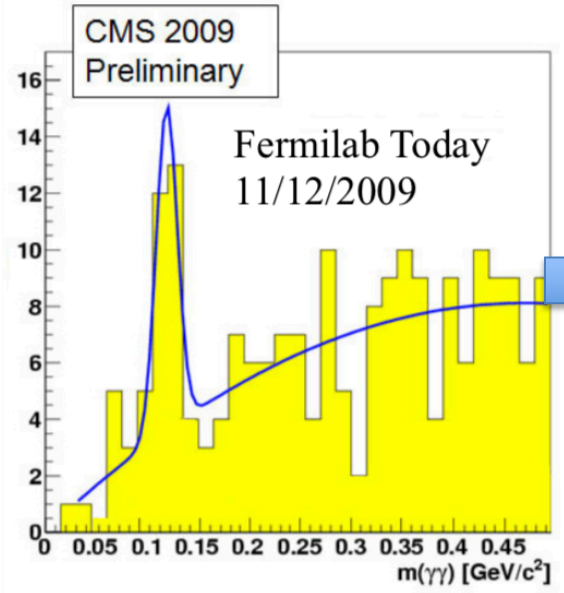
Overview of CMS results from last year: detector performance and physics highlights

Zhen Hu for the CMS Collaboration

The 12th International Workshop on Top Quark Physics

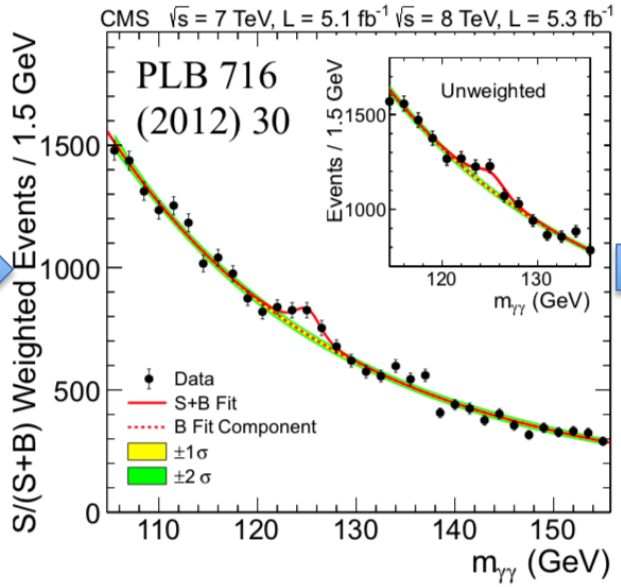
清華大學
Tsinghua University

CMS Ten Years (2009 - 2019)

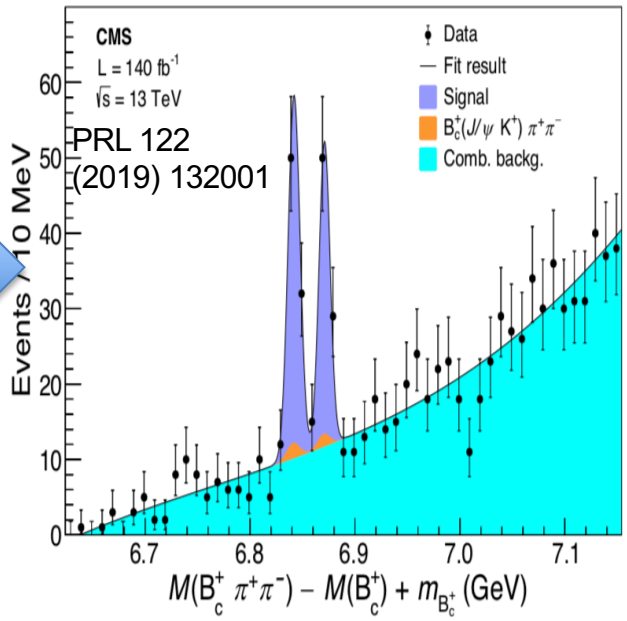


First pions from pp collisions

http://www.fnal.gov/pub/today/archive/archive_2009/today09-12-11.html



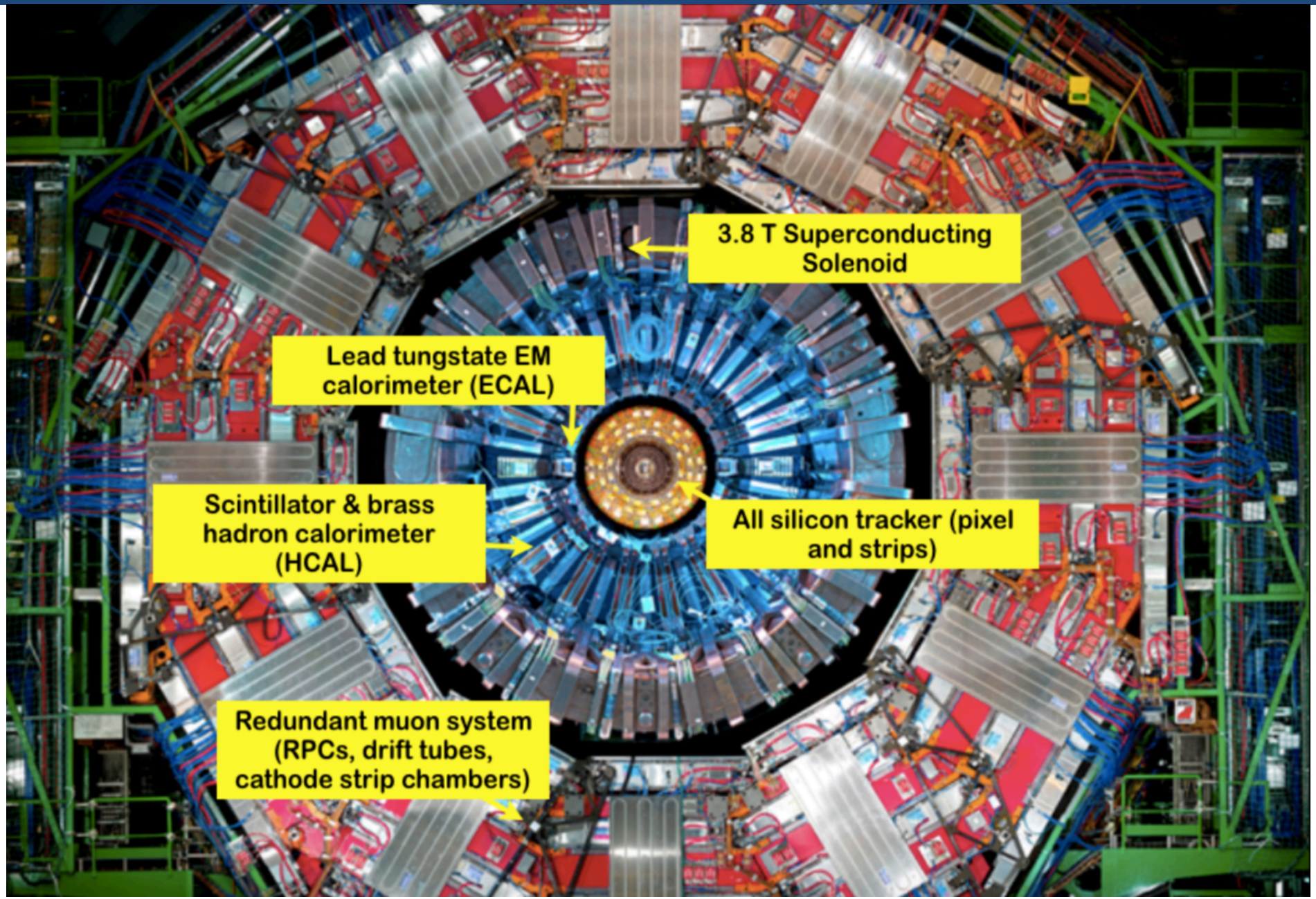
Discovery of Higgs boson



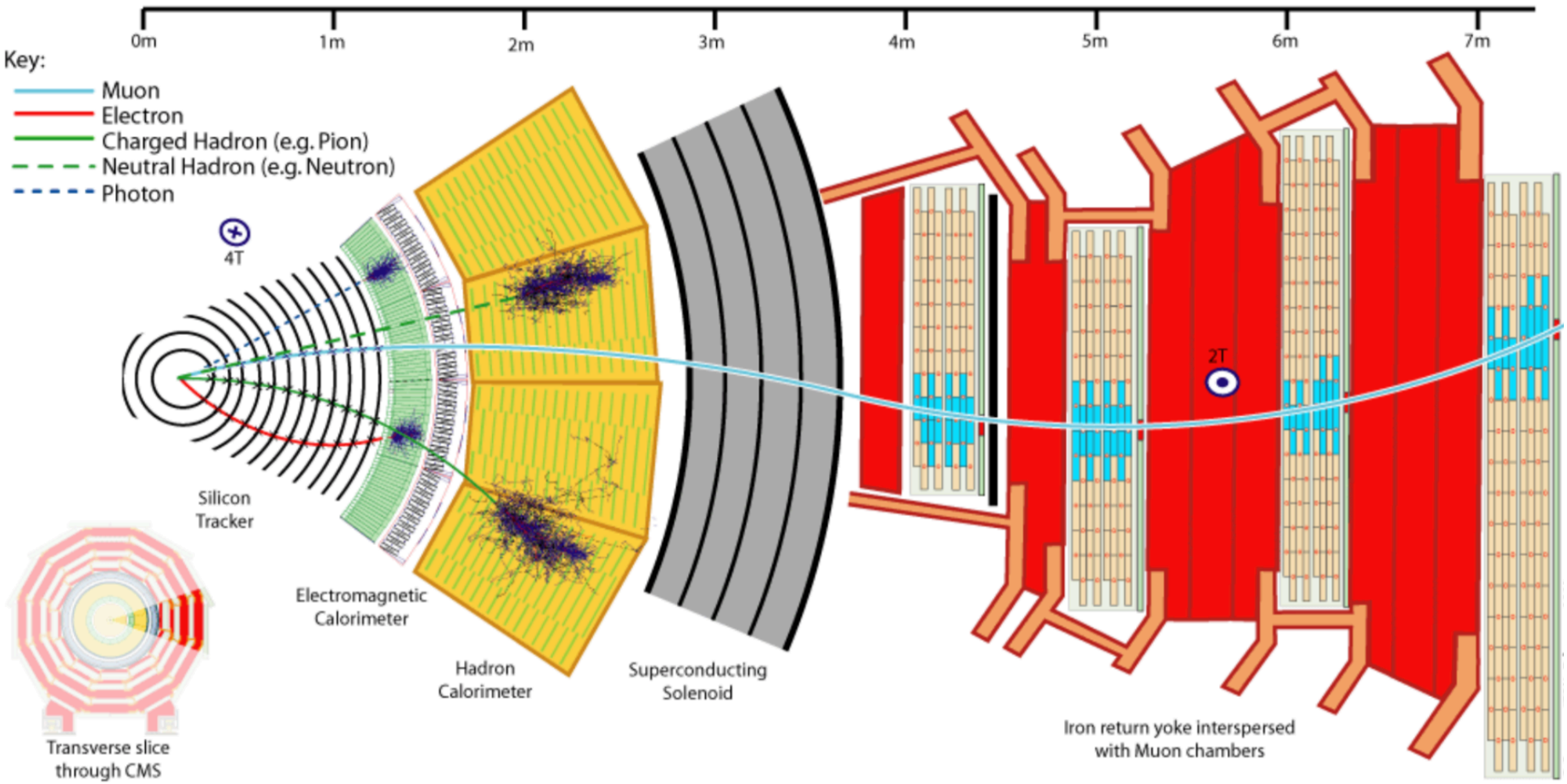
First LHC paper with the full Run 2 data by CMS

Many discoveries and important measurements in ten years

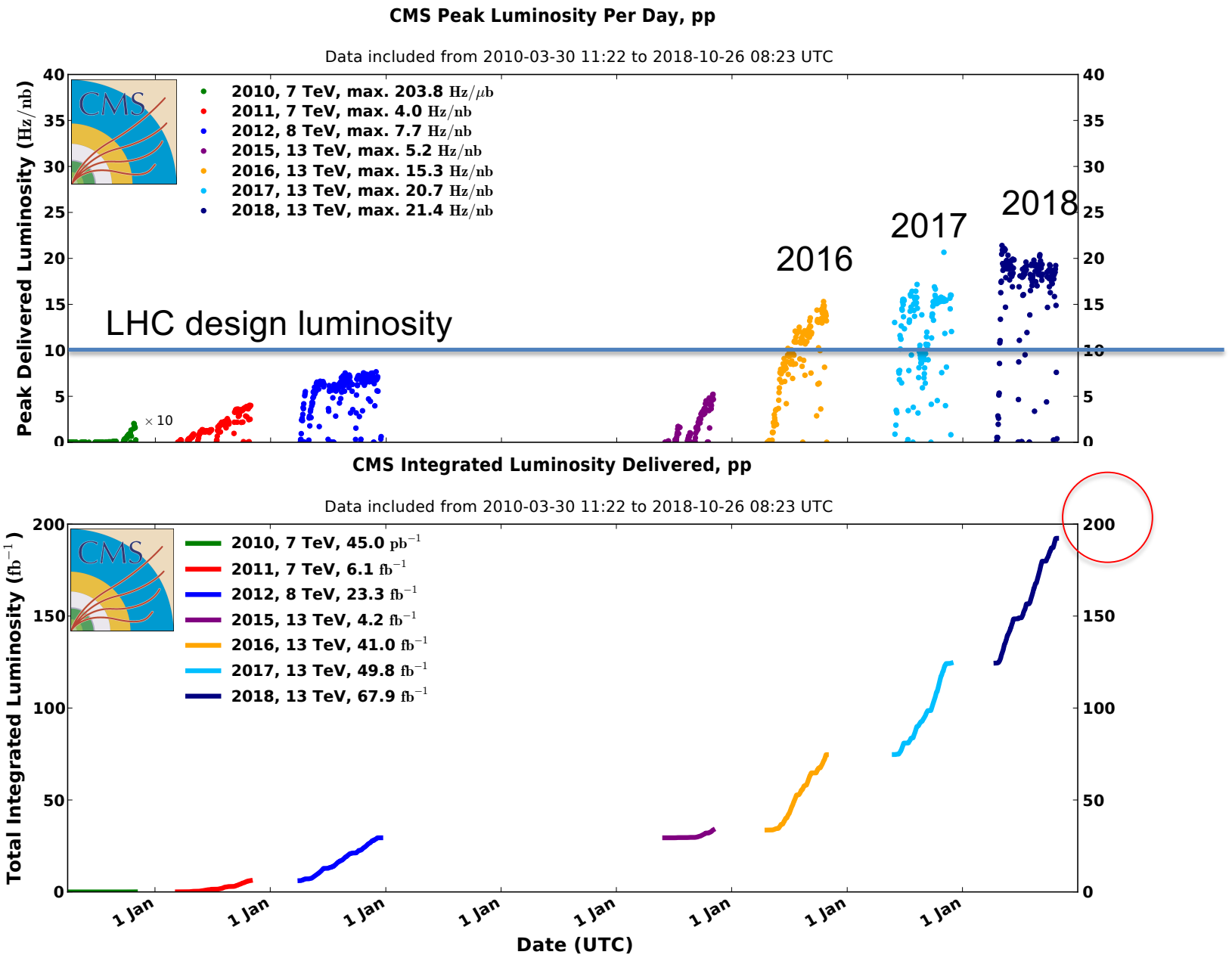
The CMS Detector



How CMS detect particles

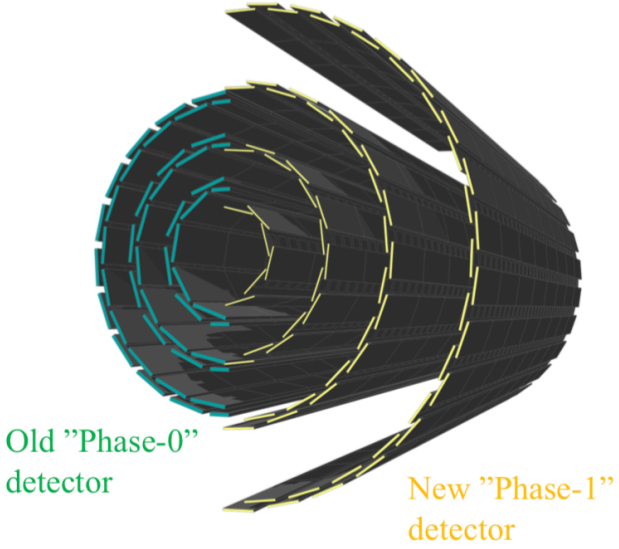


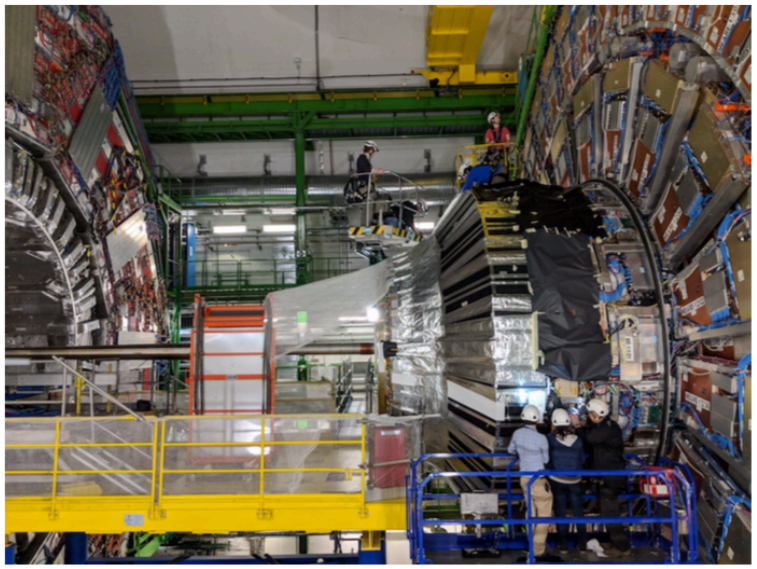
The LHC is pushing the limit



CMS upgrades during Run-2

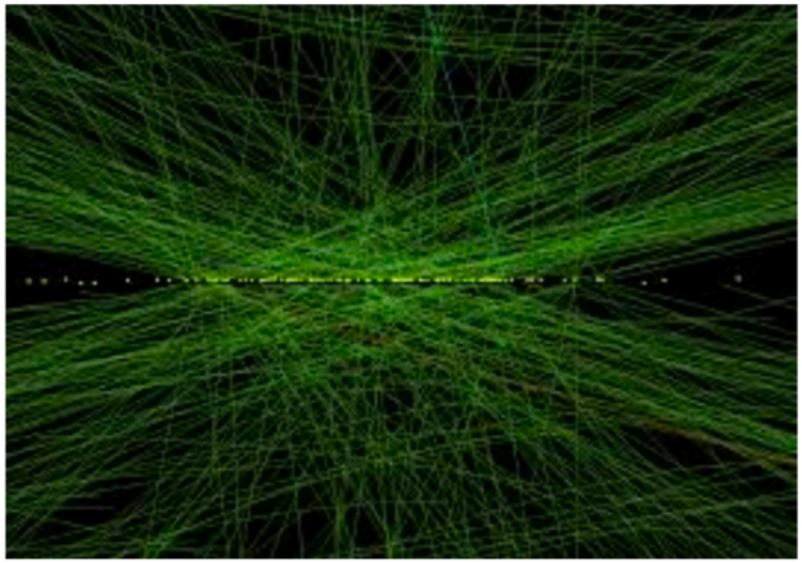
- Worked extremely well
- Evolved in the past years (Phase-1 upgrade) keeping the characteristic innovativeness
- CMS has upgraded several subsystems during Run-2
  - New μTCA-based L1 trigger (Winter 2016)
  - Pixel detector – new detector (Winter 2017)
  - Very-forward calorimeter electronics (Winter 2017)
  - Hadron endcap calorimeter electronics (Winter 2018)
  - Hadron barrel calorimeter electronics (2019)

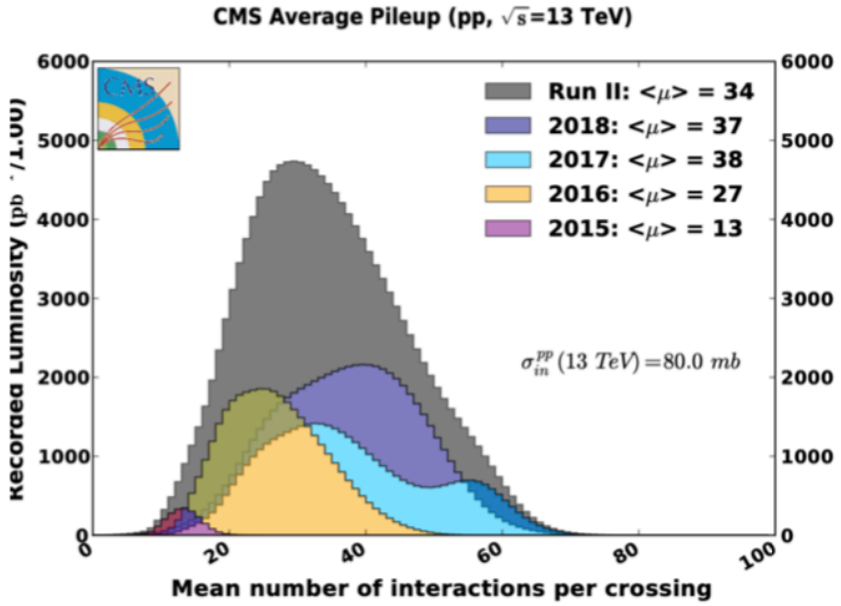




CMS data in Run-2

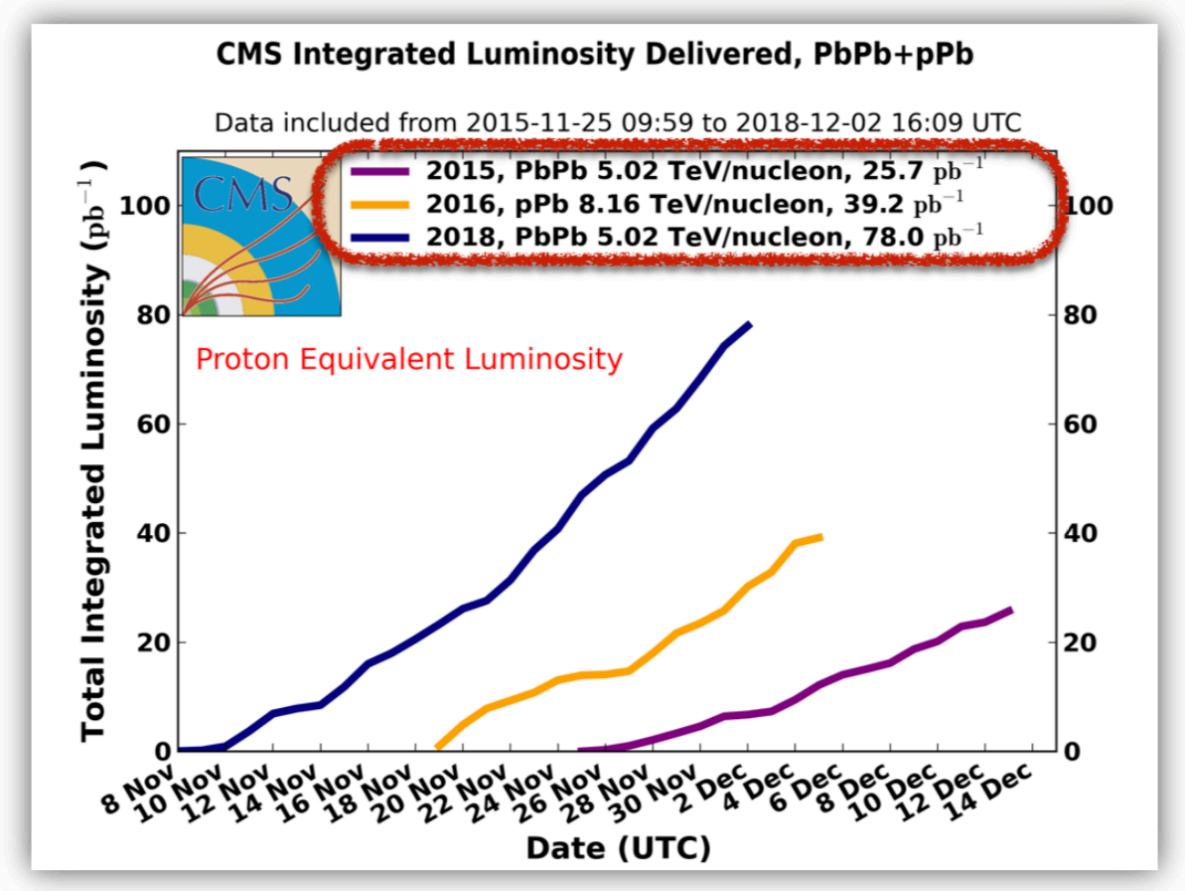
- Thanks to the excellent design and Phase 1 upgrades, CMS managed to take data with a luminosity and pile-up a factor 2 higher than design, making available for analyses about 150 fb^{-1} of data (Run-2) with excellent quality





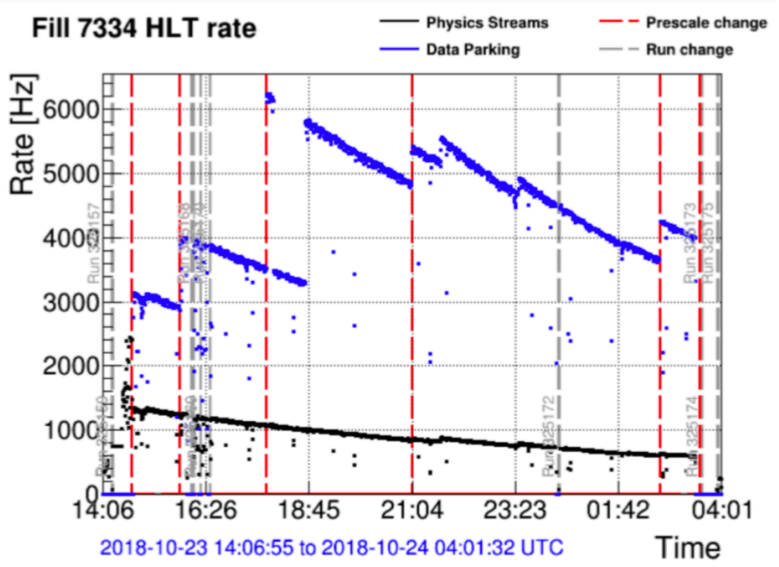
Heavy Ions data in Run 2

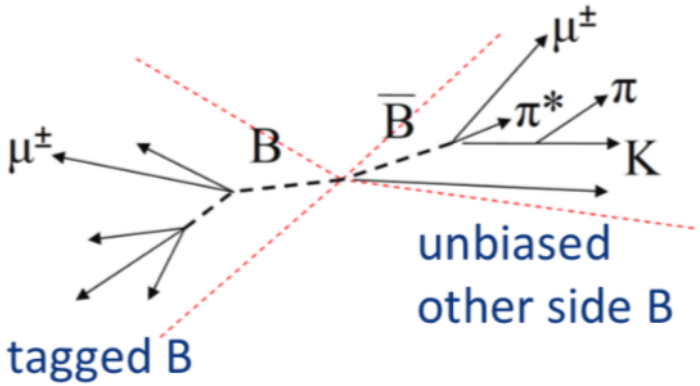
- CMS is committed also in PbPb runs (and pPb, and other heavy ions like Xe and in the future Oxygen
  - Large dataset of several billions minimum bias events collected in 2018



With special methods to maximize our physics reach

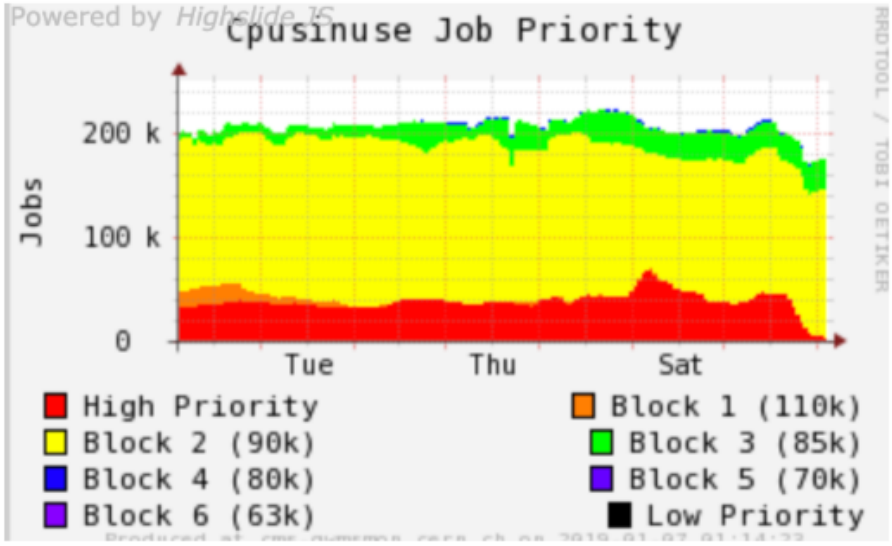
- Parking used in 2018 for B-physics
- Store additional datasets without prompt processing to avoid CPU limitations
- Displaced muon trigger → sample of unbiased B decays
- Use lower L1 trigger rates at end of fill to store events at an HLT rate
- 12B events recorded!

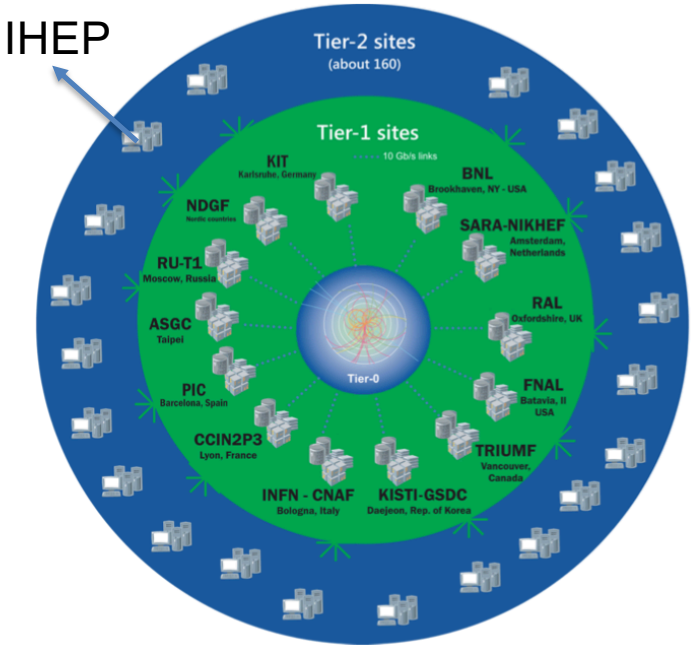




Computing

- Event rates of ~1kHz with events sizes of ~1 MB result in ~10 PB of data per year per experiment
  - CMS wrote 17 PB raw data in 2018
  - Constantly handle ~250K processes for production and analysis activities
  - World wide distributed computing system





Physics Performance & Datasets organization

Level-1

PPD Coordinators
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Norraphat Srimanobhas

PPD Resource Manager
Kirsti Aspola

Level-2

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Zhen Hu
Paolo Gunnellini

Data Quality Monitoring & Data Certification (DQM-DC)
Kaori Maeshima
Francesco Fiori
Javier Fernandez Menendez

Alignment Calibration & Database (AlCaDB)
Giacomo Govi
Tongguang Cheng
Luca Pernie

Level-3

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Muhammad Ahmad
Chayanit Asawatangtrakuldee

Monte Carlo Request Management
Anirban Saha
Scarlet Norberg
Wajid Ali Khan
TBN

Dataset Definition Team
Kai-Feng Chen
Swagata Mukherjee

Upgrade Validation and MC production
Siddhesh Sawant

Online Development
Tomas Hreus
Priyanka Priyanka

Offline Development
Marcel Schneider
Andrius Kirilovas

Data Certification
Amandeep Kaur Kalsi
Sandeep Kaur Hundal
Sandeep Kaur
Sandeep Sharma

Software Coordinator
Po-Hsun Chen

AlCa-HLT Contact
Thiago Tomei
Tongguang Cheng

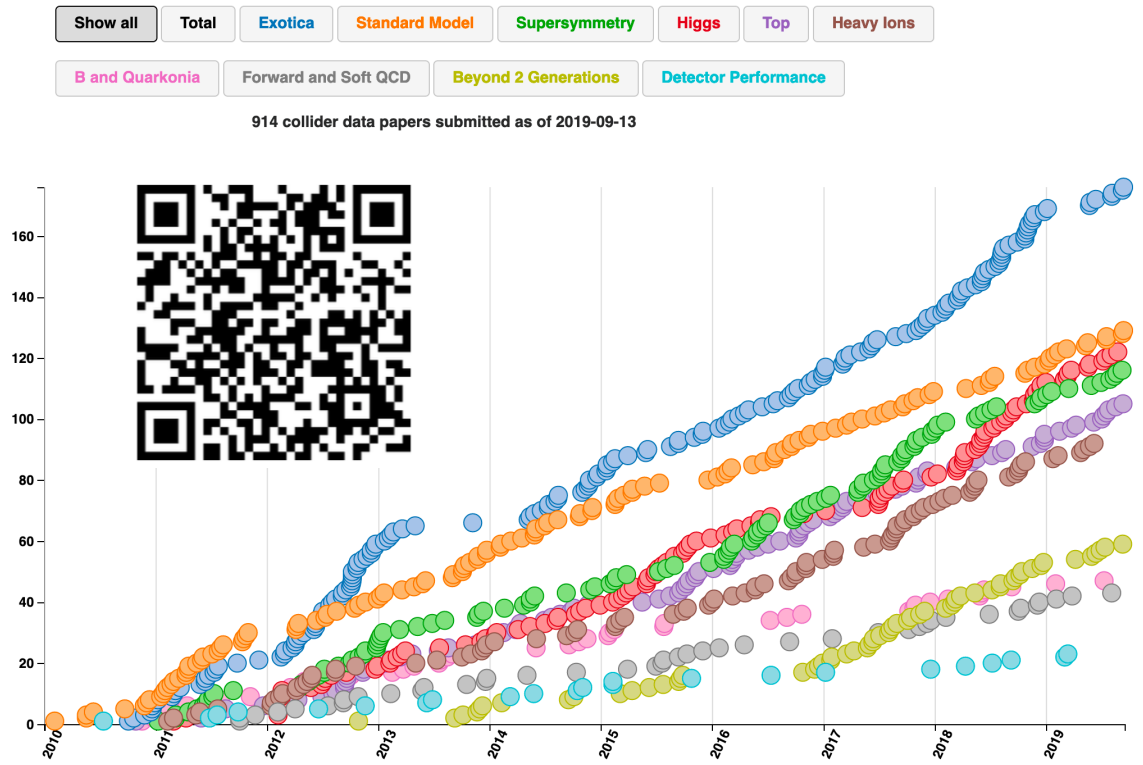
CondDB webmaster
Open Position

DPG, POG & PAG contacts and validators

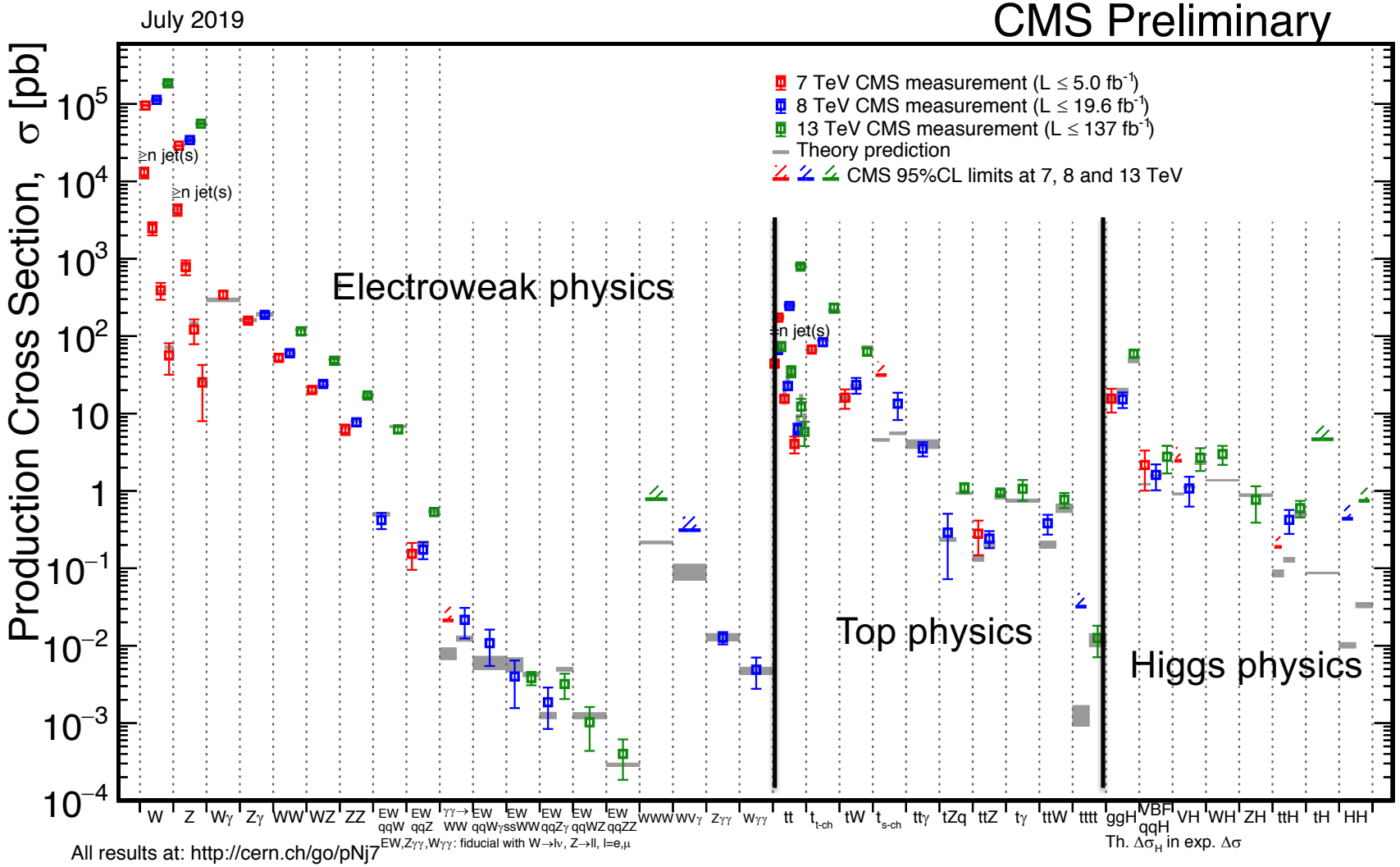
Publications

- 914 papers submitted (on collider data)
- 21 in Collaboration review or later
- Approaching approval
  - pre-app or later: 28
  - going to pre-approval: 19

- CMS released ~140 new physics results last winter and this year till now



Standard Model Measurements



Higgs in 7 years

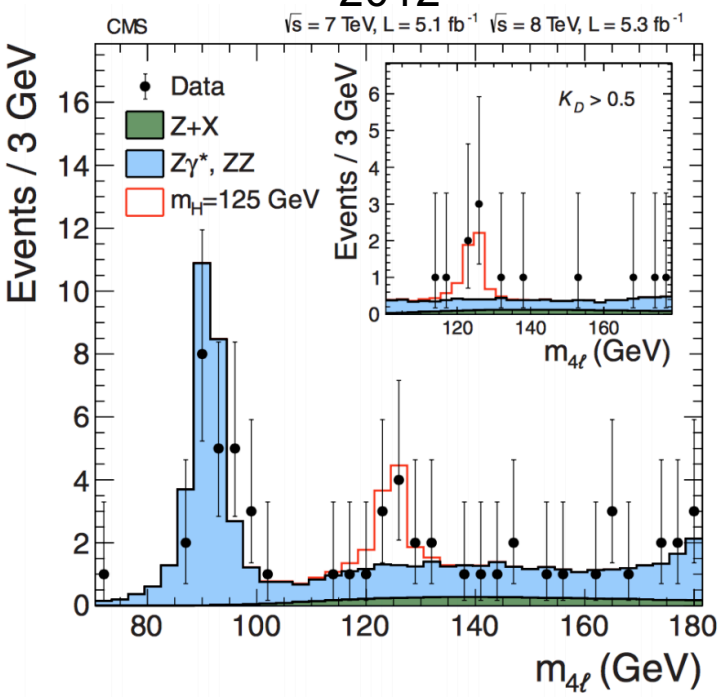
- In the 7 years there has been significant progress in the Higgs sector

  Firmly established gg, ZZ, tt, WW decays

  Tau-Higgs, bottom-Higgs and top-Higgs Yukawa couplings

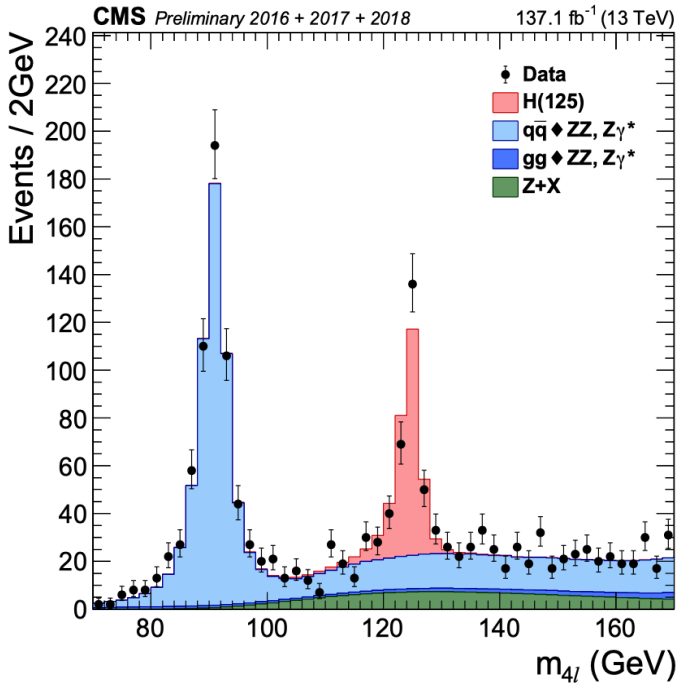
  Excellent mass measurement $m_{\mathrm{H}} = 125.26 \pm 0.21\ (\pm 0.20\ \mathrm{stat.} \pm 0.08\ \mathrm{sys.})\ \mathrm{GeV}$

2012



Phys. Lett. B 716 (2012) 30

2019

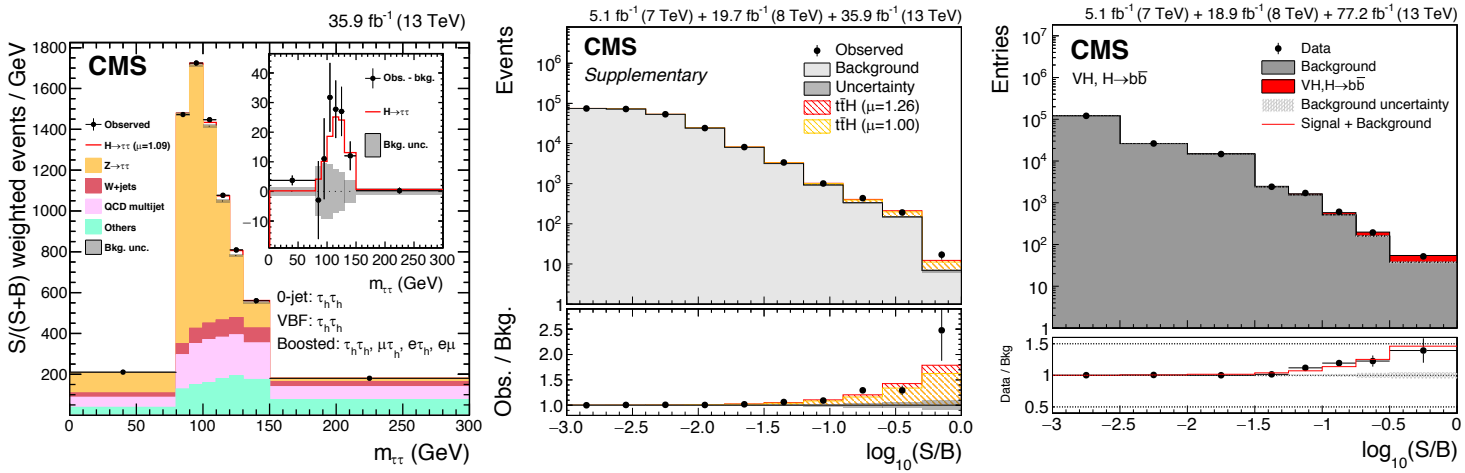


CMS-PAS-HIG-19-001

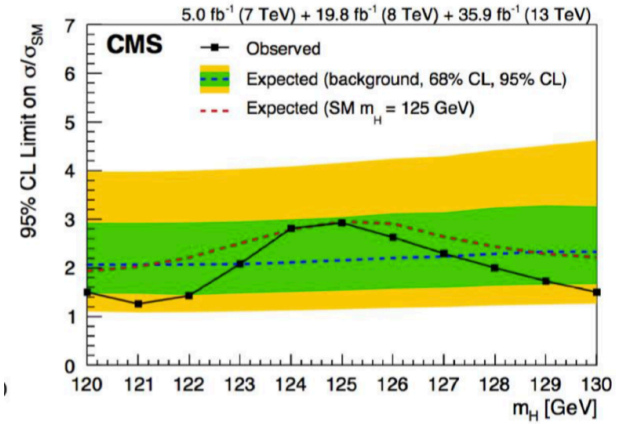
Establishing Higgs

- Couplings to 3rd generation fermions established in the last two years by the > 5 sigma observation of:

H->ττ 2017 | **ttH** 2018 | **H-> bb** 2018



- Next important goal: establish Higgs couplings to 2nd generation fermions $H \to \mu^+\mu^-$
  - BR ($H \to \mu^+\mu^-$) ~ 2.2 x 10^{-4} : small but enhanced in some BSM scenarios



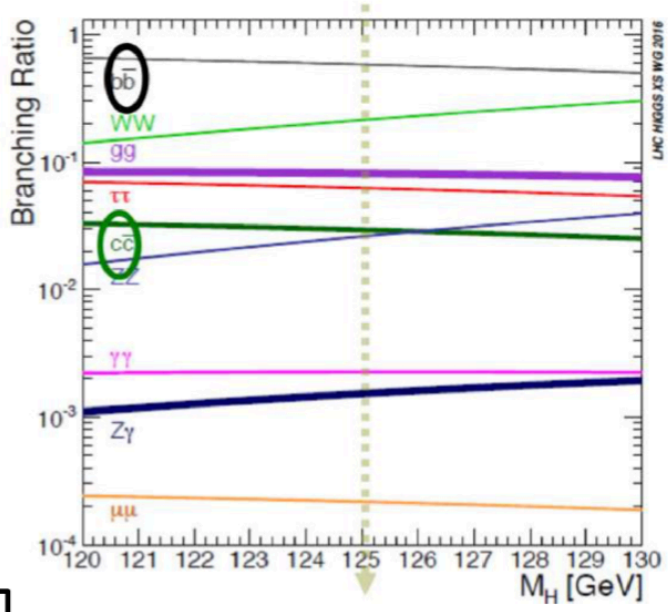
CMS w/ Run 1 + 2016

μ_{CMS}=1.0 ± 1.0(stat) ± 0.1(syst) (RunI+2016)

Obs.(exp.): 0.9 σ (1σ)

Search for Higgs → cc decays

- Motivation: establish Higgs couplings to up-type, 2nd gen. quarks
  - Higgs-charm coupling can be significantly modified by BSM physics
- H→cc: very challenging at the LHC
  - small BR: 2.9 x 10^{-2}
  - Very large backgrounds
    - H→bb is background in this search
  - **c-tagging** more challenging than b-tagging



Need innovative tools and techniques!

Target VH production: very clear signature
- Vector boson recoiling against Higgs boson
- Main BKG: V+jets and ttbar
  - QCD significantly suppressed
- Very little activity in the event

Events categorized based on leptonic decays of V boson: 0L, 1L, 2L {L=e, μ}

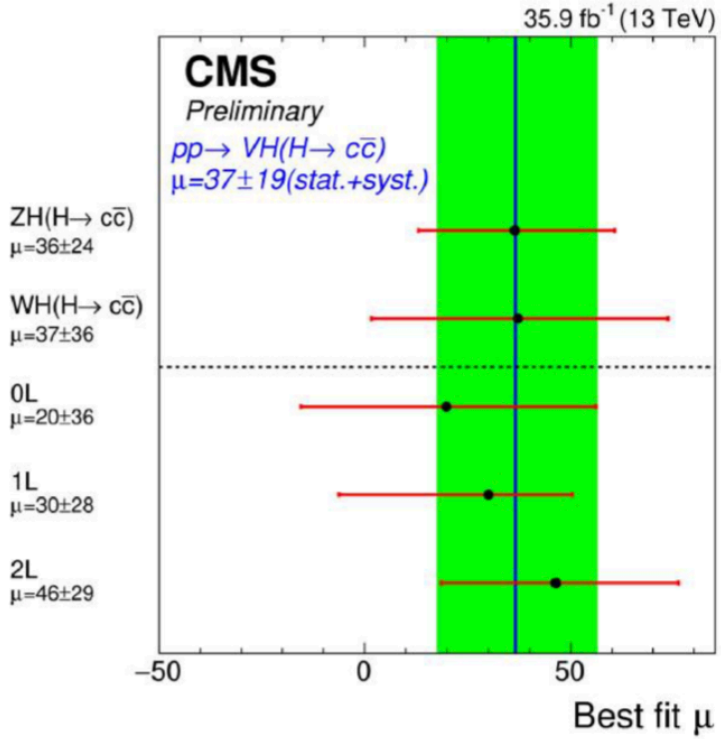
Search for Higgs → cc decays

- Combine (V)H->cc results from resolved-jet &merged-jet topologies

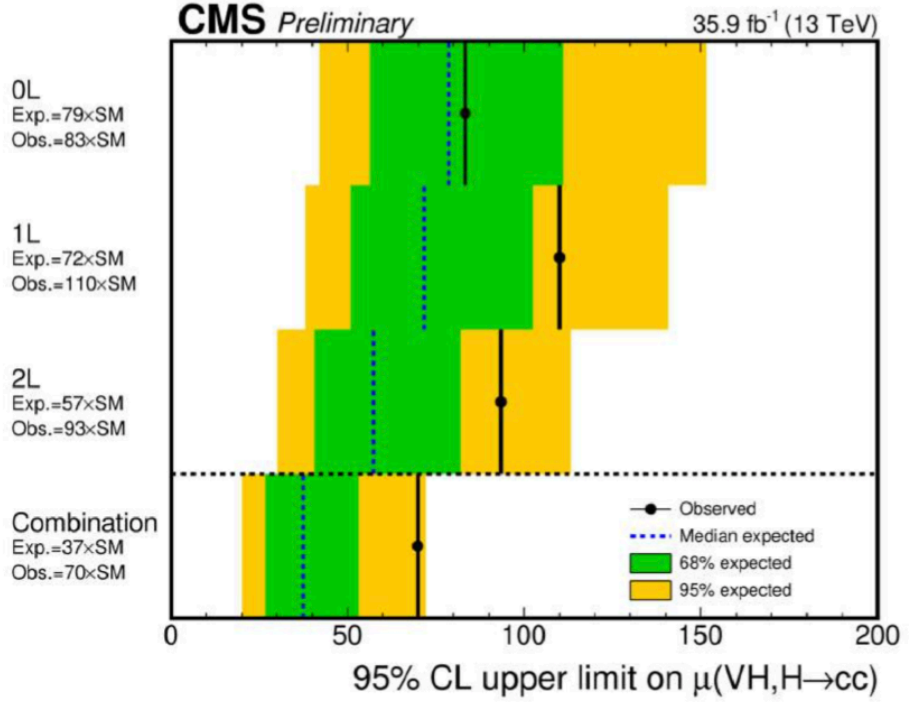
$$\mu < 70 \text{ obs. } \left(37 \left(^{+16}_{-10}\right) \left[^{+35}_{-17}\right]\right) \text{exp.}(1\sigma)[2\sigma]$$

Strongest limit to date

Best fit signal strength

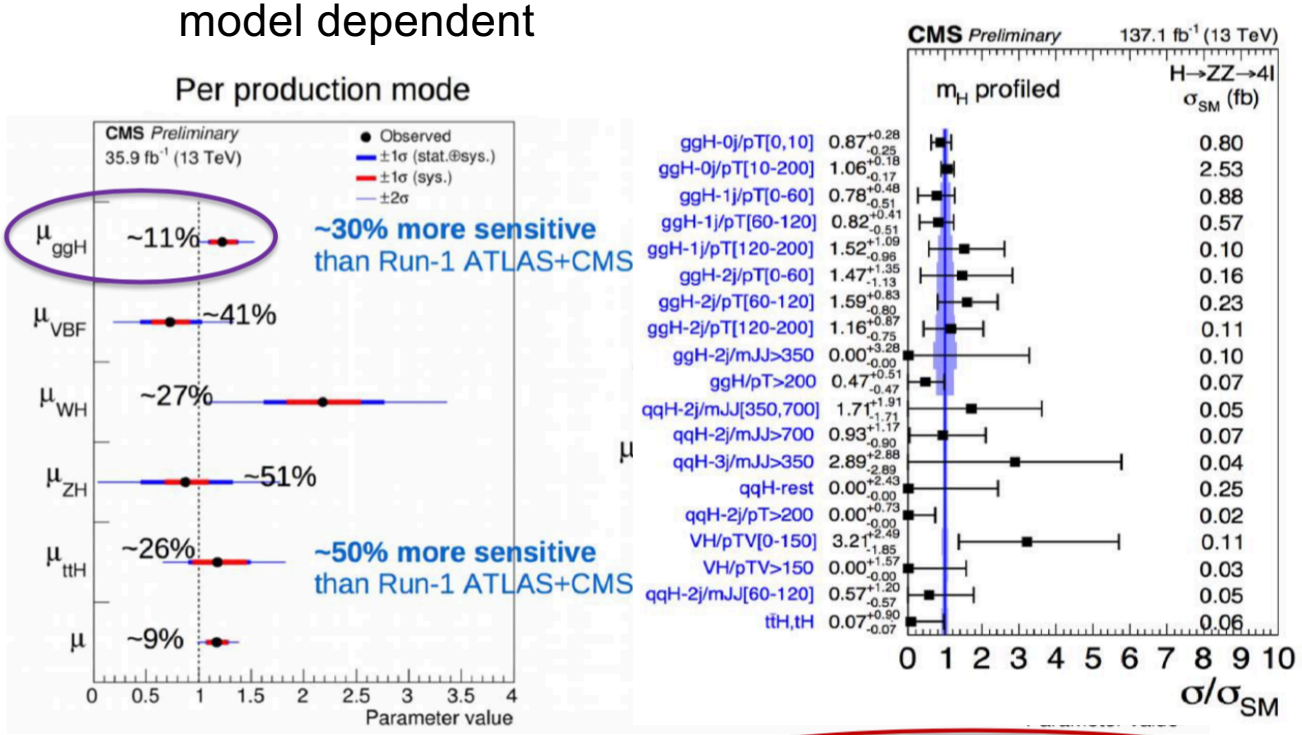


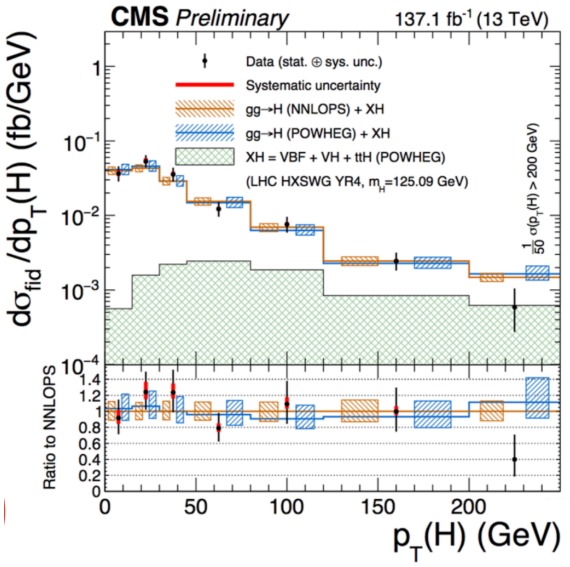
95% C.L. exclusion limit on $\mu_{VH(cc)}$



Higgs Properties and Cross-sections

- Surpassing Run 1 precision in key measurements with only 2016 data
- Higgs physics has entered the ***precision*** era
  - Fiducial and differential cross section measurements comparing data to state-of-the-art calculations
  - Simplified template cross sections enable Higgs measurements that are less model dependent

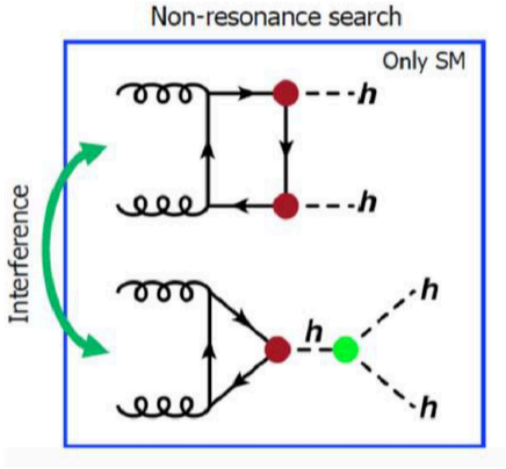


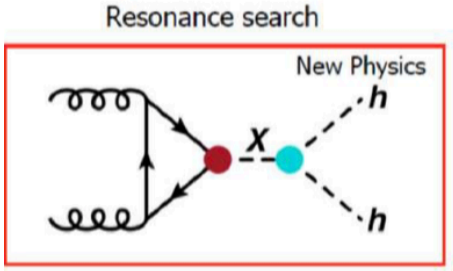


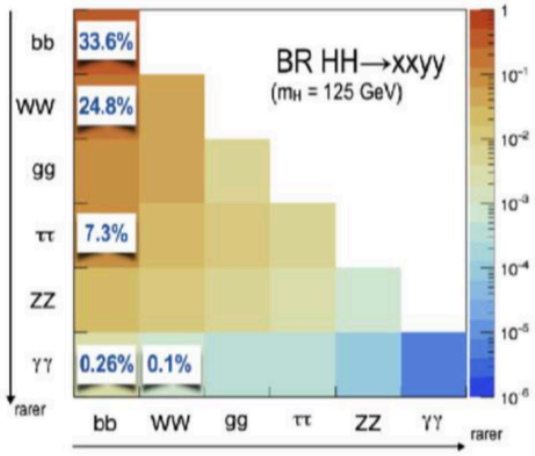
$$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$

Double Higgs

- Directly probes Higgs field potential (sensitive to the self-coupling **λ**)
- Small cross section, destructive interference with box diagram
- Puts constraints on several new-physics scenarios
  - **Non-resonant:** New/modified vertices contributing to hh production
  - **Resonant:** new narrow width particle decaying into two SM Higgs







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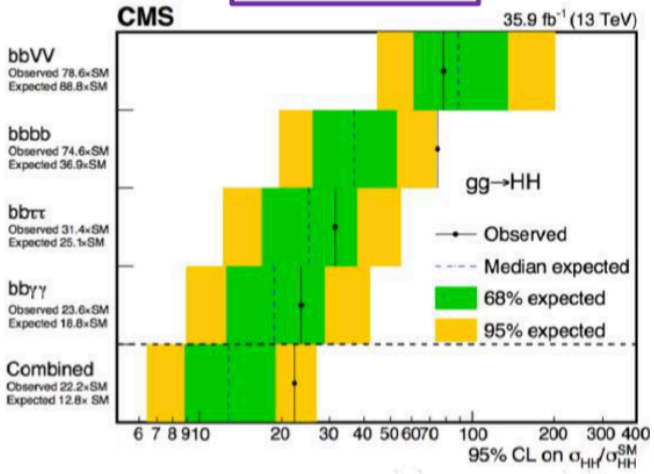
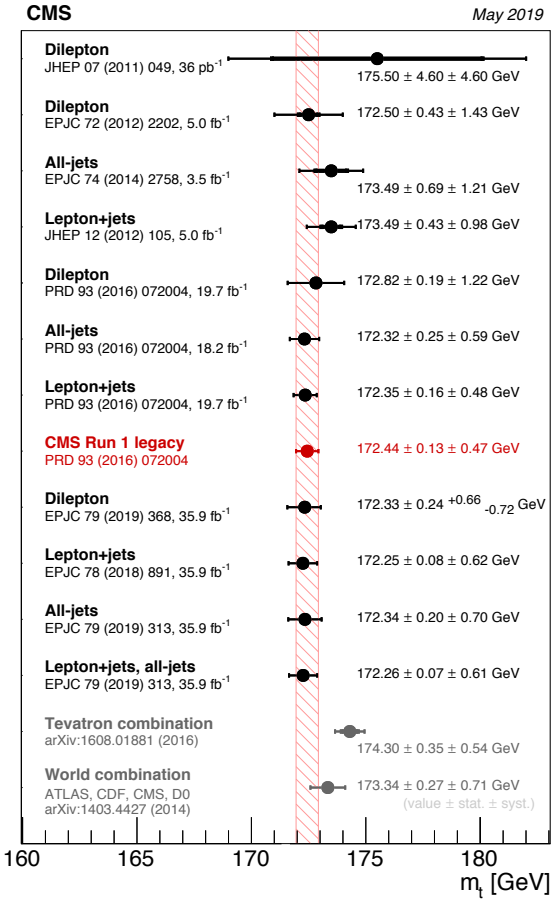


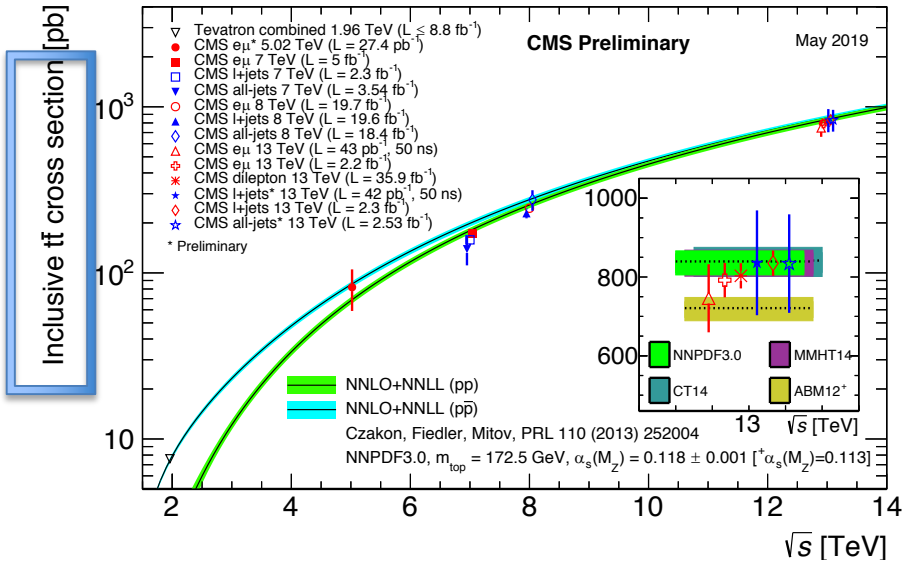
ATLAS+CMS HH significance @ HL-LHC: 4σ

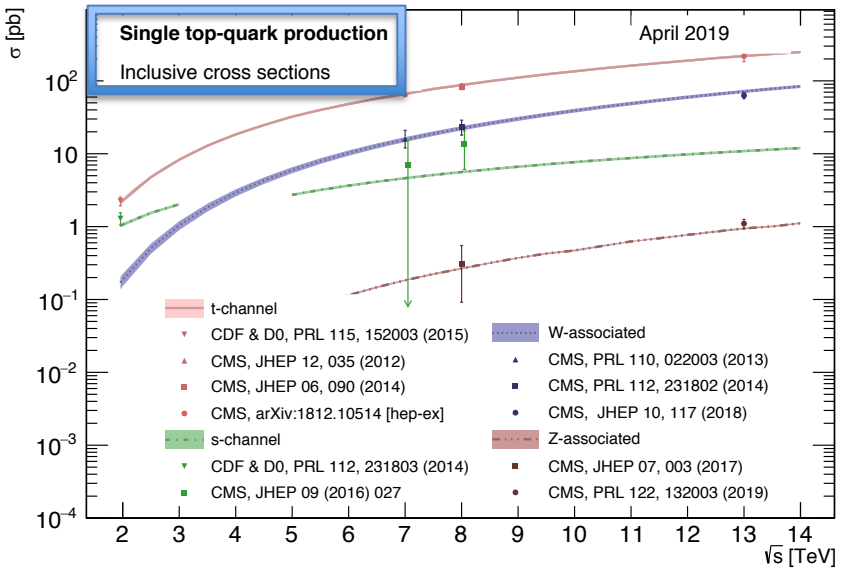
combination probes ~10 times the SM prediction

Top Quark Measurements

- After its discovery ~25 years ago, the top is still one of the hottest topics
- LHC: a top quark factory!

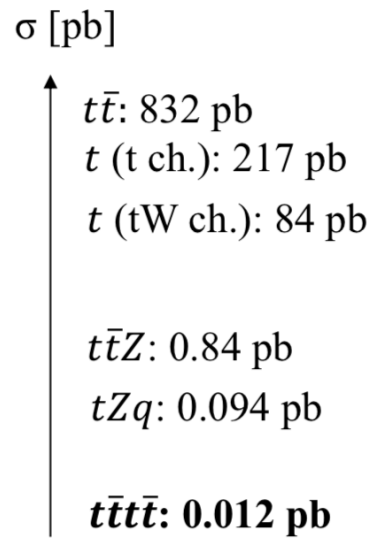


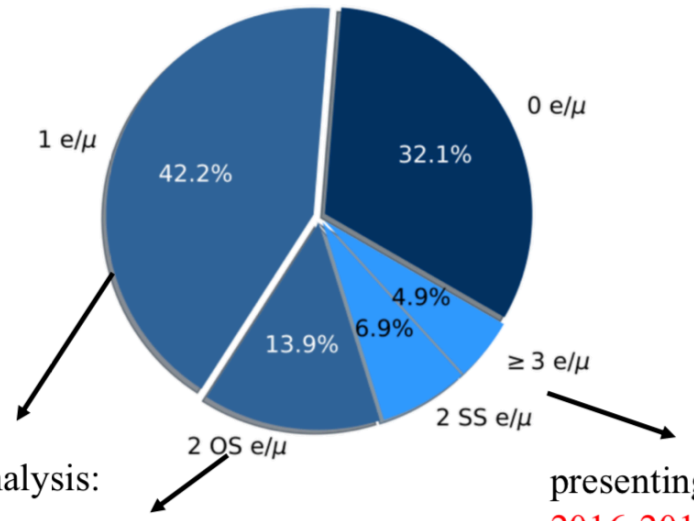




Four-top quark production

- The 4-top quark process can give valuable input to the magnitude and CP properties of the top quark Yukawa coupling
- SM: σ = 12 ± 2 fb.
- Clean search in final states of two equally charged or three charged leptons
- Very impressive signature:
  - 4 b quarks ⟵ 2, 3, or ≥4 b-tagged jets
  - 6-8 quarks ⟵ require up to ≥8 jets.

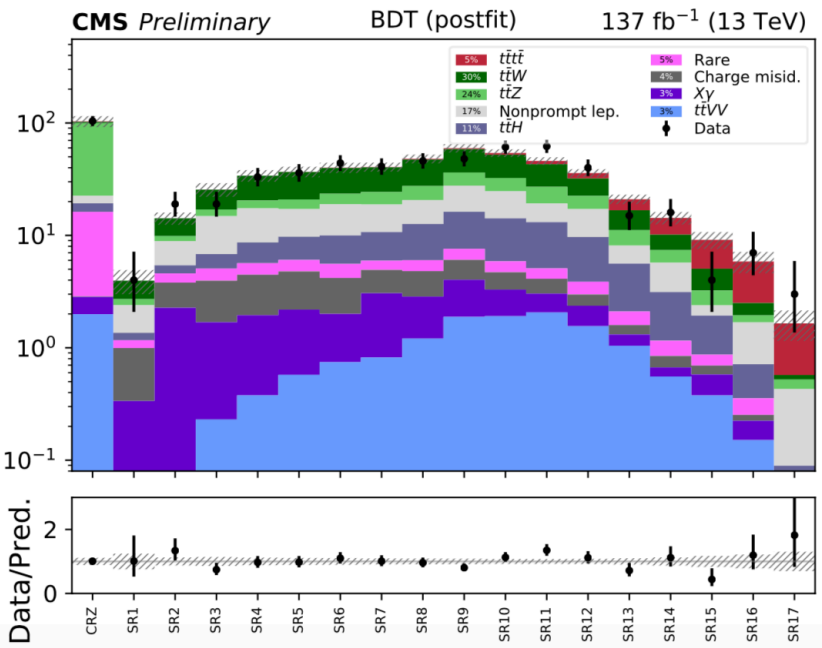




Four-top quark production

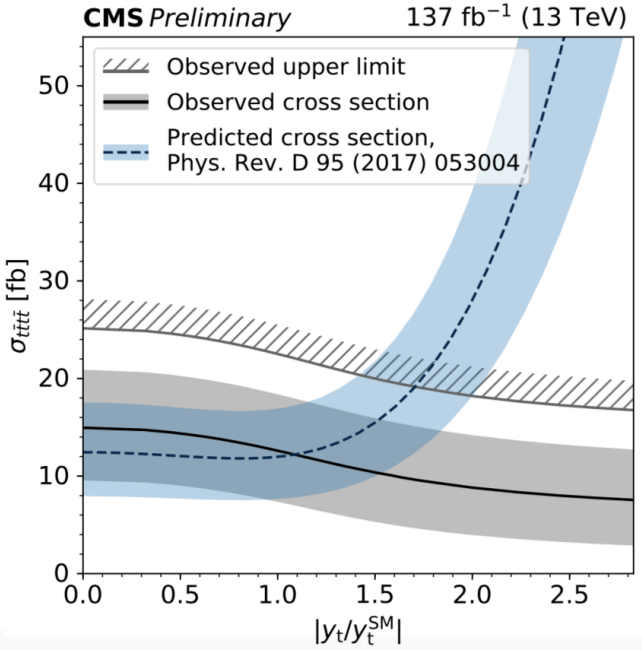
- Can use the result to constrain Top Yukawa coupling:
  - $y_t < 1.7 y_t^{\mathrm{SM}}$ at 95% CL
  - Unique sensitivity to physics that predominantly couples to top quarks

    e.g. a four-top quark analysis can set similar limits on the top Yukawa coupling compared to ttH analyses.



A simple BDT is trained:
Expected sensitivity: 2.7σ
Observed sensitivity 2.6σ.

Measured cross-section:
$12.8^{+5.9}_{-5.3}$ fb (exp. 12.0 fb)



Full Run 2 data

Rare top processes: tZq

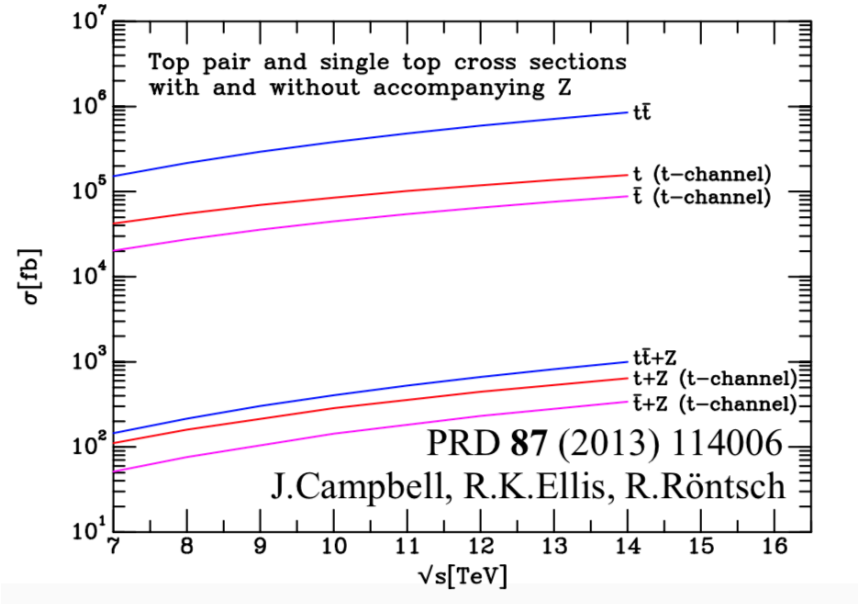
- Similar production cross section compared to ttZ:
  - Independent test of rare ttZ coupling
- Unique sensitivity to flavor-changing neutral currents tZq.
- Search in events with 3 leptons, ≥1 b-tagged jets, ≥2 jets
  - Train BDT using lepton and jet kinematics

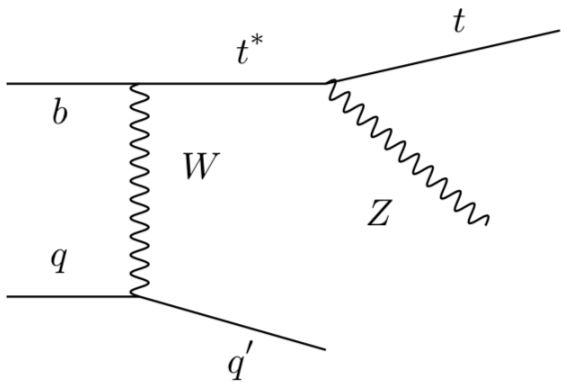
σ [pb]

$t\bar{t}$: 832 pb
t (t ch.): 217 pb
t (tW ch.): 84 pb

$t\bar{t}Z$: 0.84 pb
tZq: 0.094 pb

$t\bar{t}t\bar{t}$: 0.012 pb

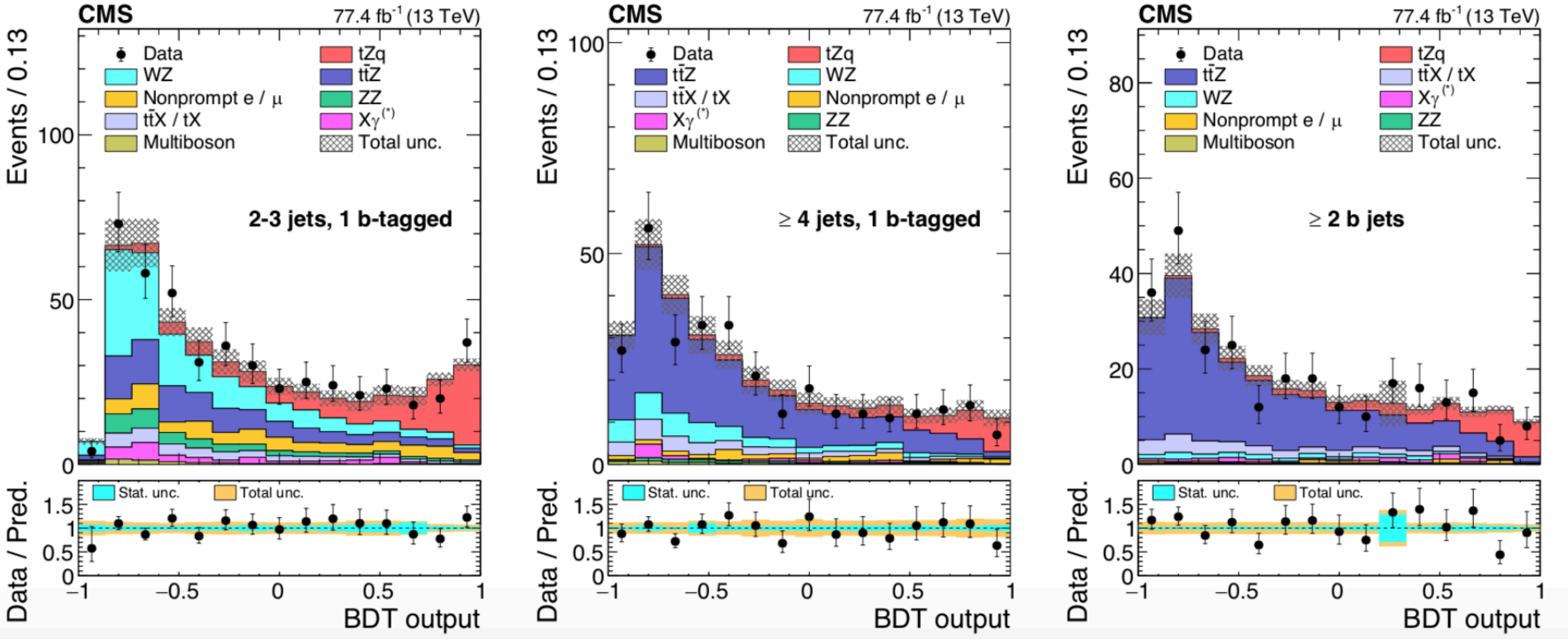




Rare top processes: tZq

- First observation of the tZq process with 8.2σ (7.7σ expected)

$$\sigma(pp \to tZq \to t\ell\ell q) = 111^{+17}_{-16}\ \text{fb} \quad (\text{SM: } 94 \pm 3\ \text{fb})$$

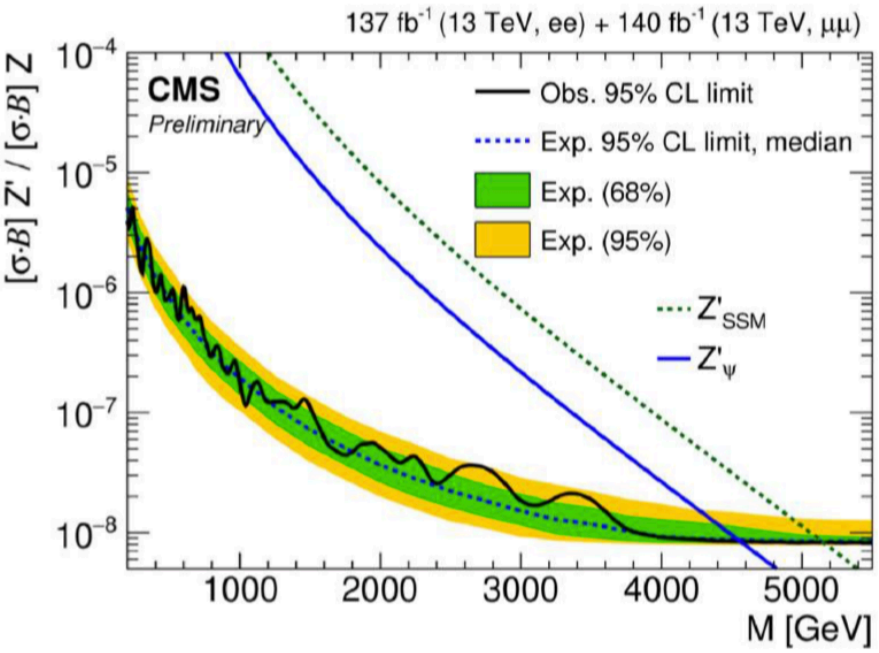


2016+2017 data

Exotic landscape circa 2019

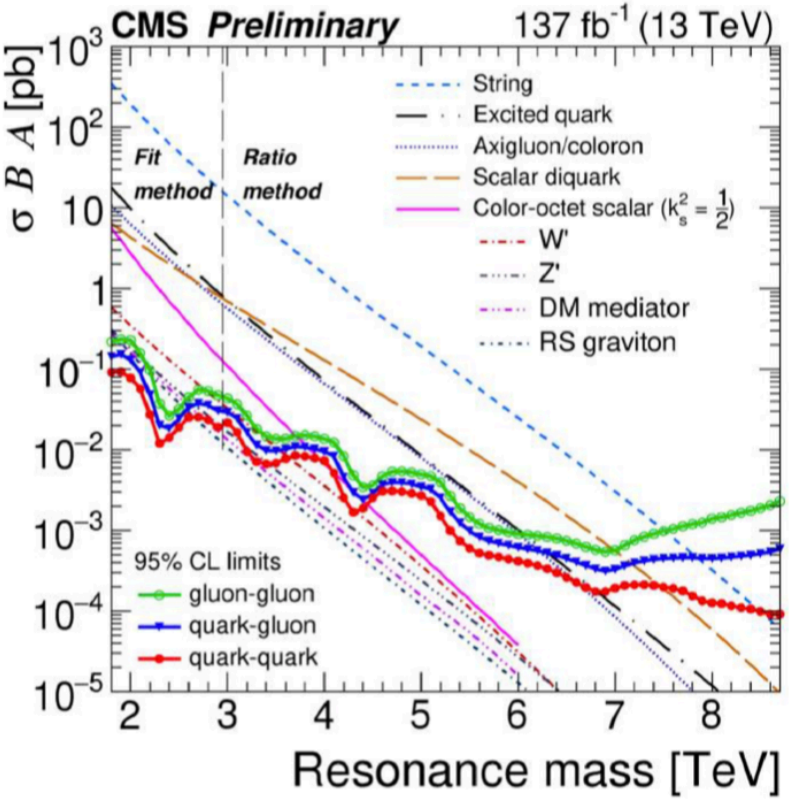
Dilepton resonance search

EXO-19-019



Dijet resonance search

EXO-19-012



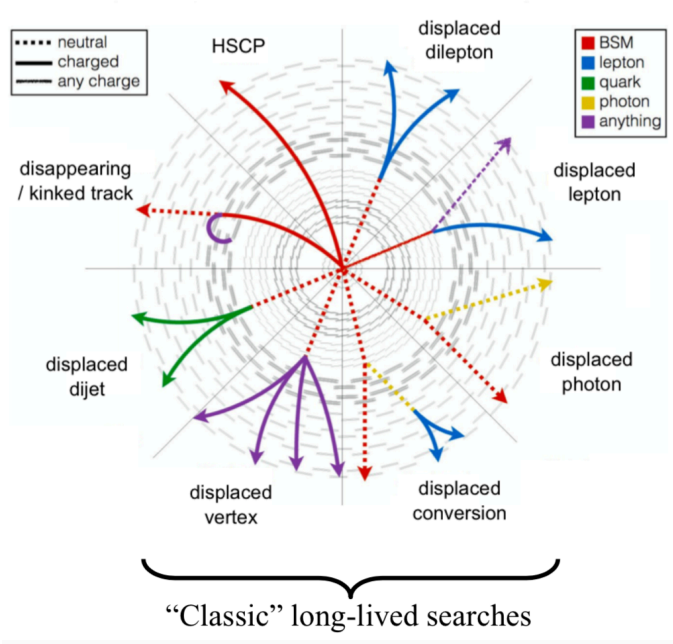
Excluding particles w/ mass ~5 TeV

i.e. > 5 times the reach from 10 years ago

Focus now on complex topologies and weakly coupled phenomenon

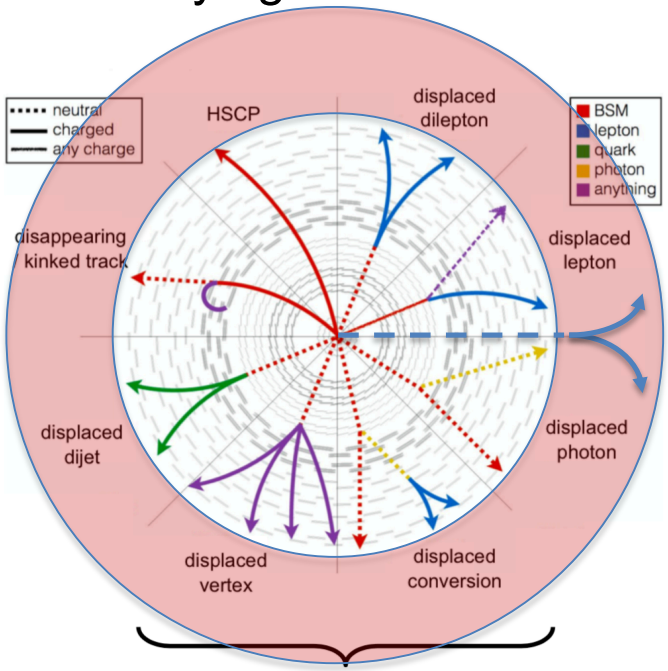
Searches for delayed jets

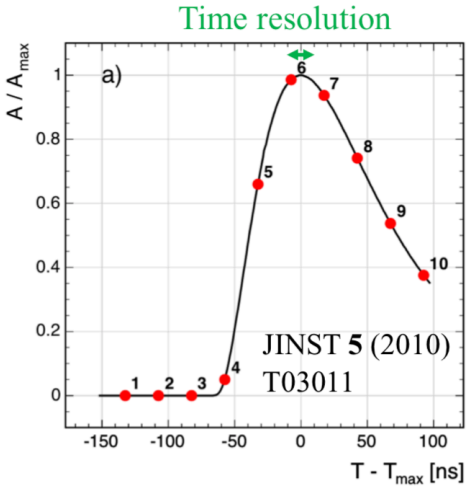
- Most of the CMS analyses search for prompt particles
  - Prompt searches have not uncovered any new physics
  - Leave no stone unturned
- Completely new search for delayed jets (2016-2018 pp collision data)
  - Looking for longlived particle that traverses the detector “slowly” before decaying within the detector



Searches for delayed jets

- Most of the CMS analyses search for prompt particles
  - Prompt searches have not uncovered any new physics
  - Leave no stone unturned
- Completely new search for delayed jets (2016-2018 pp collision data)
  - Looking for longlived particle that traverses the detector “slowly” before decaying within the detector



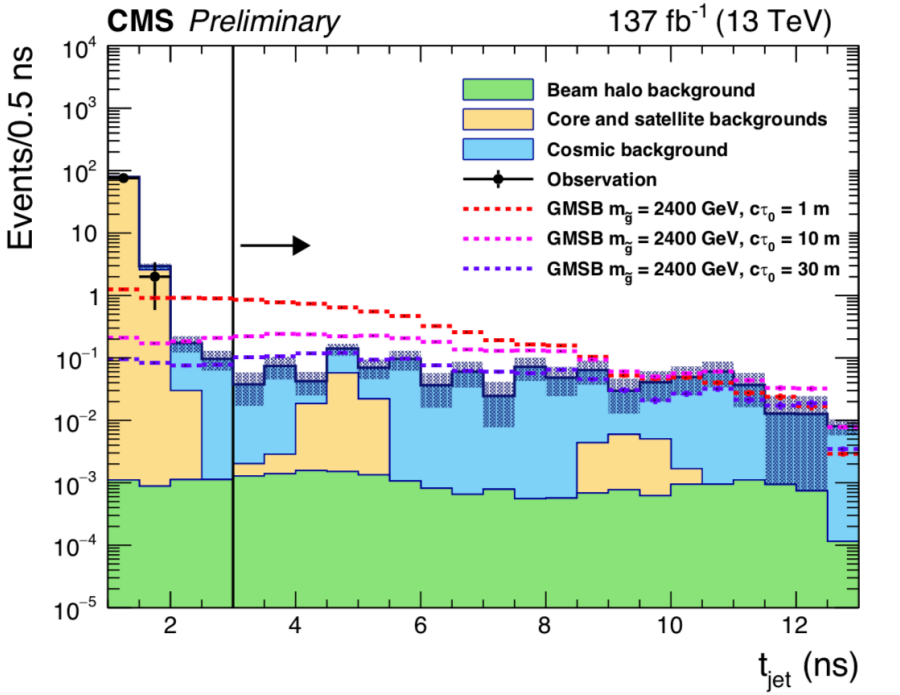


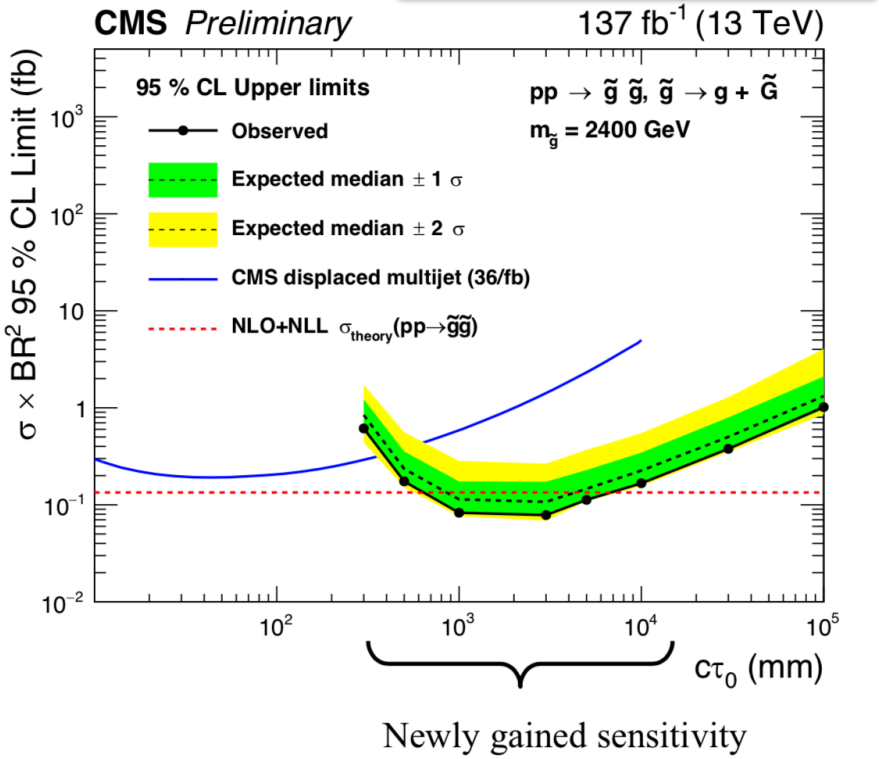
The CMS electromagnetic calorimeter has incredible timing capabilities

Searches for delayed jets

- No events observed with $1.1^{+2.5}_{-1.1}$ background events predicted
- No convincing hint for physics beyond the standard model, but a lot of phase space is unexplored
- The CMS collaboration keeps having new creative ideas how to get the best sensitivity out of our beautiful experiment.

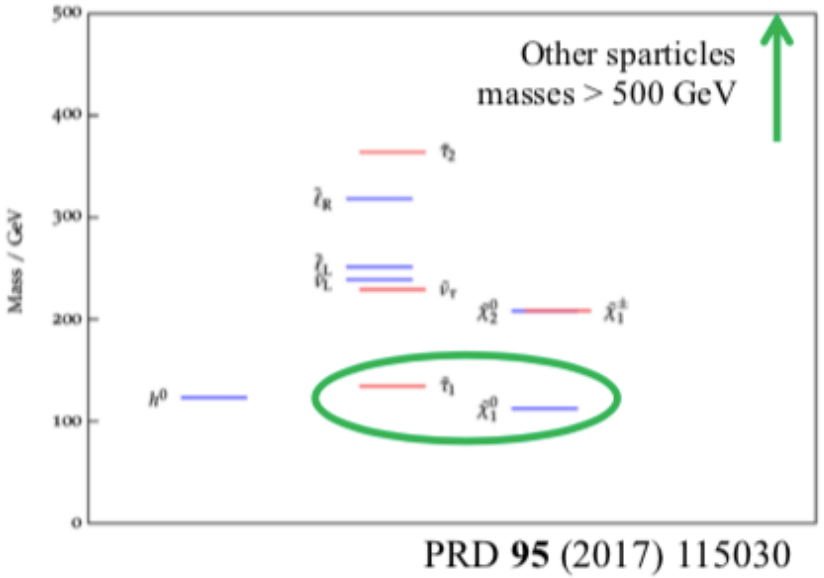
Full Run 2 data



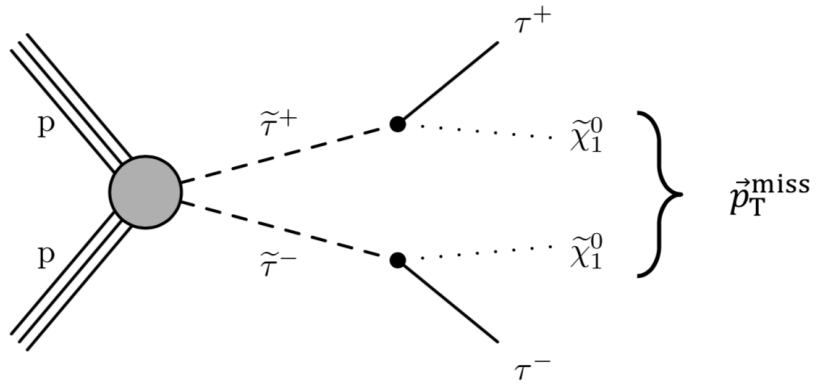


Searches for tau sleptons ("staus")

- Motivation
  - The $\tilde{\tau}$ leptons are expected to be light
  - Cross section is expected to be low
  - $\tilde{\tau} - \tilde{\chi}_1^0$ coannihilation provides a feasible way to accommodate the observed cosmological dark matter.

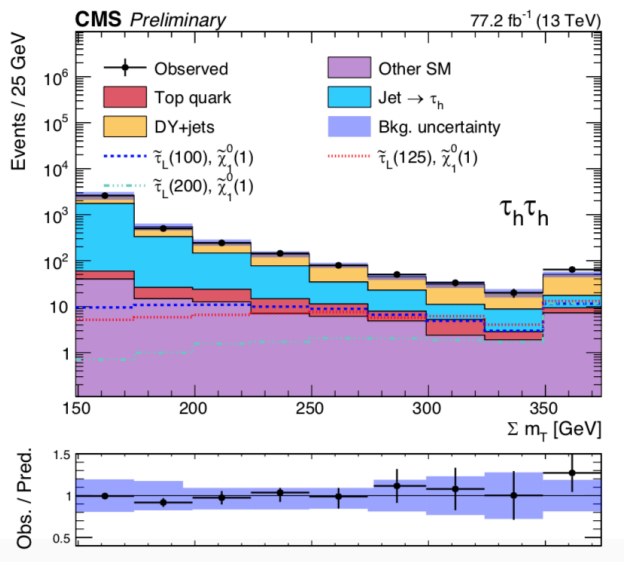


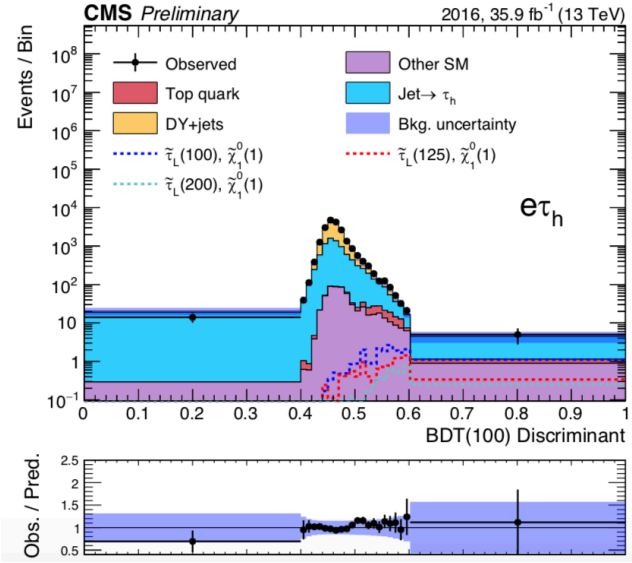
PRD **95** (2017) 115030

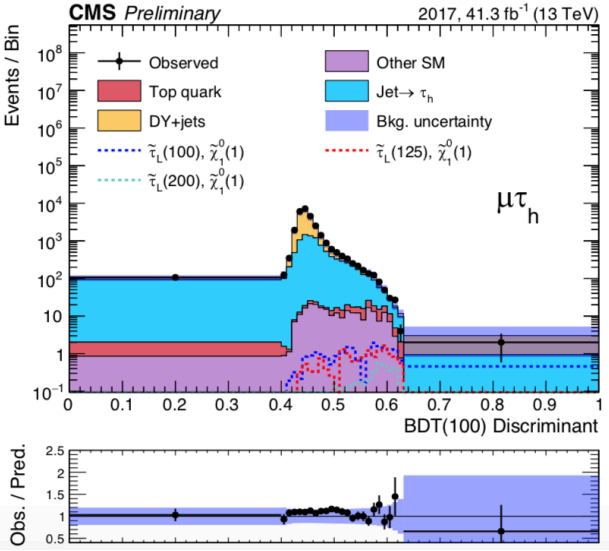


Searches for tau sleptons ("staus")

- CMS searches for $\tilde{\tau}$ leptons in the $\tau_h\tau_h$, $\tau_h e$, and $\tau_h\mu$ final states
  - $\tilde{\tau}$ lepton decays to hadrons dominant: 63% branching fraction
- Search in $\tau_h\tau_h$ final states: high values of $M_{\mathrm{T}}^{\tau 1} + M_{\mathrm{T}}^{\tau 2}$ and M_{T2}
- Search in $\tau_h e$, and $\tau_h\mu$ final states: BDT classifier

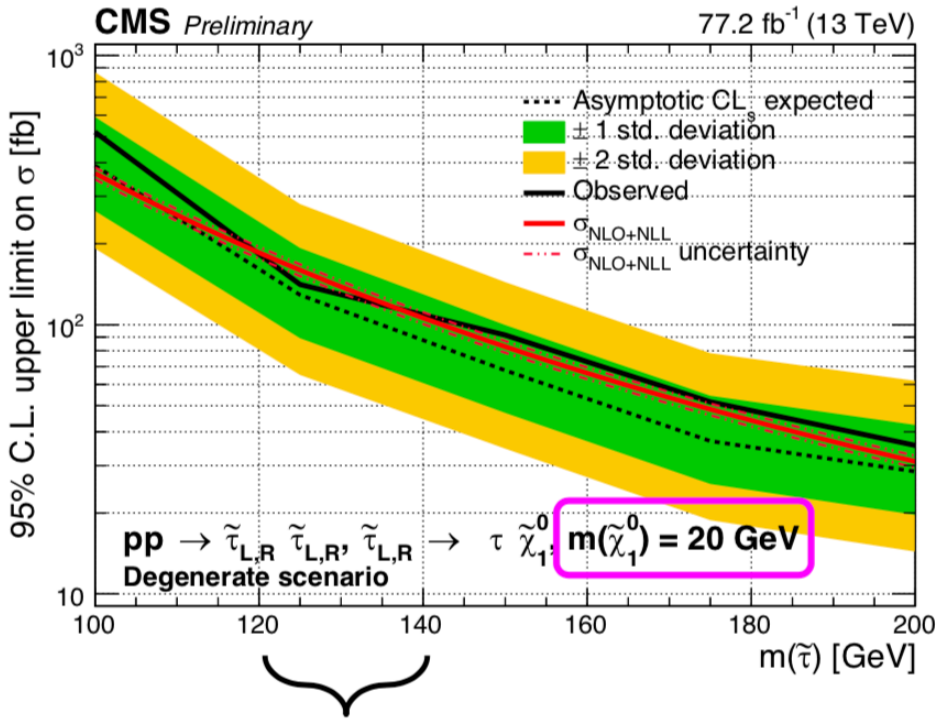




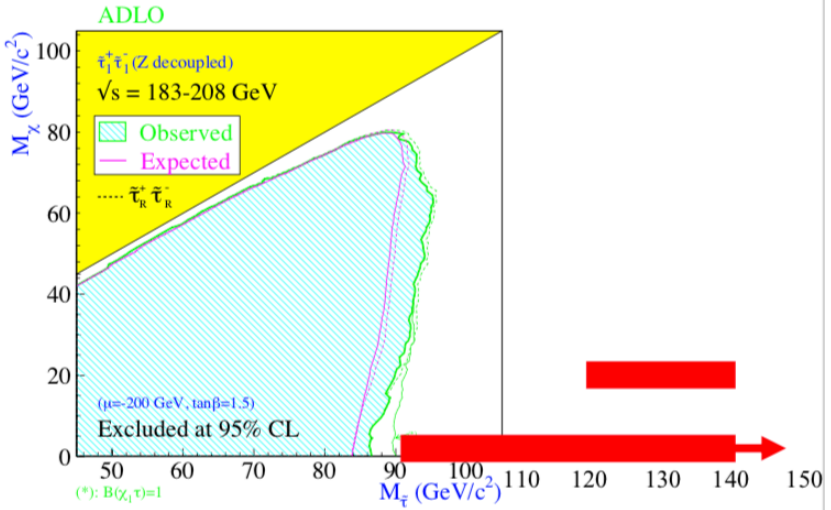


Searches for tau sleptons ("staus")

- CMS searches for $\tilde{\tau}$ leptons in the $\tau_h\tau_h$, $\tau_h\tau_e$,and $\tau_h\tau_\mu$ final states
  - Both searches do not see signs for $\tilde{\tau}$ lepton pair production
  - Interpretation for $\tilde{\tau}$ lepton pair production in terms of limits



2016+2017 data

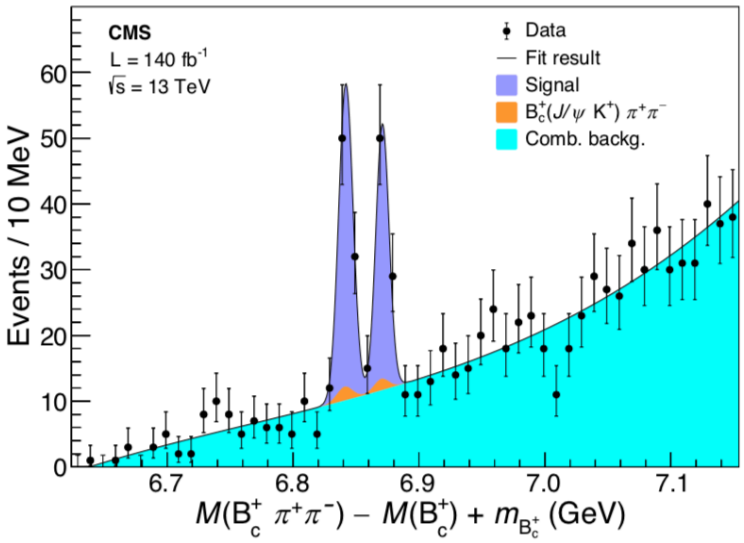


First time since LEP, that a new phase-space in $\tilde{\tau}$ searches is probed.

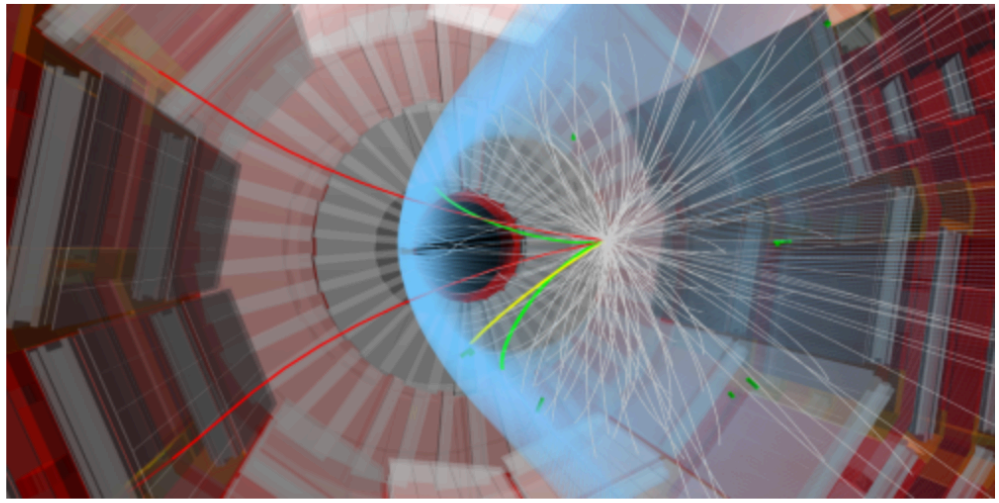
Exciting search program ahead

Observation of two excited B_c states

First full Run 2 data paper: Observation of the $B_c(2S)^{\pm}$ and $B_c^*(2S)^{\pm}$ states and measurement of the $B_c(2S)^{\pm}$ mass
Highlighted as PRL Editors' Suggestion



Physics SYNOPSIS



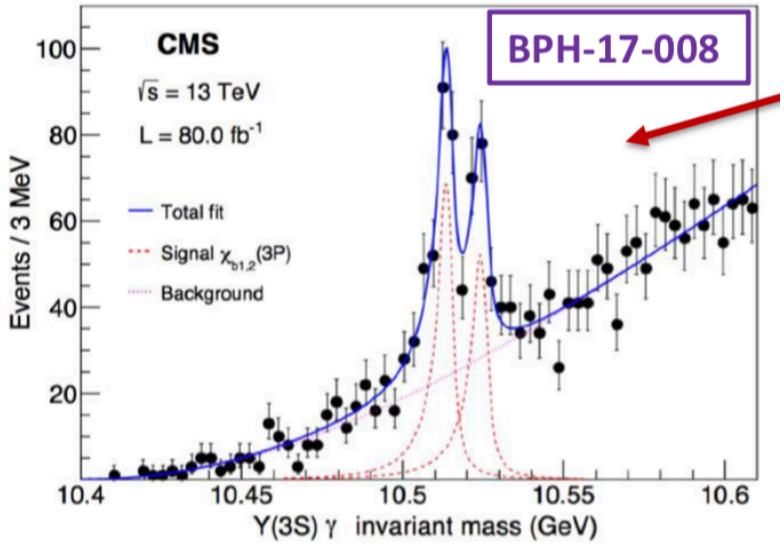
Record LHC Haul Catches Double Meson Signal

Published 2 April 2019

A huge dataset recorded at the highest particle collision energy so-far observed resolves a puzzle by revealing two meson excited states.

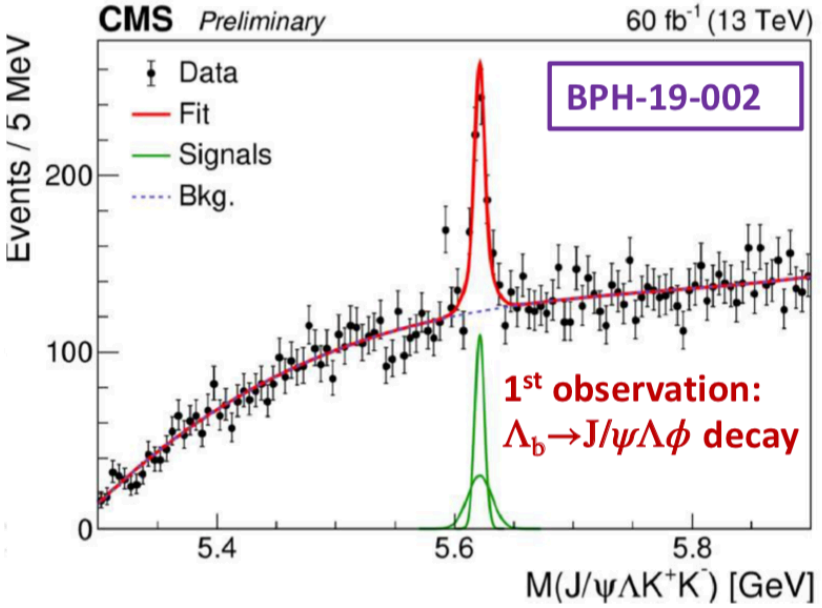
Result confirmed by LHCb

X_b and Λ_b



1st observation:
doublet structure of
$\chi_b(3P)$ resonance

- Result based on 60 fb-1 of 2018 data
  - using a J/ψ + 2 track trigger
- Observation significance 9.7 σ
- Normalization channel for BF measurement:
  $\Lambda_b \to \psi(2S)\Lambda$
  has similar topology as signal

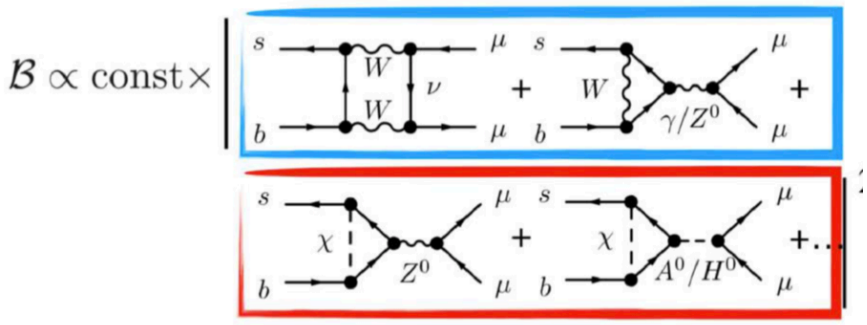


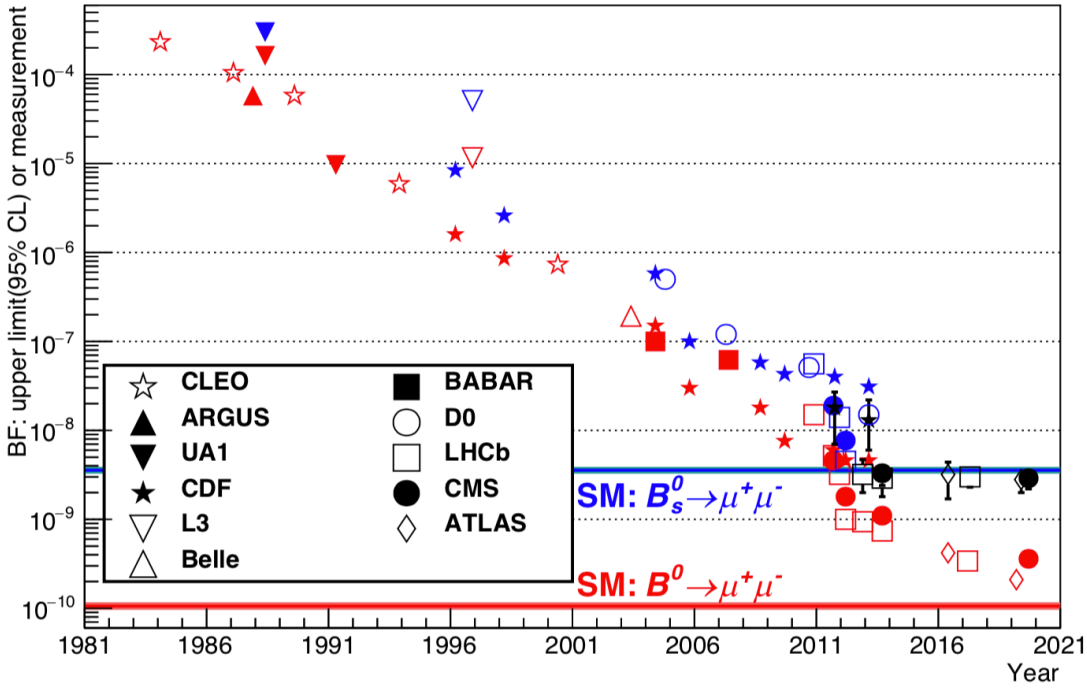
Result:

$$\frac{\mathrm{BF}(\Lambda_b \to J/\psi\Lambda\phi)}{\mathrm{BF}(\Lambda_b \to \psi(2S)\Lambda)} = 8.26 \pm 0.90(\mathrm{stat}) \pm 0.68(\mathrm{syst}) \pm 0.11(\mathrm{BF}) \times 10^{-2}$$

$B \rightarrow \mu^+\mu^-$

- Very rare $B \rightarrow \mu^+\mu^-$ decays
  - Forbidden at tree level, only through higher order diagrams
  - Cabibbo suppressed $|V_{ts(td)}|^2$
  - Helicity suppressed $(m_\mu/m_B)^2$
  - but: not in models with extended Higgs sectors

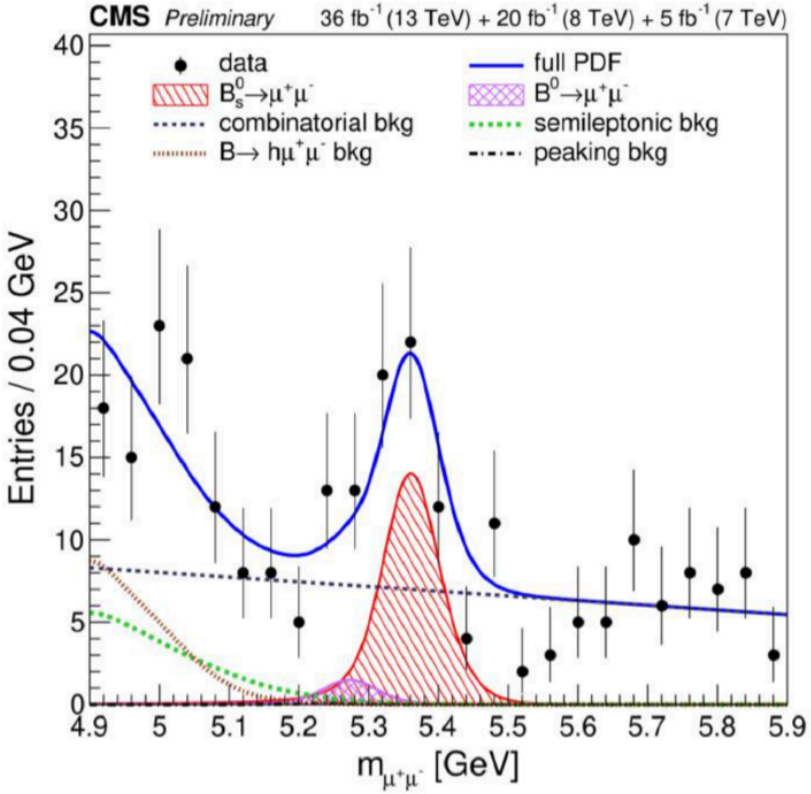




$B \rightarrow \mu^+\mu^-$

- Use Run 1 (7, 8 TeV) + Run 2 (2016 13 TeV) datasets
- $B_s^0 \rightarrow \mu^+\mu^-$ branching fraction:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = [2.9^{+0.7}_{-0.6}\,(\text{exp}) \pm 0.2(f_s/f_u)] \times 10^{-9}$$



Significance:
5.6 (6.5) σ obs (exp)

Effective lifetime $\tau(B_s^0 \rightarrow \mu\mu) = (1.70^{+0.61}_{-0.44})$ ps

$B^0 \rightarrow \mu^+\mu^-$ branching fraction:

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 3.6 \times 10^{-10}\ 95\%\ \text{C.L.}$$

Previous CMS result:
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9}$
Phys. Rev. Lett. **111**, 101804

Results consistent with SM predictions

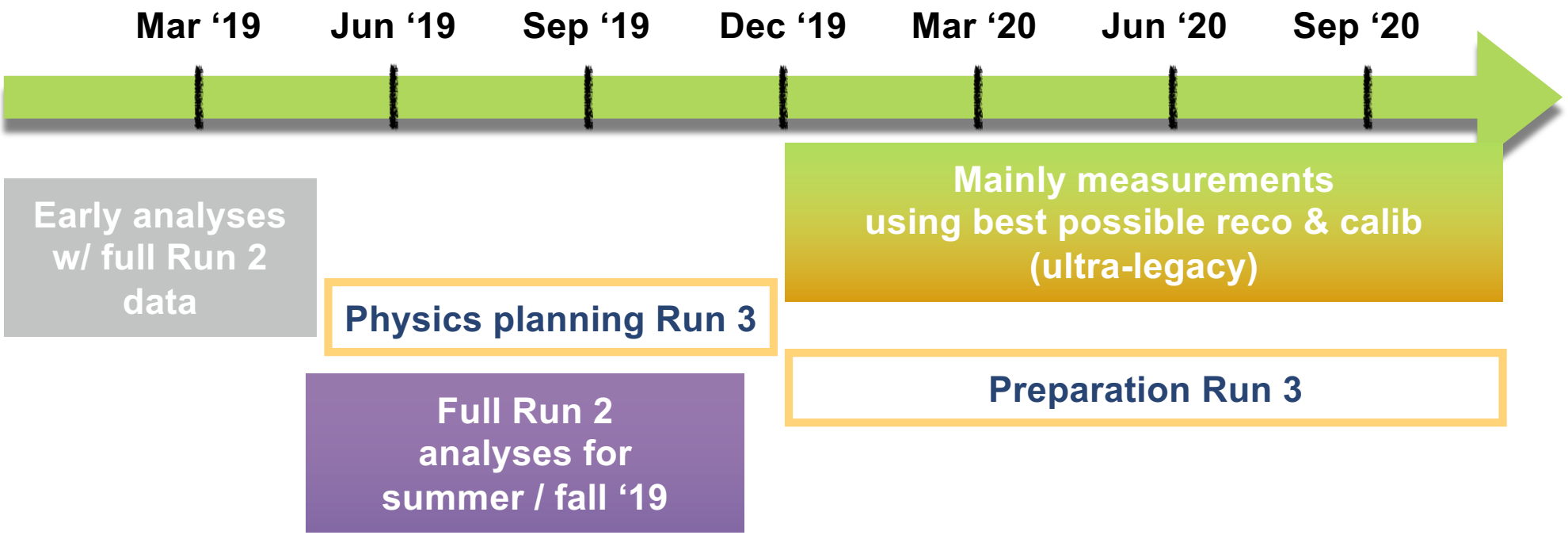
A hint of an excess in Y(1S)$\mu^+\mu^-$ final status

- CMS saw a hint of an excess near 18 GeV in Y(1S)$\mu^+\mu^-$ and Y(1S)e^+e^- final states in Run 1 data
- Preliminary result shown on APS April Meeting 2018
  - https://absuploads.aps.org/presentation.cfm?pid=14072
- Run 2 analysis is ongoing
- Recently RHIC reported evidence for a new resonance near 18 GeV in the dijet channel
  - https://arxiv.org/abs/1909.03124v1

Physics activities in LS2

Pursuing parallel activities in three areas:

1. harvest of run 2 results
2. preparation for data taking & analysis in Run 3
3. preparation for HL-LHC



Physics part for remaining phase-2 TDRs, HL-LHC prep.

Run 3 physics focus

- Precision measurements of SM processes
  - Understand SM backgrounds, look for deviations or anomalies
- Searches/measurements of rare SM processes
  - Take advantage of the large LHC datasets and look for (significant) enhancement from beyond-the-SM (BSM) particles

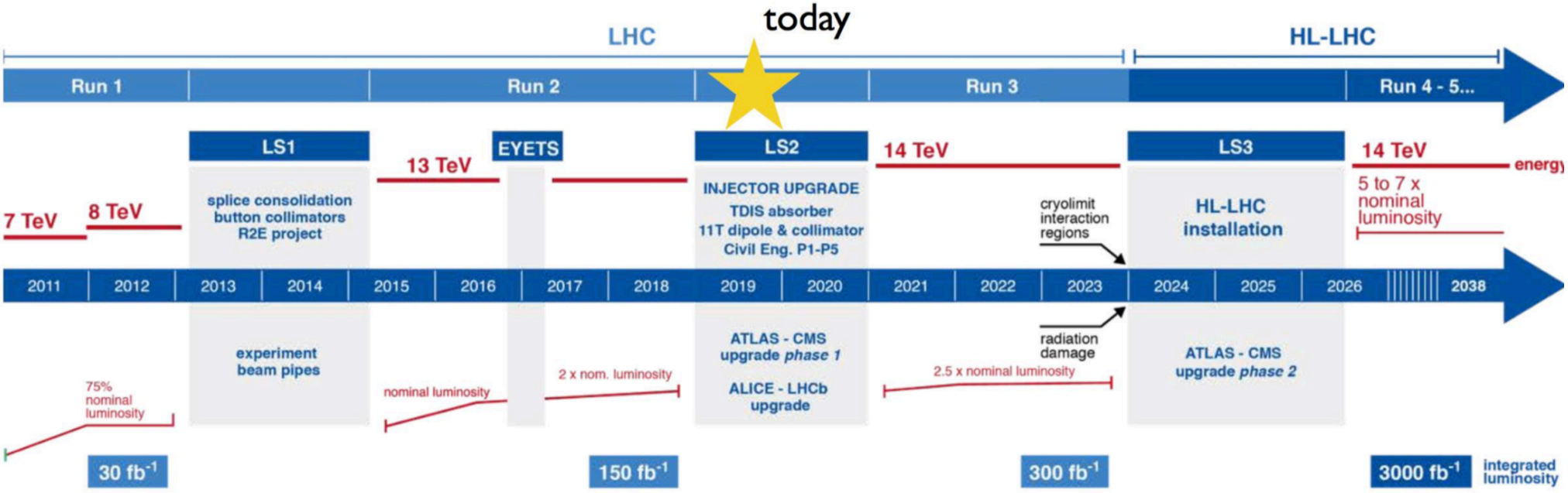
SM as a tool for discovery

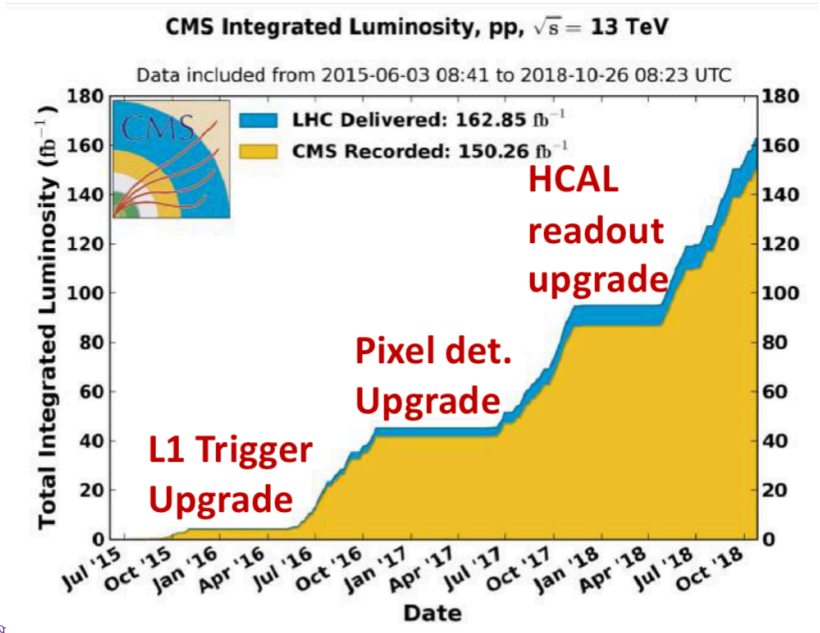
- Direct searches for BSM particles
  - Go in new directions with new models, challenging topologies, enlarged parameter space

Exploring the unknown

Take advantage of state-of-the-art analysis methods, data mining, machine learning, new technologies, upgraded detectors…

LHC long term schedule





Excellent LHC (and CMS) performance: ~140 fb^{-1} good for analysis during Run 2

But 95% of the total LHC data still to come (and be studied)!

Preparation for HL-LHC

Muon System
- new DT FE electronics, CSC FEBs in inner rings
- extended η region (GEM & iRPC)
- investigate Muon-tagging up to η ~ 3

Tracker
- higher granularity
- less material
- better p_T resolution
- extended η region
- tracks trigger at L1

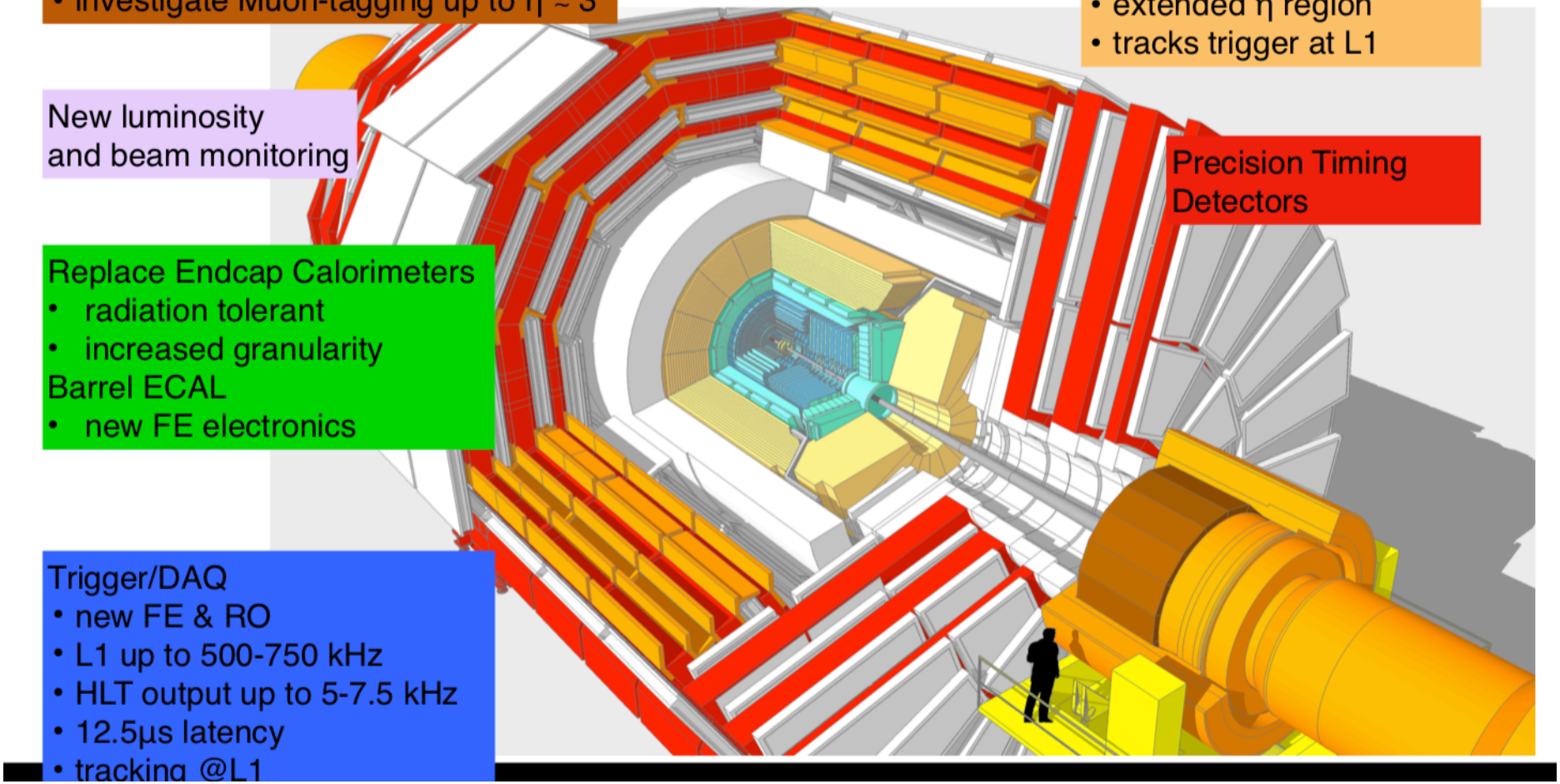
New luminosity and beam monitoring

Precision Timing Detectors

Replace Endcap Calorimeters
- radiation tolerant
- increased granularity

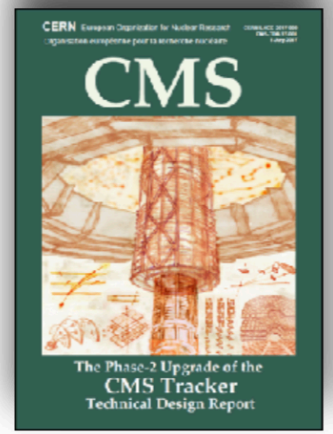
Barrel ECAL
- new FE electronics

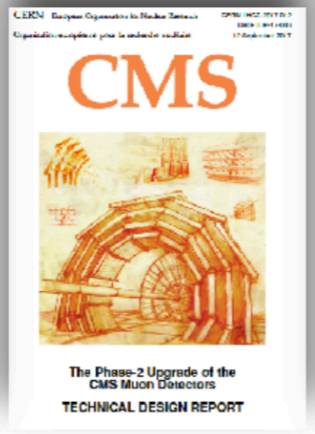
Trigger/DAQ
- new FE & RO
- L1 up to 500-750 kHz
- HLT output up to 5-7.5 kHz
- 12.5μs latency
- tracking @L1

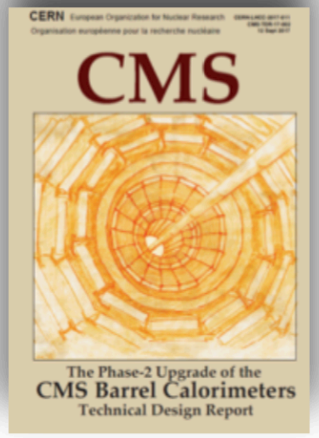


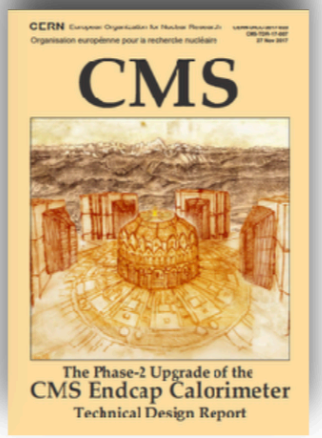
CMS HL-LHC TDRs

Completed









Entering a new phase of engineering, prototyping, construction

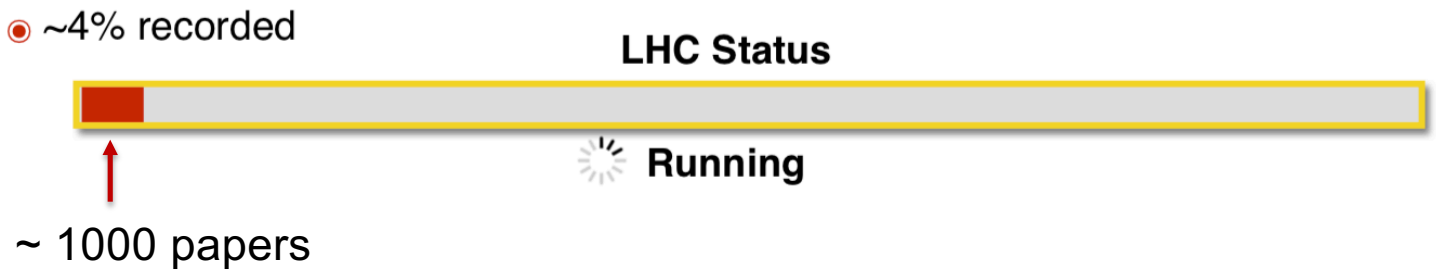
Planned

L1 Trigger	DAQ/HLT	BRIL	Plus
The Phase-2 Upgrade of the CMS Trig Interim Report to the LHCC CMS Collaboration 2020	Interim Technical Design Report for the CMS Phase-2 DAQ Upgrade CMS Collaboration 2021	2020/2021	• PPS (EOI) • Computing (2022)

Last week the CERN Research Board gave the final approval to the MTD TDR

Summary and Outlook

- The ~10 years of LHC operation has been very successful!
  - Discovery of the Higgs boson
  - Using the Higgs as a tool for discovery
- Successful push for high-quality results continues with several important results
- Long(er) term planning for Run 2 analyses is underway
- In parallel, preparations for Run 3 have started
- Considerable effort also on preparations for the HL-LHC run and related physics studies
- LHC (CMS) datasets did grow rapidly in 2018, much more to come



Thank you

Acknowledgement:
Several slides, plots, arguments are borrowed from Wolfgang Adam, Tulika Bose, Markus Klute, Hannsjorg Weber, Roberto Carlin, and many other CMS colleagues … …