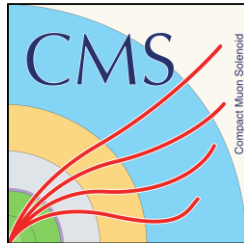


CMS Status and Overview

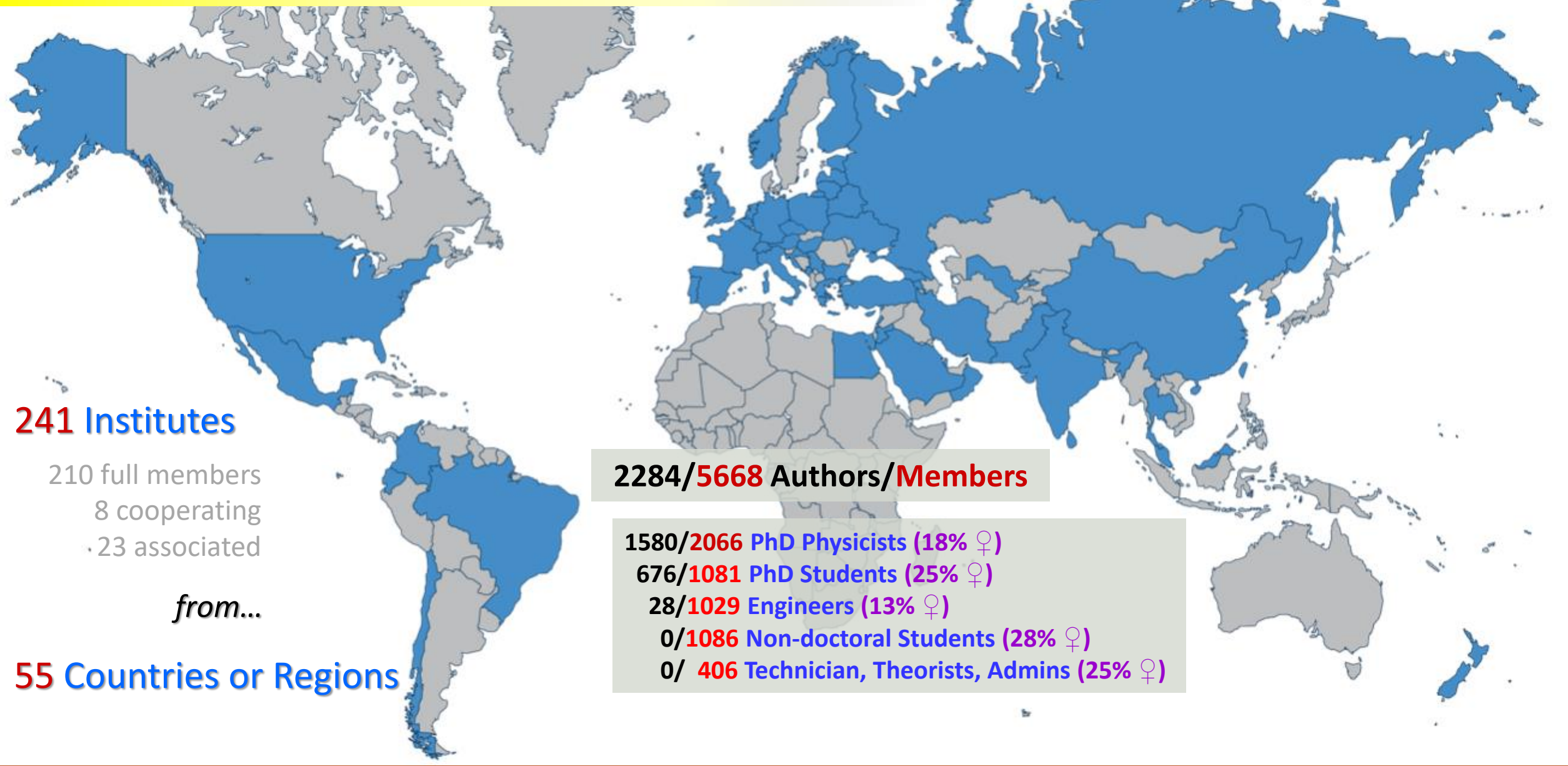


JIM OLSEN
PRINCETON UNIVERSITY
ON BEHALF OF THE CMS COLLABORATION
MAY 16, 2022



CMS Experiment at the LHC, CERN
Data recorded: 2022-Mar-11 08:17:42.214016 GMT
Run / Event / LS: 348683 / 35407138 / 1771

The CMS Collaboration



241 Institutes

- 210 full members
- 8 cooperating
- 23 associated

from...

55 Countries or Regions

2284/5668 Authors/Members

- 1580/2066 PhD Physicists (18% ♀)
- 676/1081 PhD Students (25% ♀)
- 28/1029 Engineers (13% ♀)
- 0/1086 Non-doctoral Students (28% ♀)
- 0/ 406 Technician, Theorists, Admins (25% ♀)

LS2 Activities Successfully Completed

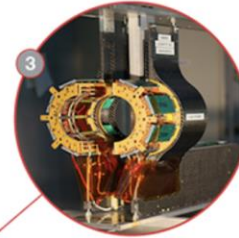
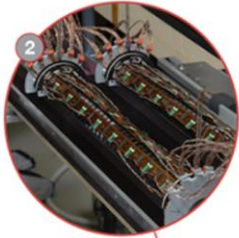
BEAM PIPE

Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.



PIXEL TRACKER

All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.



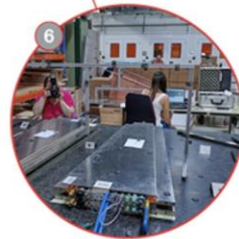
BRIL

New generation of detectors for monitoring LHC beam conditions and luminosity.



CATHODE STRIP CHAMBERS (CSC)

Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.

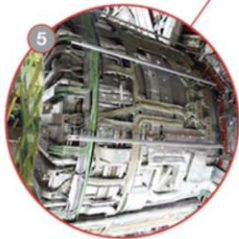


GAS ELECTRON MULTIPLIER (GEM) DETECTORS

An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.

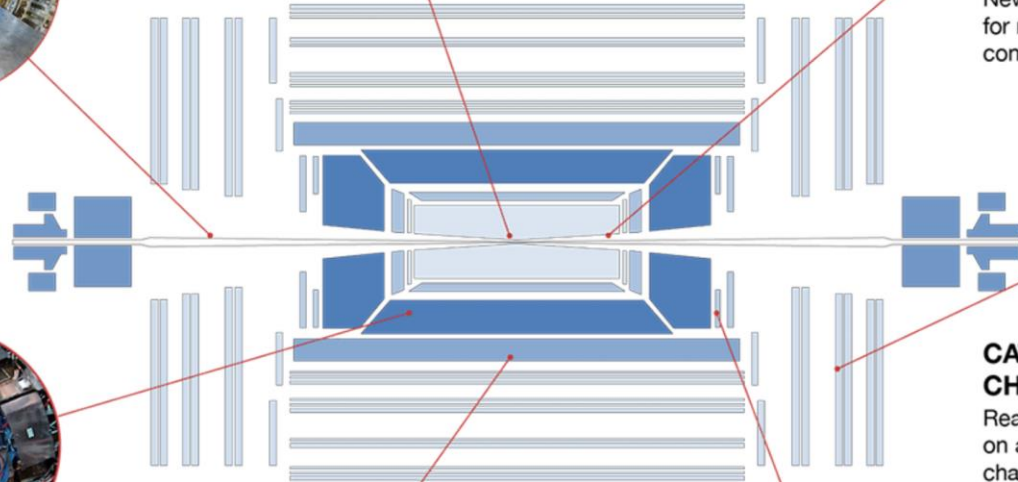
SOLENOID MAGNET

New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.



HADRON CALORIMETER

New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.



Additional Recent Highlights:

- Muon demonstrators installed
- Hybrid CPU/GPU transition complete

Successful participation in LHC Pilot Run (Oct/Nov 2021)

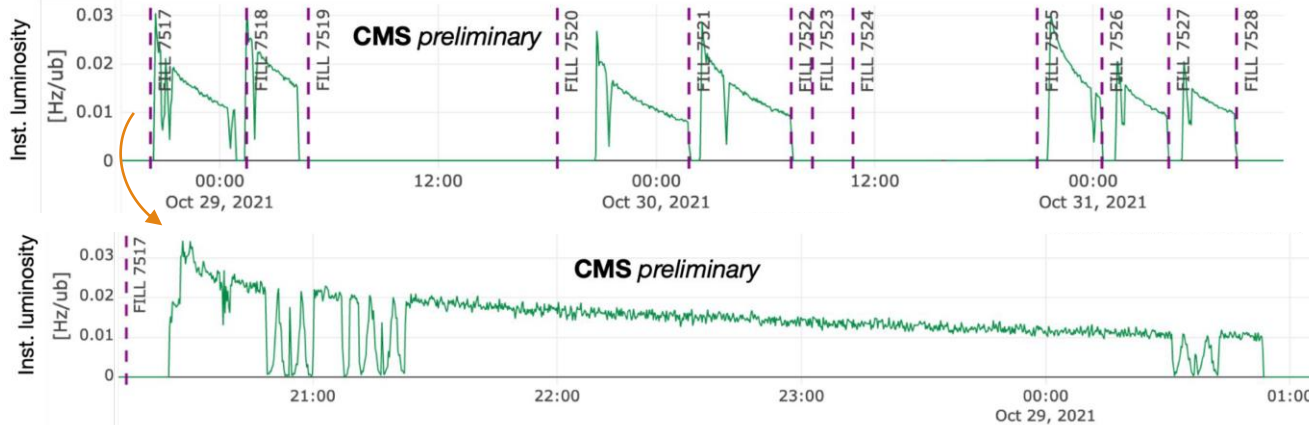
CMS closed on March 4, magnet fully commissioned at 3.8 T

We take this opportunity to thank all members of CMS who made this 1187 day endeavor a great success, and we look forward to Run 3 with much anticipation!

CMS is Back!

Pilot Beam Test (Oct 18 – Nov 1, 2021)

Online luminosity measurements



Extensive Cosmic Ray Run @ 3.8 T

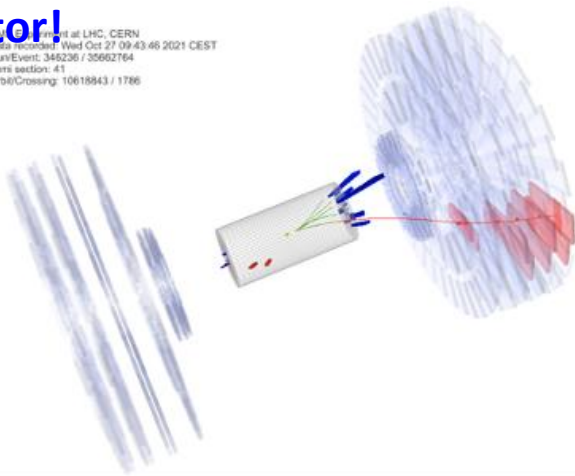
- Over 6M tracks reconstructed for alignment and calibration (well over the original goal)
- DAQ and overall detector stability confirmed
- GEM efficiency measured and trigger integration with CSC completed

CMS happily splashed by LHC beam in April

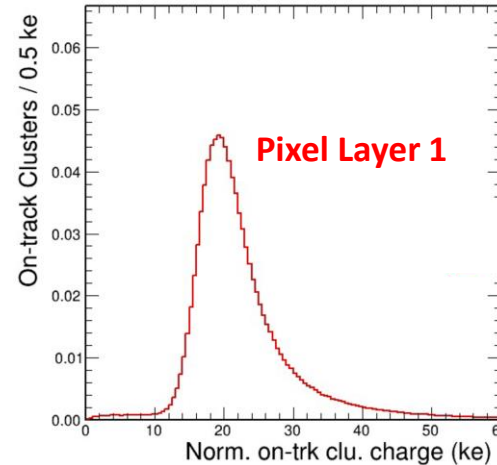


First data with GEM detector!

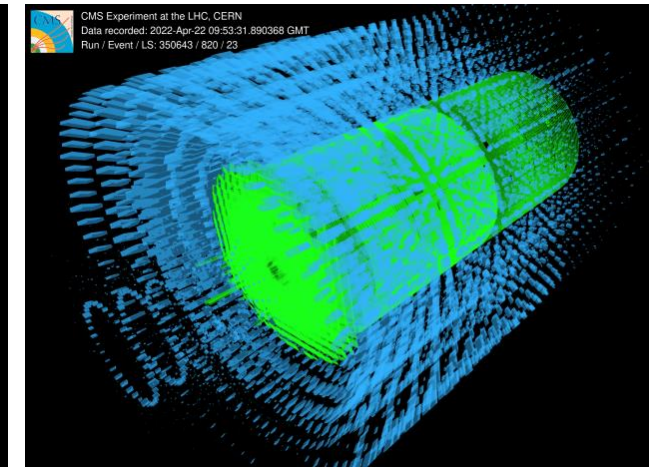
CMS Experiment at LHC, CERN
 Data recorded: Wed Oct 27 09:43:46 2021 CEST
 Run/Event: 346236 / 35662764
 Lume section: 41
 Crd0/Crossing: 10618643 / 1786



CMS Preliminary 2021 $\sqrt{s} = 900$ GeV



Cosmic ray event March, 2022

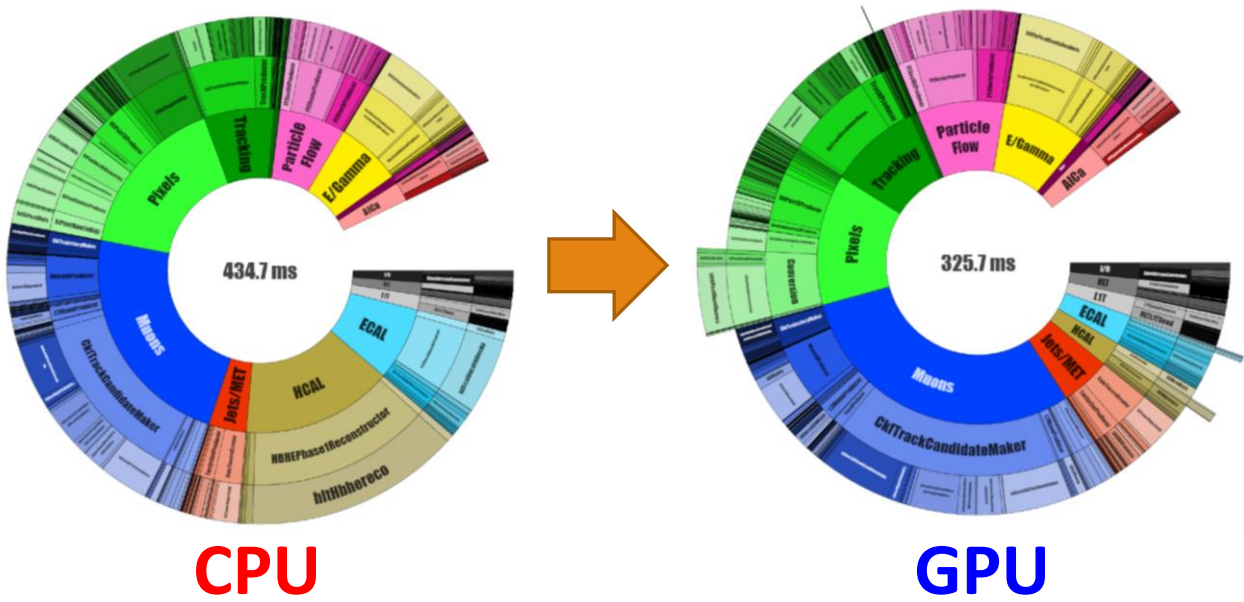


LHC beam splash April, 2022

Run 3 Preparation: DAQ/HLT/Trigger/Objects

DAQ/HLT

- Successful transition to a hybrid CPU + GPU system
- Significant reduction in processing time and corresponding increase in physics reach and performance
- Running GPU-enabled trigger menus since start of 2022



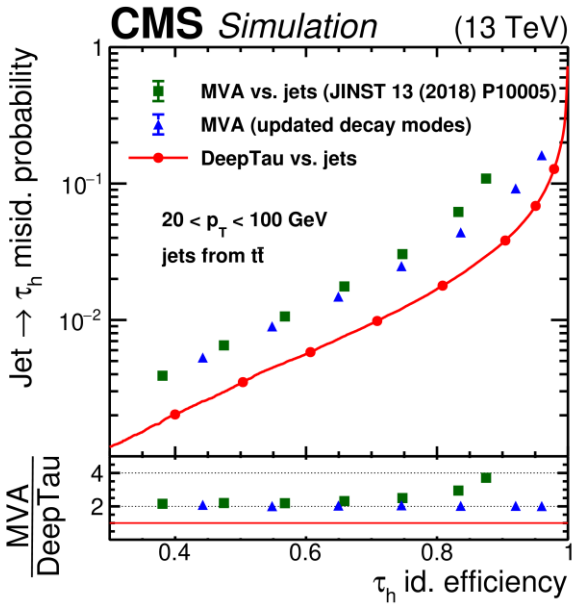
Trigger

- L1 trigger enhanced with capability to trigger on long-lived particles using calorimeter information
- High-level Trigger menus updated to include dedicated paths for long-lived particles, new paths for data “scouting” and “parking”, and much more!

Objects

TAU-20-001
Submitted to JINST

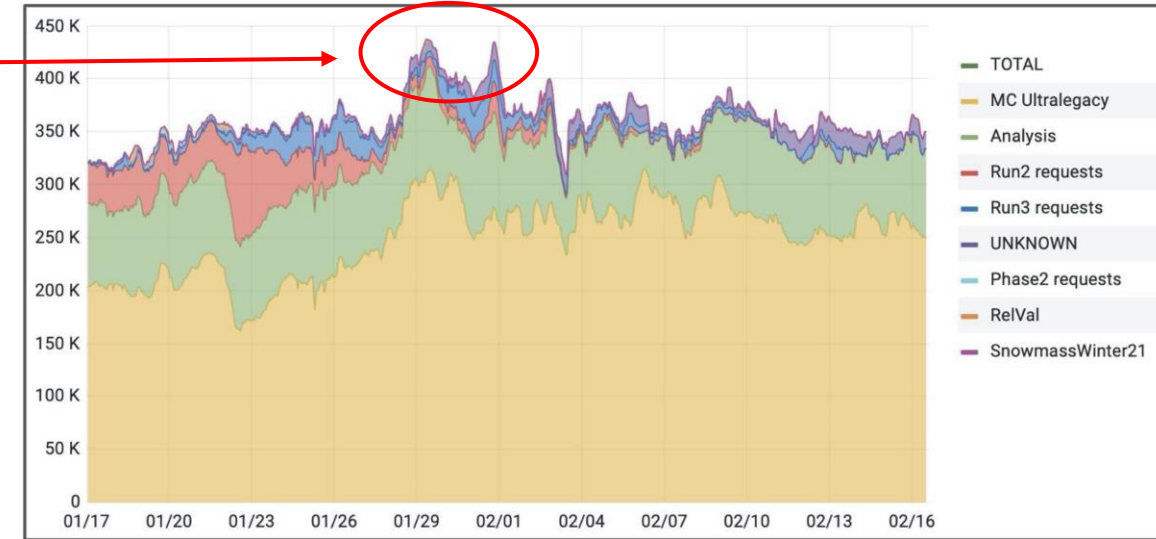
- Extensive improvements in physics object reconstruction
- Example: new algorithm to identify hadronic tau decays using a deep neural network
- **10 – 30% improvement** in tau reconstruction efficiency for a given fake rate



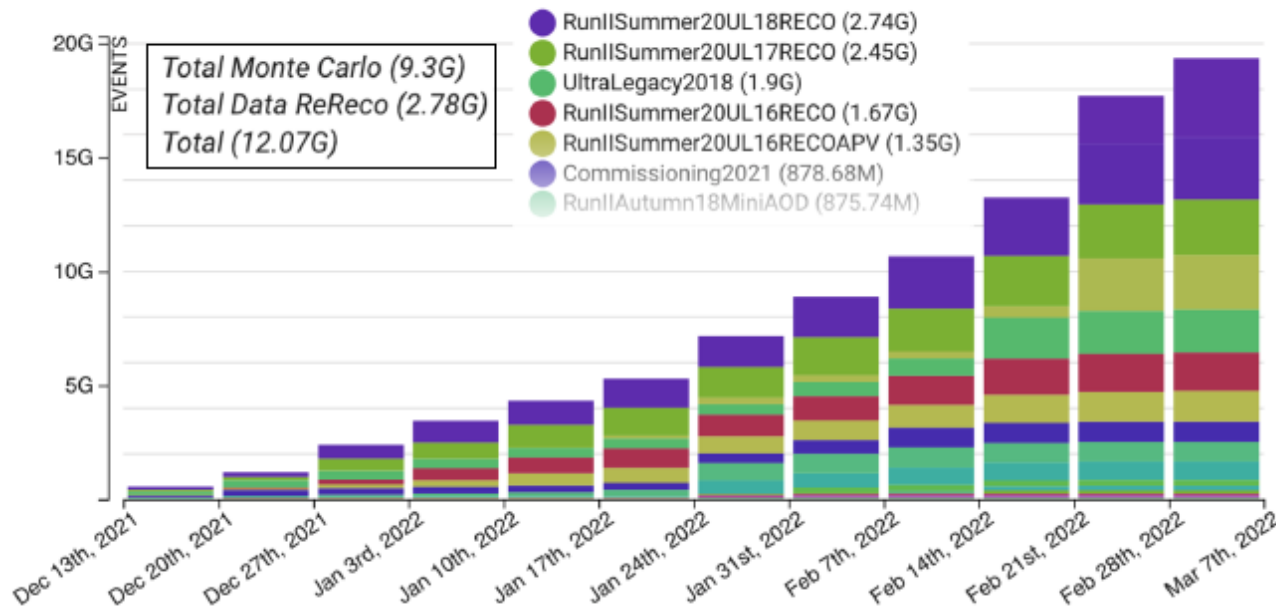
Run 3 Preparation: Computing/Software/Data Prep

- **Computing:** smooth operations with a new CMS record of **437k CPU cores** utilized worldwide simultaneously
- **Production:** consistently able to produce 1 – 1.5B per week for the past year across multiple data and MC campaigns

Computing Operations (number of cores)



Recent Data/MC Production



- **Software Releases:** consistent on-time delivery of production releases facilitating “Ultra Legacy” re-reco for Run 2, preparation for Pilot Beam and detector commissioning + physics for Run 3

CMS is Ready for Run 3!

CMS Publications

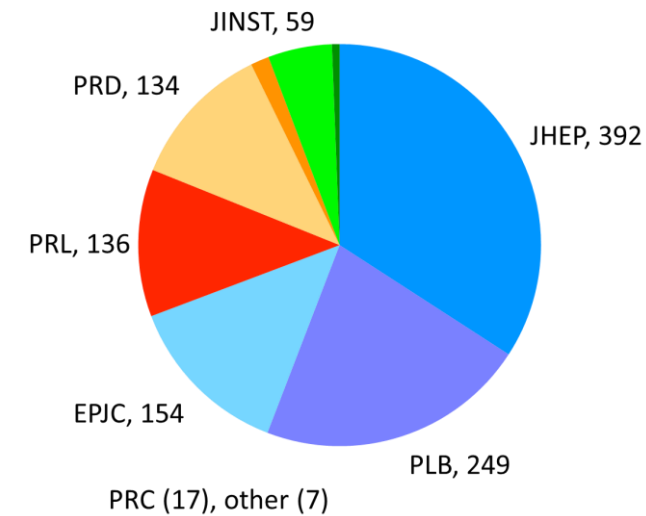
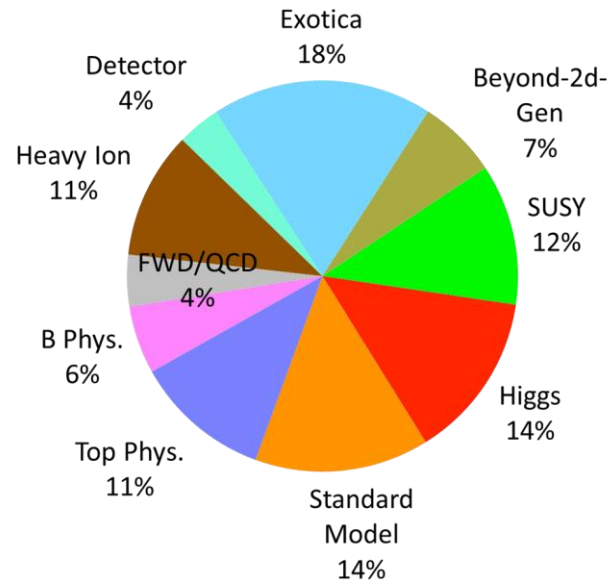
As of 15/5/2022

1155 CMS papers

- 1116 published

1130 papers based on collision data

- 1091 published
- 576 based on Run-1 data
- 554 based on Run-2 data

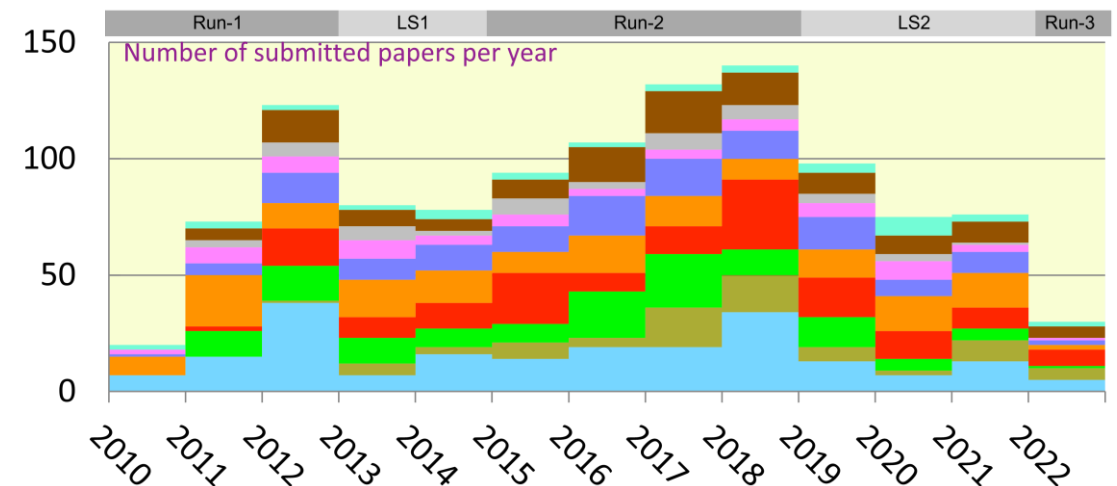


CMS titles

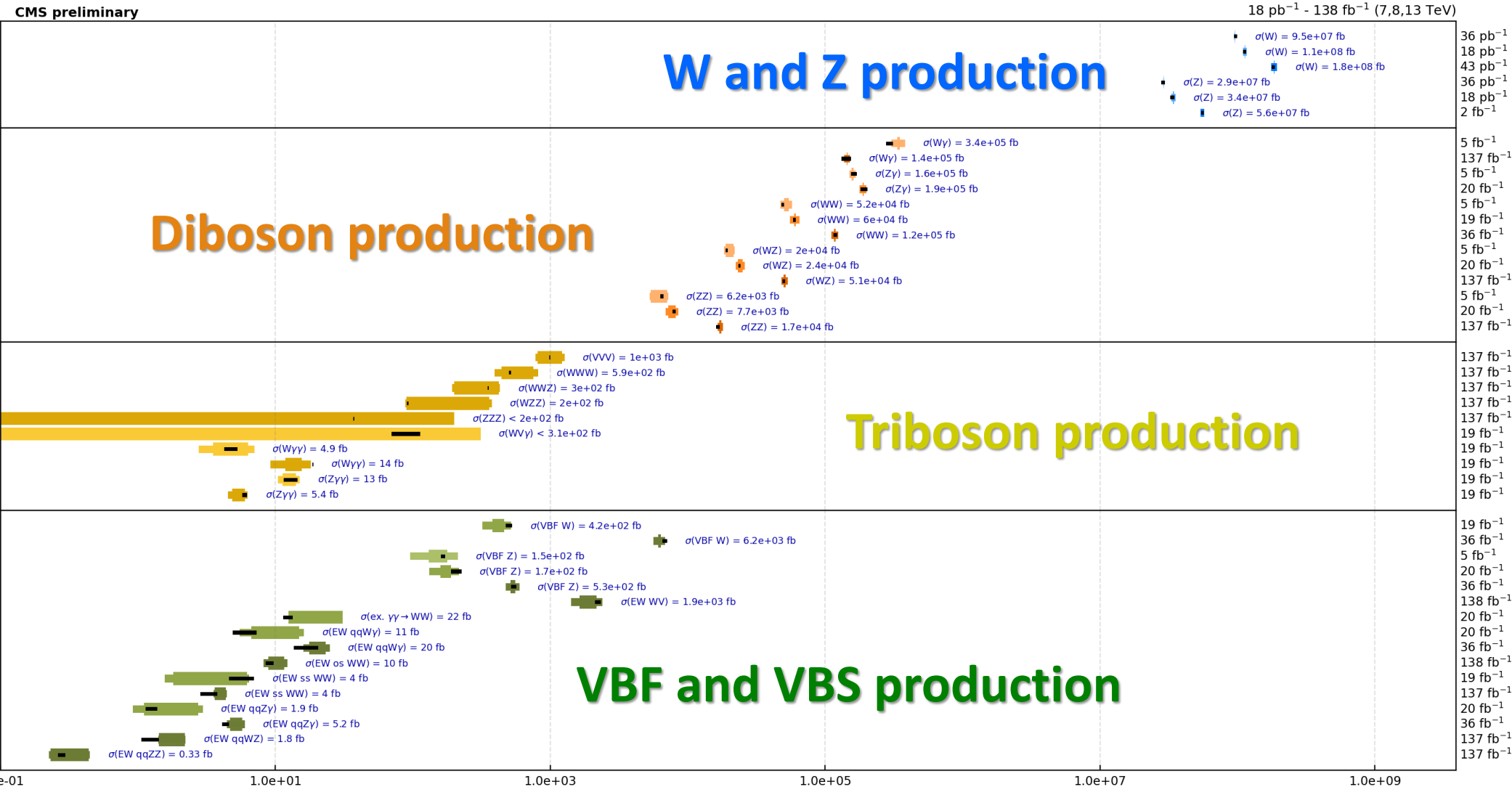
- 568 "Search"
- 45 "Observation"
- 20 "Evidence"
- 331 "Measurement"
- 31 "Study"

CMS with friends

- ATLAS: 5 (4 JHEP, 1 PRL)
- LHCb: 1 (Nature)
- TOTEM: 4 (1 JHEP, 2 EPJC, 1 PRL)



Overview of CMS cross section results



Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV, Black bars: theory prediction

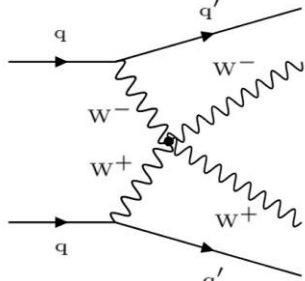
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined>

Jan 2022

Vector Boson Scattering

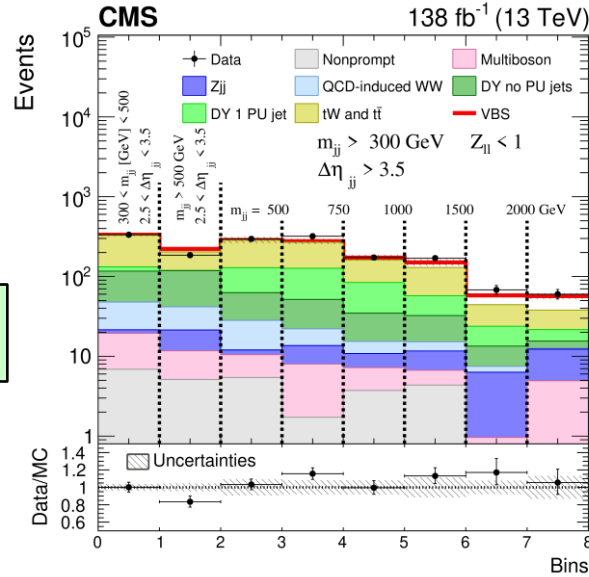
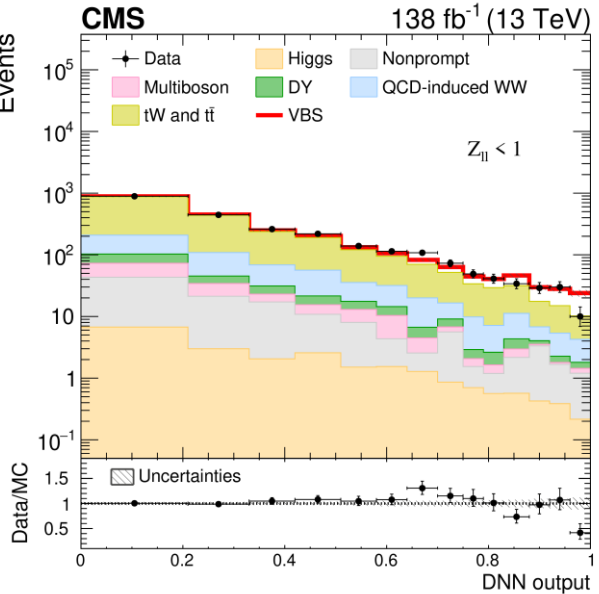


Observation of opposite-sign WW scattering



SMP-21-001
Submitted to PLB
Physics Briefing

- Large dijet mass and rapidity separation
- Large background from top-pair production

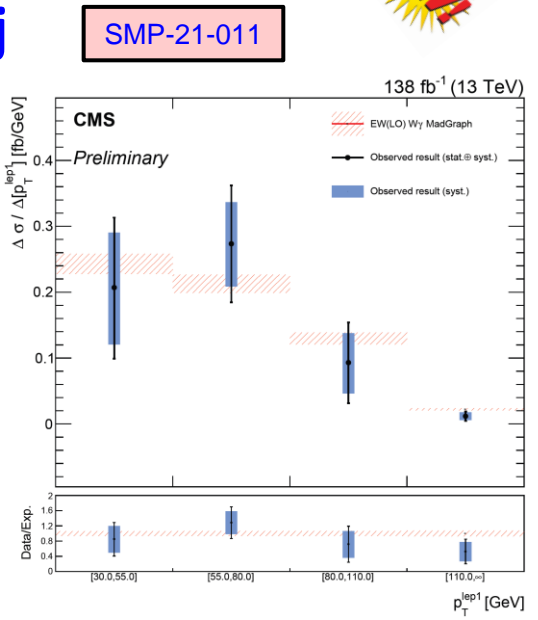
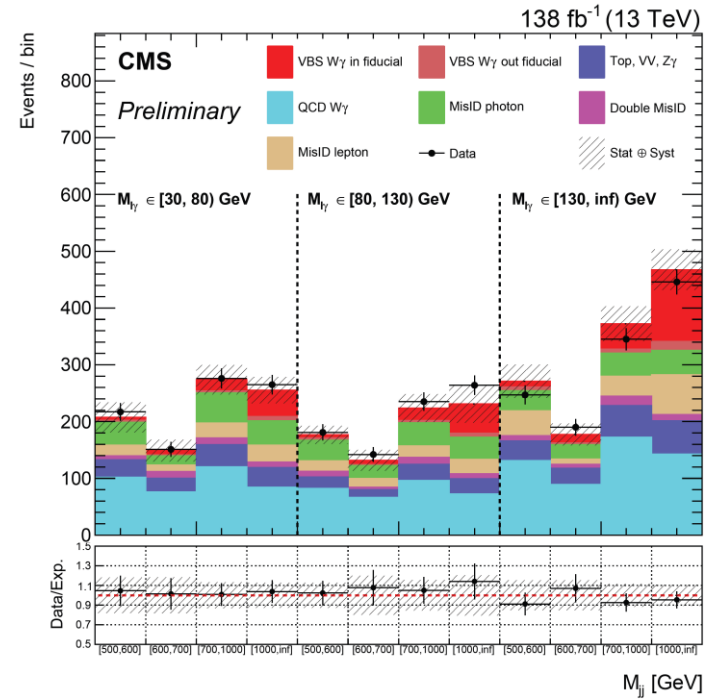
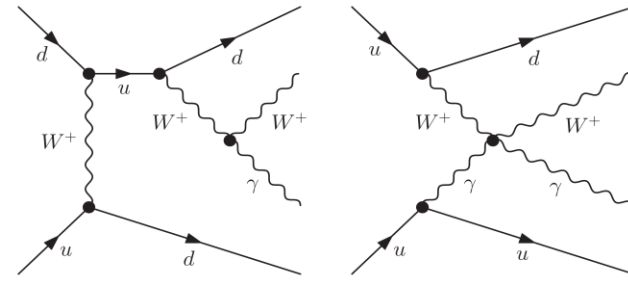


W⁺W⁻jj signal is observed with a significance of 5.6σ (5.2σ exp)

Fiducial cross section:

- **Measured = (10.2 ± 2.0) fb**
- **SM prediction = (9.1 ± 0.6) fb**

EWK production of Wγjj



EW Wγjj signal is observed with a significance of 6.0σ (6.8σ exp) and a measured fiducial cross section of (19.2 ± 4.0) fb

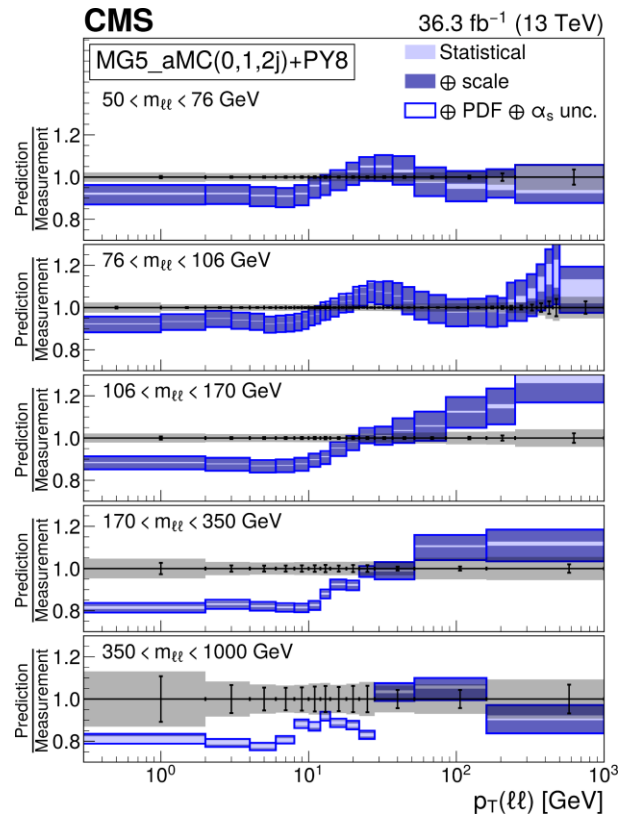
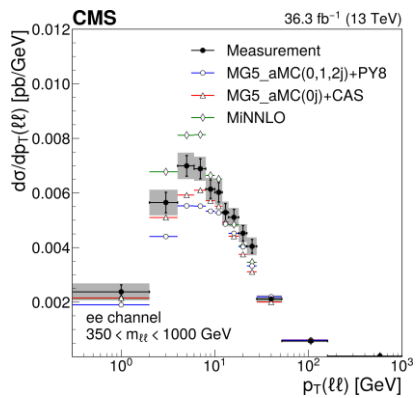
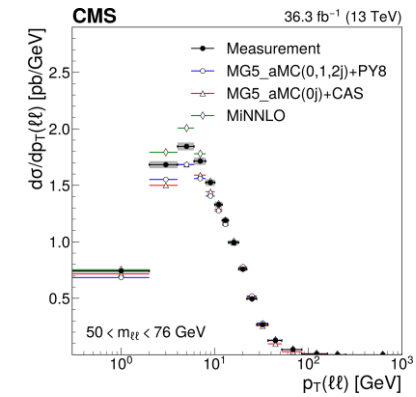
Differential distributions are measured for the first time and limits are obtained on anomalous quartic gauge couplings

Precision Drell-Yan Production

Mass dependence of dilepton p_T

SMP-20-003
Submitted to EPJC

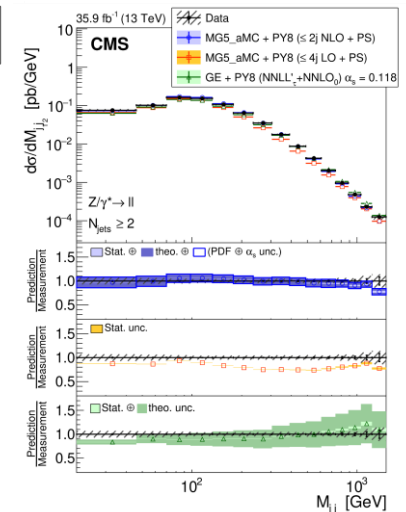
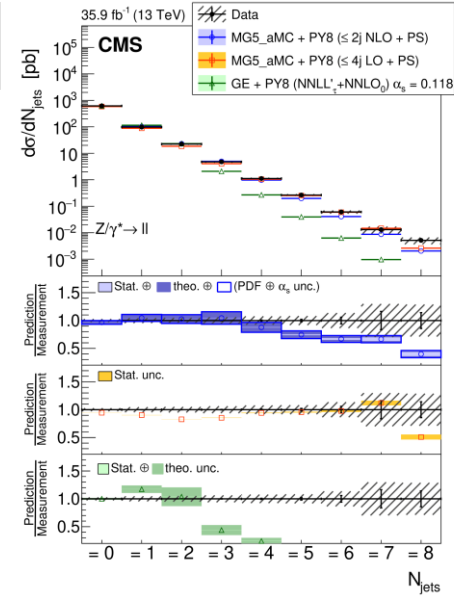
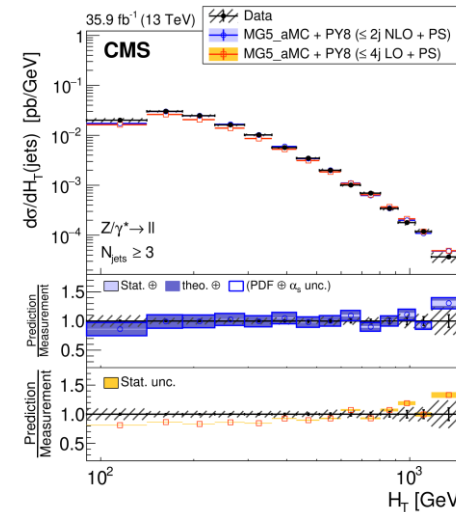
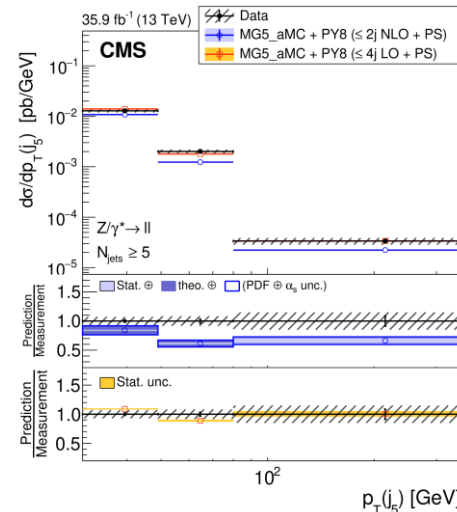
- Probing QCD from low (50 GeV) to high (1 TeV) dilepton mass
- Sensitive probe of the parton distribution functions and soft QCD effects where resummation can be tested in detail



Z + jets differential distributions

- An ideal mechanism for testing higher-order EW and QCD predictions
- Critical for understanding backgrounds to Higgs and new particle production
- Precision differential distributions across a wide range of observables with detailed comparisons to theory predictions, even with up to 8 jets!

SMP-19-009
Submitted to PRD



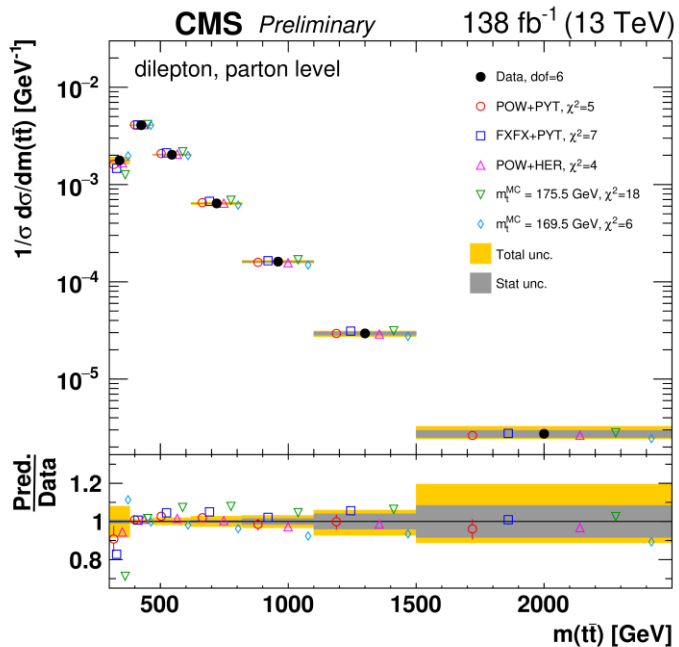
Precision Top Production with Dileptons



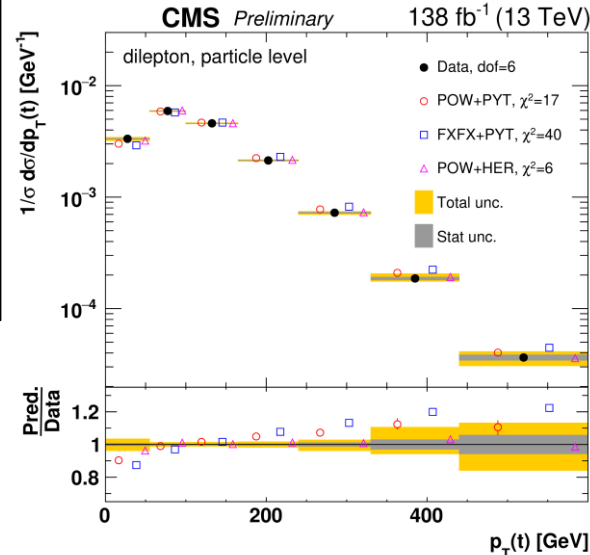
Differential cross sections in $t\bar{t}$

TOP-20-006

- Exploiting the large $t\bar{t}$ cross section at 13 TeV, and the unprecedented full Run 2 dataset
- Testing the SM **and searching for new physics**
- Differential distributions measured as functions of kinematic variables for the $t\bar{t}$ system, t and \bar{t} separately, and extra jets



- Cross sections presented at the **parton and particles levels**, and compared to a number of NLO MC and (in some cases) NNLO predictions
- Deviations from SM predictions are **observed**, which can be used to refine the theory, or characterize new physics



Cross sections in tW

TOP-21-010

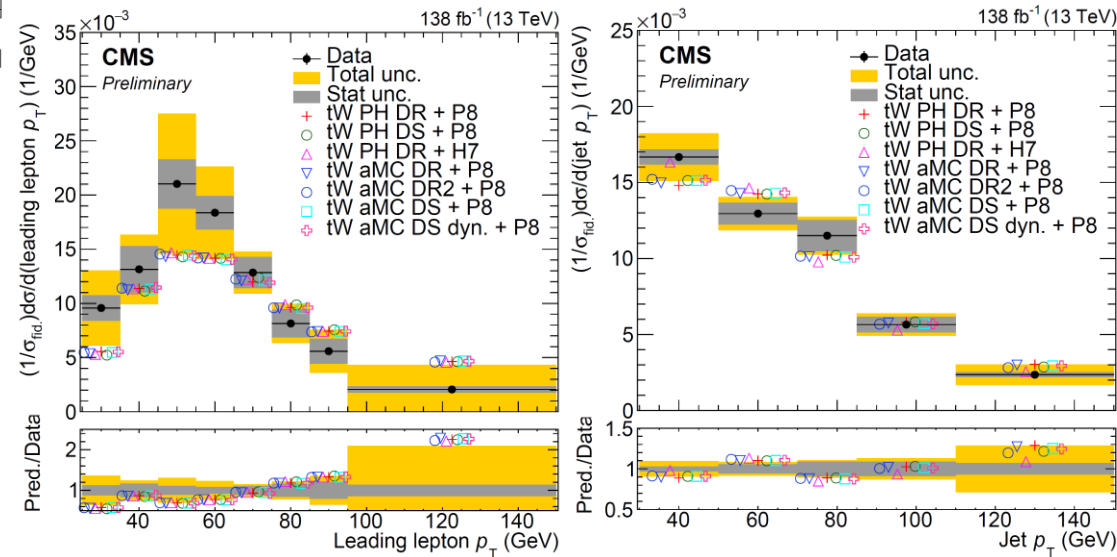
- Inclusive and differential cross sections in dilepton ($e\mu$) final states
- Sensitive probe of new physics, significant background to Higgs and new particle searches

Inclusive cross section:

$$\sigma = 79.2 \pm 0.8 \text{ (stat)} \pm 7.0 \text{ (syst)} \pm 1.1 \text{ (lumi)} \text{ pb}$$

syst dominated by jet energy scale, tW matrix element, and $t\bar{t}$ background

$$\sigma(\text{SM}) = 71.7 \pm 1.8 \text{ (scale)} \pm 1.8 \text{ (PDF)} \text{ pb}$$



Top Mass Measurements

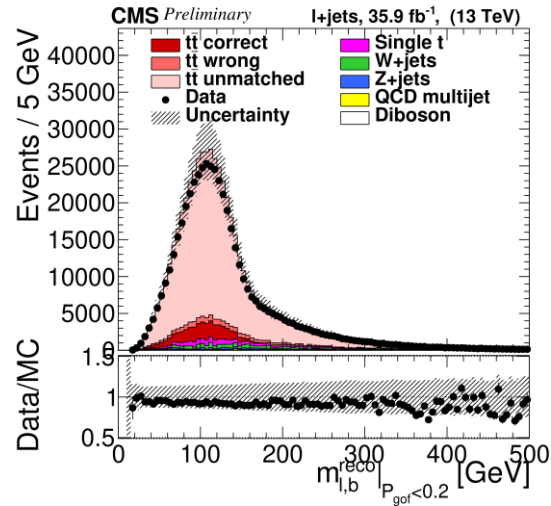


TOP-20-008

- **Direct mass measurement from profile likelihood method** using lepton + jets
- Improved precision from updated tune, more MC, more observables, more complete treatment of nuisances

$$m_t = 171.77 \pm 0.38 \text{ GeV}$$

Most precise measurement to date!



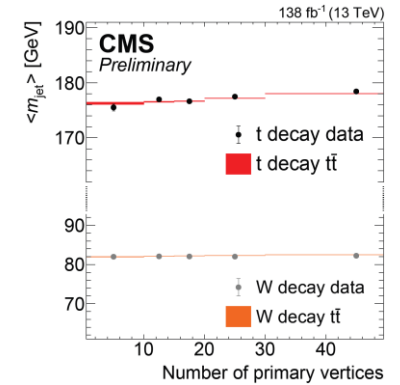
Top mass from jet mass

- **Direct mass measurement from jet mass** using lepton + jets with $p_T^{\text{jet}} > 400 \text{ GeV}$
- Top mass extracted from a fit to the differential cross section vs. m_{jet}

$$m_t = 172.76 \pm 0.81 \text{ GeV}$$

Improvement of a factor of 3 over previous analysis

TOP-21-012

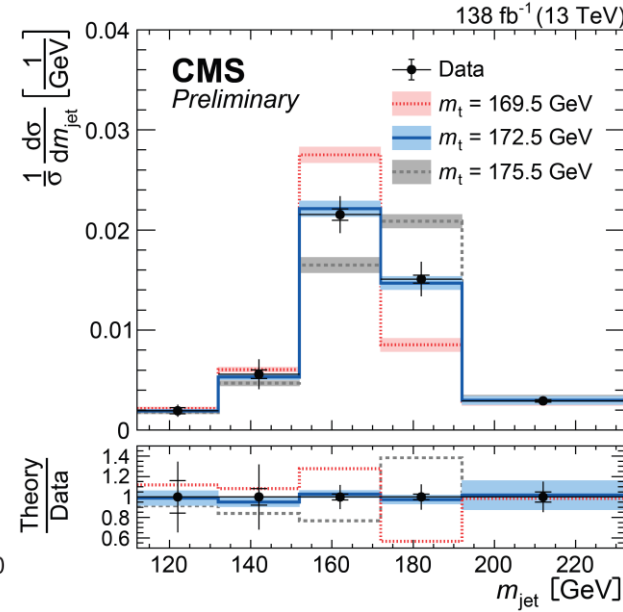
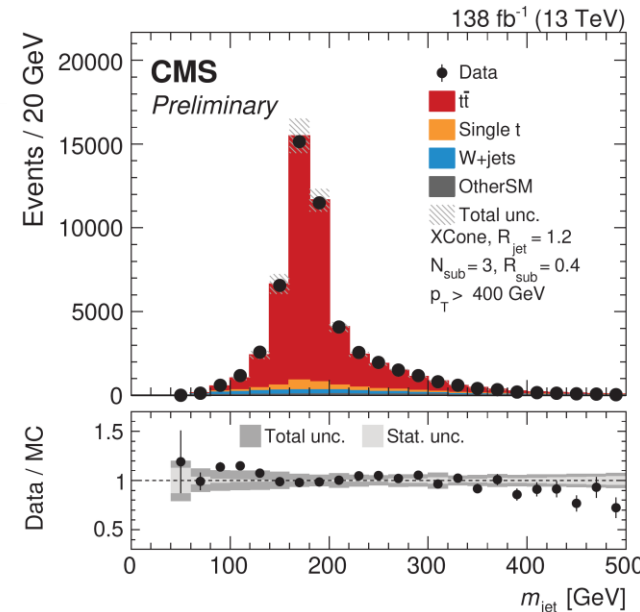
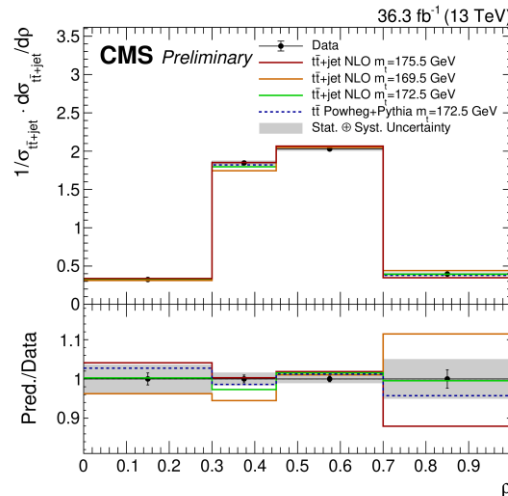


TOP-21-008

- Pole mass extracted from fit to normalized $t\bar{t}$ + jet cross section vs. ρ
- New MVA methods for observable reco and event classification

$$m_t^{\text{pole}} = 172.94 \pm 1.37 \text{ GeV}$$

Use of novel ABMP16NLO PDF set



More Top Physics

$t\bar{t}W$ cross sections

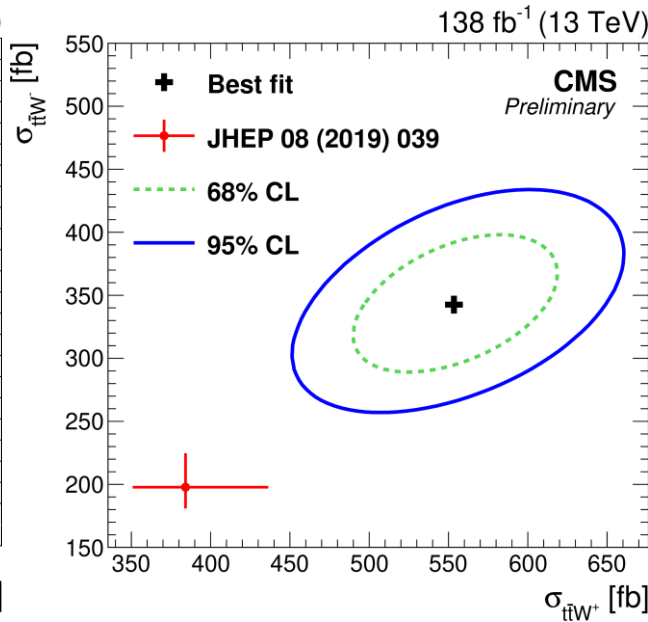
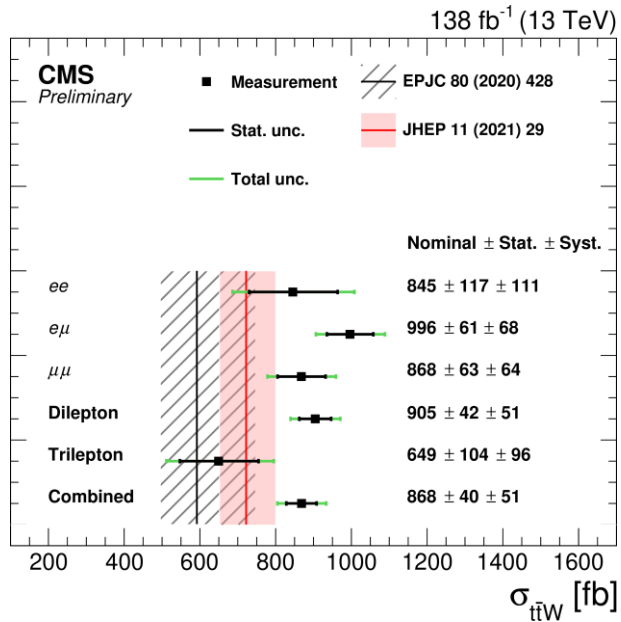
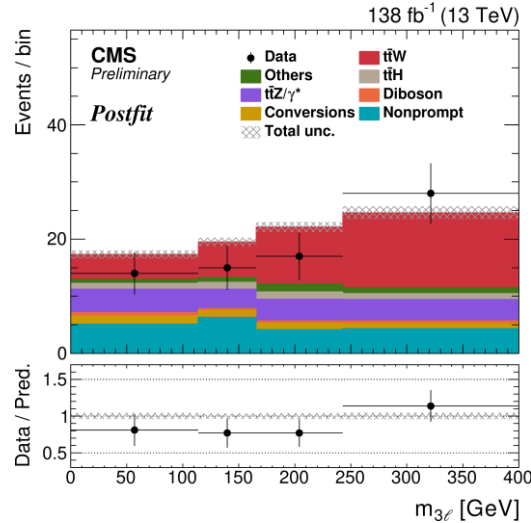
TOP-21-011

- Measurement of $t\bar{t}W$ cross section from events with 2 or 3 leptons + jets
- Significant background to $t\bar{t}H$, as well as $t\bar{t}$ and $t\bar{t}t\bar{t}$ production

$$\sigma = 868 \pm 40 \text{ (stat)}^{+52}_{-50} \text{ (syst)} \text{ fb}$$

$$\sigma_{t\bar{t}W^+} = 553^{+30}_{-29} \text{ (stat)}^{+31}_{-30} \text{ (syst)} \text{ fb}$$

$$\sigma_{t\bar{t}W^-} = 343 \pm 26 \text{ (stat)} \pm 25 \text{ (syst)} \text{ fb}$$



Top quark charge asymmetry



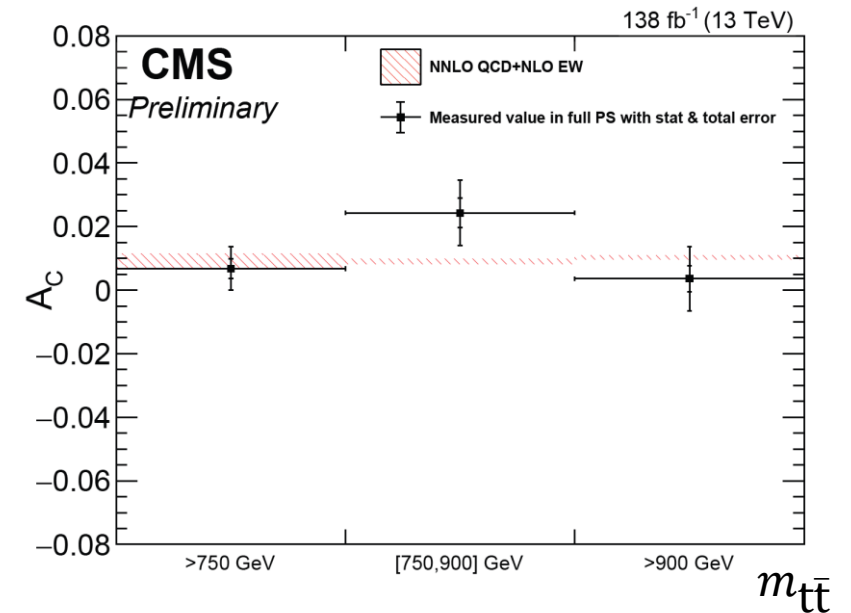
TOP-21-014

- Measurement of the top quark central-forward charge asymmetry A_C
- Small asymmetry ($\sim 1\%$) in the SM, new particles could increase it
- Boosted lep + jets events with non-isolated leptons and overlapping jets

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$A_C = 0.0069^{+0.0065}_{-0.0069}$$

$$A_C(\text{SM}) = 0.0094^{+0.005}_{-0.007}$$



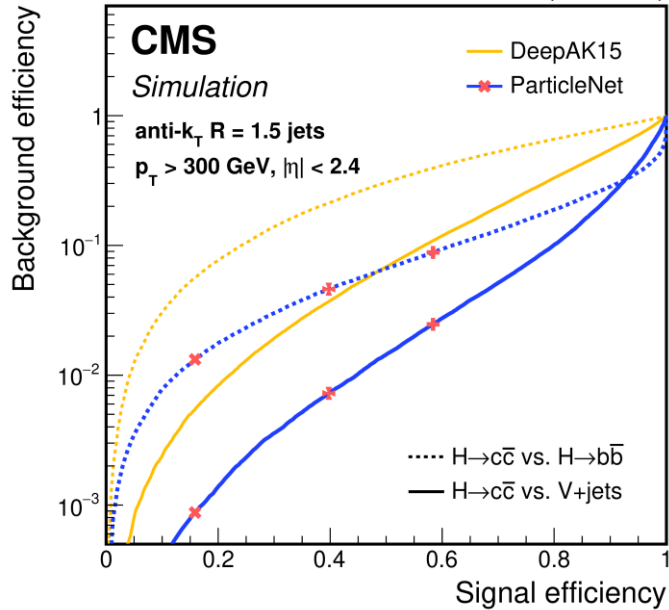
Searching for the Charming Higgs

Search for $VH(c\bar{c})$

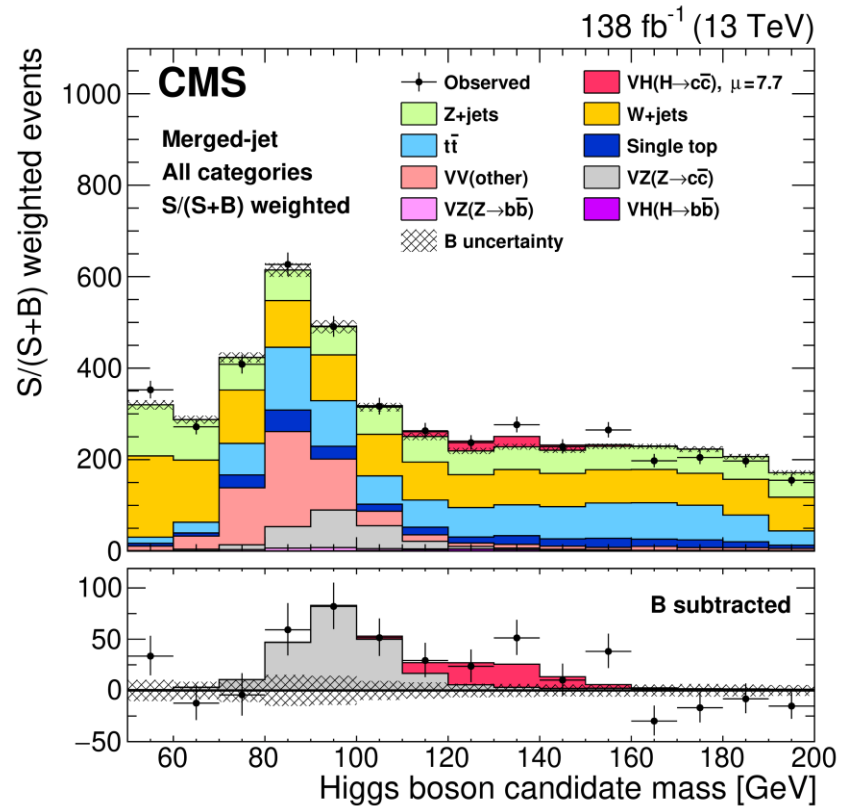
HIG-21-008
Submitted to PRL

- 2nd generation Higgs-quark coupling
- Combined resolved (AK4) and merged (AK15) jet analysis strategy

Charm tagging performance (13 TeV)

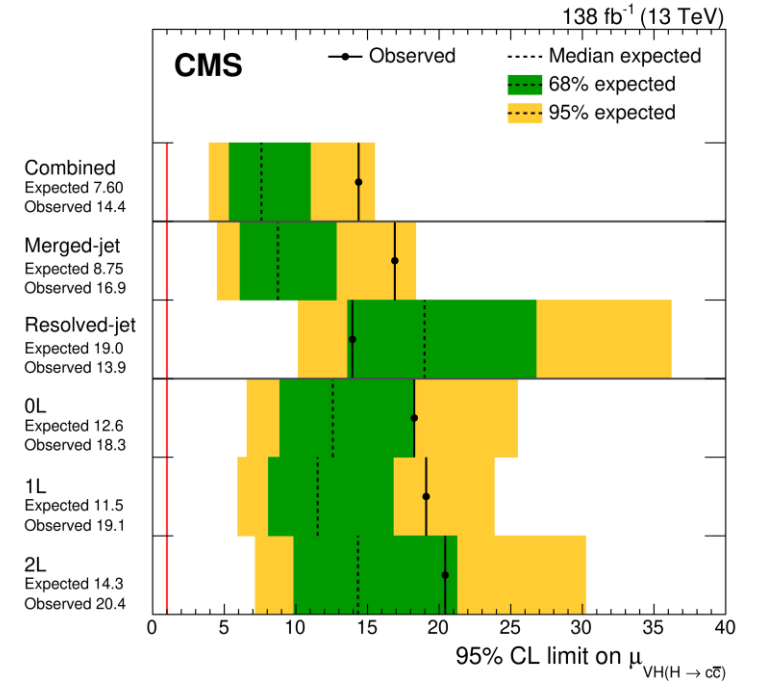


First observation of $VZ(cc)$ at a hadron collider (5.7σ)!



Limit on $pp \rightarrow VH, H \rightarrow c\bar{c}$

$\mu < 14$ (7.6) @ 95% C. L. obs (exp)

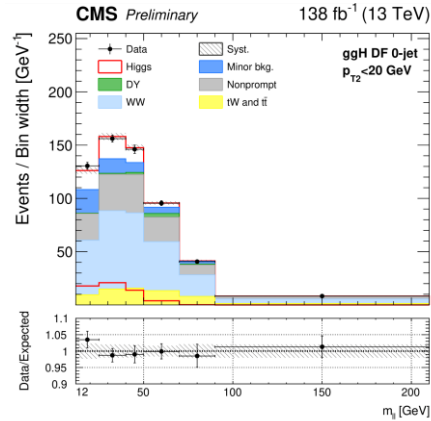


More Higgs Physics

H → WW xsecs

HIG-20-013

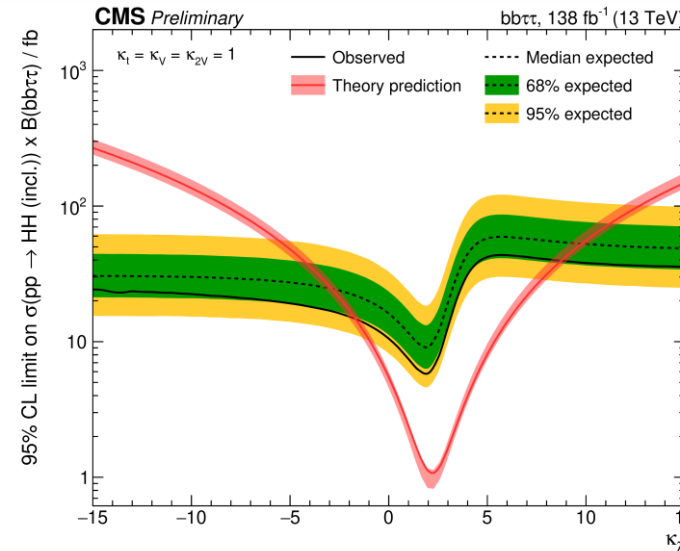
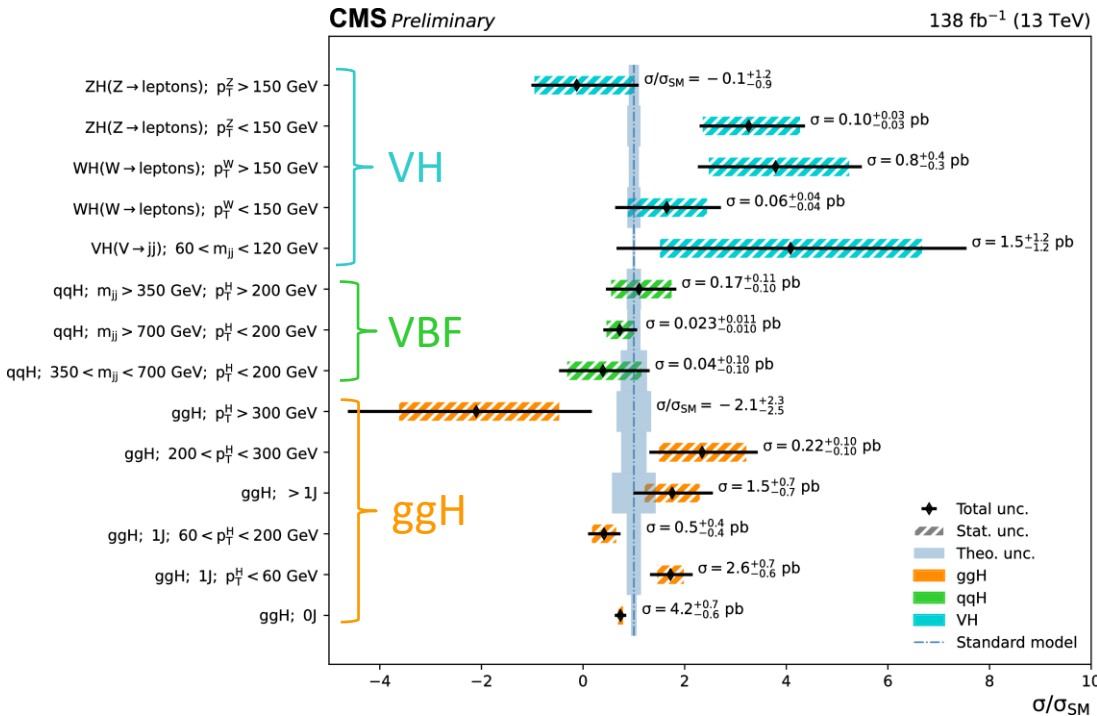
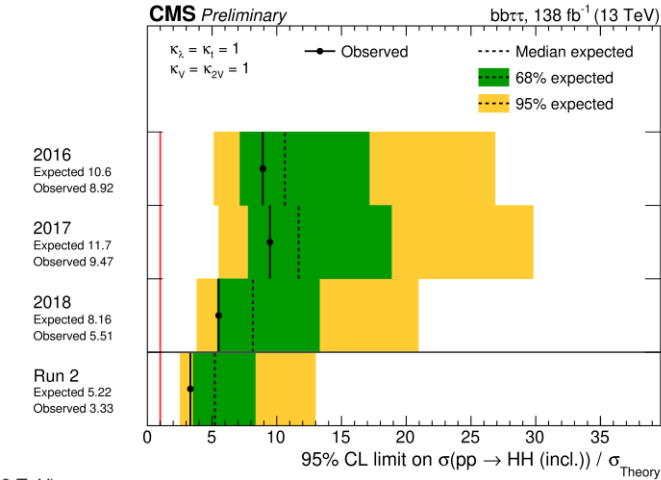
- Measurement of Simplified Template Cross Sections (STXS) in the H → WW → llvv channel
- VH, VBF, and ggH production modes all observed and explored



Search for di-Higgs production

HIG-20-010

- HL-LHC Holy Grail: measuring the Higgs self-coupling
- Search for non-resonant HH → bbττ: medium BR, low backgrounds and accessible triggers
- ggF and VBF both targeted to extract κ_λ and κ_{2V}



Limit on HH production:

$$\mu < 3.3 \text{ (5.2) @ 95\% C. L. obs (exp)}$$

Limits on Higgs self-coupling:

$$-1.8 < \kappa_\lambda < 8.8$$

Limits on Higgs-VV coupling:

$$-0.4 < \kappa_{2V} < 2.6$$

Cliffhangers from Run 2

Vector-like Leptons (VLLs)

B2G-21-004

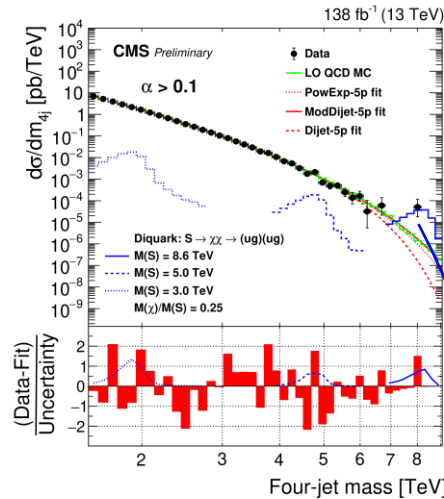
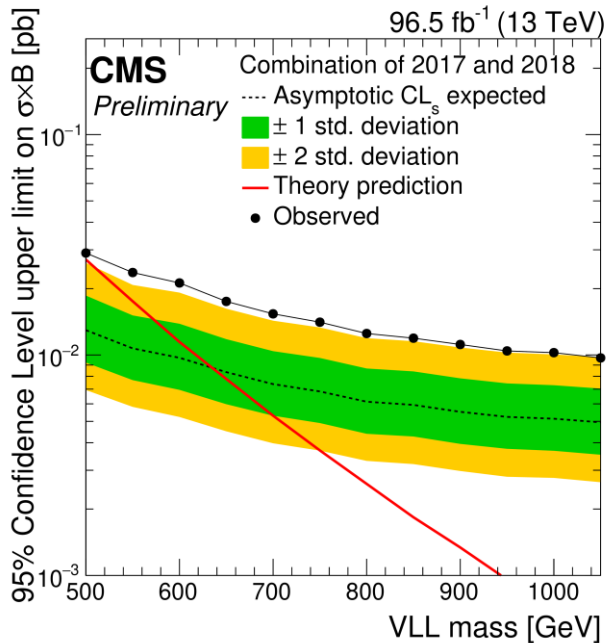
Pairs of dijets

EXO-21-010

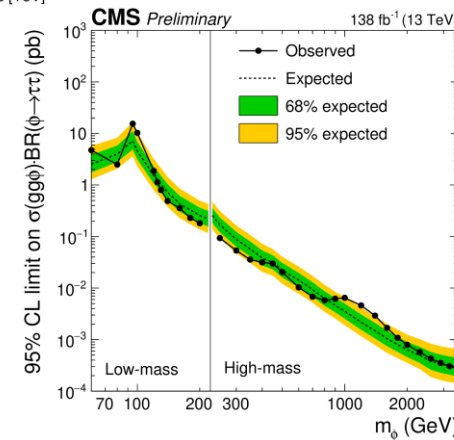
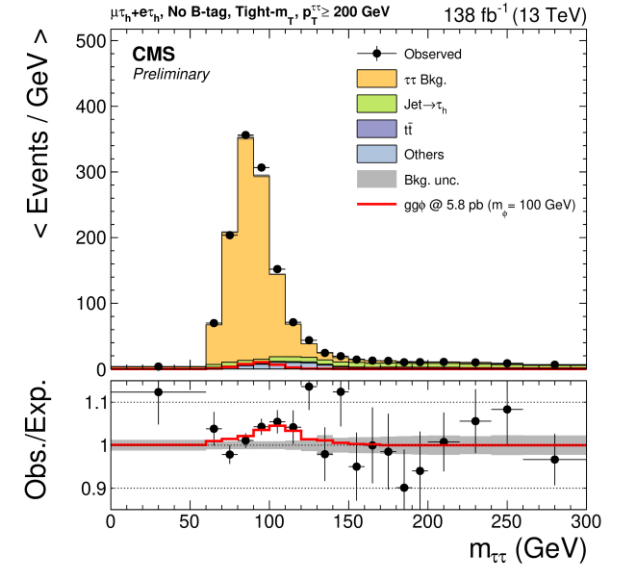
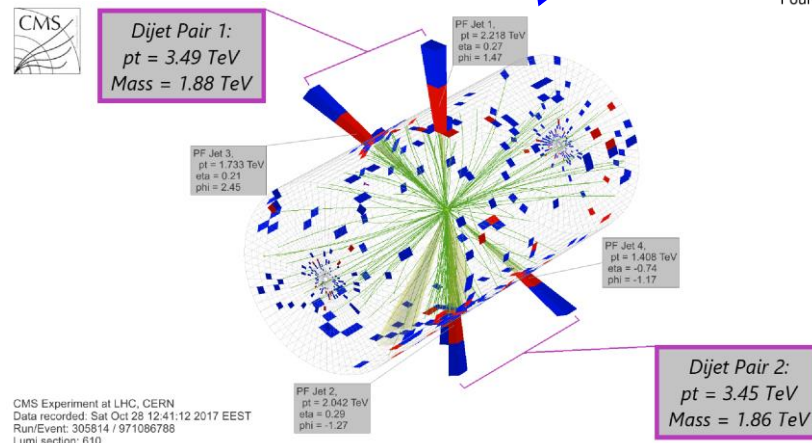
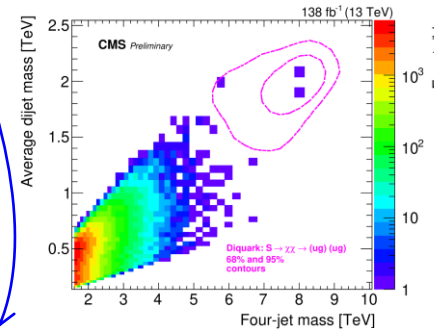
Higgs-like decay to $\tau\tau$

HIG-21-001

- Targeting pair-produced VLLs in final states with ≥ 3 b jets and up to 2 tau leptons
- In the context of 4321 model, UV-complete and relevant to describe flavor anomalies
- Mild excess at seen in 1τ and 2τ in both 2017 and 2018, combined global 2.8σ



- Search for resonant and non-resonant pairs of dijets
- Excess at 8 TeV with local (global) sig of 3.9σ (1.6σ)



- Spin-0 decaying to tau pairs in the context of extra Higgs (e.g. MSSM) and vector lepto-quarks
- In the Higgs-like search, two excess with local 3σ observed near 100 and 1000 GeV

Several enticing excesses to watch in Run 3!

More Searches for New Particles

SUSY search in 1L

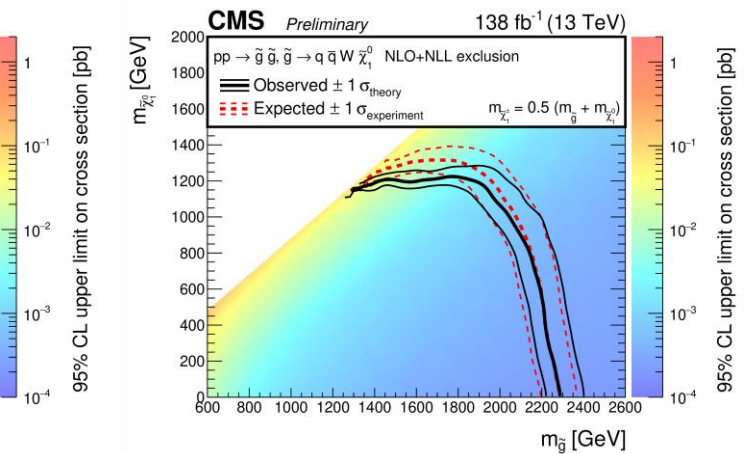
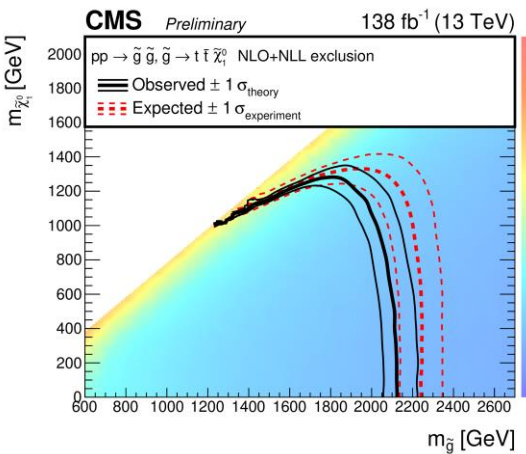
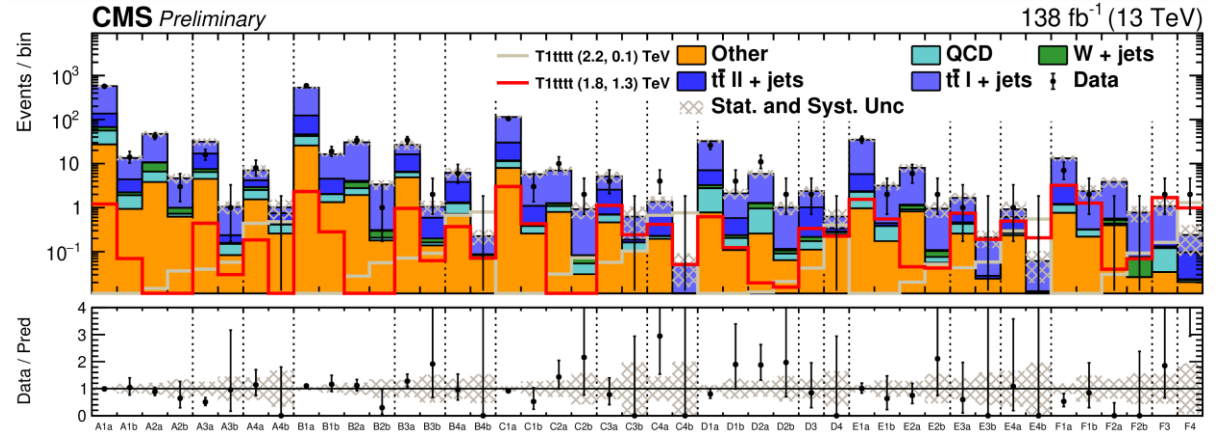
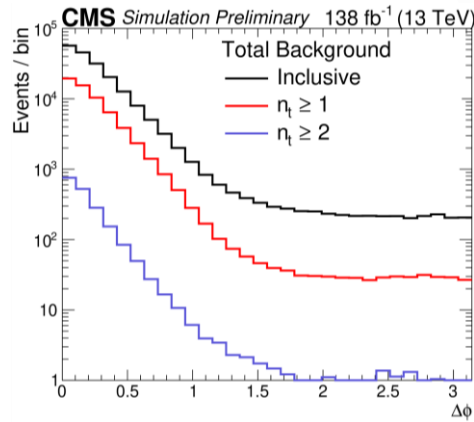
SUS-21-007



- Searching for gluinos in single leptons using angular correlations between lepton and W

$$\Delta\phi = \angle(\vec{p}_T^l, \vec{p}_T^W)$$

- Strong suppression of $t\bar{t}$ for back-to-back lep + W, where signal is ~flat
- Search separately in regions with or without b jets

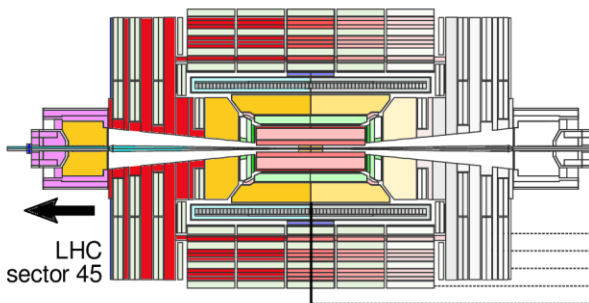


Summary of other recent (Moriond+) searches

- [EXO-21-003](#) Search for VBF production of same-sign muons through Majorana neutrinos or the Weinberg operator
- [EXO-20-006](#) Search for heavy neutrino and Z prime in events with two same flavor leptons and at least two jets
- [EXO-21-010](#) Search for paired dijet resonances
- [EXO-20-011](#) Search for heavy composite Majorana neutrino
- [B2G-21-001](#) Nonresonant HH to 4b at high invariant HH mass
- [B2G-20-009](#) Multi-dimensional search for new heavy resonances decaying to boosted WW, WZ, ZZ, WH or ZH
- [B2G-22-003](#) Nonresonant HH to 4b at high invariant HH mass (ggF+VBF combination)
- [HIG-21-010](#) Search for Charged Higgs in WH decays ($H^{\pm} \rightarrow W^{\pm} H$)
- [HIG-21-001](#) MSSM H/A \rightarrow tau tau search
- [HIG-21-016](#) Search for exotic Higgs boson decays $H \rightarrow AA \rightarrow 4\gamma \rightarrow AA \rightarrow 4\gamma$ with events containing two merged photons

Physics with the Precision Proton Spectrometer

CMS central detector

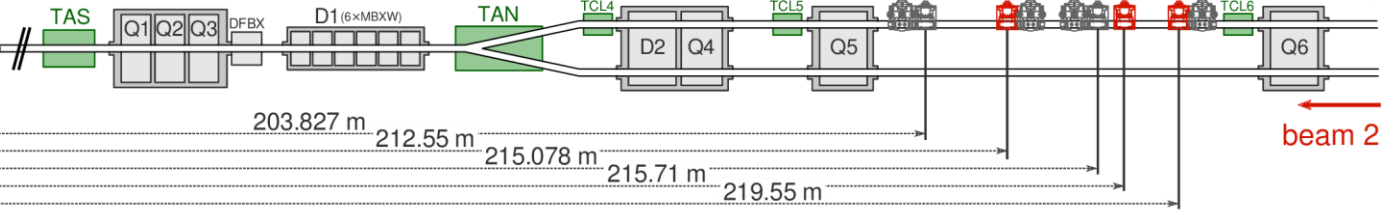


(not to scale)

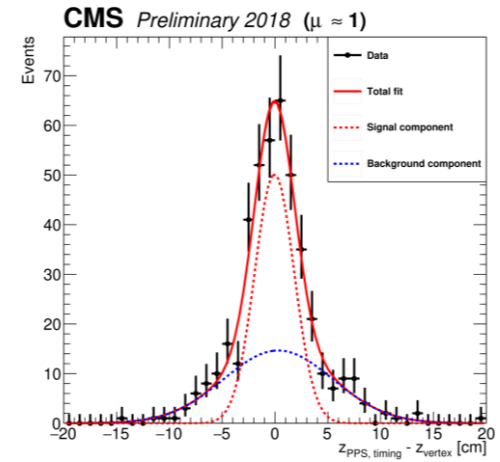
PRO-21-001

LHC sector 56

Roman Pots



CMS/TOTEM-PPS (CT-PPS) collected $\sim 100 \text{ fb}^{-1}$ in Run 2



$t\bar{t}$ production

TOP-21-007
Physics Briefing

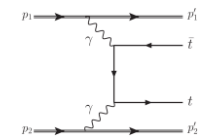
$\gamma\gamma \rightarrow WW, ZZ$

SMP-21-014

New particles

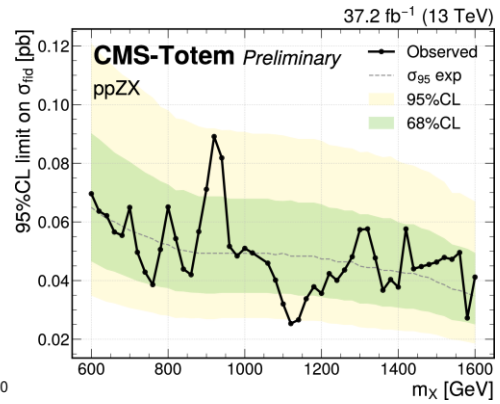
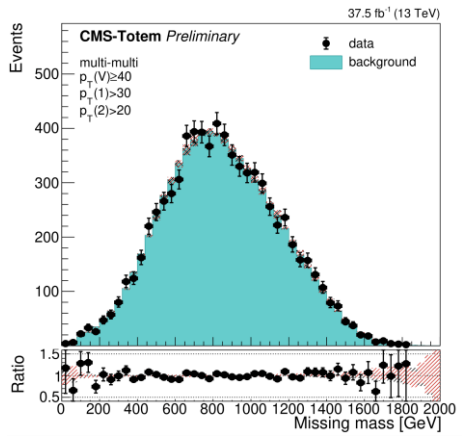
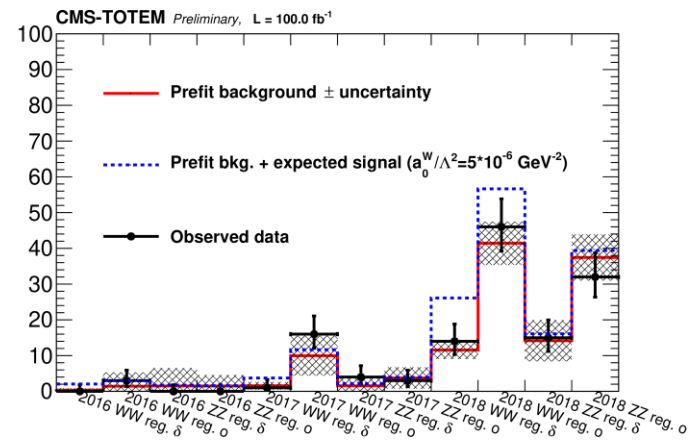
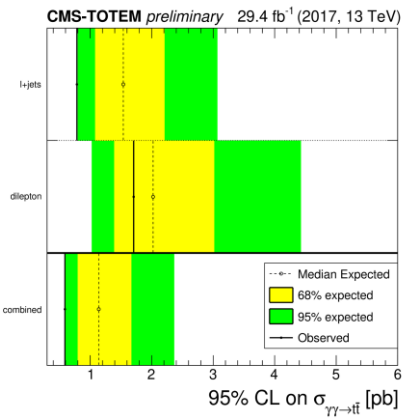
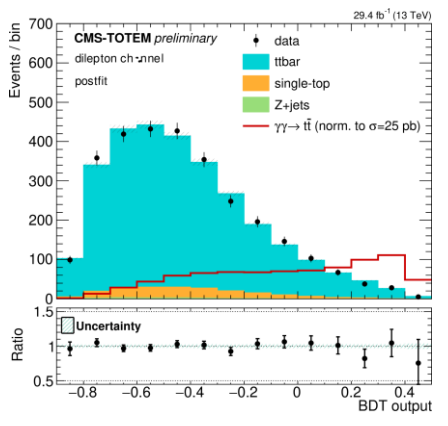
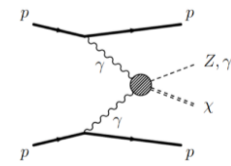
EXO-19-009

Searching for central-exclusive $t\bar{t}$ from $\gamma\gamma$ and pomeron exchange



Exclusive di-bosons decaying to boosted (merged) jets, searching for anomalous couplings

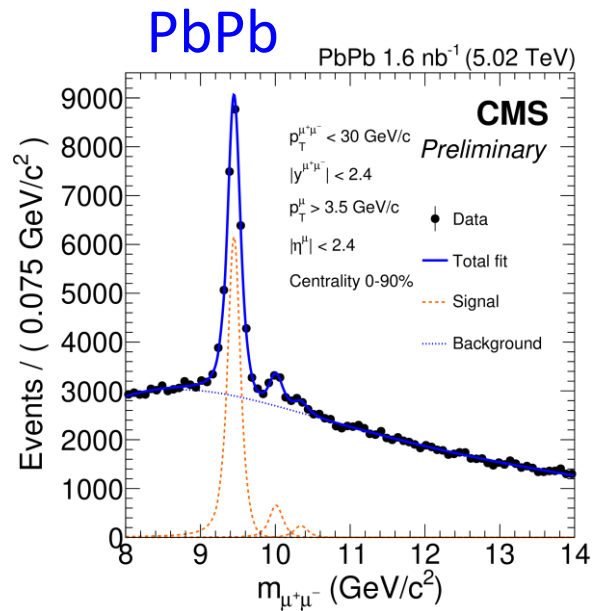
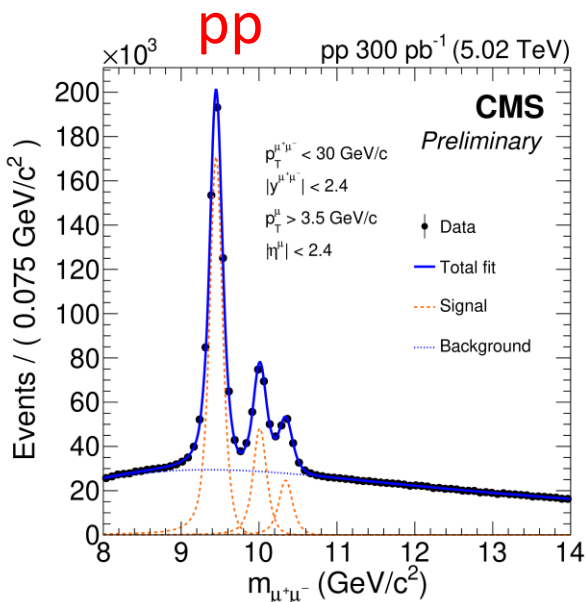
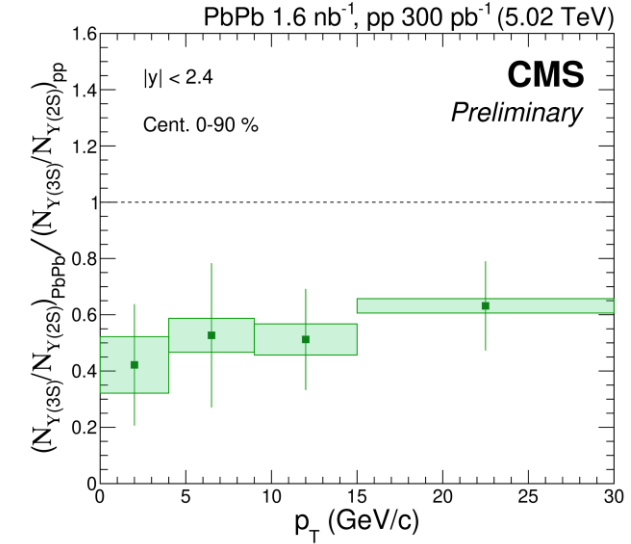
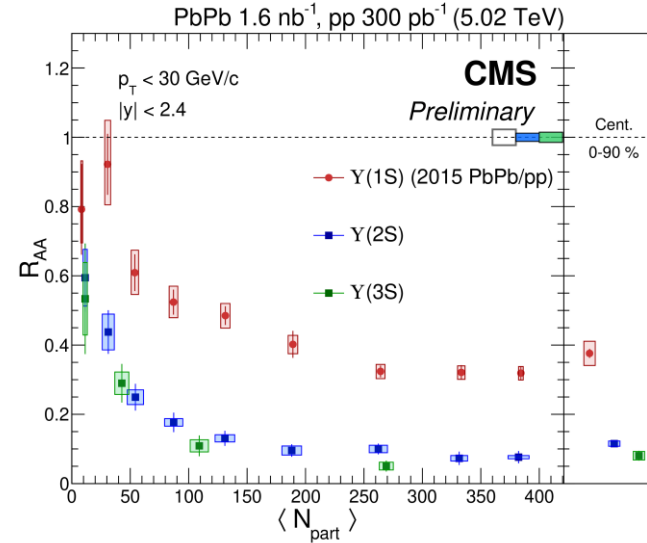
Searching for new particles produced exclusively in association with Z or γ



Observation of $Y(3S)$ in PbPb Collisions

HIN-21-007

- Production of $Y(2S)$ and $Y(3S)$ studied in PbPb
- First observation of $Y(3S)$ in heavy ion collisions!
- Suppression of $Y(3S)$ stronger than $Y(2S)$, following the trend set by $2S$ vs. $1S$



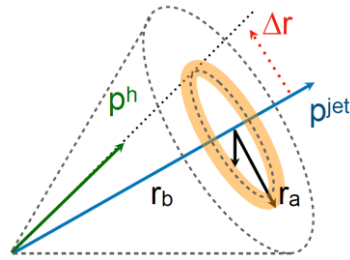
- Nuclear modification factors (R_{AA}) and relative suppression of $Y(3S)/Y(2S)$ measured as functions of $\langle N_{part} \rangle$ and p_T
- Relative suppression of $Y(3S)$ is roughly independent of p_T (right plot)
- Additional constraints for theoretical models!

More Heavy Ion Physics

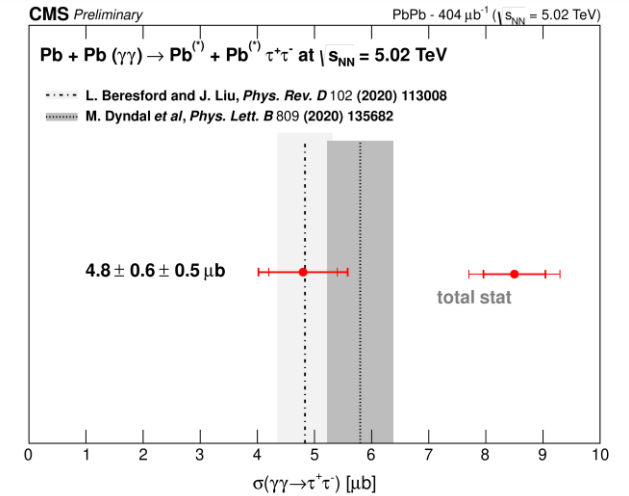
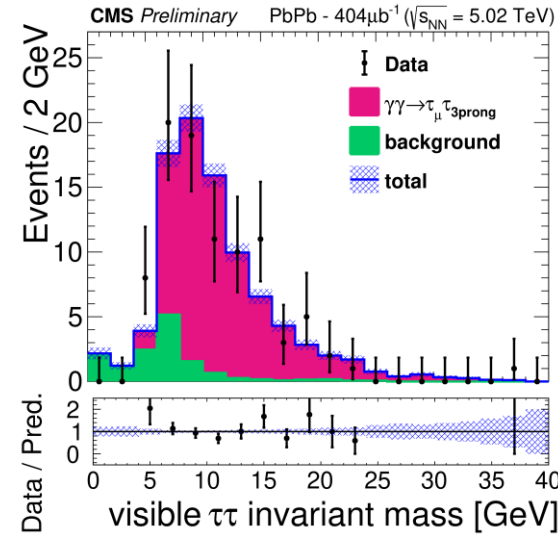
Bottom-jet shapes in pp vs. PbPb

HIN-20-003

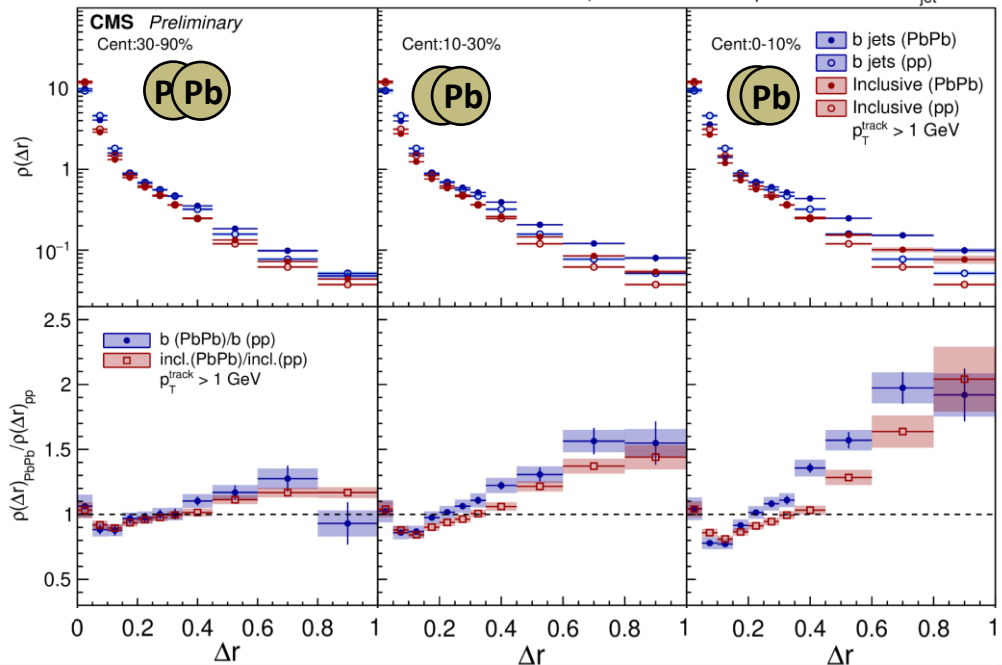
- Study of jet shapes for b vs. all and PbPb vs. pp
- Ratio $\rho(\Delta r)_{\text{PbPb}}/\rho(\Delta r)_{\text{pp}}$ measures enhancement/depletion of constituent hadrons vs. Δr
- b jets in PbPb broader than in pp



Observation of τ pairs in ultraperipheral PbPb



$\sqrt{s_{NN}} = 5.02 \text{ TeV}$, PbPb 1.7 nb^{-1} , pp 27.4 pb^{-1} , anti- k_T jet ($R = 0.4$): $p_T^{\text{jet}} > 120 \text{ GeV}$, $|\eta_{\text{jet}}| < 1.6$



Summary of CMS results at Quark Matter 2022

[HIN-20-003](#) Measurement of b jet shapes in PbPb collisions

[HIN-21-002](#) Azimuthal anisotropy of jet quenching in dijet events in PbPb

[HIN-21-008](#) Measurements of the azimuthal anisotropy of charmonia in PbPb collisions

[HIN-21-007](#) Observation of the $Y(3S)$ meson and sequential suppression of Y states in PbPb collisions

[HIN-21-012](#) Correlations between multiparticle cumulants and mean transverse momentum in small collision systems

[HIN-21-011](#) Measurement of two-particle Bose-Einstein momentum correlations and their Lévy parameters

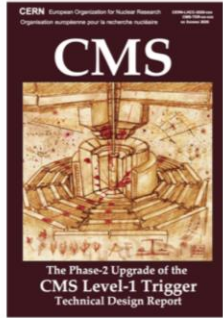
[HIN-21-001](#) Azimuthal anisotropy of $Y(1S)$ mesons in pPb collisions

[HIN-21-003](#) Azimuthal anisotropy of nonprompt D_0 mesons in PbPb collisions

[HIN-21-010](#) Probing hydrodynamics and the moments of the elliptic flow distribution using higher-order cumulants

[HIN-21-009](#) Observation of τ lepton pair production in ultraperipheral nucleus-nucleus collisions

Looking Forward: CMS Phase-II Upgrades

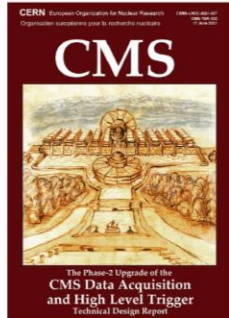


L1-Trigger HLT/DAQ

<https://cds.cern.ch/record/2714892>

<https://cds.cern.ch/record/2759072>

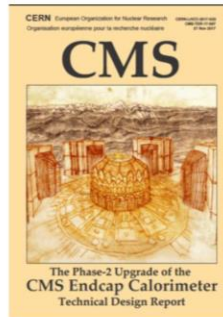
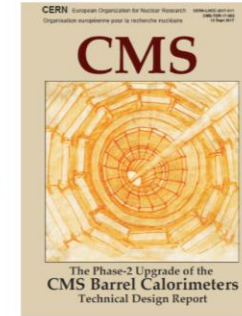
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting



Barrel Calorimeters

<https://cds.cern.ch/record/2283187>

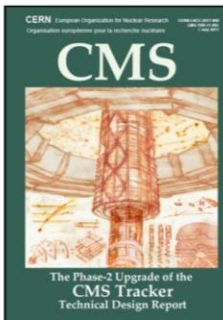
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Calorimeter Endcap

<https://cds.cern.ch/record/2293646>

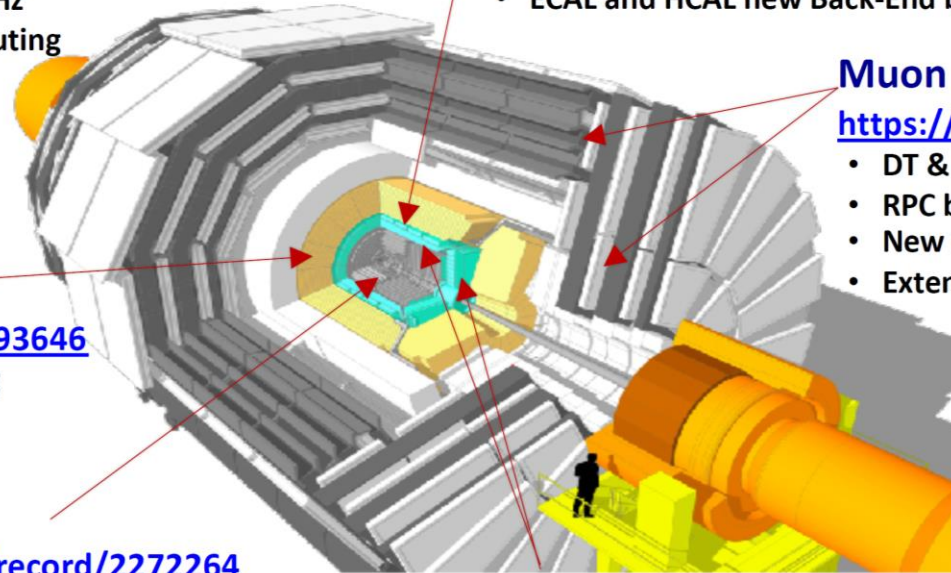
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Tracker <https://cds.cern.ch/record/2272264>

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$

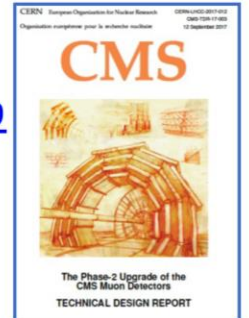
See talk by Gabriella Pasztor in the Friday Upgrade Plenary



Muon systems

<https://cds.cern.ch/record/2283189>

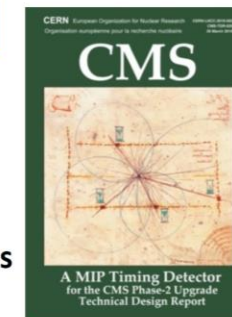
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \approx 3$



Beam Radiation Instr. and Luminosity

<http://cds.cern.ch/record/2759074>

- Bunch-by-bunch luminosity measurement: 1% offline, 2% online

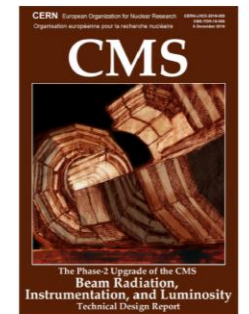


MIP Timing Detector

<https://cds.cern.ch/record/2667167>

Precision timing with:

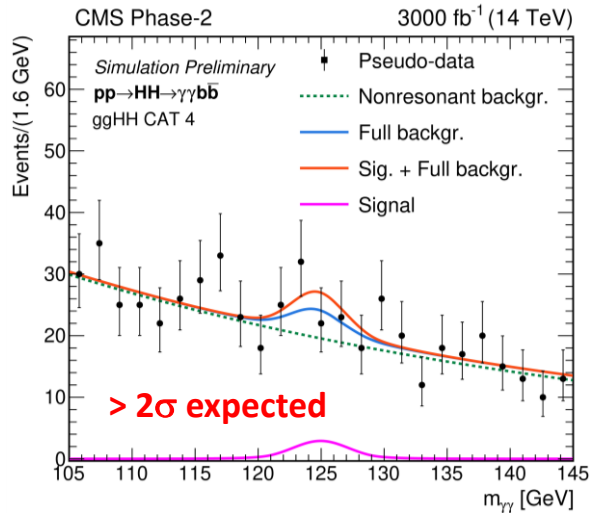
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



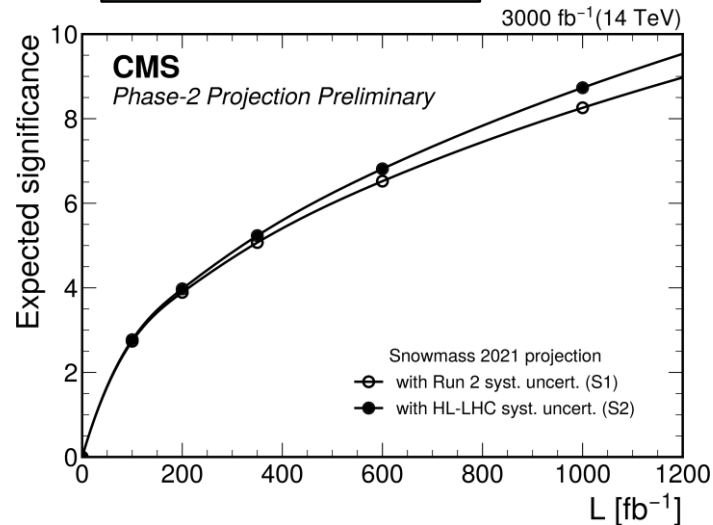
Future Performance @ HL-LHC

ATLAS + CMS* released a joint [White Paper](#) for Snowmass with updated projections for physics performance at HL-LHC

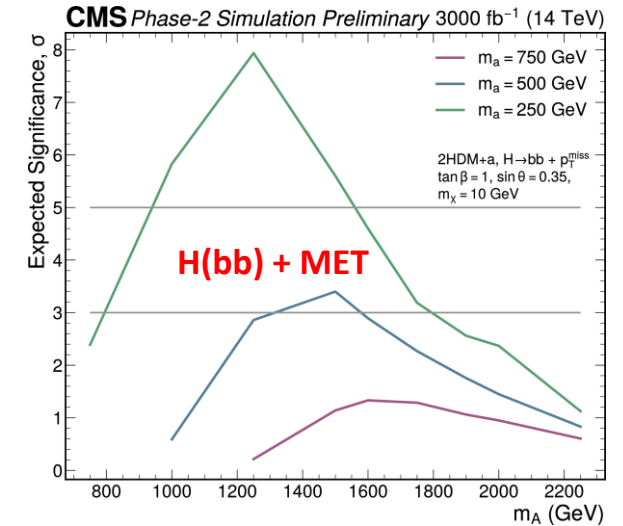
Search for $HH \rightarrow \gamma\gamma bb$



Observing $H \rightarrow \mu\mu$



Search for Dark Matter



*CMS Contributions:

- [FTR-21-001](#) Prospects for the measurement of vector boson scattering production in leptonic $W^\pm W^\pm$ and WZ diboson events at $\sqrt{s} = 14$ TeV at the High-Luminosity LHC
- [FTR-21-002](#) Prospects for the measurement of $tt^{\bar{}}H$ production in the opposite-sign dilepton channel at $\sqrt{s} = 14$ TeV at the High-Luminosity LHC
- [FTR-21-003](#) Prospects for HH measurements in the $WW\gamma\gamma$ and $\tau\tau\gamma\gamma$ final states in proton-proton collisions at $\sqrt{s} = 14$ TeV at the High Luminosity-LHC
- [FTR-21-004](#) Prospects for non-resonant Higgs boson pair production measurement in $b\bar{b}\gamma\gamma$ final states in proton-proton collisions at $\sqrt{s} = 14$ TeV at the High-Luminosity LHC
- [FTR-21-005](#) Sensitivity projections for a search for new phenomena at high dilepton mass for the LHC Run 3 and the HL-LHC
- [FTR-21-006](#) Prospects for the precise measurement of the Higgs boson properties in the $H \rightarrow \mu\mu$ decay channel at the HL-LHC
- [FTR-21-007](#) Projection of the Higgs boson mass and on-shell width measurements in $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel at the HL-LHC
- [FTR-21-008](#) A projection of the precision of the Higgs boson mass measurement in the diphoton decay channel at the High Luminosity LHC
- [FTR-21-009](#) Search for rare Higgs boson decays with mesons at HL-LHC
- [FTR-21-010](#) Search for the nonresonant $tt^{\bar{}}HH$ production in the semileptonic decay of the top pair and the Higgs pair decay into b quarks at the HL-LHC
- [FTR-21-011](#) Search for leptophobic Z' resonances decaying to charginos in the dilepton plus missing transverse momentum final state at the HL-LHC
- [FTR-22-003](#) Seesaw Model Searches Using Multilepton Final States at the HL-LHC
- [FTR-22-005](#) Search for dark matter in final states with a Higgs boson decaying to a pair of b -jets and missing transverse momentum at the HL-LHC
- [FTR-22-006](#) Prospects for a Search for Doubly Charged Higgs Bosons at the HL-LHC

Summary

- We thank CERN for their strong support during the pandemic, and the LHC accelerator team for their outstanding performance throughout Run 2, as well as their tireless efforts during LS2 to upgrade the machine and return at a new record energy!
- CMS is back online with improved detector, DAQ, trigger, computing, software, and physics capability. We await the imminent return of colliding beams with great eagerness.
- CMS continues to produce physics results covering the full range of topics from SM precision measurements to creative new searches for particles beyond the Standard Model
- We thank (again) all CMS members for their perseverance during the pandemic, and their successful completion of the LS2 upgrade work and the ongoing recommissioning campaign. We look forward to beautiful and physics results from Run 3!