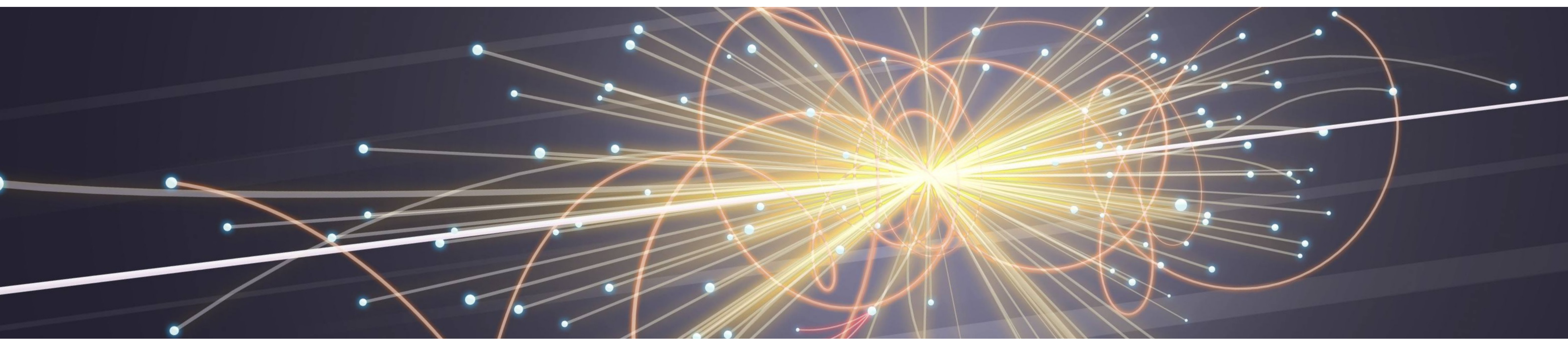
TRIBOSON MEASUREMENTS IN CMS



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SM@LHC

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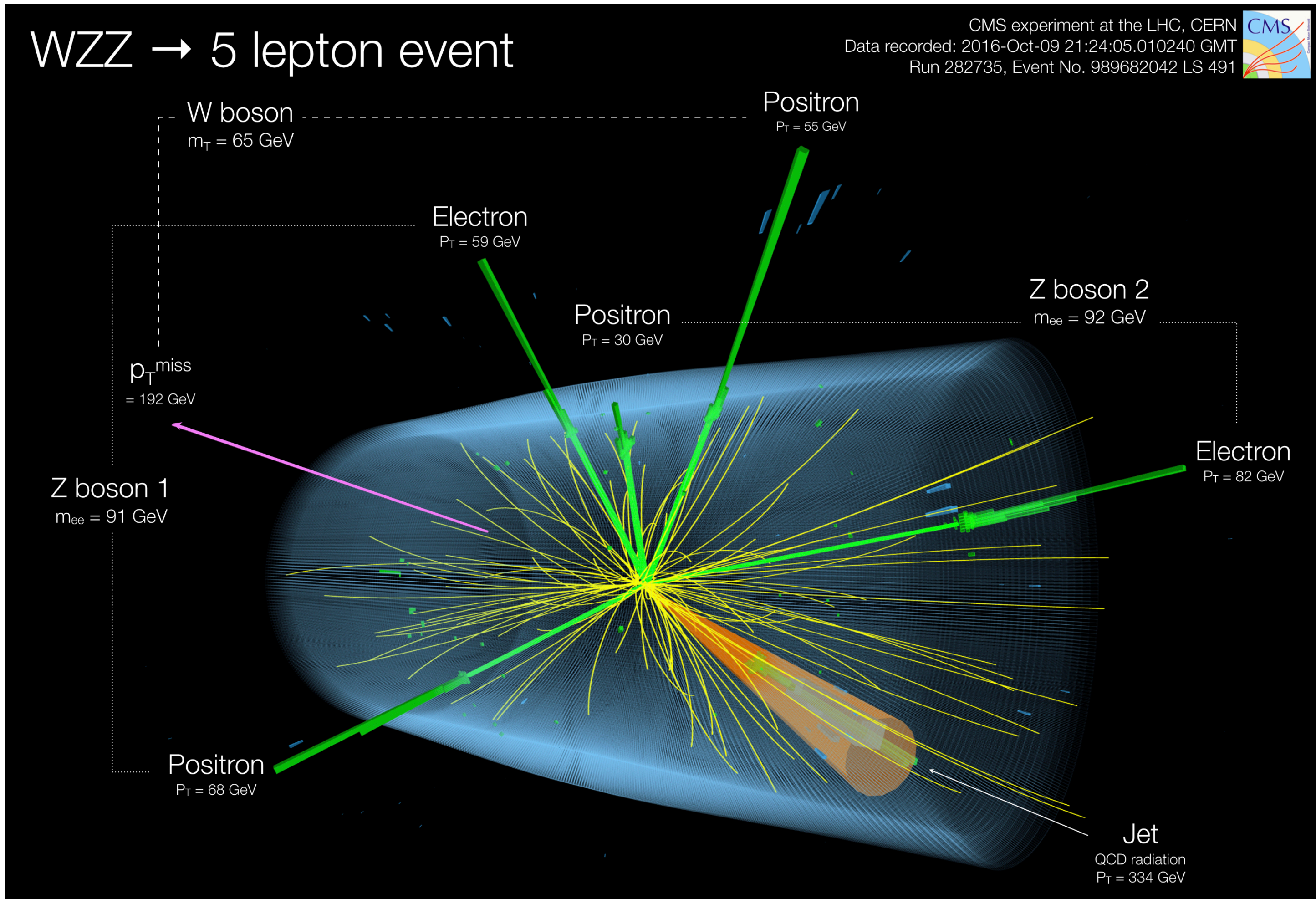
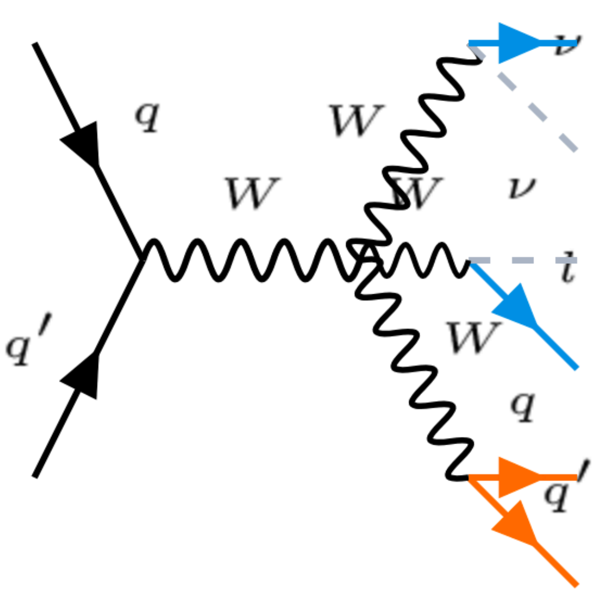
INTRODUCTION AND MOTIVATION

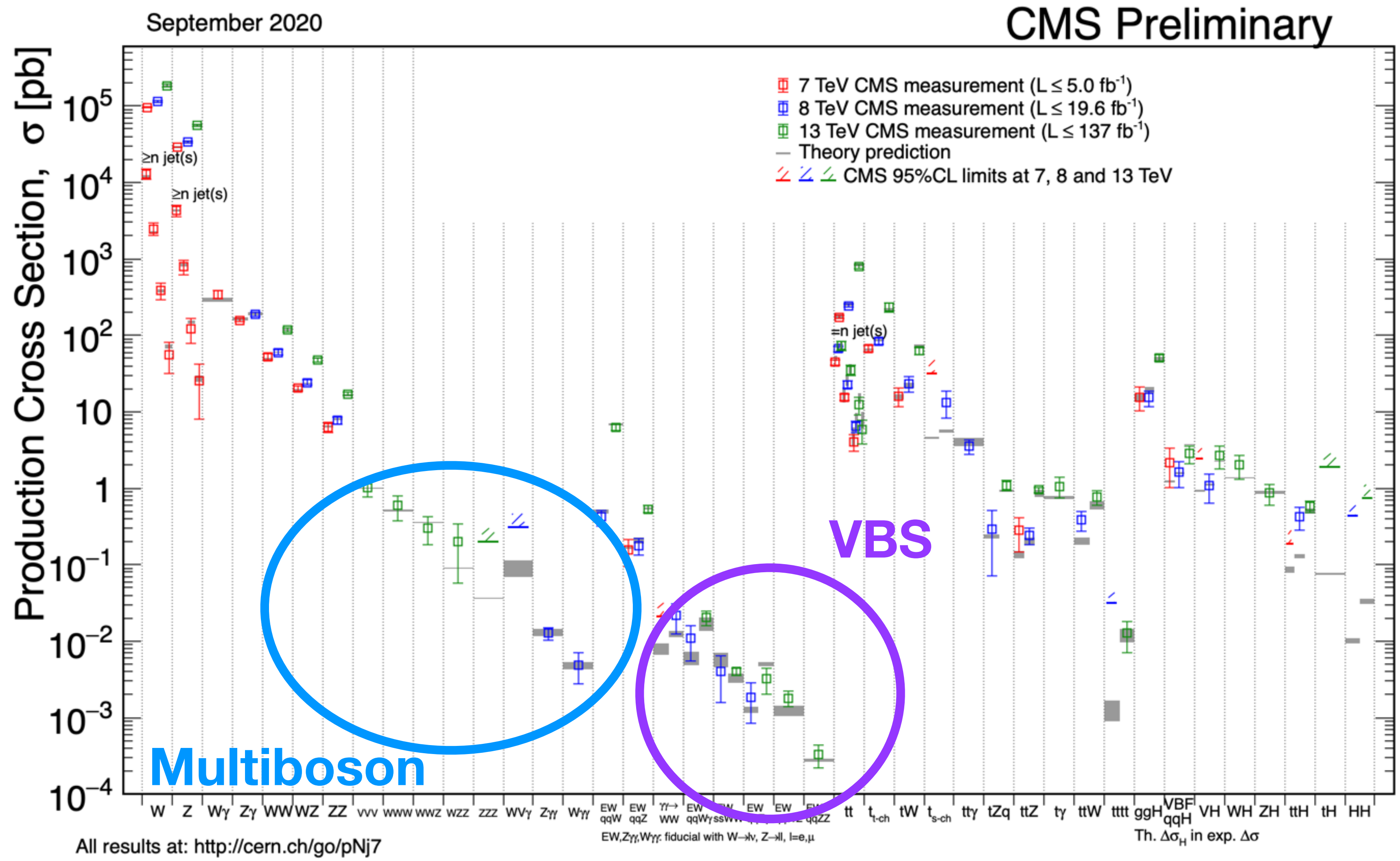
- Non-abelian gauge structure of the SM allows for **vector boson self interactions** → Triple (TGC) and Quartic Gauge Couplings (QGC)
- Multiboson final states important test of the **electro-weak sector** of the Standard Model → Precise measurement of the coupling values
- Probing the strength of the couplings is an **indirect search for new physics**
- Many multiboson final states are **backgrounds** to searches for new physics → Fundamental to have a detailed description
- Two main groups of processes: QCD production and Vector Boson Scattering (VBS)



EXPERIMENTAL CHALLENGES

- Multiboson processes have a very **low cross section** → High statistics is needed, CMS Run2 140 fb^{-1}





- Complex final state → High particle multiplicity

- **High precision** needed in the measurements → Small deviations can be linked to the presence of new physics, **EFT interpretation**

- Measurement of inclusive cross sections and evidence/observation of processes never measured before

VVV

- Measure both inclusive and single channel cross sections

$WWW \to l^{\pm}l^{\pm}\, 2\nu\, qq'$

- 2 same sign (SS) leptons, ≥ 1 jets
- 9 categories: lepton flavour (ee, eμ, μμ), 1 jet and 2 jets with $65 < m_{jj} < 95$ GeV and outside
- Backgrounds: lost lepton, SS leptons + jets, nonprompt

$W^{\pm}W^{\mp}Z \to l^{\pm}l^{\mp}\, 2\nu\, (l^{\pm}l^{\mp})$

- SFOS lepton pair with mll within 10 GeV of M_Z
- Dominant background from ZZ production

$WWW \to l^{\pm}l^{\pm}l^{\mp}\, 3\nu$

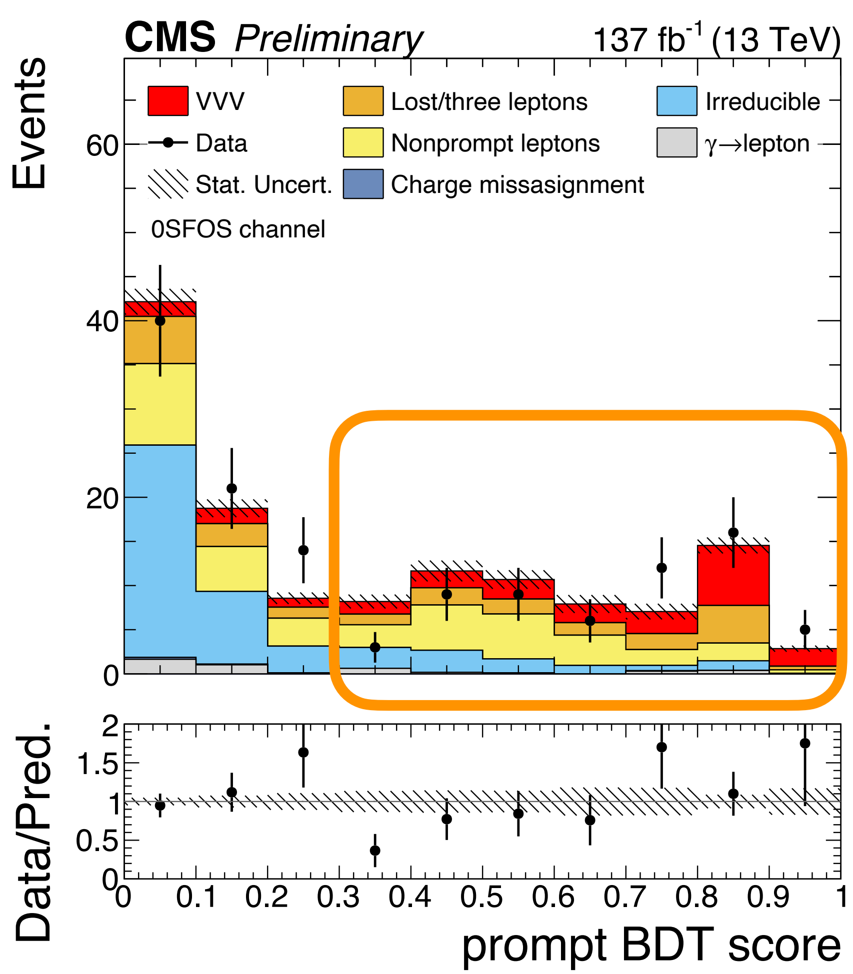
- 0, 1 or 2 same-flavour opposite charge lepton pairs (SFOS)
- m_{ll} incompatible with M_Z
- Backgrounds: lost lepton, SS leptons + jets, nonprompt

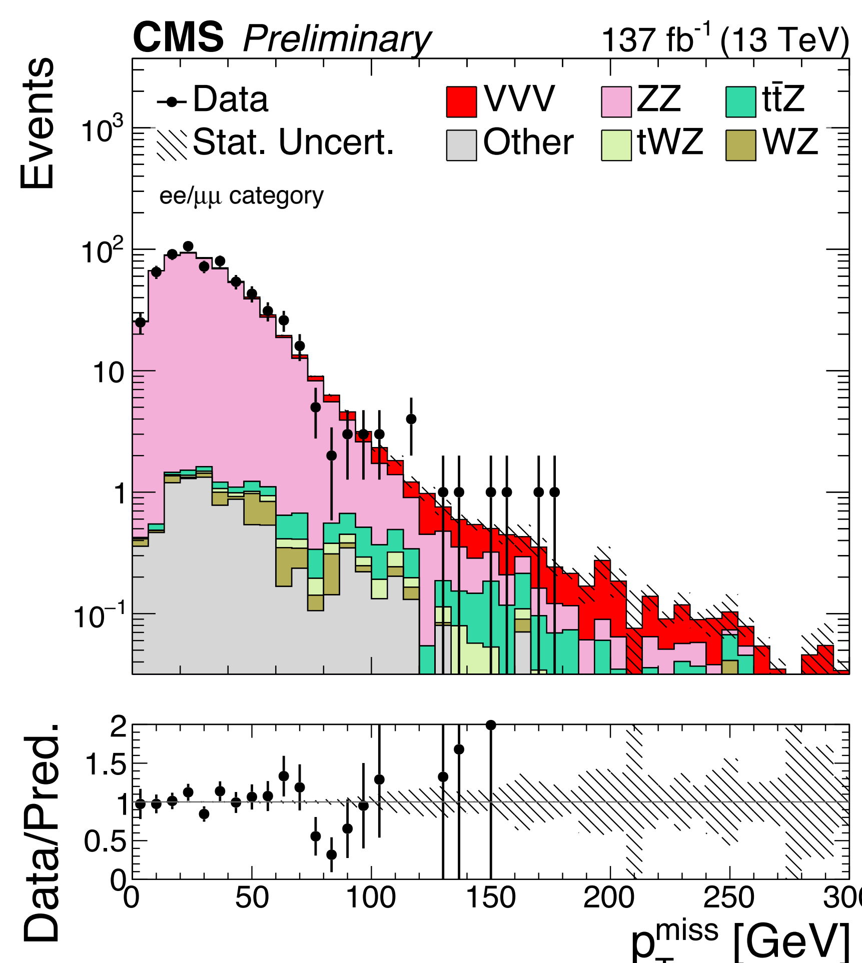
$WZZ \to l\nu\, (l^{\pm}l^{\mp})\, (l^{\pm}l^{\mp})$
$ZZZ \to (l^{\pm}l^{\mp})\, (l^{\pm}l^{\mp})\, (l^{\pm}l^{\mp})$

- Very small cross sections and BR
- 5l: must have 2 SFOS close to M_Z, $p_T^{miss} > 50$ GeV, backgrounds from ZZ and nonprompt leptons
- 6l: 3 SFOS pairs, very small background from ttH and ZZ

VVV

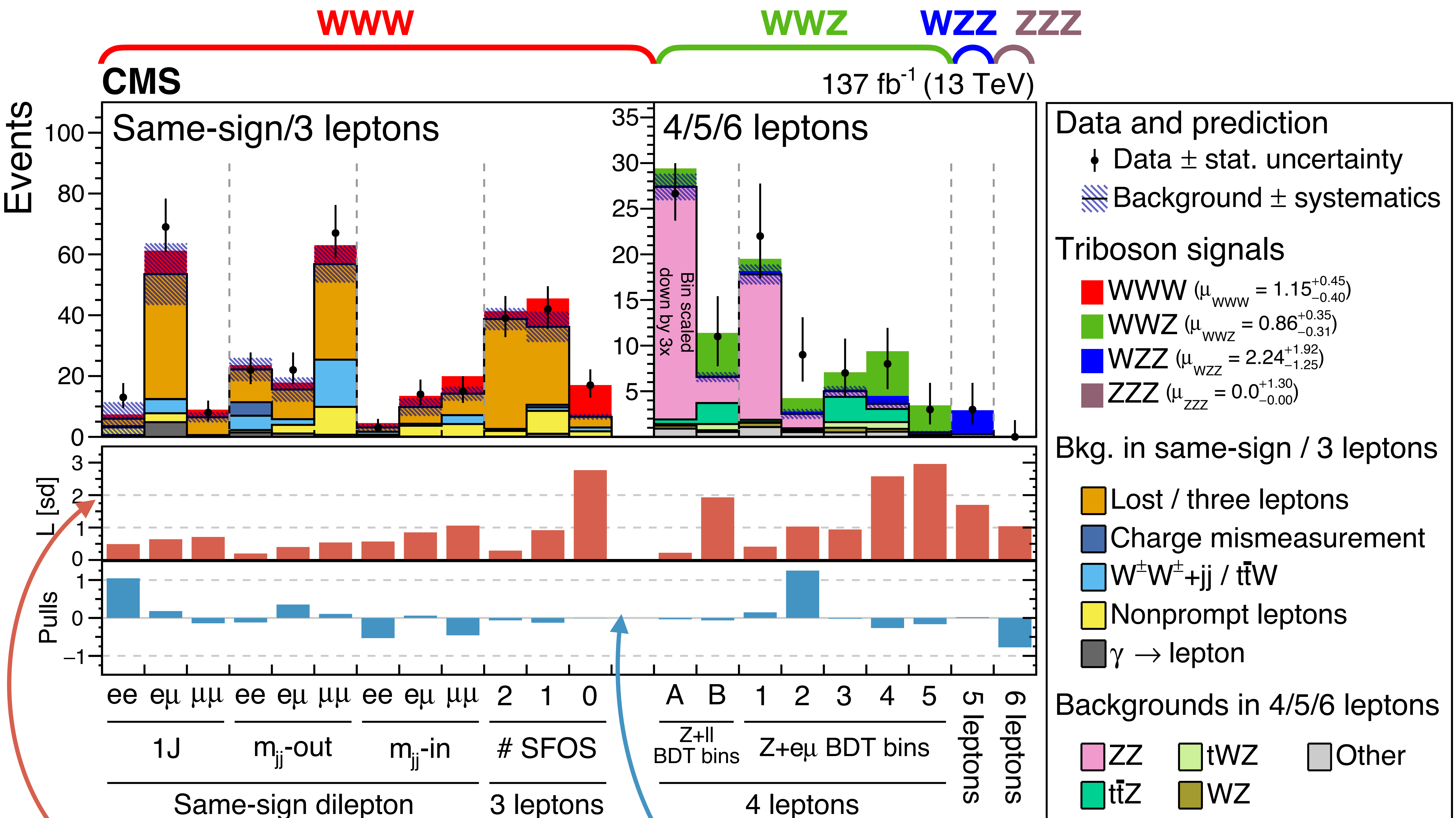
- Non-prompt lepton background **estimated form data** exploiting isolation variables
- **Boosted Decision Tree** trained with simulated background and signal
  - Two BDT applied in sequence for channels with more than one background categories (for WWW: nonprompt and others)
- 4l WWZ category main background contribution from ZZ → p_T^{miss} cut





- Systematic uncertainties
  - Limited statistic in control regions 5-25%
  - Nonprompt bkg estimation up to 50%
  - Higher order corrections and PDFs 3-15%

VVV

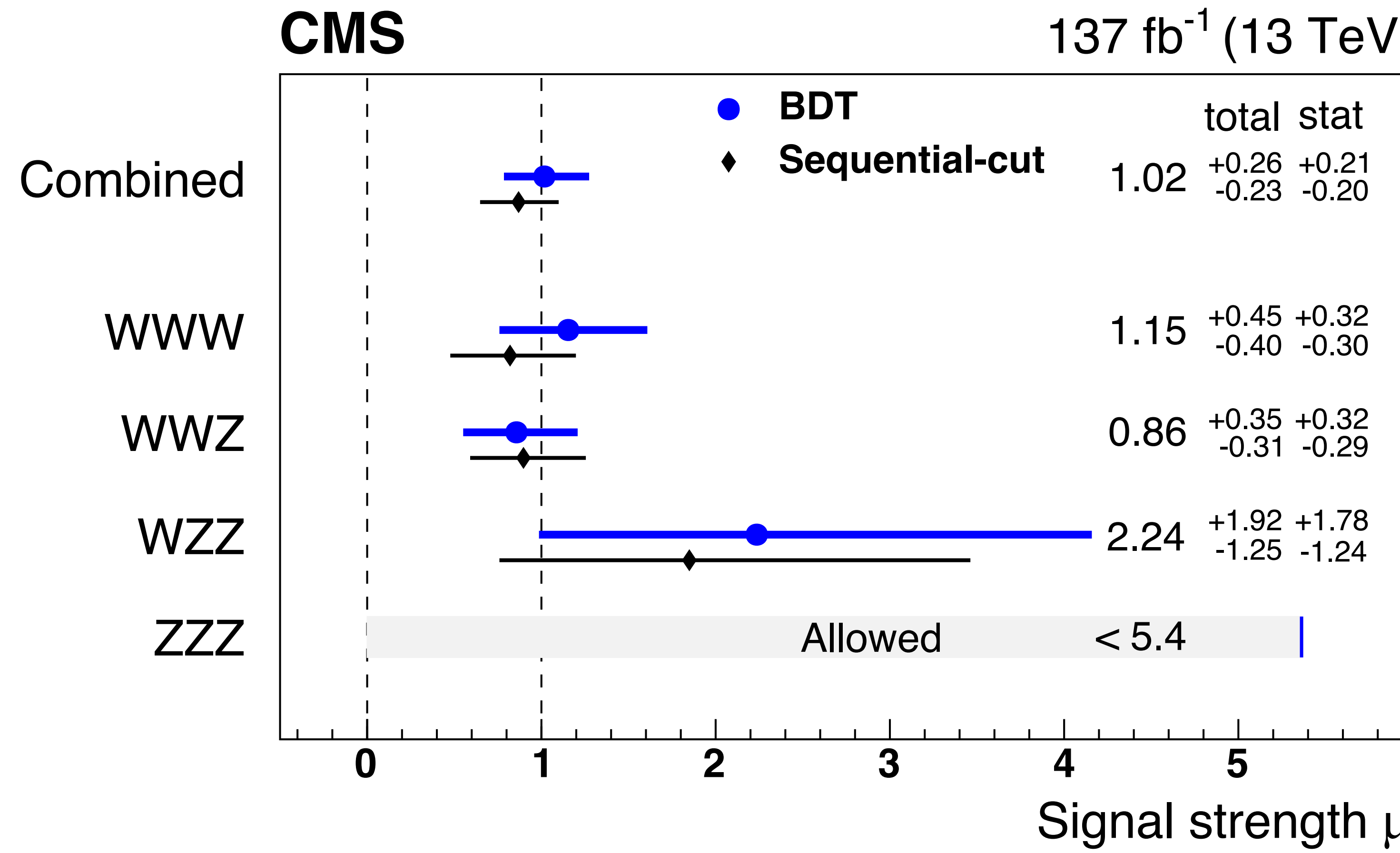


L: expected significance
in single channel

Pulls: difference between
observed and predicted

VVV

- Measured signal strength in agreement with SM prediction
- Discrimination of signal and background enhanced with BDT approach



Channel	Cross section (fb)
Higgs boson contributions as signal	
VVV	$1010^{+210}_{-200}{}^{+150}_{-120}$
WWW	$590^{+160}_{-150}{}^{+160}_{-130}$
WWZ	$300^{+120}_{-100}{}^{+50}_{-40}$
WZZ	$200^{+160}_{-110}{}^{+70}_{-20}$
ZZZ	<200
Higgs boson contributions as background	
VVV	$370^{+140}_{-130}{}^{+80}_{-60}$
WWW	$190^{+110}_{-100}{}^{+80}_{-70}$
WWZ	$100^{+80}_{-70}{}^{+30}_{-30}$
WZZ	$110^{+100}_{-70}{}^{+30}_{-10}$
ZZZ	<80

Observed (expected) significances

Channel	Cut-and-count	BDT
WWW *	2.5 (2.9)	3.3 (3.1)
WWZ	3.5 (3.6)	3.4 (4.1)
WZZ	1.6 (0.7)	1.7 (0.7)
ZZZ	0.0 (0.9)	0.0 (0.9)

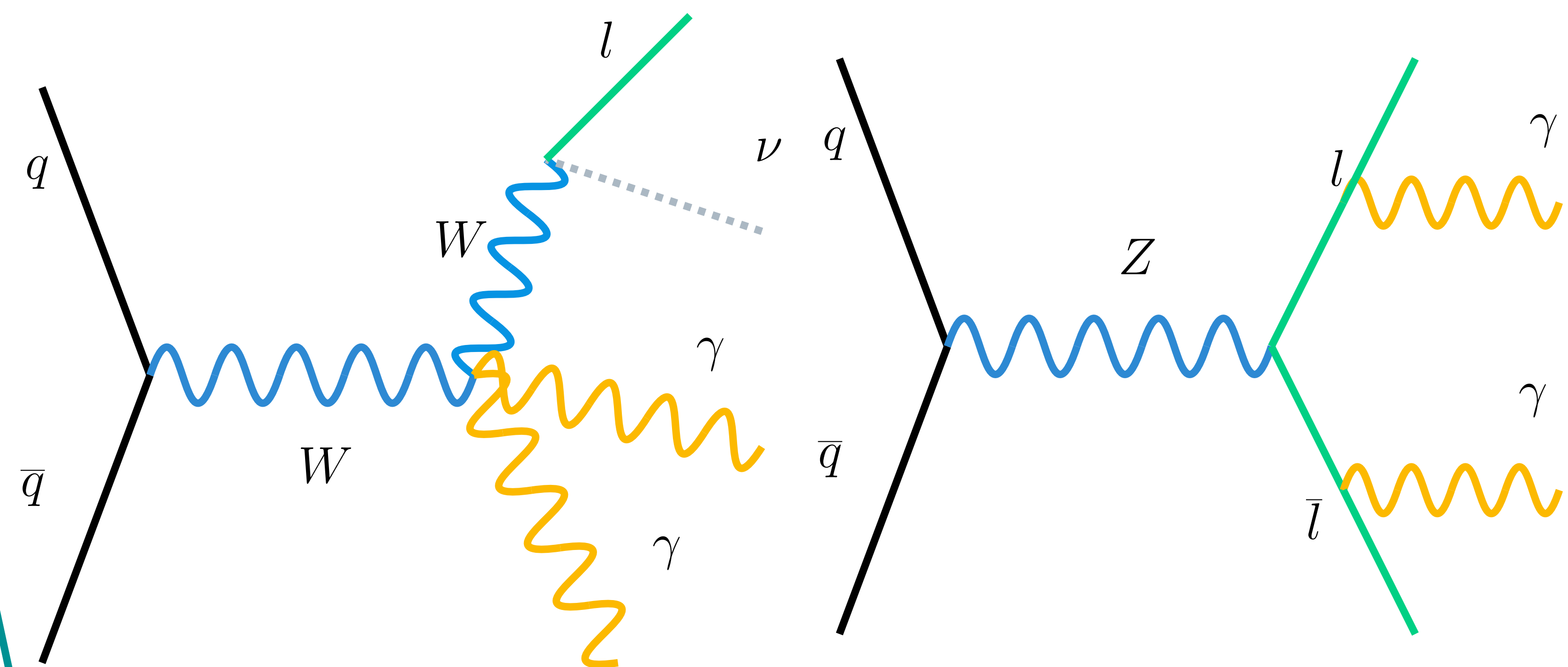
* 2016 only (35.9 fb^{-1}) result: 0.60 (1.78)

13 TeV 137 fb^{-1}

CMS-PAS-SMP-19-013

$V\gamma\gamma$

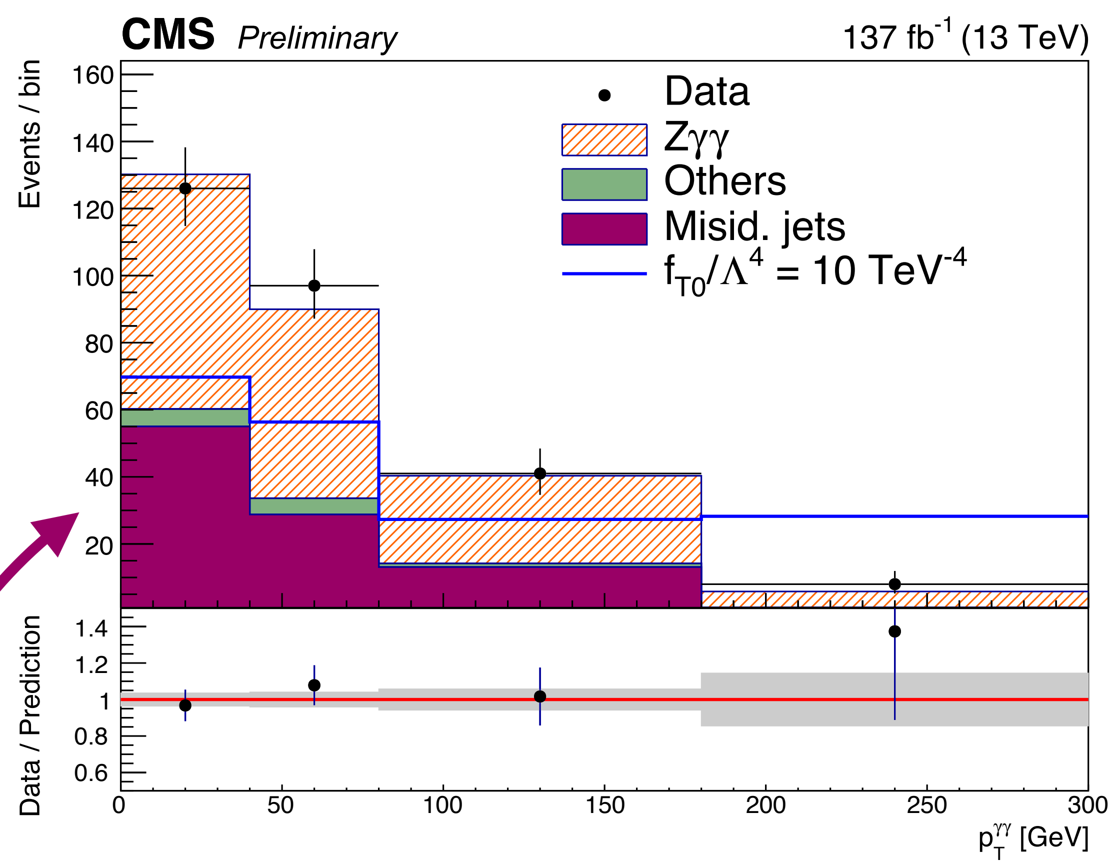
- Selection
  - W → One isolated electron (muon) with p_T > 35 (30) GeV
  - Z → Two opposite-sign same-flavour electrons (muons) with p_T^{lead} > 35 (30) GeV
  - Two photons with p_T > 20 GeV, $|M_{e+\gamma(\gamma)} - M_Z| > 5$ GeV, isolated from e and μ



- Study of the non-abelian structure of the electroweak sector of the SM
  - Sensitive to the presence of many different aQGC
    - Possible background of VH measurements ($H \rightarrow \gamma\gamma$)

$V\gamma\gamma$

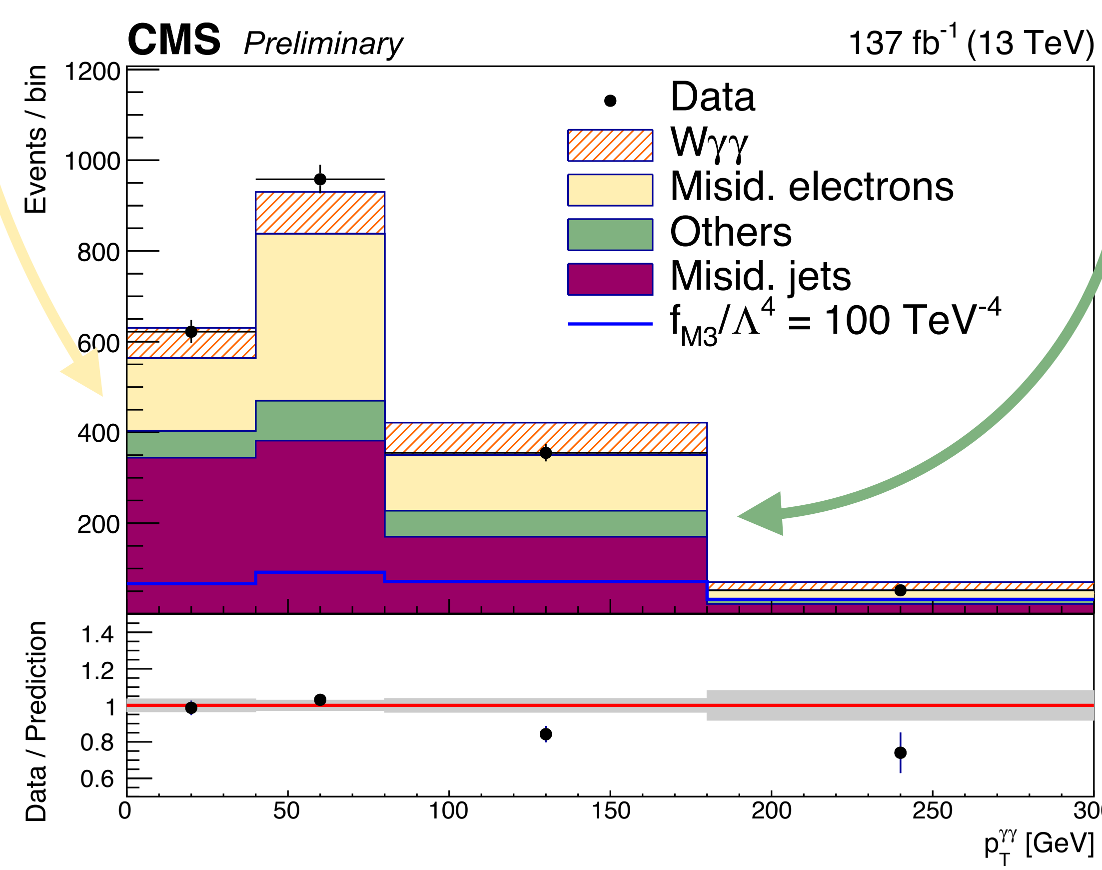
- Backgrounds



- Jet-photon misidentification → Data driven estimate from single photons events by exploiting isolation properties and then extrapolated to the di-photon signal region

- Electron-photon misidentification (mainly W(ev)$\gamma\gamma$ channel) → Exploit e+γ Z-like events to correct the Zγ simulation

- Other irreducible backgrounds from events with true photons



$V\gamma\gamma$

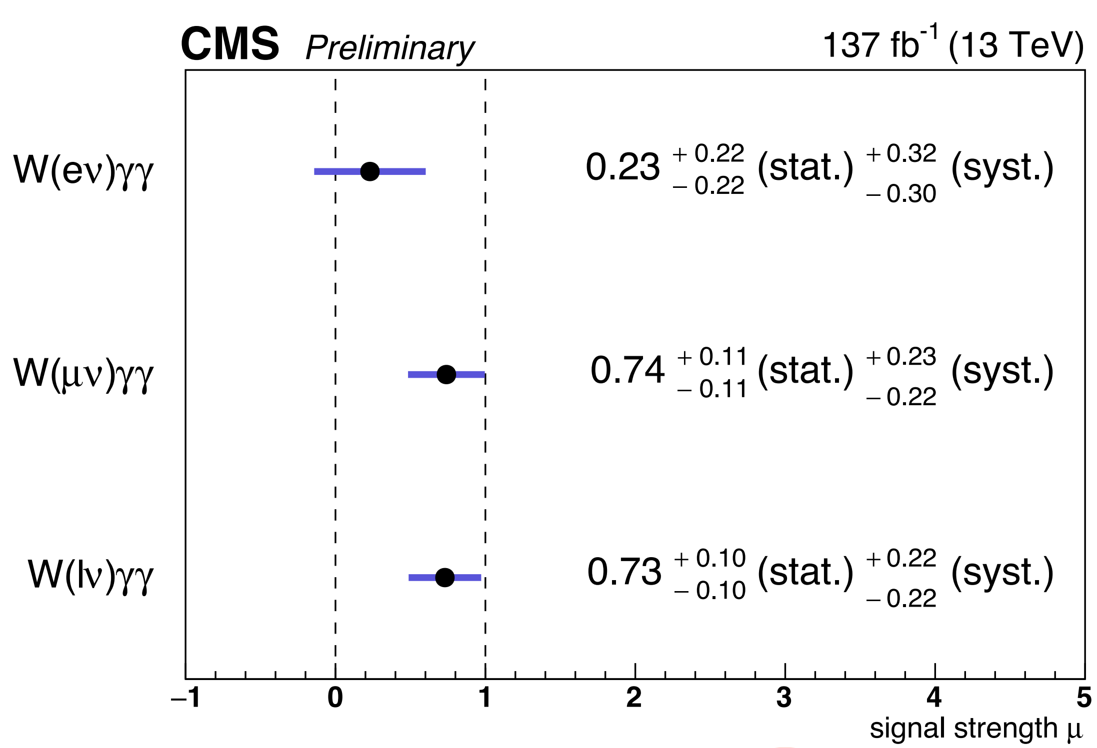
- Inclusive cross sections measured for the electron, muon channels separately and then combined

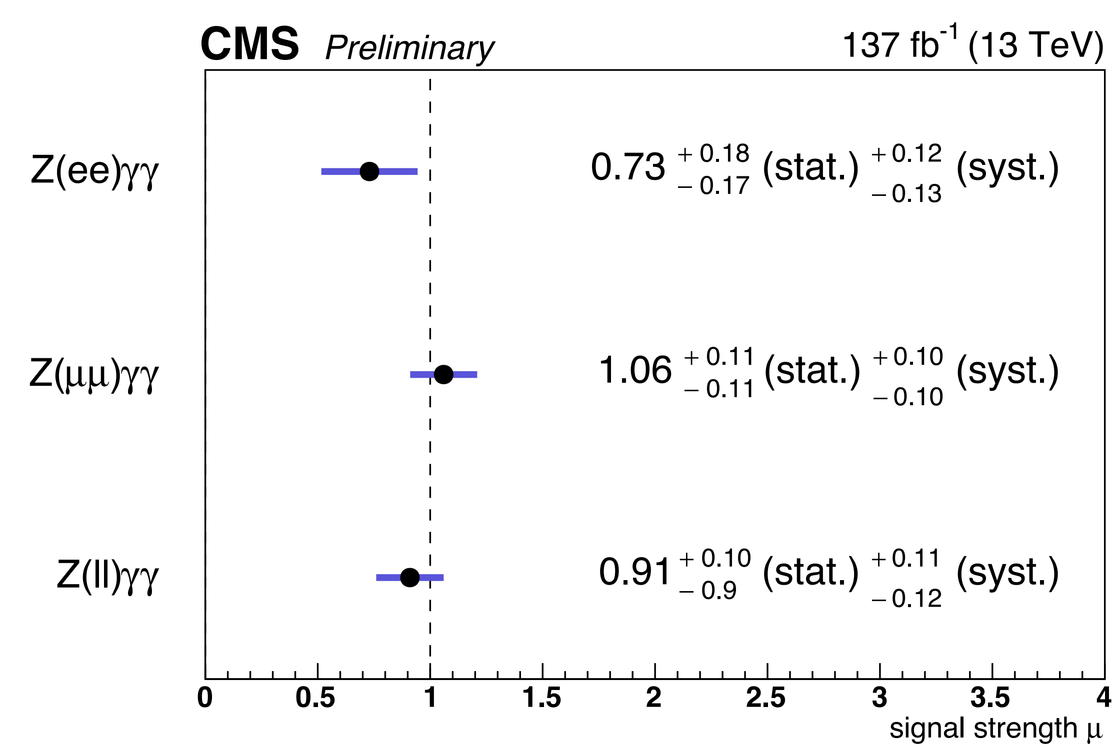
$$\sigma_{W\gamma\gamma} = 13.63^{+1.93}_{-1.89}\,(\text{stat})^{+4.04}_{-4.02}\,(\text{syst}) \pm 0.08\,(\text{PDF} + \text{scale})\,\text{fb}$$

$$\sigma_{Z\gamma\gamma} = 5.41^{+0.58}_{-0.54}\,(\text{stat})^{+0.64}_{-0.70}\,(\text{syst}) \pm 0.06\,(\text{PDF} + \text{scale})\,\text{fb}$$

- Results in agreement with SM prediction

- Systematic uncertainties
  - Data-driven jet-photon misidentification background estimation ($W\gamma\gamma$ 21%, $Z\gamma\gamma$ 6%)
  - Photon scale factors ($W\gamma\gamma$ 12%, $Z\gamma\gamma$ 5%)





FIRST EVIDENCE OF $W\gamma\gamma$ PROCESS

$W\gamma\gamma$	**Observed (expected) significance**	$Z\gamma\gamma$
3.1 (4.5) σ		4.8 (5.8) σ

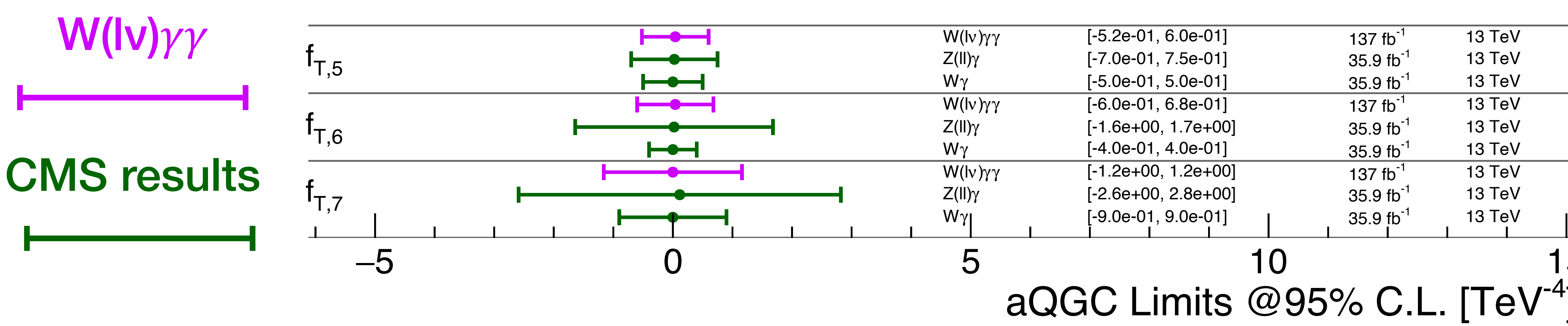
$V\gamma\gamma$

- Di-photon distribution exploited for limits computation
- High $p_T^{\gamma\gamma}$ region most sensitive to the presence of aQGC

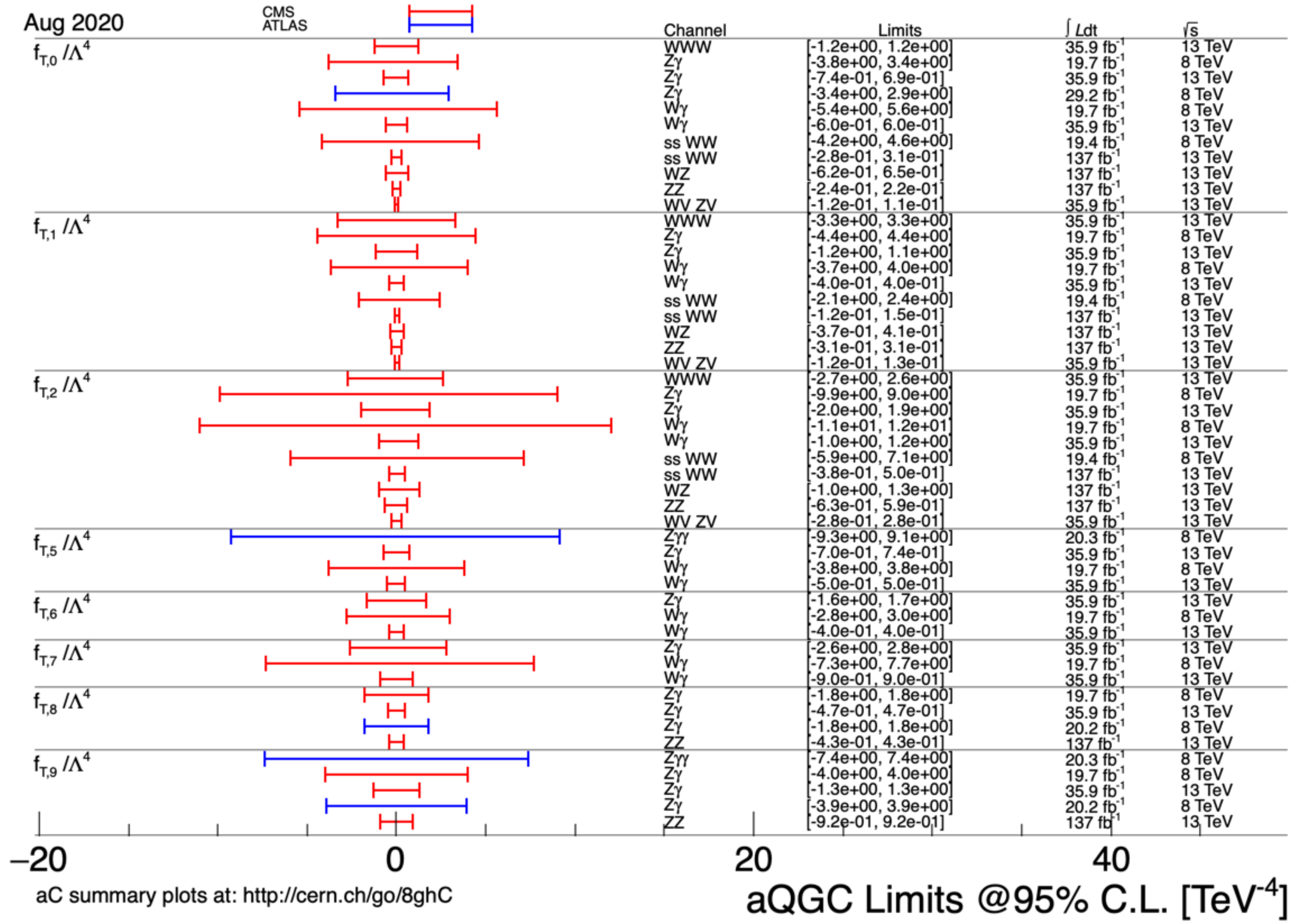
Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	$W\gamma\gamma$ (TeV^{-4}) Observed	$Z\gamma\gamma$ (TeV^{-4}) Expected	$Z\gamma\gamma$ (TeV^{-4}) Observed
$f_{M,2}/\Lambda^4$	$[-57.3, 57.1]$	$[-39.9, 39.5]$	-	-
$f_{M,3}/\Lambda^4$	$[-91.8, 92.6]$	$[-63.8, 65.0]$	-	-
$f_{T,0}/\Lambda^4$	$[-1.86, 1.86]$	$[-1.30, 1.30]$	$[-4.86, 4.66]$	$[-5.70, 5.46]$
$f_{T,1}/\Lambda^4$	$[-2.38, 2.38]$	$[-1.70, 1.66]$	$[-4.86, 4.66]$	$[-5.70, 5.46]$
$f_{T,2}/\Lambda^4$	$[-5.16, 5.16]$	$[-3.64, 3.64]$	$[-9.72, 9.32]$	$[-11.4, 10.9]$
$f_{T,5}/\Lambda^4$	$[-0.76, 0.84]$	$[-0.52, 0.60]$	$[-2.44, 2.52]$	$[-2.92, 2.92]$
$f_{T,6}/\Lambda^4$	$[-0.92, 1.00]$	$[-0.60, 0.68]$	$[-3.24, 3.24]$	$[-3.80, 3.88]$
$f_{T,7}/\Lambda^4$	$[-1.64, 1.72]$	$[-1.16, 1.16]$	$[-6.68, 6.60]$	$[-7.88, 7.72]$
$f_{T,8}/\Lambda^4$	-	-	$[-0.90, 0.94]$	$[-1.06, 1.10]$
$f_{T,9}/\Lambda^4$	-	-	$[-1.54, 1.54]$	$[-1.82, 1.82]$

First time ever with $Z\gamma\gamma$ channel

Competitive results



SUMMARY



- With LHC Run 2 data, multi-boson processes accessible
- **Cross sections measured** for many different processes
- **Limits on anomalous couplings** more and more stringent, increased sensitivity on new physics processes
- **First observation of massive triboson processes @ 13TeV**
- **First evidence of $W\gamma\gamma$, observation of $Z\gamma\gamma$ @ 13TeV**

Backup

RESULTS INTERPRETATION

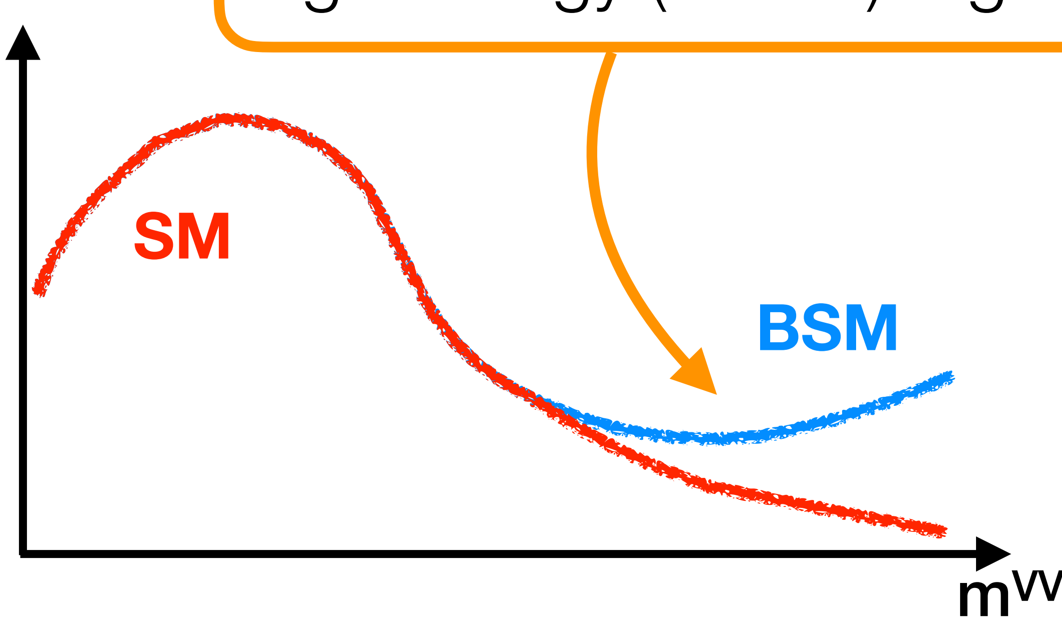
- Presence of effects beyond the SM (BSM) can change the value of the couplings
  → **Anomalous Gauge Couplings**

- **Effective Field Theories** (EFT) provide a model-independent extension of the SM

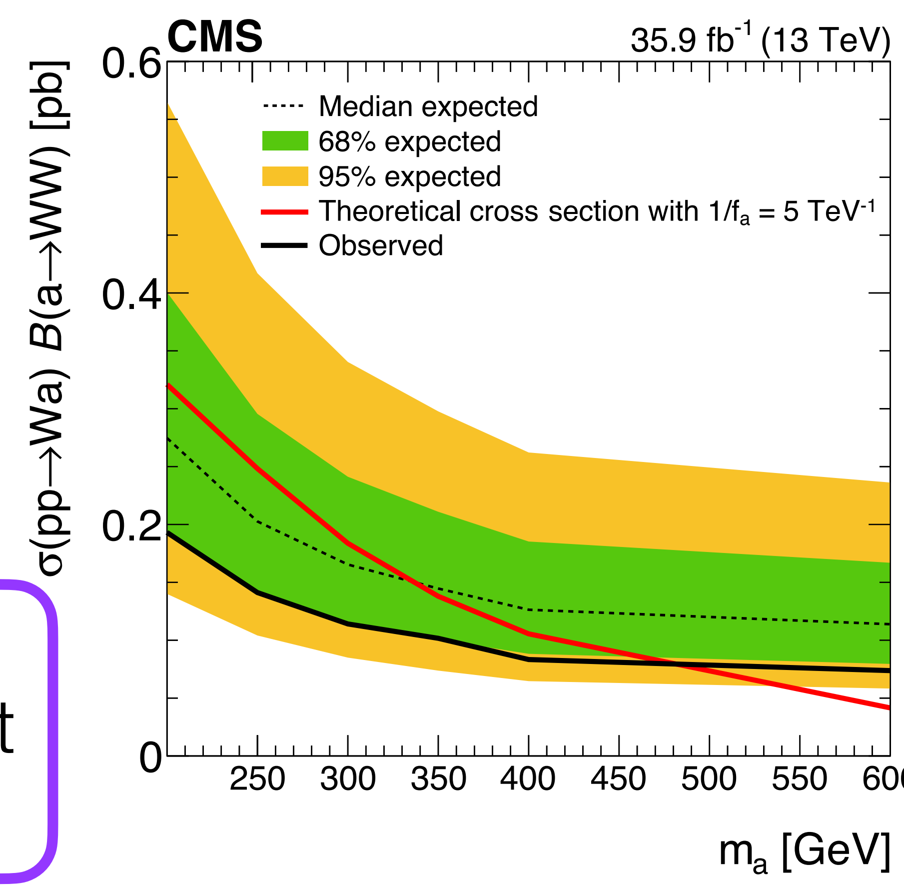
$$\mathscr{L}_{aQGC} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^{d-4}} O_i + \ldots$$

Λ is the energy scale of the new physics, d is the dimension of the operator,
f_i is the strength of the coupling

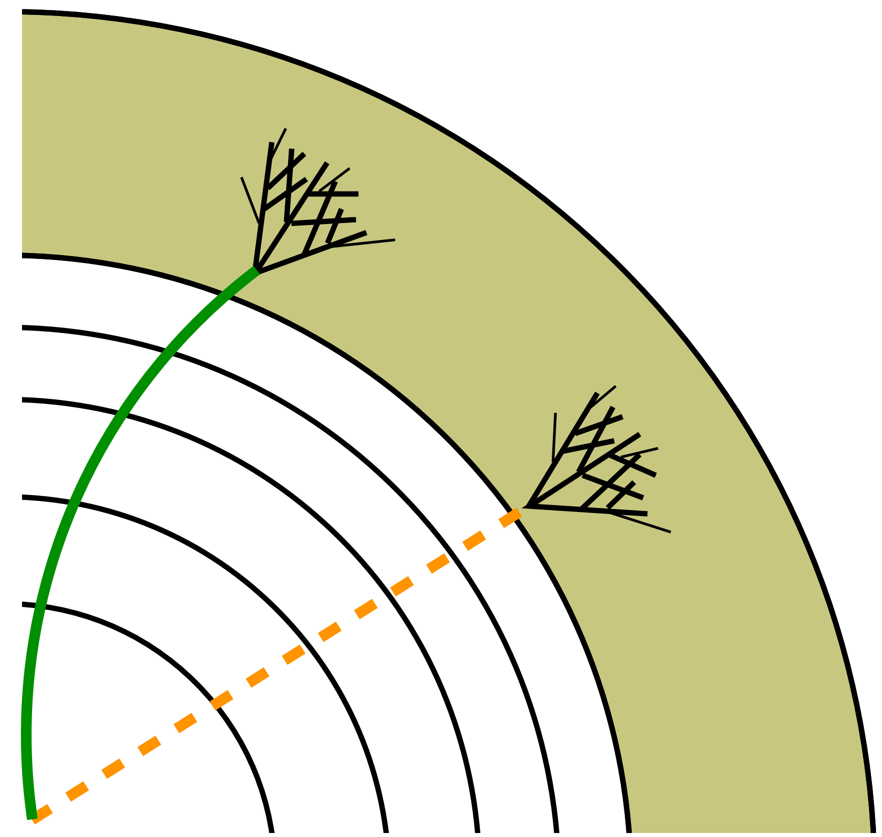
aGC effect enhanced for high-energy (-mass) regions



Probe explicit BSM models at high energies

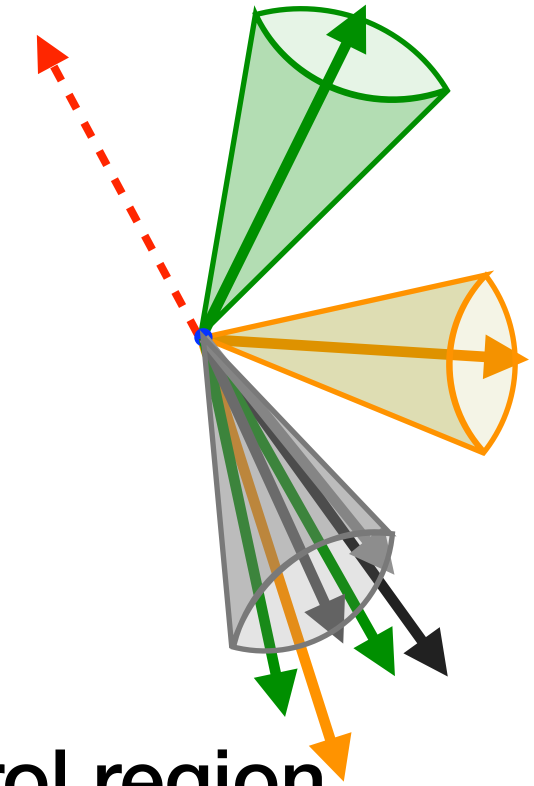


ELECTRON-PHOTON MISID



- An electron that **does not leave a track** in the tracker, but only an energy deposit in the electromagnetic calorimeter
- Simulation of the process in the Drell-Yan samples is not perfect → Correct in a **data-driven** way
- Procedure:
  - Extract **“fake” Z mass e+γ** in differential region of photon momentum and pseudorapidity in data and Monte Carlo
  - **Fit distribution** with template + background model → Systematics from analytical fit with double Crystal-Ball shape
  - Obtain a **correction factor** by comparing the number of events in the Z peak in data and simulation
  - **Correct the simulated photons** that match a generated electron for the correction factor obtained in this way

Jet-photon misid



- A **jet initiated by a neutral particle** (for example a π^0) that releases energy in the electromagnetic calorimeter has the same signature of a photon

- Use **shower shape distributions of photons in a control region** (no isolation requirement, enhance contribution of jets) in the MC to estimate the contribution of the jet-photon misid

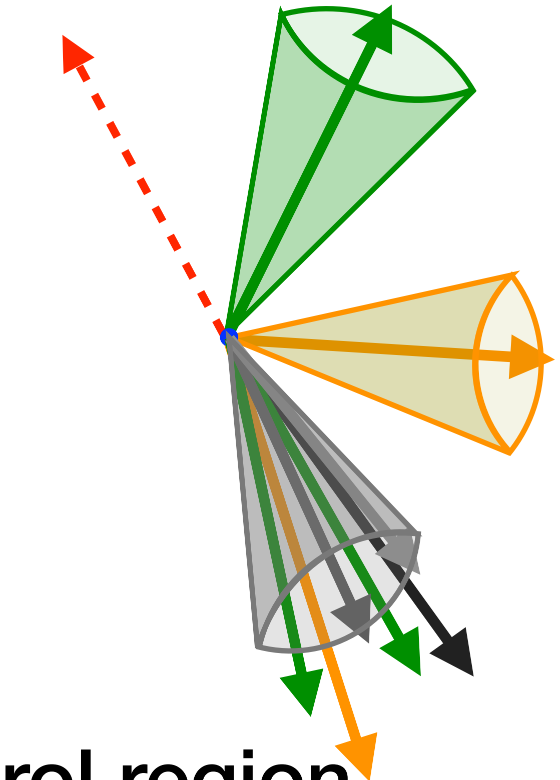
Use a variable that can discriminate photons form jets: isolation

Categorise both data and simulation in signal (Tight) and control (Loose) regions

Exploit single-photon control region to compute isolation probabilities ϵ and f

Estrapolate the background fraction to two-photon control region

JET-PHOTON MISID



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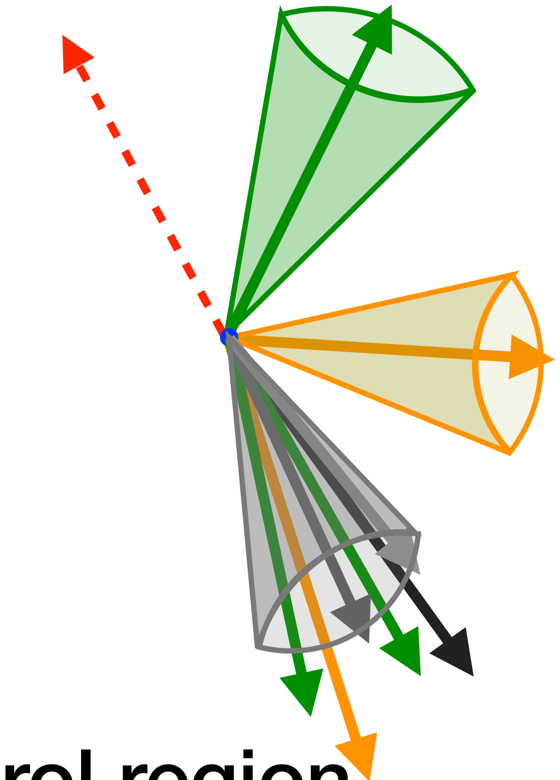
Probabilities for a photon to be isolated in single photon control region

Composition of the di-photon region in terms of "true" events and jet-photon misid ones

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1(1-\epsilon_2) & \epsilon_1(1-f_2) & f_1(1-\epsilon_2) & f_1(1-f_2) \\ (1-\epsilon_1)\epsilon_2 & (1-\epsilon_1)f_2 & (1-f_1)\epsilon_2 & (1-f_1)f_2 \\ (1-\epsilon_1)(1-\epsilon_2) & (1-\epsilon_1)(1-f_2) & (1-f_1)(1-\epsilon_2) & (1-f_1)(1-f_2) \end{pmatrix} \cdot \begin{pmatrix} N_{\gamma\gamma} \\ N_{\gamma j} \\ N_{j\gamma} \\ N_{jj} \end{pmatrix}$$

Number of events with two photons categorised by isolation in data

JET-PHOTON MISID



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Invert and extract composition of the signal region

SYSTEMATIC UNCERTAINTIES

Table 1: Summary of the systematic uncertainties (in %) for the $W\gamma\gamma$ and the $Z\gamma\gamma$ cross section measurements. The numbers indicate the impact of each systematic uncertainty on the value of the measured cross section in the corresponding channel.

Systematic source	$e\nu_e\gamma\gamma$	$\mu\nu_\mu\gamma\gamma$	$l\nu\gamma\gamma$	$ee\gamma\gamma$	$\mu\mu\gamma\gamma$	$ll\gamma\gamma$
Luminosity	< 1	2	2	3	1	3
Pile-up	2	< 1	< 1	2	< 1	1
Electron SF	4	< 1	< 1	3	< 1	1
Muon SF	1	< 1	< 1	2	< 1	1
Photon SF	18	13	12	6	5	5
Jet-photon misid.	25	22	21	6	5	6
Electron-photon misid.	4	< 1	< 1	-	-	-
$W\gamma$ theoretical cross section	3	3	3	< 1	< 1	< 1
$Z\gamma$ theoretical cross section	4	< 1	< 1	7	5	6
Other bkgs theoretical cross section	5	2	2	< 1	< 1	< 1
Monte Carlo statistics	18	7	8	7	3	4