Highlights of SM and Top results from CMS

LISHEP Workshop on High Energy Physics – Section C – Cosmology & Particle
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PROLAY MAL
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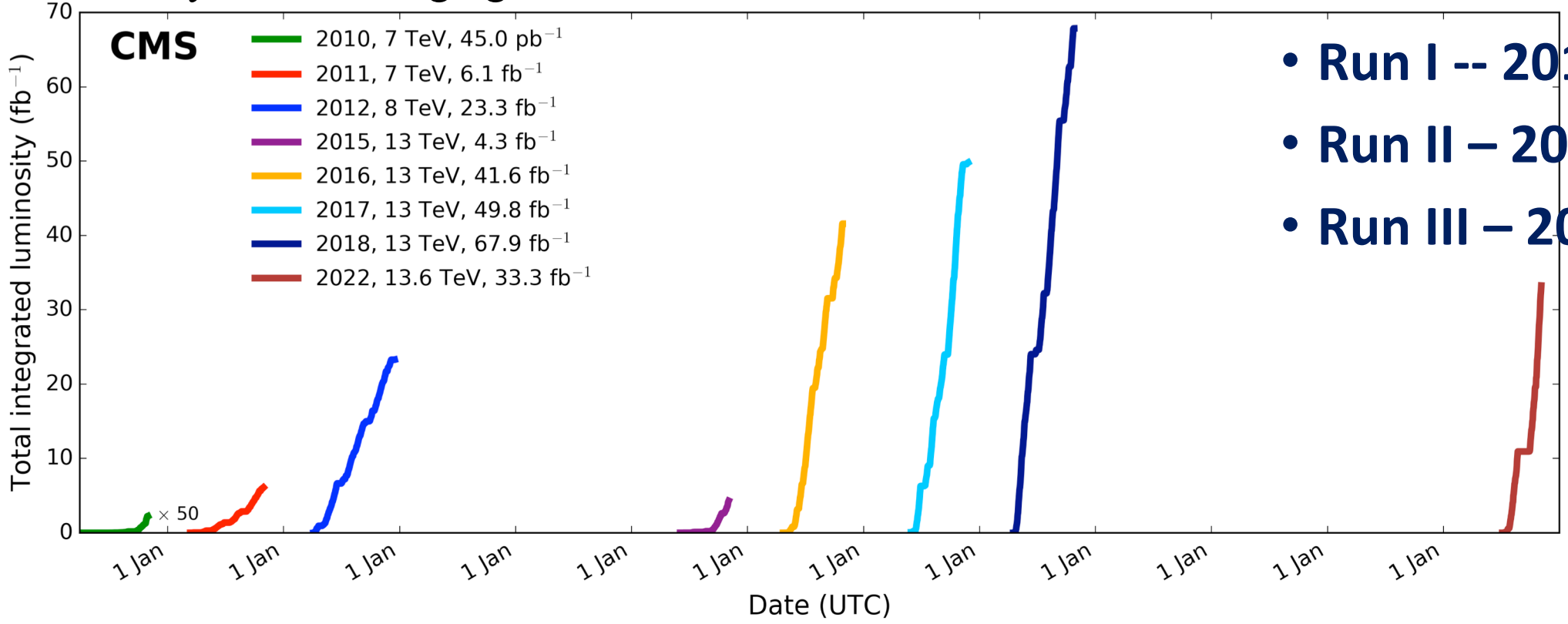
LHC Performance

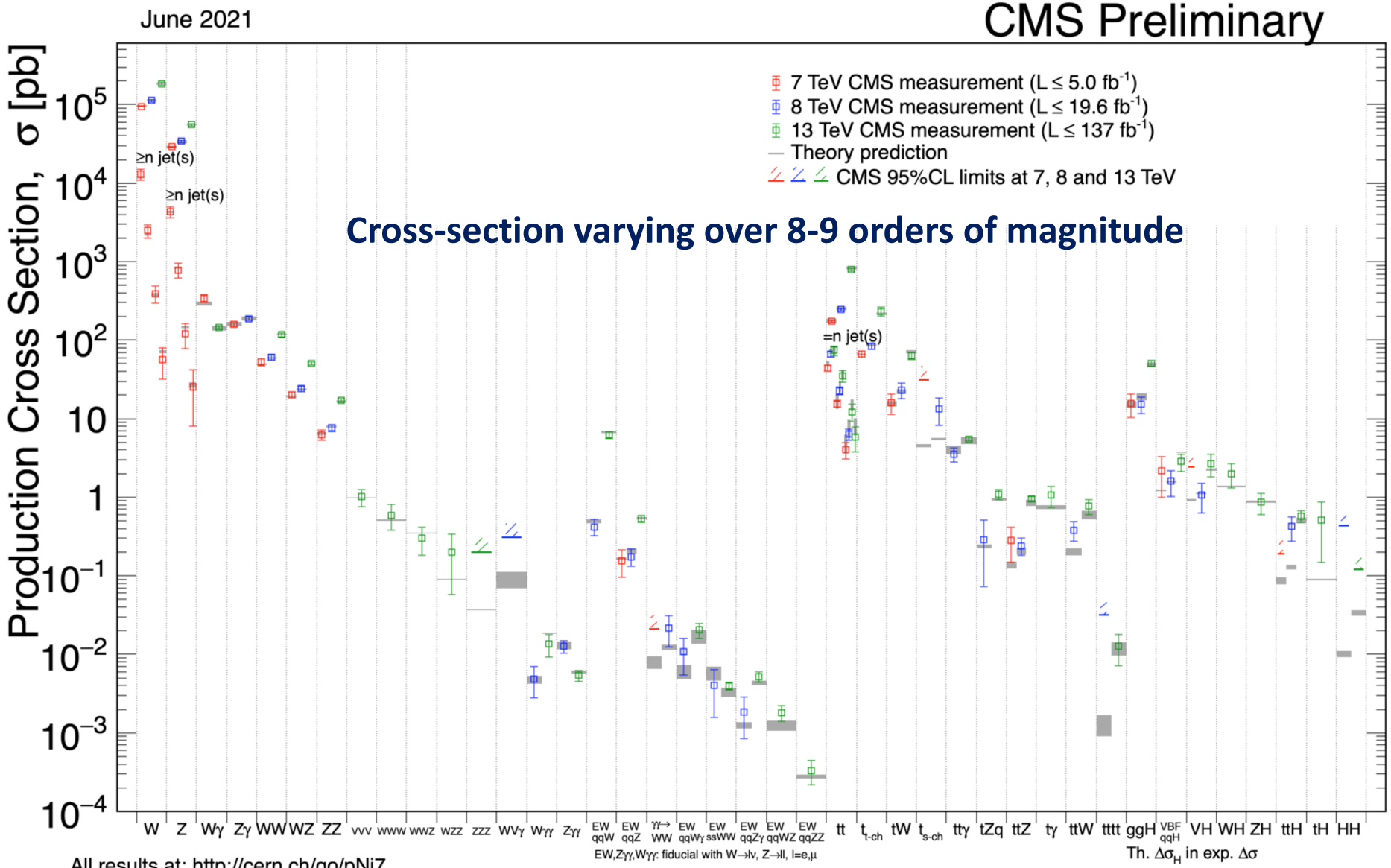
- LHC Run III started in 2022 at √s=13.6 TeV and LHC has been setting new record-breaking luminosity
- Exceedingly well performance by the LHC with delivered luminosities increasing rapidly
- Many precision measurements and rare processes studies have been plausible mostly due to the LHC performance "beyond the design goal".



- **Run I -- 2010-12**
- **Run II – 2015-18**
- **Run III – 2022-**


STANDARD
MODEL
COLLIDER

Impressive Accuracy for SM Measurements



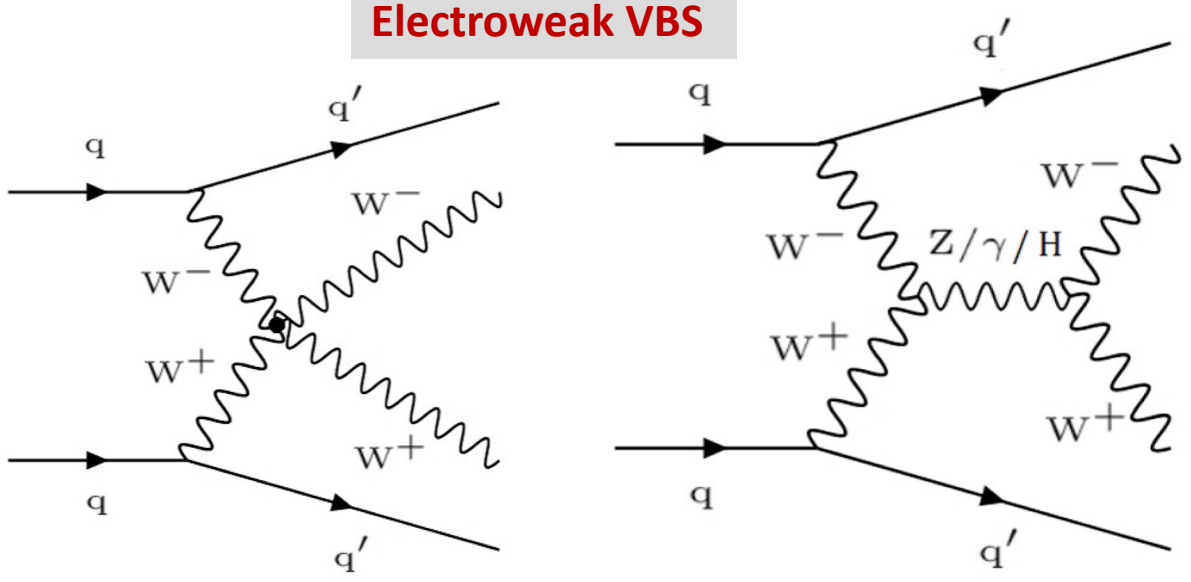
Cross-section varying over 8-9 orders of magnitude

- **Number of produced events for 137 fb^{-1}**
  - **W bosons 2.7x10^{10}**
  - **Z bosons 8x10^{9}**
  - **Top quarks 1.3x10^{8}**
  - **Higgs 8x10^{6}**

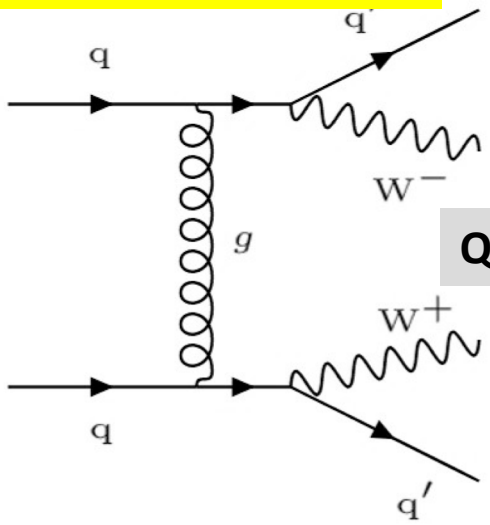
All results at: http://cern.ch/go/pNj7

Observation of W^+W^- VBS at the LHC

Electroweak VBS



arXiv:2205.05711; accepted by PLB



QCD-induced

- Precision measurement with the Vector Boson Scattering (VBS) processes are important for probing the Higgs sectors and hence understanding the electroweak symmetry-breaking
- Oppositely charged leptons with two jets (having high pseudorapidity gap) to target for the WW+2 jets events with the rejection for the QCD-induced processes and ttbar processes.
  - Full Run 2 dataset with event selection for two Isolated leptons (electron/muon) with p_T> 25 (13) GeV, and m_{ll}>50 GeV and 2 jets along with the Missing Transverse Energy p^{mis}_T> 20 GeV
  - At least two jets with pT>30 GeV , $\Delta\eta_{jj}$>2.5 and m_{jj}>300 GeV
  - Further event categorization based on final state lepton flavors

Observation of W^+W^- VBS at the LHC

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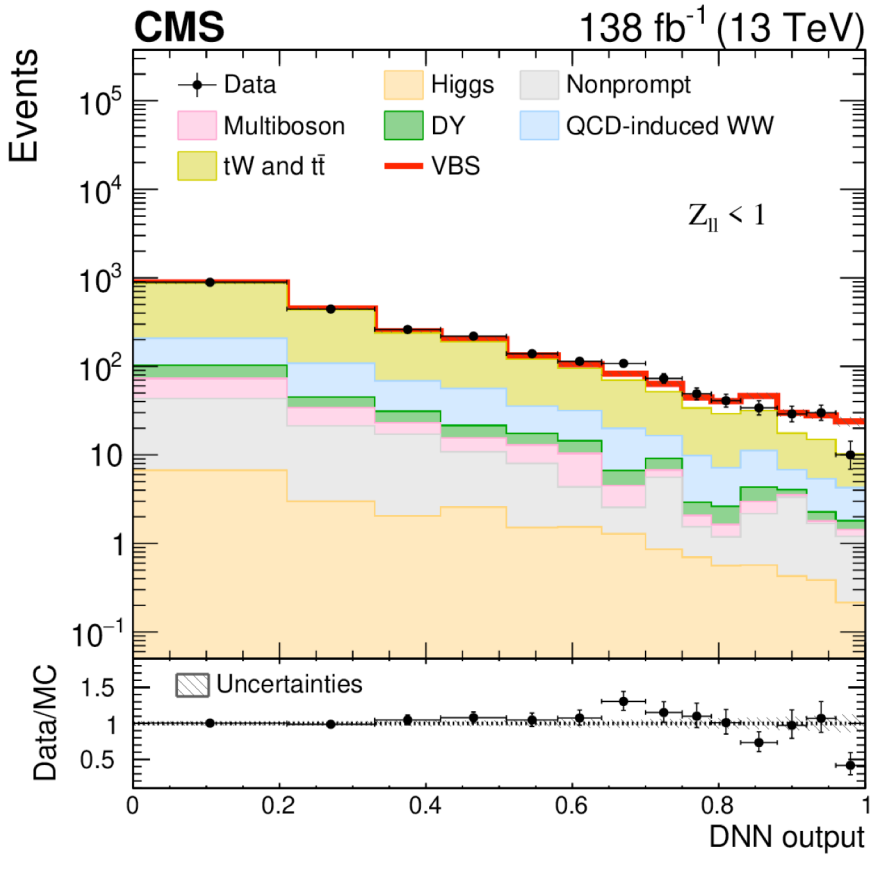
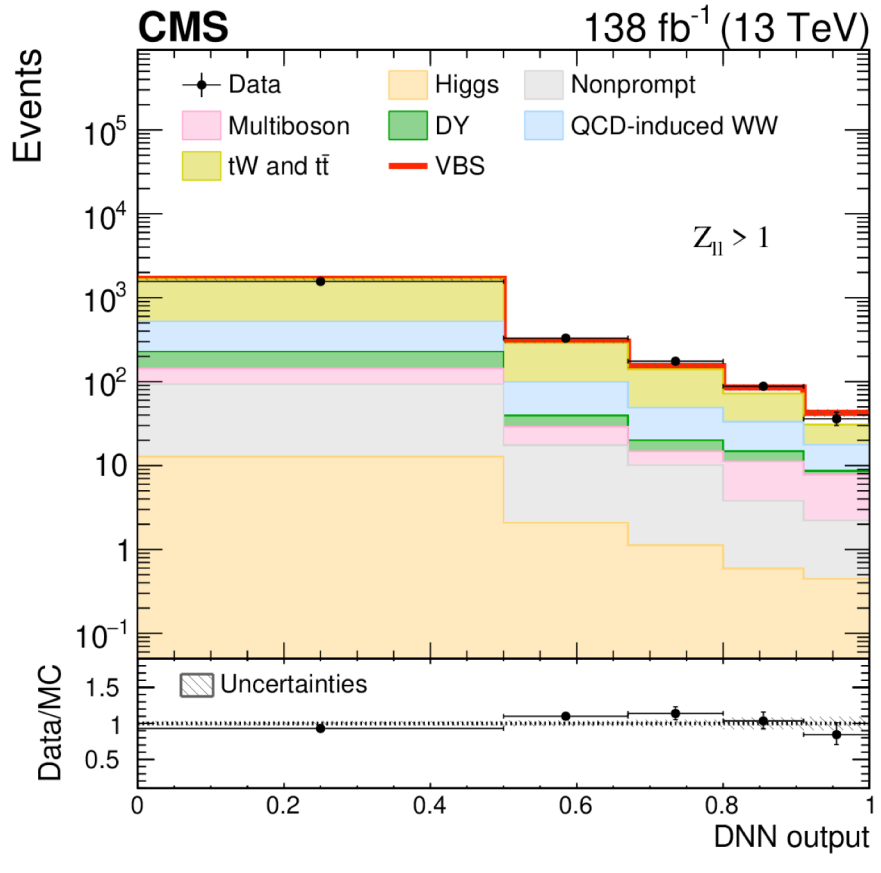
Signal enriched eμ region





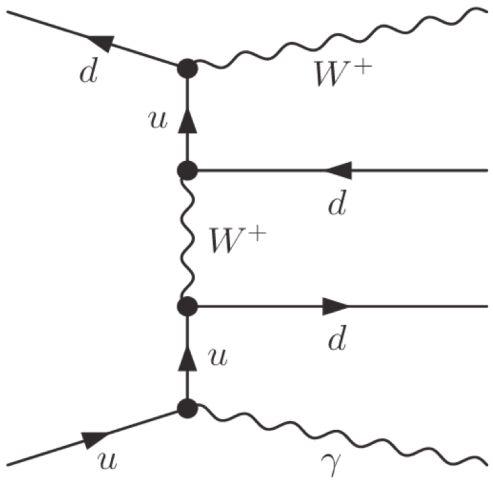
- Data-driven background normalization using dedicated control regions for major backgrounds-- Top, DY
- Deep Neural Network training to identify signal events
- W+W- VBS fiducial cross-section measured through simultaneous fits of DNN and other discriminating observables:

$\sigma_{fiducial} = 10.2 \pm 2.0$ fb
$\sigma_{SM} = 9.1 \pm 0.6$ fb

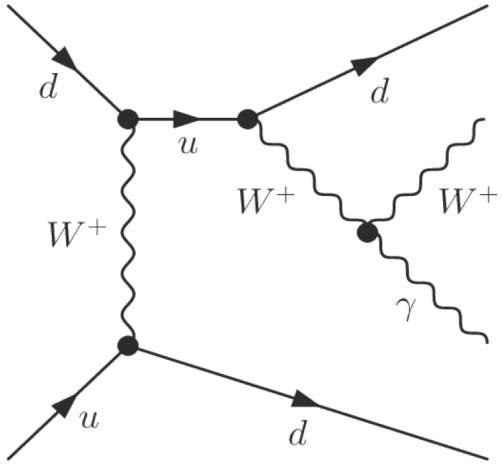
Observed (expected) signal significance of 5.6σ (5.2σ)

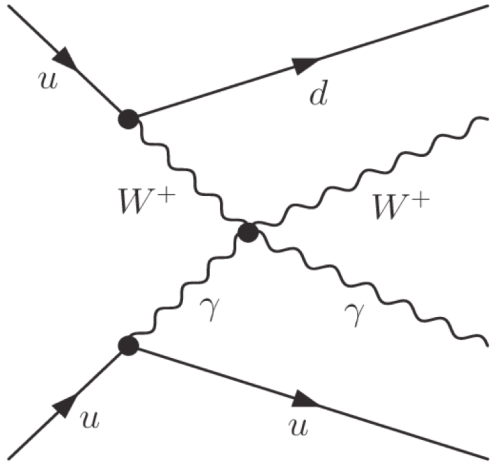
Wγ+ 2 jets production at the LHC

axXiv:2212.12592; submitted to PRD

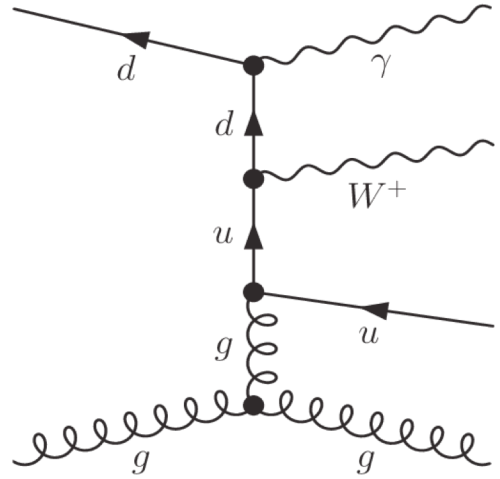


Non-VBS Electroweak





Electroweak VBS



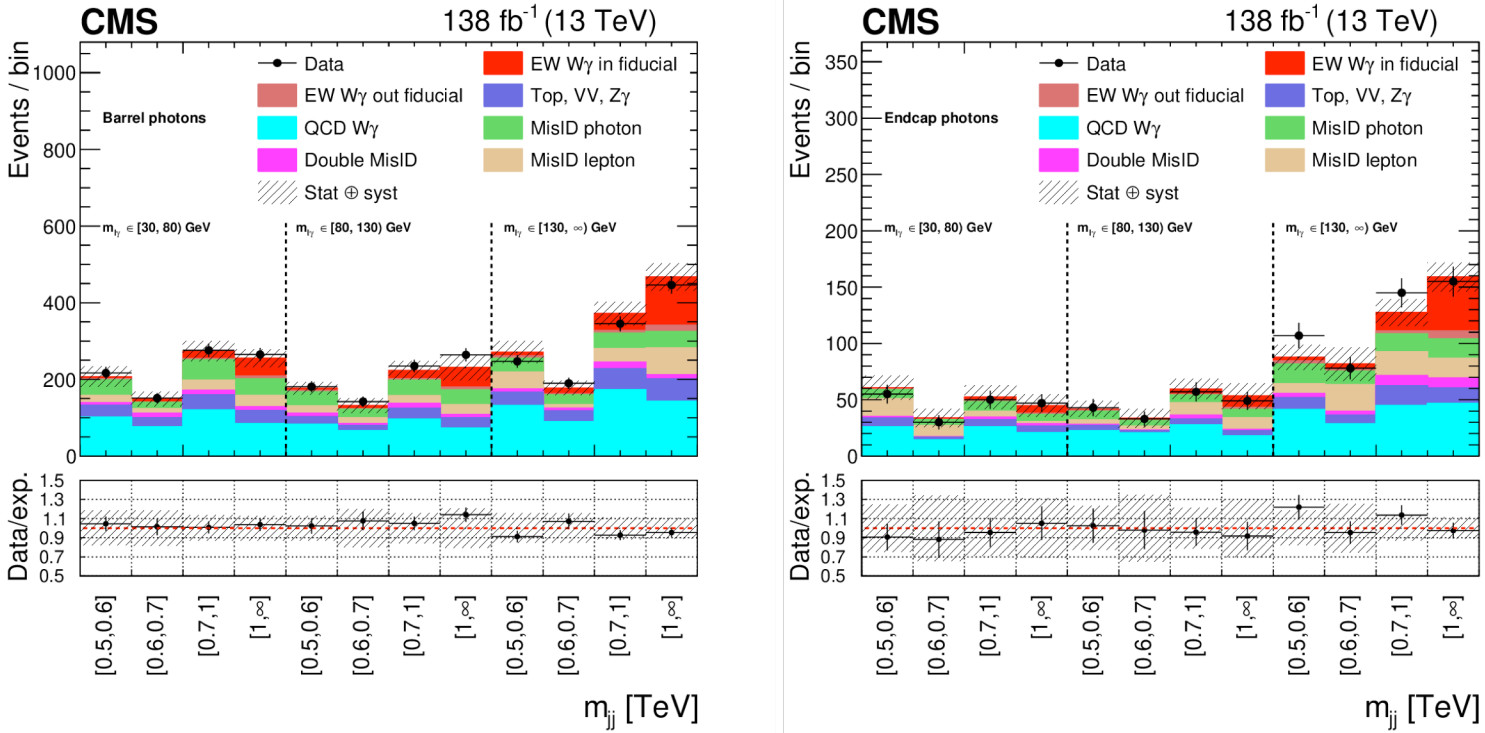
QCD-induced

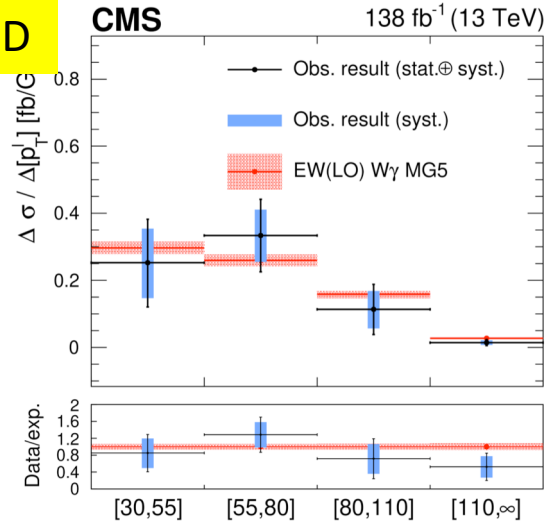
- Precision measurement with the Vector Boson Scattering (VBS) processes are important for probing the Higgs sectors and hence understanding the electroweak symmetry-breaking
- Event selection optimized for the Vector Boson Scattering (VBS) signal (Wγ+2 jets) with the rejection for the non-VBS electroweak (EWK) and QCD-induced processes
  - Isolated electron/muon p_T> 35 GeV, a photon (p_T> 25 GeV) and 2 jets along with the Missing Transverse Energy p^{mis}_T> 30 GeV
  - Large pseudorapidity difference between the jets and azimuthal balancing between (jets, Wγ) systems

Wγ+ 2 jets Cross-section Measurements

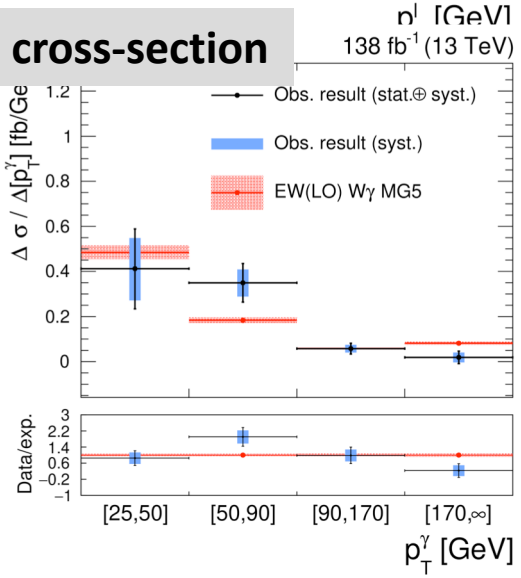
- Event categorization based on the barrel/enadcap photons and in bins of $m_{l\gamma}$ & m_{jj}
- Measurement of EWK-only and EWK+QCD fiducial and differential cross-sections in several observables -- p_T^{γ} , p_T^{l} , p_T^{j1}, m_{jj}, $m_{l\gamma}$, $\Delta\eta_{jj}$ axXiv:2212.12592; submitted to PRD
- Measurements are consistent with the SM predictions :

$\sigma_{EW}^{fid} = 19.2\ ^{+4.0}_{-3.9}$ fb & $\sigma_{EW+QCD}^{fid} = 90\ ^{+11.}_{-10}$ fb



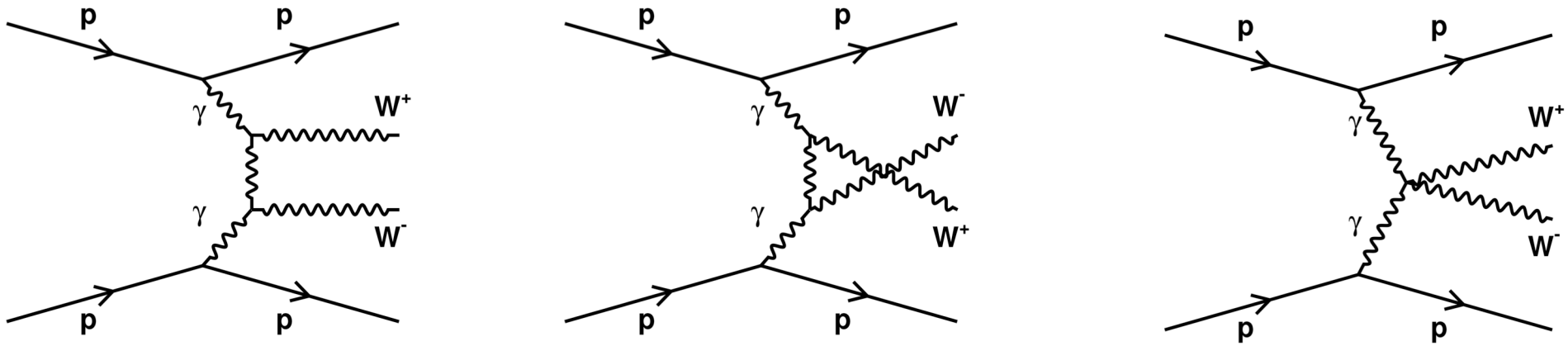


Differential cross-section

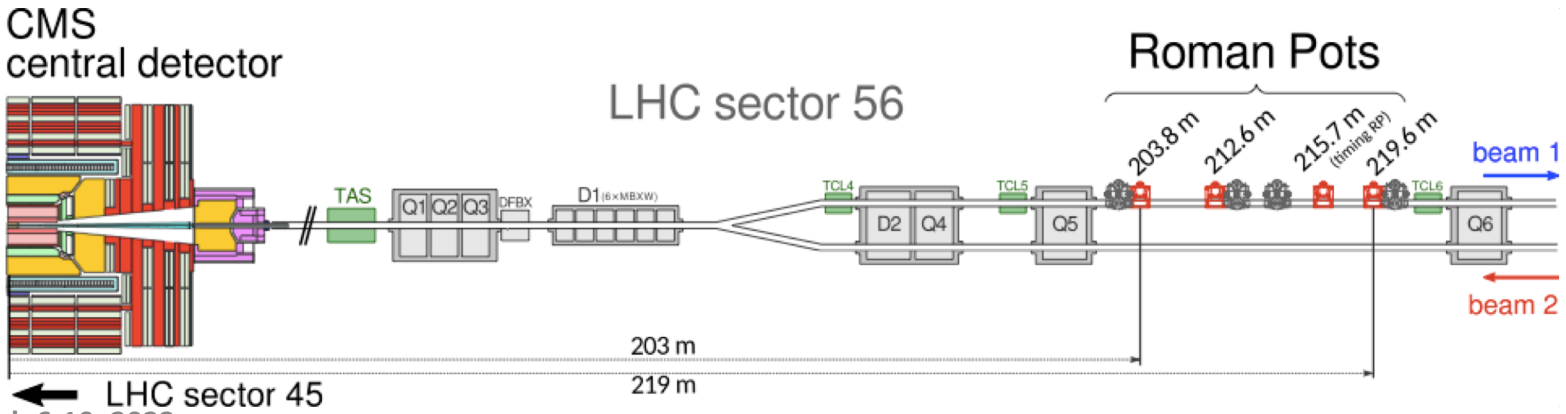


γγ→WW/ZZ production at the LHC

CMS-SMP-21-014; submitted to JHEP



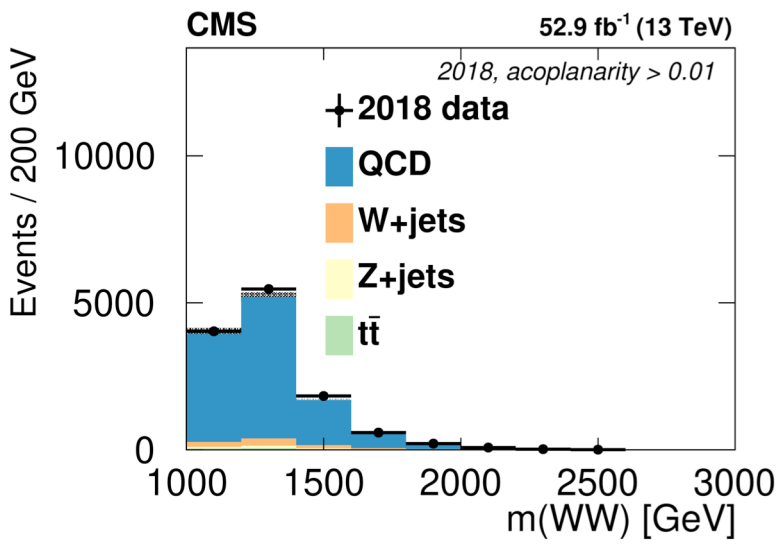
- Aim to probe SM quartic coupling at tree level :
- BSM contributions (resonant and non-resonant) accessed through effective-field-theory (EFT) approach
- Events with in-tact protons in the forward region
  - PPS can detects proton momenta ~200m from the CMS IP using the LHC magnets
  - SM cross-sections: 50 fb (γγ→WW) & 0.5 fb (γγ→ZZ)

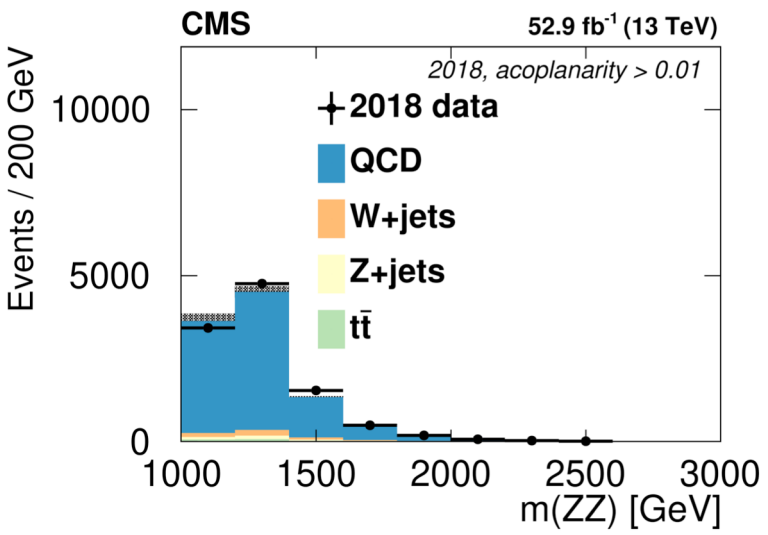


γγ→WW/ZZ production at the LHC

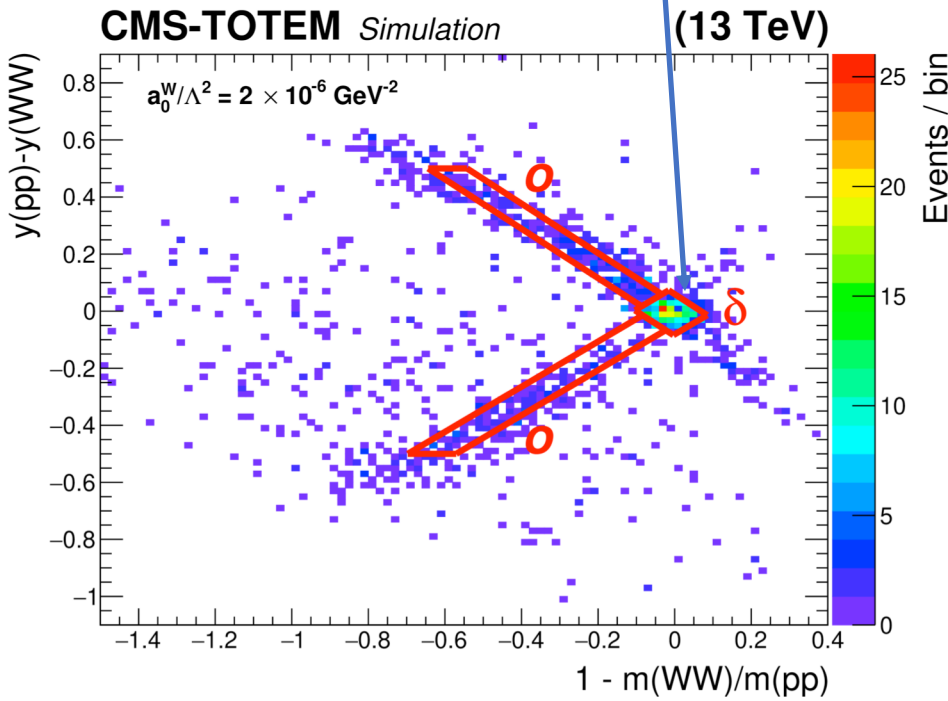
CMS-SMP-21-014; submitted to JHEP

- Search for weak vector bosons in boosted and merged jets m_{jj} >1126 GeV
- Background estimated from the control regions
  - Inverting the observables for jet topology and p-p matching
- Further discrimination between WW and ZZ events using sum of jet masses





Both protons matched



γγ→WW/ZZ production at the LHC

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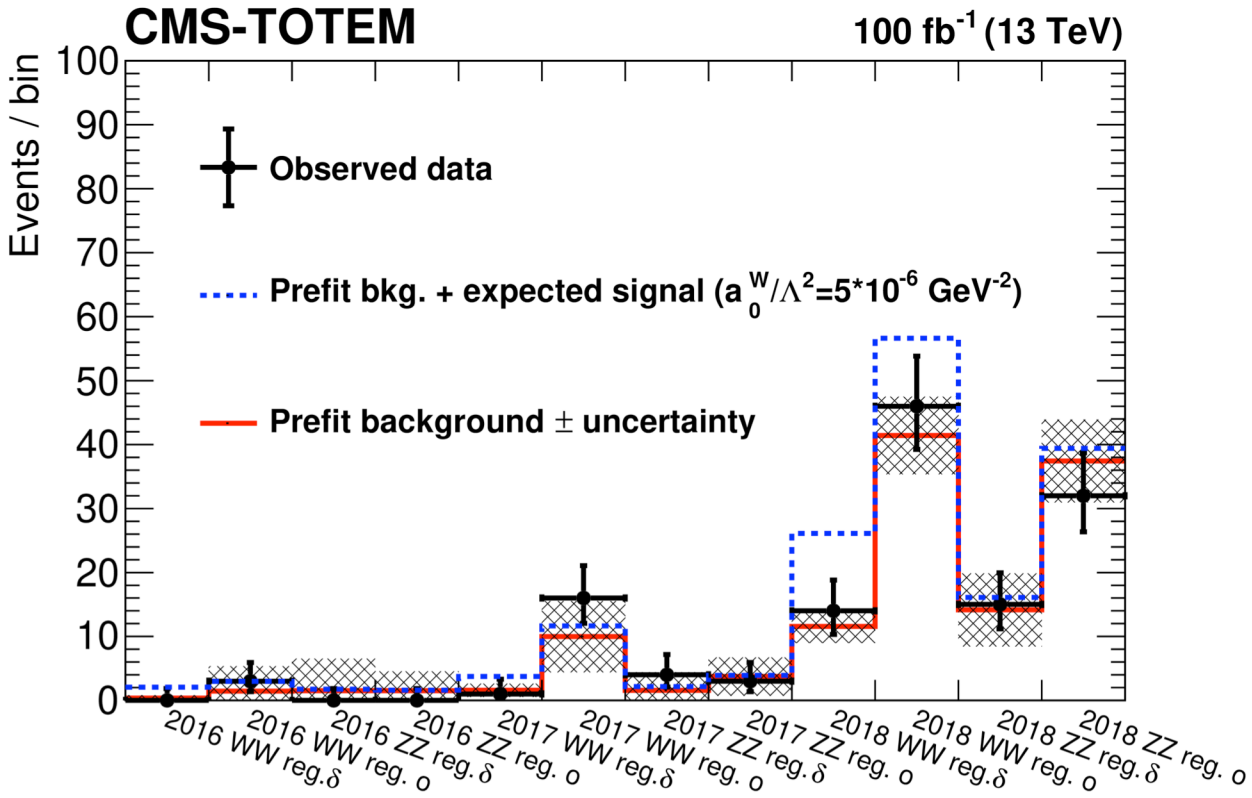
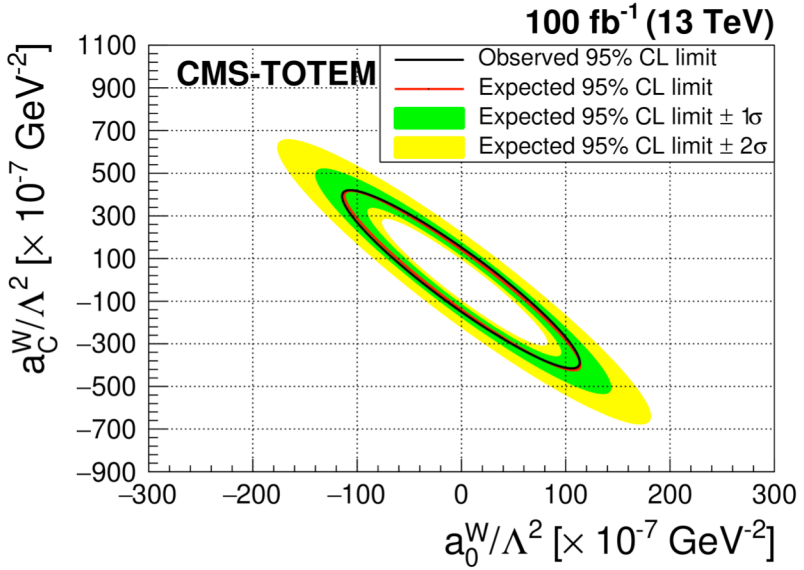
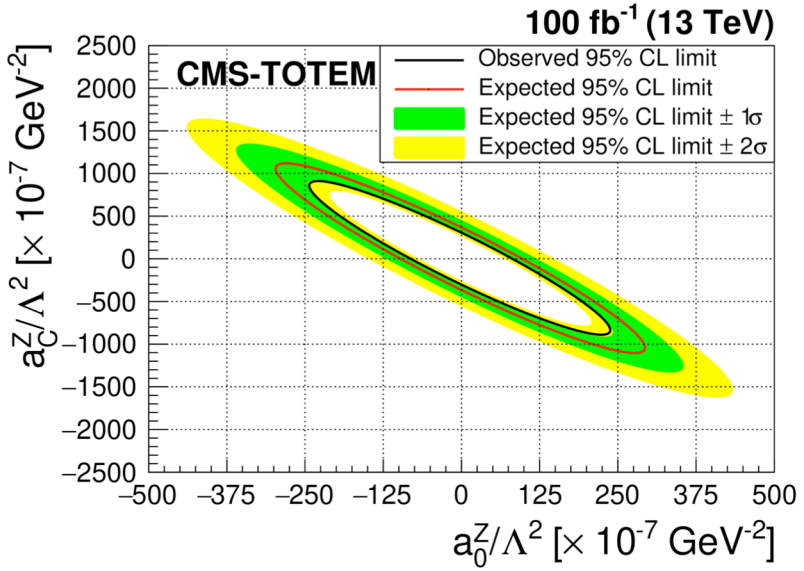
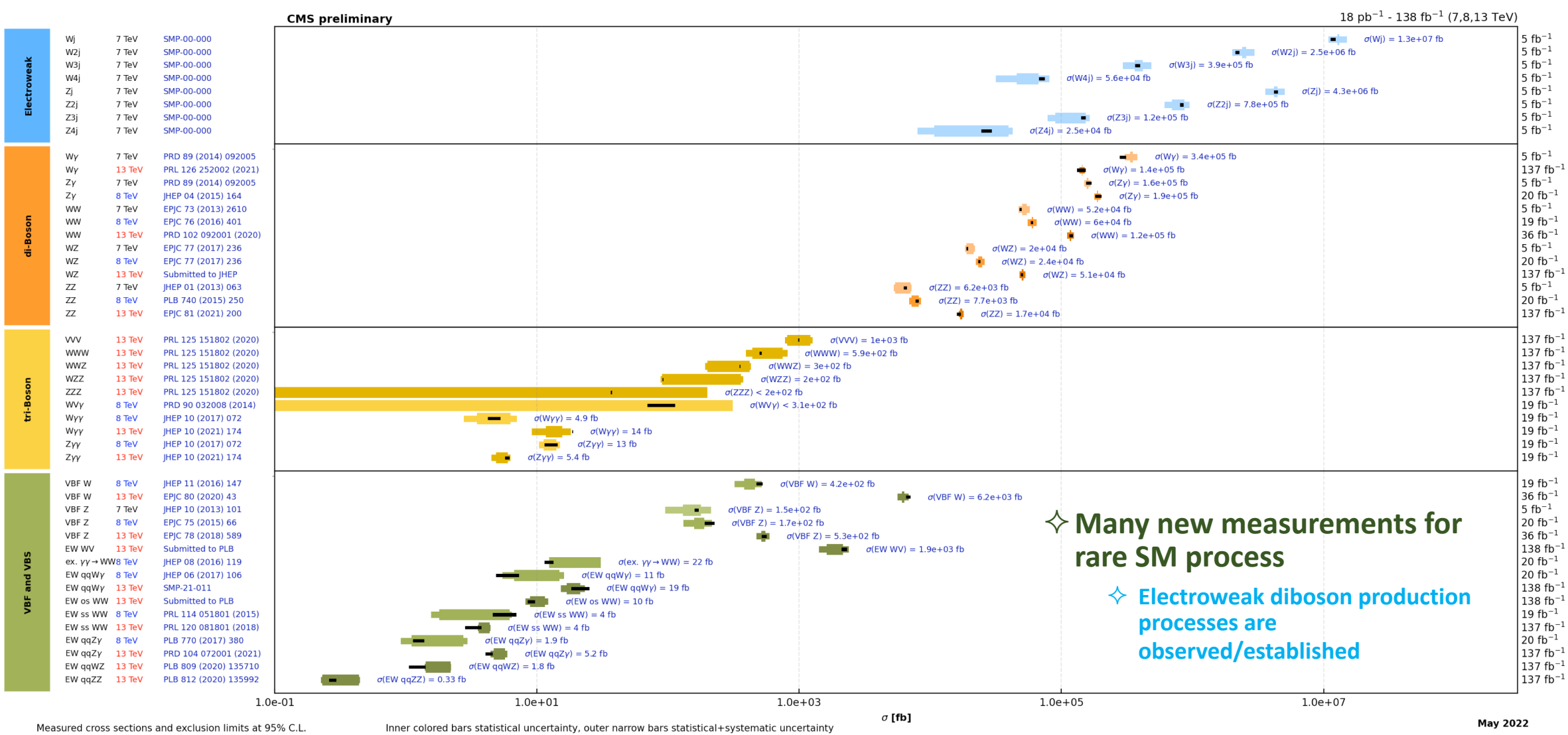






- Limits on fiducial cross-section considering m_{VV}>1 TeV and proton fractional charge <20%
- cross-section upper limit at 95%
  - σ (pp →pWWp) <67 fb
  - σ (pp→pZZp) <43 fb
- EFT Dimension-8 operators are constrained as well

Summary of SM Measurements

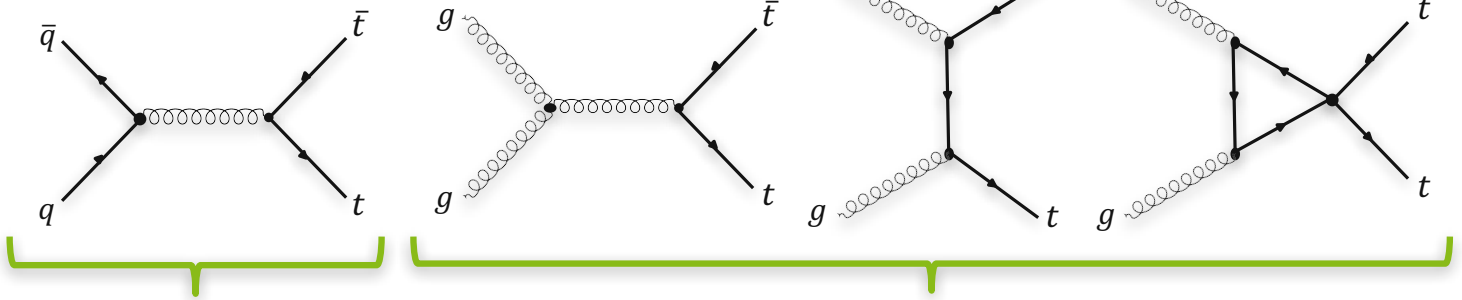


- **Many new measurements for rare SM process**
  - **Electroweak diboson production processes are observed/established**

Highlights of CMS Top results (Run II & Run III)

Top quark production modes at LHC

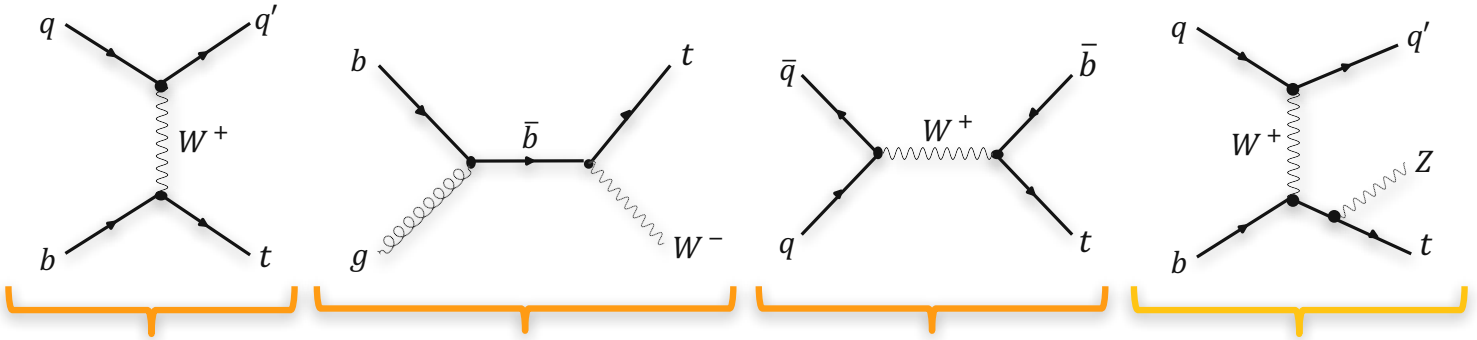
Dominated by $t\bar{t}$ pairs productions



quark-antiquark annihilation (~10%)

gluon-gluon fusions (~ 90%)

Single top-quark productions



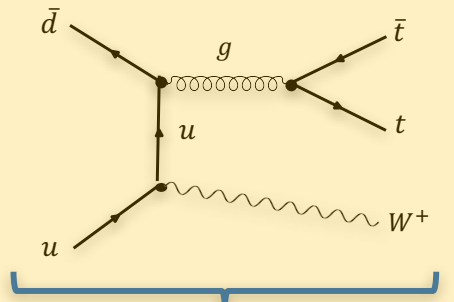
t-channel (~73%)

tW associated production (~24%)

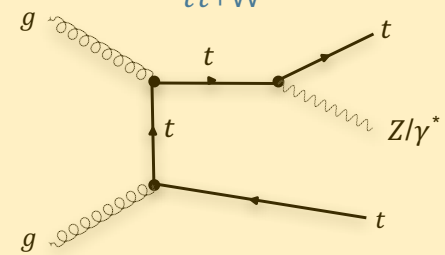
s-channel (~3%)

tZ production (<1%)

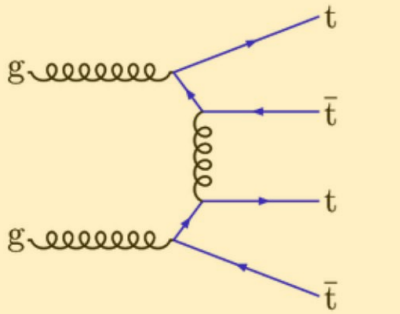
Other productions



$t\bar{t}$+W



$t\bar{t}$+Z/γ*

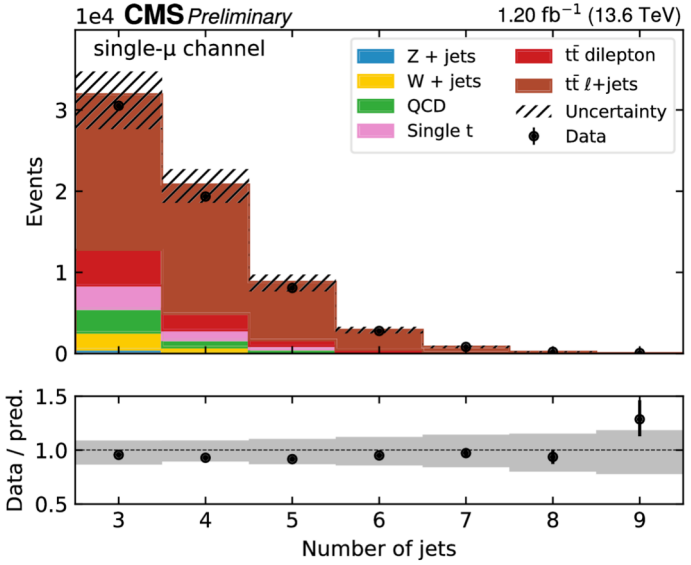


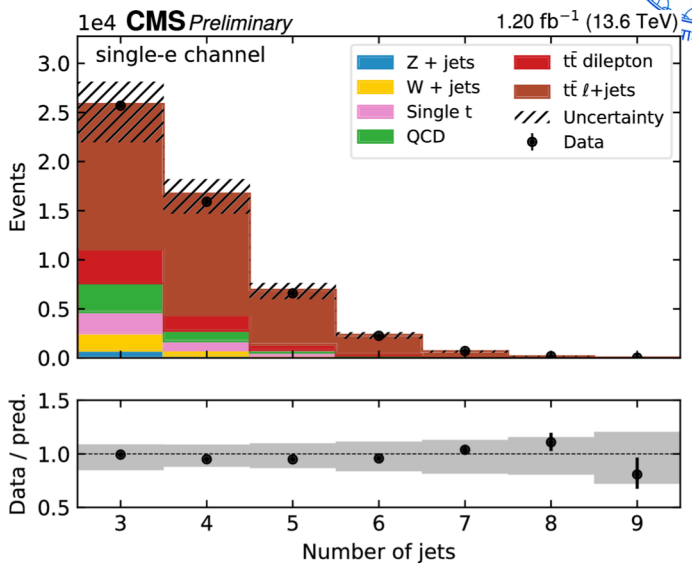
4-tops

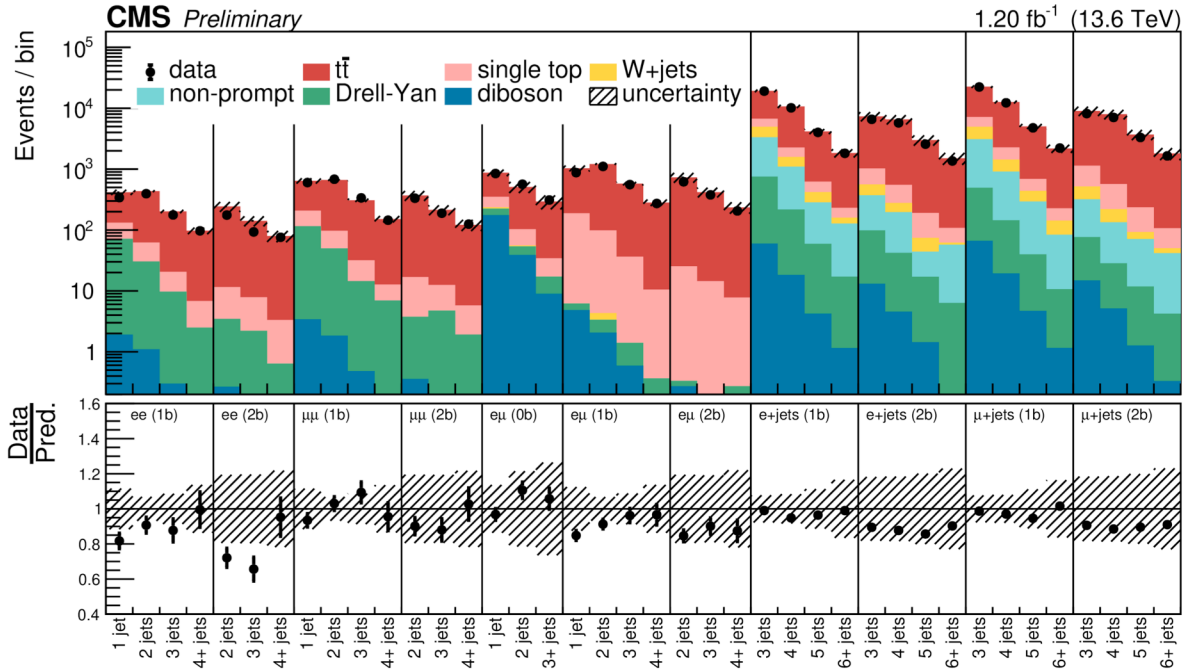
Top pair-production cross-section at √s=13.6 TeV

CMS-PAS-TOP-22-012

- First measurement of pair production cross-section using 1.2 fb^{-1} dataset in semi-leptonic and di-leptonic modes
- Event categorization based on the lepton flavor and number of b-jets
- Extraction of cross-sections fitting the yields in each category of events







Top pair-production cross-section at $\sqrt{s}$=13.6 TeV

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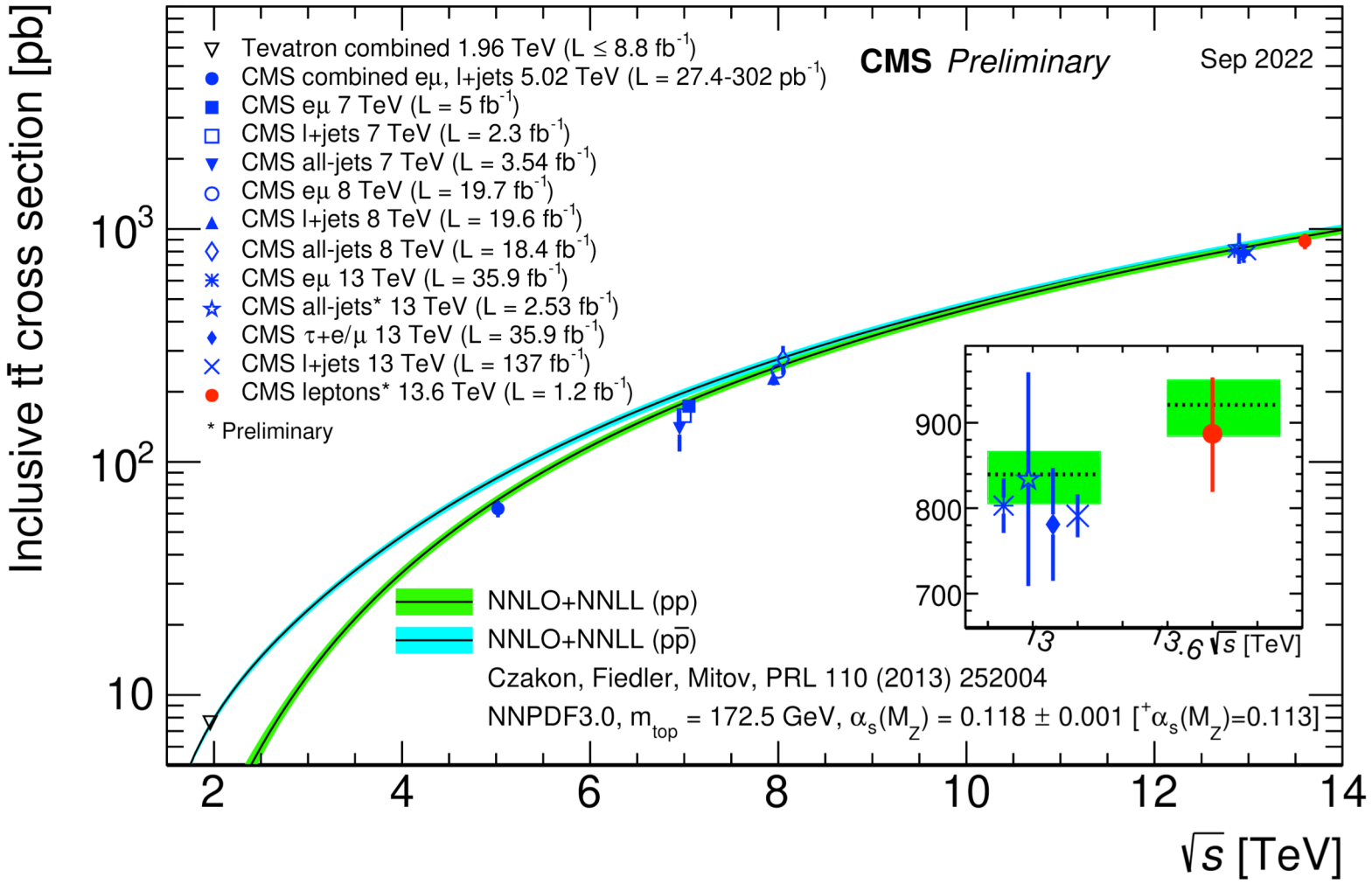


Source	Uncertainty (%)
Lepton ID efficiencies	3.4
Jet energy scale	1.6
b tagging efficiency	1.5
Pileup reweighting	0.7
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.2
PDF and α_S	0.3
ME/PS matching	1.1
ISR scale	0.4
FSR scale	0.1
Single-t background	0.6
Z+jets background	0.9
W+jets background	0.4
Diboson background	0.1
Nonprompt background	0.2
Statistical uncertainty	0.5
Combined uncertainty	4
Jet energy scale (external)	2
Integrated luminosity	6

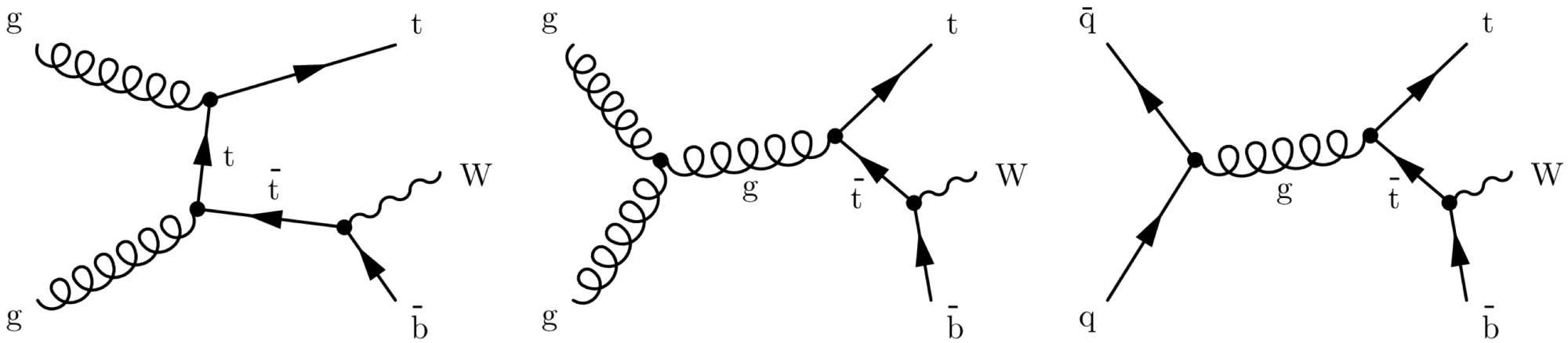
- $\sigma_{measured} = 887\ ^{+43}_{-41} \pm 53$ (lumi) pb
- $\sigma_{SM} = 921\ ^{+29}_{-37}$ pb

Inclusive/differential tW production

arXiv:2208.0092

- Inclusive and normalized differential cross-section measurements in dilepton final states with full Run 2 dataset at √s=13 TeV
- At NNLO theoretical prediction:

  σ_{SM} = 71.7 ± 1.8 (scale) ± 3.4 (PDF) pb
- Signal simulation using NLO PowHeg with Diagram Removal (DR) and Diagram Subtraction (DS) schemes due to large interference with ttbar processes
  - Nominal analysis with DR scheme, while the differences with respect to DS considered as systematic uncertainty

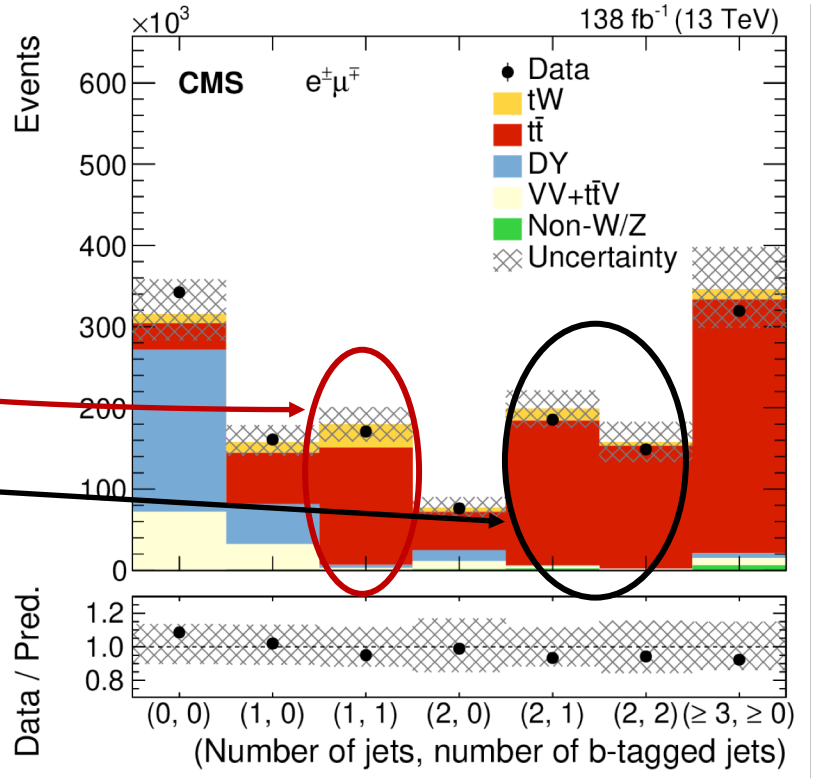


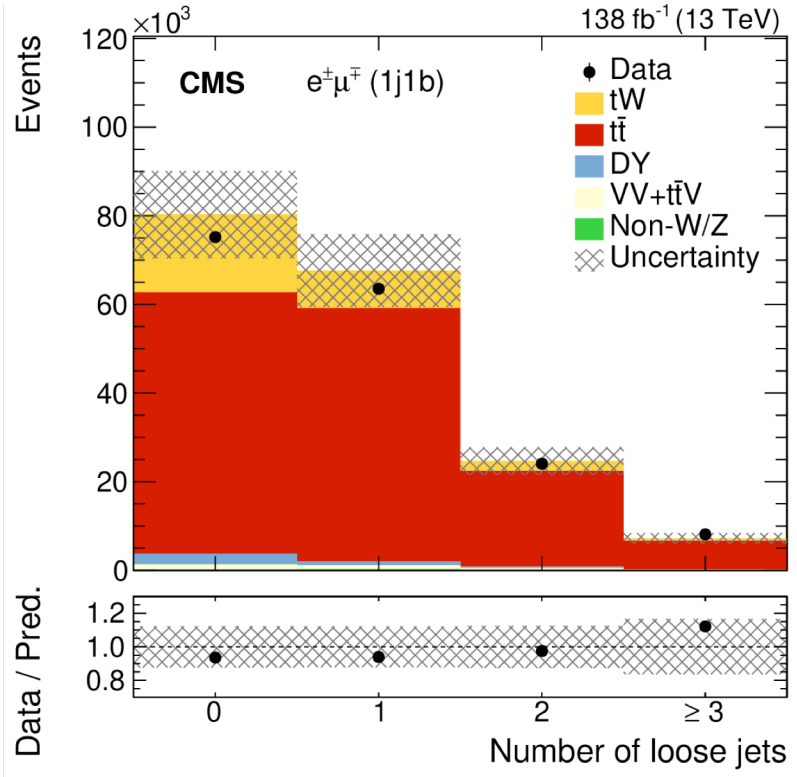
Inclusive tW production

arXiv:2208.0092

- Basic event preselection with eμ final states
  - Single lepton and dilepton triggers depending on the data-taking period
  - Isolated electrons/muons with p_T>20 GeV and |η|<2.4
  - Leading lepton p_T>25 GeV, and oppositely charged leptons with M_{ll}>20 GeV
  - Jets with p_T>30 GeV and |η|<2.4 with b-tagging

- Classification of events in bins of (N_{jet}, $N_{b\text{-}jet}$)
  - Events with one jet and 1 b-jet (1j1b) is the most signal enriched
  - 1j1b, 2j1b, 2j2b for inclusive measurements





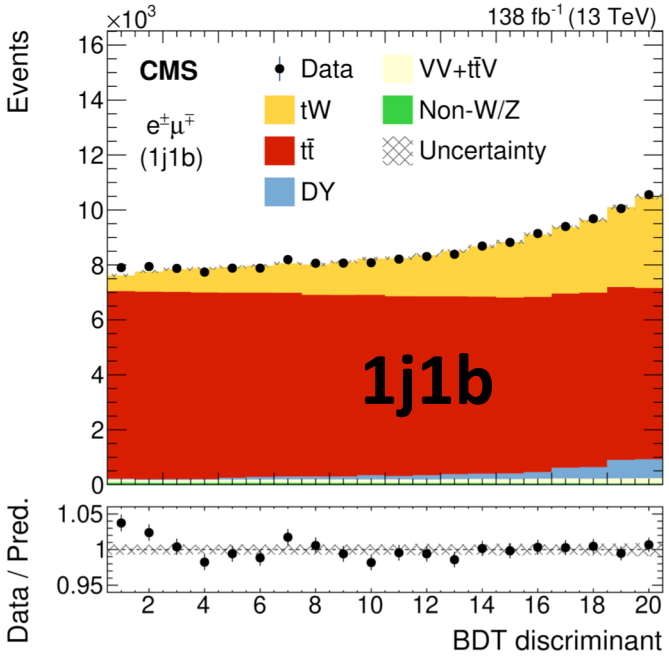
Inclusive tW production

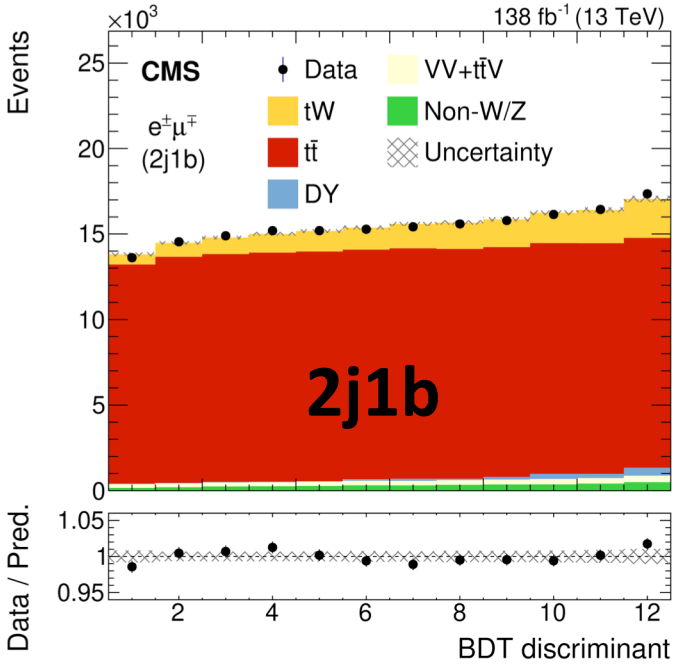
arXiv:2208.0092

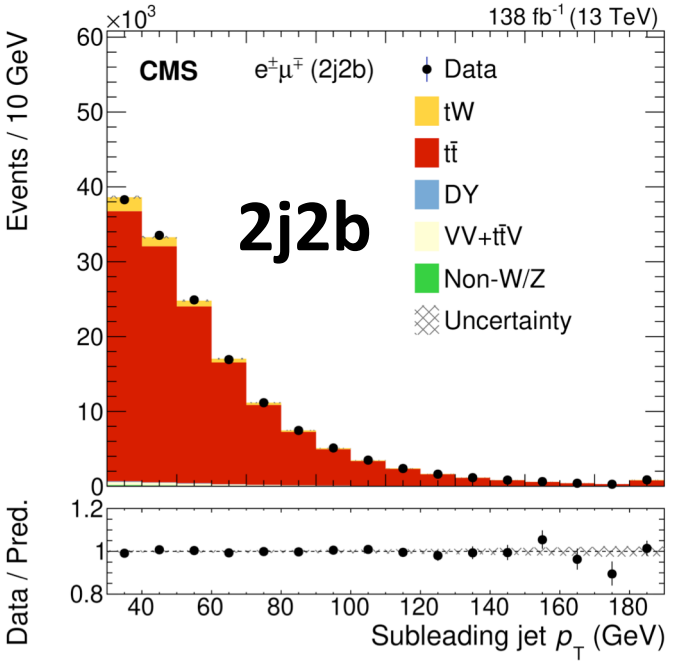
- Further discrimination based on the BDTs against the ttbar background
- Maximum likelihood fits with BDT and sub-leading jet pT (2j2b)
- Measures cross-section consistent with the SM prediction:

$\sigma_{Measured} = 79.2 \pm 0.9\ (stat)\ ^{+7.7}_{-8.0}\ (syst) \pm 1.2\ (lumi)$ pb

Process	1j1b	2j1b	2j2b
tW	31 600 ± 600	16 600 ± 500	5 500 ± 200
$t\bar{t}$	131 200 ± 500	160 300 ± 600	141 100 ± 400
Drell–Yan	3 990 ± 190	1 630 ± 100	260 ± 20
VV+$t\bar{t}$V	2 800 ± 300	3 300 ± 500	1 700 ± 400
Non-W/Z	1 140 ± 150	3 700 ± 700	470 ± 120
Total	170 800 ± 300	185 400 ± 400	149 100 ± 300
Data	170 900 ± 400	185 400 ± 400	148 900 ± 400





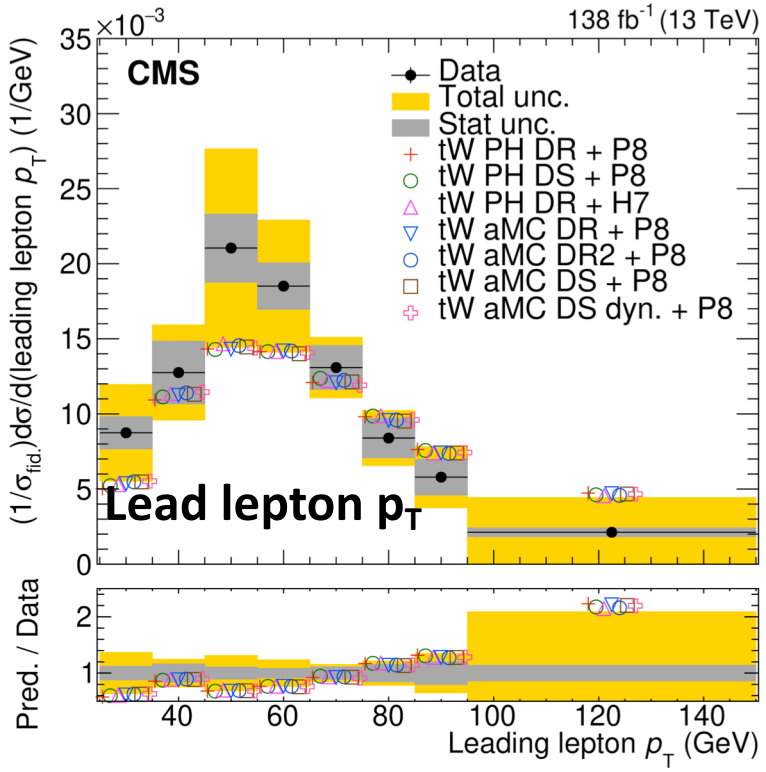


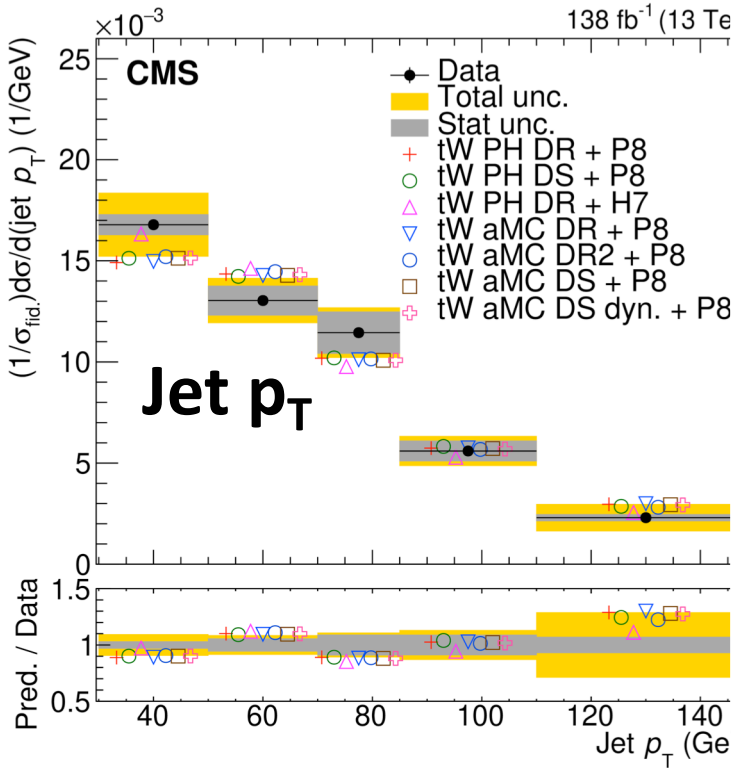
Differential tW production

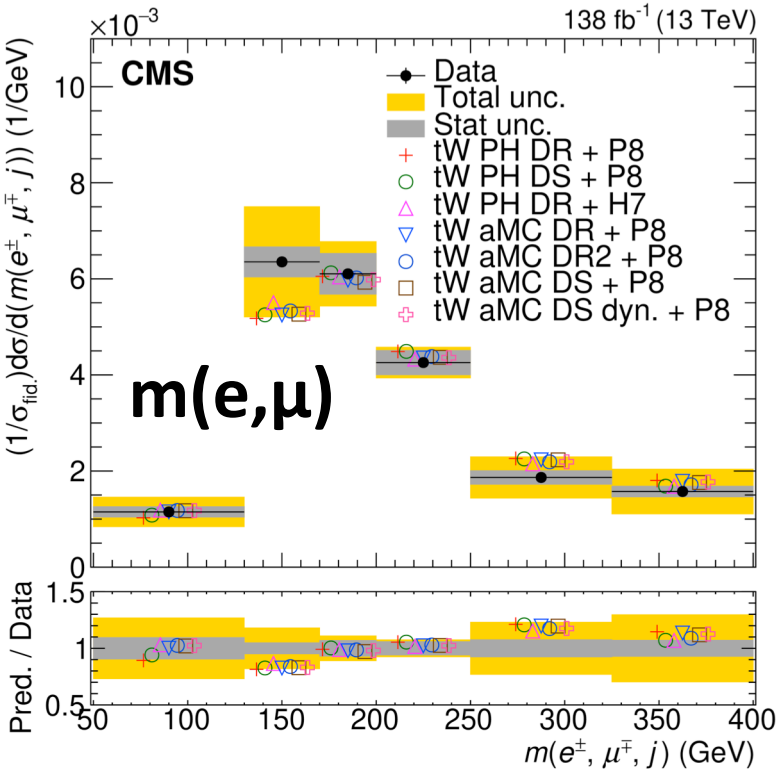
- Fiducial cross-sections are unfolded into the particle level cross-sections (with similar kinematic selection for the particle level objects)

arXiv:2208.0092

- Differential measurements performed using 1b1j events with veto on loose jets ($20<p_T<30$ GeV) in the final states
- Measured as functions of various physical observables: leading lepton p_T, jet p_T, $\Delta\phi$ (e,μ), m(e,μ), pz (e,μ,jets), m_T (e,μ, jets, missing E_T)
- Overall good agreement between Data and MC; consistent with DR and DS schemes



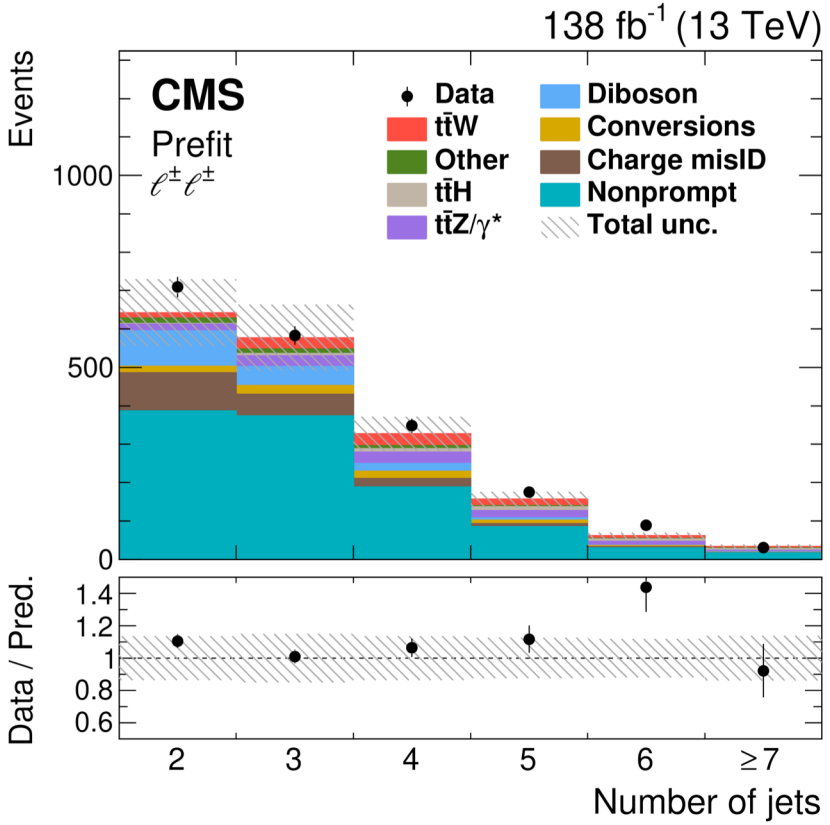




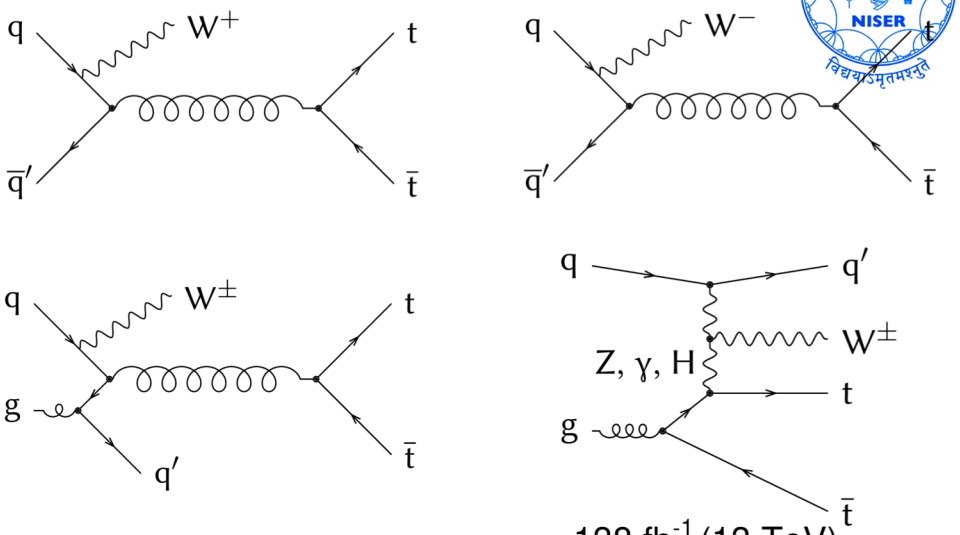
Measurements for ttW processes

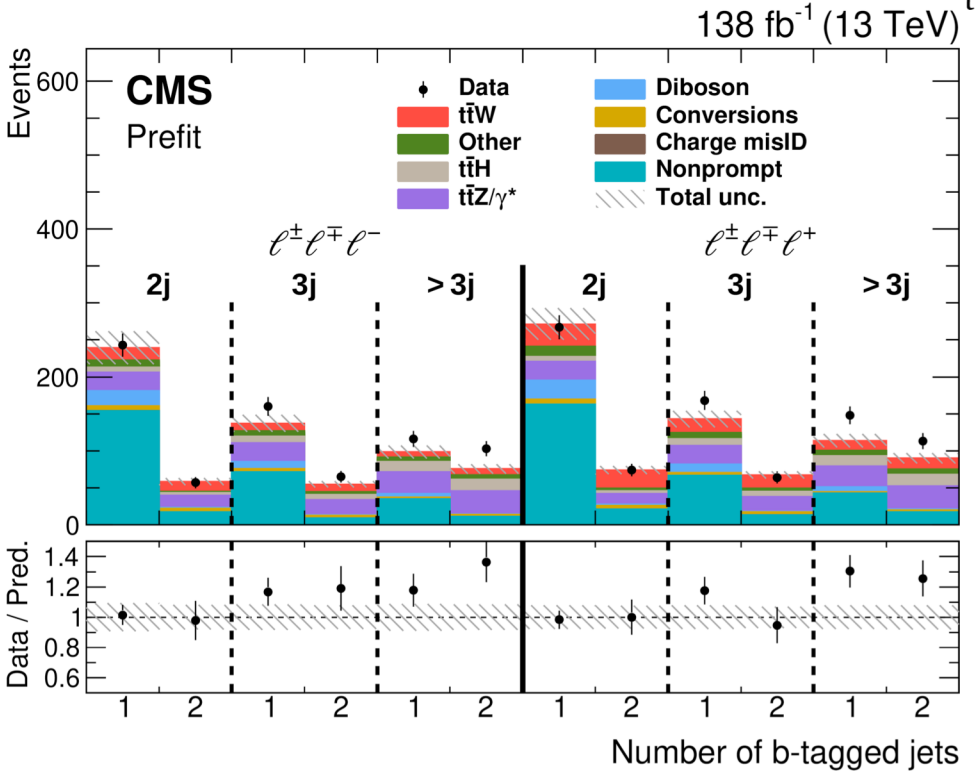
arXiv:2208.06485

- Final state signatures with multiple leptons (production mode correlated with lepton charges), jets and b-tagged jets
- **Inclusive cross-section and charge asymmetry measurements in multi-lepton final states with full Run 2 dataset at √s=13 TeV**
  - **NLO QCD+EW effects included prediction σ_{SM} ≈ 597-722 fb**

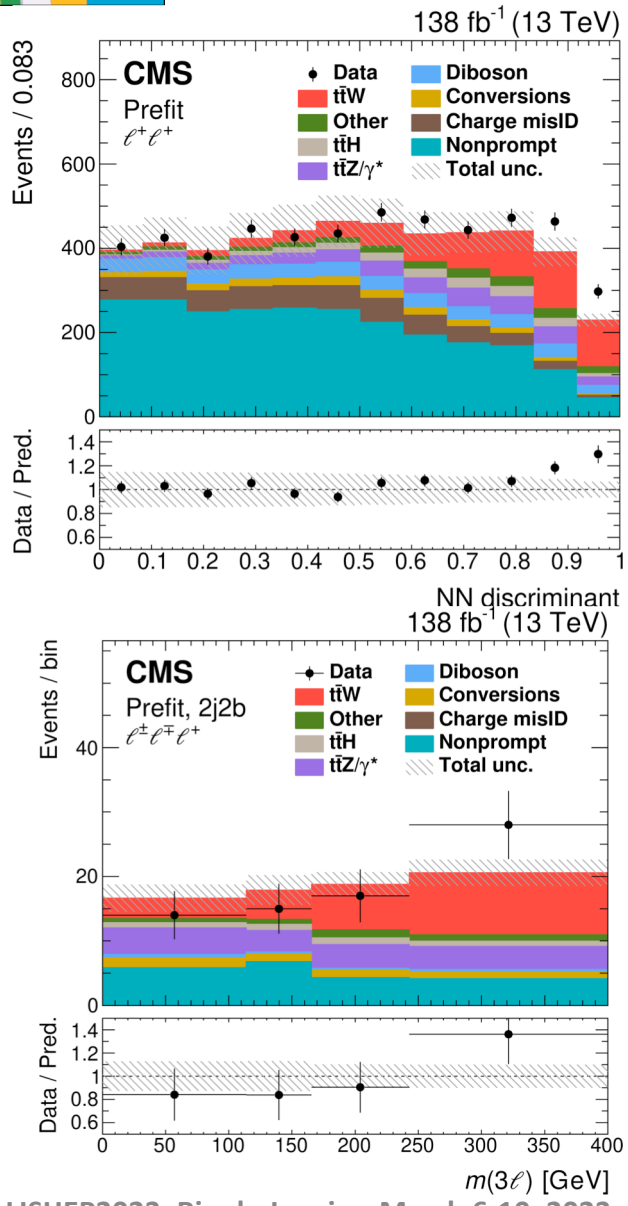


- Same-sign dilepton (2lSS) – DNN based discrimination between signal and background
- Trilepton channel (3l) with categorization of events based on the number of jets, b-jet multiplicity, charge of the leptons.
- Additional control regions (3l and 4l) to target WZ, ZZ and ttZ

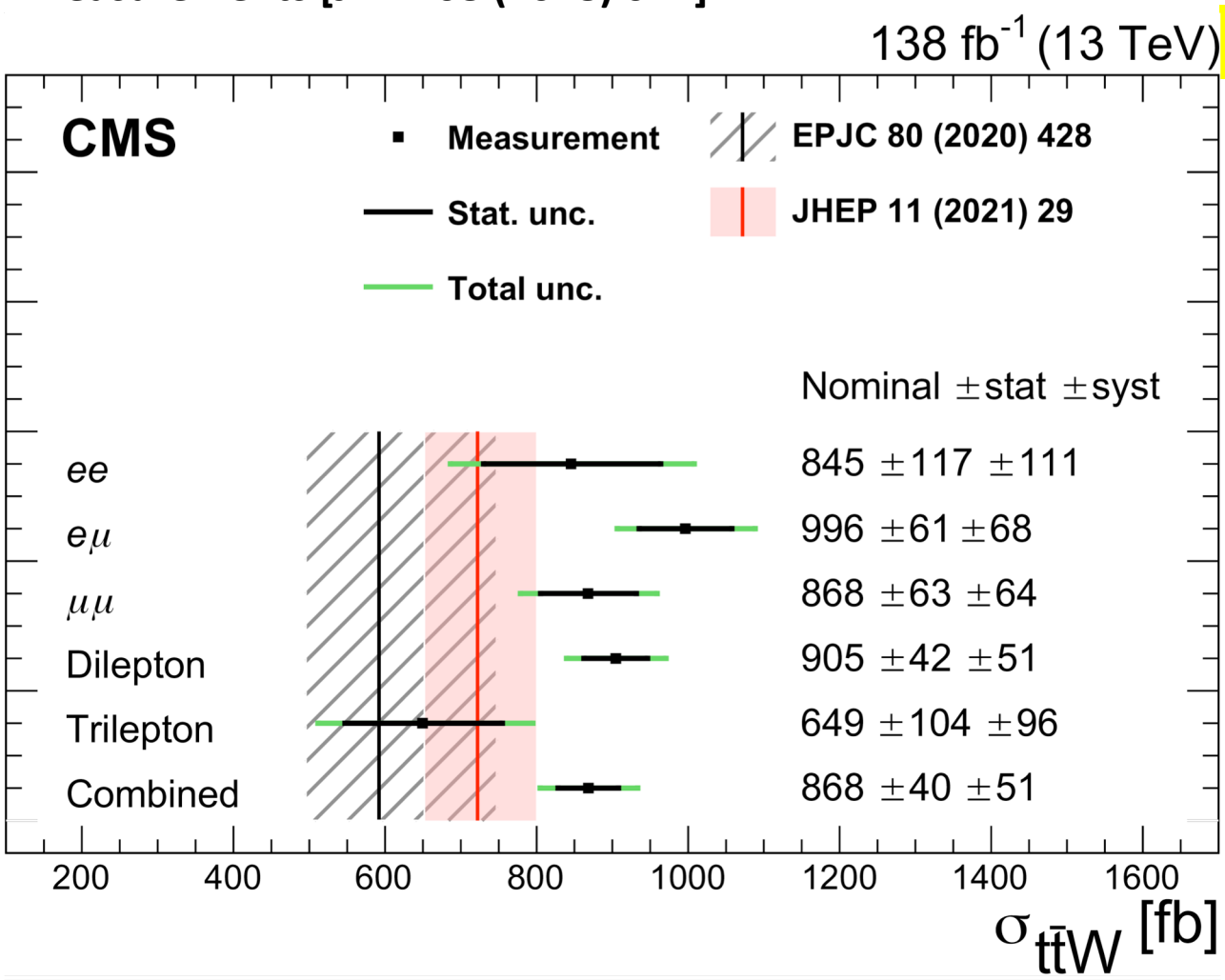




Inclusive ttW cross-section Measurements



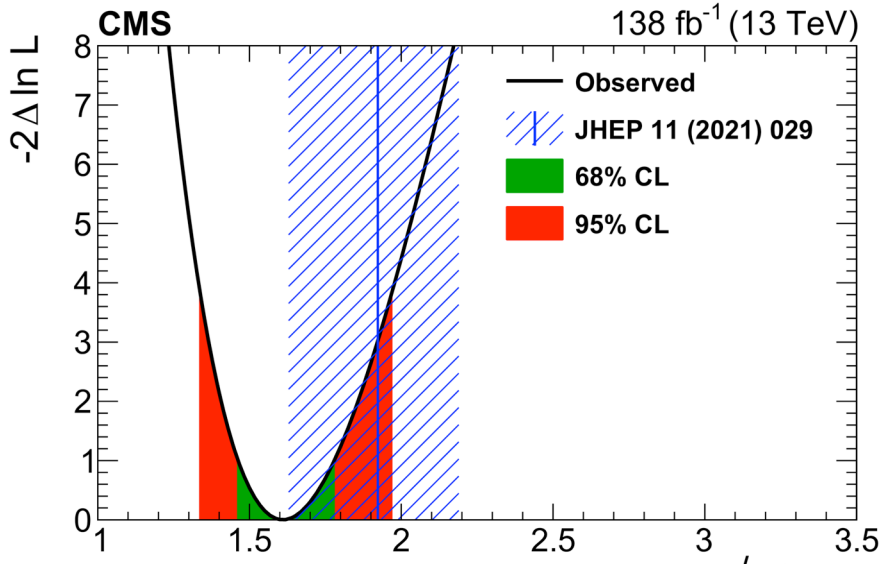
- ttW cross-section extracted using binned profile likelihood fits using the distributions of DNN output (2S) and trilepton invariant mass (3l)
- **Precision improvement by factor of 2 with respect to the 2016 measurements [JHEP 08 (2018) 011]**



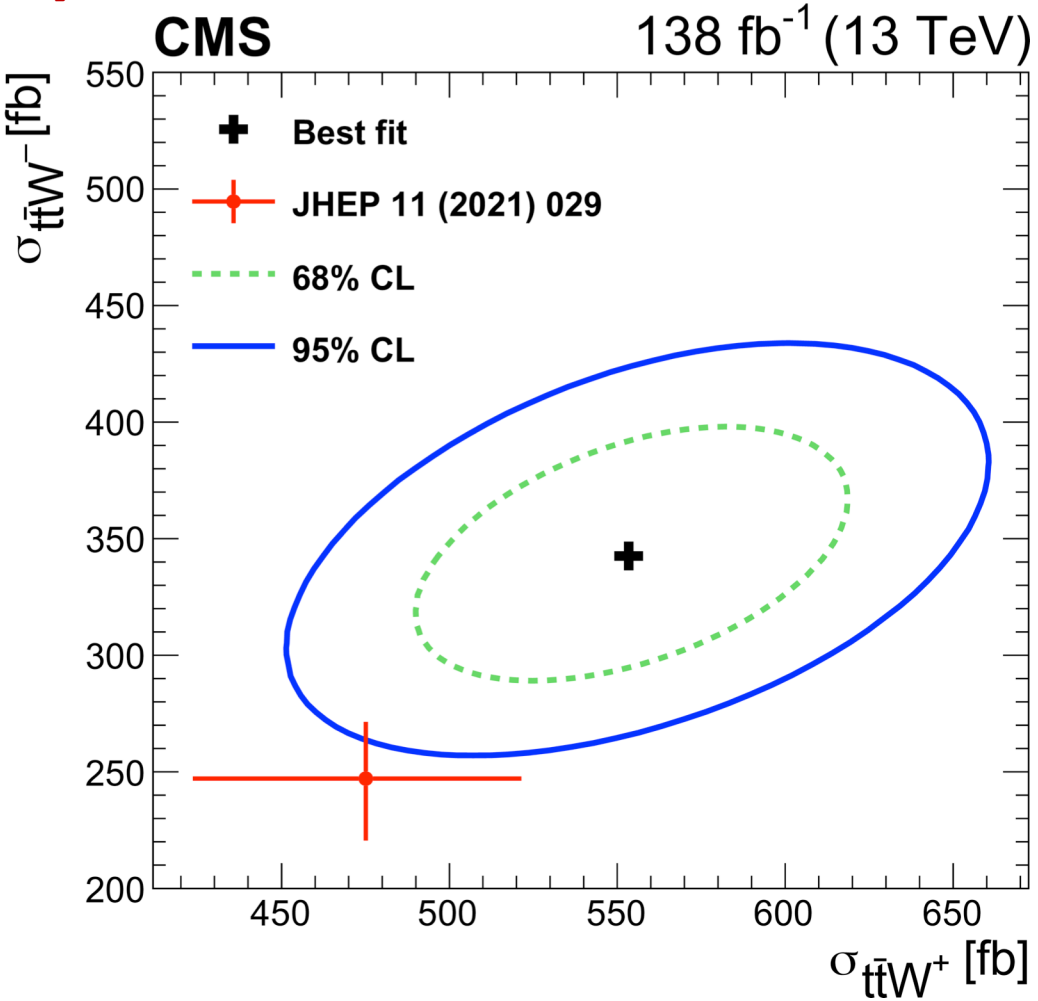
$t\bar{t}W^{\pm}$ Charge Asymmetry Measurements

- $t\bar{t}W^{\pm}$ measurements have direct implications on the proton PDFs
- Simultaneous fit for the positive and negative lepton system charges respectively for $t\bar{t}W^{+}$ and $t\bar{t}W^{-}$
- **Consistent with the latest theoretical calculations [JHEP 11 (2021) 029]**

arXiv:2208.06485



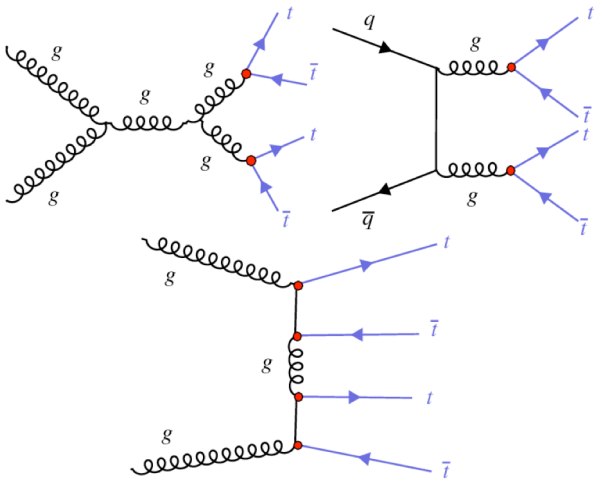
Observable	Measurement	SM prediction NLO + NNLL	SM prediction NLO + FxFx
$\sigma_{t\bar{t}W}$	$868 \pm 40\,(\text{stat}) \pm 51\,(\text{syst})$ fb	$592\,^{+155}_{-97}\,(\text{theo})$ fb	$722\,^{+71}_{-78}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W^+}$	$553 \pm 30\,(\text{stat}) \pm 30\,(\text{syst})$ fb	$384\,^{+53}_{-33}\,(\text{theo})$ fb	$475\,^{+46}_{-52}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W^-}$	$343 \pm 26\,(\text{stat}) \pm 25\,(\text{syst})$ fb	$198\,^{+26}_{-17}\,(\text{theo})$ fb	$247\,^{+24}_{-27}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W^+}/\sigma_{t\bar{t}W^-}$	$1.61 \pm 0.15\,(\text{stat})\,^{+0.07}_{-0.05}\,(\text{syst})$	$1.94\,^{+0.37}_{-0.24}\,(\text{theo})$	$1.92\,^{+0.27}_{-0.29}\,(\text{theo})$

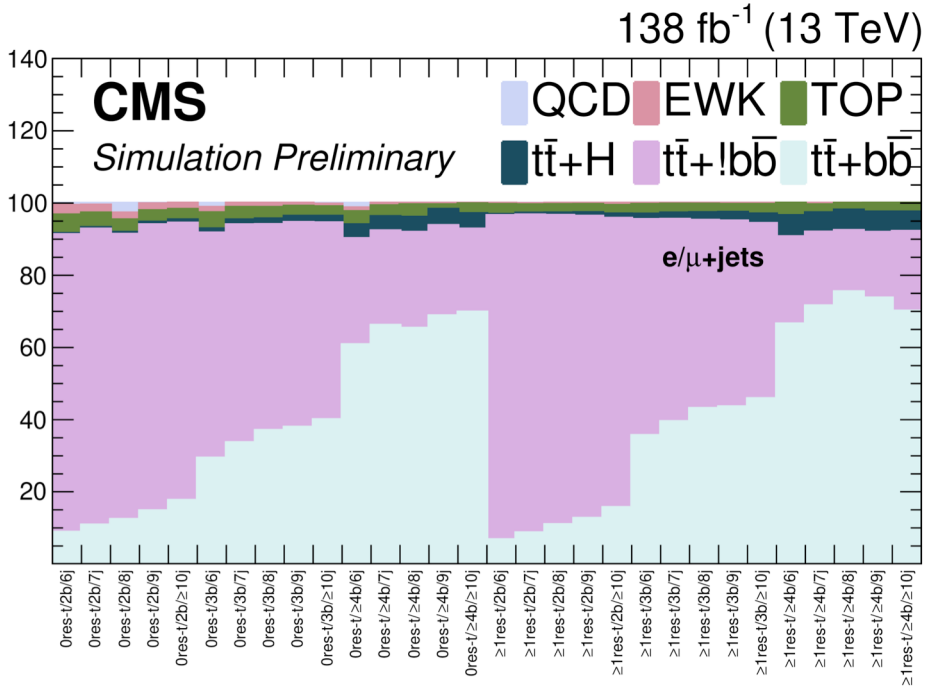


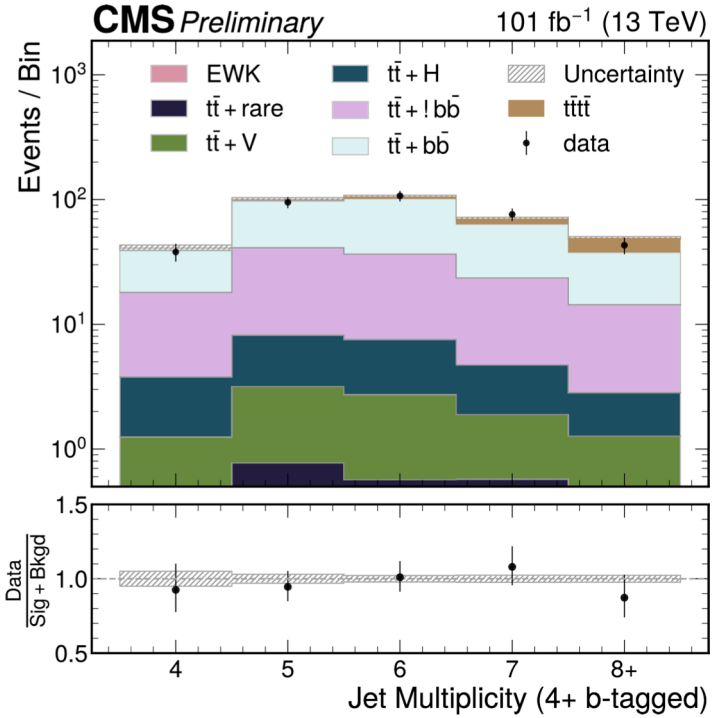
Evidence for 4 tops

CMS-PAS-TOP-21-005

- Search for 4 tops with 0, 1, 2 leptons in the final states with boosted and resolved categories
  - Hadronic final states with ≥9 jets, ≥3 b-tagged jets, event H_T≥ 700 GeV; BDT-based discriminator
  - Categorization based on b-jet multiplicity, resolved jet multiplicity and lepton flavors
- Sensitive to the New physics models variety of new physics (2HDM, compositeness, SUSY) scenarios can be probed
- 101 fb^{-1} (2017+2018) for dilepton channel; full Run 2 dataset for hadronic and single-lepton channels



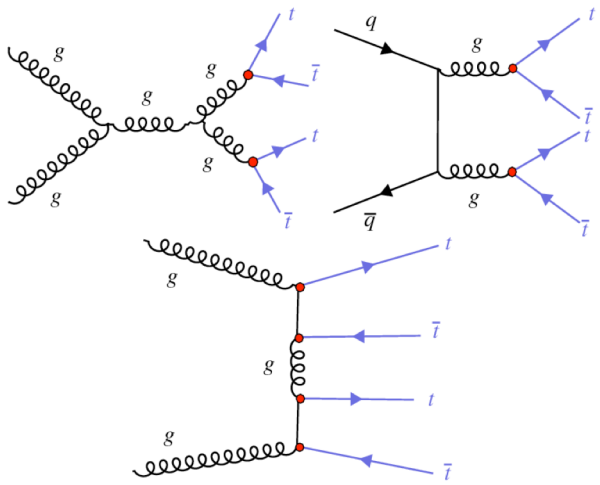


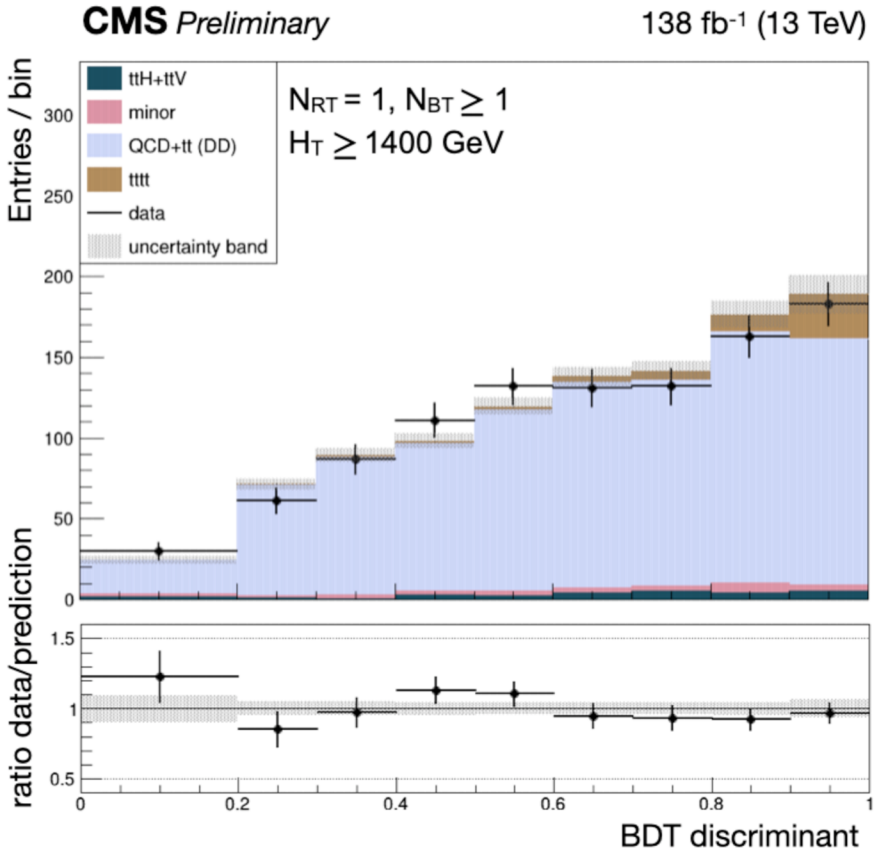


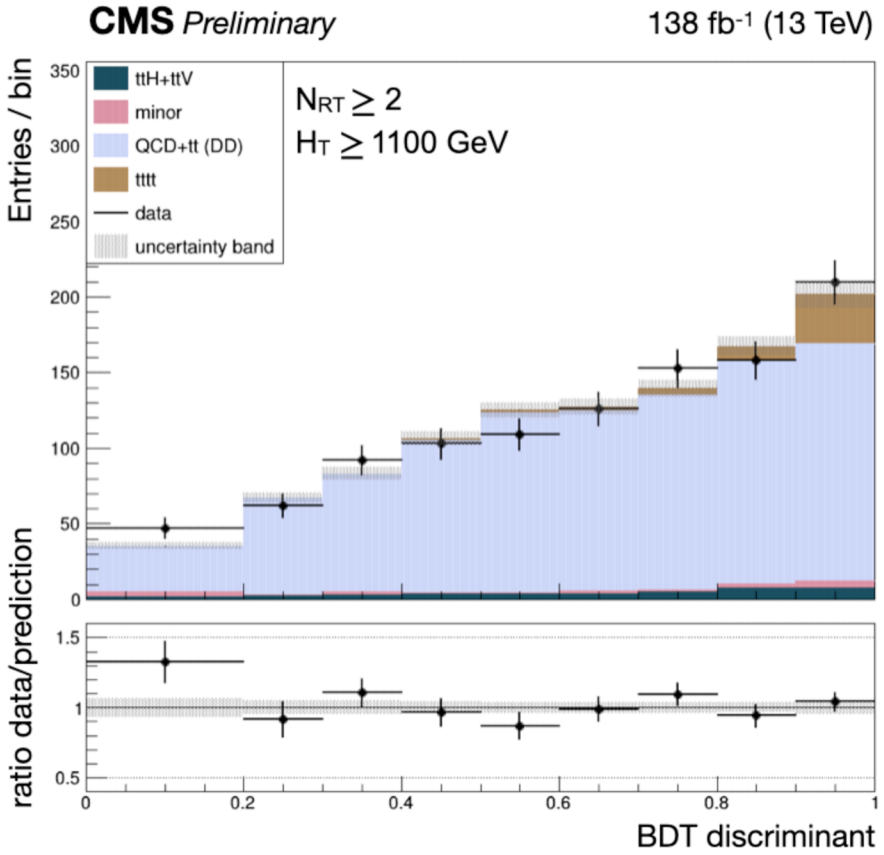
Evidence for 4 tops

CMS-PAS-TOP-21-005

- BDT discriminant based on jet kinematics, jet multiplicity, b-jet multiplicity and top tagging
- BDT distributions are the final observables for signal extraction

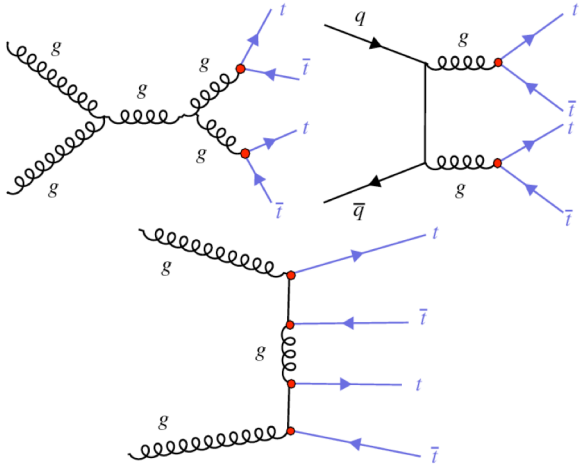


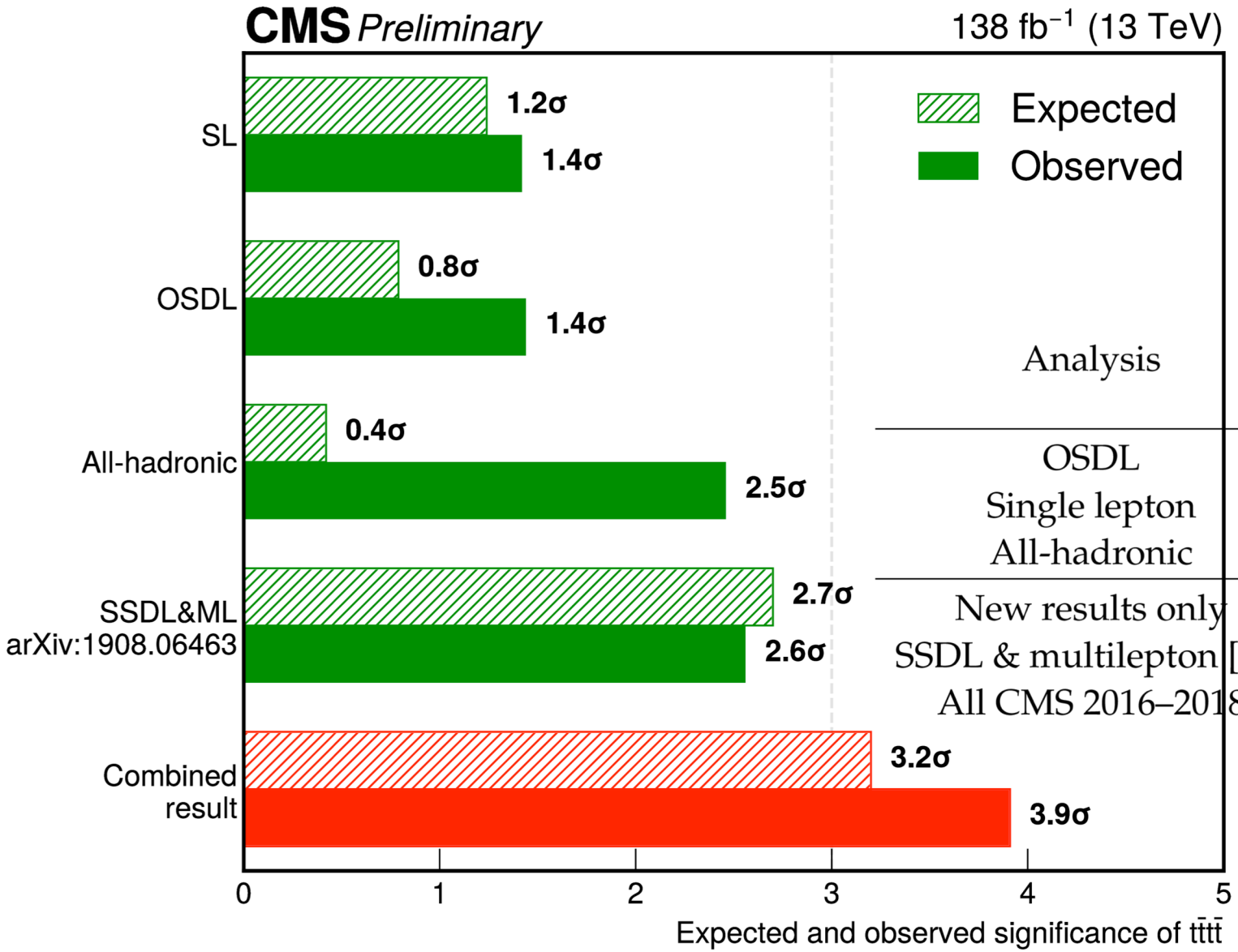




Evidence for 4 tops

CMS-PAS-TOP-21-005





Analysis	Signal strength exp	Signal strength obs	Significance exp	Significance obs	Cross section obs (fb)
OSDL	$1^{+1.6}_{-1.6}$	$2.8^{+1.8}_{-1.6}$	0.6	1.8	37^{+21}_{-20}
Single lepton	$1^{+0.9}_{-0.8}$	$1.2^{+0.9}_{-0.9}$	1.2	1.4	15^{+13}_{-11}
All-hadronic	$1^{+2.5}_{-2.4}$	$5.8^{+2.5}_{-2.4}$	0.4	2.5	70^{+30}_{-29}
New results only	$1^{+0.7}_{-0.7}$	$2.5^{+0.7}_{-0.7}$	1.5	3.7	38^{+13}_{-11}
SSDL & multilepton [26]	$1^{+0.4}_{-0.4}$	$1.0^{+0.5}_{-0.4}$	2.7	2.6	13^{+6}_{-5}
All CMS 2016–2018	$1^{+0.4}_{-0.3}$	$1.4^{+0.4}_{-0.4}$	3.2	3.9	17^{+5}_{-5}

Summary & Conclusions

- During the LHC era, the statistics of SM & top quark events in data has reached to a new level leading to the CMS measurements at an unprecedented precision
  - No deviation from the SM have been observed so far
  - Many new measurements have already been performed/completed with the full/partial Run 2 dataset
- Increased statistics allows the scope for differential cross-section measurements in SM and Top quark processes
  - EWK VBS and rare top quarks processes have been observed/established
- Run 3 statistics would improve the measurement precision further, although with additional pile-up events
  - Scope for probing the BSM physics further

References

- SM: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
- Top: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP