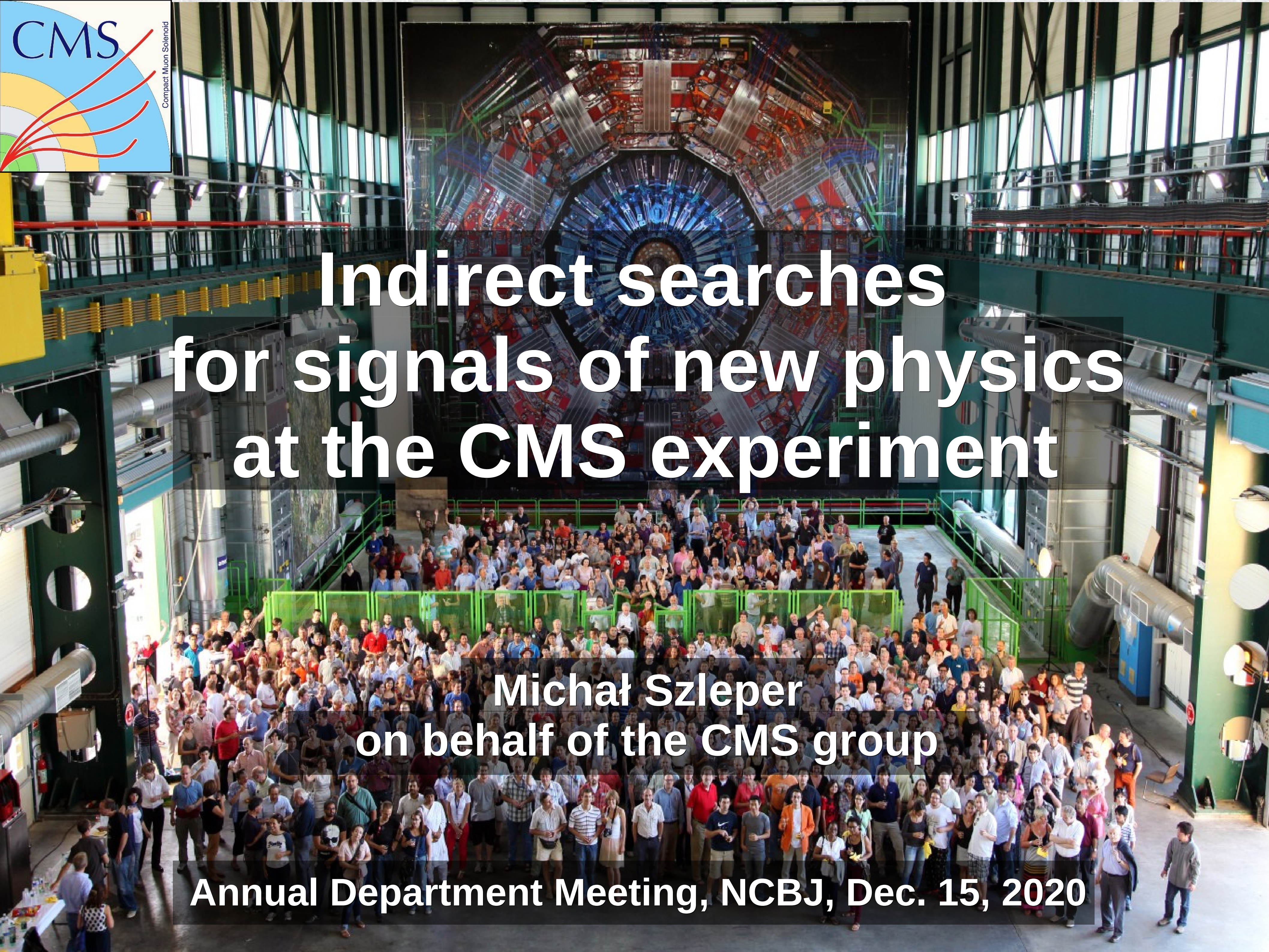


Indirect searches for signals of new physics at the CMS experiment

Michał Szleper
on behalf of the CMS group

Annual Department Meeting, NCBJ, Dec. 15, 2020

The Warsaw CMS group

- **Who we are:**

Helena Białkowska, Michał Bluj, Bożena Boimska, Maciej Górski, Małgorzata Kazana, Michał Szleper, Piotr Traczyk, Piotr Zalewski

+ colleagues from UW (head of the group: Marcin Konecki) and PW, ~20 people in total.

- **What we've been doing in 2020:**

Hardware responsibilities: Overlap Muon Track Finder.

Physics interests: Higgs physics – tau tau decay channel (MB – **D.Sc. completed this year**),
Direct searches for new physics – search for Heavy Stable Charged Particles (PZ, MK),
Heavy ion collisions (HB, BB),

(none of the above will be covered in this talk)

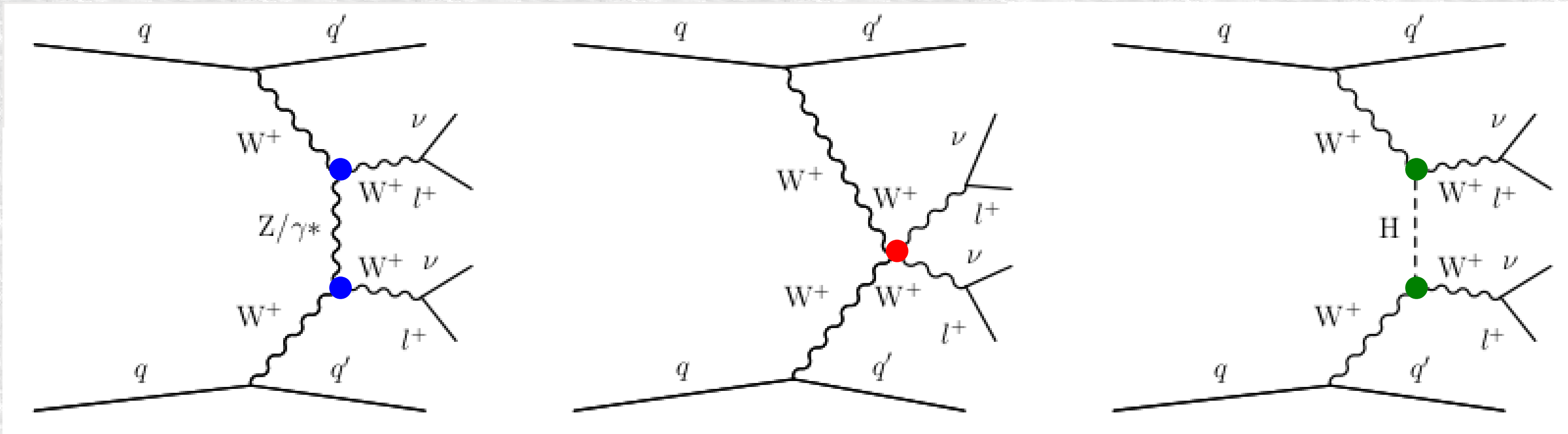
This talk → **Indirect searches for new physics – Vector Boson Scattering**

Vector Boson Scattering as an indirect probe of physics Beyond the Standard Model

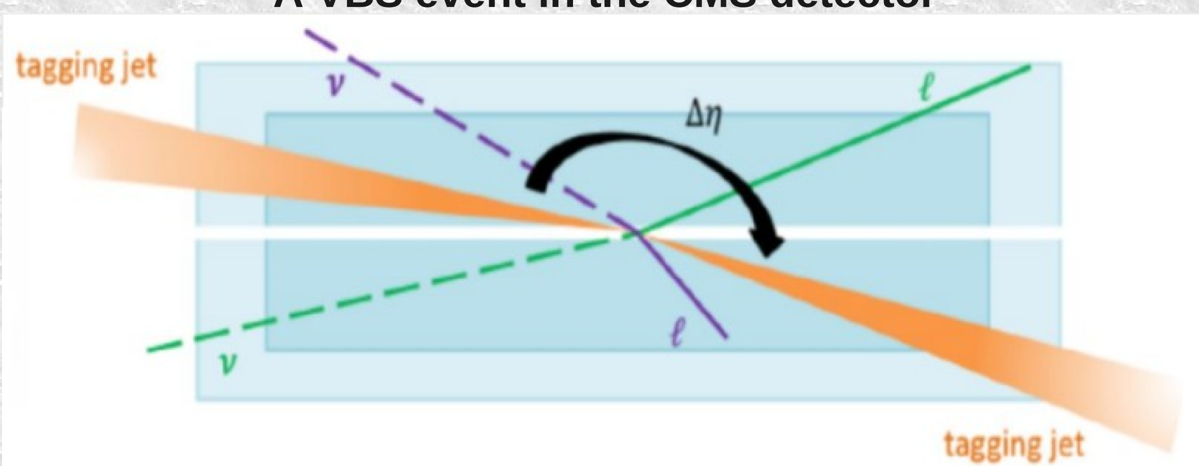
Couplings probed:

- HVV
- VVV
- VVVV

best process



A VBS event in the CMS detector



- Two energetic jets with large invariant mass and pseudorapidity separation
- 2, 3 or 4 (depending on process) energetic leptons in the central region

The Effective Field Theory approach

SM Lagrangian + higher (>4) dimension operators to parameterize the effects of hypothetical new interactions between known SM particles

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)} + \Sigma_i \frac{C_i^{(8)}}{\Lambda_i^4} \mathcal{O}_i^{(8)} + \ldots$$

$$f_i^{(6)} = \frac{C_i^{(6)}}{\Lambda^2}, \qquad f_i^{(8)} = \frac{C_i^{(8)}}{\Lambda^4}, \ldots \qquad \textbf{Wilson Coefficients}$$

Λ – the scale of new physics – sets upper limit of the validity range of the EFT expansion

Dim-8 operators that affect the WWWW and WWZZ vertices

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D_\nu\Phi\right]$$

covariant derivatives of Higgs doublets — scalar/longitudinal

$$\mathcal{O}_{M,0} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,1} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

$SU_L(2)$ gauge fields — transverse

$$\mathcal{O}_{T,0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

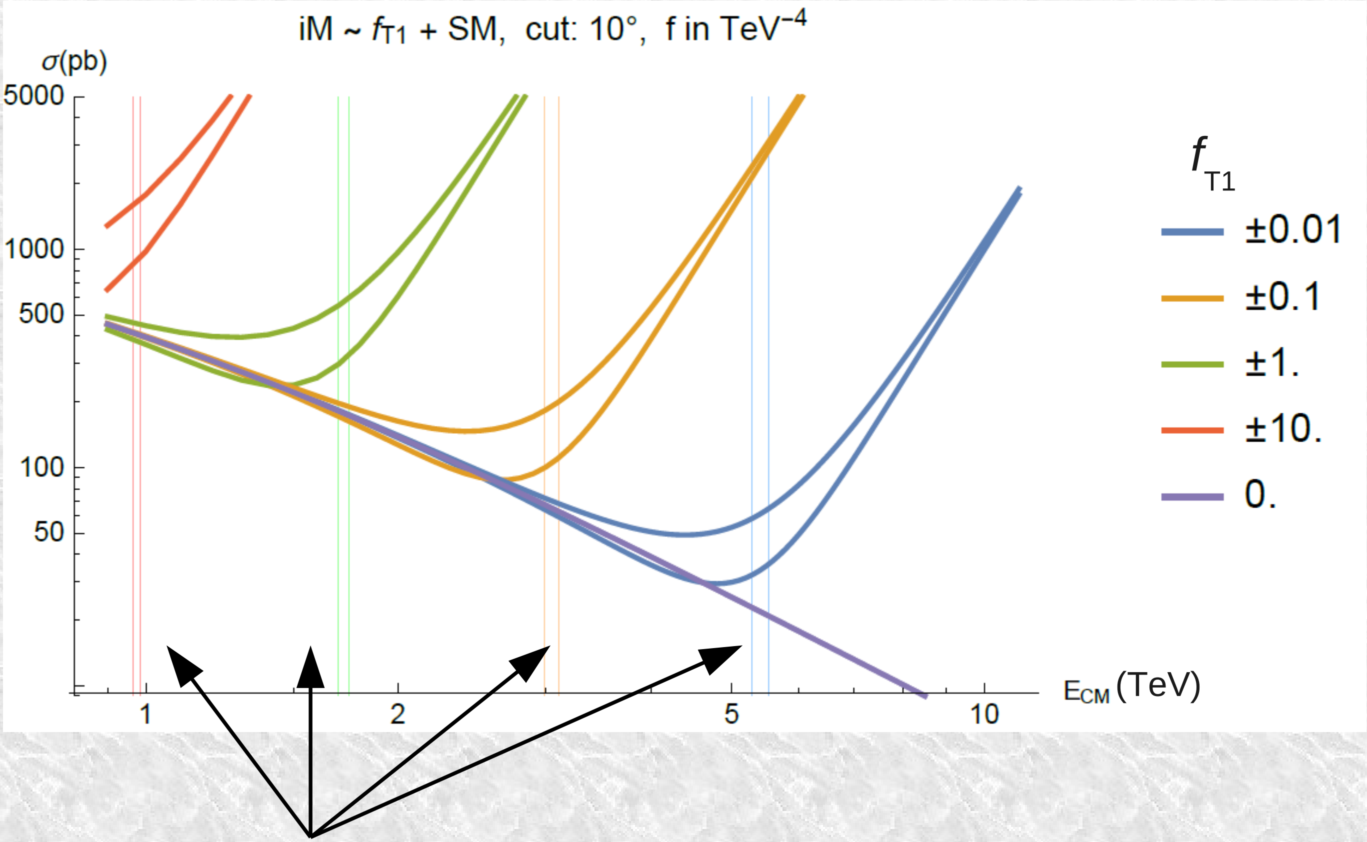
$$\mathcal{O}_{T,1} = Tr\left[W_{\alpha\nu}W^{\mu\beta}\right] \times Tr\left[W_{\mu\beta}W^{\alpha\nu}\right]$$

$$\mathcal{O}_{T,2} = Tr\left[W_{\alpha\mu}W^{\mu\beta}\right] \times Tr\left[W_{\beta\nu}W^{\nu\alpha}\right]$$

mixed transverse and longitudinal parameters

Caveats of the EFT formalism and how experiments typically dealt with them

Total cross section for $W^+W^+ \to W^+W^+$ scattering (on shell approx.)

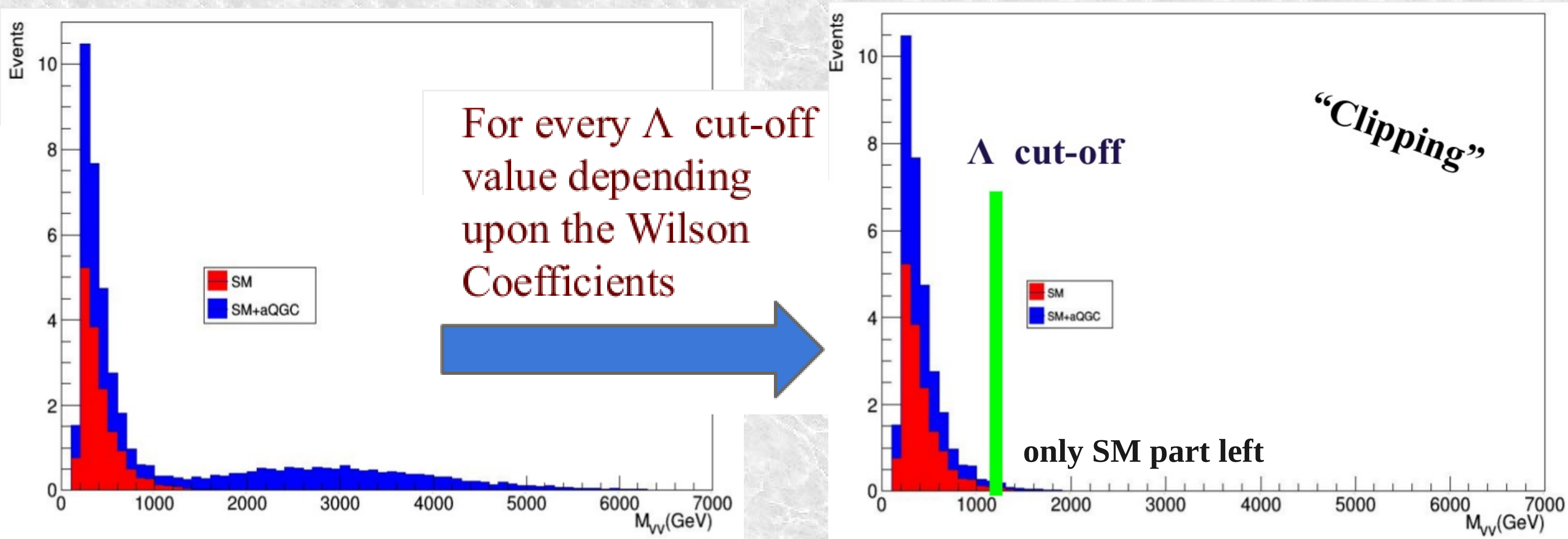


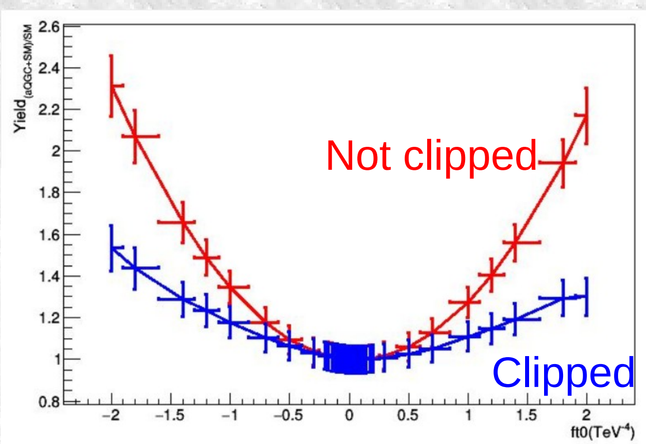
Unitarity limits!

- Cross section growth (asymptotically ~s^3) becomes unphysical above a certain scale
- **Λ** is *unknown* except that it cannot be larger than the lowest unitarity limit involved
- Previous VBS analyses:
  - apply EFT expansion as if it was valid in the entire dataset (CMS),
  - try unitarization techniques (ATLAS)

The answer: ``clipping'' method

Conceived & studied in Warsaw (NCBJ + UW theory), endorsed by the theory group of the Vector Boson Scattering Coordination and Action Network





Data outside of the EFT validity region are not used (ZZ) or assumed to be SM-like if direct omission is not possible (WW and WZ, we cannot measure the VV invariant mass)

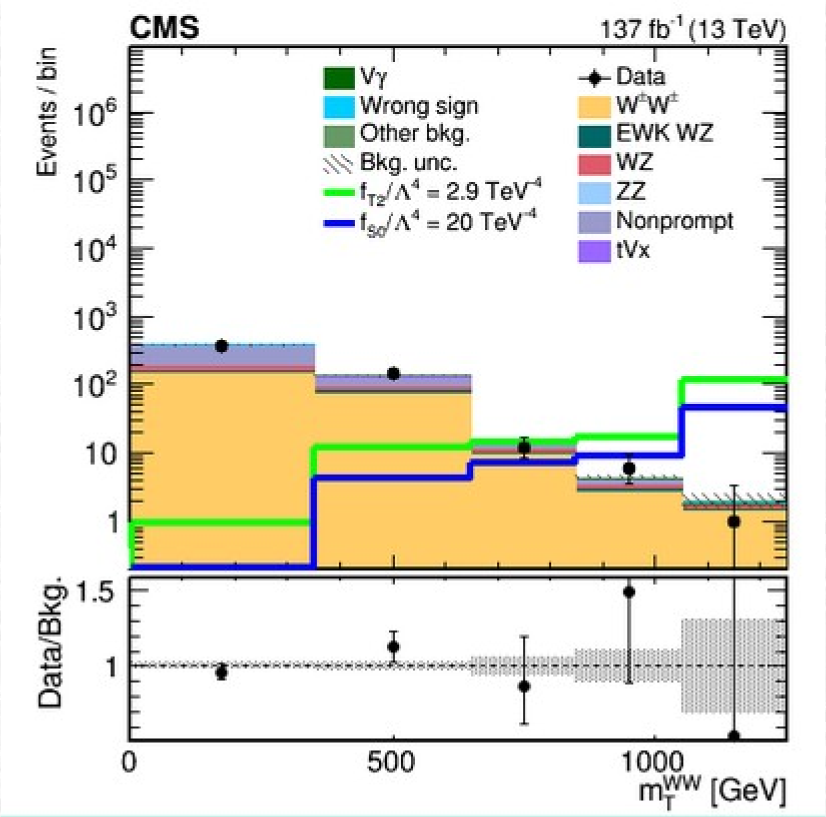
Note: smaller predicted BSM signals naturally mean weaker limits

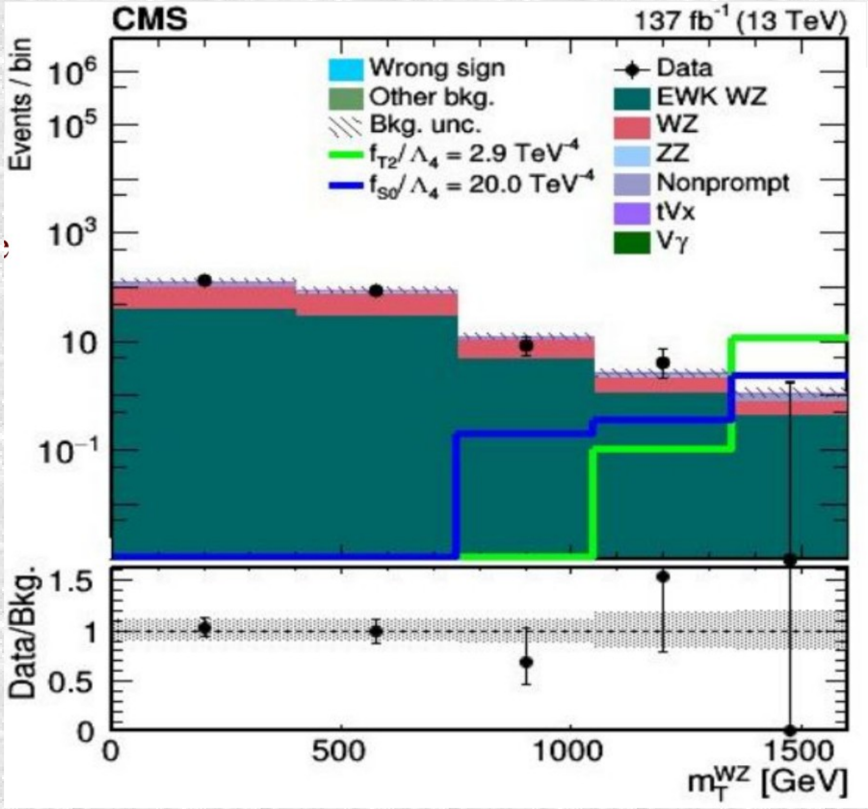
Analysis of Run II data (2016-2018), 137 fb^{-1}

Same-sign WW, WZ & combination

- Cross section measurements
- Limits on anomalous quartic couplings in the language of EFT dim-8 operators – with and without ``clipping''

$$m_{\mathrm{T}}(\mathrm{VV}) = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$





Results – current limits on BSM physics

Not clipped

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

Clipped

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

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CMS Draft Analysis Note

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2020/03/11
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Study of the vector boson scattering in leptonic $W^{\pm}W^{\pm}$ and WZ diboson events at $\sqrt{s} = 13$ TeV

A. Apyan[1], G. Chaudhary[2], M. D'Alfonso[3], G. Gómez-Ceballos[3], M. Hu[3], M. Kaur[2], M. Klute[3], D. Kovalskyi[3], B. Maier[3], M. Szleper[4], Ch. Paus[3], K. Sandeep[2], and S. Tkaczyk[1]

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ELSEVIER

Measurements of production cross sections of WZ and same-sign WW boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

CERN, Switzerland

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ABSTRACT

Measurements of production cross sections of WZ and same-sign WW boson pairs in association two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC are reported. The data sample corres to an integrated luminosity of 137 fb^{-1}, collected with the CMS detector during 2016–2018 measurements are performed in the leptonic decay modes $W^{\pm}Z \to \ell^{\pm}\nu\ell'^{\pm}\ell'^{\mp}$ and $W^{\pm}W^{\pm} \to \ell^{\pm}\nu$ where $\ell, \ell' = e, \mu$. Differential fiducial cross sections as functions of the invariant masses of the je charged lepton pairs, as well as of the leading-lepton transverse momentum, are measured for W production and are consistent with the standard model predictions. The dependence of differential sections on the invariant mass of the jet pair is also measured for WZ production. An observati electroweak production of WZ boson pairs is reported with an observed (expected) significance (5.3) standard deviations. Constraints are obtained on the structure of quartic vector boson intera in the framework of effective field theory.

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Public analysis SMP-19-012

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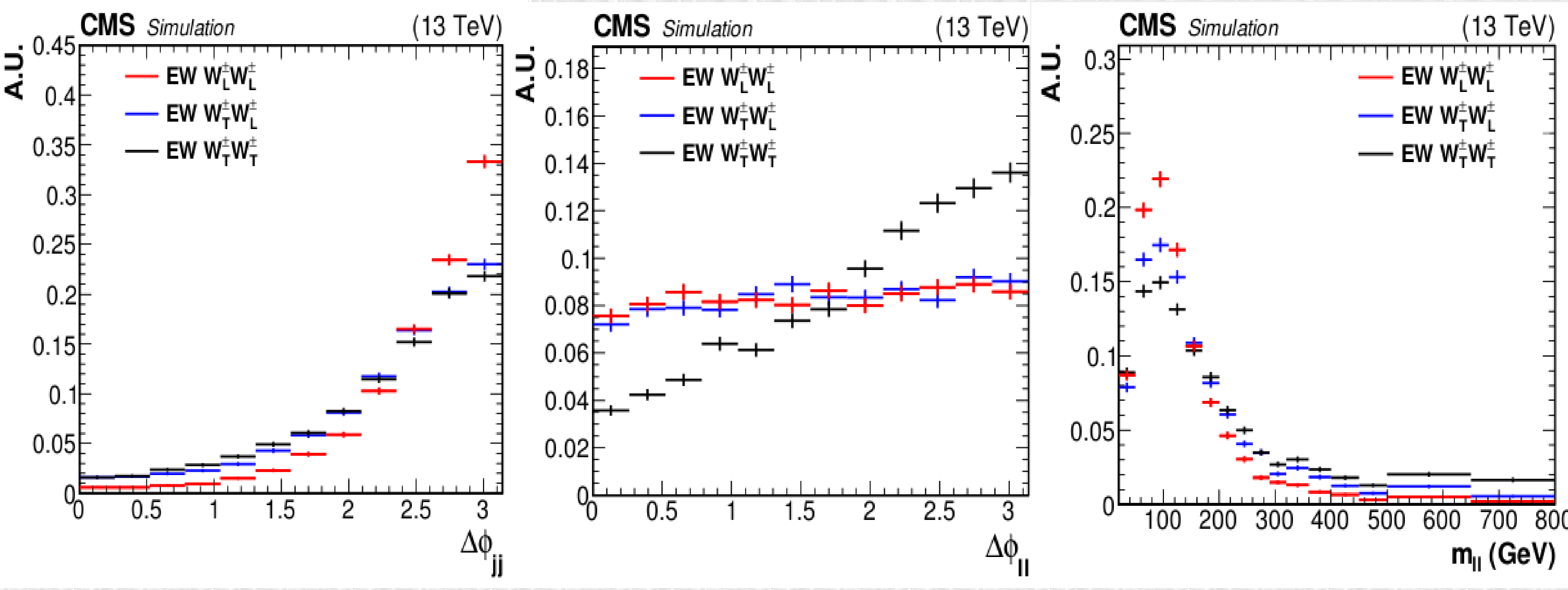
Topic 2: study of VV polarizations in the final state

Very important aspect!

1. **Longitudinal modes are most directly related to EWSB, but transverse modes are dominant in the data**
2. **For a full multi-operator EFT analysis one needs to kinematically disentangle the effects of different operators**

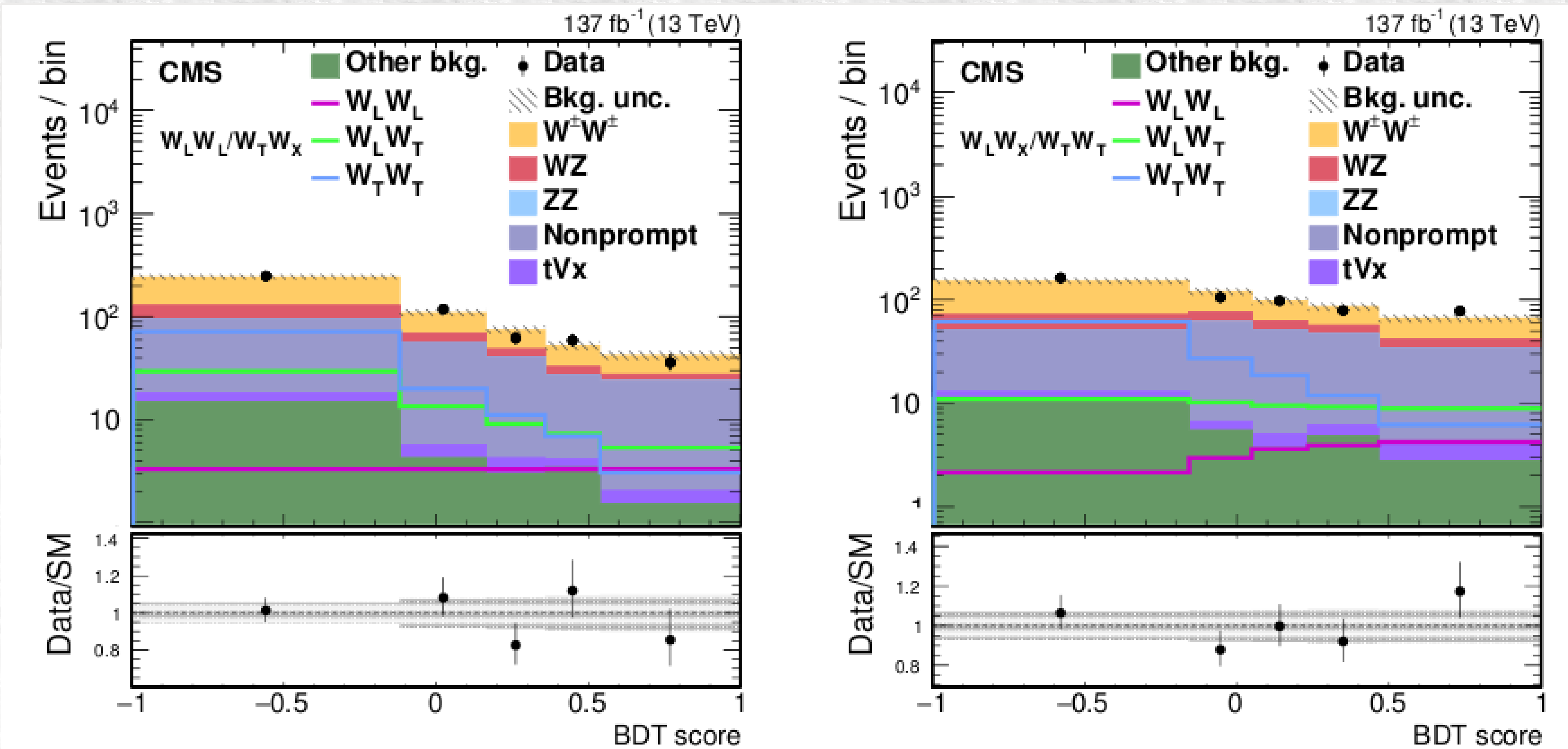


Warsaw input: polarization-sensitive variables $\Delta\Phi_{ll}$, p_T^{j1}, and $R_{pT} = p_T^{l1} p_T^{l2} / (p_T^{j1} p_T^{j2})$ for BSM

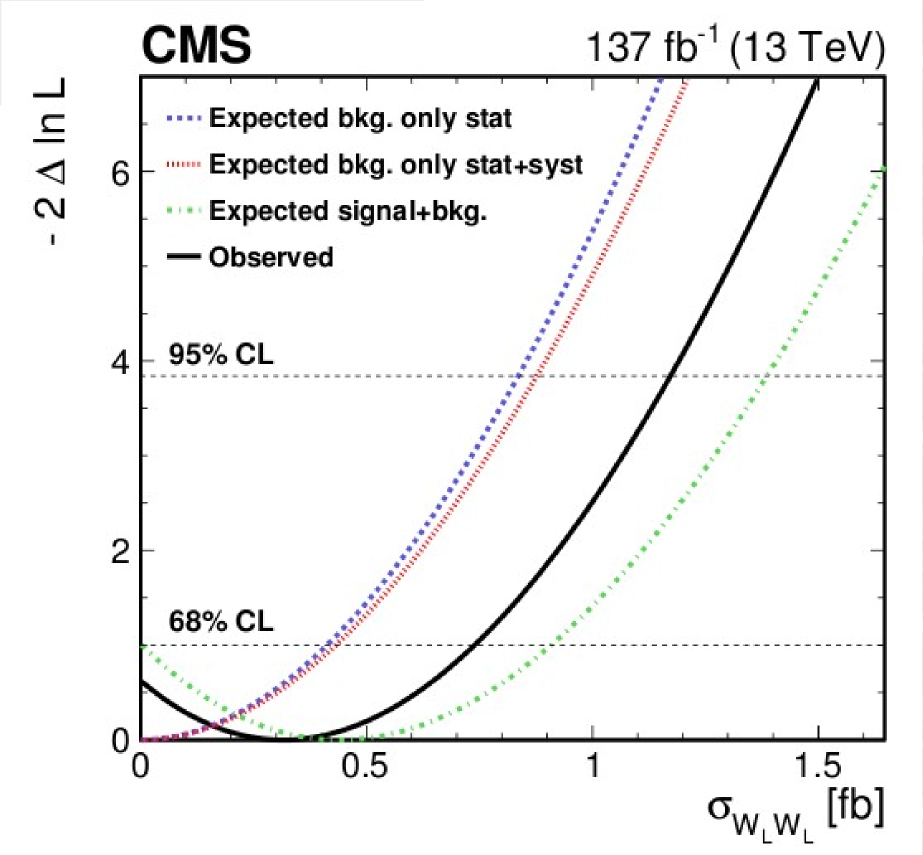
Analysis of Run II data (2016-2018), 137 fb^{-1}

Same-sign WW process

- Two independent BDTs trained to distinguish $W_L W_L$ vs. $W_T W_X$ and $W_L W_X$ vs. $W_T W_T$
- Polarization dependent templates fit to the data



Results: first experimental hint at the existence of longitudinal polarization



Helicity eigenstates defined in the WW c.o.m. frame

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

Helicity eigenstates defined in the parton-parton c.o.m. frame

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W^\pm_X W^\pm_T$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W^\pm_L W^\pm_X$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W^\pm_T W^\pm_T$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

- Upper limits on $W_L W_L$ consistent with the SM
- Hints of $W_L W_X$ at the level of 2-3 sigma (SM expected ~3)

CMS internal AN 2019/269

Public analysis SMP-20-006

Available on the CMS information server **CMS AN-19-269**

CMS Draft Analysis Note

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Scattering of longitudinally polarized same-sign W boson pairs in proton-proton collisions at 13 TeV

A. Apyan[1], G. Chaudhary[2], M. D'Alfonso[3], G. Gómez-Ceballos[3], M. Hu[3], M. Kaur[2], M. Klute[3], D. Kovalskyi[3], B. Maier[3], M. Szleper[4], Ch. Paus[3], K. Sandeep[2], and S. Tkaczyk[1]

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CERN-EP-2020-168
2020/09/22

CMS-SMP-20-006

arXiv:2009.09429v1 [hep-ex] 20 Sep 2020

Measurements of production cross sections of polarized same-sign W boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

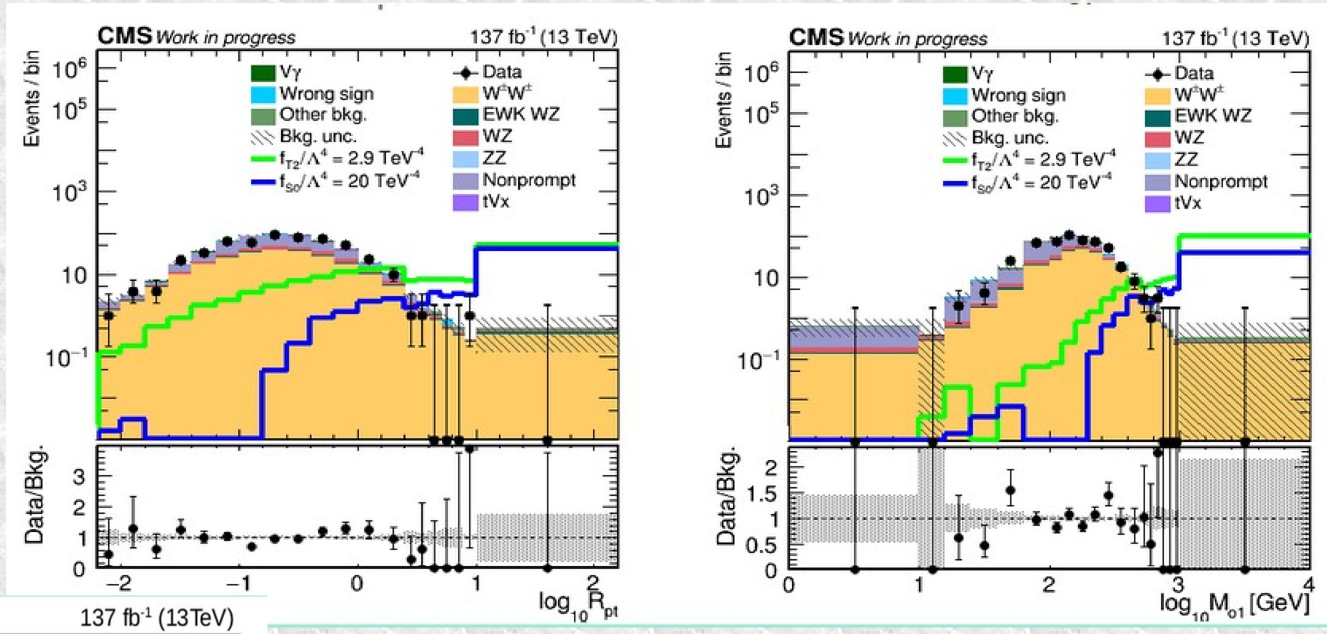
The first measurements of production cross sections of polarized same-sign $W^{\pm}W^{\pm}$ boson pairs in proton-proton collisions are reported. The measurements are based on a data sample collected with the CMS detector at the LHC at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 137 fb^{-1}. Events are selected by requiring exactly two same-sign leptons, electrons or muons, moderate missing transverse momentum, and two jets with a large rapidity separation and a large dijet mass to enhance the contribution of same-sign $W^{\pm}W^{\pm}$ scattering events. An observed (expected) 95% confidence level upper limit of 1.17 (0.88) fb is set on the production cross section for longitudinally polarized same-sign $W^{\pm}W^{\pm}$ boson pairs. The electroweak production of same-sign $W^{\pm}W^{\pm}$ boson pairs with at least one of the W bosons longitudinally polarized is measured with an observed (expected) significance of 2.3 (3.1) standard deviations.

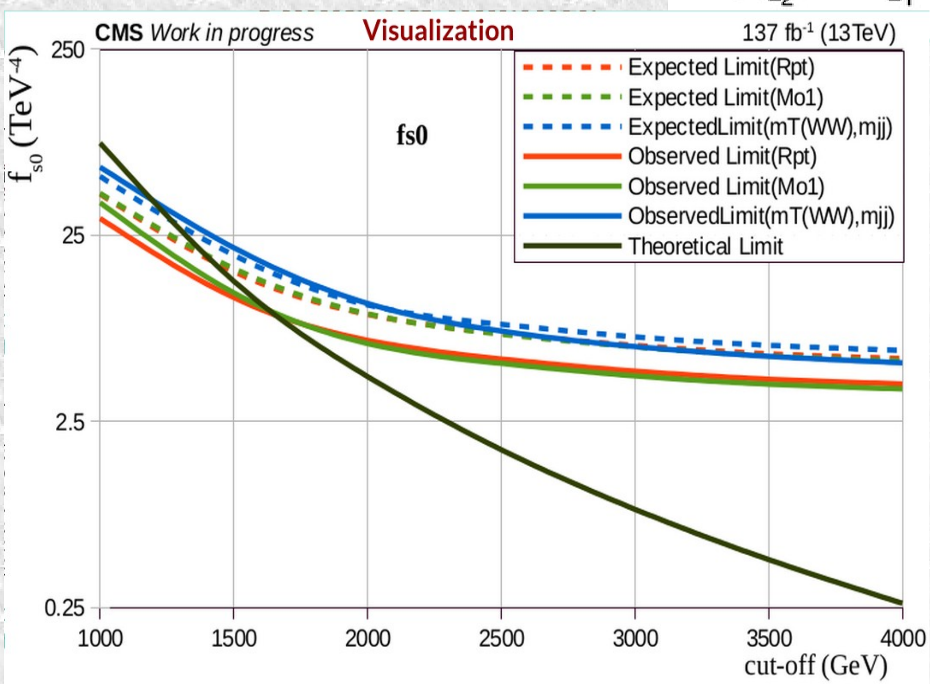
Submitted to Physics Letters B

Not quite the end yet! Brand new analysis

- **Studies of new variables with better sensitivity to BSM effects**

$$R_{pt} = (p_T^{l1} * p_T^{l2}) / (p_T^{j1} * p_T^{j2})$$





$$M_{o1} \equiv \sqrt{(|\vec{p}_T^{\,l1}| + |\vec{p}_T^{\,l2}| + |\vec{p}_T^{\,miss}|)^2 - (\vec{p}_T^{\,l1} + \vec{p}_T^{\,l2} + \vec{p}_T^{\,miss})^2}$$

- **Calculation of limits on EFT dim-8 operators as a function of the Λ cutoff parameter**

  → true physical limits = 2-dimensional exclusion curves

CMS internal
AN 2020/207

- Approved by the Collaboration to be published in form of a conference talk (hence I am showing it)

- Possibly part of a future paper

Available on the CMS information server **CMS AN-20-207**

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2020/11/29
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Determination of the limits on dim-8 operators in a new EFT unitarity observing formalism using the same-sign WW scattering results

A. Apyan[1], G. Chaudhary[2], G. Gómez-Ceballos[3], M. Hu[3], J. Kalinowski[4], M. Kaur[2], M. Klute[3], P. Kozów[4], Ch. Paus[3], K. Sandeep[2], M. Szleper[5], and S. Tkaczyk[1]

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