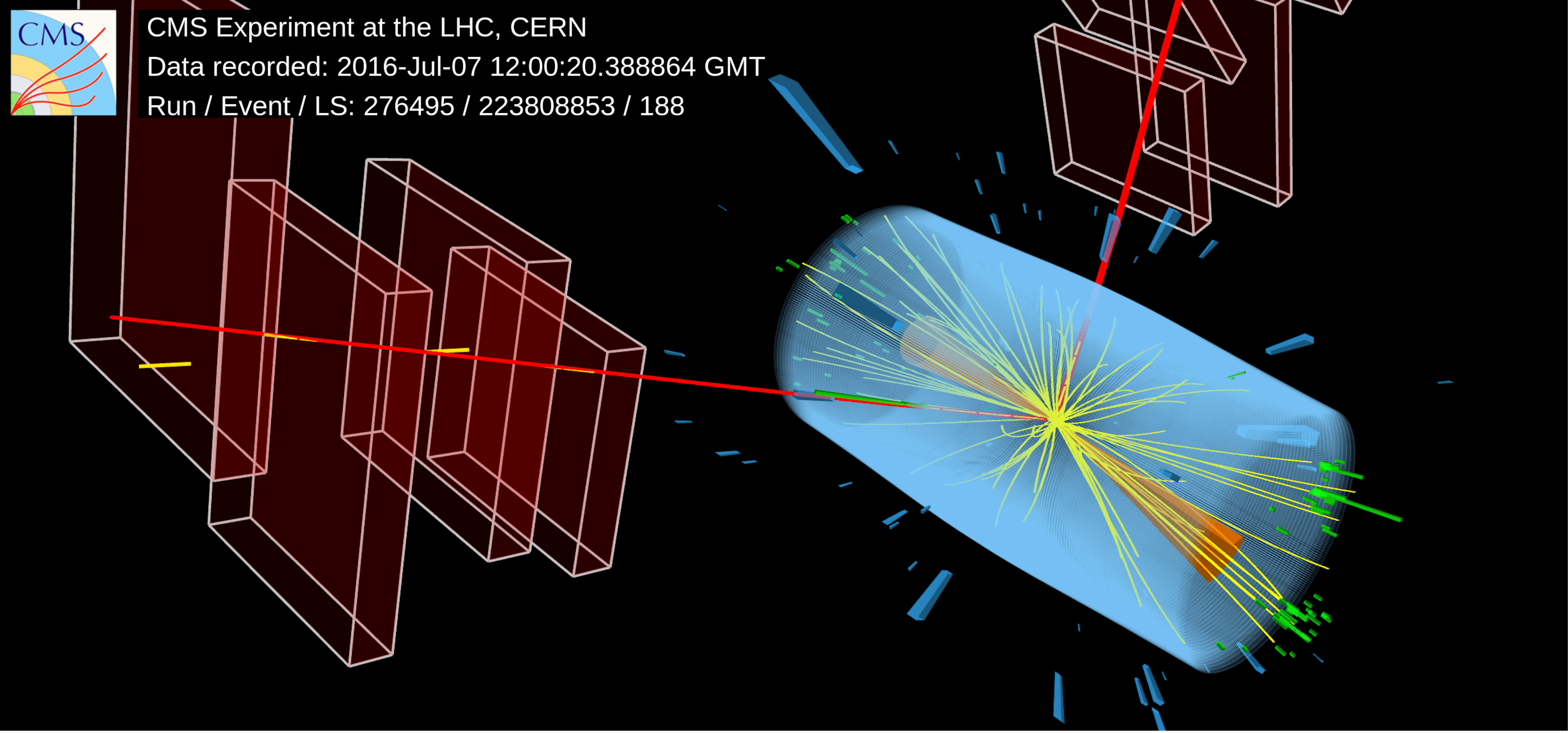
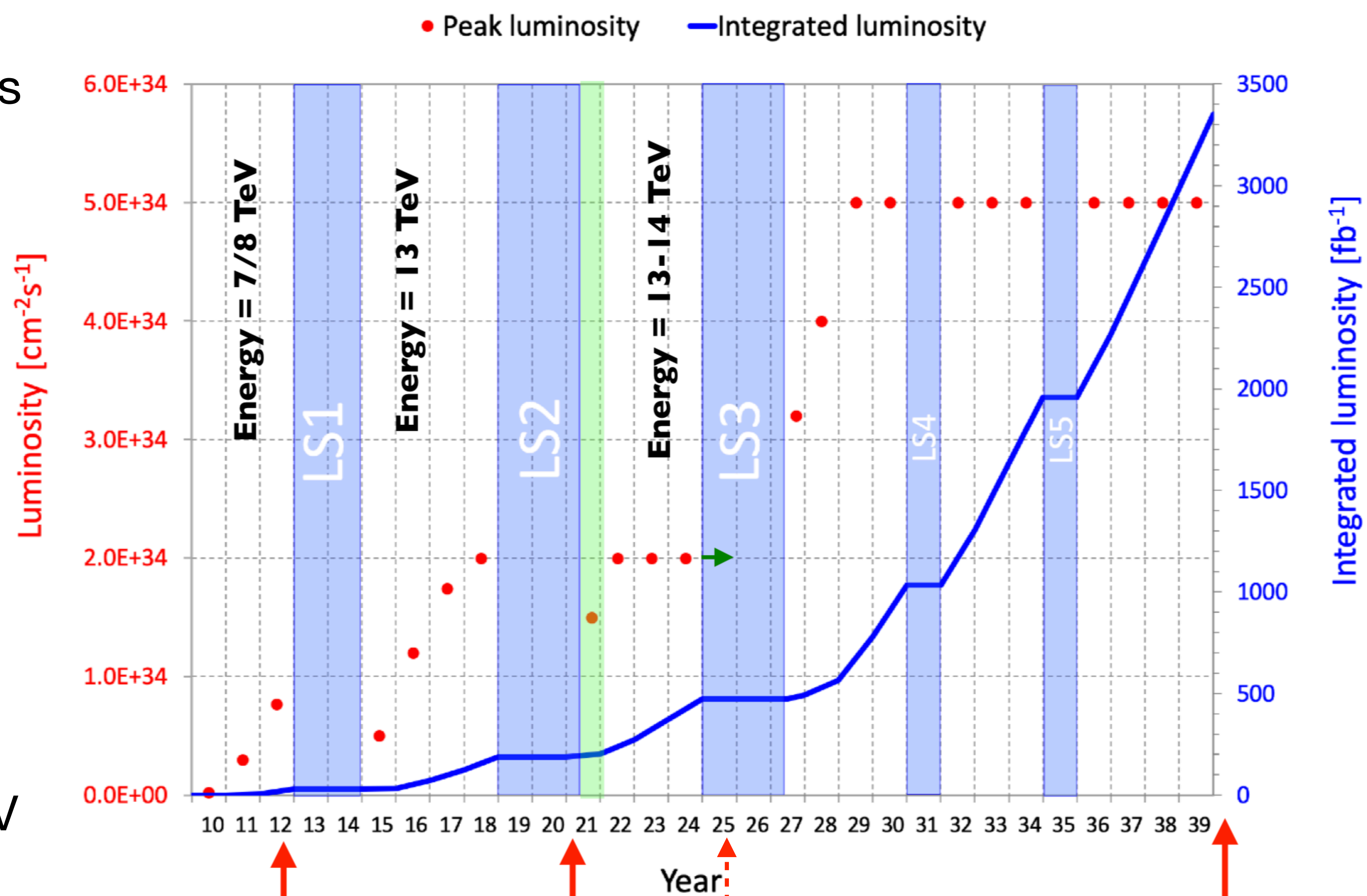


CMS overview

Minsuk Kim
Nov 5 Particle Physics Day 2020

LHC roadmap to full potential

- LHC completed 2nd physics run in 2018 with 150 fb^{-1}
  - >10 quadrillion pp collisions + heavy ion collisions
- Now in Long Shutdown 2 until ~~2021~~ **2022**
  - The LHC will try to increase the collision energy from 13 to 14 TeV
  - The integrated luminosity of Run 3 is expected to be almost the same



Discovery of the Higgs boson (10 fb^{-1})

Today (190 fb^{-1})

HL-LHC (x10L)

We will be going (3000~4000 fb^{-1})

phase I

phase II upgrades

So far LHC has delivered 5% or less of the total planned integrated L

CMS LS2 Shutdown

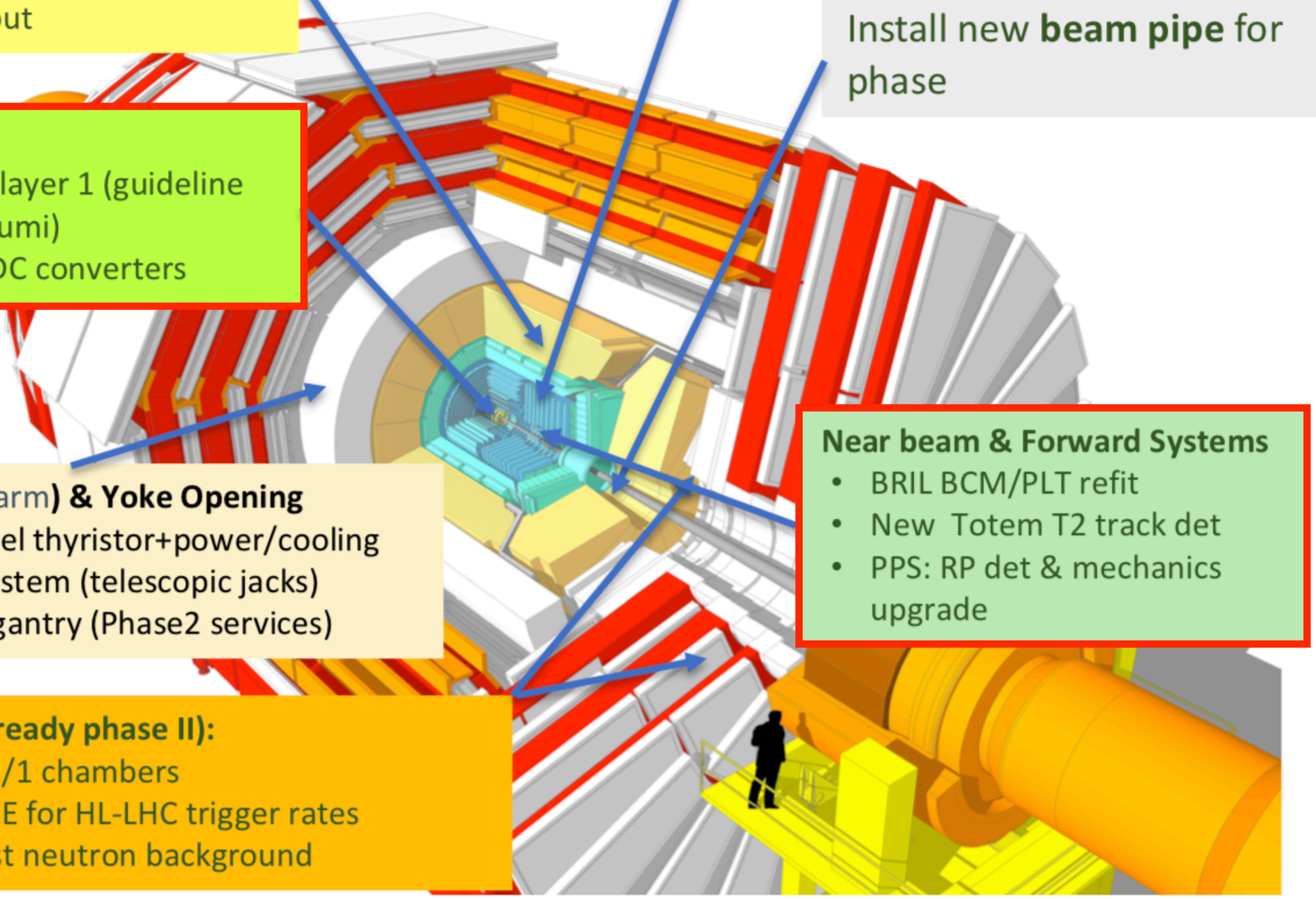
Civil engineering on P5 surface to prepare for Phase-2 assembly and logistics

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

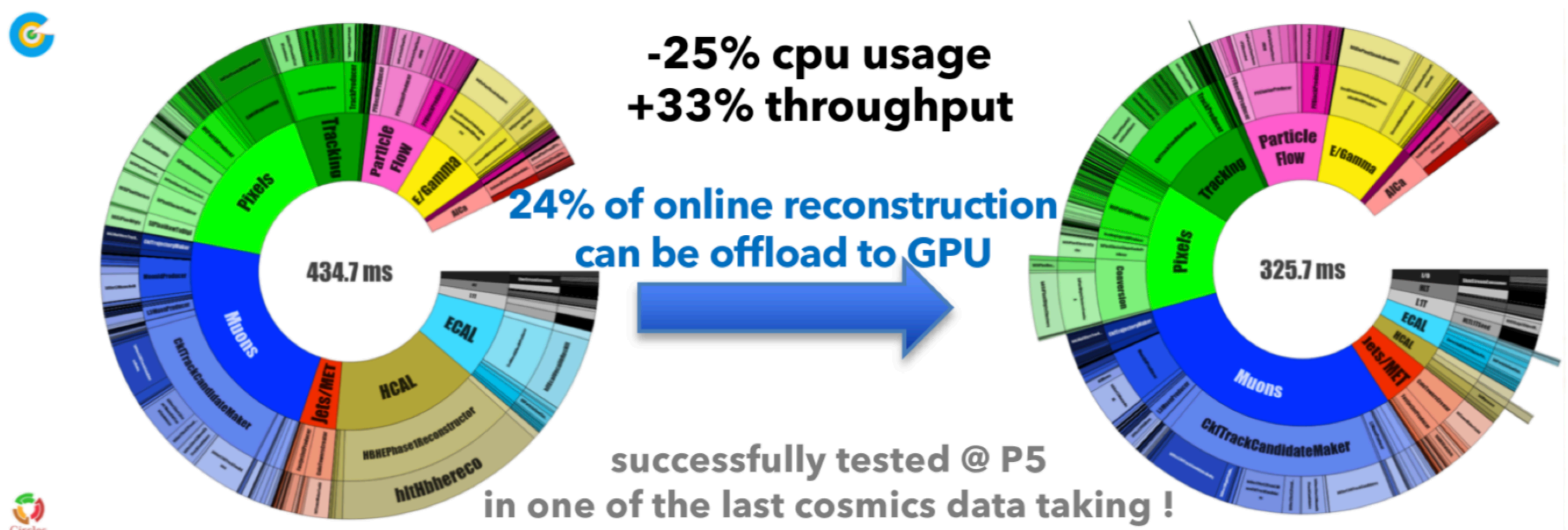
LS2 plan overview
- Some maintenance, improvement and Phase 1 upgrade
- Many activities already related to Phase 2 (HL-LHC) upgrades and related services and infrastructure

Coarse schedule:
- 2019: Muons and HCAL interleaved
- 2020→: Muons, beam pipe installation, then pixel re-installation

- Proton Precision Spectrometer (PPS) HL-LHC part of TOTEM
- New TOTEM T2 track detector
- Charged particle tracker: rad-hard pixel detectors and electronics (phase 1 & 2)
- Minimum Ionizing Particle (MIP) timing detector: Low Gain Avalanche Detectors
- Forward proton detector: diamond timing detectors

Towards Run 3

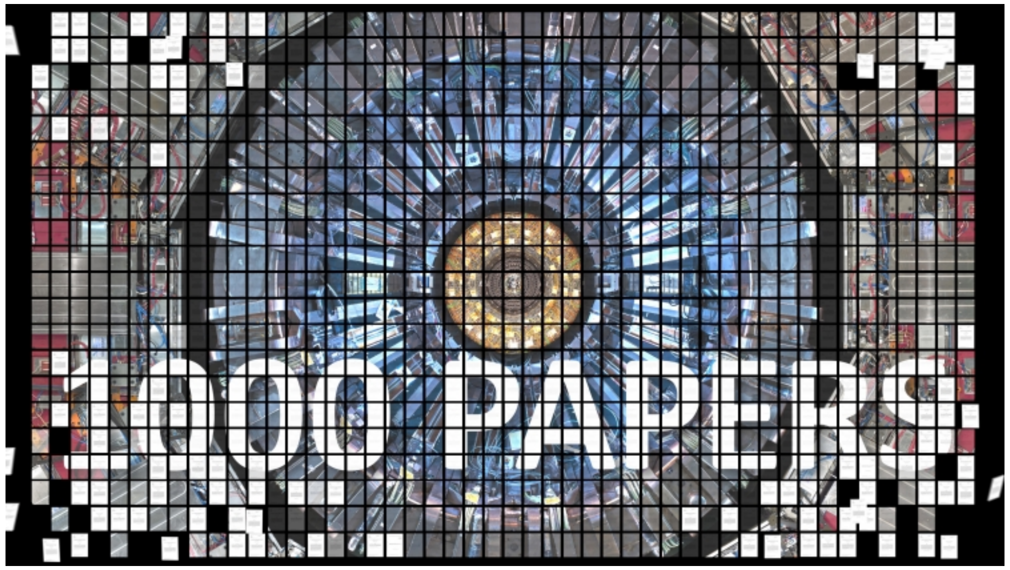
- **Improve the detector**
  - Update electronics of the Phase-1 pixel detector
  - First layer of GEM muon detectors in the forward region
  - Update electronics of Hadronic Calorimeter to support depth segmentation
- **Improve the trigger system**
  - Mixed CPU/GPU architecture for High Level Trigger system
  - Currently: 25% reduction of CPU time
  - Opens new possibilities for trigger algorithms leveraging on GPUs
  - Testing for HL-LHC. Trigger on anomalous events using machine learning



- **Improve the data taking**
  - Consider extending Scouting and B-Parking data based on their usefulness
  - Design new triggers to enlarge the phase space

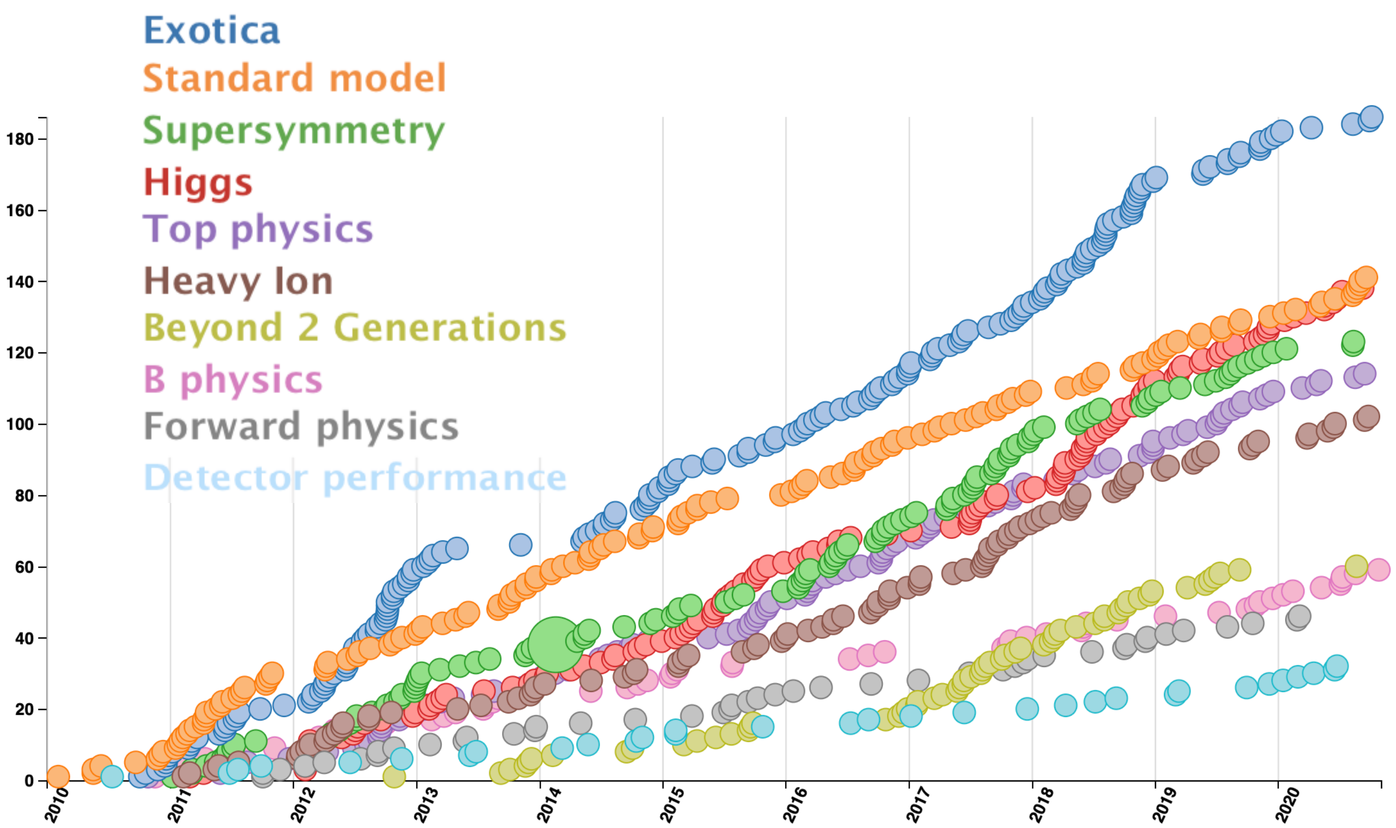
Physics Results

CMS publications

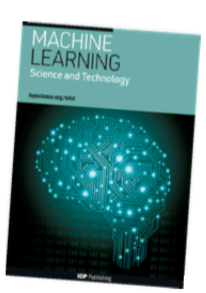


>1000 papers on collider data published or submitted to a journal as of Oct 27, 2020

https://cms.cern/news/CMS-collaboration-celebrates-1000th-paper



- First scientific paper on Jan 9, 2008
- Higgs boson discovery in 183rd paper
- Spanning a diverse range of topics
- 1000th papers on Jun 19, 2020



We have now had several CMS papers accepted in Machine Learning journals

We celebrated the 10th anniversary of the first collisions@CMS (Mar 30, 2020)

CMS:n tiedote 7 TeV:n törmäyksistä LHC:llä

Geneve, 30 maaliskuuta 2010.

CERNin Large Hadron Collider (LHC) on tänään törmäyttänyt ensimmäistä kertaa kaksi protonisuihkua 3,5 TeV:n energialla. Tämä on uusi maailmanennätys. CMS-koeasema rekisteröi menestyksellisesti heti ensimmäisiä törmäyksiä, aloittaen näin "Uuden Fysiikan" tutkimusohjelman LHC:llä.

Kello 12:58:34 LHC:n ohjauskeskus ilmoitti, että kiihdyttimessä kiertävät suihkut törmäävät toisiinsa koeasemissa, mikä havaittiin välittömästi CMS:llä. Hetken kuluttua koelaitteiston tiedonkeruu- ja käsittelyjärjestelmä oli analysoinut kerätyn datan ja rekonstruoinut ensimmäiset kuvat CMS:n keskellä tapahtuneissa 7 TeV:n törmäyksissä syntyneiden hiukkasten radoista.

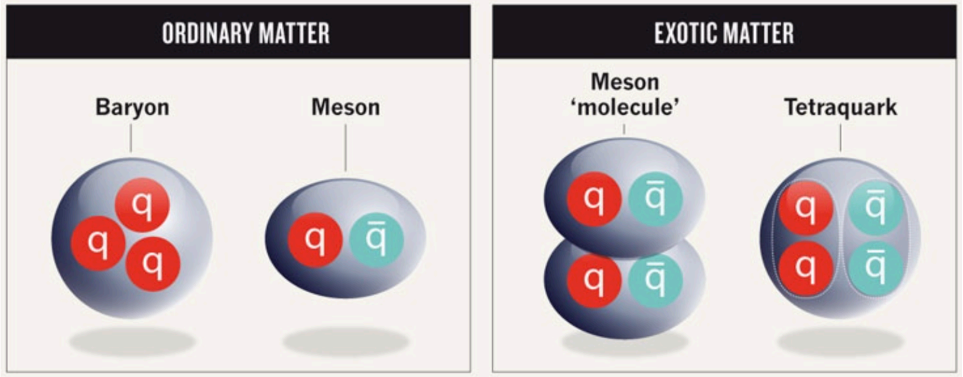
Protonisuihkuja on nyt kierrätetty LHC:ssä kolmatta tuntia. CMS-koeasema on toiminut suunnitellusti ja rekisteröinyt 200000 törmäystä ensimmäisen tunnin aikana. Törmäyksistä kerätty data tallennettiin ja perusprosessoitiin nopeasti CERNin mittavassa tietokonefarmissa, minkä jälkeen se lähetettiin CMS:n osallistujainstituutteihin ympäri maailmaa fysiikan analyysiä varten.

Observation of $B_s^0 \rightarrow X(3872)\phi$ decay

First observation!

PRL 125 (2020) 152001

- Observation of X(3872) in different B-hadron decays is important understanding the nature of this state (a molecule? or a tetraquark …)



- Search performed in the

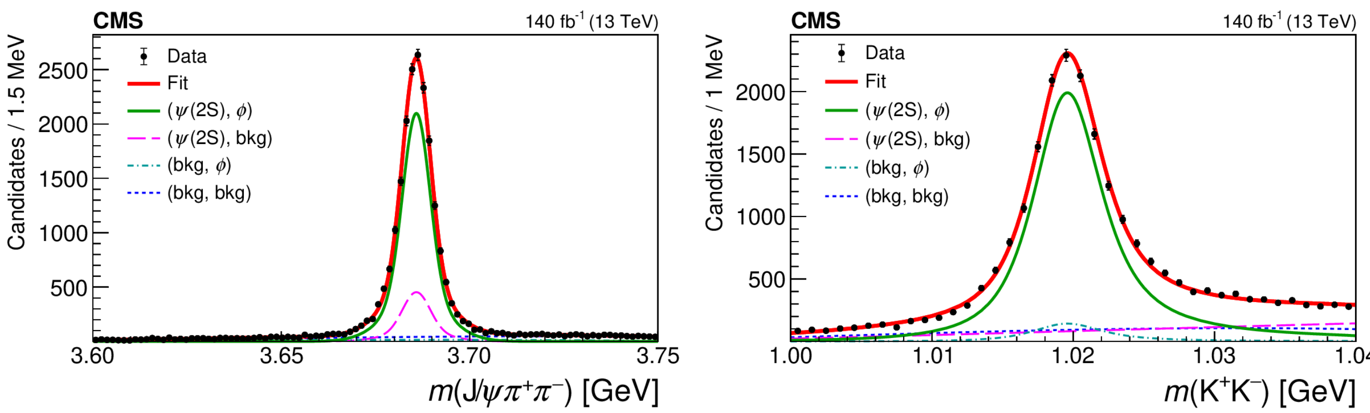
  $X(3872) \rightarrow J/\psi(\rightarrow \mu\mu)\pi\pi$ mode

- Significance from 2D fit > 6σ

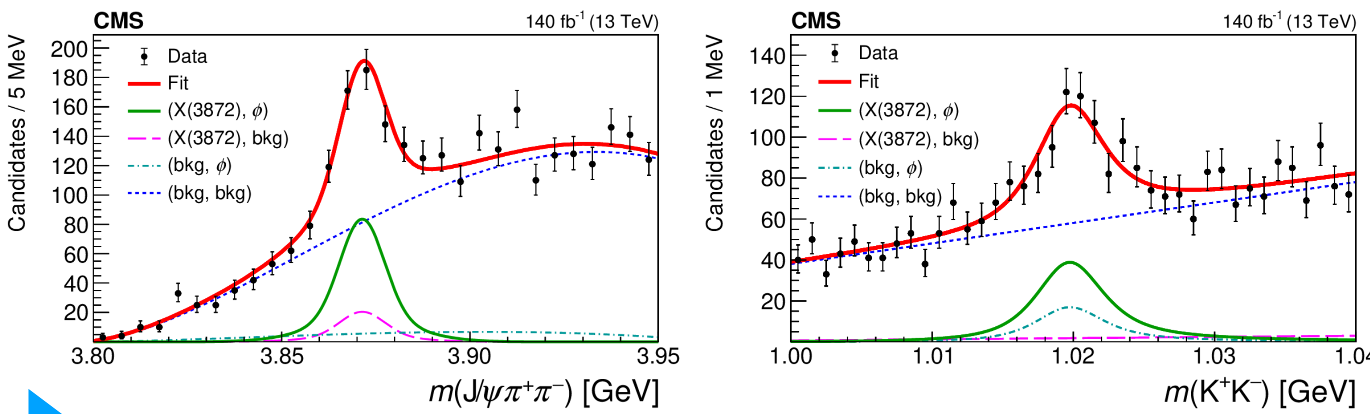
$$R = \frac{B(B_s^0 \rightarrow X(3872)\phi) \times B(X(3872) \rightarrow J/\psi\pi\pi)}{B(B_s^0 \rightarrow \psi(2S)\phi) \times B(\psi(2S) \rightarrow J/\psi\pi\pi)}$$

= 2.21 ± 0.29 (stat) ± 0.17 (syst) %

$J/\psi\pi\pi$ and KK masses for the reference channel



$J/\psi\pi\pi$ and KK masses for the signal channel

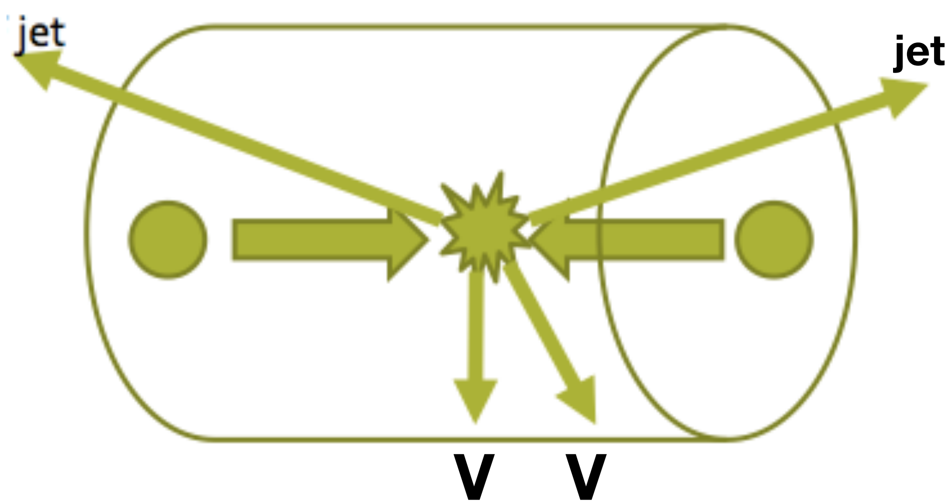


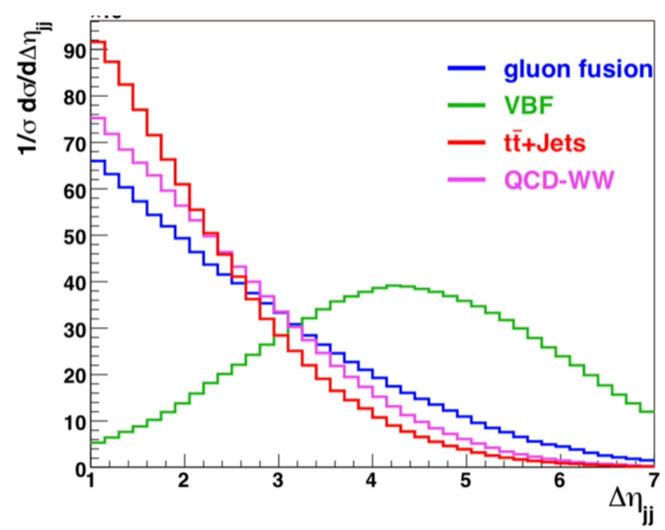
Normalization to the analogous channel (cancellation of many systematic effects)

Comparison with B^0 and B^+ indicates X(3872) formation is different from ψ(2S) formation, suggesting that X(3872) is not a pure charmonium ➔ similar conclusions to other measurements

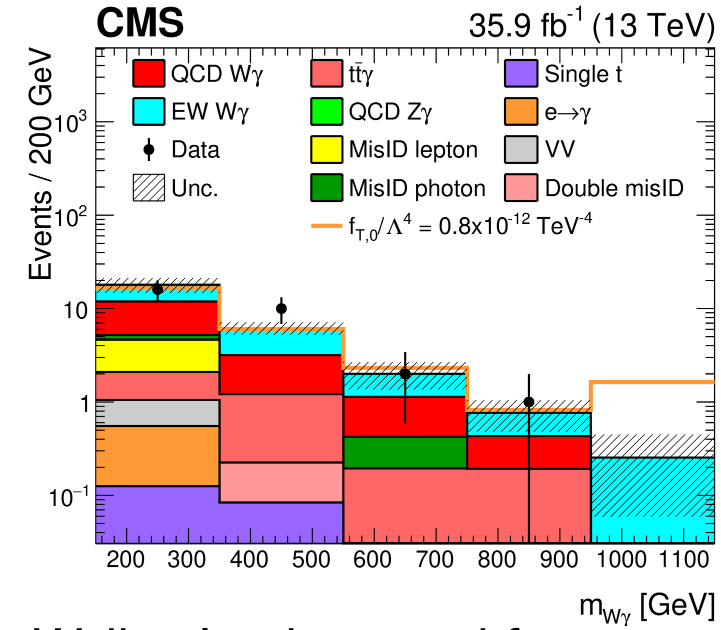
Diboson in VBS

- Vector boson scattering important to test dynamics of EWSB and nature of Higgs boson
- Signature: VV in central region + 2 forward jets



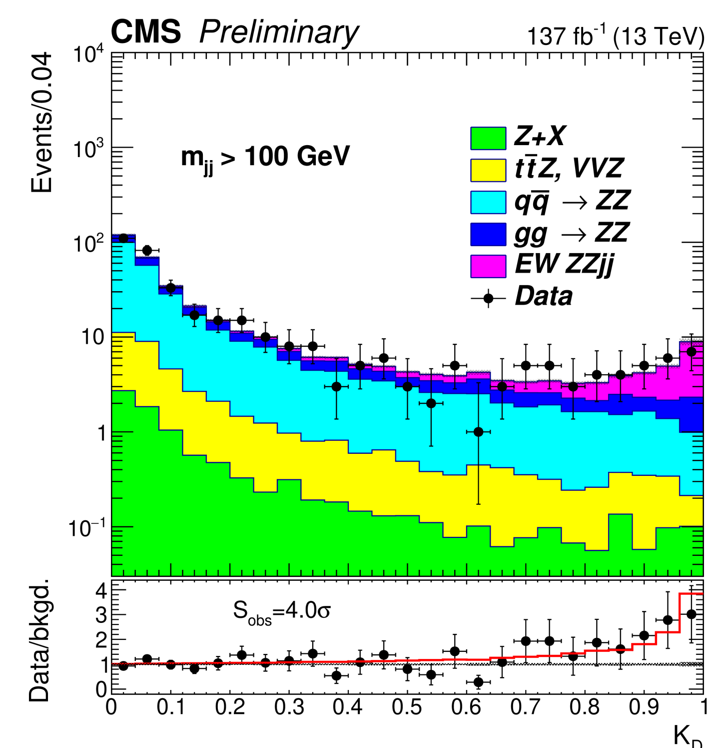


- New results: $qq \to W\gamma jj \to \ell\nu\gamma + jj$ and $qq \to ZZjj \to 4\ell + jj$



SMP-19-008

Wγjj selection used for constraints on aQGCs param.



SMP-20-001

ME discriminant in ZZ analysis

- Wγ: first observation with 5.3σ obs (4.8σ exp) for Run 1+2
- ZZ: evidence with 4.0σ obs (3.5σ exp)
- WZ and same-sign W±W±:
  - observation of WZ with 6.8σ obs (5.3σ exp) (W±W± ≫ 5σ)

Challenges: small x-sec, PLB 809 (2020) 135710

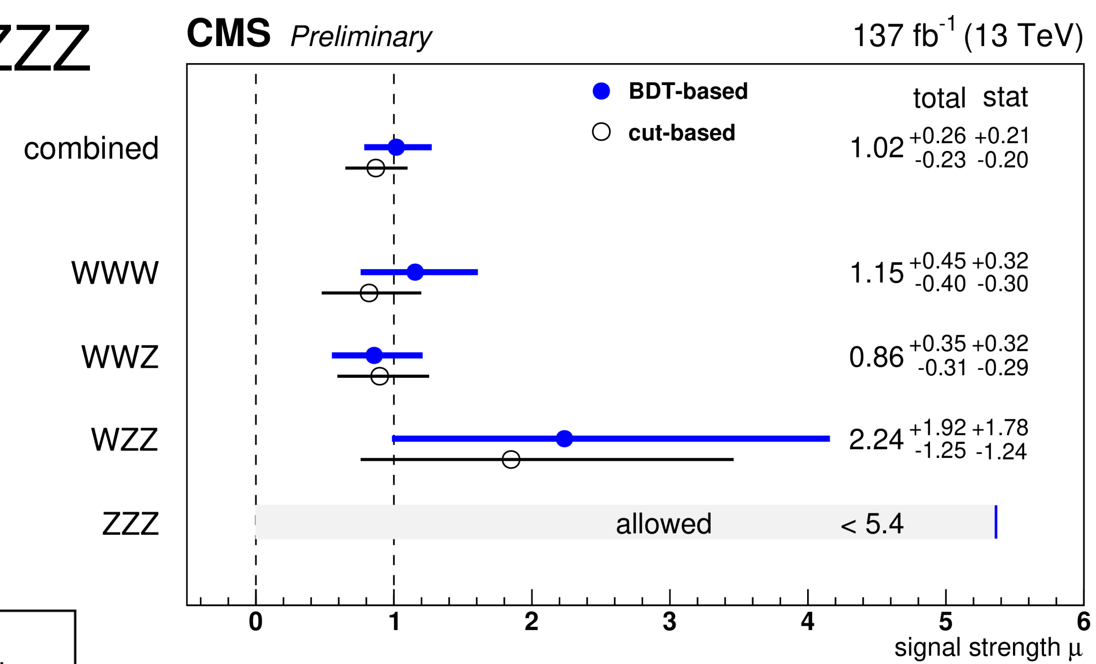
➜ Many new results with stringent constraints on aTGC and aQGCs

Observation of VVV production

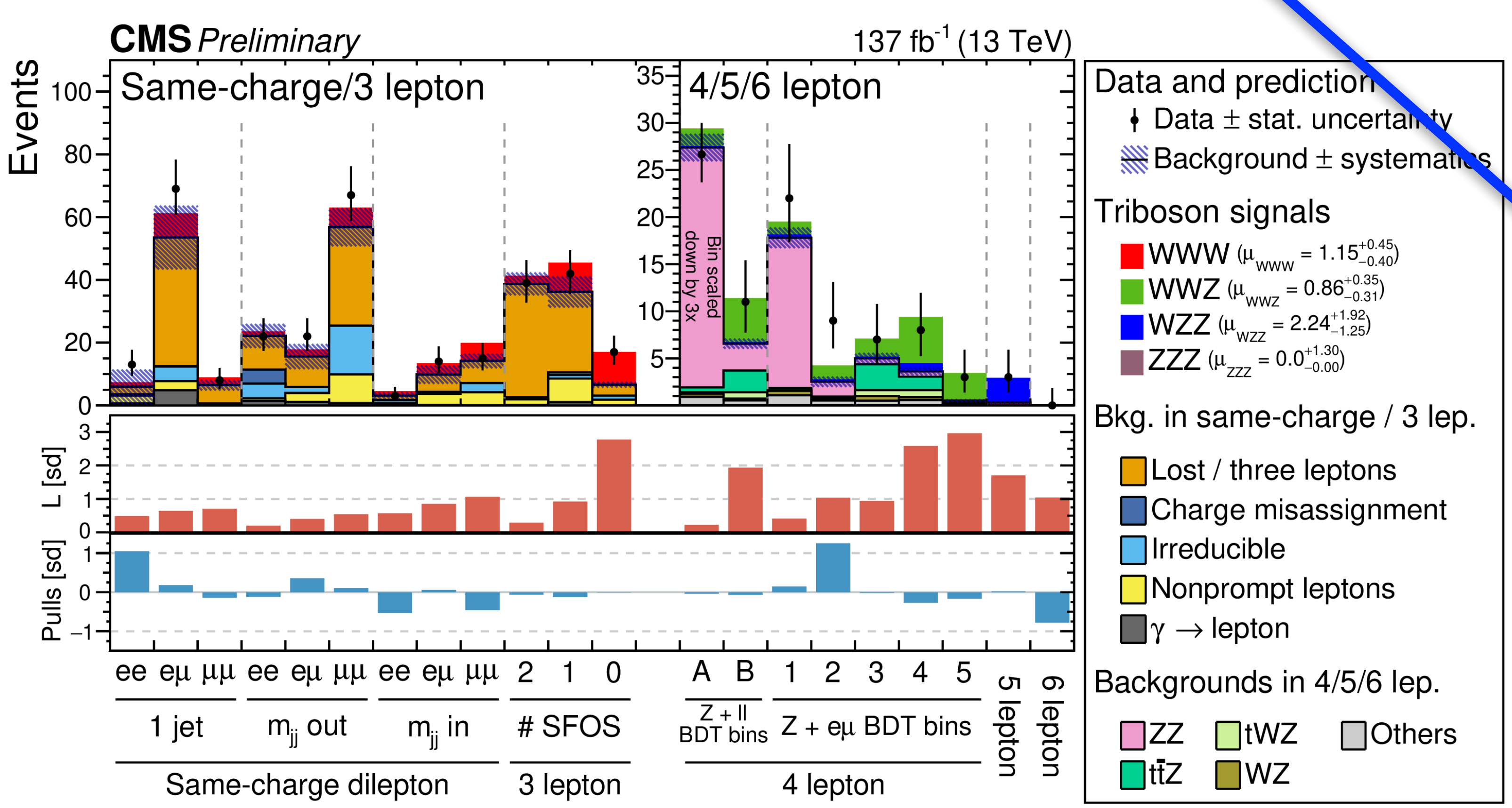
First observation! jj + VVV with V = W or Z

PRL 125 (2020) 151802

- Individual event classes for 2 same-sign, or 3-6L (e/μ)
  - targeting processes: WWW, WWZ, WZZ, and ZZZ
  - Includes VH (H→VV) contributions
- Results from two analyses (cut- and BDT-based)
  - results are consistent with SM
  - observation for VVV, combined: 5.7σ obs (5.9σ exp) and evidence for WWW and WWZ

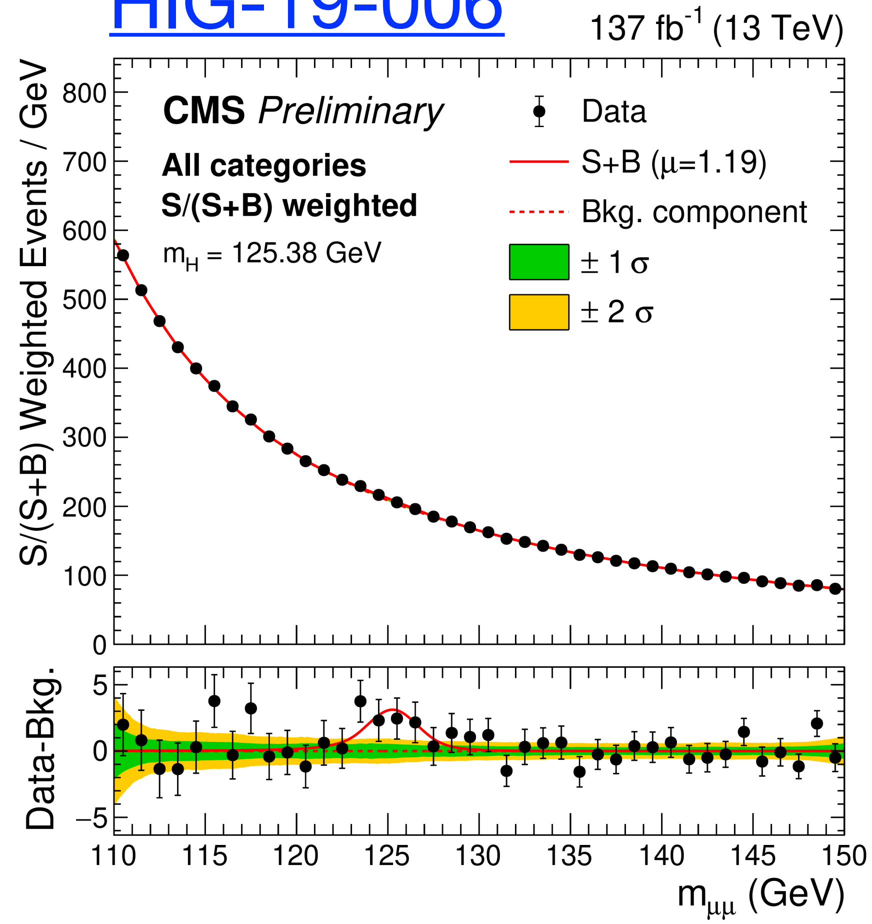


Significance	Exp. BDT based	Obs. BDT based
WWW	3.1	3.3
WWZ	4.1	3.4
WZZ	0.7	1.7
ZZZ	0.9	0.0
Total VVV	5.9	5.7



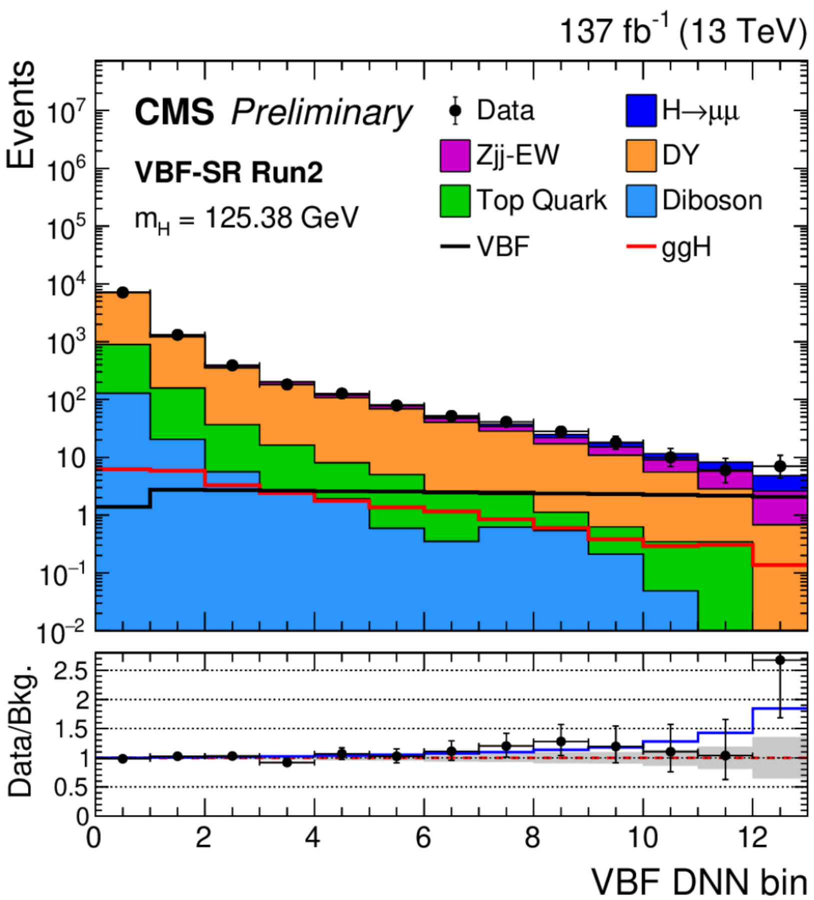
Evidence of H$\rightarrow \mu\mu$

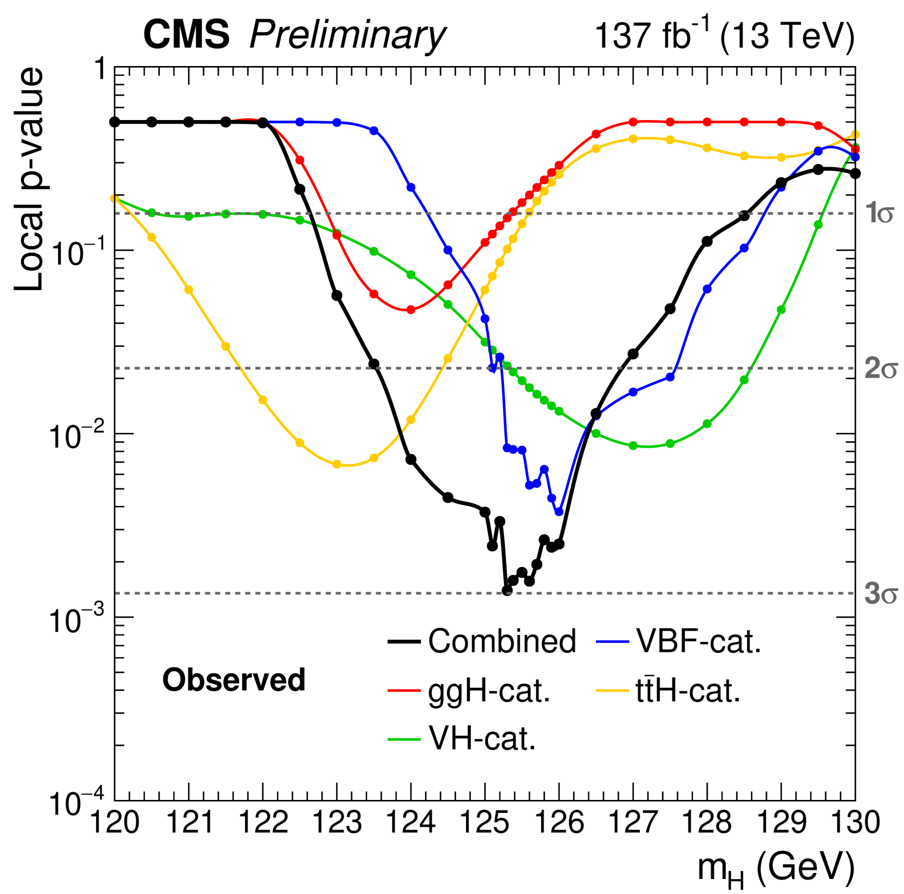
[HIG-19-006](#)

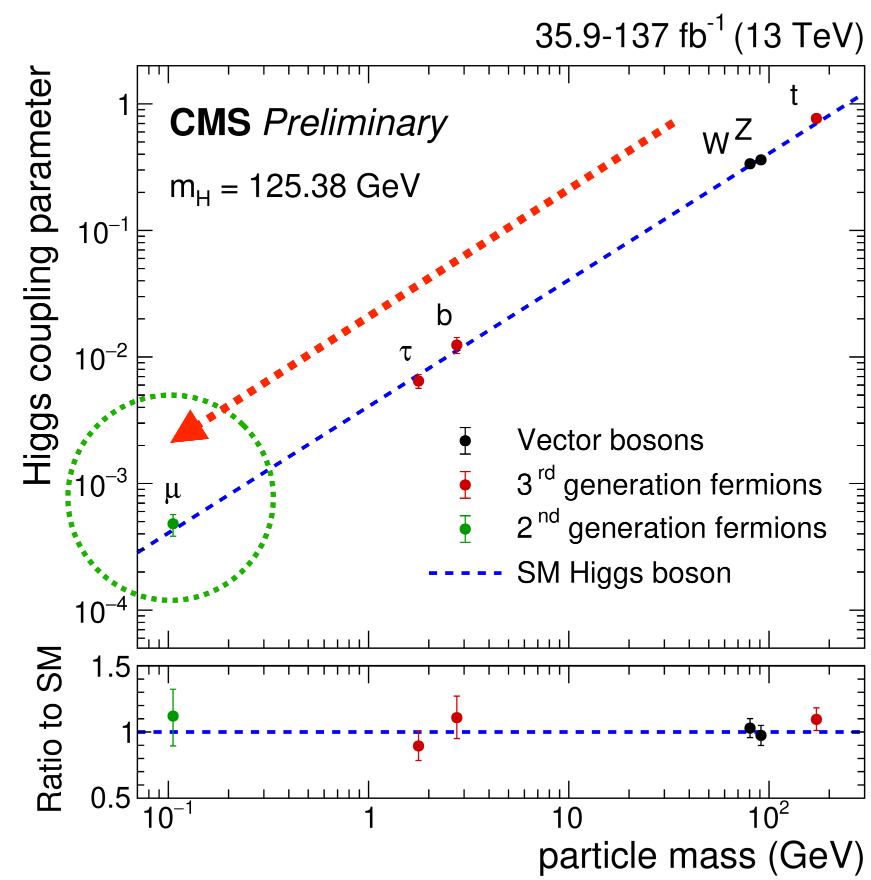


First evidence of Higgs coupling to $\mu\mu$ 3.0σ obs (2.5σ exp)

- Analysis of Run 2 data
  - four components targeting ggH, VBF, VH and ttH
  - highest core section in ggH and VBF modes
  - background suppression due to forward tag jets
  - dedicated analyses for ttH and VH
- Excess localised at 125 GeV: quoted significance for CMS best mass measurement of 125.38 GeV







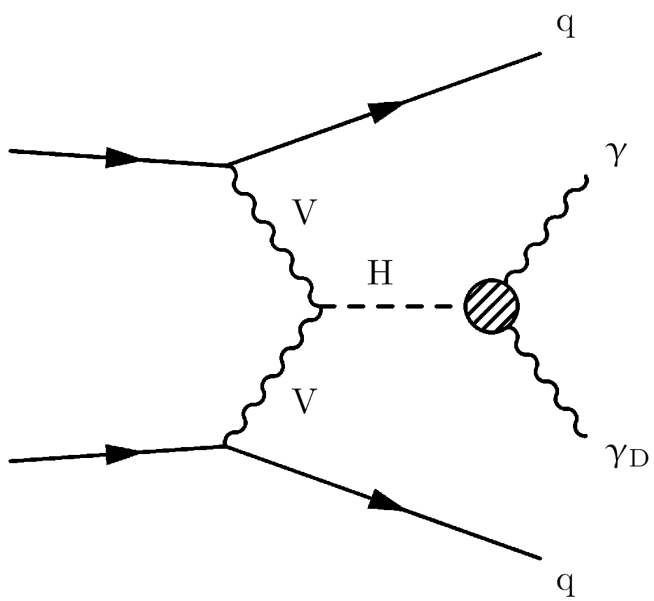
Dark photon in VBF Higgs

- Dark mater at colliders: production of DM particles and mediators, described using simplified models
  - DM particles as missing transverse energy (MET)
  - Trigger on recoiling SM particles: mono-X signature
  - Or long-lived particles,… vector boson fusion (VBF)
- Assume a massless dark photon in undetected leg
  - $\mathcal{B}$(H → γ + inv.) can be as large as 5%
- Signature: 2 VBF jets, isolated high-p_T γ, large MET
- Dominant background: V+jets and V+ γ production
- Signal extraction by fitting M_T(MET, γ)

$$m_{\mathrm{T}} \equiv \sqrt{2 p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\gamma} [1 - \cos(\Delta\phi_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\gamma}})]}$$

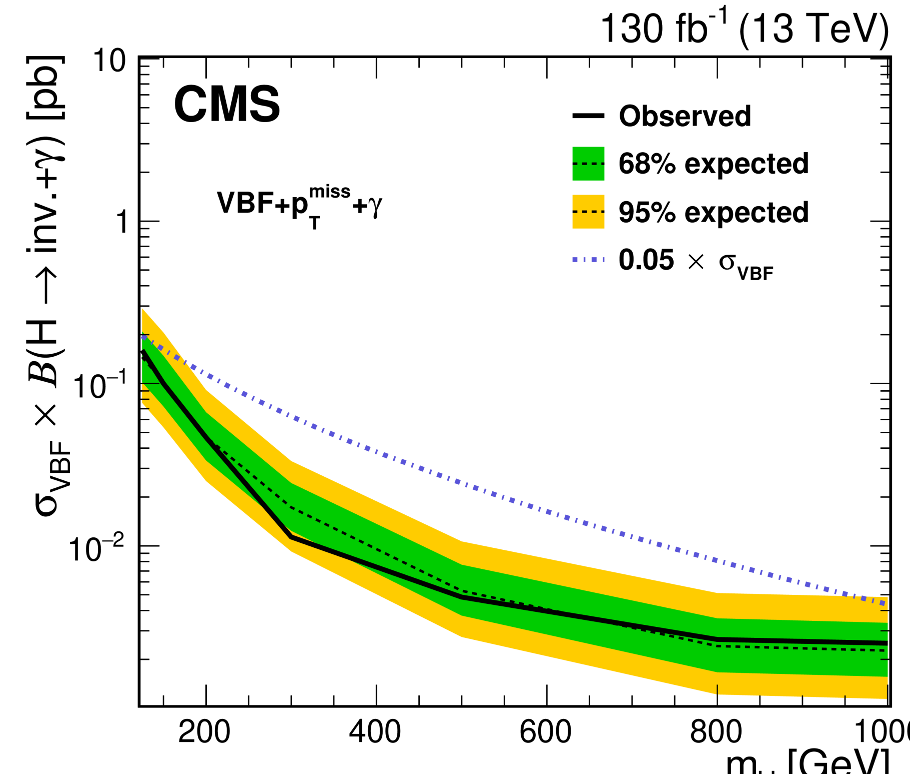
- Dominant postfit uncertainty: data and MC sample size

Using a dedicated VBF+ γ trigger



Limits on $\mathcal{B}$(H → γ + inv.) for combination with ZH (EXO-19-007)

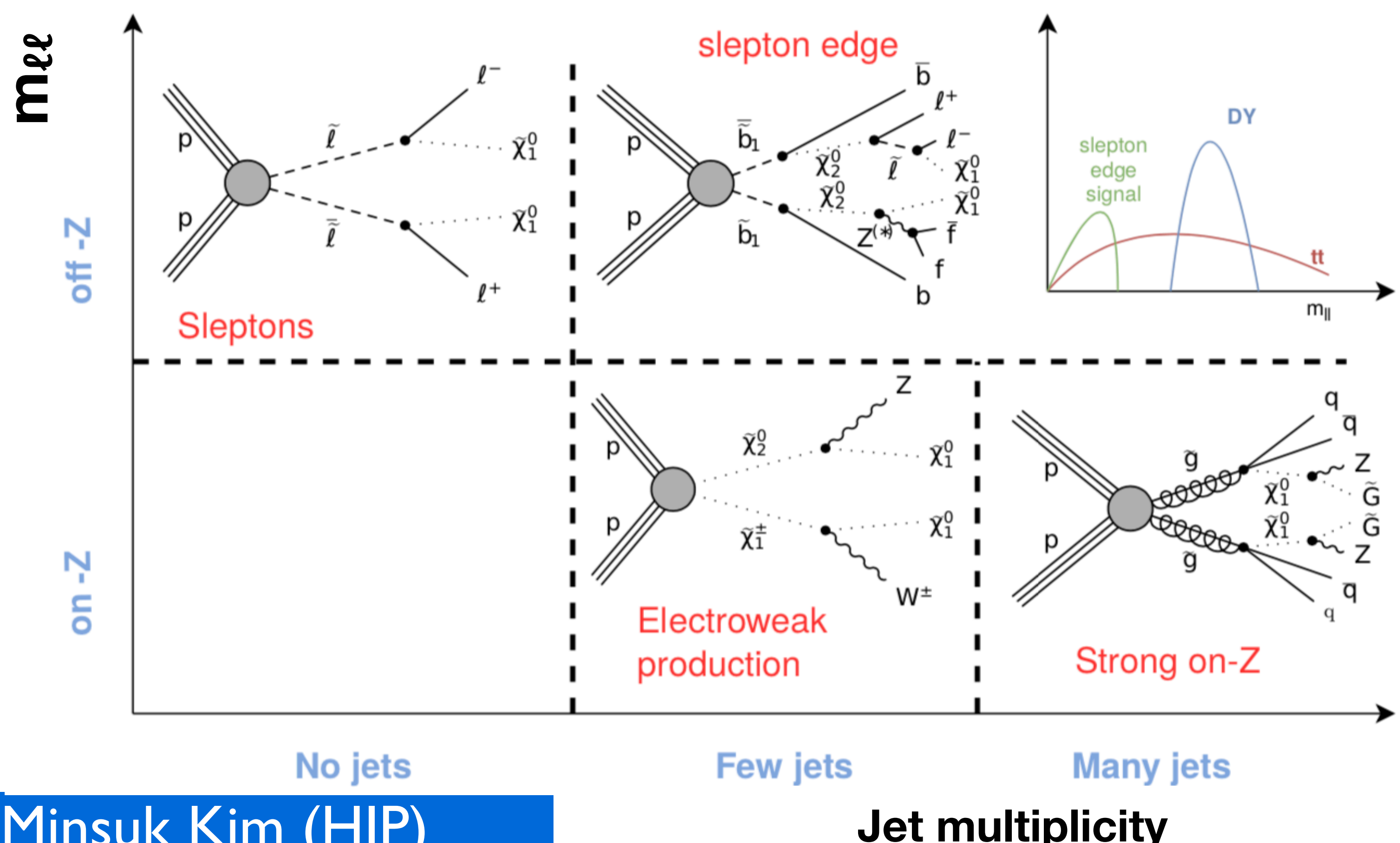
VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.4	$2.7^{+1.2}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+0.9}_{-0.6}$

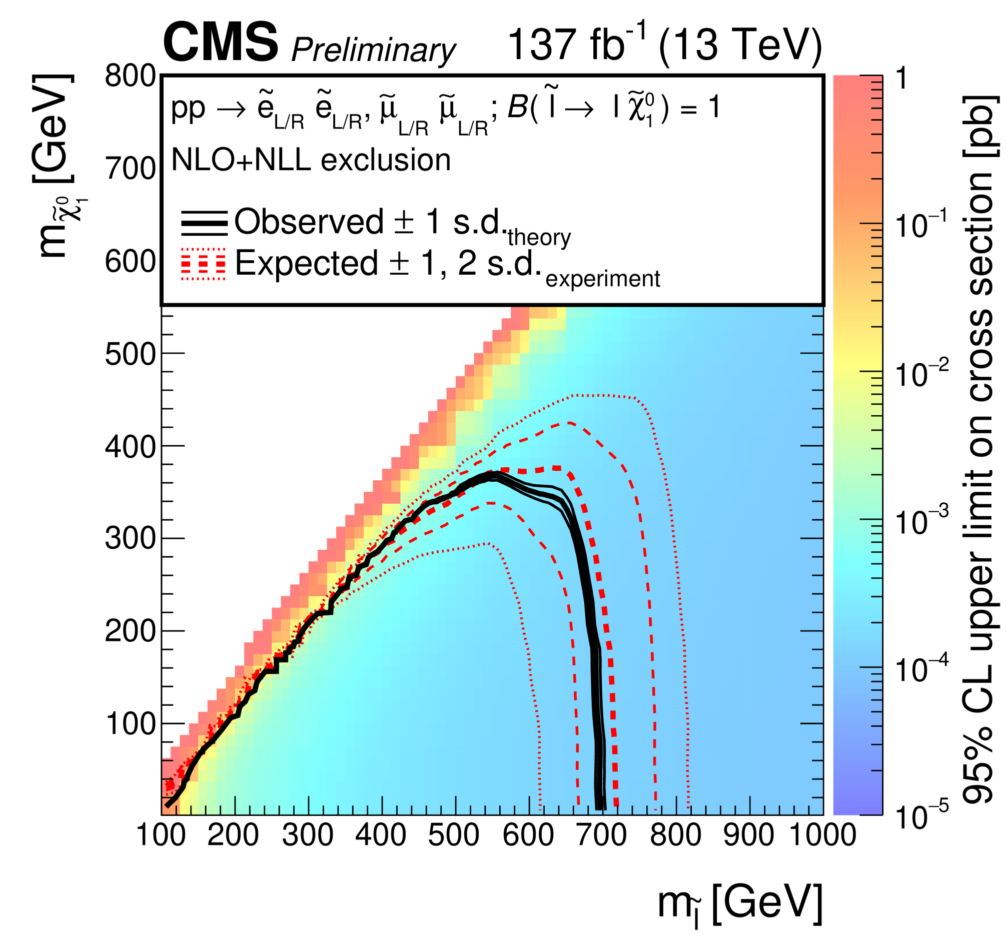


EXO-20-005, arXiv:2009.14009

SUSY with leptons

- Probe both electroweak and strong production with dilepton final states
  - moderate MET requirements to target invisible particles
- Three signal models investigated:
  - resonant dilepton at Z mass, non resonant di-lepton, edge search in m($\ell\ell$)
- Various regions (N_{jets}, $N_{b\text{-}jets}$, etc.) defined to probe different scenarios
- Background estimates: Flavor-symmetric (tt, WW, also w/ τ): estimate in opposite-flavour sideband, apply in same-flavor, and Drell-Yan: model MET from γ+jets (for sleptons, extrapolate from Z peak)
- Neutralino (chargino) masses excluded up to 750 (800) GeV (+100 GeV w.r.t. previous searches)
- Light-flavor (bottom) s-quark excluded up to 1800 (1600) GeV (+300 GeV in bottom)
- Direct slepton production excluded up to 650 GeV (+200 GeV)





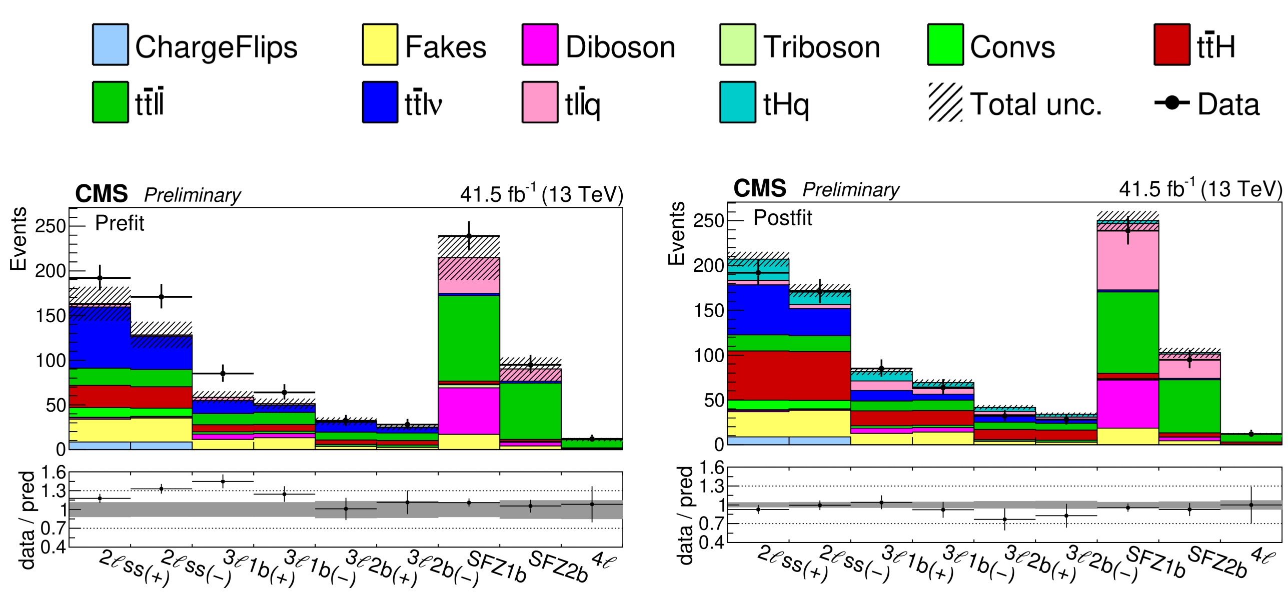
SUS-20-001

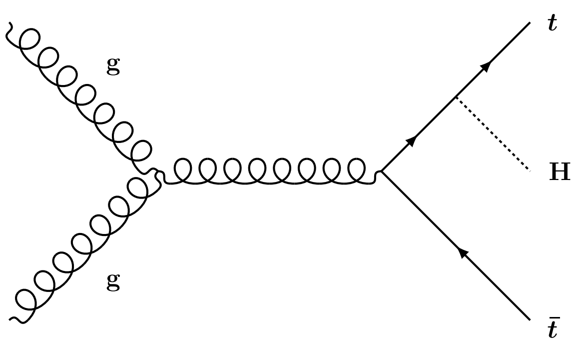
Precision fits in ttbar+X

New approach to derive constraints on 16 Wilson coefficients from analysis of tt+X and t+X production

TOP-19-001

- Search for new physics in top+leptons final states: ttH, ttll, ttlv, tllq, and tHq
- Multiple processes possibly affected by NP studied defining 35 final state categories
- Generic interpretation via EFT fitting 16 dimensions-6 operator coefficients
- Expected yields prefit and postfit:





a SM ttH diagram

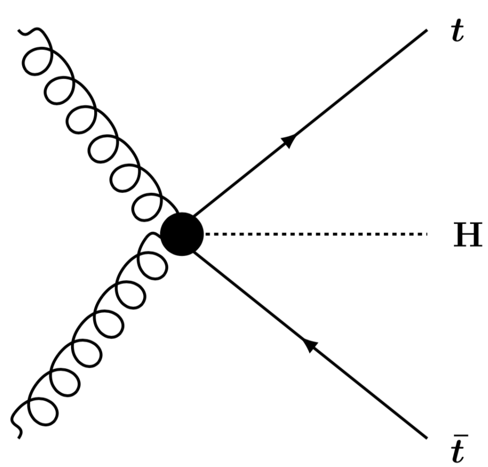
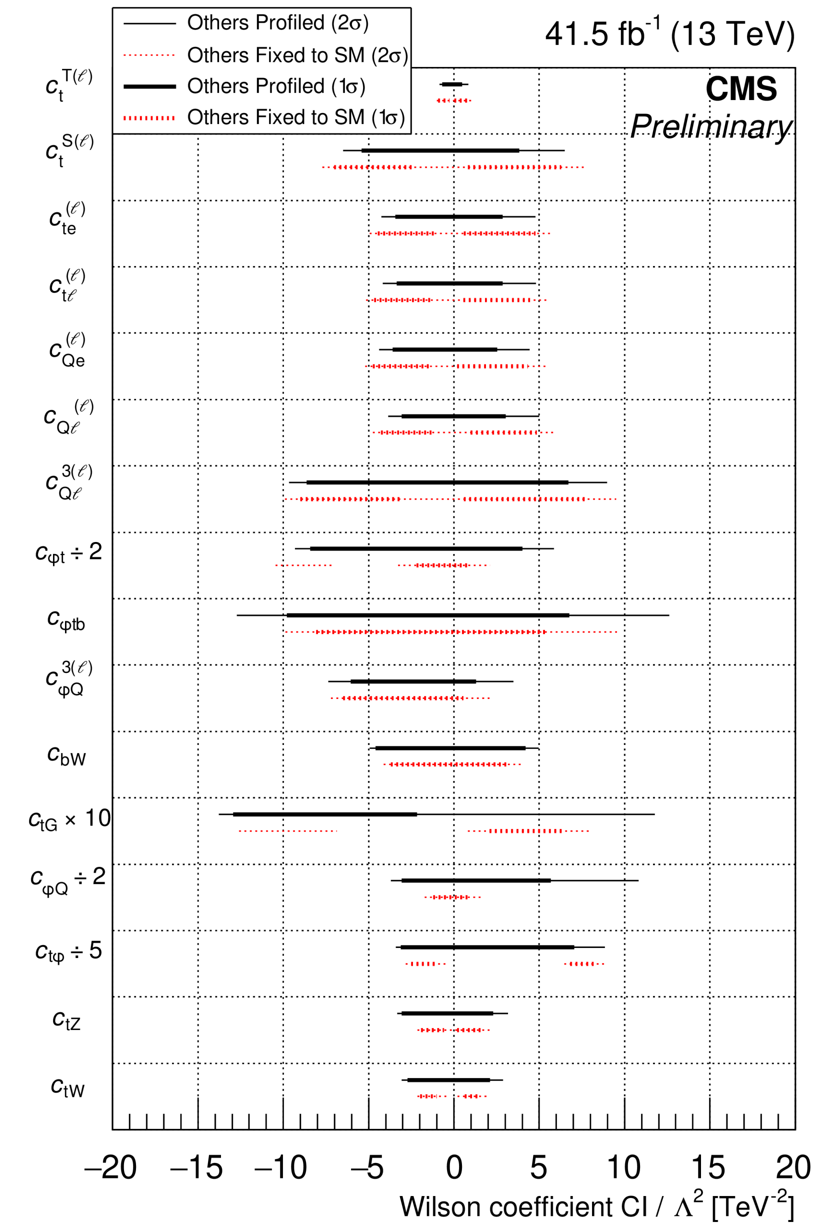
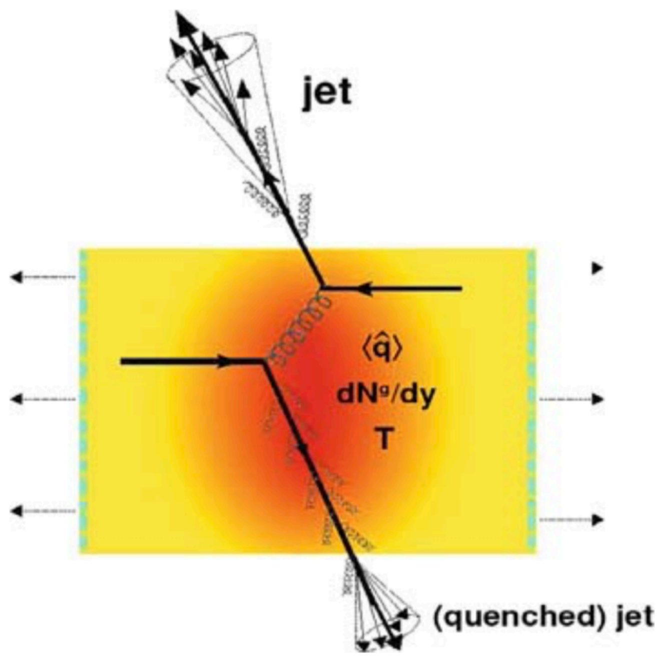


Diagram from a dim-6 operator



Jet structure in Heavy Ions



- Study of in-medium modification of jets structure in di-jets events in *PbPb* collisions (HIN-19-013)

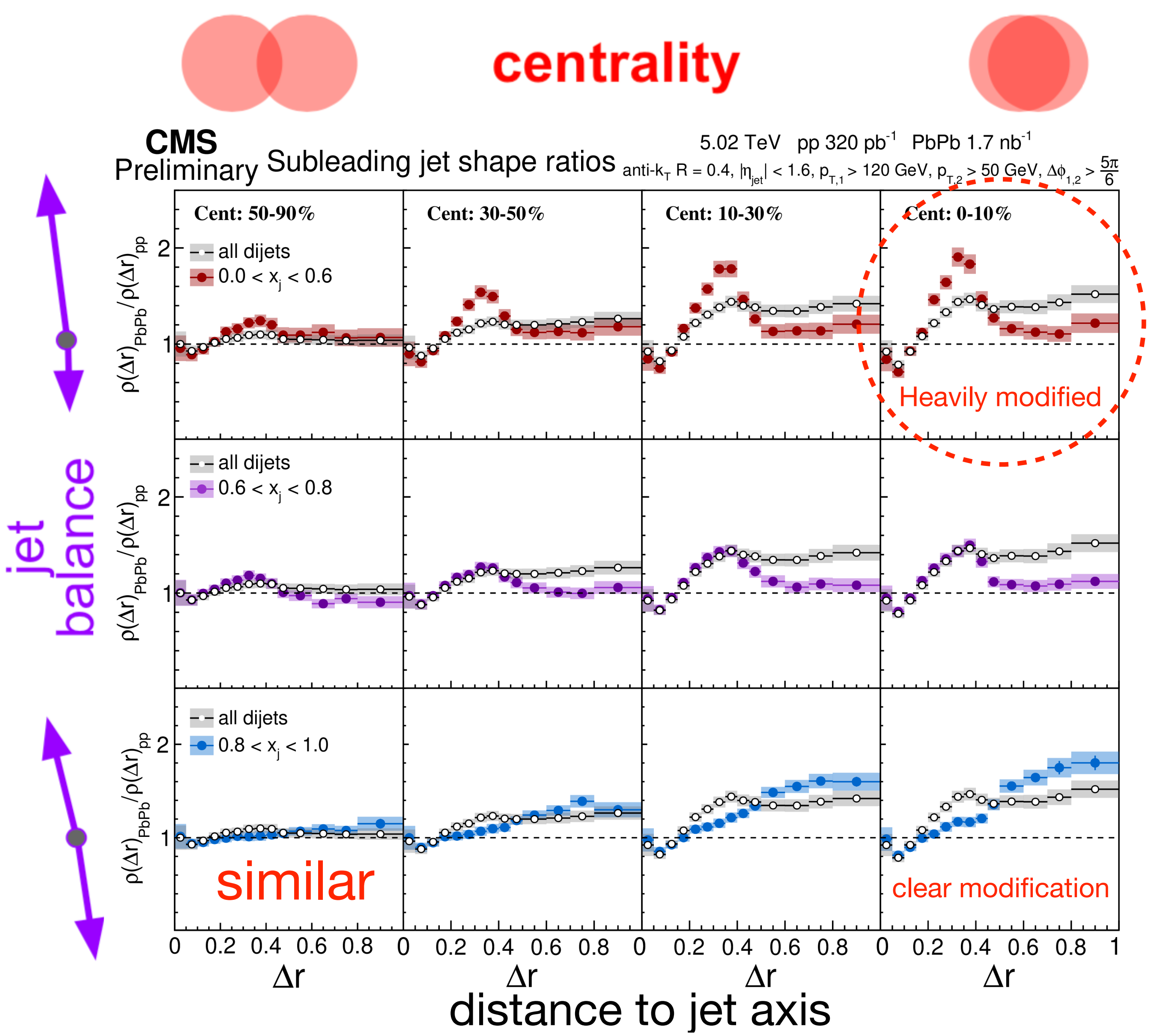
➔ measure correlations of charged particle

➔ determine jet momentum density profiles (jet shapes)

Jet quenching: one goes out directly to vacuum, the other goes through plasma formed in collision

- We compare *PbPb* and *pp* collision results
- Triple differential measurements in dijet selections: balance, centrality, distance
- Migration of jet constituents to wider angle while crossing the medium
- Different behaviour of lead vs. sublead jet when event is balanced vs. unbalanced

Subleading jet shape ratio (lead jet in backup)



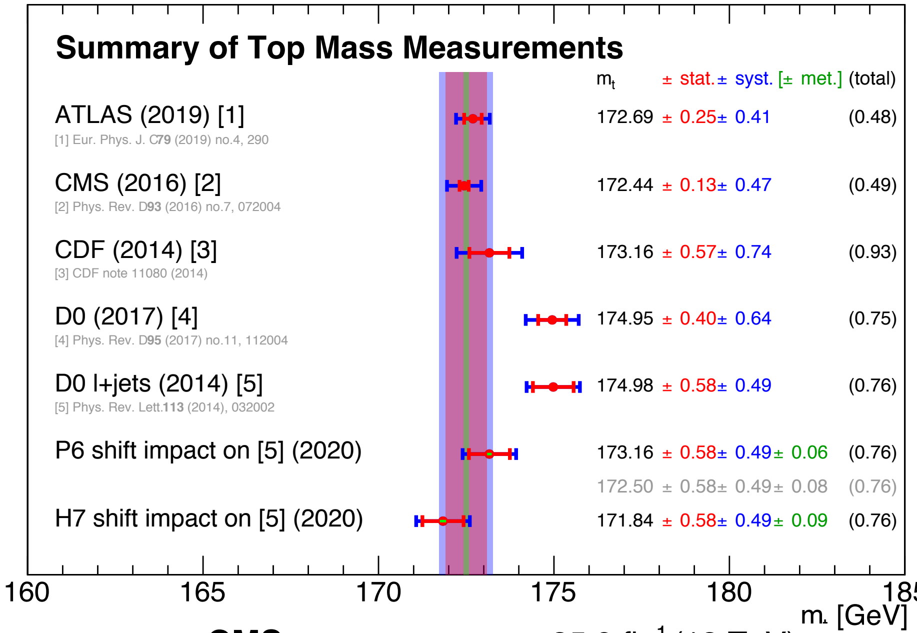
Modification more pronounced to the subleading jet for event with a larger imbalance

CMS@Helsinki

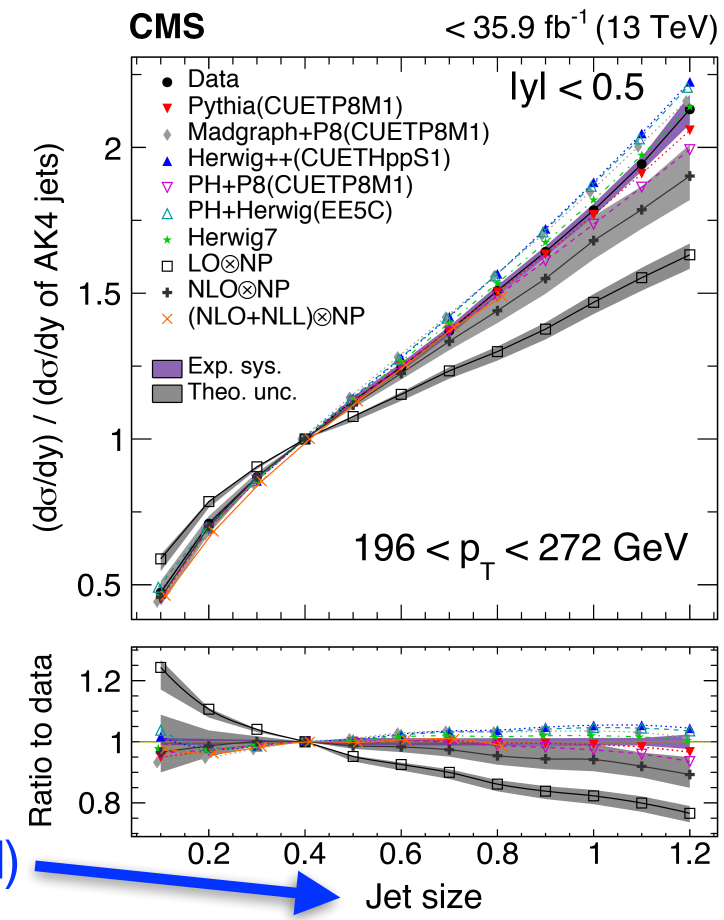
We support jets for the whole CMS physics programme

- VBS measurement in all-hadronic channel
  - Improve performance of the tag jets
  - Polarization tagging of hadronically decaying W/Z
  - Apply ML techniques in particle-level JEC
- Precision measurement of top mass in l+jets channel with updated jet energy correction
  - Recalibrated JECs impact on the reconstructed top quarks using the jets ➔ reduce uncertainty
  - Recalibrate flavor-dependent JECs in a D0 top mass measurement ➔ impact on the world average
- Precision measurements of strong coupling & PDFs
  - Dependence of inclusive jet production on radius R

Different R: 0.2(ALICE) 0.4(CMS/ATLAS) 0.6-0.7(QCD) 0.8-1.2(boosted)



TOP2020, arXiv:2002.06073

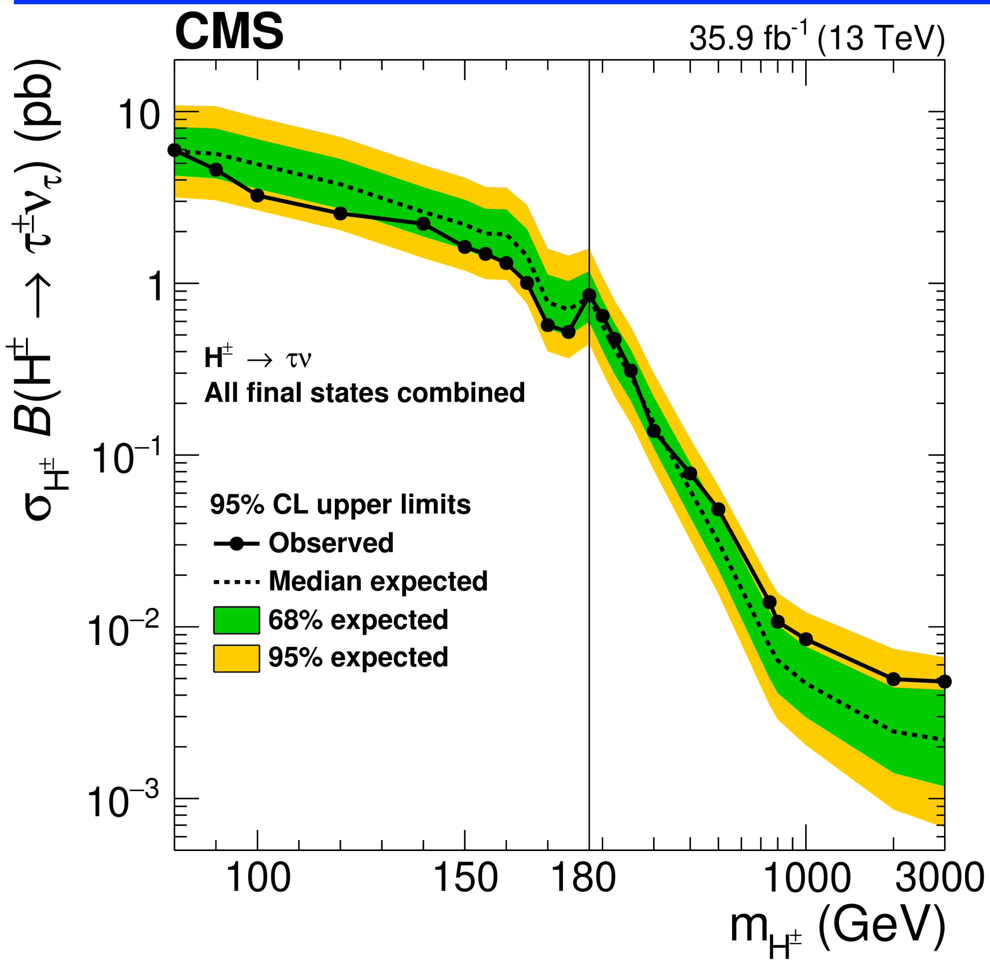


SMP-19-003

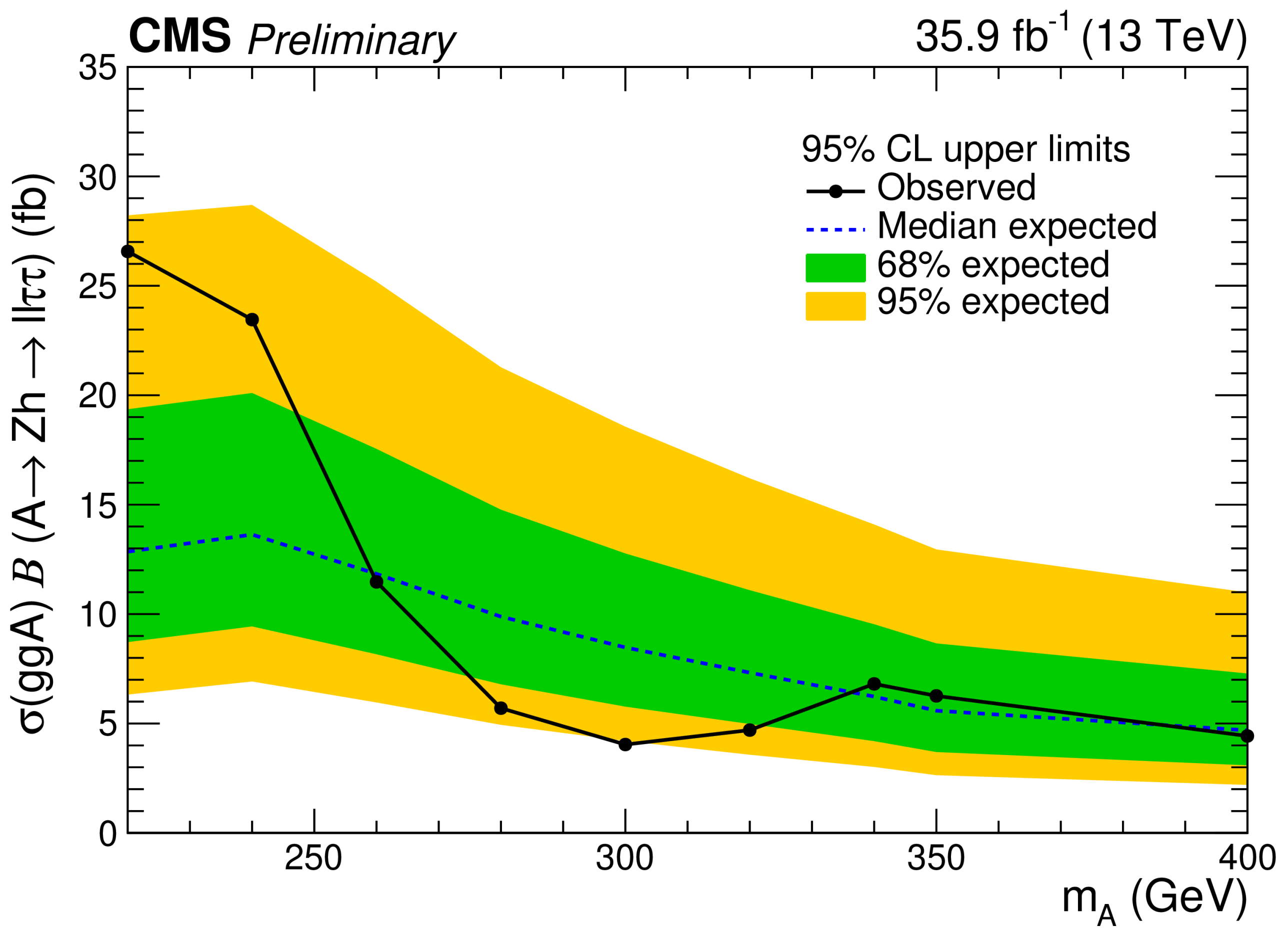
New Physics Searches@Helsinki

- **Charged Higgs bosons**
  - Additional Higgs bosons predicted in many BSM models
  - Publication on 2016 data, $H^+ > \tau\nu$ on-going with full Run2
  - New search in WH channel more sensitive to type-I models
- **Neutral Higgs bosons**
  - $A \rightarrow ZH \rightarrow 2l2\tau$ channel with CERN and Wisconsin
  - Expected sensitivity +40% compared to Run 1 methods
  - Public results on 2016 data
- **SUSY**
  - Gluino pair to tttt with Athens, CERN, DESY, FNAL
  - Most sensitive single lepton channel, advanced ML
  - On-going with full Run2 data

Search for H±: JHEP 07 (2019) 142

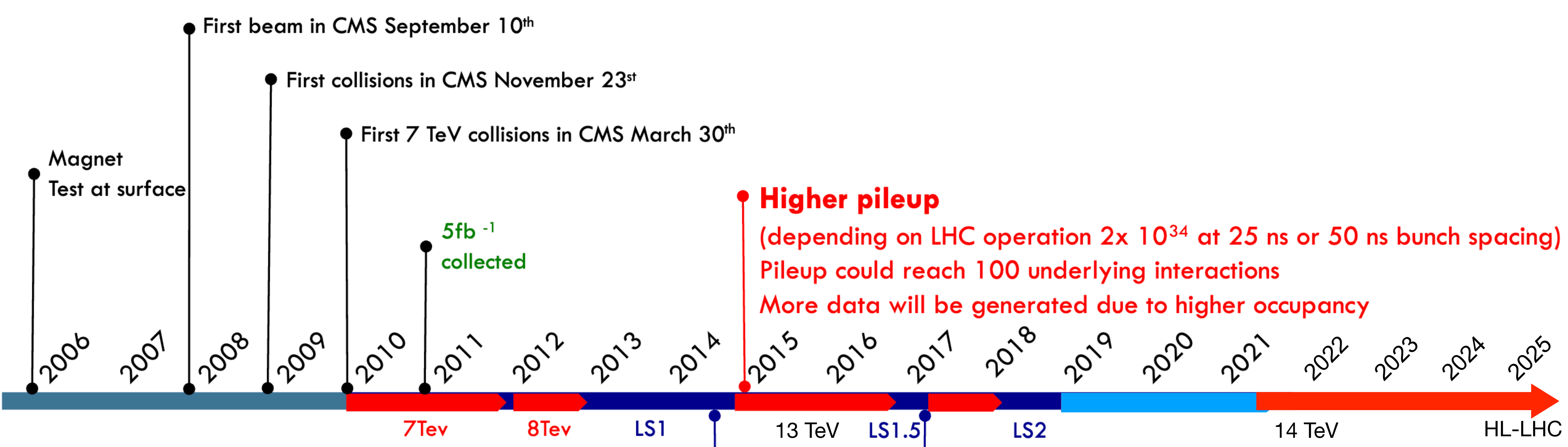


Search for A: JHEP 03 (2020) 065



Summary and outlook

- No new physics observed so far, but we are exploring the unknown
  - Have delivered about 5% of total expected integrated luminosity for HL-LHC
- We are active in several different areas
  - Analysis, development of new techniques, Run 3 preparation, HL-LHC upgrade
- Run 3 and HL-LHC will not come for free
  - Towards continuous innovation in experimental techniques



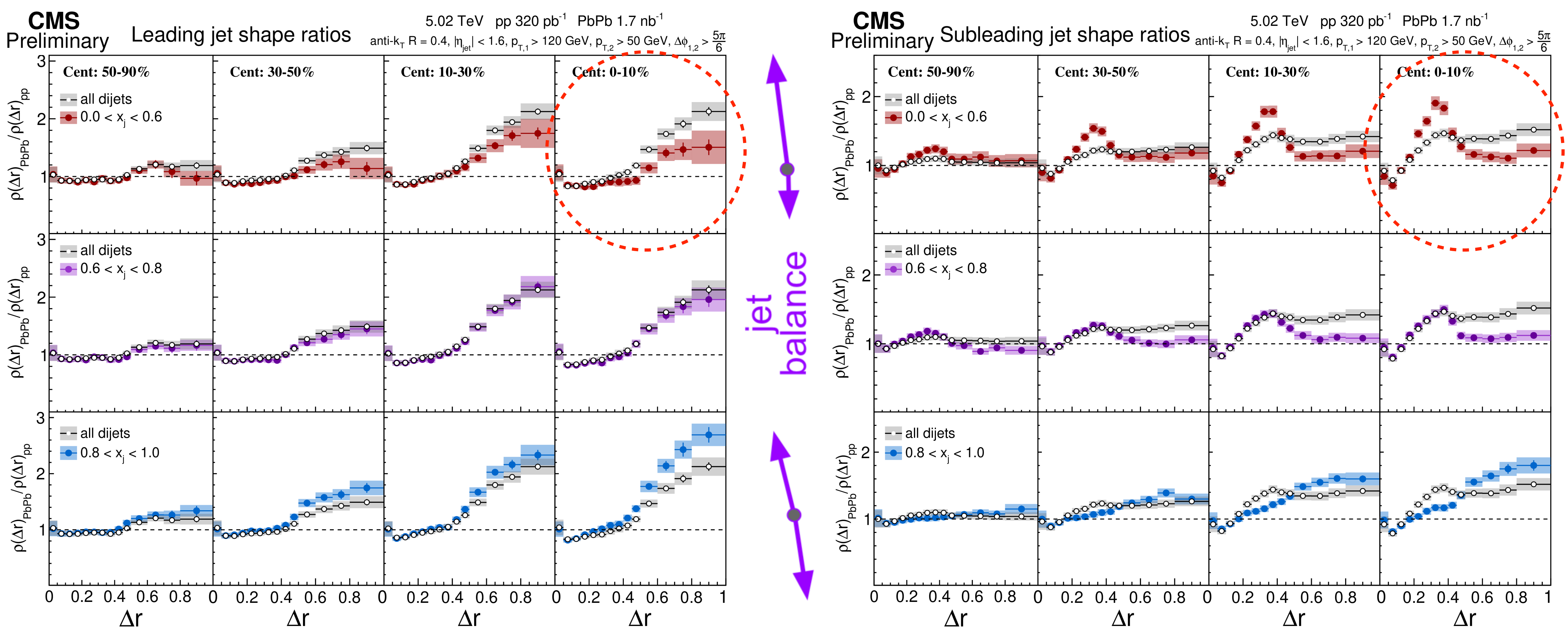
Bakcup

Jet shape ratios

Leading jet

Subleading jet

centrality



distance to jet axis

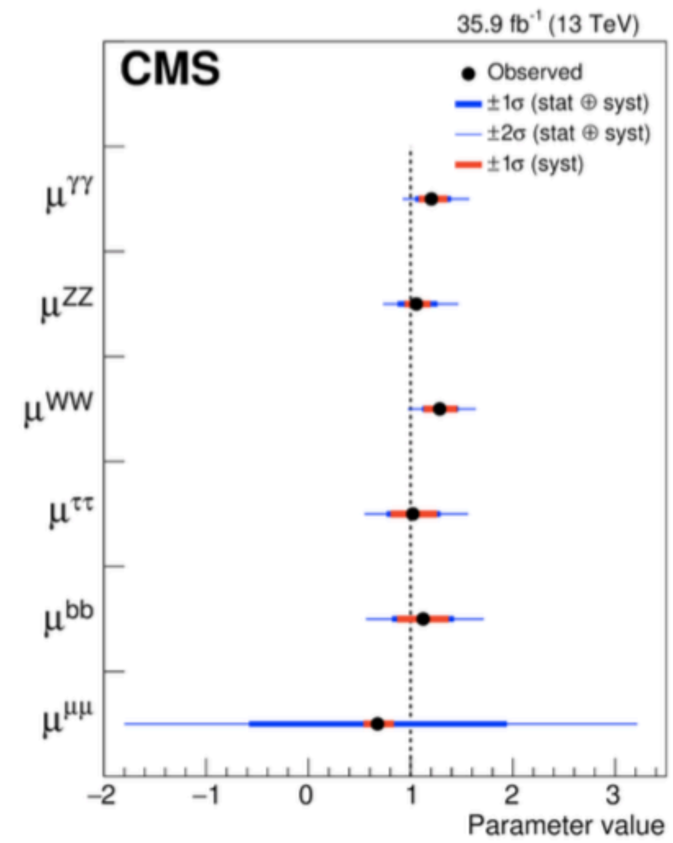
Higgs couplings to fermions

LHC Run 2 data gave us direct access to H couplings to 3rd generation fermions

- decays to tau leptons (PLB 779 (2018) 283, first observation by a single experiment, summer '17)
- associated production with top quarks (PRL 120 (2018) 231801, spring '18)
- decays to bottom quarks (PRL 121 (2018) 121801, summer '18)

The next challenge is to establish couplings to the 2nd generation

- currently best 95% CL limit on **σ**(VH)xB(H→cc): 70 (expected: 37) x SM (JHEP 03 (2020) 131, winter '19)
- decays to muons: status before ICHEP 2020
  - CMS: < 2.9 x SM @ 95% CL (2016 + Run 1, PRL 122 (2019) 021801)
  - ATLAS: signal strength μ = 1.2 ± 0.6 (Run 2, arXiv::2007.07830)

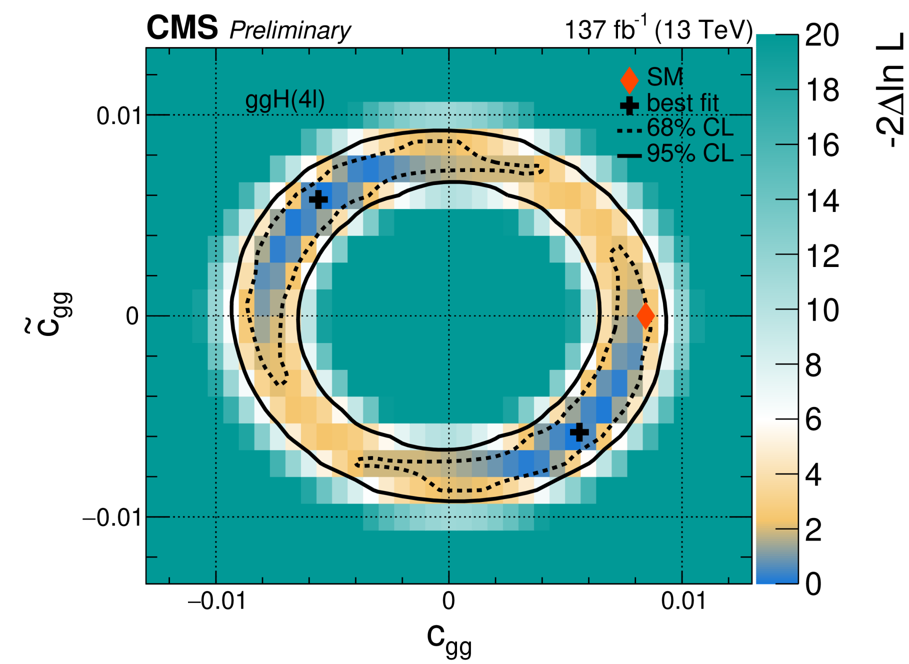


signal strength modifiers per decay mode from HIG-17-031

More precision in H properties

Multiple results for Higgs characterization:

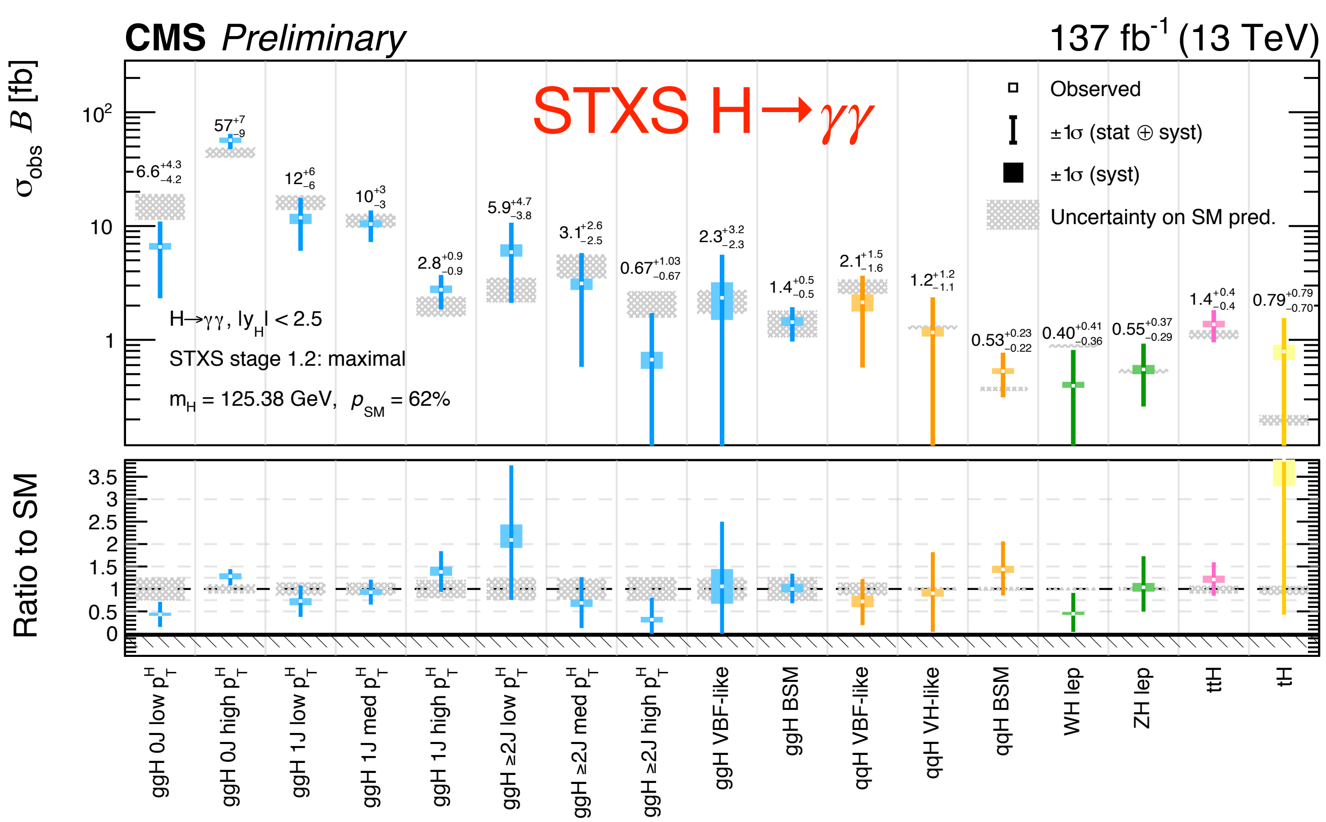
- STXS differential measurement in H→$\gamma\gamma$ (and H→$\tau\tau$)
- CP violation in H→$\tau\tau$
  - measure angular correlation in decay planes (μh vs hh)
  - mixing angle between CP-even (SM) and CP-odd τ Yukawa couplings 4±17 degree obs (±23 exp)
  - 3.2σ (2.3σ) exclusion of pure CP-odd
- Anomalous coupling with EFT interpretation in H→4L
- tH and ttH measurements in multi-lepton channel



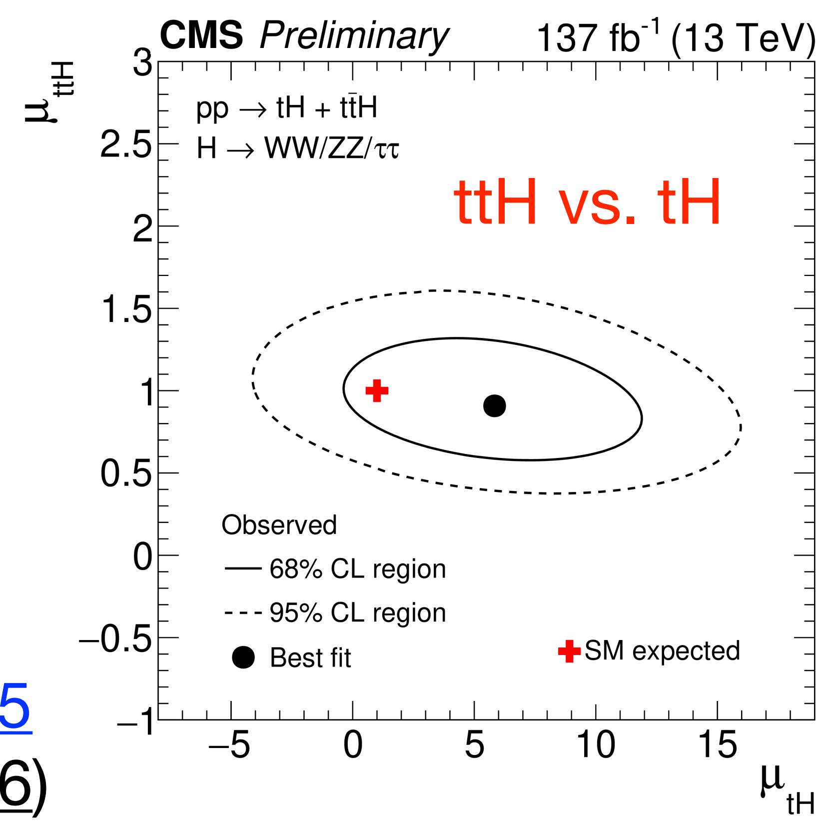
Constrains on anomalous couplings to gluons

TOP-19-009

Observed results of the maximal merging scheme STXS fit



TOP-19-015
(TOP-20-006)



2D of likelihood function vs. production rates

TOP-19-008

HIG-19-015 (Fig. 1)

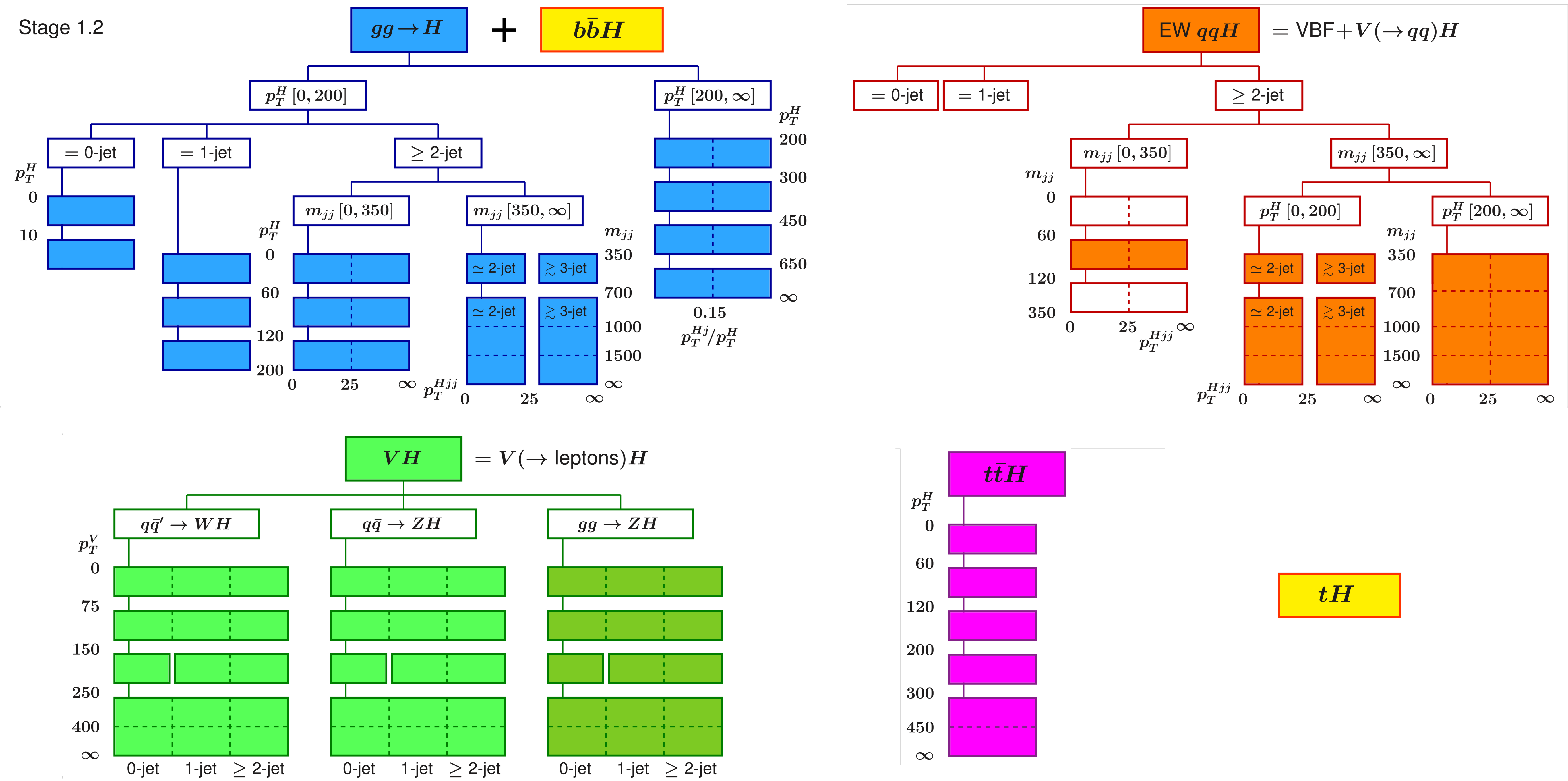
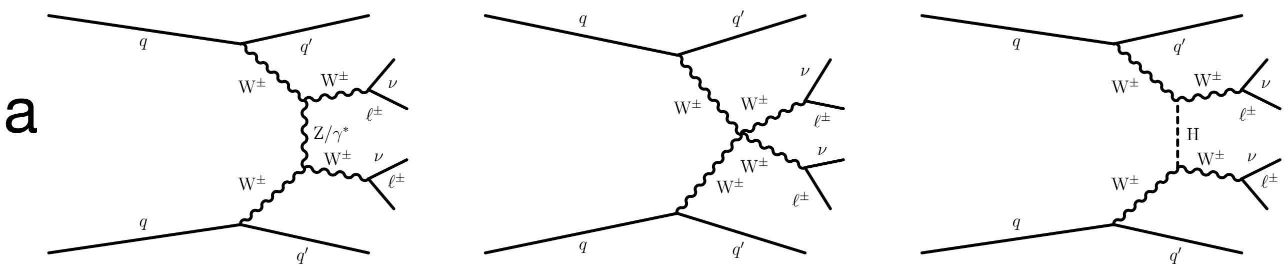


Diagram showing the full set of STXS stage 1.2 bins, adapted from Reference:
LHC Higgs Cross section WG: "Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector" doi:10.23731/CYRM-2017-002, arXiv:1610.07922

Polarized WW in VBS

First measurements! SMP-20-006



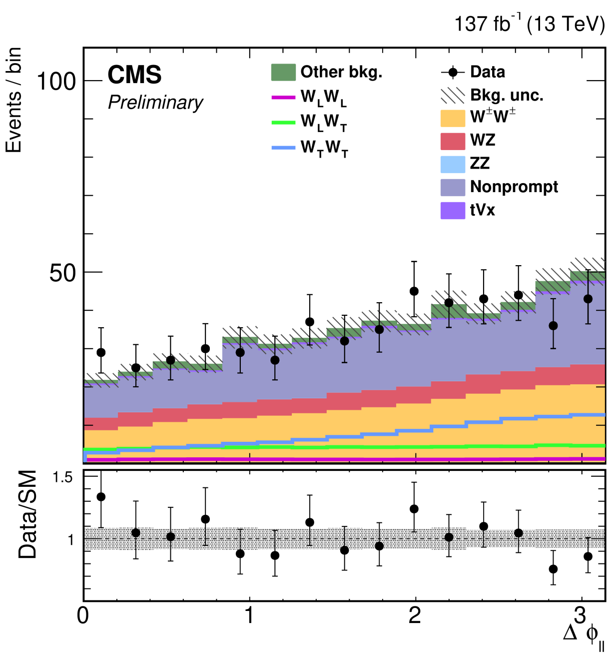
- Longitudinally polarized WW production is a probe for symmetry breaking mechanism
- Multiple angular variables combined to distinguish the polarisations

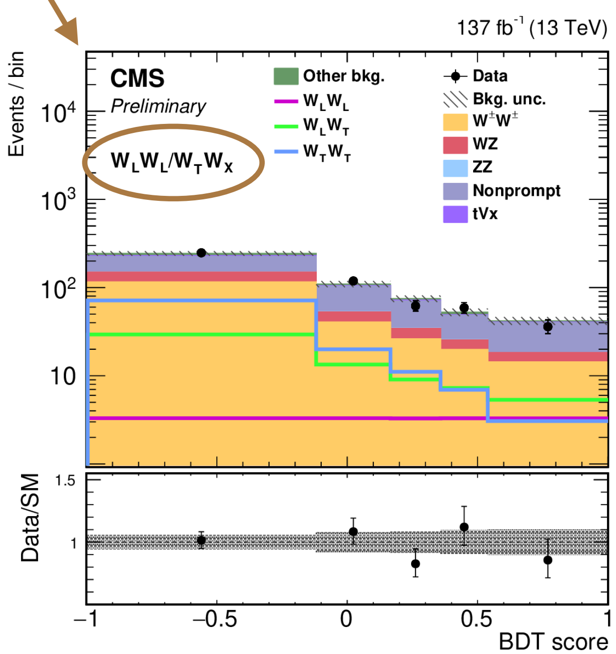
L+L vs T+any or **L+any vs T+T**

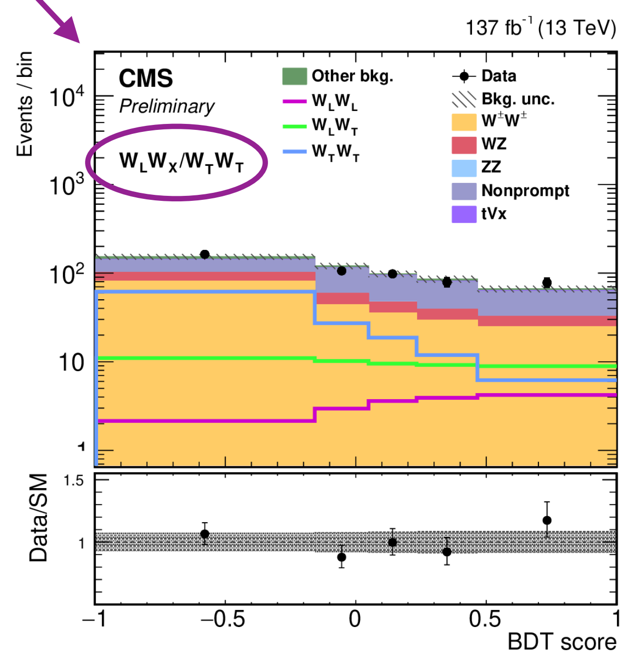
- EWK production of at least one longitudinally polarised W measured with significance of 2.3σ obs (3.1σ exp)

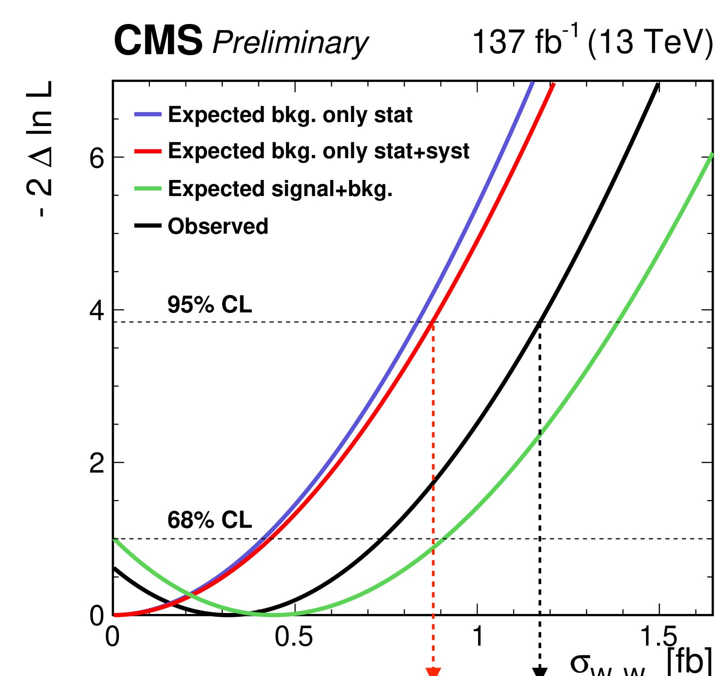
Fiducial x-sec in $W^\pm W^\pm$ centre-of-mass frame

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









Limit: 0.88 (exp) 1.17 (obs)

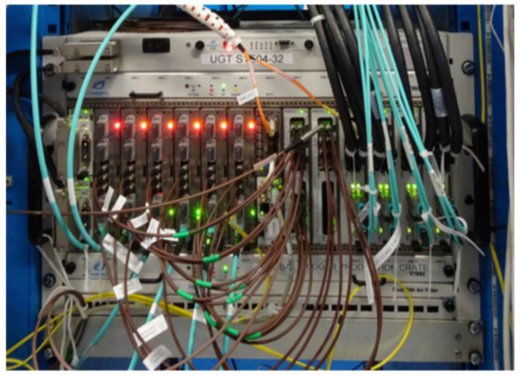
CMS Phase-1 Upgrades

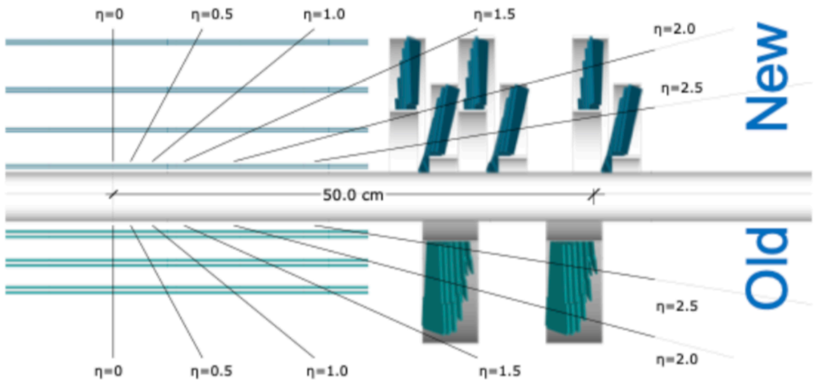
Many Phase 1 upgrades were installed for Run 2

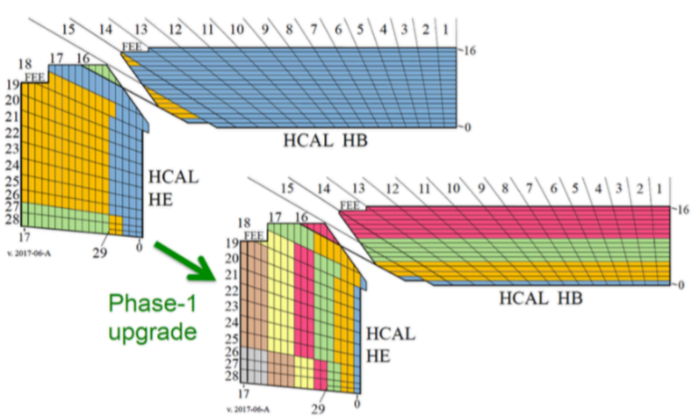
- The Muon Upgrade, **CSCs and RPCs**, was completed during LS1 2013/14
- The **Drift tubes trigger** upgrade done in YETS 2015/16
- **The L1 Trigger μTCA** based upgrade was installed in 2015 and used starting in 2016
- The **Hadron forward calorimeter** readout upgrade was started in LS1, completed in the EYETS 2016/17, and ran successfully in 2017
- **The new Pixel detector** was installed in the EYETS 2016/17
- The **Drift tube readout upgrade** was done during YETS 2017/18 and took data smoothly
- **Hadron endcap calorimeter** front-end electronics and photosensors were upgraded in YETS 2017/18 and ran smoothly in 2018

Hadron Barrel (HB) calorimeter front-end electronics and photosensors upgrades were the last of the Phase-1 installations

HB installation finished at the end of October 2019







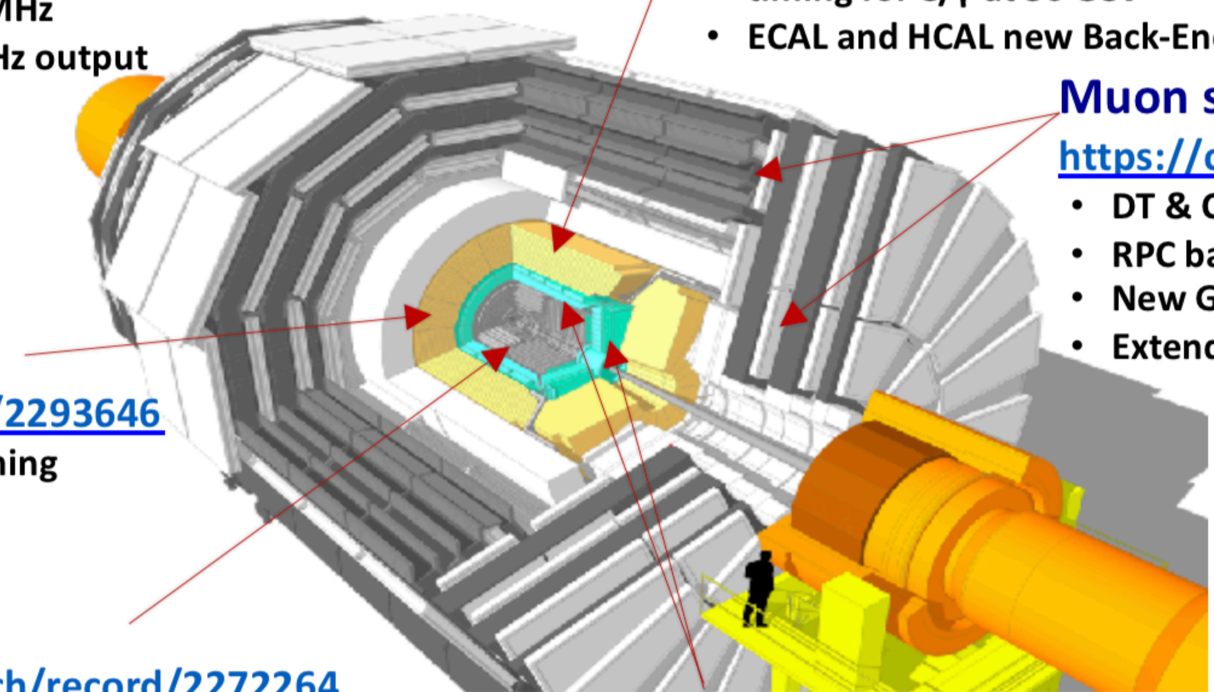
CMS HL-LHC Upgrade

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/002706512

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

New paradigms (design/tech) for an HEP experiment to fully exploit HL-LHC luminosity