THE CMS RUN 2 PHYSICS LANDSCAPE

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@PITT LHC Run 3 Workshop
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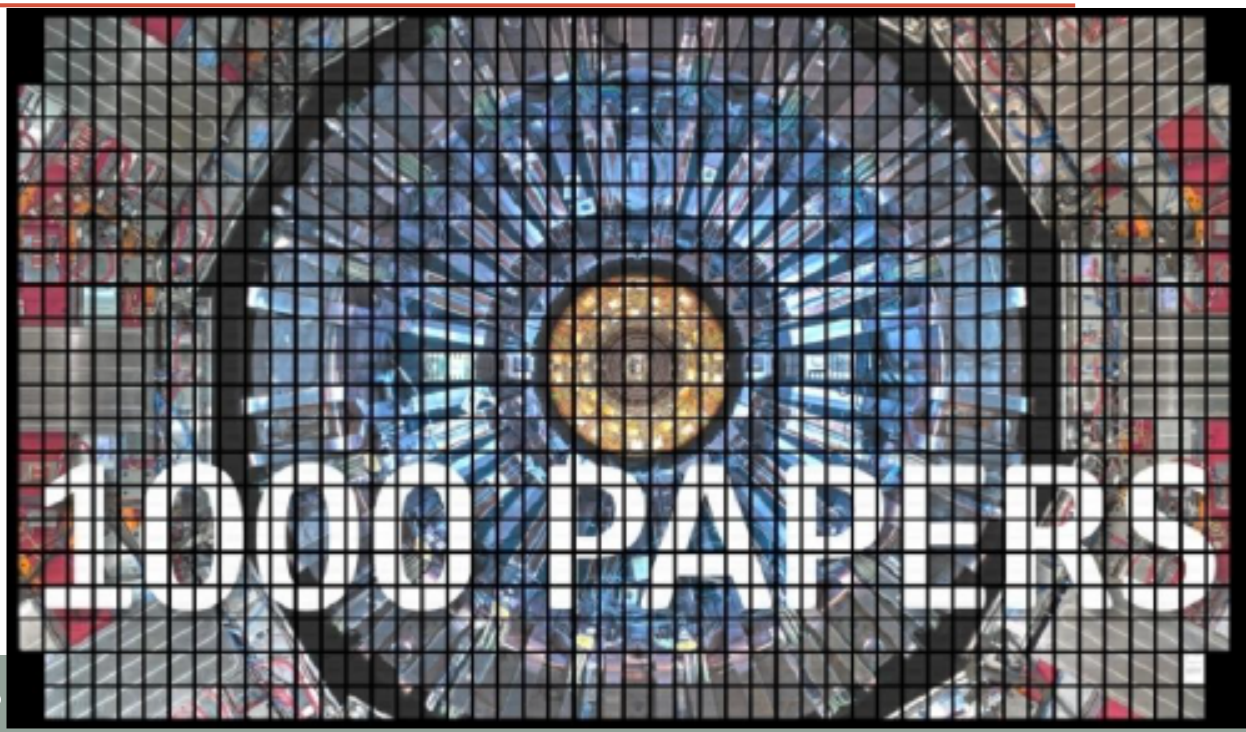


Operation of Large Hadron Collider

Nominal luminosity 1.0 x $10^{34}cm^{-2}s^{-1}$

X2 Run 2

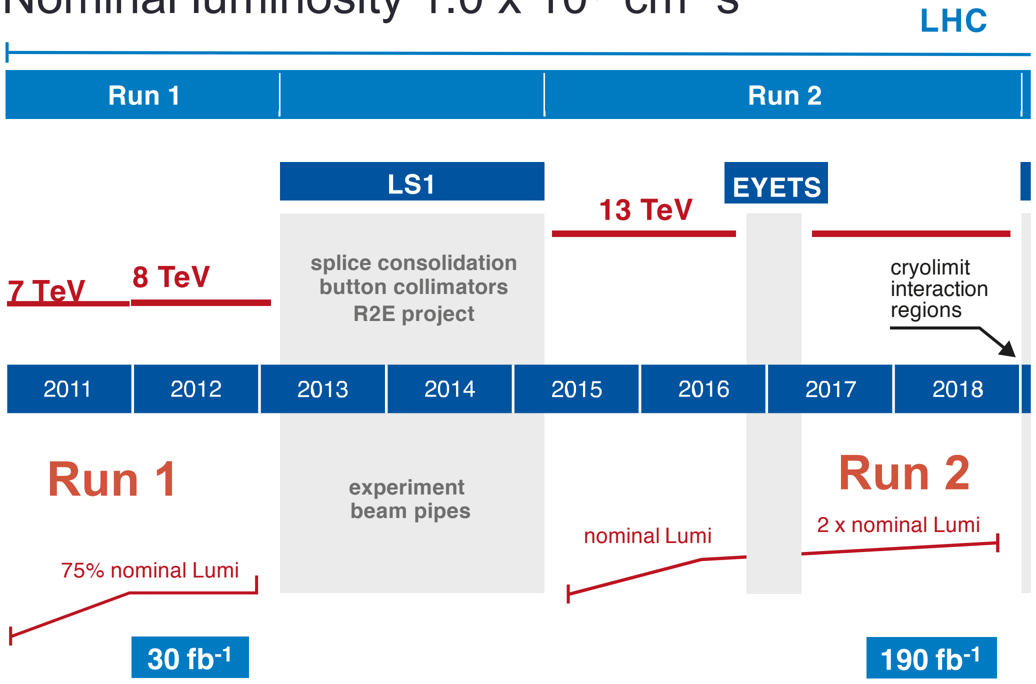
X10 Run 3

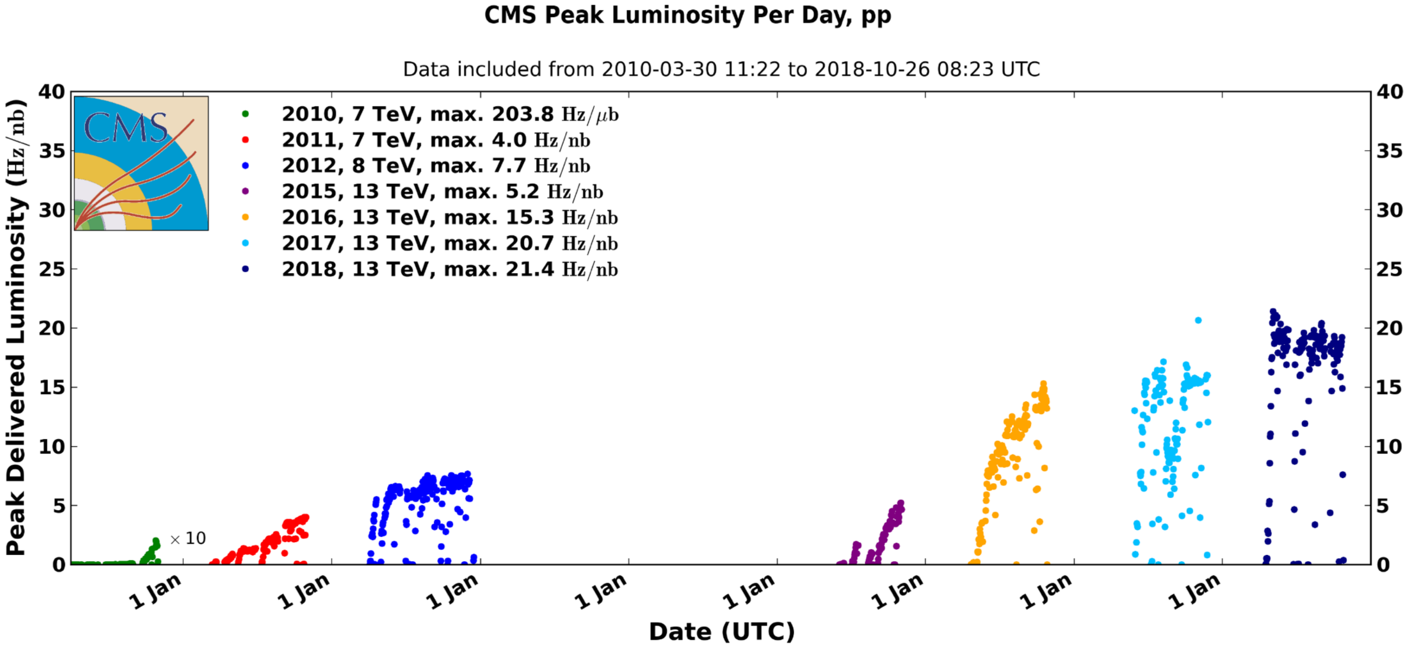
Integrated Luminosity is a measure of the data set size
Instantaneous Luminosity is the measure of rate of collisions ands related to the intensity of the beams

Operation of Large Hadron Collider

Eight years of excellent performance

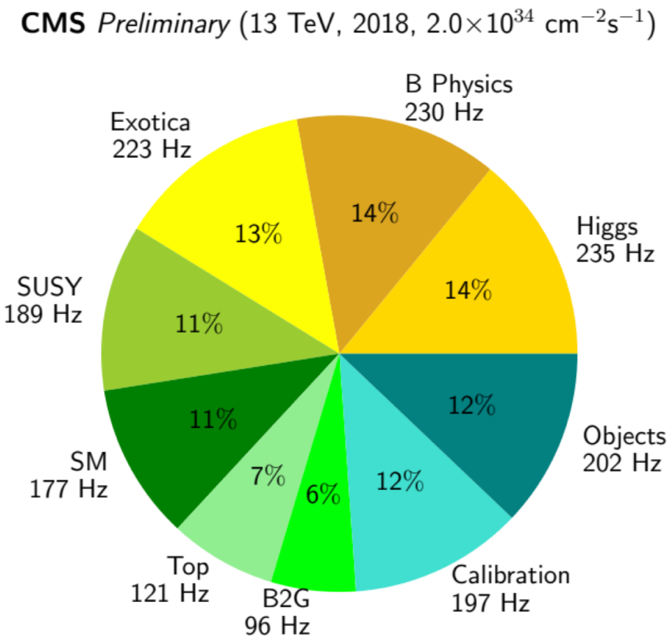
Nominal luminosity 1.0 x $10^{34} cm^{-2} s^{-1}$





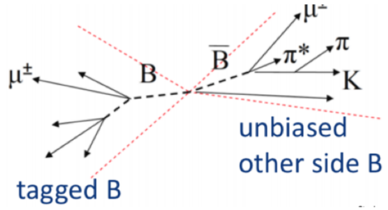
Integrated luminosity:
163 fb^{-1} delivered ⟶ 150 fb^{-1} collected ⟶ 140 fb^{-1} good for physics

CMS performance for Run 2

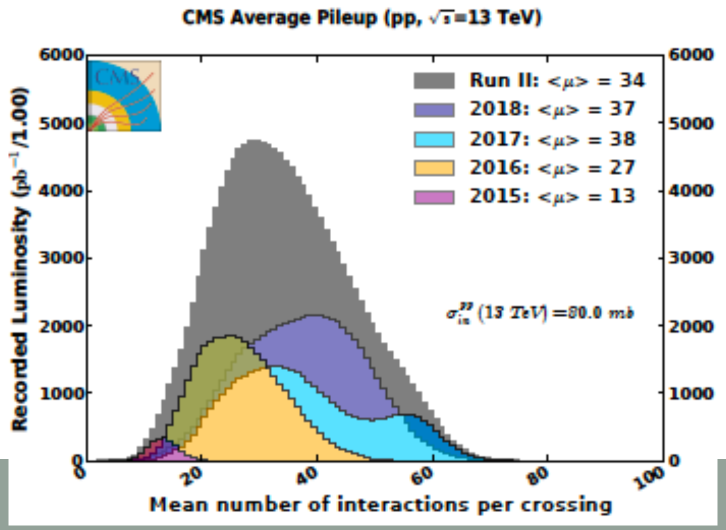


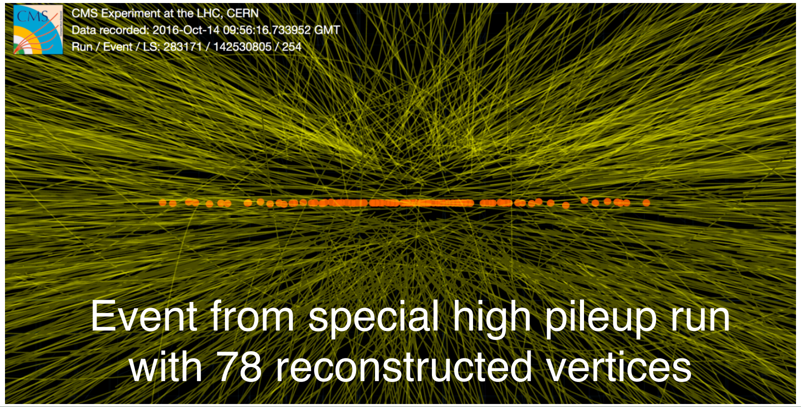
- Rich physics program provided by the CMS Run 2 Triggers:
  - standard (vertex, leptons, jets, MET), B-parking (11B events),
  - scouting triggers with event size O(10kB) and avoiding full reco!

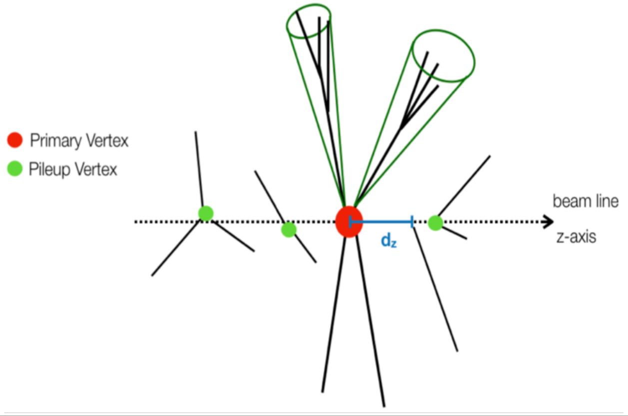
B-parking: enriched in unbiased B-decays



- Extensive modifications to the software & computing system to handle large increases in (and complexity of) data (and simulation) events
- PUPPI algorithm for pileup suppression (will be default in Run 3)

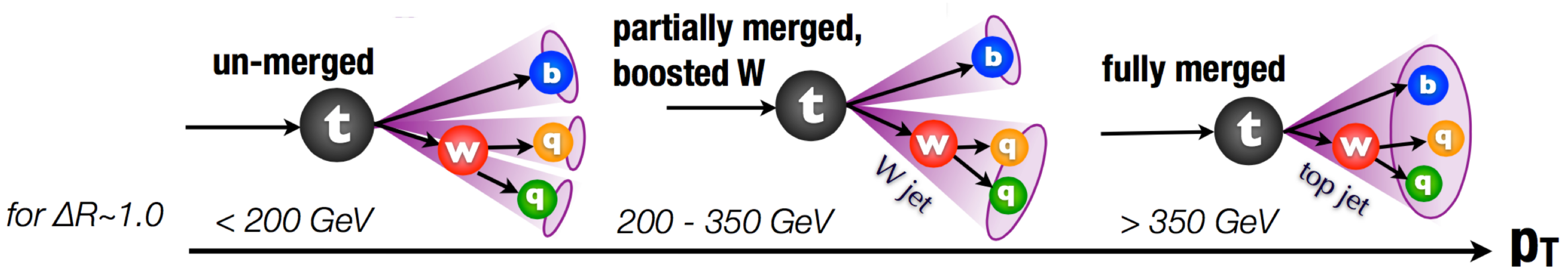


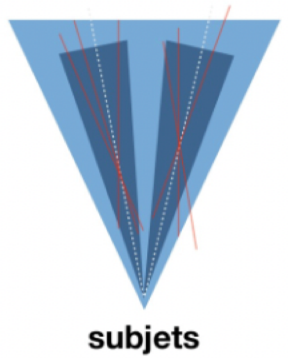




Diverse search strategies

- Enhanced focus on complex topologies and weakly coupled phenomenon
- Higher energy → boost
  - Reconstruction of boosted particles can be a challenge ⟶ may appear as a large radius jet
  - Rule of thumb: $p_T \sim 2M/R$

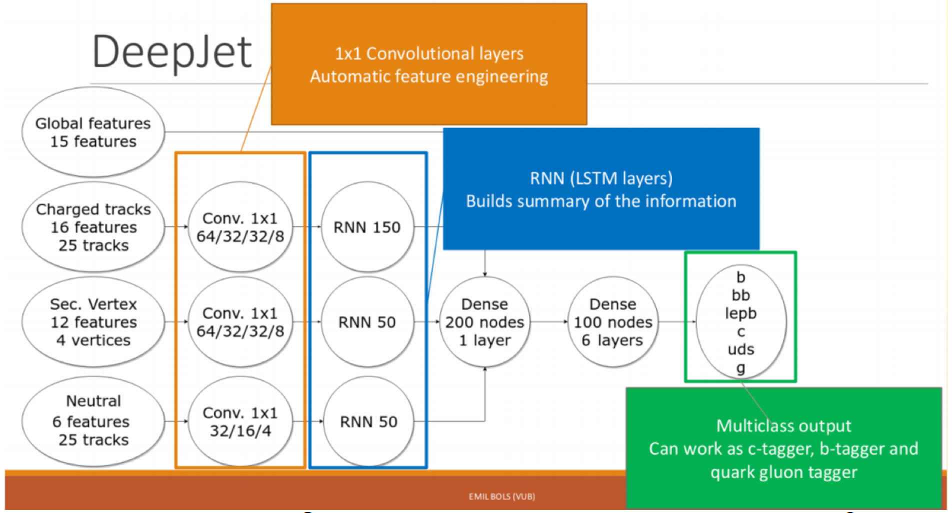


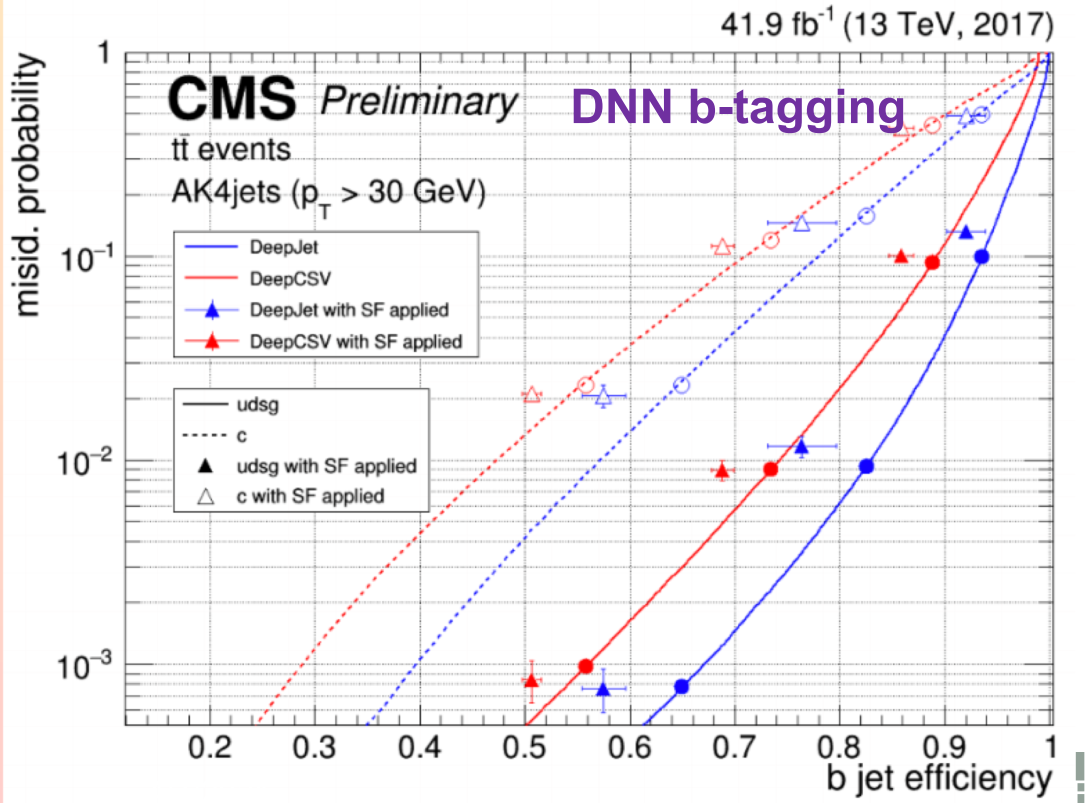


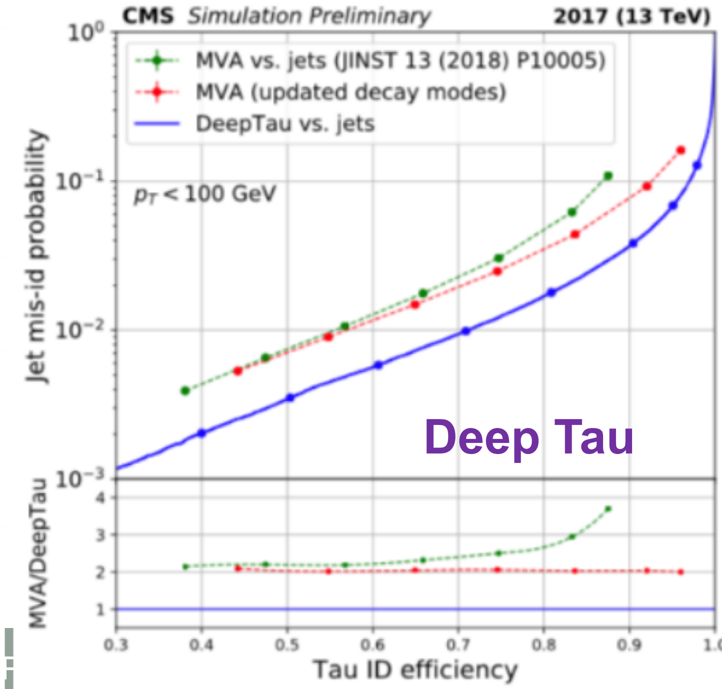
- Jets with large distance parameter (R) pick up all the radiation from original decay
  - Use “substructure” techniques to analyze constituents of “fat” jets (find subjets)
  - Is it a 1-prong, 2-prong or 3-prong decay ?
  - Many observables/discriminators
- These strategies are now also being implemented in the trigger!
- Incorporate machine learning for Top tagging, W tagging, Higgs tagging, double-b/c tags

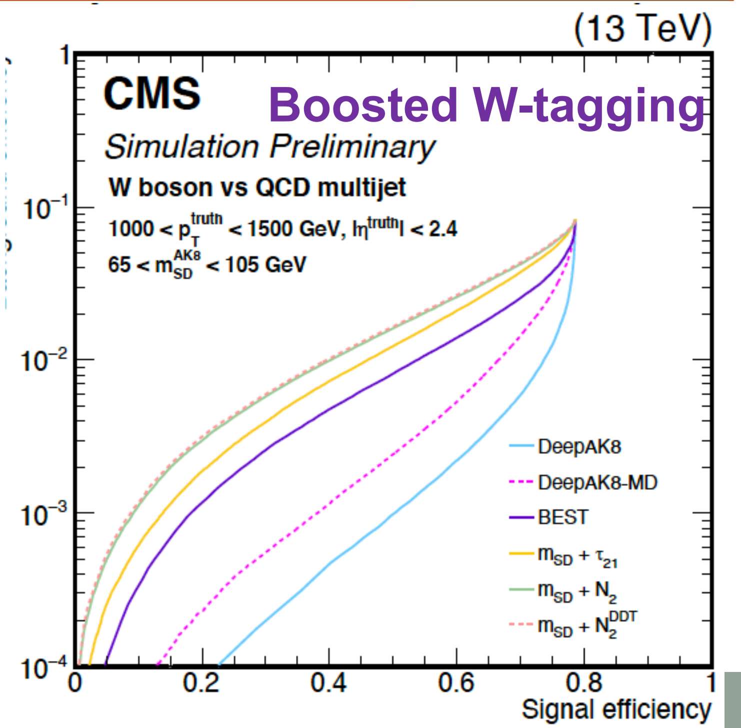
CMS Object performance & improvements for Run 2

- Object reconstruction and identification with Machine learning
  - Existing ID/Reco algorithms are improved and consolidated
  - New avenues explored the era of mathematical representations
- From MVA to DeepNN algorithms: Jet, Tau, b-tags, c-tags
- MVA and/or DNN algorithms for boosted W/t/H





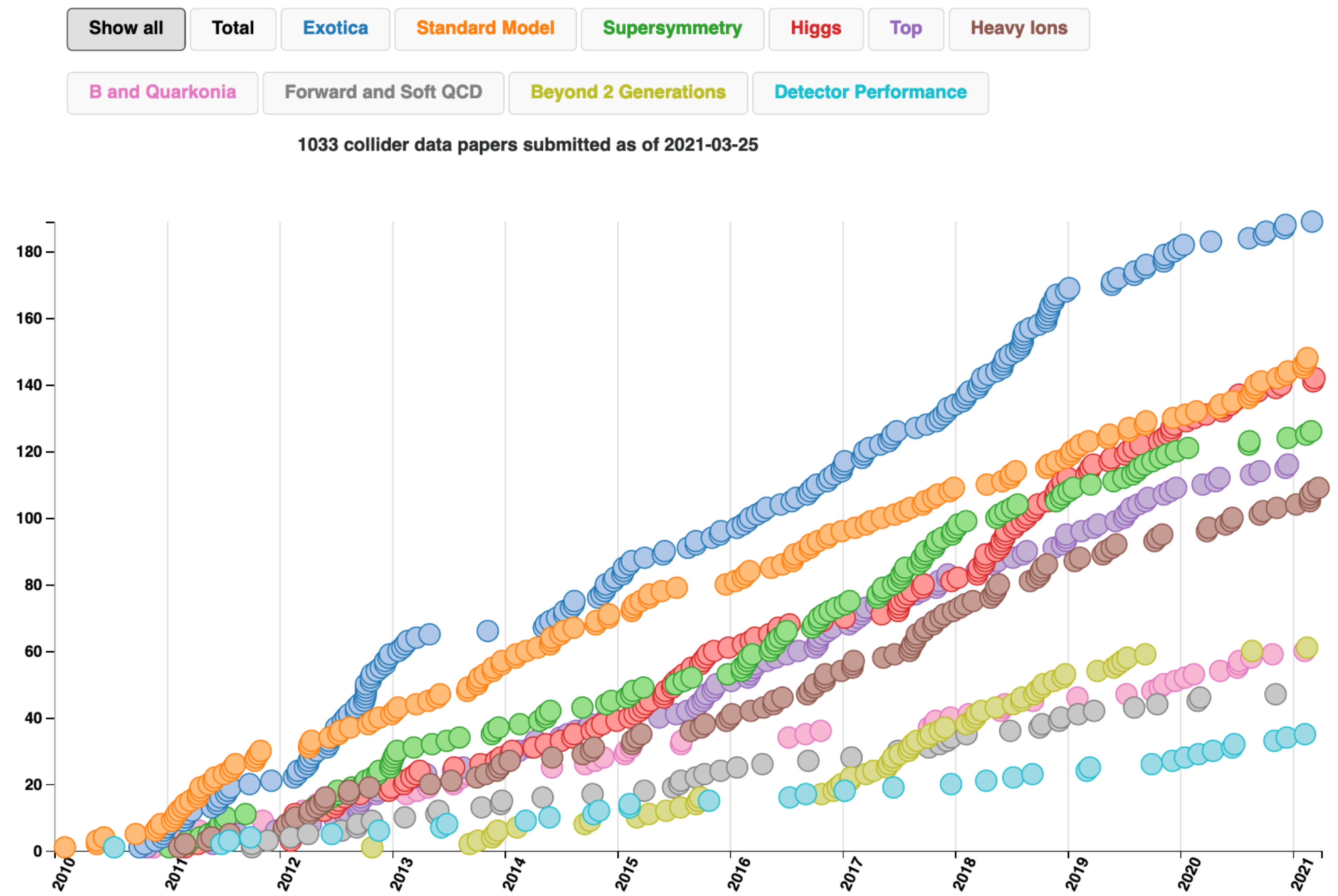




THE PHYSICS PROGRAM

Publications

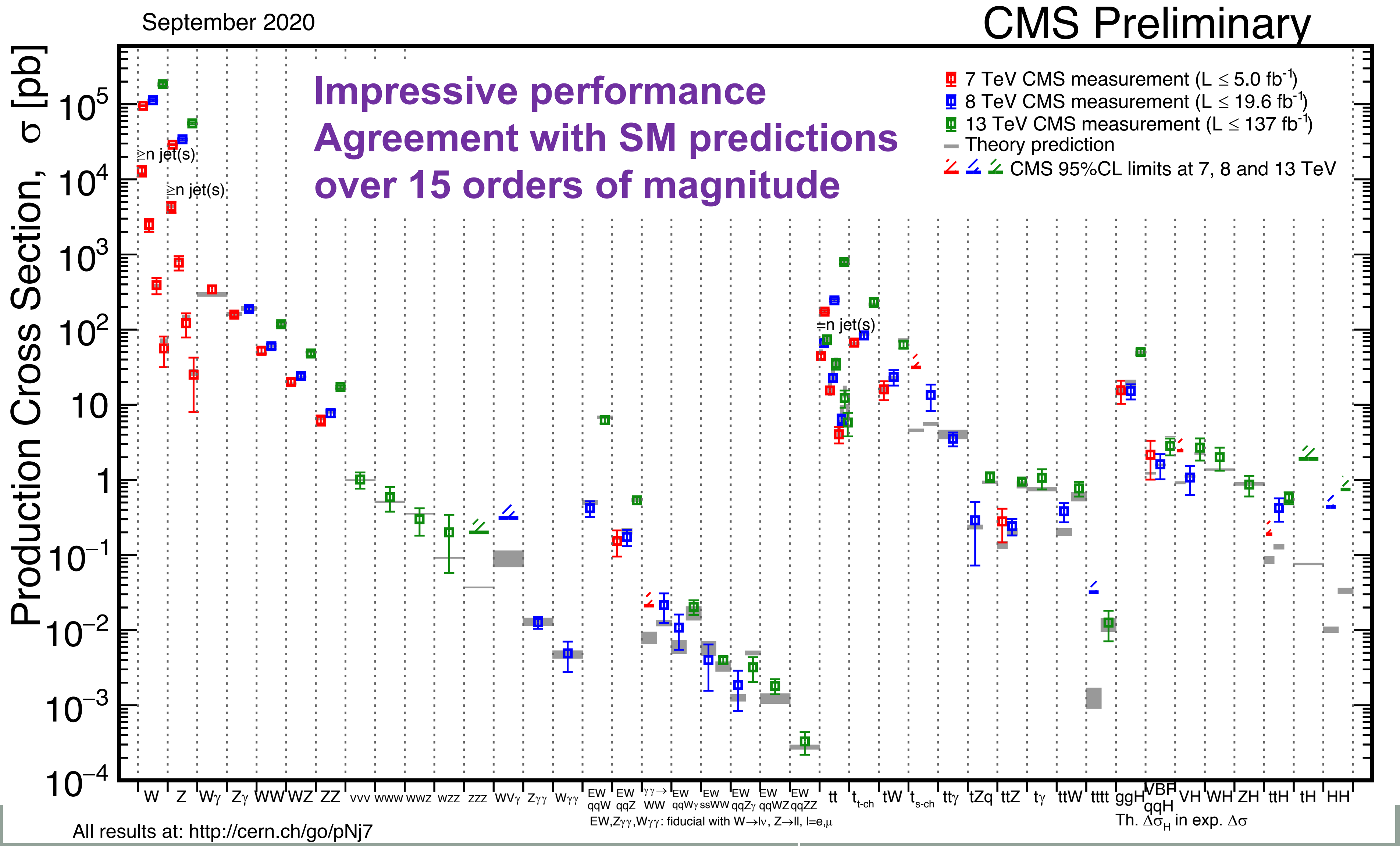
- CMS has published 1033 papers on collision data (~100 papers/year)!



THE PHYSICS PROGRAM
- SELECTIVE HIGHLIGHTS

SM Stairway…precision tests of the Standard Model

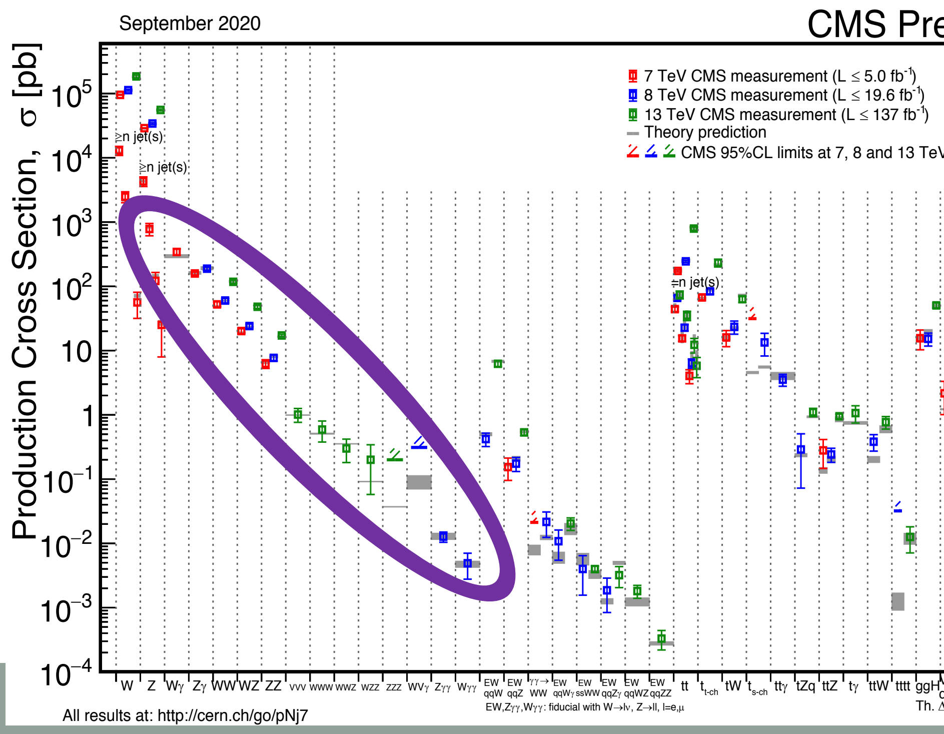
- We can probe rare processes and start to perform many differential measurements



Electroweak Multi-boson measurements

- Studies of vector boson scattering are the ultimate SM measurements to be done at the LHC
- Need to experimentally verify the unitarization of the amplitudes to the Higgs boson contributions
- With Run 2 data, we finally reached the sensitivity to observe first VBS processes:
  - Electroweak production: WW (including W±W±), WZ, ZZ, Wɣ, Zɣ, VVV
- Sensitive to anomalous couplings
  - Triple and quartic gauge

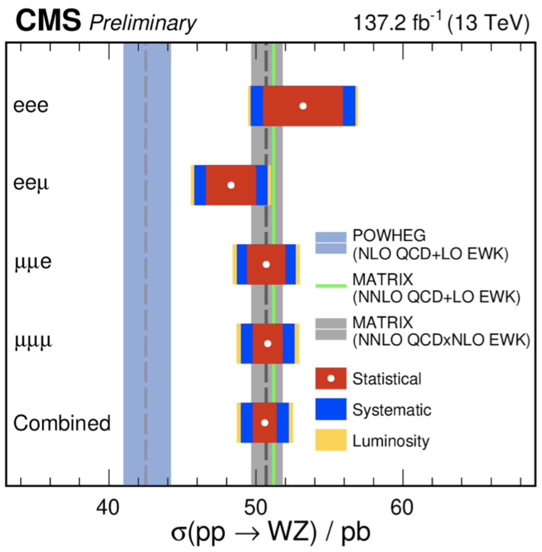
7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
13 TeV CMS measurement (L ≤ 137 fb^{-1})
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV

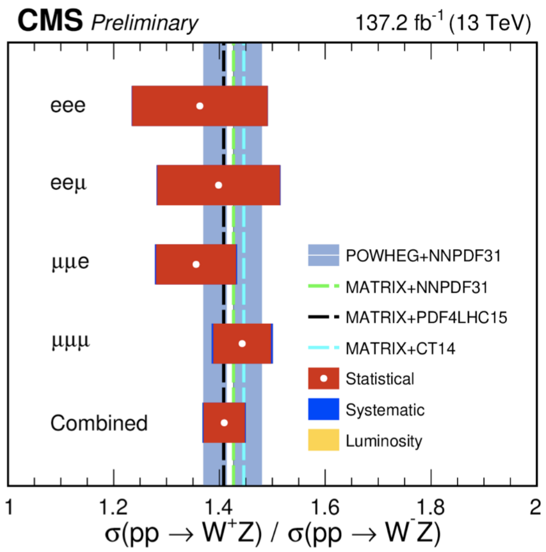


$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{\bar{C}_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{\bar{C}_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

WZ production

- Leptonic final state signatures
- Comprehensive study of WZ production!
  - Inclusive total and differential cross sections
  - Charge asymmetry and polarization
  - Search for anomalous triple gauge couplings



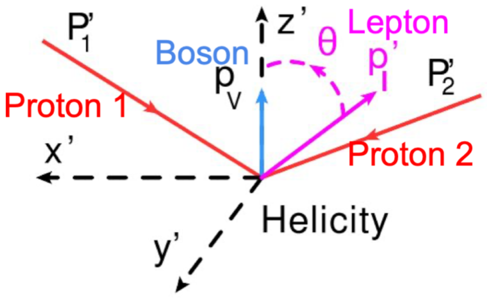


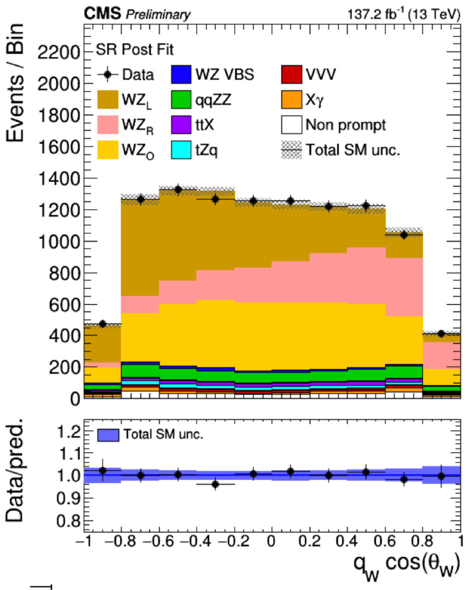
$\boldsymbol{\sigma}$: $50.6 \pm 0.8(\text{stat.}) \pm 1.5(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{theo.})\text{pb}$

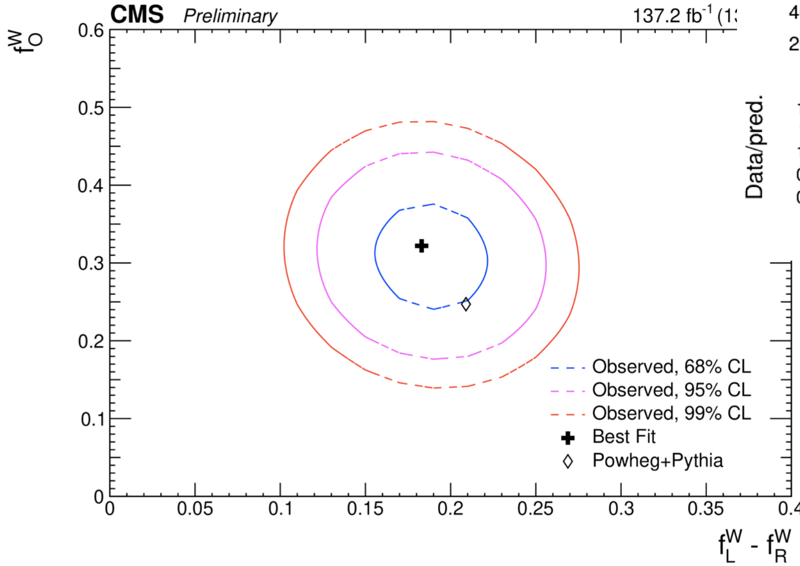
Charge Ratio: $1.41 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.}) \pm 0.01(\text{lumi.})$

- Polarization of W and Z bosons in WZ production

$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8}f_L[(1 \mp \cos\theta_{\ell,W})^2] + \frac{3}{8}f_R[(1 \pm \cos\theta_{\ell,W})^2] + \frac{3}{4}f_0 \sin^2\theta_{\ell,W}$$

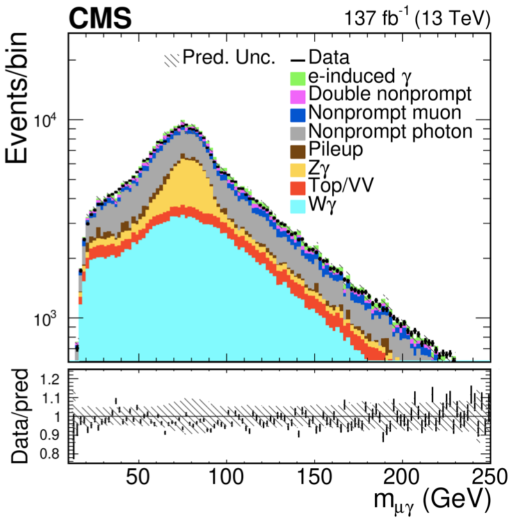


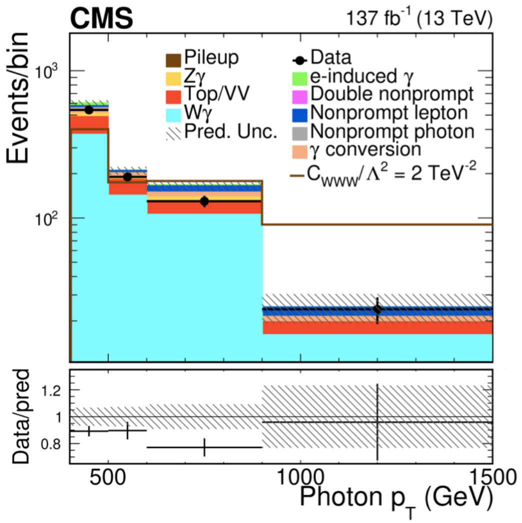




$W\gamma$ production and EFT constraints

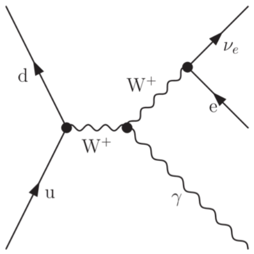
- $W\gamma$ is produced through ISR, FSR or aTGC
- Probe of the $WW\gamma$ Triple Gauge Coupling
- Low-dim EFT operator alter the $WW\gamma$ TGC





- **Signal strength extracted using binned likelihood fit to the $ml\gamma$ distribution**
- Measured x-sec is: σ = 15.58 ± 0.75 pb
- MadGraph5_aMC@NLO and POWHEG:
  - σ = 15.4 ± 0.75 (scale) ± 0.1 (PDF) pb (M)
  - σ = 22.4 ± 3.2 (scale) ± 0.1 (PDF) pb (P)

- New physics results in anomalous contributions to the cross section at high mass scale Λ.
- Consider an EFT in which dimension-six operators are added to the SM.
- Operators relevant to $W\gamma$:



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

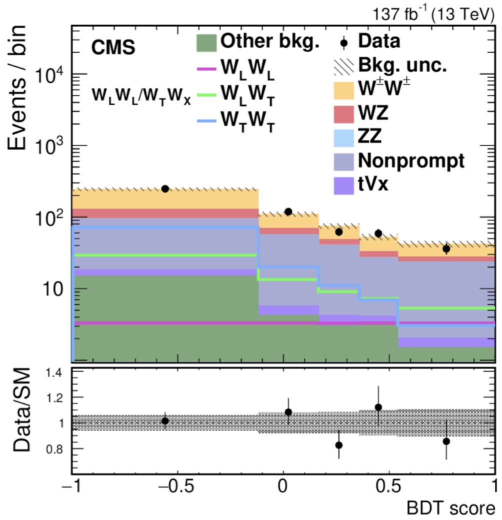
- **Limit on operators extracted using Photon p_T**

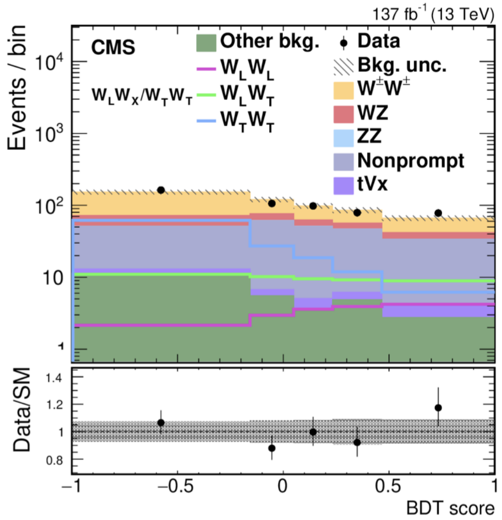
Coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper
c_{WWW}/Λ^2	−0.85	0.87	−0.90	0.91
c_B/Λ^2	−46	45	−40	41
$c_{\overline{W}WW}/\Lambda^2$	−0.43	0.43	−0.45	0.45
$c_{\overline{W}}/\Lambda^2$	−23	22	−20	20

- Observed limits on c_{WWW}/Λ^2 are factor 1.75 lower than the previous result

Polarized same-sign WW in VBS

- **First measurement of production cross sections for polarized same-sign WW scattering!**
- Longitudinal W polarization cross section sensitive to BSM effects
- Require VBS topology (SS-lep, 2 fwd jets, rapidity gap)
- Separate polarization states for EWK WW production
  - $W_L W_L$ and $W_T W_X$ (one BDT)
  - $W_T W_T$ and $W_L W_X$ (one BDT) (X is either of two polarization state
  - The W_L has smaller p_T compared to the W_T
- Constrain SM backgrounds from data in fit (WZ, tZq, ZZ)
- EWK production: 2.3 σ (3.1σ exp)
- 95% CL limit for WLWL production 1.17fb(0.88fb exp)
- Fiducial Cross section from 2D fit of the polarization-separating BDT shapes





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 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

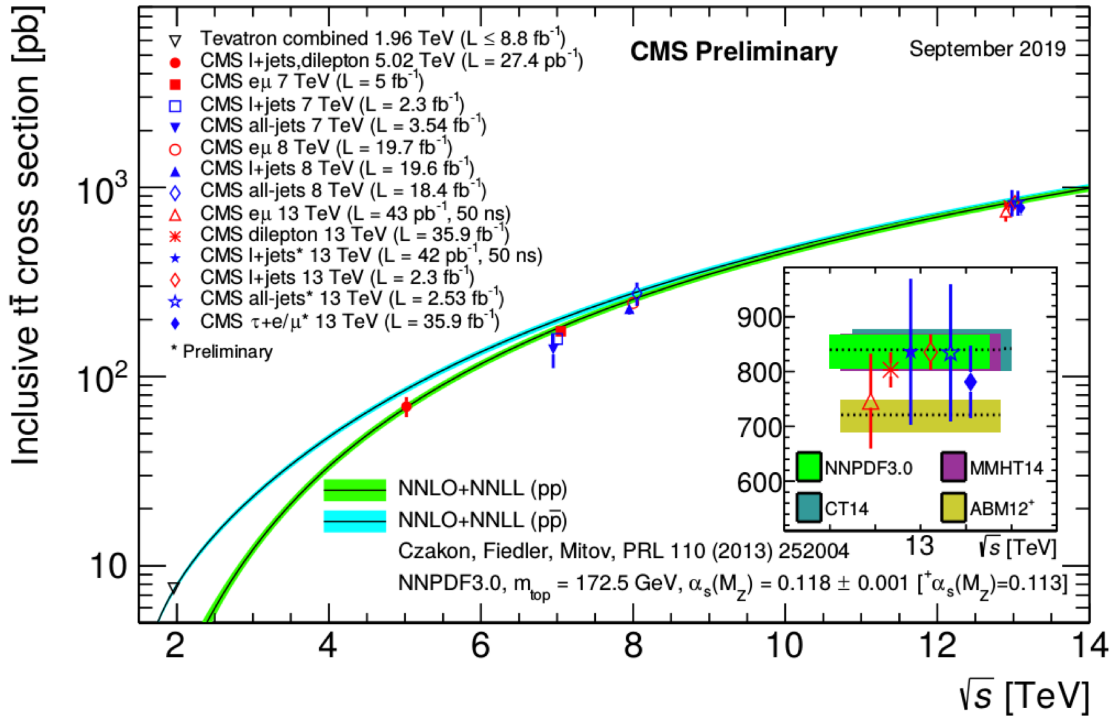
parton-parton center of mass frame

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

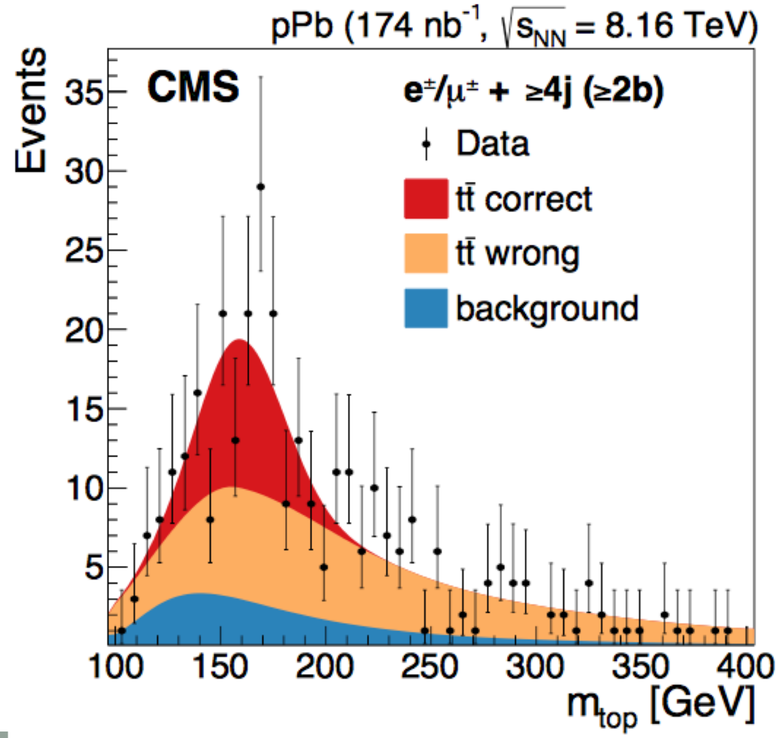
THE TOP PHYSICS PROGRAM - SELECTIVE HIGHLIGHTS

Precision top quark Physics

- LHC is a top quark factory!
- Over ~25 years since its discovery, the top quark is still one of the hottest topics…
- Inclusive cross section well understood; agrees with NNLO predictions



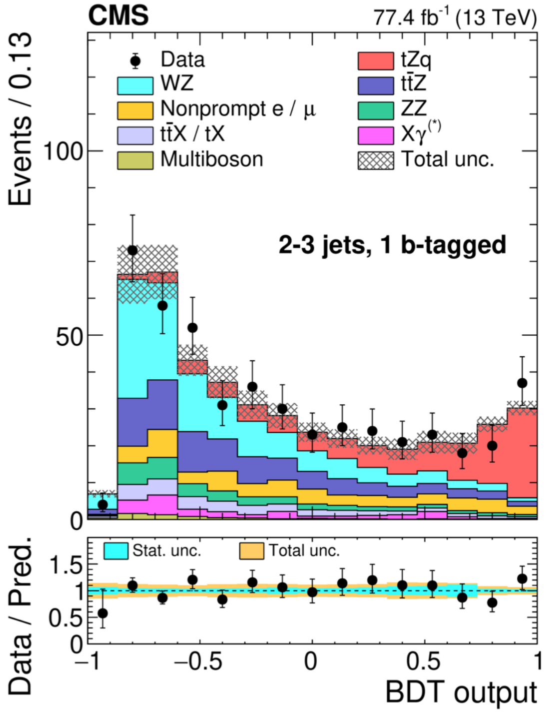
Observation of top quarks in heavy ion collisions



PRL 119, 242001

Rare top quark processes

- tZq: sensitive to tZ coupling and WWZ coupling, FCNC
- rare process: σtZq ≈ 1 pb



First observation!

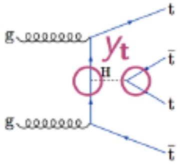
$$\sigma(pp \to tZq \to t\ell^+\ell^-q) = 111 \pm 13\,(\text{stat})\,^{+11}_{-9}\,(\text{syst})\,\text{fb}$$

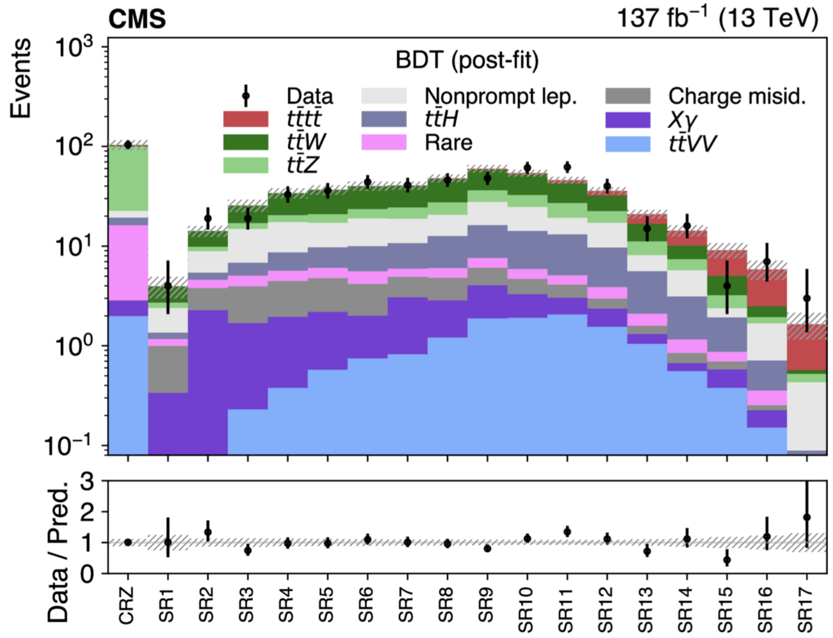
15% precision

- 4 top quarks:
- unobserved very rare process σtttt ≈ 0.01 pb
- Sensitive to top yukawa coupling

$|y_t / y_t^{SM}| < 1.7,$

@ 95% CL

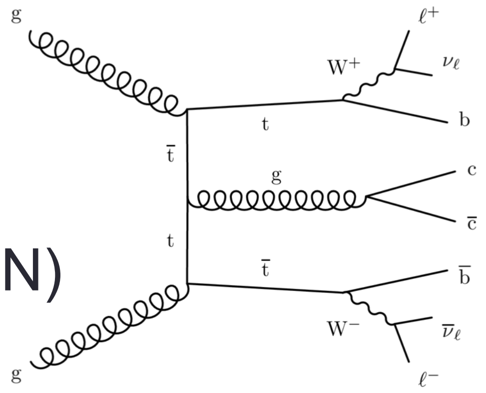


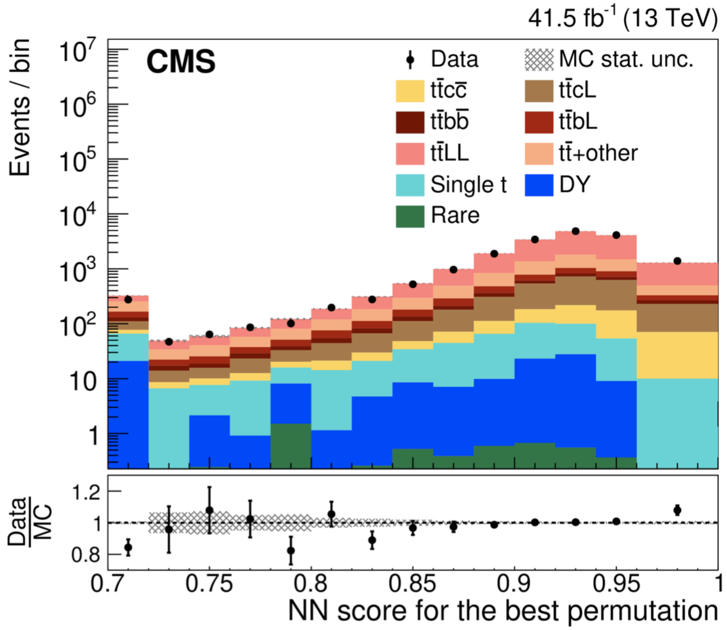


Approaching sensitivity to 4 top!
obs. (exp.): 2.6 (2.7)

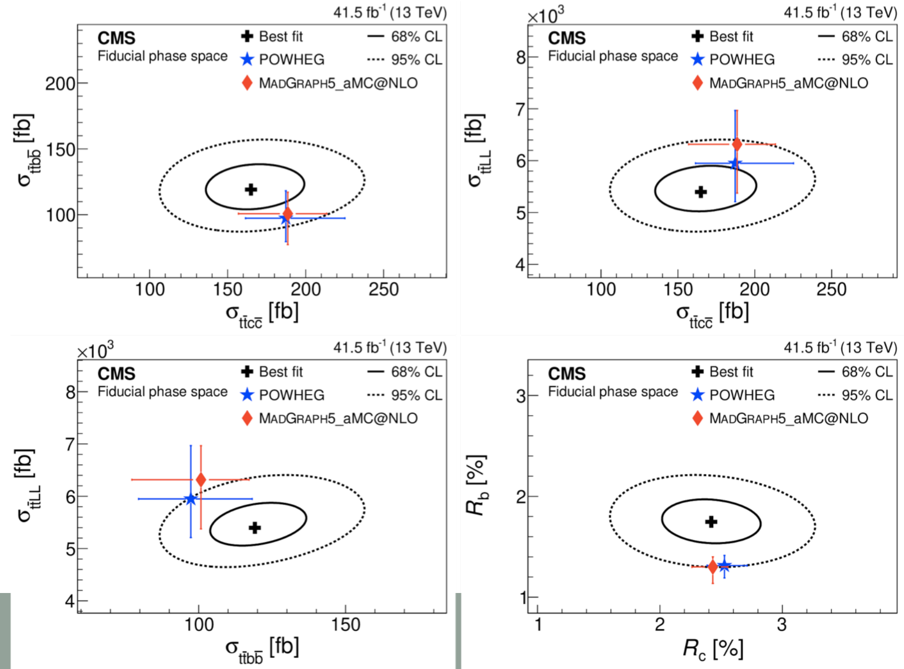
Top pair + charm production

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





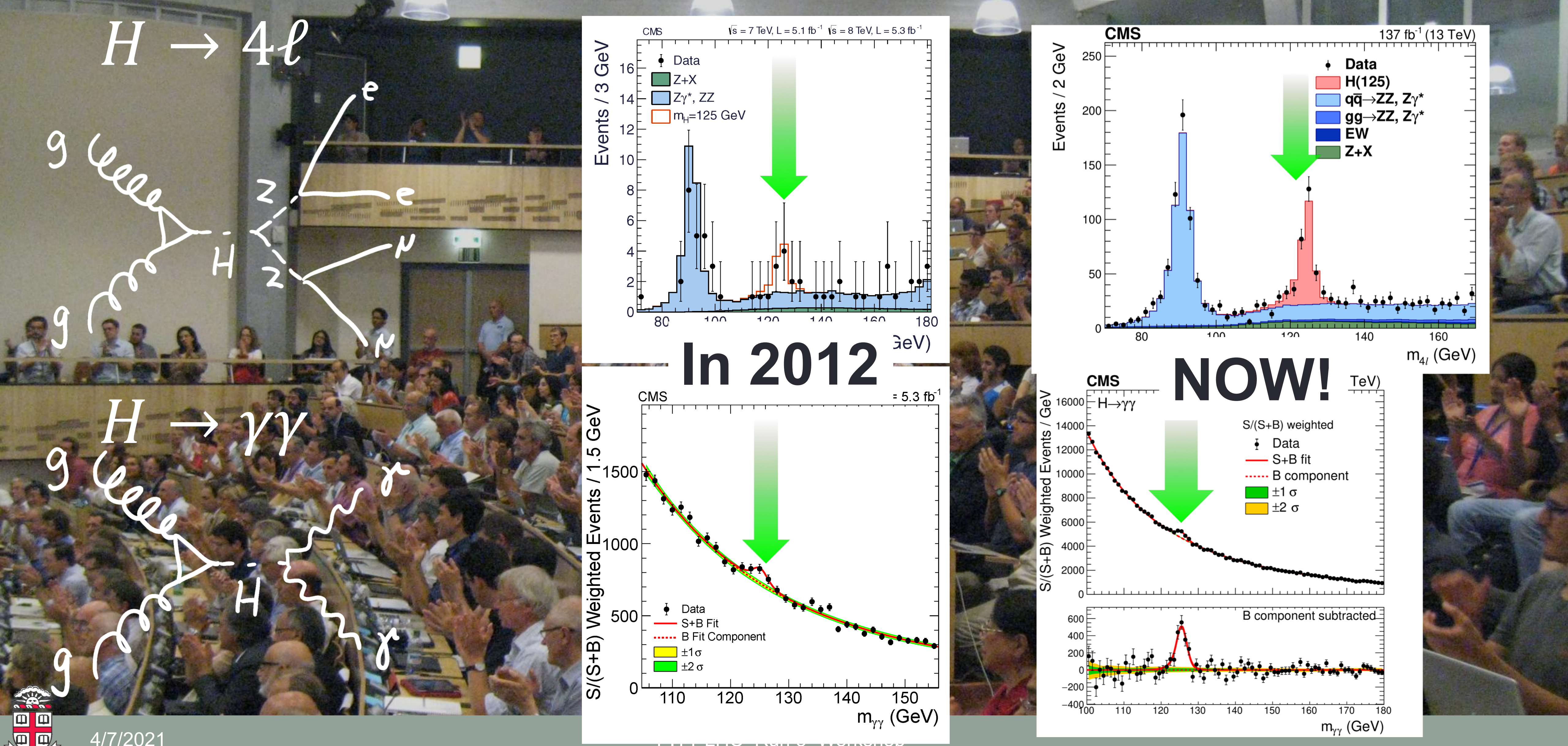
- **σ** (tt + cc) measured for the first time!
  - Fiducial space: 0.152 ± 0.022 (stat) ± 0.019 (syst) pb
  - Full phase space: 7.43 ± 1.07 (stat) ± 0.95 (syst) pb
- First measurement of R_c = (tt + cc)/(tt + jj)
  - Fiducial space: 2.37± 0.32 (stat) ± 0.25 (syst)%
  - Full phase space: 2.64± 0.36 (stat) ± 0.28 (syst)%
- Fiducial space: full flavor content splitting



- 2D likelihood scans agree within 1-2 σ with the corresponding theoretical predictions; σ (ttbb) and R_b slightly above prediction

THE HIGGS PHYSICS PROGRAM - SELECTIVE HIGHLIGHTS

The Discovery of the Higgs Boson – a crowning achievement



Measurement of Higgs Boson Properties

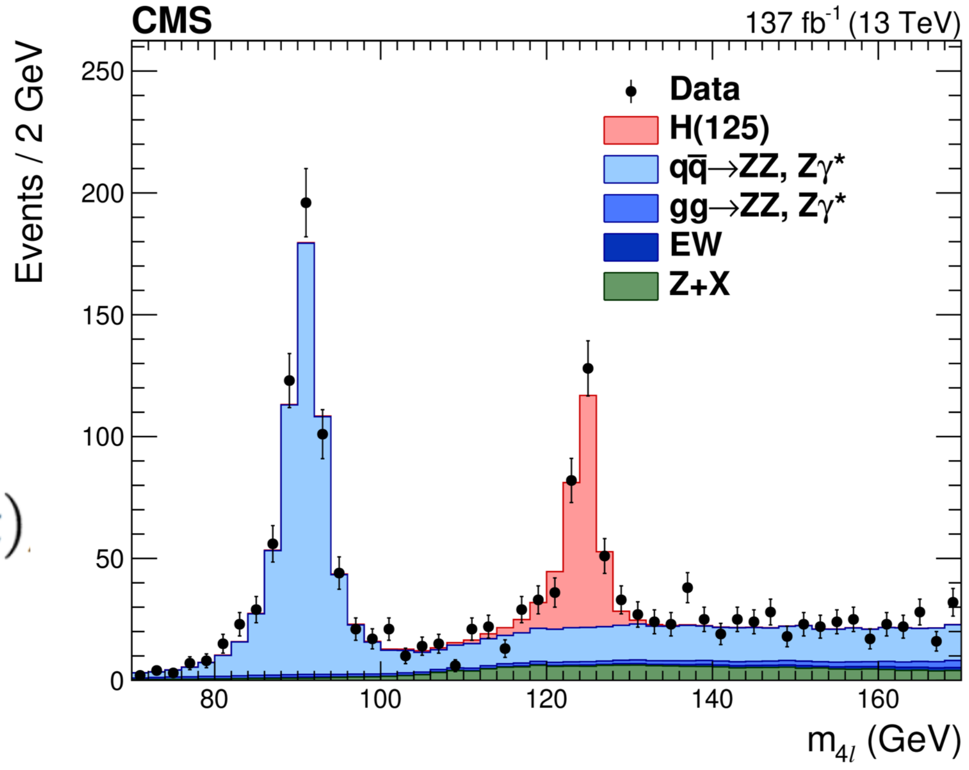
- With the full Run2 dataset, significant progress in the Higgs sector:
  - Firmly established decays of Higgs to $\gamma\gamma$, ZZ, WW,
  - Yukawa coupling measurements: tau-Higgs, bottom-Higgs and top-Higgs
  - Move to precision mass measurement: 125.38 ± 0.14 GeV
    - Precision reaching 0.1%, still dominated by statistical uncertainty

Fiducial and differential cross section measurements comparing data to state-of-the-art calculations

The experimental precision is at the level of the theoretical precision

$$\sigma/\sigma_{SM} = 1.02 \pm 0.04(\mathrm{th}) \pm 0.04(\mathrm{exp}) \pm 0.04(\mathrm{stat})$$

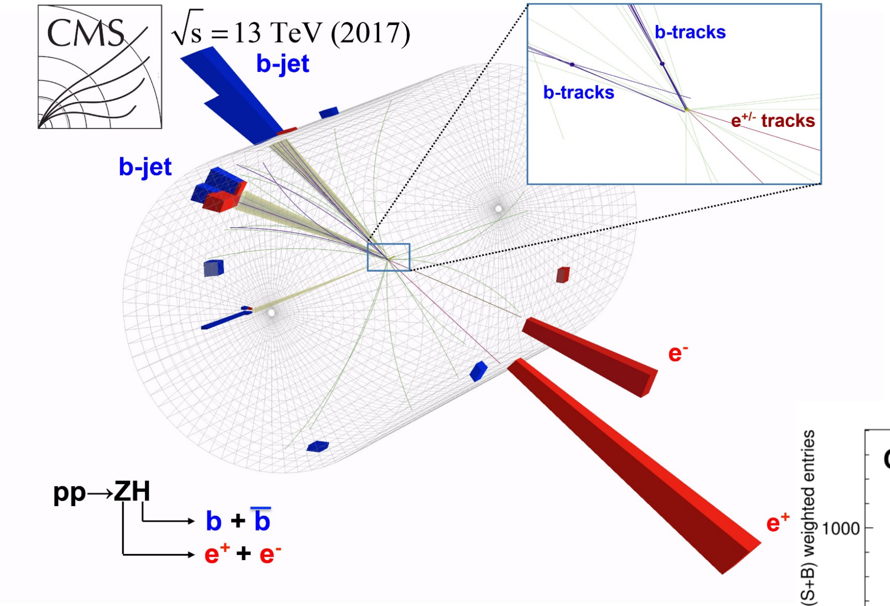
~6.5% measurement!

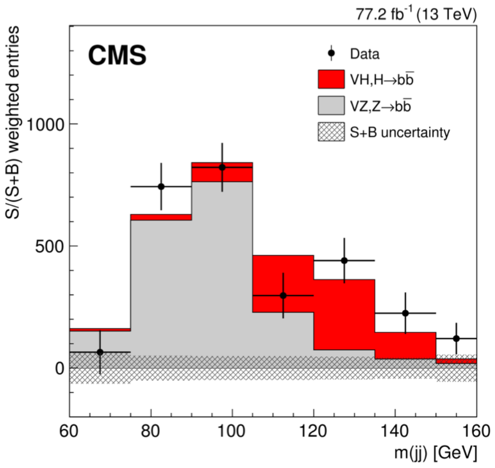


Observation of Higgs boson coupling to third generation fermions

Highlights of 2018:

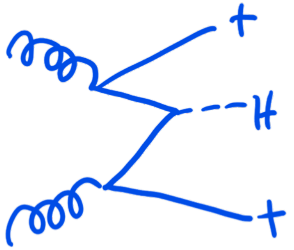
Higgs boson decays to $b\bar{b}$

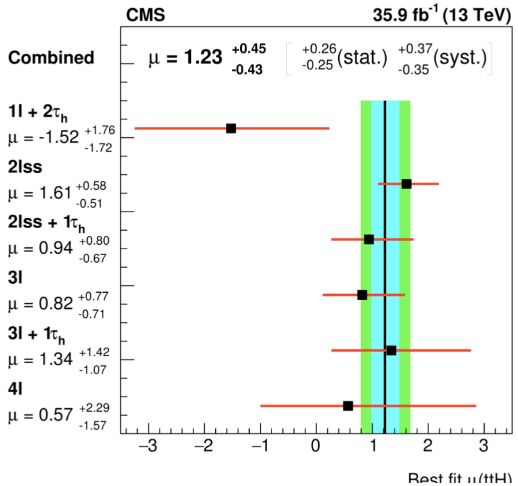


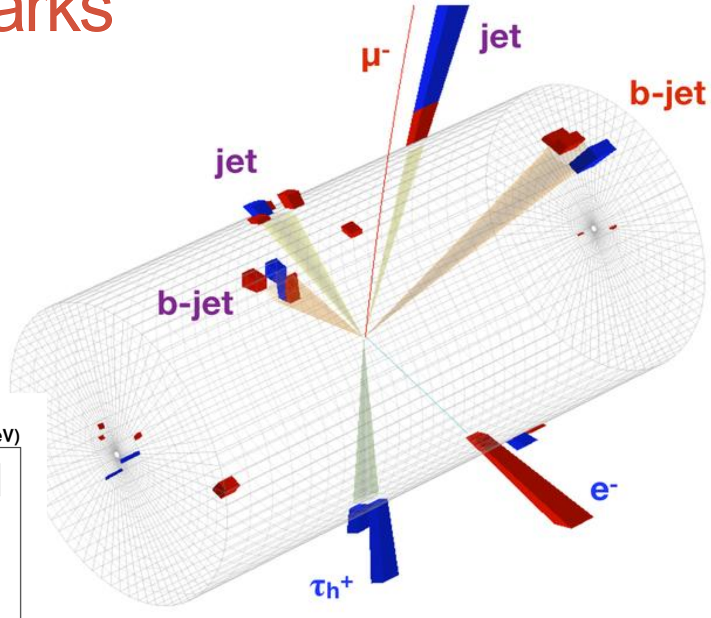


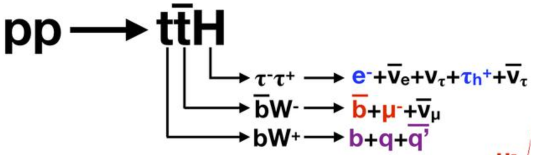
CMS-HIG-18-016

Higgs boson produced together with top quarks







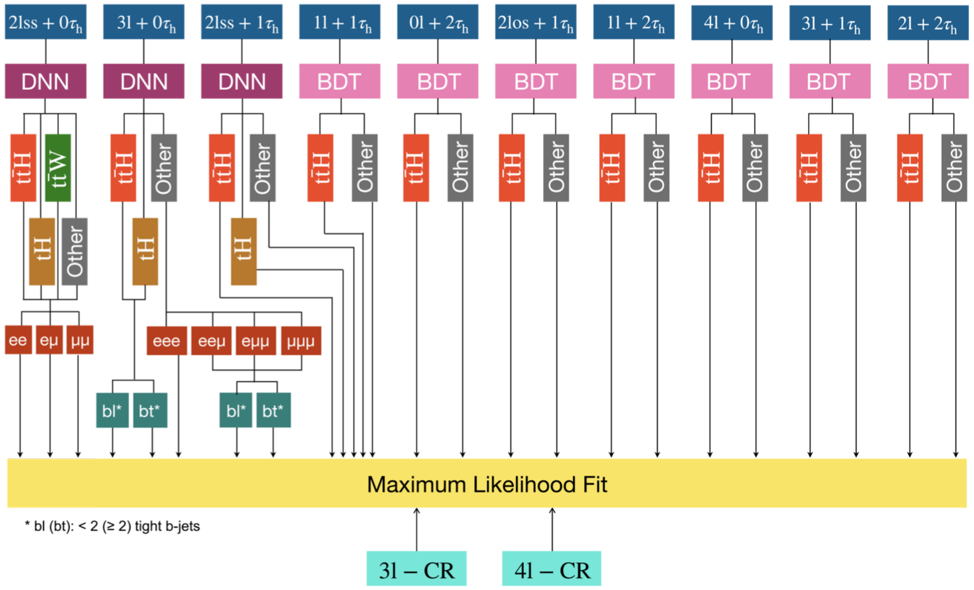


Innovative algorithms based on Machine Learning techniques (Boosted decision trees, Deep learning methods) were employed.

CMS-HIG-17-018

tt+H multileptons

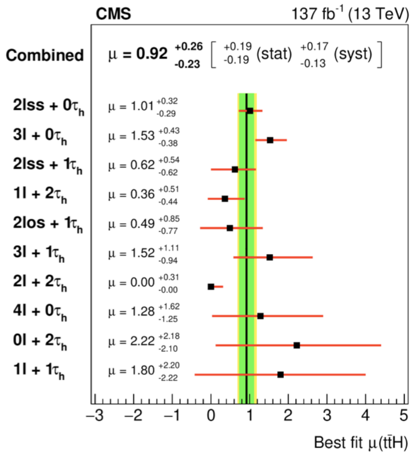
- 2018: observation of ttH production in combined final states
- Now: tH and ttH analysis using full Run 2 dataset
- Observe in each individual channel, and measure properties
  - Signal extraction in many final states with DNN, multiclass ANN, BDT
  - Non-prompt and flips backgrounds determined in data
  - Conversions and the irreducible background determined from simulation

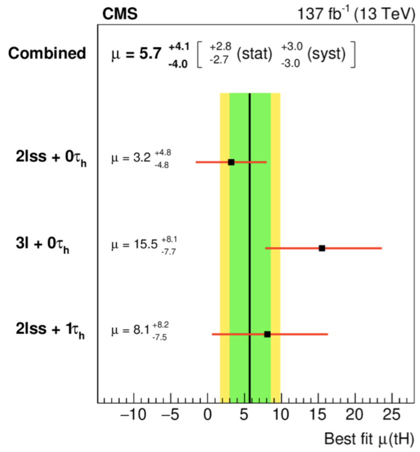


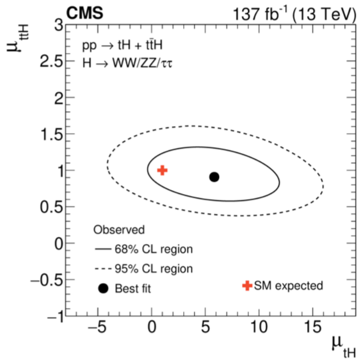
CMS-HIG-19-008

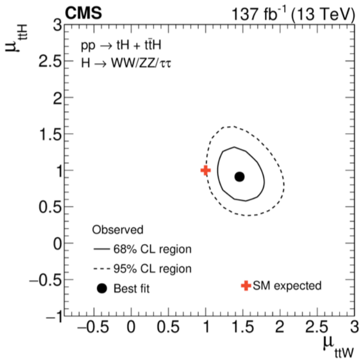
tt+H multileptons

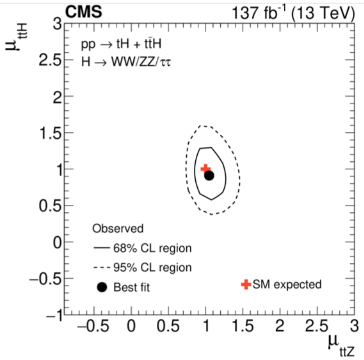
- 2018: observation of ttH production in combined final states
- Now: tH and ttH analysis using full Run 2 dataset
- Observe in each individual channel, and measure properties
  - Signal extraction in many final states with DNN, multiclass ANN, BDT
  - Non-prompt and flips backgrounds determined in data
  - Conversions and the irreducible background determined from simulation
- 4.7 obs. (5.2 exp.) significance just in multilepton!

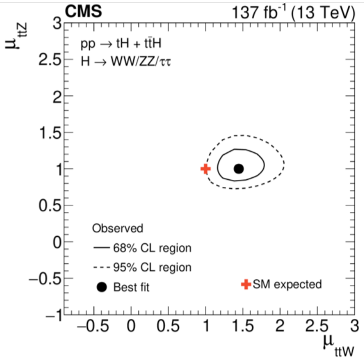












CMS-HIG-19-008

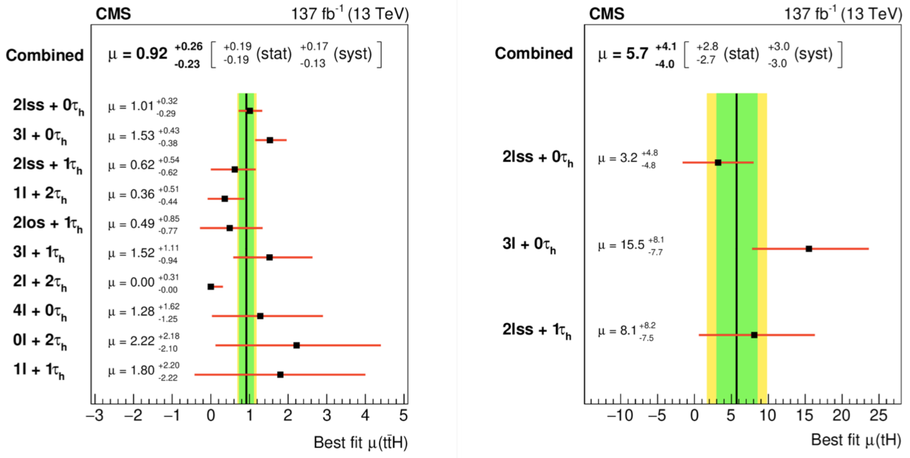
tt+H multileptons

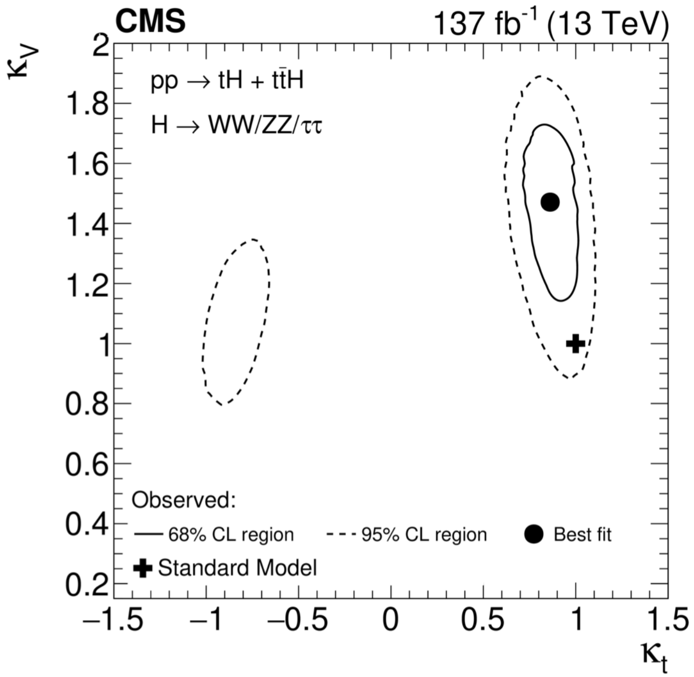
- Observe in each individual channel, and measure properties
  - 4.7 obs. (5.2 exp.) significance in multilepton!
- Obtained 2D confidence regions for (κ_t; κ_V)
- When profiling y_V, obtain at 95% CL

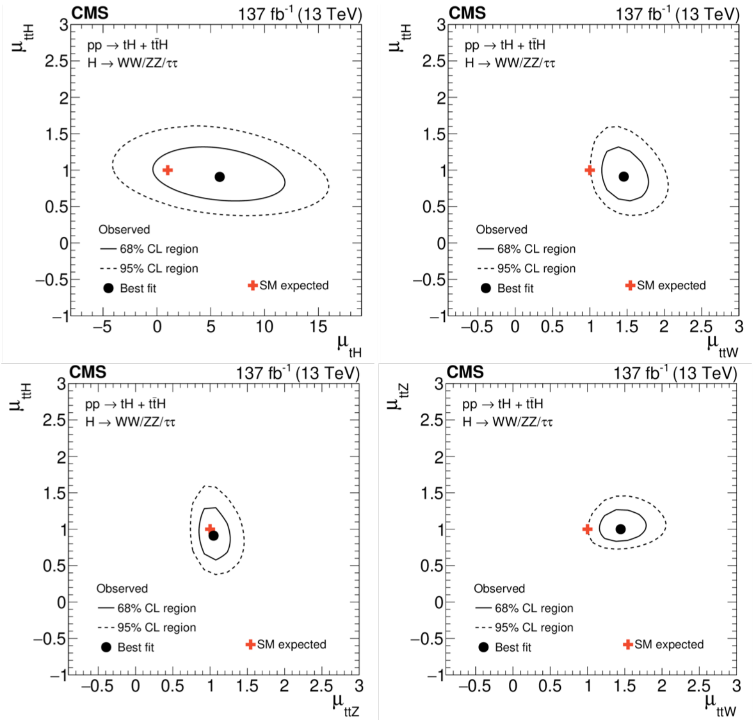
$-0.9 < y_t < -0.7$ or

$0.7 < y_t < 1.1$

times the SM expectation





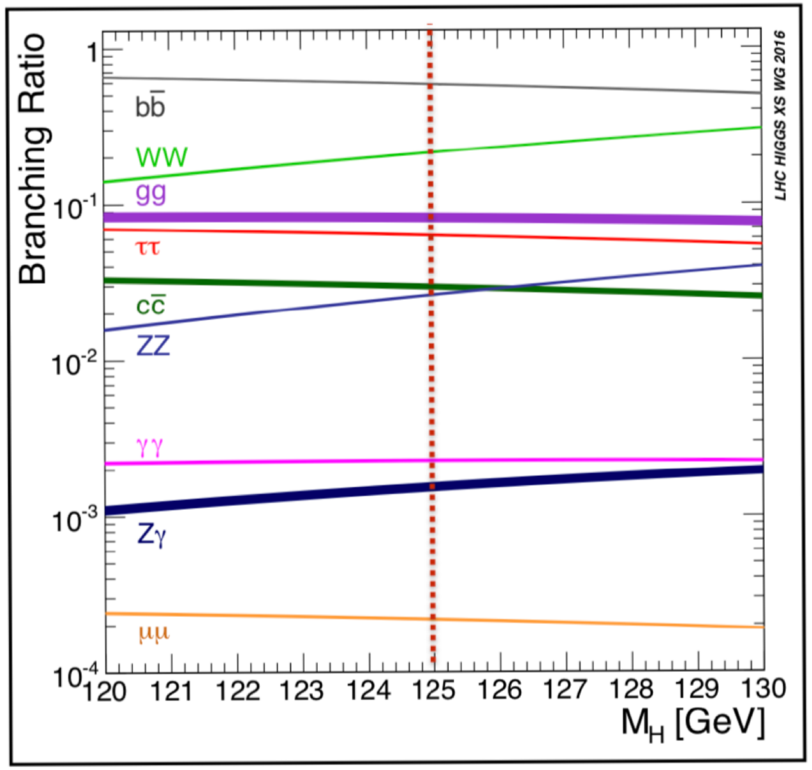


CMS-HIG-19-008

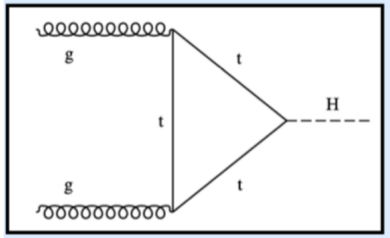
Evidence of Higgs boson coupling to 2nd generation fermions

Highlights of 2020:

Goal: Observe Higgs boson decays to μμ



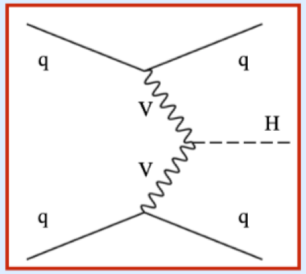
Gluon fusion: σ ~ 49 pb



Main production mode

Veto non-μ objects

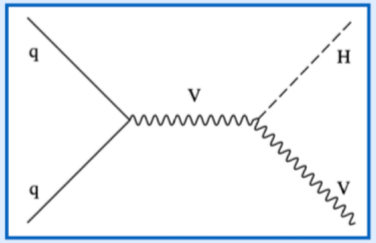
VBF: σ ~ 3.8 pb



VBF-jets: large $\Delta\eta_{jj}$ & m_{jj}

VBF dijet selection
Large , dijet mass

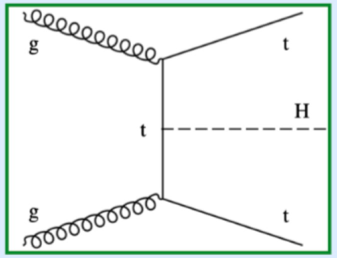
VH: σ ~ 2.3 pb



Tag decays of W and Z

Leptonic decays select Z(ll)/W(lν)

ttH: σ ~ 0.5 pb



Offers "rich" topologies

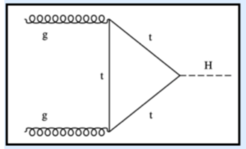
tt-specific selection

- Signal extraction by topology of production mode
- Strategy: excellent m(μμ) resolution, characteristic kinematics
- Challenge: rare decay with non-negligible backgrounds

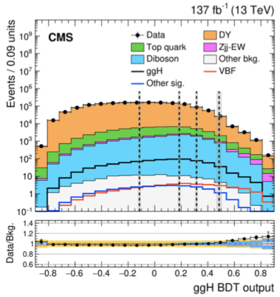
Evidence of Higgs boson coupling to 2nd generation fermions

- **ggH**

Gluon fusion: σ ~ 49 pb



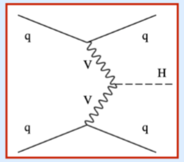
Main production mode



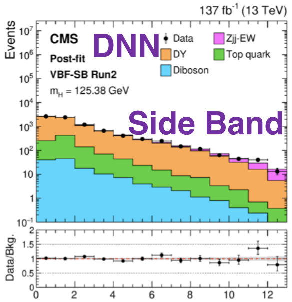
BDT used to categorize bins in dimuon mass

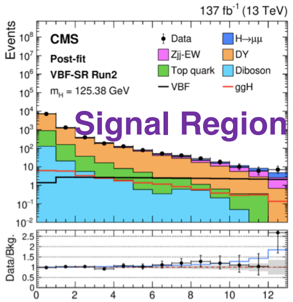
- **VBF**

VBF: σ ~ 3.8 pb



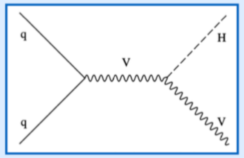
VBF-jets: large $\Delta\eta_{jj}$ & m_{jj}



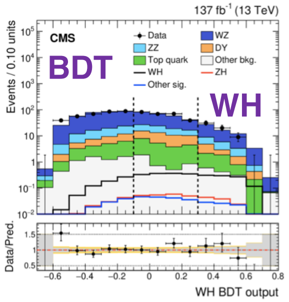


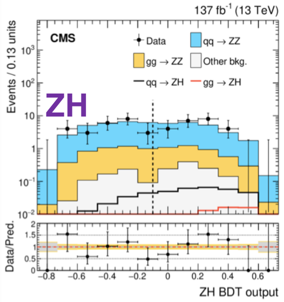
- **VH**

VH: σ ~ 2.3 pb



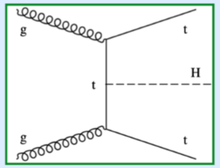
Tag decays of W and Z



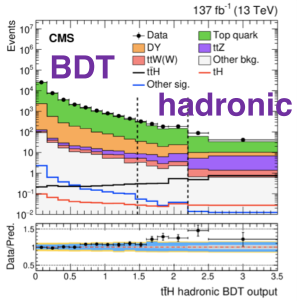


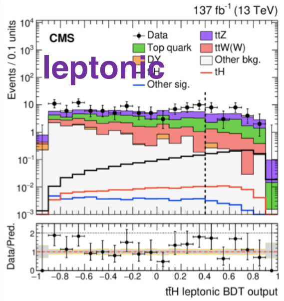
- **ttH**

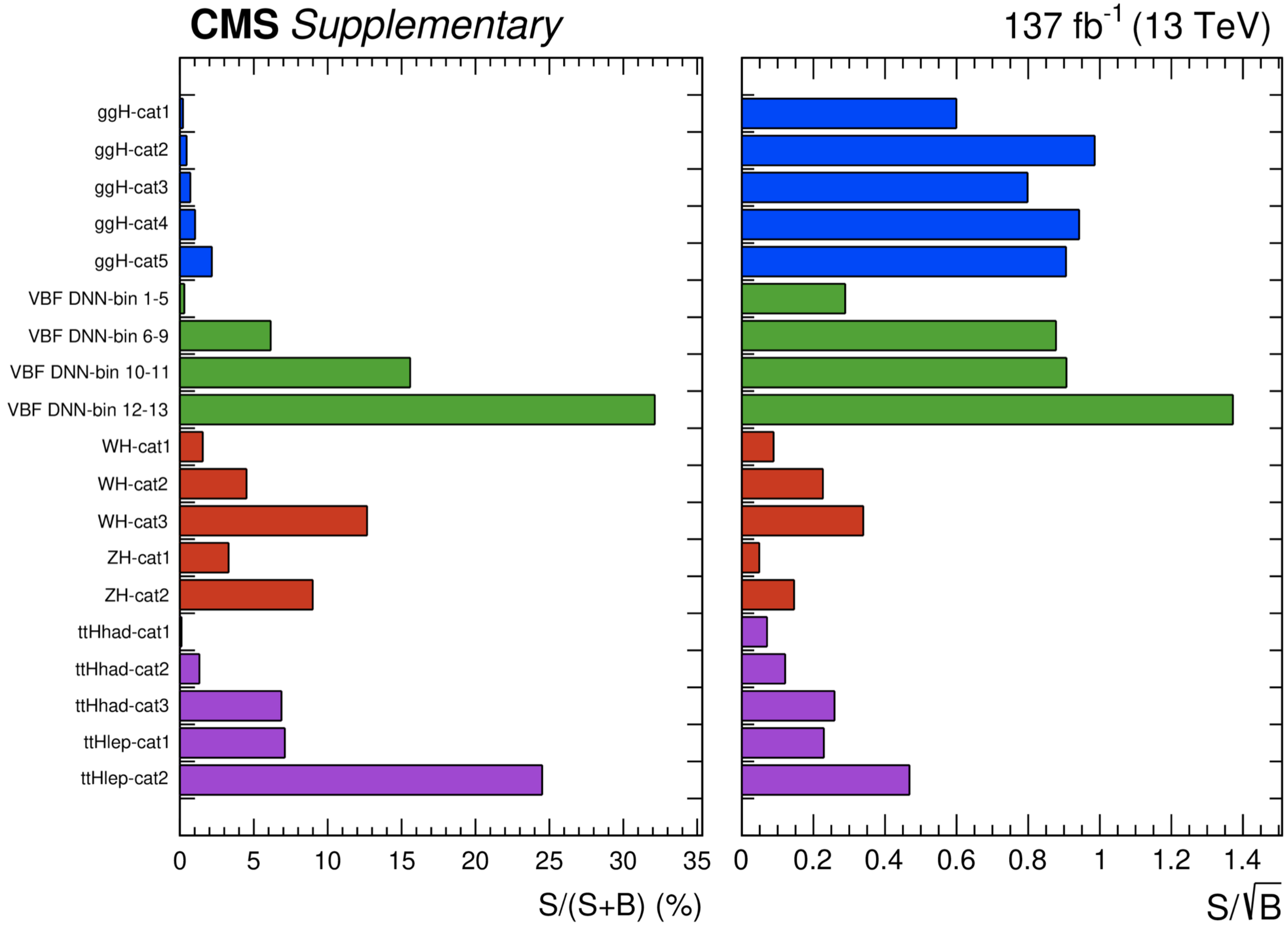
ttH: σ ~ 0.5 pb



Offers "rich" topologies





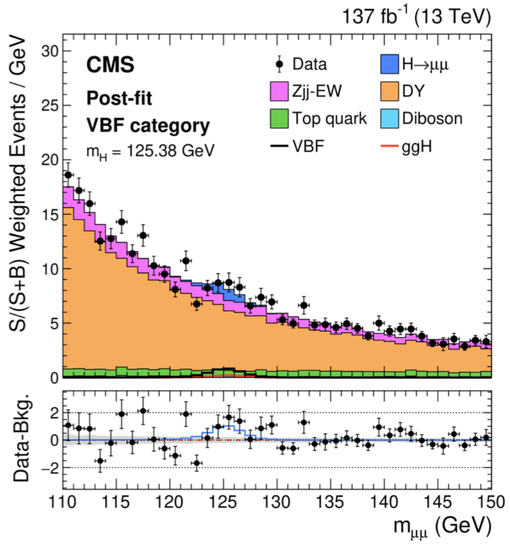


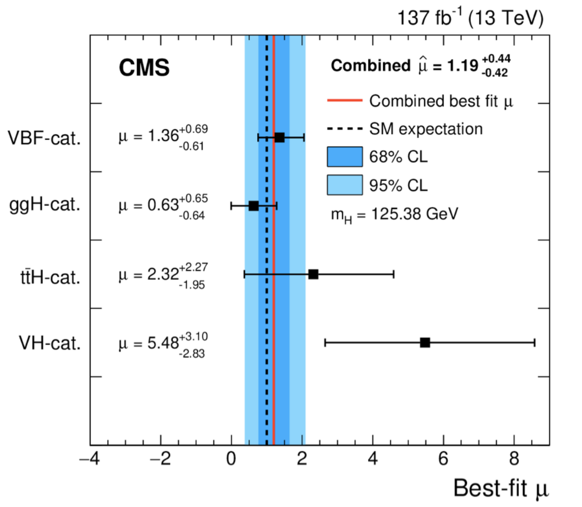
Evidence of Higgs boson coupling to 2nd generation fermions

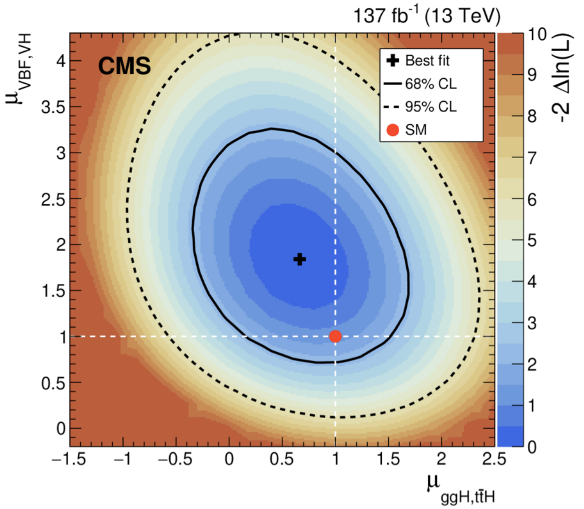
- First Evidence:
  3.0(2.5)σ obs(exp)

- Signal strength:

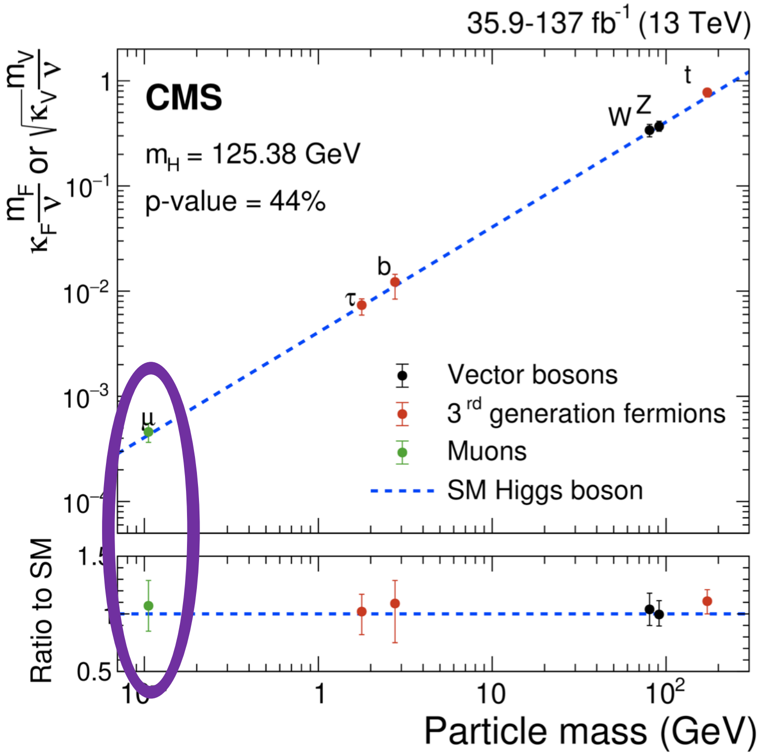
$$\mu = 1.19\ ^{+0.40}_{-0.39}(\text{stat.})\ ^{+0.15}_{-0.14}(\text{syst.})$$







Additional point probing the dependence of coupling strength on the fermion & boson mass!



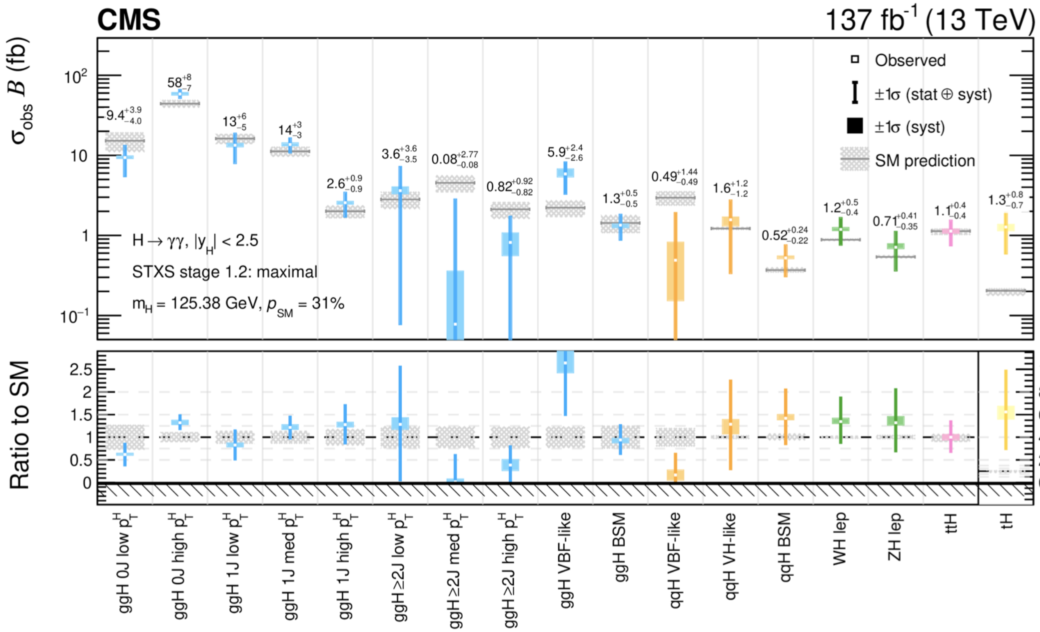
Couplings to fermions ∝ mass
Couplings to gauge bosons ∝ (mass)^2
Higgs self-couplings ∝ M_H^2

- Likelihood scan to fermion or vector boson couplings

Higgs boson properties in H $\longrightarrow\gamma\gamma$

CMS-HIG-19-015

- Full Run 2 dataset, ggH, VBF, VH and (t)tH channels
- BDT discriminators for photon ID and diphoton vertex ID
- BDT discriminator for analysis categories: diphoton BDT, dijet BDT for VBF, VH_{had} BDT, DNN for tH vs ttH
- Total Higgs boson signal strength: $1.03^{+0.11}_{-0.09}$
- First Simplified template cross section measurement at Stage 1.2
  - Minimizes model-dependent measurement
  - Partition major production processes into different kinematic regions by:
    - matching experimental selections
    - avoiding large theory uncertainties
    - isolating possible BSM deviations
  - Partition performed over p_T^H, m_{jj}, p_T^{Hjj}, n_{jet}, and p_T^V



What are the implications of a light Higgs…

- the world has changed
  - SM-like Higgs boson with m_H = 125 GeV

- is such a light Higgs boson consistent with naturalness?
  - is m_H stabilized by ~TeV scale new physics or is it fine-tuned ?

- a window to new physics
  - Higgs is a signal to scrutinize for hints of what the physics beyond the SM may be
  - Are there additional Higgs bosons ?
  - Is the Higgs elementary or composite?
  - Are there exotic Higgs decays ?

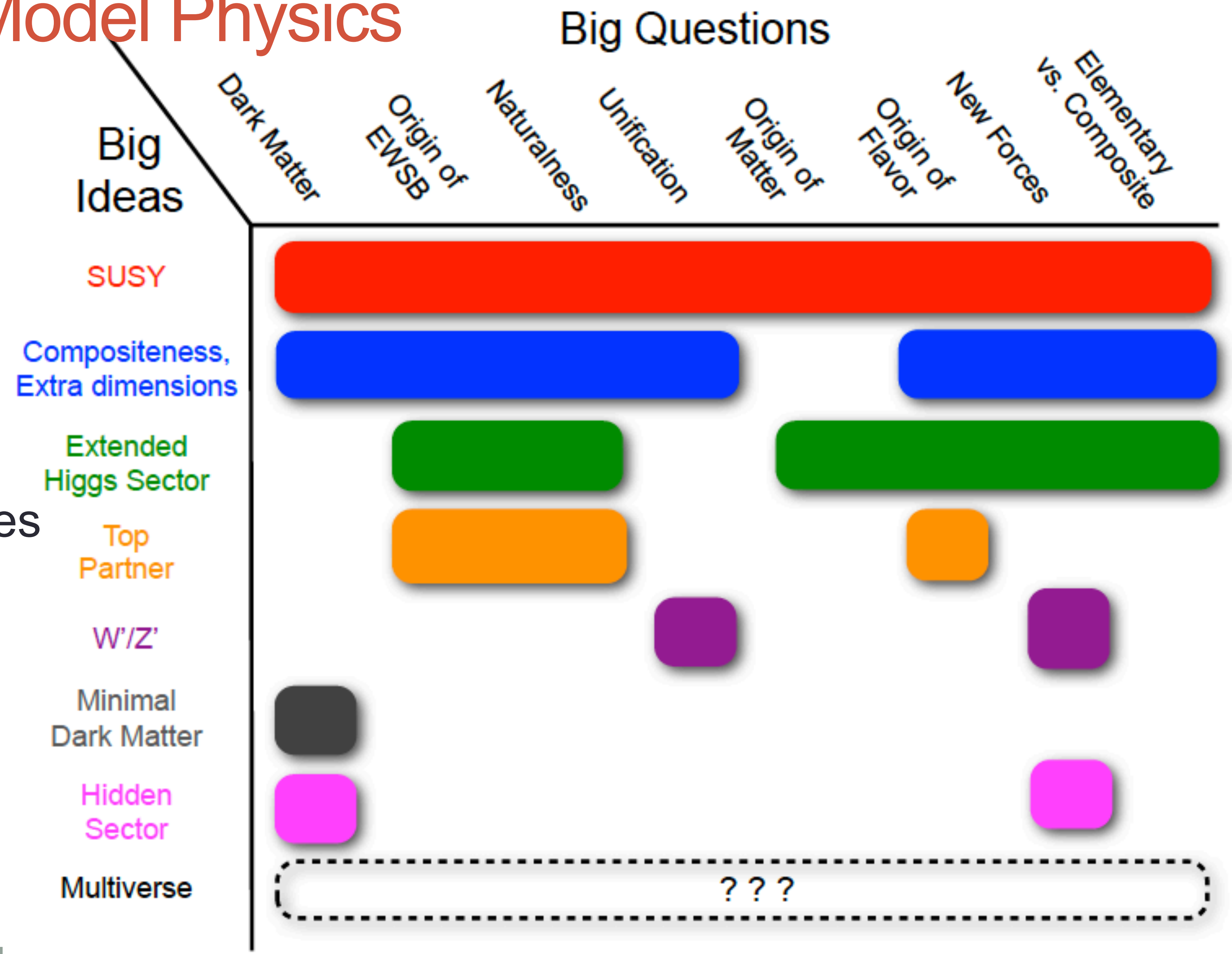
- what is the shape of the higgs potential?

- +….more

THE BEYOND SM PHYSICS PROGRAM - SELECTIVE HIGHLIGHTS

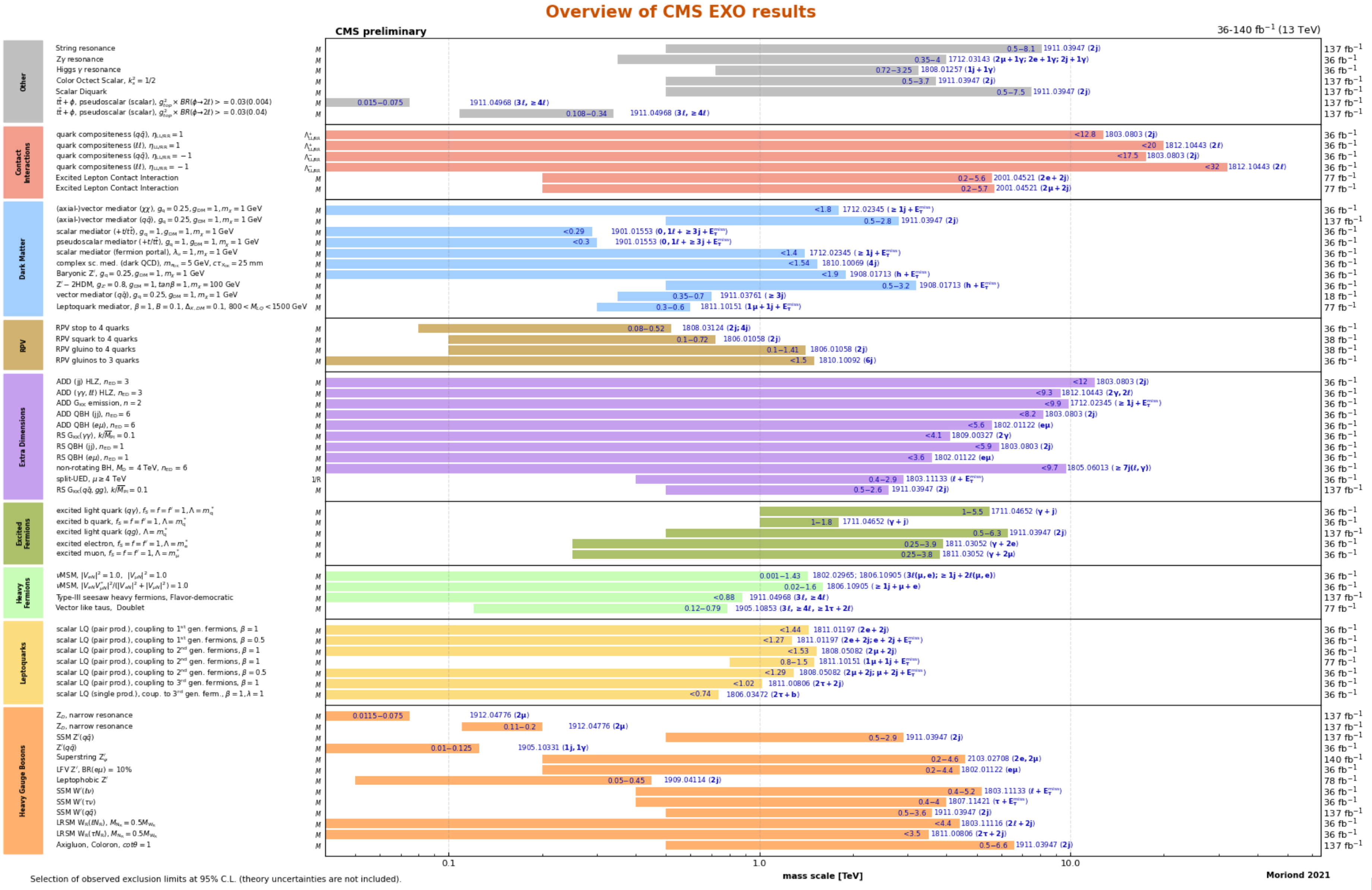
Beyond Standard Model Physics

- Plethora of models
- Predict:
  - New heavy particles
    - Some with large lifetimes
  - New signatures



Current Status of Beyond Standard Model Searches:

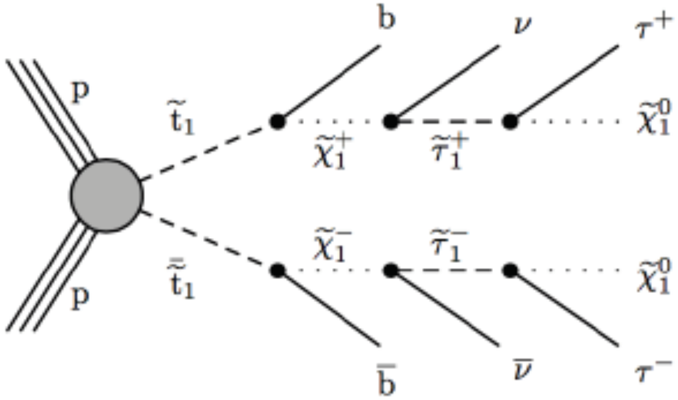
- Probe new particles with mass ~ few TeV
- Leaving no stone unturned in the search.
- Going from traditional searches to exploiting new techniques.
- Is BSM hiding in difficult corners of the phase-space?



Diverse search strategies

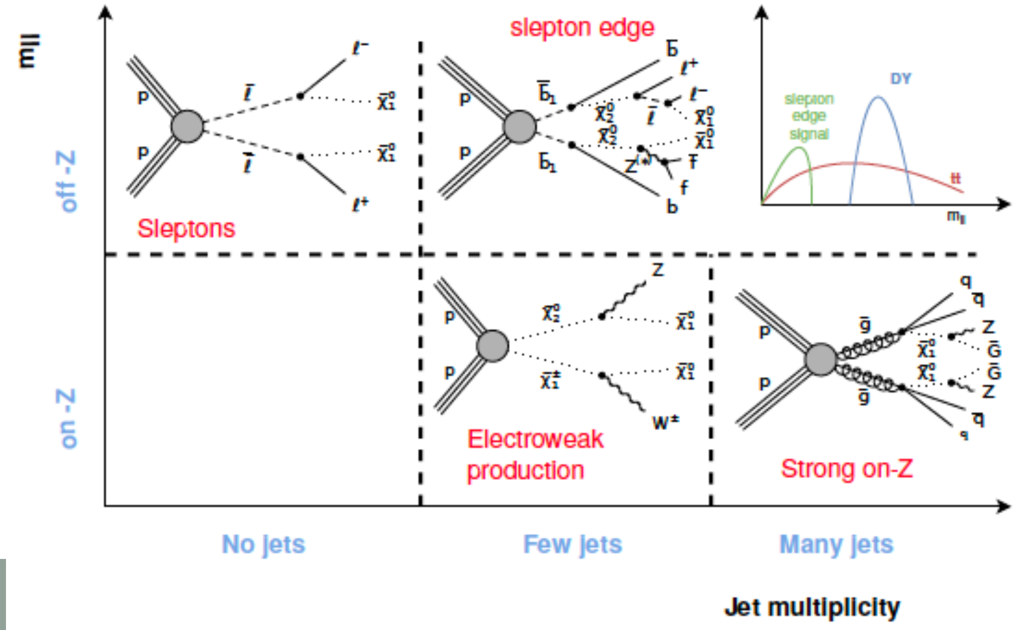
- Enhanced focus on complex topologies and weakly coupled phenomenon
- Inclusive searches complemented by dedicated searches that target gaps in coverage
- Challenging topologies
  - As mass limits on SUSY particles, particularly colored ones, are pushed up, further extension of the sensitivity requires special reconstruction techniques
  - In particular, decay products in SUSY chains are highly Lorentz-boosted, resulting in the overlapping particles/jets in the final state. Need to use jet substructure techniques, widely used in other massive resonance searches.
  - The results of first searches of this type are now becoming available
- Unconventional analyses
  - Displaced jets, emerging jets, delayed jets etc.
- Longer decay chains

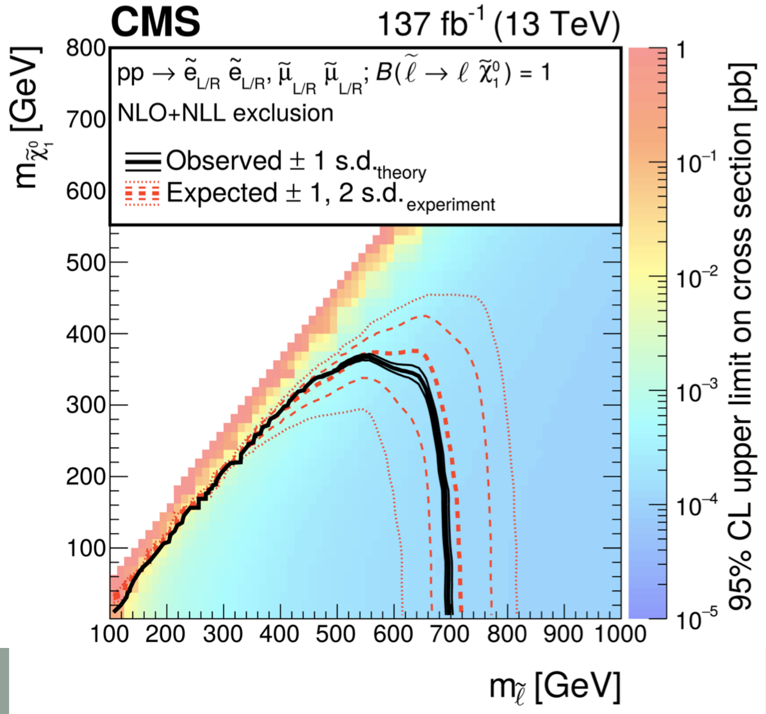
e.g. consider taus in stop decay chains (traditional searches veto taus or don't focus on them



SUSY sleptons (and ewkinos and squarks)

- Probe both electroweak and strong production with dilepton final states
  - Moderate E_{miss}^{T} requirements to target invisible particles. Per-model signal regions
- Backgrounds estimates:
  - Flavor-symmetric (tt, WW, & taus): estimate in opposite-flavor sideband, apply in same-flavor
  - Drell-Yan: model E_{miss}^{T} from γ+jets events (for sleptons, extrapolate from Z peak)
- Neutralino (chargino) masses excluded up to 750 (800) GeV (+100 GeV w.r.t. previous searches)
- Light-flavour (bottom) squark masses excluded up to 1800 (1600) TeV (+300 GeV in bottom)
- Direct slepton production excluded up to 650 GeV (+200 GeV)

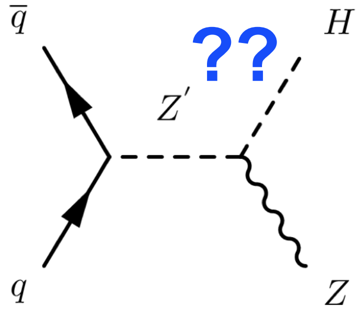




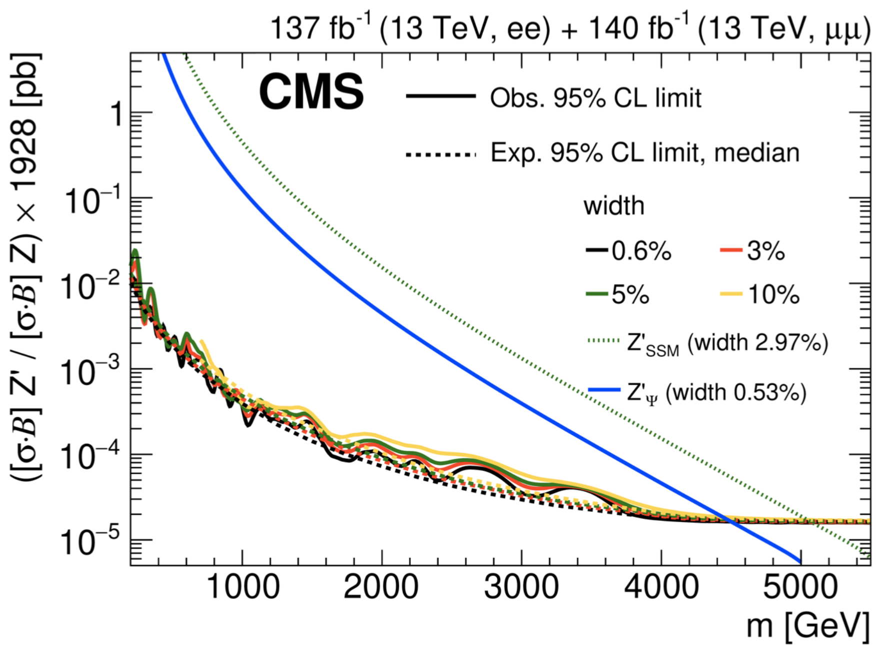
CMS-PAS-SUS-20-001

Search for New Particles: bump hunting

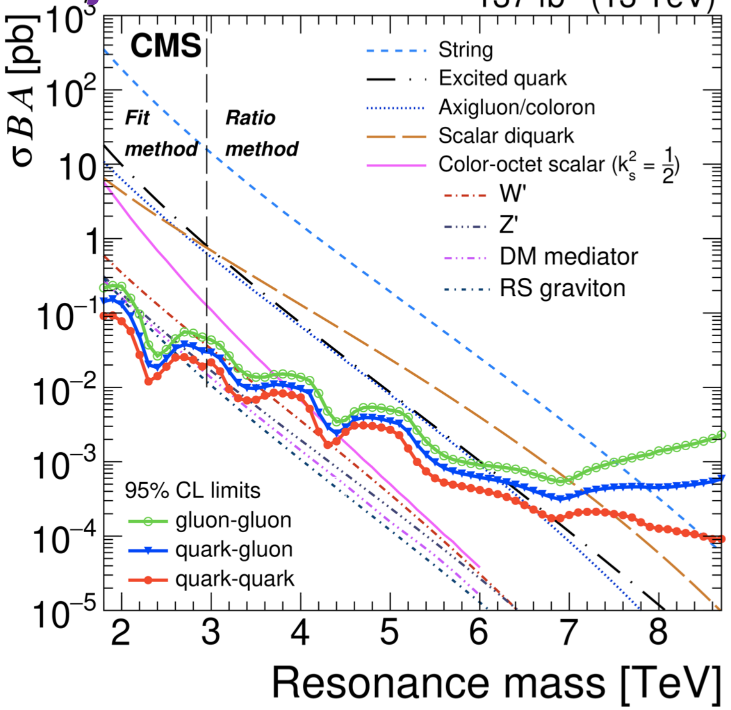
- Plethora of new models predicting new heavy resonances.
  - Look for bumps is a powerful search technique
  - model-independent as long as resonance is narrow
- Mass reach dilepton resonances : exclusion up to ~5 TeV
- Mass reach dijet resonances : exclusion 2 -8.5 TeV

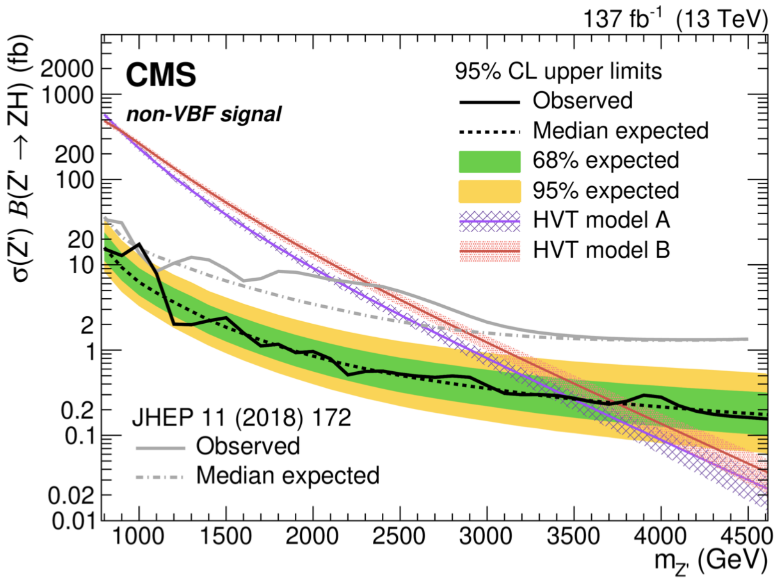


Di-lepton Resonances



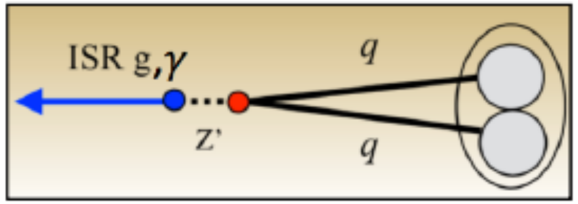
Di-jet Resonances

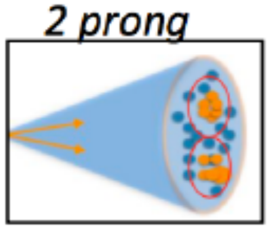


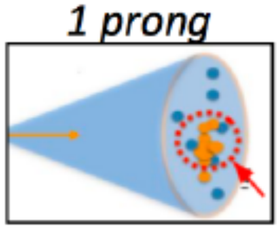


Dijet “Low Mass” Resonance Searches

- Large dijet cross section at low mass; study limited by resources to process and store data
- Benefits from
  - Scouting approach for trigger trades-off between trigger rate and event size
    - Reconstruction only at the HLT stage, keeping limited information (HLT objects)
    - needs calibration of HLT against full reconstruction.
  - Inclusion of ISR photon-tag





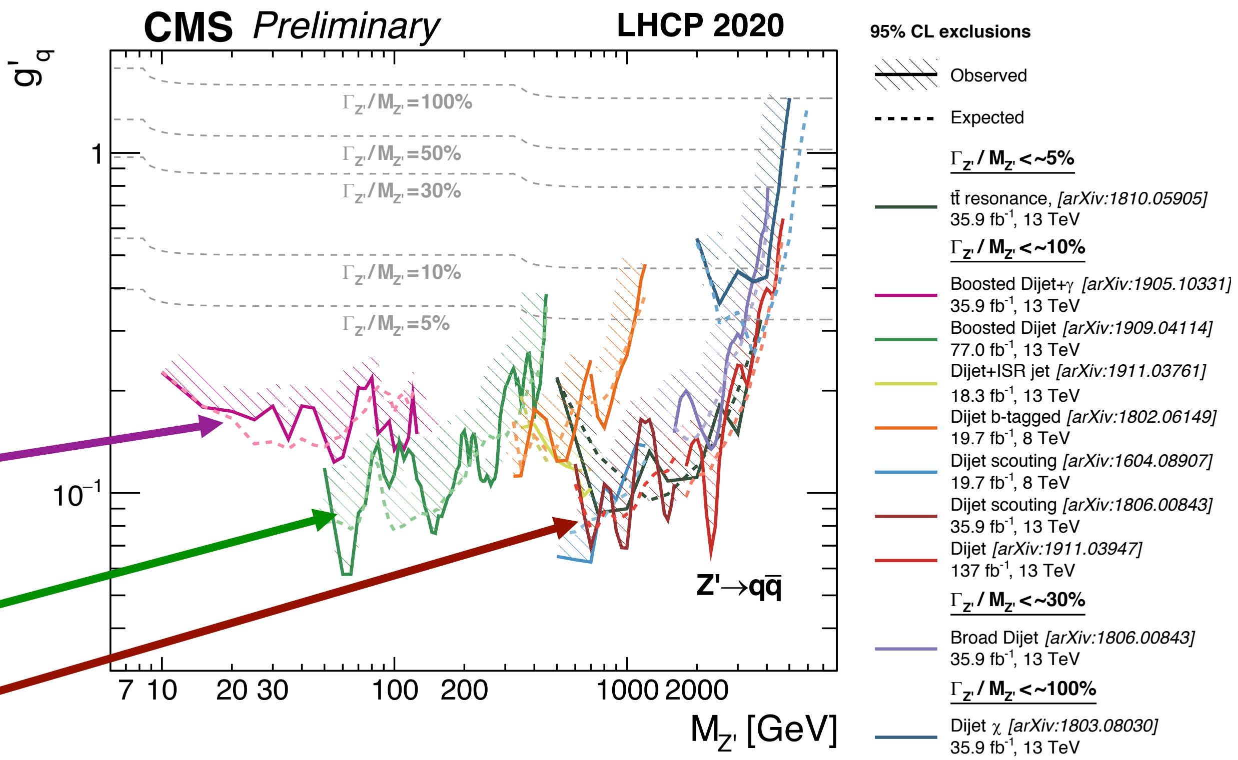


  - Use of “Jet Substructure” trigger @ HLT
  - Boosted jet identification at reconstruction

Boosted dijet + photon-tag

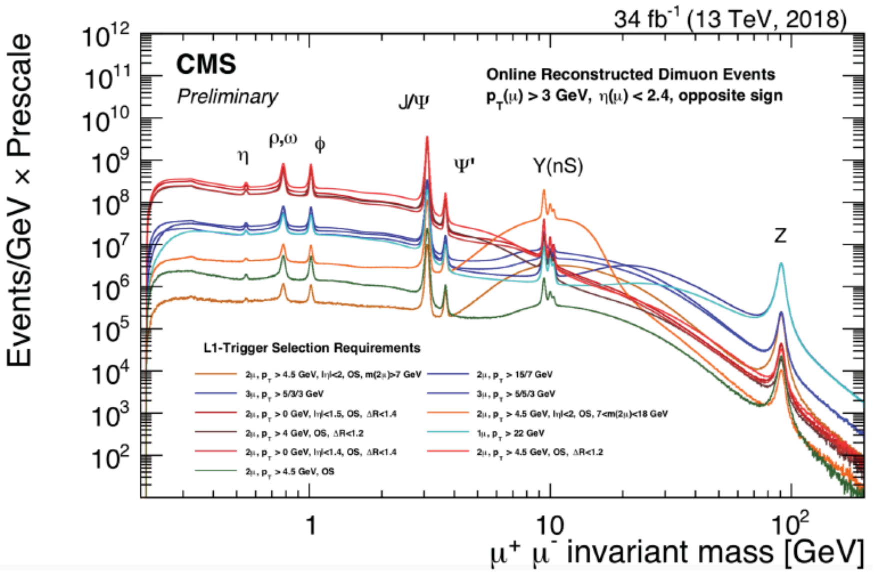
Boosted dijet + jet substructure trigger

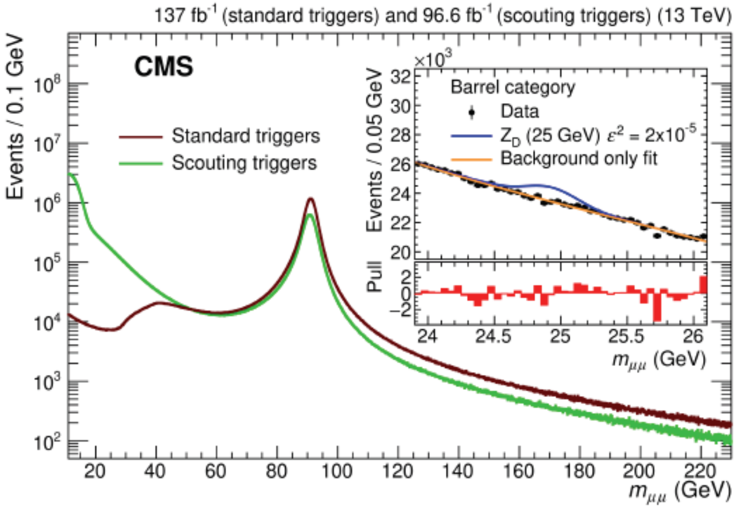
Dijet scouting

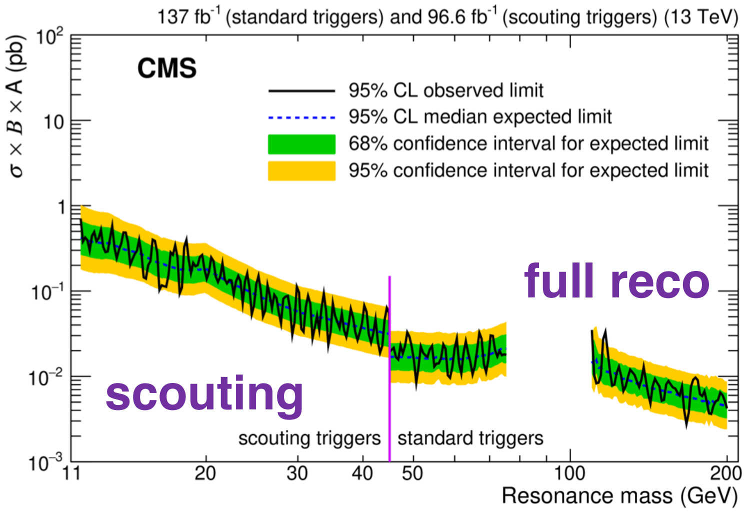


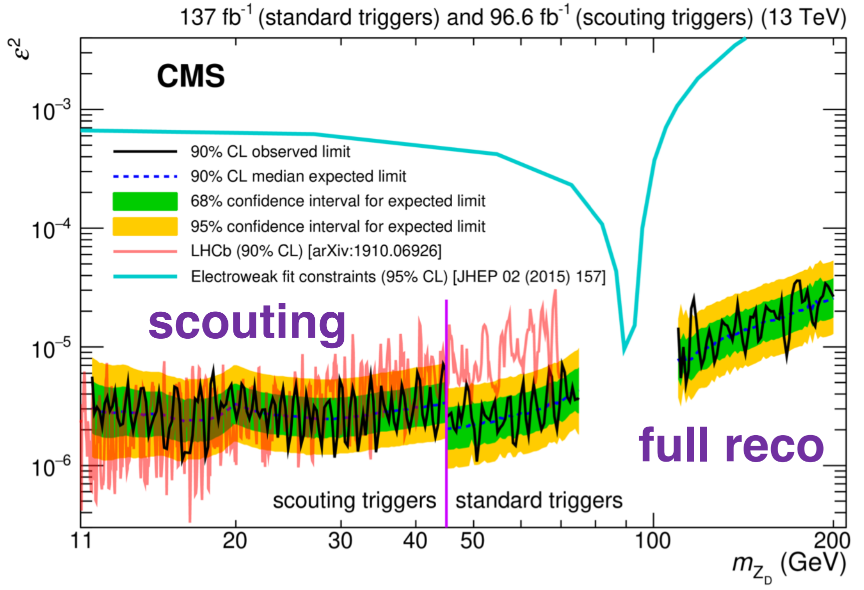
Dimuon Resonances & Dark Photons

- For $m_{\mu\mu}$ > 45 GeV, use “standard” muon triggers
  - Dimuon HLT trigger thresholds 17, 8 GeV
- For $m_{\mu\mu}$ < 45 GeV, use high rate “dimuon data scouting triggers”
  - Record muon triggers with much lower threshold
  - Ave. HLT rate: 5.6 (4.4) kHz in 2017 (2018)
- Dark Photons at the LHC:
  - Couples to SM particles via kinetic mixing parameter ϵ
  - possible decay modes to 2μ final states



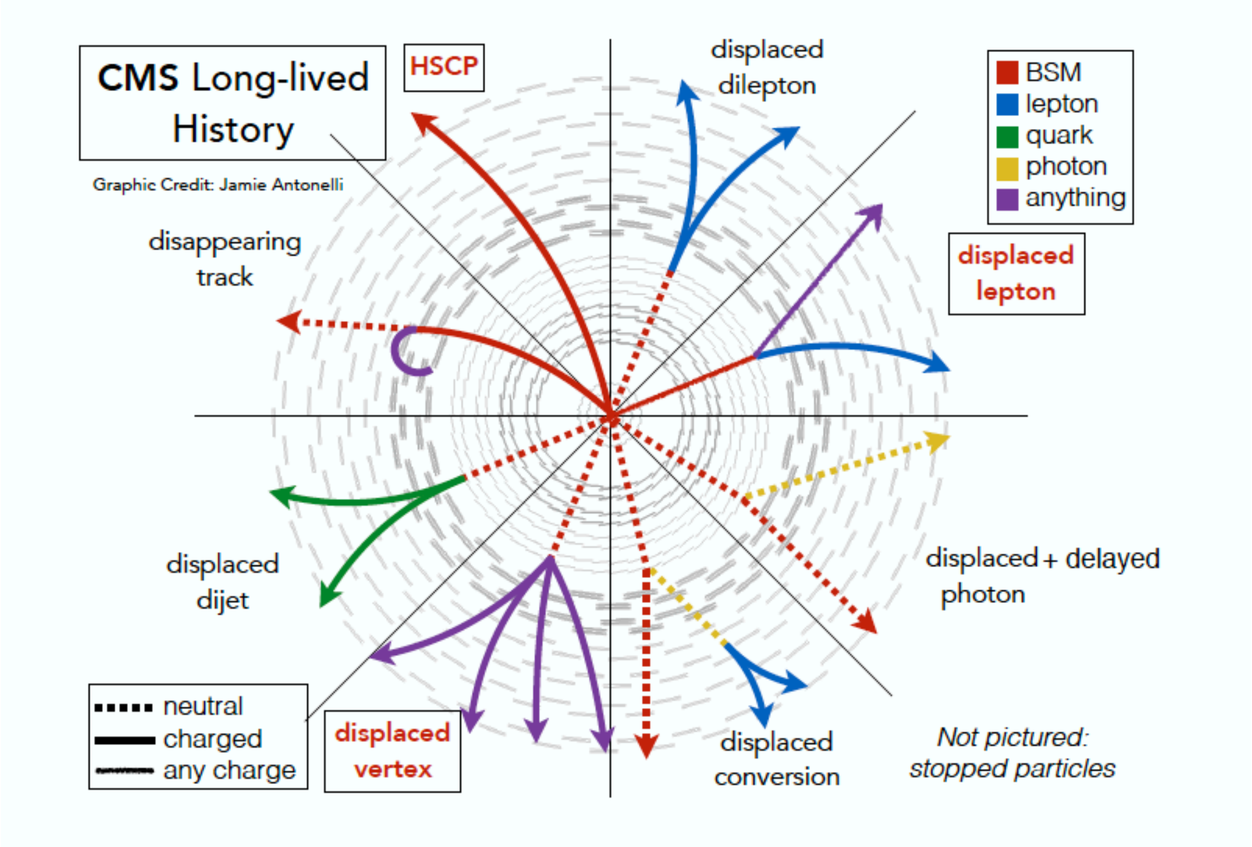


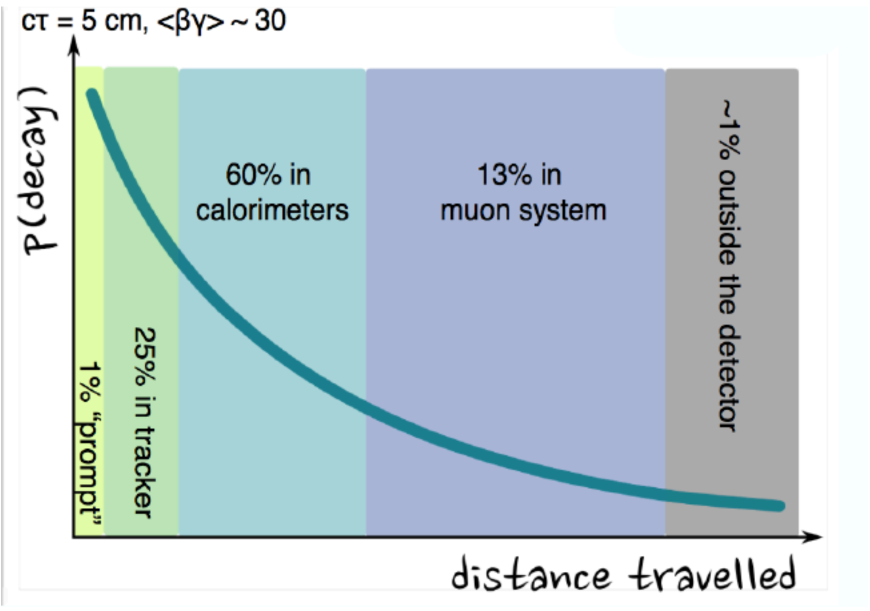




Long Lived Particles (LLP)

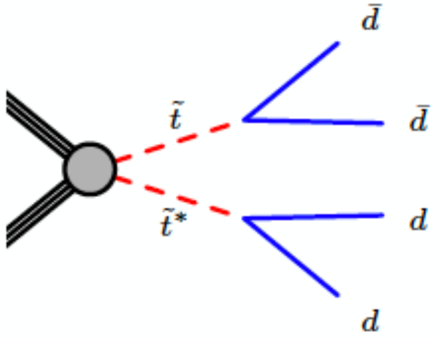
- Unconventional searches:
- Many BSM models have long-lived particles/ displaced vertices.
- Challenging measurements; important to use all sub-detectors

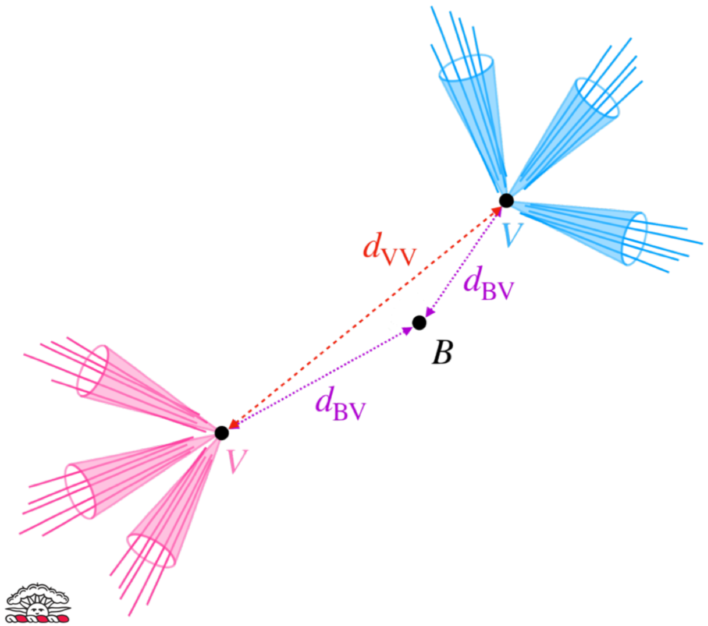


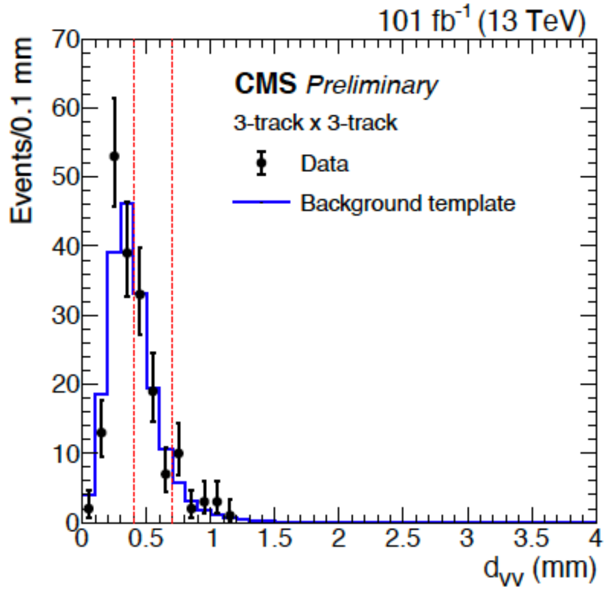


LLPs decaying to jets with displaced vertices

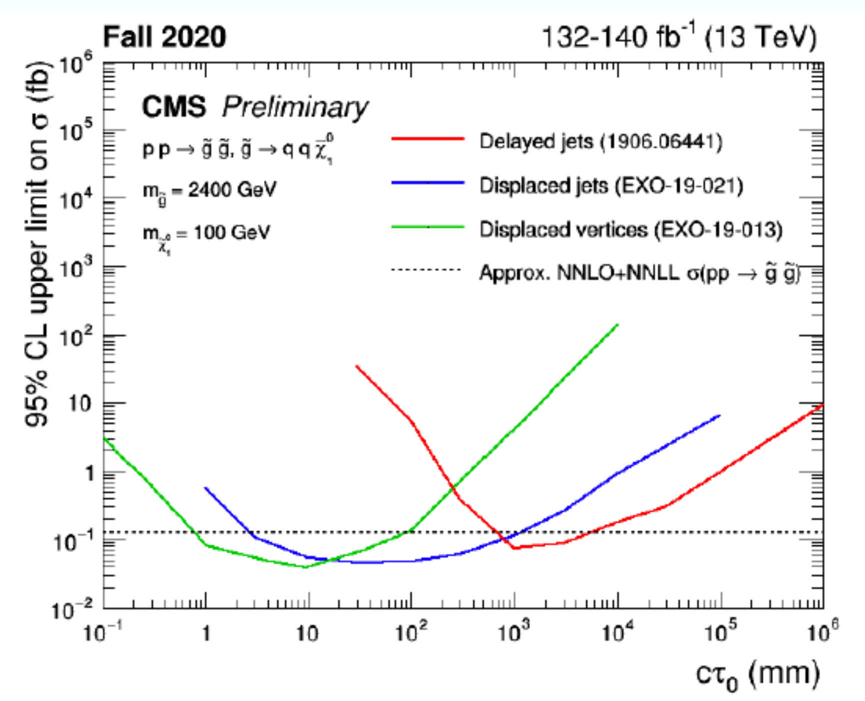
- Long-lived particles decaying to 2 or 3 quarks (≥5 track vertex)
- Displaced vertex reconstruction benefits from upgraded inner detector & improved pileup rejection techniques
- Scan d_{VV}: data-driven background template from 1-vertex events
- Low-lifetime search complements limits from displaced and delayed jet analyses
- Limits set on long-lived gluino (2.5 TeV), stop (1.5 TeV), & neutralino (1.1 TeV) with mean lifetimes between 0.1 → 100 mm







2-vertex template validation
(3-track vertices)



CMS-PAS-EXO-19-013

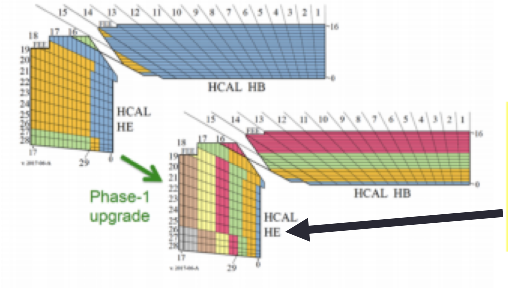
THE NEAR FUTURE: RUN 3

- **widened scope from large accumulated statistics**
  - **Helps with low energy or unusual signatures**
  - **Helps rare processes with small production cross section**
  - **More model-independent, not to miss anything**
- **How to prepare for physics?**
  - Pursue novel trigger algorithms
  - Continue benchmark analyses.
  - Develop new analysis strategies

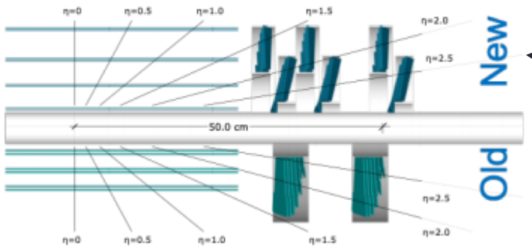
CMS Phase-I upgrades and LS2 Status

- A small delay accumulated during the previous 12 months and the LHC will restart in 2022
- Maintenance, improvement and completing Phase1 upgrade

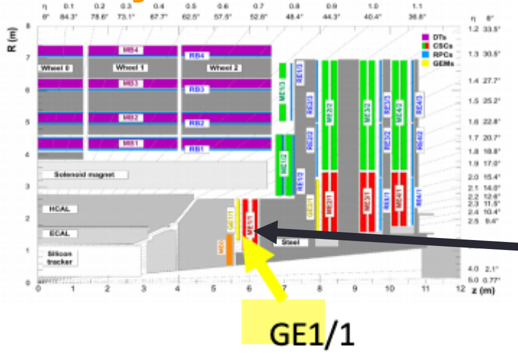
Depth segmentation from new electronics in HCAL



Update electronics of the Phase-1 pixel detector



First layer of GEM detectors

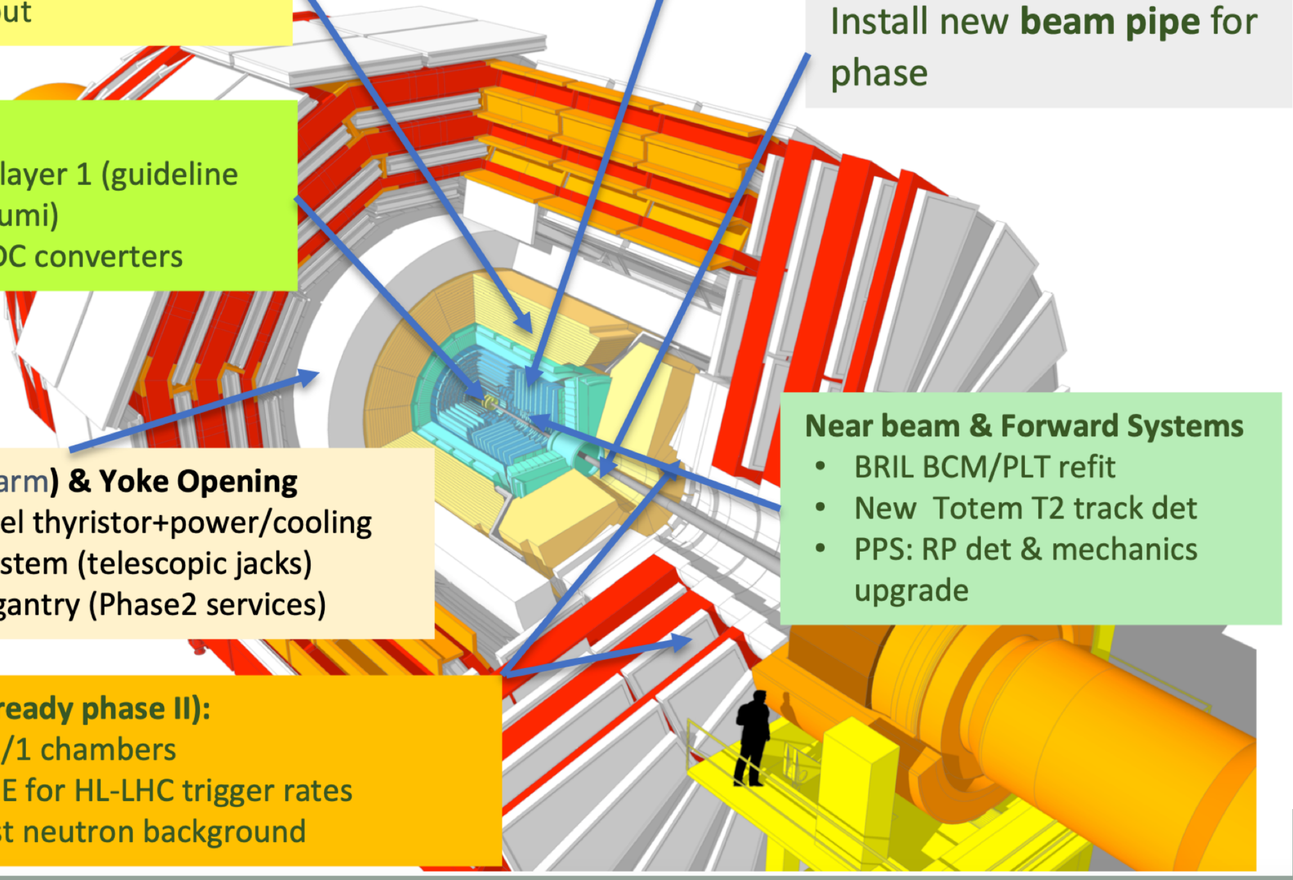


HCAL barrel (completed): install SiPM+QIE11-based 5Gbps readout

Keep **strip tracker** cold to avoid reverse annealing

Install new **beam pipe** for phase

Pixel detector:
- replace barrel layer 1 (guideline 250 fb-1 max lumi)
- replace all DCDC converters



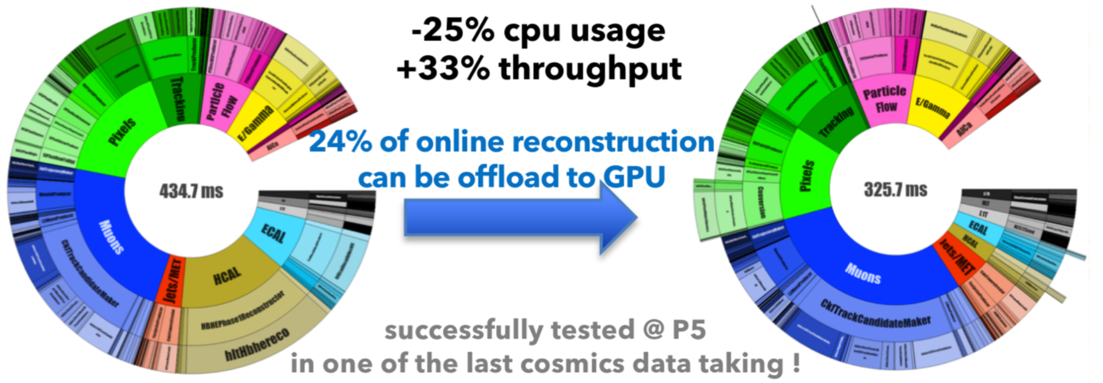
MAGNET (now warm) **& Yoke Opening**
- Cooled freewheel thyristor+power/cooling
- New opening system (telescopic jacks)
- New YE1 cable gantry (Phase2 services)

Near beam & Forward Systems
- BRIL BCM/PLT refit
- New Totem T2 track det
- PPS: RP det & mechanics upgrade

Muon system (already phase II):
- install GEM GE1/1 chambers
- Upgrade CSC FEE for HL-LHC trigger rates
- Shielding against neutron background

CMS Run 3 Plans

- Expanding not only just “more of the same”
- Increase of stats for searches and precision measurements
  - Machine learning techniques will continue flooding into the realm of reconstruction and triggering
  - Exploiting new detectors, some designed for Phase 2
- Improve the data taking/triggers
  - Consider extending Scouting and B-Parking data based on their usefulness in Run 2
  - Design new triggers to enlarge the phase space; trigger on anomalous events using ML methods
- Improve analysis ⟶ embed statistical inference into machine learning algorithms
- Planning to move to heterogeneous architecture in HLT, with mixed CPU/GPU
  - Already achieved 25% reduction of CPU time
  - Opens new possibilities for trigger algorithms leveraging on GPUs



CONCLUSIONS

Conclusions

- Excellent detector, reconstruction, dedicated techniques, dedicated triggers, and sophisticated models and analysis methods, have enable high quality scientific results and >1000 publications!

- CMS produced a wealth of results in all areas of particle physics demonstrating the power of general-purpose experiments
- They highlight new milestones in particle physics and pave road for future exciting results

- Towards Run 3
- Improvements in all aspects: detector, trigger, data taking, analysis algorithms!