Recent results on VBF and VBS measurements

29 November 2022

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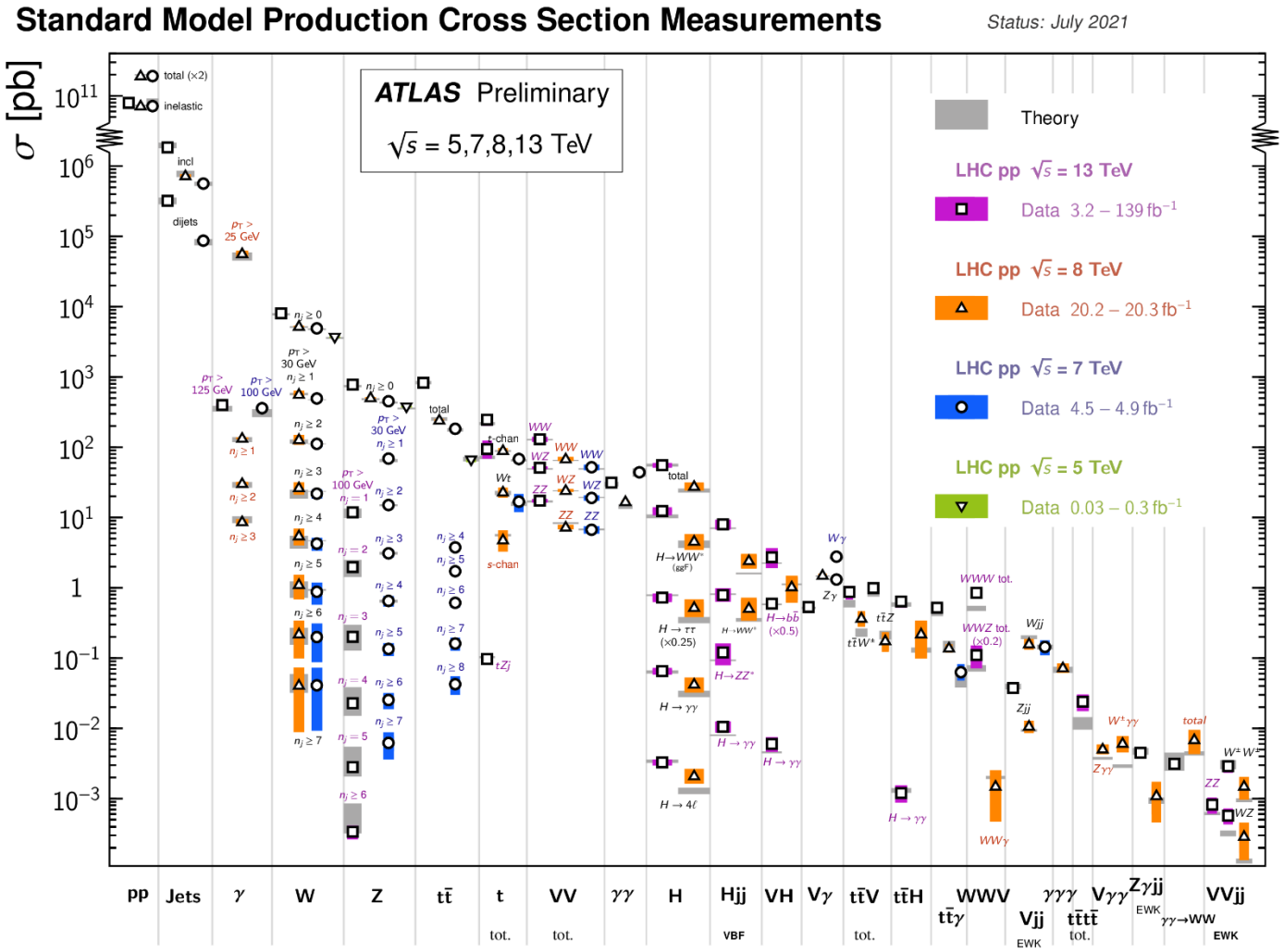
On behalf of the ATLAS and CMS Collaborations

Motivation for VBF/VBS Measurements

Since LHC is a QCD machine, electroweak (EWK) production cross-sections are the smallest measured processes



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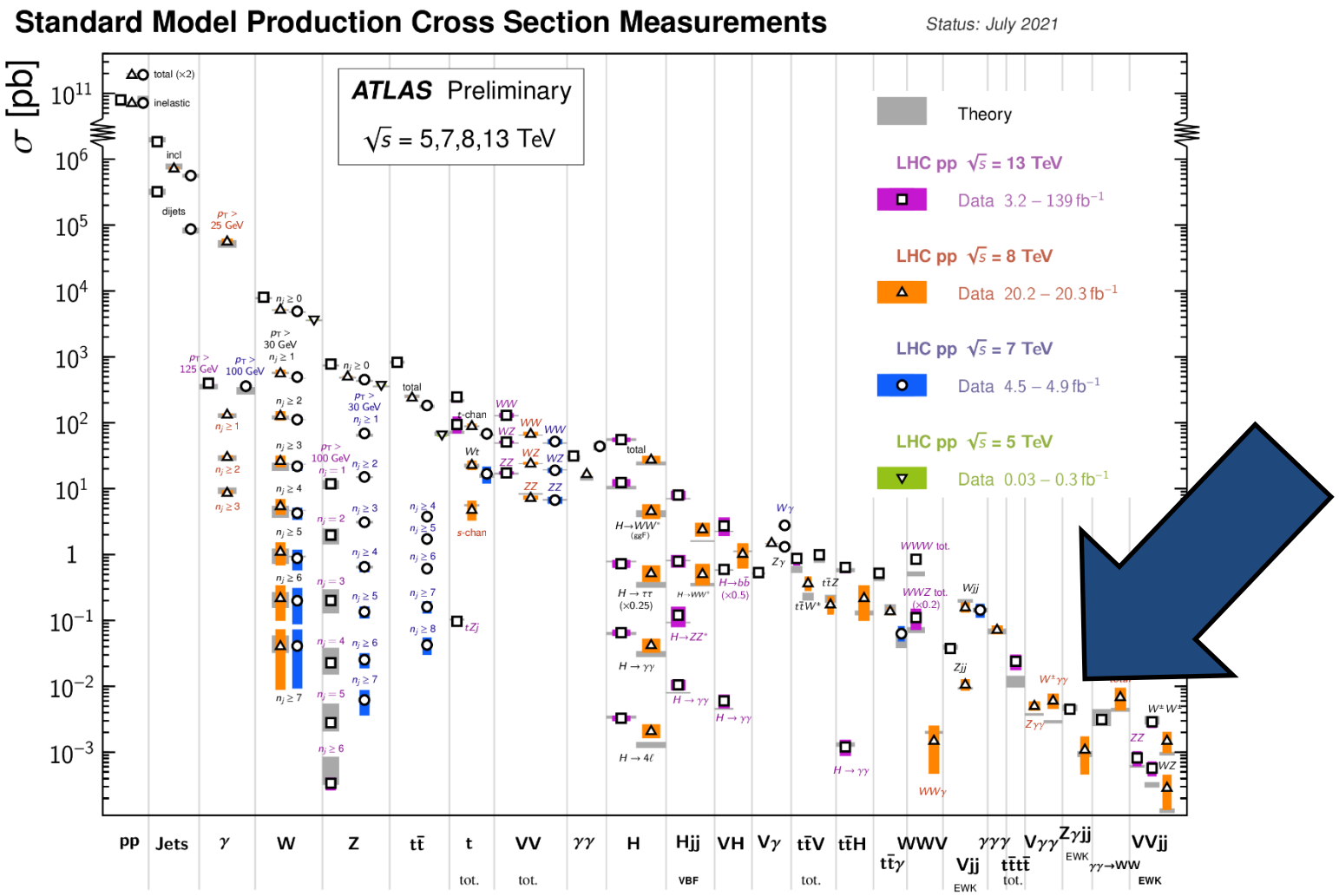
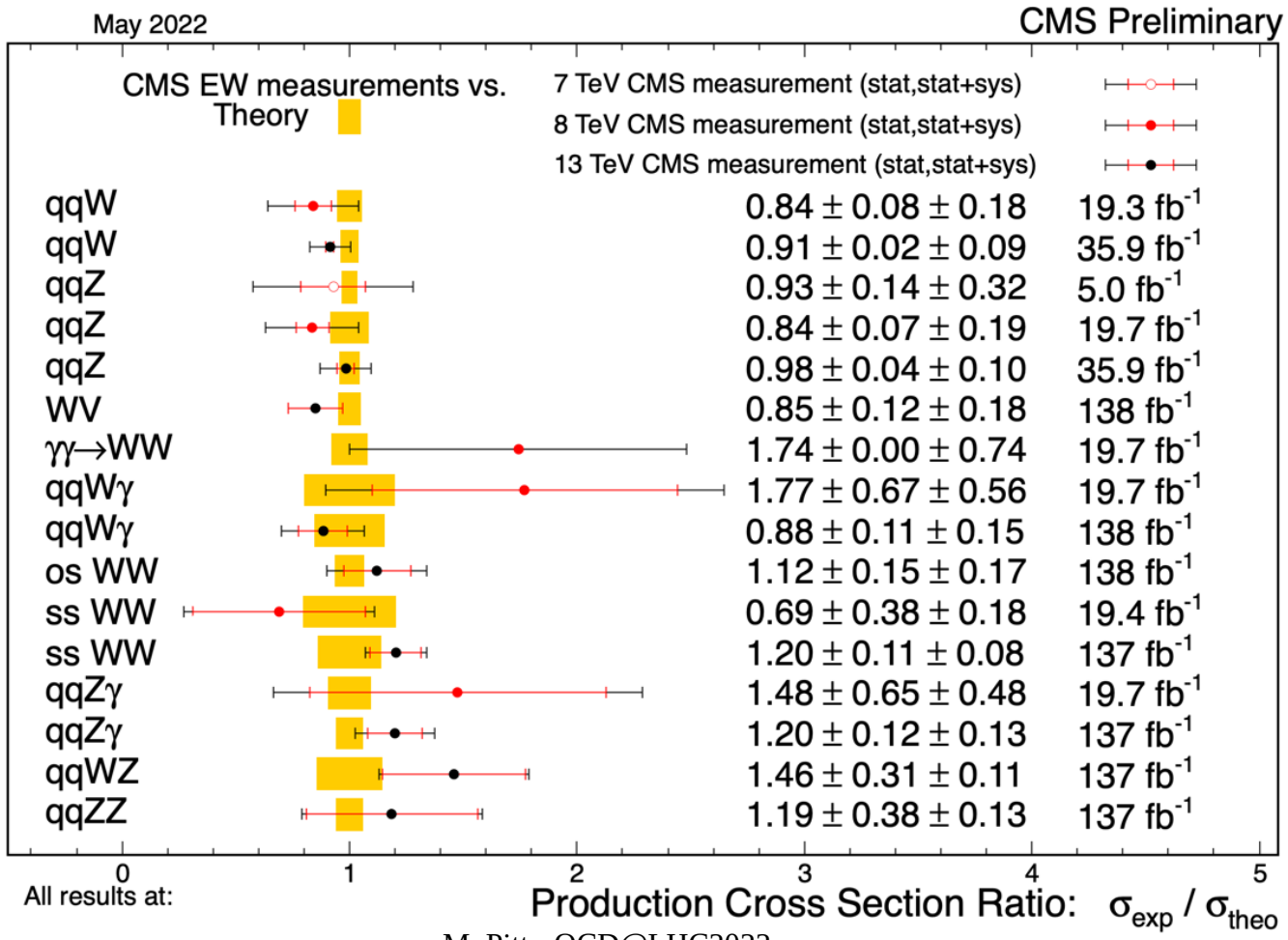


Motivation for VBF/VBS Measurements

Experimental uncertainties are much larger the theoretical
EW sector can serve as a portal to discoveries in the near future

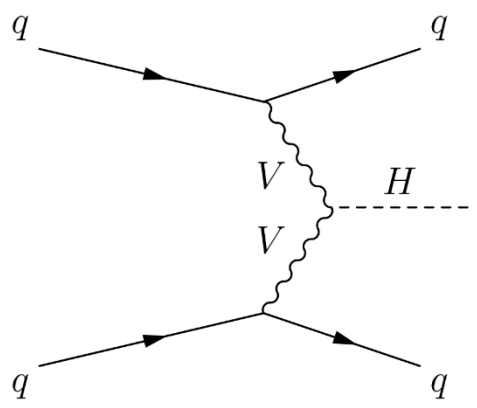


Standard Model processes – constrains on particle properties and gauge couplings

HVV coupling with VBF (2208.02338)
EWK Zγ+jj (2208.12741)
EWK Wγ+jj (SMP-21-011)
Exclusive WW/ZZ (2211.16320)
Exclusive γγ (CMS-PAS-EXO-21-007)

HVV coupling with VBF

2208.02338, Submitted to PRL

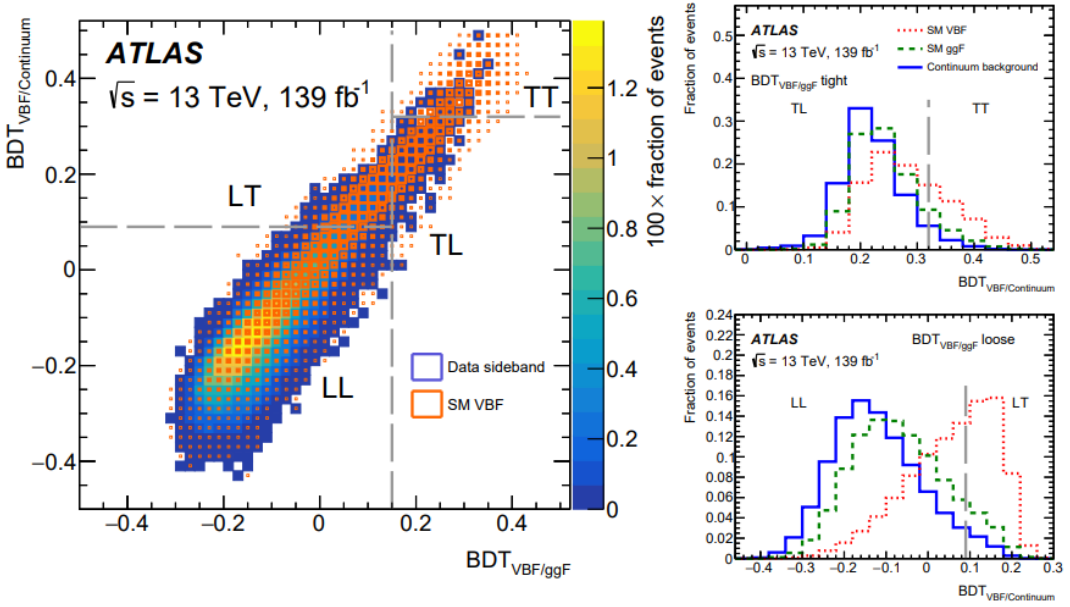


https://atlas.cern/glossary/vector-boson-fusion

- Probe of the CP structure of HVV interactions
- SM Lagrangian augmented with CP-odd dim-6 operators involving Higgs and EW gauge fields in EFT formalism

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2 \cdot c_i \cdot \mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}} \mathcal{M}_{\text{CP-odd}}) + c_i^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2.$$

- H→γγ channel was studied, and the results were combined with 36 fb^{-1} H→ττ (PLB 805 2020 135426)
- Analysis used BDT-based event categorization

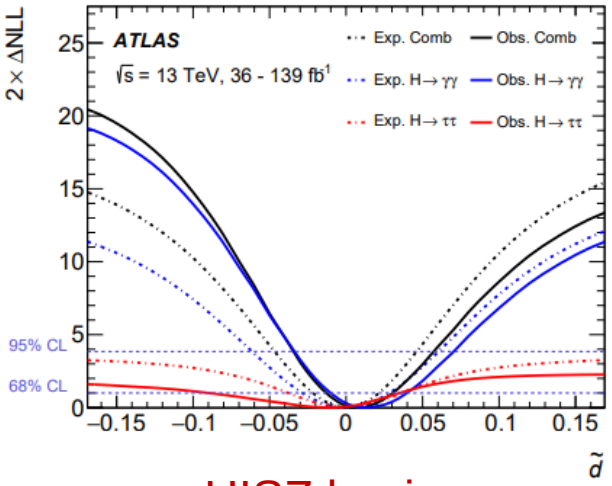


HVV coupling with VBF

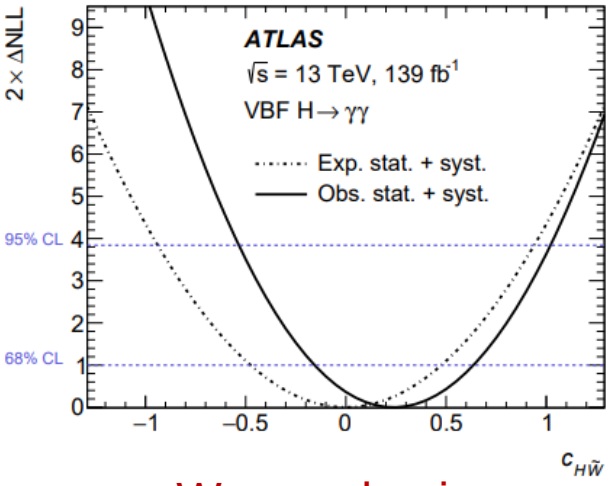
2208.02338,
Submitted to PRL

- Optimal Observable method used to probe the CP structure of interactions:

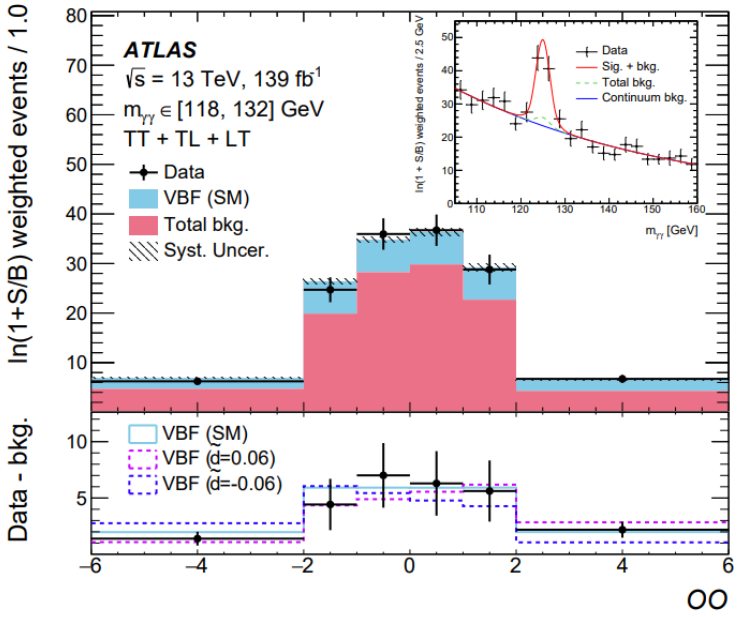
$$OO = 2 \cdot Re\left(\mathcal{M}_{SM}^{*} \cdot \mathcal{M}_{cp-odd}\right)/|\mathcal{M}_{SM}|^{2}$$



HISZ basis



Warsaw basis



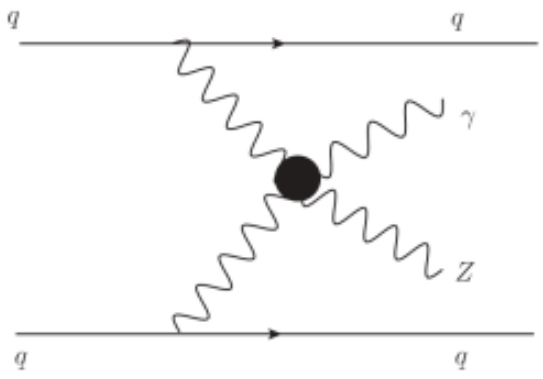
	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

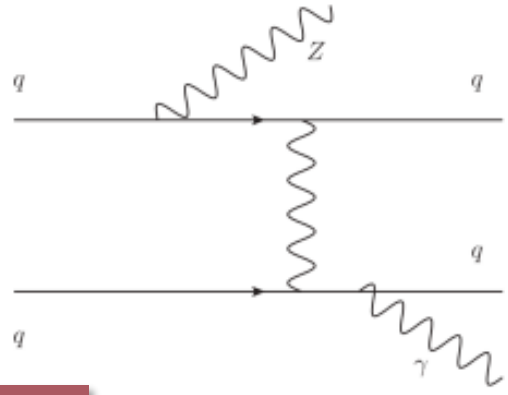
The most stringent constraints on CP-properties of HVV coupling to date

EWK Zγ+jj

STDM-2018-59,
Submitted to JHEP

- Electro-Weak production of Zγ, in $Z \rightarrow \nu\nu$ decay mode
- Produced via WW scattering and characterized by two forward jets
- High p_T^γ region serves as an important probe of the QGC
- First Observation of EWK $Z(\nu\nu)\gamma$+2j at 5.2σ was reported by ATLAS collaboration (*EPJC 82 (2022) 105*) with $p_T^\gamma \in [60,115]$ more details later
- Early measurements of EWK $Z(\ell\ell)\gamma$+2 reported last year by ATLAS (ATLAS-CONF-2021-038) and CMS (PRD 104 (2021) 072001) collaborations, with measured σ_{fid} of 4.49 ± 0.58 fb and 5.21 ± 0.76 fb respectively



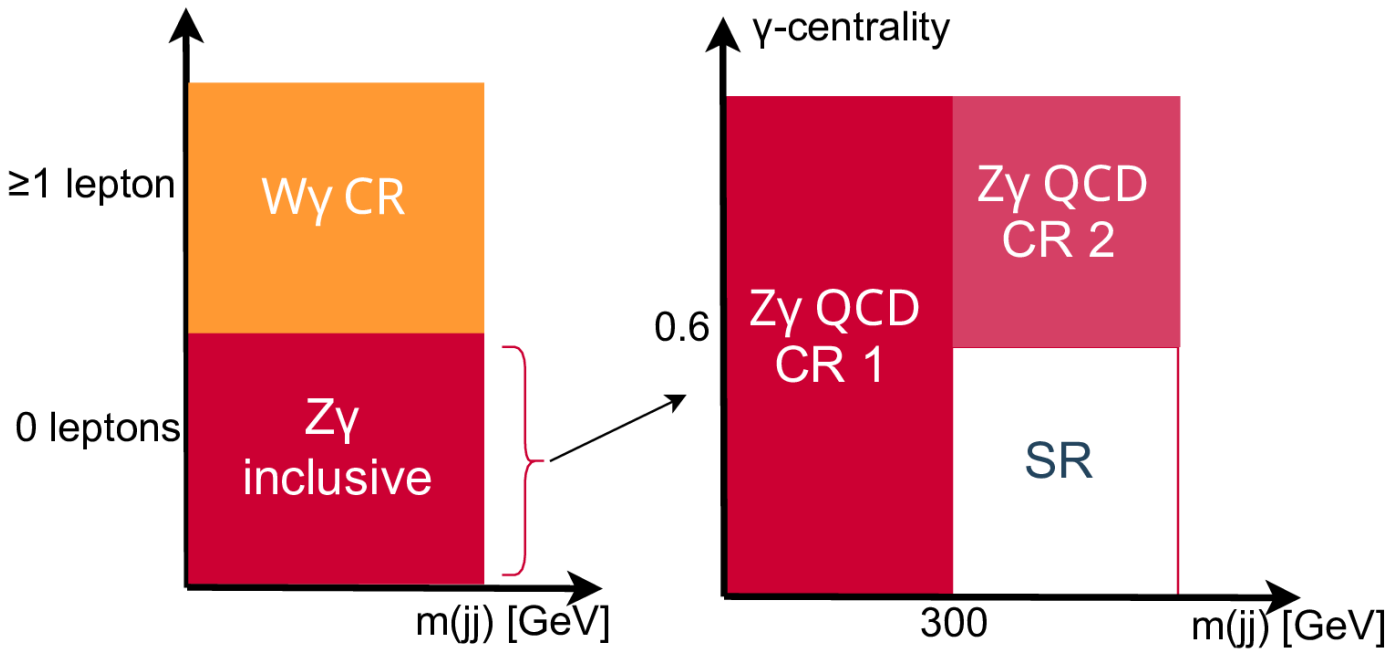


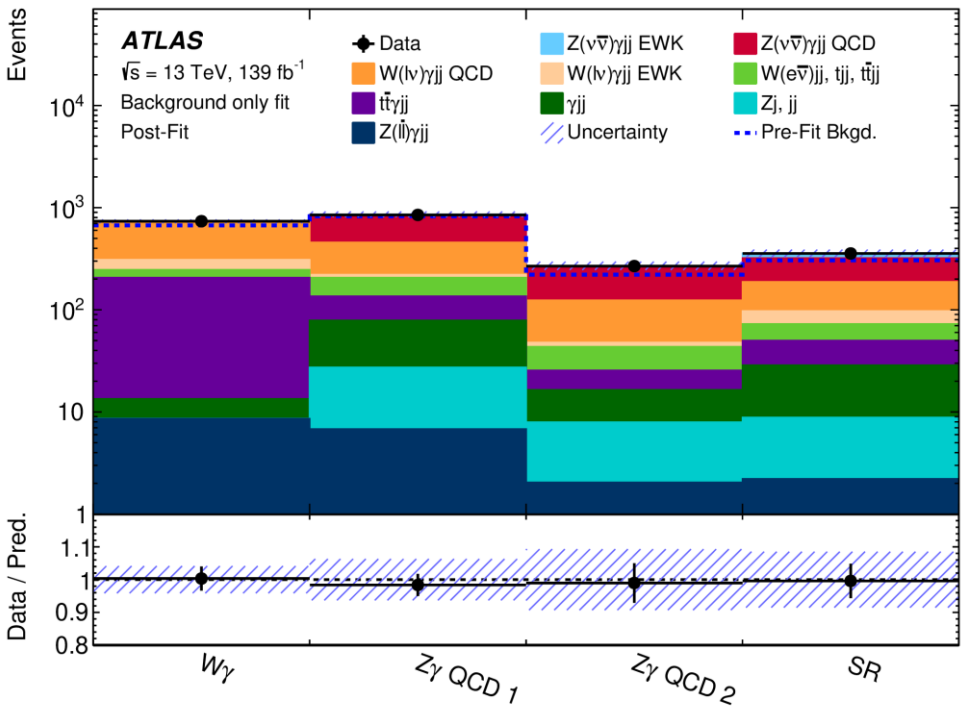
Signature: highly energetic photon, high MET and two jets

STDM-2018-59, Submitted to JHEP

Backgrounds:

- Main backgrounds: **QCD $Z(\nu\nu)\gamma$+2j (36%)** and **QCD $W(\ell\nu)\gamma$+2j (25%)**



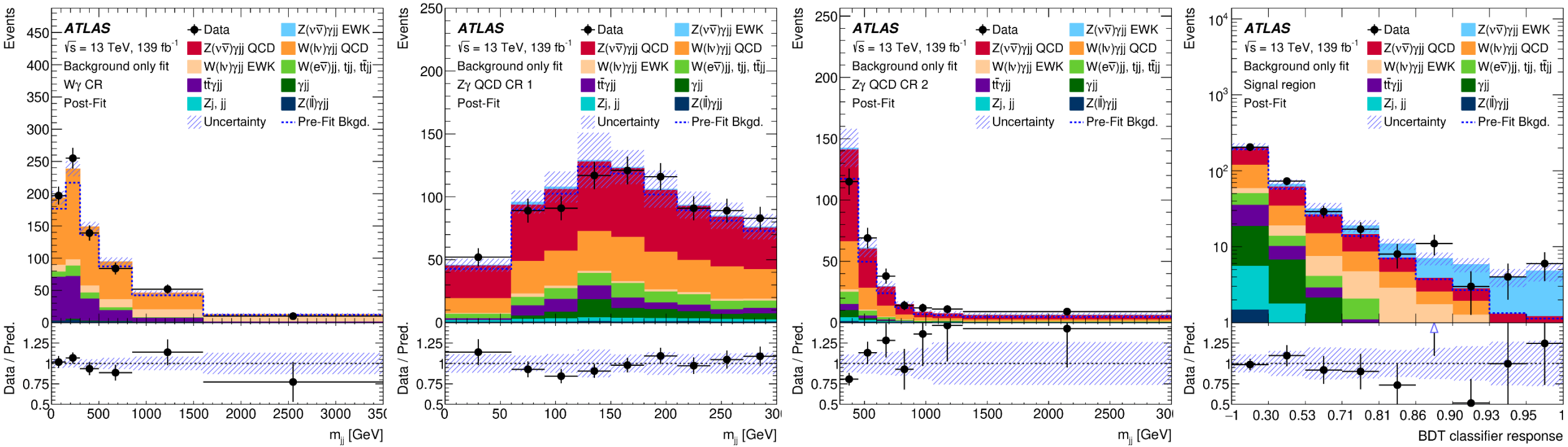


EWK Zγ+jj

STDM-2018-59,
Submitted to JHEP

Validation:

- Fitted distributions in the Wγ CR, Wγ CR and the SR

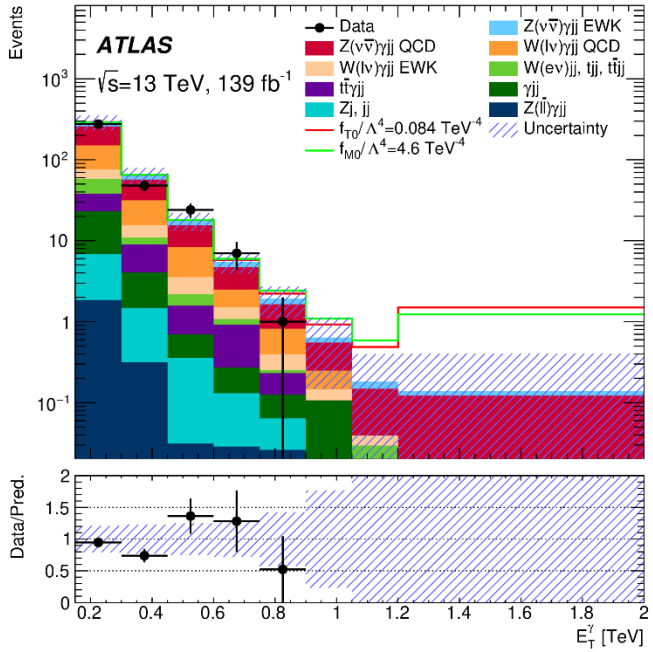


EWK Zγ+jj

STDM-2018-59,
Submitted to JHEP

Results:

- Observed (expected) significance: 3.2 σ (3.7σ)
- Fiducial cross-section: $0.77^{+0.34}_{-0.30}$ fb
- Dim-8 aQGC limits are based on MET distribution, results with and w/o cut-off scale were extracted



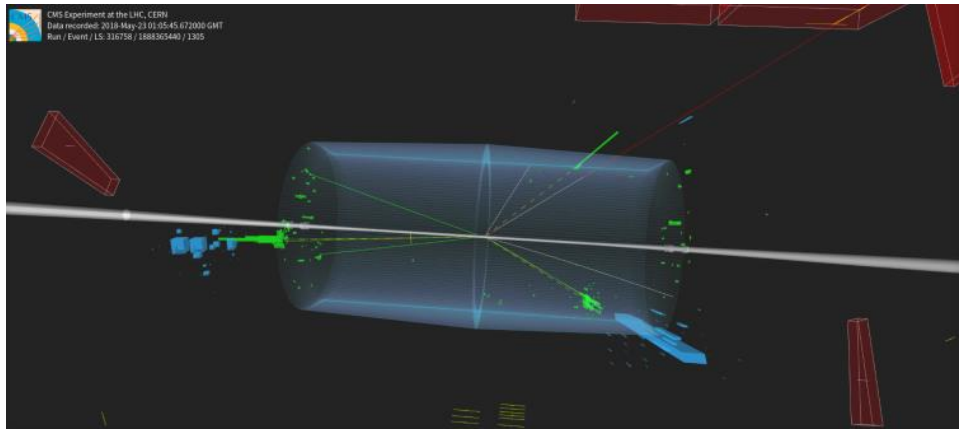
Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

Coefficient	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
f_{T5}/Λ^4	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
f_{T8}/Λ^4	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
f_{T9}/Λ^4	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
f_{M0}/Λ^4	$[-4.6, 4.6]$	$[-6.2, 6.2]$
f_{M1}/Λ^4	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
f_{M2}/Λ^4	$[-1.9, 1.9]$	$[-2.6, 2.6]$

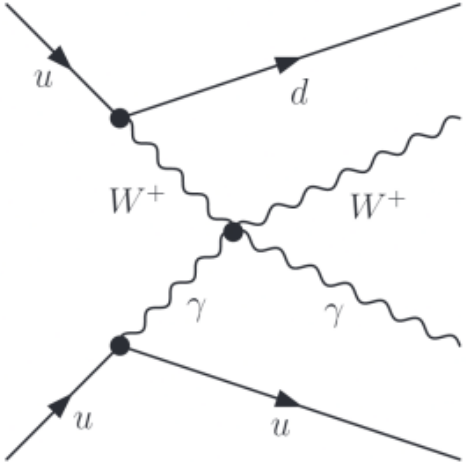
EWK Wγ+jj

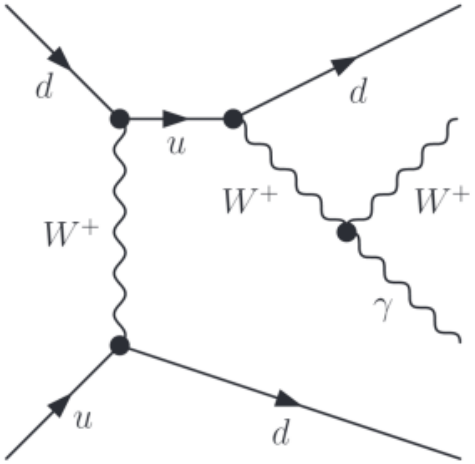
CMS-PAS-SMP-21-011

- Electro-Weak production of Wγ, in W → $\ell\nu$ decay mode
- Produced via Wγ scattering and characterized by two forward jets
- Extend the first observation paper, PLB 811 (2020) 135988, to full Run 2 dataset
- The first Observation of EWK $W\gamma$+2j at 5.3σ obs. RunI+20106EWK production is sensitive to TGC and QGC couplings
- Fiducial and differential cross-section measurement



https://cms.cern/news/lhc-w-photon-collider





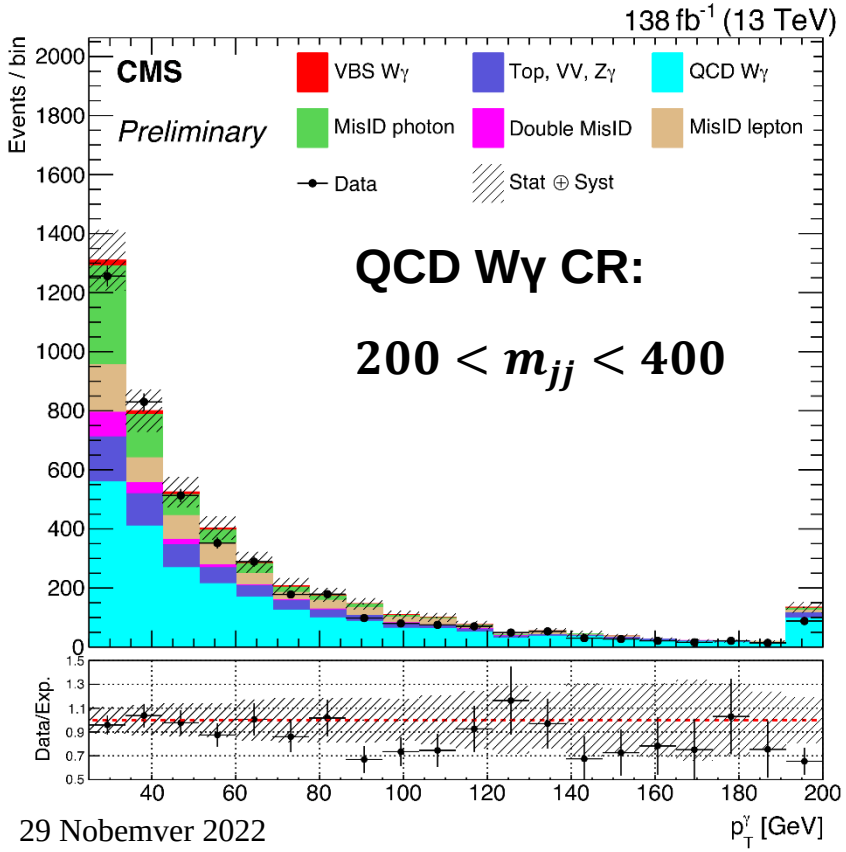
Signature: Isolated lepton, high $M_{W\gamma}$ and two jets

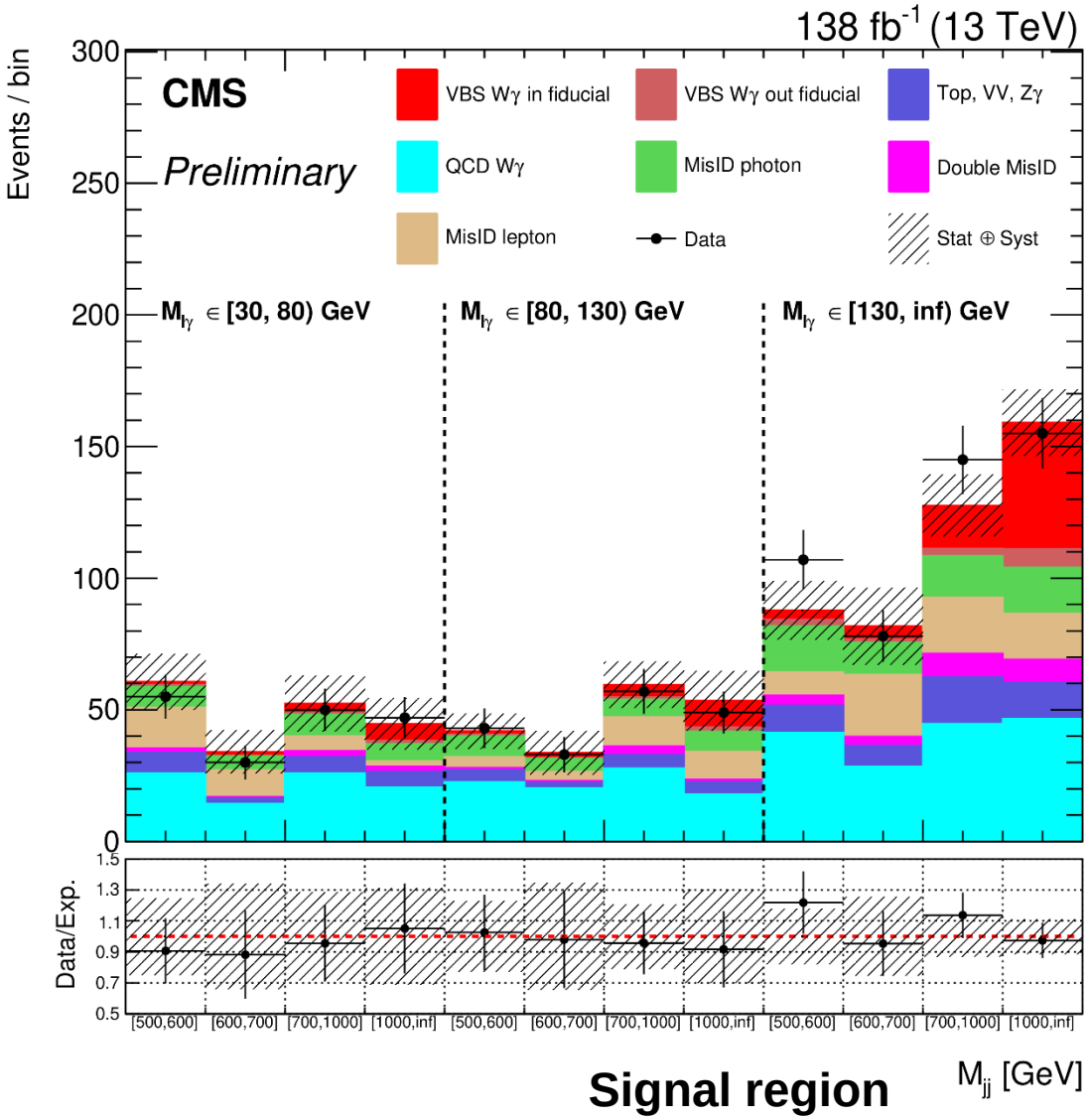
EWK Wγ+jj

CMS-PAS-SMP-21-011

Signal and Background:

- Main background **QCD $W(\ell\nu)\gamma$**
- Fit performed in 2D distribution of m_{jj} and $m_{\ell\nu}$





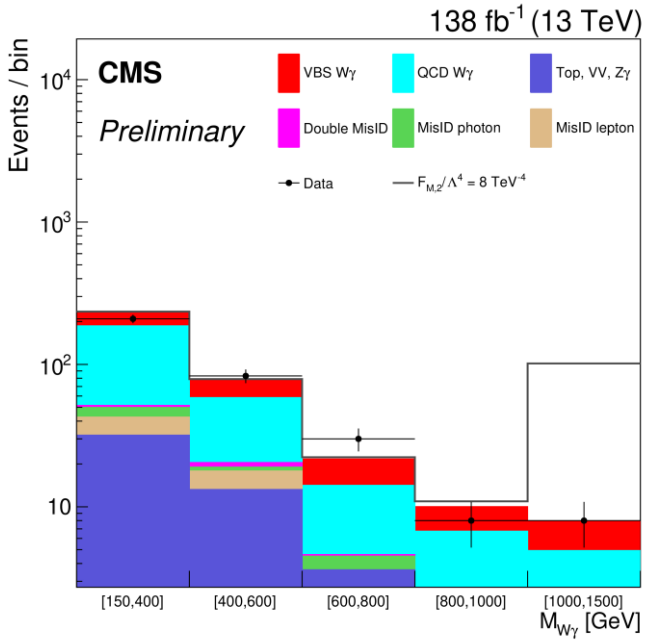
Signal region

EWK Wγ+jj

CMS-PAS-SMP-21-011

Results:

- Observed (expected) significance: 6.03 σ (6.79σ)
- Fiducial cross-section: $90.2^{+10.7}_{-10.3}$ fb, differential: see backup
- Dim-8 aQGC limits are based on $M_{W\gamma}$ distribution, tightening selection cuts: $m_{jj} > 800$ (SR=500), photon pT > 100 GeV (SR=25)



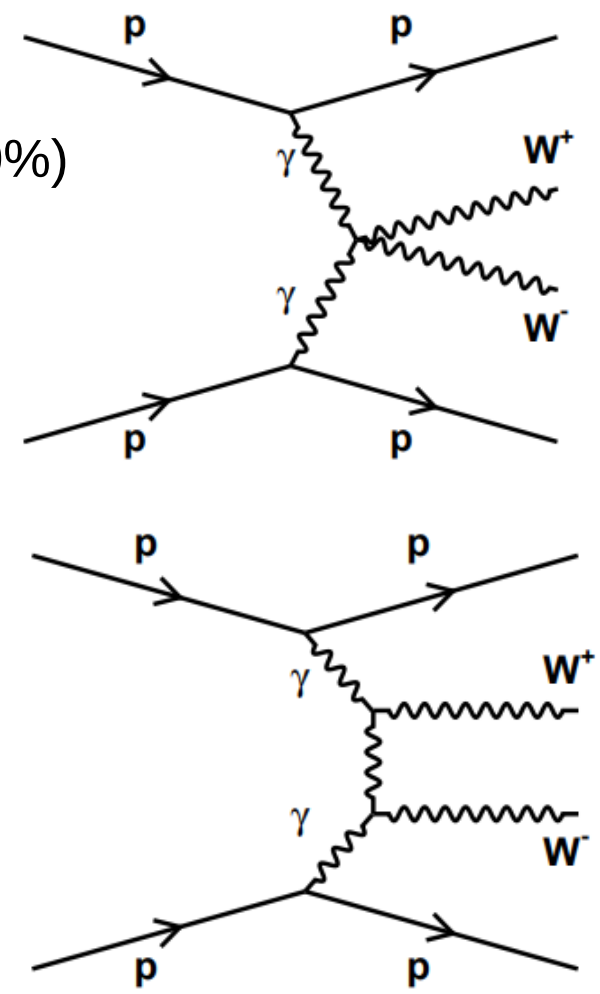
Expected. limit	Observed. limit	U_{bound}
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2

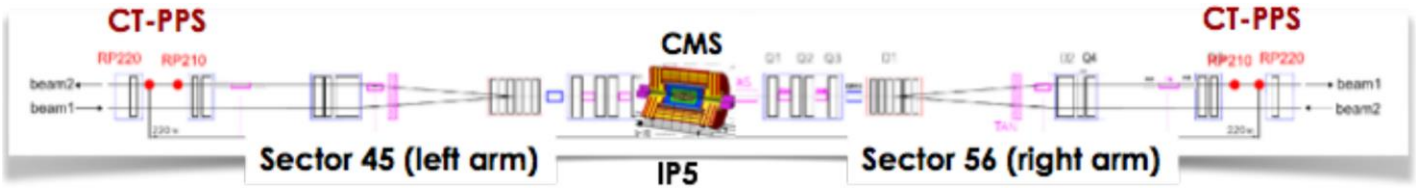
Expected. limit	Observed. limit	U_{bound}
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1

Exclusive WW/ZZ

2211.16320
Submitted to JHEP

- Electro-Weak production of WW/ZZ pairs, in fully hadronic decay mode
- Produced via γγ scattering and characterized by two forward protons using forward proton spectrometers (sensitive to proton momentum loss of 4%-20%)
- Sensitive to TGC and QGC, QGC enhance high mass spectra





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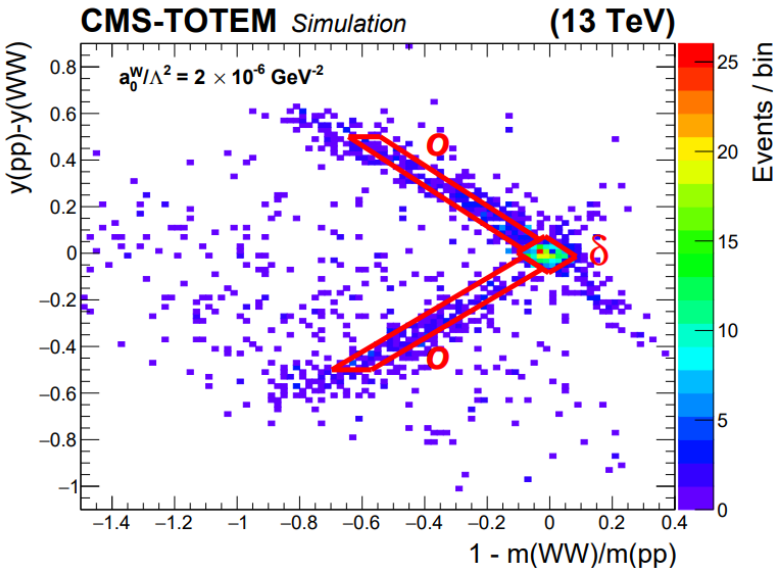
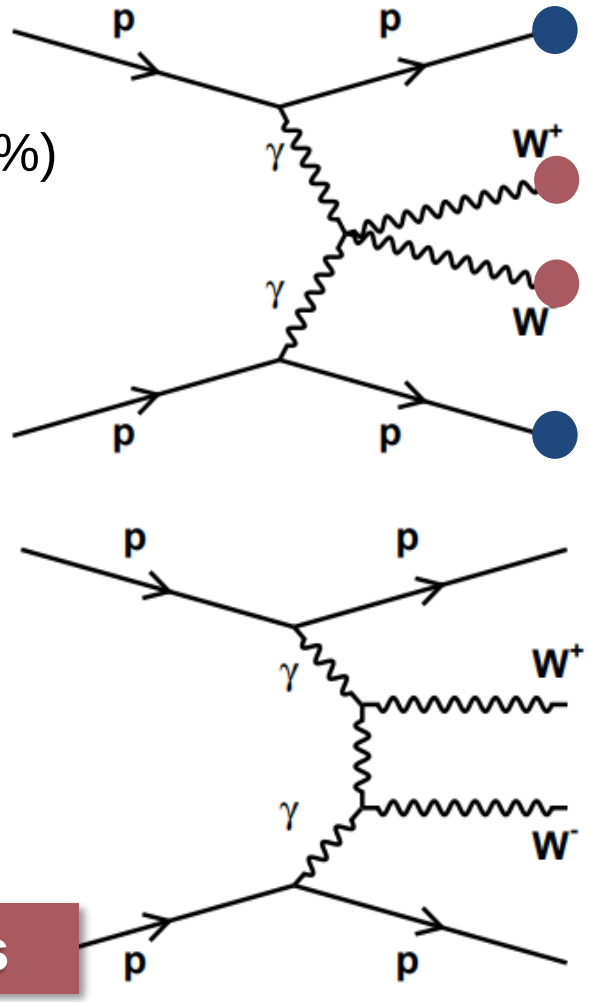
- In Central exclusive production:

Central system kinematics

=

Proton kinematics





Signature: Two V-tagged jets, two tagged forward protons

Exclusive WW/ZZ

2211.16320
Submitted to JHEP

Results:

- At high mass, SM cross-sections are very small
- The obtained limit on SM fiducial cross-section:

  $\boldsymbol{\sigma_{WW} < 67}$**fb and** $\boldsymbol{\sigma_{ZZ} < 43}$**fb** for $0.04 < \xi < 0.2$ and m_{VV}>1TeV
- Limits on EFT operators (clipping at 1.4 TeV)

Observed 95% CL upper limit
(No clipping)

$|a_0^W/\Lambda^2| < 4.3 \times 10^{-6}$ GeV^{-2}
$|a_C^W/\Lambda^2| < 1.6 \times 10^{-5}$ GeV^{-2}
$|a_0^Z/\Lambda^2| < 0.9 \times 10^{-5}$ GeV^{-2}
$|a_C^Z/\Lambda^2| < 4.0 \times 10^{-5}$ GeV^{-2}

Coupling	Observed (expected) 95% CL upper limit
$\lvert f_{M,0}/\Lambda^4\rvert$	66.0 (60.0) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4\rvert$	245.5 (214.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4\rvert$	9.8 (9.0) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4\rvert$	73.0 (64.6) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	36.0 (32.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4\rvert$	67.0 (58.9) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4\rvert$	490.9 (429.6) TeV^{-4}

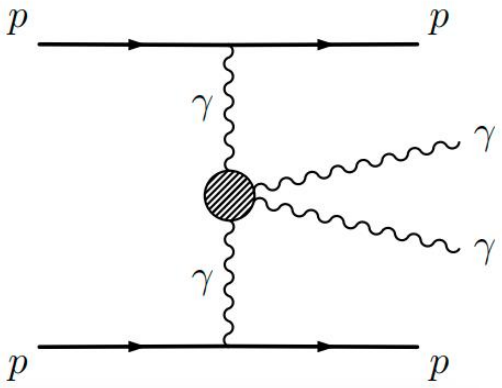
Coupling	Observed (expected) 95% CL upper limit	Clipping
$\lvert f_{M,0}/\Lambda^4\rvert$	79.8 (78.2) TeV^{-4}	1.4 TeV
$\lvert f_{M,1}/\Lambda^4\rvert$	306.8 (306.8) TeV^{-4}	1.4 TeV
$\lvert f_{M,2}/\Lambda^4\rvert$	11.9 (11.8) TeV^{-4}	1.4 TeV
$\lvert f_{M,3}/\Lambda^4\rvert$	91.3 (92.3) TeV^{-4}	1.4 TeV
$\lvert f_{M,4}/\Lambda^4\rvert$	43.5 (42.9) TeV^{-4}	1.4 TeV
$\lvert f_{M,5}/\Lambda^4\rvert$	83.7 (84.1) TeV^{-4}	1.4 TeV
$\lvert f_{M,7}/\Lambda^4\rvert$	613.7 (613.7) TeV^{-4}	1.4 TeV

Exclusive γγ (LbyL scattering)

CMS-PAS-EXO-21-007

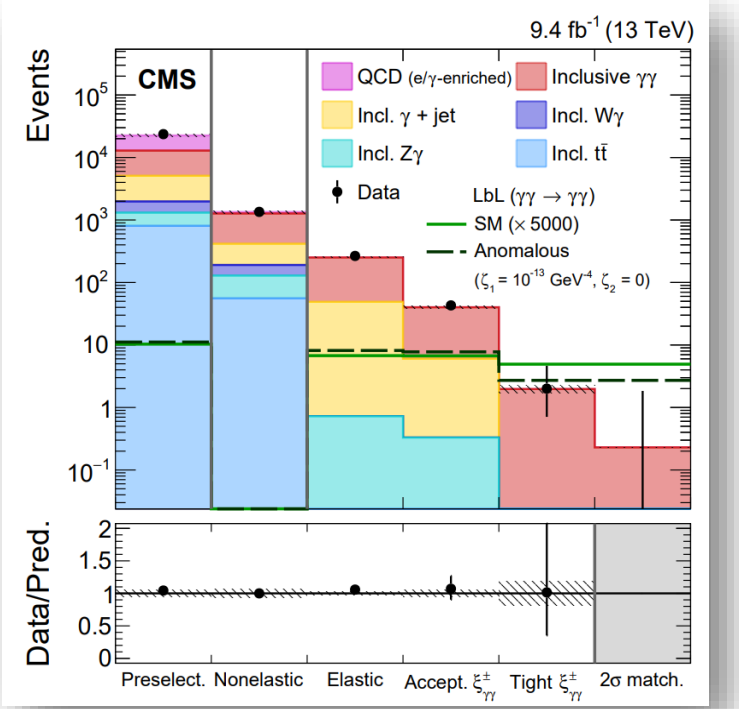
- Motivated by sensitivity to BSM

PRD 89 (2014) 114004, JHEP 1502 (2015) 165, *JHEP 1806 (2018) 131*



- Almost background free after requiring matching between proton and photon kinematics

- First measurement with 2016 (~10fb^{-1}) publish the first limit on 4-photon coupling, *PRL 129 (2022) 1, 011801*



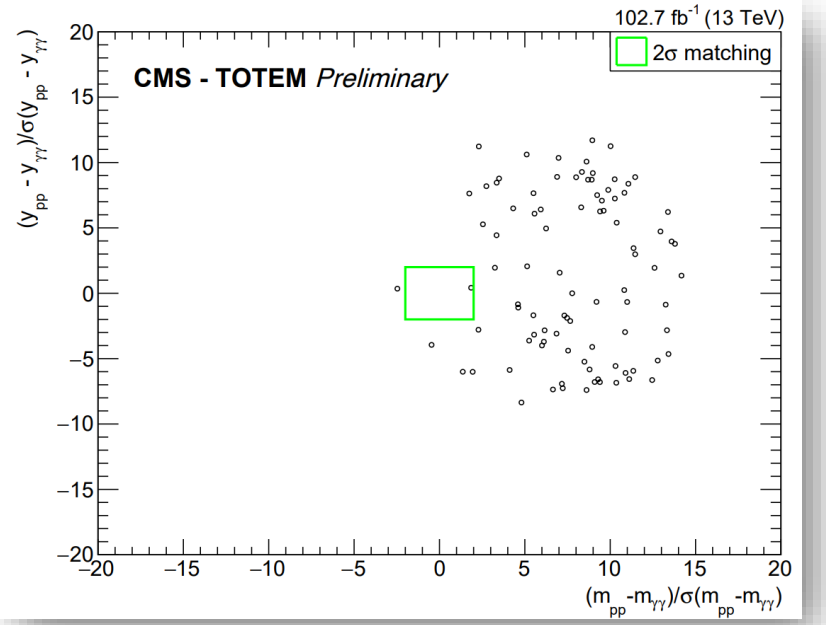
$$|\zeta_1| < 2.9 \times 10^{-13}\ \text{GeV}^{-4}\ (\zeta_2 = 0)$$
$$|\zeta_2| < 6.0 \times 10^{-13}\ \text{GeV}^{-4}\ (\zeta_1 = 0)$$

Exclusive γγ (LbyL scattering)

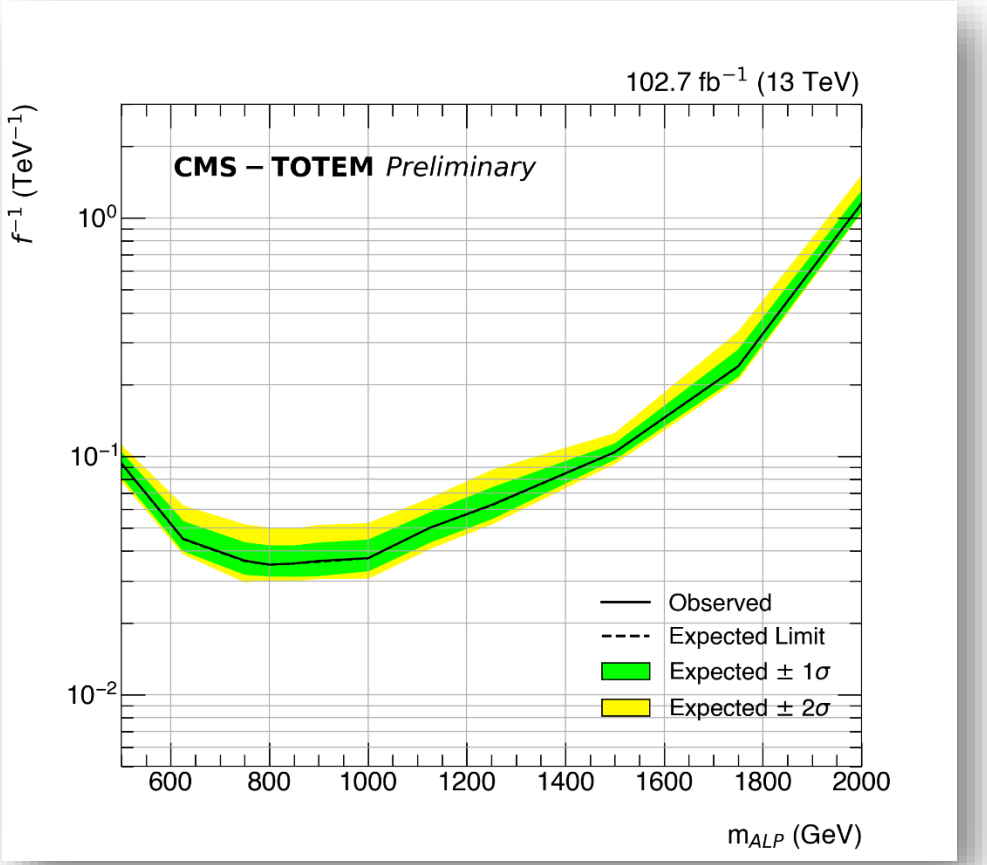
CMS-PAS-EXO-21-007

Results:

- The full Run 2 data – low background
- Limit on 4-photon coupling improved by x4(!)



$|\zeta_1| < 7.3 \times 10^{-14}$ GeV^{-4} $(\zeta_2 = 0)$
$|\zeta_2| < 1.5 \times 10^{-13}$ GeV^{-4} $(\zeta_1 = 0)$



First search for ALPs in mass range between 500 GeV to 2000 GeV

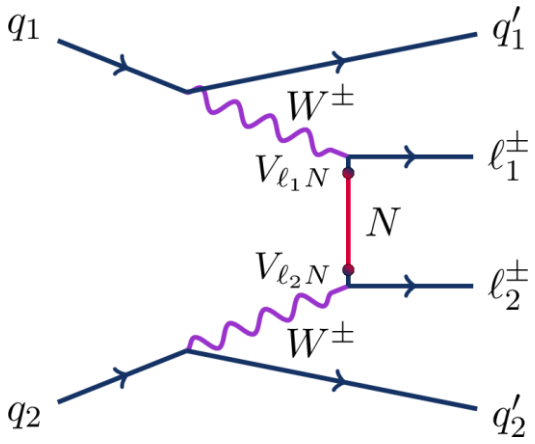
Searches Beyond the Standard Model using VBS / VBF production processes

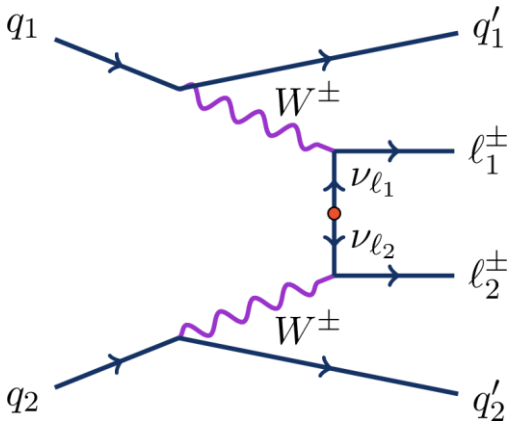
VBF Majorana neutrinos (2206.08956)
VBF H→Inv. (PRD 105 2022 092007, JHEP 08 2022 104)
EW MET+γ+jj (*EPJC 82 2022 105*)
Exclusive missing mass (CMS-PAS-EXO-21-007)

VBF Majorana neutrinos

arxiv:2206.08956
Submitted to PRL

- Many ways to explain $m_\nu \neq 0$: the neutrinos may be either Dirac or Majorana fermions (Majorana → Lepton Number Violation)
- Neutrinoless ββ-like process at colliders: VBF process $pp \to \ell\ell jj$
- Motivated by PRD.103.055005 (heavy neutrino) or PRD.103.115014
- Produced via WW scattering and characterized by two forward jets



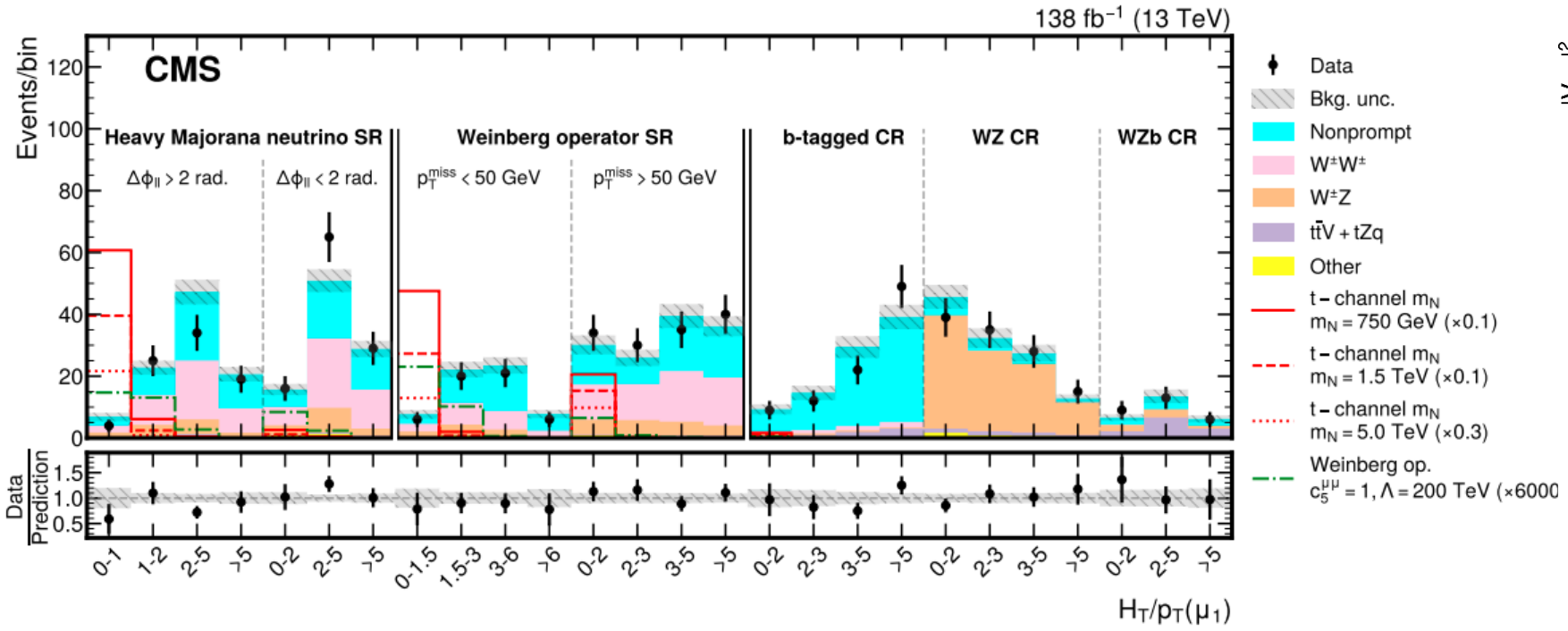


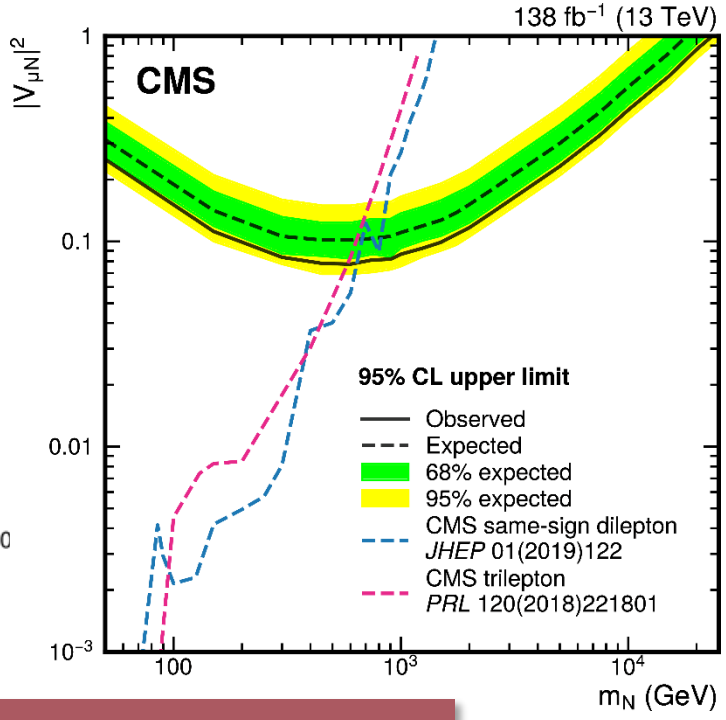
Signature: Two same-sign leptons, two VBF jets

VBF Majorana neutrinos

arxiv:2206.08956
Submitted to PRL

- Heavy Majorana neutrino and Weinberg operator analyses are defined in bins of $\Delta\varphi_{ll}$ and MET , respectively, apply VBF selection
- Discriminating variable: HT / leading lep pT





The most stringent constraints at the LHC to date for m > 650 GeV!!!

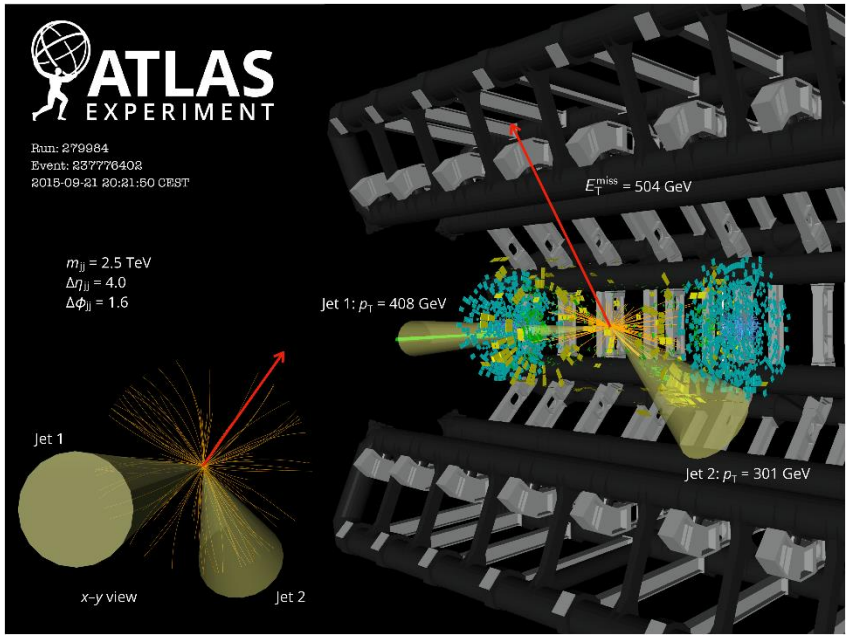
Higgs to invisible

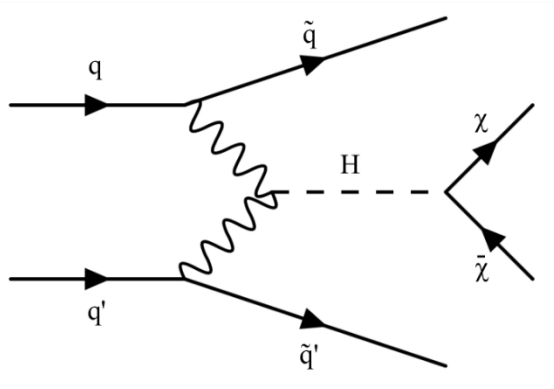
JHEP 08 2022 104
PRD 105 2022 092007

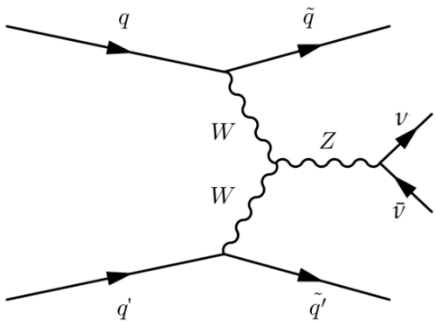
- Exploit VBF topology – events with a pair of jets with large angular separation on the η plane and large invariant mass
- Produced via WW scattering and characterized by two forward jets
- Backgrounds:

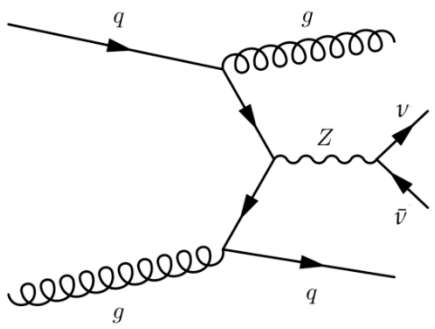
$Z \to \nu\nu$ (QCD and EWK), $W \to \ell\nu$ with lost lepton

Systematic strongly reduced exploiting 2ℓ and 1ℓ CRs







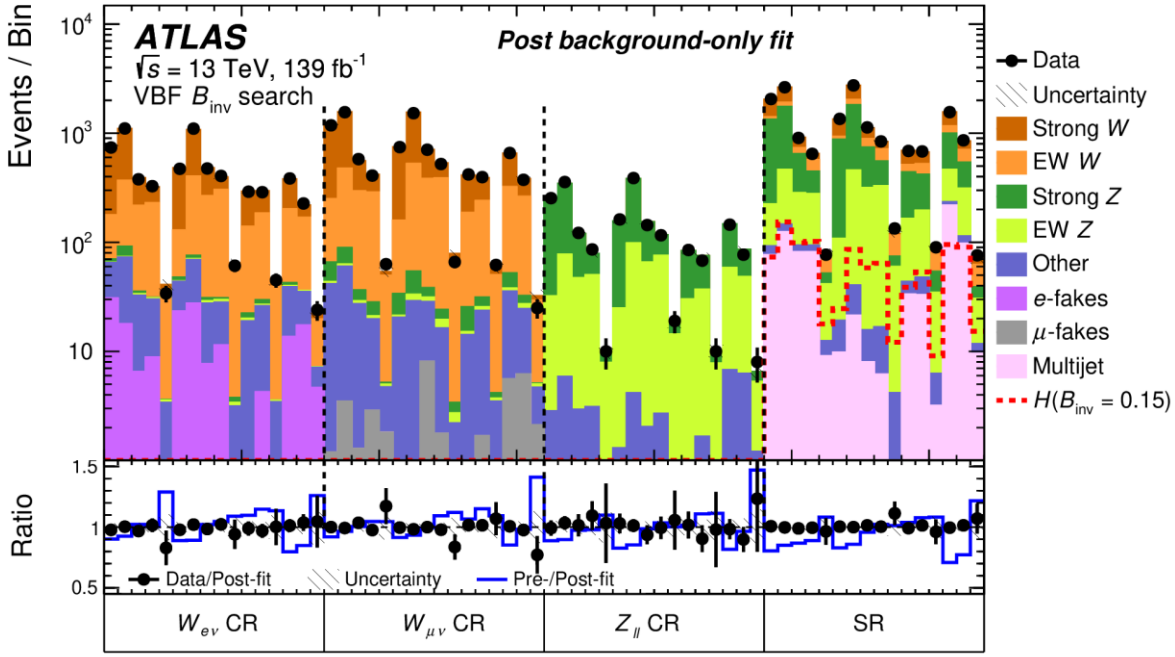


Higgs to invisible

JHEP 08 2022 104
PRD 105 2022 092007

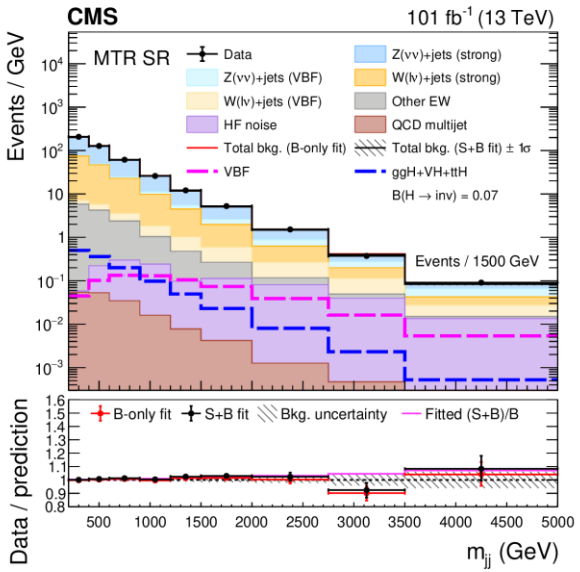
- Categorize event selection to 16 bins of MET, m_{jj}, $\Delta\varphi_{jj}$
- Results (observed):

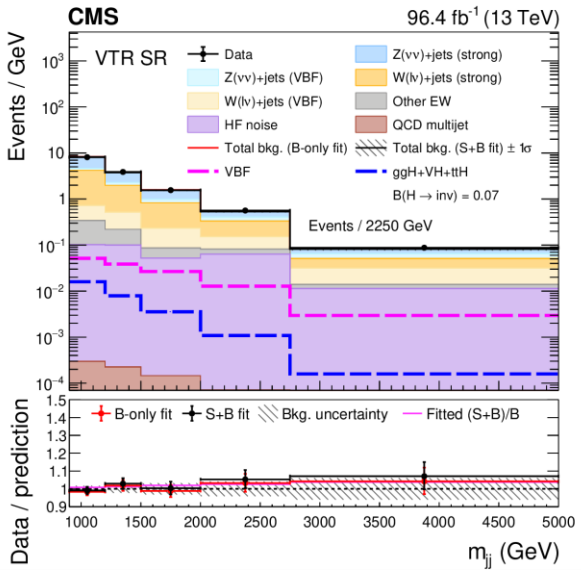
Upper limit of BR(H125→inv) = 0.145



- Categorize event selection to 2 regions: MET Triggered, VBF jet triggered
- Results (observed):

Upper limit of BR(H125→inv) = 0.18





Higgs to invisible

JHEP 08 2022 104
PRD 105 2022 092007

- Categorize event selection to 16 bins of MET, m_{jj}, $\Delta\varphi_{jj}$
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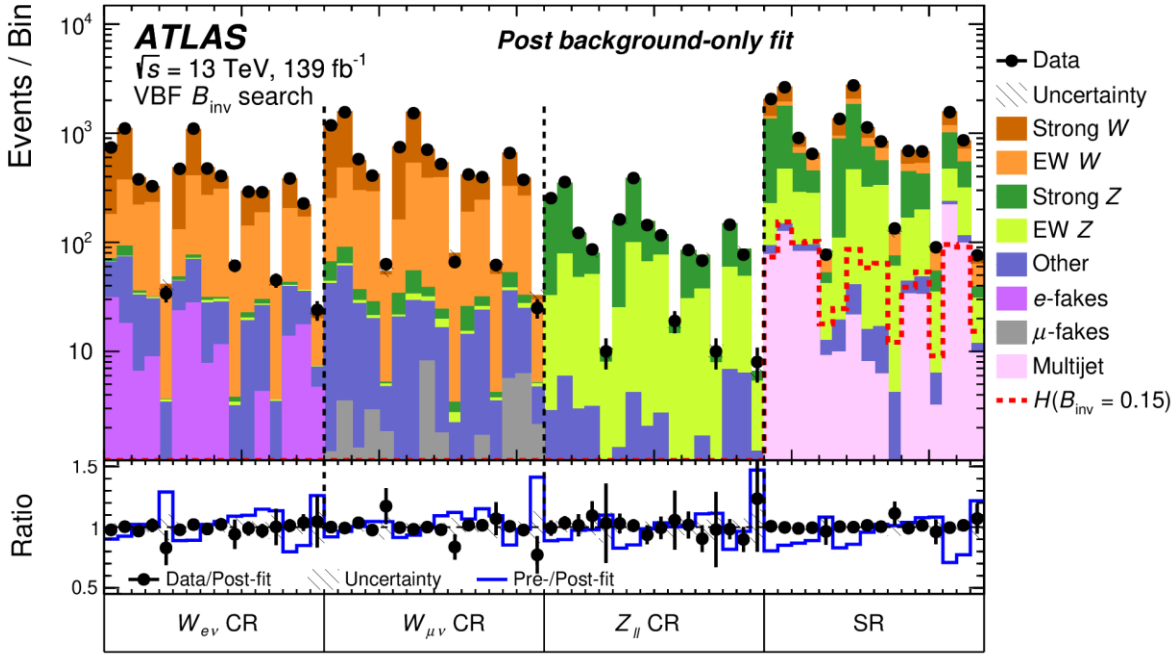

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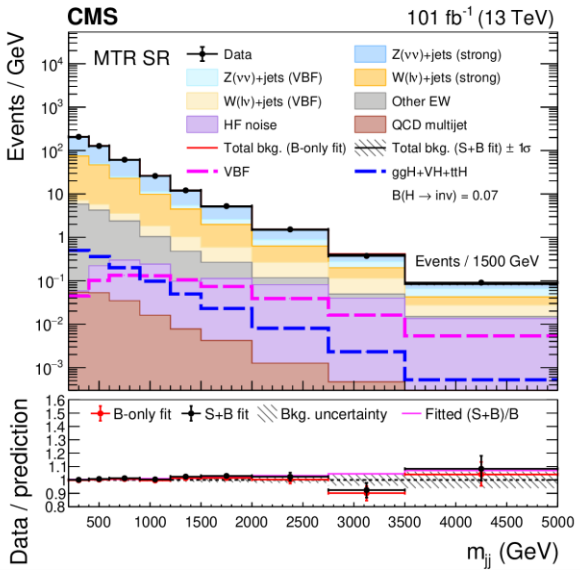
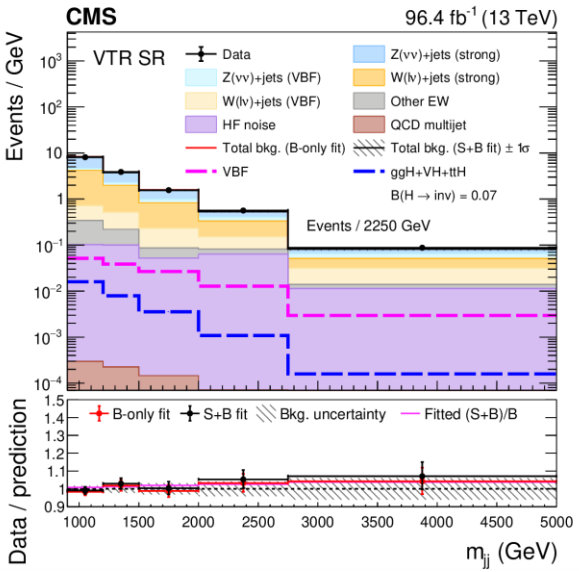
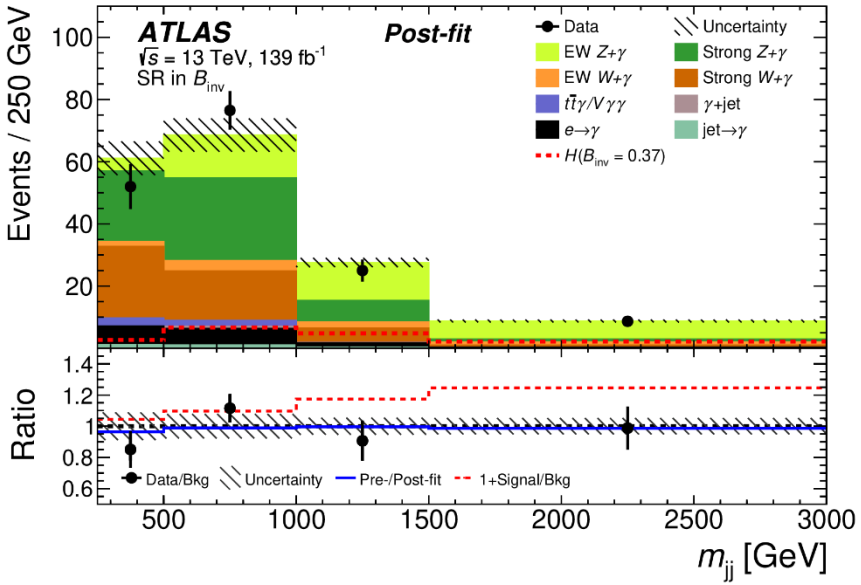


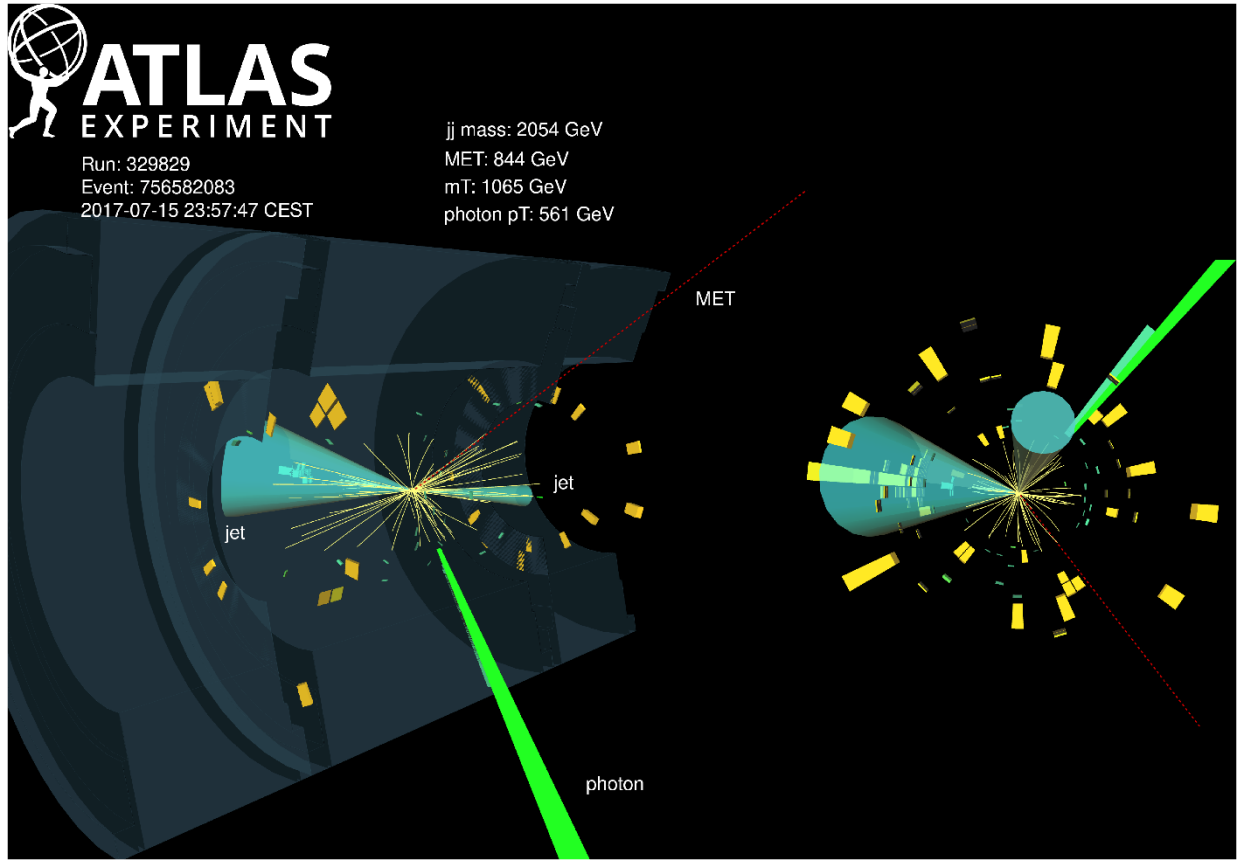


EWK MET+γ+jj

EPJC 82 (2022) 105

- Similar VBF-like selection + one extra photon
- Usually radiated from the scattering W within the large rapidity gap between two VBF jets
- Final state dominated by **EWK $Z(\nu\nu)\gamma$+2j**





Paper reports first observation of this process at the LHC!!!

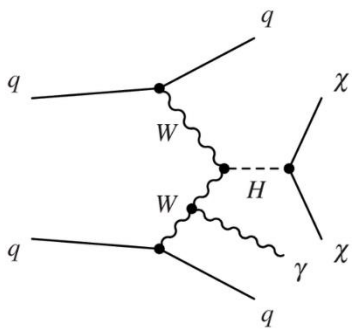
EWK MET+γ+jj

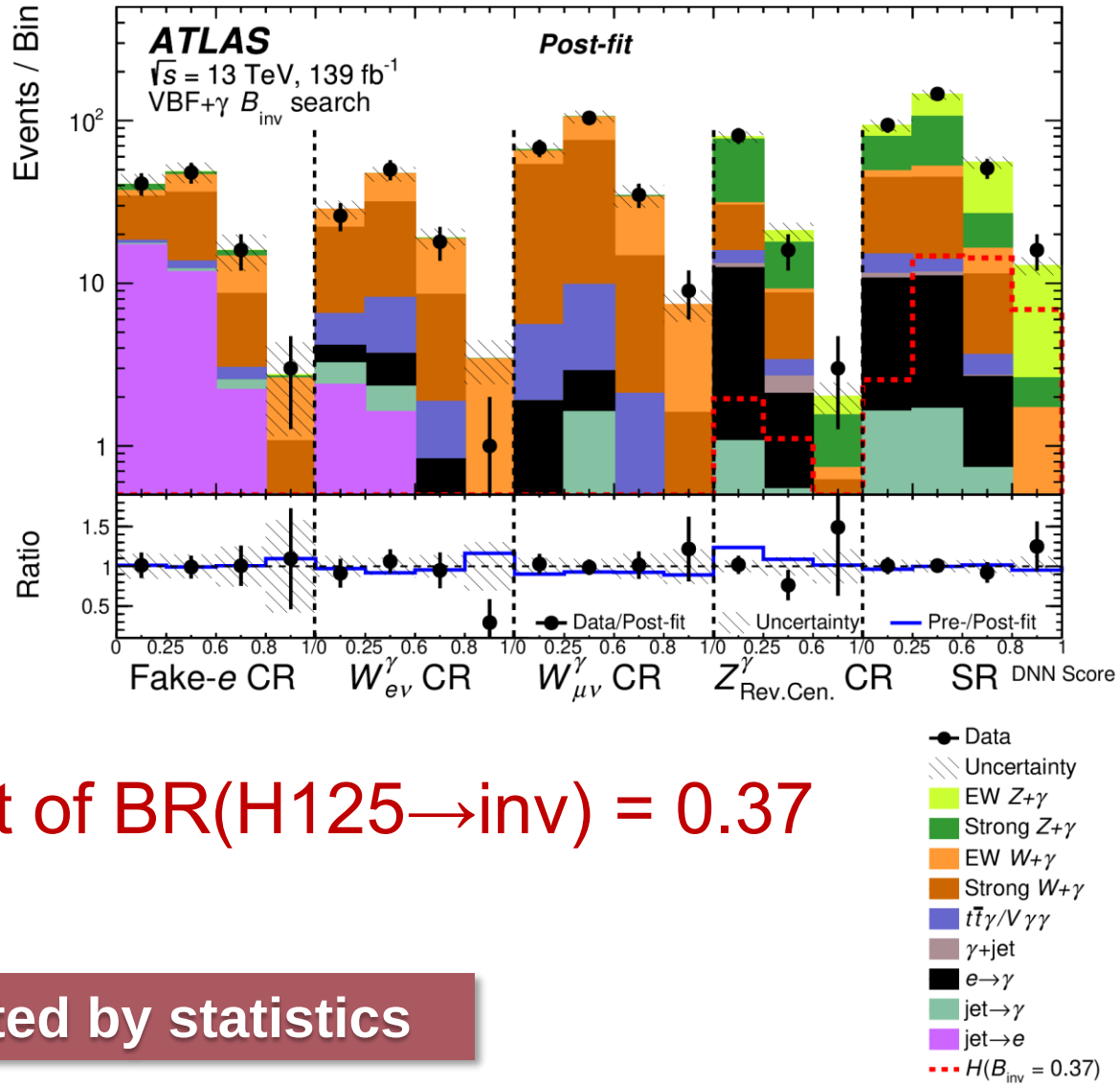
EPJC 82 (2022) 105

DNN-based classification used as a discriminating variable

Most important inputs:

- Leading jet kinematics and angular separation
- Invariant mass of two VBF jets
- Missing energy
- Photon pseudorapidity





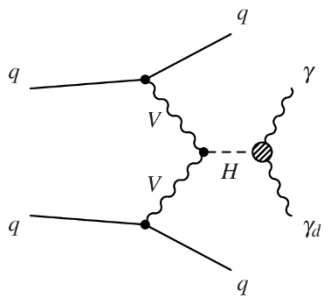
Assuming SM cross-section, Upper limit of BR(H125→inv) = 0.37

Results are limited by statistics

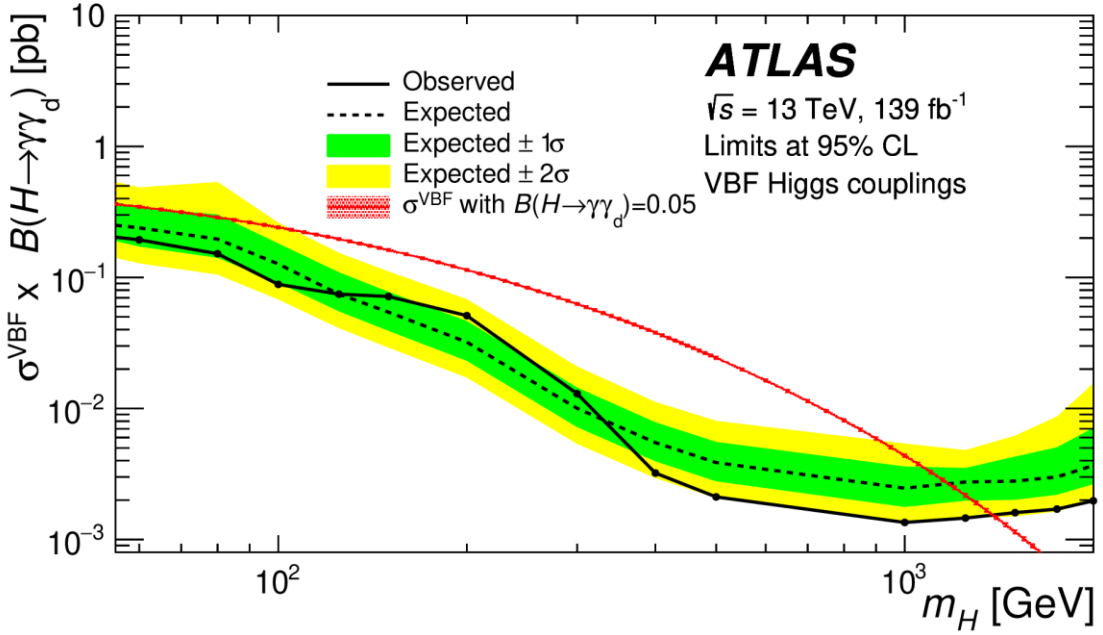
EWK MET+γ+jj

EPJC 82 (2022) 105

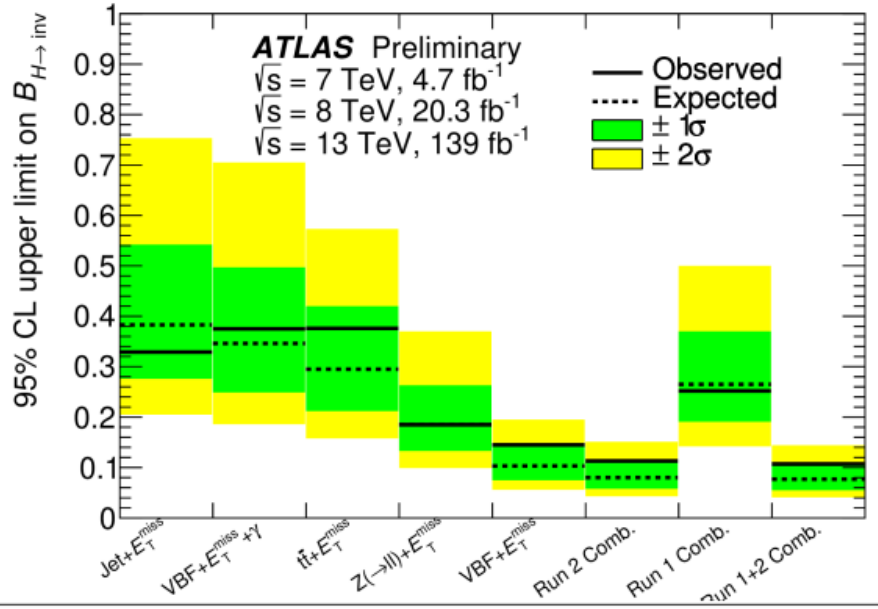
- Dark photon interpretation of semi-invisible Higgs decays



Upper limit of: BR(H125→$\gamma\gamma_D$) = 0.018



- ATLAS Combination among all Higgs production modes: BR(H125→inv) = 0.107



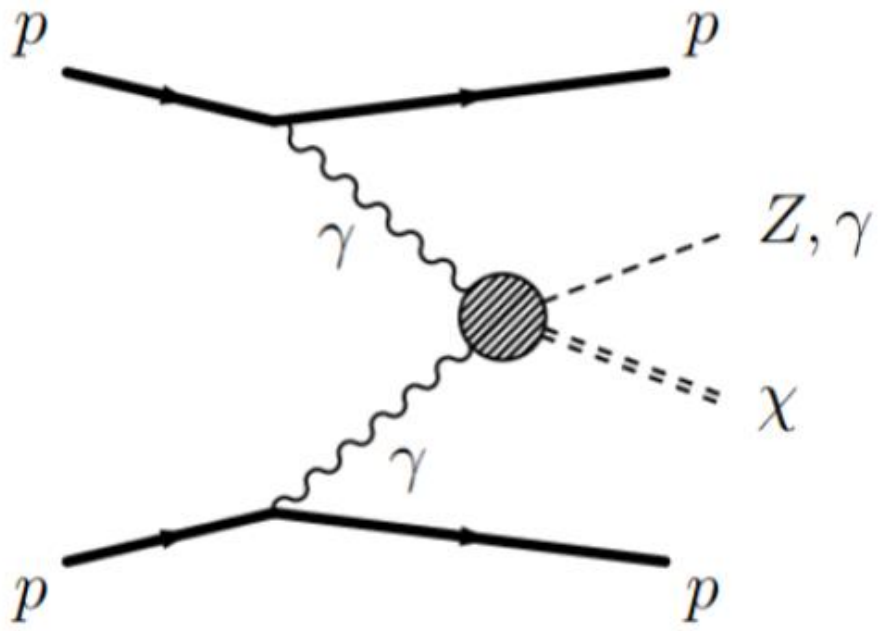
Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

Song-Ming Wang, Higgs 2022 @ PISA

Exclusive missing mass

CMS-PAS-EXO-19-009

- Searching for unknown particles using the “missing mass”
  - Implemented for the first time in hadron collider, based on 4π event reconstruction

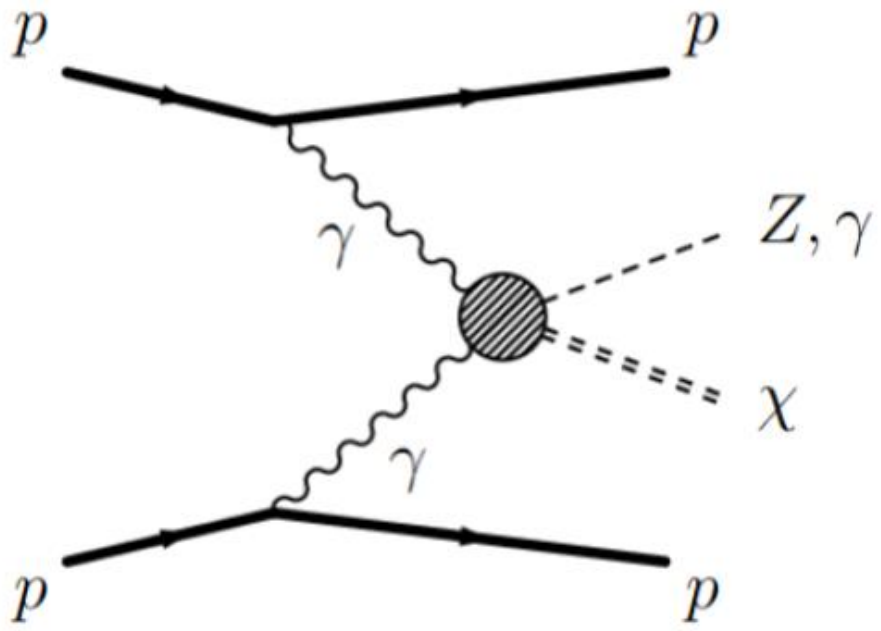


Exclusive missing mass

CMS-PAS-EXO-19-009

- Searching for unknown particles using the “missing mass”
  - Implemented for the first time in hadron collider, based on 4π event reconstruction
  - The 4-vector of unknown state χ is determined from protons and measured boson

$$m^2_{\text{miss}} = \left[(P^{\text{in}}_{p_1} + P^{\text{in}}_{p_2}) - (P_V + P^{\text{out}}_{p_1} + P^{\text{out}}_{p_2}) \right]^2$$

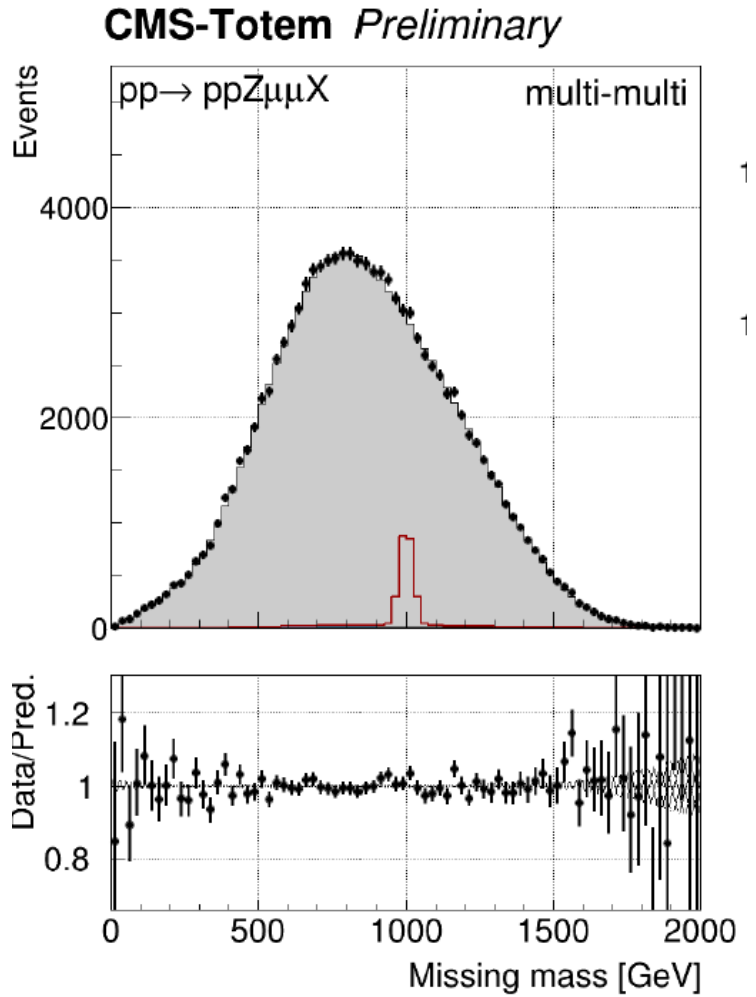


  - Bump hunt of mass of χ state is performed in Z+χ and γ+χ channels

Exclusive missing mass

CMS-PAS-EXO-19-009

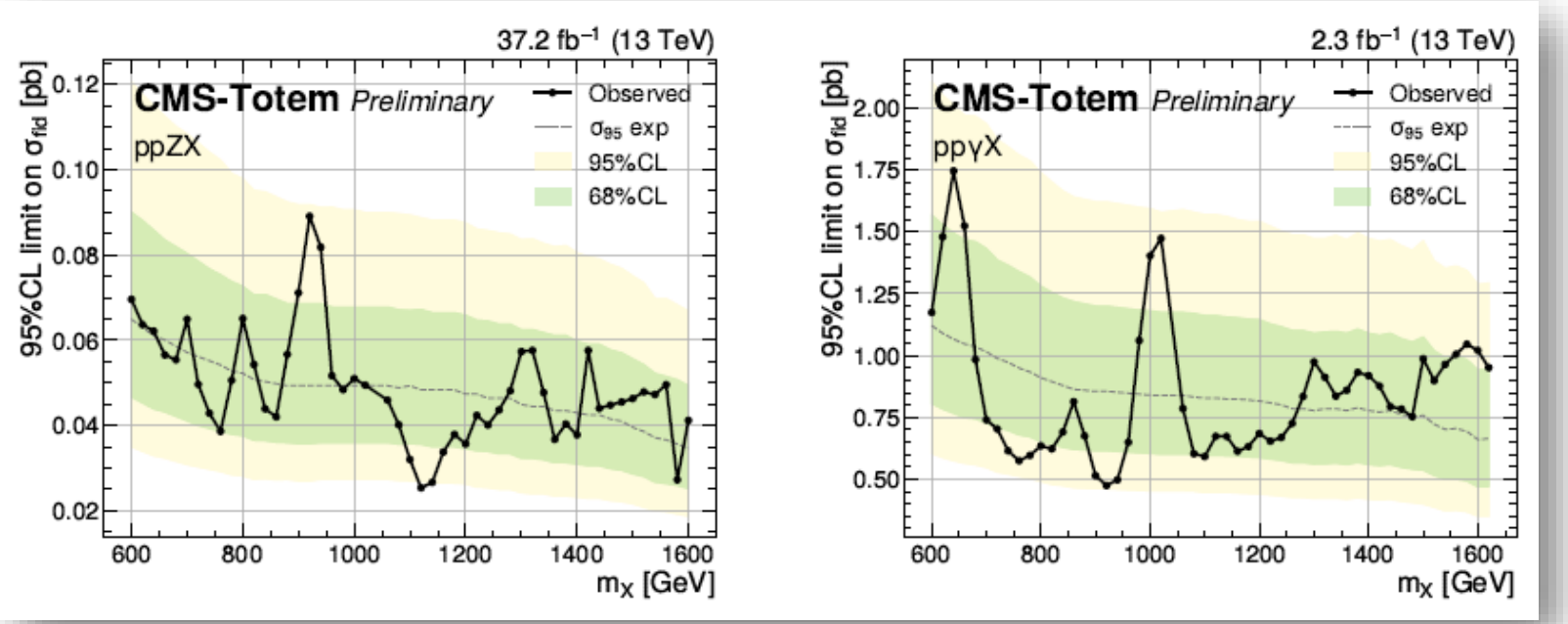
- Searching for unknown particles using the “missing mass”
  - Benefit from supreme mass resolution

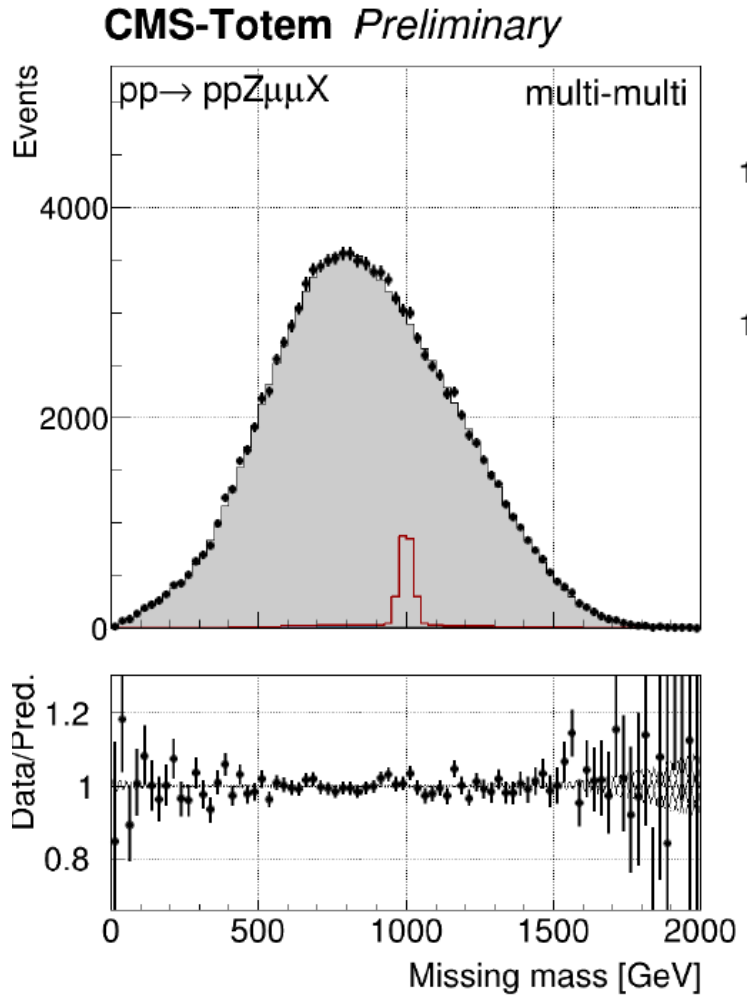


Exclusive missing mass

CMS-PAS-EXO-19-009

- Searching for unknown particles using the “missing mass”
  - Benefit from supreme mass resolution
  - Data agree with the background-only model, a limit on the production cross-section of Z/γ+χ was derived





Summary

- Recent measurements of VBF and VBS topologies were presented, with no discrepancies with Standard Model predictions.
- The newly presented probes in the EW sector are limited by statistical uncertainties – to be pursued with Run 3 and beyond
- VBF / VBS topologies can serve as a tool to look at new physics, in particular, to search for invisible decay modes (H->invisible, missing mass, etc)

Backup

References to public plots

Standard model (constraints on aQGC)

- EW Zγjj (STDM-2018-59), via Z(νν) decay
- EW Wγjj (CMS-PAS-SMP-21-011)
- Exclusive WW/ZZ (CMS-PAS-SMP-21-014)
- Exclusive γγ (CMS-PAS-EXO-21-007)

Beyond the Standard model

- VBF Majorana neutrinos (EXO-21-003)
- VBF H→Inv. (HIG-20-003, EXOT-2020-11)
- EW MET+γ+jj (EXOT-2021-17)
- Exclusive missing mass (CMS-PAS-EXO-19-009)

Dim-8 Operators

- Eboli and Gonzalez-Garcia parametrization (1310.6708)

M operators

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[\left(D_\beta\phi\right)^\dagger\left(D^\beta\phi\right)\right]$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[\left(D_\beta\phi\right)^\dagger\left(D^\mu\phi\right)\right]$$
$$\mathcal{O}_{M,2} = B_{\mu\nu}B^{\mu\nu} \times \left[\left(D_\beta\phi\right)^\dagger\left(D^\beta\phi\right)\right]$$
$$\mathcal{O}_{M,3} = B_{\mu\nu}B^{\nu\beta} \times \left[\left(D_\beta\phi\right)^\dagger\left(D^\mu\phi\right)\right]$$
$$\mathcal{O}_{M,4} = \left[\left(D_\mu\phi\right)^\dagger\widehat{W}_{\beta\nu}\left(D^\mu\phi\right)\right] \times B^{\beta\nu}$$
$$\mathcal{O}_{M,5} = \left[\left(D_\mu\phi\right)^\dagger\widehat{W}_{\beta\nu}\left(D^\nu\phi\right)\right] \times B^{\beta\mu}$$
$$\mathcal{O}_{M,6} = \left[\left(D_\mu\phi\right)^\dagger\widehat{W}_{\beta\nu}\widehat{W}^{\beta\nu}\left(D^\mu\phi\right)\right]$$
$$\mathcal{O}_{M,7} = \left[\left(D_\mu\phi\right)^\dagger\widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu}\left(D^\nu\phi\right)\right]$$

T operators

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right]$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right]$$
$$\mathcal{O}_{T,3} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\widehat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$
$$\mathcal{O}_{T,4} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\alpha\mu}\widehat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\alpha\beta}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,9} = B_{\alpha\nu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

EWK Zγ+jj

STDM-2018-59, Submitted to JHEP

Event selection: highly energetic photon, high MET and two jets

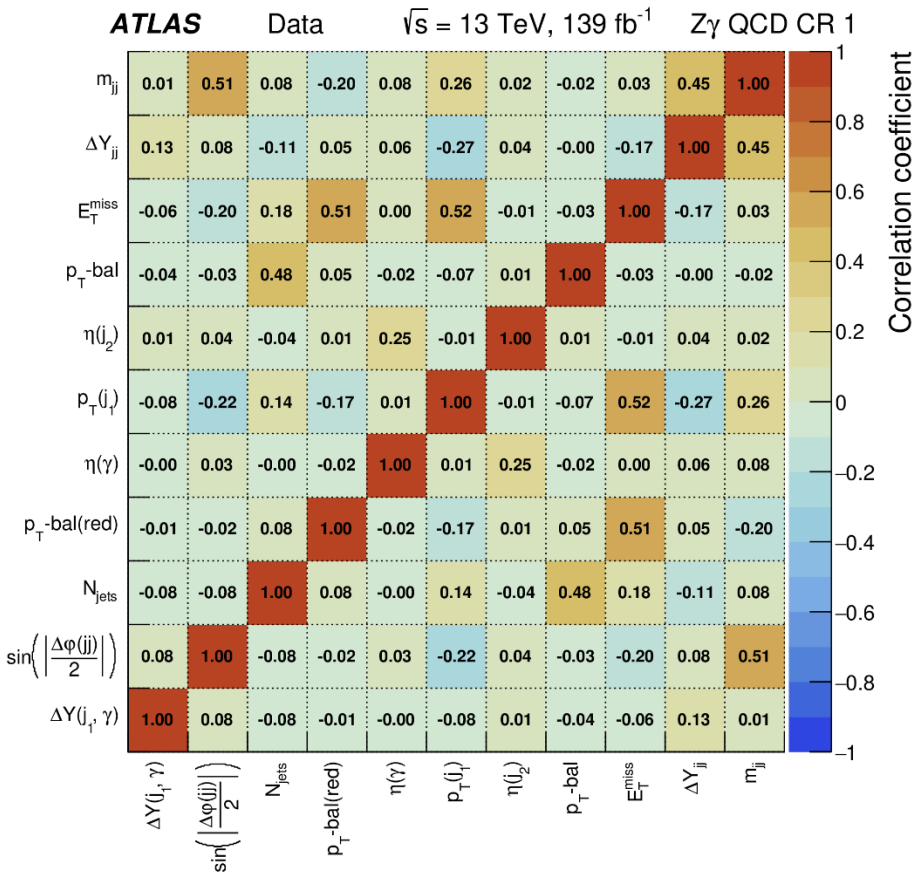
- Trigger: Single photon trigger, with pT > 140 GeV with loose ID
- Exactly one photon, lepton veto, missing energy above 120 GeV, at least two jets (j_1, j_2)
- Angular separation $\Delta\phi\left(j_{1,2}, E_T^{miss}\right) > 0.3$ and $\Delta\phi\left(\gamma, E_T^{miss}\right) > 0.4$
- VBS selection: $m_{jj} > 300$ GeV, γ-centrality $\zeta = \frac{y(\gamma) - 0.5\left(y(j_1) + y(j_2)\right)}{y(j_1) + y(j_2)} < 0.6$

Object selection:

- Photons with pT > 150 GeV and |η|<2.37, Electrons with pT > 7 GeV and |η|<2.47, both outside calorimeter transition region (1.37<|η|<1.52)
- Muons with pT > 7 GeV and |η|<2.47
- Jets with pT > 50 GeV and |η|<4.5, Radius parameter R = 0.4

Discriminating variable:

- BDT used as final discriminator, where the BDT was trained against Zγ inclusive region
- The following input variables are used in the training
  - m_{jj}
  - Δy_{jj}, $\sin(\Delta\phi_{jj}/2)$, $\Delta y_{\gamma j_1}$
  - E_T^{miss}
  - pT-balance (+reduced) $\Sigma\vec{p}_T/\Sigma E_T$
  - $\eta(j_2), \eta(\gamma)$
  - $p_T(j_1)$
  - N_{jets}

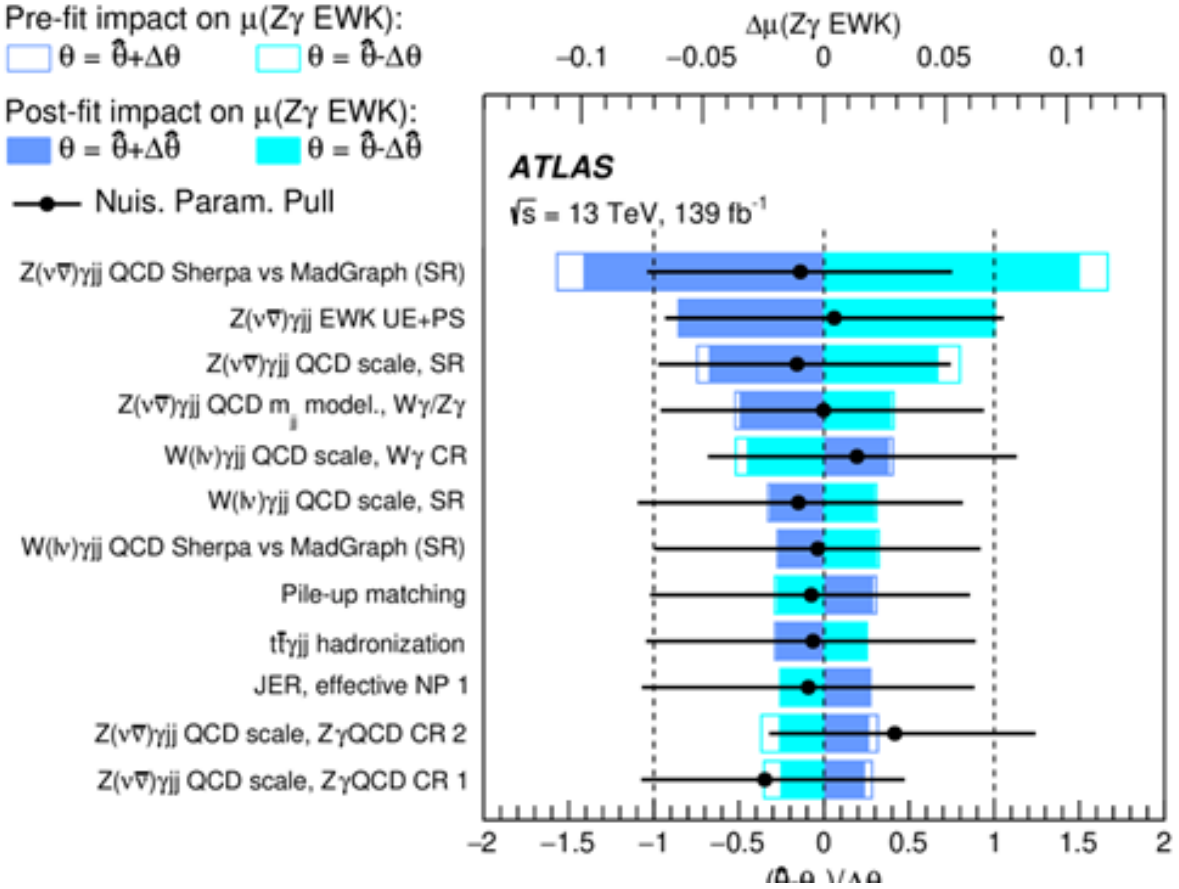


EWK Zγ+jj

STDM-2018-59,
Submitted to JHEP

Systematics:

- Fitted distributions in the Wγ CR, Wγ CR and the SR



Source of uncertainty	$\Delta\sigma/\sigma$ [%]
Experimental	
Jets	−3.2 / +3.4
Electrons and photons	−0.3 / +1.7
Muons	−0.4 / +0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$	−1.8 / +2.2
Pile-up modelling	−1.7 / +3.2
Trigger efficiency	−0.9 / +2.1
Luminosity	−1.2 / +2.6
Theory	
$Z(\nu\bar{\nu})\gamma jj$ EWK/QCD interference	−0.6 / +2.6
$Z(\nu\bar{\nu})\gamma jj$ EWK process	−6 / +12
$Z(\nu\bar{\nu})\gamma jj$ QCD process	−15 / +16
Other processes	−5.3 / +7.7
Other sources	
Data-driven backgrounds	−0.9 / +1.2
Pile-up background	−1.2 / +2.6
$Z(\nu\bar{\nu})\gamma jj$ QCD m_{jj} modelling	−4.4 / +4.4

EWK Wγ+jj

CMS-PAS-SMP-21-011

Event selection: Isolated lepton, high $M_{W\gamma}$ and two jets

- Trigger: Single lepton trigger
- Exactly one lep + γ, transverse mass of W > 100 GeV, in electron channel $|m_{\ell\gamma} - m_Z| > 10$ GeV
- Missing energy above 30 GeV, at least two jets (j_1, j_2), veto additional leptons with pT>10 GeV
- Angular separation $\Delta R > 0.5$,
- VBS selection: $m_{jj} > 500$ GeV and $|\eta_{jj}| > 2.5$, $y(W\gamma) - 0.5\big(y(j_1) + y(j_2)\big) > 1.2$ and $\Delta\phi(W\gamma) > 2$

Object selection:

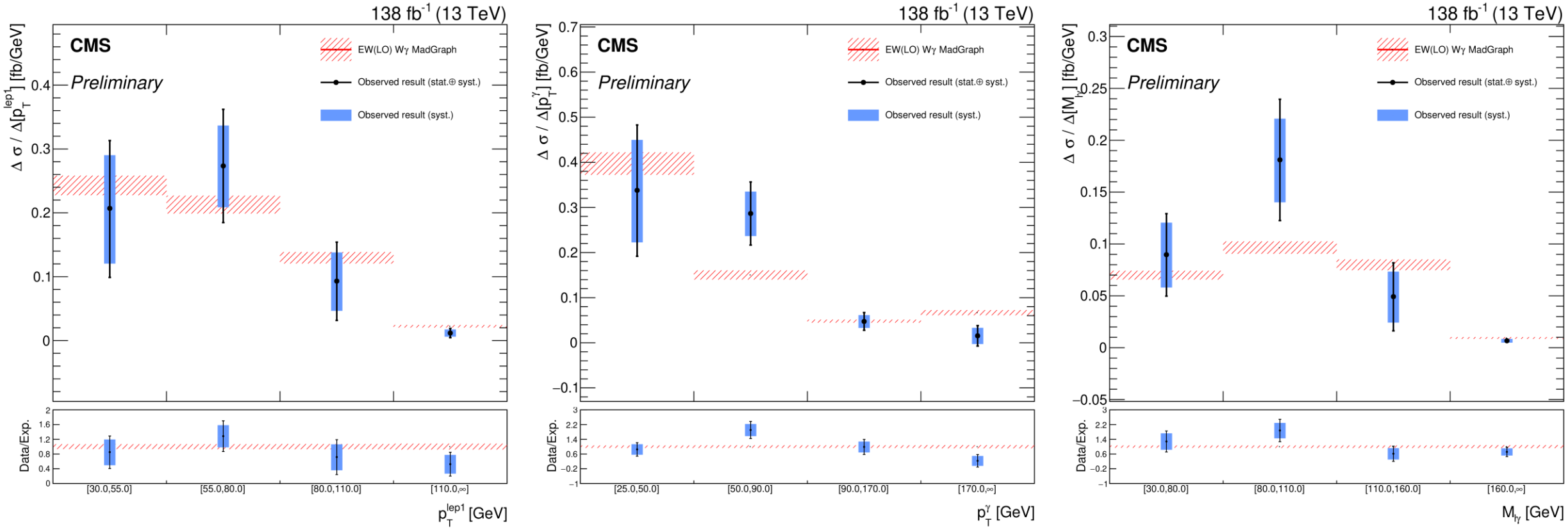
- Photons/Electrons with pT > 25/35 GeV, |η|<2.5, both outside transition region (1.444<|η|<1.566)
- Muons with pT > 35 GeV and |η|<2.4
- Jets with pT > 50 GeV and |η|<4.5, Radius parameter R = 0.4

EWK Wγ+jj

CMS-PAS-SMP-21-011

Results:

- Differential cross-section obtained for EWK only

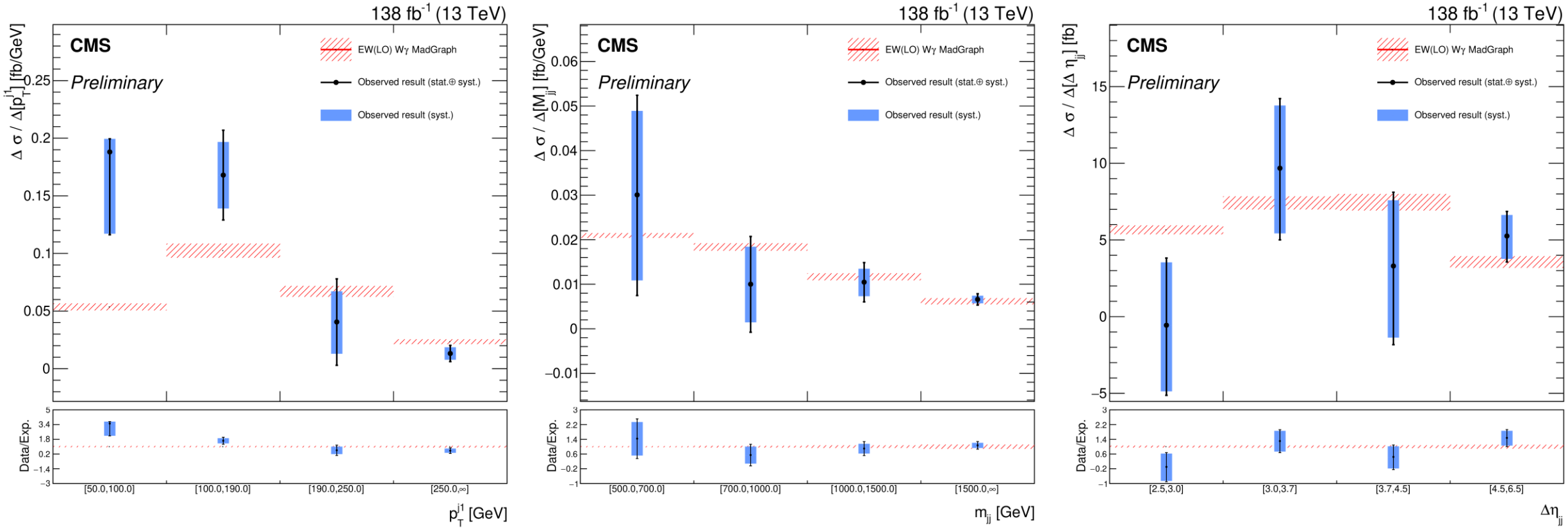


EWK Wγ+jj

CMS-PAS-SMP-21-011

Results:

- Differential cross-section obtained for EWK only

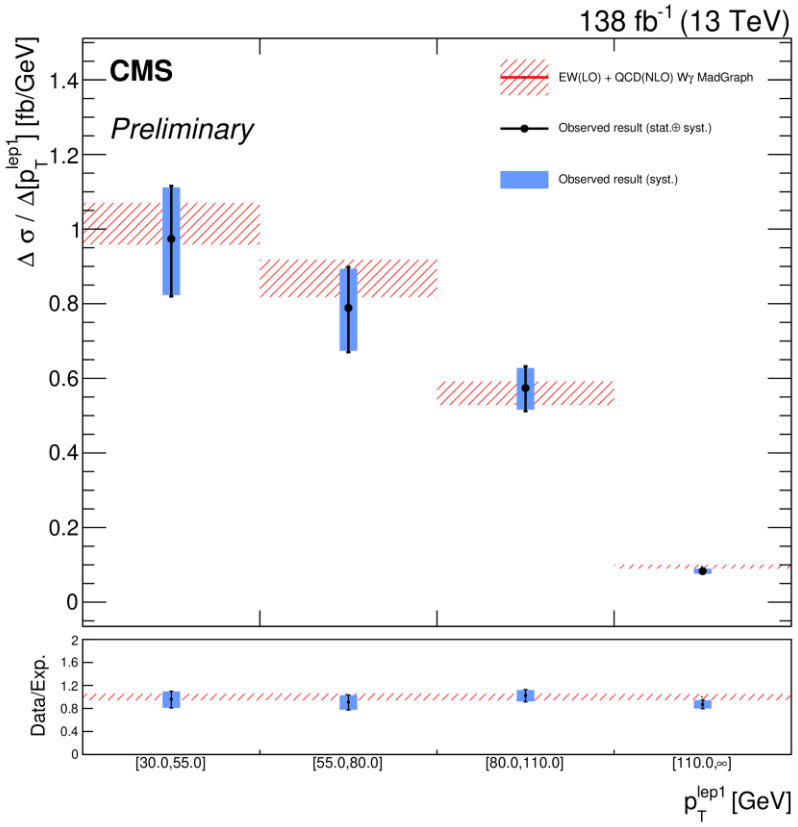


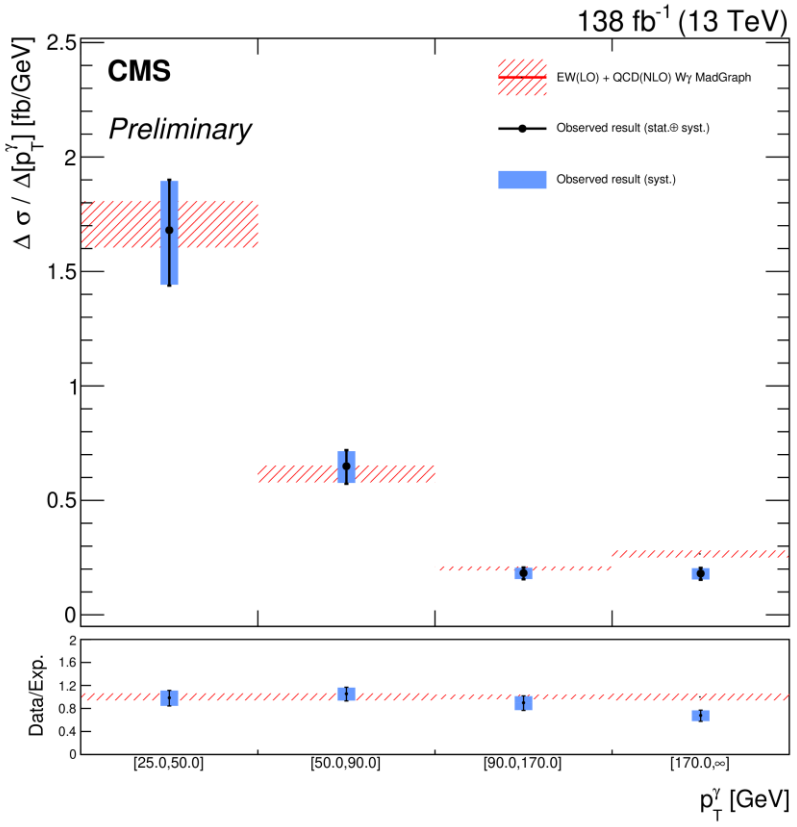
EWK Wγ+jj

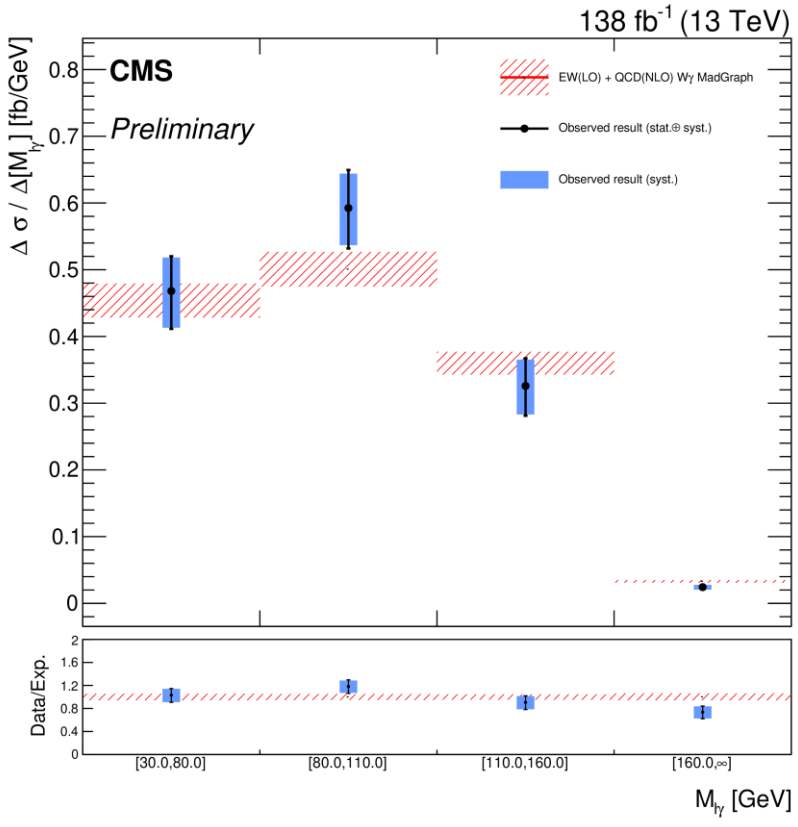
CMS-PAS-SMP-21-011

Results:

- Differential cross-section obtained for EWK+QCD





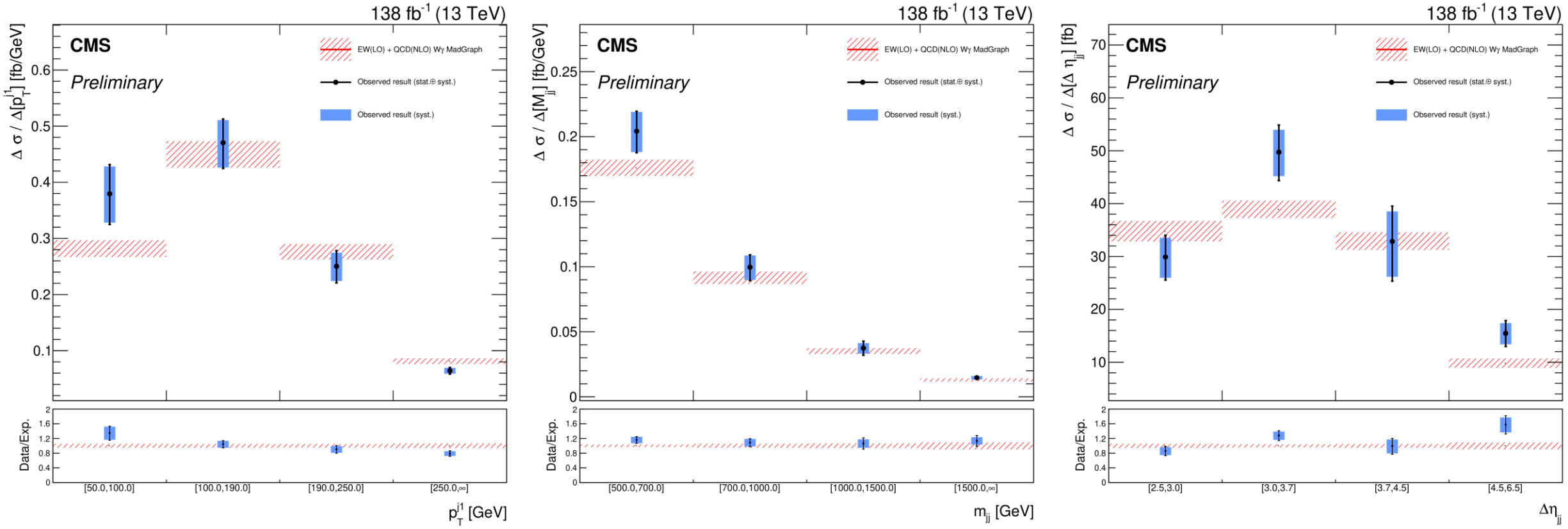


EWK Wγ+jj

CMS-PAS-SMP-21-011

Results:

- Differential cross-section obtained for EWK+QCD



Exclusive WW/ZZ

CMS-PAS-SMP-21-014

Event selection: Two V-tagged jets, two tagged forward protons

- Trigger: jet triggers (pT or HT) depends on year
- At least two V-tagged jets
- Jet1 p_T / Jet2 p_T < 1.3,$|\Delta\eta_{jj}|$<1.3 1126 < m_{jj}/GeV < 2500,
- Elastic selection: $|1 - \varphi_{jj}/\pi|$<0.01, two forward protons matched kinematically to VV

Object selection:

- Jets with pT > 200 GeV and |η|<2.5, Radius parameter R = 0.8

Exclusive WW/ZZ

2211.16320
Submitted to JHEP

Backgrounds:

- Dominated by inclusive QCD dijet production
- Estimated using the ABCD method – $N_A = N_B \cdot N_C / N_D$