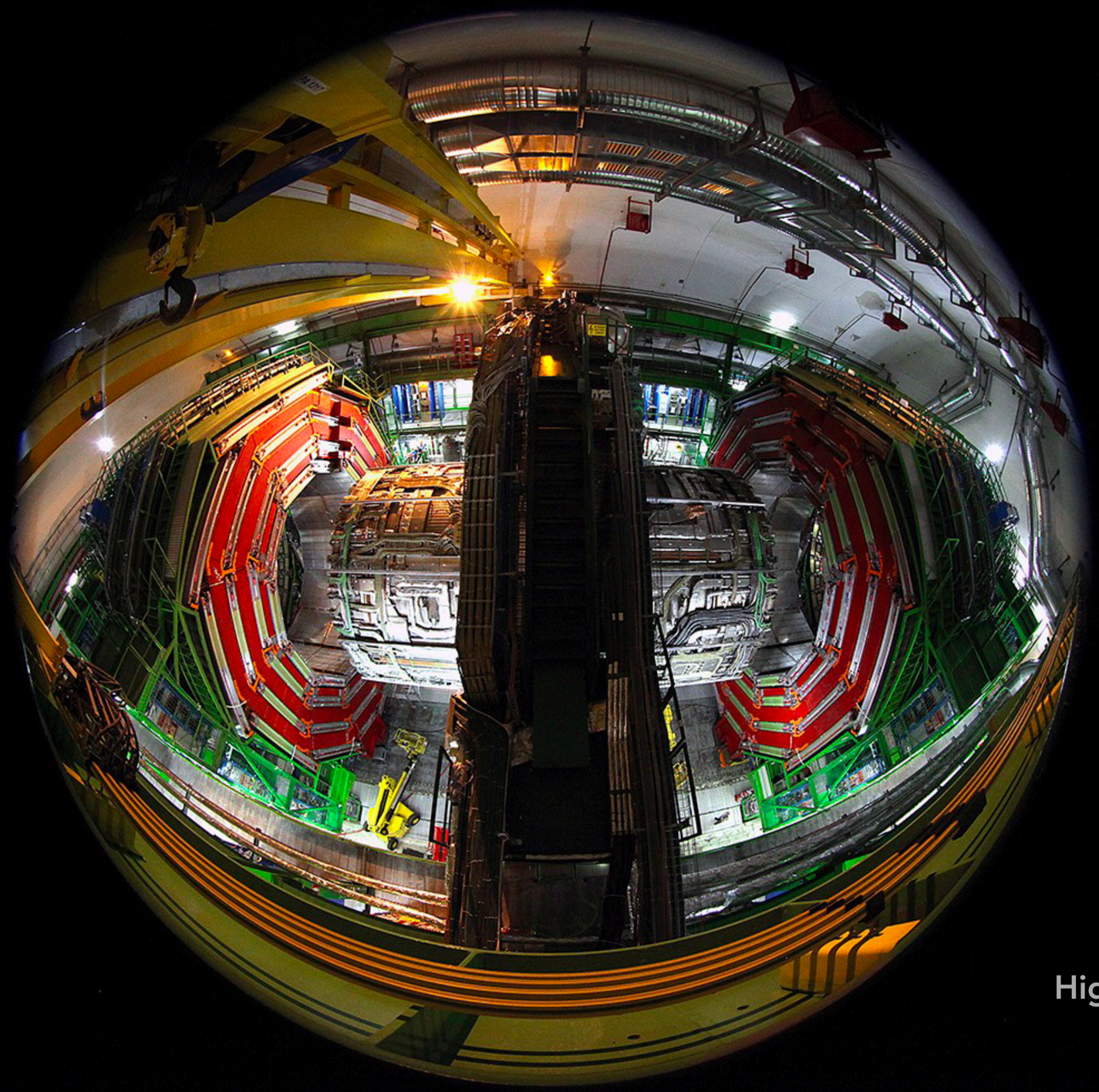


Highlights
and perspectives
from the
CMS
experiment

Gautier Hamel de Monchenault

HEP 2021 — Conference on
Recent Developments in
High Energy Physics and Cosmology
Thessaloniki, Greece. ONLINE
Wednesday June 16, 2021

Irfu
CEA - Saclay

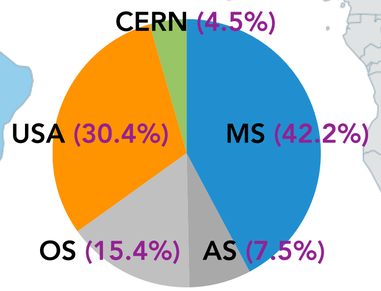
The CMS Collaboration

(May 2021)

>5300 Members

2105 Authors

241 Institutes
(including 23 Associated and 8 Cooperating)
from
54 Countries



MS: **Italy** (12%), **Germany** (8%), UK (3%), France (3%), Switzerland (3%), Spain (3%), Belgium (3%) … **Greece (1.5%)** …
AS: India (3%), Turkey (2%) …
OS: **Russia** (5%), Korea (3%), China (2%), …

Greece: 63 members, **32 authors**

- **Athens** (33/**12**) L1-trigger, PPD, …
- **Athens/NTUA** (9/**5**) DAQ, HGCAL, …
- **Demokritos** (9/**5**) Tracker, …
- **Ioànnina** (12/**10**) L1-trigger, …

LS2 Activities

LS2 = Long Shutdown 2 since 2019
Collisions to return mid 2022

Strip tracker
- kept cold to avoid reverse annealing
- currently warm during beam pipe bake-out

HCAL
- completion of Phase-I upgrades

Pixel detector
- replace first barrel layer
- replace all DCDC converters

Magnet
- at room temperature since mid 2020
- maintenance work: free wheel thyristor, cryo-cooling, power, pumps, etc.

Beam pipe
- new version Phase-II design

Muon system
- installation of GE1/1 chambers
- upgrade of CSC FEE to sustain HL-LHC trigger rates
- shielding against neutron background

CT-PPS
- upgrade of RP and moving system

BRIL
- BCM/PLT refit
- new T2 tracker

Civil engineering at P5
- prepare for Phase-II assembly and logistics

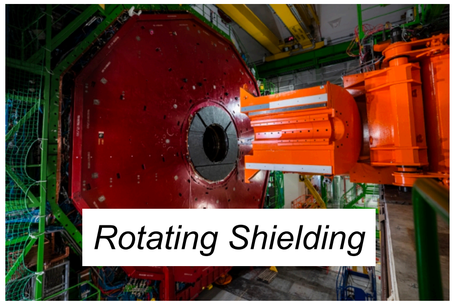
Work on HCAL Barrel (SiPM readout) completed in Oct. 2019

Muon critical path completed in Dec. 2020

Beam-pipe installation and bake-out completed in May 2021

Remaining activities:
- pixel detector installation (starting June 22)
- yoke closing (starting July 19)
- magnet restart (3.8T) and tests
- comics runs at ~4T (CRAFT, 24/7)

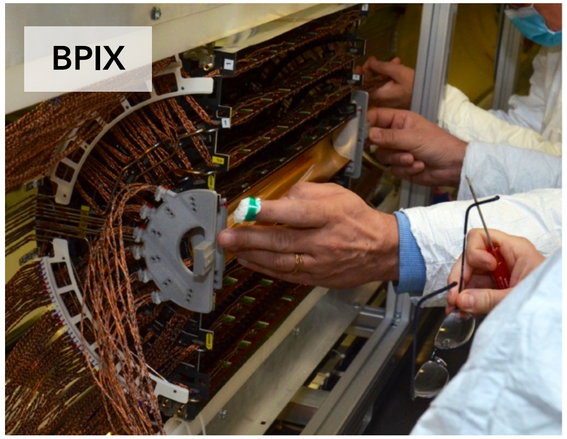
After Pilot Beam Test
- Phase-II muon demonstrators
- new forward shielding



Some Highlights of LS2

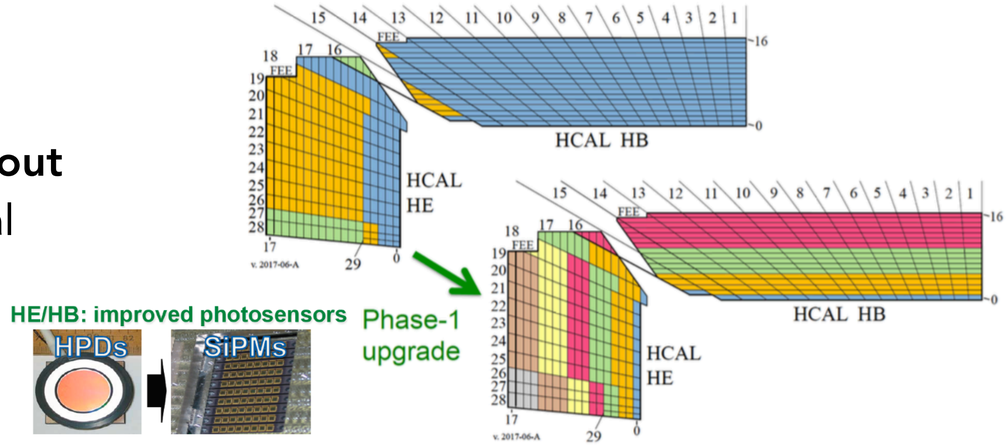
New GEM detector GE1/1
- first Phase-II detector to be integrated in CMS!

New CMS beam pipe for Phase-II
- installation complete, fully aligned and leak tested
- bake-out just completed



Fully-refurbished pixel detector
- new BPIX layer 1: new chip with lower thresholds and better radiation tolerance
- replacement of DCDC converters

New HCAL SiPM readout
- improved longitudinal segmentation
- improved photon detection efficiency

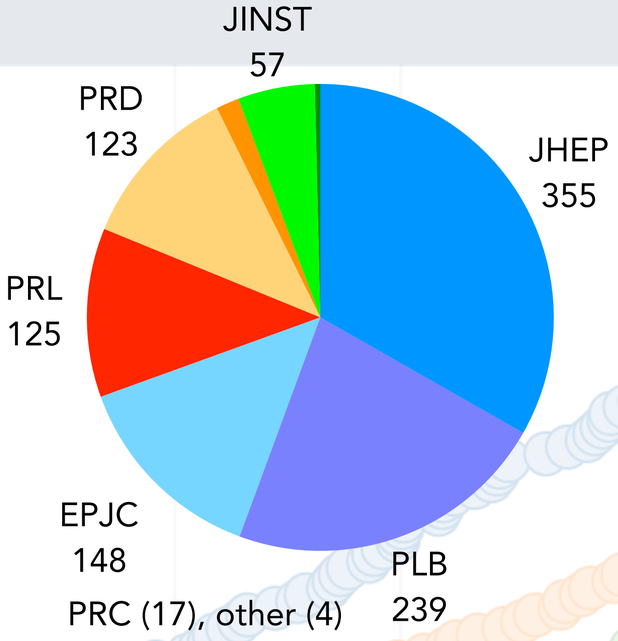


CMS fully on track for the Pilot Beam Test (Oct. 21) and for the start of Run-3 (Feb. 22)

CMS Publications

Phys. Briefing

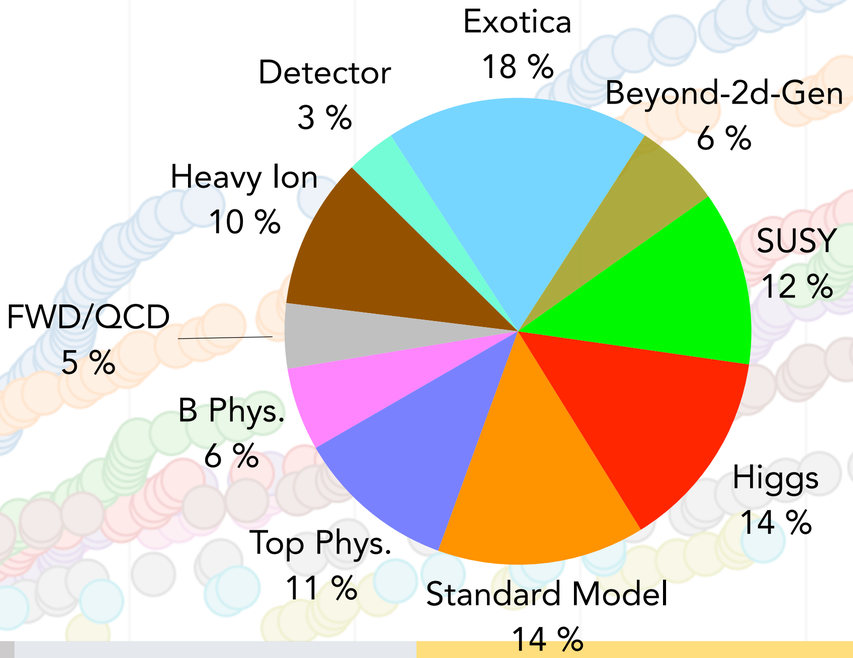
On Nov. 24, 2020 CMS announced the **publication of its 1000th paper** in a peer-reviewed journal



As of June 16, 2021

1068 CMS papers
- **1040** published

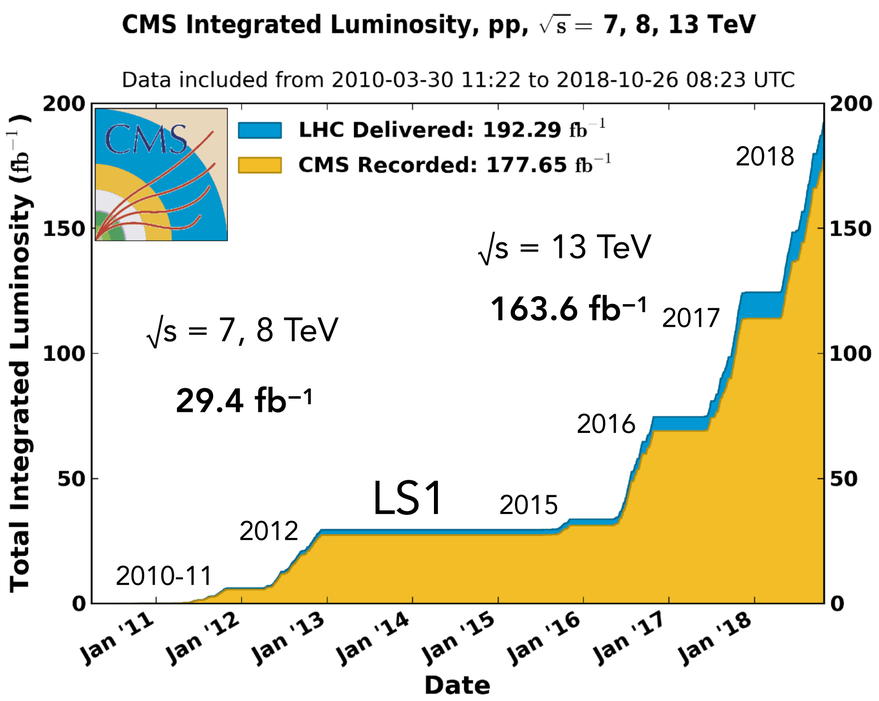
1043 papers based on **collision data**
- **1015** published
- 574 based on Run-1 data
- 469 based on Run-2 data



CMS titles
- 527 "Search for"
- 39 "Observation"
- 18 "Evidence"
- 308 "Measurement"

CMS with friends
- **ATLAS**: 5 (4 JHEP, 1 PRL)
- **LHCb**: 1 (Nature)
- **Totem**: 3 (1 JHEP, 2 EPJC)

CMS pp Data at LHC Run-2

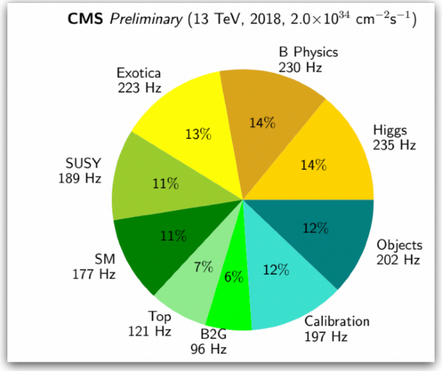


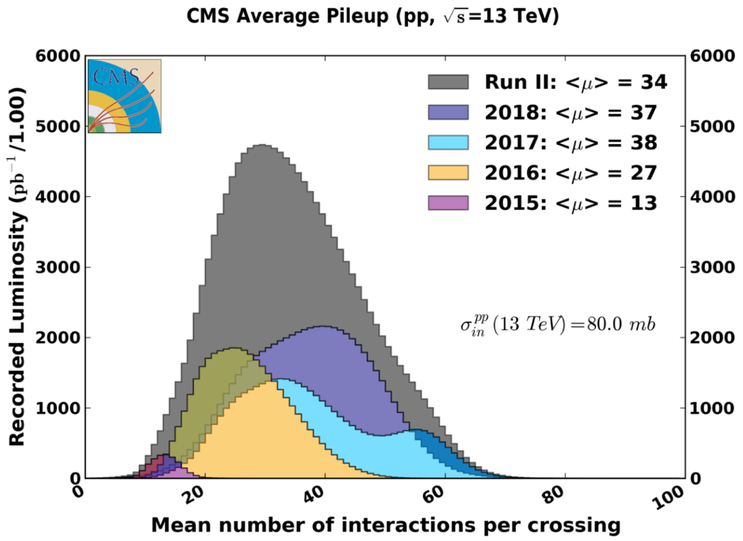
Excellent performance of the LHC in Run-2

- max LHC luminosity (2018):
  $\mathscr{L}_{max} = 2.14 \times 10^{34}$ cm^{-2}s^{-1}
  (factor of 2 higher than designed 10^{34} cm^{-2}s^{-1})

CMS Dataset Run-2

- 2016-2018: **137 fb^{-1}** of pp data "good for physics"
- data-taking efficiency > 92% (2018: 94%)
- number of pp interactions per beam crossing (PU): <μ> = 34





CMS Triggers for Run-2 (1.6 kHz)

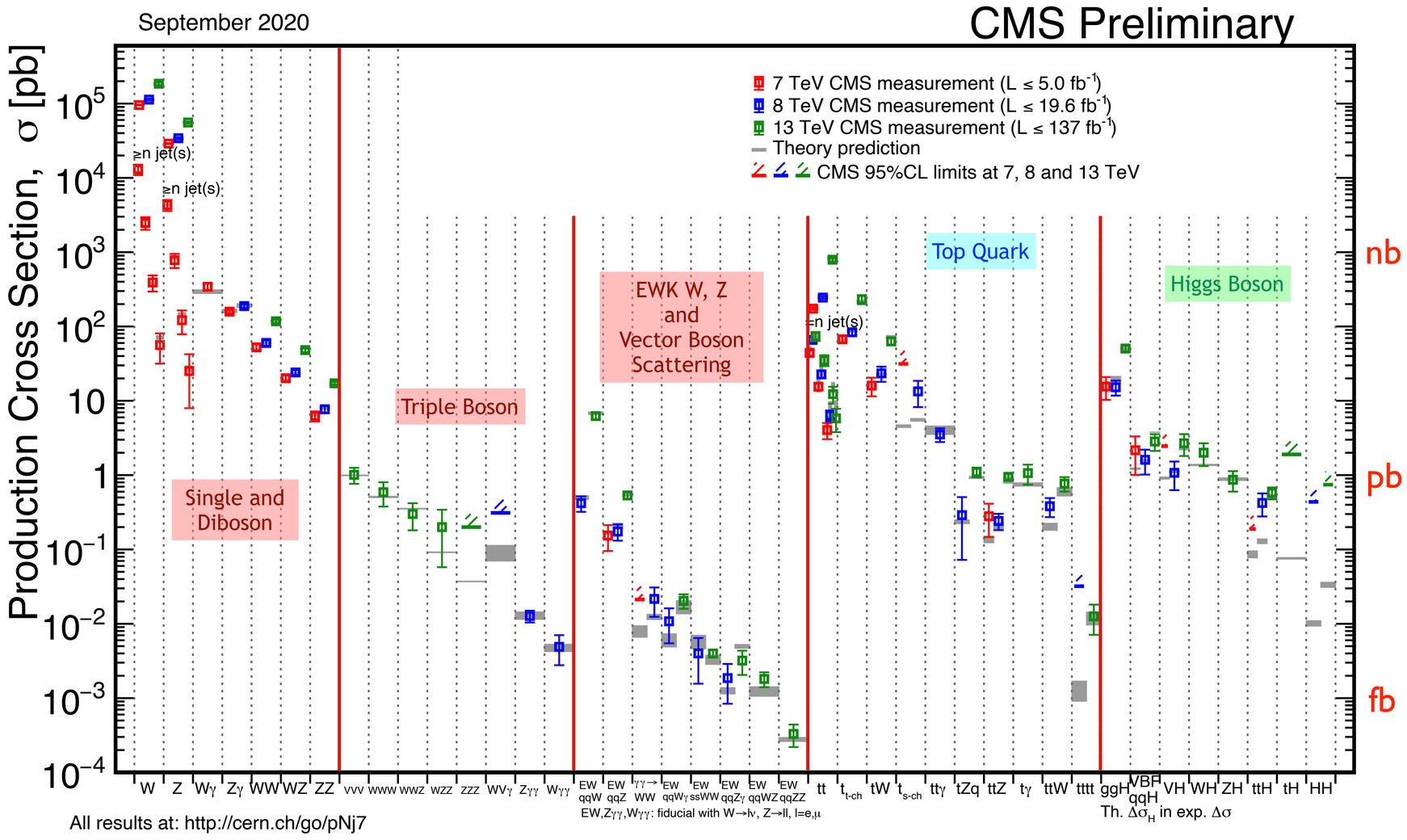
- Standard triggers (leptons, jets, MET)
- **B-parking triggers** (up to 5 kHz)
  10B events enriched in un-biased B decays
- Scouting triggers
  reduced events with physics objects

Luminosity measurements: 1.2% in 2016, overall 1.6% for Run-2

CMS-LUM-17-003
Submitted to EPJC

Phys. Briefing

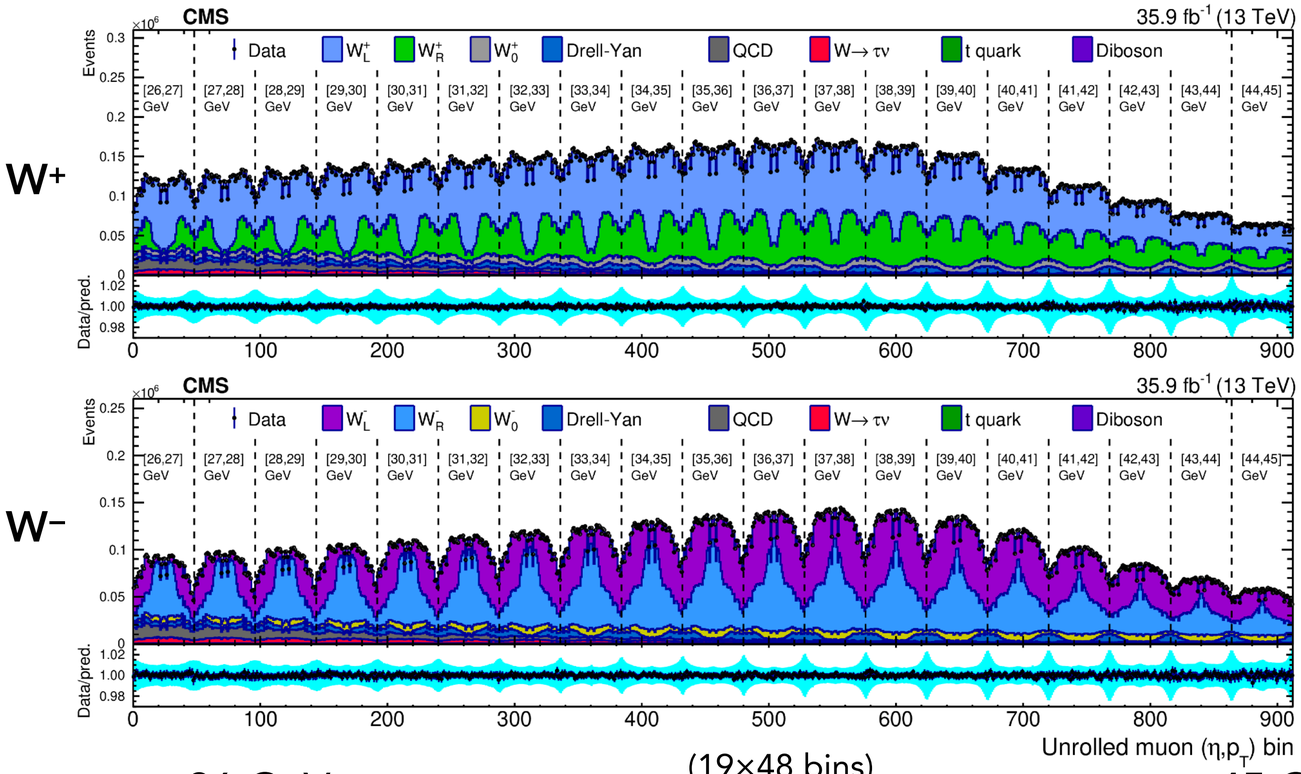
SM Production Cross Sections



W Helicity Measurements

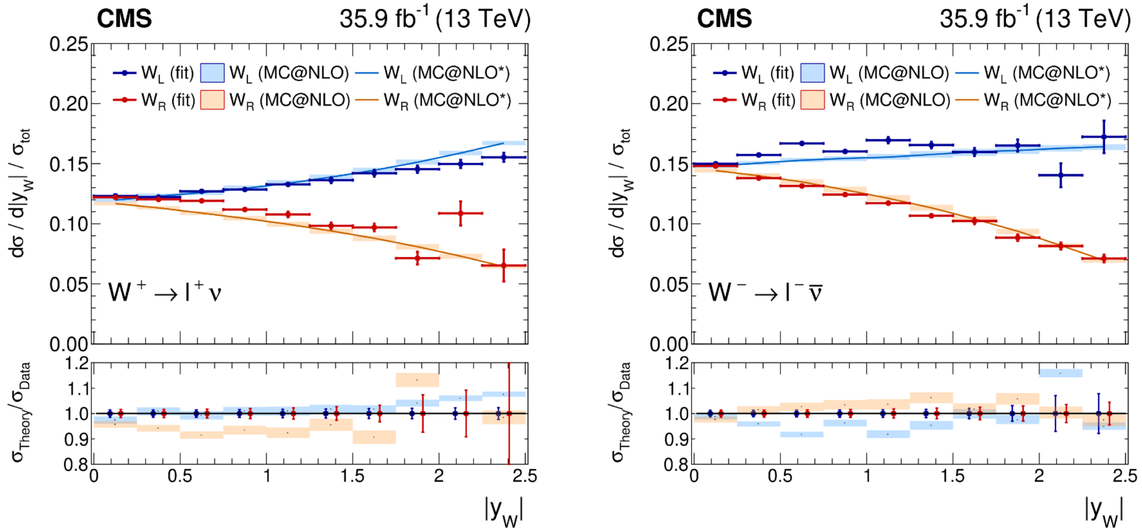
Run-2 2016, 35.9 fb^{-1}

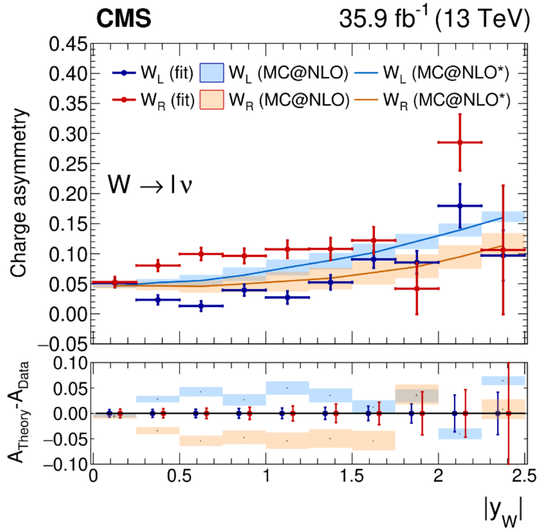
Double-differential cross-sections in p_T^ℓ and η^ℓ (ℓ = e, μ) for W$^+$ and W$^-$



p_T^μ = 26 GeV → 45 GeV (19×48 bins)

$\eta \in [-2.4, 2.4]$





- constraints on PDFs
- milestone towards the W mass measurement

CMS-SMP-18-012
PRD 102 (2020) 092012

Template fit to extract **differential cross-sections** and **charge asymmetries** for the two **helicity states**

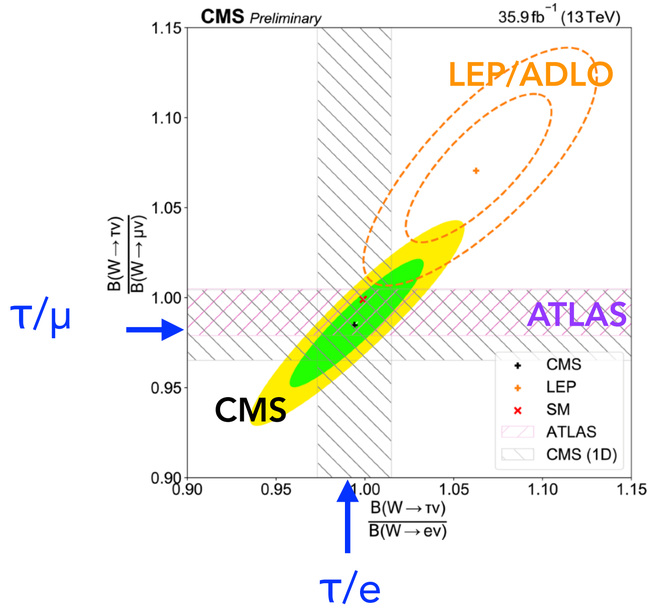
Test of τ/μ and τ/e Universality in W Decays

Using $t\bar{t}$ events in the dilepton channel, select relatively **unbiased samples** of **on-shell W bosons**

Trailing lepton p_T used to discriminate between prompt W → e/μ decays from W → τ → e/μ decays in ee, μμ, and eμ events

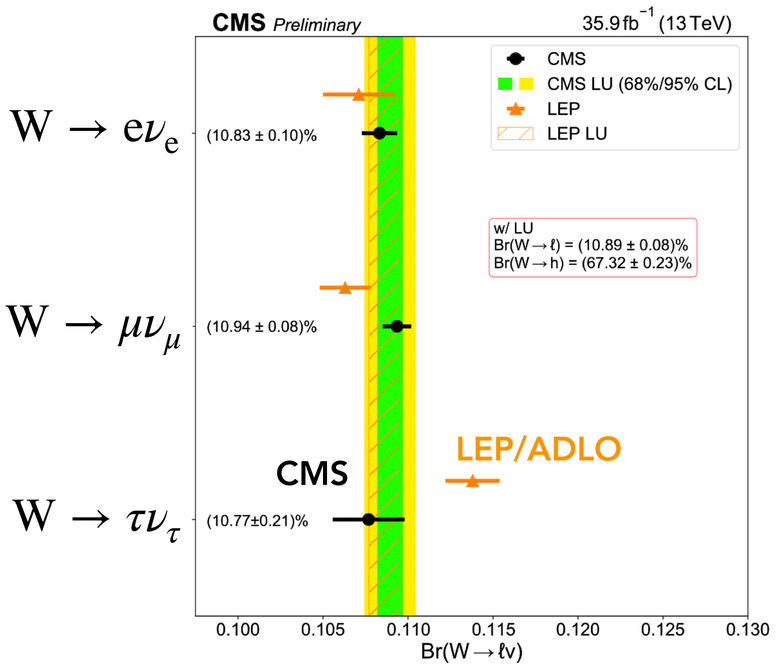
Run-2 2016, 35.9 fb^{-1}

CMS-PAS-SMP-18-011



result consistent with SM and with recent ATLAS (most-precise) τ/μ result

Branching fractions W → e, μ, τ



CMS LU result is consistent with and improves on LEP/ADLO result

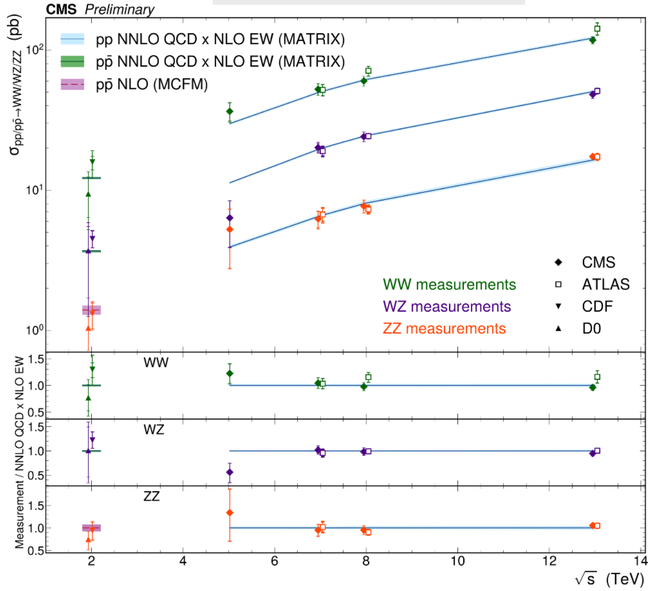
A long-standing LEP "tension" (>2.5σ) is **gone**

Diboson Production

Precision studies of **diboson production**

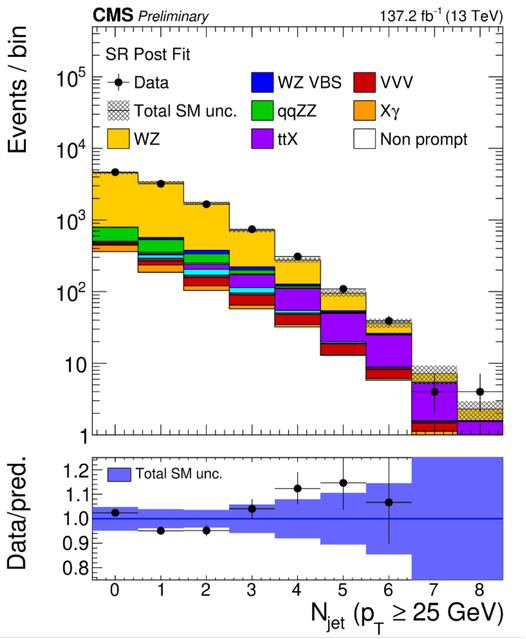
- abundant samples, well-controlled backgrounds
- 3-10% level measurements at $\sqrt{s}$ = 7, 8 and 13 TeV
- a new measurement at $\sqrt{s}$ = 5.02 TeV

CMS-PAS-SMP-20-012

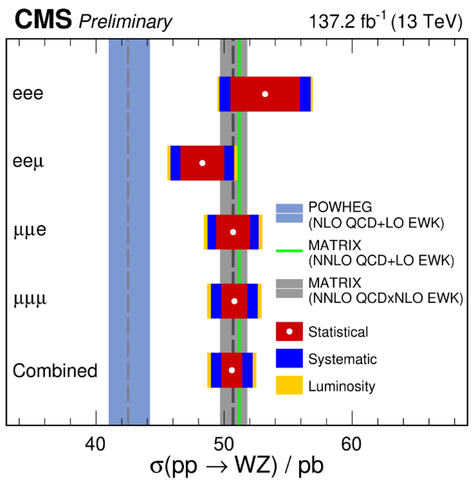


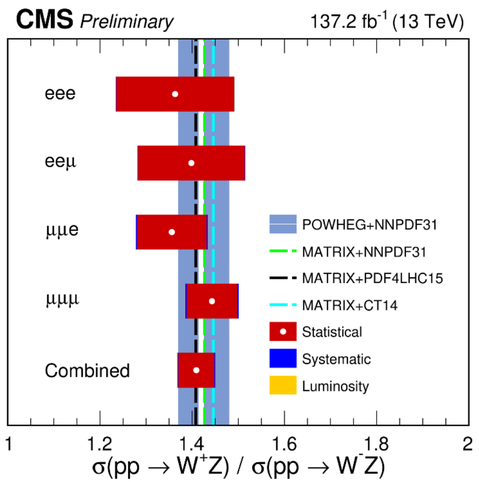
Luminosity uncertainty:
1.9% at $\sqrt{s}$ = 5.02 TeV (302 pb^{-1})

CMS-PAS-LUM-19-001



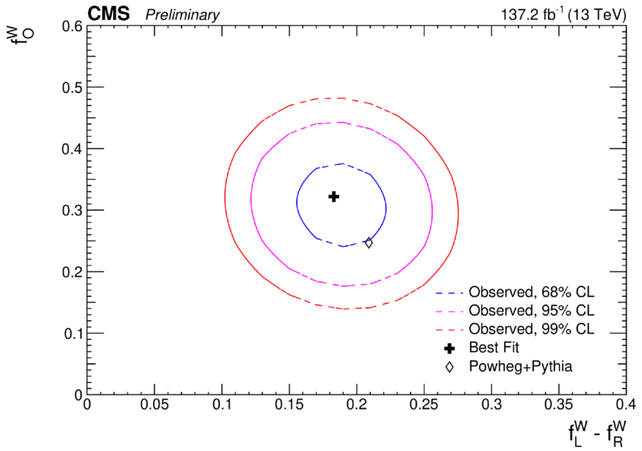
stringent limits on **anomalous triple gauge couplings** in terms of dim-6 EFT operators





Full Run-2, 137 fb^{-1}

CMS-PAS-SMP-20-014

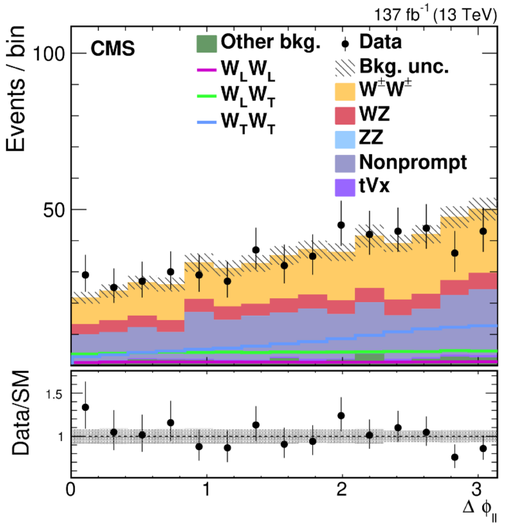


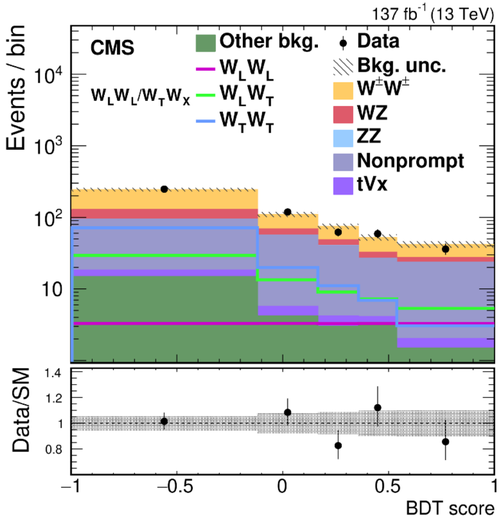
first observation of **longitudinally polarized W bosons** in WZ production

Vector Boson Scattering

Same-sign W pairs
with measurement of the polarisation

VBS signature: two jets with large rapidity separation and dijet mass





Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^\pm W_X^\pm$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^\pm W_T^\pm$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

Exploiting event kinetics, extract polarisation components

CMS-SMP-20-006
PLB 812 (2020) 136018

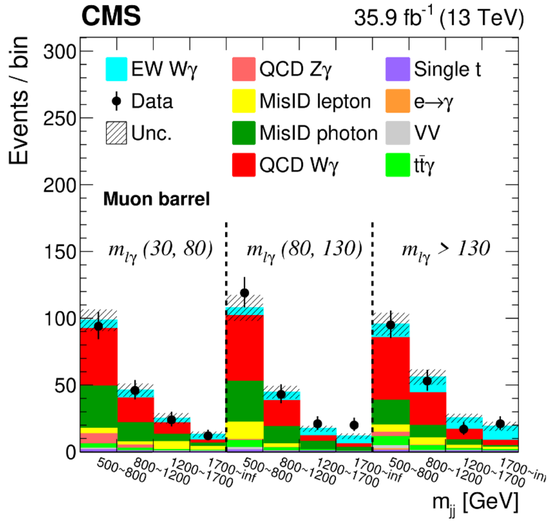
first hint the scattering of at least one W_L at the 2.3σ (3.1σ exp) level

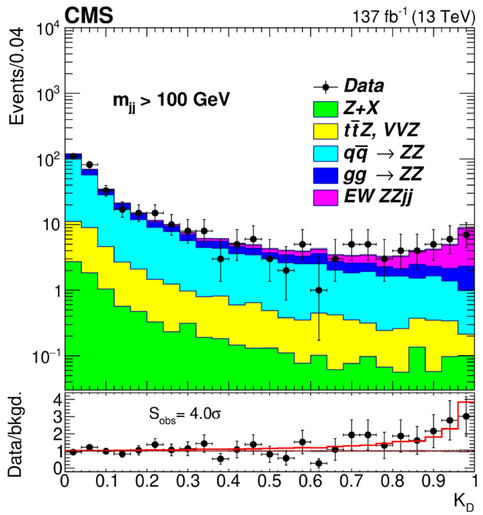
Full Run-2, 137 fb^{-1}

pp → Wγ jj

signal significance: 4.9σ (4.6σ exp)

CMS-SMP-19-008
PLB 811 (2020) 135988





pp → ZZ jj

signal significance: 4.0σ (3.5σ exp)

CMS-SMP-20-001
PLB 812 (2020) 135992

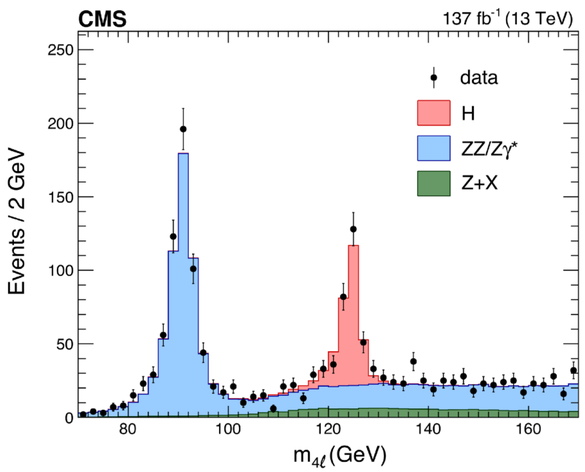
limits on **anomalous quartic gauge couplings** in terms of dim-8 EFT operators

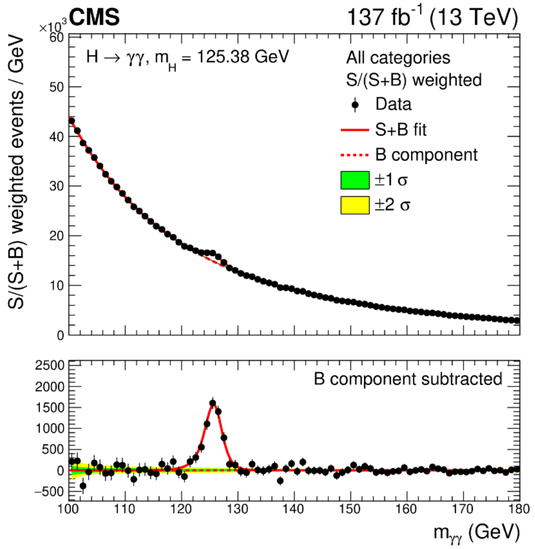
Fiducial cross section:

$$\sigma_{\mathrm{EW}}(\mathrm{pp} \to \mathrm{ZZjj} \to \ell\,\ell\,\ell'\ell'\,\mathrm{jj}) = 0.33^{+0.11}_{-0.10}\,(\mathrm{stat})^{+0.04}_{-0.03}\,(\mathrm{syst})\,\mathrm{fb}$$

SM: $0.28 \pm 0.02\,\mathrm{fb}$

Higgs Mass Measurements





H → ZZ → 4ℓ

$$m_{\mathrm{H}} = 125.26 \pm 0.21\,(\mathrm{total})\,\mathrm{GeV}$$

CMS-HIG-16-041
JHEP 11 (2017) 047

H → γγ

- using a refined calorimeter calibration

$$m_{\mathrm{H}} = 125.78 \pm 0.26\,(\mathrm{total})\,\mathrm{GeV}$$

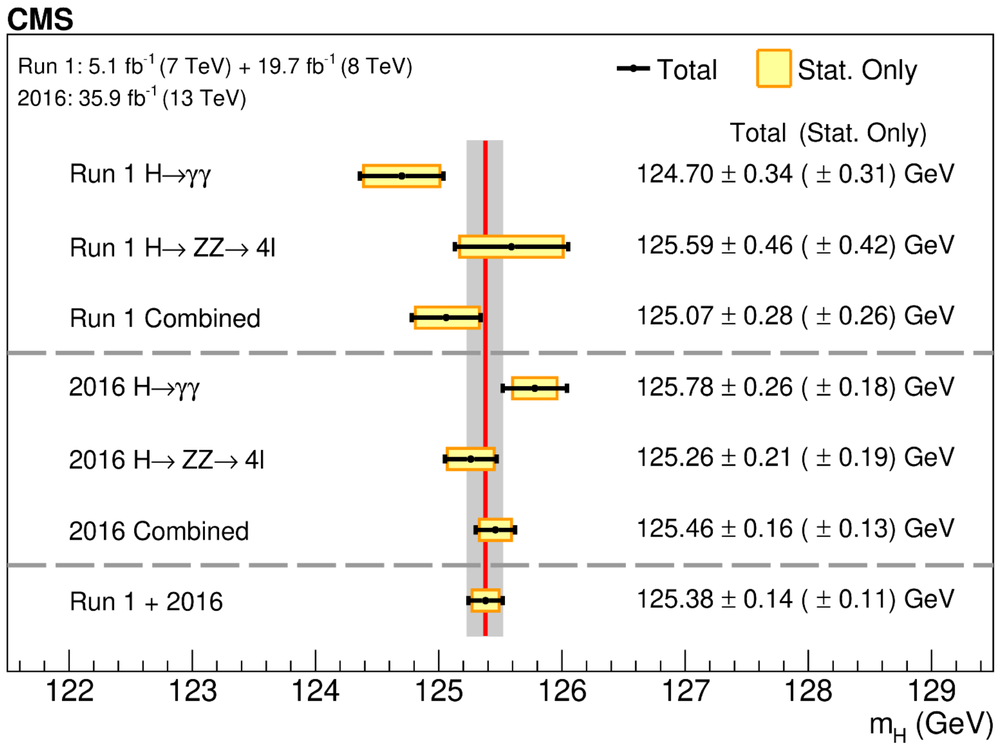
Run-2/2016 combination

$$m_{\mathrm{H}} = 125.46 \pm 0.16\,(\mathrm{total})\,\mathrm{GeV}$$

CMS-HIG-19-004
PLB 805 (2020) 135425

The Higgs boson mass measurement uncertainty is still dominated by statistics

Run-2 2016, 35.9 fb^{-1}



Combination with Run-1 result

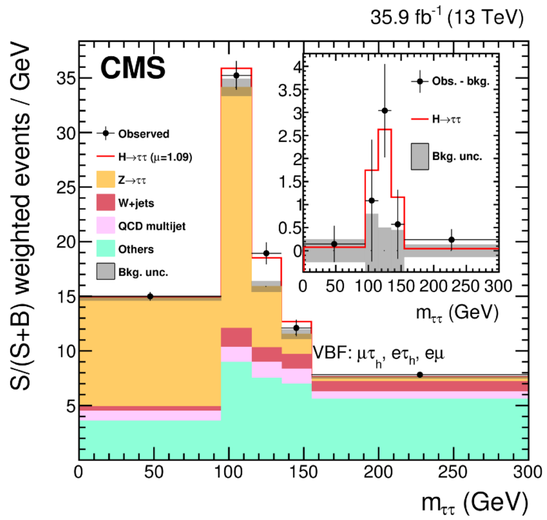
$$m_{\mathrm{H}} = 125.38 \pm 0.14\,(\mathrm{total})\,\mathrm{GeV}$$

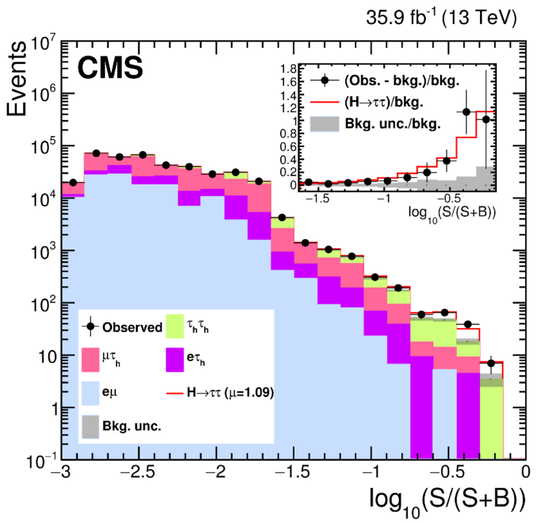
- currently the most precise measurement (1.1‰)
- central value consistently used in CMS analyses

Higgs Decays to Fermions

Summer 2017:
first observation by CMS of $H \to \tau^+\tau^-$

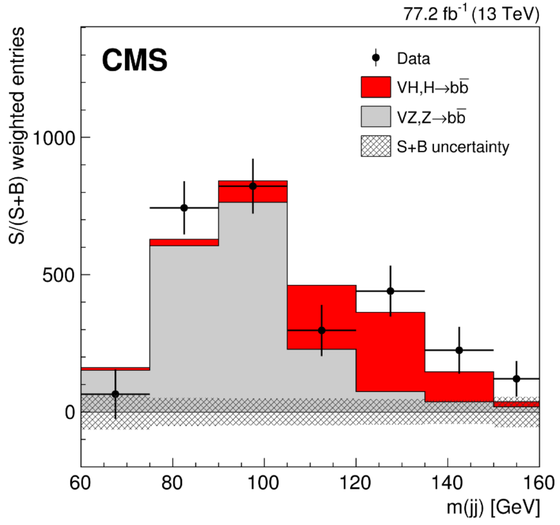
CMS-HIG-16-043
PLB 779 (2018) 283

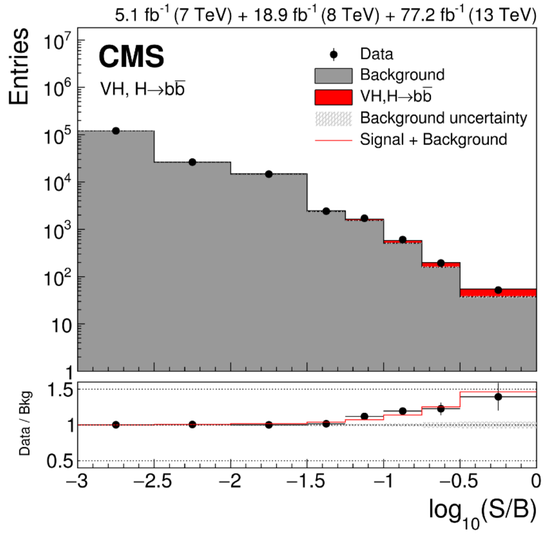




Summer 2018:
first observation by CMS of $H \to b\bar{b}$

CMS-HIG-18-016
PRL 121 (2018) 121801

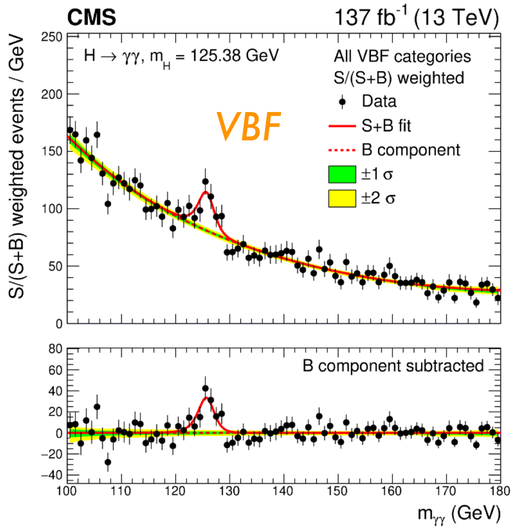


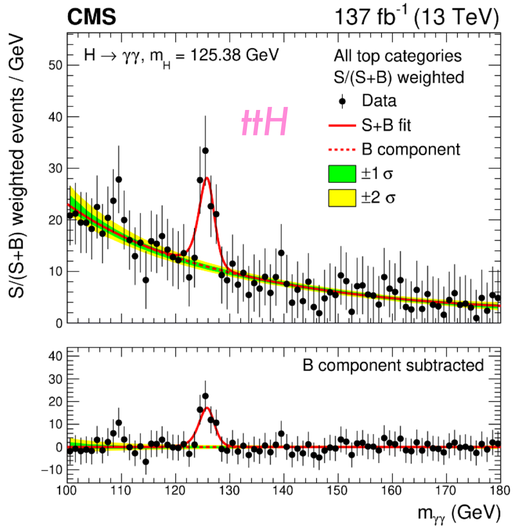


Winter 2019:
Obs. (exp.) limit on $pp \to VH(H \to c\bar{c})$
70 (35) × SM (35.9 fb^{-1})

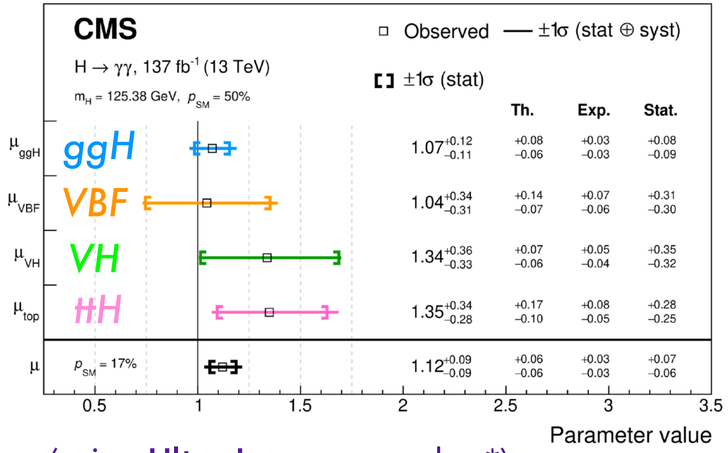
CMS-HIG-18-031
JHEP 03 (2020) 131

H → γγ and STXS





Clear H → γγ signals in all four main production modes, including $pp \to t\bar{t}H$ (5.2σ)



(using **Ultra-Legacy** samples *)

$$\mu(pp \to H \to \gamma\gamma) = 1.12 \pm 0.09$$

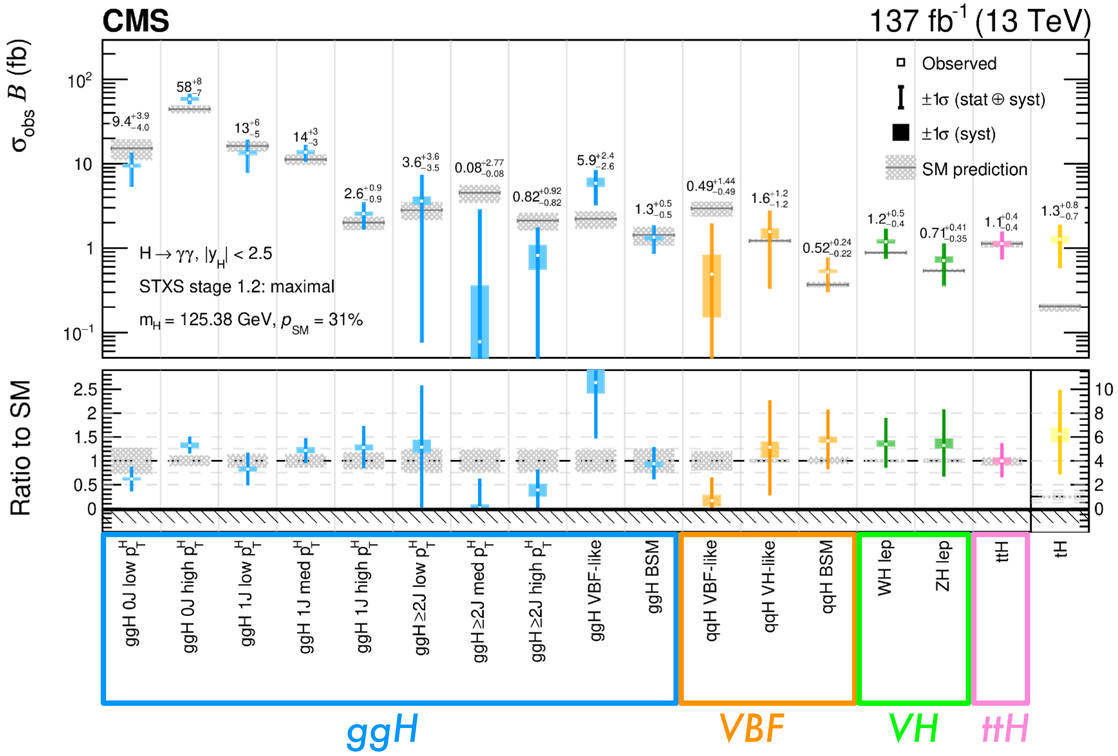
Also, strong evidence for $pp \to t\bar{t}H$ (4.7σ) in multi-lepton final states

CMS-HIG-19-015
Submitted to JHEP

Phys. Briefing

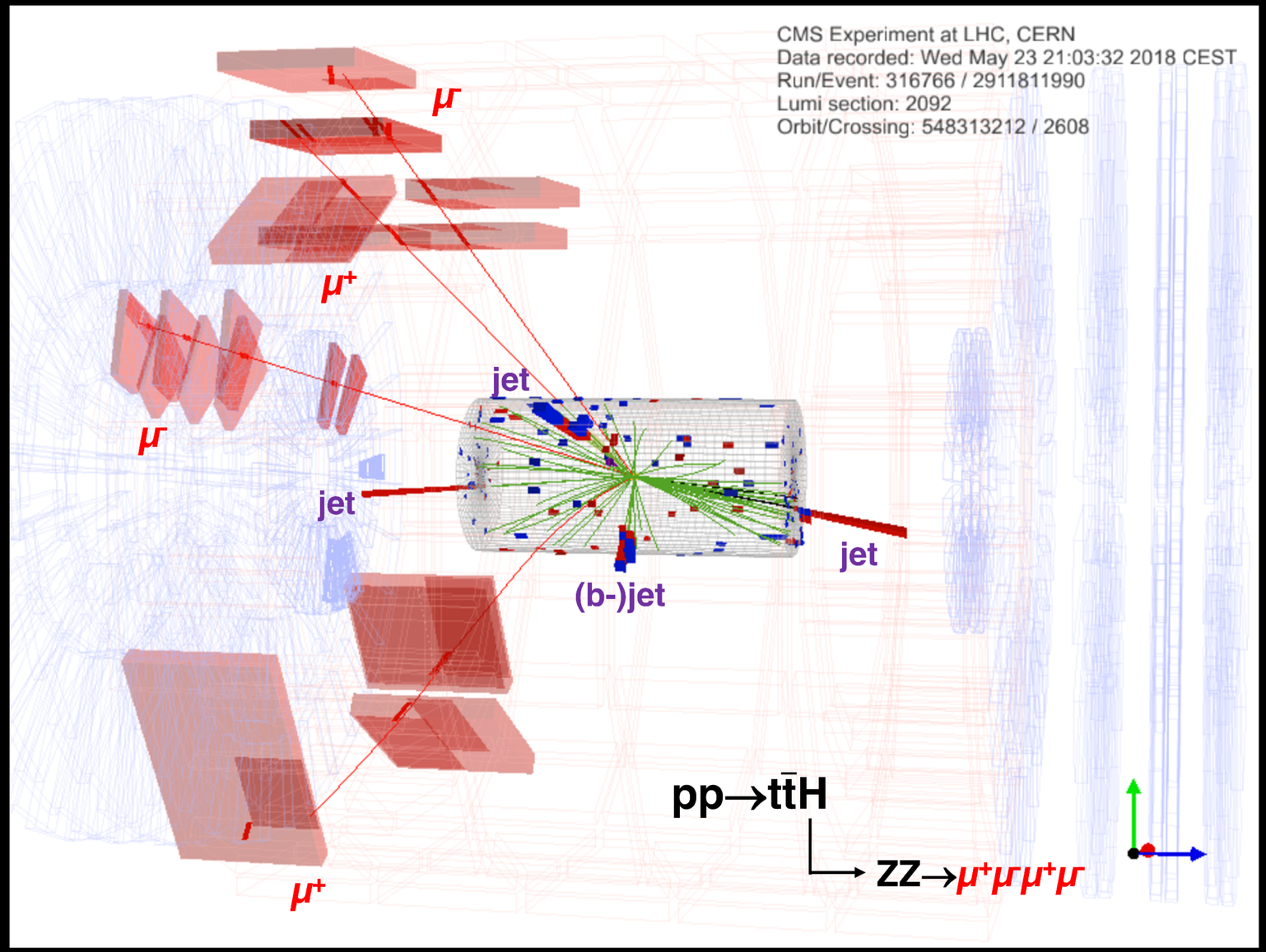
Full Run-2, 137 fb⁻¹

Measurements by production mode in various kinematic regions (STXS = Simplified Template Cross Sections)

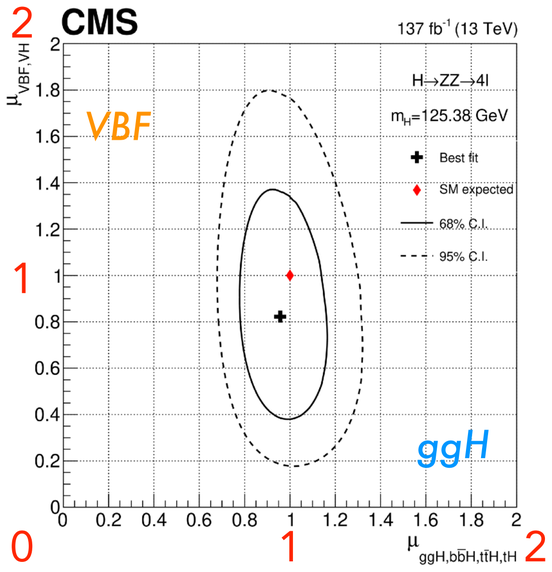


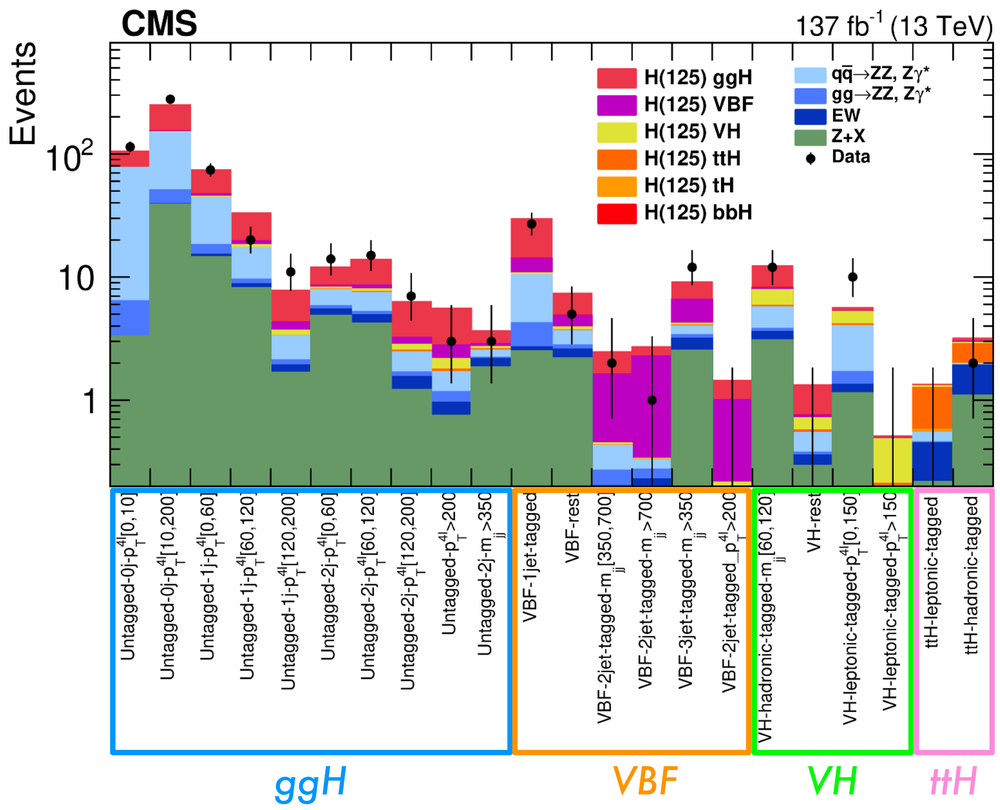
(* already 40 analyses switched to Ultra Legacy re-reconstruction)

ttH (H → 4ℓ) Candidate



$H \to ZZ^* \to 4\ell$ and STXS





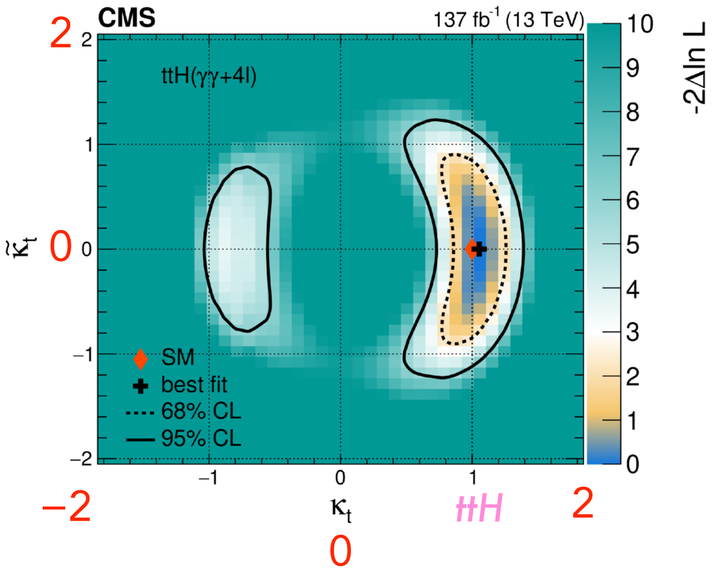
Full Run-2, 137 fb^{-1}

Also: comprehensive study of CP structure and anomalous couplings

CMS-HIG-19-009
Submitted to PRD

Phys. Briefing

Contraints on ttH anomalous CP coupling, combining $\mathrm{H} \to 4\ell$ and $\mathrm{H} \to \gamma\gamma$



$$\mu(4\ell) = 0.94 \pm 0.07\,(\mathrm{stat})^{+0.09}_{-0.08}\,(\mathrm{syst})$$

$$\sigma_{\mathrm{fid}}(4\ell) = 2.84^{+0.23}_{-0.22}\,(\mathrm{stat})^{+0.26}_{-0.21}\,(\mathrm{syst})\ \mathrm{fb}$$

SM: $2.84 \pm 0.15\,\mathrm{fb}$

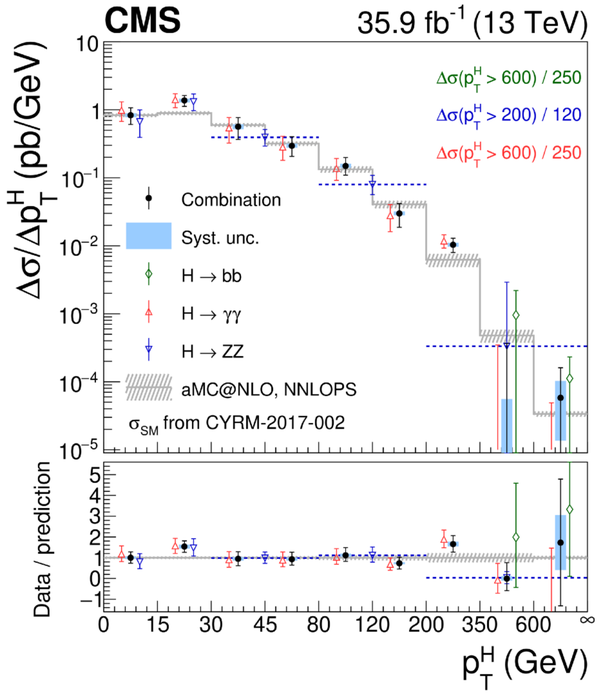
CMS-HIG-19-001
Accepted by EPJC

Higgs Differential

Differential distributions unfolded for selection efficiency and resolution effects and compared to theoretical calculations

- $H \to b\bar{b}, \gamma\gamma, ZZ^*$

Run-2 2016, 35.9 fb^{-1}



no significant deviation from SM predictions

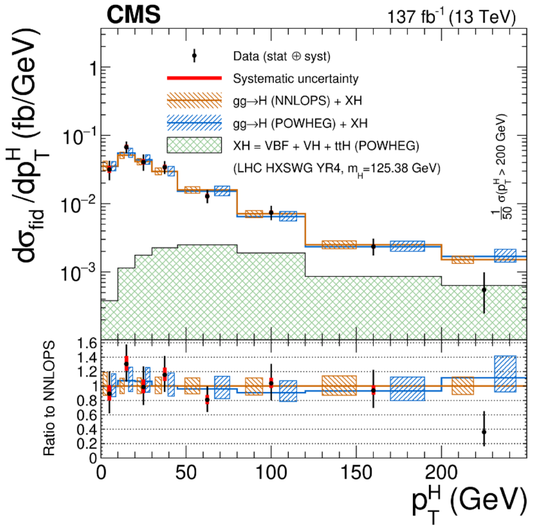
CMS-HIG-17-028
PLB 792 (2019) 369

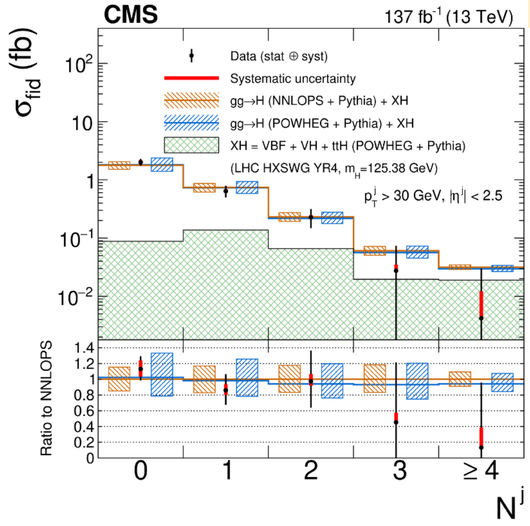
Also in $H \to \tau\tau$:

CMS-PAS-HIG-20-015

- $H \to ZZ^* \to 4\ell$

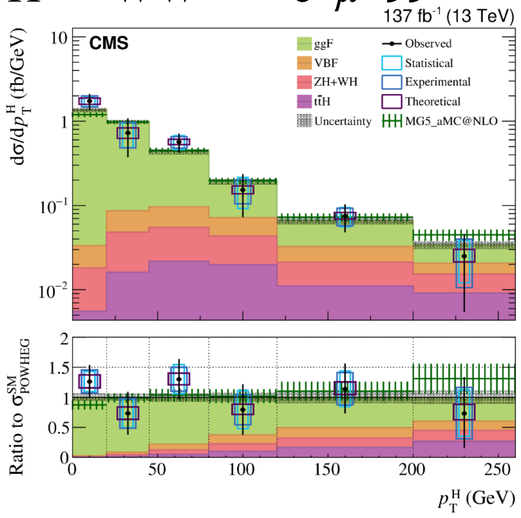
Full Run-2, 137 fb^{-1}

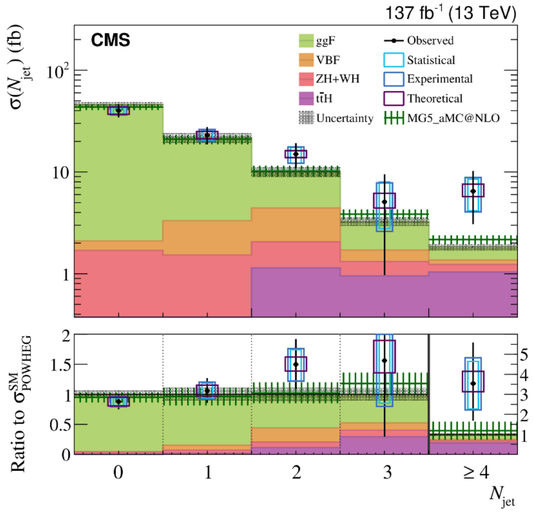




CMS-HIG-19-001
Accepted by EPJC

- $H \to WW^* \to e^{\pm}\mu^{\mp}\nu\bar{\nu}$





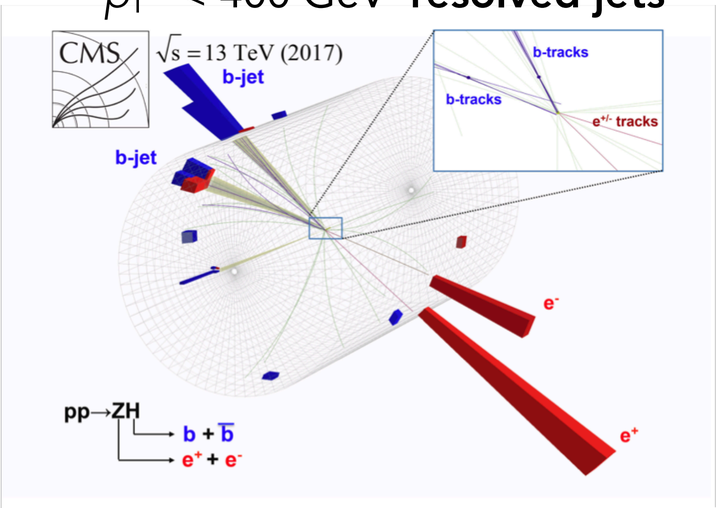
CMS-HIG-19-002
JHEP 03 (2021) 003

Phys. Briefing

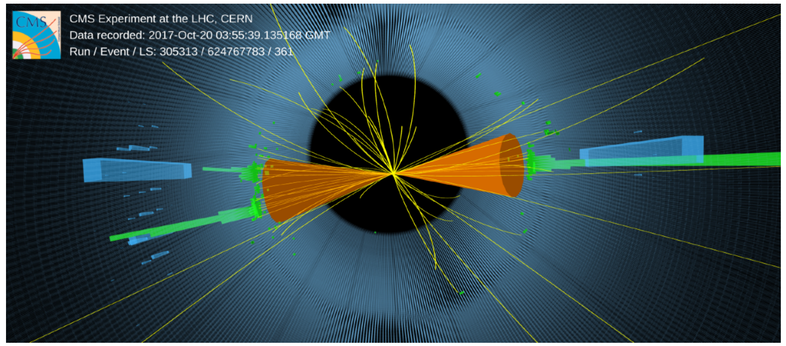
$$\sigma_{fid}(H \to WW^* \to e^{\pm}\mu^{\mp}\nu\bar{\nu}) = 86.5 \pm 9.5\,\text{fb} \quad (\text{SM: } 82.5 \pm 4.2\,\text{fb})$$

Boosted Higgs Boson to Bottom Quarks

p_T^H < 400 GeV **resolved jets**



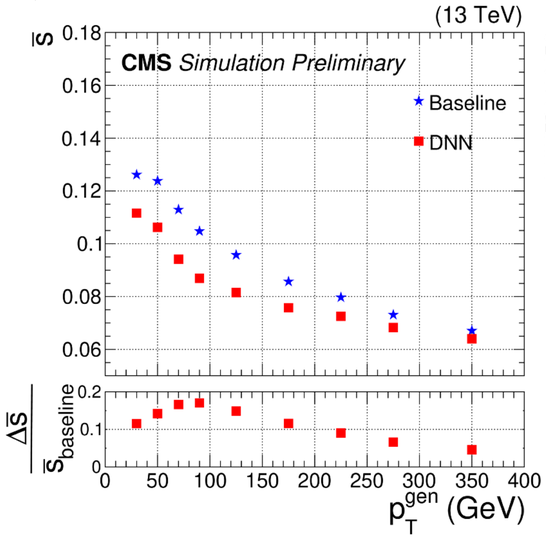
p_T^H > 400 GeV **merged jets**

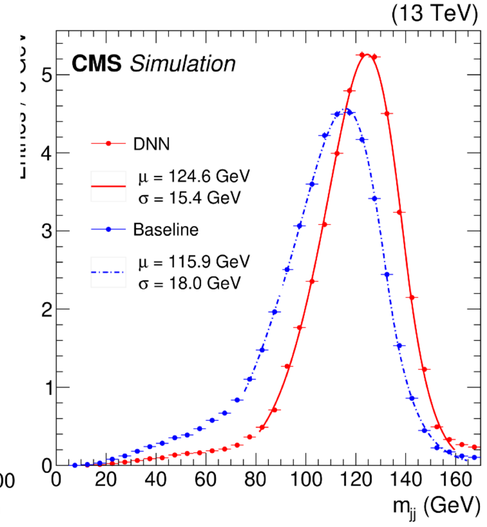


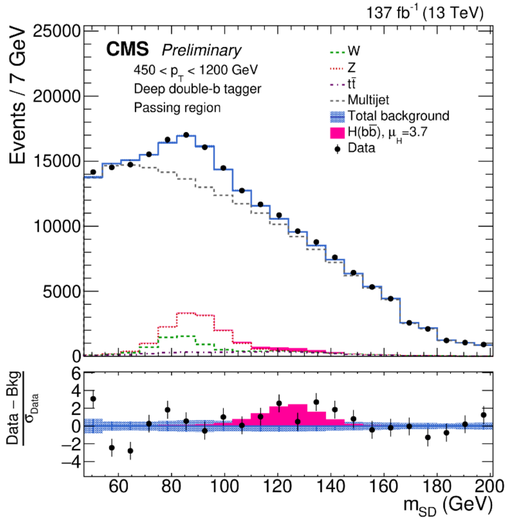
An Inclusive search for highly boosted Higgs bosons decaying to bottom quark-antiquark pairs

A Deep Feed-Forward Neural Network using jet properties information and secondary vertices associated to the jets (43 input variables)

- 13% improvement in jet resolution
- 20% improvement in di-jet mass resolution (as measured in data)







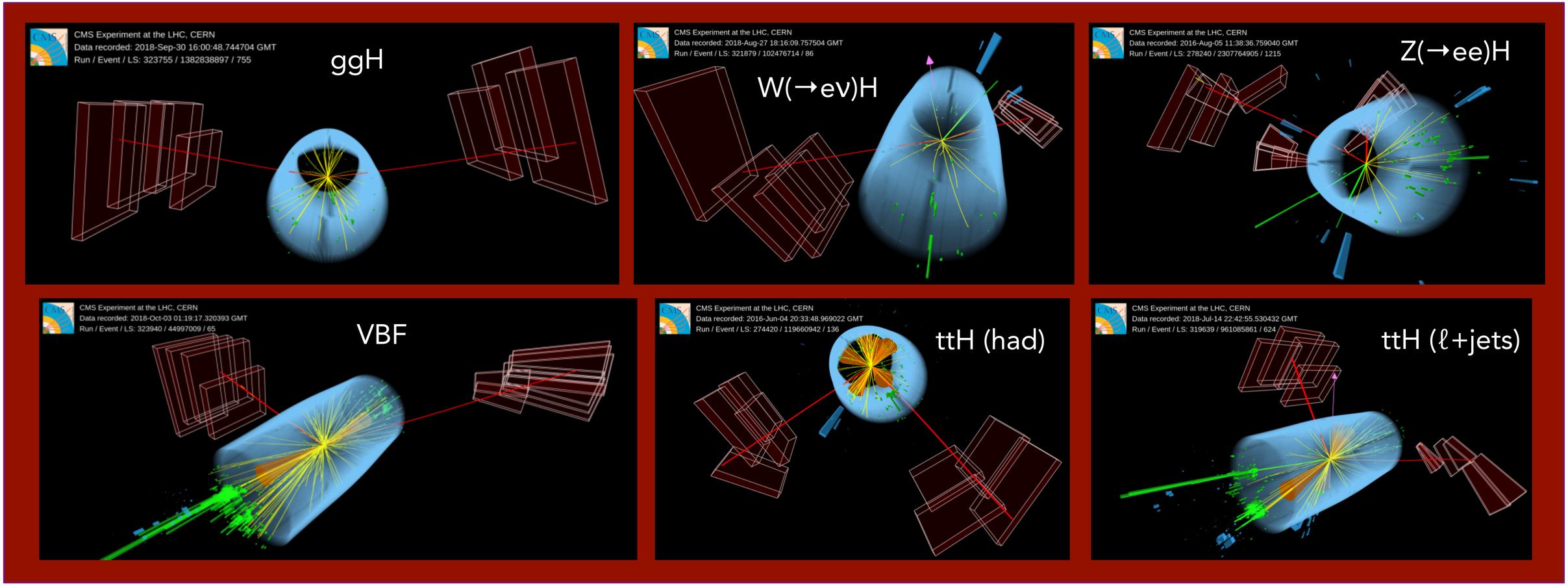
CMS-HIG-18-027
CSBS 4 (2020) 10

CMS-HIG-19-003
JHEP 12 (2020) 085

Phys. Briefing

First Evidence for H → μμ

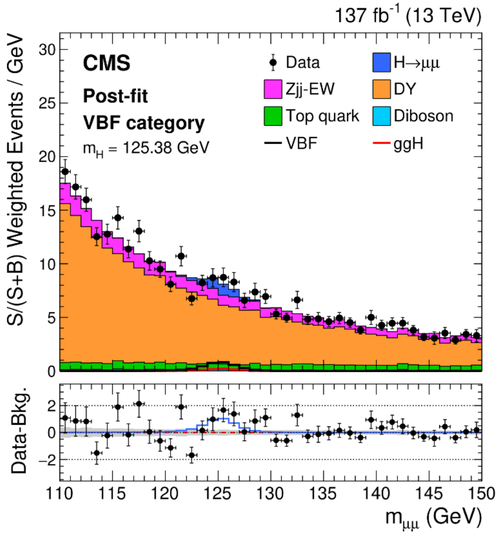
Exclusive categories: ggH, VBF, VH and ttH

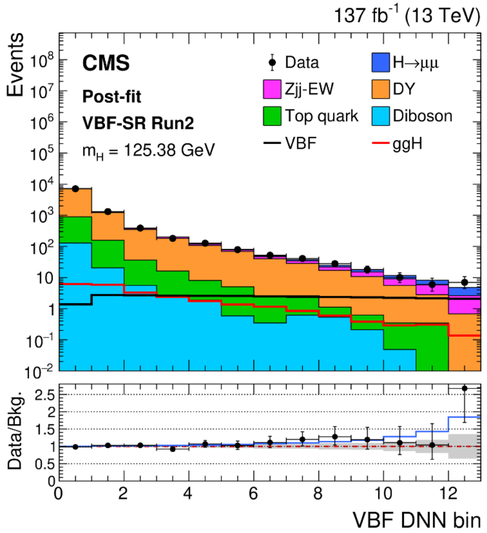


First Evidence for H → μμ

Analysis in VBF category

- makes use of advanced machine learning techniques
- provides sensitivity similar to that in ggH





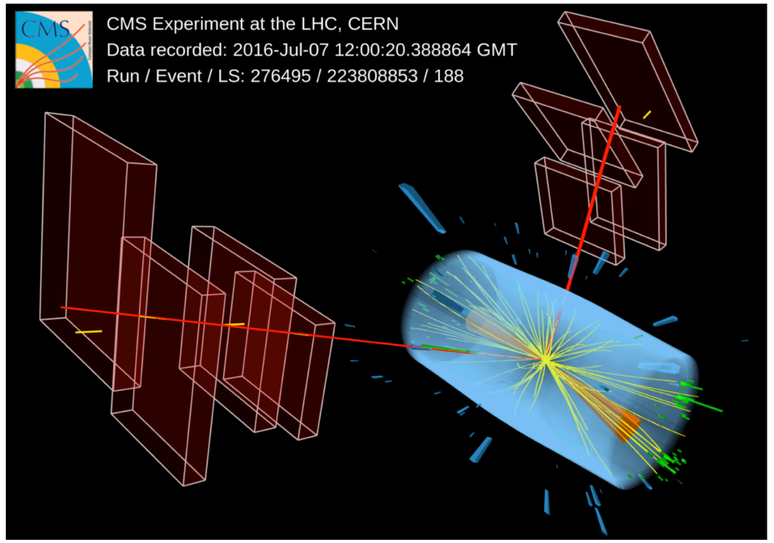
$$\mu(\mu\mu) = 1.19^{+0.41}_{-0.39}\,(\text{stat})^{+0.17}_{-0.16}\,(\text{syst})$$

Obs. (exp.) significance: 3.0 (2.5) σ

[CMS-HIG-19-006](#)
JHEP 01 (2021) 148

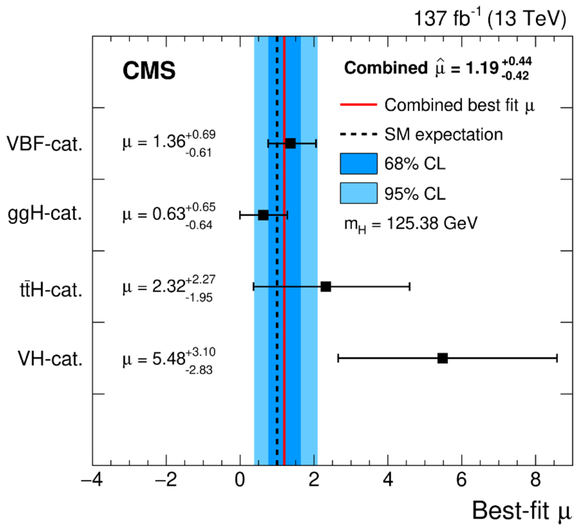
[Phys. Briefing](#)

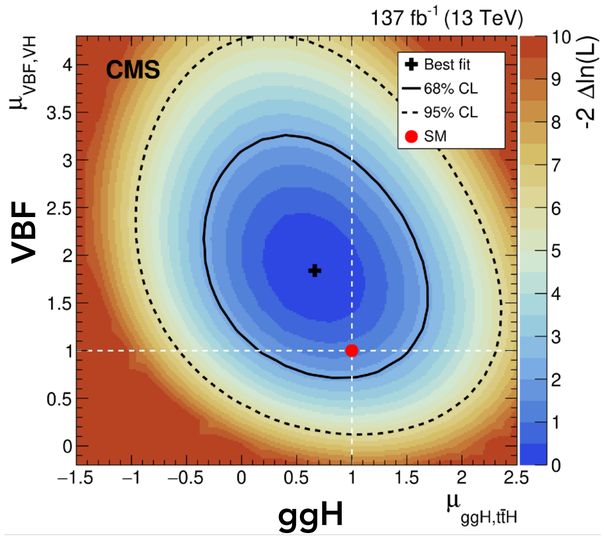
Combining with Run-1 (7 and 8 TeV) improves significance by 1%



Full Run-2, 137 fb⁻¹

Drell-Yan background considerably reduced by VBF topology requirement (two forward jets)



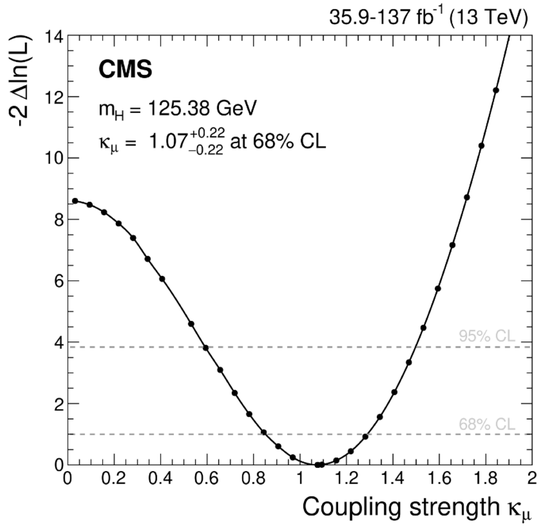


using $m_{\mathrm{H}} = 125.38$ GeV (best CMS result)

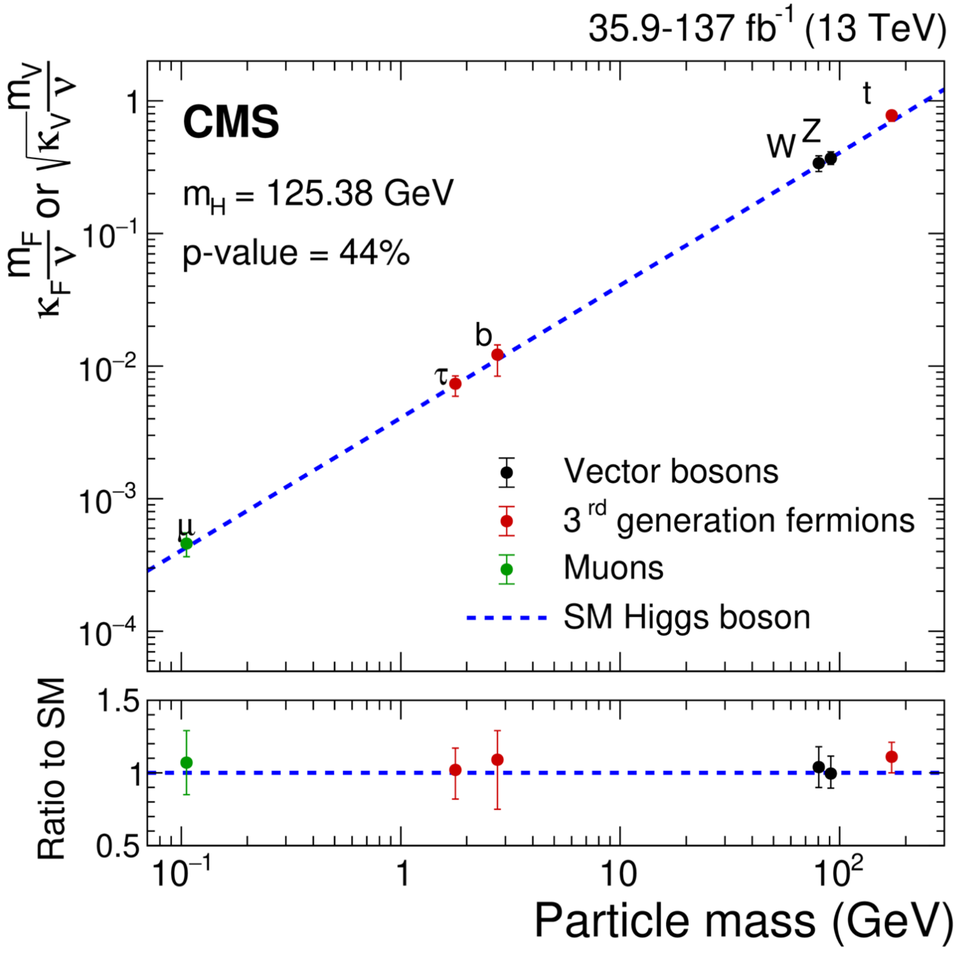
Summary of Higgs Couplings

In the **kappa framework** , fit for 6 coupling strength modifiers (κ) for $m_{\mathrm{H}} = 125.38\,\mathrm{GeV}$

$$\kappa_\mu = 1.07 \pm 0.22\,(\mathrm{at}\ 68\%\mathrm{CL})$$



CMS-HIG-19-006
JHEP 01 (2021) 148

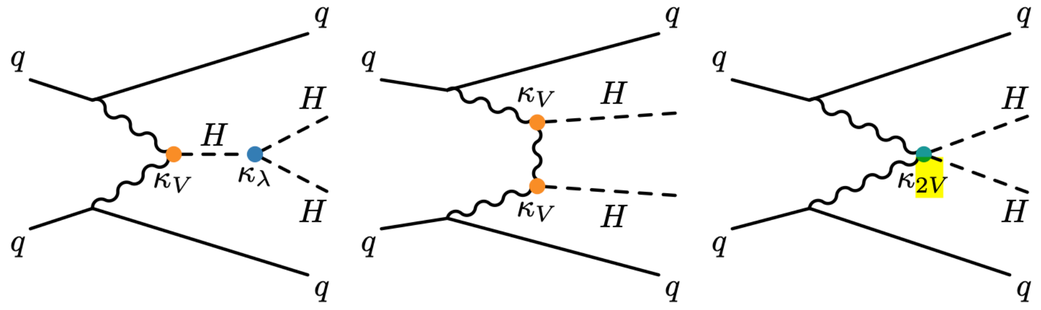


for the first time, meaningful 68% and 95% confidence intervals for a Higgs boson coupling to a second generation fermion

CMS *p*-value for SM hypothesis (all κ=1): **44%**

Double Higgs Production

The observation of double Higgs production is one of the main motivations for HL-LHC



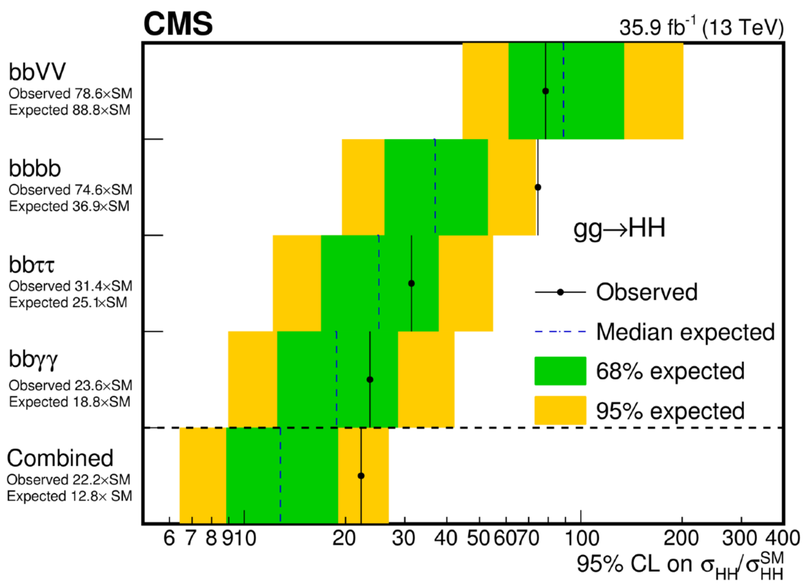
Constraints on anomalous HHH (κ_λ) and VVHH (c_{2V}) couplings

The goal in Run-3 is either to find an anomalous production (resonant or non-resonant) or to set cross-section limits closer to the SM expectation

In the SM: $\lambda_{\mathrm{HHH}} = \lambda = m_{\mathrm{H}}^2/2v^2$

Run-2 2016, 35.9 fb^{-1}

CMS-HIG-17-030
PRL 122 (2019) 121803



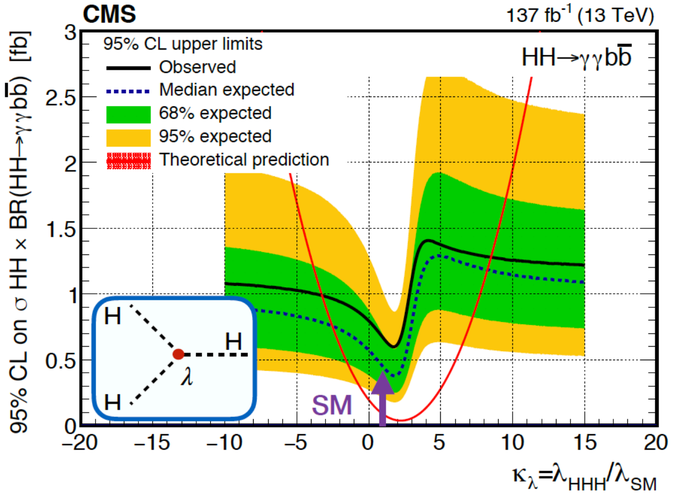
Combination of HH searches $\sigma/\sigma_{SM} < 22$ (13) at 95% CL

Search for Double Higgs Production

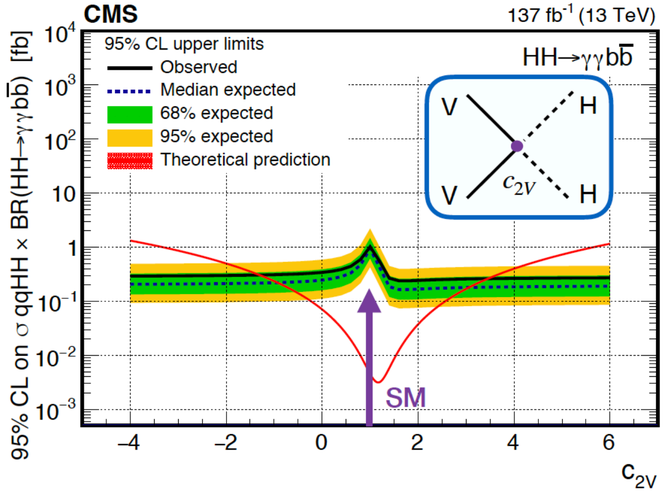
Full Run-2, 137 fb^{-1}

CMS-HIG-19-018
JHEP 03 (2021) 257

Phys. Briefing



Driven by ggF categories

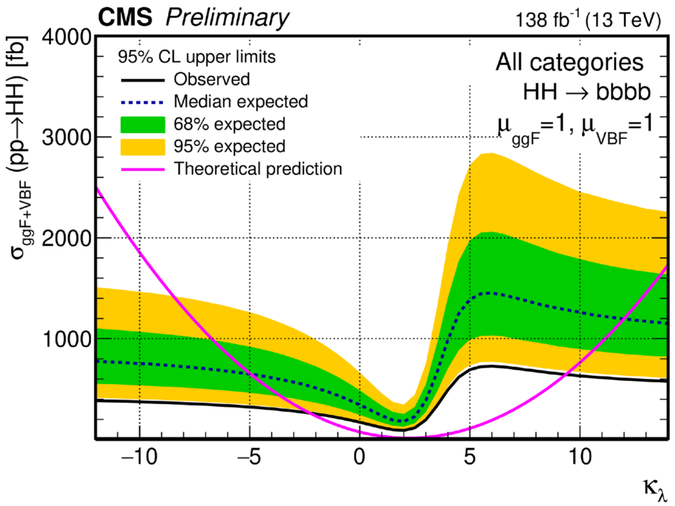


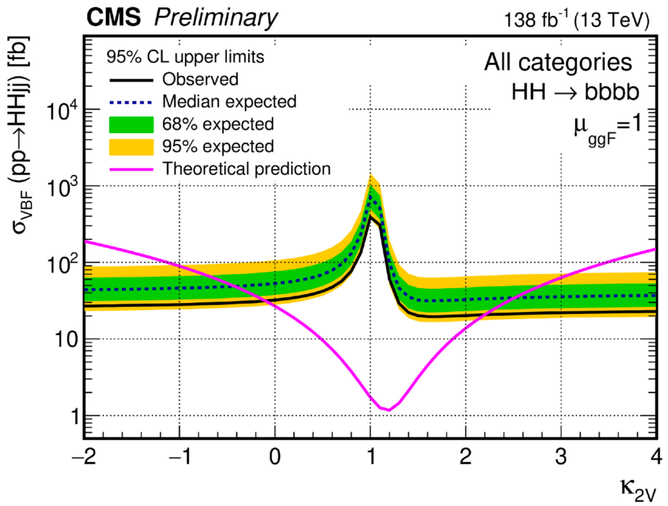
Driven by VBF categories

Inclusive $HH \to \gamma\gamma b\bar{b}$ ($\kappa_\lambda = 1$)
$\sigma/\sigma_{SM} < 7.7$ (5.2) at 95% CL

VBF $HH \to \gamma\gamma b\bar{b}$ ($\kappa_{2V} = 1$)
$\sigma/\sigma_{SM} < 225$ (208) at 95% CL

Run-2 analyses already reaching much higher sensitivity than anticipated





Inclusive $HH \to b\bar{b}b\bar{b}$ ($\kappa_\lambda = 1$)
$\sigma/\sigma_{SM} <$ **3.6** (7.3) at 95% CL

VBF $HH \to b\bar{b}b\bar{b}$ ($\kappa_{2V} = 1$)
$\sigma/\sigma_{SM} < 226$ (412) at 95% CL

Best ***observed*** limit so far

NEW

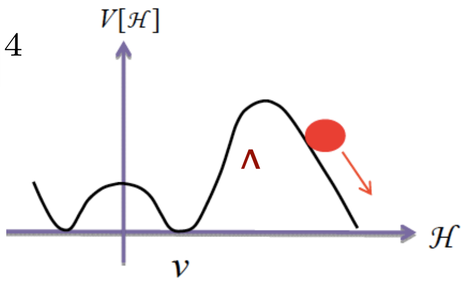
CMS-PAS-HIG-20-005

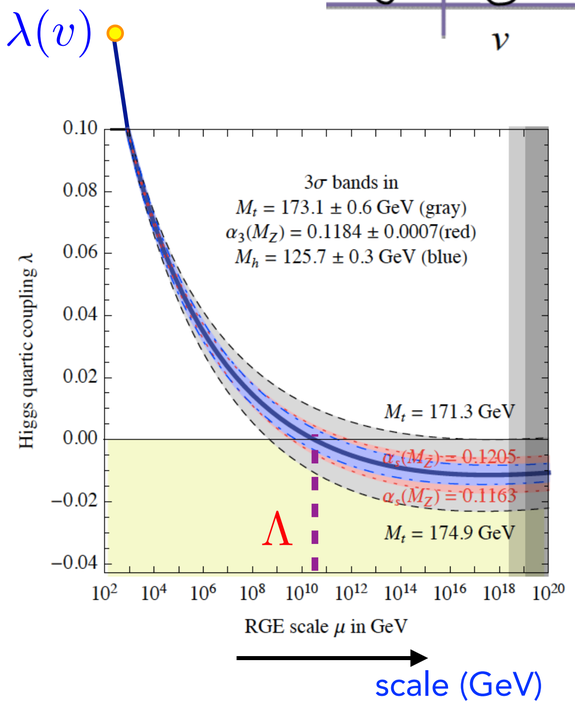
Top-Quark Mass Measurements

Higgs potential

$$V_{\mathrm{H}} = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

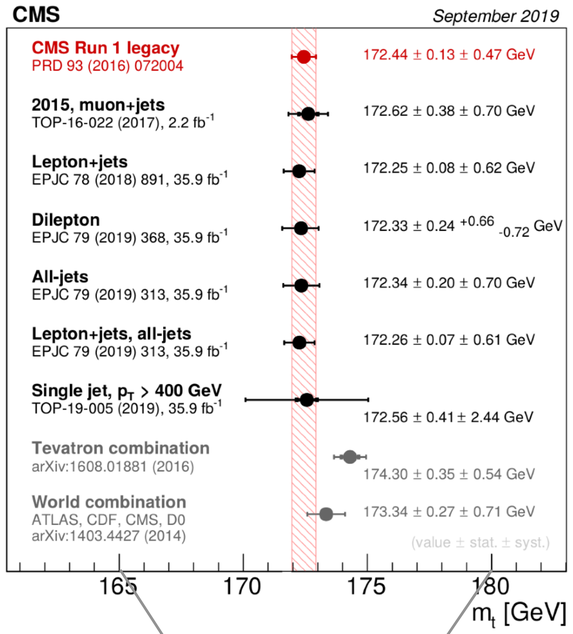
$$\lambda(v) = m_{\mathrm{H}}^2/2v^2$$



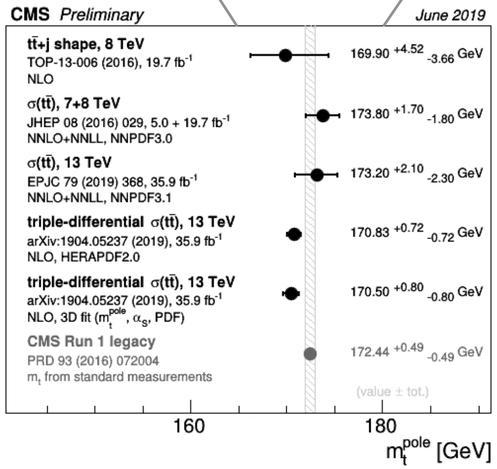


The value of the *Instability Scale* Λ (> 10^9 GeV) depends on $\alpha_S(m_Z)$ and the **top-quark mass**

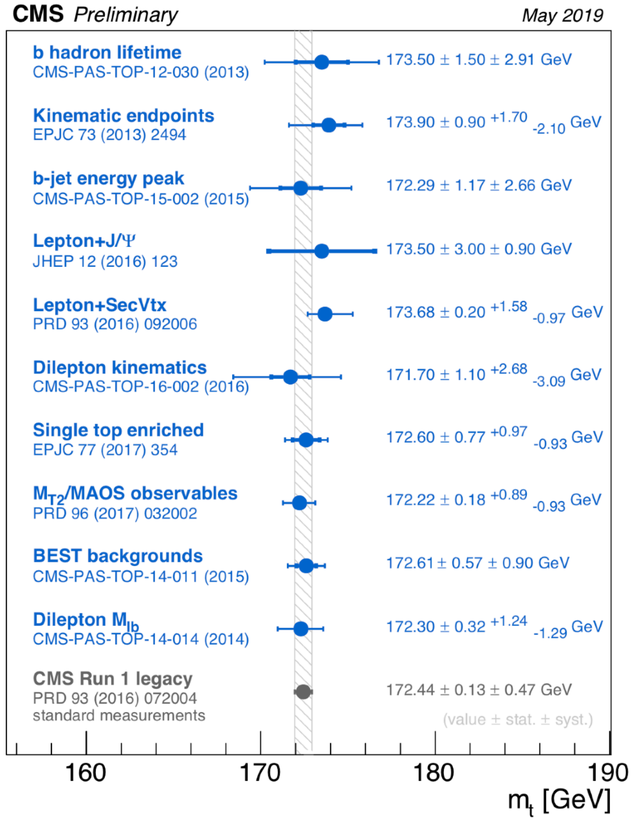
Direct measurements



"pole" measurements



Alternative measurements



Top-Quark Mass Measurements

From $t\bar{t}$ events

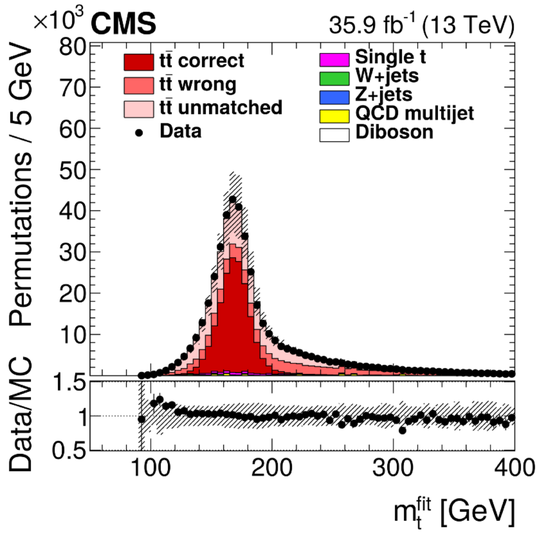
- **Run-1 legacy**

  $m(\mathrm{t}) = 172.44 \pm 0.13 \pm 0.47\,\mathrm{GeV}$

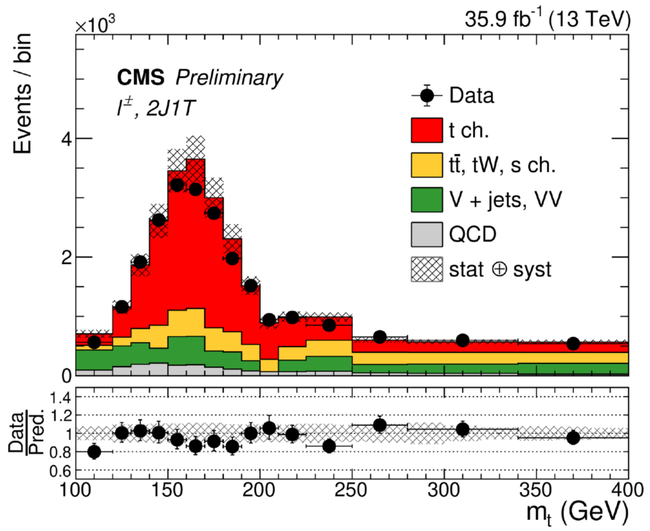
- **Run-2 lepton+jets**

  $m(\mathrm{t}) = 172.25 \pm 0.08 \pm 0.62\,\mathrm{GeV}$

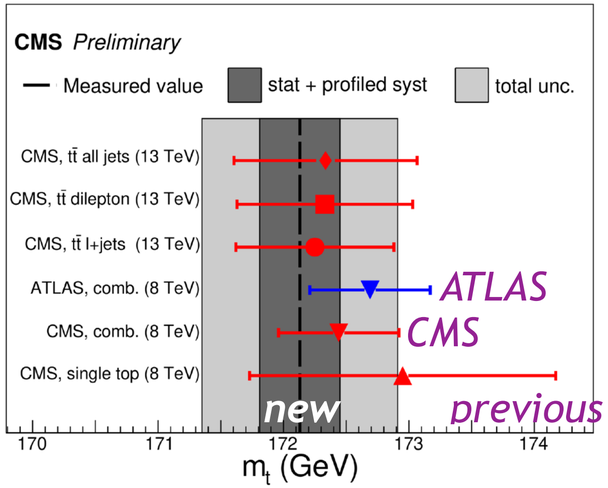
CMS-TOP-17-017
EPJC 78 (2018) 891



Run-2 2016, 35.9 fb^{-1}



CMS-PAS-TOP-19-009



From single top events

Different phase space, different kinematics, and separate measurements of top and anti-top:

- $m(\mathrm{t}) = 172.44 \pm 0.77\,\mathrm{GeV}$
- $m(\bar{\mathrm{t}})/m(\mathrm{t}) = 0.995 \pm 0.006$
- $m(\bar{\mathrm{t}}) - m(\mathrm{t}) = 0.83^{+0.77}_{-1.01}\,\mathrm{GeV}$

Alternative methods

- M_{T2}, Dilepton $M_{\ell\mathrm{b}}$, kinematic endpoints, b-hadron lifetime, ℓ+SecVtx, ℓ+J/ψ, etc.
- less precise but different systematic uncertainties
- in agreement with main measurement

Running of the Top-Quark Mass

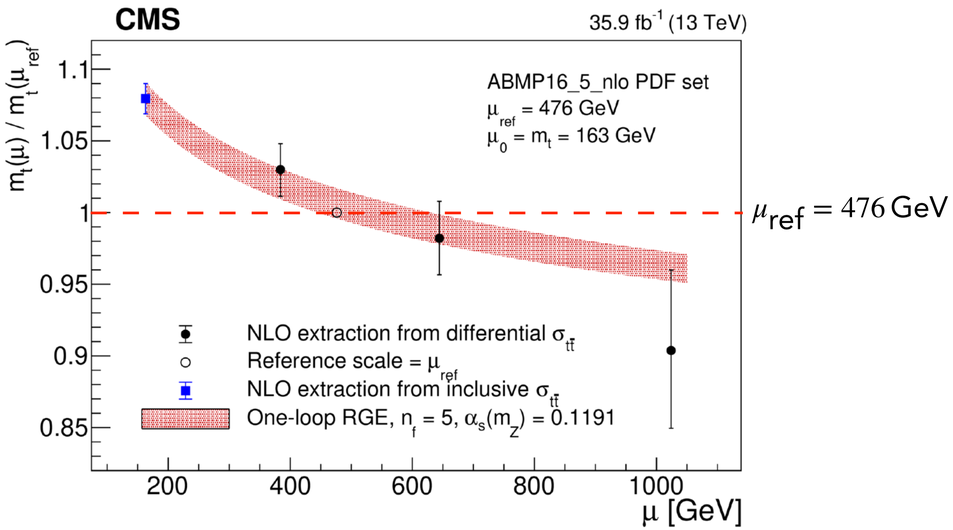
"Pole" mass from multi-differential cross section measurements

- in $e^{\pm}\mu^{\mp}$ final state
- as functions of mass and rapidity of the $t\bar{t}$ system, and jet multiplicity
- unfolded at parton level
- compared with NLO predictions in $\overline{\text{MS}}$ scheme

$$m(\mathrm{t}) = 170.83 \pm 0.72\,\text{GeV}$$

CMS-TOP-18-004
EPJC 80 (2020) 658

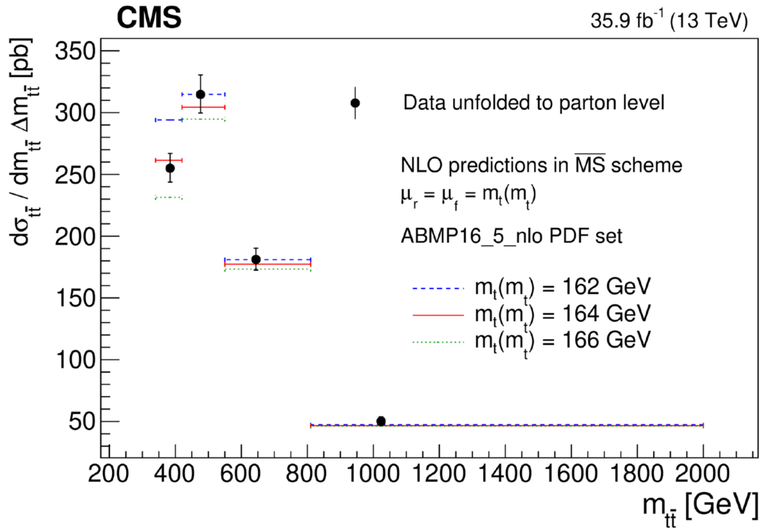
Run-2 2016, 35.9 fb^{-1}



uncertainty evolved from inclusive measurement at scale $\mu_0 = 163$ GeV

Evolution of the top quark mass from the differential cross section as a function of $m_{t\bar{t}}$

$d\sigma_{t\bar{t}}/dm_{t\bar{t}}$

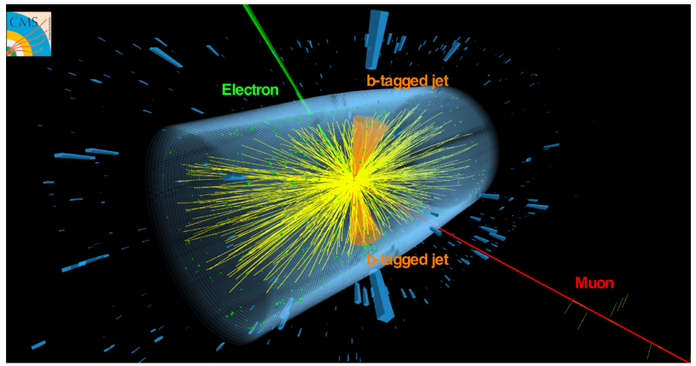


CMS-TOP-19-007
PLB 803 (2020) 135263

Top-quark running mass probed up a scale of order 1 TeV

- compared to RGE prediction at one-loop precision ($n_f = 5$)
- scale dependance found consistent with predictions at the 1.1σ level
- no-running hypothesis excluded at the 95% CL

Heavy Quark Production in PbPb Collisions

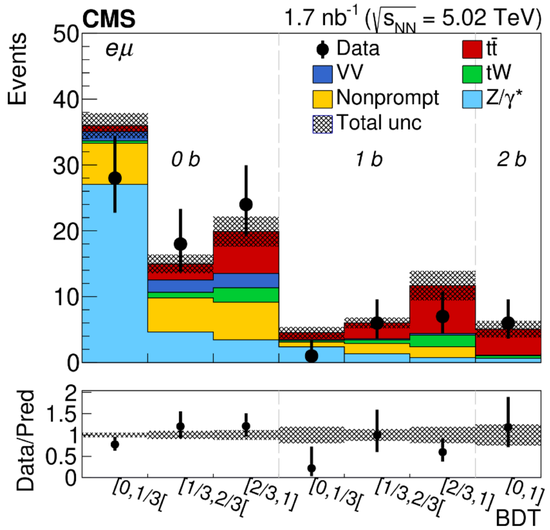


Run-2, $\sqrt{s_{NN}}$ = 5.02 TeV, PbPb 1.7 nb^{-1} + pp 320 pb^{-1}

NEW

Evidence for $t\bar{t}$ production

- in the eμ channel
- 4.0σ obs. (6.0σ exp.)
- following a first observation in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV



CMS-HIN-19-001
PRL 125 (2020) 222001

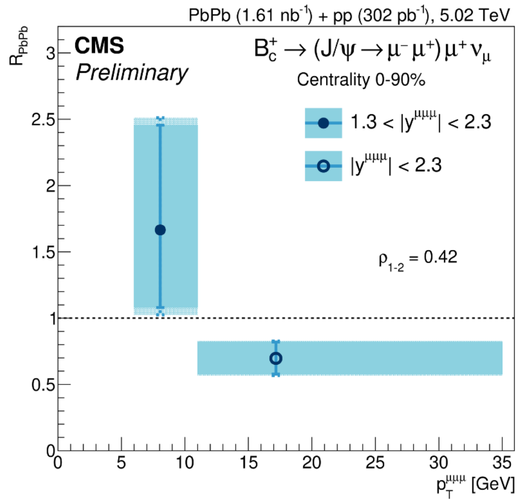
Phys. Briefing

Top quarks are thought to decay before QGP formation

- probes for nPDF at high-x
- tools to study parton energy loss in the QGP

Observation of B_c meson production

- in the decay channel $B_c \to J/\psi(\to\mu\mu)\mu\nu$ (≫5σ)
- bridge between charm and charmonium



CMS-PAS-HIN-20-004

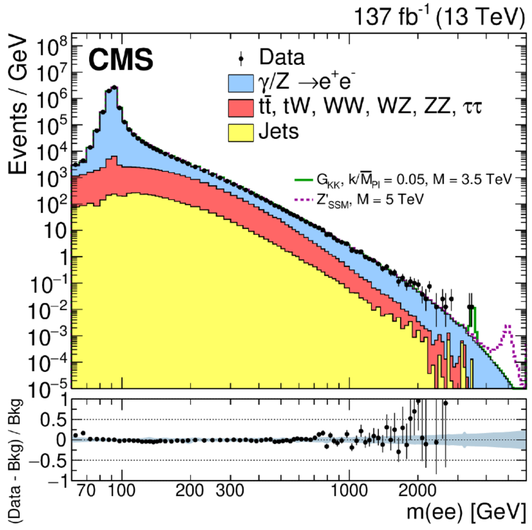
- hint of soften p_T spectrum
- rules out some (extreme) models of charm recombination

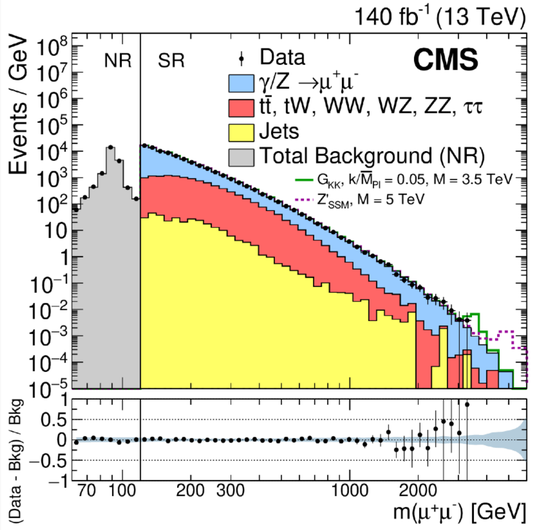
will help disentangle the enhancement and suppression mechanisms at play in the evolution of heavy quarks through the QGP

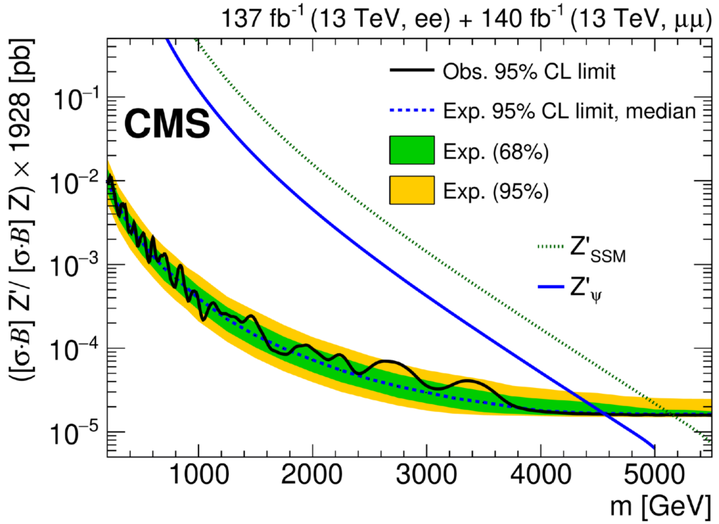
Search for Heavy Resonances

Dilepton resonances

Full Run-2, ≥137 fb⁻¹







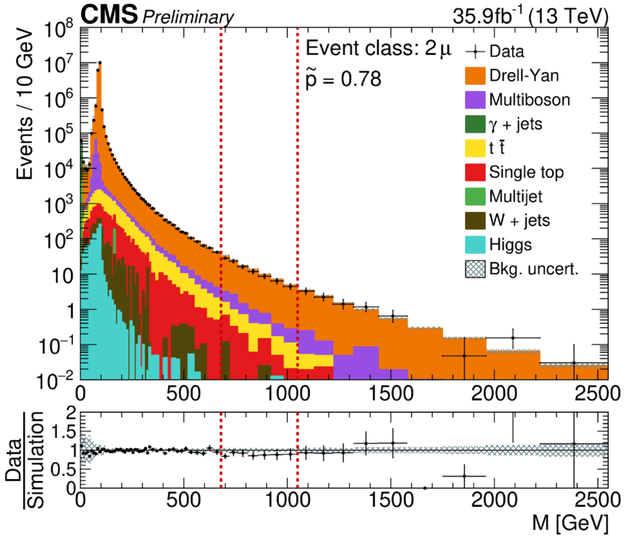
Limits on cross section × BF translate into limits on resonance masses

CMS-EXO-19-019
Submitted to JHEP

Phys. Briefing

depending on models new W′ or Z′ resonances with masses up to > 4 TeV are excluded

Unspecific search for New Physics

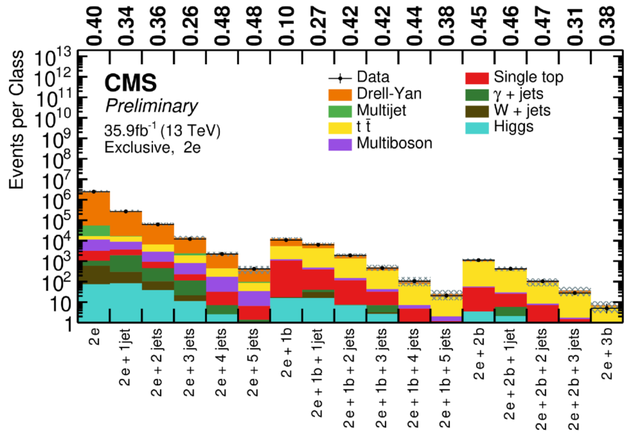


MUSiC = Model Unspecific Search in CMS

CMS-EXO-19-008
Accepted by EPJC

Phys. Briefing

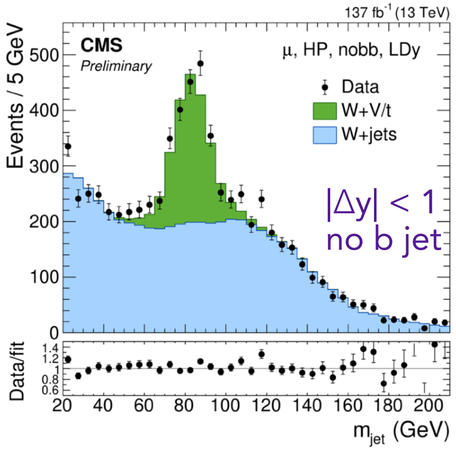
Wide range of final state topologies

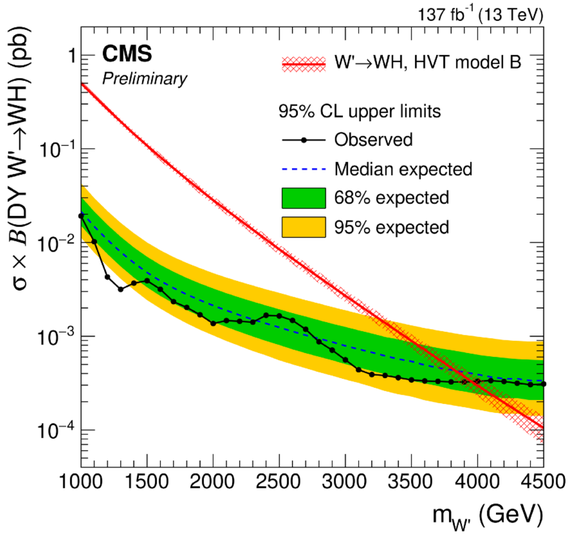


Excellent agreement is found between the data and SM predictions

Search with Merged Jets in the Final State

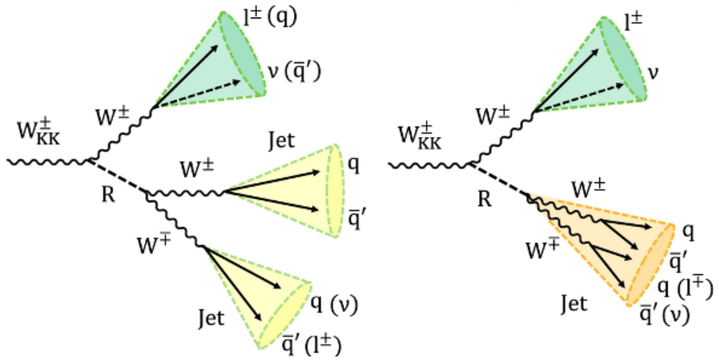
Search for WV resonances (V = W, Z, H)

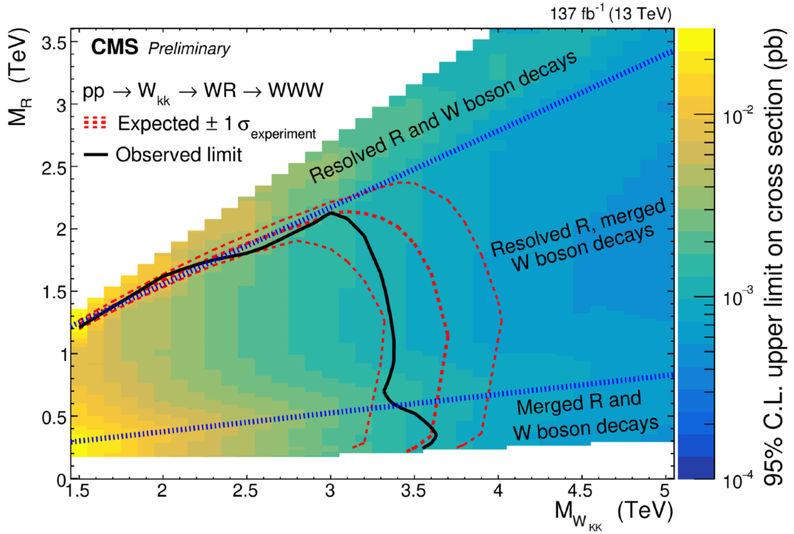




CMS-PAS-B2G-19-002

Search for resonances decaying in cascade through to three W bosons



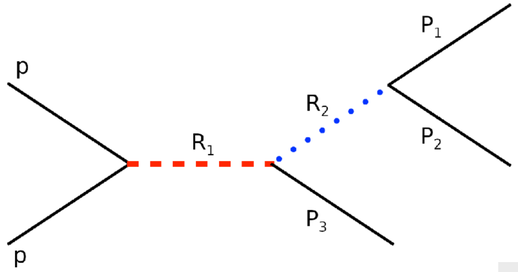


CMS-PAS-B2G-20-001

Phys. Briefing

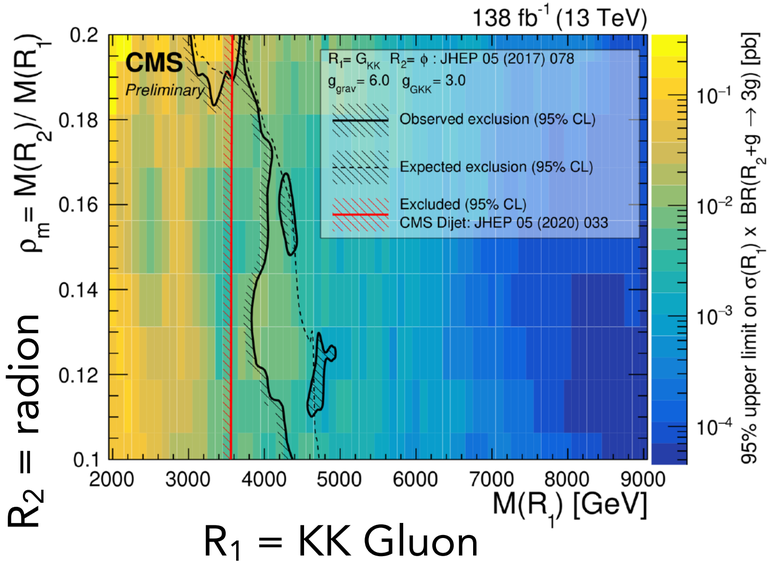
Search for resonances in 3 jets final states where 2 jets are merged

NEW



boosted dijet resonance reconstructed as single jet containing jet substructure consistent with a two-body decay

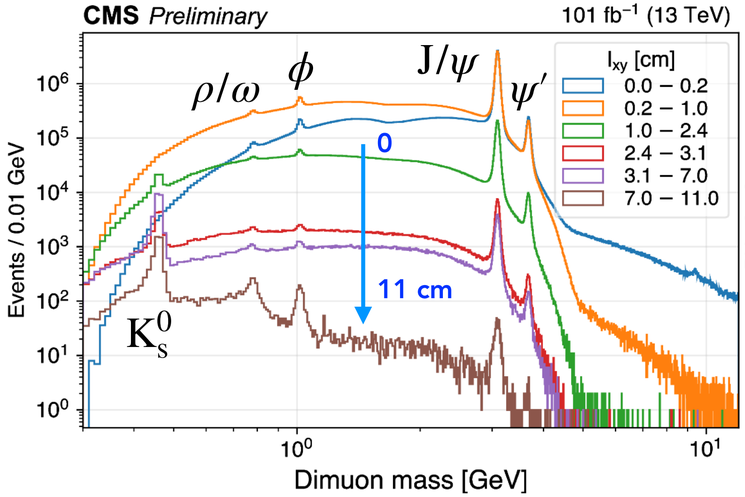
CMS-PAS-EXO-20-007

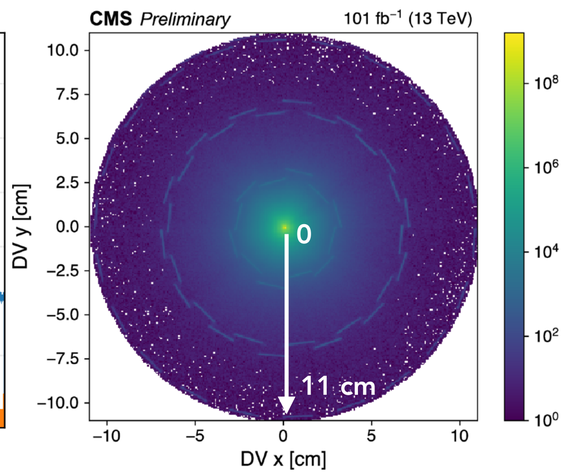


Search for Displaced Muon Mass Peak

Scouting data: low threshold dimuon triggers reconstructed at HLT in real time

- exclusion limits derived in different models an in a wide range of signal mass and lifetime hypotheses





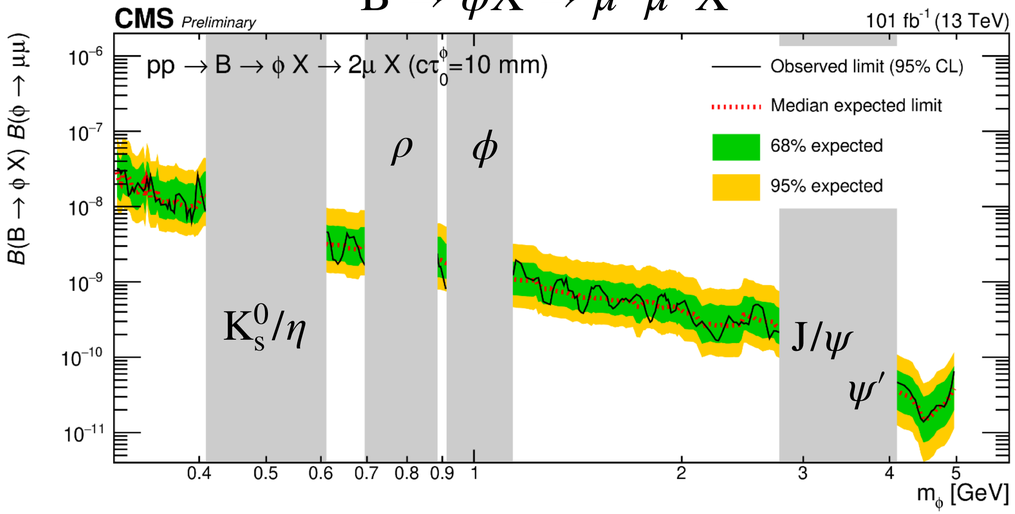
CMS-PAS-EXO-20-014

NEW

B decays to long-lived scalar

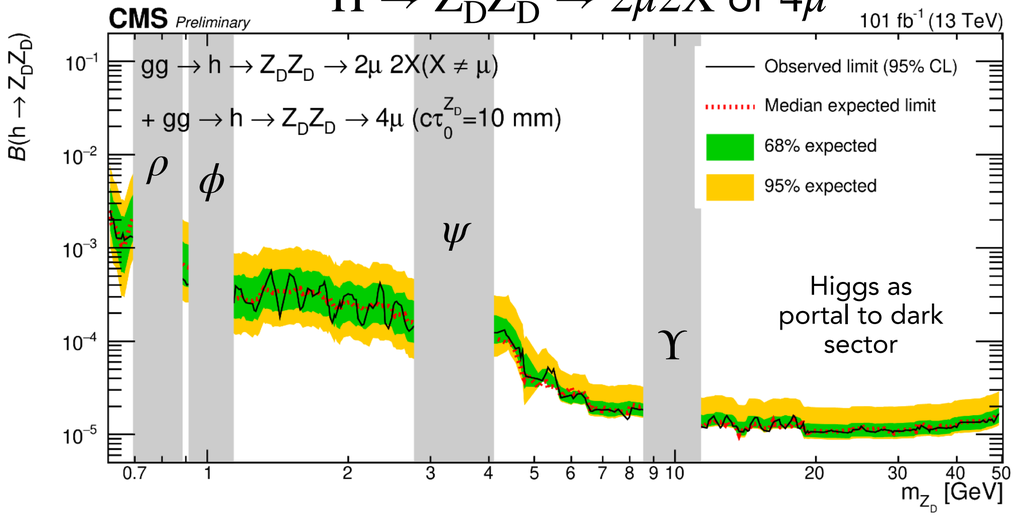
$B \to \varphi X \to \mu^+\mu^- X$

exclusion examples for $c\tau = 10\,\text{mm}$



Higgs decays to long-lived dark photons

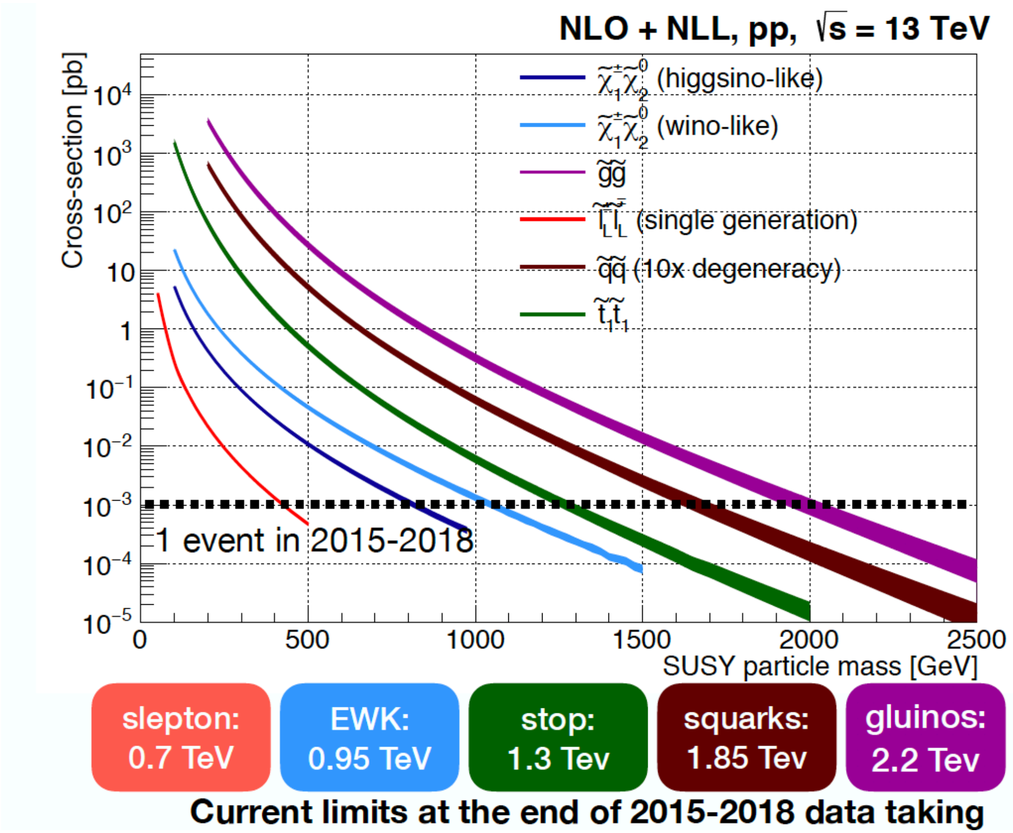
$H \to Z_D Z_D \to 2\mu 2X$ or 4μ



Supersymmetry

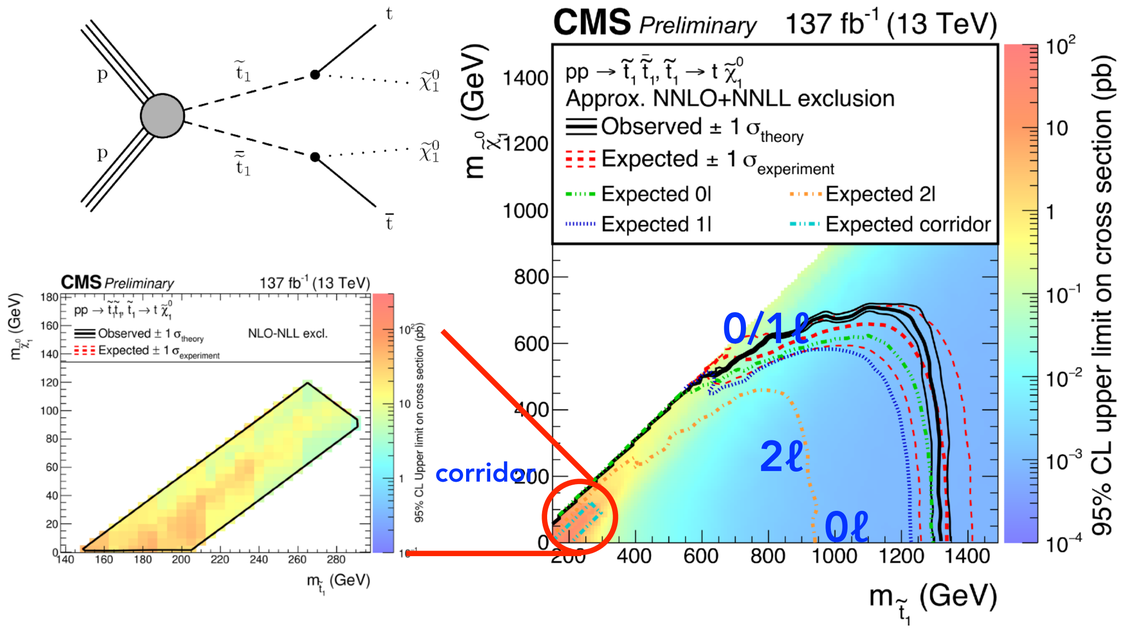
CMS has **a rich SUSY search program** setting strong limits on many models

- analyses optimised to tackle difficult corners of the phase space (stop corridor, compressed scenarios)



Full Run-2, 137 fb^{-1}

Combined Searched for Stops



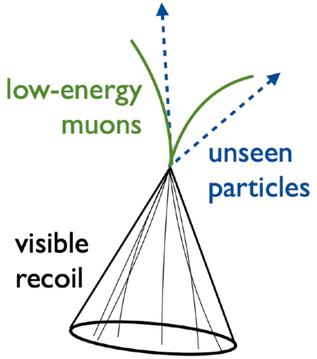
stops excluded up to 1300 GeV

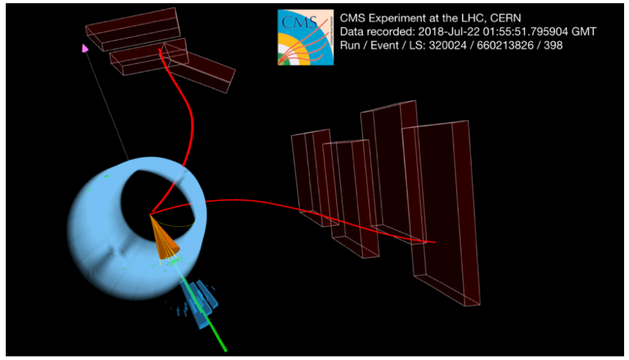
CMS-PAS-SUS-20-002

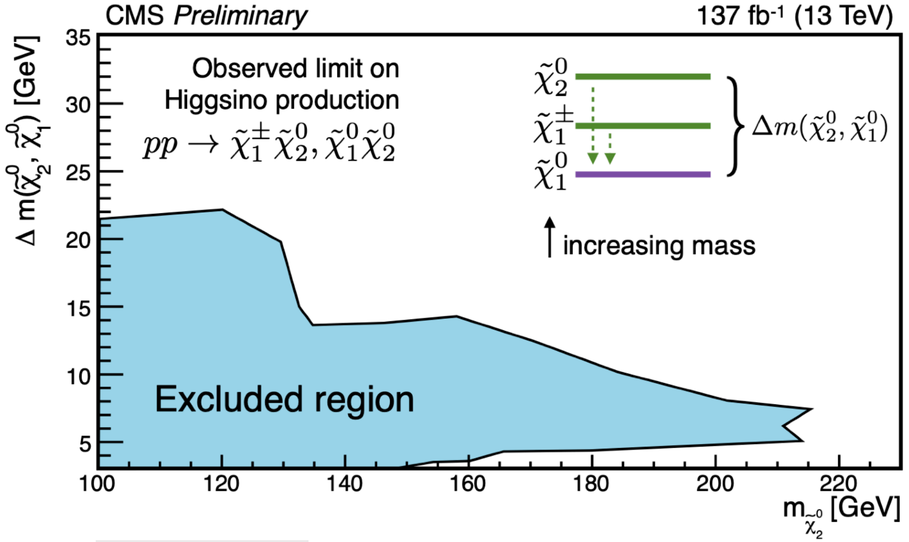
Soft Muons, Disappearing Tracks

model involving weakly massive particles with nearly degenerate masses

two or three soft muons + missing transverse momentum







Results interpreted in terms of pair-produced
- **electroweakinos** with compressed mass spectra
- **stops** nearly mass-degenerate with the lightest neutralino

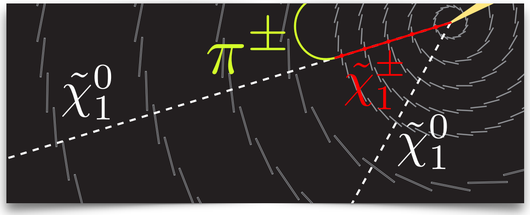
CMS-PAS-SUS-18-004

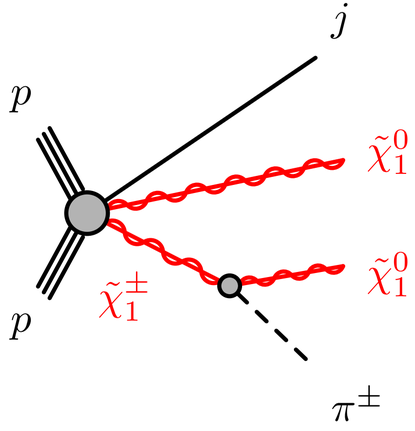
Phys. Briefing

AMSB model, with Wino-like DM

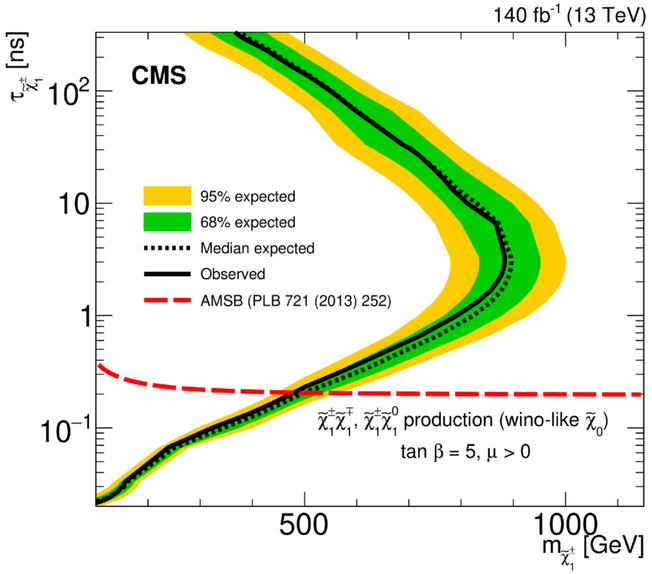
$$\chi = \begin{pmatrix} \chi^+ \\ \chi^0 \\ \chi^- \end{pmatrix}$$

dark matter





Full Run-2, 140 fb^{-1}

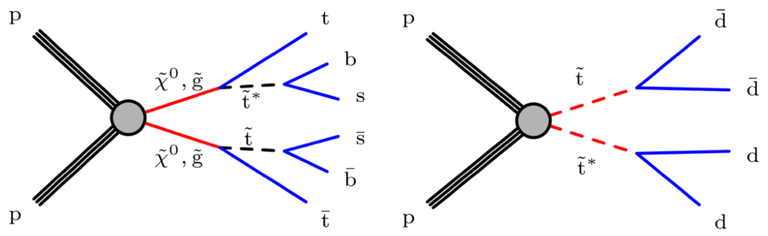


Pure wino exclusion up to 490 GeV (46.4 fb)

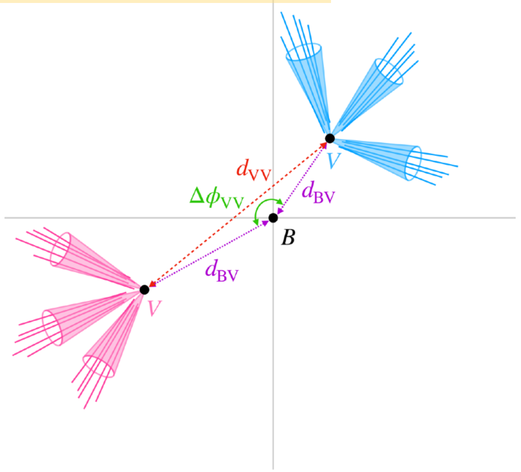
Charginos excluded up to 880 GeV for a lifetime of 3 ns

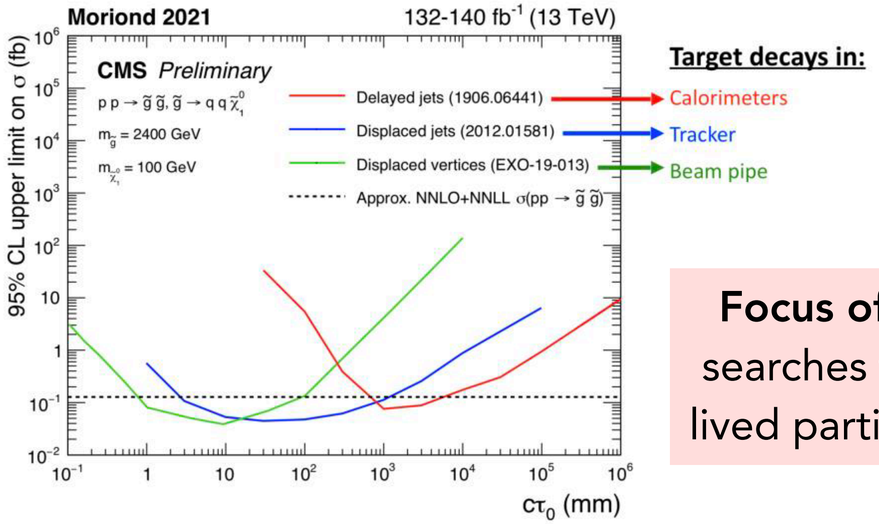
CMS-EXO-19-010
PLB 806 (2020) 135502

Long-Lived Particles



Full Run-2, 140 fb^{-1}

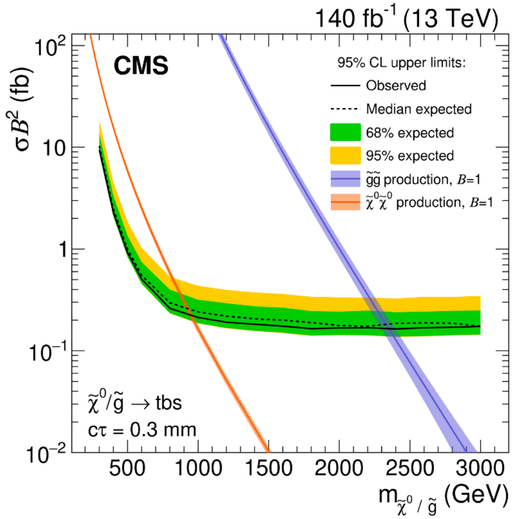


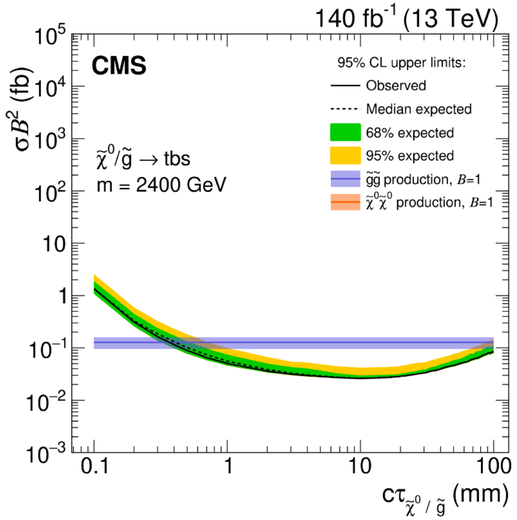


Search for LLPs produced in pairs

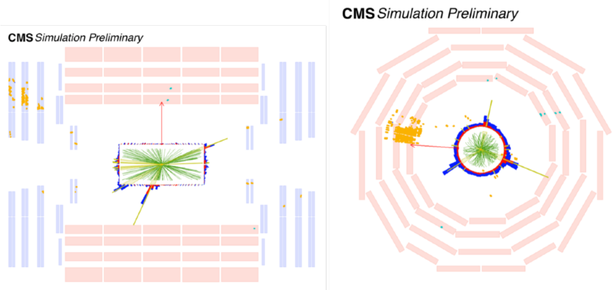
- with a mean decay length between 0.1 and 100 mm (i.e. within the beam pipe)
- each decaying into two or more quarks

Focus of Run-3: searches for long-lived particles (LLP)



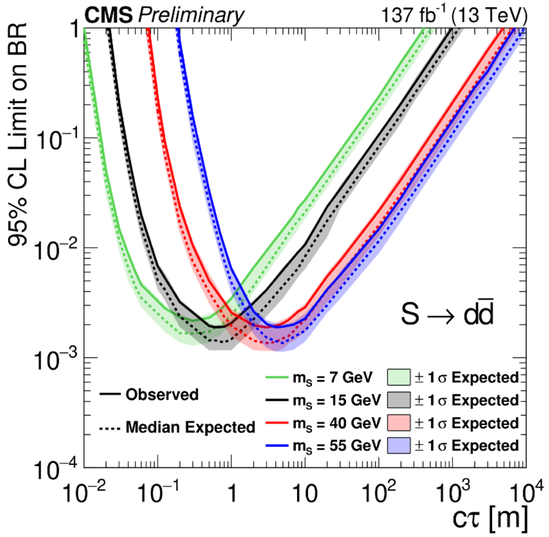


CMS-EXO-19-013
Submitted to PRD



Search for Higgs boson decaying to long-lived scalars

- decaying to quarks or tau leptons within the forward muon chambers

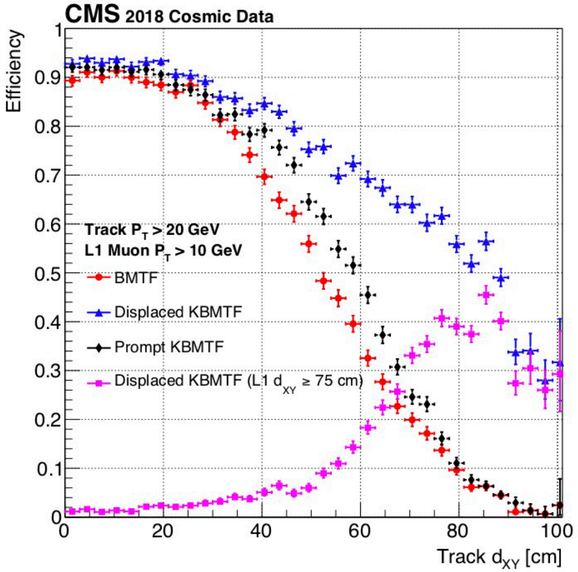


CMS-PAS-EXO-20-015

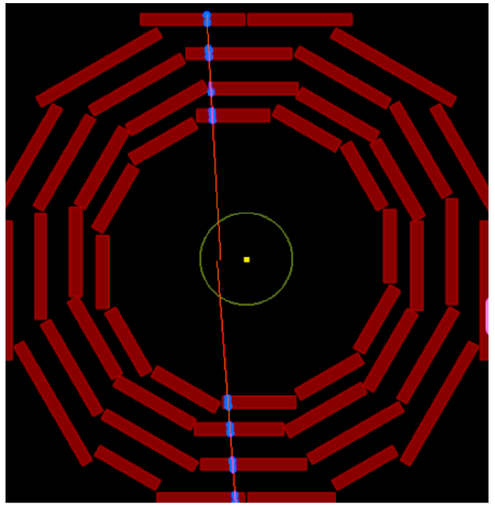
Preparation for Run-3

L1-Muon trigger

- **Barrel muon track finder** (BMTF) → 50% background reduction
- **Kalman track finding** → better efficiency for displaced muons (without vertex constraint)



tested in parallel in 2018 and commissioned with cosmic rays

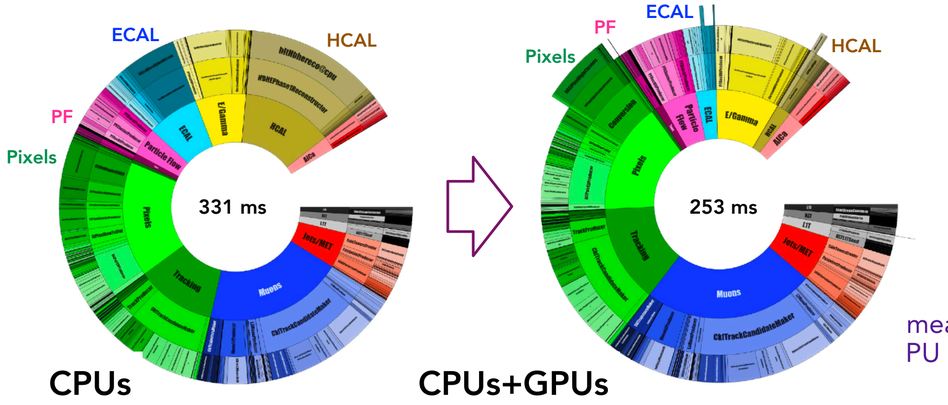


Athens, Ioànnina

Computing and Offline software

- increased use of opportunistic computing (HPC: 10-15%)
- 10% faster full simulation
- improved fast simulation
- development of event lighter data formats

Heterogeneous online reconstruction



measured on PU 50 events

GPUs in High-Level Trigger (HLT)

A significant (and growing) fraction of the online reconstruction code is off-loaded from CPUs to GPUs

- HCAL and ECAL local reconstruction and calibration
- pixel tracking and electron seeding
- some particle flow and jet algorithms

A significant improvement in speed (>20%) already with present 30% of Run-3 workflow

CMS Phase-II Upgrades

Tracker
- all silicon (strips and pixels)
- higher granularity (>2B channels)
- less material
- coverage extended to |η| = 4

Barrel Calorimeters
- crystal granularity readout at 40 MHz
- precise timing for e/γ > 30 GeV
- ECAL operation at low temperature (10°)
- upgraded laser monitoring system

A MIP Timing Detector (MTD)
- precision timing on single charged tracks (30 to 40 ps resolution)
- Barrel (BTL): LYSO crystals + SiPMs
- Endcaps (ETL): Low Gain Avalanche Diodes

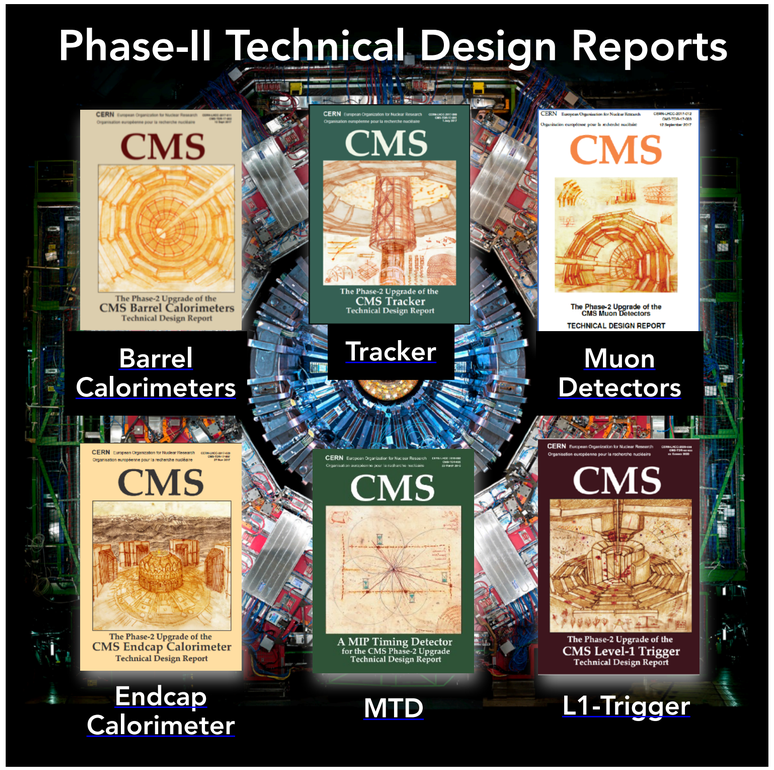
Endcap Calorimeter (HGCAL)
- silicon pixels (EM) and scintillators + SiPMs (HAD)
- 3D shower reconstruction with precise timing

Muon Detectors
- DTs & CSCs: new FE/BE readout electronics
- RPCs: new electronics
- new GEM/iRPC chambers
- extended muon coverage to |η| = 3

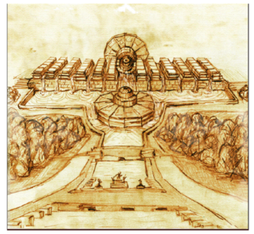
L1-Trigger
- track trigger at L1 (40 MHz)
- latency up to 12.5 μs
- triggers on displaced muons and long-lived particles

DAQ/HLT
- HLT output at 7.5 kHz

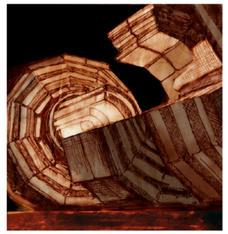
Beam Radiation Instrumentation and Luminosity (BRIL)
- BCM/PLT refit
- new T2 tracker



Yet to come (June 2021):



DAQ/HLT



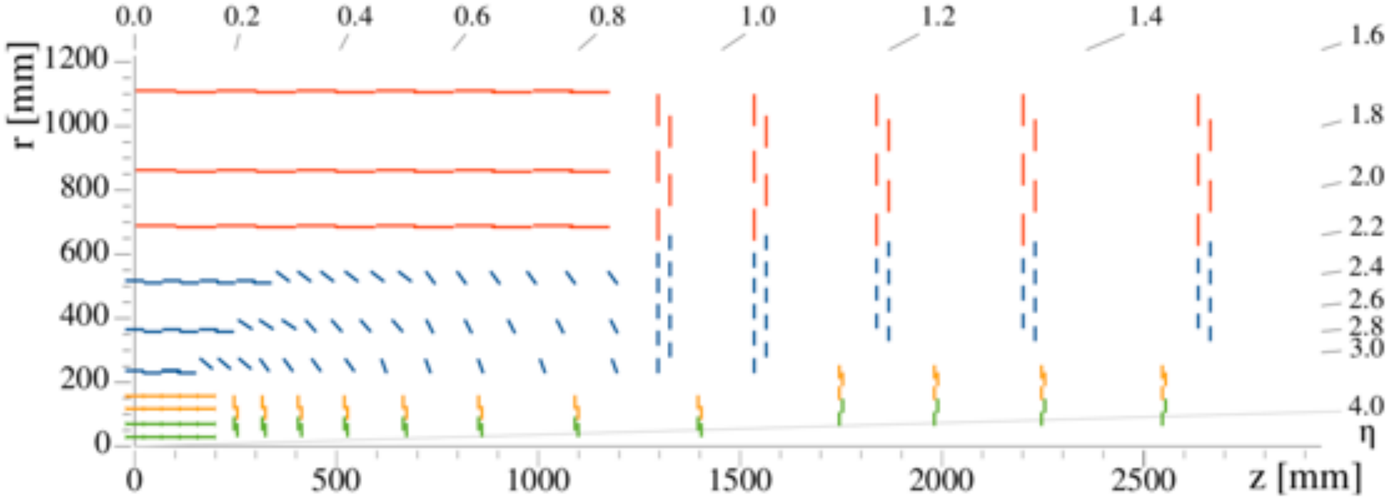
BRIL

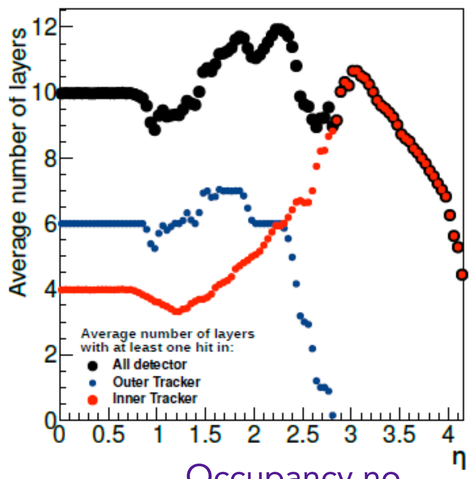
See talk by **Santiago Folgueras** on Friday

Phase-II Tracker Upgrade

Key features

- more granularity
- lower material budget
- extended coverage
- tracking included at L1-trigger level

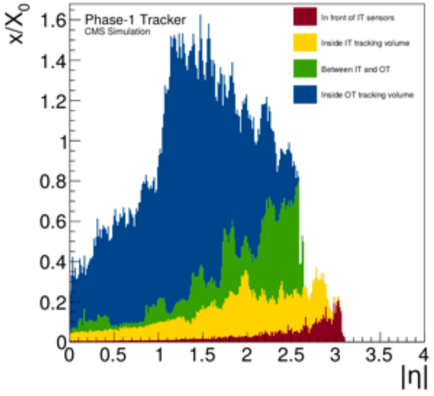




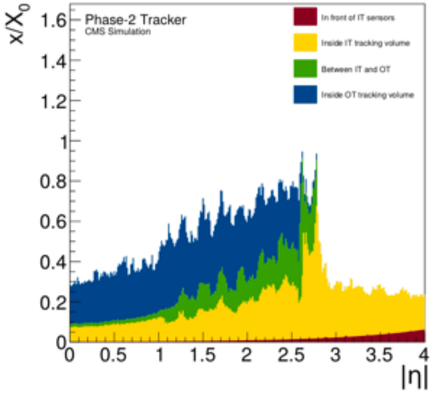
Occupancy no larger than 3%

Material budget

present tracker

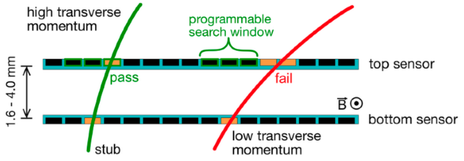


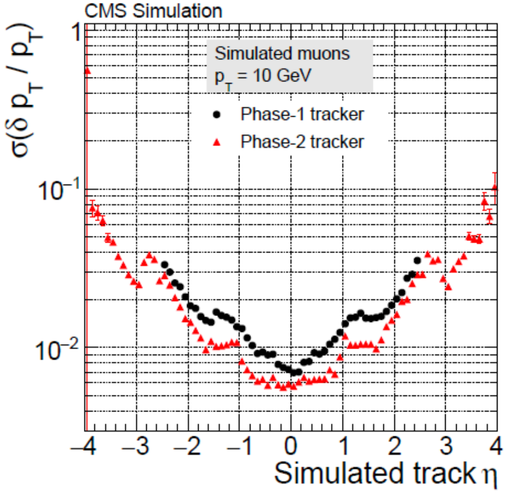
upgraded tracker



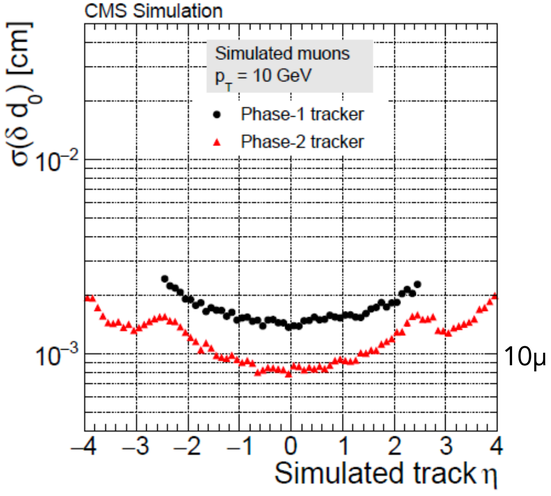
Expected performance compared to present tracker

Local rejection of low p_T tracks



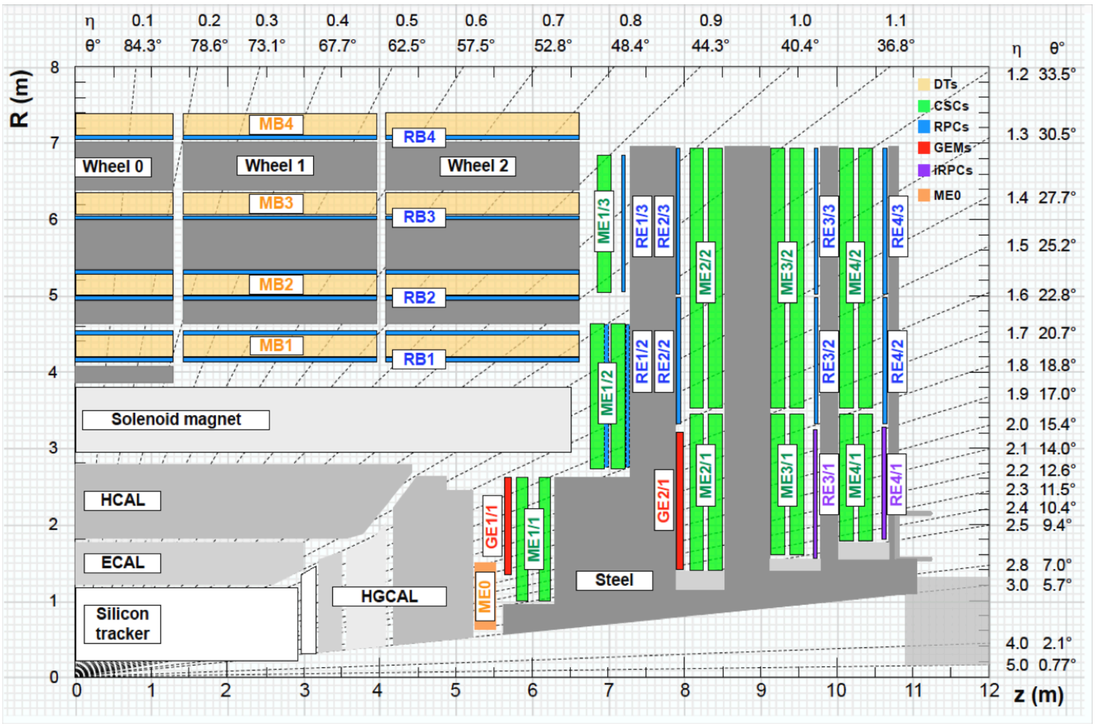


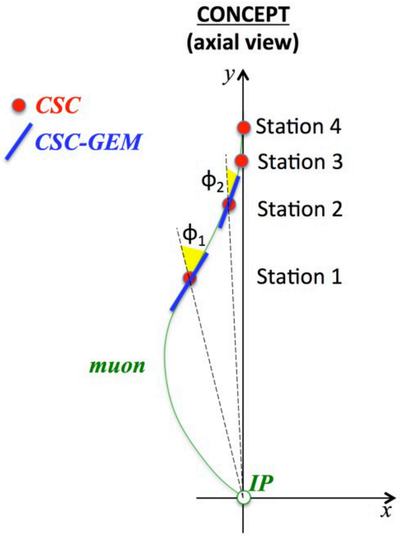
transverse momentum

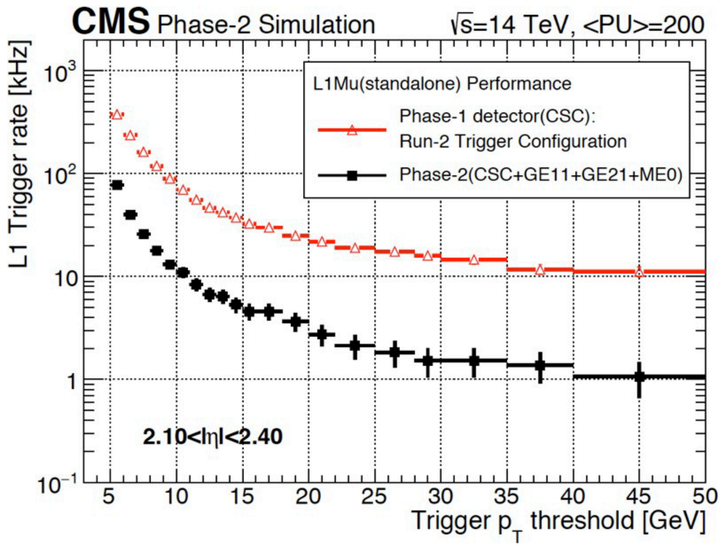


transverse impact parameter

Muon Detectors







Barrel and Endcaps

- Replacement of readout electronics for the new L1 trigger conditions

Athens/Ioànnina responsible for BMT Layer-1 HW and FW

Endcaps

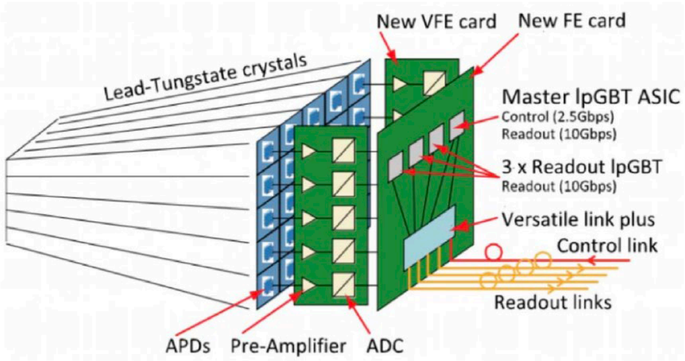
- Robust trigger up to |η| = 2.4 thanks to **RPC stations** RE3/1 and RE4/1 and 2-layer **GEM stations** GE1/1 and GE2/1
- Trigger extension up to |η| = 2.8 6-layer **GEM station** ME0

2 GEM/CSC "tandems"

- measurement of "local" μ direction (sensitive to p_T)
- standalone L1-trigger rate drops by factor up to 10
- important for off-pointing muon triggers (search for LLPs)

Calorimeters

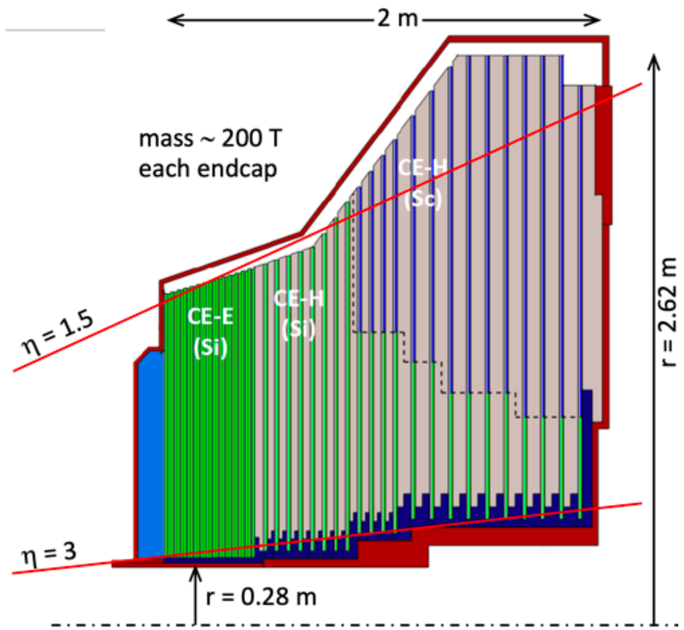
Barrel

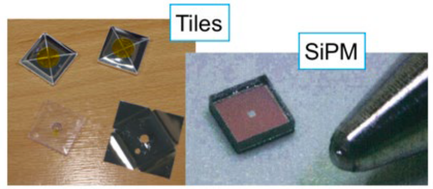


New ECAL on-detector electronics

- digitisation at 160 MHz
- online pulse shape discrimination against spikes
- trigger granularity = single crystal
- 30 ps time resolution (E_γ > 50 GeV)
- cooled at 9°C to mitigate APD ageing

Endcaps: High-Granularity Calorimeter (HGCAL)





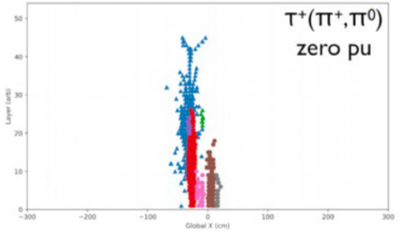
Electromagnetic (CE-E)

- Cu/CuW/Pb absorbers
- Si sensors, hexagonal modules
- 28 layers
- 25.5Xo and 1.7λ

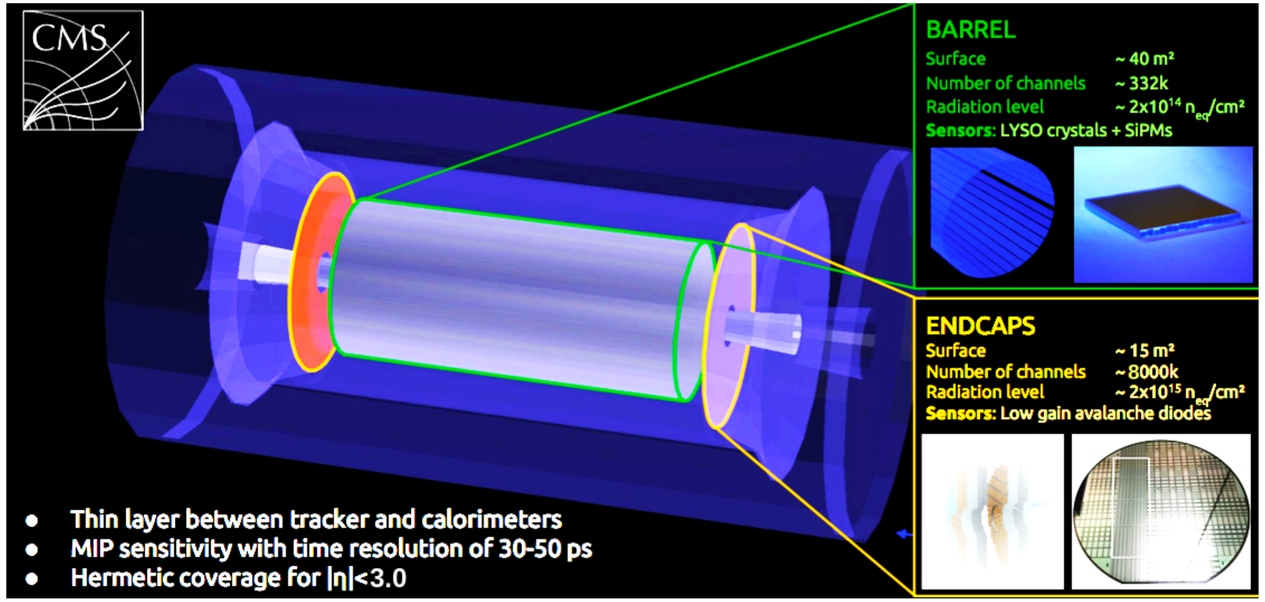
Hadronic (CE-H)

- steel absorbers
- High-radiation regions: Si sensors
- Low-radiation regions: scintillation tiles with SiPM readout
- 22 layers
- 9.5λ (including CE-E)

6M Si channels
240k scint. channels

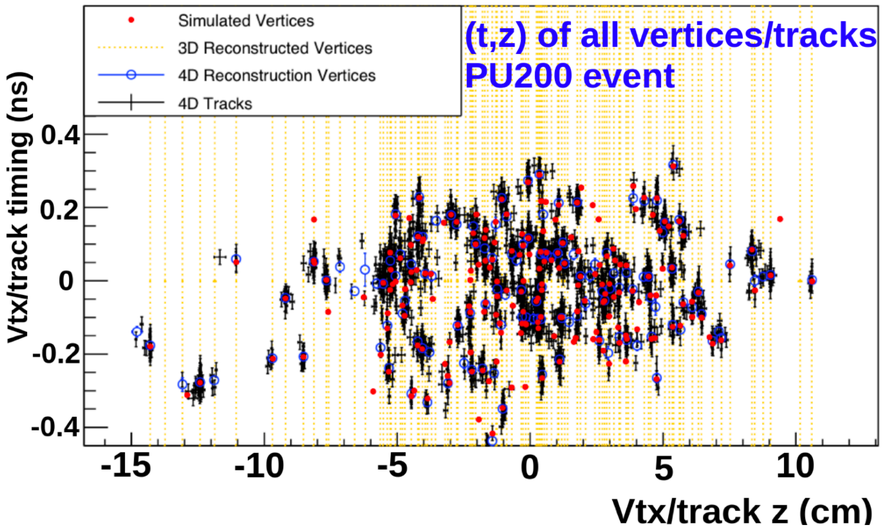


MIP Timing Detector



The MTD features

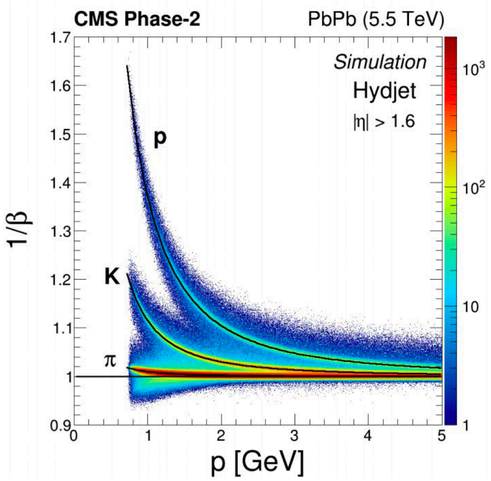
- a time resolution of 30-50 ps for MIPs
- a 4th dimension for PU rejection



Precise timing allows for the removal of spurious tracks from PU, this improving on

- lepton isolation and identification
- jet reconstruction and flavour tagging
- missing p_T reconstruction

Precise timing also offers time-and-flight identification at low momenta (relevant in HI)



The MTD uses well-established technologies

- Barrel:
  LYSO crystals with dual end SiPM readout
- Endcaps:
  Low Gain Avalanche Detectors (LGAD)

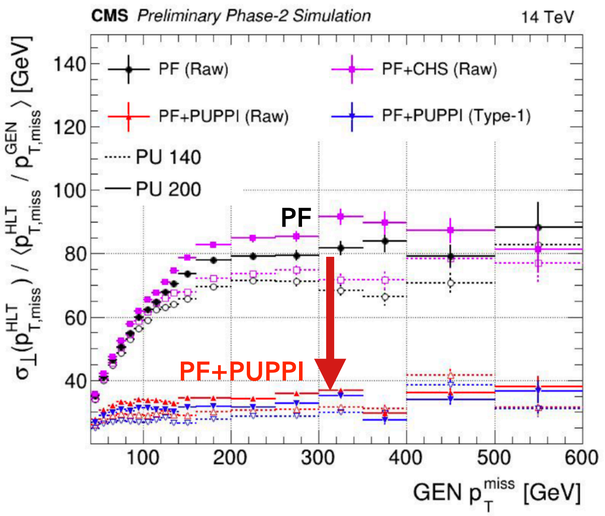
Highlights of Coming TDRs

Phase-II HLT (not aiming at demonstrating final performance)

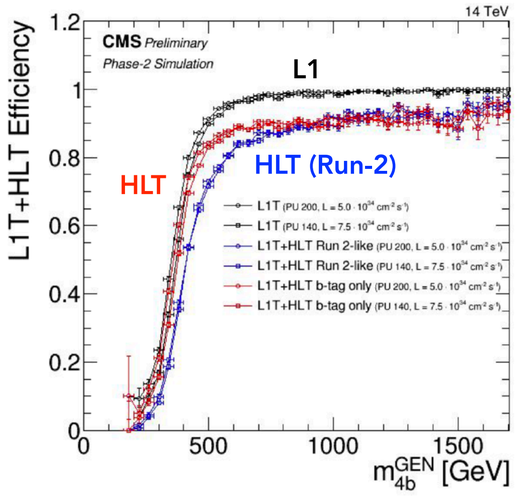
- Physics performance already matching expectations with thresholds similar to that of Run-2
- Timing-wise, **only** a factor ~2 still to be gained for Run-4

Phase-II Luminosity

- **Offline** bunch-by-bunch luminosity with **1%** precision
- **Online** & orbit integrated luminosity with **<2%** precision
  - even outside CMS data taking



Response-corrected MET resolution
The PUPPI algorithm (red) mitigates PU effectively.



$HH \to b\bar{b}b\bar{b}$ **trigger efficiency**
L1T (black), L1T+HLT with Run-2 algorithm (blue), L1T+HLT with lower p_T and H_T thresholds and DeepCSV b-jet tagging (red) for same rate (50Hz)

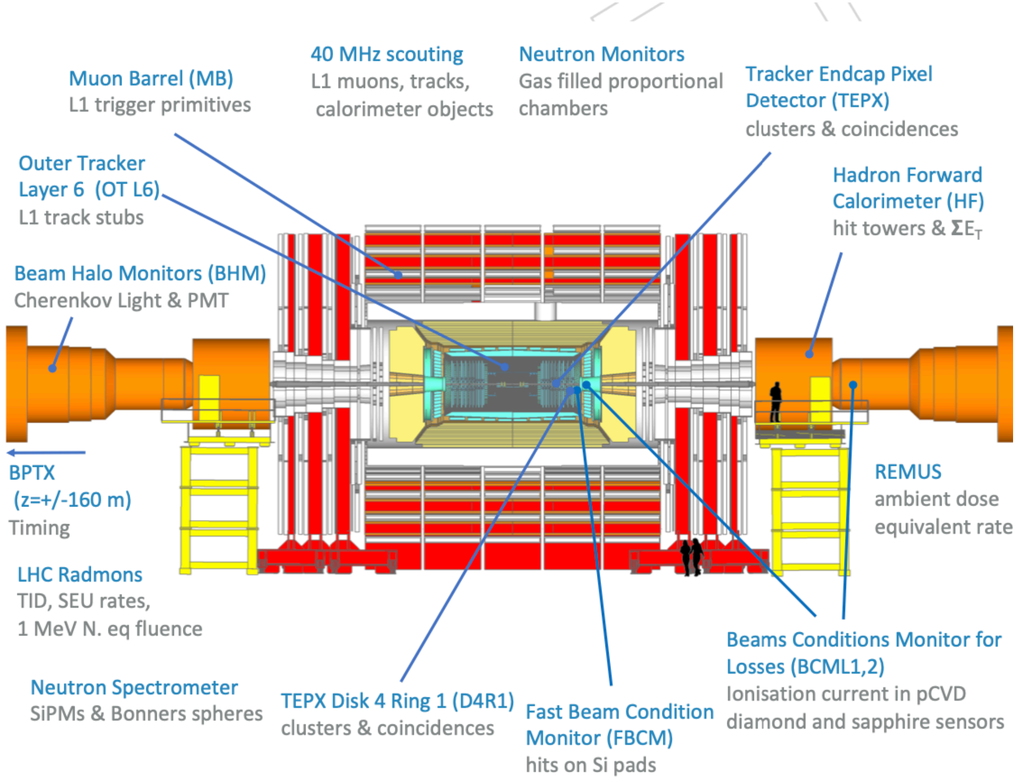


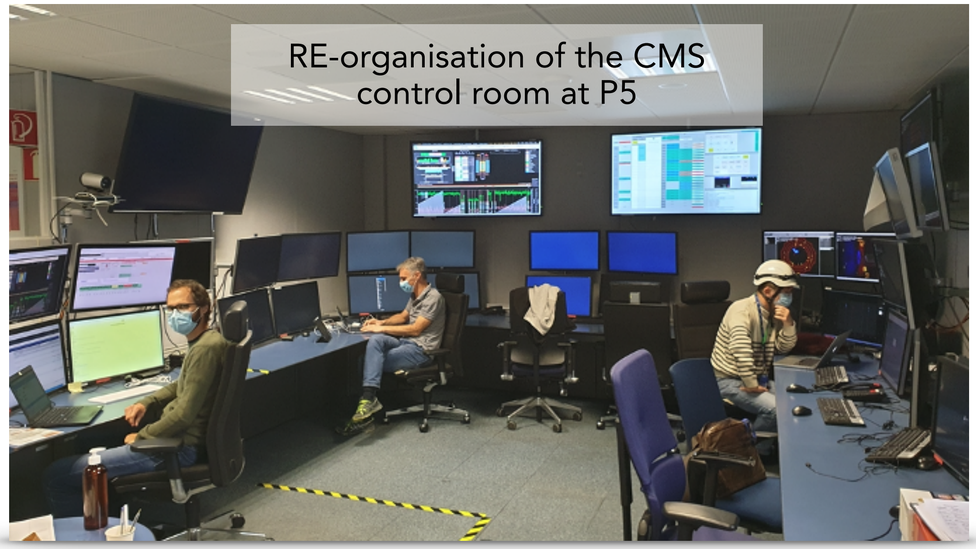
Figure 1.5: Subsystems to be used for the CMS BRIL Phase-2 measurements for HL-LHC.

Summary

Despite the pandemic, the CMS LS2 activities are progressing well

- upgrade of the Hadron Calorimeter *completed*
- first Phase-II muon detector *installed*
- new beam-pipe for Phase-II *installed*
- pixel detector *fully refurbished*

CMS is looking forward to the **LHC Pilot Beam Test** and the **start of the Run-3**



Phase-II Upgrades

- excellent progress in all projects, but tighter schedule due to the pandemic
- two upcoming TDRs: **DAQ/HLT** and **BRIL**

CMS continues to deliver physics results at a steady pace

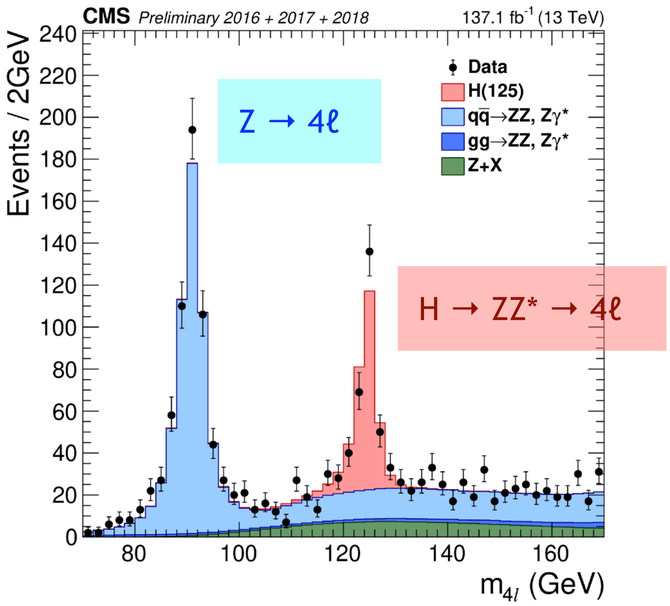
- no indication of loss of productivity
- however, signs of stress, especially among our younger collaborators

Great physics ahead of us!

We are continuously monitoring the **impact of the pandemic** on our activities and our collaborators. We are mindful of the **long-term effects** that the pandemic may have.

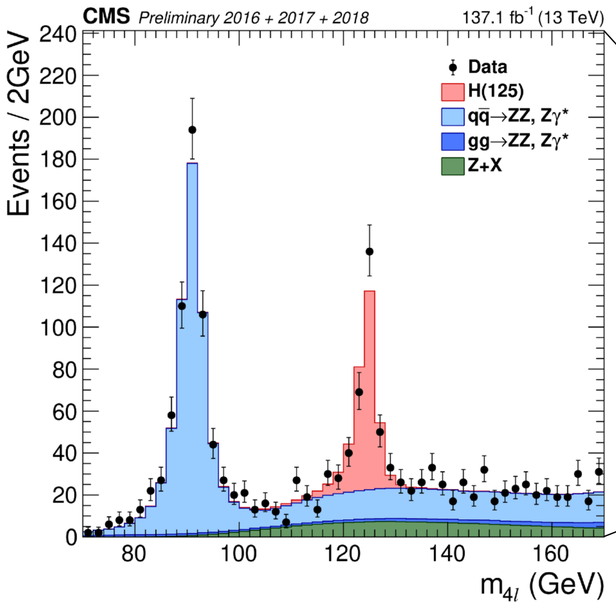
It's Only the Beginning!

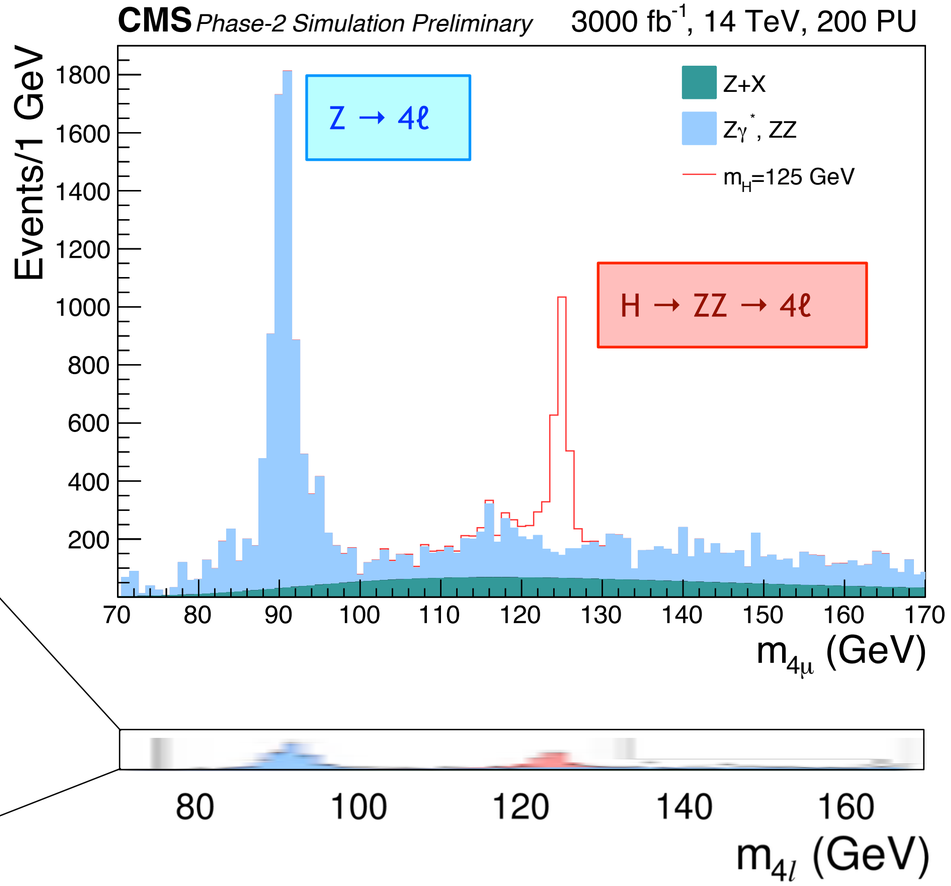
CMS Run-2
$\sqrt{s}$ = 13 TeV
L = 137 fb^{-1}



It's Only the Beginning!

CMS Run-2
$\sqrt{s}$ = 13 TeV
L = 137 fb^{-1}





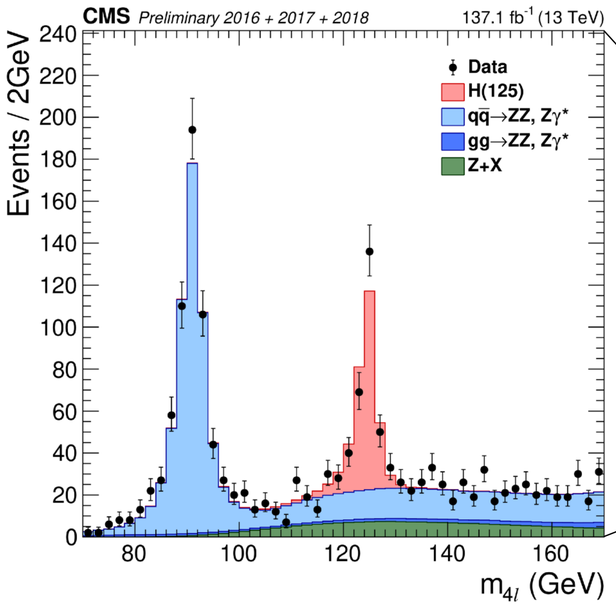
CMS HL-LHC
$\sqrt{s}$ = 14 TeV
L = 3 ab^{-1}

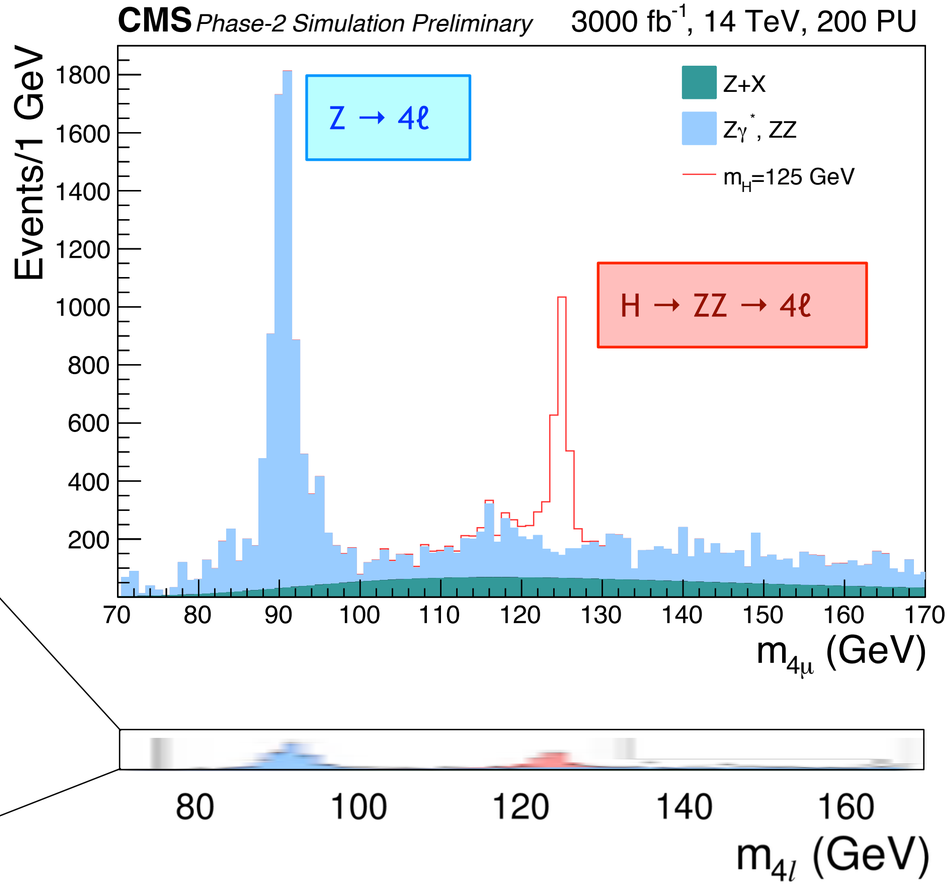
It's Only the Beginning!

LS3 = Long shutdown 3
- 2.5 years
- starting end of 2024
- installation of upgraded detectors

HL-LHC (Run 4-5)
- starting mid-2027
- $\sqrt{s}$ = 14 TeV
- $<\mu>$ = 140-200
- $\mathscr{L}$ up to 7.5 10^{34}
- L > 3000 fb^{-1}

CMS Run-2
$\sqrt{s}$ = 13 TeV
L = 137 fb^{-1}





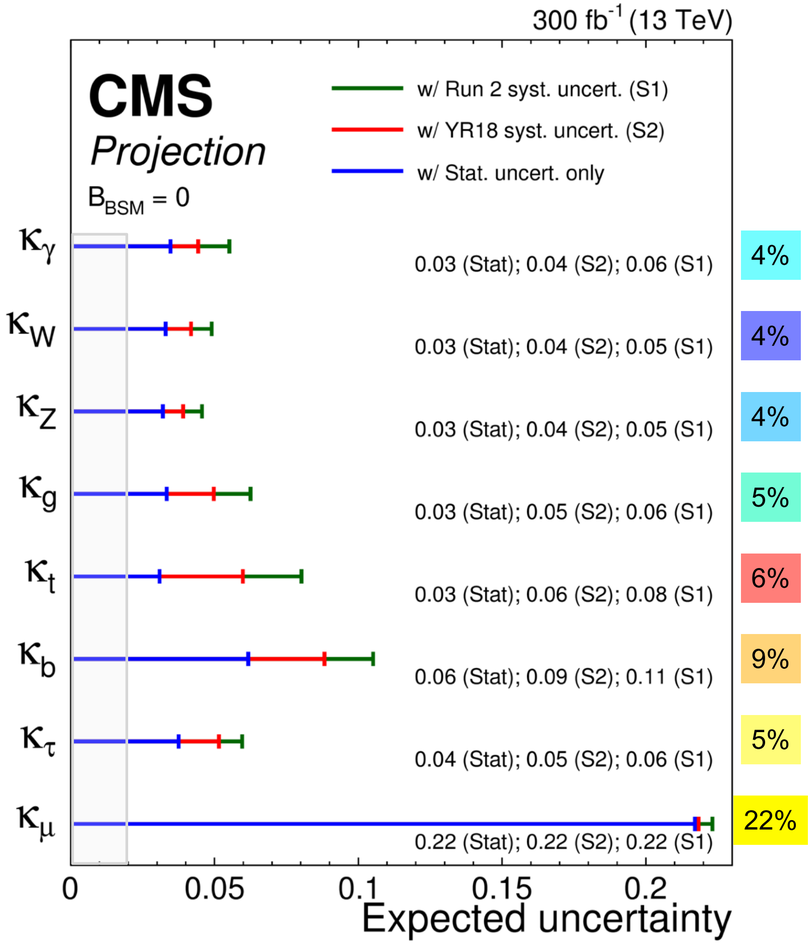
CMS HL-LHC
$\sqrt{s}$ = 14 TeV
L = 3 ab^{-1}

CMS-TDR-17-002

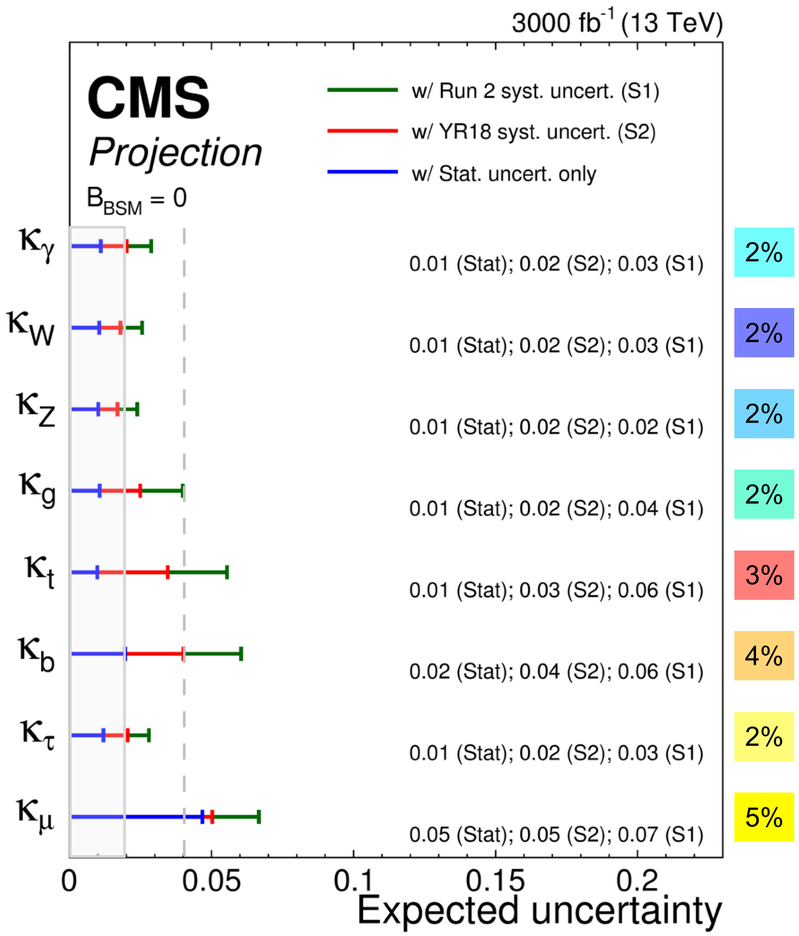
➠ HL-LHC ATLAS/CMS: expect 20-30 MeV resolution on Higgs boson mass

HL-LHC: Coupling Modifiers

CMS End of Run-3
13 TeV
300 fb^{-1}



CMS HL-LHC
13 TeV
3 ab^{-1}



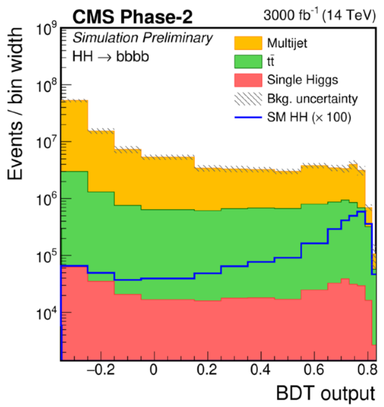
Most Higgs couplings known to better than 4%, dominated by systematic uncertainties

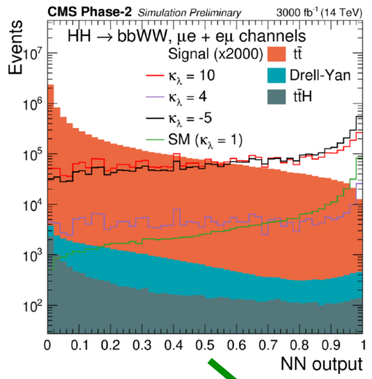
CMS-PAS-FTR-18-011

HL-LHC: Higgs Self Coupling

for most channels, $t\bar{t}H$ is the main background

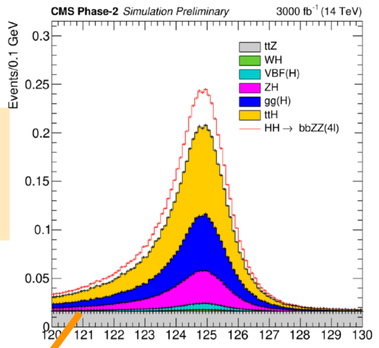
$b\bar{b}b\bar{b}$
exploit resolved and boosted b-jets



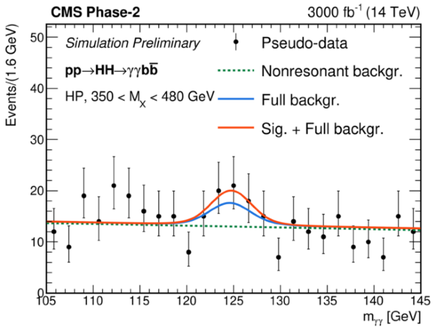


$b\bar{b}WW^*(\ell\nu\ell\nu)$
main bkg: $t\bar{t}$

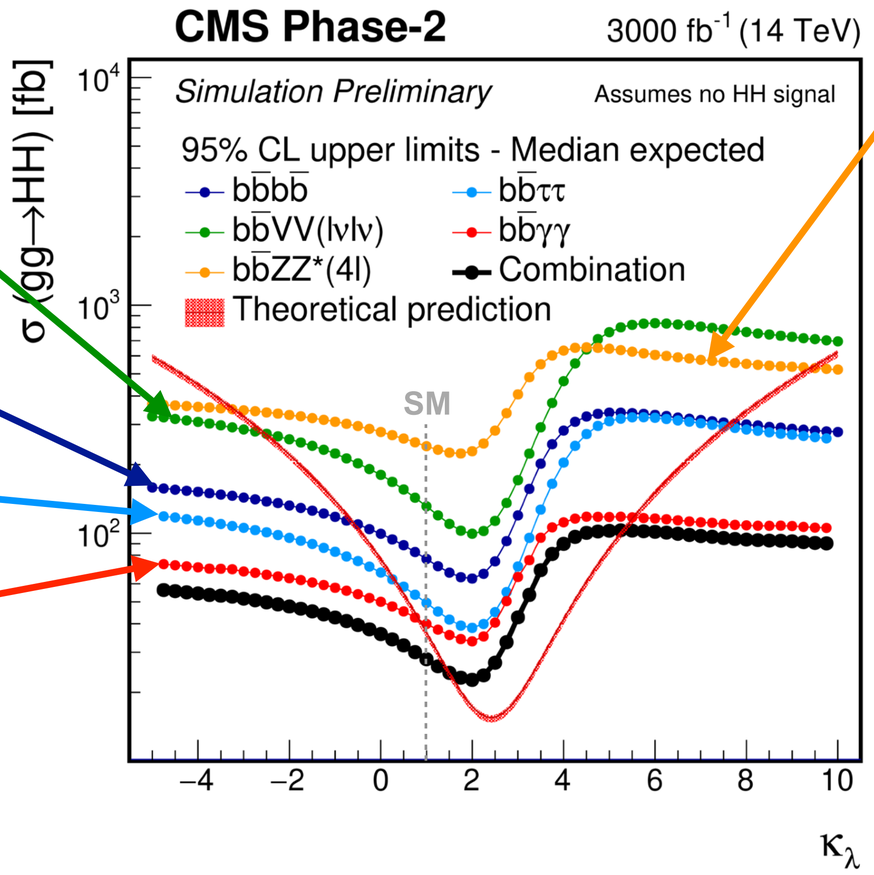
$b\bar{b}ZZ^*(4\ell)$
very rare but clean final state



$b\bar{b}\tau\tau$
irreducible bkg: $Z(\tau\tau)b\bar{b}$

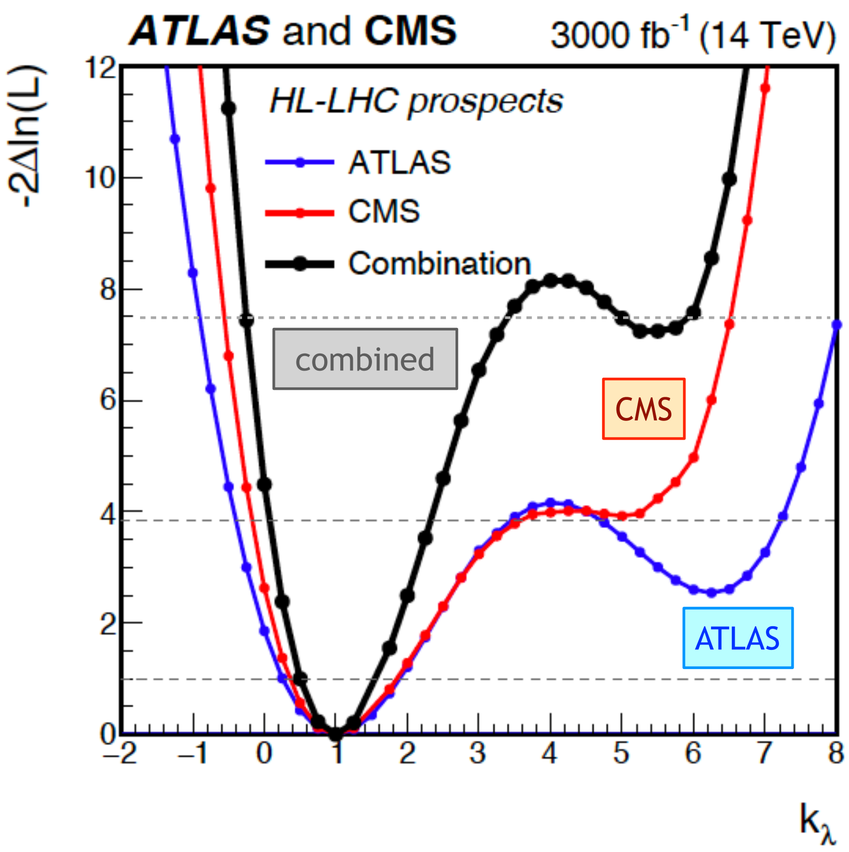


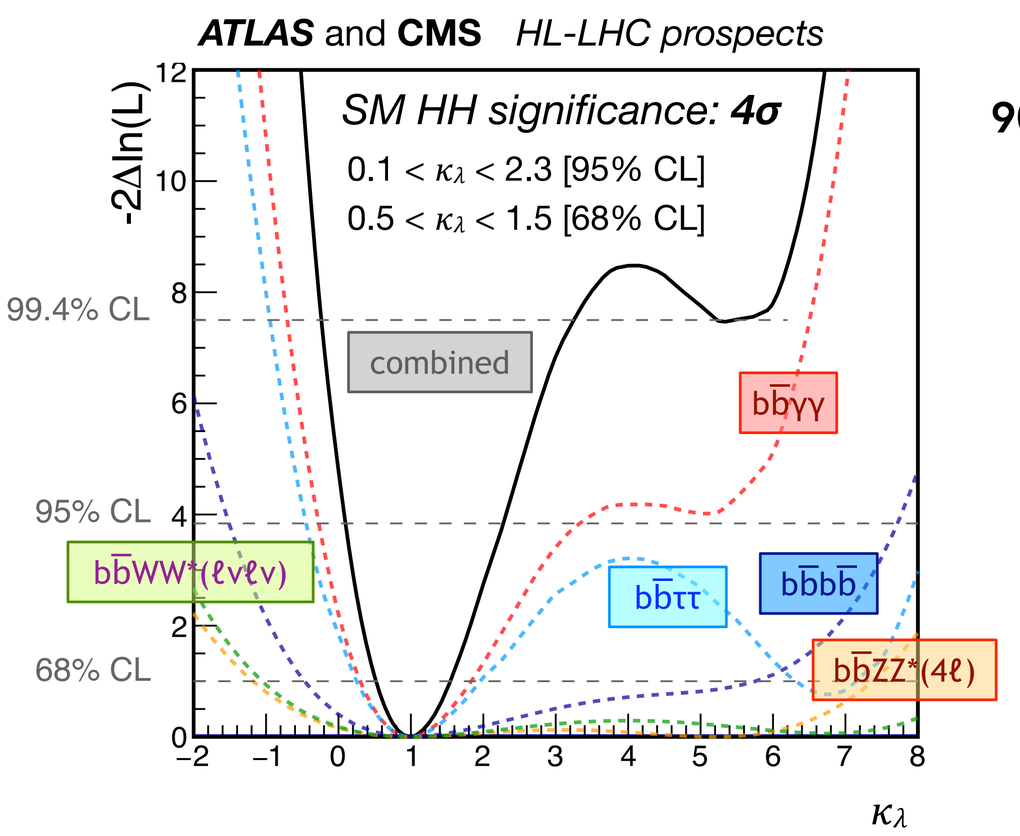
$b\bar{b}\gamma\gamma$
peaking $t\bar{t}H$ and non-resonant $b\bar{b}\gamma\gamma$



CMS-PAS-FTR-18-019

HL-LHC: Higgs Self-Coupling



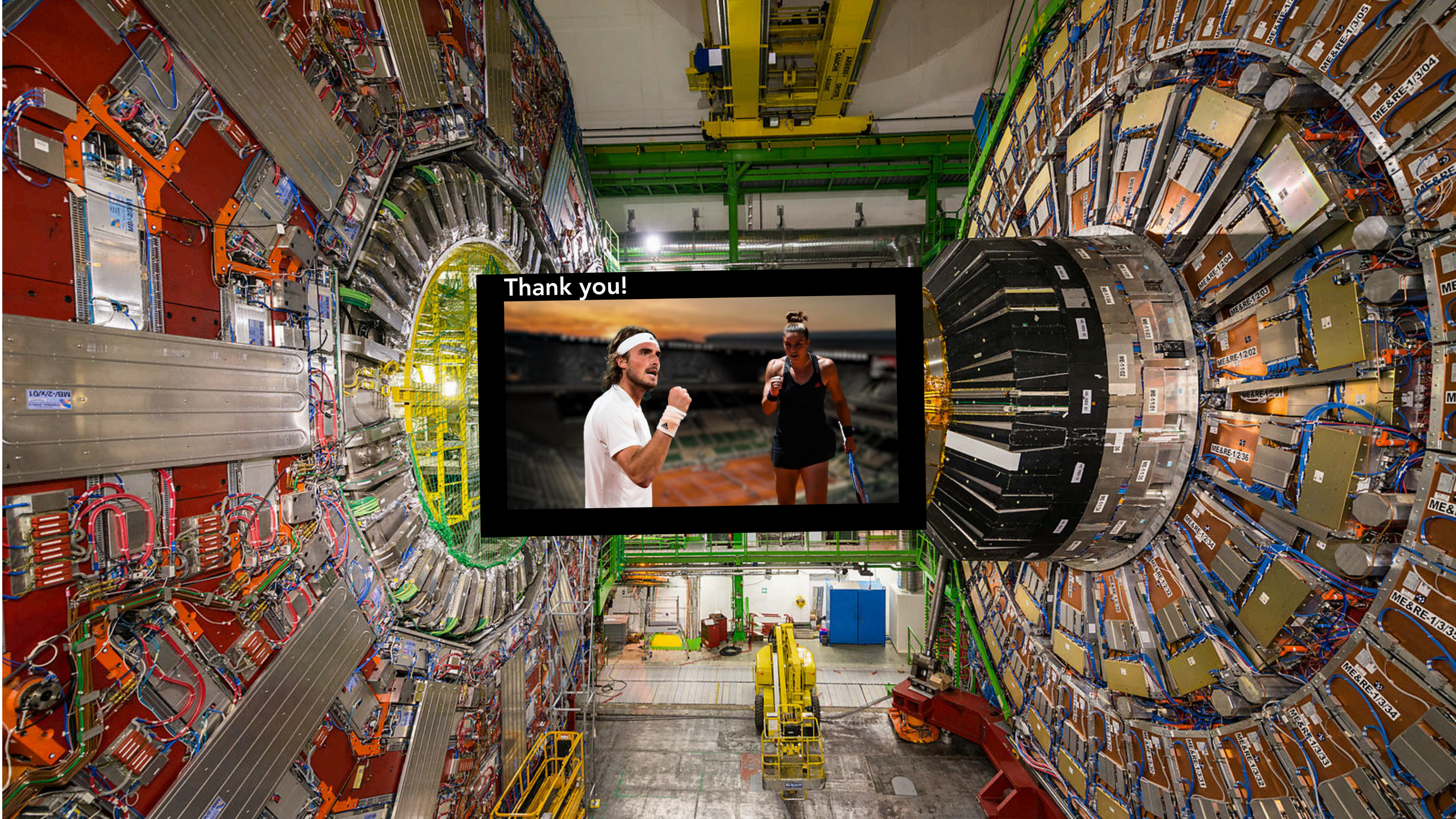


90k HH pairs produced

combined significance: 4σ

κ_λ "measured" with a precision of ±50%

HL/HE-LHC WG2


Thank you!

Recent CMS Preliminary Results

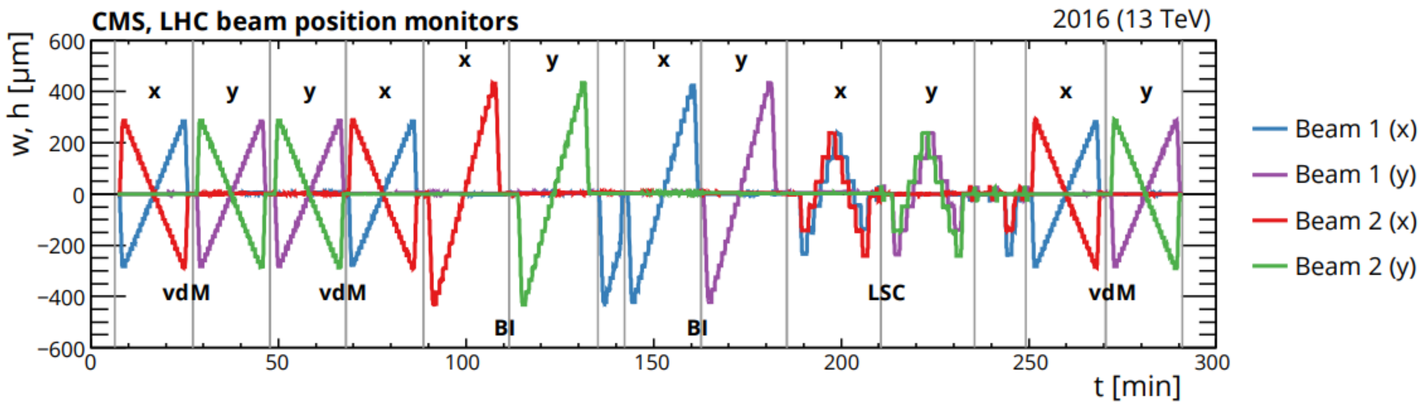
- Search for Higgs boson pair production in the four b quark final state
  CMS-PAS-HIG-20-005
- Search for high mass trijet resonances using final states with boosted dijet resonances in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-EXO-20-007
- Inclusive and differential cross section measurements of single top quark production in association with a Z boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-TOP-20-010
- Measurement of the shape of the b quark fragmentation function using charmed mesons produced inside b jets from tt pair decays
  CMS-PAS-TOP-18-012
- Measurement of the inclusive and differential Higgs boson production cross sections in the decay mode to a pair of τ leptons
  CMS-PAS-HIG-20-015
- Search for flavor-changing neutral current interactions of the top quark and the Higgs boson in the diphoton decay channel in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-TOP-20-007
- Search for charged lepton flavor violation in top quark production and decay in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-TOP-19-006
- Probing effective field theory operators in the associated production of top quarks with a Z boson in multilepton final states at $\sqrt{s}$ = 13 TeV
  CMS-PAS-TOP-21-001
- Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-EXO-20-004
- Measurement of multi-differential cross sections for the production of a Z boson in association with jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-SMP-19-009
- Search for long-lived particles decaying into two muons in proton-proton collisions at $\sqrt{s}$ = 13 TeV using data collected with high rate triggers
  CMS-PAS-EXO-20-014
- Search for Higgs boson decays into long-lived particles in associated Z boson production
  CMS-PAS-EXO-20-003
- Search for long-lived particles decaying in the CMS endcap muon system in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-EXO-20-015
- Observation of the B_c^+ meson in PbPb and pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  CMS-PAS-HIN-20-004
- Strange particle collectivity in pPb and PbPb
  CMS-PAS-HIN-19-004
- Luminosity measurement in proton-proton collisions at 5.02 TeV in 2017 at CMS
  CMS-PAS-LUM-19-001
- Measurement of mass dependence of the transverse momentum of Drell Yan lepton pairs in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-SMP-20-003
- Search for resonances decaying to triple W-boson final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  CMS-PAS-B2G-20-001

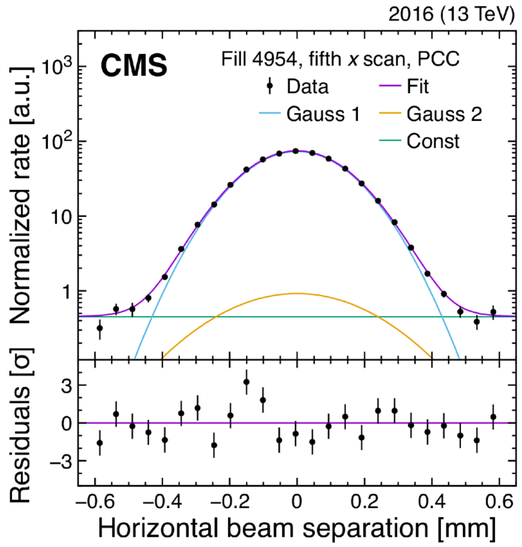
Back up Slides

Precision Luminosity Measurements

Absolute luminosity scale measured for individual bunch crossings

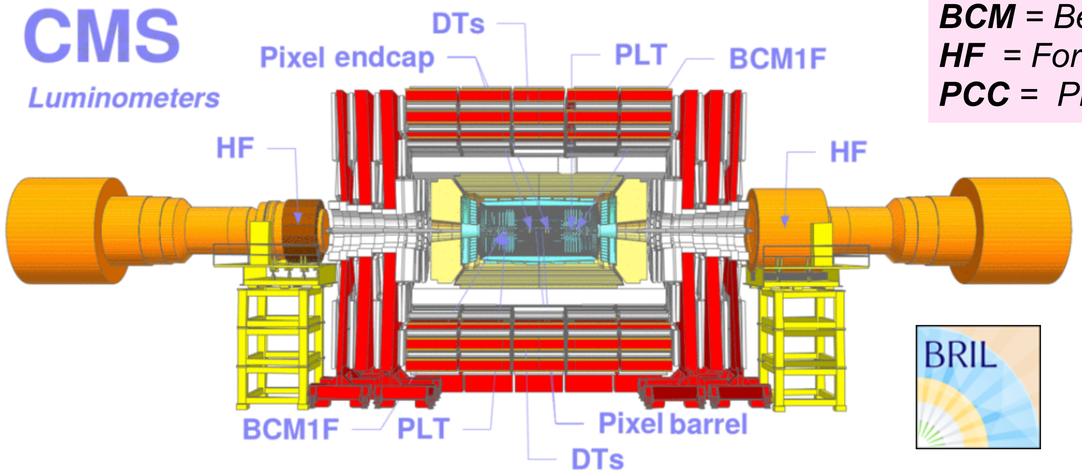
beam-separation
van der Meer scans





Obtained **relative precision**
- **1.6% in 2015** (2.2 fb^{-1})
- **1.2% in 2016** (36.3 fb^{-1})

Main sources of uncertainties
- differences between measured beam positions and the ones provided by the LHC
- factorizability of the transverse spatial distributions of proton bunches
- modelling of interactions among protons in the colliding bunches



PLT *= Pixel Luminosity Telescope*
BCM *= Beam Conditions Monitor*
HF *= Forward Hadron Calorimeter*
PCC *= Pixel Cluster Counting*

CMS-LUM-17-003
Submitted to EPJC

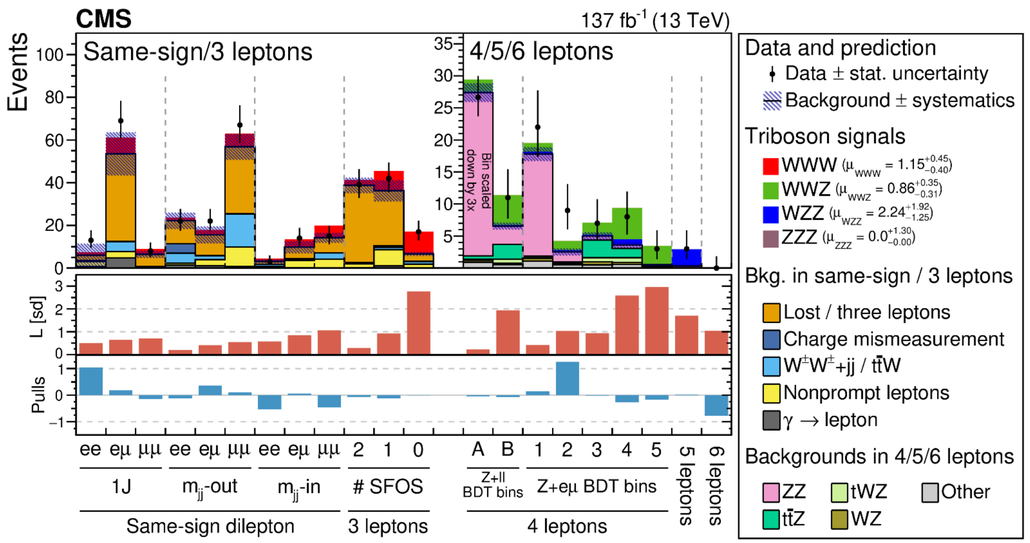
Phys. Briefing

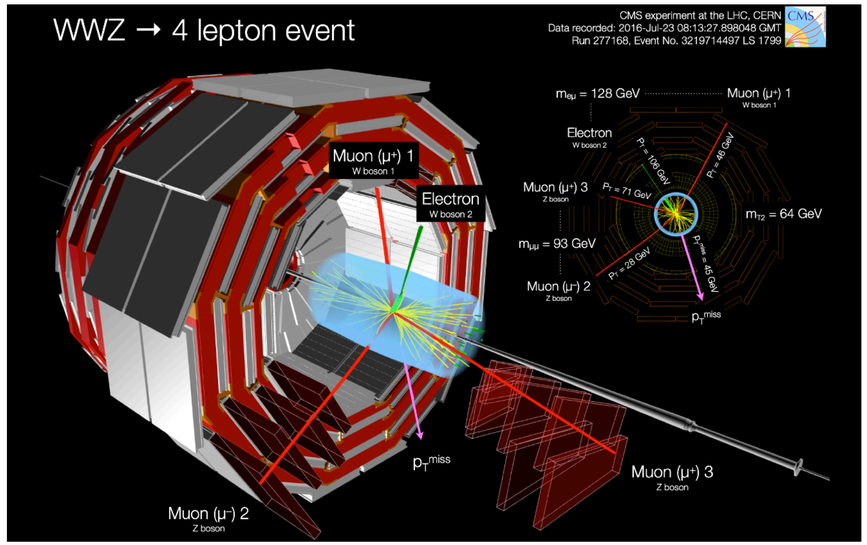
And also:
- 1.9% in 2017 at $\sqrt{s}$ = 5.02 TeV (302 pb^{-1})

CMS-PAS-LUM-19-001

Observation of 3-Boson Production

Leptonic final states



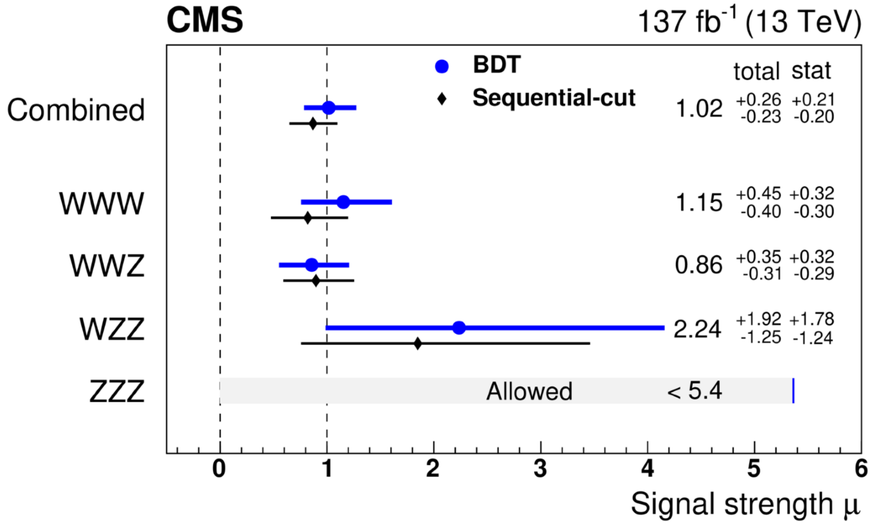


Full Run-2, 137 fb^{-1}

Observation of VVV production (5.7σ), **evidence for WWW and WWZ** (3.3σ)

CMS-SMP-19-014
PRL125 (2020) 151802

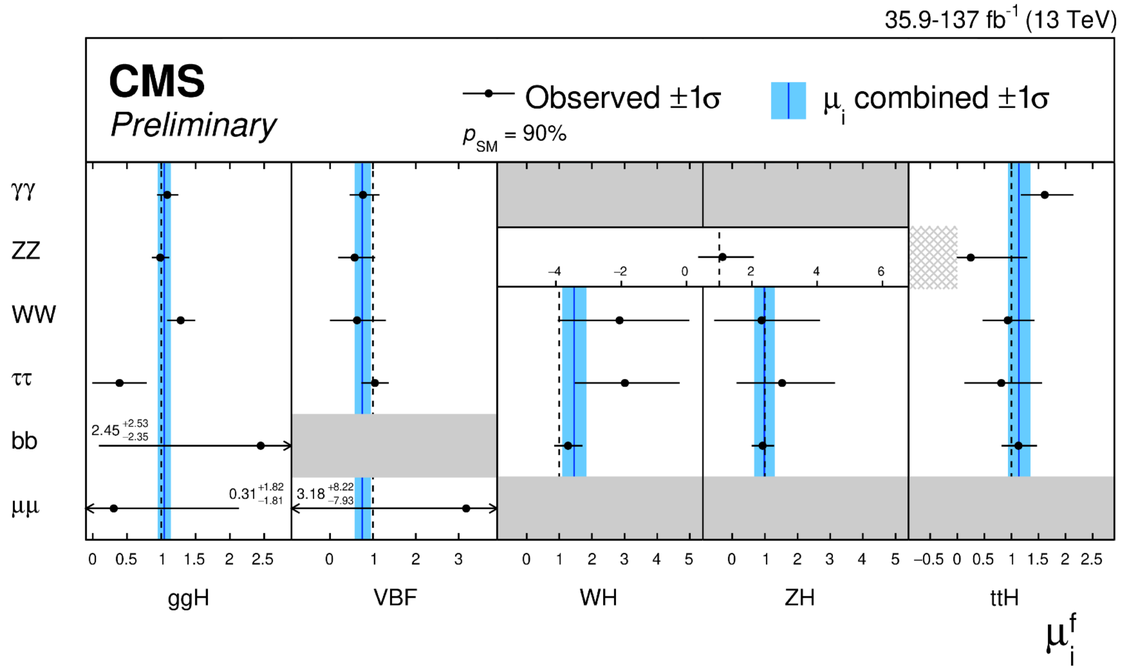
Phys. Briefing

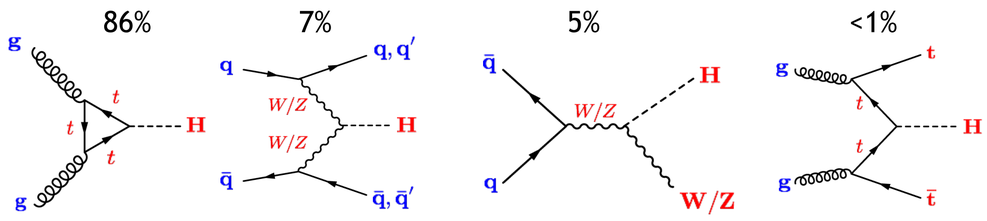


Process	Cross section (fb)
Treating Higgs boson contributions as signal	
VVV	$1010^{+210}_{-200}{}^{+150}_{-120}$
WWW	$590^{+160}_{-150}{}^{+160}_{-130}$
WWZ	$300^{+120}_{-100}{}^{+50}_{-40}$
WZZ	$200^{+160}_{-110}{}^{+70}_{-20}$
ZZZ	<200
Treating Higgs boson contributions as background	
VVV	$370^{+140}_{-130}{}^{+80}_{-60}$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

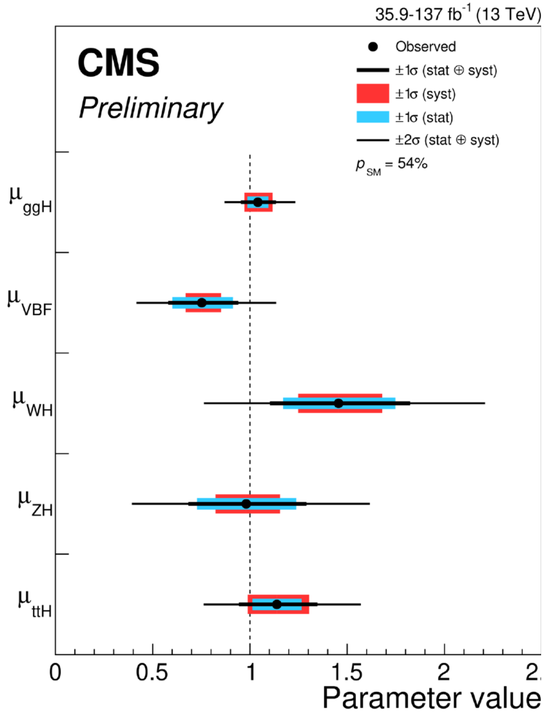
Higgs Production and Decay

Signal strength modifiers for the production × decay mode

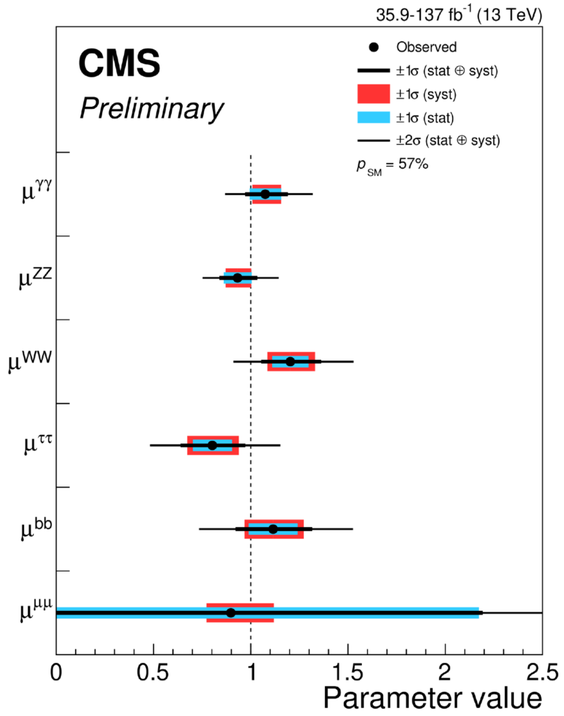




Production



Decay



CMS-PAS-HIG-19-005

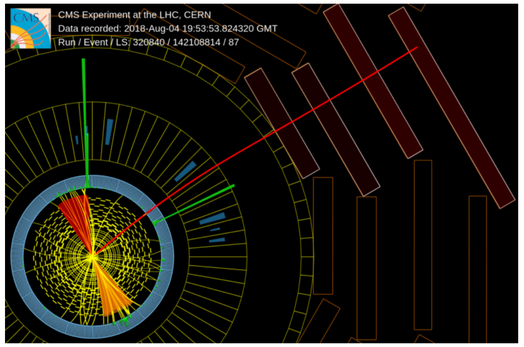
ttH Measurements

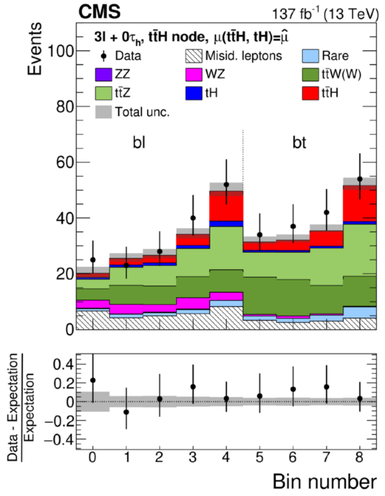
Multi-lepton final states (e, μ, τ_h)

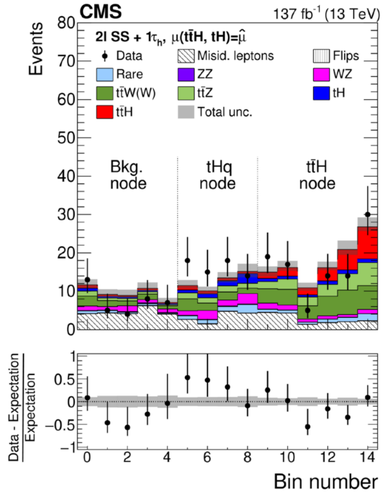
mostly $H \to WW, ZZ, \tau\tau$

CMS-HIG-19-008
Accepted by EPJC

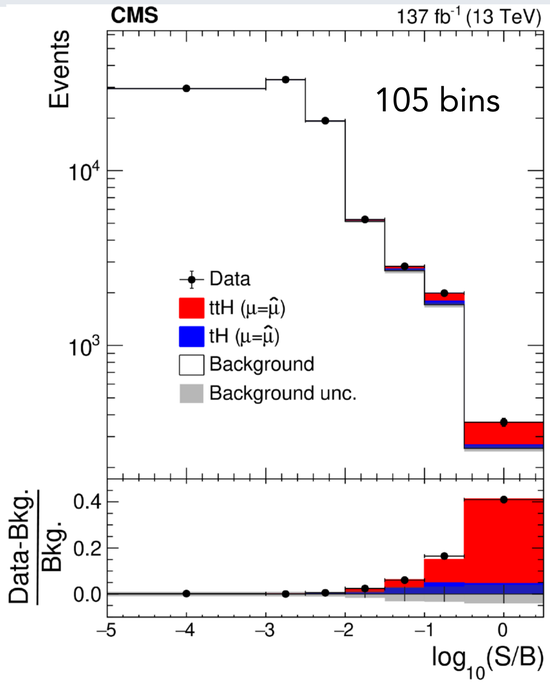
Phys. Briefing

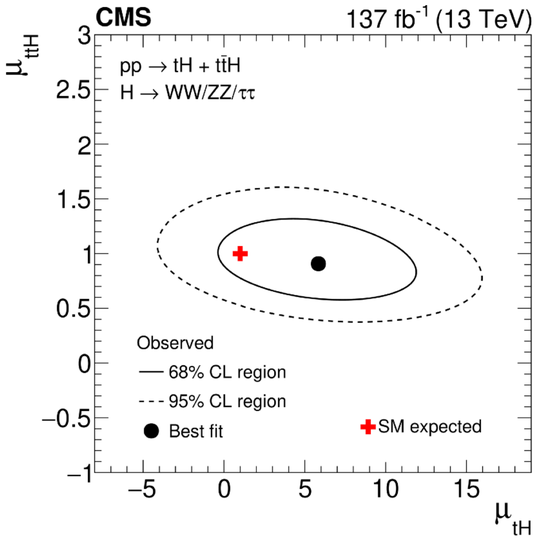




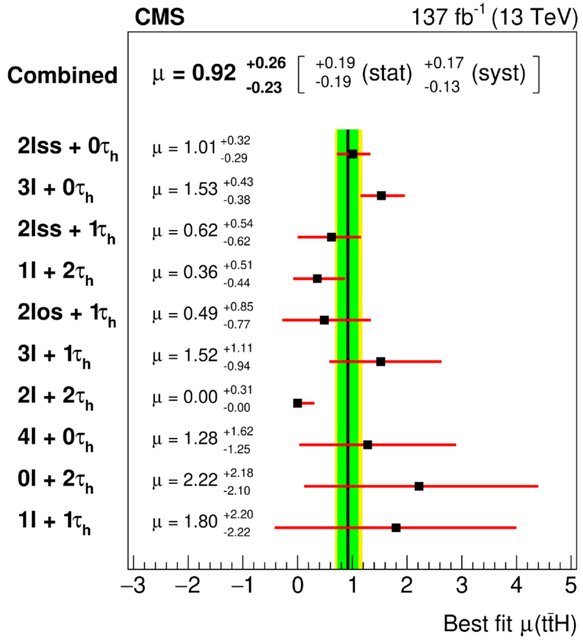


activation value of the ANN output node
with the highest activation value





Full Run-2, 137 fb^{-1}



$$\mu(t\bar{t}H) = 0.92 \pm 0.19\,(\text{stat})^{+0.17}_{-0.13}(\text{syst})$$

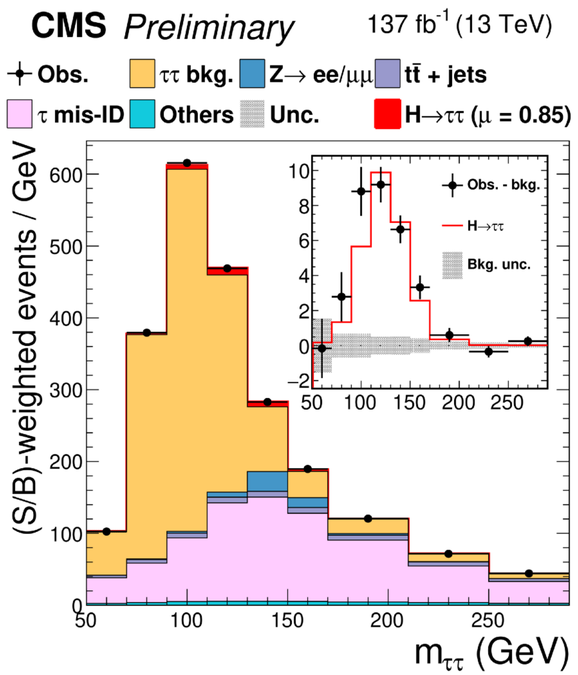
Obs. (exp.) significance: 4.7 (5.2) σ

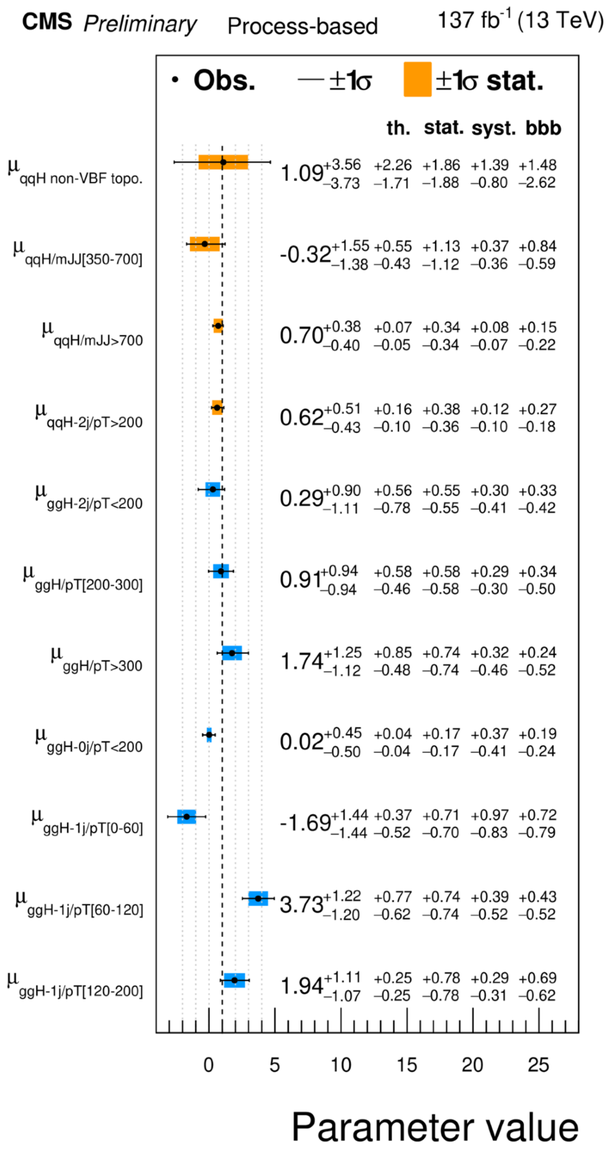
$$\mu(tH) = 5.7 \pm 2.7\,(\text{stat}) \pm 3.0\,(\text{syst})$$

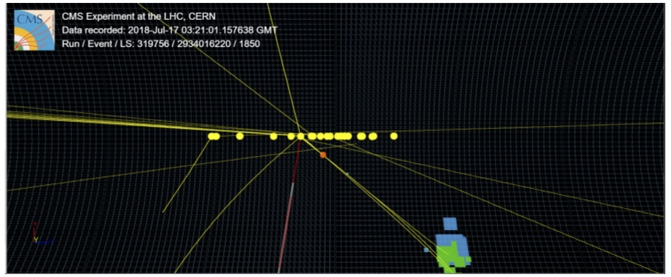
Phys. Briefing

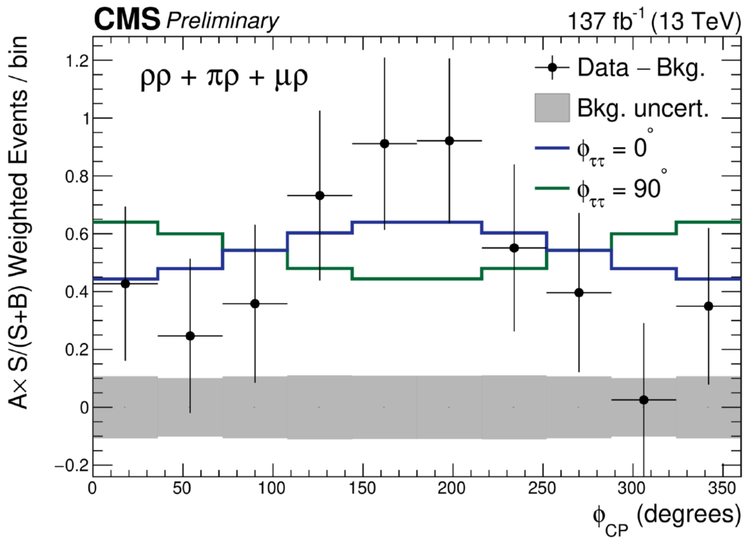
$H \to \tau\tau$ and STXS

Full Run-2, 137 fb^{-1}









3.2σ exclusion of pure CP-odd

[CMS-PAS-HIG-19-010]

[CMS-PAS-HIG-20-006]

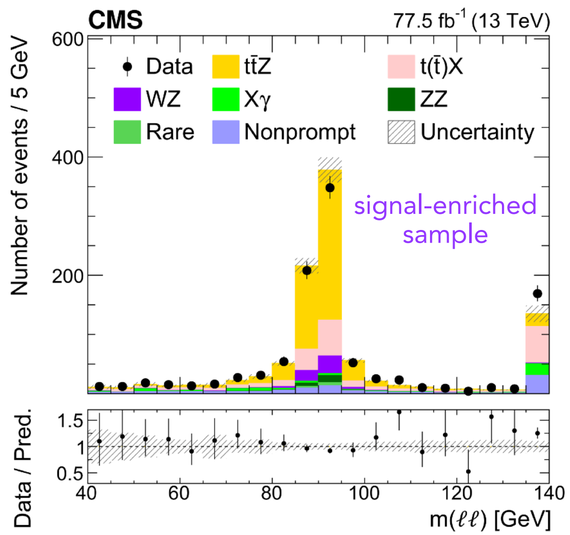
[Phys. Briefing]

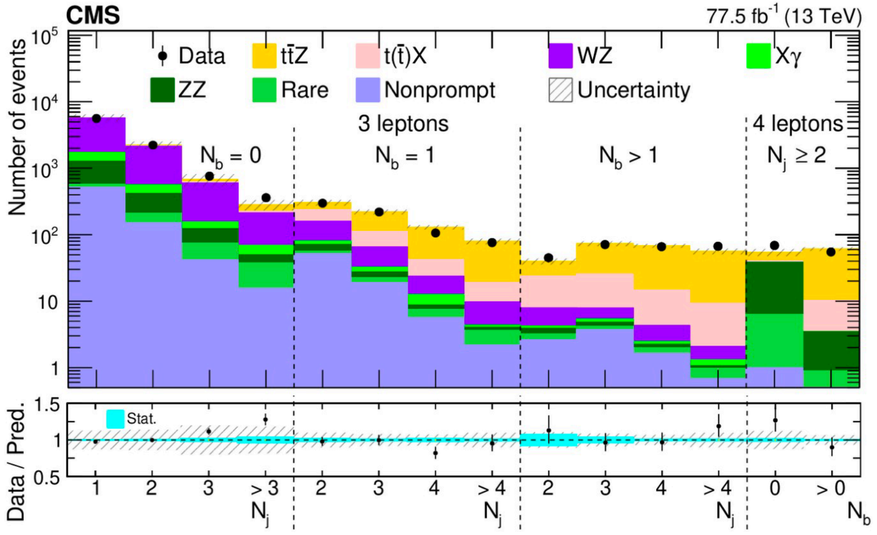
tt+Z and tt+γ

CMS-TOP-18-009
JHEP 03 (2020) 056

Run-2 2016-17, 77.5 fb⁻¹

Events with one Z(→ℓℓ) plus at least one lepton (e or μ), $N_j > 0$ and $N_b \geq 0$



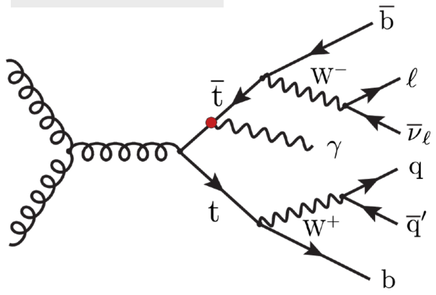


$$\sigma(t\bar{t}Z) = 0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}$$

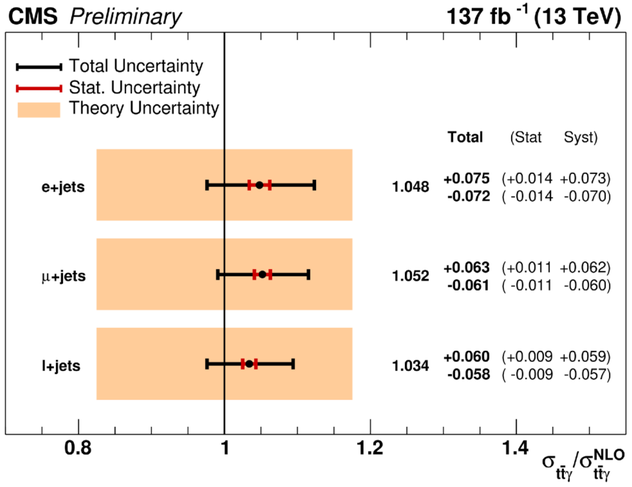
good agreement with theory NLO(QCD+EWK) +NNLL

CMS-PAS-TOP-18-010

Phys. Briefing

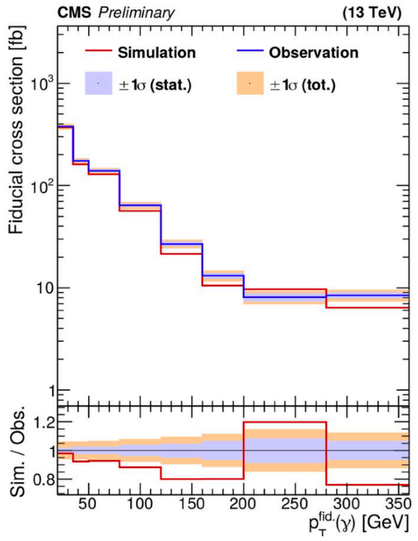


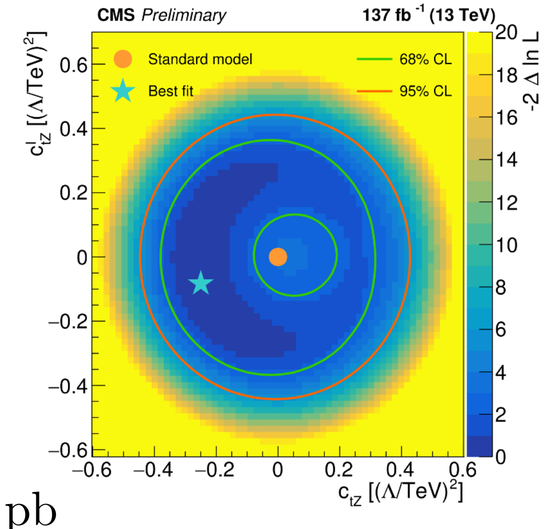
Hard isolated photons in ℓ+jets events



$$\sigma(t\bar{t}\gamma, p_T^{\gamma} > 20\,\text{GeV}) = 0.800 \pm 0.007\,(\text{stat}) \pm 0.046\,(\text{syst})\,\text{pb}$$

Full Run-2, 137 fb⁻¹





Jet Structure in Heavy Ion Collisions

Run-2 $\sqrt{s_{NN}}$ = 5.02 TeV, pp 320 pb^{-1}, PbPb 1.7 nb^{-1}

Study of in-medium modification of jets structure in back-to-back di-jets events in PbPb versus pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

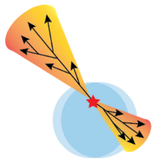
- jet shape (normalised distance to jet axis Δr) in bins of jet unbalance x_j and centrality

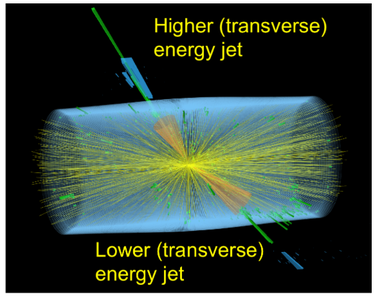
Excess of low-pT particles in PbPb compared to pp

- larger excess in subleading jets

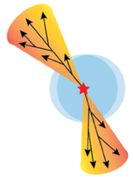
Redistribution of energy from smaller to larger angles in PbPb vs pp

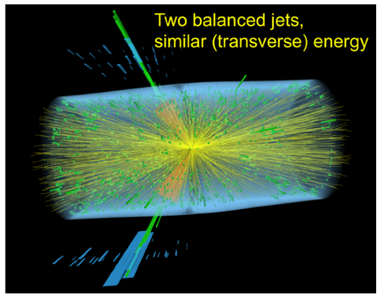
- larger for leading jets



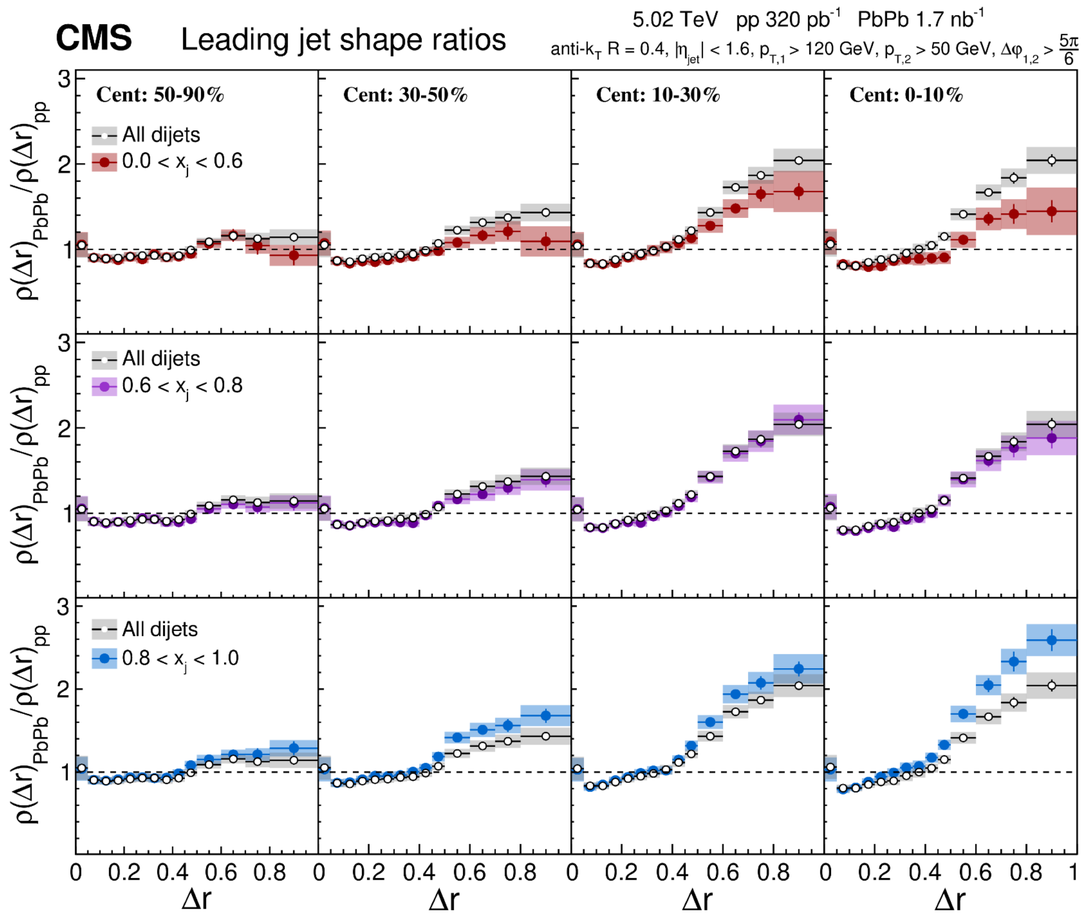


jet balance





centrality



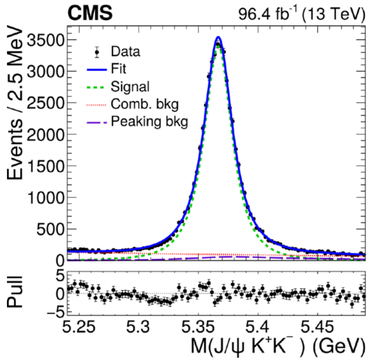
CMS-HIN-19-013
Approved by JHEP

Phys. Briefing

new constraints to the theoretical models

Angular Analysis of $B_s^0 \to J/\Psi\ \phi$ Decays

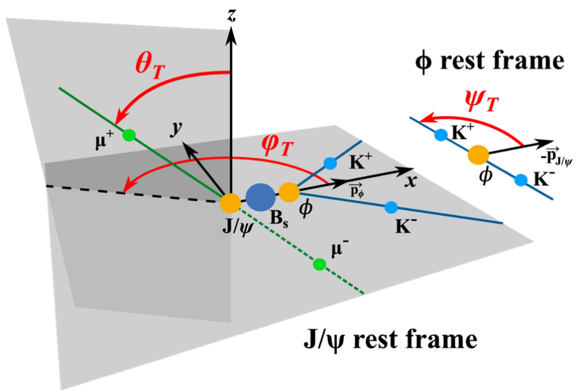
Phys. Briefing

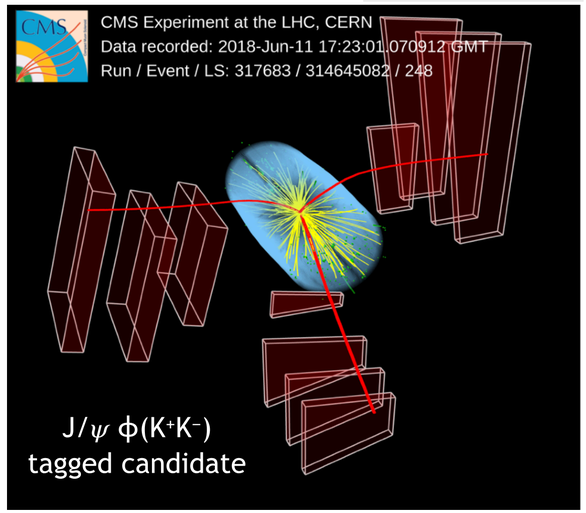


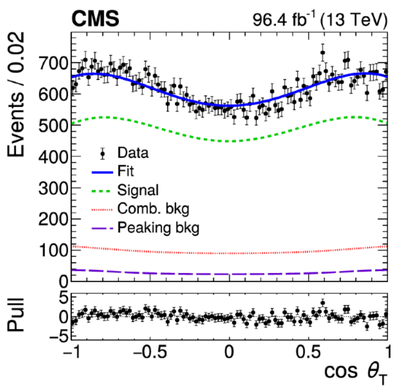
Run-2 2017-18, 96.4 fb^{-1}

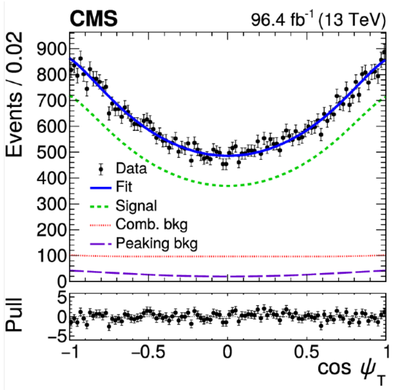
CMS-BPH-20-001
PLB 816 (2021) 136188

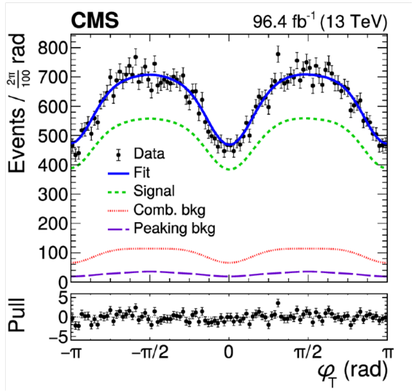
48,500 signal
$B_s^0 \to J/\psi\ \phi(K^+K^-)$ events











novel opposite-side muon tagger based on deep neural networks (tagging power ~10%)

Combining with Run-1 (8 TeV, 19.7 fb^{-1}):

- CP phase:
  $\phi_s = -21 \pm 45$ mrad
- decay width difference:
  $\Delta\Gamma_s = 0.1073 \pm 0.0097$ ps^{-1}