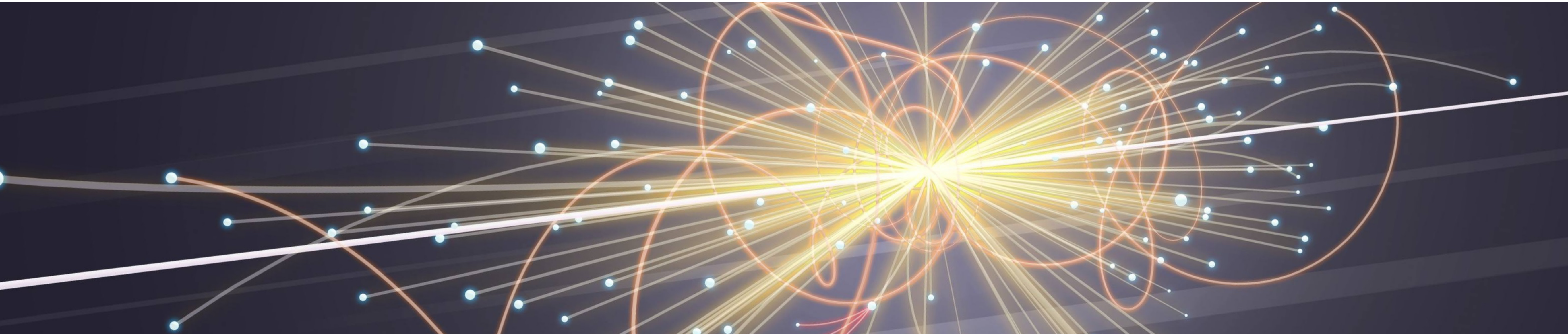
Multiboson measurements with Run 2 data at CMS



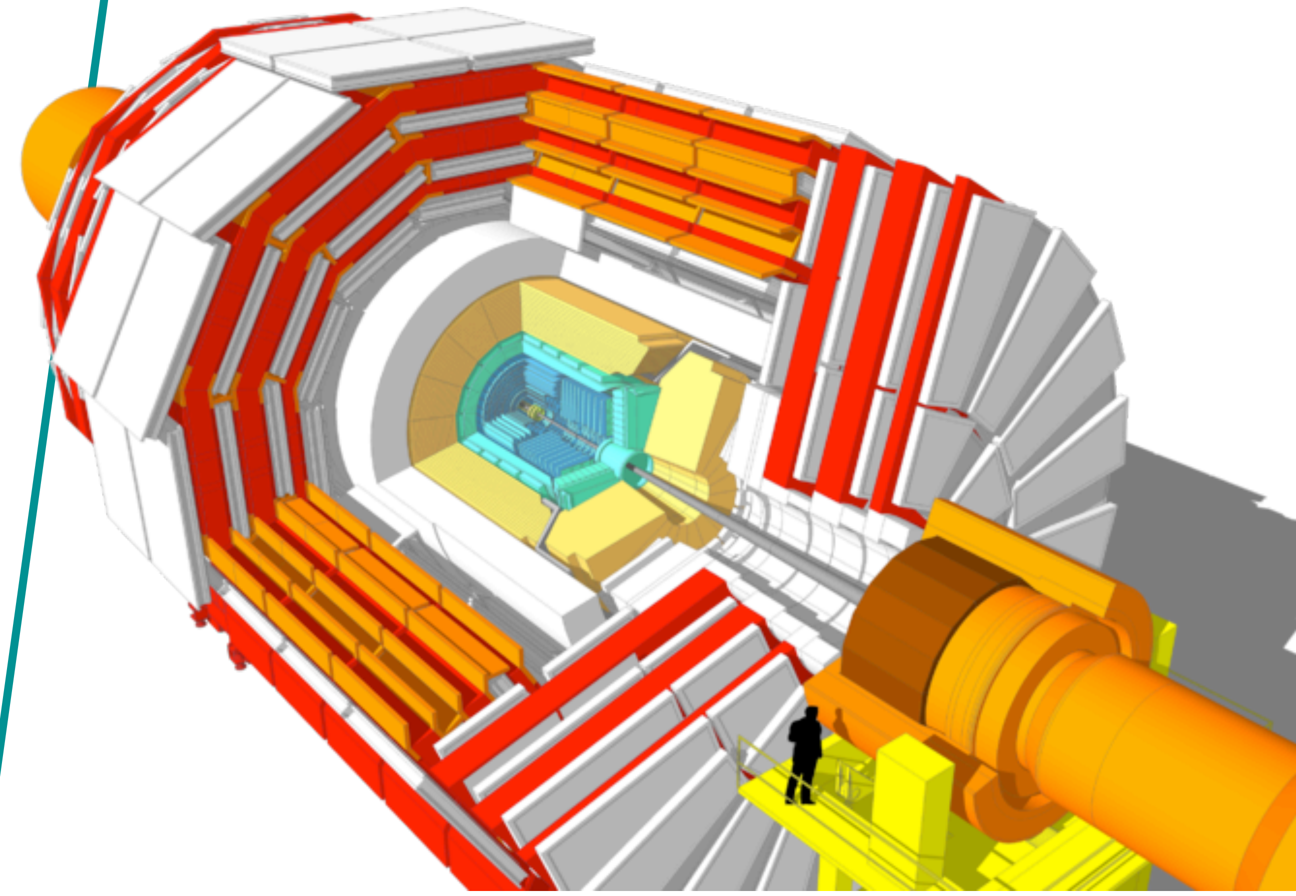
Alessandro Da Rold, on behalf of the CMS Collaboration

LHCP 2020

Paris (Virtual), 27 May 2020

OVERVIEW

- **Introduction**
  - Introduction and motivation
  - Experimental features
  - EFT and interpretation of results
- **Multi-boson analyses**
  - W^+W^- CMS-PAS-SMP-18-004
  - VVV CMS-PAS-SMP-19-014
  - WWW CERN-EP-2019-074



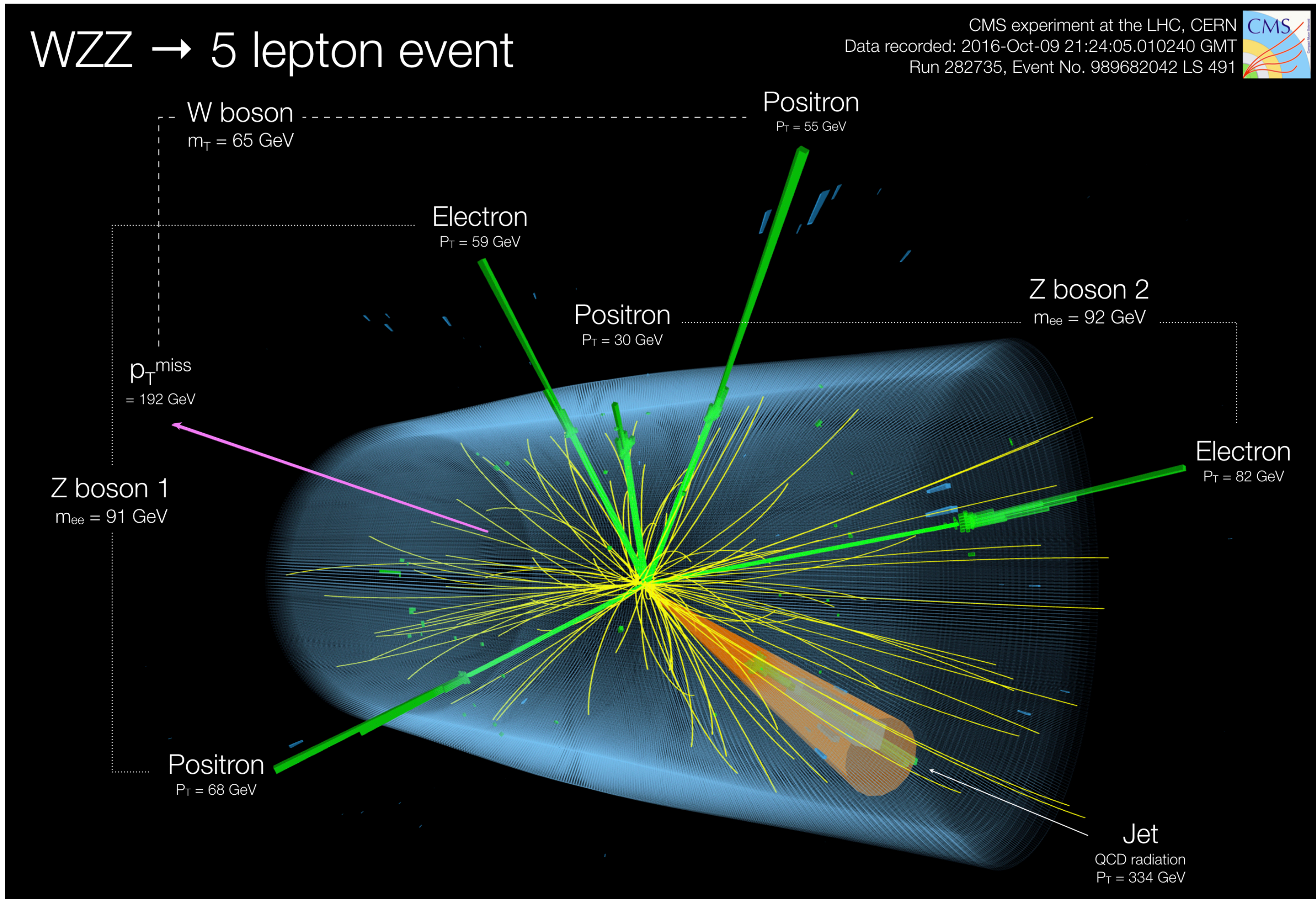
Vector Boson Scattering

↓

See Mariarosaria's talk on Friday!

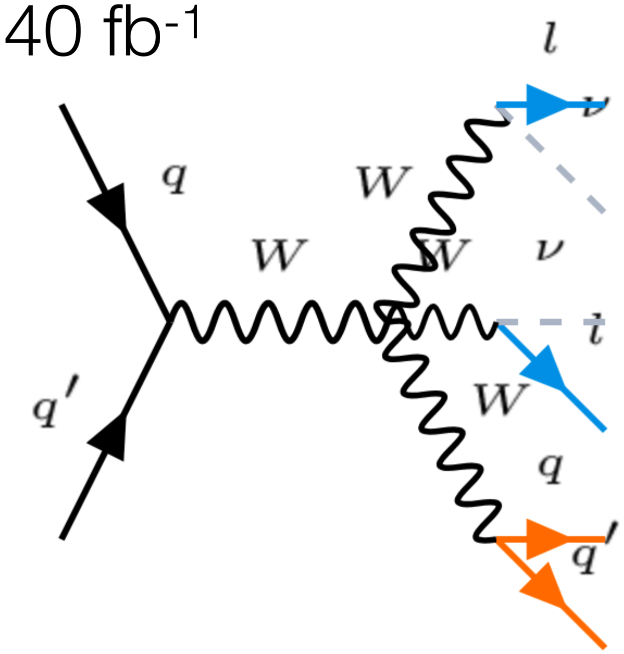
INTRODUCTION AND MOTIVATION

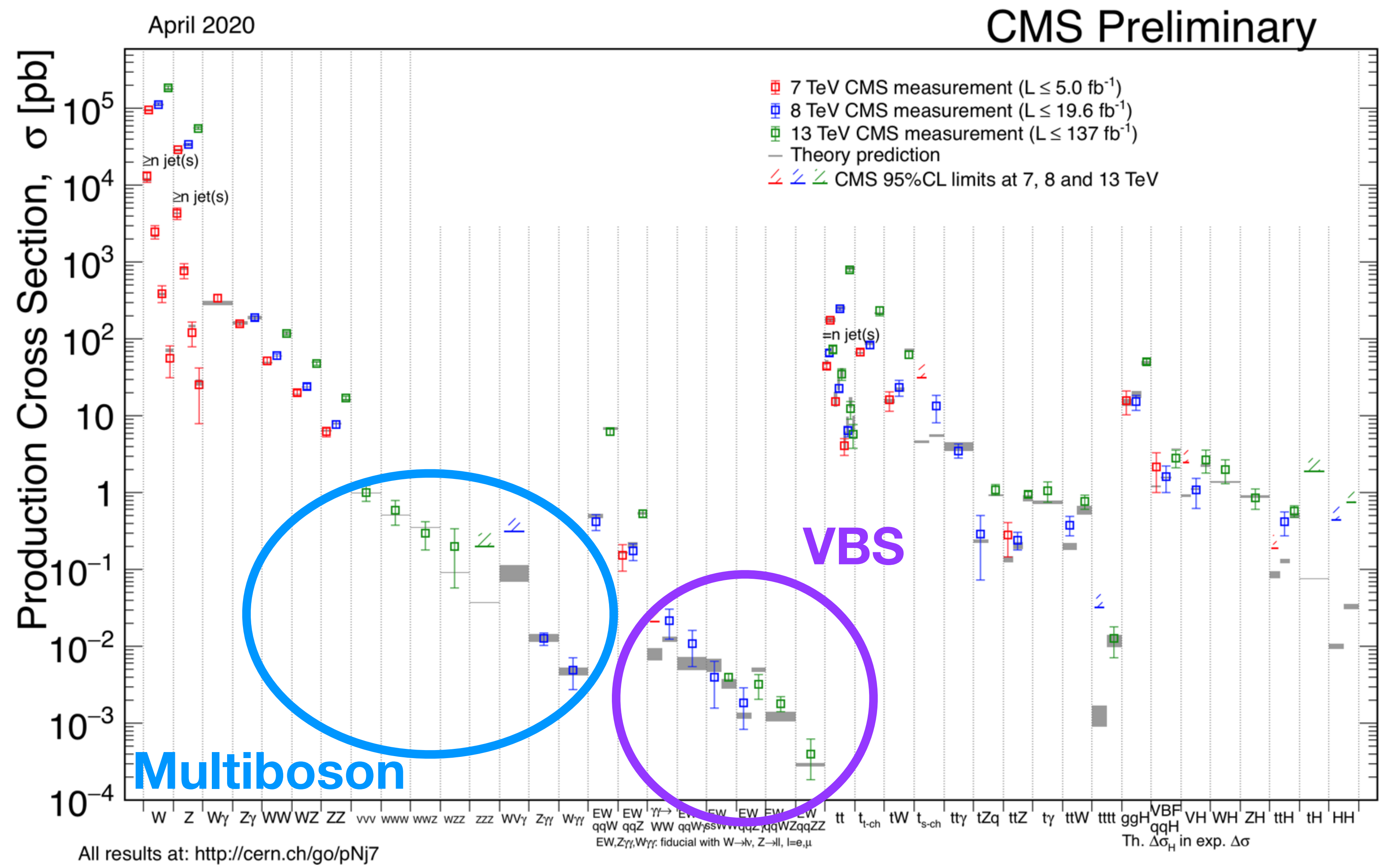
- Non-abelian gauge structure of the SM allows for **vector boson self interactions** ➞ Triple (TGC) and Quartic Gauge Couplings (QGC)
- Multiboson final states important test of the **electro-weak sector** of the Standard Model ➞ Precise measurement of the coupling values
- Probing the strength of the 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)

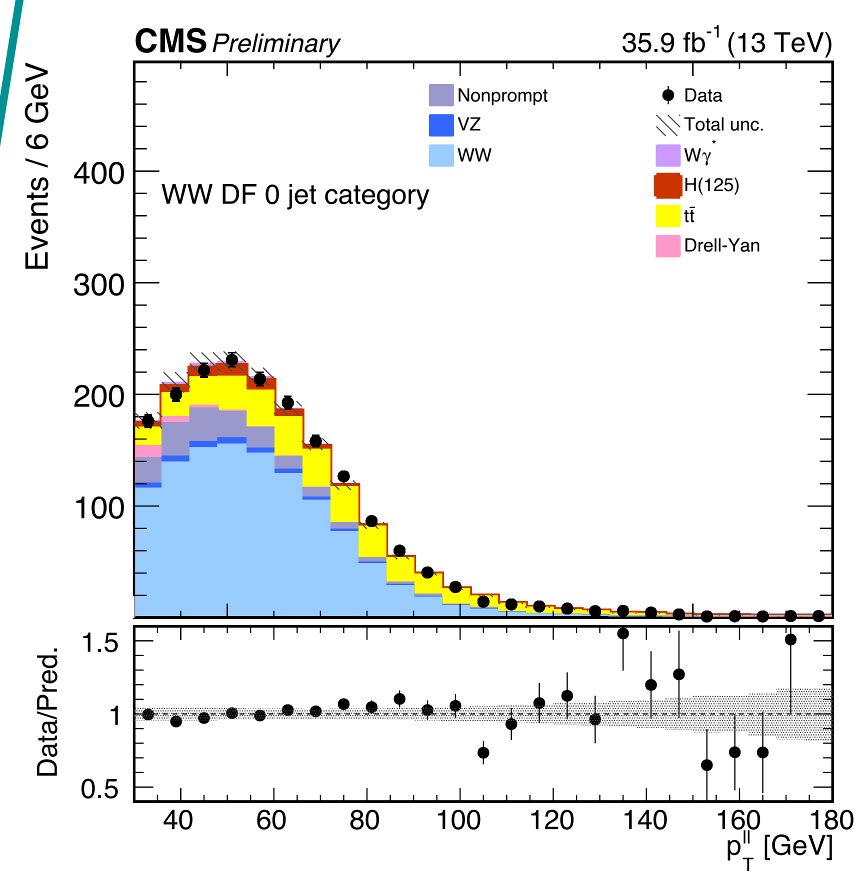
- **High precision** needed in the measurements → Small deviations can be linked to the presence of new physics, **EFT interpretation**

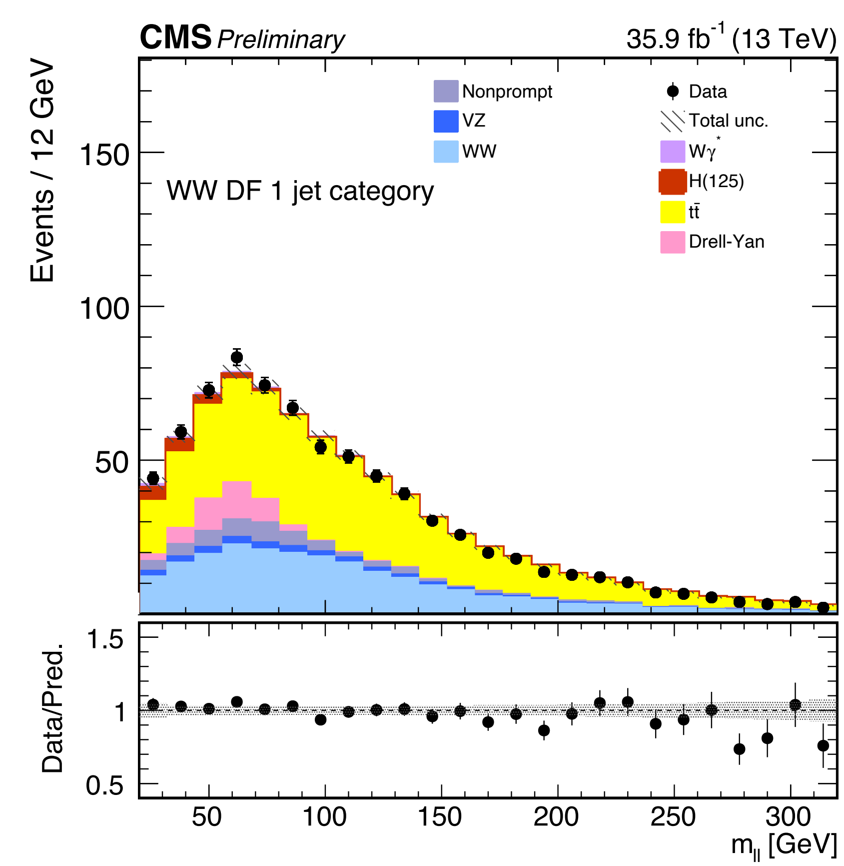
- Measurement of inclusive cross sections and evidence/observation of processes never measured before

W^+W^-

- **Sequential cuts selection**
  - 2 opposite charge isolated leptons (e, μ), m_{ll} > 20 GeV
  - Projection of p_T^{miss} perpendicular to lepton momentum > 20 GeV → Reduce nonprompt background
  - MVA to discriminate DY background, for same flavour leptons $|m_{ll} - M_Z|$ > 15 GeV
  - 0 or 1 jets with p_T > 30, b-jet veto

- Important background source in searches for new particles
- Production from $q\bar{q}$, gg (at higher order) or H→WW
- Analysis performed with **sequential cuts** and **Random Forest Classifiers**



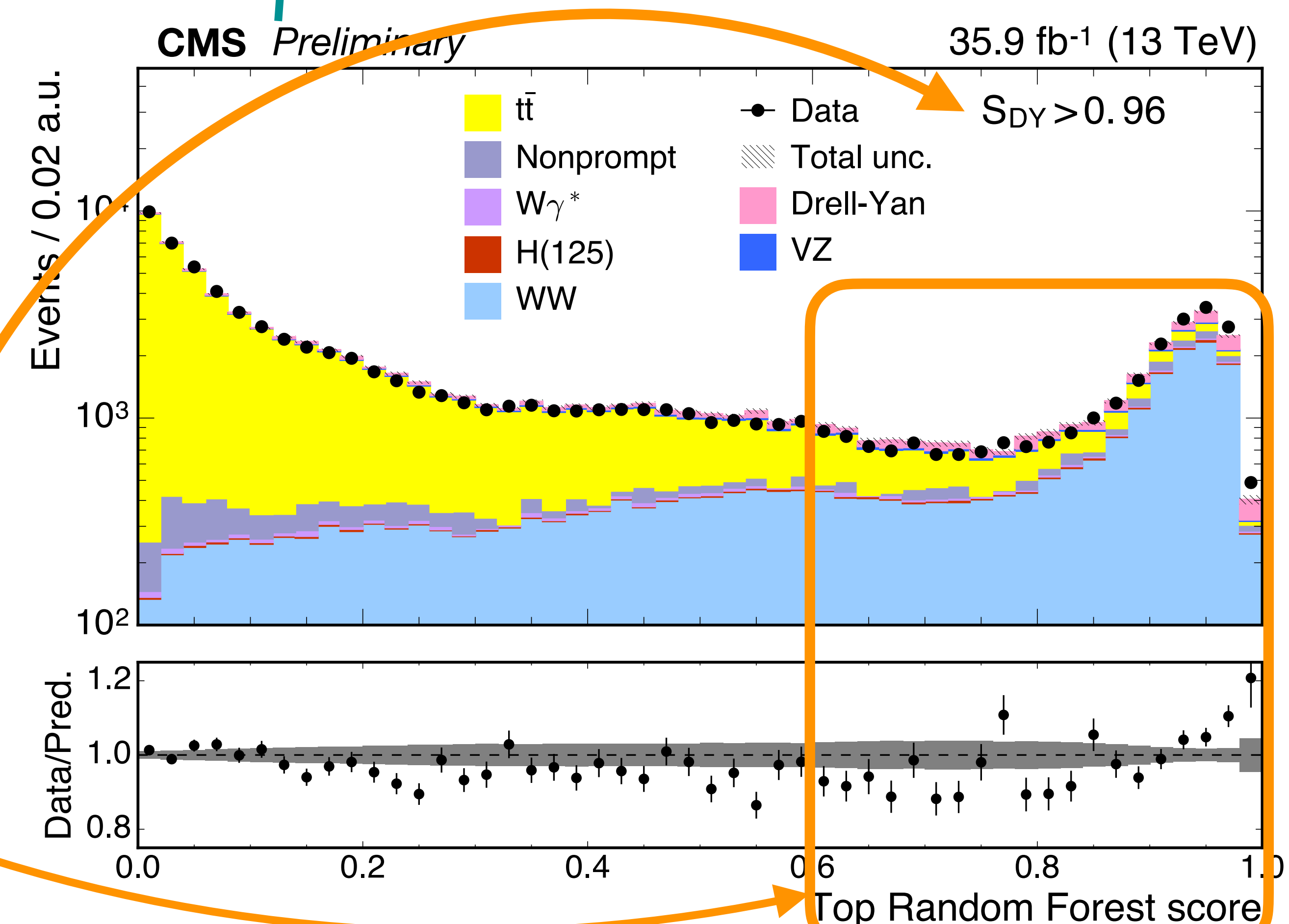


Random Forest Classifier

- Random Forest Classifier (RFC): aggregate of binary decision trees trained independently and in parallel → **Mitigates overfitting**
- Main background sources form DY and $t\bar{t}$ → Build **two RFC to better reduce contamination**
- RFC score ≈1 for the signal and ≈0 for background
- Signal **efficiency and purity higher** than sequential cuts analysis

RFC score	Signal region	DY control	$t\bar{t}$ control region
S_{DY}	> 0.96	< 0.6	> 0.6
S_{tt}	> 0.6	> 0.6	< 0.6

- Selection
  - 2 opposite charge isolated leptons (e, μ), $m_{ll} > 30$ GeV
  - For same flavour leptons $|m_{ll} - M_Z| > 15$ GeV
  - b-veto applied to jets



Pure signal region after $t\bar{t}$ and DY suppression

Backgrounds

	$t\bar{t}$ and single top	Drell-Yan	Nonprompt (W+jets)
Sequential cuts	CR with at least 1 b-jet to normalise	SF: normalisation from events inside and outside peak region DF: $Z \rightarrow \tau\tau$, CR with $m_{e\mu} < 80$ GeV	Fake rate from data-driven pass-fail (p_T, η)
Random Forest Classifier	CR with $S_{DY}>0.6$ & $S_{tt}<0.6$ to normalise	CR with $S_{DY}<0.6$ & $S_{tt}>0.6$, good data-MC agreement, yield use to normalise	CR with 2 same sign leptons (dominated by nonprompt), transfer factor from CR to SR

Systematics

Sequential cuts

Statistical	1.2 %
$t\bar{t}$ normalisation	2.0 %
DY normalisation	1.4 %
Lepton efficiencies	2.1 %
JES and JER	2.3 %
Total experimental	4.6 %

μ_R μ_F	0.4 %
Higher order QCD	1.4 %
PDFs	0.4 %
Total theoretical	1.6 %
Total	5.7 %

TOTAL CROSS SECTION

Theoretical prediction: σ_{tot}^{NNLO}=118.8±3.6 pb

Sequential cuts

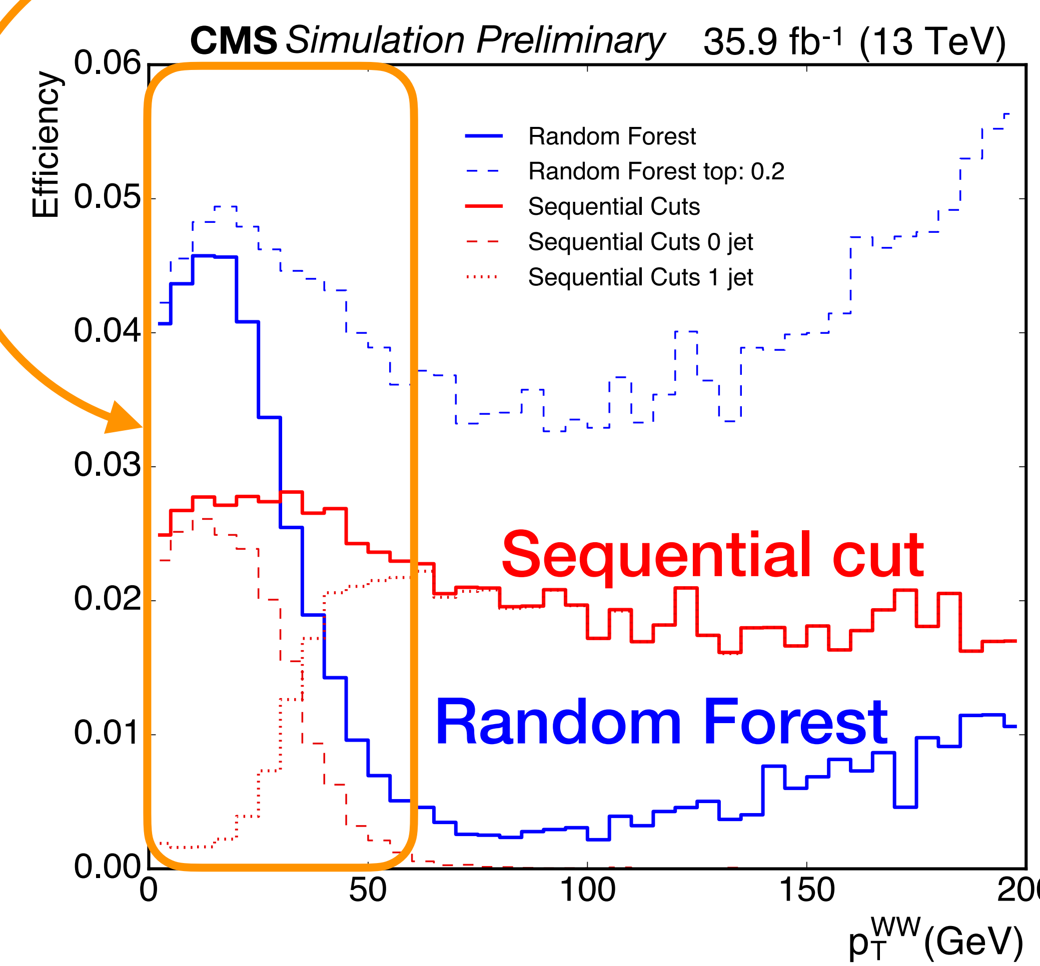
- Fit SR + $t\bar{t}$ CR, same and different flavour, 0 and 1 jets
- Consistency of signal strength proves consistency of the model

Category		Signal strength
0-jet	DF	1.054 ± 0.083
0-jet	SF	1.011 ± 0.160
1-jet	DF	0.930 ± 0.124
1-jet	SF	0.757 ± 0.200
0-jet & 1-jet	DF	1.027 ± 0.071
0-jet & 1-jet	SF	0.892 ± 0.157
0-jet & 1-jet	DF & SF	0.990 ± 0.057

σ_{tot}^{SC}=117.6±1.4(stat)±5.5(syst)±3.2(lumi) =117.6±6.8 pb

Random Forest Classifier

- Higher order QCD calculations taken into account by reweighting **p_T^{WW}** spectrum
- Result more sensitive to theoretical correction
- Sensitive to smaller p_T^{WW} → Mainly 0 jet



σ_{tot}^{RFC}=131.4±1.3(stat)±6.0(syst)±3.5(lumi) =131.4±8.7 pb

FIDUCIAL AND DIFFERENTIAL σ

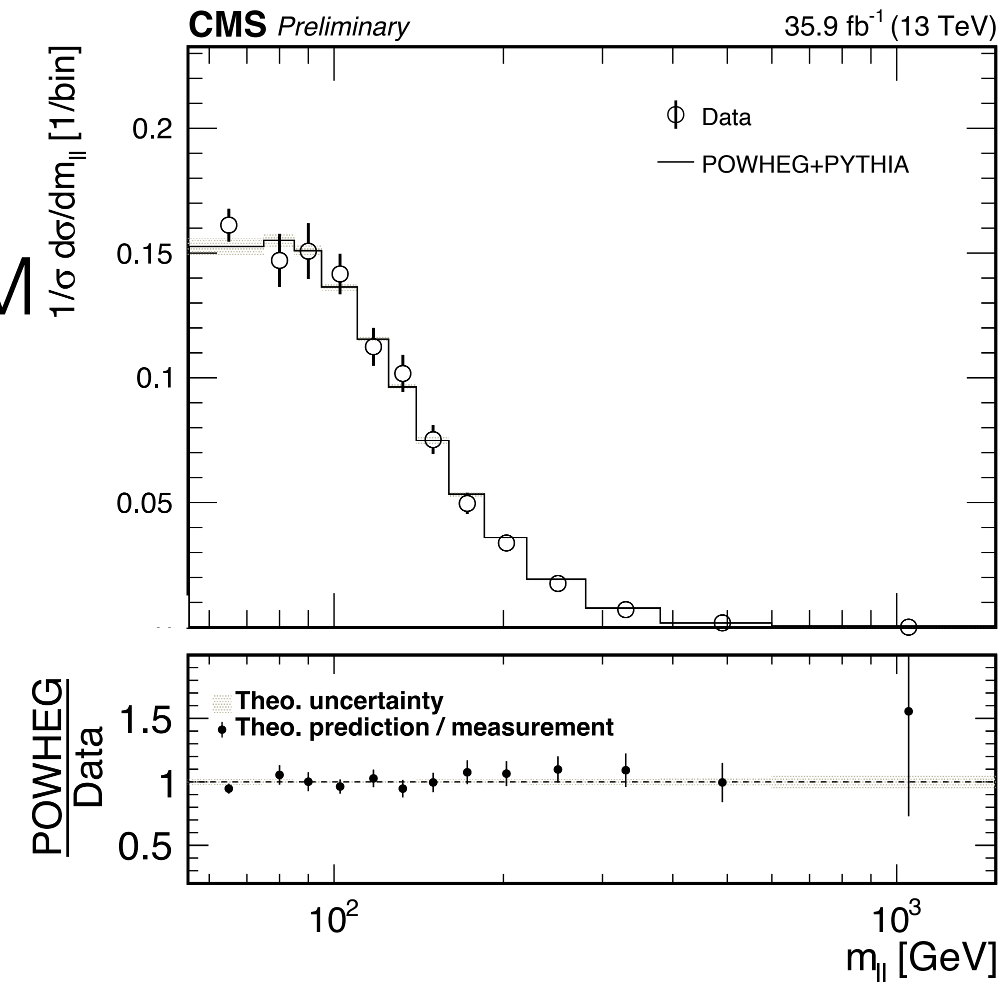
- **Fiducial cross section** in agreement with SM

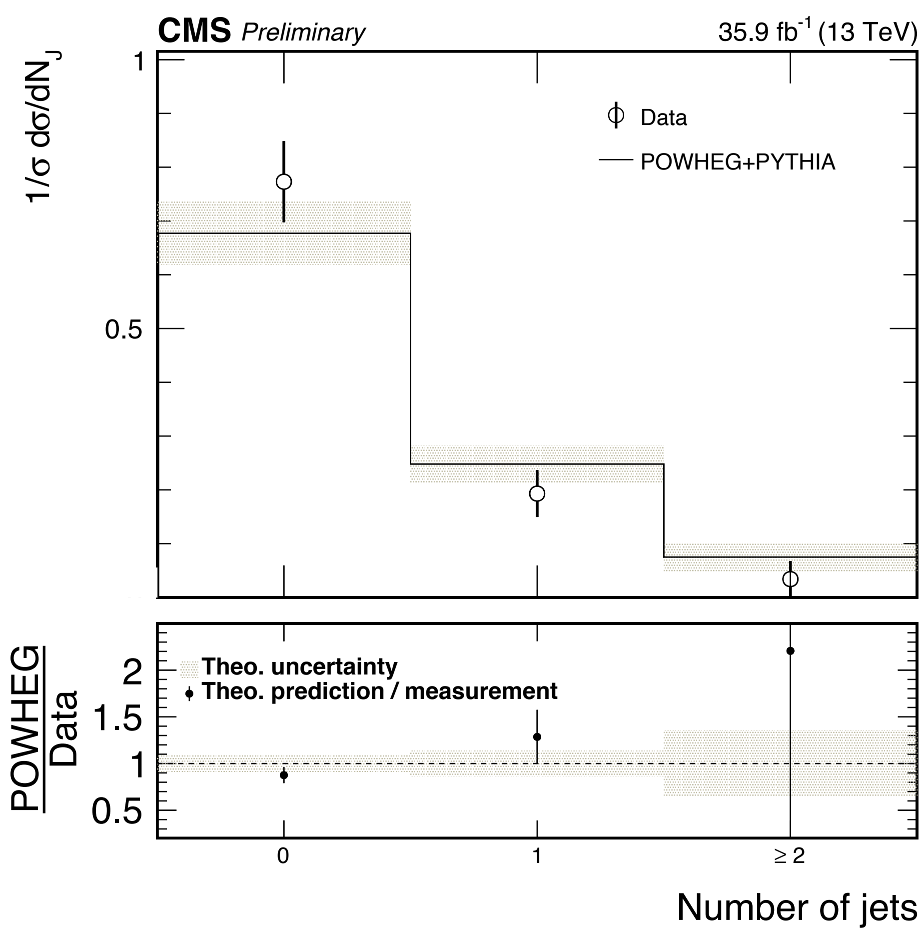
  σ^{fid}=1.529±0.087 pb σ_{NNLO}^{fid}=1.531±0.043 pb

- Measured **jet dependent** cross section

  σ^{fid}(0-jet)=1.61±0.10 pb σ^{fid}(1-jet)=1.35±0.11 pb

- **Differential** cross sections measured for m_{ll}, p_T^l and $\Delta\phi_{ll}$



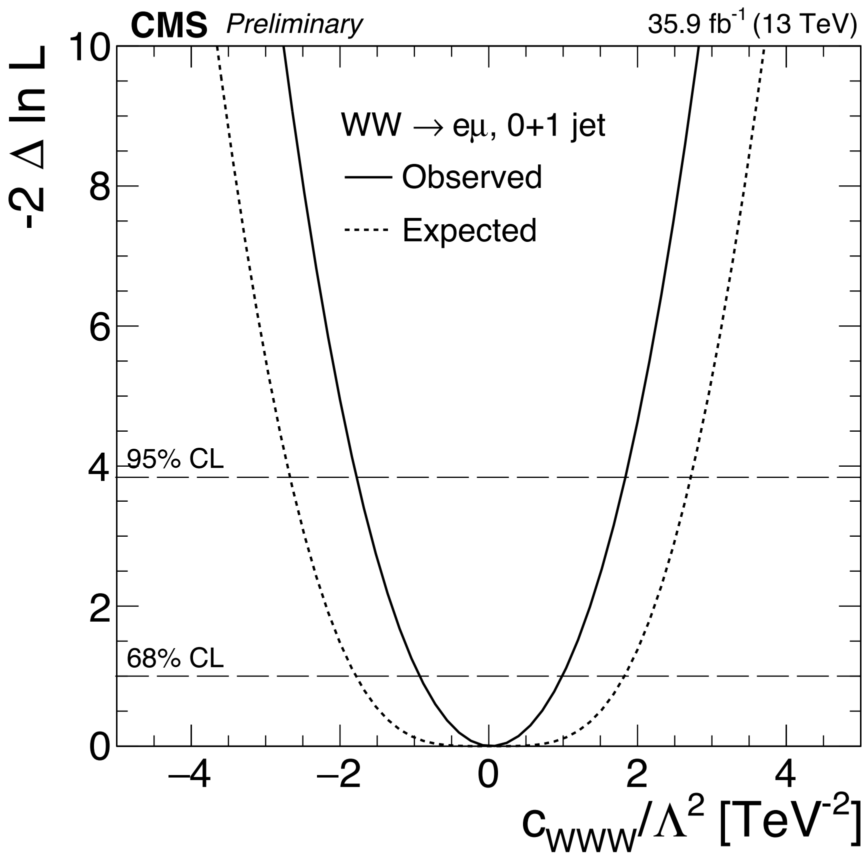


JETS MULTIPLICITY

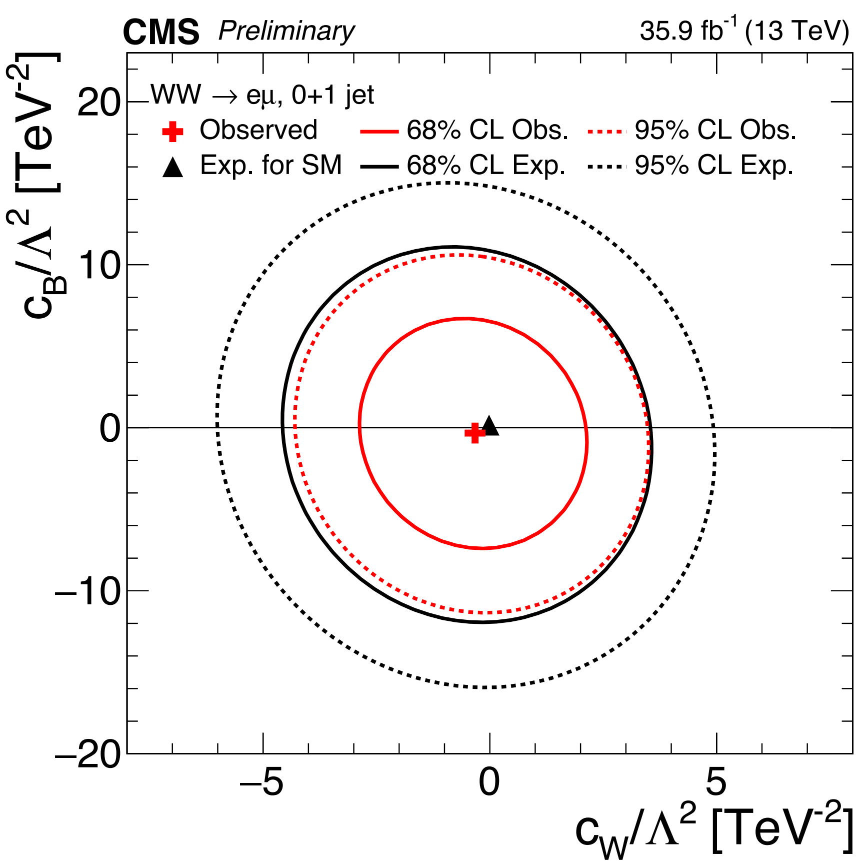
- **Probe of theoretical calculations** and events generators
- Signal region with S_{DY}>0.96 & S_{tt}>0.2 to reduce efficiency dependence on p_T^{WW}
- Possible migration of N_j events due to pileup and jet energy measurement → **Unfolding** with R_{PU} and R_{DET}

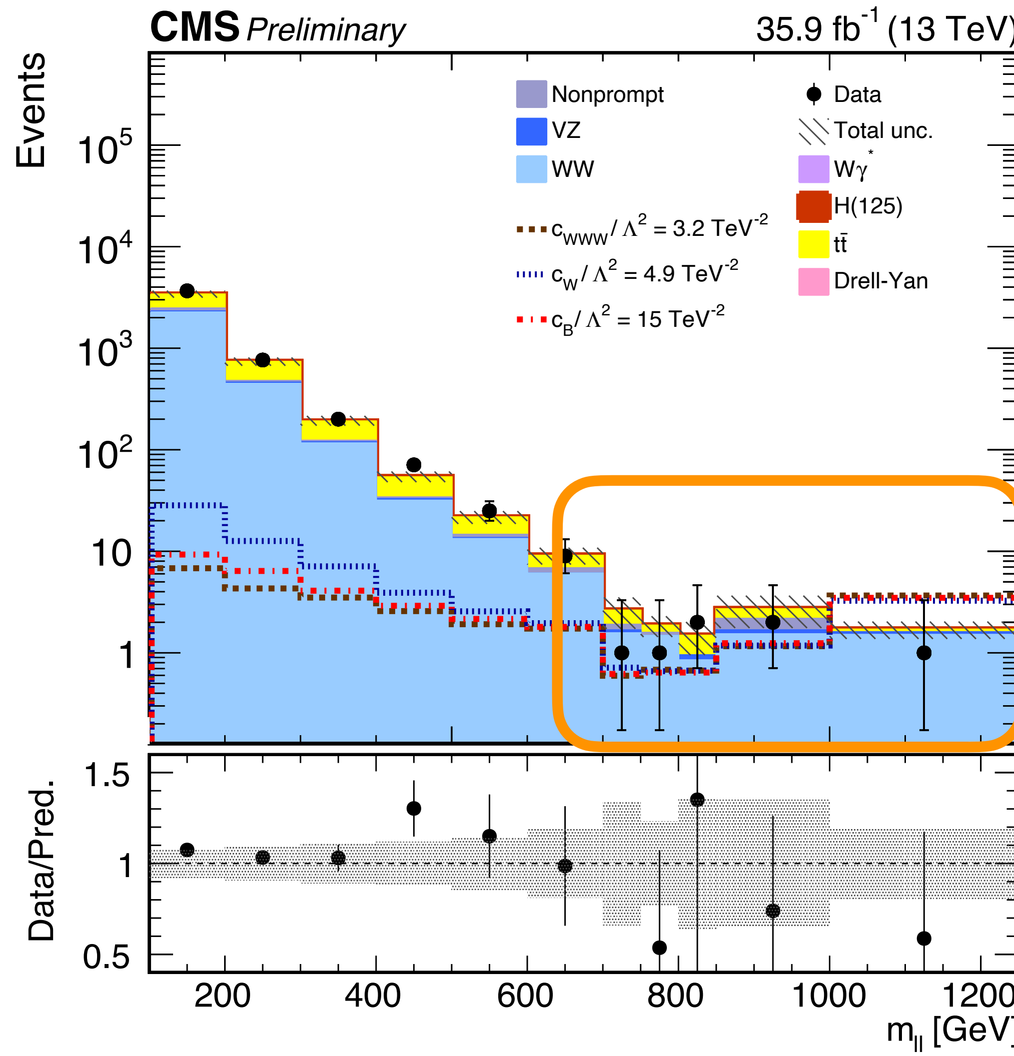
LIMITS ON aTGC

One parameter scan

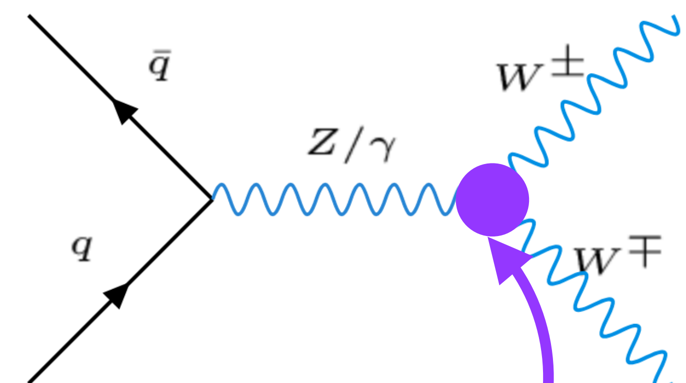


Two parameters scan





Different flavour $m_{e\mu}$ mass, high mass values more sensitive



Dimension 6 operators with massive boson fields O_{WWW}, O_W, O_B

Coefficients (TeV^{-2})	68% CL interval expected	68% CL interval observed	95% CL interval expected	95% CL interval observed
c_{WWW}/Λ^2	[−1.78, 1.82]	[−0.93, 0.99]	[−2.67, 2.71]	[−1.78, 1.84]
c_W/Λ^2	[−3.67, 2.68]	[−2.03, 1.33]	[−5.28, 4.22]	[−3.56, 2.78]
c_B/Λ^2	[−9.45, 8.40]	[−5.14, 4.30]	[−13.9, 12.8]	[−9.35, 8.46]

137 fb^{-1}

VVV

CMS-PAS-SMP-19-014

- Measure both inclusive and single channel cross sections

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

- 2 same sign 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

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

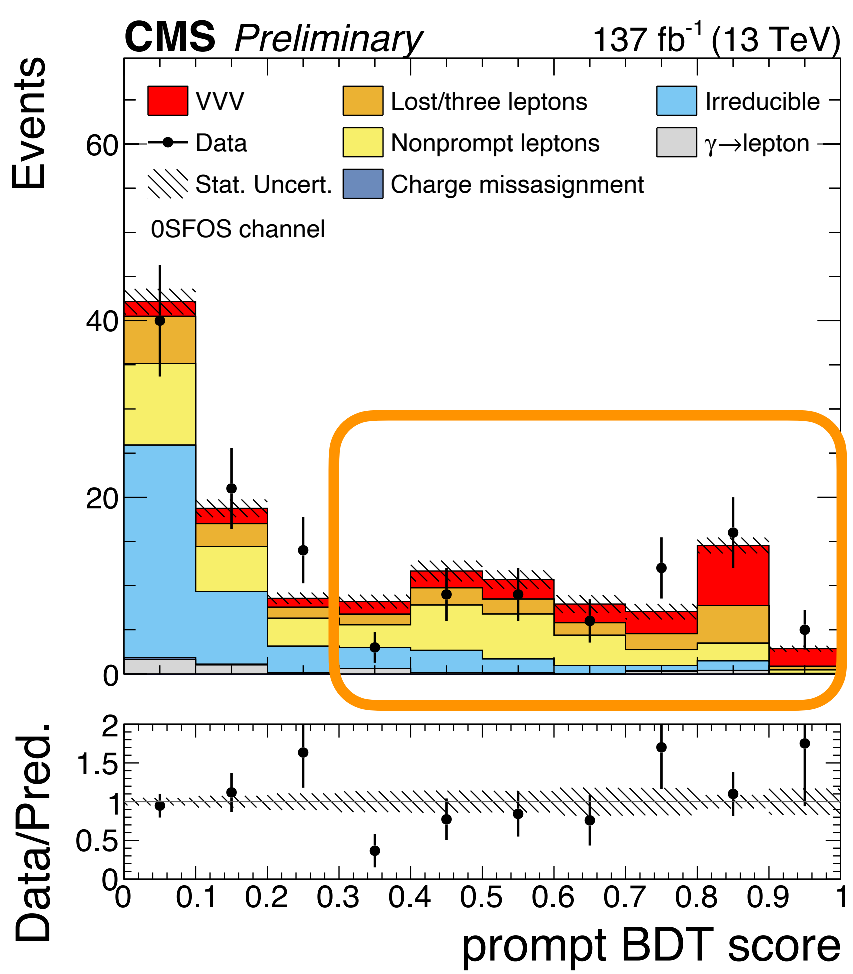
- 0, 1 or 2 same-flavour opposite charge lepton pairs (SFOS)
- m_{ll} incompatible with M_Z
- Backgrounds: lost lepton, SS leptons + jets, nonprompt

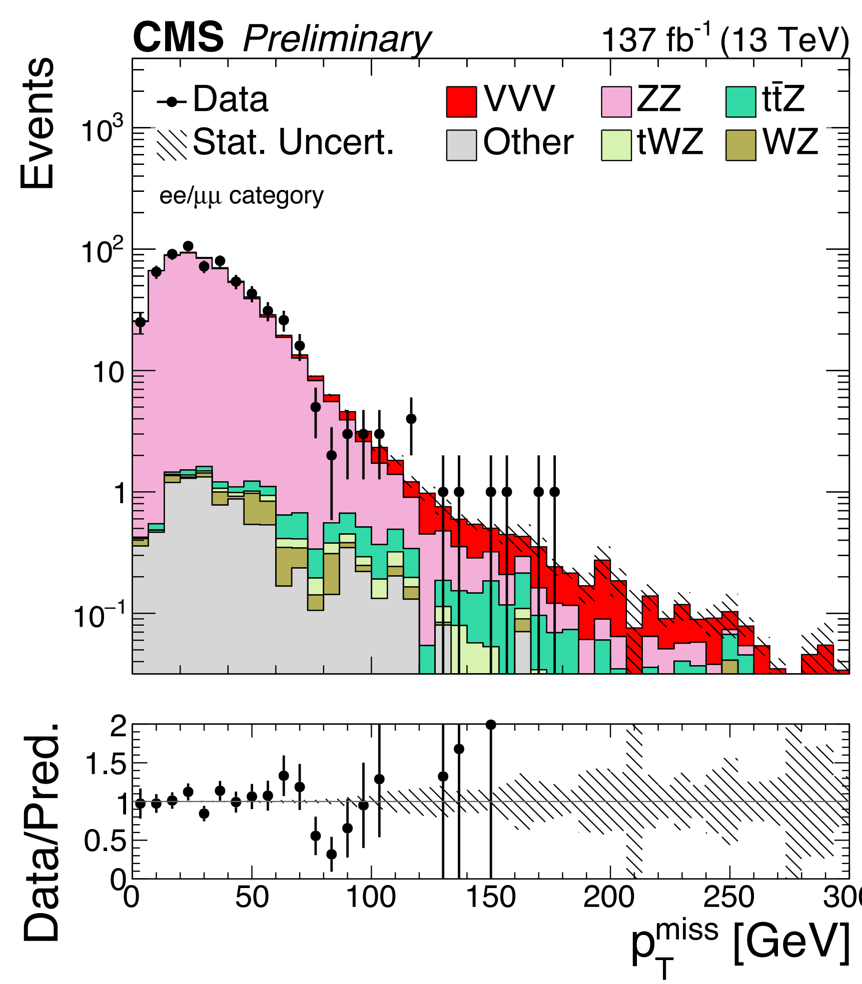
$WZZ \to l\nu\ (l^{\pm}l^{\mp})\ (l^{\pm}l^{\mp})$
$ZZZ \to (l^{\pm}l^{\mp})\ (l^{\pm}l^{\mp})\ (l^{\pm}l^{\mp})$

- 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

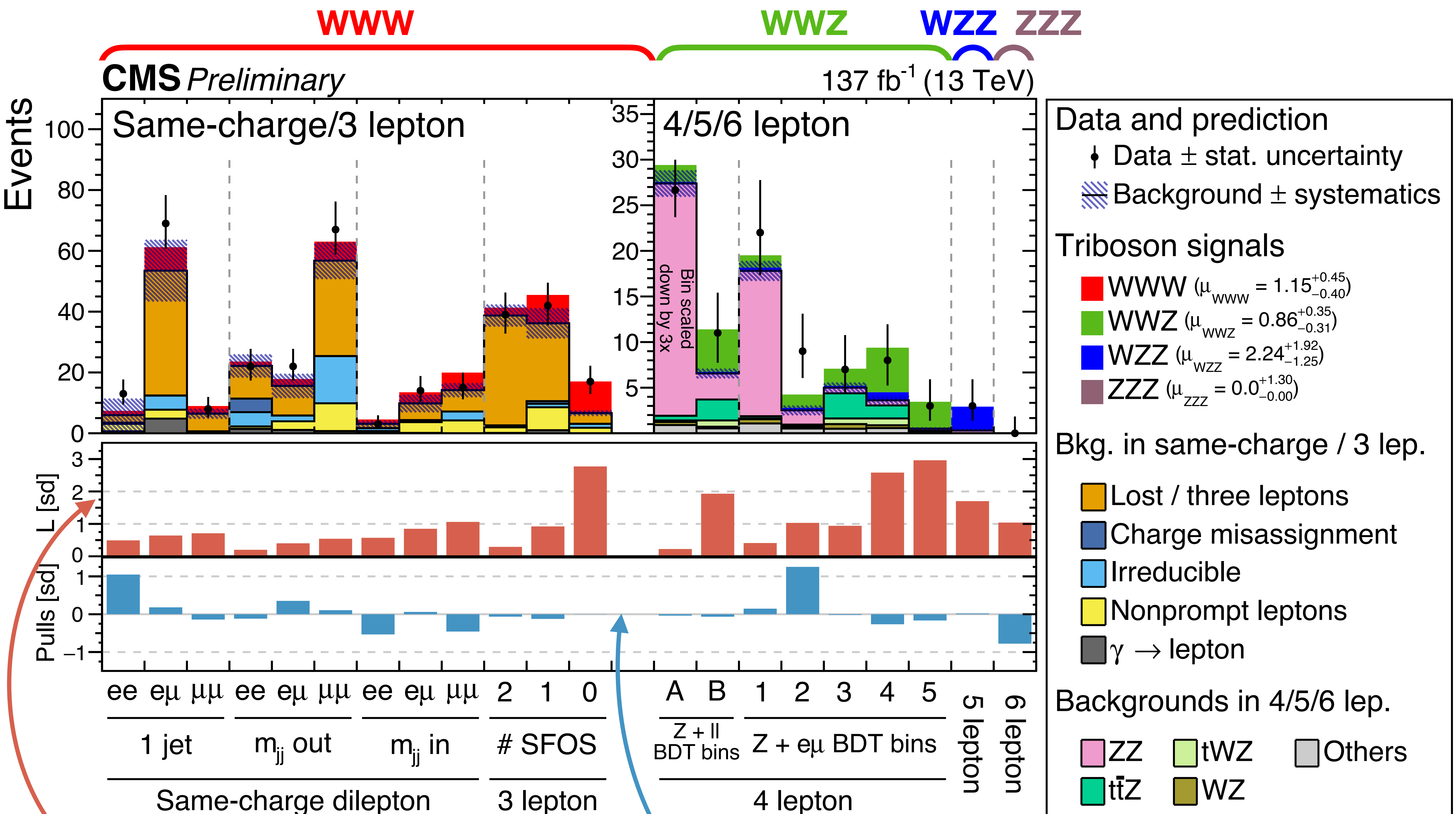
- Nonprompt lepton background **estimated form data** exploiting isolation variables
- **Boosted Decision Tree** trained with simulated background and signal
  - Two BDT applied in sequence for channels with more than one background categories (for WWW: nonprompt and others)
- 4l WWZ category main background 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

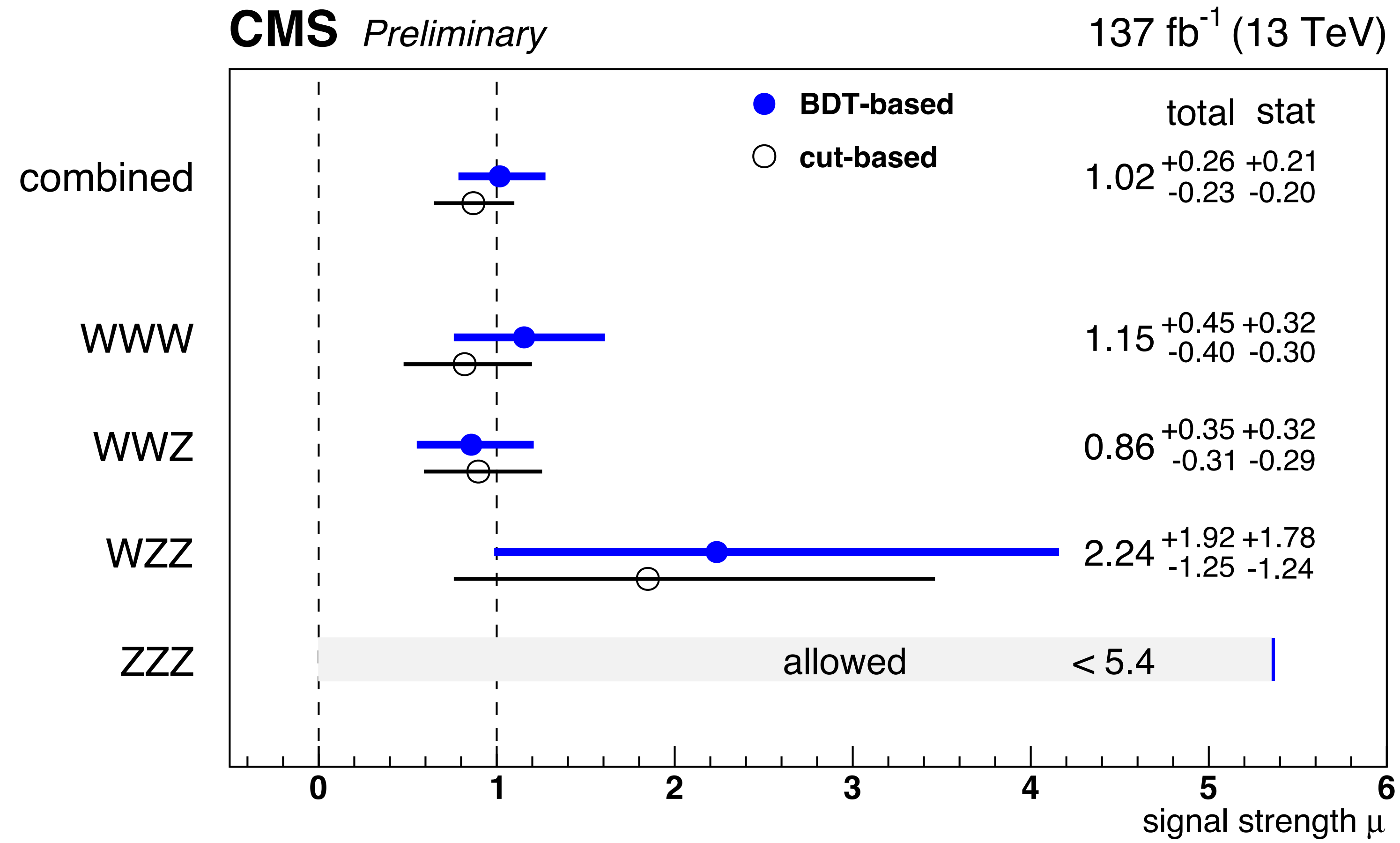


L: expected significance in single channel

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)

WWW

Results from 2016-only data

35.9 fb^{-1}

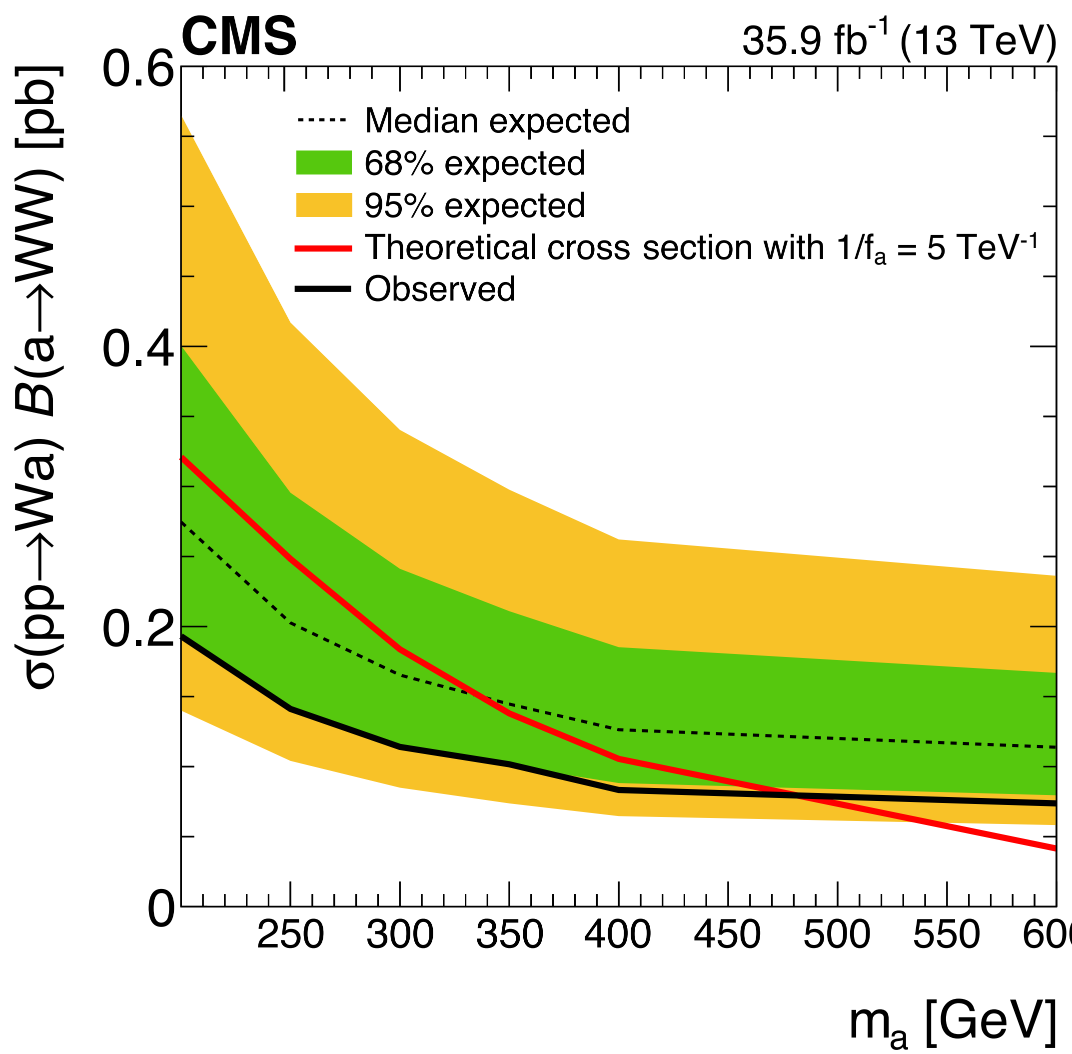
- Sum of p_T of leptons and jets (S_T) exploited to study aQGC at high values (S_T > 1.5 TeV in 2l+2j and > 2 TeV in 3l)

Anomalous coupling	Allowed range (TeV^{-4})	
	Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

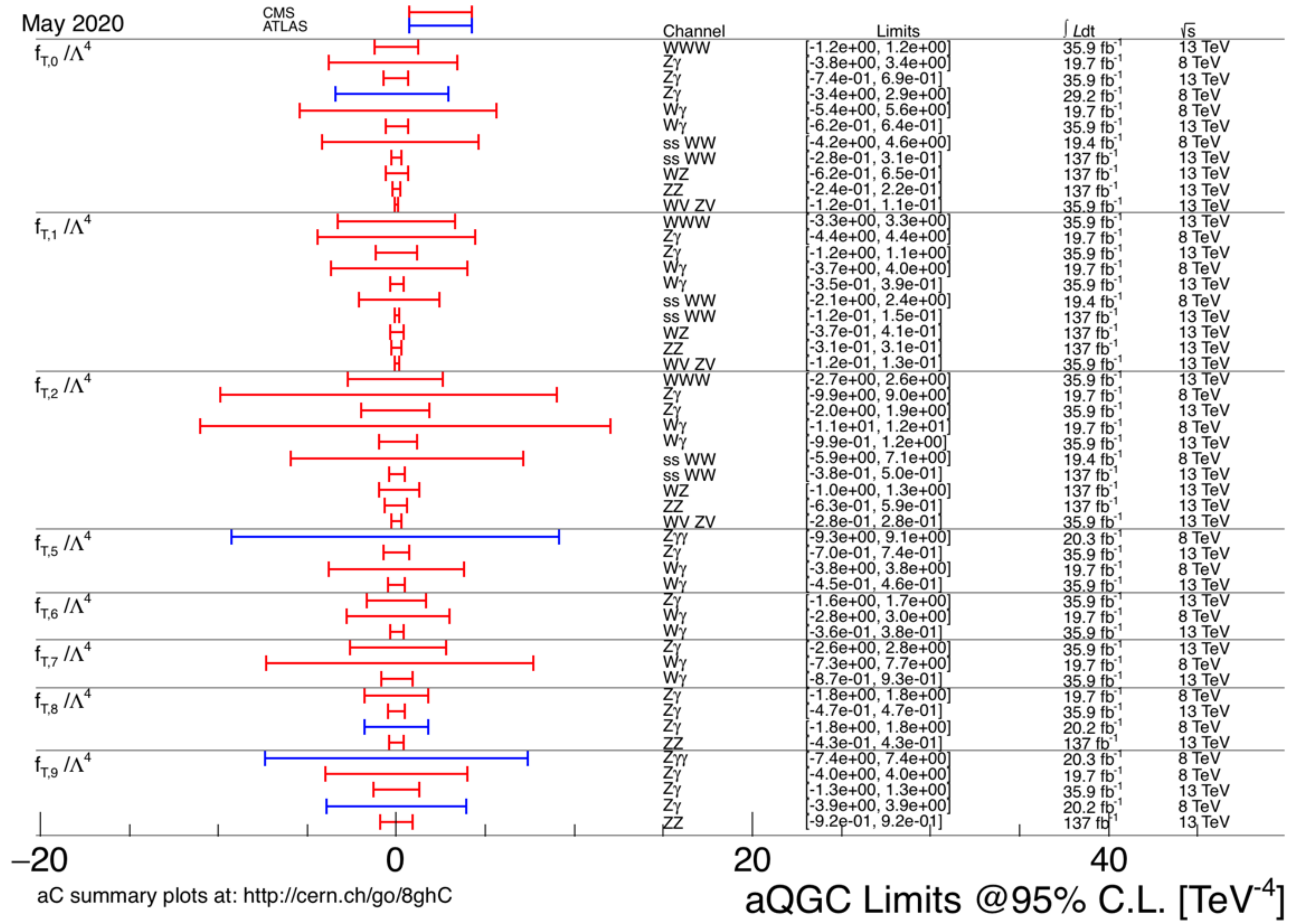
- Study of **axion like particle (ALP) production:** Wa→WWW has largest production cross section for $m_a > 2m_W$

- SM WWW treated as background, no evidence for an excess

- W+ALP production excluded up to 480 GeV



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
- Some explicit BSM models tested and excluded up to high energies
- From experimental measurements, **information on processes at theoretical level** (improvement of Monte Carlo simulations)

For further discussion, Zoom link: 516-275-3909

Backup

Results interpretation

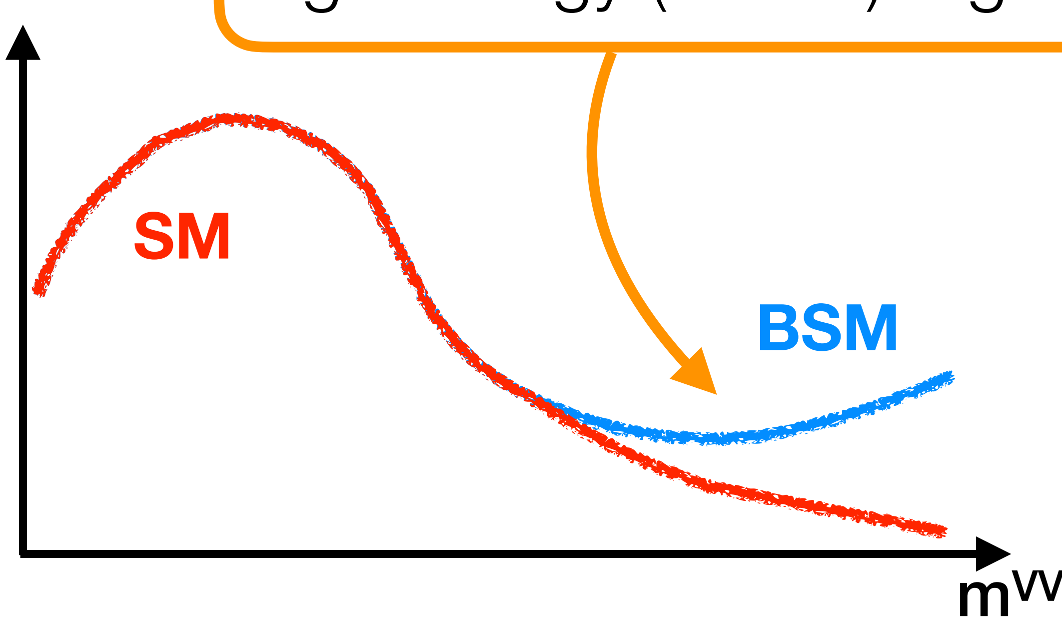
- Presence of effects beyond the SM (BSM) can change the value of the couplings
  → **Anomalous Gauge Couplings**

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

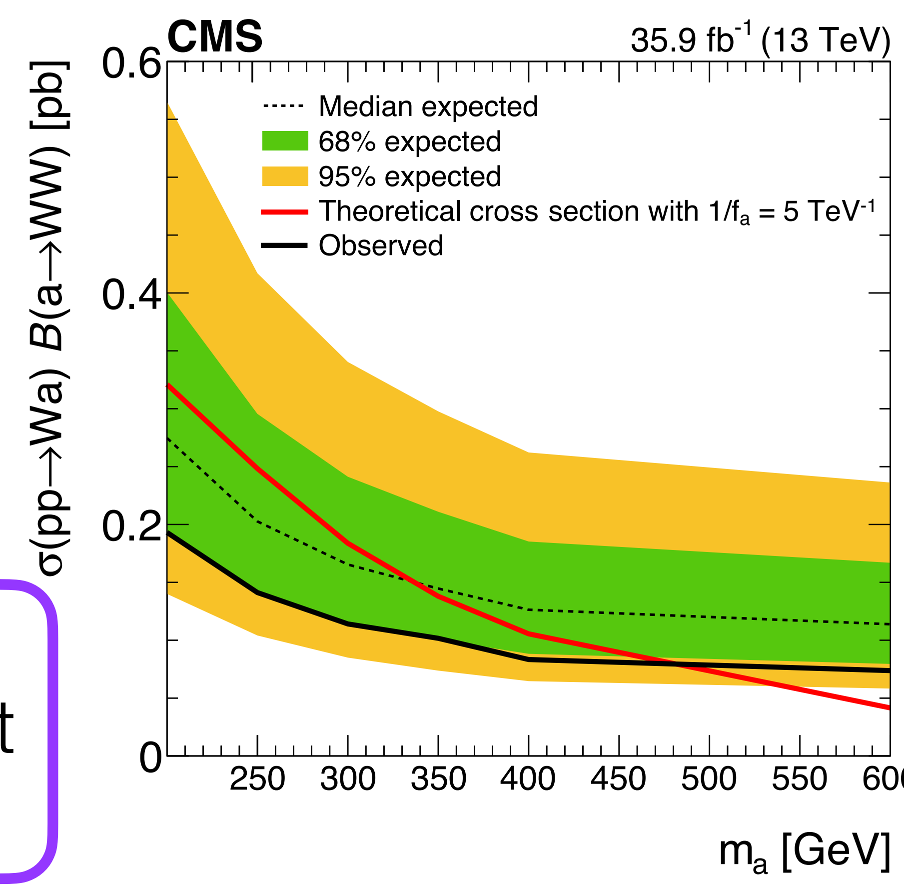
$$\mathscr{L}_{aQGC} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^{d-4}} O_i + \ldots$$

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



137 fb^{-1}

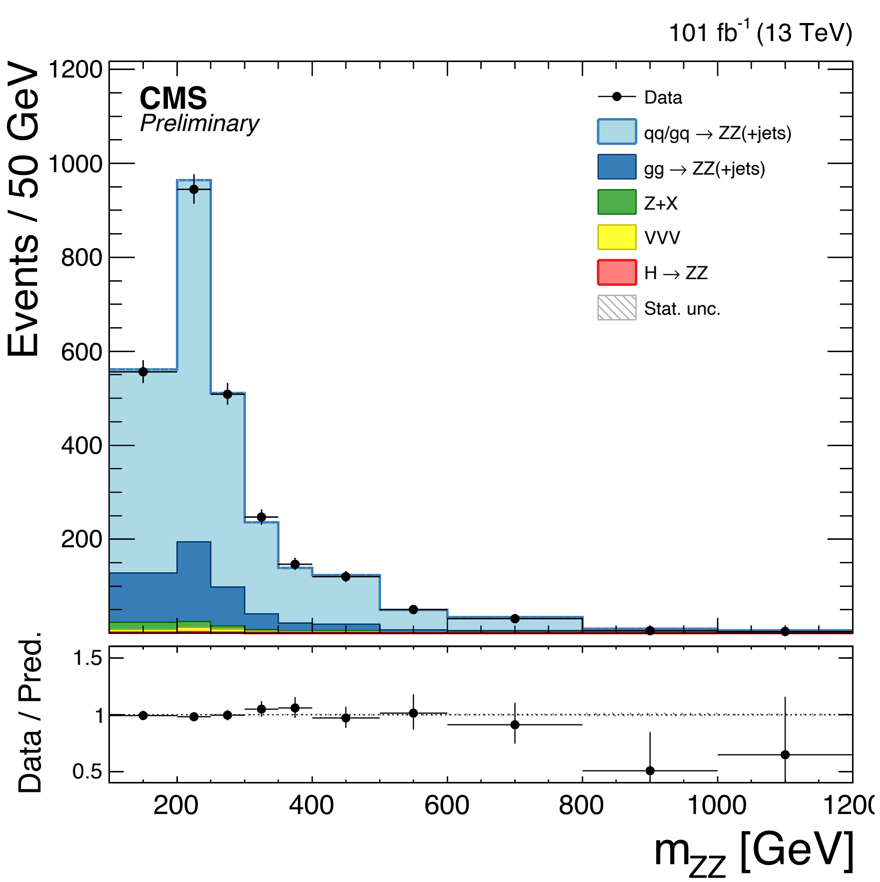
CMS-PAS-SMP-19-001

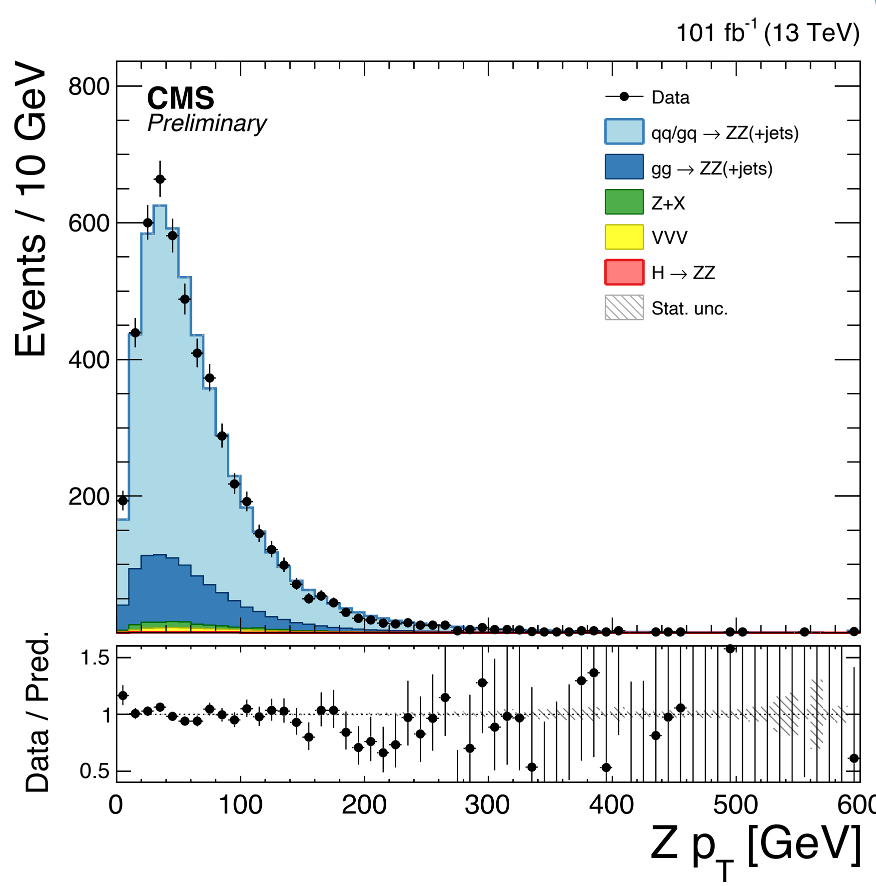
ZZ

- Important **test of NNLO QCD calculations** (production via $q\bar{q}$ and gluon fusion at higher order)
- Backgrounds from Z+jets and WZ+jets estimated with “contamination factors” from data control regions

- Selection
  - 2 pairs of opposite sign isolated leptons (e, μ)
  - Combinatorial solved with closeness to M_Z
  - $60 < m_{Z1}, m_{Z2} < 120$ GeV

- Systematic uncertainties
  - Lepton efficiency 2-8%
  - PDF + scale variations 1%
  - Lepton misidentification probability 1%

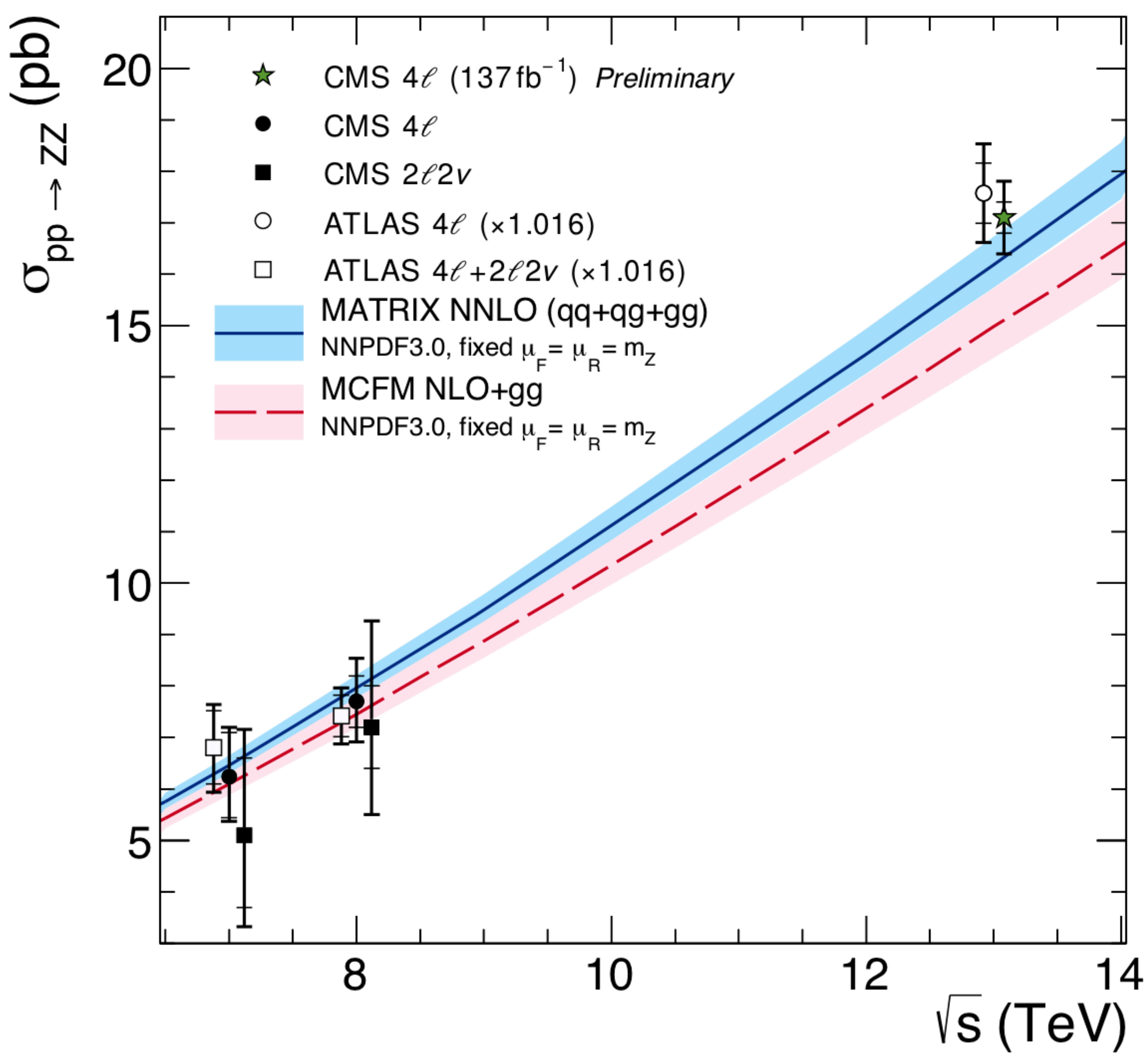




ZZ

- Analysis performed for 2017 and 2018 and then combined with previous CMS results with 2016 data (CERN-EP-2017-219)
- **Simultaneous fit** performed on all decay channels (eeee, eeμμ, μμμμ)
- Measured cross section in agreement with SM predictions (both POWHEG and MCFM)
- Both CMS and ATLAS results in **agreement with theoretical prediction** at different energies

Year	Total cross section, pb
2016 [5]	$17.5^{+0.6}_{-0.5}\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2017	$16.8 \pm 0.5\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2018	$16.8 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
Combined	$17.1 \pm 0.3\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})$



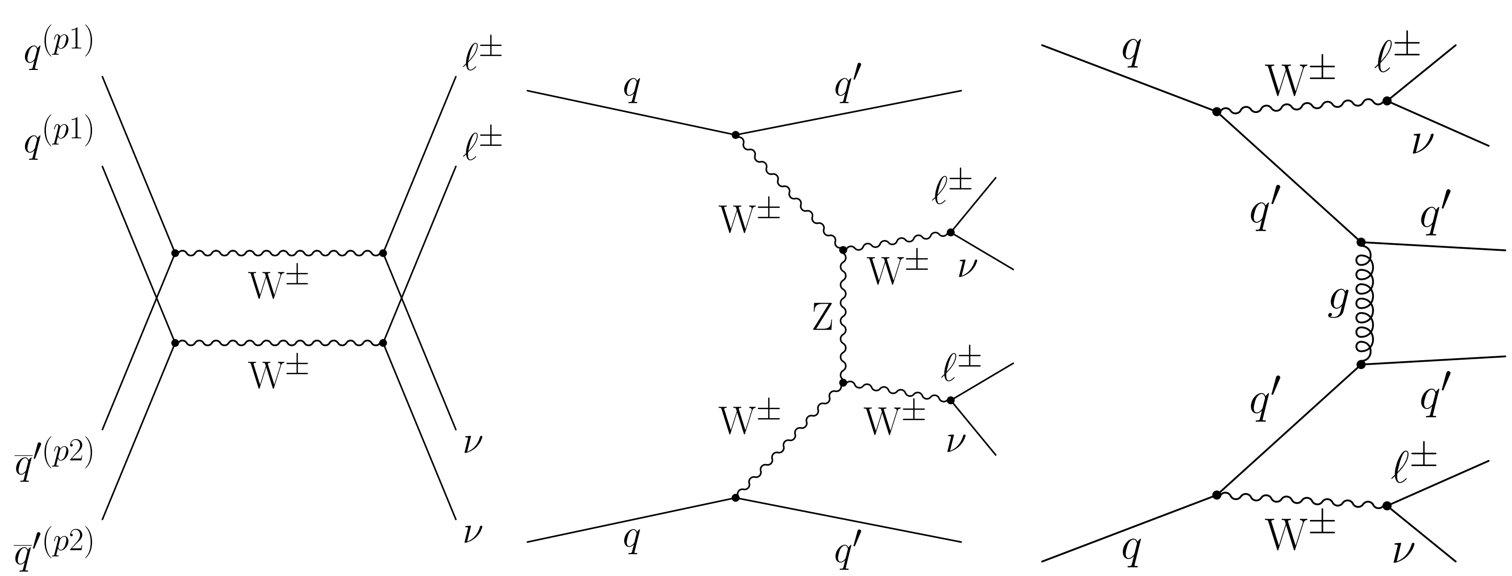
WW DOUBLE PARTON SCATTERING

$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

$\sigma_A \sigma_B$: Single hadron scattering xsec

σ_{eff}: Double parton scattering xsec

- SM WW production has two additional jets
- Two same-sign leptons final state is clean
- **DPS WW never observed**
  - Test of factorisation approach (useful for MC simulations)
  - Background for SUSY searches



- Selection
  - Same charge eμ or μμ
  - p_T^{miss} > 15 GeV
  - At most one non-b jet
- Backgrounds
  - True same charge leptons (WZ)
  - Nonprompt leptons (tight-to-loose in data)
- Boosted Decision Tree based on presence of Lorentz boost in WZ processes
- Two classifier for the two backgrounds

WW DOUBLE PARTON SCATTERING

- **Theoretical prediction of DPS xsec has very low precision**
  - PYTHIA prediction σ_{DPS}=1.92 pb, expected significance 5.4σ
  - Factorisation approach σ_{DPS}=0.87 pb, expected significance 2.5σ
- Measured cross section and significance do not depend on predicted ones

$\sigma_{DPS}(WW)=1.41\pm0.20(stat)\pm0.28(syst)$ pb   Significance 3.9σ

- $\sigma_{EFF}=12.7^{+5.0}_{-2.9}$ mb consistent with previous measurements with different final states
- Systematics
  - Estimation of nonprompt lepton contribution 25-40%
  - Charge misid background 30%
  - WZ (ZZ) bkg 16(6)%