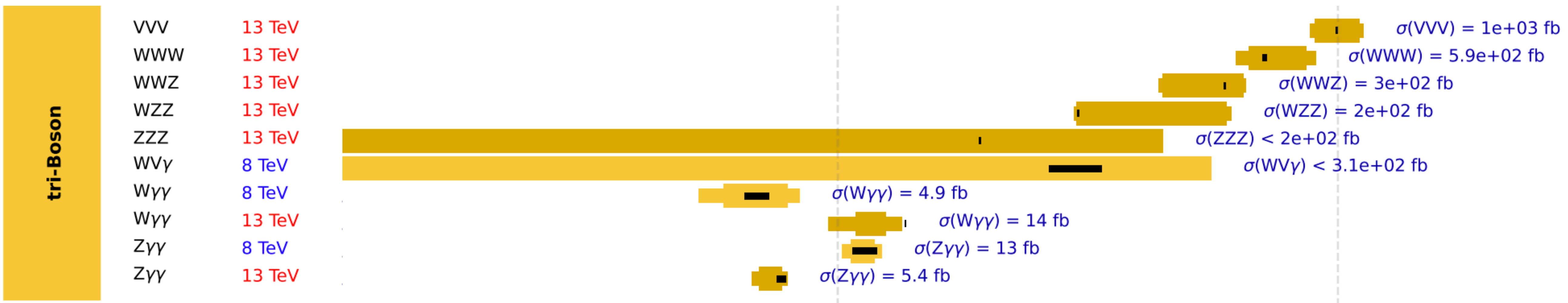
LHC Run 3 schedule

- Will take data until at least ~ end of 2024 (may be extended by 1 year)
- Will run p-p collisions at 13.6 TeV
- Total integrated luminosity ~ 160-200 fb^{-1} (compared to ~ 140 fb^{-1} in Run 2)

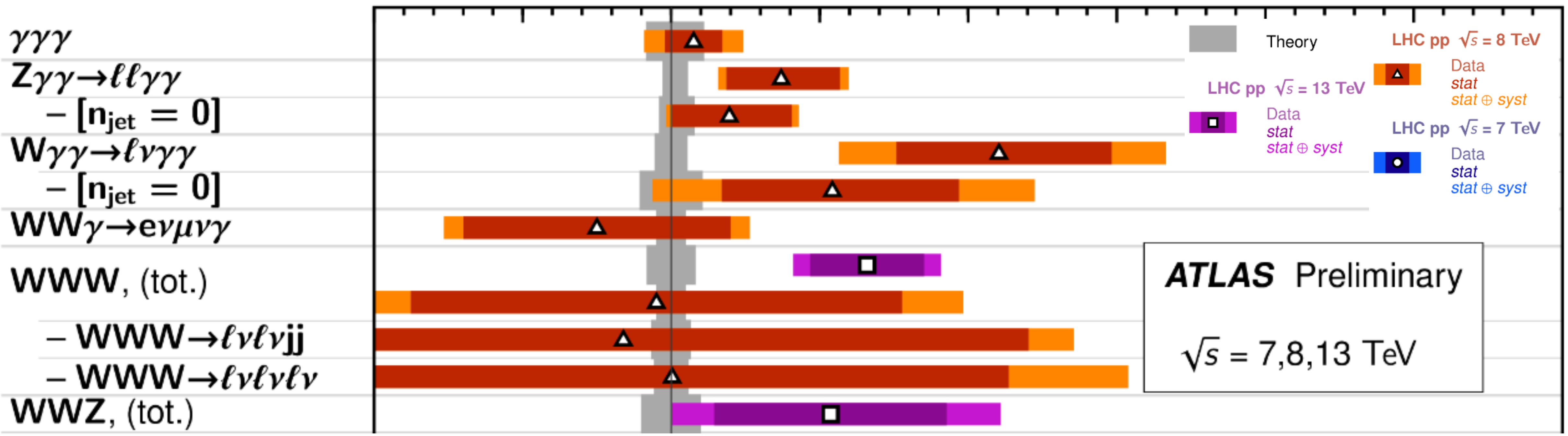
Backup

Triboson overview

CMS Triboson Cross Section [1]



ATLAS Triboson Cross Section [2]



[1] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined
[2] https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/

Published/Approval results

Triboson with γ	Final states	CMS Journal	CMS Lumi fb^{-1} / $\sqrt{s}$ TeV	ATLAS Journal	ATLAS Lumi fb^{-1}/ $\sqrt{s}$ TeV
γγγ	γγγ	—	—	PLB 781 (2018) 55	20.2/ 8
Zγγ	ℓℓγγ	JHEP 10 (2017) 072	19.4/ 8	PRD 93, 112002 (2016)	20.3/ 8
Wγγ	ℓνγγ	JHEP 10 (2017) 072	19.4/ 8	PRL 115, 031802 (2015)	20.3/ 8
WVγ	ℓνjjγ	PRD 90 (2014) 032008	19.3/ 8	EPJC 77, 646 (2017)	20.2/ 8
Vγγ	ℓνγγ ℓℓγγ	JHEP 10 (2021) 174 SMP-19-013	137/ 13	**Zγγ: 2211.14171** **Wγγ: ATLAS-CONF-2023-005** **New!**	139/ 13
VVV	multi-ℓ+jets	PRL 125 151802 SMP-19-014	137/ 13	PRL 129 061803 (WWW production)	139/ 13
WWγ	eμννγ	**SMP-22-006** **New!** **(Target PRL)**	138/ 13	EPJC 77, 646 (2017)	20.2/ 8
WZγ	ℓℓℓγ	-	-	**ATLAS-CONF-2023-014** **New!**	139/ 13

Uncertainties

Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Trigger	-	-	-	-	-
Electron Efficiency	0.42 %	0.38 %	0.66 %	0.36 %	0.26 %
Muon Efficiency	0.05 %	0.06 %	0.07 %	0.09 %	0.08 %
Jet energy resolution	0.0	0.07 %	1.72 %	1.65 %	0.8 %
JES correction	0.0	0.17 %	1.77 %	1.95 %	0.97 %
Reducible background	0.18 %	0.18 %	0.32 %	0.33 %	0.96 %
Pileup	0.02 %	0.05 %	0.11 %	0.13 %	0.35 %
Luminosity	0.01 %	0.01 %	0.02 %	0.02 %	0.05 %
Monte Carlo choice	0.35 %	0.65 %	0.94 %	0.48 %	0.35 %
gg cross section	0.02 %	0.03 %	0.09 %	0.06 %	0.09 %
QCD Scales	0.15 %	0.16 %	0.58 %	0.54 %	0.62 %
PDF	0.05 %	0.05 %	0.15 %	0.15 %	0.21 %
α_S	0.02 %	0.01 %	0.05 %	0.03 %	0.02 %