Physics of the Electroweak sector at CMS

DIS2023

The 30th International Workshops on Deep-Inelastic Scattering and Related Subjects

Michigan State University(United States)

27-31 Mar 2023

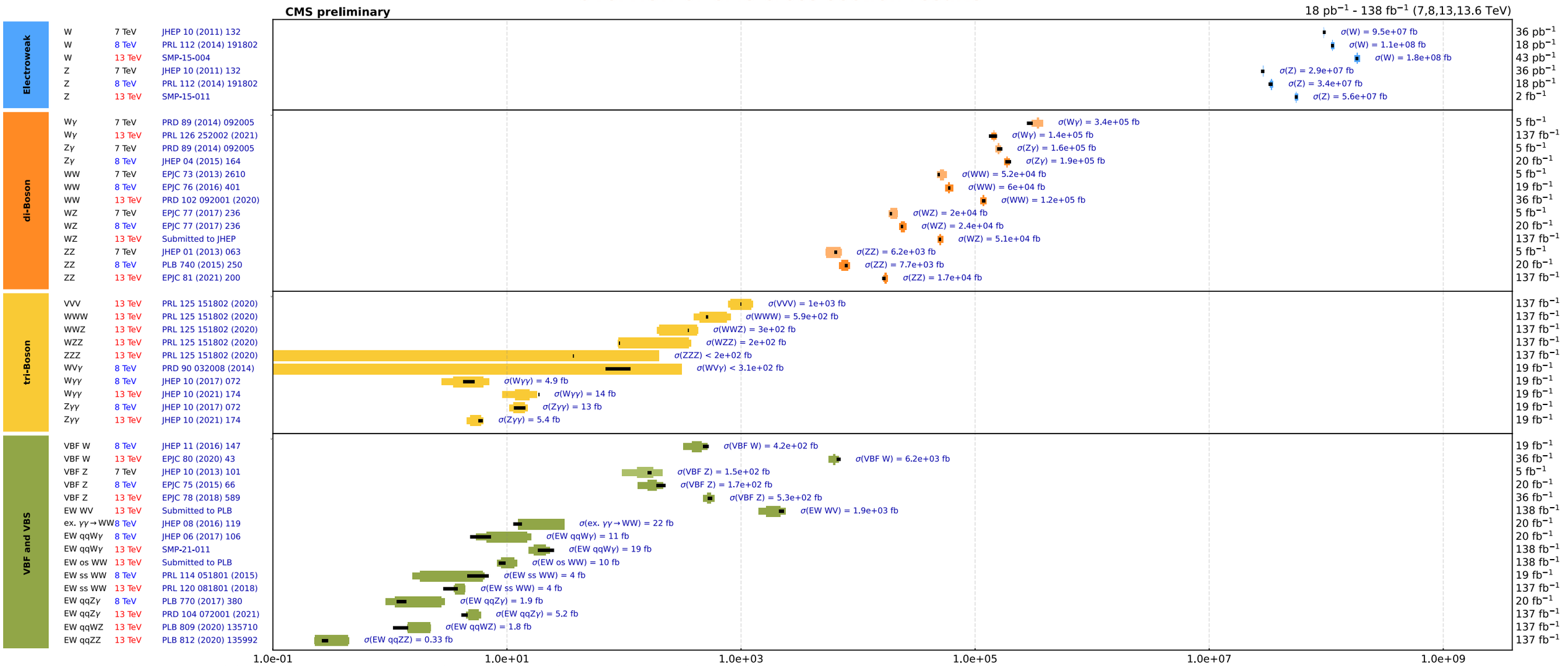
Monika Mittal
Beihang University, China

On behalf of the CMS Collaboration

Accuracy for SM Measurement

Link

Spanning 9 Orders of Magnitude in Cross Section



The LHC is currently in its Run 3 phase, expected to have twice the luminosity of Run 2 by mid-2024.

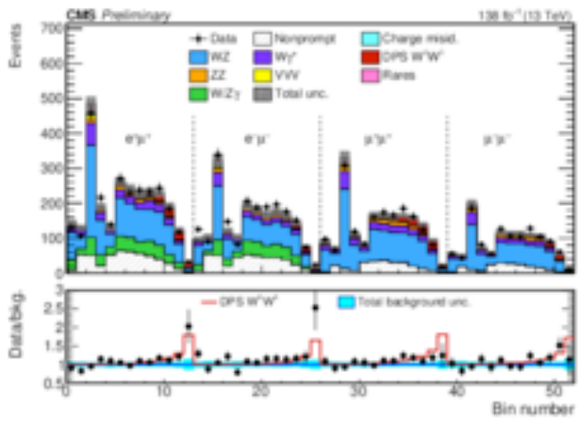
Timeline of SM results (2022-2023)

Link

Drell-Yan measurements in CMS by **Duong**
Vector boson scattering results in CMS by **Irene**

Observation of WW from DPS

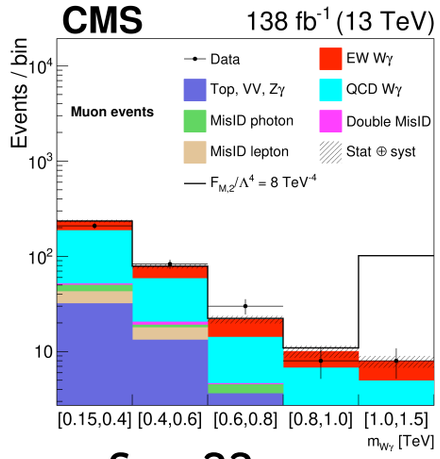
[CMS-PAS-SMP-21-013](#)



Jul 22

Electroweak production of Wγ with two jets

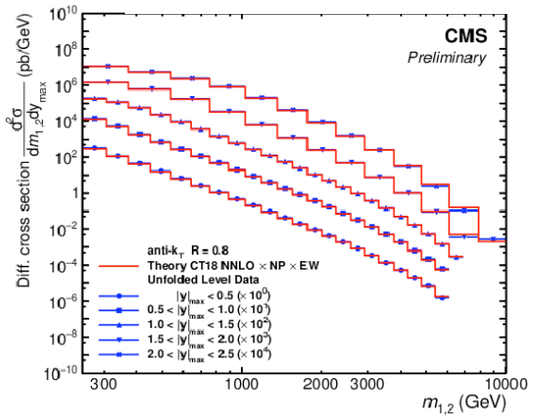
[CMS-PAS-SMP-21-011](#)



Sep 22

Multi-differential dijet cross section

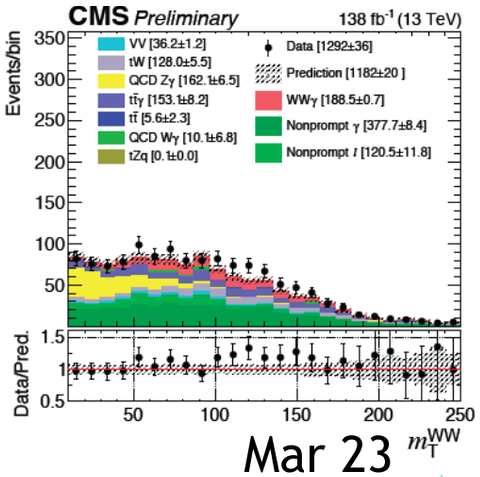
[CMS-PAS-SMP-21-008](#)



Nov 22

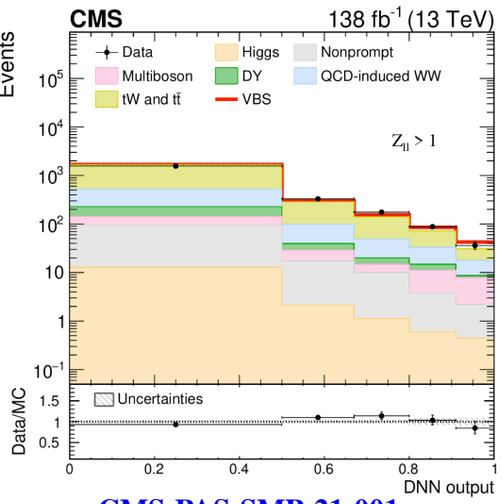
Observation of WWγ production

[CMS-PAS-SMP-22-006](#)



Jan 23 — Mar 23

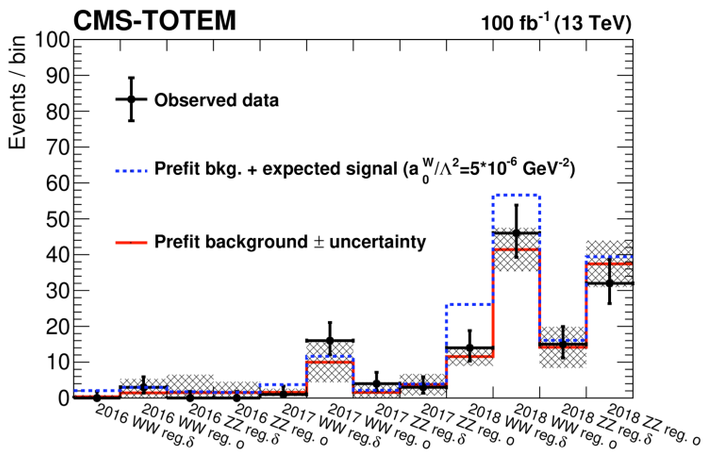
Jun 22



[CMS-PAS-SMP-21-001](#)

Observation of electroweak WW +2jets

Aug 22

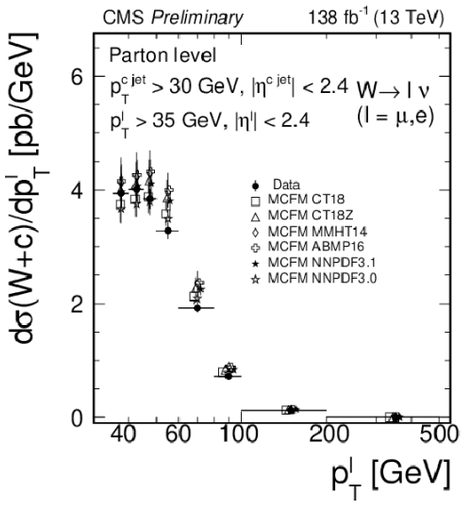


[CMS-PAS-SMP-21-014](#)

Exclusive γγ→WW/ZZ production

Oct 22

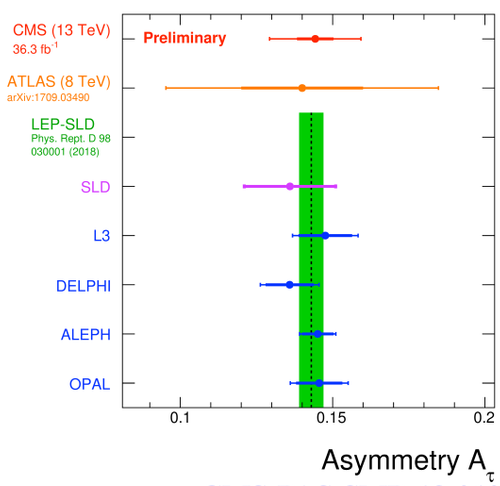
Dec 22



[CMS-PAS-SMP-21-005](#)

Production cross section of a W+c

Feb 23



[CMS-PAS-SMP-18-010](#)

τ lepton polarization

The coming years are expected to be an exciting time for particle physics research, with the potential for significant advancements in our understanding

Timeline of SM results (2022-2023)

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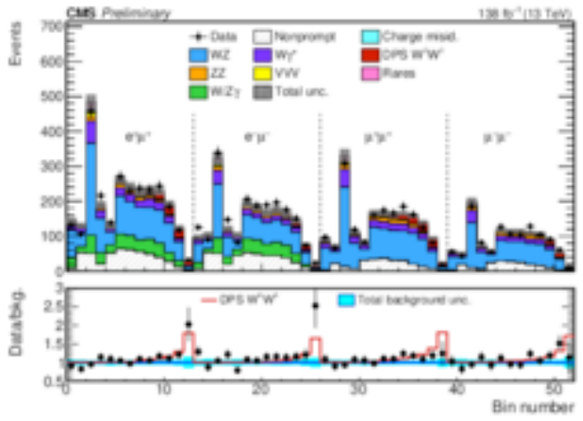
CMS-PAS-SMP-21-013



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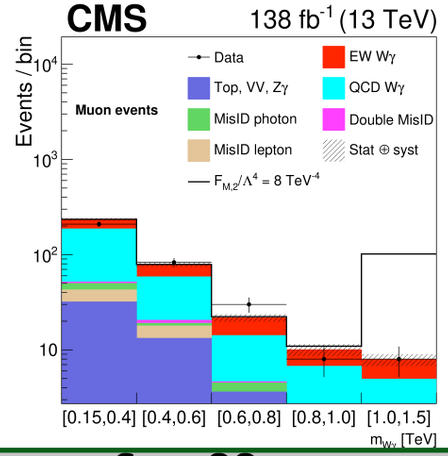
CMS-PAS-SMP-21-011



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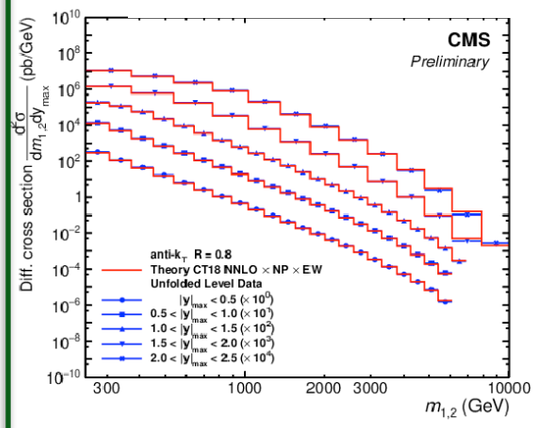
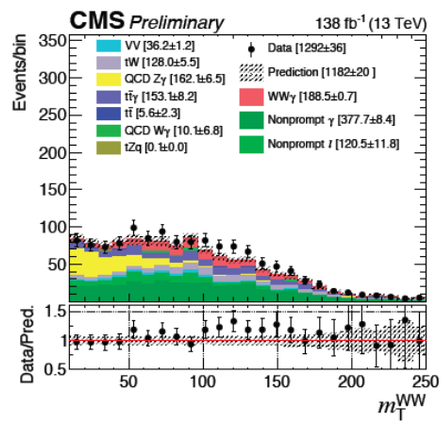


Nov 22

Observation of WWγ production

CMS-PAS-SMP-22-006



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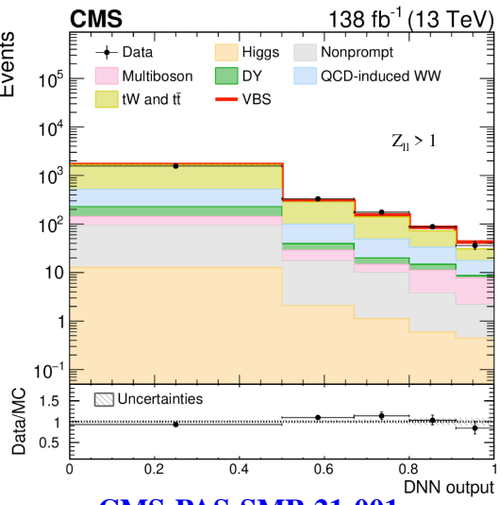

CMS-PAS-SMP-21-001

Observation of electroweak WW +2jets

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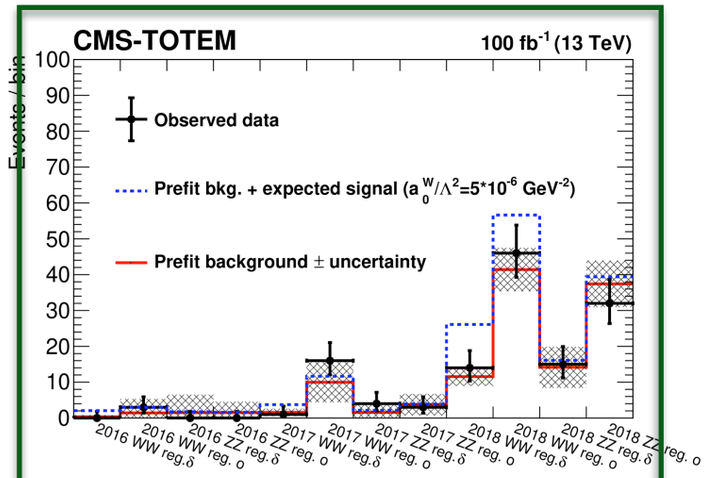

CMS-PAS-SMP-21-014

Exclusive γγ→WW/ZZ production

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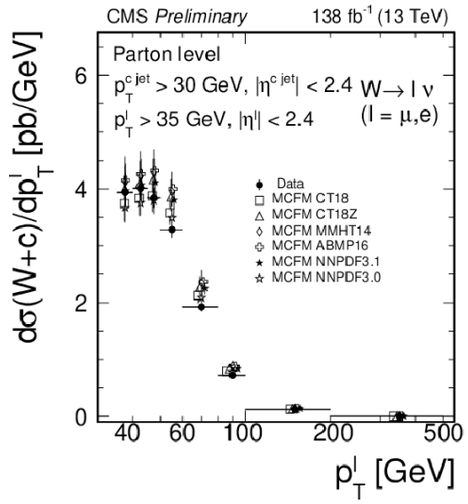
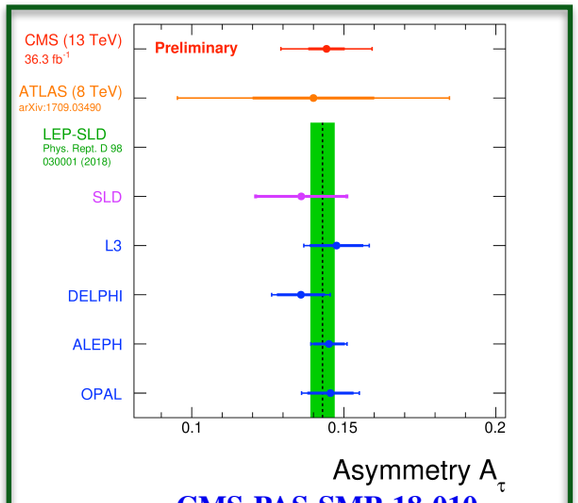


CMS-PAS-SMP-21-005

Production cross section of a W+c

Feb 23



CMS-PAS-SMP-18-010

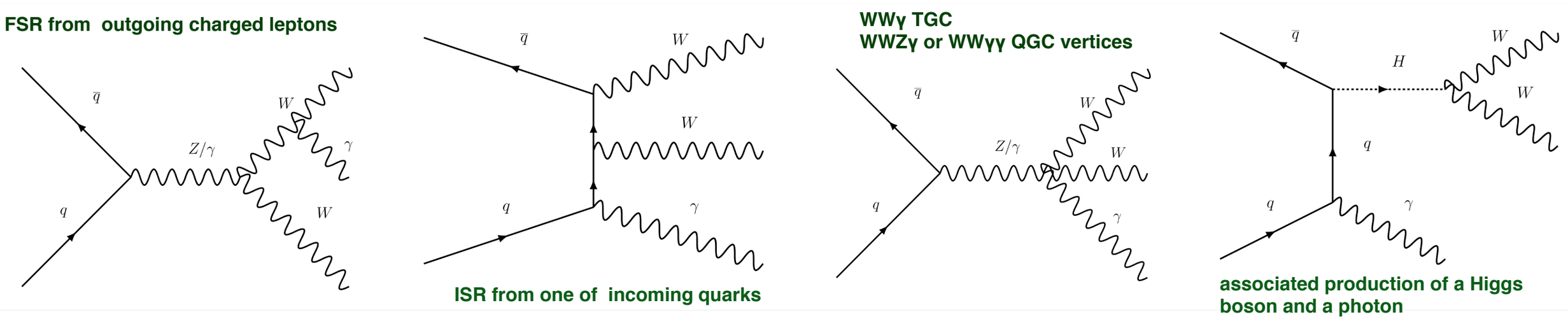
τ lepton polarization

The coming years are expected to be an exciting time for particle physics research, with the potential for significant advancements in our understanding

WWγ production

CMS-PAS-SMP-22-006

- Multiboson production at the LHC provides a unique opportunity to study electroweak sector in detail
  - Direct measurement of gauge boson self-couplings and precision test of SM

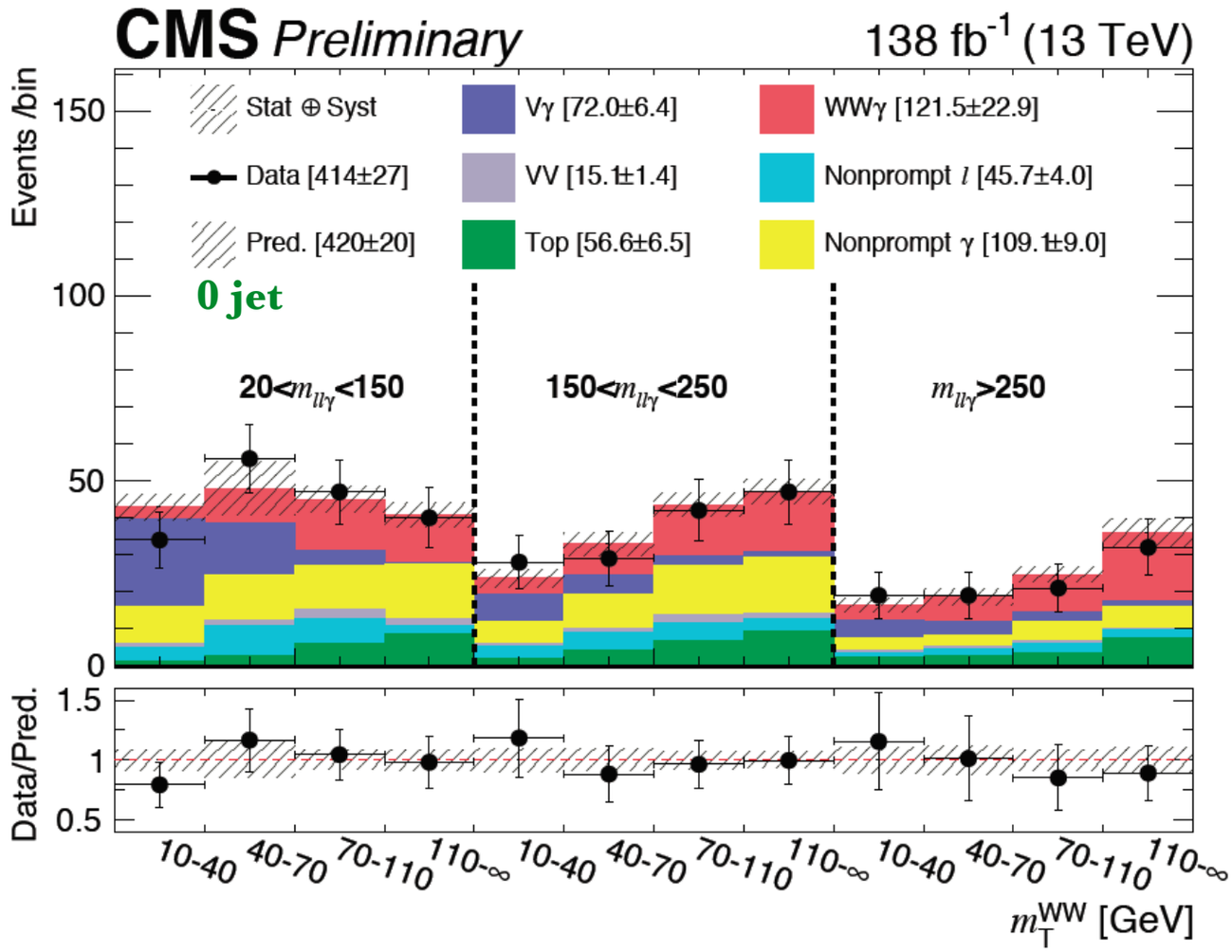


  - The LHC's high collision energy and large data collection make it the only way to access.
    - Measurements of WWγ performed by the CMS and ATLAS collaborations at $\sqrt{s}$ =8 TeV
      - only upper limits on the production cross sections were reported
        - due to a lack of statistical power and sensitivity.

- Objective :
  - Fiducial cross section for WWγ and first observation
  - Study the coupling between Higgs and light quarks by Hγ (H->WW*) process

WWγ production : Event Selection

- Final states : two opposite charge leptons plus a photon : $e^+\nu_e\,\mu^-\nu_\mu\,\gamma$ and $\mu^+\nu_\mu\,e^-\nu_e\,\gamma$
- Backgrounds :
  - Zγ, ttγ, Single Top, ZZ/WW
    - estimated using simulations with normalisation extracted from dedicated CR in data
  - Non-prompt leptons and photons backgrounds
    - Data-driven estimation
    - **SSWWγ CR** : validate non-prompt photons
      - ☆ opposite sign charge requirement is inverted
    - **Topγ CR**: validate non-prompt leptons
      - ☆ b-jets ≥ 1



- Simultaneous fit is performed using **SSWWγ** , **Topγ** CR and **WWγ SR**
- Signal significance and strength are extracted using binned maximum likelihood in bins of $m_{T(WW)}$, $m_{ll\gamma}$

	WWγ		Topγ	SSWWγ
	0 jet	≥ 1 jet		
m_T^{WW}	[10,40,70,110,∞]	[10,40,70,110,∞]	[10,∞]	[10,40,70,110,∞]
$m_{ll\gamma}$	[20,150,250,∞]	[20,150,250,∞]	[20,∞]	[20,∞]

WWγ production : Results

- The first observation on tri-boson WWγ production at LHC at 13 TeV
  - Observed Signal significance is 5.6 σ (expected 4.7 σ)
- Measured fiducial cross-section for WWγ

$$\sigma = 6.04 \pm 1.69\,\text{fb} = 6.04 \pm 1.03\,(\text{stat}) \pm 0.97\,(\text{syst}) \pm 0.85\,(\text{theo})\,\text{fb}$$

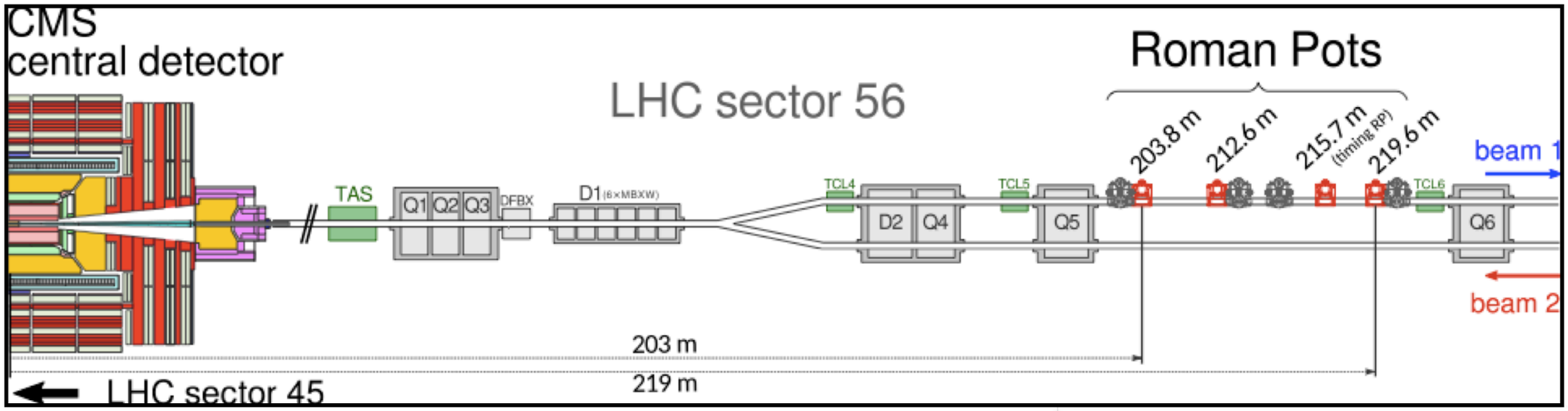
  - In agreement with next-to-leading order QCD prediction
- Search for associated production of Higgs boson and a photon
  - upper limit on cross-section and 95% confidence limit on Higgs coupling to light quark are provided
    - Assuming Higgs is produced by Yukawa direct coupling to light quarks

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)	$\lvert\kappa_c\rvert \leq 110(200)$

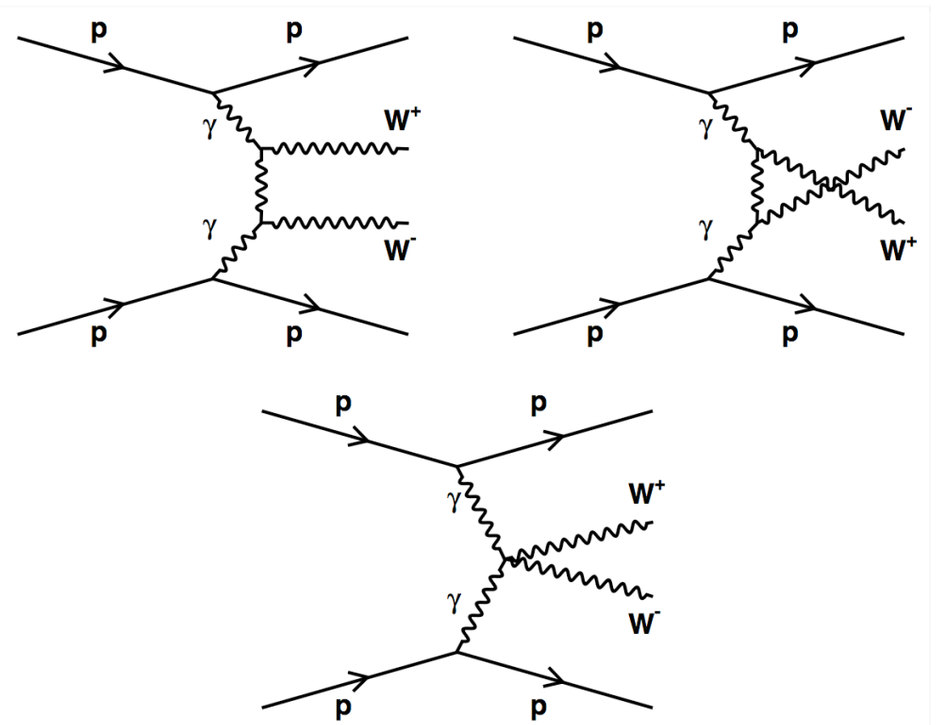
Exclusive γγ→WW/ZZ production

CMS-SMP-21-014
Submitted to J. High Energy Phys

- Probing gamma-gamma collisions at hadron collider
  - Addition of PPS to CMS allows to reconstruct the full 13 TeV collision energy in signal events
    - PPS detects in-tact protons momenta ~200m from the CMS IP using LHC magnets



- Objectives :
  - to probe SM quartic coupling at tree level
    - γγ→WW allowed and concentrated at low values of m(WW)
    - γγ→ZZ neutral quartic coupling not allowed
  - BSM contributions (non-resonant) enhancements over the SM in high mass tails (aQGC/EFT)

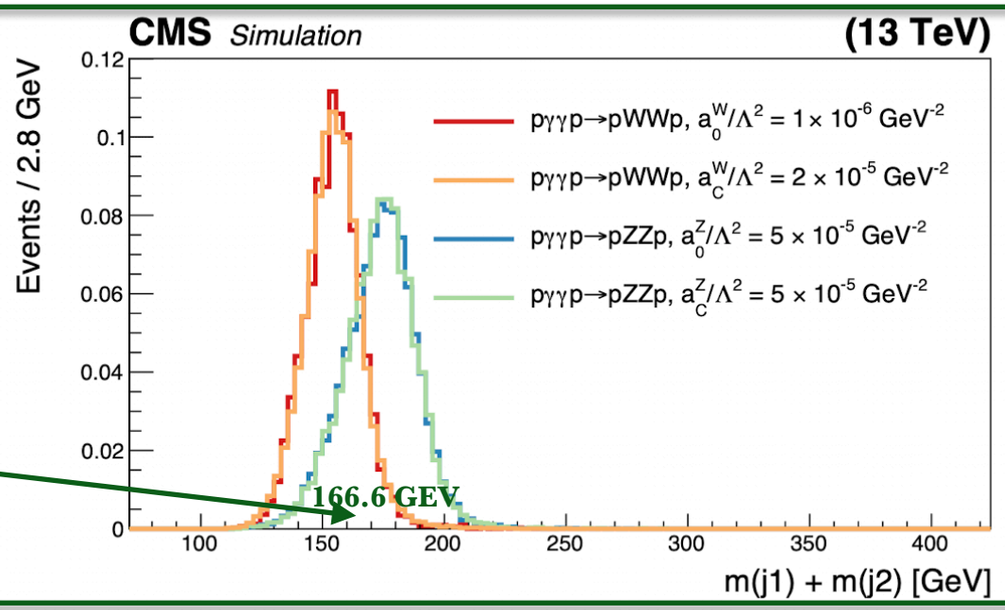


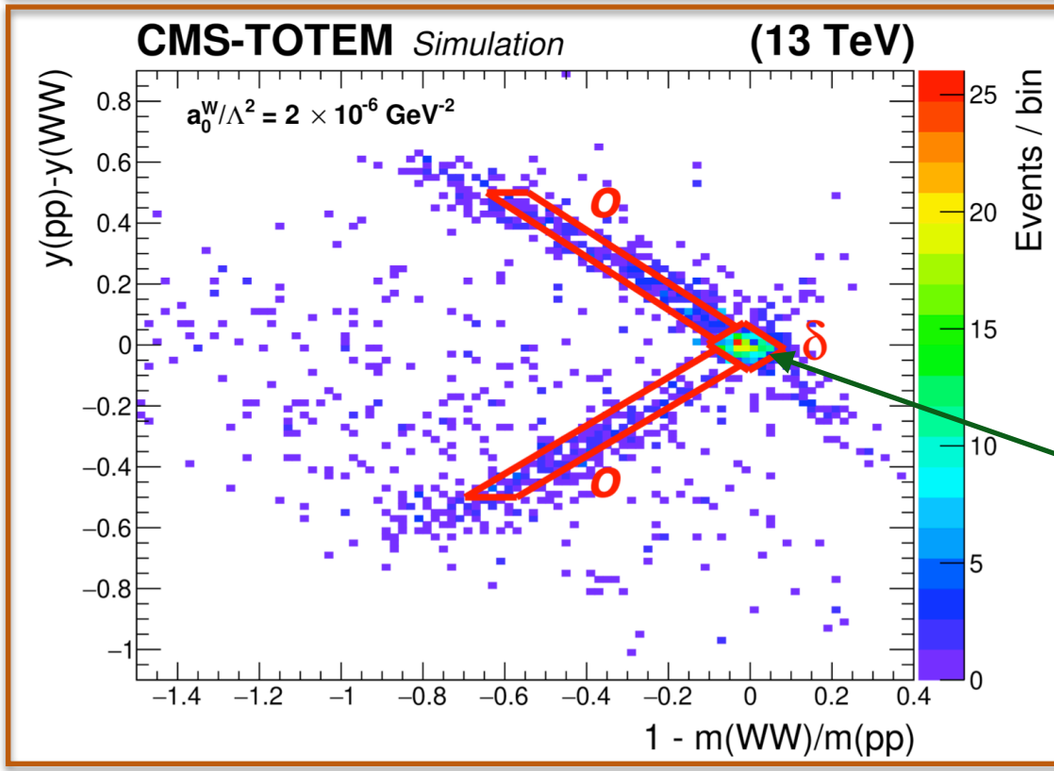
Exclusive γγ→WW/ZZ production: Event Selection

- Final state : two bosons (hadronically decaying) in CMS and scattered protons in PPS

Boosted/Merged jet from weak vector boson

- selected using N-subjettiness after pruning where $m_{jj} > 1126$ GeV
- sum of jet masses discriminate between WW and ZZ events





Forward Protons

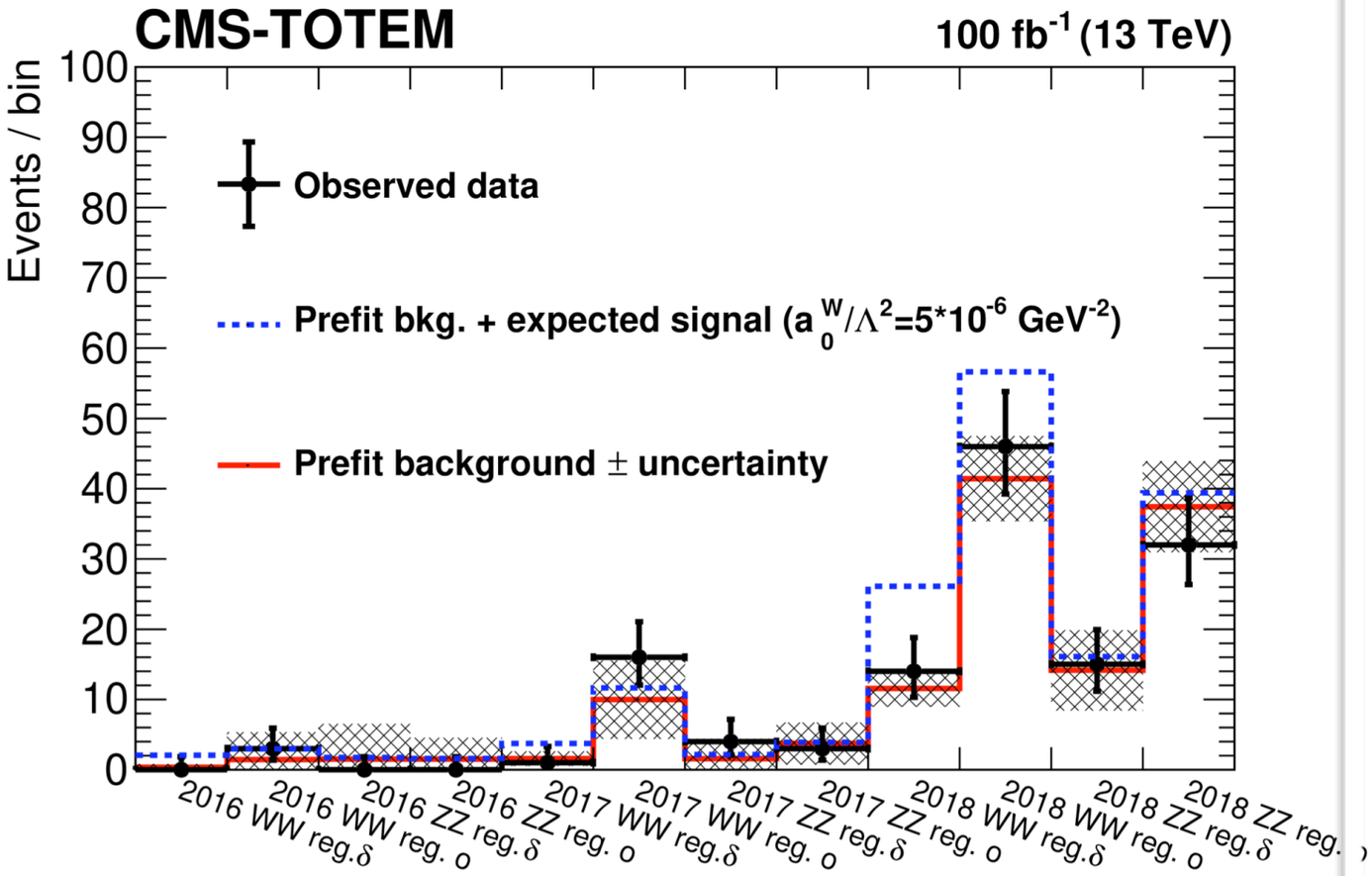
- reconstructed using "multi-RP" algorithm ; combine tracks reconstructed in both Roman Pots in each arm

Match forward protons to jets

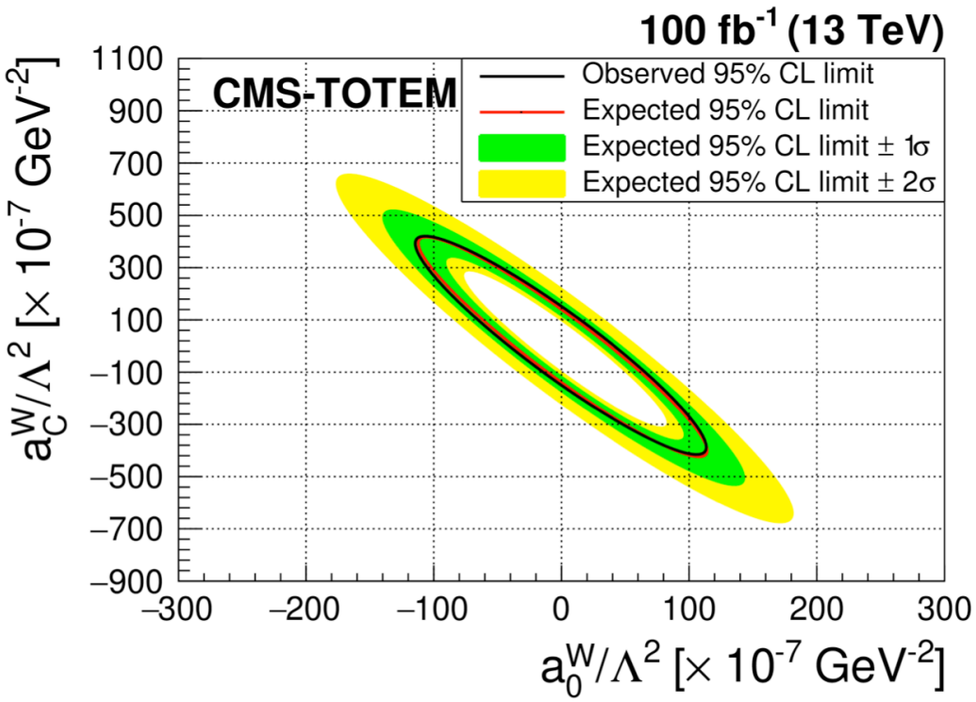
- comparing mass and rapidity of bosons to pp system
- define two SR: 1**(δ)** **or** 2(*o*) protons are correctly matched

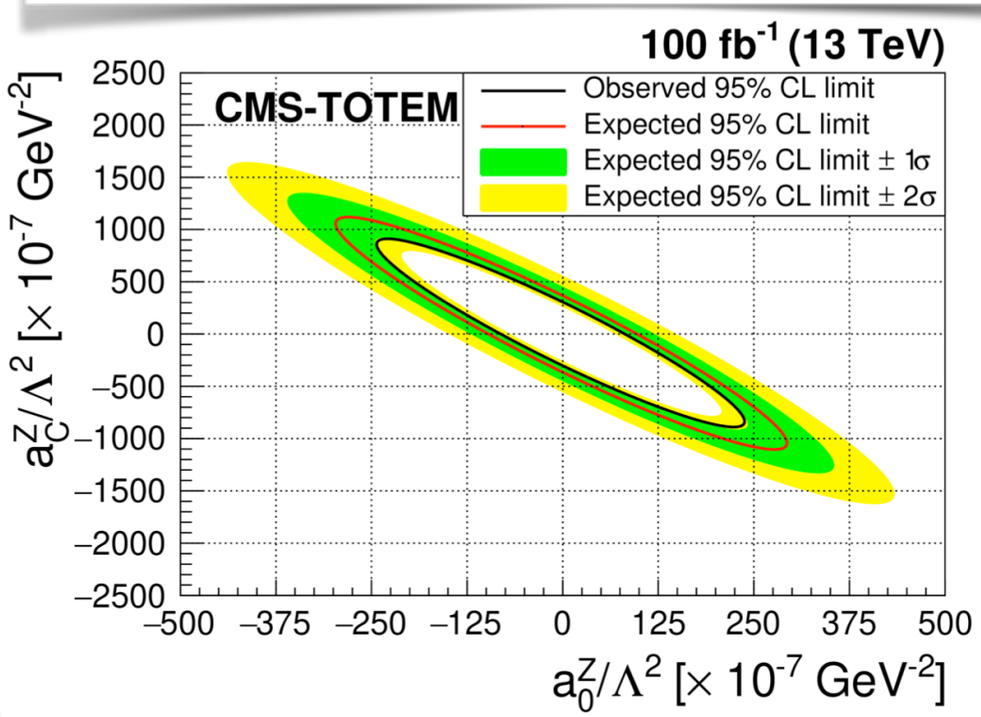
- Background estimated from the control regions
  - Inverting the observables for jet topology and pp matching

Exclusive γγ→WW/ZZ production : Results



- No excess above the SM background prediction is observed
  - limits on dim-6 and dim-8 aQGC
    - More stringent than Run1 data
  - EFT Dimension-8 operators are constrained as well
- Limits on fiducial cross-section considering m_{vv} >1 TeV and proton fractional charge <20%
  - cross-section upper limit at 95%
    - σ (pp →pWWp) < 67 fb
    - σ (pp→pZZp) < 43 fb

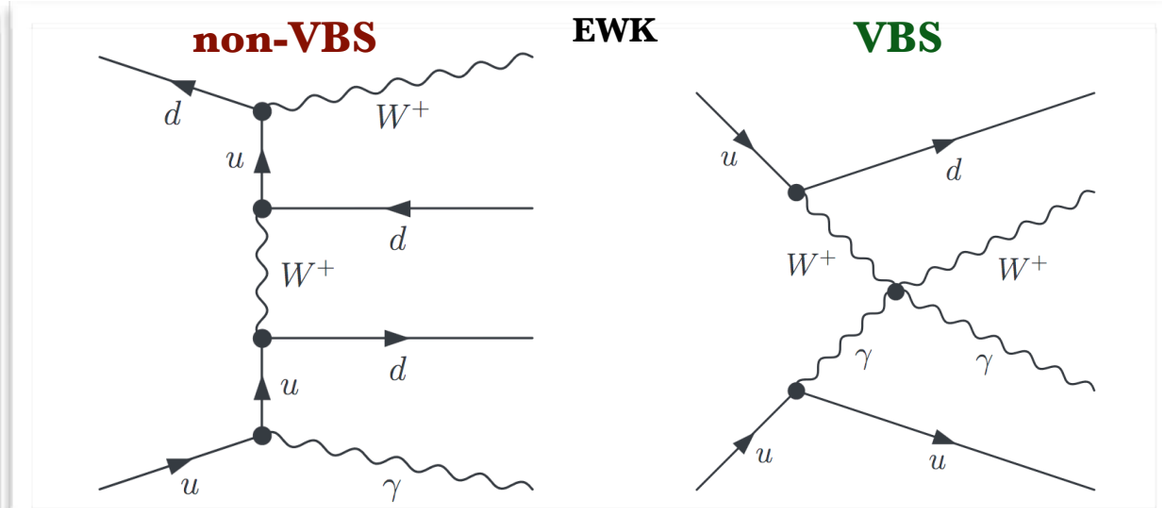


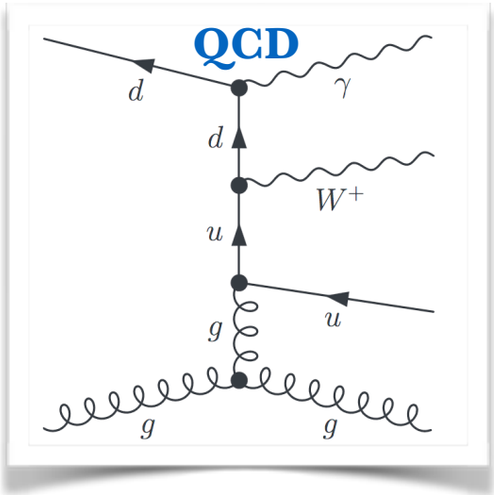


Electroweak production of Wγ with two jets

CMS-SMP-21-011
Accepted by PRD

- Vector boson scattering (VBS) processes are crucial
  - understanding electroweak symmetry breaking
  - probe new physics beyond the SM
- Objectives :
  - Measure the Electroweak (EW) production of Wγ
    - fiducial and differential cross section.
    - search for anomalous coupling
- Exploiting the VBS Wγjj topology ;
  - the two jets with
    - large invariant mass mjj
    - large separation in pseudorapidity |Δηjj|.
  - momentum of the Wγ system is balanced by that of the dijet system
- suppresses the contamination from the QCD-induced production of Wγjj, as well as the non-VBS EWK contribution





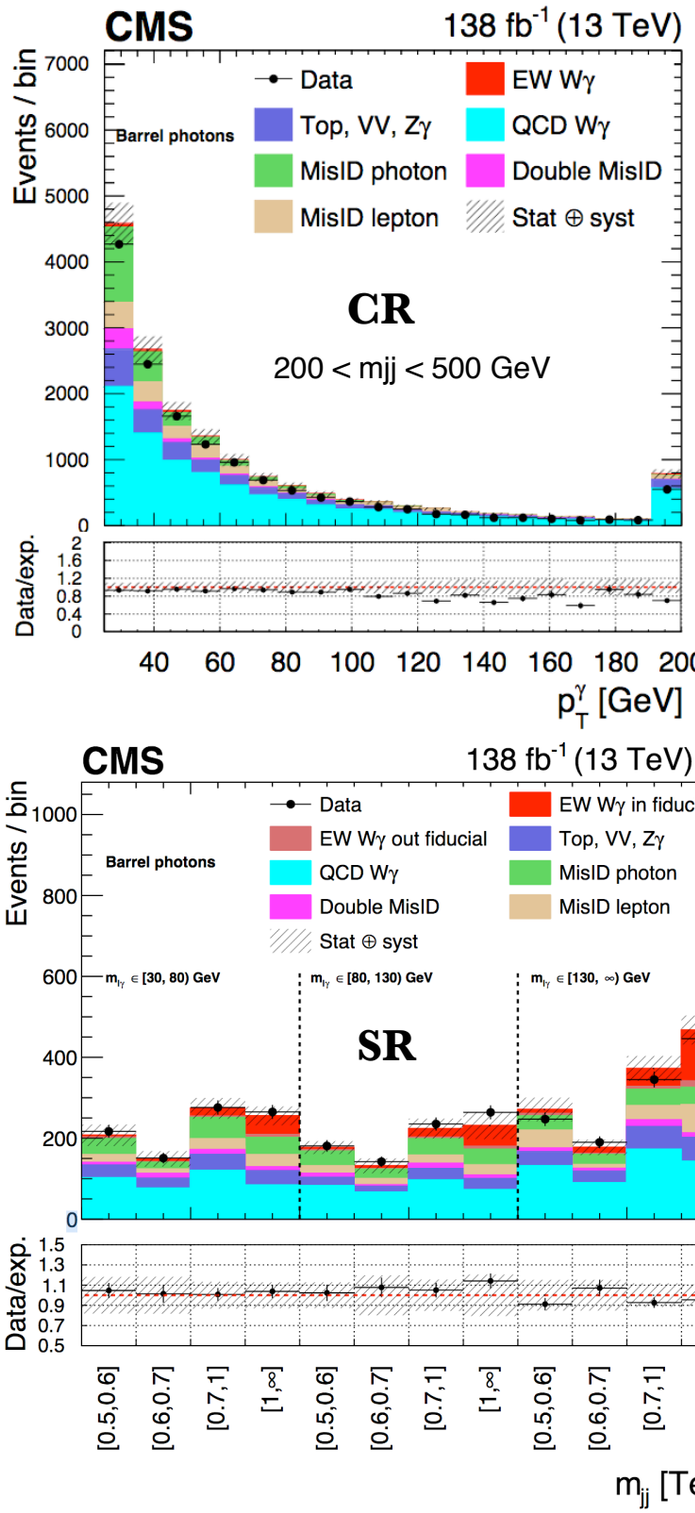
Electroweak production of Wγ with two jets : Event Selection

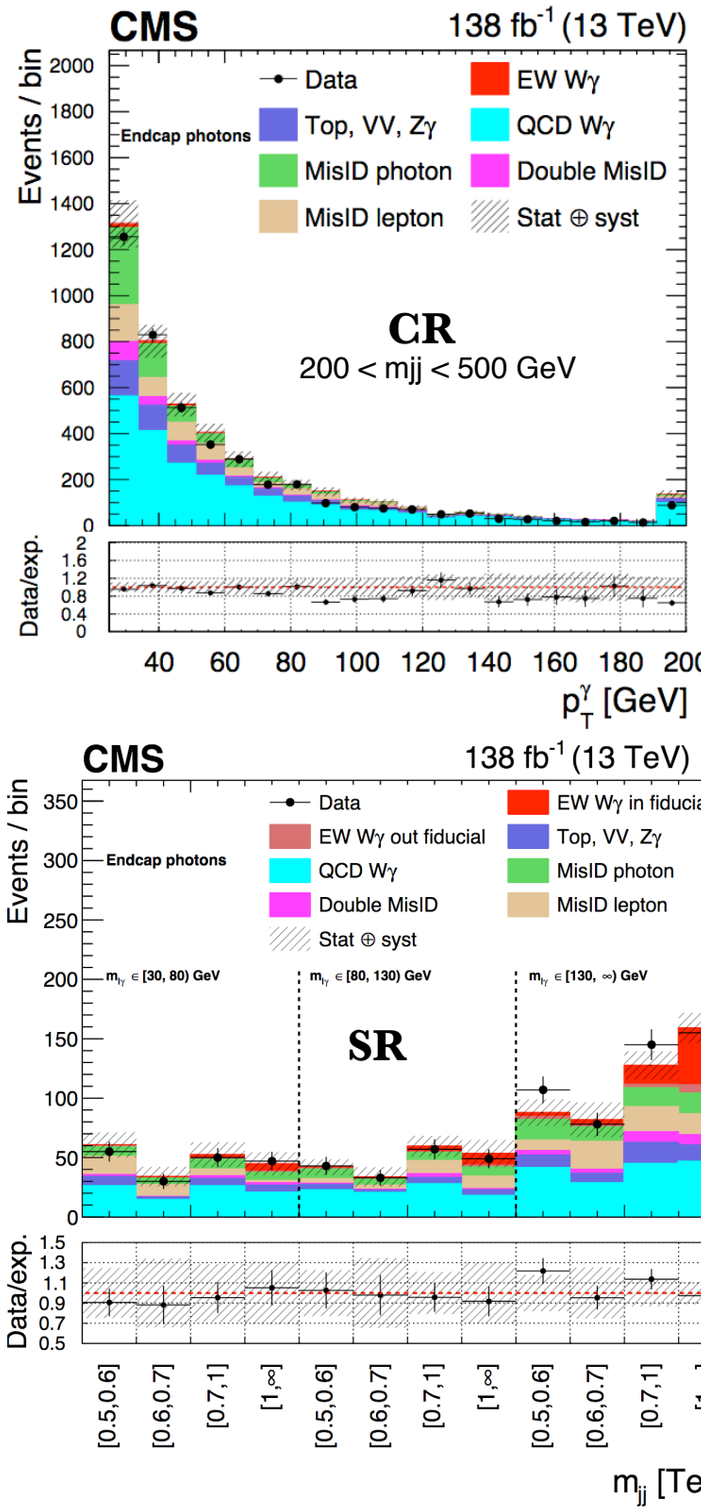
- Final State: Events with leptonic W decay (e/μ + p_T^{miss}), photon and two jets

- Background
  - QCD $W(\ell\nu)\gamma$
  - MisID photon/leptons
    - W+jets and top quark processes where the jet constituents are misidentified
    - Data driven estimation
  - Other background (top quark, diboson and Zγ) estimated from MC simulation

- Separated into barrel and endcap to account for differences in photon performance

- Fit performed in
  - 2D distribution of m_{jj} and $m_{\ell\nu}$





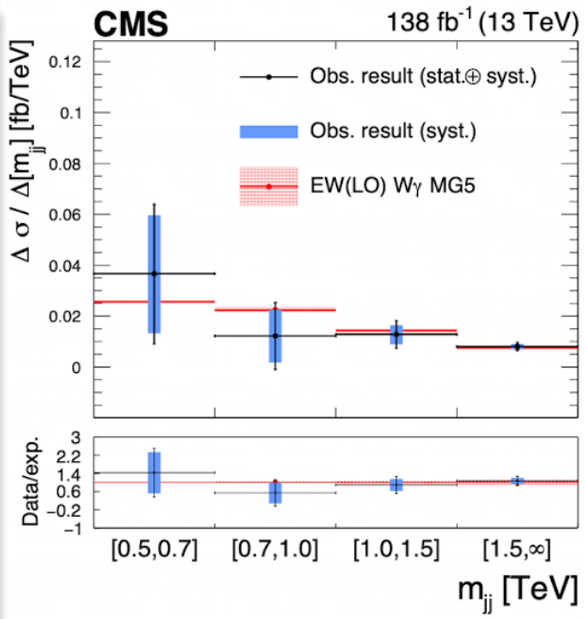
Electroweak production of Wγ with two jets : Results

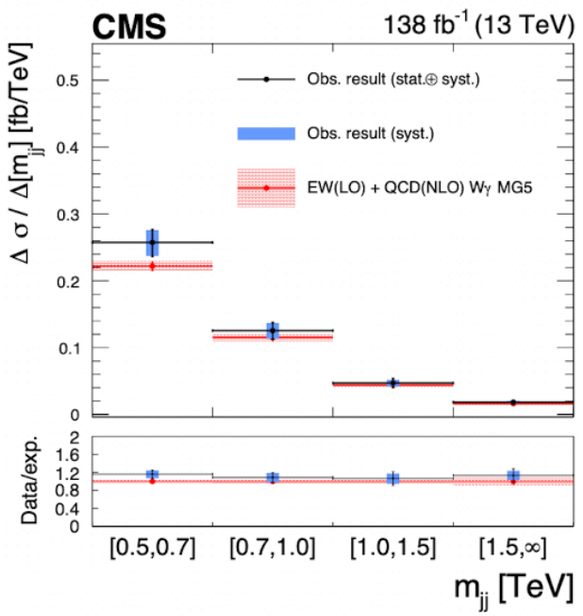
- **Observed (expected) significance: 6.0σ (6.79σ)**
- **Measurement of EWK-only and EWK+QCD**
  - **fiducial cross-section**

$$\sigma_{\mathrm{EW}}^{\mathrm{fid}} = 23.5 \pm 2.8\,(\mathrm{stat})^{+1.9}_{-1.7}\,(\mathrm{theo})^{+3.5}_{-3.4}\,(\mathrm{syst})\,\mathrm{fb} = 23.5^{+4.9}_{-4.7}\,\mathrm{fb}.$$

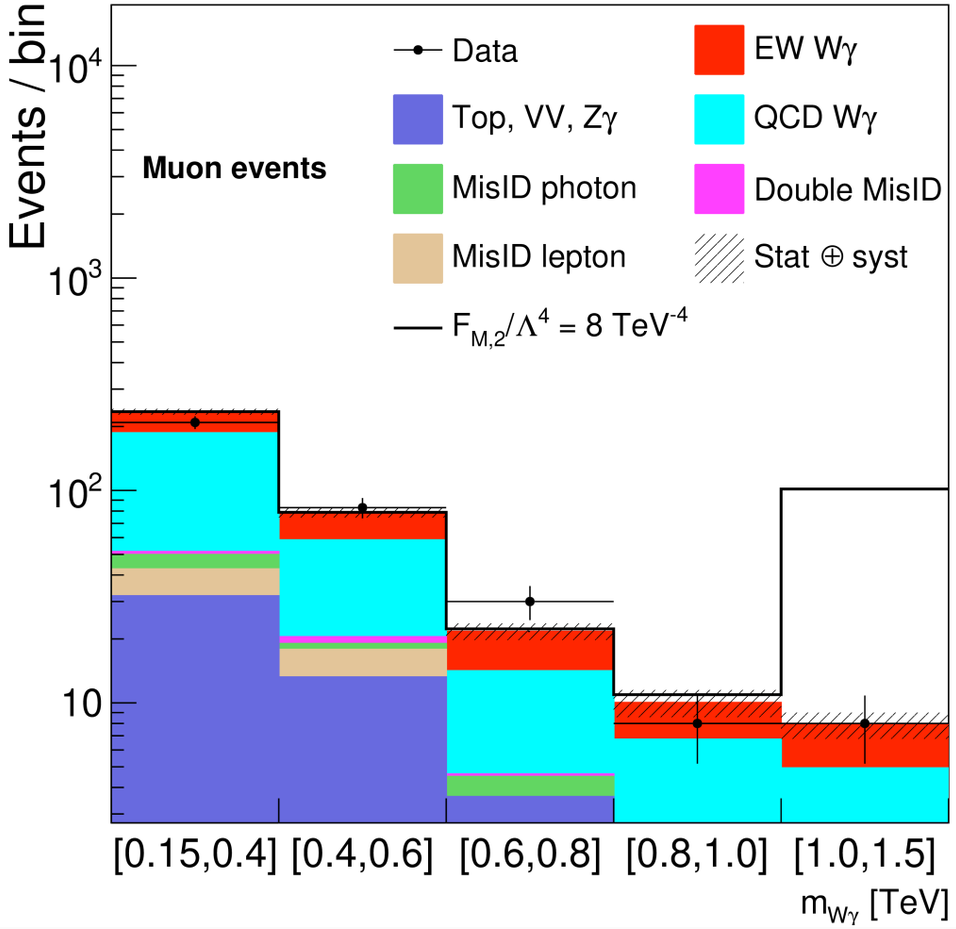
$$\sigma_{\mathrm{EW+QCD}}^{\mathrm{fid}} = 113 \pm 2.0\,(\mathrm{stat})^{+2.5}_{-2.3}\,(\mathrm{theo})^{+13}_{-13}\,(\mathrm{syst})\,\mathrm{fb} = 113 \pm 13\,\mathrm{fb}.$$

    - **consistent with SM predictions**
  - **differential cross-sections in several observables: $p_{T\gamma}$, p_{Tl}, p_{Tj1}, m_{jj}, $m_{l\gamma}$, $\Delta\eta_{jj}$**





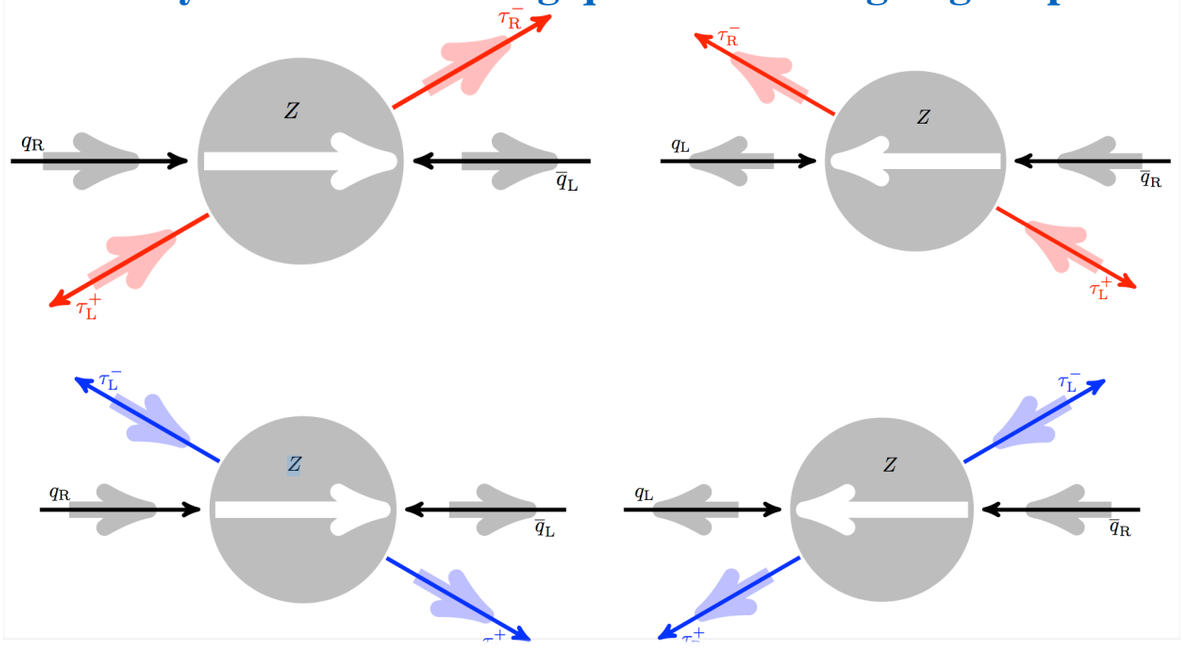
- Constraints placed on anomalous quartic gauge couplings
  - Dim-8 aQGC limits based on $M_{W\gamma}$ distribution
  - tightening selection: mjj >800 pTγ> 100 GeV
  - most stringent limits



τ lepton polarization in Z boson decays

CMS-PAS-SMP-18-010

- Precise measurement of SM input parameters is crucial to
  - identify any deviations
  - discover new physics
- Electroweak Mixing Angle $\sin^2\theta_W$
  - Key (free) parameter in Electroweak sector of the SM
- Objective :
  - Measure average polarisation of τ leptons in Z/γ events



$$P\tau = (\sigma+ - \sigma-)/(\sigma+ + \sigma-)$$

σ are the cross sections of the production of the τ- with positive and negative helicity

- Convert polarisation into effective weak mixing angle $\sin^2\theta_W$ $P\tau \approx -2(1-4\sin^2\theta_W)$

- τ leptons decay rapidly inside the detector, polarization is measured
  - by analyzing the energy and direction of their decay products
    - angular or momenta distributions of the visible tau decaying leptonically or hadronically, with respect to the τ flight direction

τ lepton polarization in Z boson decays : Event Selection

- 11 combinations hadronic and leptonic τ decays measurement

- 11 templates of discriminants used to extract polarisation

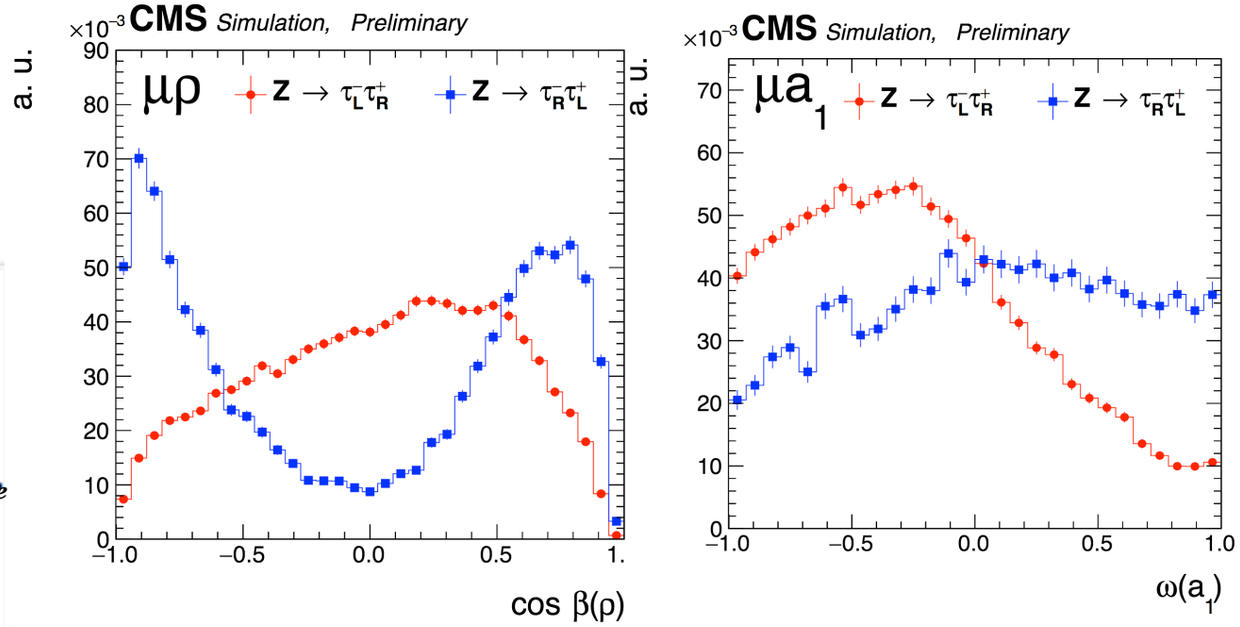
Channel	Category	Discriminator
$\tau_e\tau_\mu$	$e+\mu$	$m_{\text{vis}}(e,\mu)$
$\tau_e\tau_h$	$e+a_1$	$\omega(a_1)$
	$e+\rho$	$\omega_{\text{vis}}(\rho)$
	$e+\pi$	$\omega(\pi)$
$\tau_\mu\tau_h$	$\mu+a_1$	$\omega(a_1)$
	$\mu+\rho$	$\omega_{\text{vis}}(\rho)$
	$\mu+\pi$	$\omega(\pi)$
$\tau_h\tau_h$	a_1+a_1	$m_{\text{vis}}(a_1,a_1)$
	$a_1+\pi$	$\Omega(a_1,\pi)$
	$\rho+\tau_h$	$\omega_{\text{vis}}(\rho)$
	$\pi+\pi$	$m_{\text{vis}}(\pi,\pi)$

$m_{vis}(1,2)$ = visible mass

$\boldsymbol{\omega_{vis}(\rho)} = \cos\boldsymbol{\beta}$

$\omega(\pi), \omega(a_1) =$ ***Optimal obeservable***

$\boldsymbol{\Omega(a_1,\pi)} = \frac{\omega(\pi)+\omega(a_1)}{1+\omega(\pi)\omega(a_1)}$

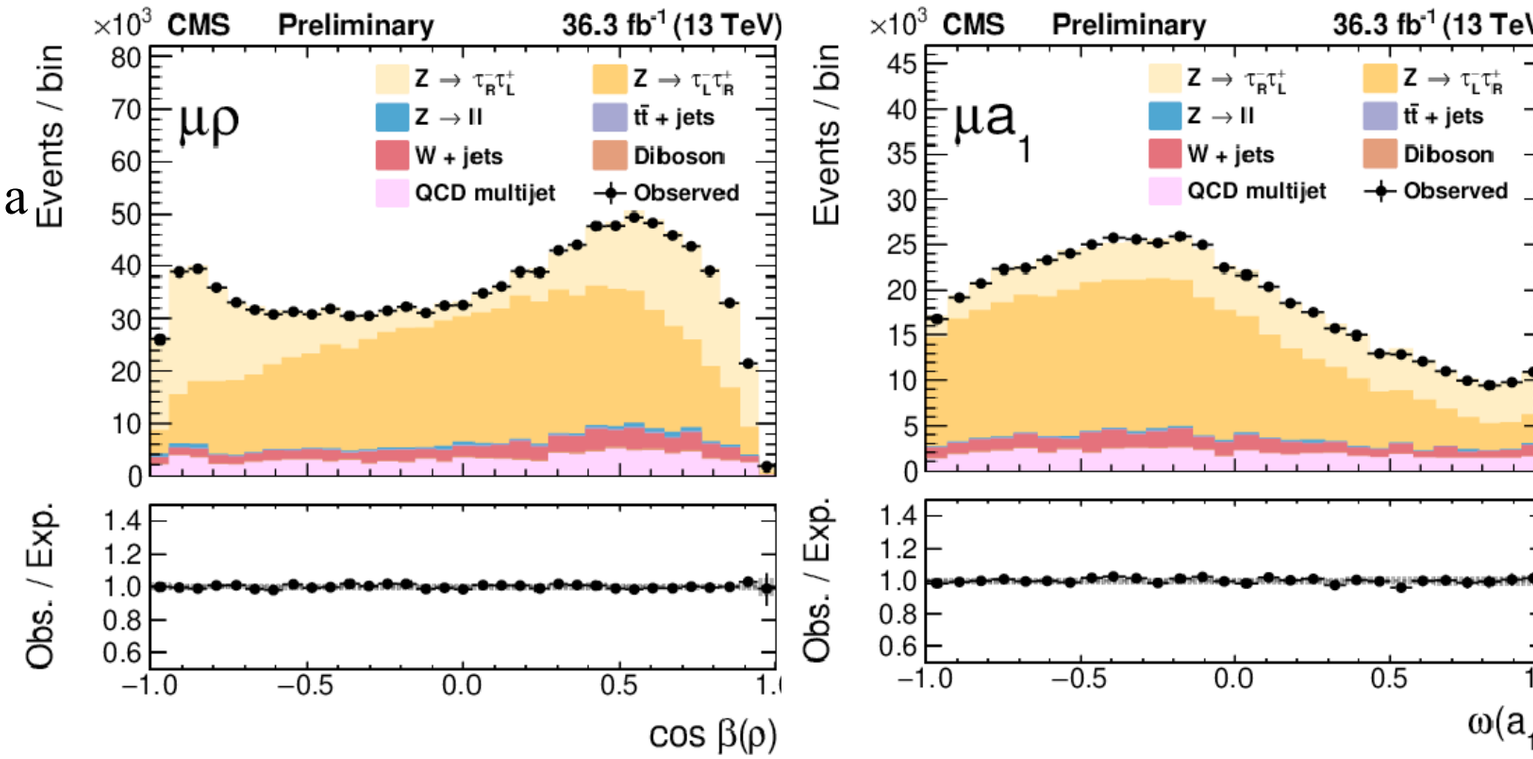


- The average polarisation $\langle P_\tau \rangle$ is obtained by a template fit to the observed optimal τ-polarisation observables

  - Global maximum-likelihood fit is performed

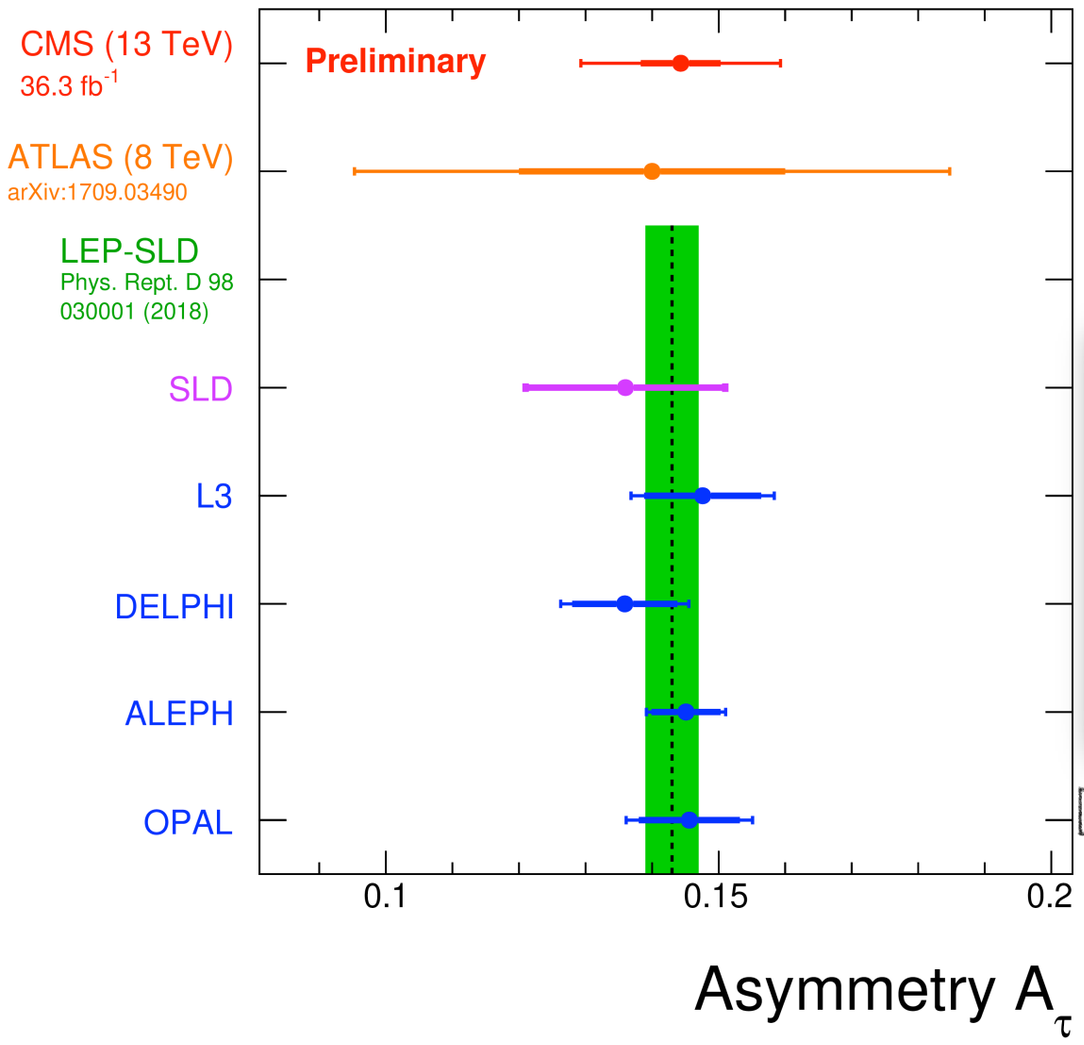
  - Unbaised procedure closure test using MC simulated events

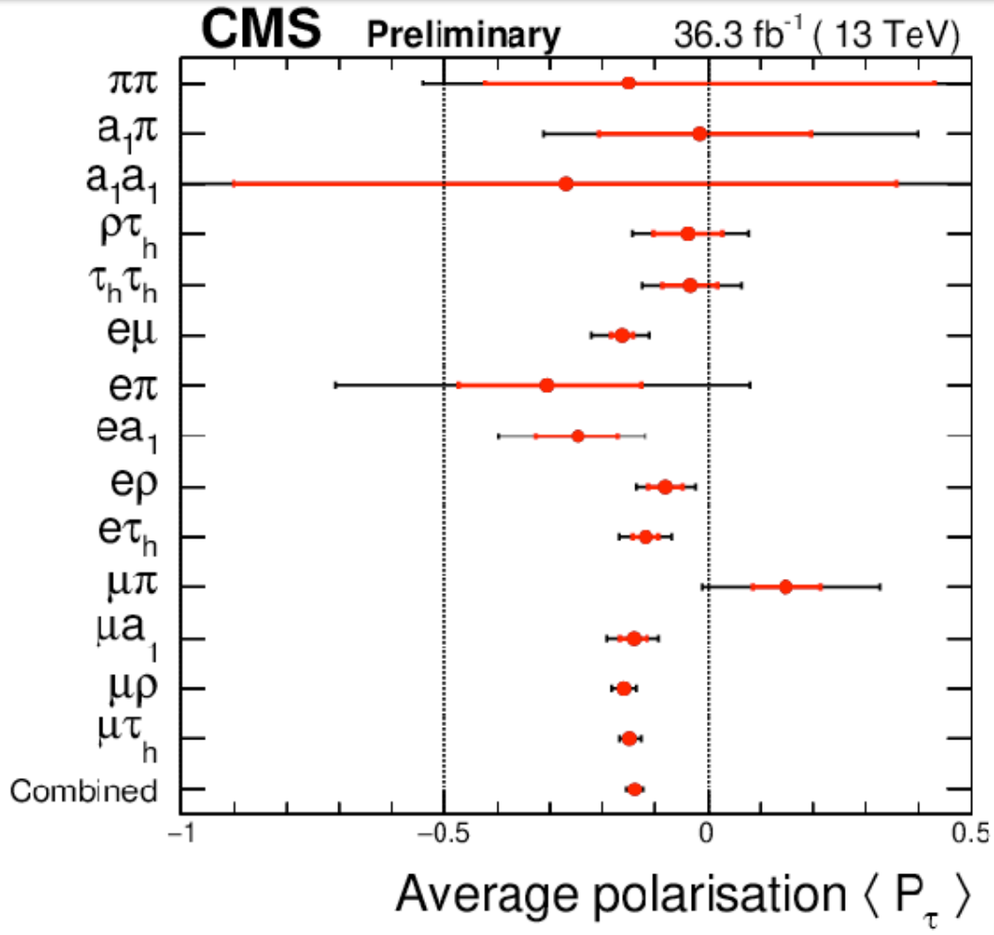
  - τ invariant mass in the range 75–120 GeV



τ lepton polarization in Z boson decays : Results

- best sensitivity : $\mu\tau_h$; Good selection efficiency and reconstruction of the spin observable
- $\tau_h\tau_h$: suffers from higher trigger thresholds, which lead to fewer events and distortions of the templates





Average τ polarisation is corrected to the value at the Z pole

$$\mathcal{P}_\tau(Z^0) = -0.144 \pm 0.015 = -0.144 \pm 0.006\,(\text{stat}) \pm 0.014\,(\text{syst})$$

The effective weak mixing angle

$$\sin^2\theta_W^{\text{eff}} = 0.2319 \pm 0.0019 = 0.2319 \pm 0.0008\,(\text{stat}) \pm 0.0018\,(\text{syst})$$

Precision of 0.8% and is independent of the production process of the Z boson.

- Harsh environment than LEP
- provide precise determinations of the polarisation of the τ lepton, and spin correlations between τ-lepton pairs

Summary

- Electroweak sector at CMS
  - allows for the testing and refinement of the Standard Model
  - search for new physics phenomena.
- The Run 2 data has enabled CMS to achieve an unparalleled level of precision in its measurements.
  - No deviation from the SM have been observed so far
  - Numerous new measurements are in pipeline with the full/partial Run 2 dataset
- Expanded the possibilities for measuring differential cross-sections and rare electroweak phenomena
  - EWK VBS or rare diboson processes have been observed/established

Stay tuned for a continuation of results from CMS during Run 2, as well as initial findings from Run 3 !!