New results from CMS

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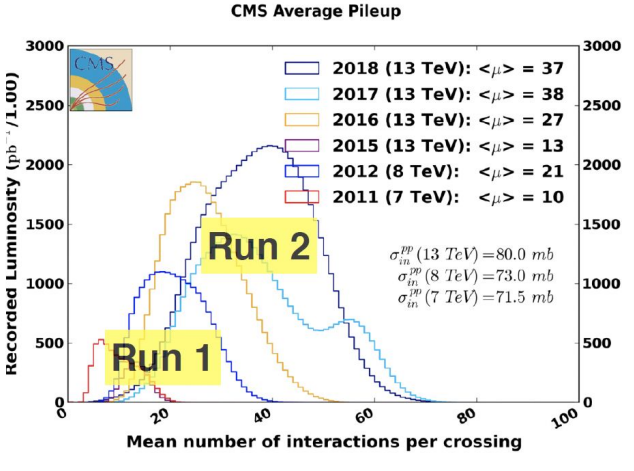
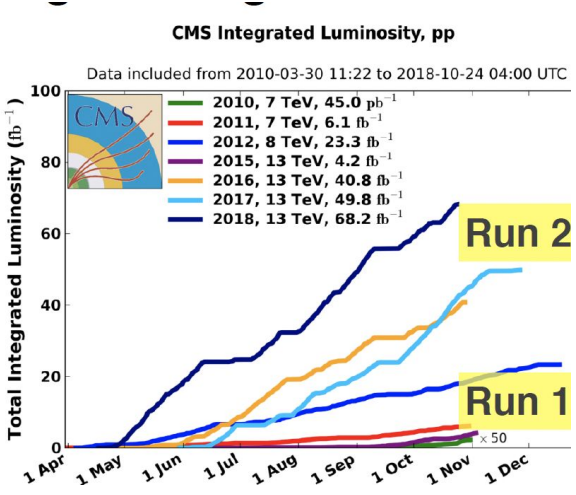
Challenges during Run 2

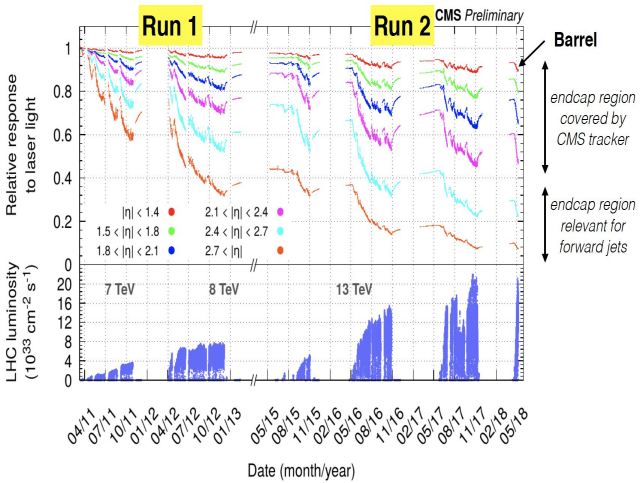
Increase pile up



Higher integrated luminosity

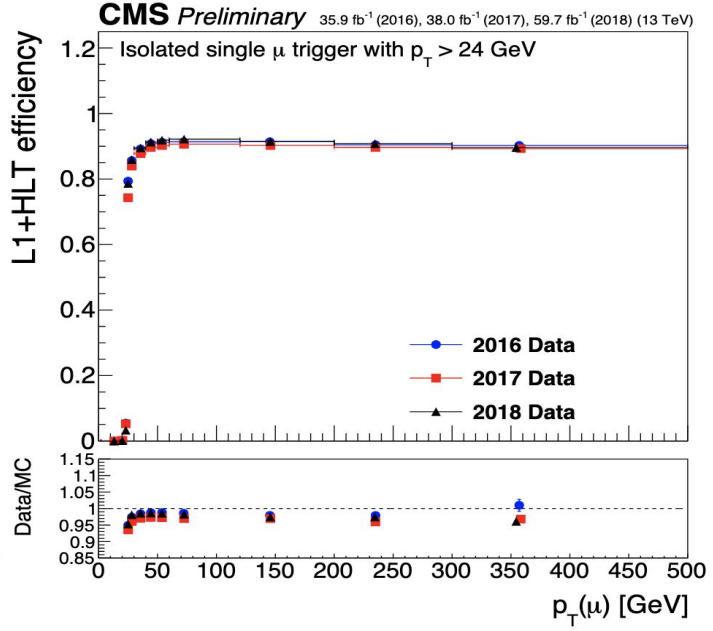


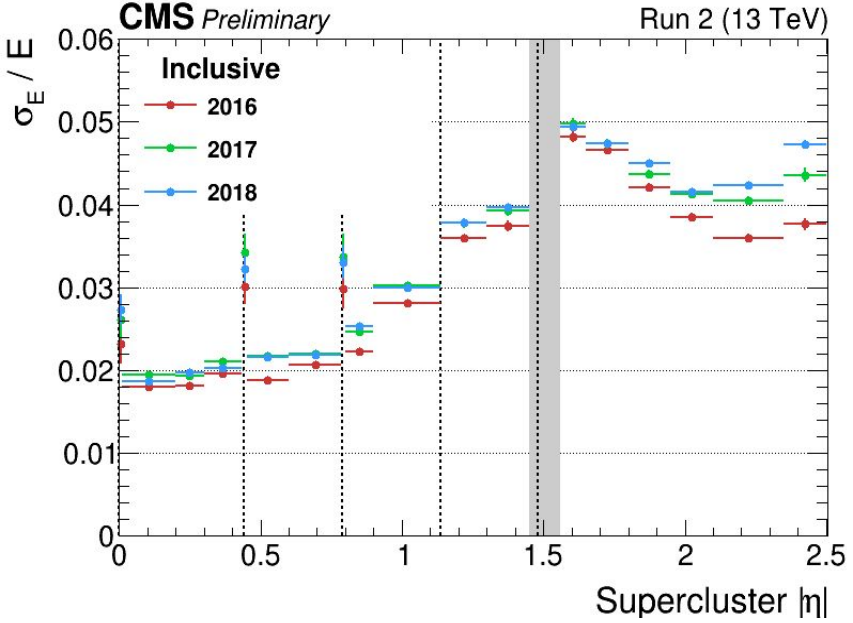
Evolution of ECAL



- Larger radiation dose: ageing of sub-detector e.g. ECAL
- Larger pile-up: Adds to the object signal and hence impact on the object energy/momentum reconstruction
- Dedicated calibration and reconstruction techniques to deal with this situation

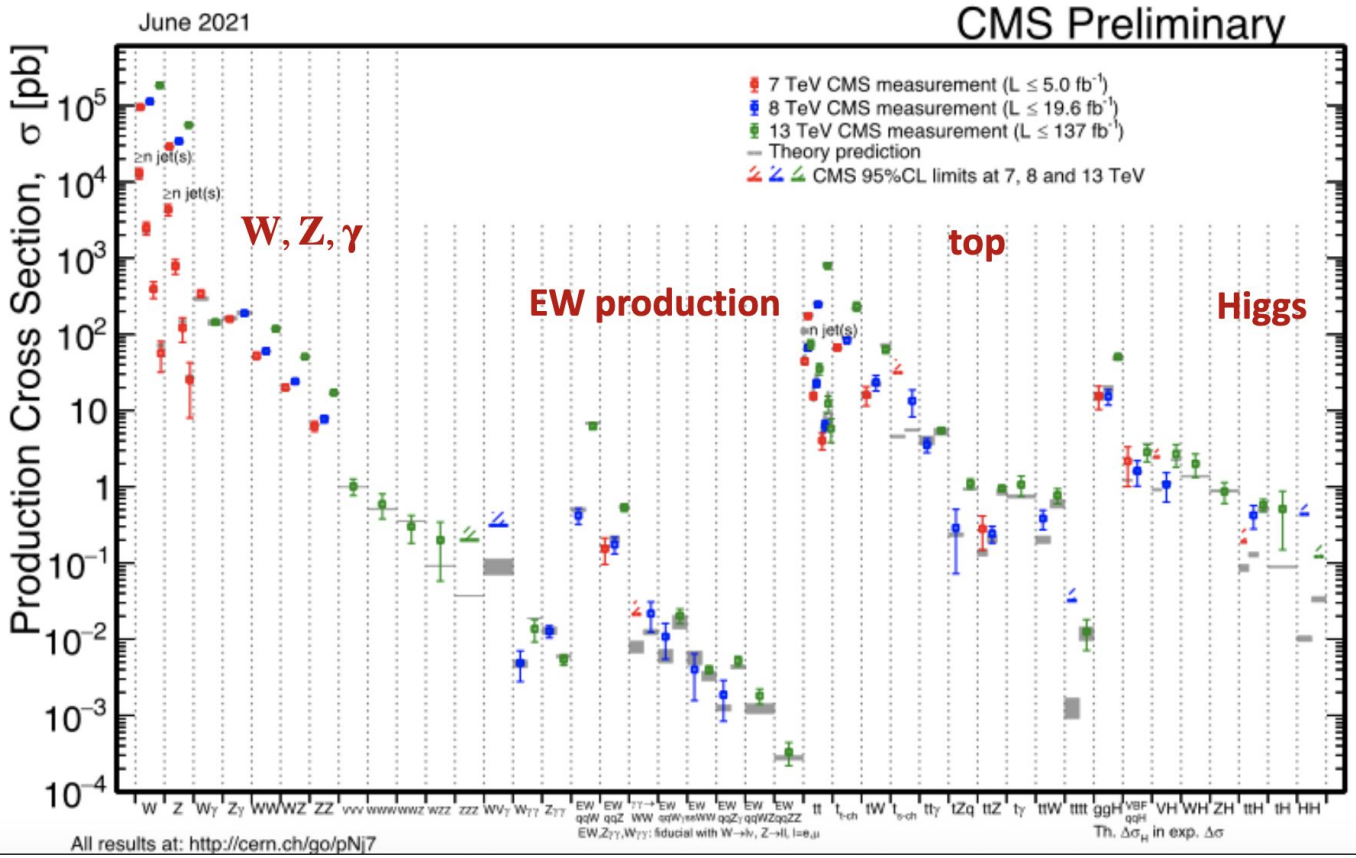
Physics object performance





- Stable trigger efficiencies and stable resolution

SM cross-section measurement

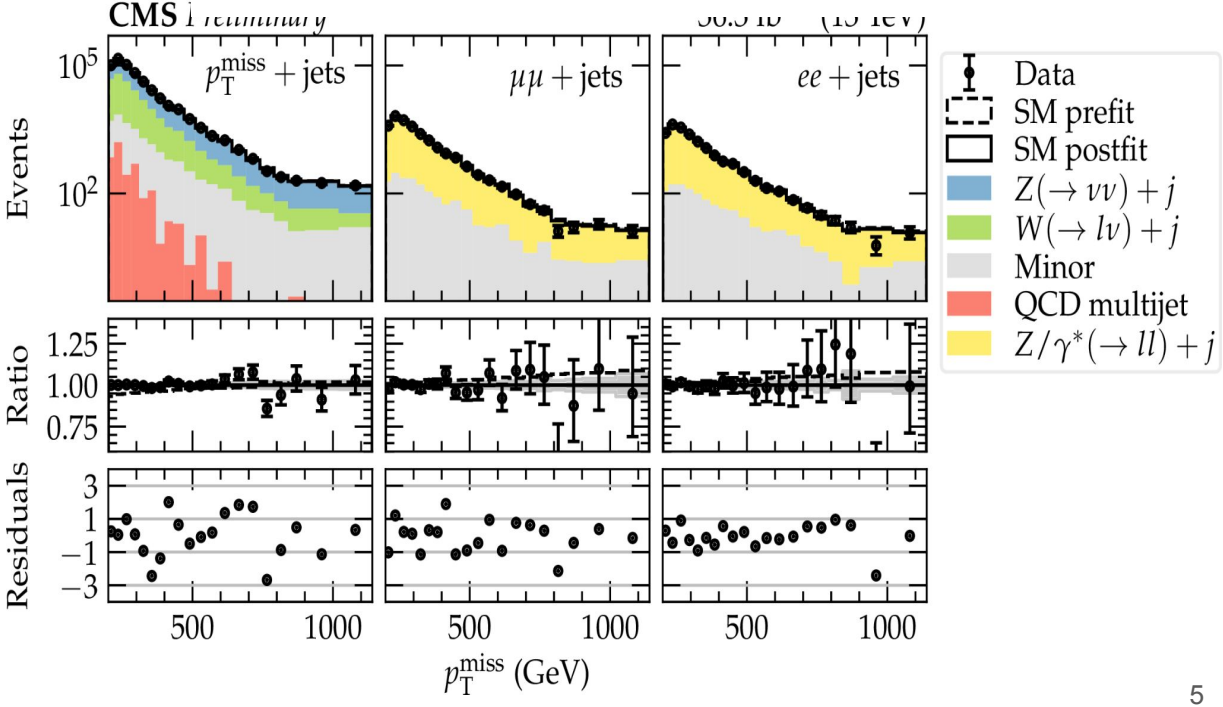


- More differential measurements of SM cross-sections continue
- Deviations may indicate the presence of new physics and hence the need of EFT interpretation

Precision measurement of the Z invisible width SM-18-014

- First direct measurement of the Z invisible width in hadron collider.
- Measured from the ratio of experimentally measured cross-section of Z(→νν)+jets to Z(→ll)+jets and LEP measured partial width for Z→ll
- Events with missing E_T > 200 GeV selected
- Major background to jets+MET from W+jets measured from data-driven methods
- Backgrounds to Z→ll is negligible

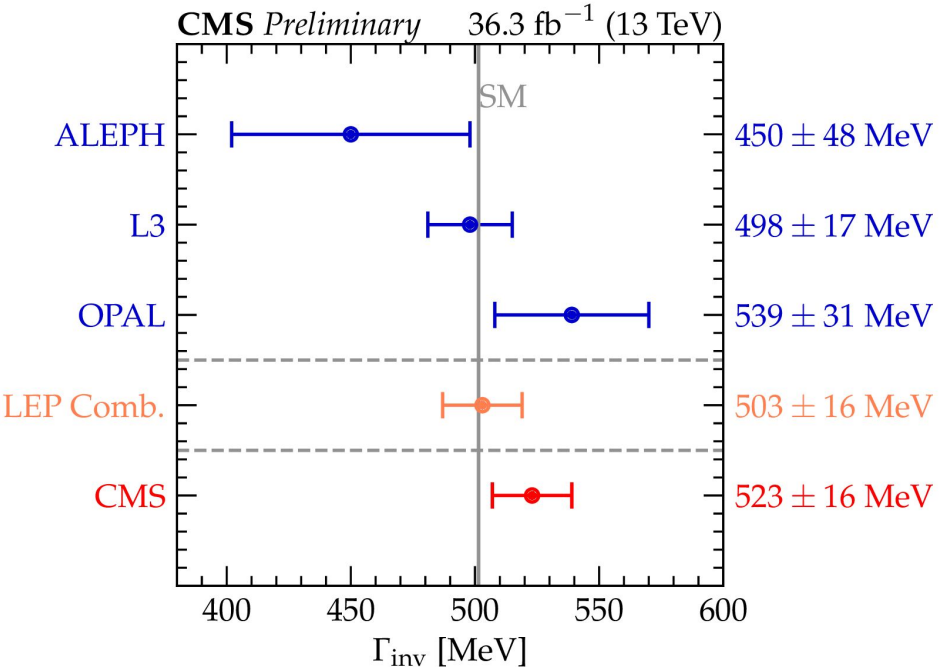
$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$



Precision measurement of the Z invisible width

- Simultaneous fit to data containing events invisible decays of Z and Z decays to di-electrons and di-muons.
- Major uncertainties from lepton efficiencies and jet energy scale

$$\Gamma_{inv} = 523 \pm 3(stat) \pm 16(syst)\ MeV$$



Search for Higgs boson decays to a pair of muons

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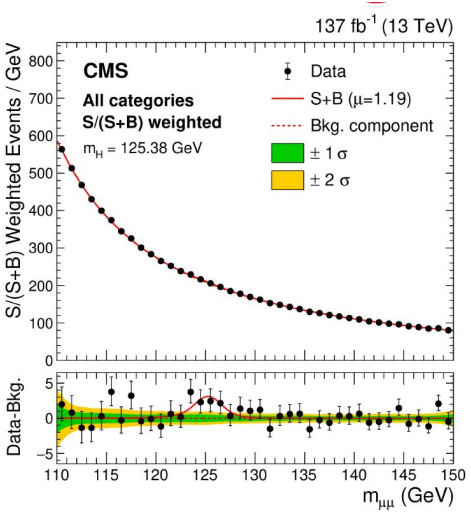
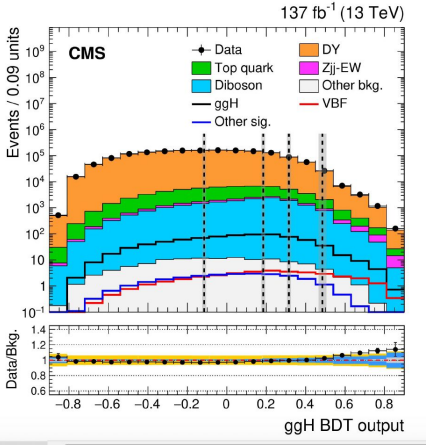
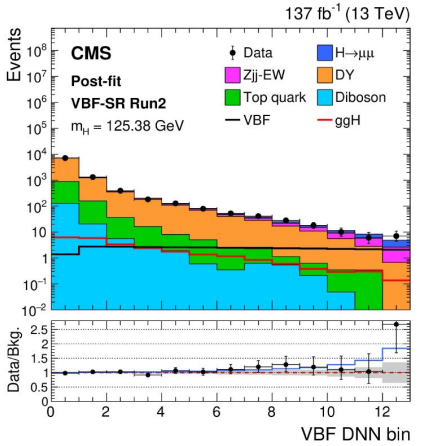
- Most sensitive probe of Higgs coupling to second generation fermions (Branching 2.18 x 10^{-4})
- Require at least two well isolated muons with opposite charges (p_T>20 GeV and |η|<2.4)
  - Muon tracks refitted using primary vertex information (3-10% improvement)
  - Final state radiation (FSR) energy recovered (3% improvement)
- Fit the Higgs boson peak dimuon mass
  - Narrow resonant peak at 125 GeV (few percent resolution) - shape obtained from simulation
  - Smoothly falling background from data



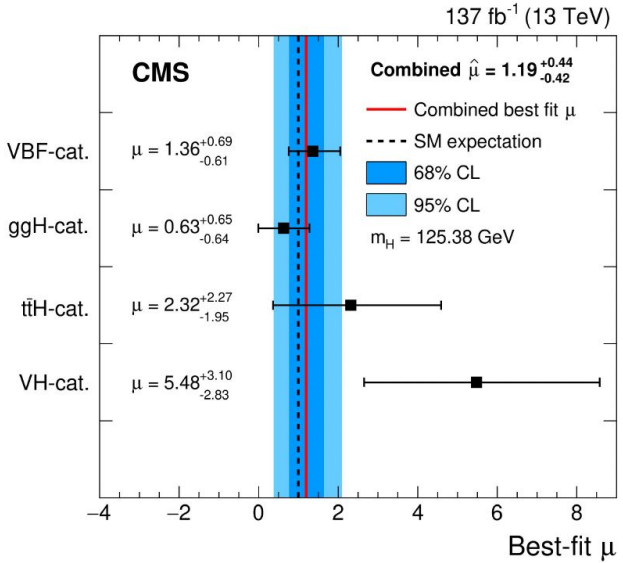


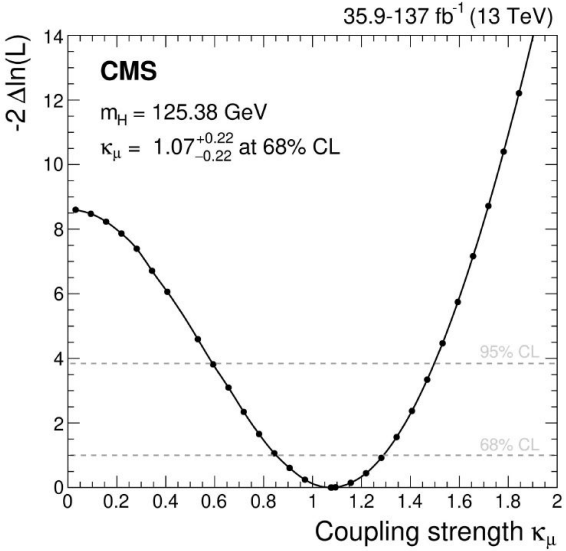
- The search is divided by the production modes, for which multivariate discriminators are trained:
  - Leptonic and hadronic ttH
  - VBF (bkg estimated from MC, fit BDT score)
  - WH and ZH
  - ggH
- Categories with different signal purity chosen from MVA discriminator scores

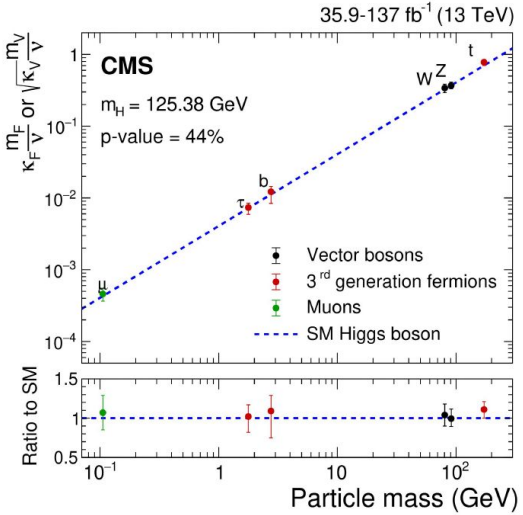


Search for Higgs boson decays to a pair of muons

- Results: evidence for H→μμ
  - p-value: 3σ (2.5σ exp.)
  - μ = 1.19 +/- 0.4 (stat) +/- 0.15 (sys) → statistically limited
  - No deviation from SM observed

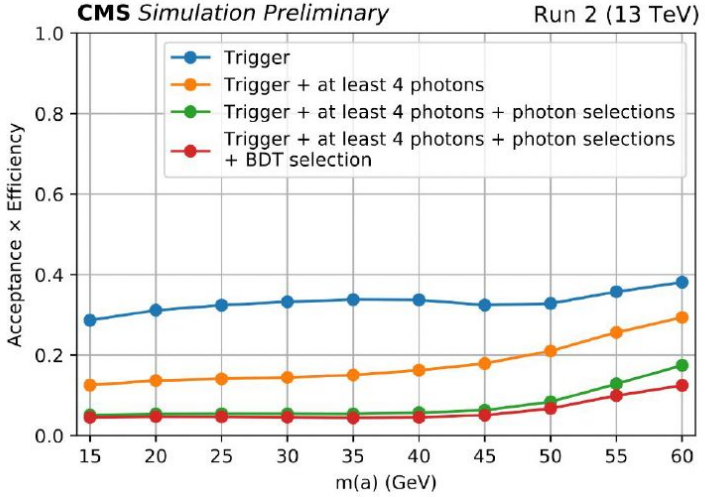


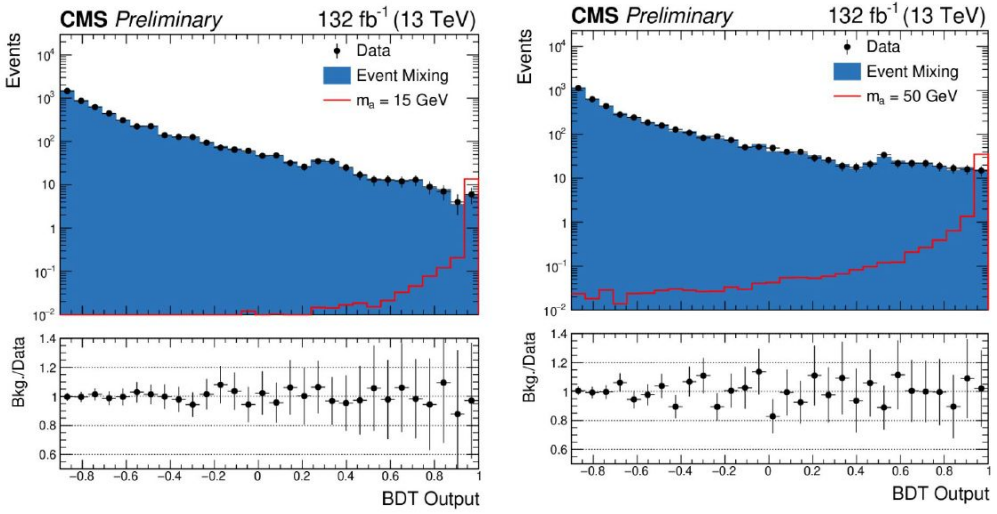




Search for Higgs boson decays to H→aa→4 photons

- First search of this type for CMS
  - ATLAS run I: EPJC 76(2016) 210
- Model independent analysis with 4 fully resolved photons, $m_a \subseteq [15,60]$ GeV
  - Photon pairs have wide opening angle
  - Photons reconstructed separately
- In theoretical models:
  - Coupling of 'a' to fermions can lower BR(a→γγ)
  - Low backgrounds in 4γ's (photon+jets)

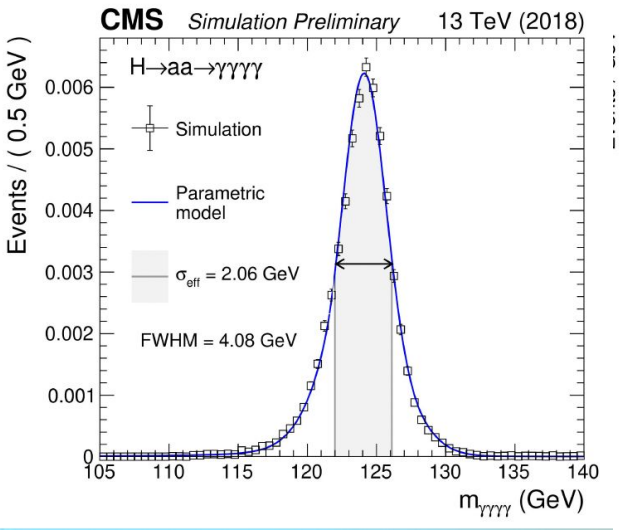


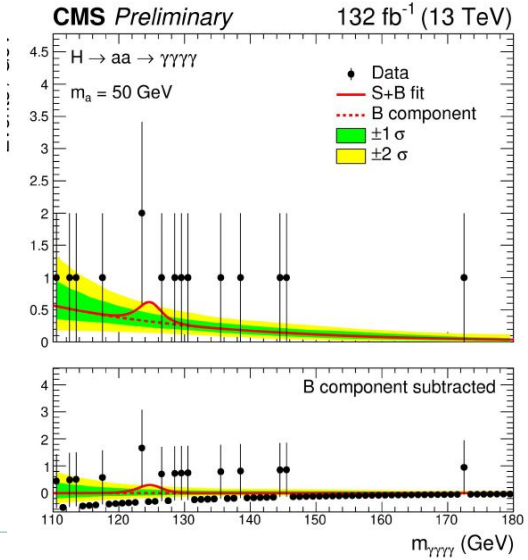


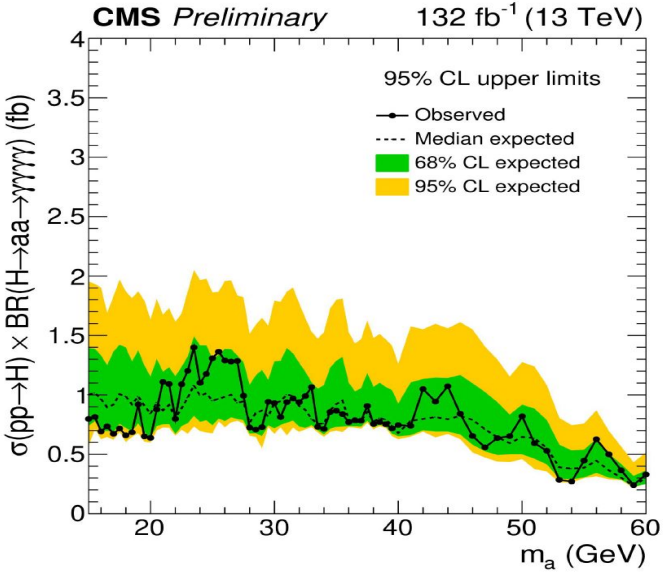
- Categorization BDT, after base selections on 4 photons:
  - Exploits the identification and kinematic information of γ and 'a'
  - Data driven description of background obtained by mixing photons between events (only used for training)
  - Parametric training: output uniform and sensitive to full m_a range
- BDT selection:
  - Optimized by maximizing S/√B for all the possible categories
  - For each m_a, only the best category is chosen

Search for Higgs boson decays to H→aa→4 photons

- Signal model:
  - Built from MC for each nominal m_a
  - Modelled using double sided crystal ball function
- Background model:
  - Built from selected data (3 years merged) for each nominal m_a
  - Modelled using envelope method





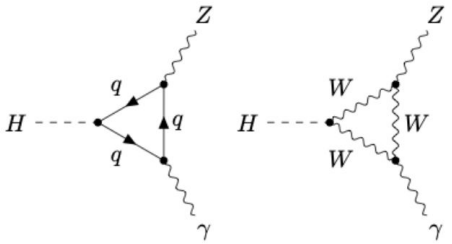


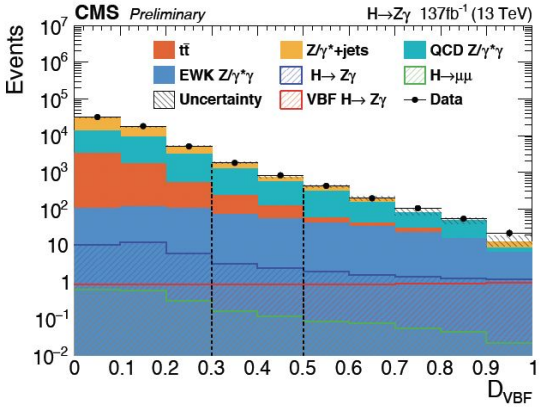
- Results:
  - No excess and observed limits are in agreement with the expected ones

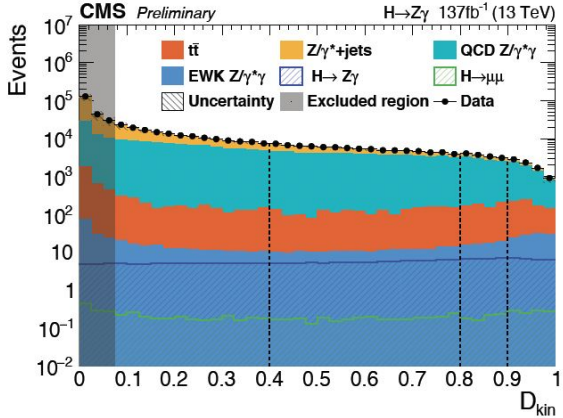
Search for Higgs boson decays to H→Zγ

HIG-19-014

- One of the rare decay channels sensitive to the new physics effects appearing in the loop
  - BR(H→Zγ)/BR(H→γγ) ~ 0.69
- Analysis strategy
  - 8 categories targeting the production mode of Higgs
    - MVA discriminant further used to form sub categories of the VBF production mode
    - Another MVA (kinematic) discriminant used to categorize ggF mode further using the kinematic properties of the llγ system



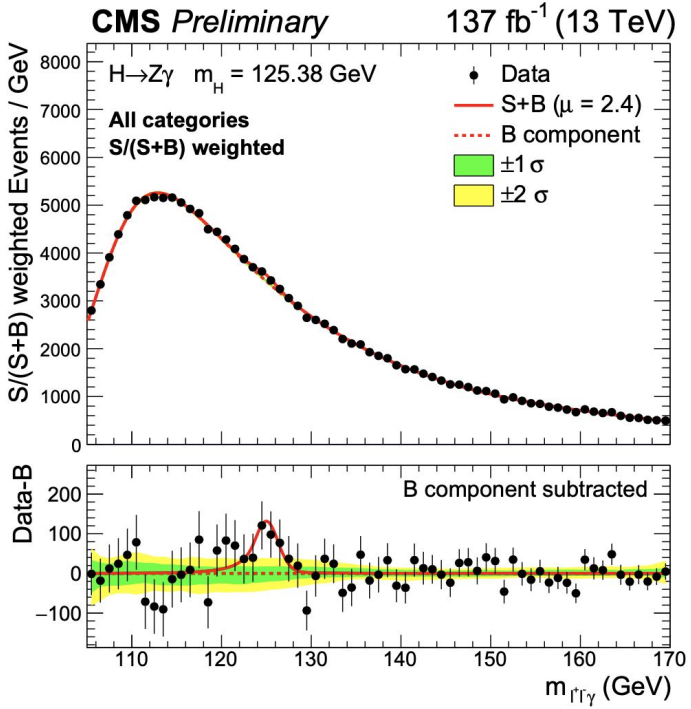




- VBF MVA employs the VBF characteristics of the process:
  - High pseudorapidity differences, high mjj, zeppenfeld variable etc
- ggF MVA employs $\Delta R_{l\gamma}$, $p_T^{\gamma}/m_{ll\gamma}$, photon energy resolution etc

Search for Higgs boson decays to H→Zγ

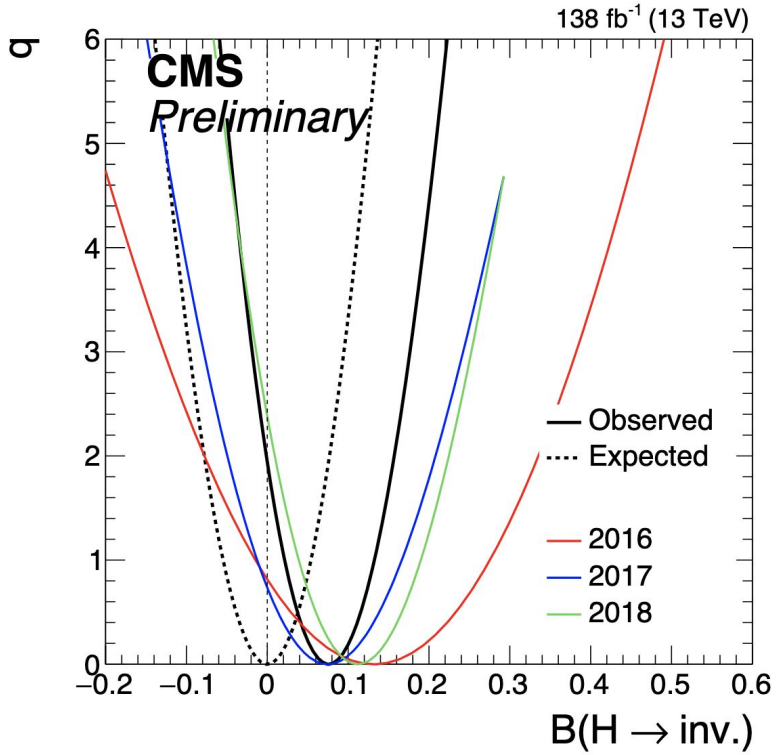
- Statistical procedure:
  - Signal shape: Obtained from simulation by fitting with double sided crystal ball
  - Background shape: Obtained from data using envelope method
- Results:
  - Observed (expected) local significance is 2.7 (1.2) standard deviations
  - Measured value of σ(pp→H) x BR(H→Zγ) is 0.21 +/- 0.08 pb



Search for invisible decay of a Higgs boson produced via vector boson fusion

HIG-20-003

- Most sensitive channel due to VBF topology
- Signature: Two high P_T jets with large invariant mass and large rapidity gap
- Dominating backgrounds: Z(vv)+jets and W+jets
- Background estimation: Simultaneous fit of signal and control regions: 1e/μ, 2e/μ and γ+jet
- Observed (expected) 95% CL UL on BR(H→vv) < 0.17(0.11)



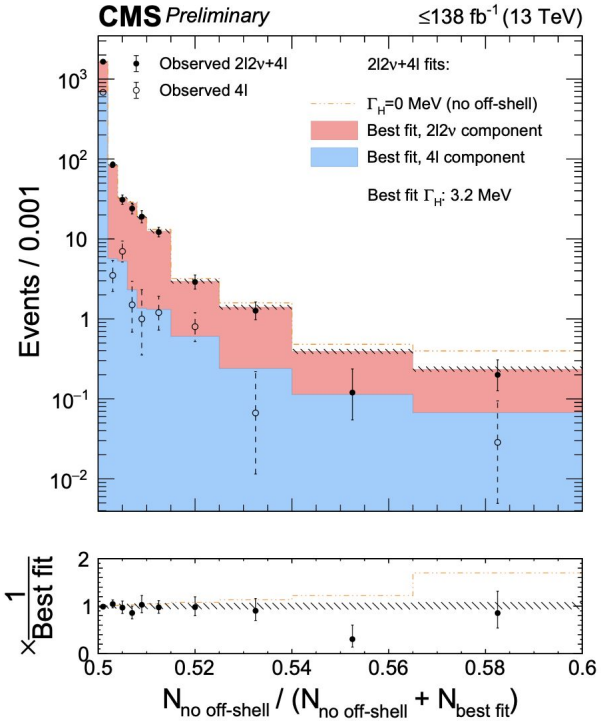
Evidence for off-shell Higgs boson production and first measurement of its width

HIG-21-013

- In SM H→VV, since $m_V < m_H < 2m_V$, 10% of the events lie in the off-shell region ($m_H^* >= 2m_V$)
- Off-shell results interpreted in terms of on-shell
- 2l2v final state used

$$\sigma^{\text{on-shell}} \propto \frac{g^2_{\text{prod}}\, g^2_{\text{dec}}}{\Gamma_H} \propto \mu_{\text{prod}}$$

$$\sigma^{\text{off-shell}} \propto \int \frac{g^2_{\text{prod}}\, g^2_{\text{dec}}}{\left(q^2_H - m^2_H\right)^2} dq^2_H \propto \mu_{\text{prod}} \cdot \Gamma_H$$

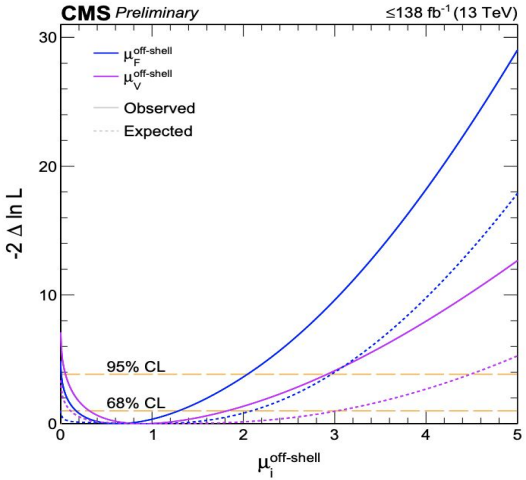


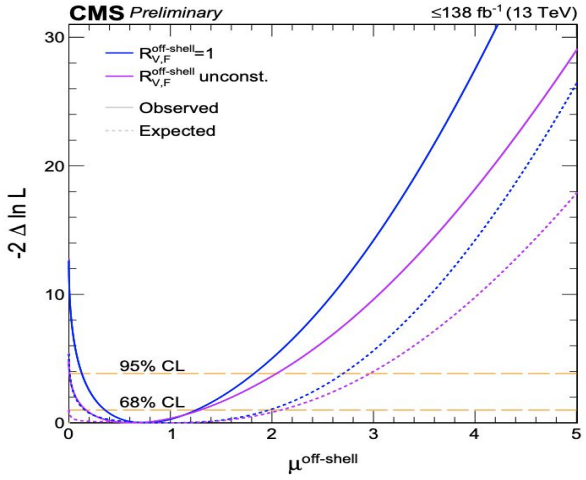
Evidence for off-shell Higgs boson production and first measurement of its width

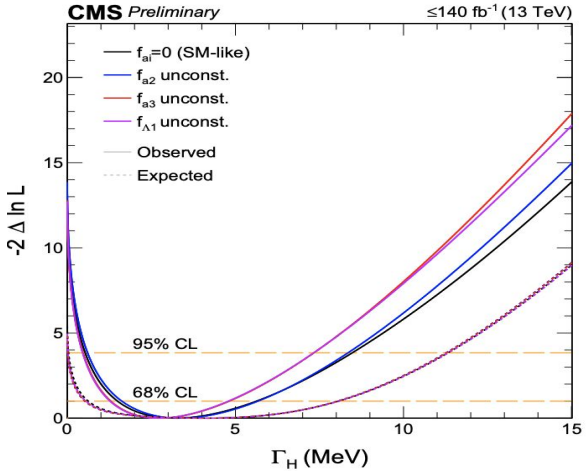
- Interference with the SM ZZ production taken into account
- Extracted quantities: Γ_H, anomalous coupling constants

Γ_H = 3.2 + 2.4 - 1.7 MeV

(current experimental limit on lifetime < 1.9×10^{-13}s)

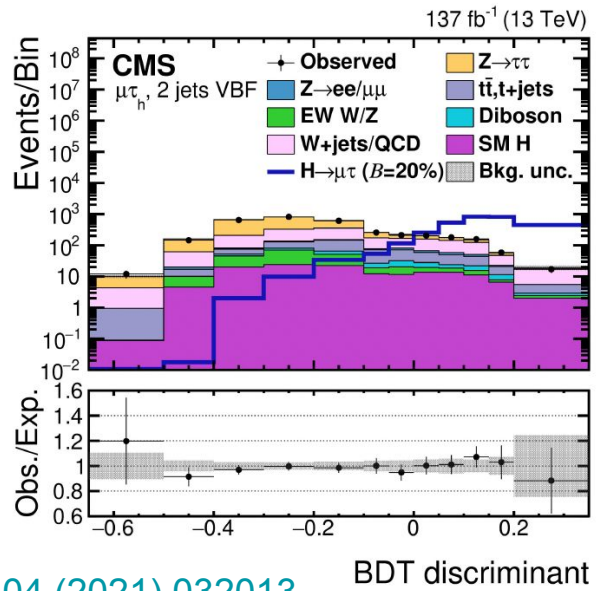


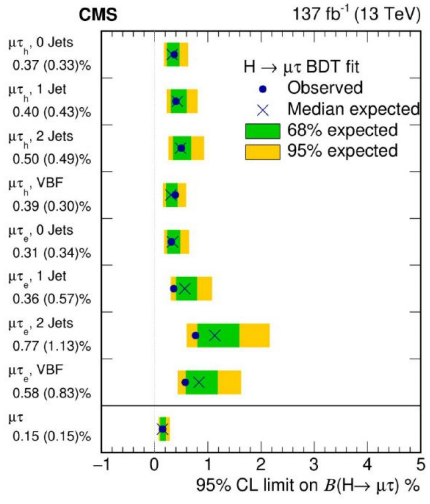


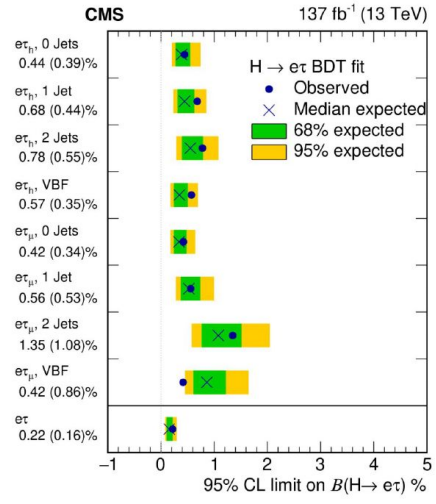


Lepton flavour violation in H→ eτ and μτ decays

- Lepton flavour violation
  - $Y_{e\mu}$, $Y_{\mu\tau}$ and $Y_{e\tau}$ Yukawa couplings in SUSY and composite Higgs models
  - Constraints from electron and muon magnetic moments on BR(H→ μτ) < 10% and BR(H→eτ) < 10%
- Analysis strategy
  - Decay channels: $\mu\tau_h$, $\mu\tau_e$, $e\tau_h$ and $e\tau_\mu$
  - Categories: 0 jet, 1 jet, 2jet ggH and 2 jets VBF (m_{jj} discriminant)
  - Backgrounds estimated from data and simulation







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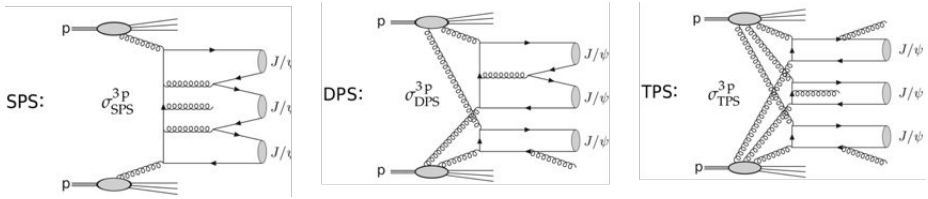
- Results with full Run 2: No deviation from the SM
  - BR(H→ μτ) < 0.15% and BR(H→eτ) ~ 0.22%

Observation of triple J/ψ production

BPH-21-004

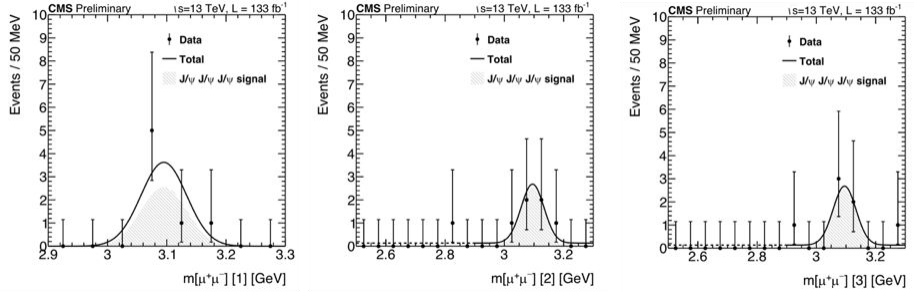
- Contributions to the production from single parton scattering (SPS), double parton scattering (DPS) and triple parton scattering (TPS)

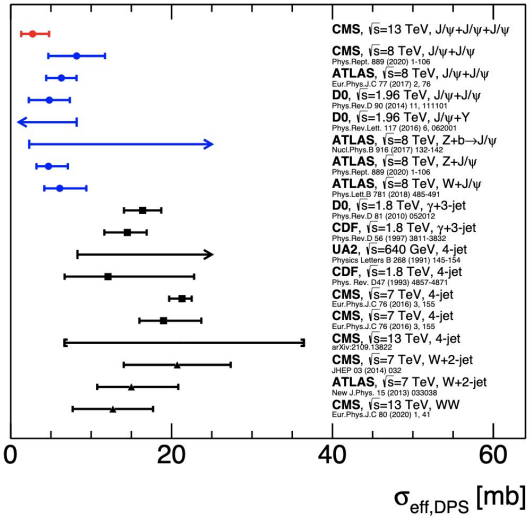


- After all the selections, 5 events found consistent with the triple J/ψ production
- $\sigma(pp \to J/\psi\ J/\psi\ J/\psi) = 272^{+141}_{-104}(sys) +/- 17\ (stat)$ fb
- Measured final states dominated by DPS and TPS

$$\sigma_{DPS}^{pp\to\psi_1\,\psi_2+X} = \left(\frac{m}{2}\right)\frac{\sigma_{SPS}^{pp\to\psi_1+X}\,\sigma_{SPS}^{pp\to\psi_2+X}}{\sigma_{eff,DPS}}$$

Three J/ψ candidates in each event ordered by pT





Observed significance > 5σ

Observation of $B^0 \to \psi(2S) K^0_S \pi^+\pi^-$ and $B^0_s \to \psi(2S) K^0_S$ decays

CP violation measurements, exotic intermediate resonances.

$\psi \to \mu\mu$ and $K_s^0 \to \pi^+\pi^-$ decays used

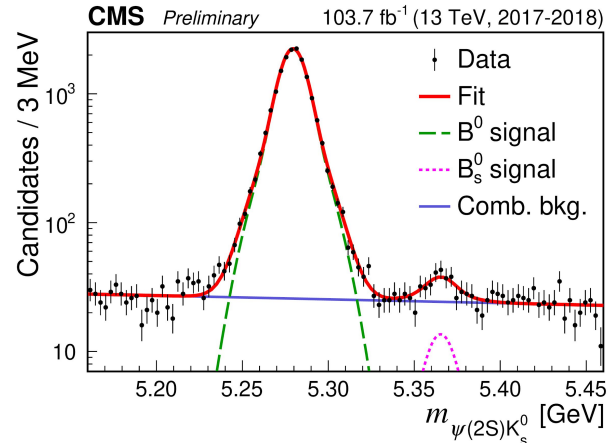
Systematics of muon and track reconstructions cancel in ratio

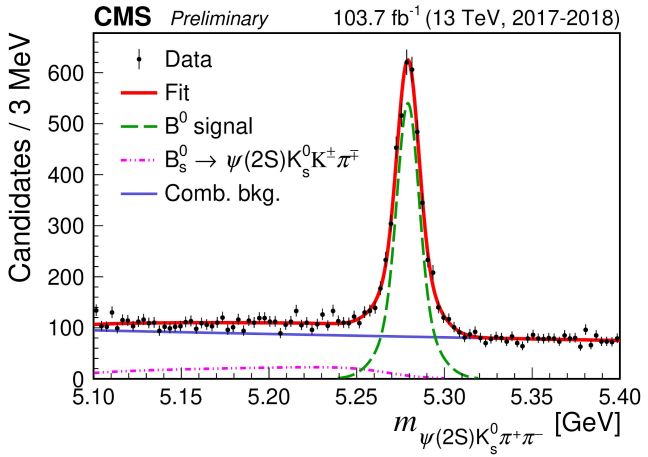
Main systematics:

Background modeling for R_s, tracking efficiency and absence of intermediate resonance in MC for $R_{\pi\pi}$

$$R_s \cdot \frac{f_s}{f_d} = \frac{f_s}{f_d} \cdot \frac{\mathcal{B}(B_s^0 \to \psi(2S) K_S^0)}{\mathcal{B}(B^0 \to \psi(2S) K_S^0)} = (0.69 \pm 0.14\,(\text{stat}) \pm 0.02\,(\text{syst}))\%,$$

$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \to \psi(2S) K_S^0 \pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S) K_S^0)} = (48.0 \pm 1.3\,(\text{stat}) \pm 3.2\,(\text{syst}))\%.$$

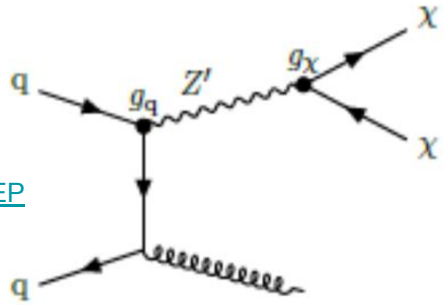


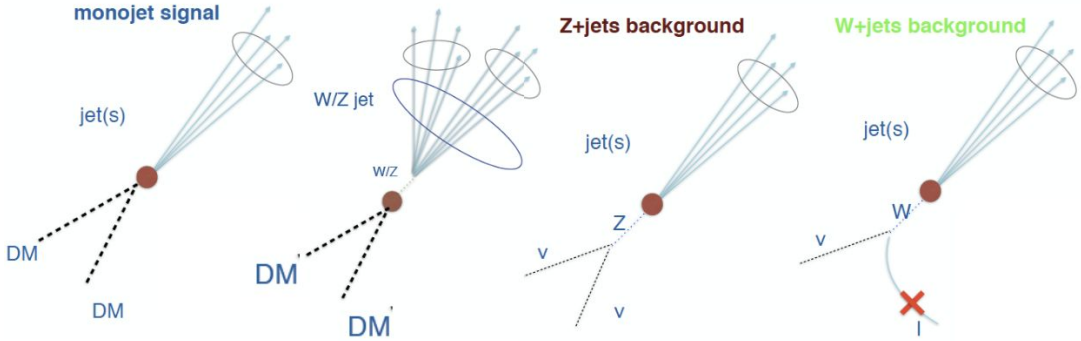


Dark matter search in monojet/V final state

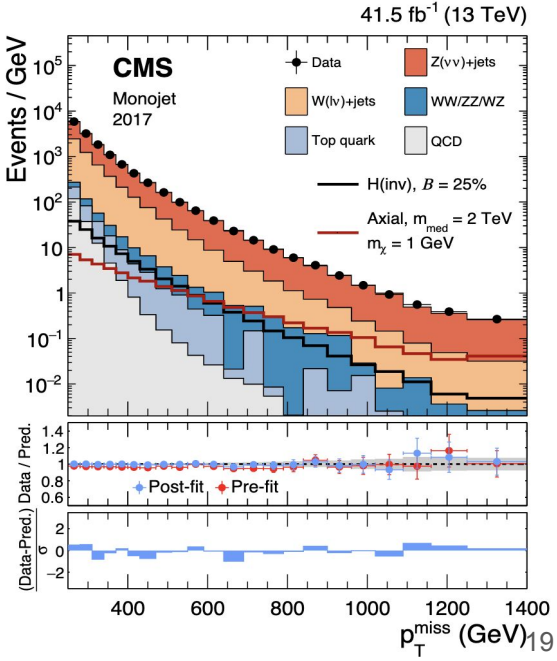
- Detector signature: high pT jet and nothing else
- Major backgrounds: Z(vv)+jets and W+jets

EXO-20-004: Submitted to JHEP





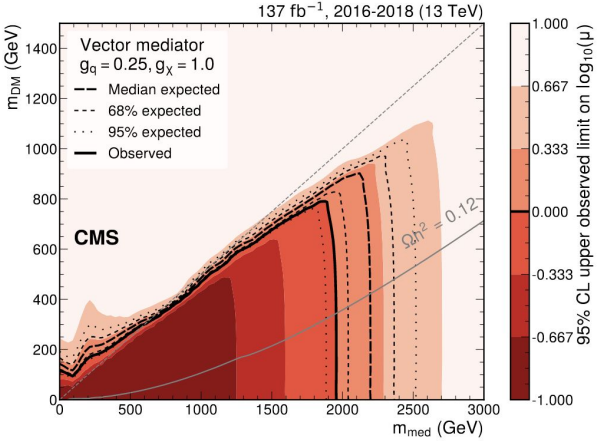
- Mono-jet : 1 AK4 jet
- Mono-V: Boosted V reconstructed as 1 AK8 jet
- Mono-V: sub-divided into 2 sub-categories based on the purity

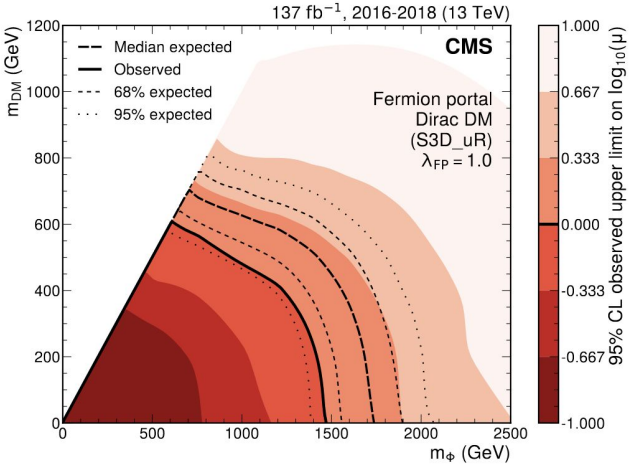


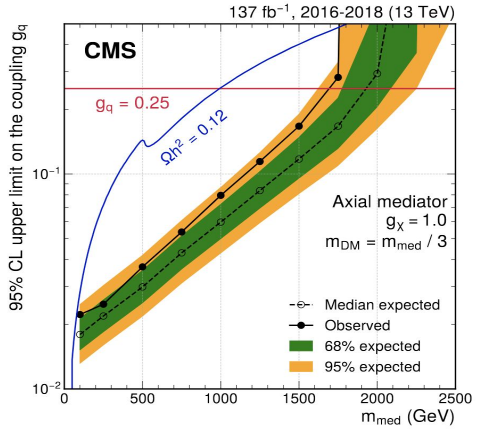
- Simultaneous fit of the signal region with γ, 1e/μ, 2e/μ control regions. Normalization and shape extracted via binned transfer factors obtained from simulation are constrained, within theoretical and experimental uncertainties

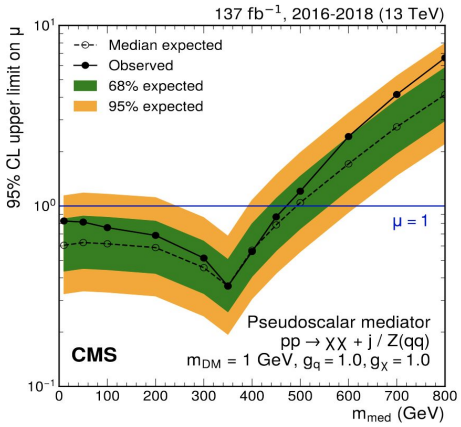
Dark matter search in monojet/V final state

- The results are interpreted for vector, axial-vector and fermion portal models
- Vector mediator: excluded $m_{med} < 1.95$ TeV
- Pseudo-scalar mediator: excluded $m_{med} < 460$ GeV
- Fermion portal: excluded $m_{med} < 1.5$ TeV



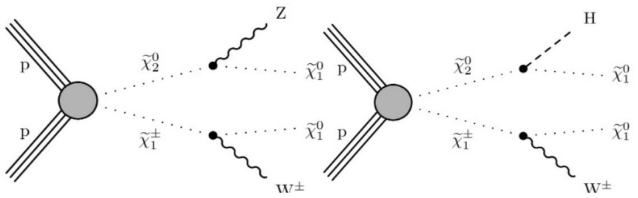






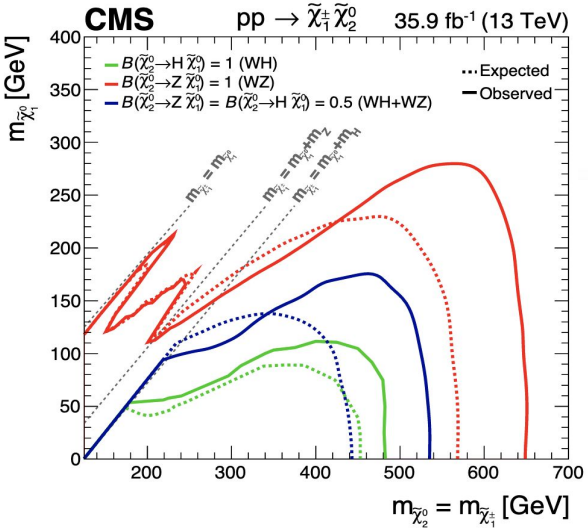
Electroweak production of charginos and neutralinos

- Production of $\chi^0_2\chi^{+/-}_1$ and decay via Z, H and W bosons
- Models explored: Higgsino-like, Wino-like and WZ corridor
- Final states searches example:
  - Targets WH topology: 1 lepton, 2 b jets and P_T^{miss}
  - 4b and P_T^{miss} targeting HH topology
  - Z→ll + jets + P_T^{miss} targeting WZ, ZZ and ZH topologies
- Backgrounds predicted from simulation with constraints from data control regions
- Statistical combinations of 6 analyses within CMS

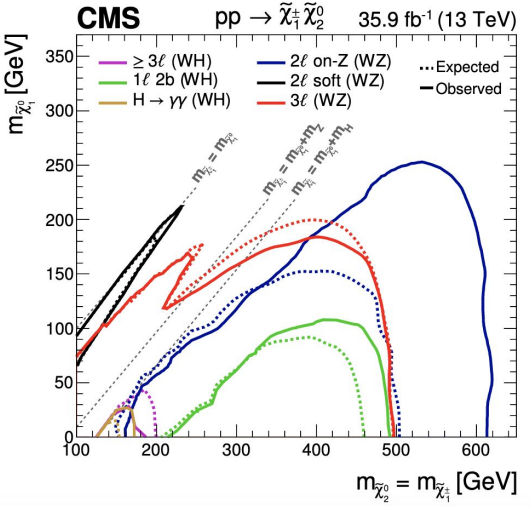


SUS-17-004

combination



Individual



Exclusion at 95% CL:
Mass of chargino < 650 GeV excluded

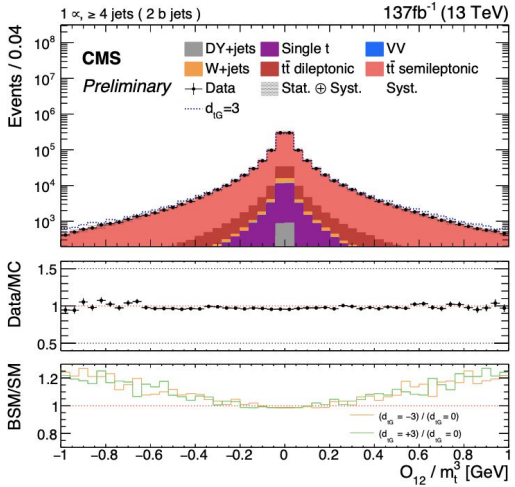
CP violation in top pair events with lepton jet channel

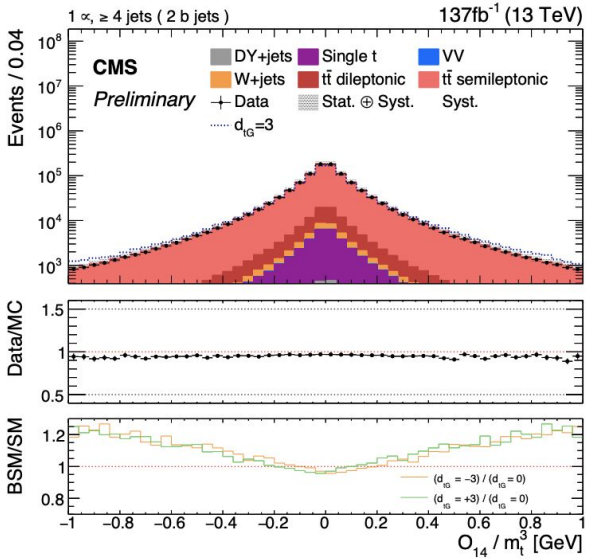
Top-20-005

- Measure asymmetry of 4 T-odd observables which if CPT is conserved are also odd under CP transformation
- Measured asymmetries ACP are affected by dilution effects due to (e.g.) to the mis-assignment of the quark/antiquark

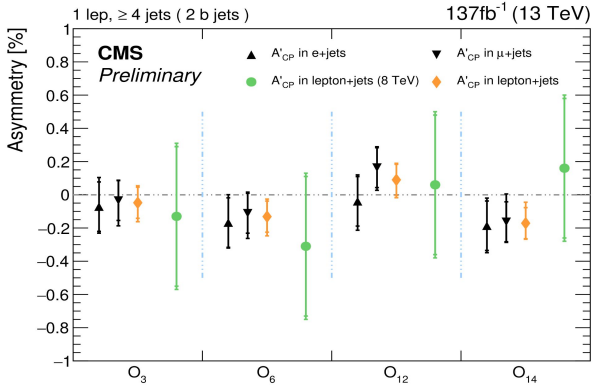
$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p'}_b \cdot (\vec{p'}_\ell \times \vec{p'}_{j_1})$$
$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$
$$O_{12} = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z$$
$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}, i = 3, 6, 12, 14$$





Raw asymmetries



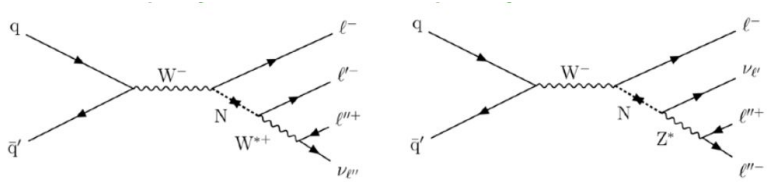
All measures asymmetries consistent with 0indicating no CPV

Search for long lived heavy neutral leptons

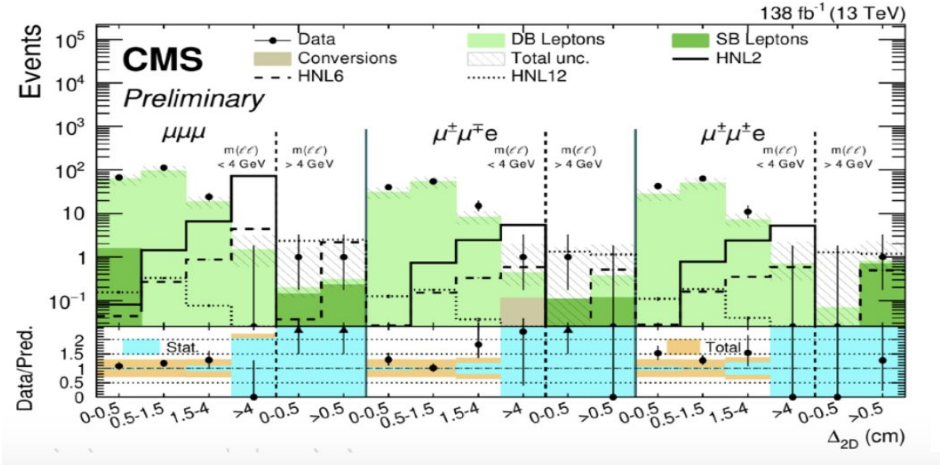
EXO-20-009

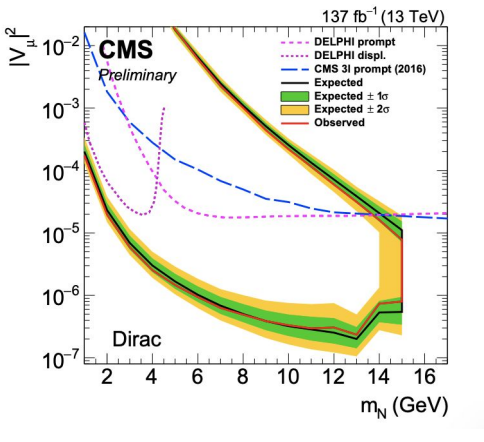
- Search for new HNL produced with mixing with SM neutrinos , final states with three charged leptons and a neutrino
- For small values of the HNL mass (<20 GeV) and of the HNL-SM neutrino, mixing parameter HNL may be long lived
  - $\tau_N \propto M_N^{-5} V_{Nl}^{-2}$
- Search for 3 lepton events (e and μ) with two forming a displaced vertex and the third prompt

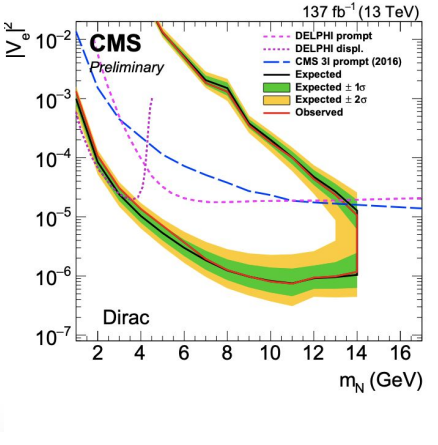
Several diagrams with LNV (Majorana N) and LNC (Majorana or Dirac N) are possible



Exclusion in the 2D plane of mixing VS N mass

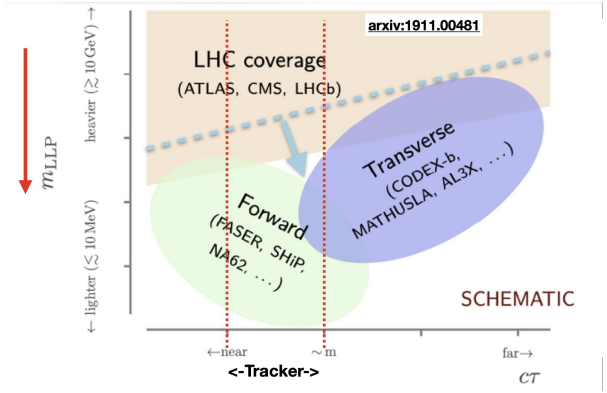


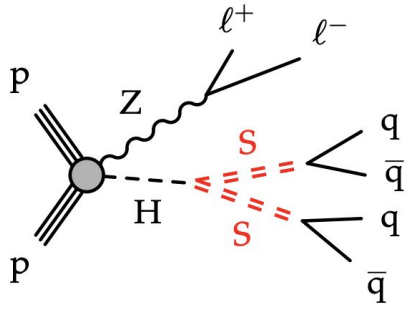




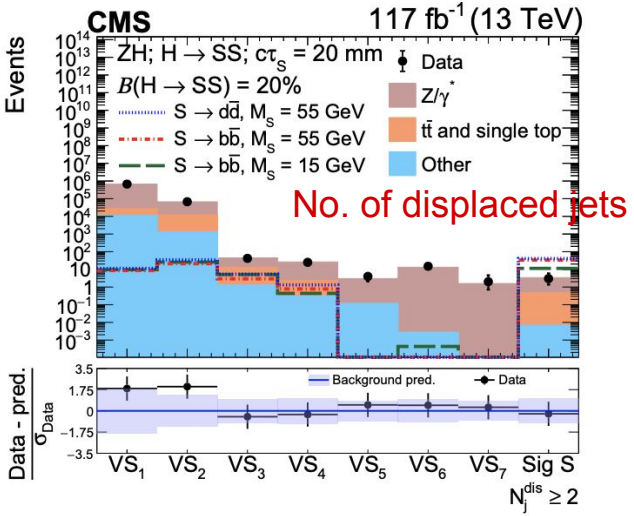
Search for long-lived particles in association with a Z boson

- Surpasses trigger difficulty by requiring an associated Z(→ll)
- Targets LLP decays to quarks in the tracker (displaced jets with low pT)
- Targeted event topology: Associated ZH production
- Jet level variables derived from tracker
- Two main backgrounds:
  - Z/γ* (90%): estimated via the low ZpT region
  - Top (~10%): estimated via eμ control region

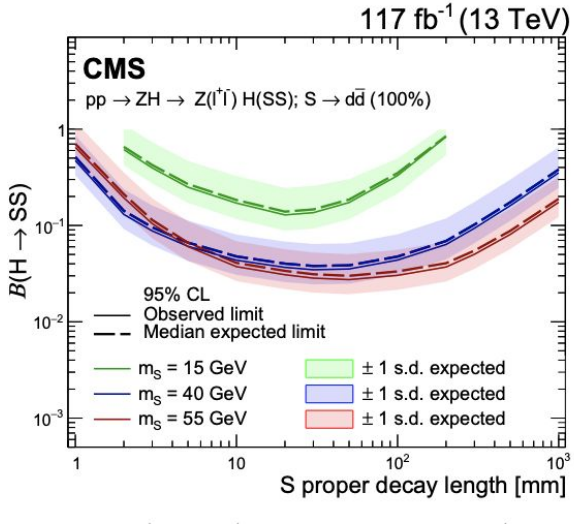


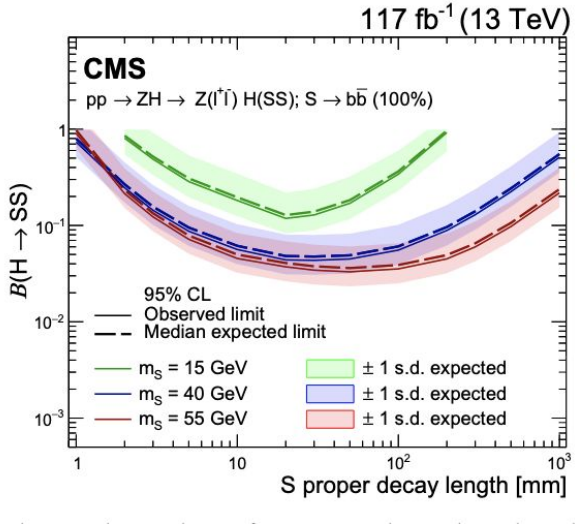


EXO-20-003



Search for long-lived particles in association with a Z boson



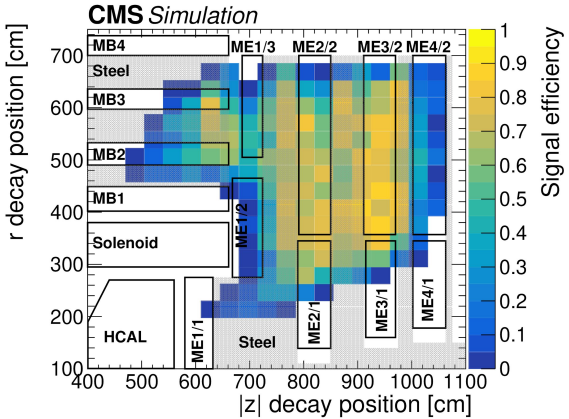


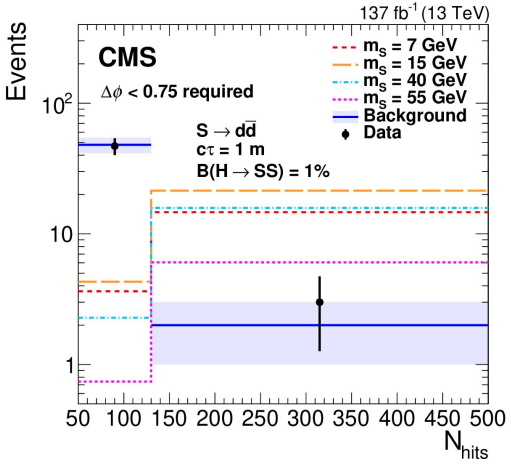
A factor 2 improvement w.r.t gluon fusion searches

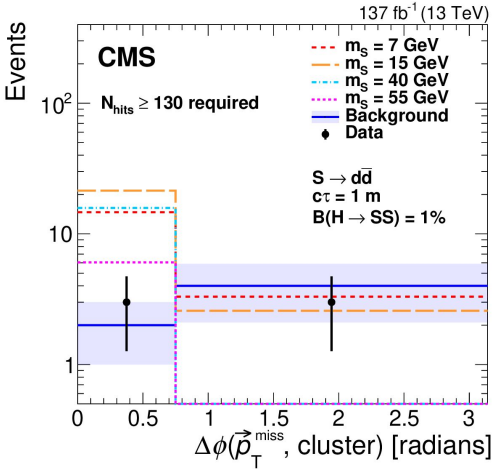
- No excess over the SM
- Upper limit on BR(H→SS) <
  - 6% for proper decay length of 10-100mm and for LLP mass between 40 and 55 GeV
  - 20% for proper decay length of 10-50mm for low mass (~15 GeV) and decays to b quarks

Search for long lived particles decaying in the muon endcap detectors

EXO-20-015







- 137 fb-1 in 2016-18
- Endcap muon detector as sampling calorimeter.
- 10-15% acceptance for LLP CT 1-10 meters, mass 10-55 GeV
- DBSCAN: 80% efficiency for babar and dd, 65% for tautau
- Punch through mostly stopped in 20-27 interaction length of HCAL, then veto associated jets

2+- 1.0 expected, 3 observed

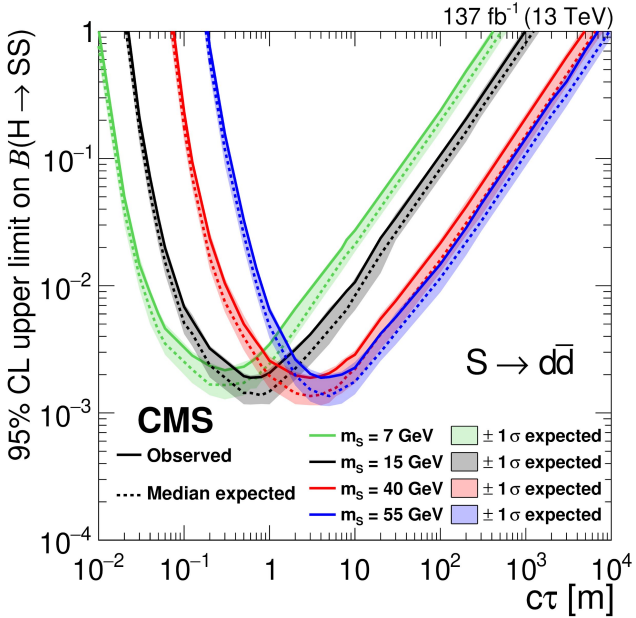
Search for long lived particles decaying in the muon endcap detectors

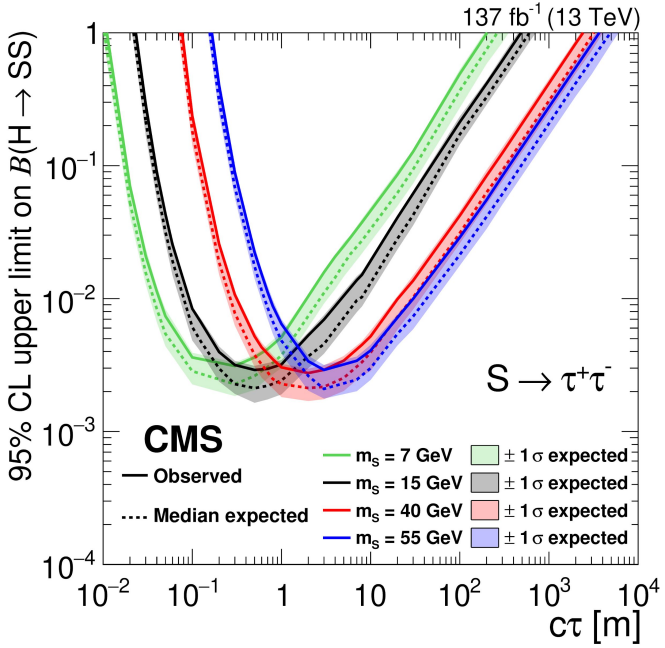
EXO-20-015

- 6 times improved significance for LLP mass 7 GeV, CT > 100m compared to the previous best limit,

doi:10.1103/PhysRevD.99.052005,

arXi





Outlook

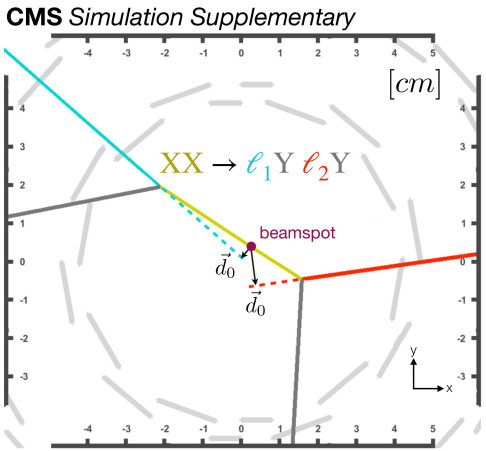
- Run 2 had been full of challenges with high pile-up and high integrated luminosity
  - Performance has remained stable throughout - thanks to the robust reconstruction algorithms
- Many new recent results from CMS
  - Full Run 2 data analyses presented
- New Z invisible width measurement
- ~3σ significance in H→μμ and H→ Zγ analysis
  - Analyses very important for upcoming Run 3
- Tighter constraints on Higgs width measurement from off-shell Higgs production
- First observation of 3 J/ψ production
- The list is many, Run 3 is approaching next year

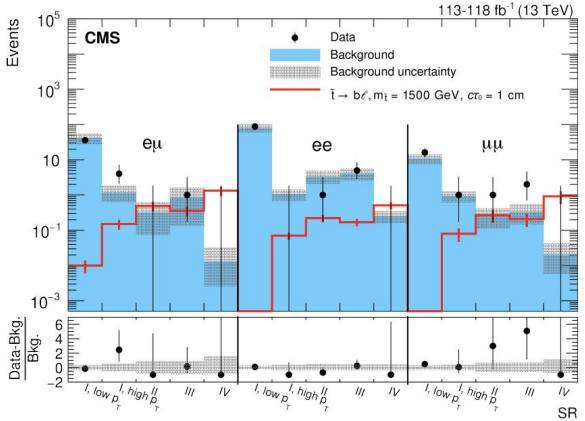
Exciting times lie ahead

Backup

Search for long lived particles decaying to leptons with large impact parameter

- Inclusive search for displaced leptons without requiring a common vertex
- Final states of ee, eμ and μμ with large transverse impact parameter (d0)
- |η|<1.5 to remove poorly measured d0 of the leptons
- Background removal: Timing and 3D angle cuts (removes cosmics)
- Background estimation: using data control samples

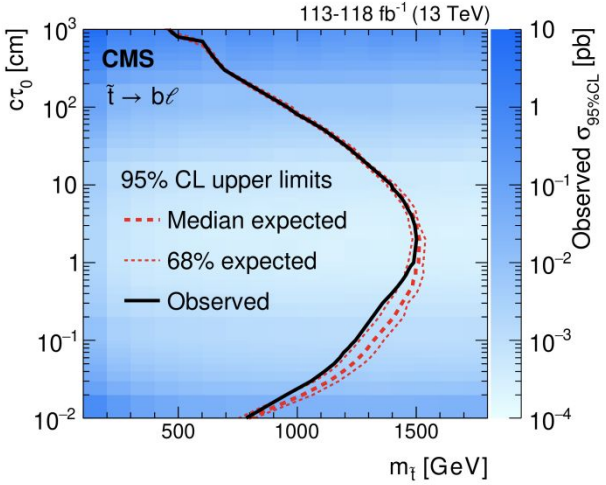




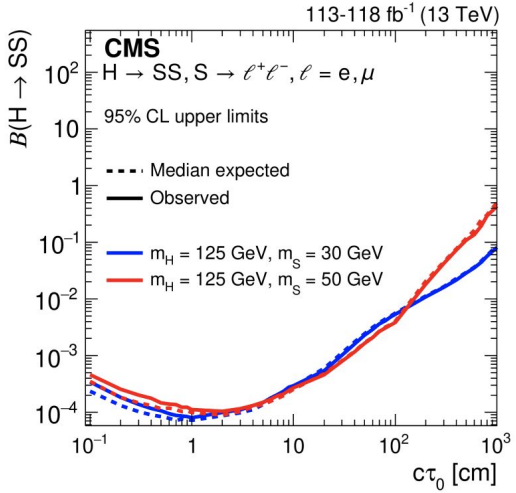
[EXO-18-003]

Search for long lived particles decaying to leptons with large impact parameter

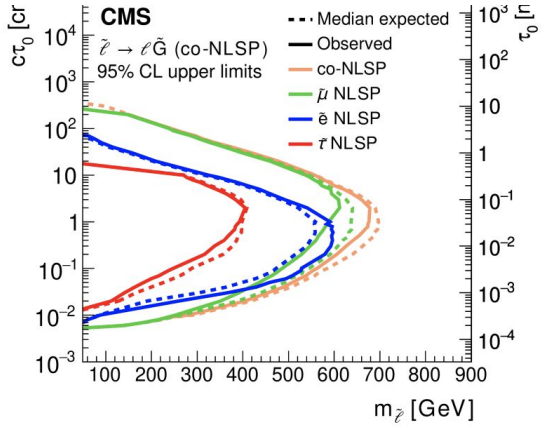
- Sensitive to any model with displaced, isolated electrons or muons
- Several interpretations: Top squarks, GMSB Sleptons and Exotic Higgs bosons



Squarks



Sleptons



Exotic Higgs

Evidence for off-shell Higgs boson production and first measurement of its width

- Interference with the SM ZZ production taken into account
- Extracted quantities: Γ_H, anomalous coupling constants

Γ_H = 3.2 + 2.4 - 1.7 MeV

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} - e^{i\Phi\Lambda_1} \frac{q_1^2 + q_2^2}{\Lambda_1^2} + \ldots \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + |a_2| e^{i\Phi a_2} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + |a_3| e^{i\Phi a_3} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$