
# Highlights of results by CMS

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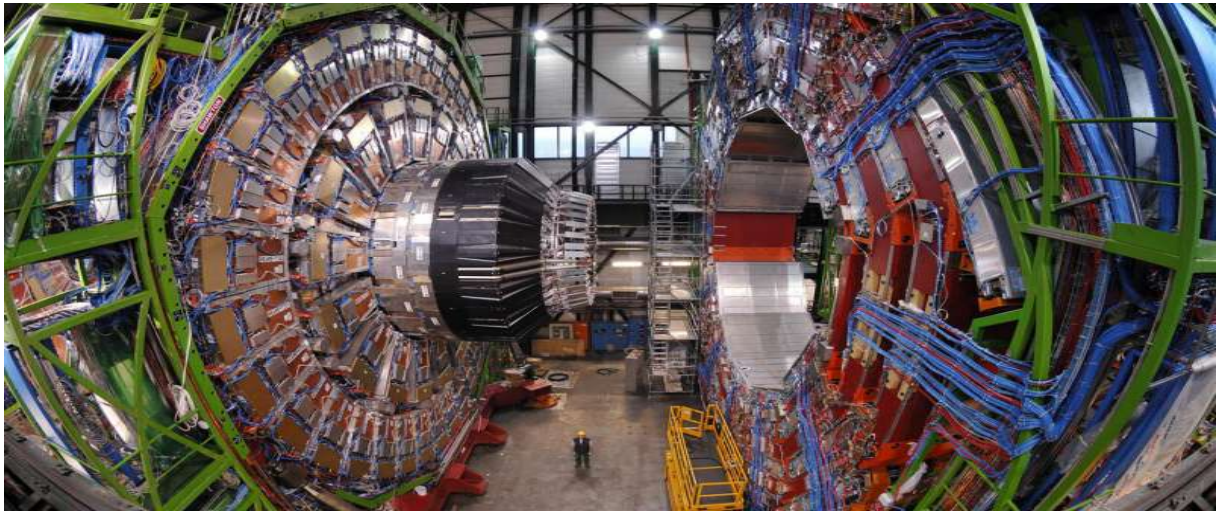
# From LHC to HL-LHC: Project Schedule

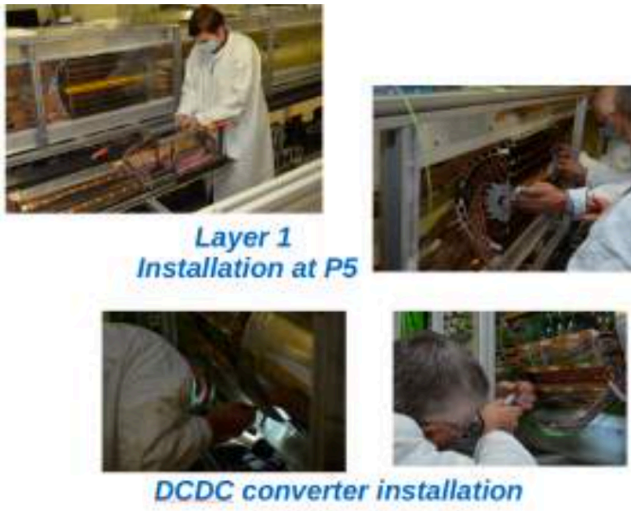
Higgs boson discovery → Precision & differential measurements → New discoveries?


(from HL-LHC official project schedule)

# CMS Phase-1 Upgrades (2014– 2019)

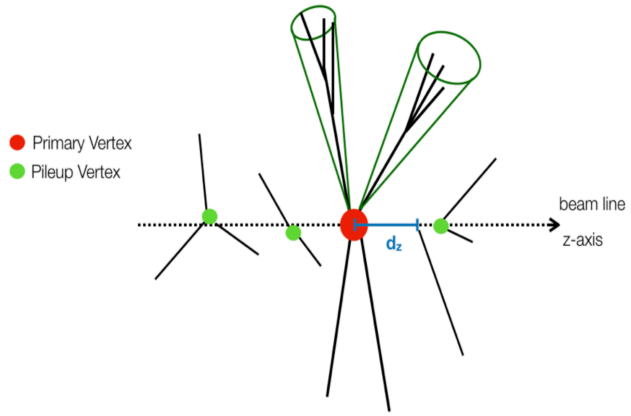
- **Silicon tracker**
  - 4th Pixel layer added in 2017, Microstrips from -15°C (2015 - 2017) to -20 °C (2018)
  - Barrel layer 1 replacement ongoing, DC-DC converters installed, now Forward Pixel
- **Trigger**
  - L1 (hardware) ~ 100kHz by 2016, High Level Trigger-HLT (software) ~ 1kHz by 2016
- **ECAL**
  - New DAQ links (2018)
- **HCAL**
  - Replaced HPDs with SiPMs in endcaps (2018)
- **Muon detectors**
  - Drift tubes: from VME to $\mu$TCA readout (2018), new RPC stations, new GEM detector (first Phase-2 detector), upgrade CSC FEE, add shielding against neutron background

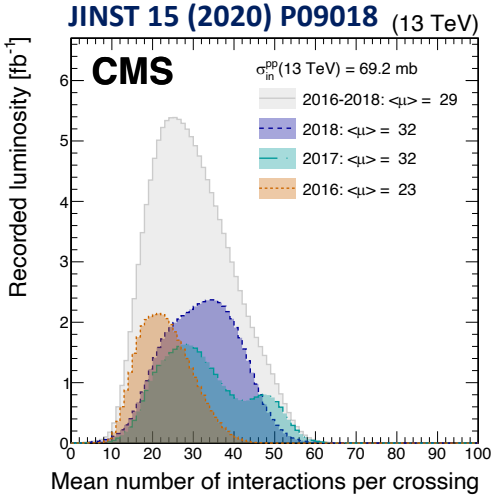


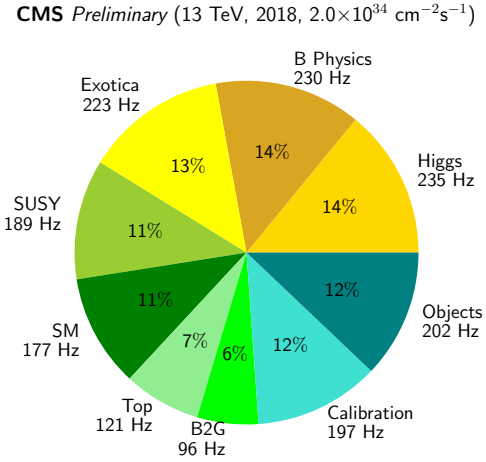


# CMS Performance in LHC Run 2

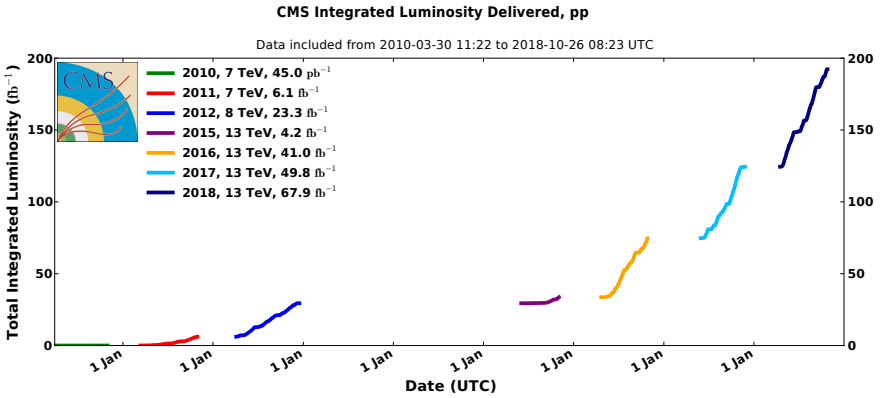
- 163 fb$^{-1}$ delivered/150 fb$^{-1}$ collected/**140 fb$^{-1}$ good for physics**
- PUPPI algorithm for pileup suppression in jet and MET becoming default in Run 3

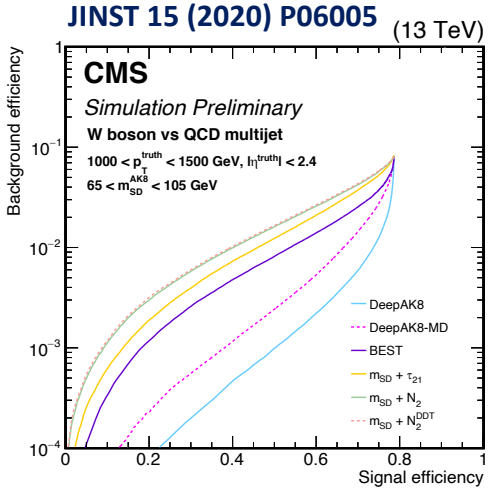


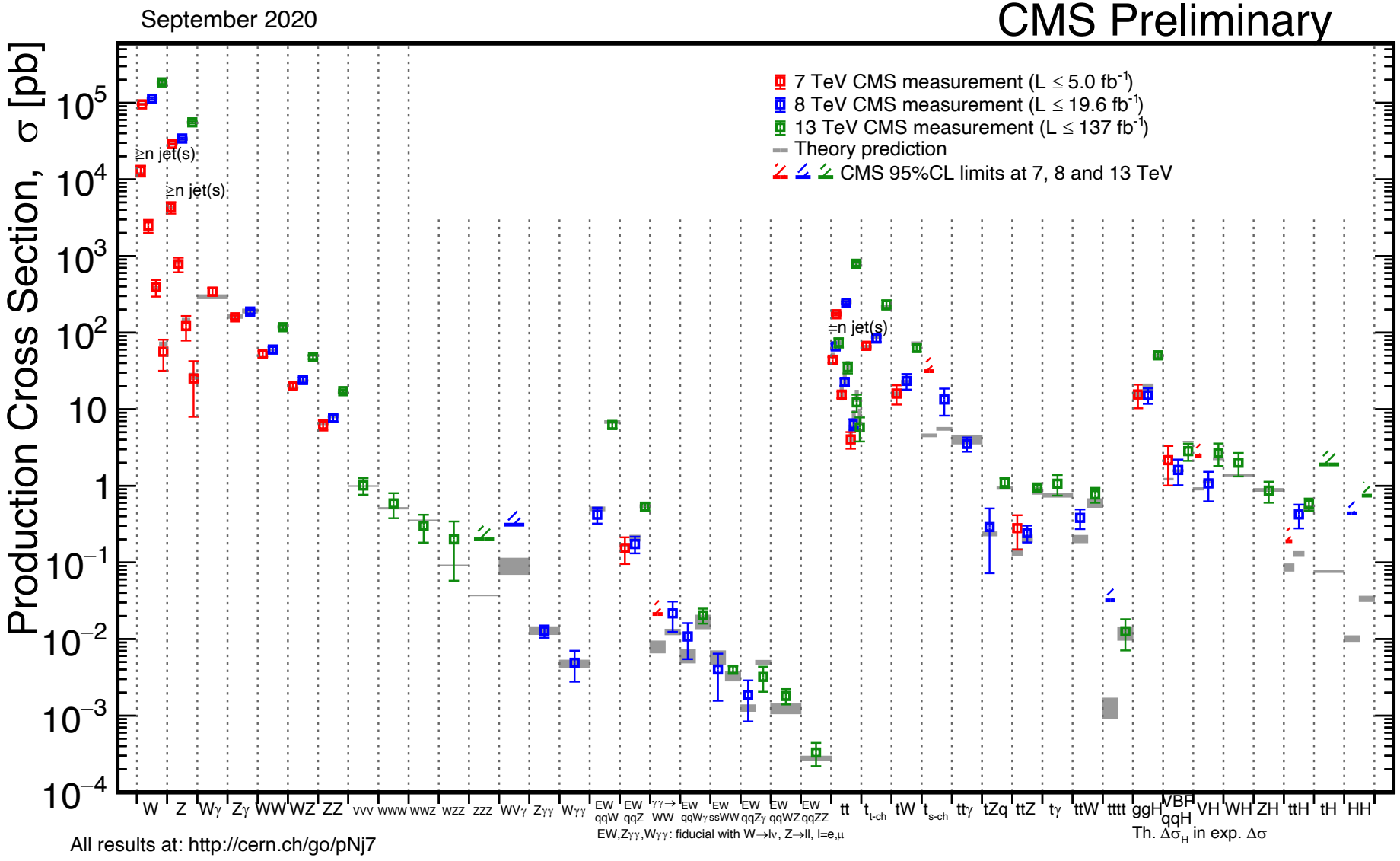




- Rich physics program provided by the CMS Run 2 Triggers: standard (vtx, leptons, jets, MET), B-parking (11B events), scouting triggers and special (the Heavy-ions and Low-PU)
- From MVA to DeepNN algorithms:
  - DeepJet algos
  - DeepTau (DNN)
  - New b-tagging



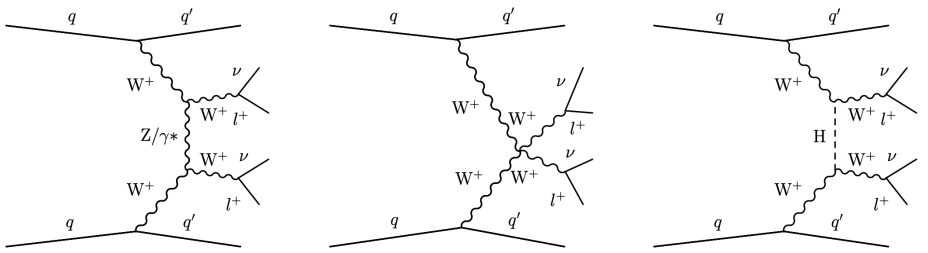
# Standard Model Cross Sections



# Polarized same-sign WW in VBS

- BSM models predict modification of VBS with a longitudinally polarized W bosons
- VBS topology: ss-leptons, 2 fwd jets, η gap

CMS-SMP-20-006

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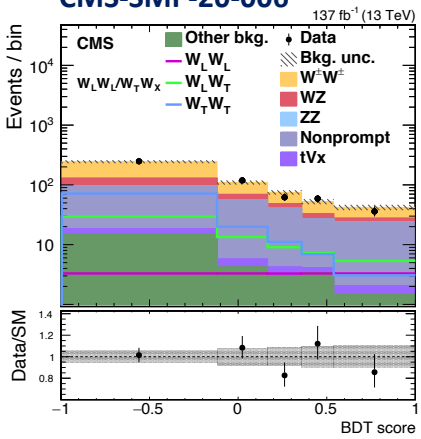


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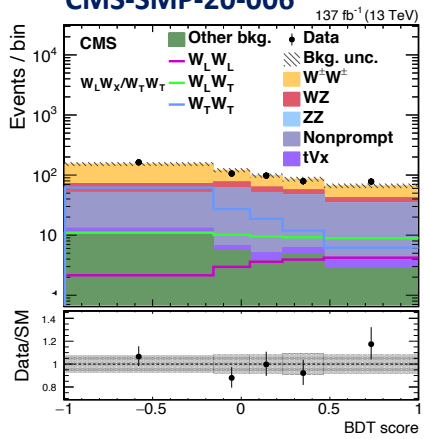



- Two separate EWK WW polarization states
  - $W_LW_L$ and $W_TW_X$ - dedicated BDT
  - $W_TW_T$ and $W_LW_X$ - dedicated BDT (X is either of two polarization states)
- The $W_L$ has smaller $p_T$ compared to the $W_T$

- Fiducial x-sec in WW center of mass frame

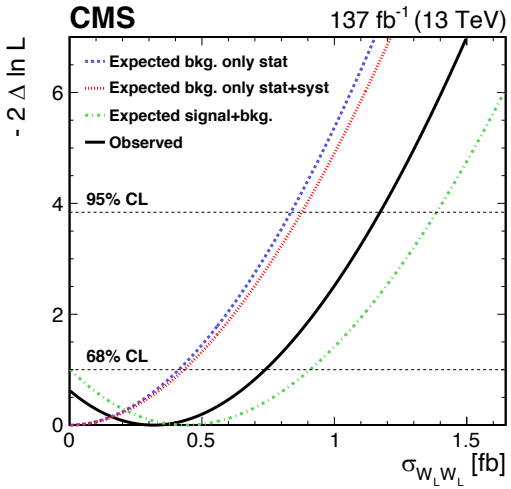
| Process | $\sigma\,\mathcal{B}$ (fb) | Theoretical prediction (fb) |
|---|---|---|
| $W^\pm_L W^\pm_L$ | $0.32^{+0.42}_{-0.40}$ | $0.44 \pm 0.05$ |
| $W^\pm_X W^\pm_T$ | $3.06^{+0.51}_{-0.48}$ | $3.13 \pm 0.35$ |
| $W^\pm_L W^\pm_X$ | $1.20^{+0.56}_{-0.53}$ | $1.63 \pm 0.18$ |
| $W^\pm_T W^\pm_T$ | $2.11^{+0.49}_{-0.47}$ | $1.94 \pm 0.21$ |

- Fiducial x-sec: in initial state parton-parton c. mass frame

| Process | $\sigma\,\mathcal{B}$ (fb) | Theoretical prediction (fb) |
|---|---|---|
| $W^\pm_L W^\pm_L$ | $0.24^{+0.40}_{-0.37}$ | $0.28 \pm 0.03$ |
| $W^\pm_X W^\pm_T$ | $3.25^{+0.50}_{-0.48}$ | $3.32 \pm 0.37$ |
| $W^\pm_L W^\pm_X$ | $1.40^{+0.60}_{-0.57}$ | $1.71 \pm 0.19$ |
| $W^\pm_T W^\pm_T$ | $2.03^{+0.51}_{-0.50}$ | $1.89 \pm 0.21$ |

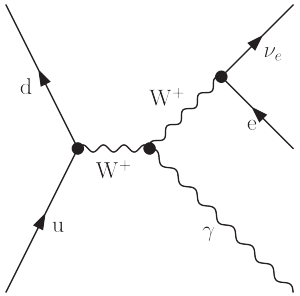
- 95% CL limit for $W_LW_L$ production 1.17fb(0.88fb exp)
- EWK production 2.3 $\sigma$ (3.1$\sigma$ exp)

CMS-SMP-20-006



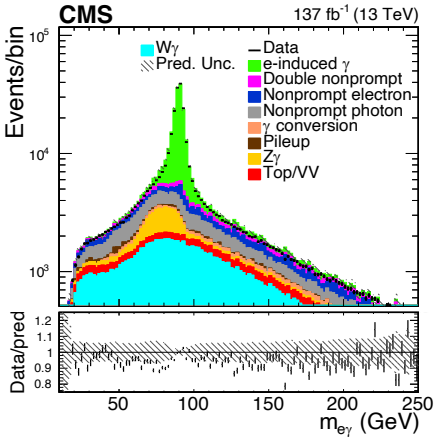
# Wγ production and EFT constraints

- Wγ is produced through ISR, FSR or aTGC
- Probe of the WWγ Triple Gauge Coupling
- Low-dim EFT operator alter the WWγ TGC




$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}],$$
$$\mathcal{O}_{B} = (D_{\mu}\Phi)^{\dagger}B^{\mu\nu}(D_{\nu}\Phi),$$
$$\mathcal{O}_{W\tilde{W}W} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}], \text{and}$$
$$\mathcal{O}_{\tilde{W}} = (D_{\mu}\Phi)^{\dagger}\tilde{W}^{\mu\nu}(D_{\nu}\Phi),$$

CMS-SMP-19-002

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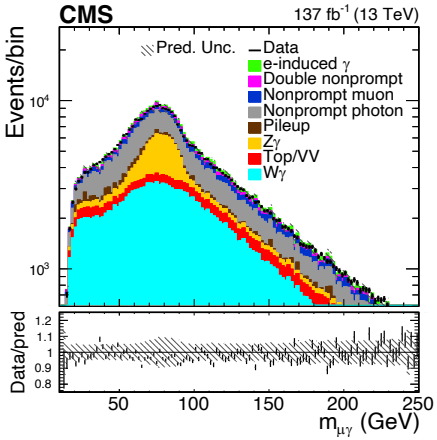
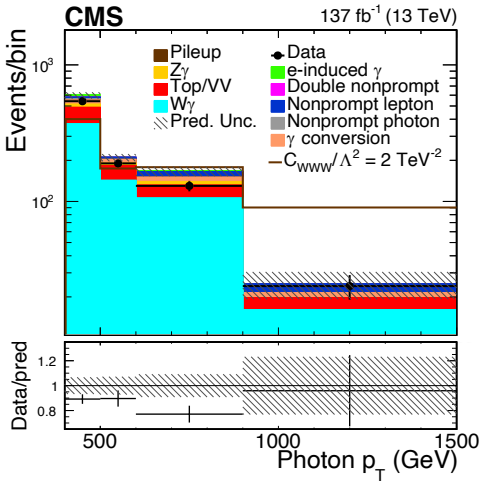



- Measured x-sec is: $\sigma$ = 15.58 ± 0.75 pb
- MadGraph5_aMC@NLO and POWHEG:
  $\sigma$ = 15.4 ± 0.75 (scale) ± 0.1 (PDF) pb (M)
  $\sigma$ = 22.4 ± 3.2 (scale) ± 0.1 (PDF) pb (P)

| Coefficient | Exp. lower | Exp. upper | Obs. lower | Obs. upper |
|---|---|---|---|---|
| $c_{WWW}/\Lambda^2$ | −0.85 | 0.87 | −0.90 | 0.91 |
| $c_B/\Lambda^2$ | −46 | 45 | −40 | 41 |
| $c_{\overline{W}WW}/\Lambda^2$ | −0.43 | 0.43 | −0.45 | 0.45 |
| $c_{\overline{W}}/\Lambda^2$ | −23 | 22 | −20 | 20 |

- Binned likelihood fit to the $m_{l\gamma}$ distribution
- Photon $p_T$ is used to extract limits on the four operators
- Observed limits on $c_{WWW}/\Lambda^2$ are factor 1.75 lower w.r.p to the previous result

CMS-SMP-19-002



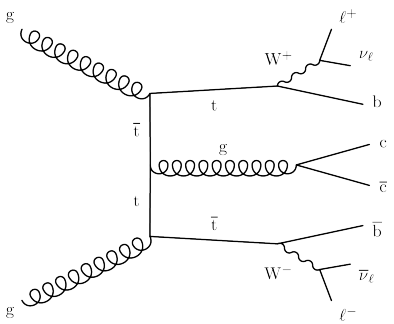

- The exp. (obs.) limits in LEP parametrization:

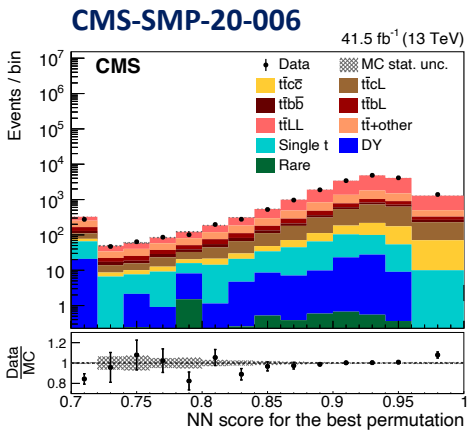
$-0.0033 < \lambda_\gamma < 0.0033$, $-0.074 < \tilde{\kappa}_\gamma < 0.072$, and $-0.0016 < \tilde{\lambda}_\gamma < 0.0016$

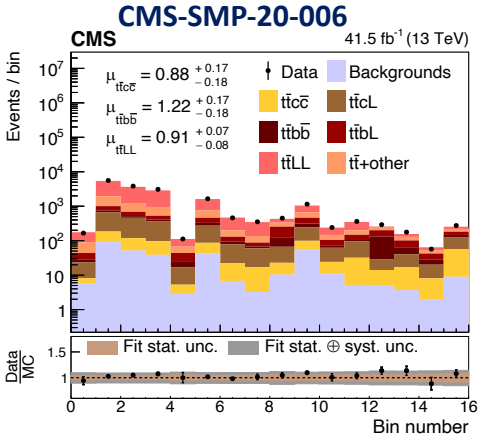
$-0.0035 < \lambda_\gamma < 0.0035$, $-0.066 < \tilde{\kappa}_\gamma < 0.065$, and $-0.0017 < \tilde{\lambda}_\gamma < 0.0017$

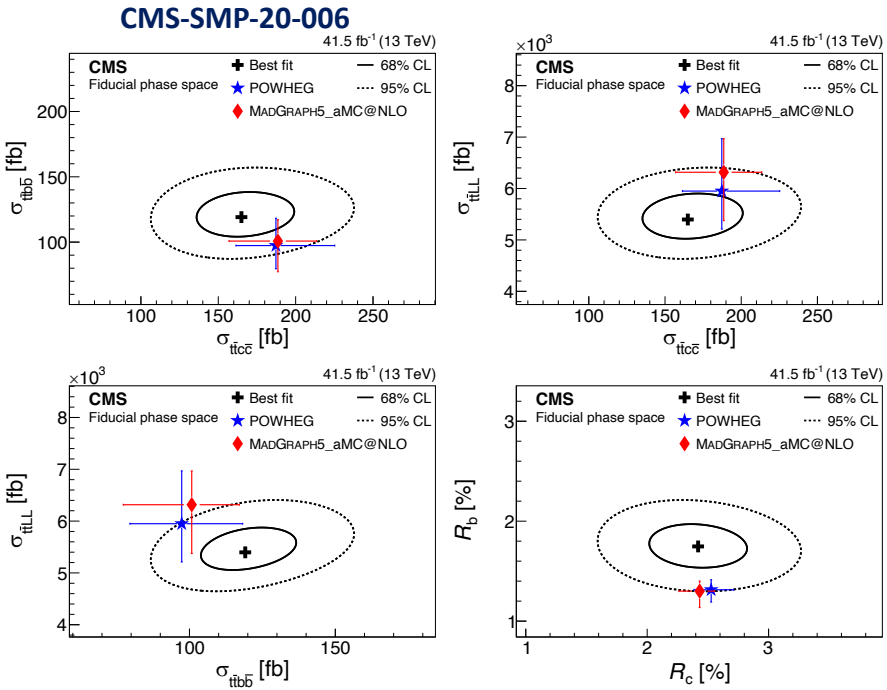
# Top pair + charm jets production

- First measurement of tt+cc production
- Important also for future ttH analysis
- The new charm-jet identification (DNN)
  - NN trained for the jet-parton assignment



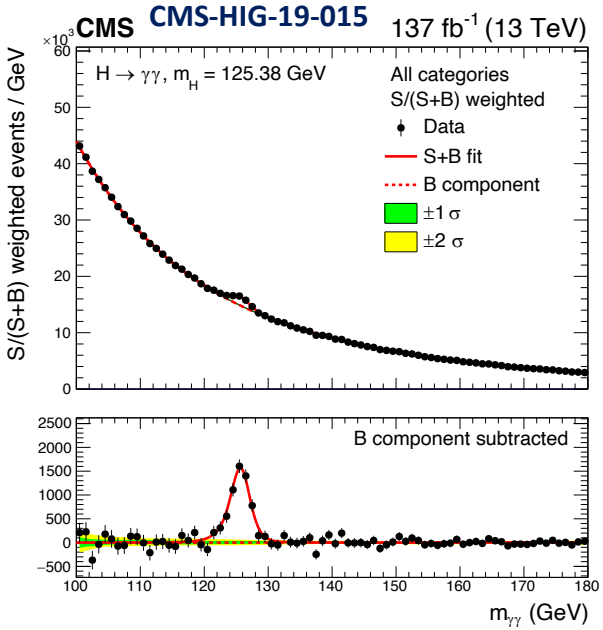



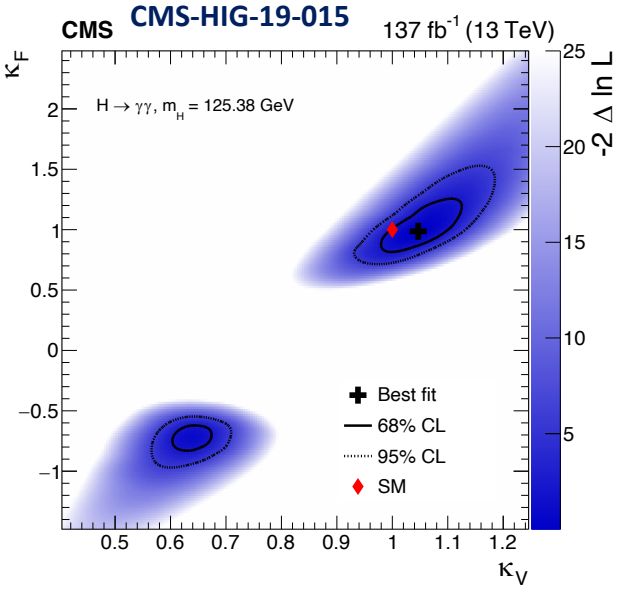

- Measured tt + cc production cross section:
  - Fiducial: 0.165 ± 0.023(stat) ± 0.025(syst)pb
  - Full-space: 8.0 ± 1.1(stat) ± 1.3 (syst)pb
- First time measured $R_c = \sigma(tt + cc)/\sigma(tt + jj)$:
  - Fiducial: 2.42 ± 0.32(stat) ± 0.29(syst)pb
  - Full-space: 2.69 ± 0.36(stat) ± 0.32 (syst)pb

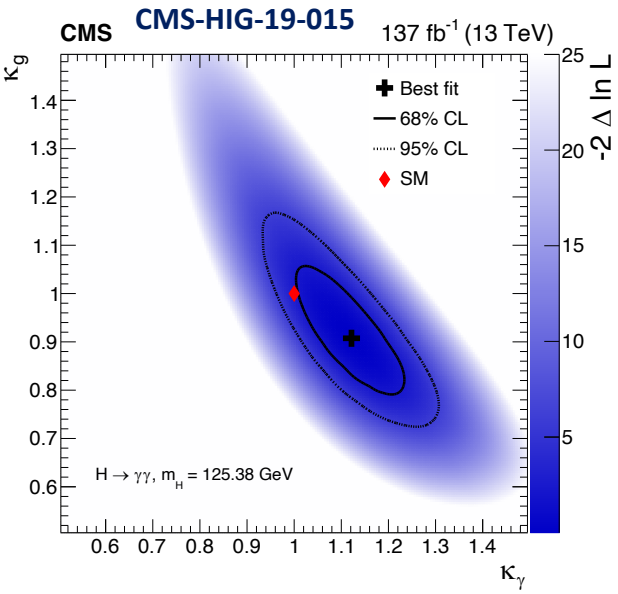
  (agree to POWHEG and MadGraph5_aMC@NLO)
- 2D likelihood scans agree within 1-2 $\sigma$ with the corresponding theoretical predictions:
  - $\sigma_{ttbb}$ and $R_b$ slightly above prediction

# Higgs boson studies: H → $\gamma\gamma$

- Full Run 2 dataset, ggH, VBF, VH and (t)tH channels
- BDT discriminator for analysis categories, diphoton BDT, dijet BDT for VBF, $VH_{had}$ BDT, DNN for tH vs ttH
- Total Higgs boson signal strenght found: $1.03^{+0.11}_{-0.09}$
- First STXS measurement of cross section at Stage 1.2



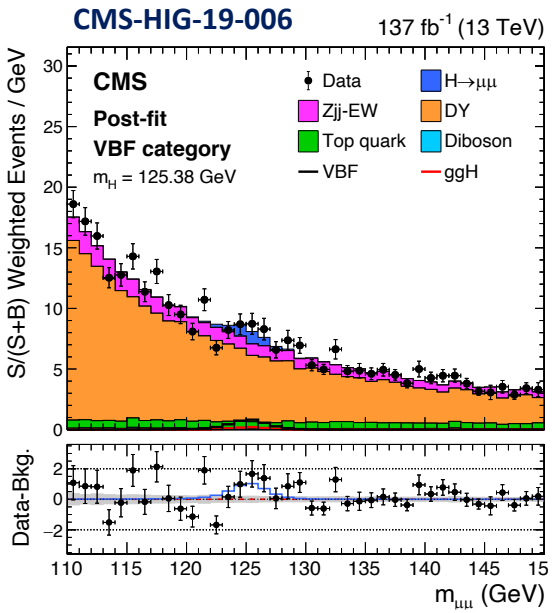



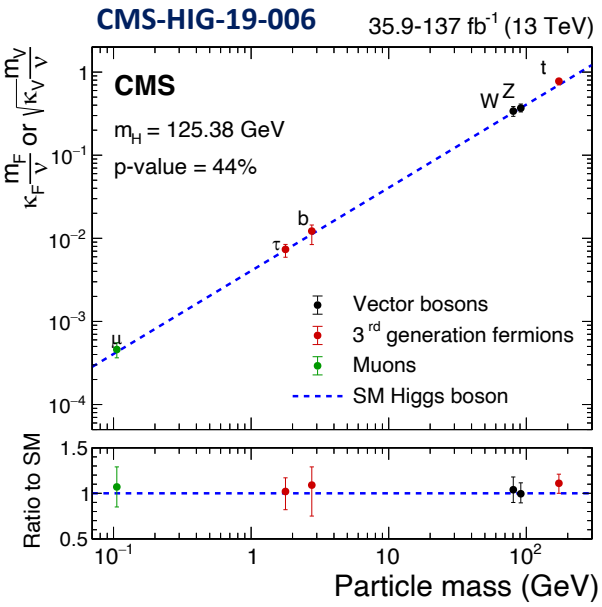



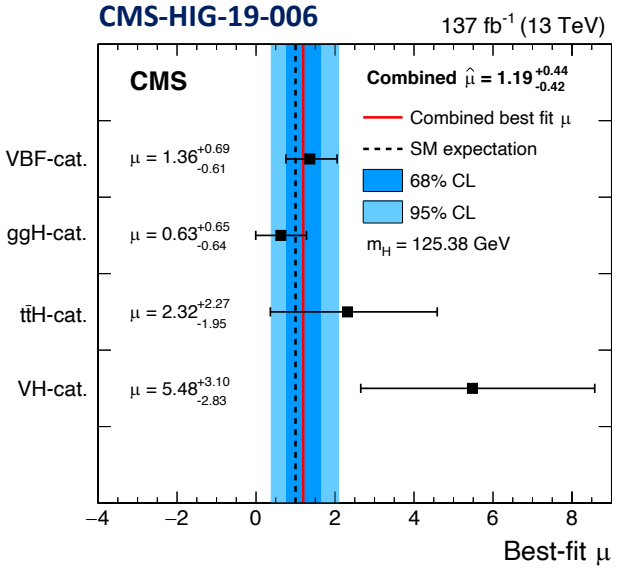

- 2D scans in $\kappa$ framework:
  - $\kappa_V$, $\kappa_f$ with ggH and H → $\gamma\gamma$ resolved in to SM components
  - $\kappa_g$, $\kappa\gamma$ with ggH and H → $\gamma\gamma$ resolved in eff. scaling factors
- Obs(exp) 95% CL UL on tH: 12(9) x the SM prediction

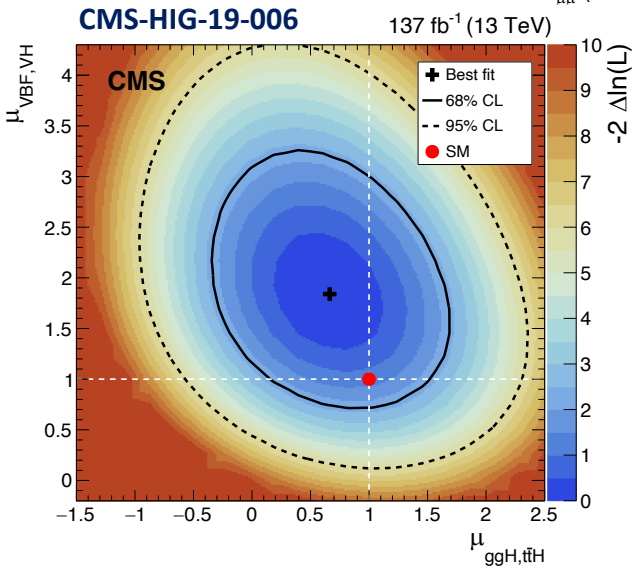
# Higgs boson studies: H → $\mu\mu$

- First evidence: 3.0(2.5)σ obs(exp), assuming SM H ($M_H$=125.38 GeV)
- Signal from 4 production modes:
  - VBF: DNN (dimuon & dijet)
  - ggH, VH, ttH: $m_{\mu\mu}$, BDT bins
- New point on the graph showing coupling strength vs fermion mass



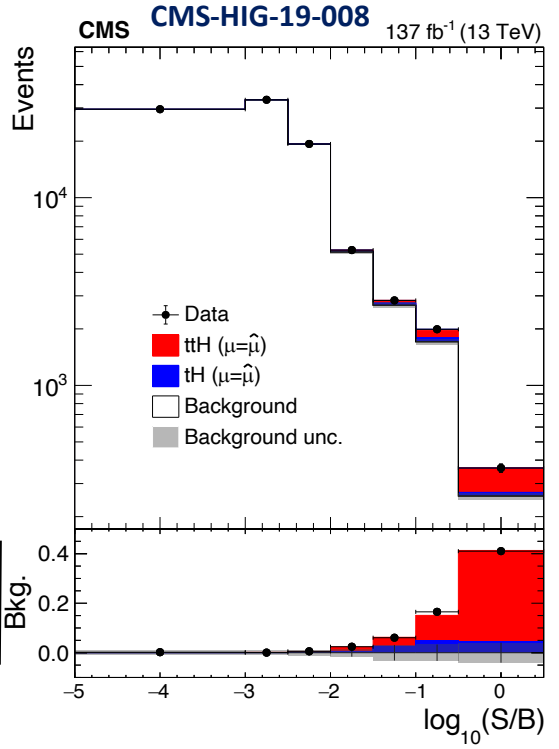

- Results agree with the SM:

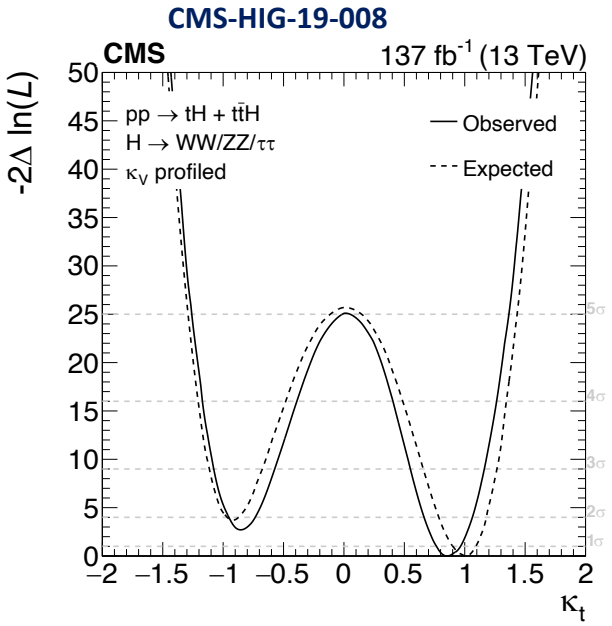
$$\mu = 1.19\ ^{+0.40}_{-0.39}(\text{stat.})\ ^{+0.15}_{-0.14}(\text{syst.})$$

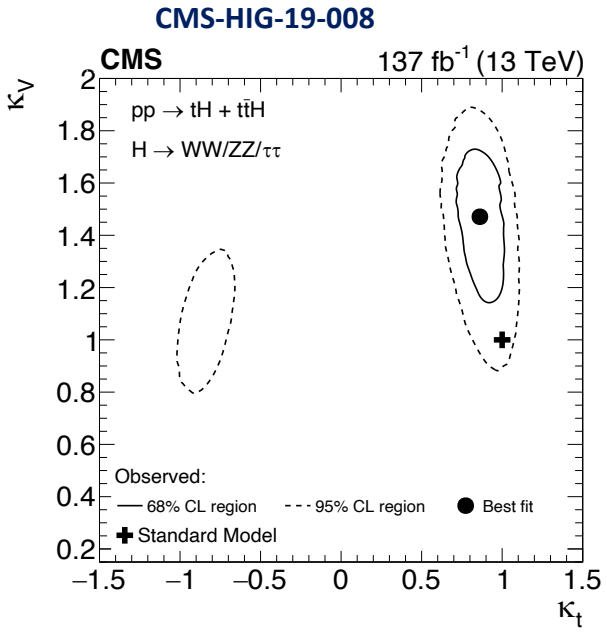
- Likelihood scan to fermion or vector boson couplings
- Combination with 7 and 8 TeV data: 1% improvement

# Higgs boson studies: ttH multilepton

- Observation of ttH production: PRL 120, 231801 (2018) from combination of analyses using several final states
- Now 4.7(5.2)σ obs.(exp.) significance just in multilepton
  - tH and ttH analysis using full Run 2 dataset (137fb$^{-1}$)
  - 10 different signatures based on lepton multiplicity
  - New multivariate techniques (DNN, multiclass ANN, using TensorFlow with Keras interface, scikit-learn)




- t-H coupling constrained:

$-0.9 < y_t < -0.7$ or

$0.7 < y_t < 1.1$

times the SM expectation

# Fully-hadronic top squark production (1/2)

- Natural SUSY: R-parity conserved and stop produced in pairs of cascade gluino decays
- Multiple jets, no leptons and a large MET
- Direct (T2tt, T2bW, T2tb, T2ttC, T2bWC, T2cc) & gluino-mediated (T1tttt, T1ttbb & T5ttcc)

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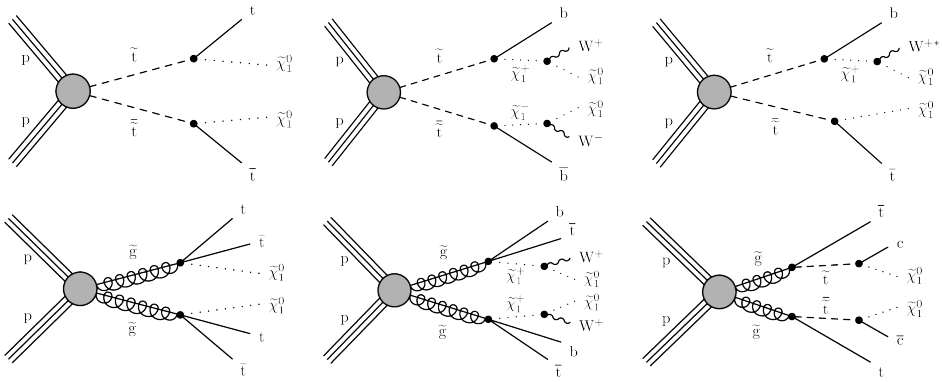

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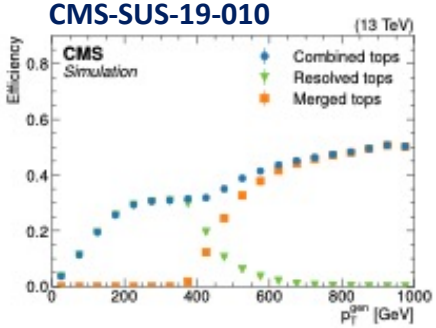


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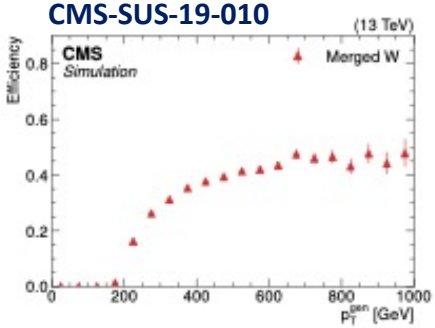
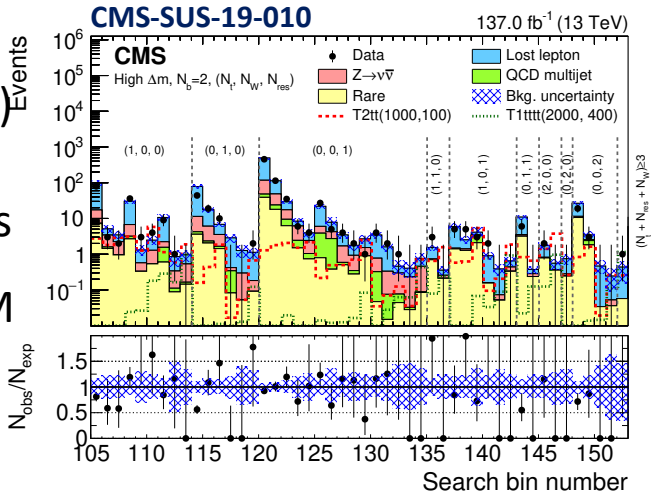



- Merged and resolved t and W taggers (DNN):
  - DeepAK8 multiclass for boosted t & W
  - DeepResolved algorithm for low $p_T$ top
- Derrived from MC, then corrected from data

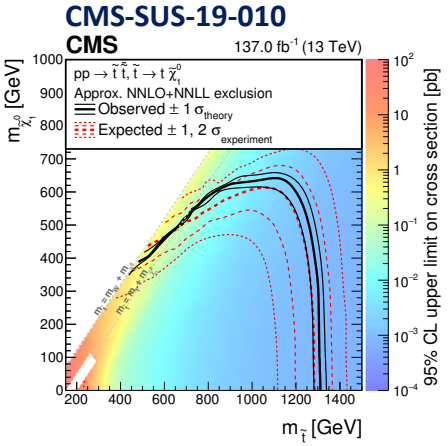
- 2 regions: high Δm (>$m_W$) & low Δm (<$m_W$)($\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$)
  - these are further divided into a total of 183 search bins
  - no statistically significant excess of events w.r.p. the SM
    - ❖ 6/183 bins with >2σ & no bins >3σ disagreement

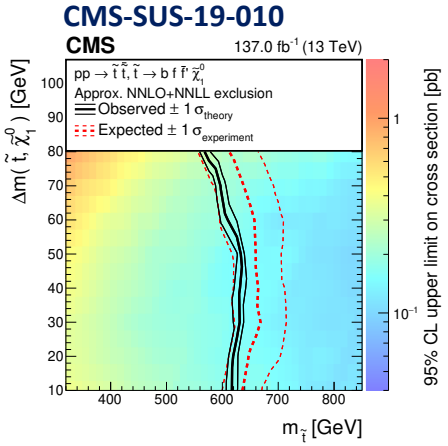
CMS-SUS-19-010

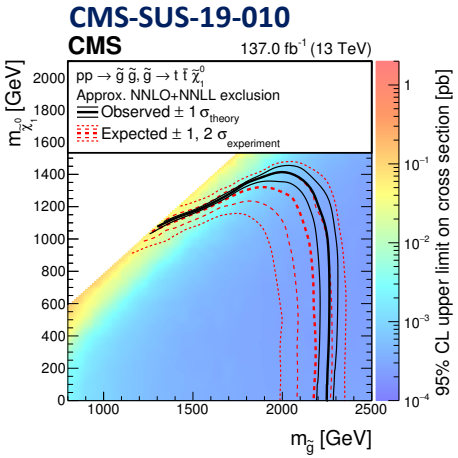


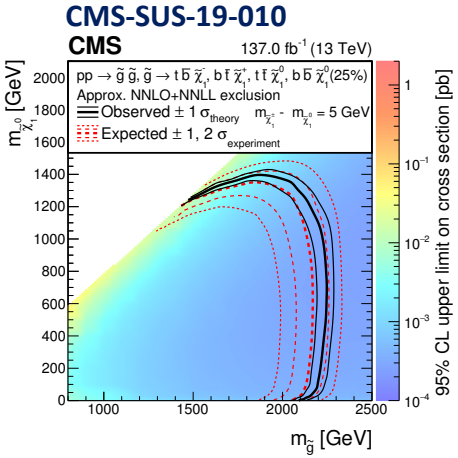
# Fully-hadronic top squark production (2/2)

- 95% CL upper limits on direct stop production:
  - 1150 to 1310 GeV in region of $\Delta m > m_W$
  - and 630 to 740 GeV in region: $\Delta m < m_W$
- These are the most stringent constraints to date

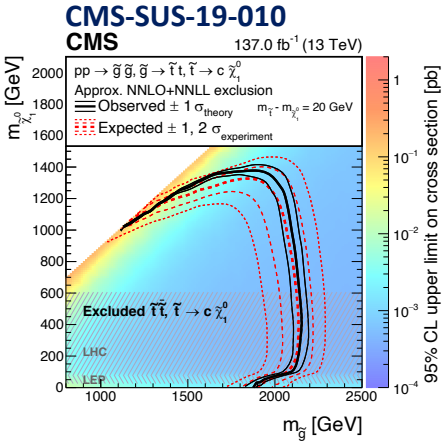



- 95% CL upper limits on gluino-mediated stop:
  - gluino masses below 2150 to 2260 GeV




- Exclusion based on T5ttcc model without contributions from direct stop
- Significantly extended previous fully-hadronic stop searches from CMS by 100 to 300 GeV, due to 4 times larger dataset and improved analysis

# Observation of a new barion: $\Xi_b(6100)^-$

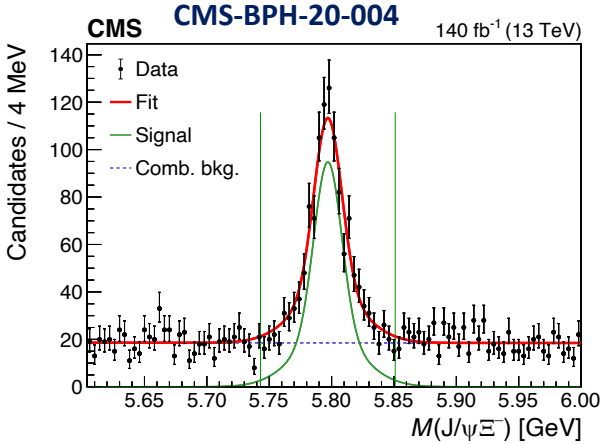
- Search for excited beauty strange state $\Xi_b(6100)^-$ in the $\Xi_b^-\,\pi^+\pi^-$ invariant mass spectrum
- Two fully reconstructed states:

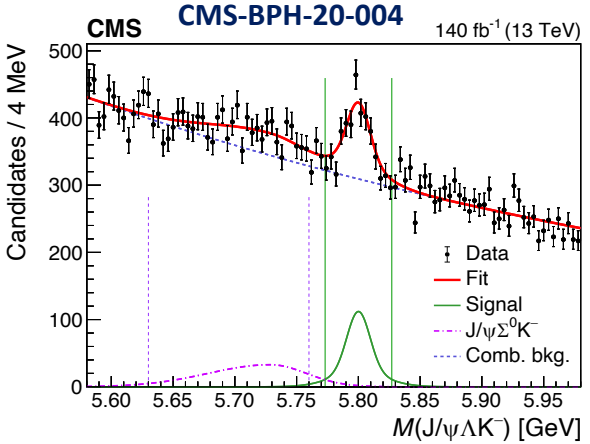
  $\Xi_b^- \to J/\psi\Xi^-$, $\Xi_b^- \to J/\psi\Lambda K^-$

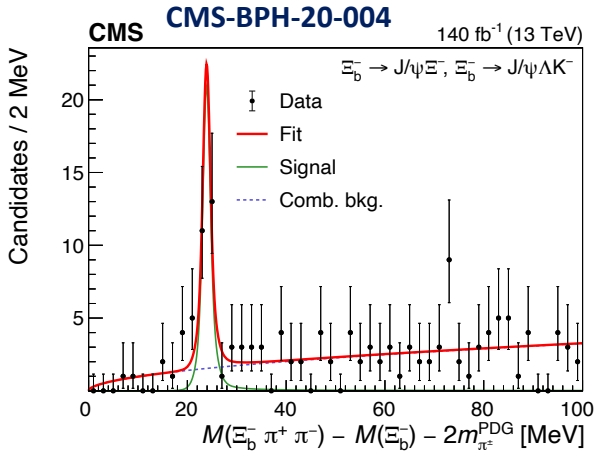
  followed by the decays of:

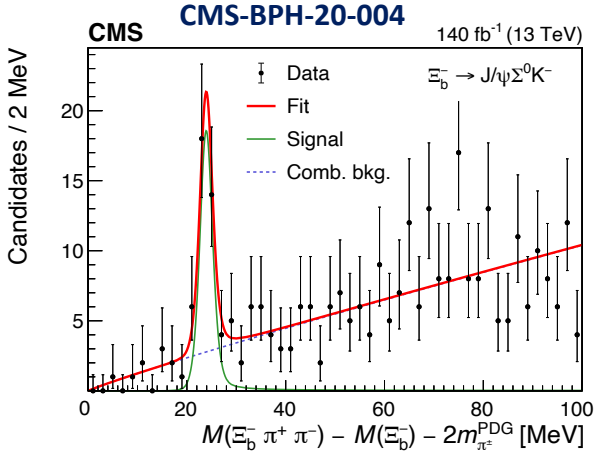
  $J/\psi \to \mu\mu$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$
- One partially reconstructed:

  $\Xi_b^- \to J/\psi\Sigma^0 K^-$ $(\Sigma^0 \to \Lambda\gamma)$




- ΔM with an improved resolution, also is insensitive to photon shift
- The resulting signal significance varies between 6.2 and 6.7 sigma
- The upper limit to natural width:

$$M(\Xi_b(6100)^-) = 6100.3 \pm 0.2(\text{stat}) \pm (0.1)\text{syst} \pm 0.6(\Xi_b^-)\text{MeV}$$

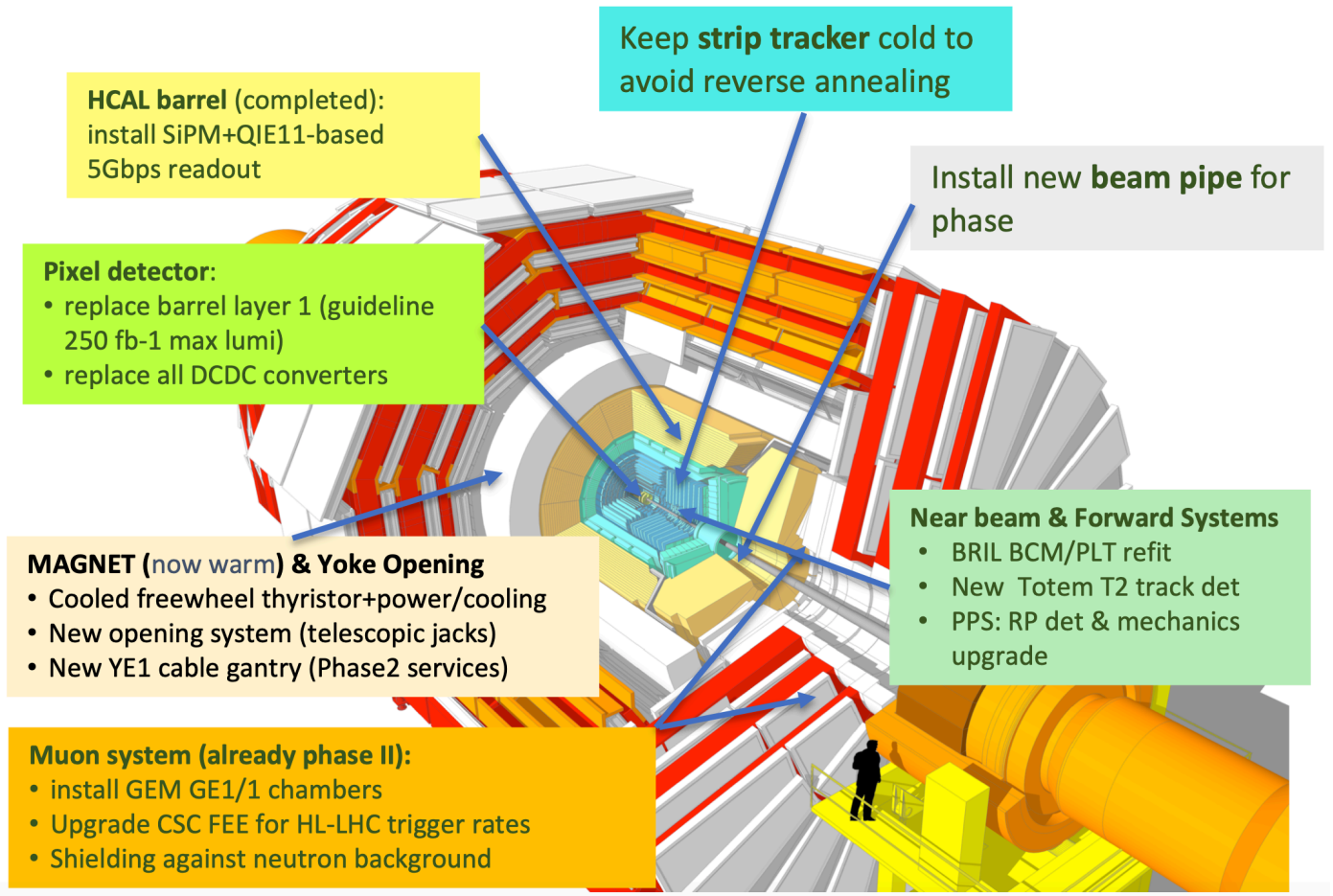
$$\Gamma(\Xi_b(6100)^-) < 1.9\text{MeV}\ (95\%\ \text{c.l.})$$

# CMS activities during LS2

- Only a small delay accumulated during the previous 12 months and the LHC will restart in 2022

- Maintenance, improvement and completing Phase1 upgrade

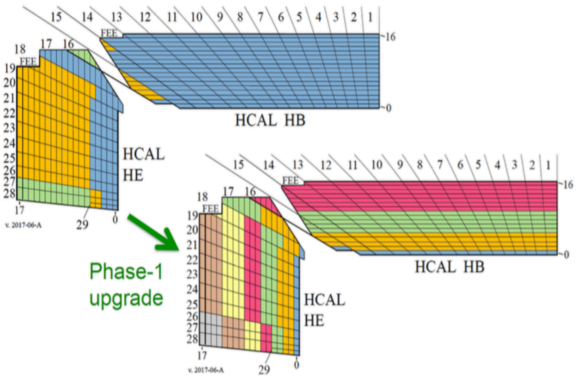
- Many activities already related to Phase2 (HL-LHC) upgrades and related services and infrastructure

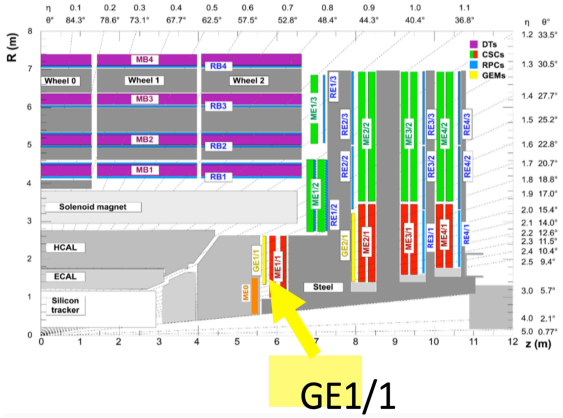


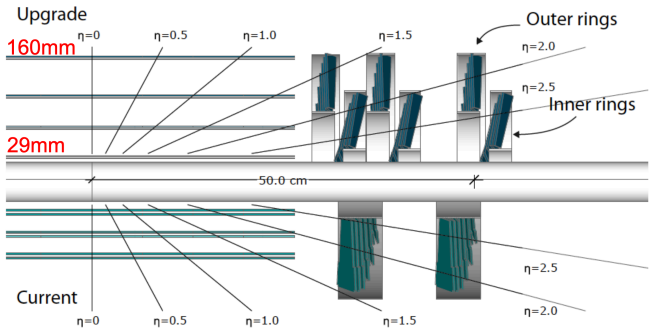

- All planned CMS LS2 activities to be performed in time for the first short test beam in Sep 2022

# CMS Plans for Run 3

- Increase of stats for searches and precision measurements
  - Use machine learning (DeepNN) to improve the S/B
  - Exploiting new detectors, some designed for Phase 2
- Phase-1 pixel detector with updated Layer 1 electronics →
- Depth segmentation ↓ from new electronics in the HCAL

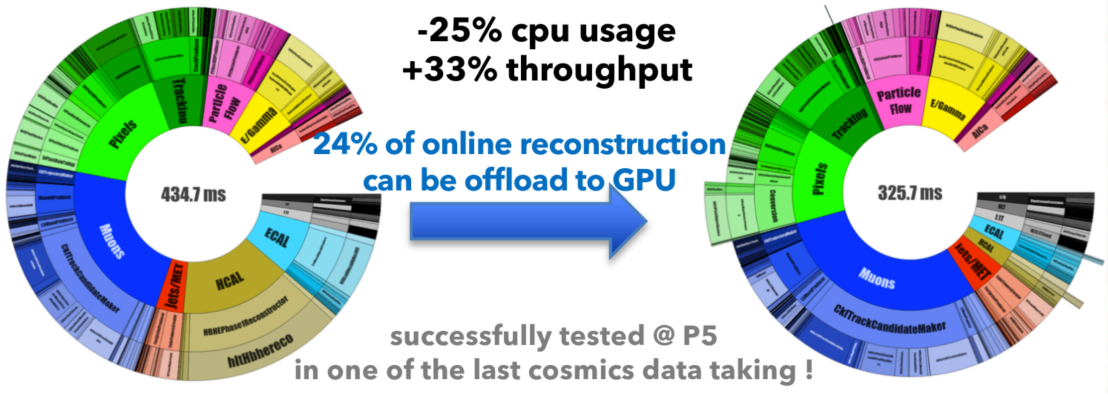



- First layer of GEM muon detectors in the forward ← region (GE1/1) installed

- Heterogeneous architecture in HLT, with mixed CPU/GPU, 25% reduction of CPU time achieved already → new possibilities for trigger algorithms usage on GPU

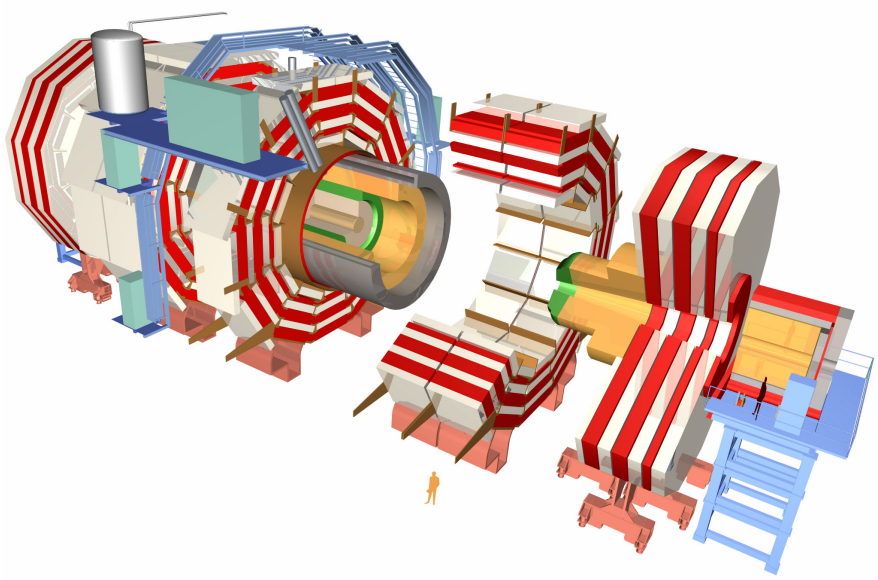


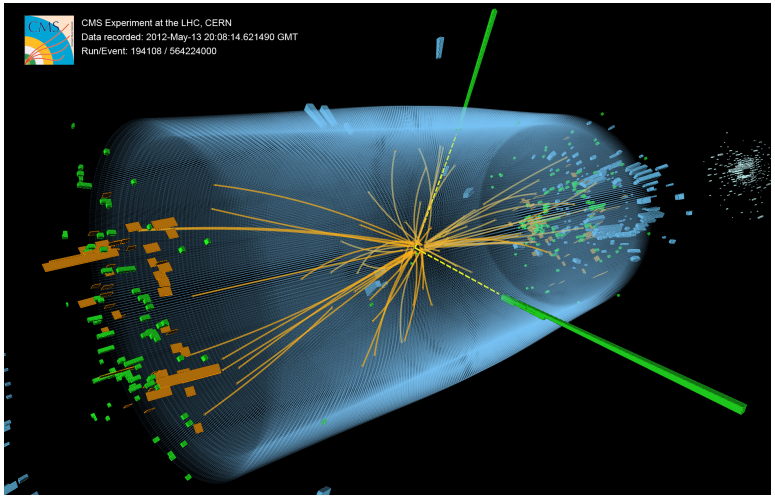
# Summary and outlook

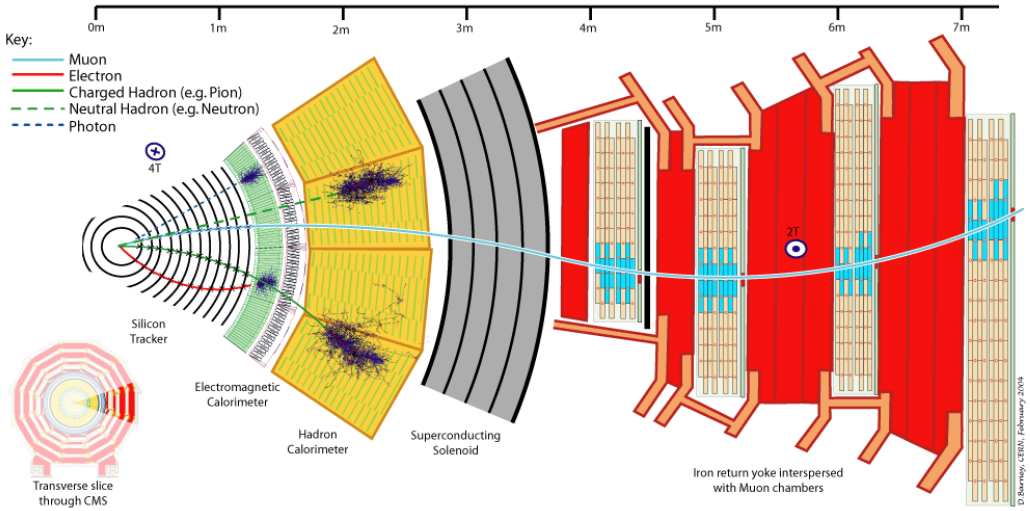
- Various new results from CMS released, exploiting the full Run 2 dataset:
  - SM measurements:
    - long. polarized WW VBS, W$\gamma$ with EFT,  top pair + charm tagger
  - Higgs boson studies:
    - H $\rightarrow \gamma\gamma$ full Run2 STSX, evidence for H $\rightarrow \mu\mu$, ttH multilepton
  - Direct BSM searches:
    - The most stringent limits on direct fully-hadronic stop production
- Many analyses are profiting from the novel machine learning algorithms:
  - widespread usage of DNN in analysis, also in reconstruction & Trigger
- Much more to come-> LHC Run 3: expected 300 $fb^{-1}$ and HL-LHC: 3000 $fb^{-1}$

# BACKUP SLIDES

# The CMS experiment at CERN

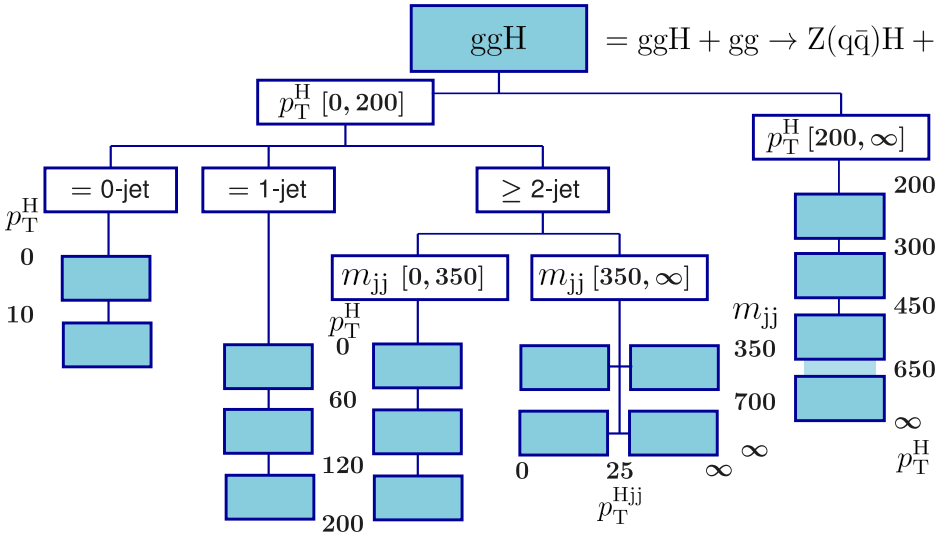


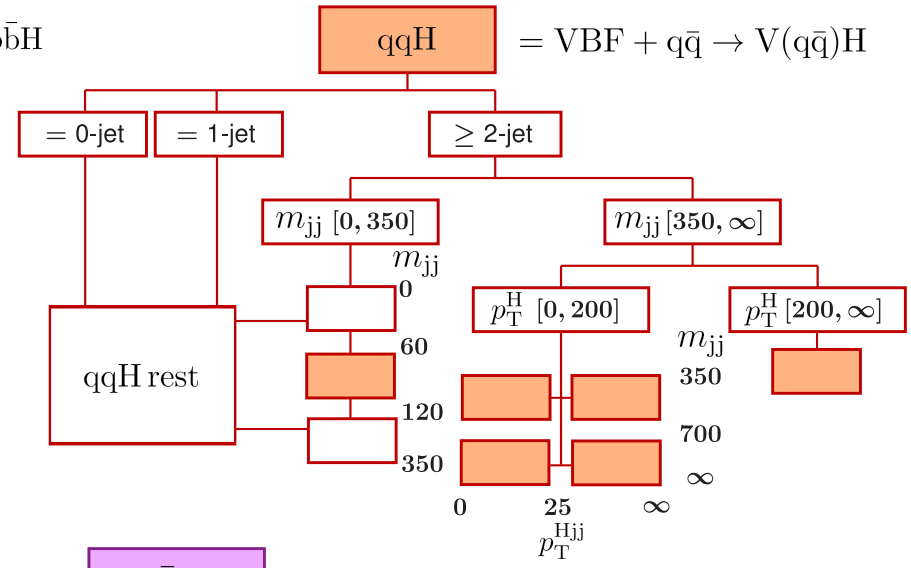


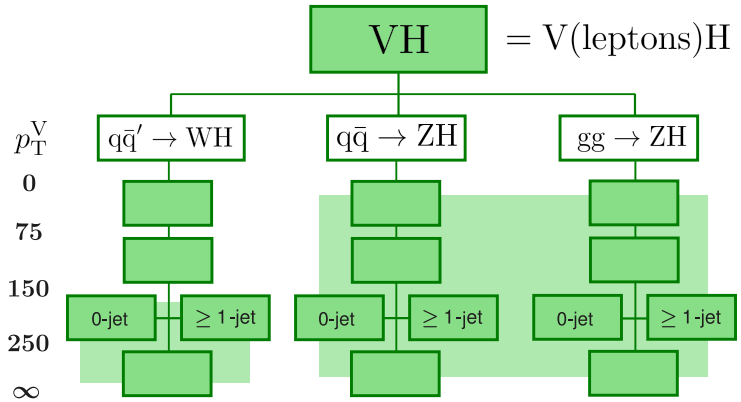



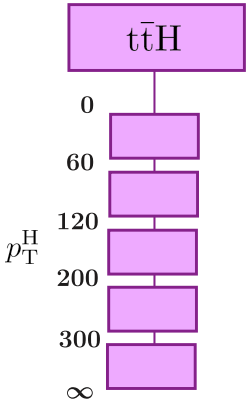
# H → $\gamma\gamma$: STXS stage-1.2 bins

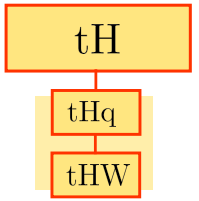
CMS-HIG-19-015



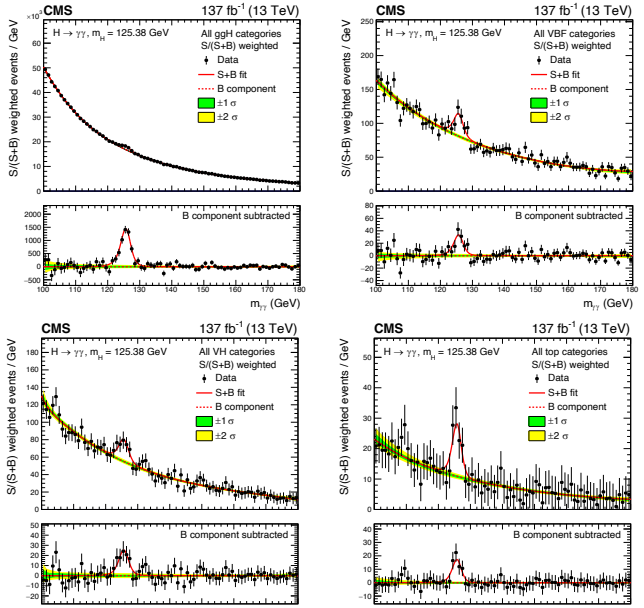



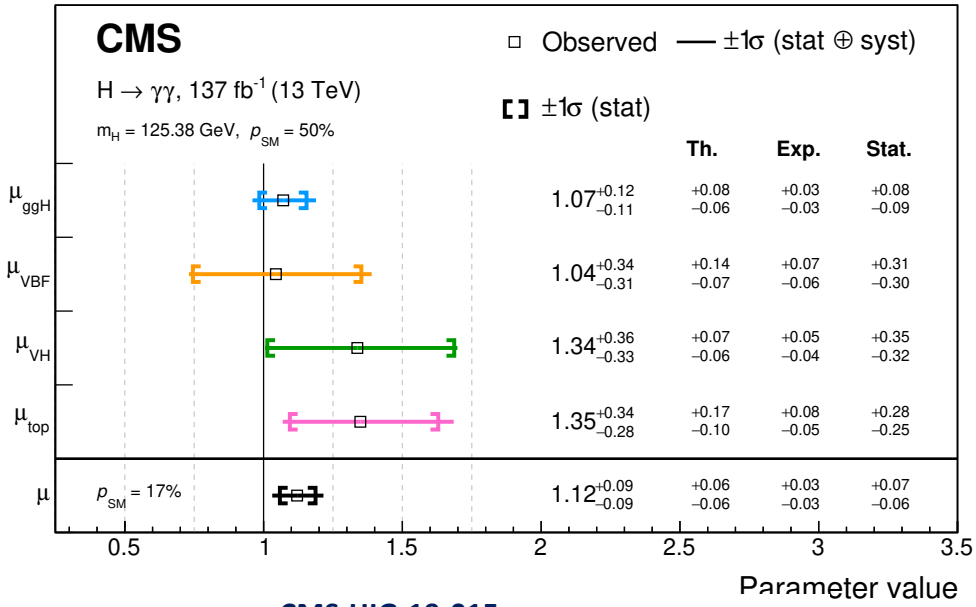



# H → $\gamma\gamma$: More results

CMS-HIG-19-015




CMS-HIG-19-015

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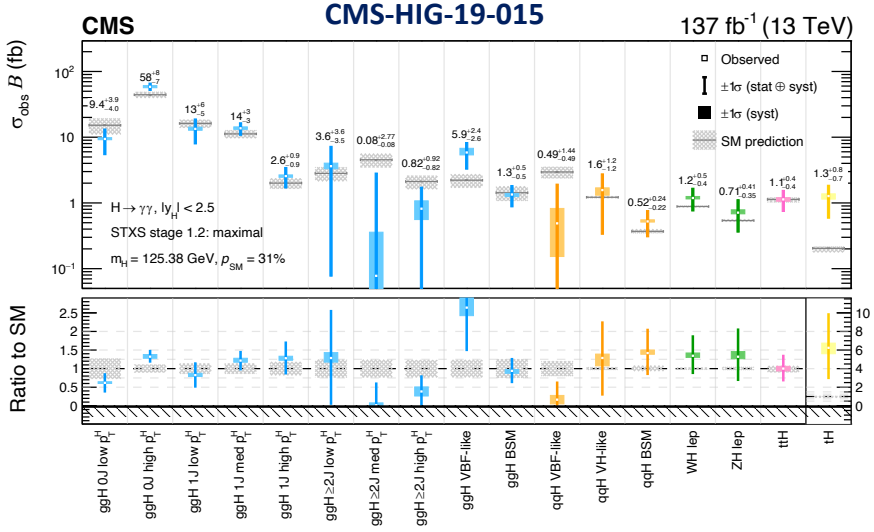


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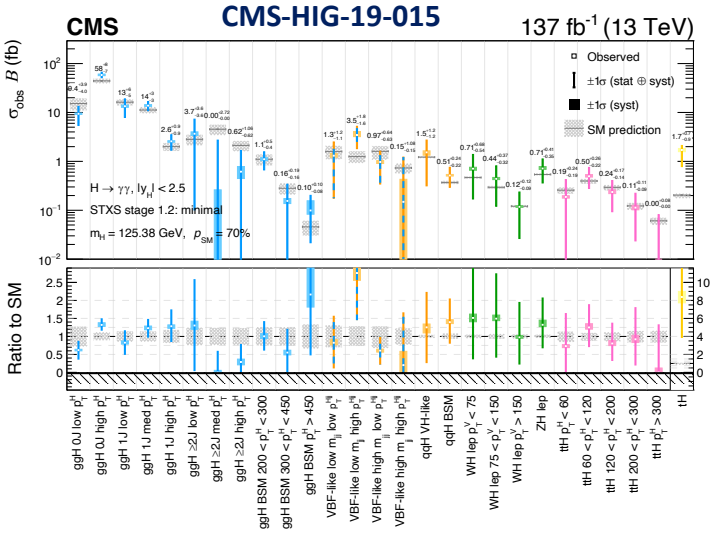
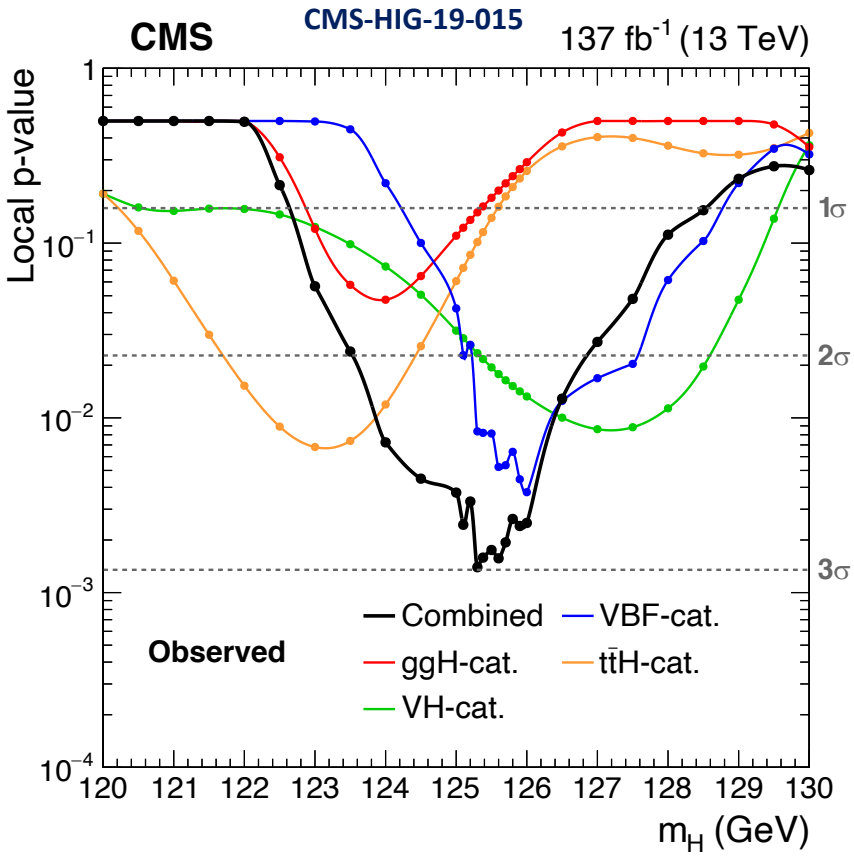
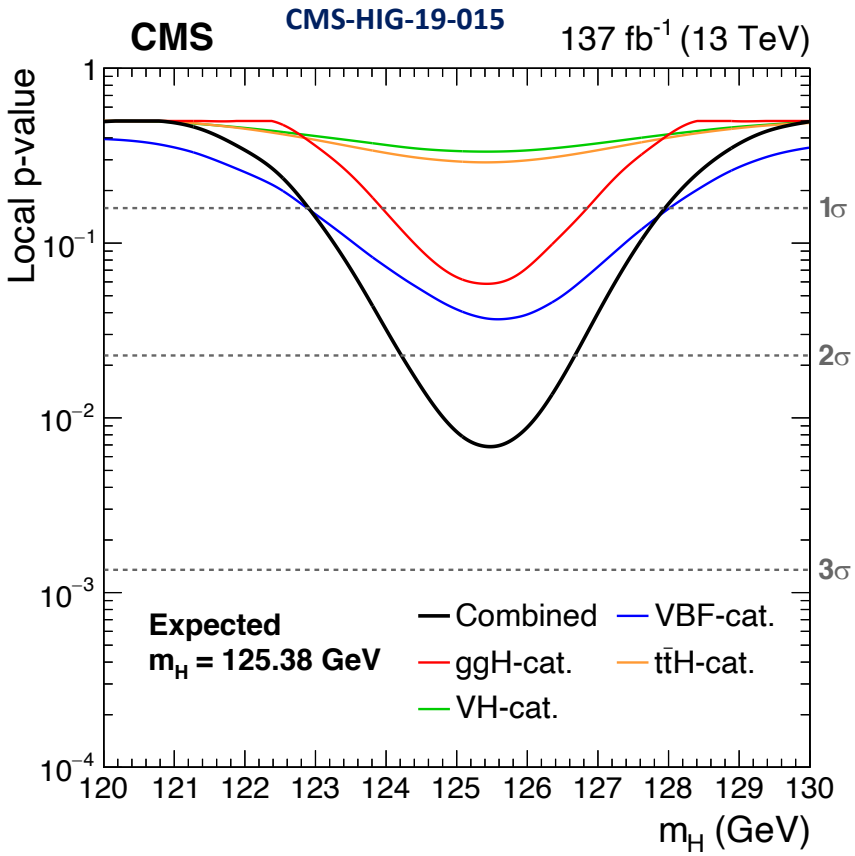
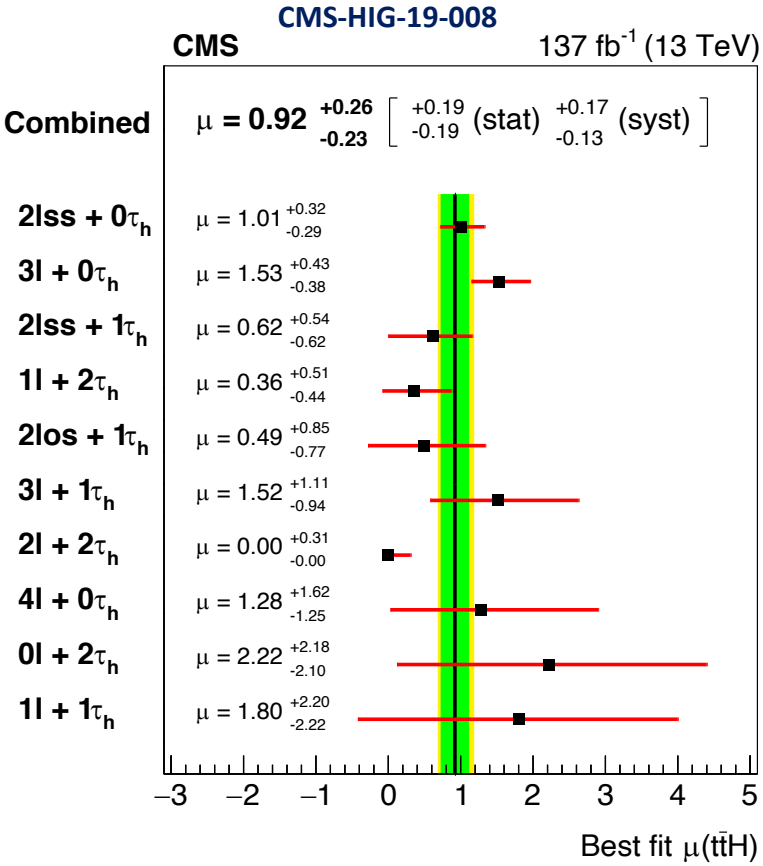


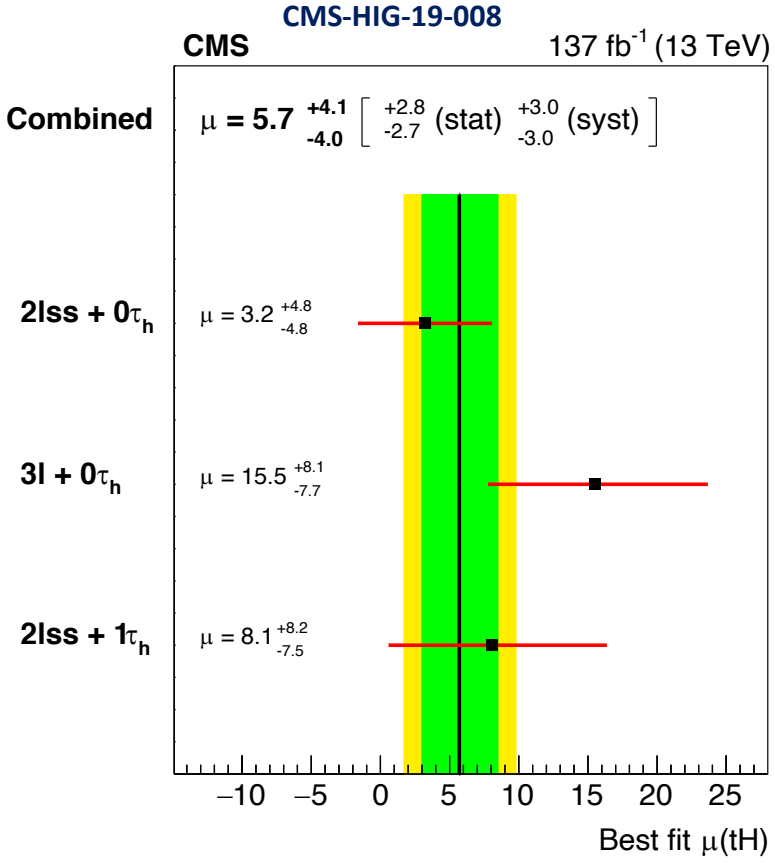
# Higgs boson studies: H → $\mu\mu$



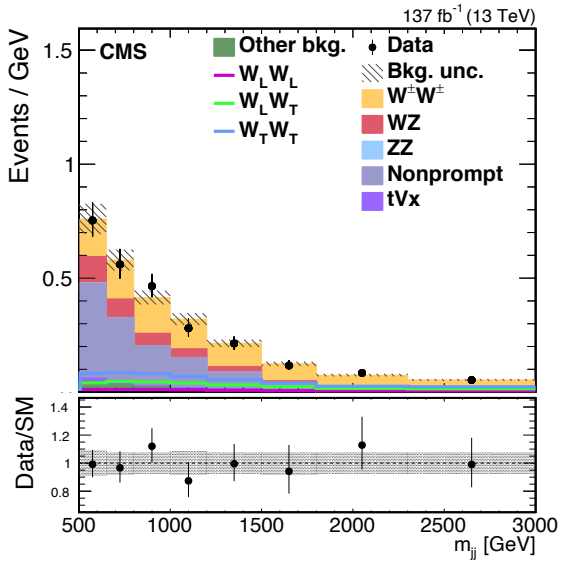
# Higgs boson studies: ttH multilepton

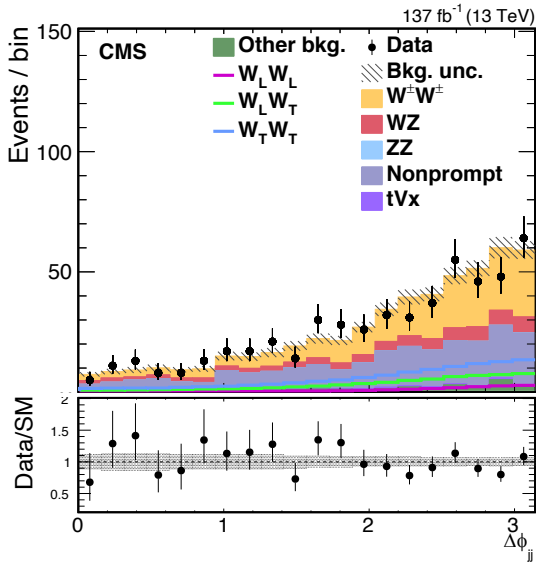


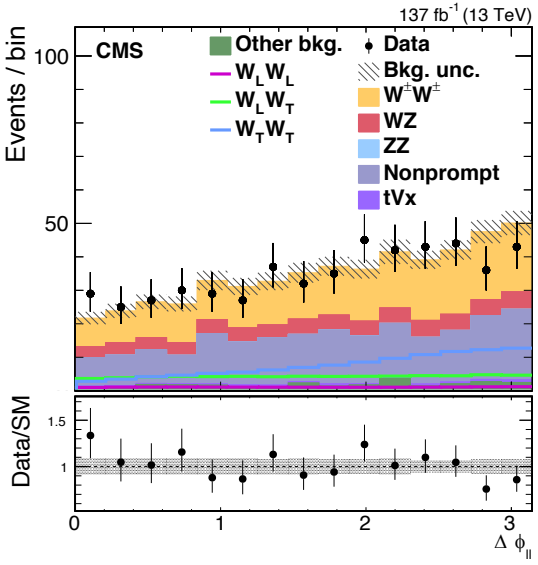



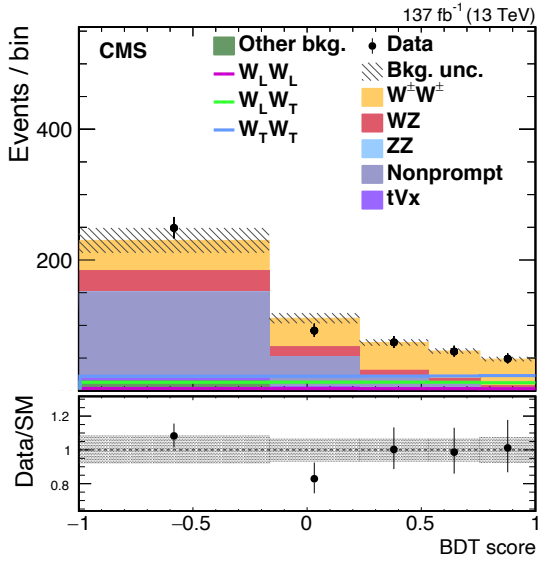
# Polarized same-sign WW in VBS

CMS-SMP-20-006



# Top pair + charm jets production

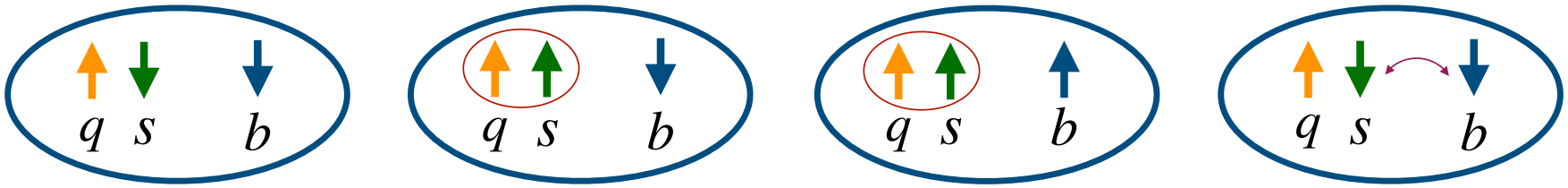
CMS-SMP-20-006

| | Result | POWHEG | MadGraph5_aMC@NLO |
|---|---|---|---|
| | **Fiducial phase space** | | |
| $\sigma_{t\bar{t}c\bar{c}}$ [pb] | $0.165 \pm 0.023 \pm 0.025$ | $0.187 \pm 0.038$ | $0.189 \pm 0.032$ |
| $\sigma_{t\bar{t}b\bar{b}}$ [pb] | $0.119 \pm 0.010 \pm 0.015$ | $0.097 \pm 0.021$ | $0.101 \pm 0.023$ |
| $\sigma_{t\bar{t}LL}$ [pb] | $5.40 \pm 0.11 \pm 0.45$ | $5.95 \pm 1.02$ | $6.32 \pm 0.94$ |
| $R_c$ [%] | $2.42 \pm 0.32 \pm 0.29$ | $2.53 \pm 0.18$ | $2.43 \pm 0.17$ |
| $R_b$ [%] | $1.75 \pm 0.14 \pm 0.18$ | $1.31 \pm 0.12$ | $1.30 \pm 0.16$ |
| | **Full phase space** | | |
| $\sigma_{t\bar{t}c\bar{c}}$ [pb] | $8.0 \pm 1.1 \pm 1.3$ | $9.1 \pm 1.8$ | $8.9 \pm 1.5$ |
| $\sigma_{t\bar{t}b\bar{b}}$ [pb] | $4.09 \pm 0.34 \pm 0.55$ | $3.34 \pm 0.72$ | $3.39 \pm 0.66$ |
| $\sigma_{t\bar{t}LL}$ [pb] | $231 \pm 5 \pm 21$ | $255 \pm 43$ | $261 \pm 37$ |
| $R_c$ [%] | $2.69 \pm 0.36 \pm 0.32$ | $2.81 \pm 0.20$ | $2.72 \pm 0.19$ |
| $R_b$ [%] | $1.37 \pm 0.11 \pm 0.14$ | $1.03 \pm 0.08$ | $1.03 \pm 0.09$ |

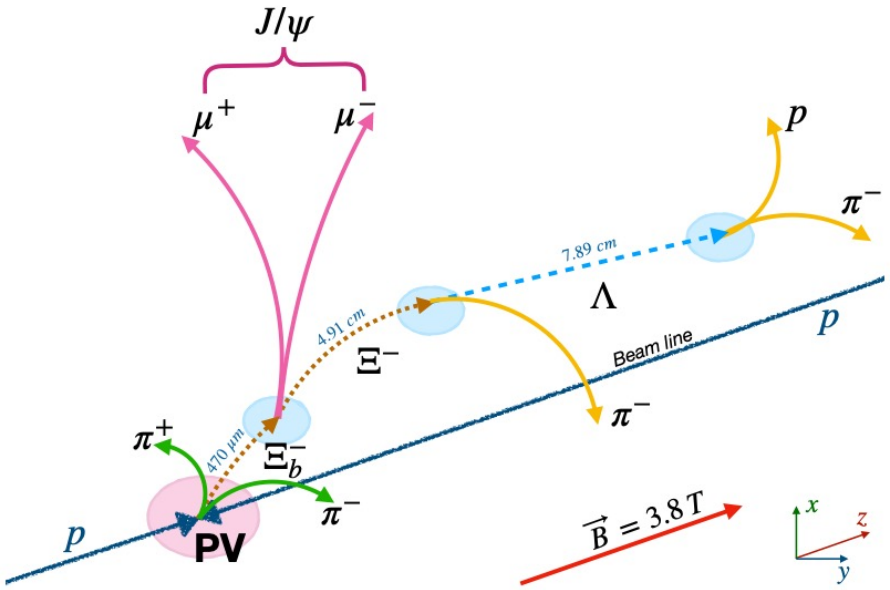
# Observation of a new barion: $\Xi_b(6100)^-$

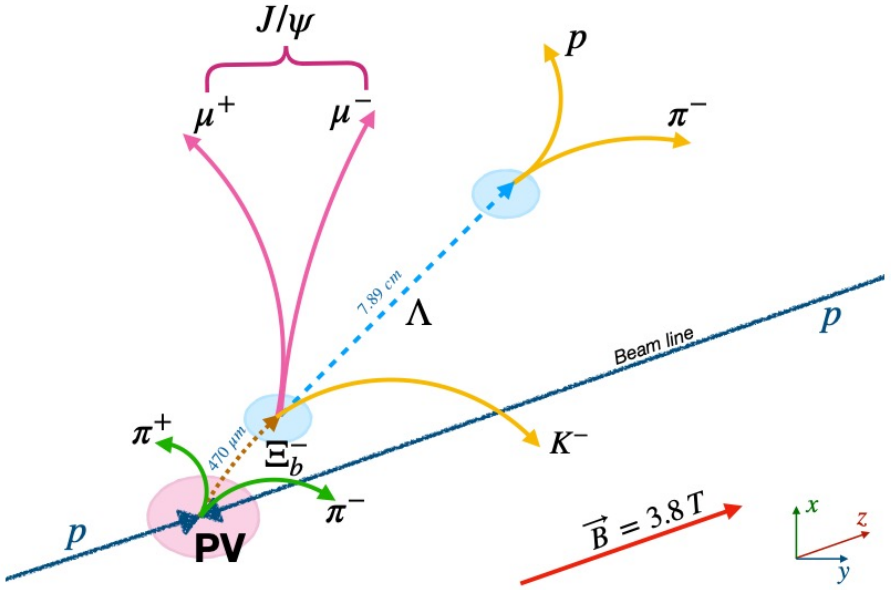
CMS-SMP-20-006

$\Xi_b$ $\Xi_b'$ $\Xi_b^*$ $\Xi_b^{**}$



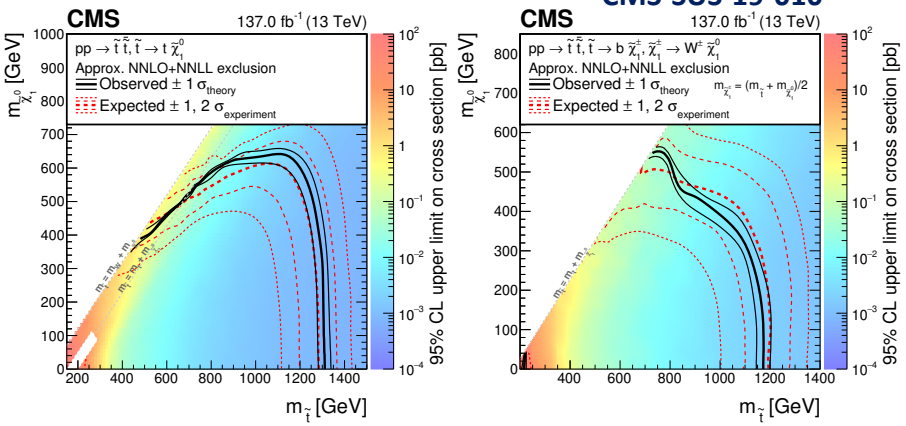

$j_{qs} = 0$, $J^P = \frac{1^+}{2}$ | $j_{qs} = 1$, $J^P = \frac{1^+}{2}$ | $j_{qs} = 1$, $J^P = \frac{3^+}{2}$ | $j_{qs} = 1$, $J^P = \frac{1^-}{2}$ or $\frac{3^-}{2}$, $L = 1$



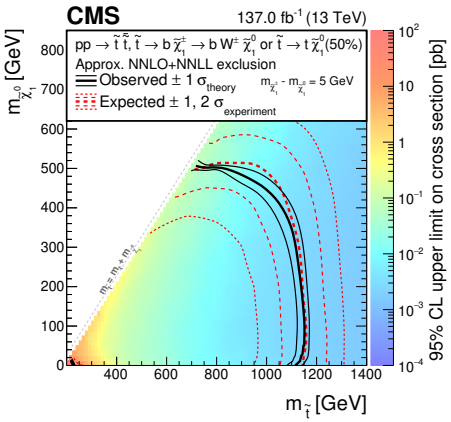
# Fully-hadronic top squark production (2/2)

CMS-SUS-19-010










CMS-SUS-19-010