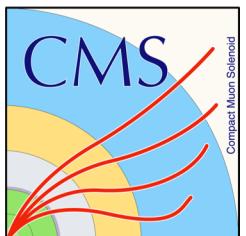




# Recent Physics Results from CMS



John Strologas  
*University of Ioannina*

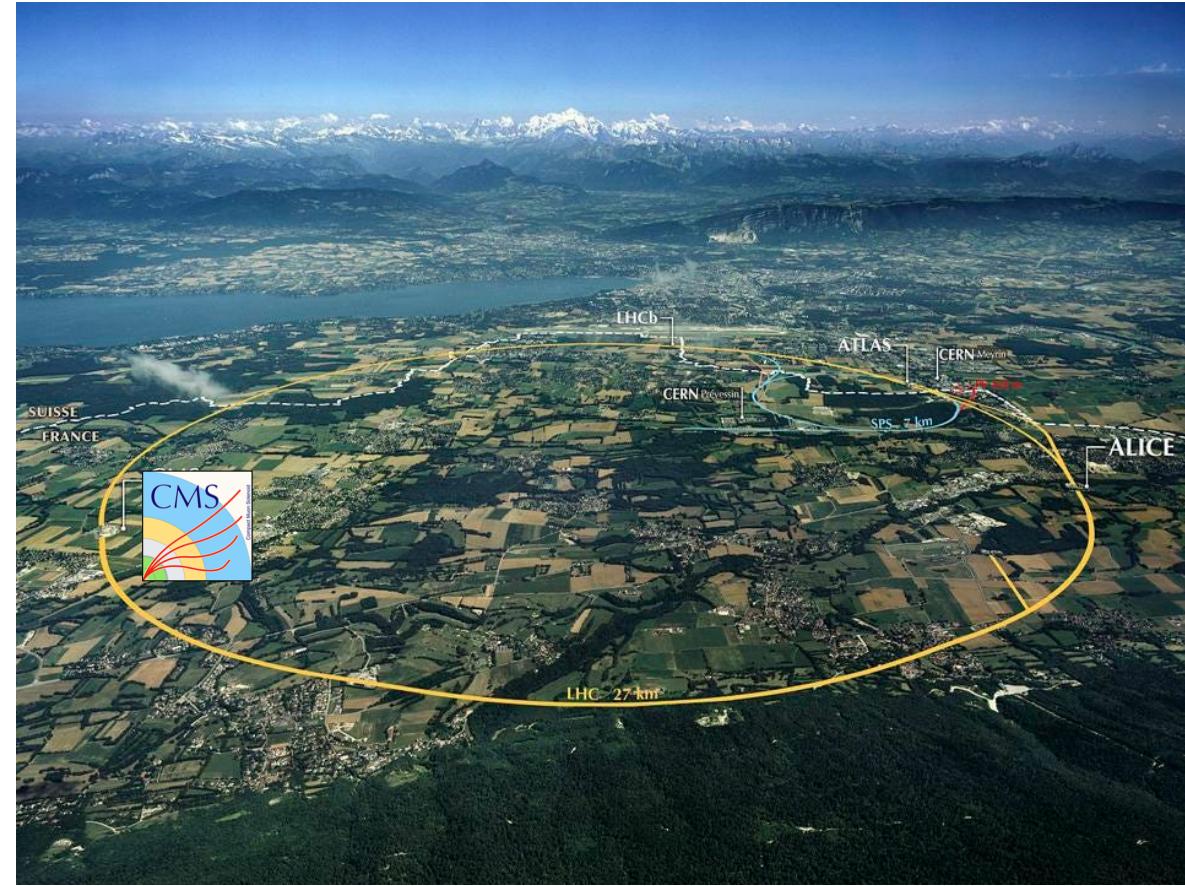
(For the CMS Collaboration)

HEP2023, Ioannina

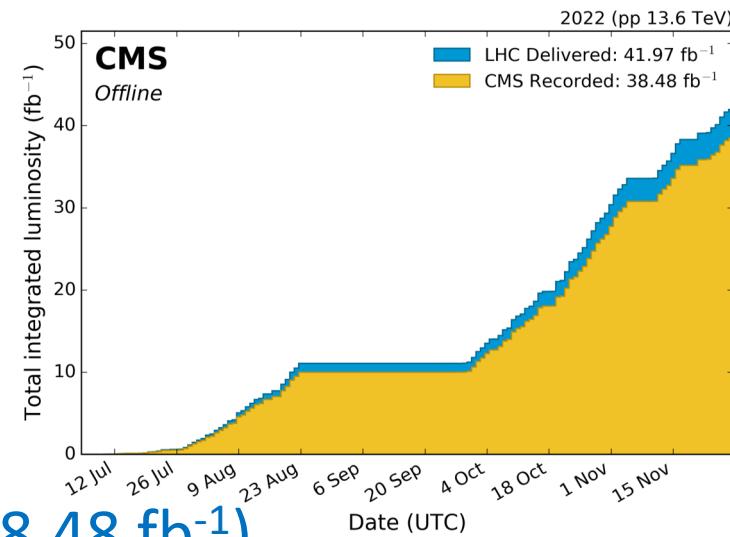
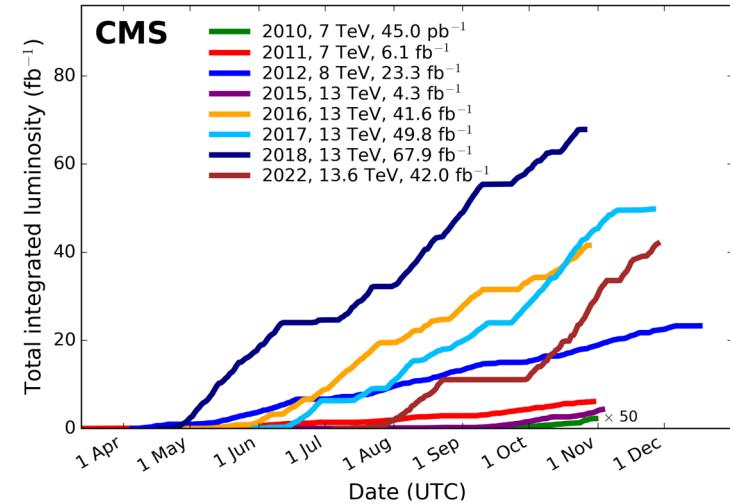




# The LHC (with CMS)



- Run2 total recorded luminosity:  $138 \text{ fb}^{-1}$  (Run3:  $38.48 \text{ fb}^{-1}$ )
- Unless otherwise noted, the presented analyses are Run2 with total recorded luminosity





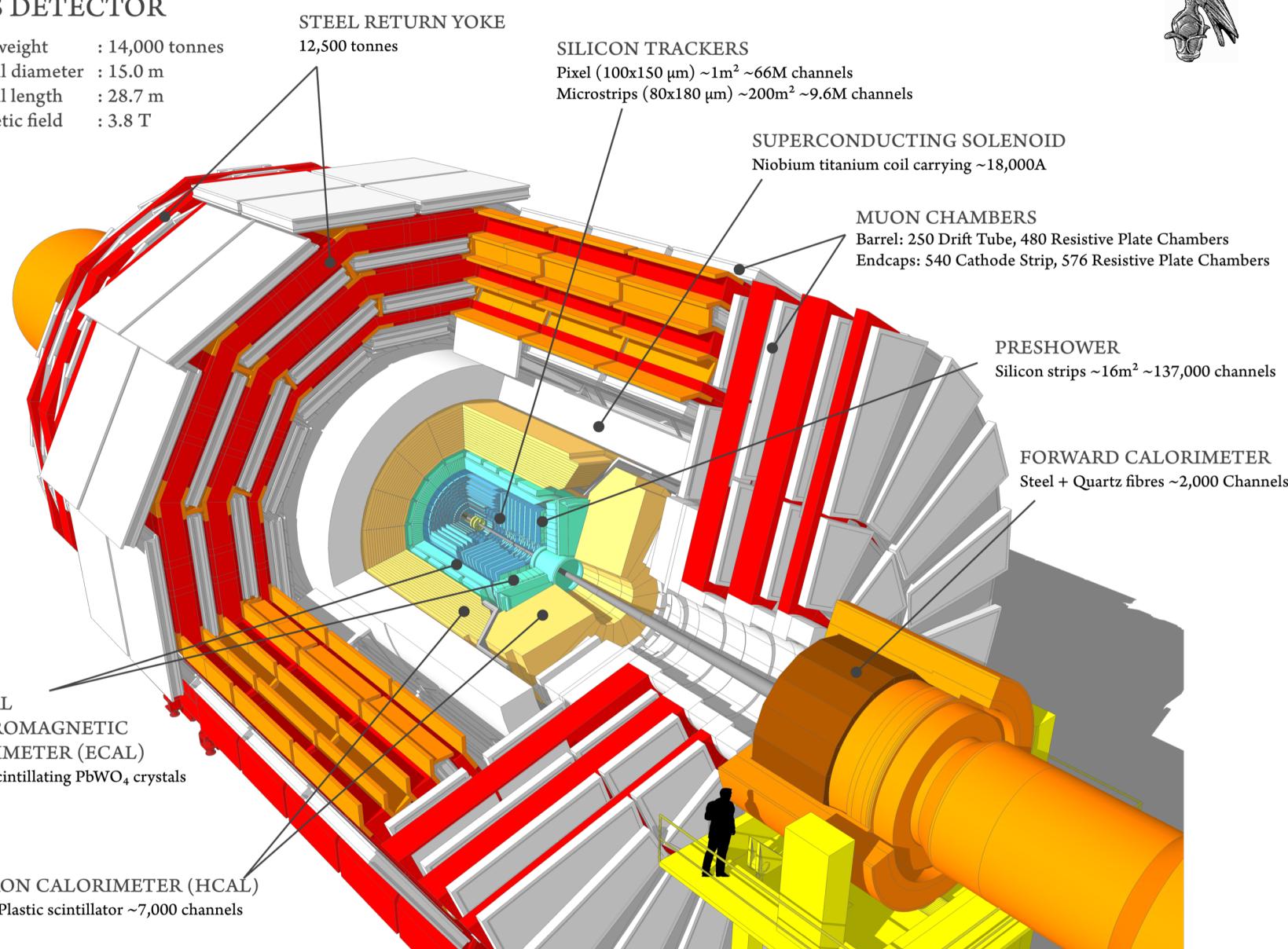
# The CMS detector



- 3.8 T magnet
- Silicon pixel + strip tracker
- Lead/Tungstate EM calorimeter
- Brass/Scintillator Had calorimeter
- Muon system embedded in return yoke
- Tungsten/quartz forward calorimeter

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T





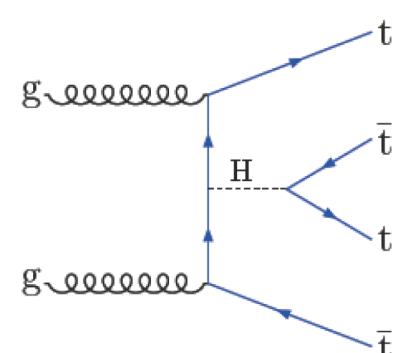
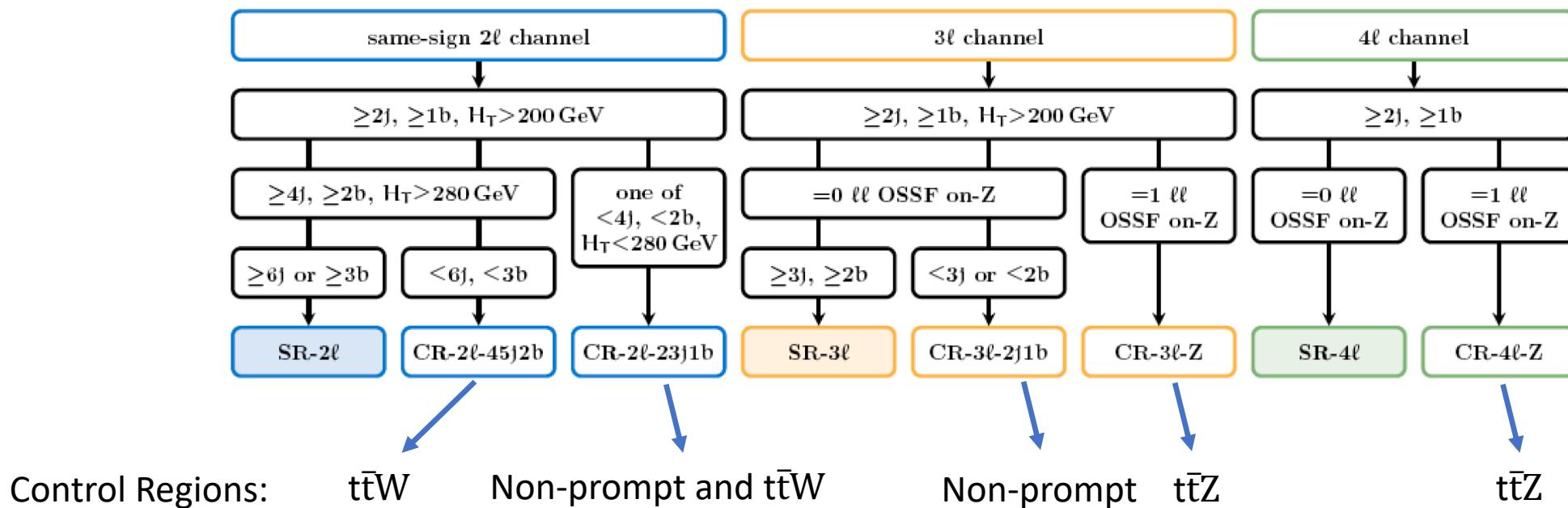
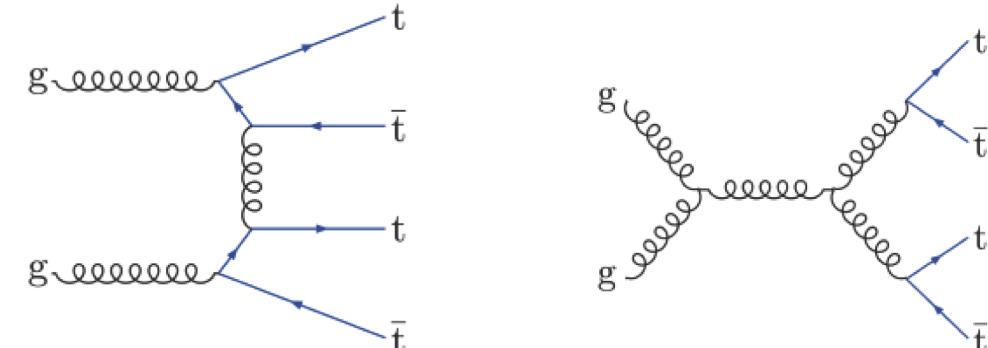
# Outline of this talk

- When we say “recent” we mean recent
  - All result presented were released last month !
- Actually is not possible to present them all. We will concentrate on
  - First observations of new channels
  - Searches for Dark Matter
  - Search for Heavy Neutral Leptons
  - Search for Higgs pairs
  - Search for SM-like extra Higgs
  - First result from Run3



# First observation of $t\bar{t}t\bar{t}$

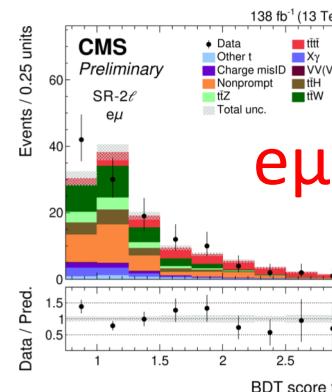
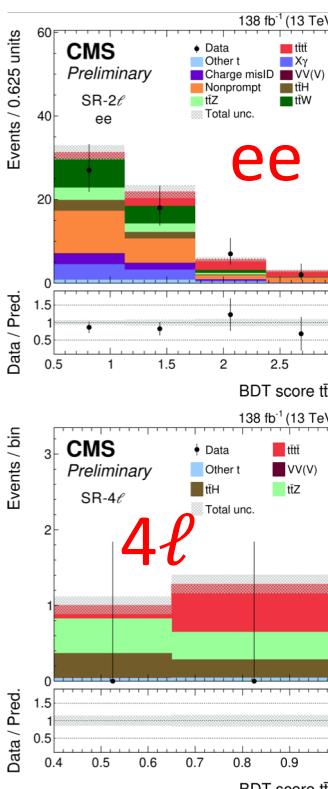
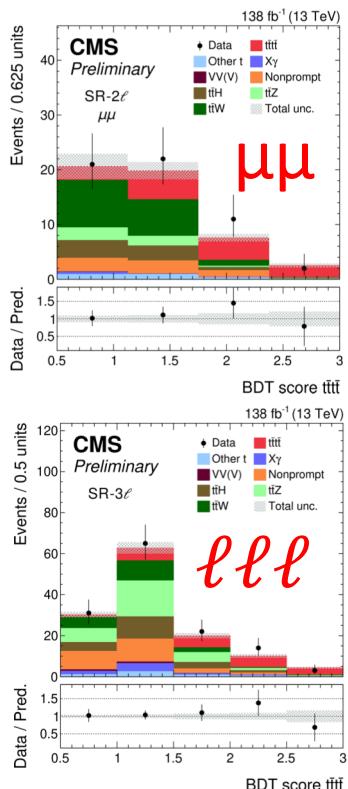
- 13 TeV,  $138 \text{ fb}^{-1}$
- Final states with **leptons+jets**
  - ( $e/\mu$ , tight (BDT), isolated,  $p_T^\ell > 25, 20, 10, 10 \text{ GeV}$ )
- Three signal regions: SS dileptons, 3lep, 4lep
  - With AK4 jets,  $p_T^{\text{jet}} > 25 \text{ GeV}$ , b-tagged (DeepJet) – additional lepton veto





# First observation of $t\bar{t}t\bar{t}$ (2)

- A BDT classifies the events as  $t\bar{t}t\bar{t}$  or  $t\bar{t}X$  (X:vector boson) or  $t\bar{t}$  (includes photon conversions and non-prompt)
- These BDT scores in signal regions as well as control-regions scores/properties are fitted in simultaneous log-likelihood fit



| Channel  | Obs. (exp.) significance | $\sigma(pp \rightarrow t\bar{t}t\bar{t})$              |
|----------|--------------------------|--|
| $2\ell$  | 4.1 (4.1) s.d.           | $17.6^{+4.7}_{-4.3}$ (stat) $^{+2.8}_{-2.7}$ (syst) fb |
| $3\ell$  | 3.5 (3.0) s.d.           | $19.4^{+7.1}_{-6.4}$ (stat) $^{+2.9}_{-2.3}$ (syst) fb |
| $4\ell$  | 0.0 (0.8) s.d.           | —  |
| Combined | 5.5 (4.9) s.d.           | $17.9^{+3.7}_{-3.5}$ (stat) $^{+2.4}_{-2.1}$ (syst) fb |

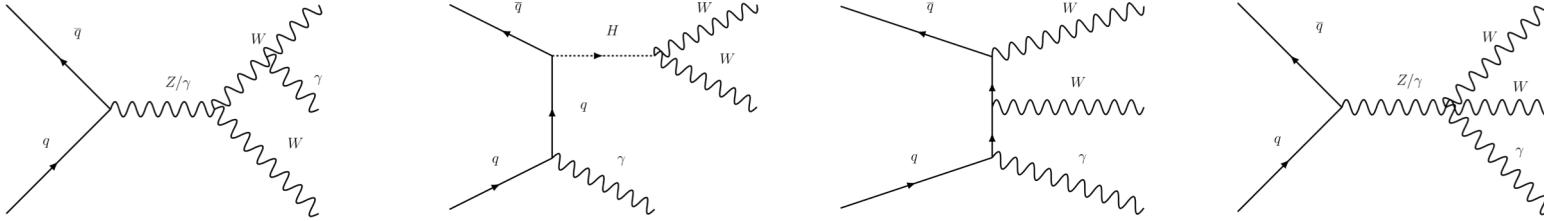
SM (NLO in QCD):  $12.0^{+2.2}_{-2.5}$  fb

(R. Frederix, D. Pagani, and M. Zaro, JHEP 02 (2018) 031)

CMS-TOP-22-013



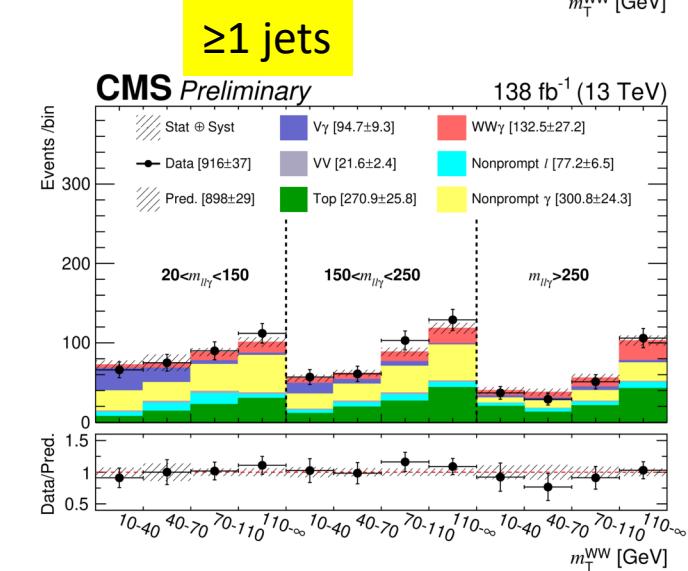
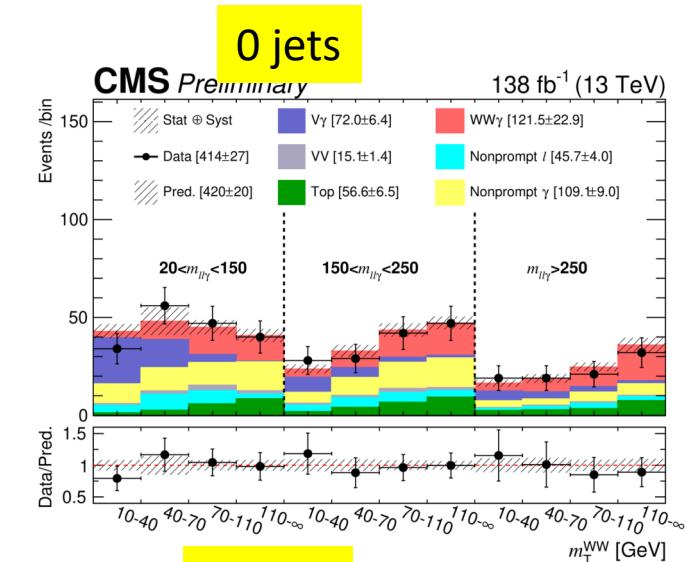
# First observation of $WW\gamma$



- $WW\gamma$  and  $H\gamma$  searches, final state:  $e\mu\gamma$
- $p_T^e > 25 \text{ GeV}$ ,  $p_T^\mu > 20 \text{ GeV}$ ,  $p_T^\gamma > 20 \text{ GeV}$  ( $> 25, 20$  for  $H\gamma$ ),  $\Delta R_{\ell\gamma} > 0.5$
- Additional-lepton  $> 10 \text{ GeV}$  veto, b-tag veto (reduce top and  $WZ\gamma$  bkg), exclude low dilepton pT and mass and low  $WW$  transverse mass
- For  $H\gamma$  exclude large lepton separation
- **Signal regions** with 0 and  $\geq 1$  jet, **control regions** of SS dileptons and b tag to validate non-prompt and top backgrounds
- The final fit includes both signal and control regions (2D in  $m_T^{WW}$  and  $m_{\ell\ell\gamma}$ )

CMS-SMP-22-006

5.6 (4.7)  $\sigma$



$$\sigma = 6.0 \pm 1.0 \text{ (stat)} \pm 1.0 \text{ (syst)} \pm 0.9 \text{ (theo)} \text{ fb}$$

$$\sigma_{SM} (NLO) = 4.61 \pm 0.34 \text{ (scale)} \pm 0.05 \text{ (PDF)} \text{ fb}$$





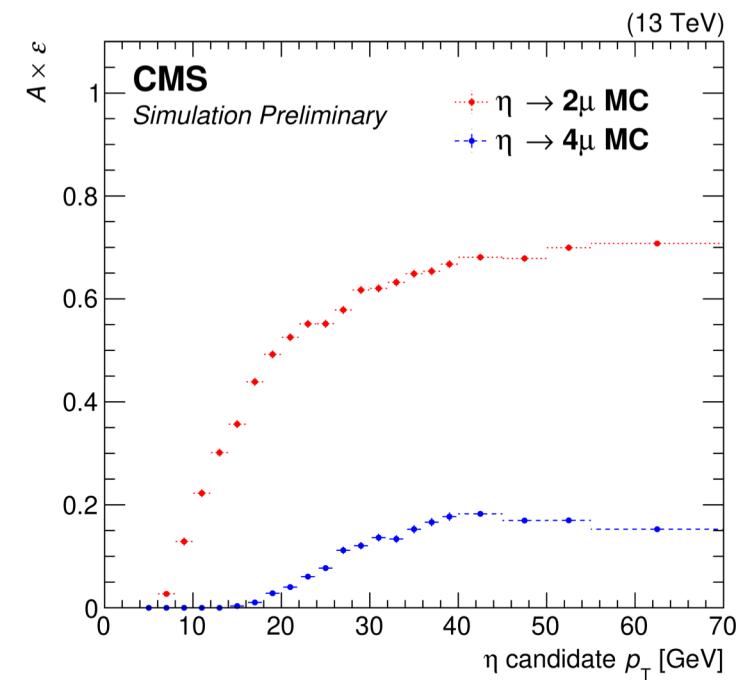
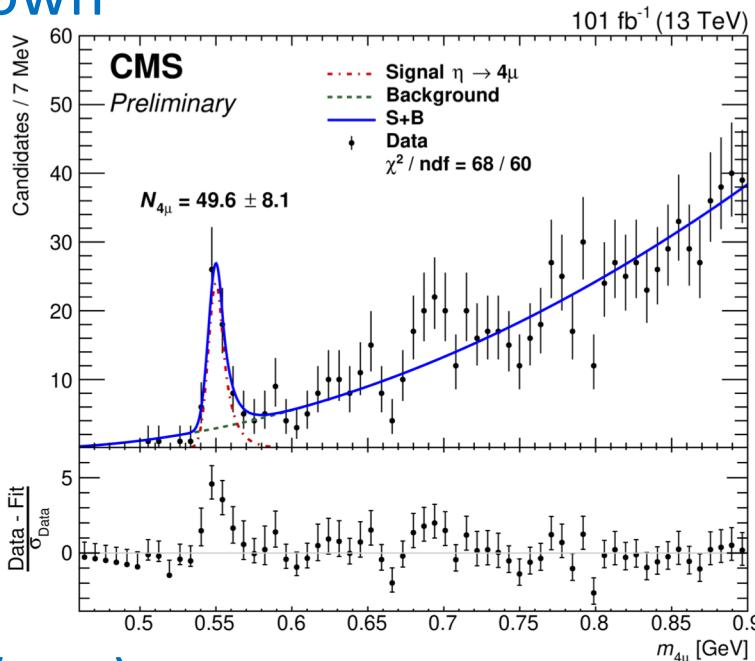
# First observation of $\eta \rightarrow \mu\mu\mu\mu$

- Utilization of high-rate low- $p_T$  muon triggers (down to 3 GeV)
- Branching fraction of  $\eta \rightarrow \mu\mu\mu\mu$  is given by

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

- Measured BF:  $[5.0 \pm 0.8(\text{stat}) \pm 0.7 (\text{syst}) \pm 0.7 (\text{B})] \times 10^{-9}$
- SM:  $(3.98 \pm 0.15) \times 10^{-9}$

i n  $p_T$  bin  
j n  $\eta$  bin

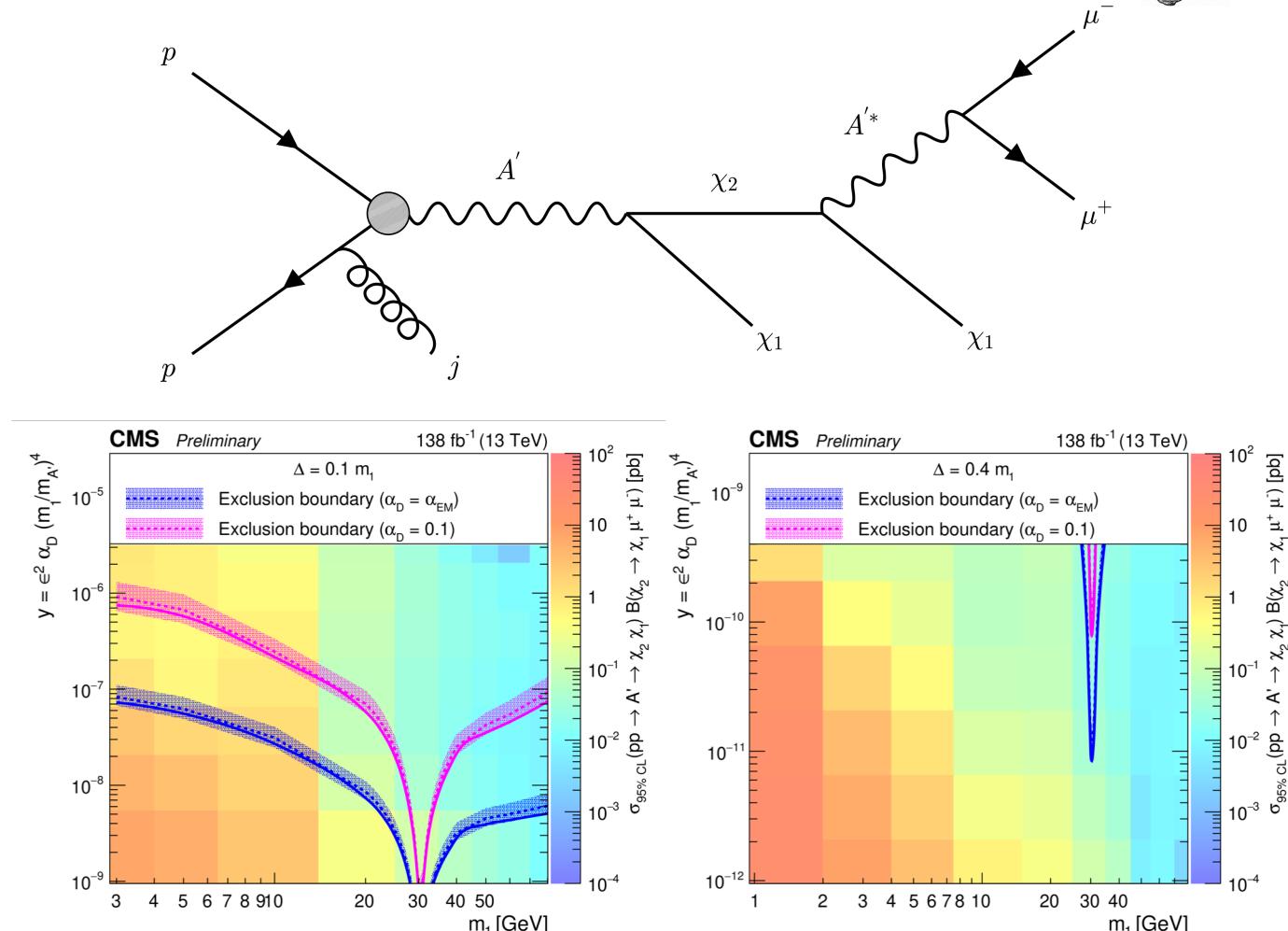


CMS-BHP-22-003

# Search for inelastic Dark Matter in displaced muons



- Signature : **two muons** (soft, displaced, collimated), aligned with  $p_T^{\text{miss}}$  and a **jet recoil**
- Trigger:  $p_T^{\text{miss}} > 120 \text{ GeV}$ ,  $H_T^{\text{miss}} > 120 \text{ GeV}$
- Muons are reconstructed with **displaced stand-alone (dSA) algorithm** based on muon chambers only. 2 muons with  $\Delta R_{\mu\mu} < 0.9$  and  $\Delta\phi_{\mu\mu}^{\text{MET}} < 0.5$
- Exactly one jet for reduction of QCD multijet background
- Matching with PF muons creates 0 (strongly displaced), 1, 2 matched categories
- **Background:** QCD multijet and W/Z+jets, estimated with ABCD method (Iso vs impact parameter (1, 2 match) and Iso vs  $\Delta\phi_{\mu\mu}^{\text{MET}}$  (0 match))
- Observation consistent with expectation → set limits



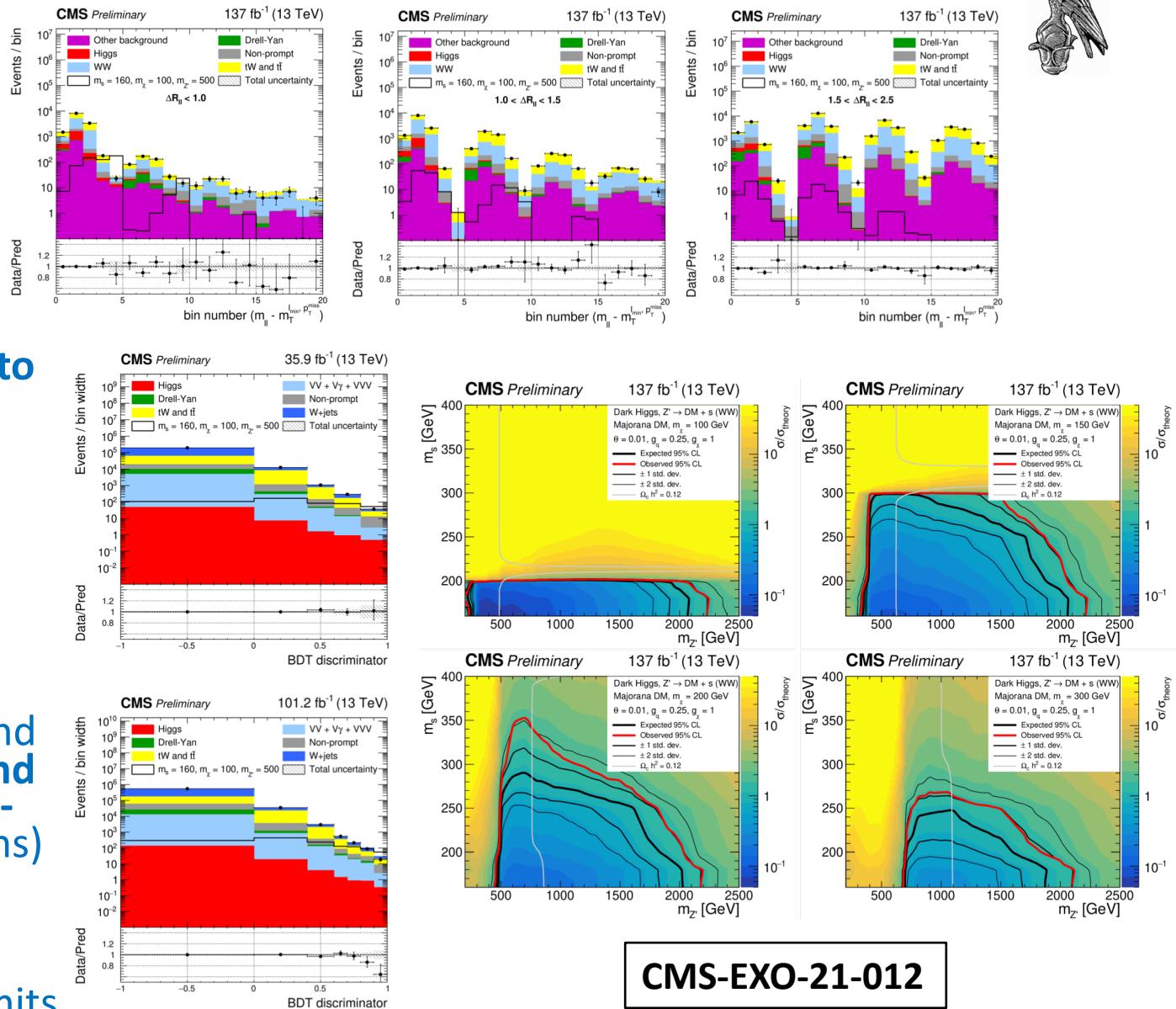
CMS-EXO-20-010



# Search for inelastic Dark Matter in WW+MET



- Final state : **WW (decay of dark Higgs) +  $p_T^{\text{miss}}$** 
  - Dilepton and lepton+jets channels
- Single-lepton and dilepton triggers
- $I_e^{\Delta R < 0.3} < 6\%$  and  $I_\mu^{\Delta R < 0.4} < 15\%$
- Dilepton:**  $e\mu$  (to reduce Drell Yan),  $p_T > 25, 20 \text{ GeV}$ ,  $m_{\ell\ell} > 20 \text{ GeV}$ ,  $p_T^{\ell\ell} > 30 \text{ GeV}$ ,  $p_T^{\text{miss}} > 20 \text{ GeV}$ , **b-tag veto** and extra leptons veto – 3 boost signal-regions based on  $\Delta R_{\ell\ell}$ 
  - Observable:  $m_T^{\text{trailingLepton-MET}}$ , used in bins of  $m_{\ell\ell}$
- Lepton+Jets:** one lepton and  $\geq 2$  jets,  $65 < m_{jj} < 105 \text{ GeV}$ ,  $p_T^{\ell jj}, p_T^{\text{miss}} > 60 \text{ GeV}$ ,  $m_T^{\ell MET} > 80 \text{ GeV}$ , object-separation cuts, **b-tag veto** –
  - Observable from BDT
- Background:** Non-prompt from looser selection and applying jet to lepton fake rates – Prompt: **WW and DY for dilepton, W+jets for lepton+Jets, tW and t-tbar for both** (MC, validated in data control regions)
- Fits of the above observables with systematics as nuisance
- Observation consistent with expectation → set limits

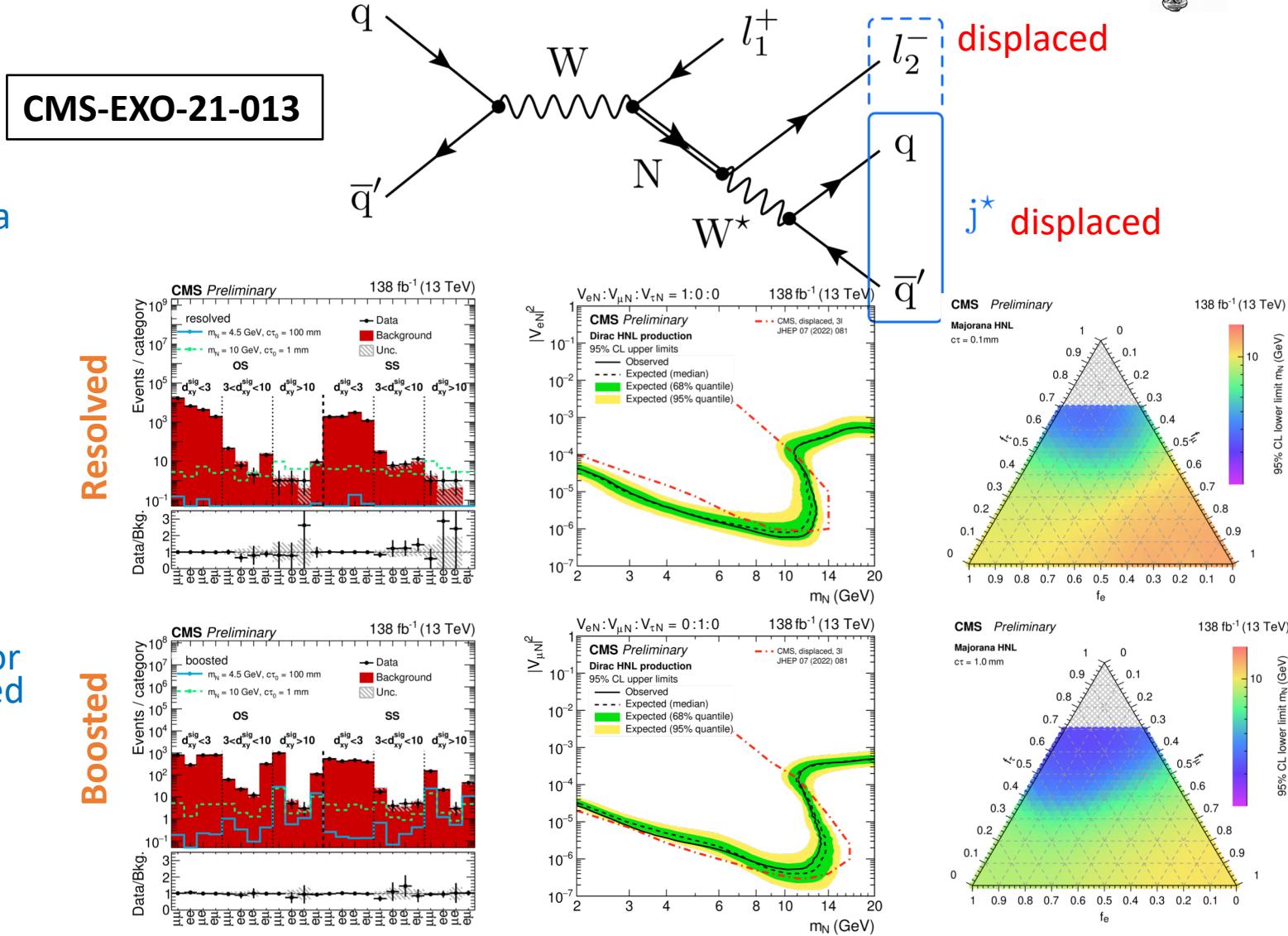


CMS-EXO-21-012



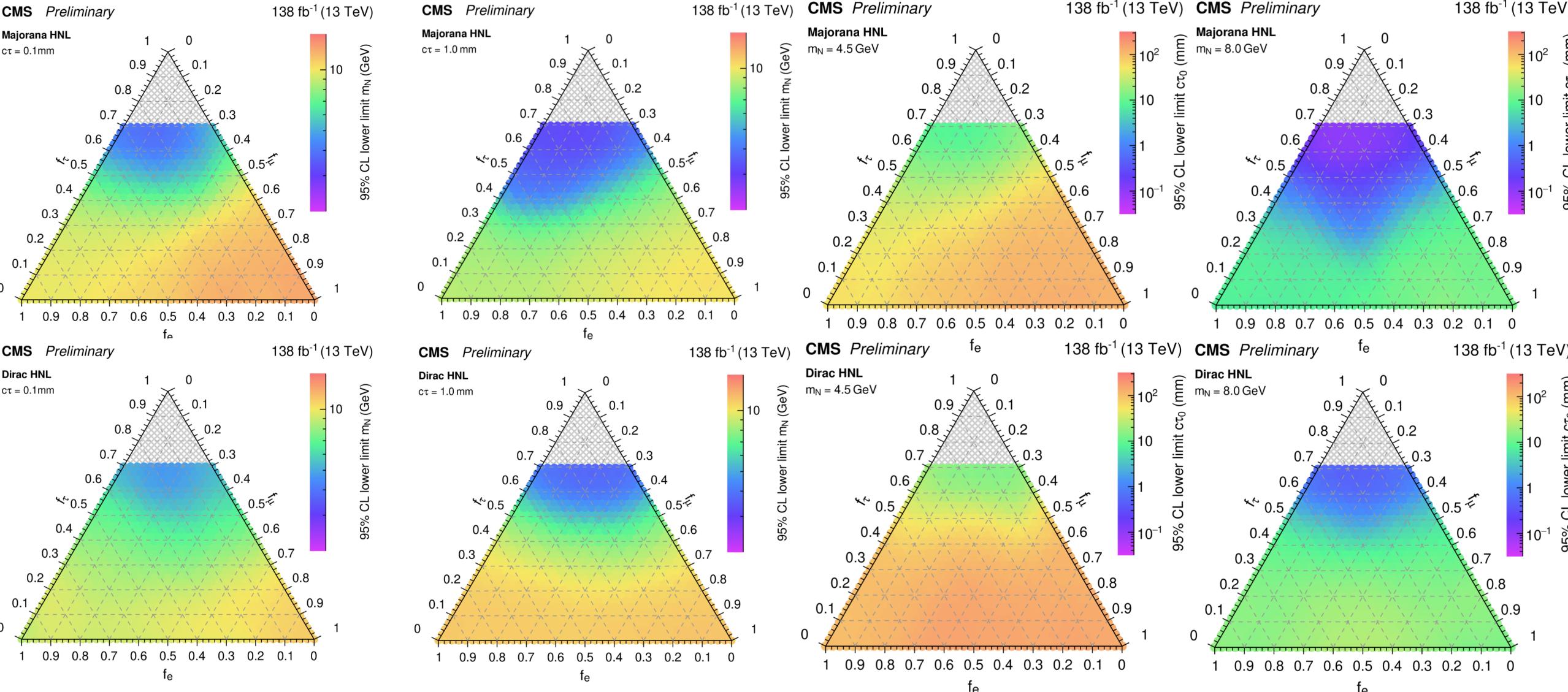
# Long-lived Heavy Neutral Leptons

- They can explain the small masses of neutrinos via the seesaw mechanism
  - Also provide Dark Matter candidate
- Signature: tight lepton, loose lepton (displaced), jet (displaced, determined with a NN)**
  - OS dileptons for study of Dirac HNL and SS for study of Majorana
- Signal region:**  $20 < m_{\ell\ell} < 80 \text{ GeV}$ ,  $p_T^{\text{miss}} < 60 \text{ GeV}$ , 1-4 jets.
- Displaced jet within  $\Delta R$  within 1.3 from displaced lepton
  - If  $\Delta R(\text{displacedJet}, \text{displacedLepton}) < 0.4$  then **Boosted** event. Otherwise **Resolved**
- Z+jets control region :  $m_{\ell\ell} > 80 \text{ GeV}$
- Signal region is **divided** based on lepton flavor combinations (4), OS/SS (2), resolved/boosted (2), impact parameter significance of loose lepton (3)
- Main background: Z+jets for OS dileptons and W(Vy)+jets for SS
  - Determined from data with the ABCD method





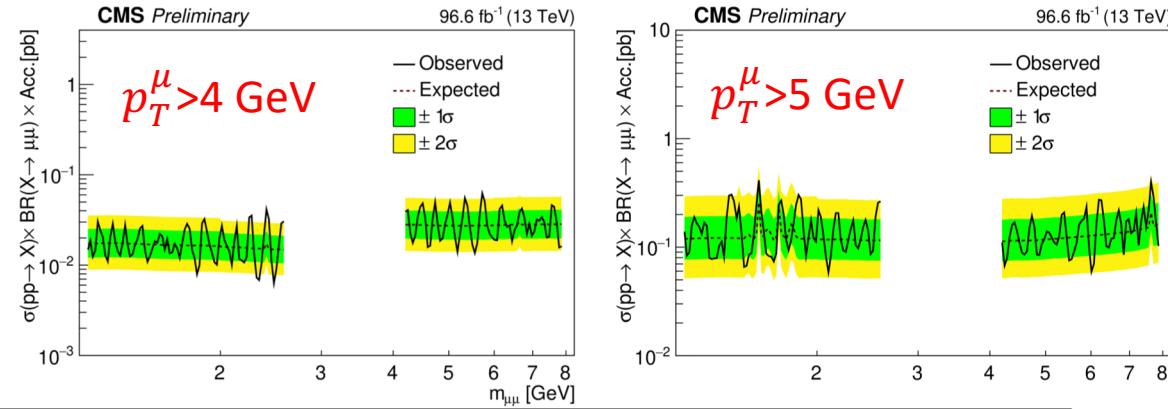
# Long-lived Heavy Neutral Leptons



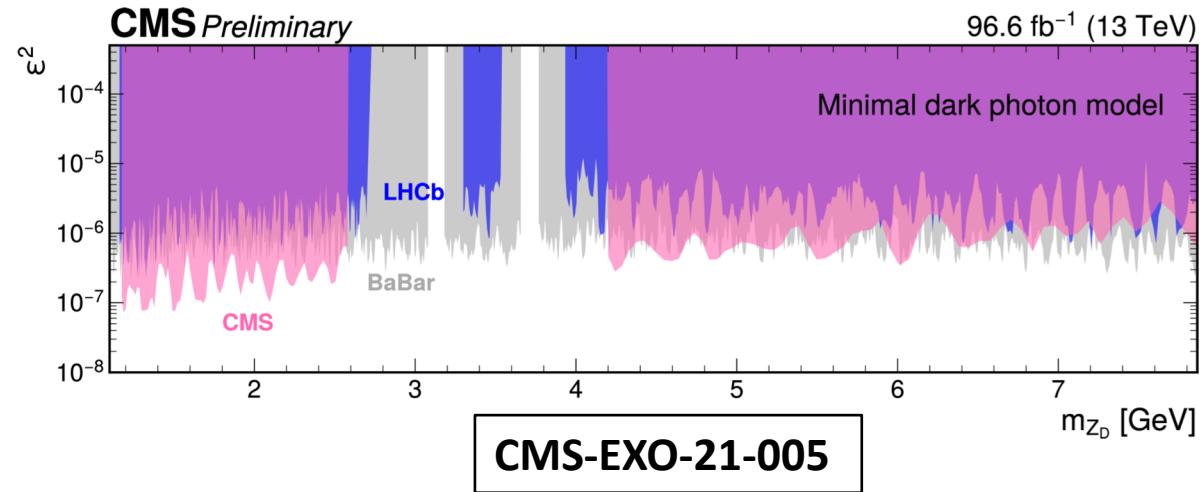


# GeV-scale resonance to pair of muons

- High-rate dimuon scouting triggers,  $96.6 \text{ fb}^{-1}$
- SM processes simulated: low-mass DY and  $\text{J}/\psi$ ,  $\Upsilon(1S)$  resonances
- BSM: 1) **Dark photon**  $Z_D$  produced by DY and decaying to dimuons (coupling to SM suppressed by parameter  $\epsilon$ ) and 2) **Higgs doublet**, light pseudoscalar decays to dimuons (coupling is determined by the mixing angle  $\theta$  and ratio of the v.e.v of the Higgs's)
- **Selection:** 2 OS muons,  $p_T^\mu > 4 \text{ GeV}$ ,  $|\eta| < 1.9$ , BDT muon ID (quality of muon tracks, relative isolation, vertex) --- for pseudoscalar search,  $p_T^\mu > 5 \text{ GeV}$
- **Simultaneous signal+background fits to dimuon invariant mass**
  - Assume the width of resonance is much smaller than the mass resolution (1.3%)
- **Systematics:** mass resolution, luminosity, muon ID efficiency, trigger efficiency
- Observation consistent with continuum  $\rightarrow$  Set modeled-independent limits

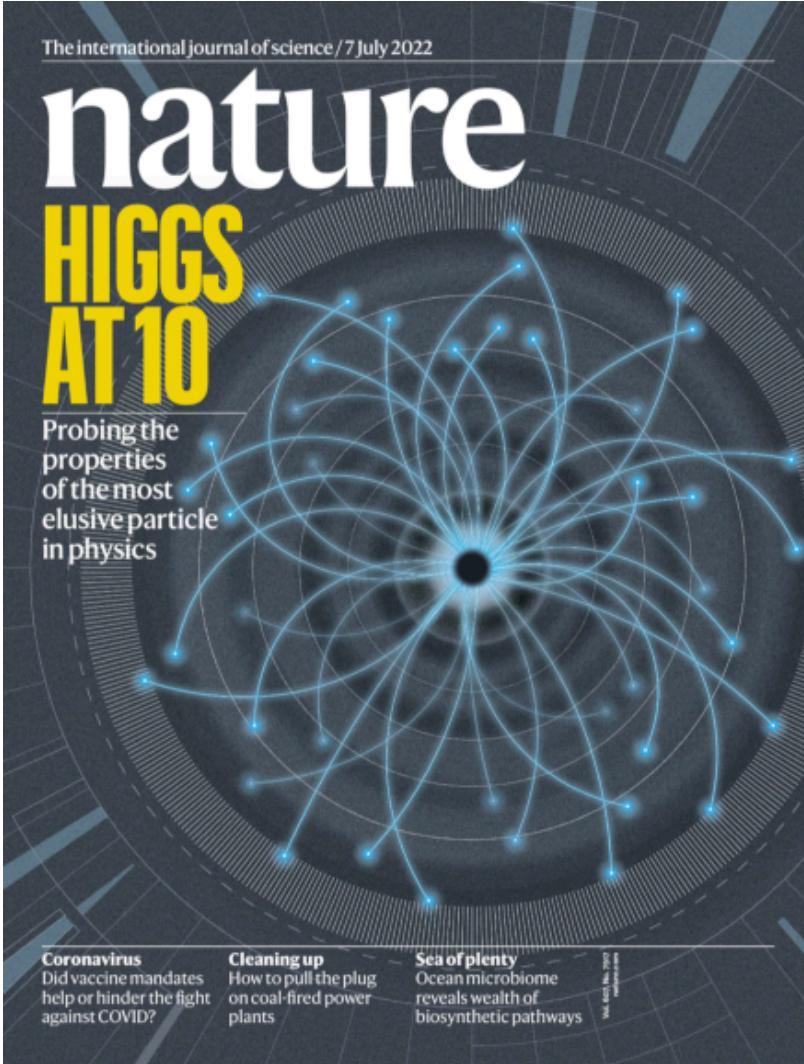


A local  $3.2\sigma$  (global  $1.3\sigma$ ) excess at  $2.41 \text{ GeV}$  (high- $p_T$  selection) interestingly consistent with a  $3.1\sigma$  excess at  $2.42 \text{ GeV}$  of LHCb





# Nature Higgs publication



## Article

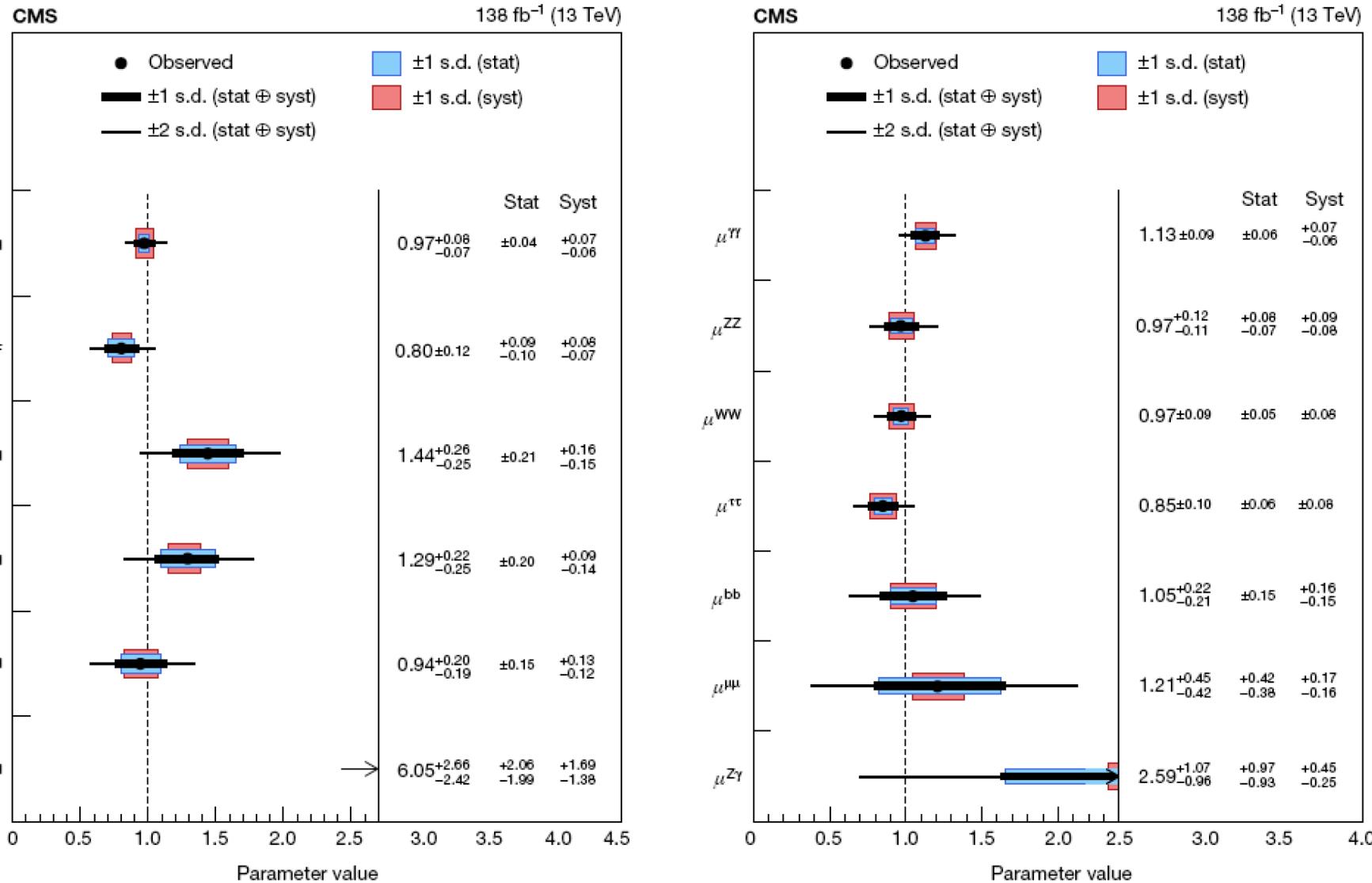
### A portrait of the Higgs boson by the CMS experiment ten years after the discovery

<https://doi.org/10.1038/s41586-022-04892-x> The CMS Collaboration<sup>1,2</sup>

Received: 21 March 2022  
Accepted: 23 May 2022  
Published online: 4 July 2022  
Open access  
Check for updates

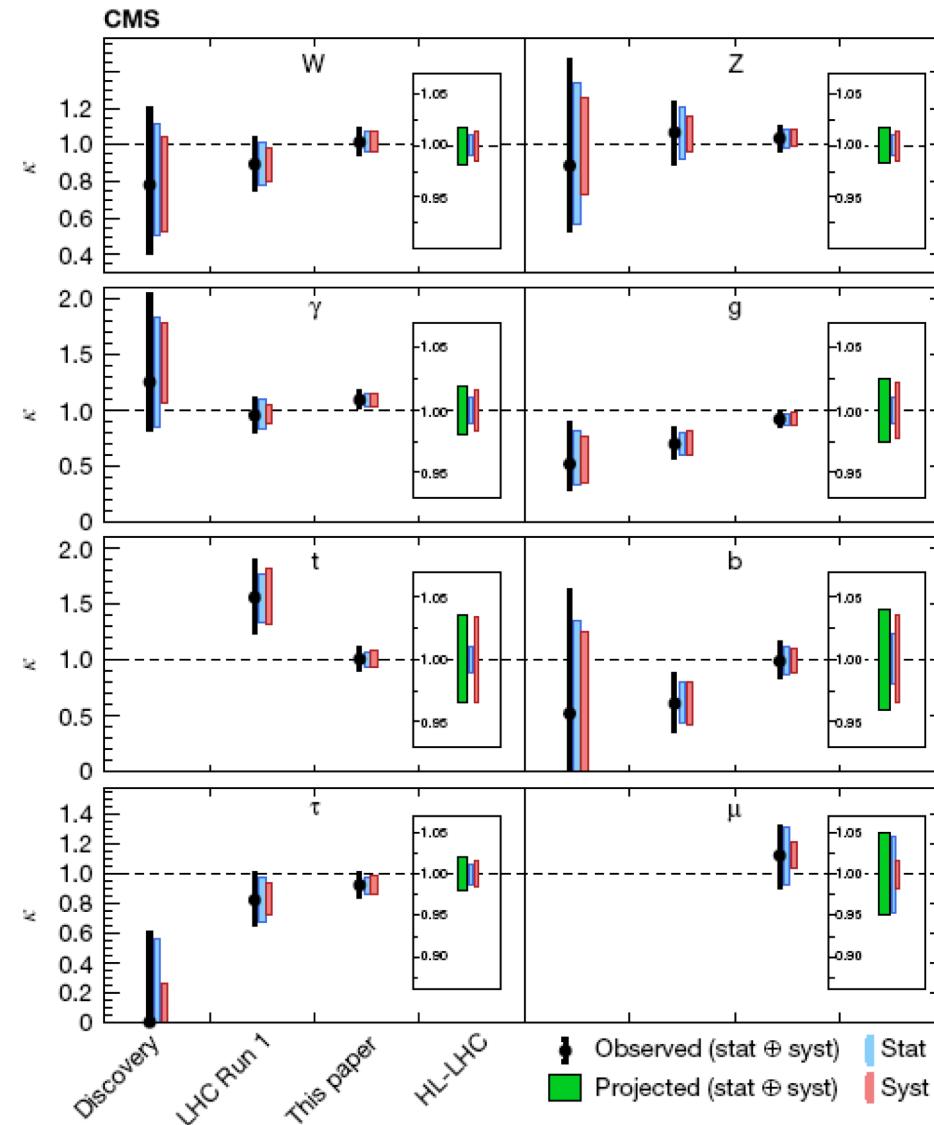
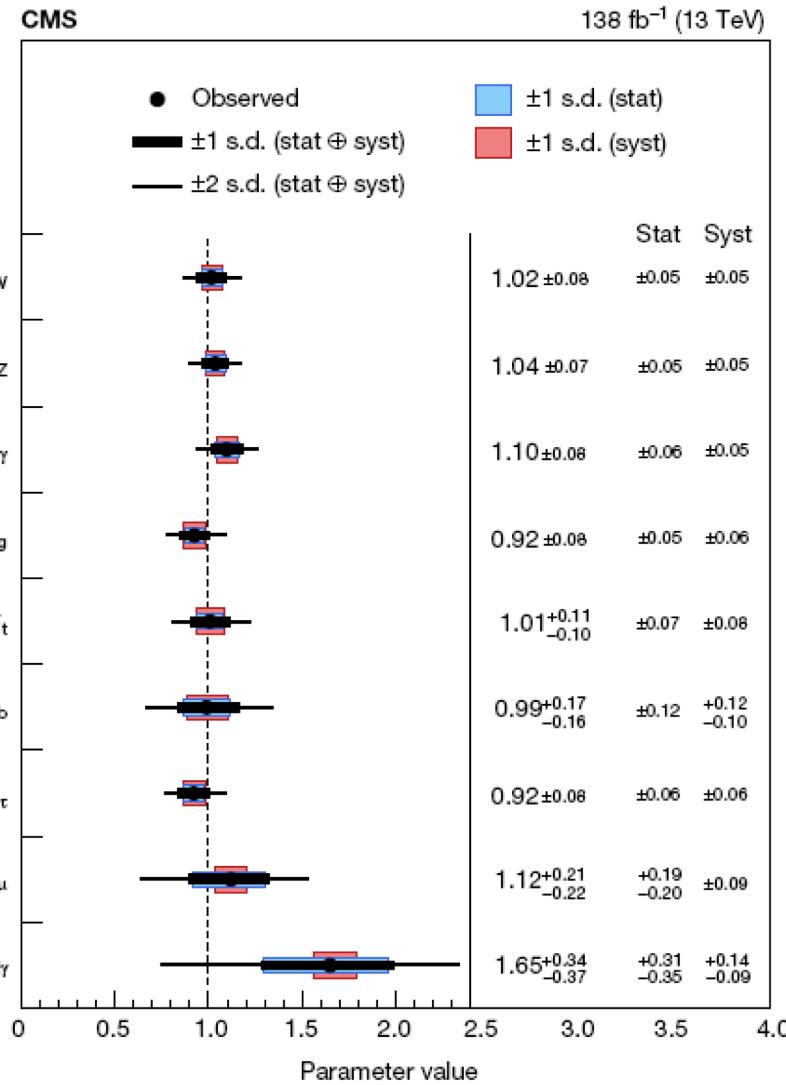


# Nature (production and decay strengths)



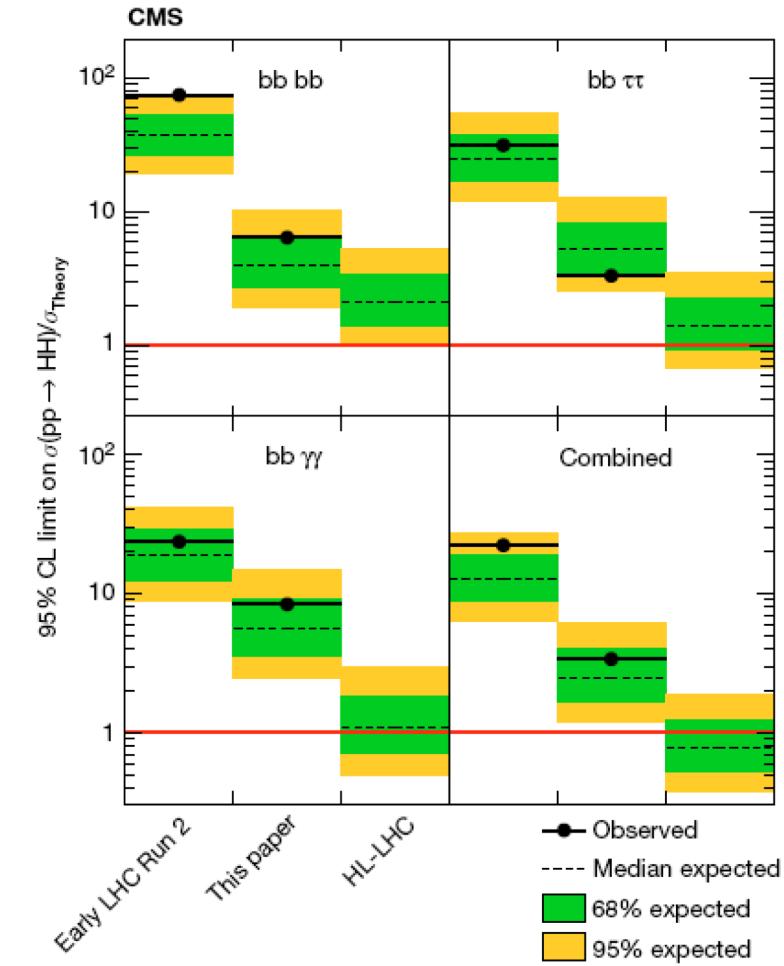
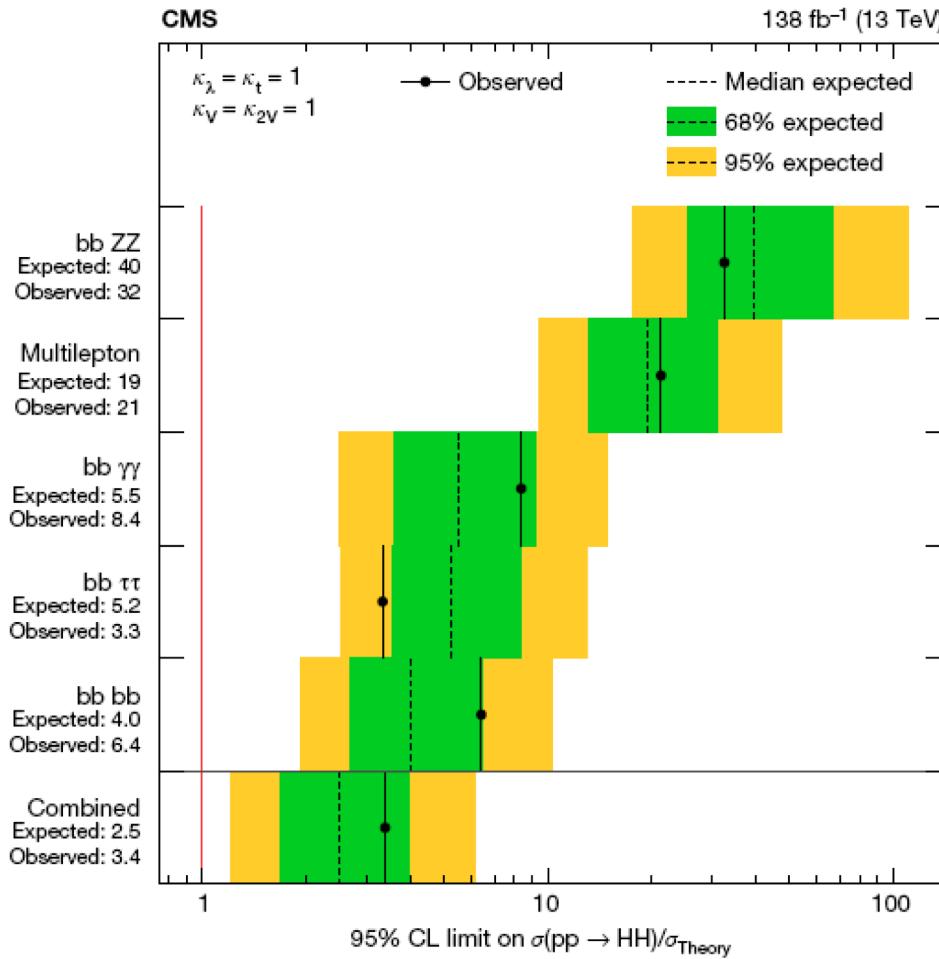


# Nature (couplings)



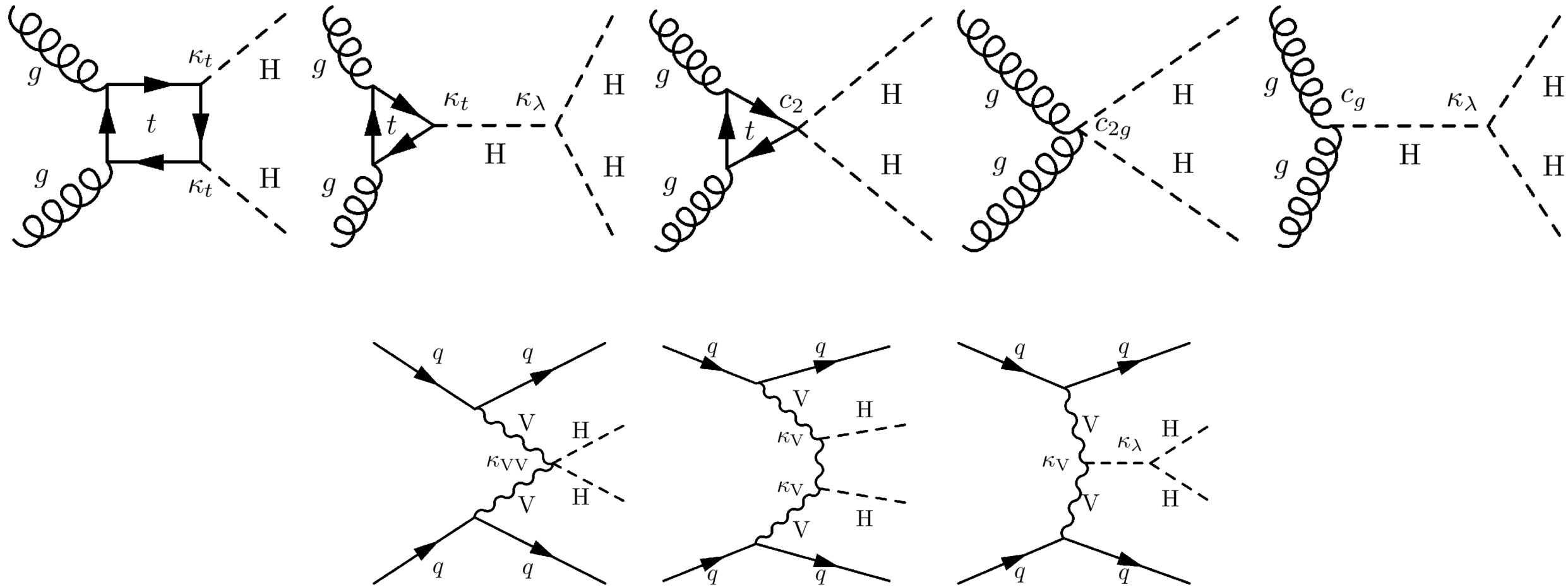


# Nature (HH limits)



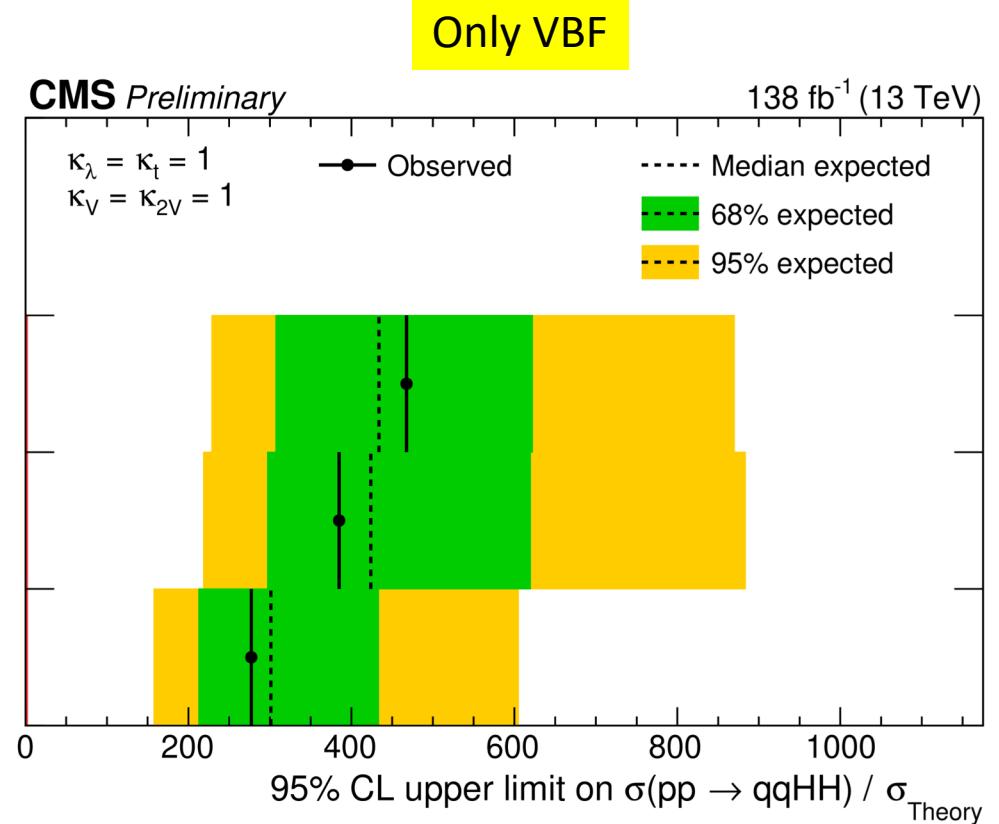
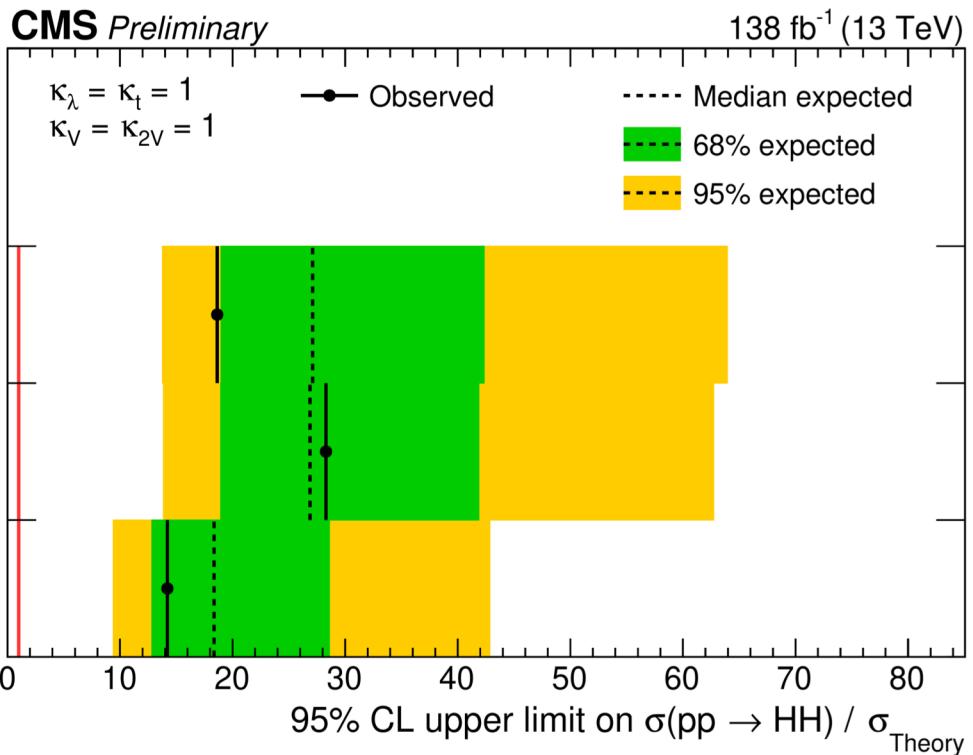


# HH $\rightarrow$ b $\bar{b}$ WW





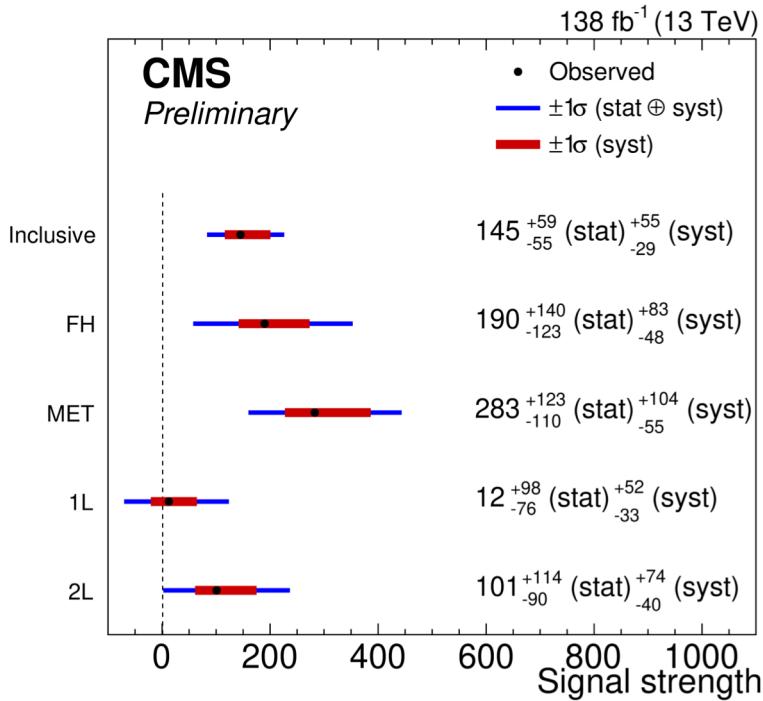
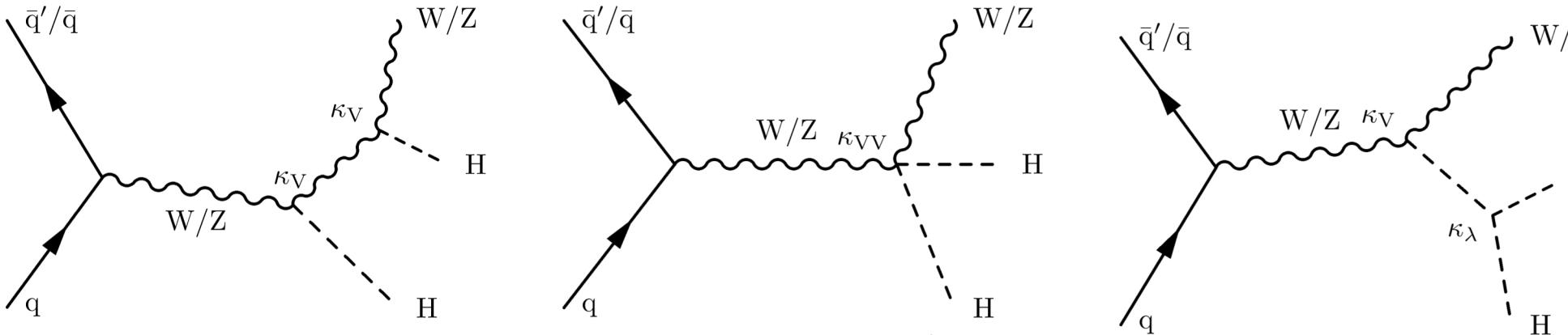
# HH $\rightarrow$ b $\bar{b}$ WW



**CMS-HIG-21-005**



# Search for HH+W/Z



**CMS-HIG-22-006**

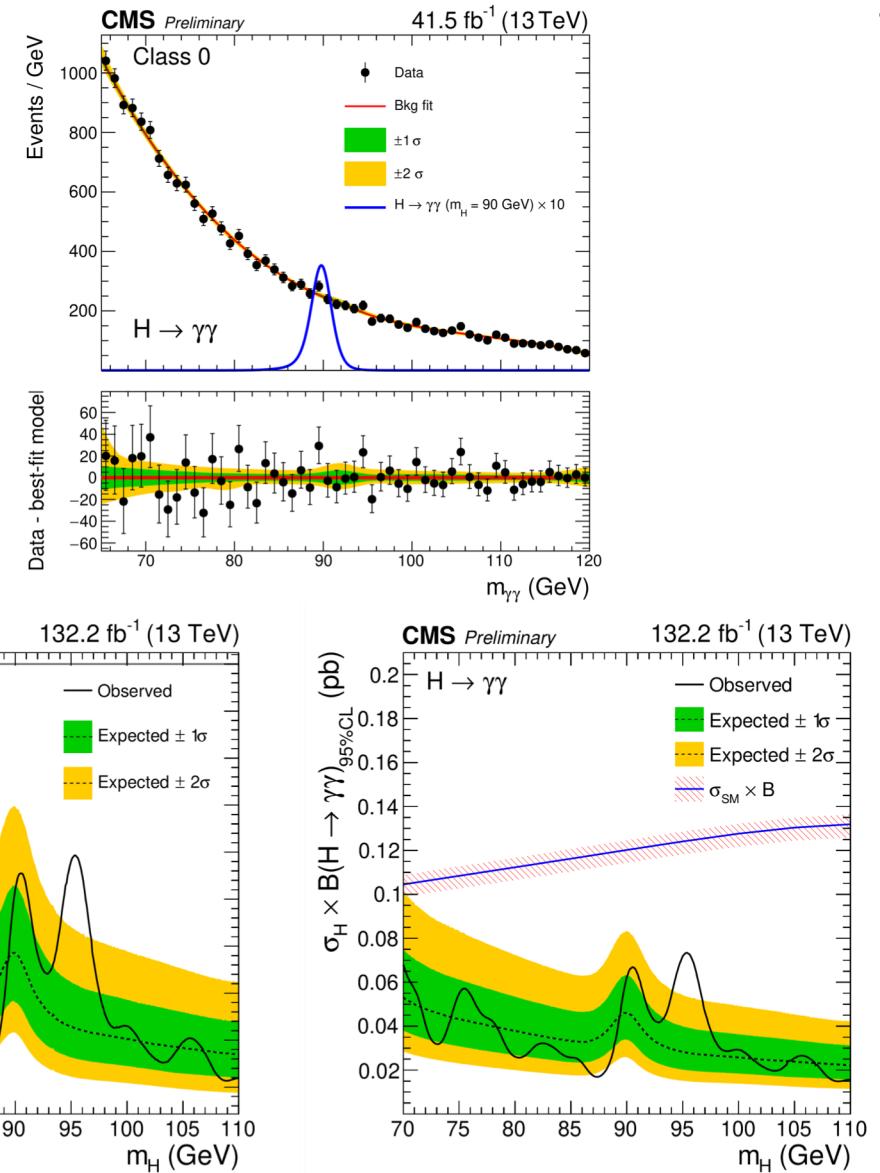


# Search for an SM-like H-> $\gamma\gamma$ in range 70 - 110 GeV



- Asymmetric diphoton triggers
- Background: SM  $\gamma\gamma$ , dijet, jet+ $\gamma$
- BDT photon ID
- $\gamma_1 : p_T > 30 \text{ GeV}, p_T/m_{\gamma\gamma} > 0.47$   
 $\gamma_2 : p_T > 18 \text{ GeV}, p_T/m_{\gamma\gamma} > 0.28$
- Event classes with extra jet activity to target VBF
- An excess at 95.4 GeV with a local (global) significance of 2.9 (1.3)  $\sigma$

CMS-HIG-20-022





# Recent Supersymmetry Results



[CMS-PAS-SUS-21-008](#)

Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at  $\sqrt{s} = 13$  TeV

24 March 2023

[CMS-PAS-SUS-21-009](#)

Search for new physics in multijet events with at least one photon and large missing transverse momentum in proton-proton collisions at 13 TeV

18 March 2023

[CMS-PAS-SUS-19-001](#)

Search for stealth SUSY in final states with two photons, jets, and low missing transverse momentum

13 March 2023

Will be covered by **Costas Vellidis**  
Friday at 4 pm



|       |  |   |
|-------|--|---|
| 15:00 | tba<br>Main Auditorium, Conference Centre "Karolos Papoulias"  | Loukas Gouskos<br>15:00 - 15:30   |
|       | Higher-order corrections at the LHC: current status and prospects<br>Main Auditorium, Conference Centre "Karolos Papoulias"              | Konstantinos Papadopoulos<br>15:30 - 16:00  |
| 16:00 | Recent results of searches for Supersymmetry with the full CMS Run II data set<br>Main Auditorium, Conference Centre "Karolos Papoulias" | Konstantinos Vellidis<br>16:00 - 16:30  |
|       | Coffee break<br>Conference Centre "Karolos Papoulias", University of Ioannina (GR)   | 16:30 - 17:00   |
| 17:00 | Gravitational focusing effects on streaming dark matter a...<br>Abaz Kryemadhi   | T-Model Higgs Inflation In Supergravity Constantinos Pallis                           |
|       | Measurement of azimuthal correlations of jets and determ...<br>Paris Giannelis   | Anomalous and axial Z' contributions to g-2 Dr Pascal Anastasopoulos                  |
|       | Results using data from proton-proton collisions at the L...<br>Kosmas Adamidis  | Aspects of Relativistic and Carrollian fluids Konstantinos Siampos                    |
| 18:00 | An ATCA Processor for Level-1 Trigger Primitive Generati...<br>Ioannis Bestintzanos  | Goldstino condensation Fotis Farakos  |
|       | Multi-differential measurement of the dijet cross section i...<br>Polidamas Georgios Kosmogl...  | Compact objects in gravity theories Dr Athanasios Bakopoulos                          |
|       | Multijet cross sections and ratios in pp collisions at 13 Te...<br>Argyro Ziaka  | Universal Relations for rapidly rotating neutron stars usi... Mr Grigoris Papigkiotis |
| 19:00 | END<br>Conference Centre "Karolos Papoulias", University of Ioannina (GR)  | 19:00 - 19:30   |



# And some SMP jet results

**Paris Gianneios:** Measurement of azimuthal correlations of jets and determination of the strong coupling in pp collisions at 13 TeV with CMS

**Polidamas Kioseoglou:** Multi-differential measurement of the dijet cross section in proton-proton collisions at  $\sqrt{s} = 13$  TeV with CMS

**Argiro Ziaka:** Multi-differential measurement of the dijet cross section in proton-proton collisions at  $\sqrt{s} = 13$  TeV with CMS

|       |  |  |
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| 19:00 | END<br>Conference Centre "Karolos Papoulias", University of Ioannina (GR)  | 19:00 - 19:30  |

Friday evening parallel session



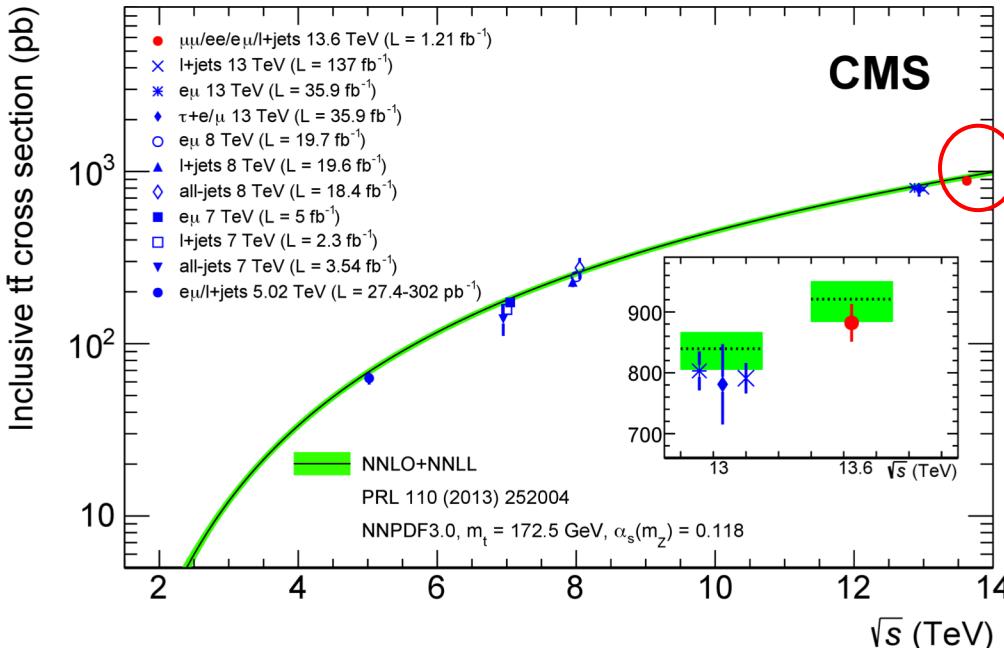
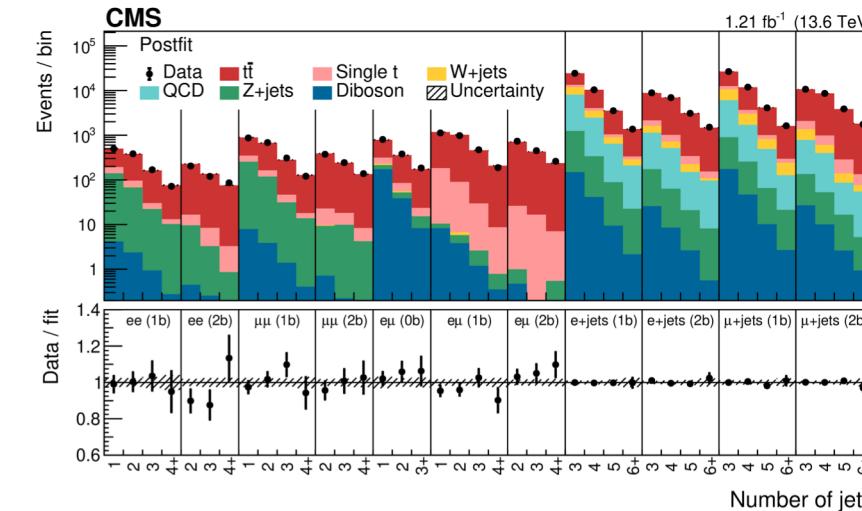


# First measurement of $\sigma_{t\bar{t}}$ in Run3



CMS-TOP-22-012

- 13.6 TeV,  $1.21 \text{ fb}^{-1}$
- Single-lepton ( $e, \mu$ ) and dilepton triggers ( $ee, \mu\mu$ )
- Lepton+jets :  $p_T^\ell > 35 \text{ GeV}$  and  $\geq 3$  jets ( $> 30 \text{ GeV}, |\eta| < 2.4$ )
- Dileptons:  $p_T^\ell > 35 \text{ GeV}$ , OS
- DeepJet b-tagging
  - $ee, \mu\mu, \ell+\text{jets} \rightarrow 0, 1$  b-jet categories
  - $e\mu \rightarrow 0, 1, 2$  b-jet categories
- Backgrounds: Z+jets ( $ee, \mu\mu$ ), W+jets ( $\ell+\text{jets}$ ), single top ( $e\mu$ ), QCD multijets ( $\ell+\text{jets}$ ), diboson (minor)
- Major Systematics: luminosity, lepton and b-tagging efficiencies, single top background
- Measured:  $882 \pm 23(\text{stat+syst}) \pm 20 \text{ (lumi)} \text{ pb}$
- SM(NNLO, NNLL):  $921^{+29}_{-37} \text{ pb}$





# Conclusions

- We presented some of the most recent CMS Physics Results
  - All of them became public within about a month
- All results, including the recent publications can be found at the public physics results web page
  - <https://cms.cern/news/physics-results>
- We are excited about Run3 of the LHC !!!



# Thank you





# Backup



# First observation of $t\bar{t}t\bar{t}$ (tight lepton ID BDT)

| Symbol                           | Definition  |
|----------------------------------|---|
| $p_T$                            | Lepton $p_T$  |
| $ \eta $                         | Absolute value of the lepton $\eta$   |
| $I_{\text{rel}}^{\text{fixed}}$  | Relative isolation using a fixed distance $\Delta R < 0.4$  |
| $I_{\text{rel}}^{\text{ch}}$     | Relative isolation using a $p_T$ -dependent distance and including only charged particles   |
| $I_{\text{rel}}^{\text{neu}}$    | Relative isolation using a $p_T$ -dependent distance and including only neutral particles   |
| $N_{\text{ch}}(j_{\text{near}})$ | Number of charged particles associated with the jet   |
| $p_T^{\text{ratio}}$             | Ratio of the lepton $p_T$ to the nearest jet $p_T$ , $p_T(\ell)/p_T(j_{\text{near}})$ , or $1/(1 + I_{\text{rel}}^{\text{fixed}})$ if no nearest jet is found |
| $p_T^{\text{rel}}$               | Component of the lepton momentum in direction transverse to the nearest jet, $p(\ell) \sin \theta(\vec{p}(\ell), \vec{p}(j_{\text{near}}))$                   |
| $DJ(j_{\text{near}})$            | DEEPJET score of the nearest jet  |
| $\log  d_{xy} $                  | Distance of closest approach of the lepton track to the PV in the transverse plane  |
| $\log  d_z $                     | Distance of closest approach of the lepton track to the PV in the longitudinal plane  |
| $d/\delta d$                     | Significance of the distance of closest approach of the lepton track to the PV  |
| $P_{\text{ID}}^e$                | Electron ID discriminant  |
| $P_{\text{seg}}^\mu$             | Muon segment compatibility  |



# First observation of $t\bar{t}t\bar{t}$ (event classification BDT)

| Symbol                             | Definition   |
|------------------------------------|--|
| $\text{max}_2 \text{ DJ}$          | Second-highest DEEPJET score of any jet  |
| $\Delta R(\ell_1, \ell_2)$         | $\Delta R$ between leading and subleading lepton   |
| $\min \Delta R(b, b)$              | Smallest $\Delta R$ between any two b jets   |
| $\min_2 \Delta R(\ell, b)$         | Second smallest $\Delta R$ between any lepton and b jet  |
| $\Delta\phi(\ell_1, \ell_2)$       | $\Delta\phi$ between leading and subleading lepton   |
| $\min_1 \Delta R(\ell, b)^\dagger$ | Smallest $\Delta R$ between any lepton and b jet   |
| $m(t_1)$                           | Invariant mass of any three jets, of which one is a b jet, that is closest to the top quark mass   |
| $\text{max}_3 \text{ DJ}$          | Third-highest DEEPJET score of any jet   |
| $\text{DJ}(j_1)$                   | DEEPJET score of the leading jet   |
| $m(W_1)$                           | Invariant mass of any two jets used for $m(t_1)$ that is closest to the W boson mass   |
| $p_T(j_4)$                         | Fourth-highest $p_T$ of any jet  |
| $\text{DJ}(j_2)$                   | DEEPJET score of the subleading jet  |
| $p_T(j_5)$                         | Fifth-highest $p_T$ of any jet   |
| $H_T$                              | Scalar sum of $p_T$ of all jets  |
| $p_T(\ell_2)$                      | Second-highest $p_T$ of any lepton   |
| $\text{DJ}(j_3)$                   | DEEPJET score of the jet with the third-highest $p_T$  |
| $m_T(\ell_1)$                      | Transverse mass of the leading lepton and $p_T^{\text{miss}}$  |
| $p_T(j_1)$                         | Highest $p_T$ of any jet   |
| $p_T(\ell_1)$                      | Highest $p_T$ of any lepton  |
| $p_T^{\text{miss}}$                | Missing transverse momentum  |
| $m_T(\ell_2)$                      | Transverse mass of the subleading lepton and $p_T^{\text{miss}}$   |
| $p_T(j_2)$                         | Second-highest $p_T$ of any jet  |
| $m(t_2)$                           | † Invariant mass of any three jets, of which one is a b jet and none of which is used for $m(t_1)$ , that is closest to the top quark mass |
| $N_j$                              | Number of jets   |
| $m_{T2}(b)$                        | † $m_{T2}$ variable constructed from the leading and subleading b jet  |
| $m_{T2}(\ell+b)$                   | † $m_{T2}$ variable constructed from two lepton+jet systems built with the leading two leptons and the leading two b jets                  |
| $N_b^{\text{tight}}$               | Number of jets passing the "tight" DEEPJET working point (tighter than in the event selection)   |
| $m(W_2)$                           | † Invariant mass of any two jets used for $m(t_2)$ that is closest to the W boson mass   |
| $\text{max}_4 \text{ DJ}$          | Fourth-highest DEEPJET score of any jet  |
| $N_b^{\text{medium}}$              | † Number of jets passing the "medium" DEEPJET working point (tighter than in the event selection, but looser than "tight")                 |
| $p_T(\ell_3)$                      | ‡ Third-highest $p_T$ of any lepton  |
| $p_T(j_3)$                         | ‡ Third-highest $p_T$ of any jet   |
| $m_{T2}(\ell)$                     | ‡ $m_{T2}$ variable constructed from the leading and subleading lepton   |
| $\text{DJ}(j_4)$                   | ‡ DEEPJET score of the jet with the fourth-highest $p_T$   |

† not used for  $3\ell + 4\ell$

‡ used only for  $3\ell + 4\ell$



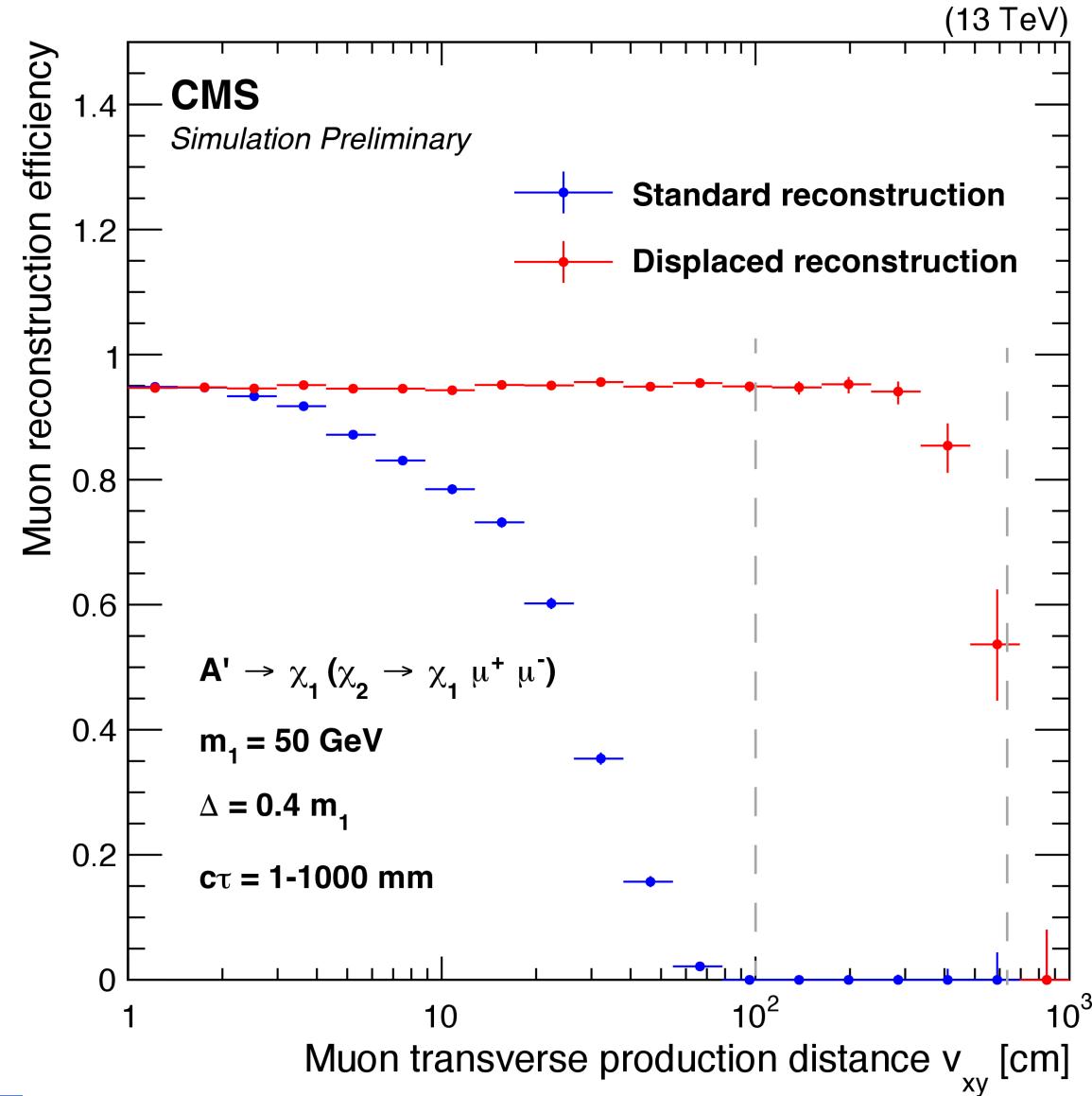
# Dark Matter in displaced muons (yields)



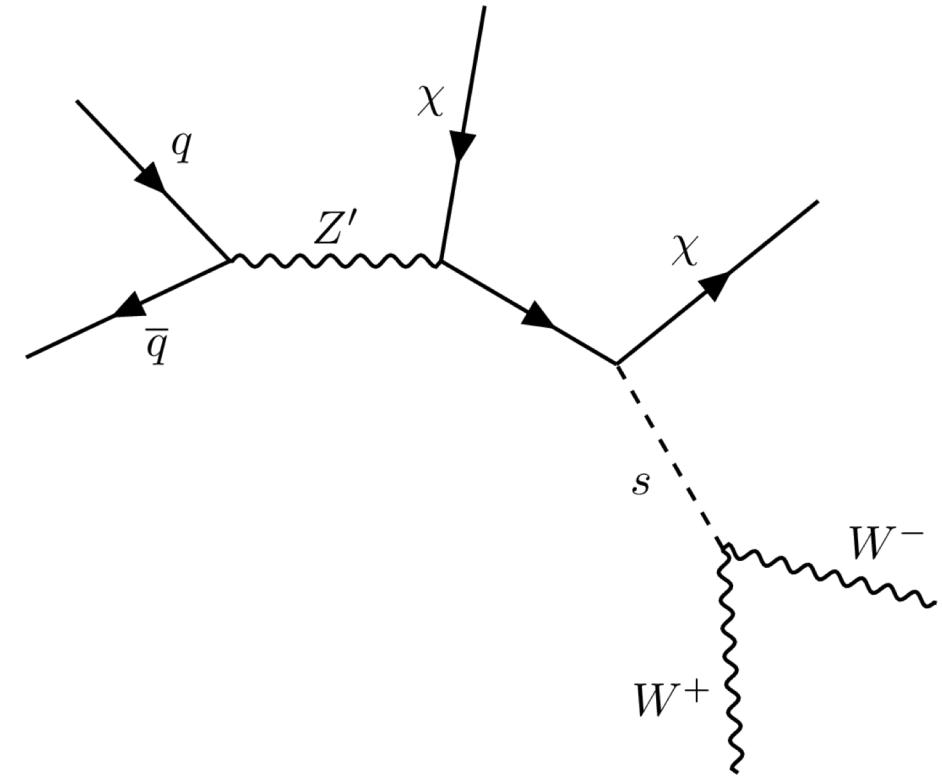
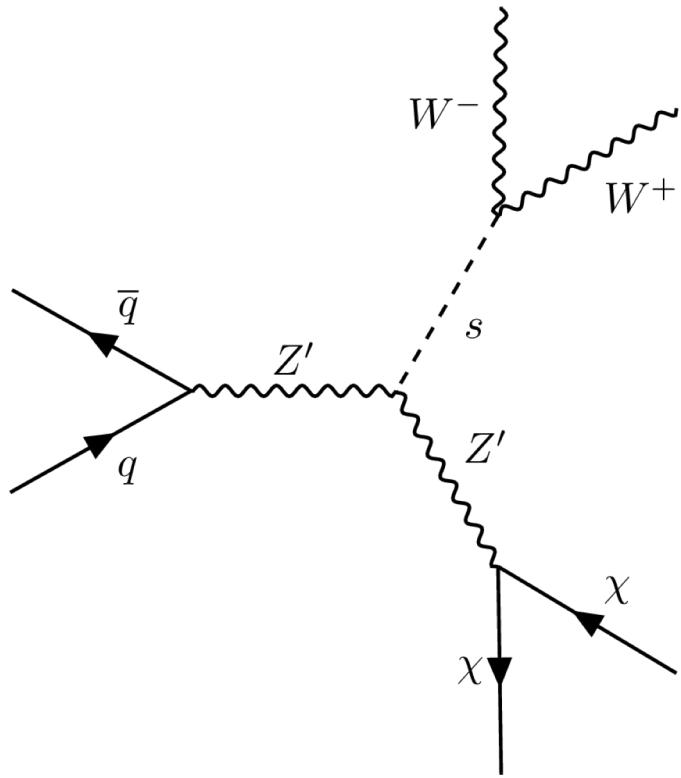
| Bin     | 0-match                     |                    |               | 1-match               |                    |               | 2-match               |                    |               |
|---------|-----------------------------|--------------------|---------------|-----------------------|--------------------|---------------|-----------------------|--------------------|---------------|
|         | $\Delta\phi_{\mu\mu}^{MET}$ | min- $d_{xy}$ [cm] | Events        | $I_{PF}^{\text{rel}}$ | min- $d_{xy}$ [cm] | Events        | $I_{PF}^{\text{rel}}$ | min- $d_{xy}$ [cm] | Events        |
| Obs. A  | 0–0.1                       | 3–15               | 68            | > 0.25                | 0.02–0.75          | 716           | > 0.25                | 0.02–0.15          | 424           |
| Obs. B  | 0.1–0.5                     | 3–15               | 9             | < 0.25                | 0.02–0.75          | 33            | < 0.25                | 0.02–0.15          | 22            |
| Obs. C  | 0–0.1                       | > 15               | 9             | > 0.25                | > 0.75             | 12            | > 0.25                | > 0.15             | 10            |
| Pred. D | 0.1–0.5                     | > 15               | $1.2 \pm 0.6$ | < 0.25                | > 0.75             | $0.5 \pm 0.3$ | < 0.25                | > 0.15             | $0.5 \pm 0.3$ |
| Obs. D  |                             |                    | 2             |                       |                    | 0             |                       |                    | 0             |



# Dark Matter in displaced muons (dSA)



# Dark Matter in WW+MET





# Dark Matter in WW+MET

| Quantity  | Selection          |
|---|--------------------|
| Number of leptons   | 2                  |
| Lepton flavors  | $e\mu, \mu e$      |
| Lepton charges  | Opposite           |
| Additional leptons  | 0                  |
| $p_T^{\ell, \text{max}}$  | $> 25 \text{ GeV}$ |
| $p_T^{\ell, \text{min}}$  | $> 20 \text{ GeV}$ |
| $p_T^{\ell\ell}$  | $> 12 \text{ GeV}$ |
| $p_T^{\ell\ell, \text{miss}}$                                     | $> 30 \text{ GeV}$ |
| $p_T^{\ell\ell, \text{miss}}$                                     | $> 20 \text{ GeV}$ |
| $\min(p_T^{\text{miss, PF proj}}, p_T^{\text{miss, track proj}})$ | $> 20 \text{ GeV}$ |
| $m_T^{\ell\ell, p_T^{\text{miss}}}$                               | $> 50 \text{ GeV}$ |
| $\Delta R_{\ell\ell}$   | $< 2.5$            |
| Number of b-tagged jets   | 0                  |

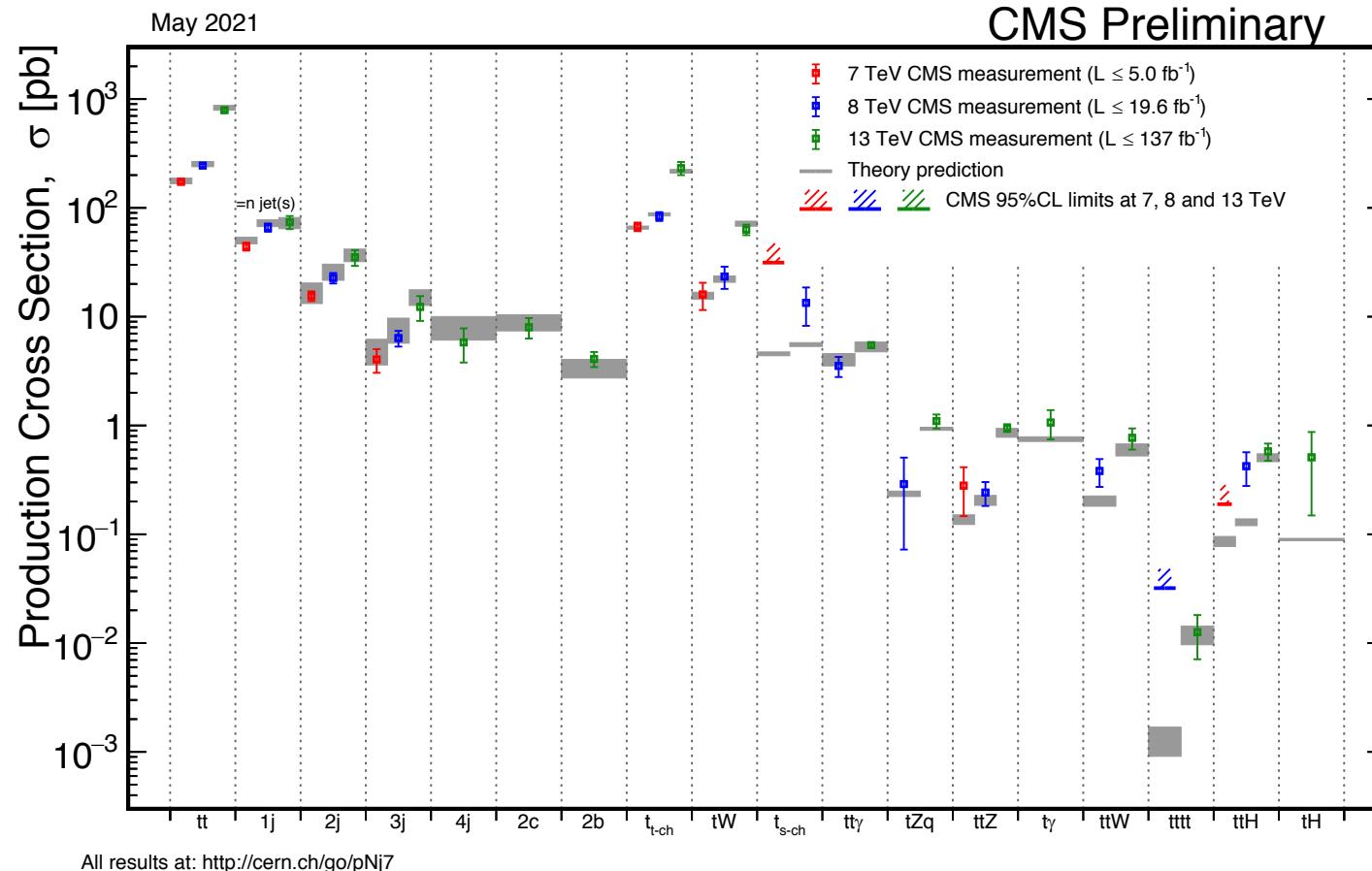
| Quantity                                  | Selection                             |
|---|---------------------------------------|
| Number of leptons                         | 1                                     |
| Additional leptons                        | 0                                     |
| Number of jets                            | $\geq 2$                              |
| Non W-candidate b-tagged jets             | 0                                     |
| $m_{jj}^{\ell\ell}$                       | $> 65 \text{ GeV}, < 105 \text{ GeV}$ |
| $p_T^{\ell\ell, \text{miss}}$             | $> 60 \text{ GeV}$                    |
| $p_T^{\ell jj}$                           | $> 60 \text{ GeV}$                    |
| $p_T^{\ell, p_T^{\text{miss}}}$           | $> 80 \text{ GeV}$                    |
| $\Delta R_{\ell, jj}$                     | $< 3$                                 |
| $\Delta\phi_{\ell, jj}$                   | $< 1.8$                               |
| $\Delta\phi_{\ell jj, p_T^{\text{miss}}}$ | $> 2$                                 |

## Lepton+Jets BDT

| Variable  | Definition  |
|---|---|
| $p_T^{jj}$  | $p_T$ of the vectorial sum of the W candidate jets  |
| $p_T^{\ell jj}$   | $p_T$ of the vectorial sum of the visible particles   |
| $p_T^{\text{miss}}$   | Size of the missing transverse momentum vector  |
| $\Delta\eta_{\ell, jj}$ and $\Delta\phi_{\ell, jj}$                               | $\Delta\eta$ and $\Delta\phi$ between the lepton and the di-jet system  |
| $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$   | $\Delta\eta$ and $\Delta\phi$ between the W candidate jets  |
| $\Delta\eta_{\ell, p_T^{\text{miss}}}$ and $\Delta\phi_{\ell, p_T^{\text{miss}}}$ | $\Delta\eta$ and $\Delta\phi$ between the lepton and $\vec{p}_T^{\text{miss}}$  |
| $\Delta\phi_{\ell jj, p_T^{\text{miss}}}$   | $\Delta\phi$ between the vectorial sum of the visible particles and $\vec{p}_T^{\text{miss}}$   |
| $\min(p_T^{\ell}, p_T^{\ell jj}) / p_T^{\text{miss}}$                             | Minimum of the lepton $p_T$ and the trailing jet $p_T$ , divided by $p_T^{\text{miss}}$   |
| $\max(p_T^{\ell}, p_T^{\ell jj}) / p_T^{\text{miss}}$                             | Maximum of the lepton $p_T$ and the leading jet $p_T$ , divided by $p_T^{\text{miss}}$  |
| $\max(p_T^{\ell}, p_T^{\ell jj}) / m_{\ell jj, p_T^{\text{miss}}}$                | Maximum of the lepton $p_T$ and the leading jet $p_T$ , divided by the invariant mass of the vectorial sum of the visible particles and the $p_T^{\text{miss}}$ where the missing energy is considered to be massless |

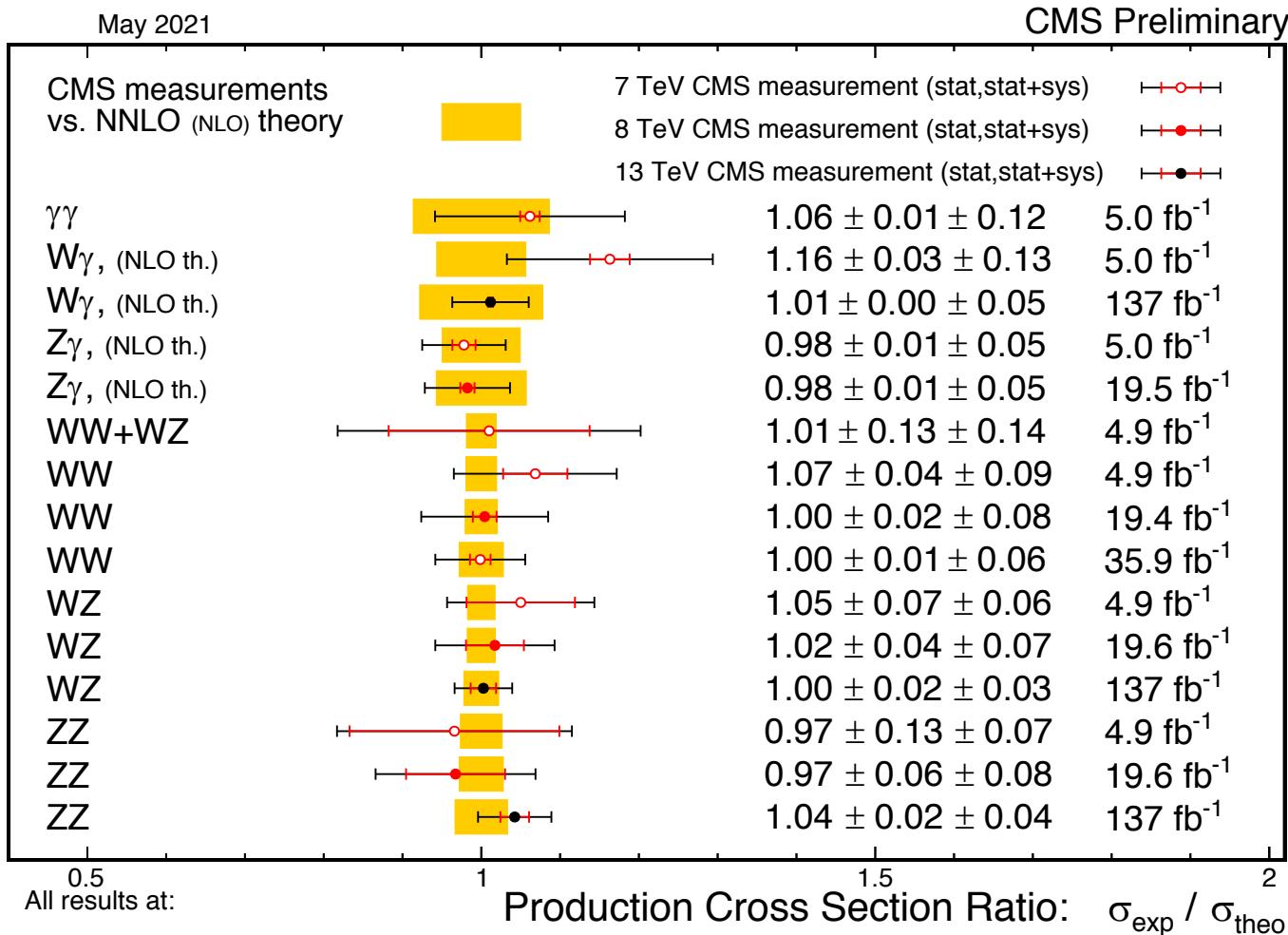


# Summary of SM cross sections





# Summary of SM cross sections





# Summary of SM cross sections

