CMS Experiment: Status and Perspectives

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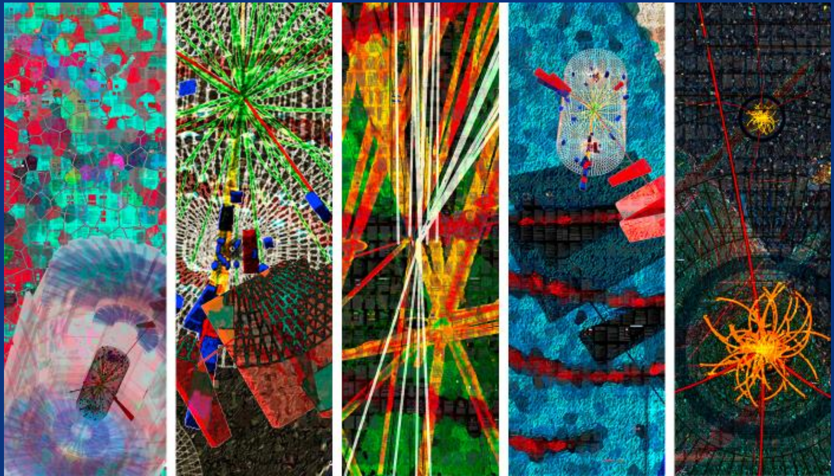
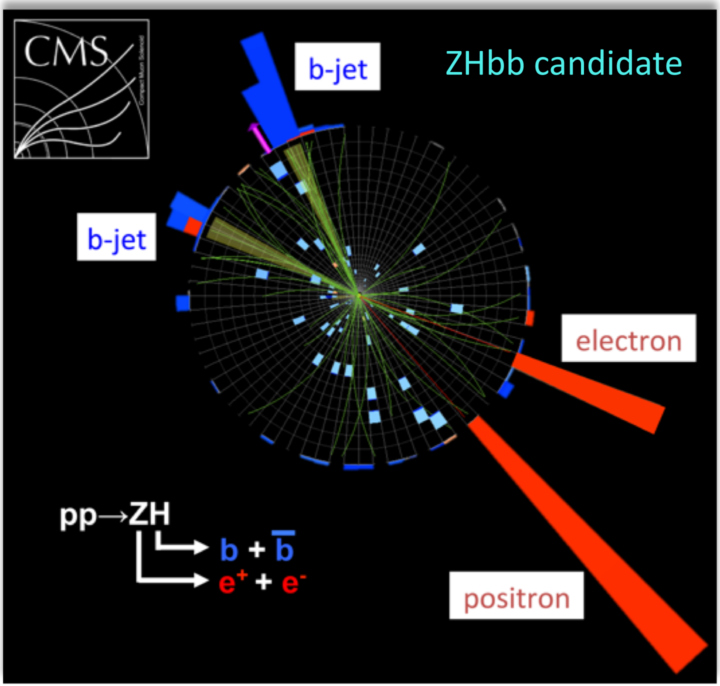
DAE BRNS 2018 conference at IIT Madras, India

Dec. 10, 2018

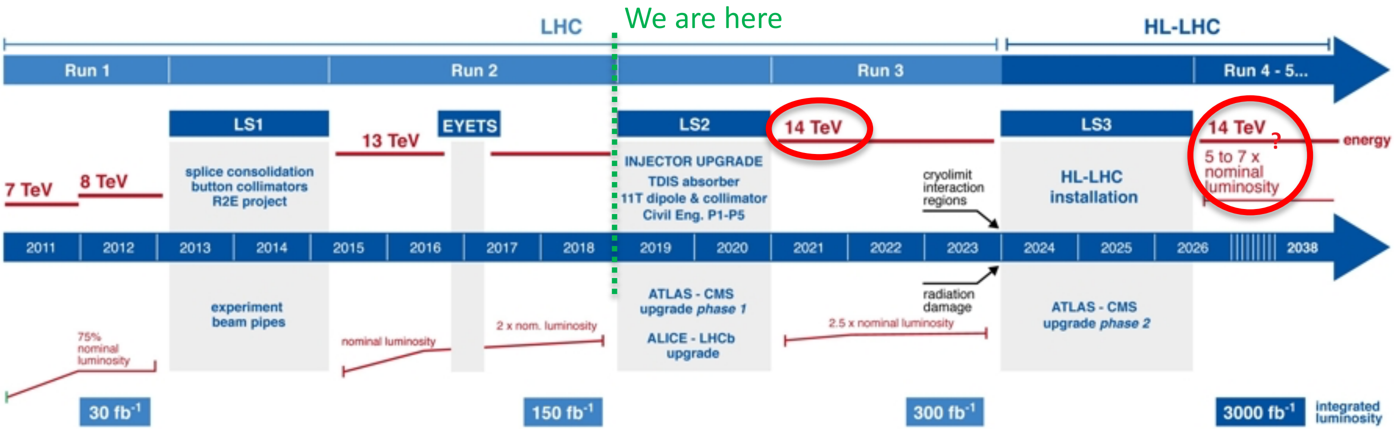


Outline

- CMS in 2018
- Status of publications and highlights of Physics Analyses
- The coming years
- Summary and Outlook



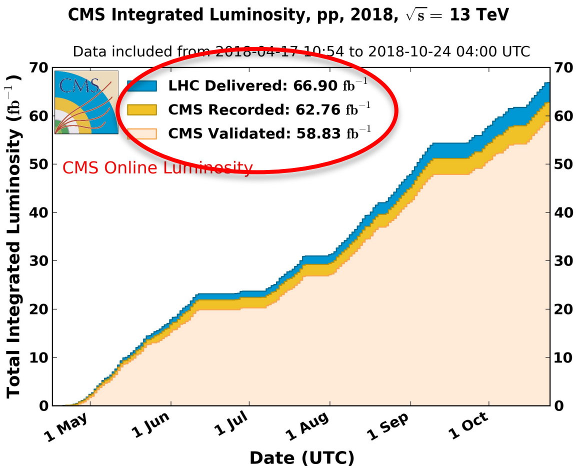
The LHC Luminosity Timeline

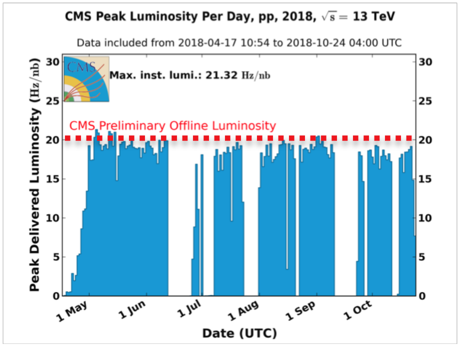


- We are at the end of a very successful pp run at 13 TeV
- We will have another pp run at 14 TeV starting in 2021, where the luminosity should at least double
- Then, after a shutdown for major upgrades, in 2026 LHC will start the high-luminosity run (HL-LHC) where the luminosity will increase x10
- **So far LHC has delivered 5% or less of the total planned integrated luminosity!**

CMS proton-proton run in 2018

- Excellent performance of CMS
  - About 94% recording efficiency, never so high in CMS
  - With peak luminosity grazing 2 10^{34} Hz/cm^2, a factor 2 higher than the initial design

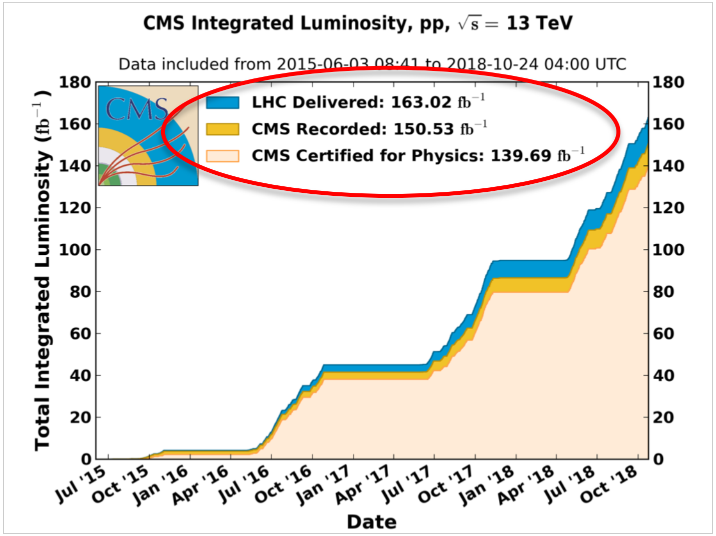




Every time I look at the complexity of CMS, I find astonishing that we can reach these extremely high efficiencies

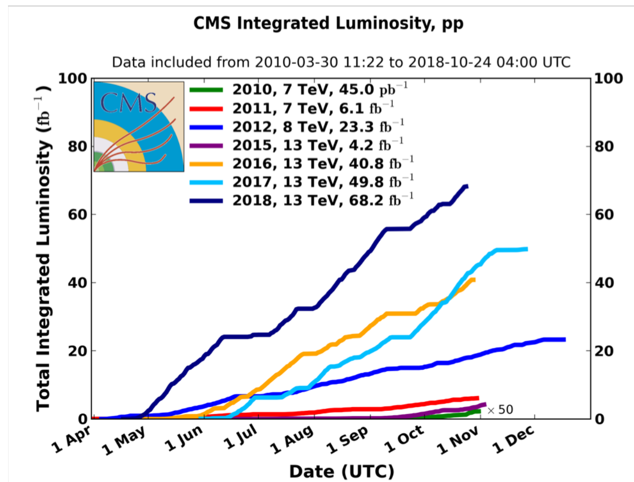
- CMS is a very well built detector, but most of all we have great people working hard to guarantee such a smooth performances

Run 2 pp final score



- Final score is:
  - 68.2 fb^{-1} (offline preliminary) delivered to CMS in 2018
  - 163 fb^{-1} delivered overall in Run 2
  - 192.5 fb^{-1} from 2010

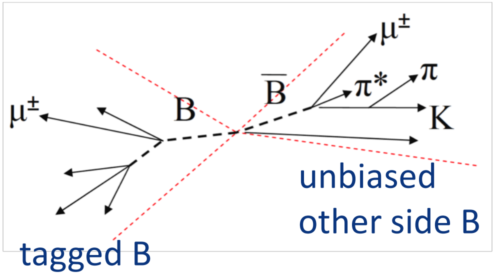
A large dataset to analyse in the coming years, before starting again in 2021

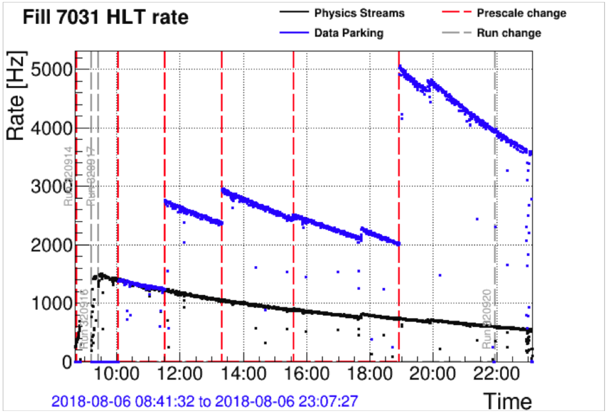


B parking

Plan: store a large unbiased B hadron sample by tagging on the «opposite side» B

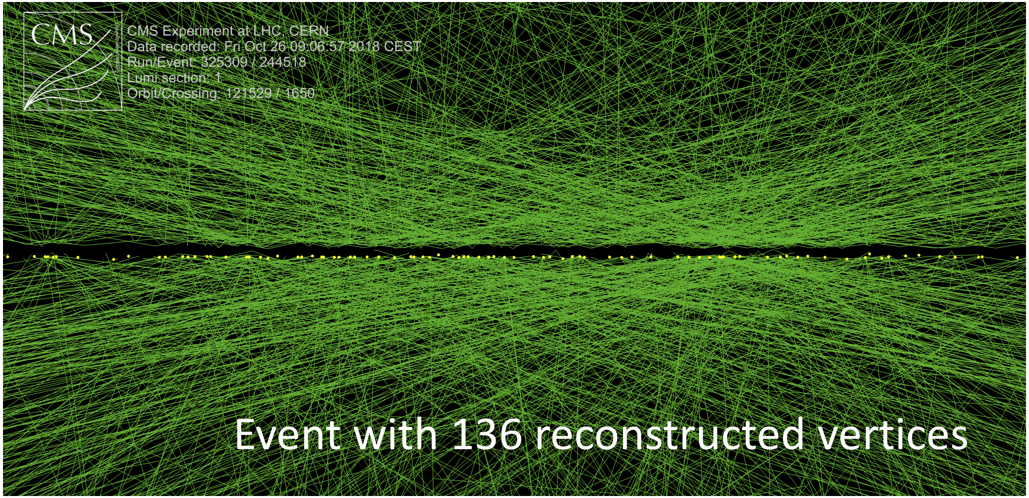
- CMS parked (→ no prompt reconstruction) 12 billions of B triggers
- Fit with present computing resources, no additional requests
- Now working on improved reconstruction, in particular for low p_T electrons, to enhance the sensitivity to rare decays and flavour anomalies





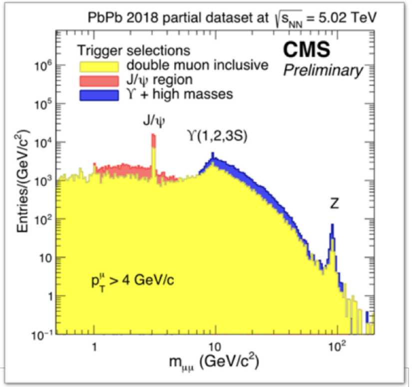
High Pile-Up events

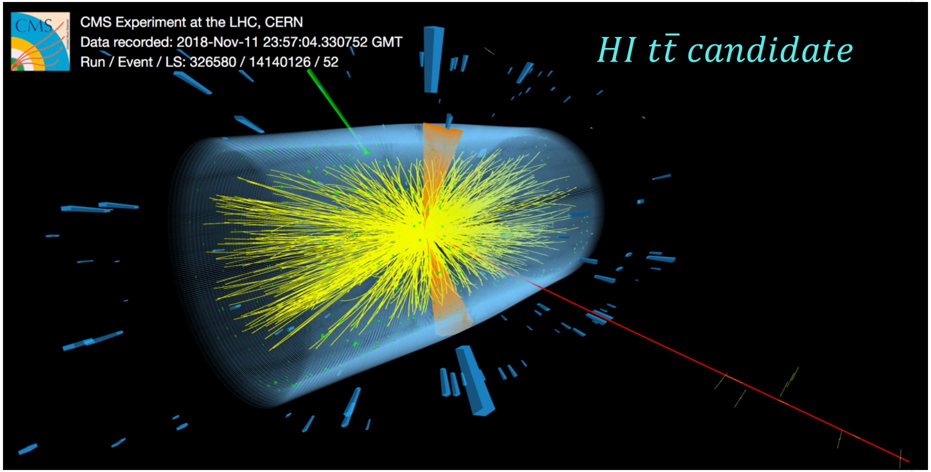
- LHC has provided a short run with few high intensity bunch trains
- CMS took data successfully with pile-up > 120
  - Outlook to what we will see after the HL-LHC upgrade

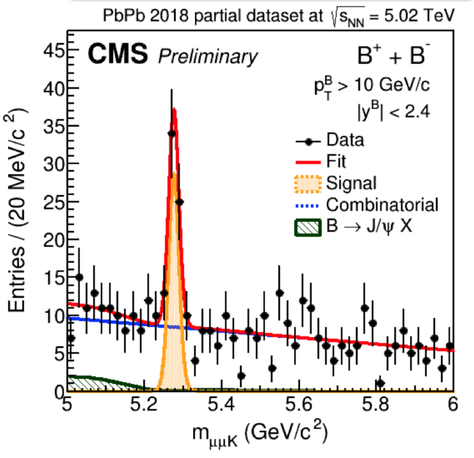


Pb Pb Heavy Ion run ended recently

- We got collected 1.80 nb^{-1}, almost 4 times more than the latest run in 2015
- And more than 4 billions minimum bias triggers
- Data quality looks very good

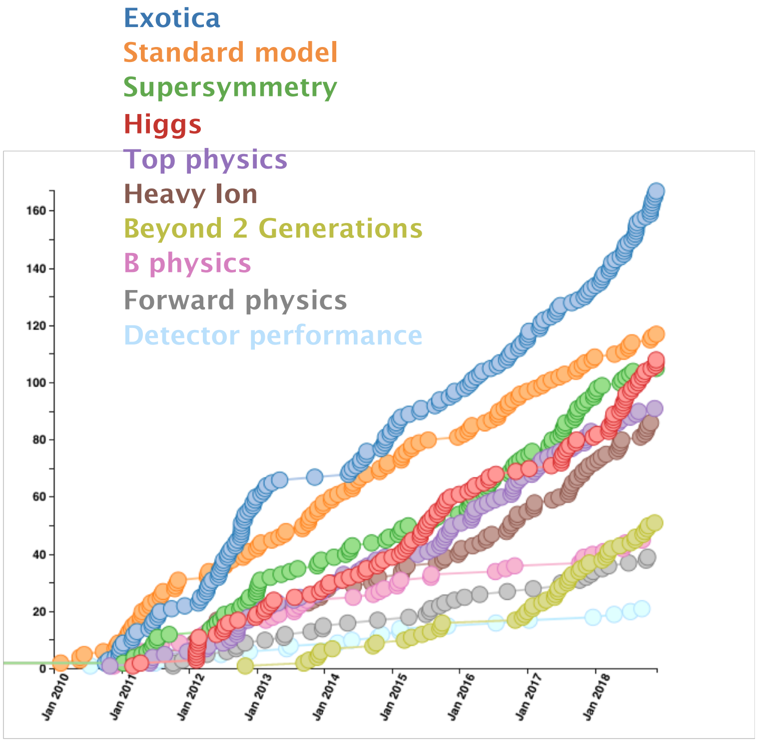






Status of publications and highlights of Physics Analyses

CMS Publications

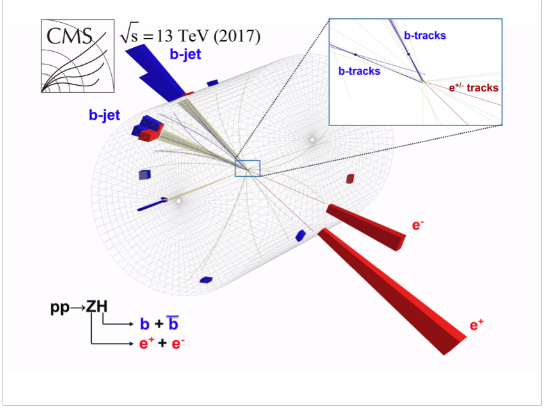


CMS has submitted, as of last week, 829 publications on collisions data in a wide variety of physics (and detector) topics.

- Staggering publication rate: 104 per year since Jan 2010, and growing
- 126 publications in 2018 so far
- 265 Run 2 publications

2018 is the year of the Yukawa couplings

- This summer CMS and ATLAS, presented the **observation** of the Higgs boson coupling to b quarks. With the recent observation of the couplings to τ lepton and top quark, we completed the observation of the coupling to 3rd generation fermions
  - A great success of LHC and the experiments, much earlier than expected thanks to the outstanding performance of LHC but also to very refined analysis techniques



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

$$+|D_\mu\phi|^2 - V(H)$$

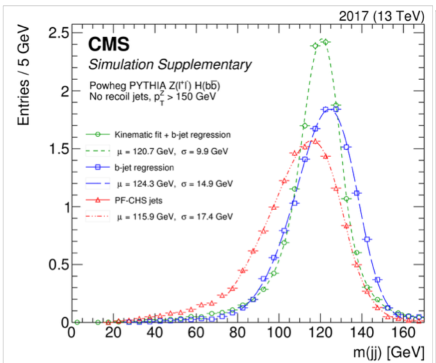
$$+Y_{ij}\psi_i\psi_j\phi + \mathrm{h.c.}$$

Observation of H→bb

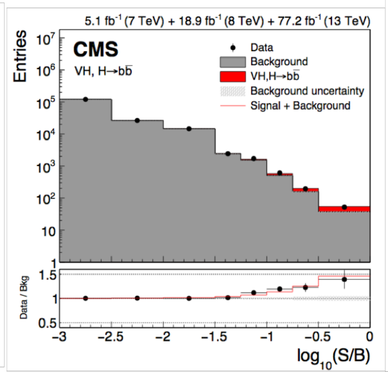
Phys. Rev. Lett. 121, 121801

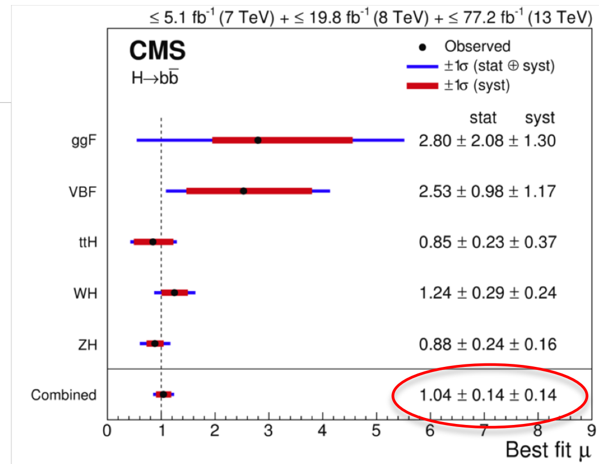
- improved VH(bb) analysis with 2017 data
  - among others: better b-jet identification, energy regression for b jets, use of deep neural networks for these items and S/B discrimination
- combination VH(bb): 4.8σ observed; all production modes: 5.6σ observed

Z(→ℓℓ) H(→bb)



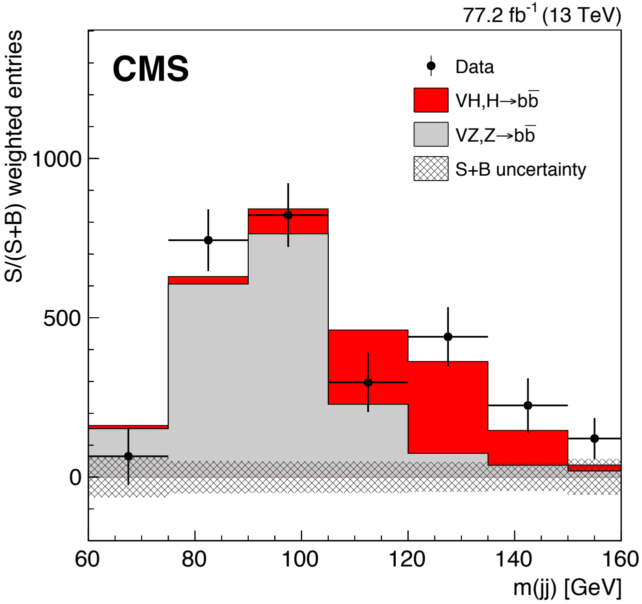
VH, H(→bb)





bb mass distribution

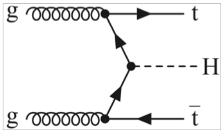
- Instead of DNN output, analyse M(bb) to visualize signal.
- Signal strengths compatible with main analysis.

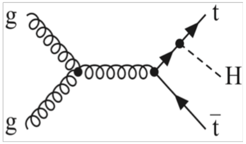


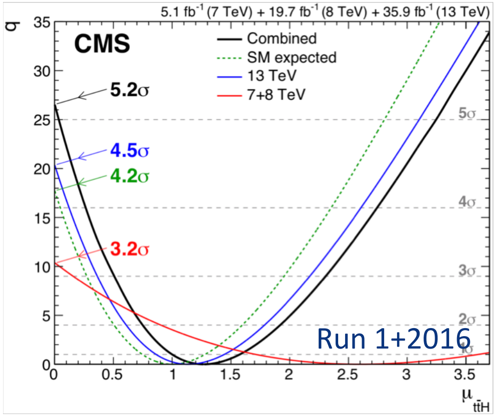
2016+2017

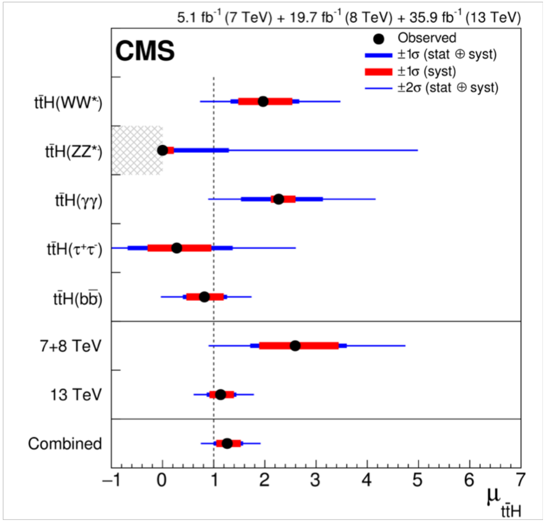
Observation of ttH production: 7, 8 and 13 TeV combined

Phys. Rev Lett. 120 (2018) 231801









$$\mu_{ttH} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat.})\,^{+0.17}_{-0.15}(\text{exp.})\,^{+0.14}_{-0.13}(\text{bkg. th.})\,^{+0.15}_{-0.07}(\text{sig. th.})$$

Observed significance is 5.2σ [4.2σ expected] with respect to the background-only hypothesis ($\mu_{t\bar{t}H} = 0$)

Overall signal strength μ_{ttH} **compatible with SM within 1σ**

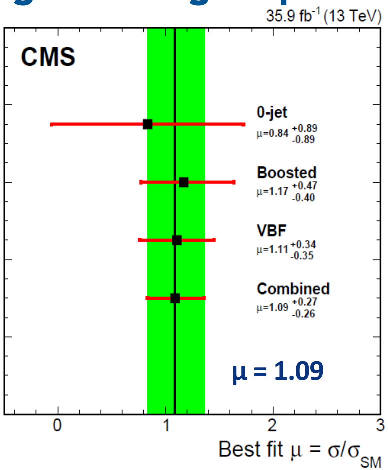
- **Only tt$(H \to ZZ, \gamma\gamma)$ still dominated by statistics uncertainties**

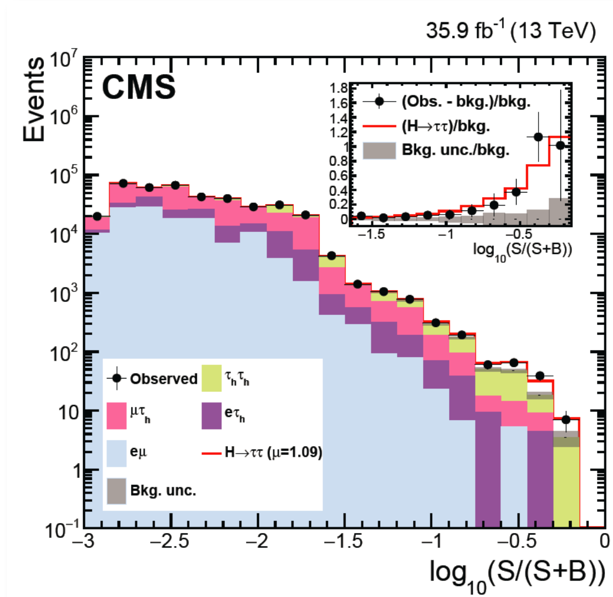
Observation of H → $\tau^+\tau^-$ using 7, 8, and 13 TeV data

PLB 779 (2018) 283

- **Combination with 7, 8 TeV data: 5.9σ obs. (5.9σ exp.) and μ = 0.98 ± 0.18**

"signal strength" $\mu = \sigma/\sigma_{SM}$



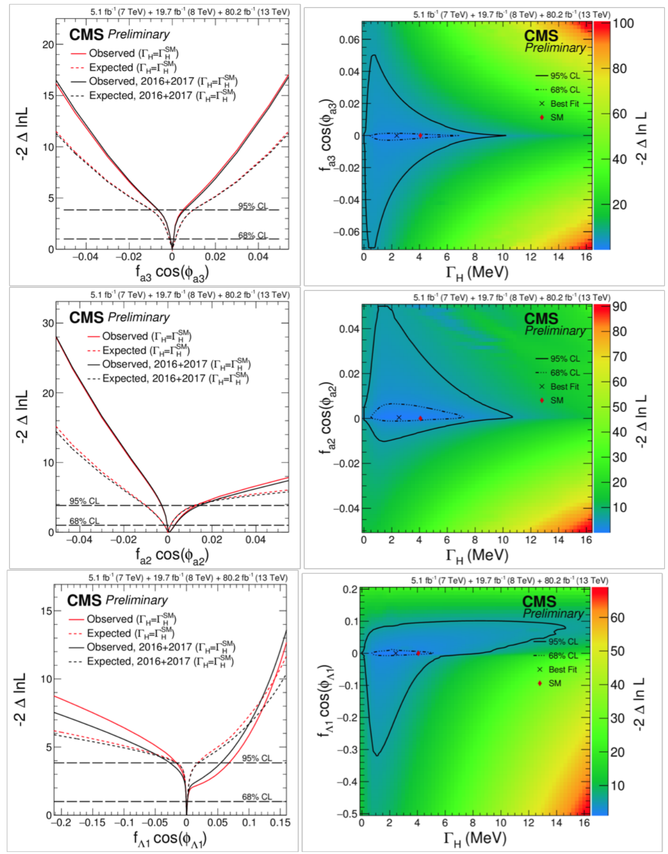


First direct observation of H coupling to leptons and to fermions of the 3rd generation!

2016

Higgs boson properties

HIG-18-02: Measurements of Higgs boson properties from on-shell and off-shell production in the four-lepton final state



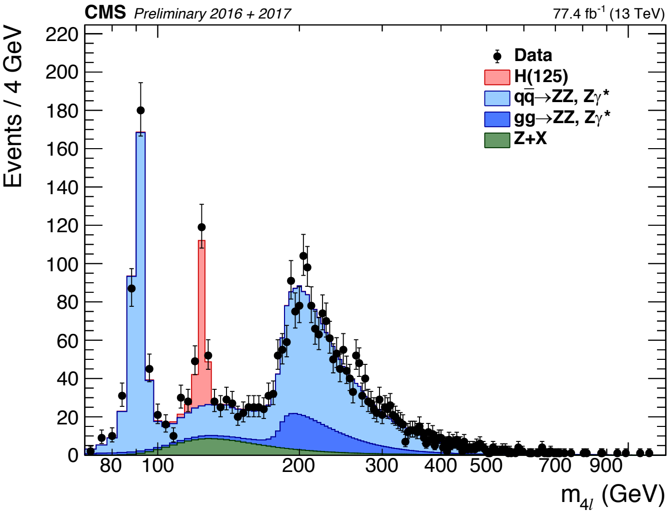
Higgs boson being studied in detail:

- Analysis using the 2016+2017 Run 2 data, and also Run 1 (7+8 TeV) to tests the properties of Higgs boson, such as its **width and anomalous HVV couplings**
- **Includes 2017 data**

$H \to ZZ^* \to 4l$

CMS-PAS-HIG-18-001

- One of the Higgs boson "discovery" channels
- Low statistics but clean signal from the combined 77.3 fb^{-1} dataset (2016+2017)
  - 2017 analysis improved with upgraded detector, new multivariate tool for better electron ID, new discriminant for enhanced VH and VBF categories, new categories targeting ttH production



Signal strength for the combined 2016-2017 CMS $H \to 4l$ measurement:

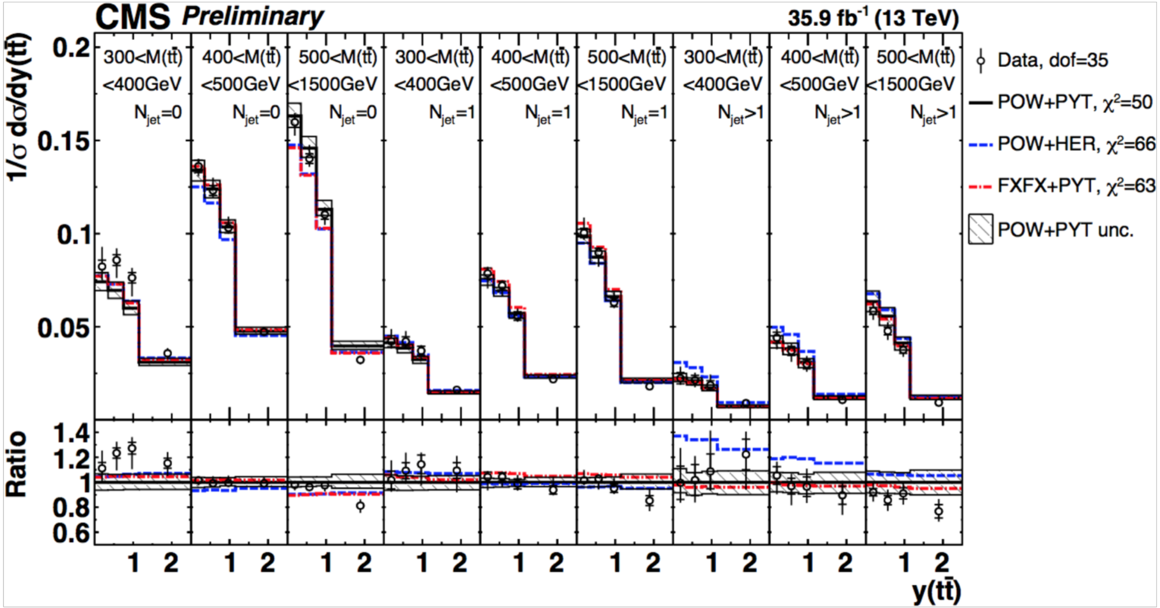
$$\mu = \frac{\sigma}{\sigma_{SM}} = 1.06^{+0.15}_{-0.13} = 1.06^{+0.10}_{-0.10}(\text{stat.})\ ^{+0.08}_{-0.06}(\text{sys. exp.})\ ^{+0.07}_{-0.05}(\text{sys. th.})$$

In very good agreement with Standard Model

2016+2017

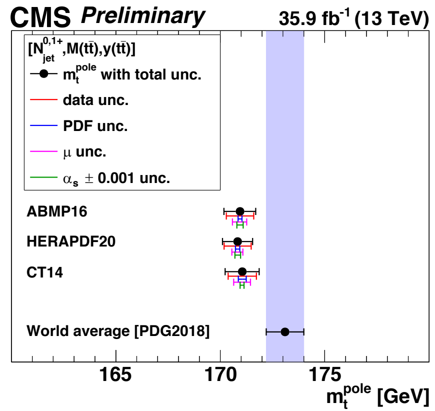
top physics

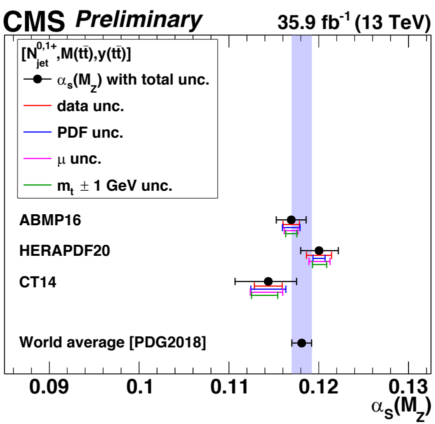
- Measurements of ttbar production cross sections taken to a new level of precision with **multi-differential measurements**
  - Can be exploited to extract → α_S, m_t^{pole}, PDFs



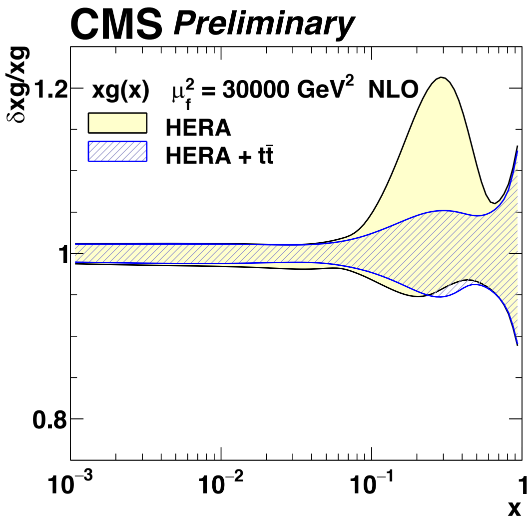
3D cross sections $[N^{0,1,2+}_{jet}, M(t\bar{t}), y(t\bar{t})]$

top physics





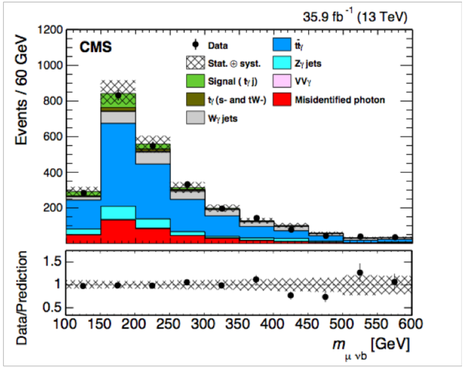
The α_S , m_t^{pole} values extracted at NLO using different PDFs, and the relative gluon PDF uncertainties showing a significant impact at large x

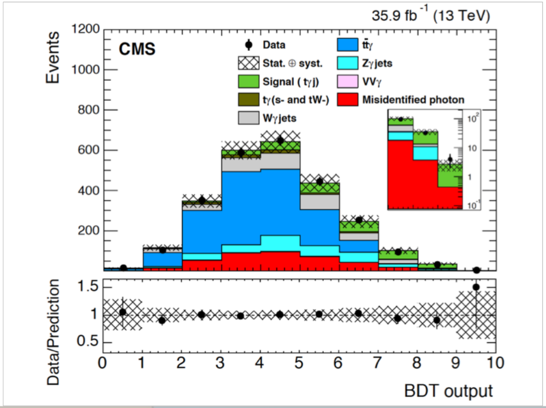


Phys. Rev. Lett. 121, 221802

top physics

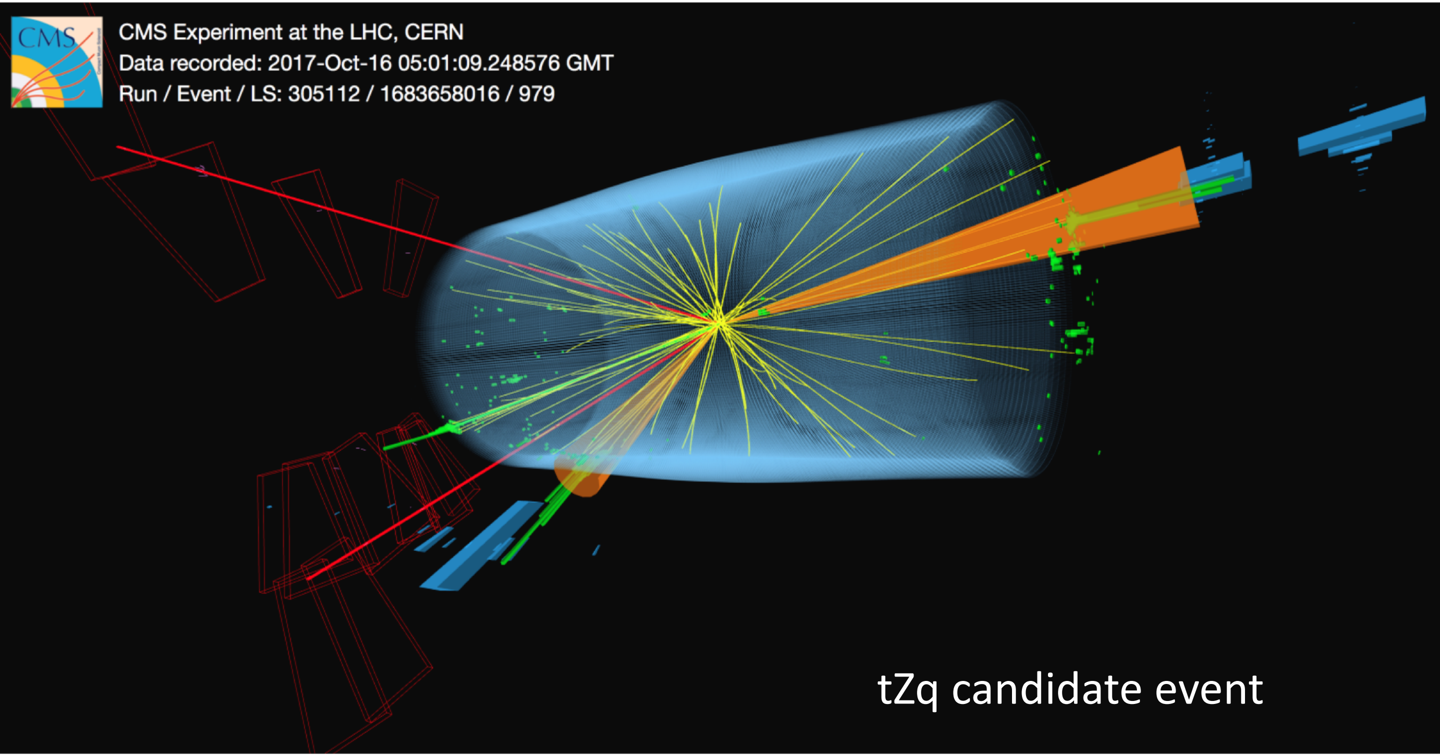
- First evidence for single-top production associated with a photon
  - in events with a top decay to b$\mu\nu$, at least one more jet, and a photon
    - event selection based on a boosted decision tree combining eight variables
  - evidence at 4.4σ observed, the measured σ*BR is compatible with the SM prediction: $\boldsymbol{\sigma(pp \rightarrow t\gamma j)\mathcal{B}(t \rightarrow \mu\nu b) = 115 \pm 17(stat) \pm 30(syst) fb}$



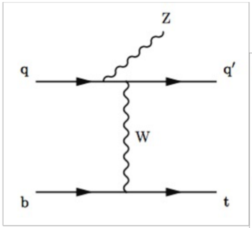


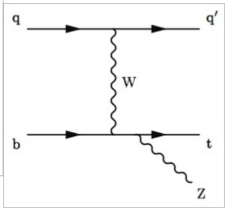
2016

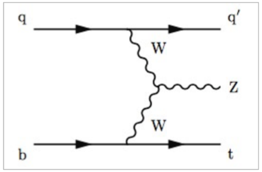
Observation of tZq production



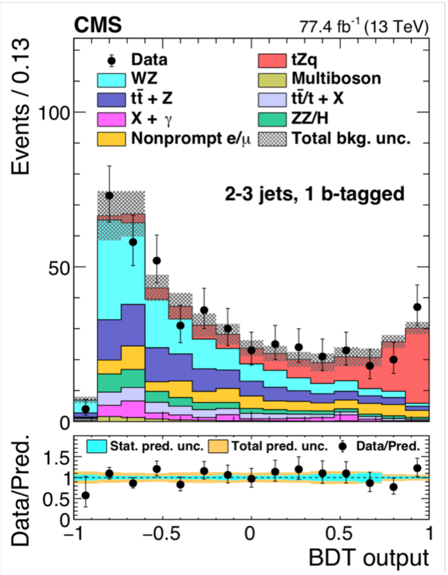
Observation of tZq production







- Rare SM process
  - Sensitive to t-Z coupling, FCNCs, triple WWZ coupling
  - Signal: 3,leptons,and at least 2 jets (incl.1 b jet)
  - BDT based lepton selection and optimized analysis
  - Strategy leads to significance well above 5σ



$$\mu = 1.18^{+0.14}_{-0.13}(\text{stat})\ ^{+0.11}_{-0.10}(\text{sys})$$

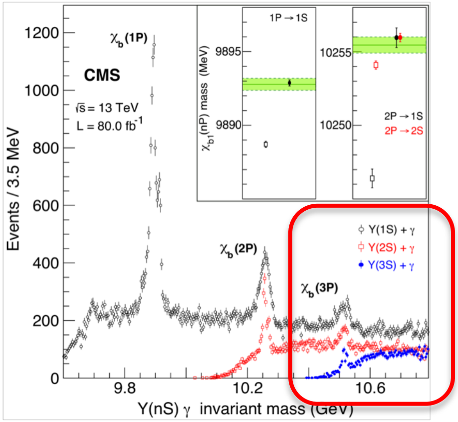
$$\sigma(\text{tZq} \to \text{t}\ell^+\ell^-\text{q}) = 111\ ^{+13}_{-13}\,(\text{stat})\ ^{+11}_{-9}\,(\text{syst})\ \text{fb}$$

Next, differential cross sections

Observation of the states $\chi_{b1}(3P)$ & $\chi_{b2}(3P)$

PRL 121 (2018) 09200

$\chi_b(3P)$ $b\bar{b}$ state has been discovered by ATLAS in 2011 and observed by D0 and LHCb

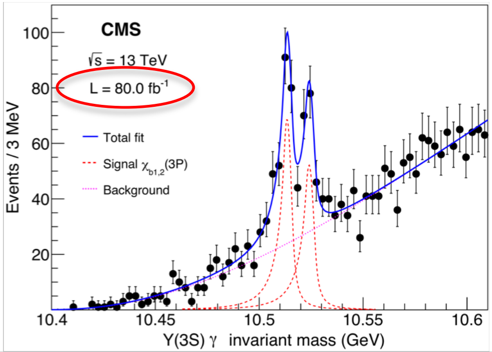


$\chi_b(3P)$ is measured through the radiative decay $\chi_b(3P) \rightarrow \Upsilon(3S)\gamma \rightarrow \mu\mu\gamma$

- Low statistics but best resolution for the low energy γ converted to e^+e^- pair in the silicon tracker

For the first time the two states $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$, corresponding to J=1,2, are resolved

- The mass difference is measured to be: $\Delta M = 10.60 \pm 0.64(\text{stat.}) \pm 0.17(\text{syst.})\ \text{MeV}$
- Predictions from non-perturbative QCD range from -2 to 18 MeV



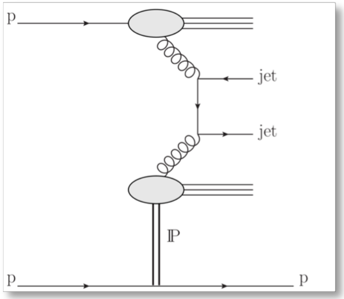
2015+2016+2017

Dijet with leading proton

FSQ-12-033 + TOTEM-NOTE-2018-001

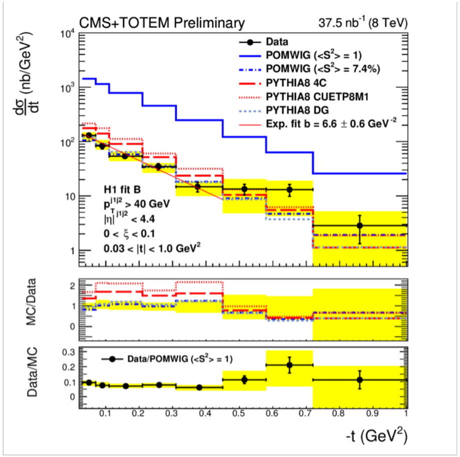
Joint CMS+TOTEM measurement of dijet production cross section with leading proton, from a β^*=90m run at 8 TeV (37.5 nb^{-1})

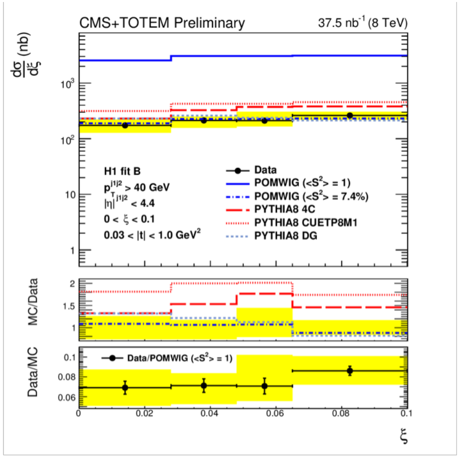
- Cross section and differential cross sections measured



σ^{pX}_{jj} = 21.7 ± 0.9 (stat) $^{+3.0}_{-3.3}$ (syst) ± 0.9 (lumi) nb.

(p_T > 40 GeV, |η| < 4.4, ξ < 0.1 and 0.03 < |t| < 1 GeV_2)

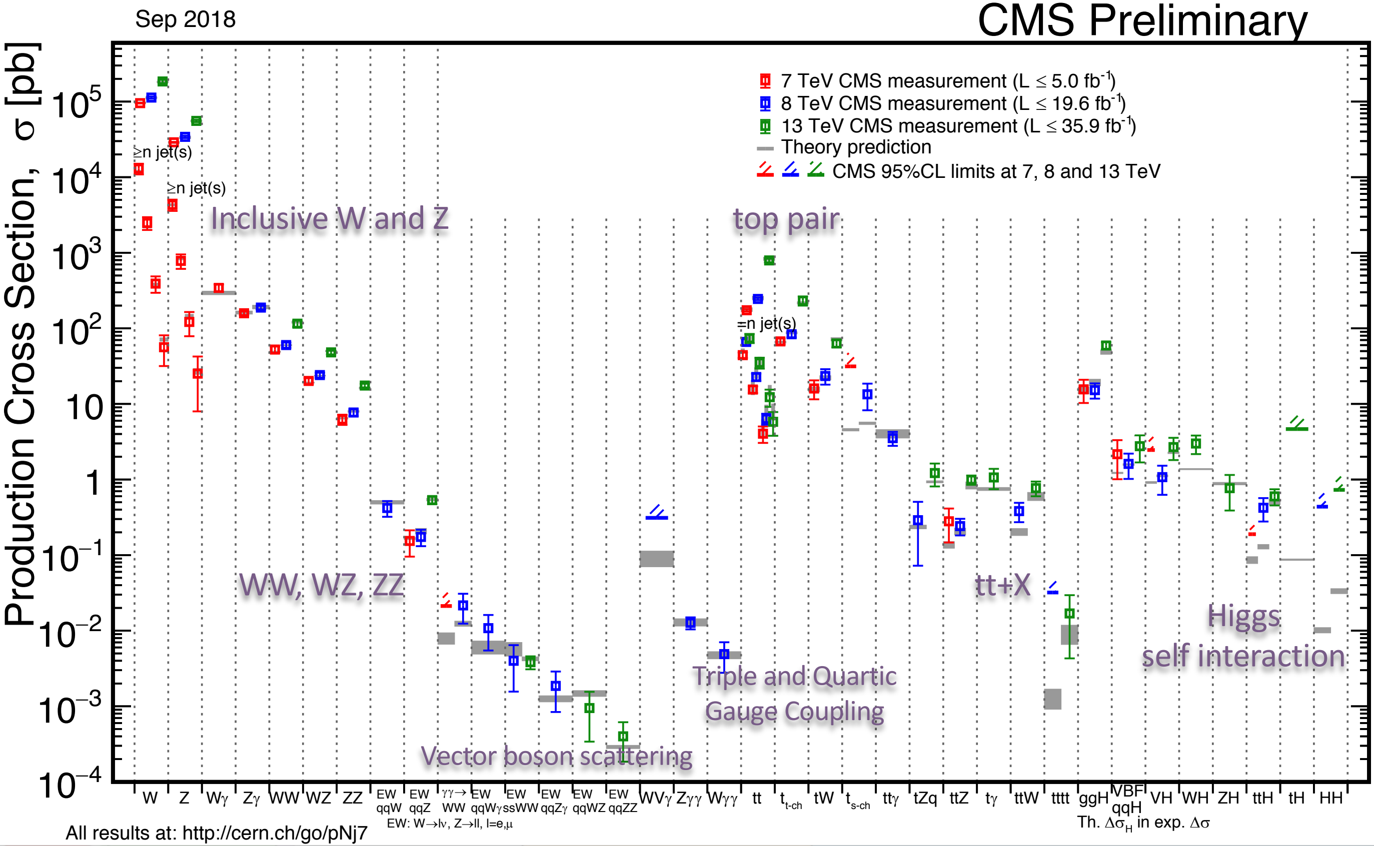




$$t = (p_f - p_i)^2$$

$$\xi = 1 - \frac{|p_f|}{|p_i|}$$

SM cross sections range at LHC

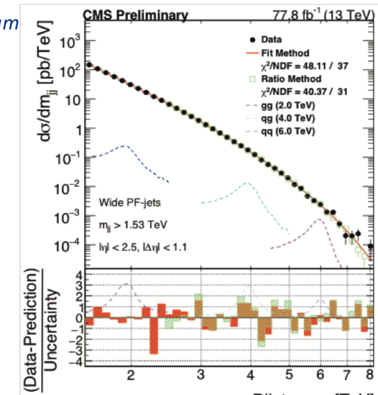


High-mass di-jet resonances

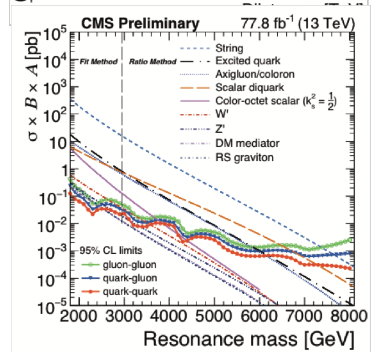
PAS-EXO-17-026

- Di-jet resonances with 2016+2017 data-sets
  - Improved analysis methods: complement parametric background estimation with prediction from high $\Delta\eta$ sideband
    - reduces systematics
    - used at higher resonance masses
  - Interpretations in a variety of models
  - Extends limits obtained with 2016 data

Dijet mass spectrum with background predictions



Model-independent upper limits compared to predicted cross sections

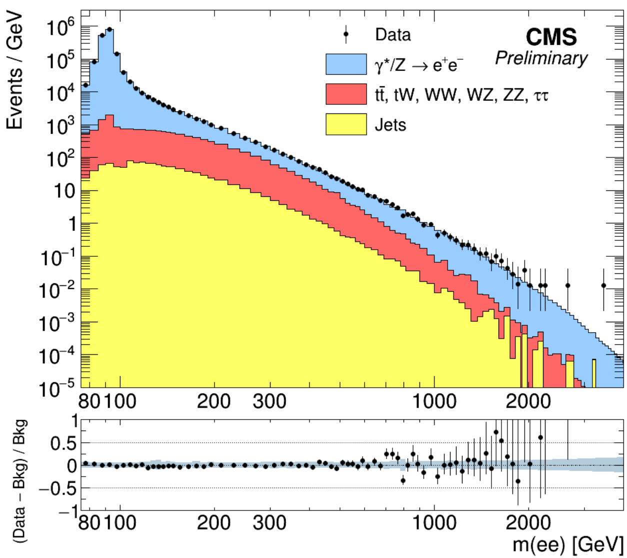


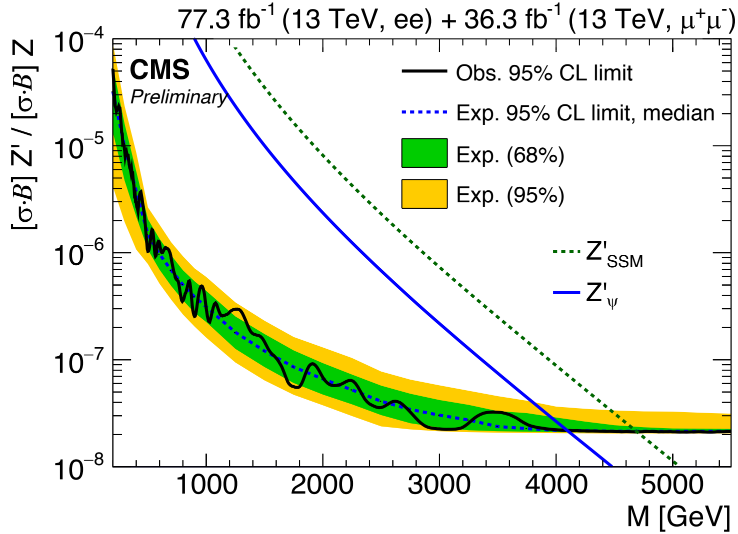
2016+2017

Searches for high-mass di-electron resonances

CMS-PAS-EXO-18-006

First 2017 analysis presented





Channel	Model	Obs. limit (TeV)	Exp. limit (TeV)
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_{ψ}	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_{ψ}	4.1	4.1

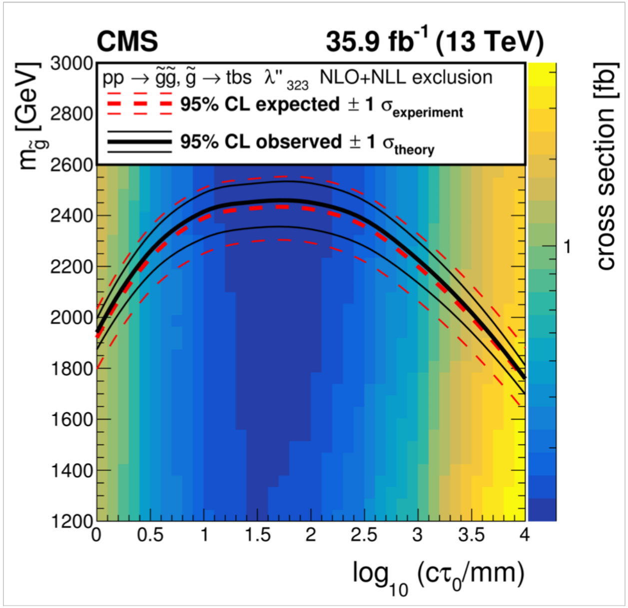
Limits for high mass searches extending beyond 4 TeV

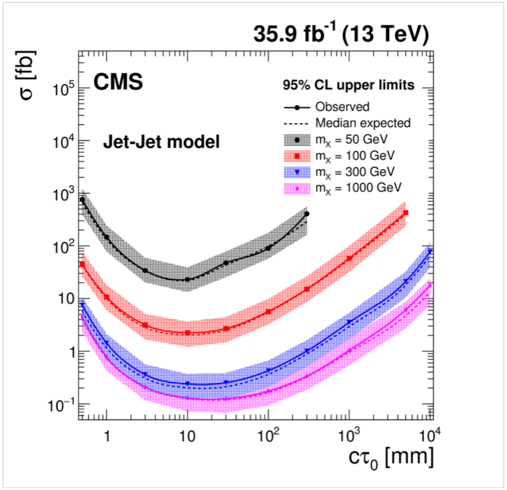
2017

Displaced jets

arXiv:1811.07991

Search for long-lived particles decaying into displaced jets in proton-proton collisions at √s = 13 TeV





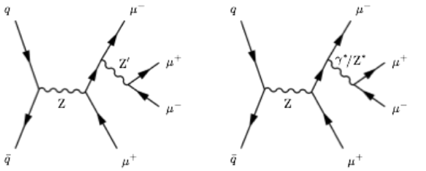
- Several models with long-lived particles, including gluinos or top squarks, with displaced jets in the final states tested, limits set

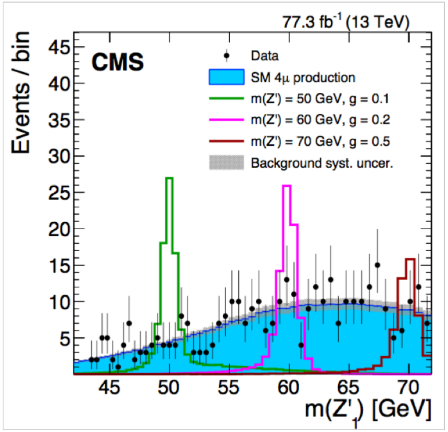
Additional light gauge bosons

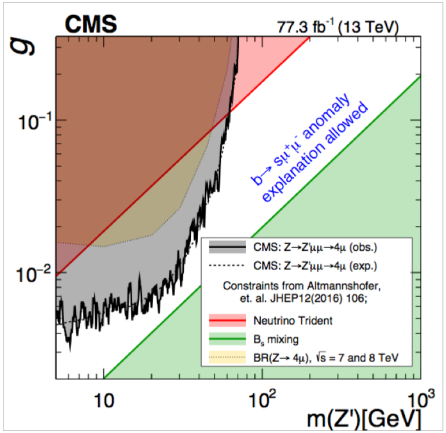
EXO-18-008, arXiv:1808.03684, subm. to PLB

Search for a narrow Z′ boson with a Lμ-Lτ symmetry

- proposed in several contexts, including as an explanation of Lepton Flavor Universality violations and of muon g-2 anomalies
- search in events with 4 muons compatible with M(Z) in 2016+2017 data
- excluding products of BRs (Z→$\mu\mu$, Z′→$\mu\mu$) above 10^{-8}-10^{-7}





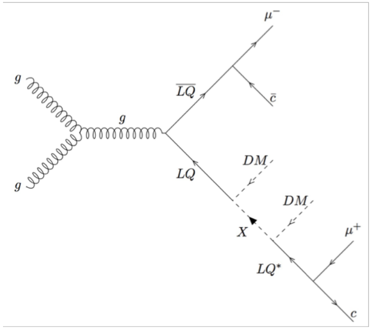


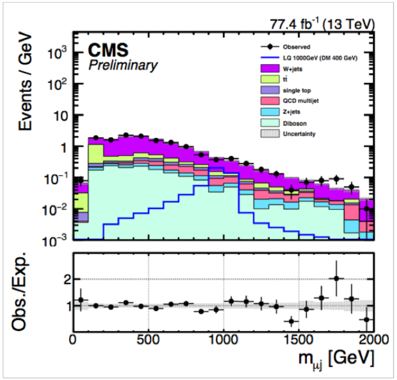
2016+2017

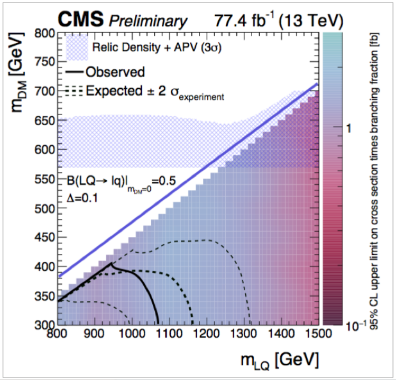
Search for DM: LQ + MET

PAS-EXO-17-015 arXiv: 1811:10151 Sub to PLB

- Search for DM in final states with a LQ and E_T^{miss}
  - DM produced with a co-annihilation partner (here a Maiorana fermion), mediator: LQ coupling to 2nd generation only
  - search in events with at least one muon and E_t^{miss}, look for a LQ mass peak in $m_{\mu j}$
  - no excess observed





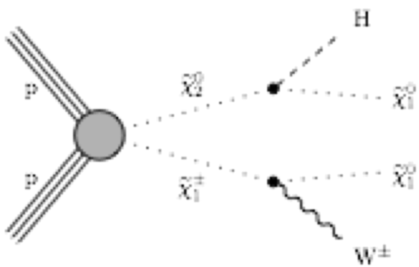


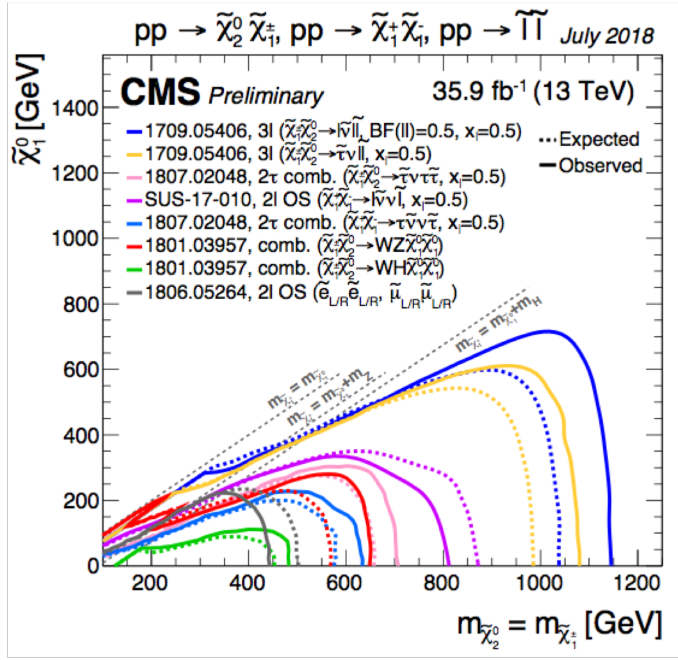
2016+2017

Supersymmetry

JHEP 03 (2018) 160

- Among several searches, also Higgs boson now used to probe electroweak production of supersymmetry
  - In just 6 years from discovery to Higgs tagging

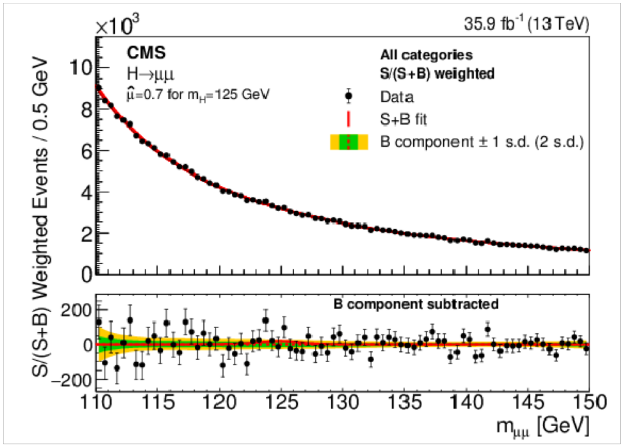


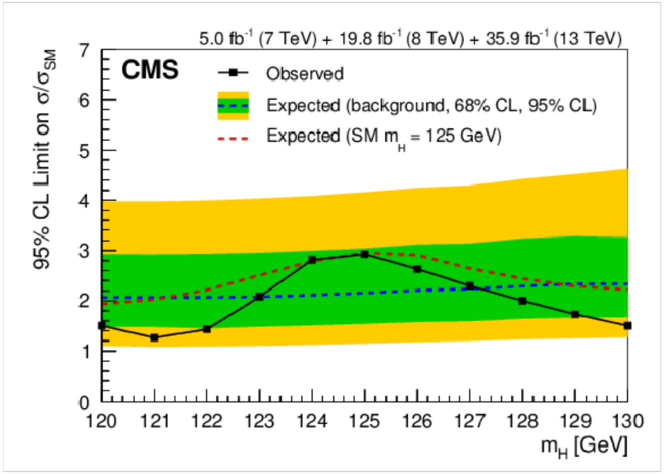


2016

Higgs to two muons

arXiv:1807.06325 , Accepted by PRL





Already tackling H →μμ thanks to excellent detector performance

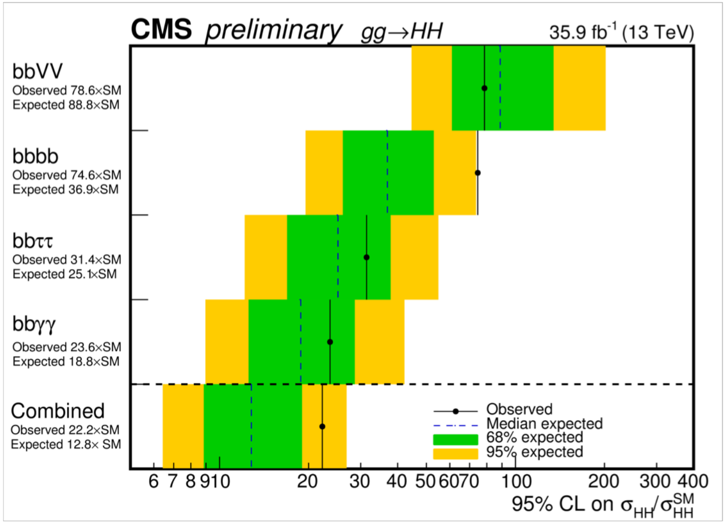
- Looking forward to updated result with > 150 fb^{-1}

2016

Upper limit on the SM Higgs branching fraction to muons of 6.4 x 10^{-4}. UL observed (expected) is 2.92 (2.16) times the SM value.

Higgs boson pair production

PAS-HIG-17-030



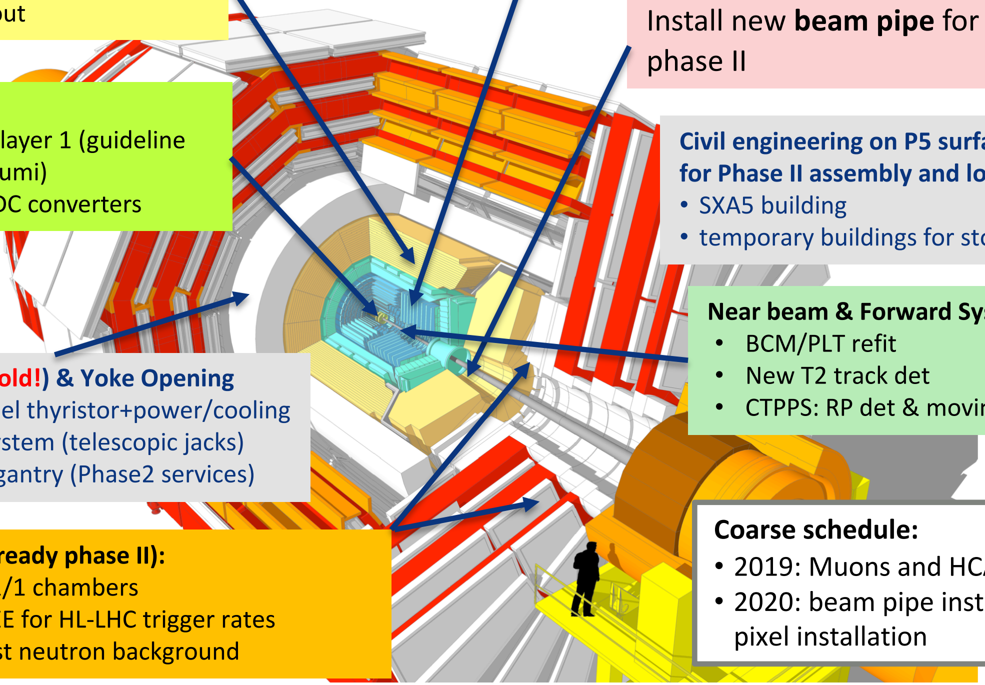
Observed (expected) 95% confidence level upper limit corresponds to 22.2 (12.8) times the prediction for the SM cross section.

95% confidence level exclusion limits on the SM non-resonant Higgs boson pair production cross section.

2016

The coming years

A challenging shutdown in the next 2 years



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

HCAL barrel (last phase I): install SiPM+QIE11-based 5Gbps readout

Install new **beam pipe** for phase II

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

Civil engineering on P5 surface to prepare for Phase II assembly and logistics
- SXA5 building
- temporary buildings for storage/utility

Near beam & Forward Systems
- BCM/PLT refit
- New T2 track det
- CTPPS: RP det & moving sys upgrade

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

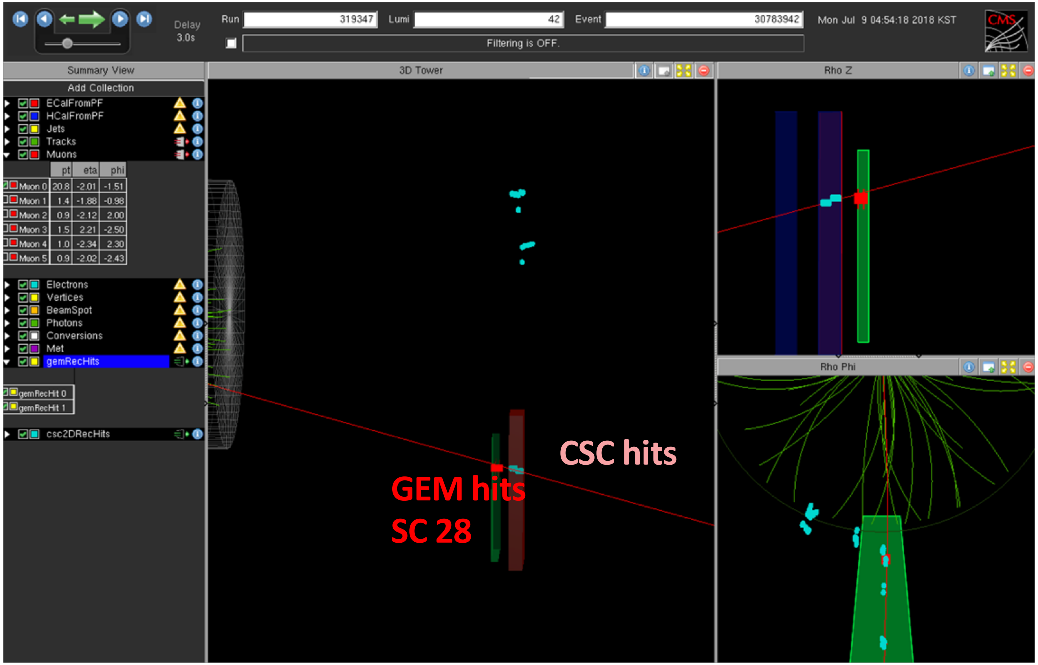
Muon system (already phase II):
- install GEM GE1/1 chambers
- Upgrade CSC FEE for HL-LHC trigger rates
- Shielding against neutron background

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

GE1/1 production

Very significant contribution from India!

GE1/1 slice in CMS



The GE1/1 slice is integrated in CMS runs. The GE1/1 will be the first Phase II detector to be integrated in CMS, already in 2019-20

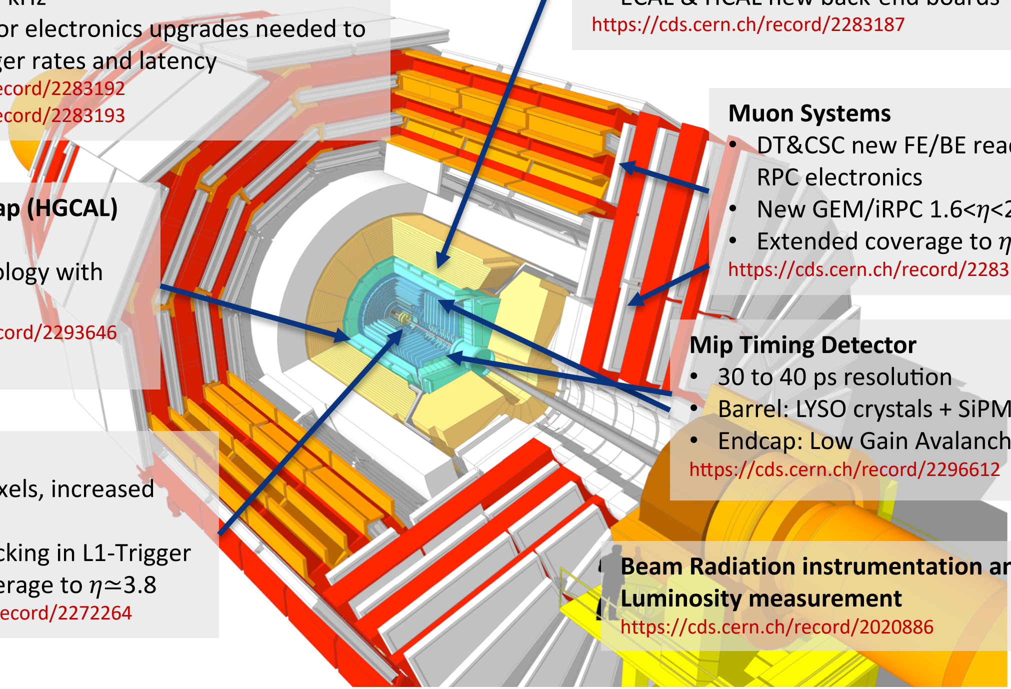
CMS Phase-II upgrades for HL-LHC

L1-Trigger/HLT/DAQ
- Tracks in L1-trigger at 40MHz for 750 kHz PFlow-line selection rate
- Latency up to 12.5 μs
- HLT output 7.5 kHz
- Several detector electronics upgrades needed to cope with trigger rates and latency

https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

Barrel Calorimeters
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30GeV
- Low operating temperature $\simeq$ 10C
- ECAL & HCAL new back-end boards

https://cds.cern.ch/record/2283187



Muon Systems
- DT&CSC new FE/BE readout, new RPC electronics
- New GEM/iRPC 1.6<η<2.4
- Extended coverage to $\eta\simeq3$

https://cds.cern.ch/record/2283189

Calorimeter Endcap (HGCAL)
- Si, Scint+SiPM
- 3D shower topology with precise timing

https://cds.cern.ch/record/2293646

Mip Timing Detector
- 30 to 40 ps resolution
- Barrel: LYSO crystals + SiPMs
- Endcap: Low Gain Avalanche Diodes

https://cds.cern.ch/record/2296612

Tracker
- Si-Strip and pixels, increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta\simeq3.8$

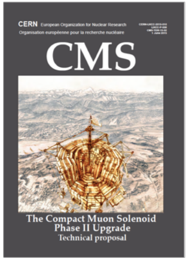
https://cds.cern.ch/record/2272264

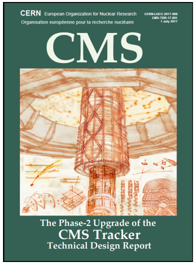
Beam Radiation instrumentation and Luminosity measurement

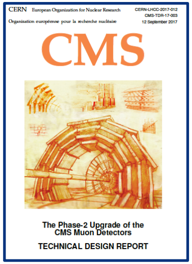
https://cds.cern.ch/record/2020886

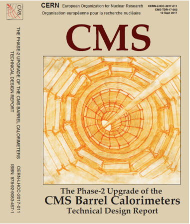
CMS is proud of the design of an upgrade with many innovative detectors

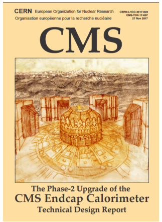
- **Tracker** is AGAIN ALL SILICON but now with much higher granularity, **and out to |η| =4** with >2 billion pixels and strips
  - Tracker designed to find all tracks with P_T>~2 GeV < 4 μs.
  - Tracking information in "L1 track-trigger"
- **High Granularity Endcap Calorimeters**
  - With combination of silicon pixels and scintillator to map full 3-dimensional development of all showers (~6M channels in all)
- **Precision timing of all objects**, including single charged tracks, provides a 4th dimension to CMS object reconstruction to combat pileup
- **Extended muon coverage** up to η < 3 and ability to trigger on long-lived particles



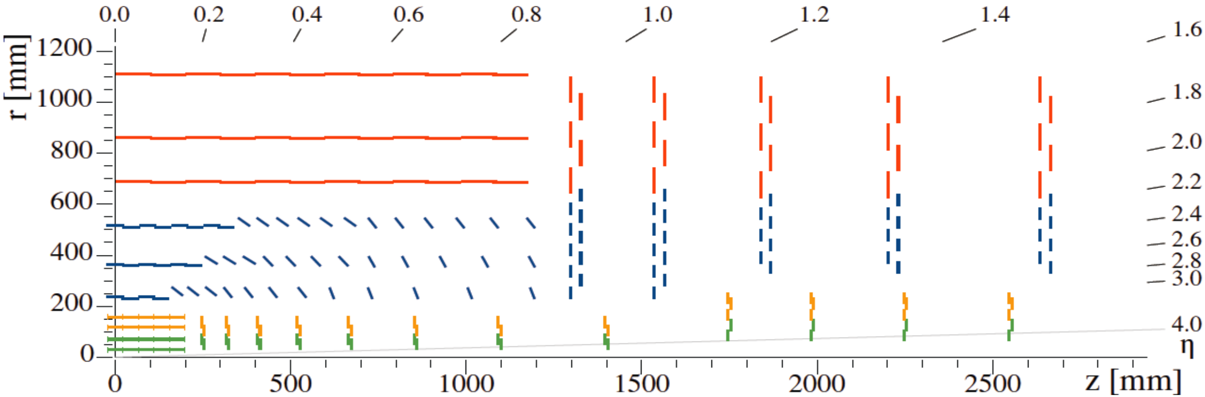






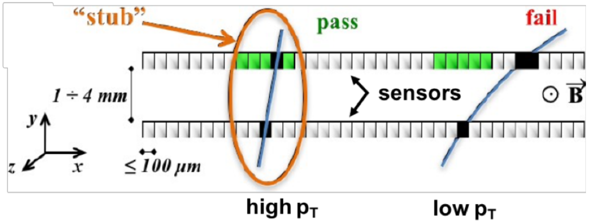


Tracker



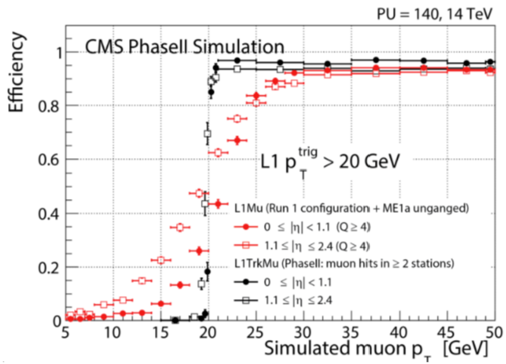
- **Acceptance up to |η| ~ 4**
- **Inner Tracker**
  - 4.9m^2, 2 x 10^9 pixels (6x smaller pixels than Phase-1 pixel detector)
- **Outer Tracker** with two types of modules: **s**trip **s**trip (2S) and **s**trip macro-**p**ixel (PS)
  - 192m^2, 42M strips, 170M macro-pixels (25m^2)
  - **Innovative tilted geometry in inner barrel layers of the outer tracker**

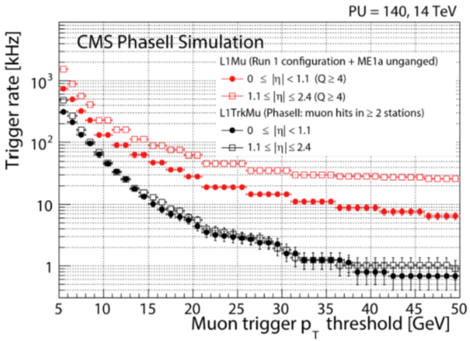
Tracker provides trigger primitives to L1



Outer tracker

- **"p_T modules"** with 2 sensors
- **Tracking at 1st trigger level** down to p_T~2GeV, |η|<2.4
- **"on detector" data reduction**
- **Fully independent source of trigger primitives (no "Region Of Interest" from outside)**





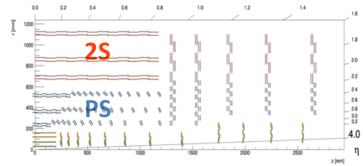
Outer Tracker key design features: p_T modules

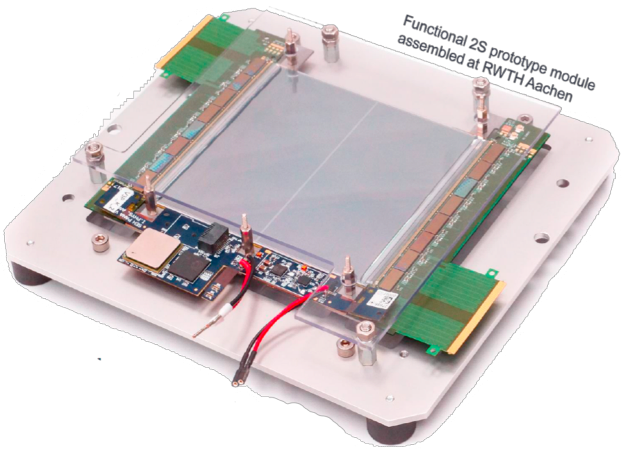
2 Strip sensors

2 × 1016 Strips: ~ 5 cm × 90 µm
2 × 1016 Strips: ~ 5 cm × 90 µm
P ~ 5.4 W
~ 2 × 90 cm^2 active area
For R > 60 cm
Spacing 1.8 mm and 4.0 mm

Pixel + Strip sensors

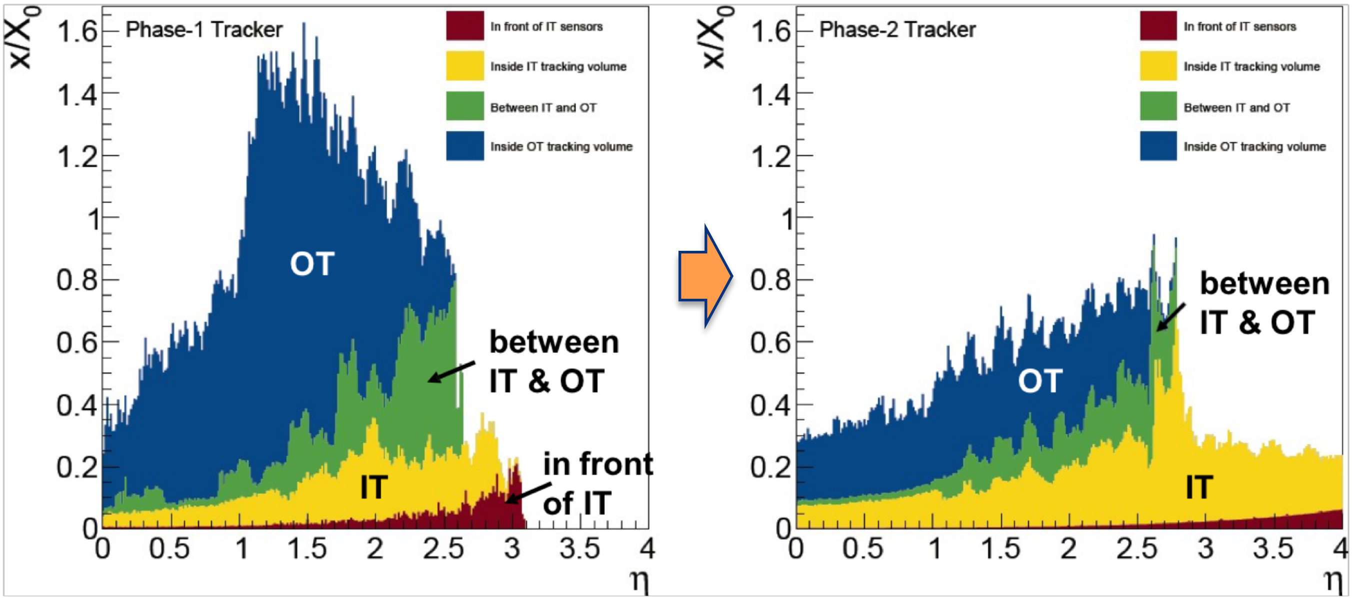
2 × 960 Strips: ~ 2.5 cm × 100 µm
32 × 960 Pixels: ~ 1.5 mm × 100 µm
P ~ 8.5 W
~ 2 × 45 cm^2 active area
For r > 20 cm
Spacing 1.6 mm, 2.6 mm and 4.0 mm





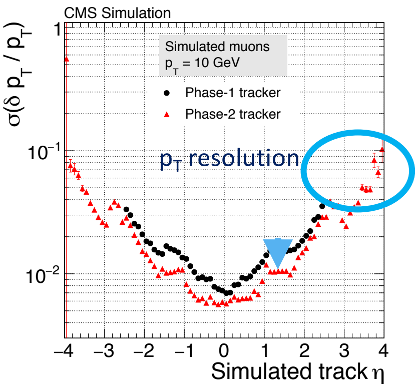
India pledged to assemble 2000 2S modules

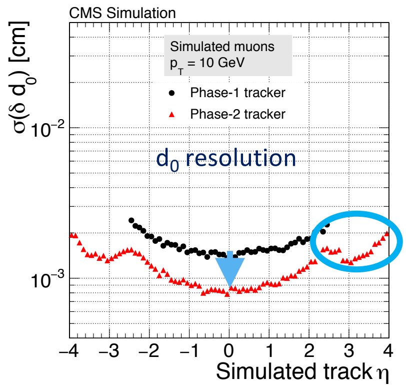
Phase II tracker is lighter



Very significant reduction, in particular around $|\eta| = 1.5$

Phase 2 CMS tracker, a substantial improvement of an already great detector





- Innovative, aggressive design
  - Extended coverage
  - Reduced material
  - Higher granularity
  - Provides independent input to L1 trigger for all tracks with p_T>2 GeV

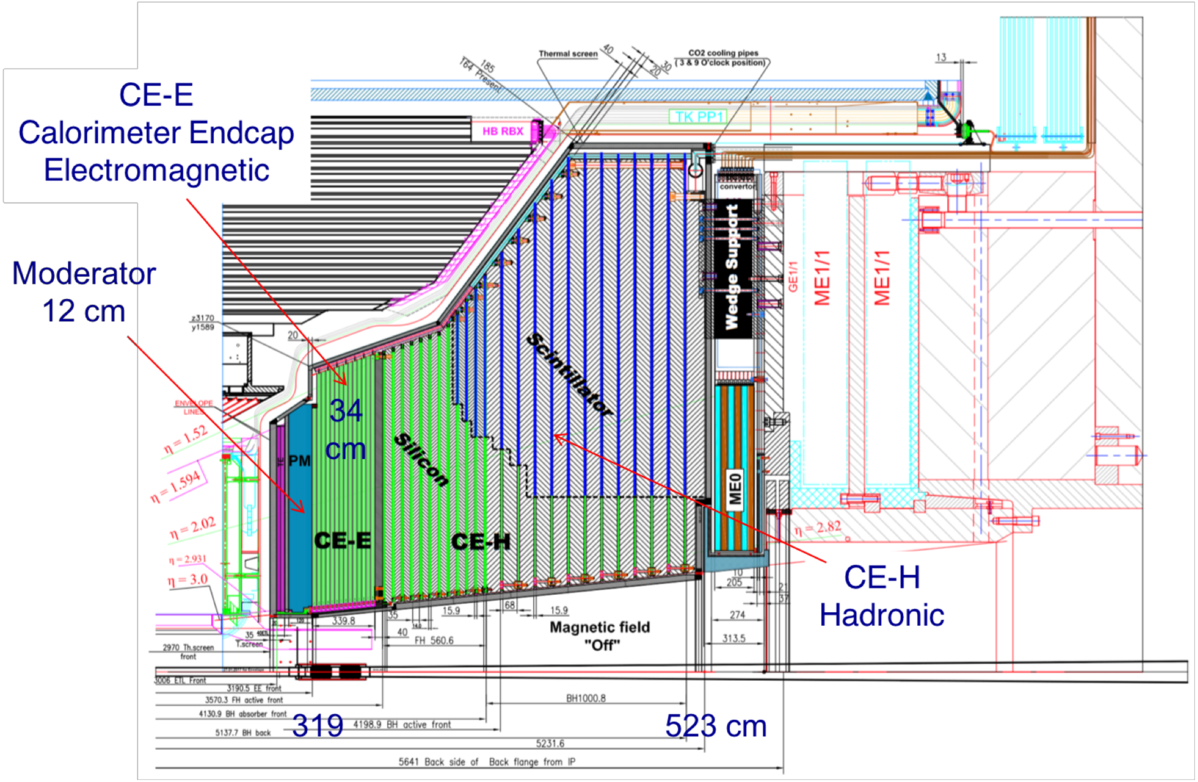
$H \rightarrow \mu\mu$: coupling to muons

- 65% improvement on $m_{\mu\mu}$ in barrel-barrel category (0.65% mass resolution)
- 5% precision on coupling to muons possible with 3000fb^{-1}

Di-Higgs production in $HH \rightarrow bbbb$ channel

- +8% acceptance
- +50-70% efficiency for tagging 4 b-jets at 200 pileup events w.r.t. Run 2

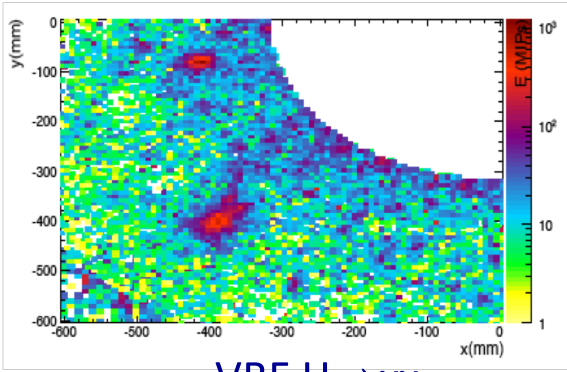
Endcap Calorimeter



Endcap Calorimeter

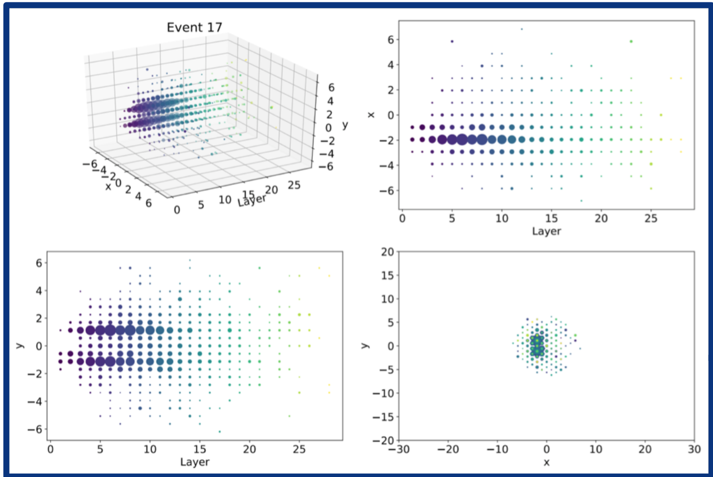
Another challenging design of CMS: highly-granular calorimeter endcap

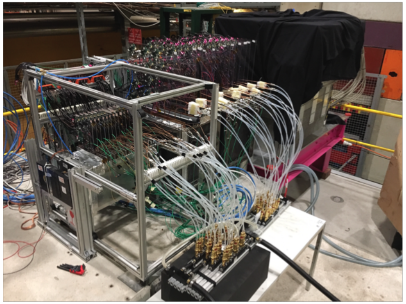
- Mixed Si-Scintillator design, to guarantee the needed radiation hardness in different areas, and the granularity to survive in the high density environment of LH-LHC
- ~6M channels
  - 2% energy resolution for unconverted photons
  - As good or better e/γ identification as in Run 2
  - As good or better jet reconstruction
  - ~30-100 ps time resolution
  - Sensitivity to off-pointing γ, e, τ and jets
  - MIP (muon) tracking and identification capability



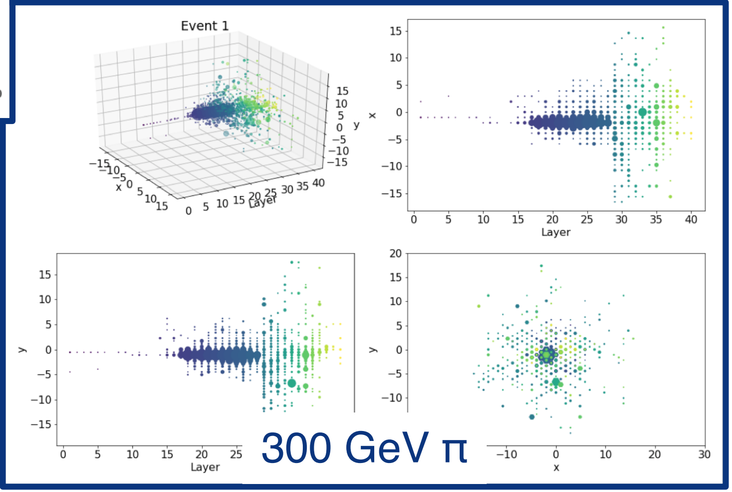
VBF H→γγ

Displays from recent HGCAL test beams



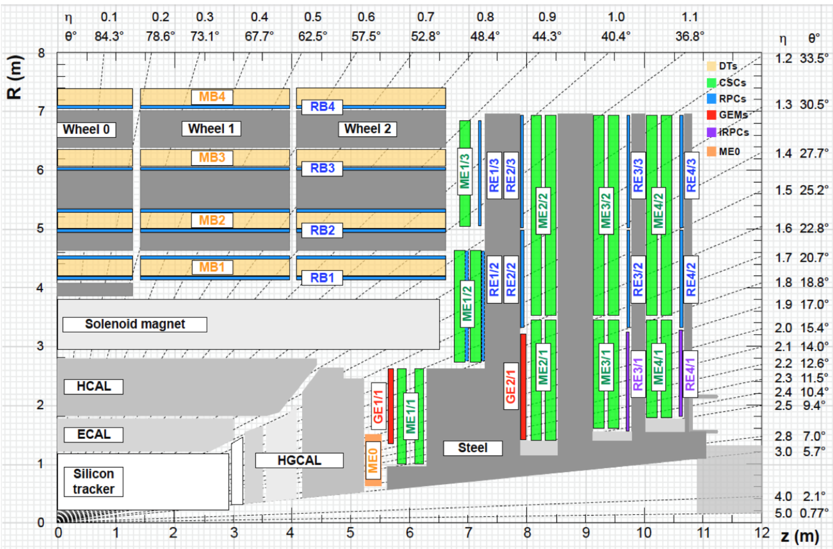


Two EM clusters spatially resolved



300 GeV π

Muon system



Barrel and endcaps:

- replacement of readout electronics for the new L1 trigger conditions

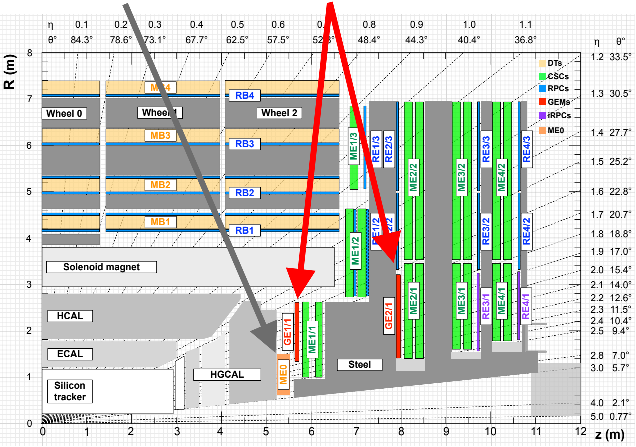
Endcaps:

- **Robust trigger up to |η|=2.4** thanks to new RE3/1 and RE4/1 RPC stations and GE1/1 and GE2/1 GEM stations
- **Coverage extension up to |η|=2.8** by ME0 GEM station
- Standalone p_T measurement for **off-pointing muons** with 2 combined GEM/CSC stations

New GEM stations GE1/1 GE2/1, ME0

ME0 station

GEM stations

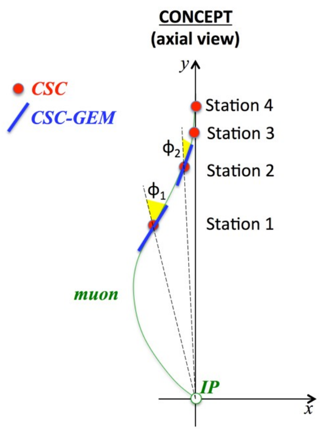


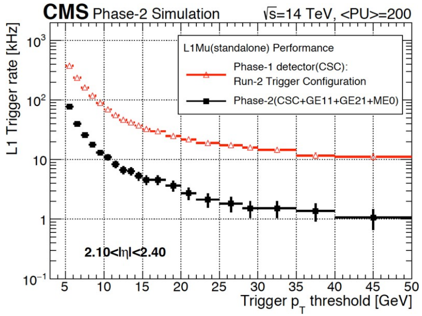
- Goals
- ME0: add trigger capabilities and offline acceptance for 2.4 <|η|<2.8 and large trigger rate reduction for 2.1 <|η|<2.4
- GE1/1, GE21: add redundance and complementarity to ME1/1 and ME2/1, substantial rate reduction for displaced muons

ME0: 6-layer GEM detectors covering 2.0 < |η| < 2.8
GE2/1: 2-layer GEM detectors covering 1.6 < |η| < 2.4

NB GE1/1 to be installed soon, GE2/1 during the short technical stops in Run 3. GEM are the first new HL-LHC detector to be installed in CMS

Improvements-GEM



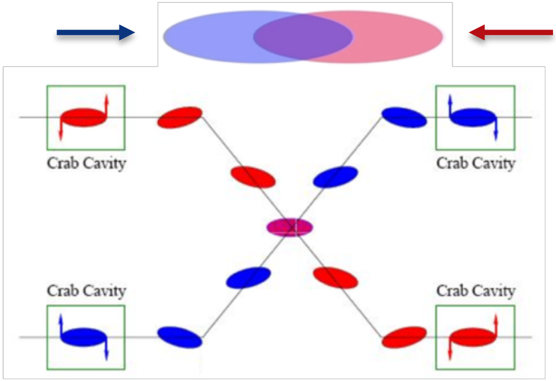


IMPROVED TRIGGER:

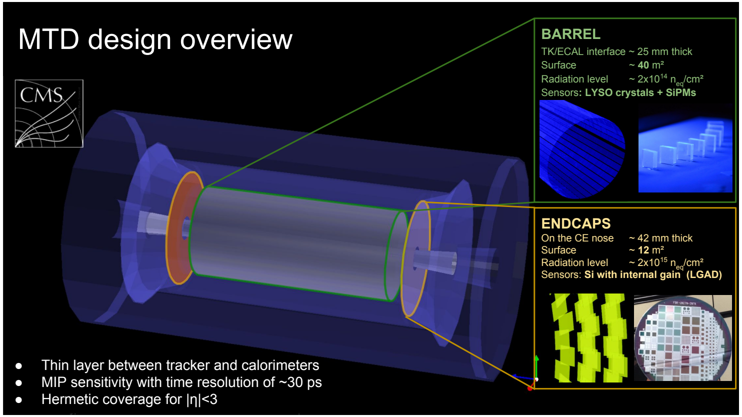
- GEM-CSC tandems in ME1 and ME2 stations will give better measurement of muon "local" direction sensitive to muon p_T
- p_T measurement improves and, hence, the L1-trigger rate drops; the gain is as large as a factor of 10
- This is true for stand/alone trigger, combination with the new tracker trigger would help, but stand-alone muon trigger are important for long-lived particles
- ME0 extends η coverage to 2.8

MIP timing detector (MTD)

- Proton Collision in the LHC bunches are Spread in Time over an RMS of ~180 ps
  - **Currently CMS sees only the integral of this process over time**
  - An additional high resolution (~ 30 ps) **MIP Timing Detector** can help in discriminating charge particles from different vertices

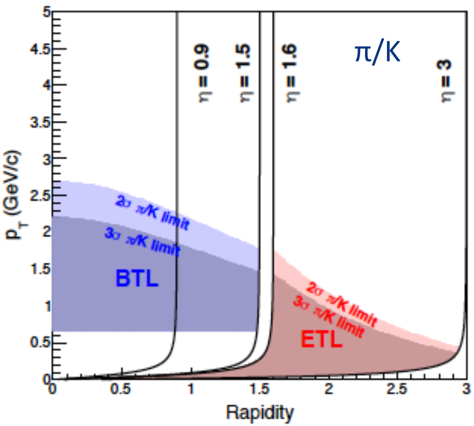


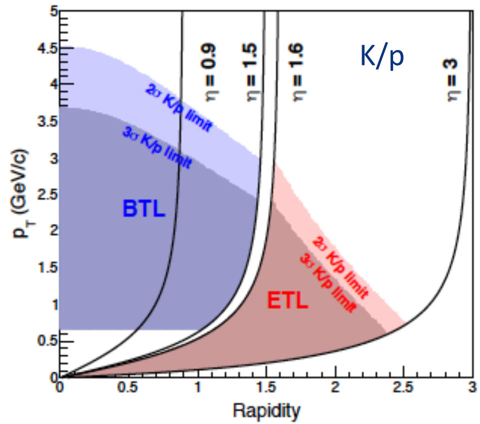
~ 180 ps RMS



MTD as Particle id detector

- New Physics case is being developed for HI physics in Run-4 (LS3 to LS4)
  - MTD ToF measurement can provide efficient PID
    - With 30 ps CMS would approach ALICE performance at central rapidity (|y|<0.9) and have extended PID coverage up to |y|=2.9
    - A resolution of 50 ps would still provide acceptance gain and a better separation than the STAR-TOF experiment (the irradiation in Run-4 should not yet affect resolution)

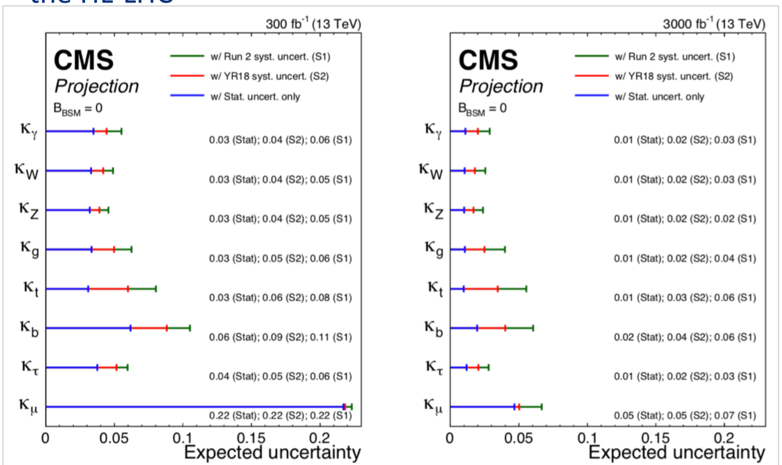




What for? Yellow Report on the HL/HE Physics Workshop

HL_LHC as Higgs factory (>150M Higgs boson produced

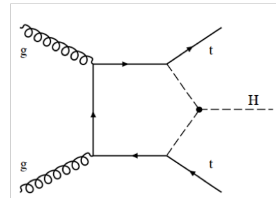
FTR-18-011: Sensitivity projections for Higgs boson properties (e.g. coupling modifiers) measurements at the HL-LHC

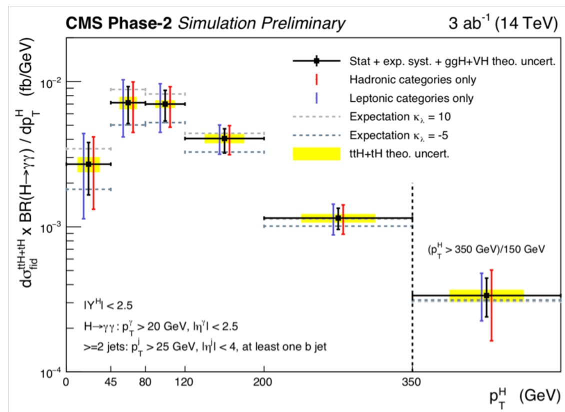


YR expected by the end of the year, strong contribution from CMS with about 30 results being approved now

And ~120k of HH pair produced events

But: FTR-18-020: Constraints on the Higgs boson self-coupling from ttH+tH, H → γγ differential measurements at the HL-LHC





Summary and Outlook

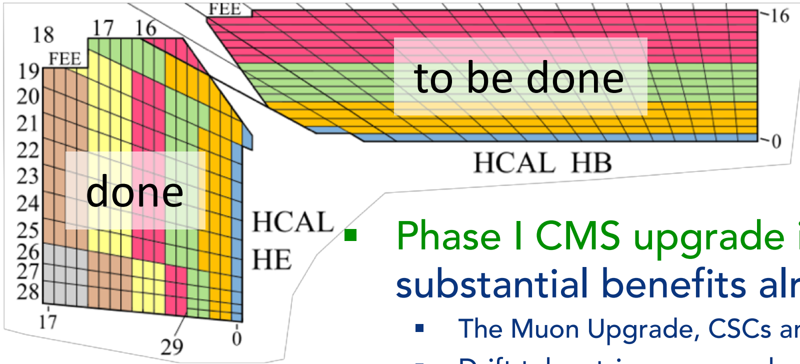
- We are doing well
  - CMS has taken good data and expect to do excellent physics with it
  - **The quality of CMS Physics results continues to be excellent with many exciting analyses ahead that will use the full Run 2 dataset, including the parked events, a large HI dataset and the results of 2018 special runs**
  - **Thanks also to the contribution from India, one of the big countries in the CMS collaboration**
- **LS2 will mark the last Phase 1 upgrades and the start of the installations for HL_LHC, our next very large, challenging and engaging enterprise**

Closing Remarks

- It is a very interesting time for (young) people working at LHC. We are at the same time:
  - Developing and building new detectors
  - Maintaining and upgrading present detector
  - Taking (a lot of) data
  - Analyzing an unprecedented amount of data, and developing new strategies to do that
- It is not common to have to do all this together, and it it is a unique opportunity for a student to learn all aspects of a very complex job.

Backup slides

CMS Phase I Upgrade



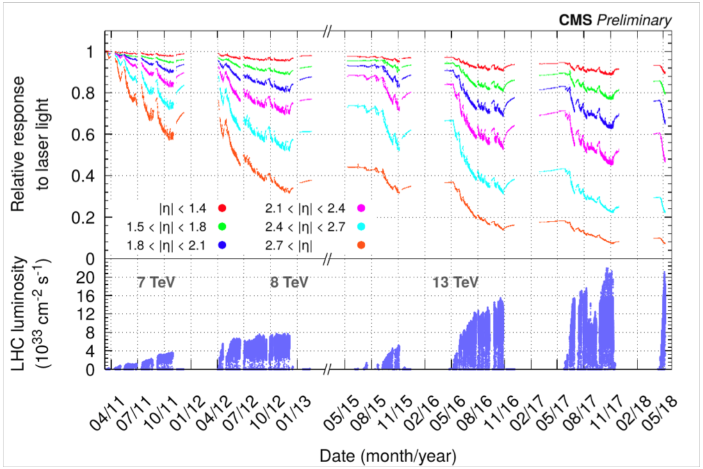
- Phase I CMS upgrade is almost done, providing substantial benefits already during Run 2
  - The Muon Upgrade, CSCs and RPCs, were done in LS1
  - Drift tubes trigger upgrade done in YETS 2015/16
  - L1 Trigger upgrade was installed in 2015 and used starting in 2016
  - Hadron forward calorimeter upgrade was started in LS1, completed in the EYETS 2016/17, and ran successfully in 2017
  - Pixels were installed in the EYETS 2016/17
  - Drift tubes readout upgrade has been done during YETS 2017/18 and is taking data smoothly
  - Hadron endcap calorimeter front-end electronics and photosensors have been upgraded in YETS 2017/18 and running smoothly
- The only remaining part of Phase I CMS upgrade is the front-end electronics and photosensors of the hadron barrel calorimeter

Preparation for Run 3

- Looking forward for the indications from LHC on the conditions for Run 3, potentially a non negligible increase of integrated luminosity per year
  - We are by now used to LHC exceeding expectations

- Studying the impact of O($300fb^{-1}$) on our detector from Run 3
  - Radiation damage on pixels, tracker, ECAL
  - impact on calibration procedures, trigger, reconstruction …

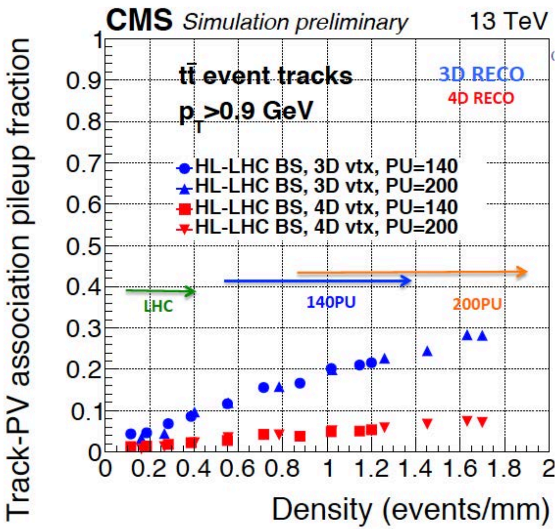
Loss in light yield on ECAL



Preparation for Run 3

- Having the detector ready is not enough
  - Discussions with the physics groups on early Run 3 topics have started
  - The Run 2 legacy data sets with ultimate precision will be the basis for combinations with Run 3 data
  - Preparing a new study group on particle flow in order to reinforce the activity for Run 3 and beyond
- We need to plan early as the collaboration will become more and more involved in the HL-LHC upgrade
  - Try to leverage on the studies for HL-LHC on trigger and algorithms, and backport what possible to Run3

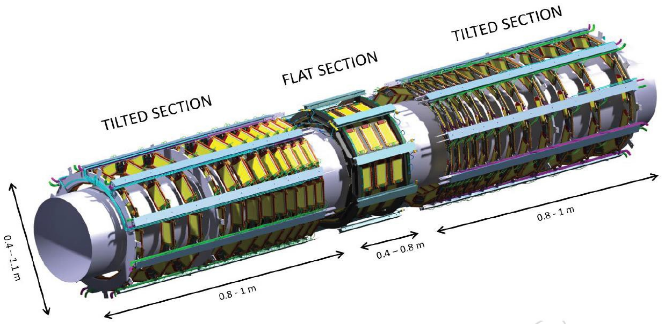
MIP timing detector



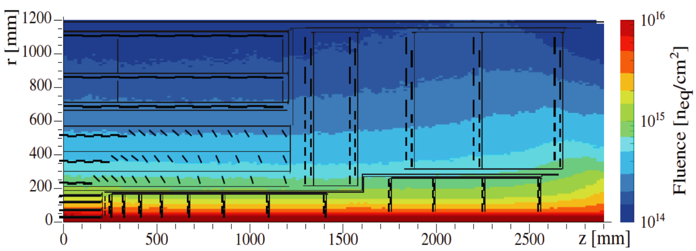
~ 30ps TOF precision for individual tracks just outside the tracker, $|\eta|<3$

- Complements similar time resolution for showers in the upgraded calorimeters
- Provides a factor 4-5 effective pileup reduction
- Reduces merged vertices in high density events
- Provides flexibility adding a 4th coordinate to CMS event reconstruction

State of the art detector for a harsh environment

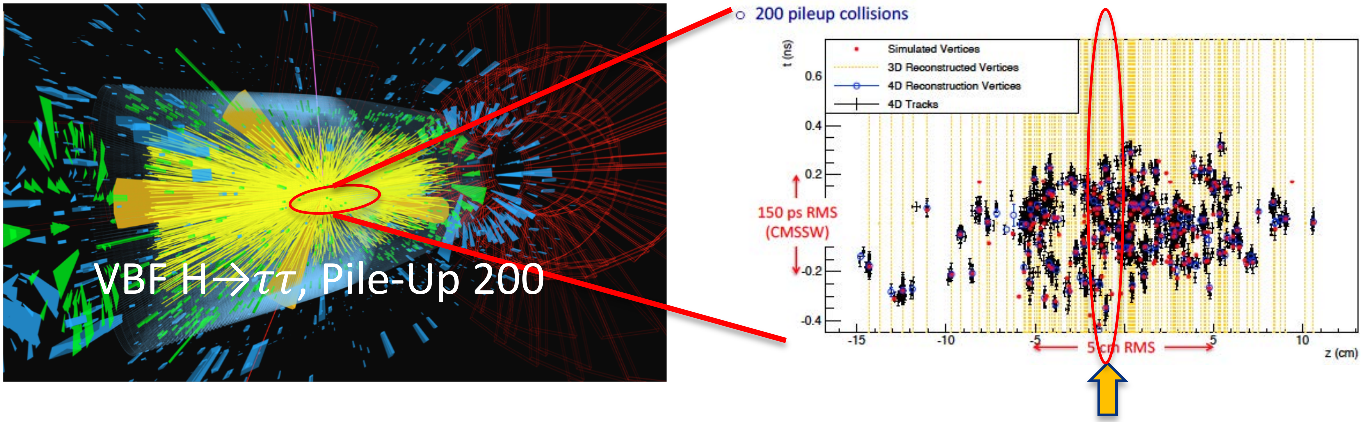


State of the art mechanics, CO_2 cooling (150kW w.r.t the present 15 kW of the pixel detector), electronics.



- Fluence (1-MeV neutron equivalent) and total ionizing dose (TID) maps from FLUKA simulations
- Maximum expected levels:
  - Outer Tracker: 9.6 x 10^{14} n_{eq}/cm^2 and 56 Mrad TID
  - Inner Tracker: 2.3 x 10^{16} n_{eq}/cm^2 and 1.2 Grad TID

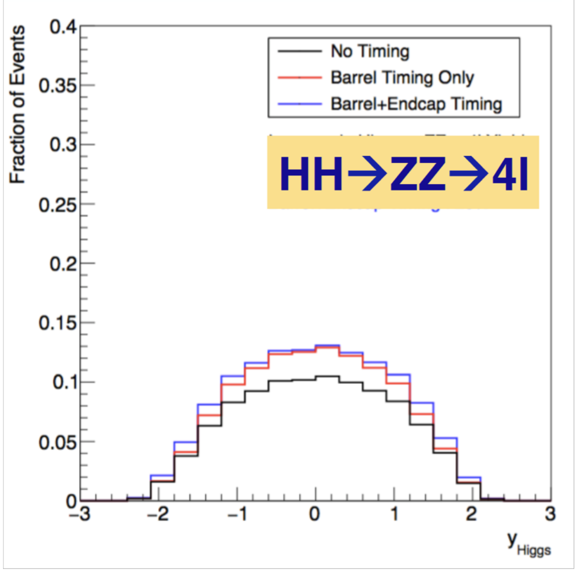
MIP timing detector

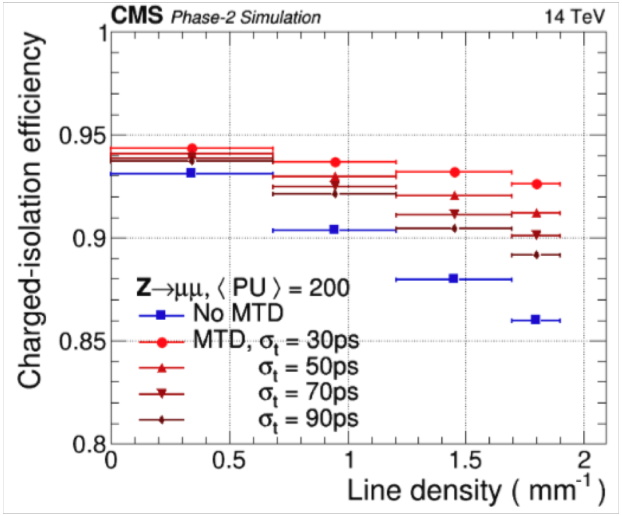


At a given z position, different vertices can be discriminated by time if the resolution is enough w.r.t. the time spread

MIP timing detector

- A hermetic MTD improves the full range of Phase 2 physics



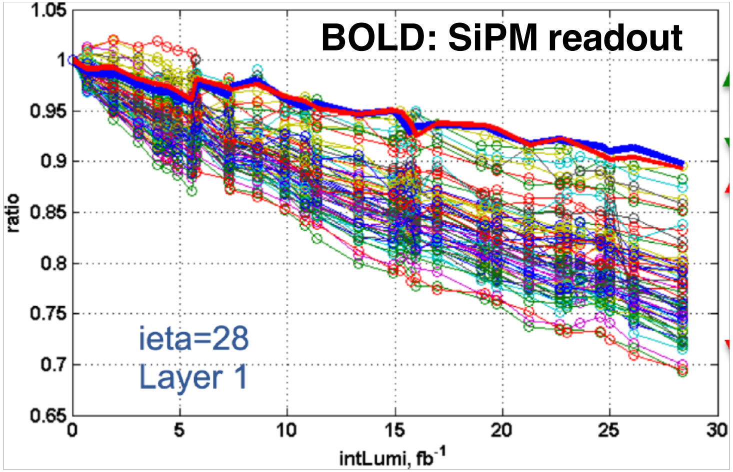


- Need to guarantee a sufficient time resolution also after irradiation
  - Values around 50ps still provide significan gain

Barrel Calorimeter

Thanks to the studies on the HE phase 1 upgrade we could decide that we do not need to replace scintillator layers in the Barrel HCAL, much of the observed HE damage was due to HPD deterioration.

- **Upgrade scope in EB and HB is "limited" to the electronics an cooling**



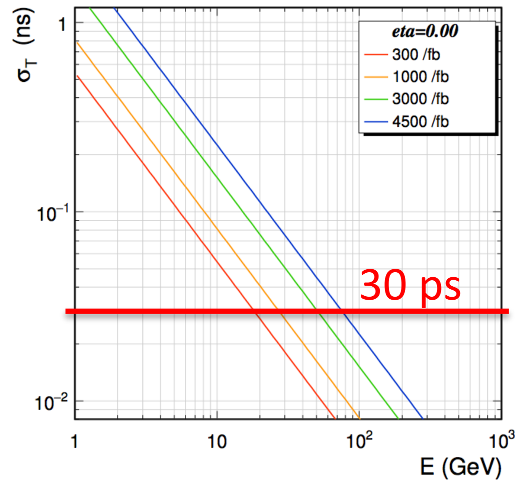
Barrel Calorimeter

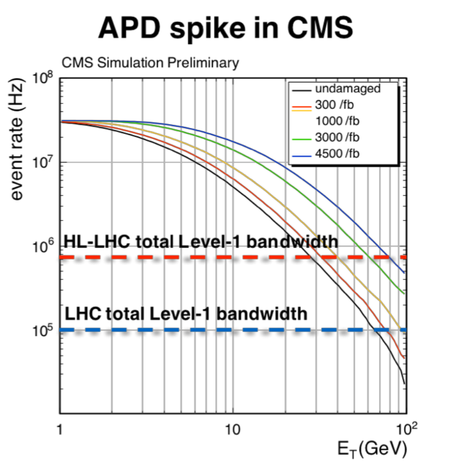
improve !

- The aim of the upgraded detector is ~~to preserve~~ the current Run 1 performance in the challenging HL-LHC conditions
- EB+HB
  - New <u>common</u> backend board to cope with increased L1 trigger rate and latency
- EB
  - Cool supermodules to 9°C to mitigate APD noise increase
  - New on-detector electronics
    - <u>Full granularity to L1 trigger</u> and APD spike rejection
    - Shorter signal shape to minimize noise and allow 30ps time resolution for >30 GeV showers

Barrel Calorimeter

- 30ps time resolution reachable for reasonable photon energies, significantly improving the vertex localization

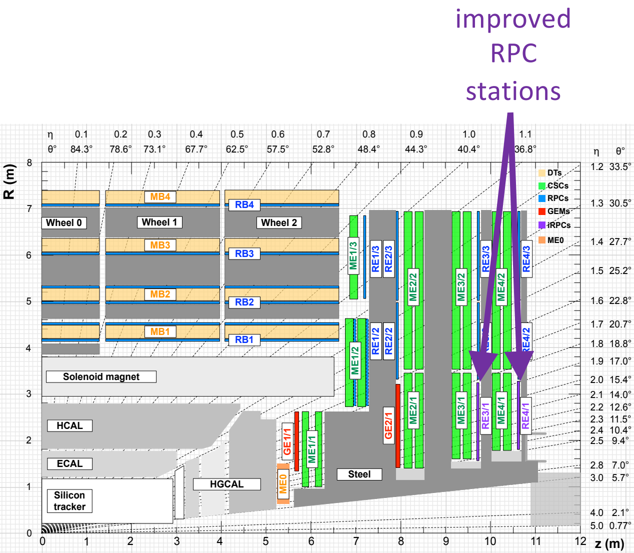


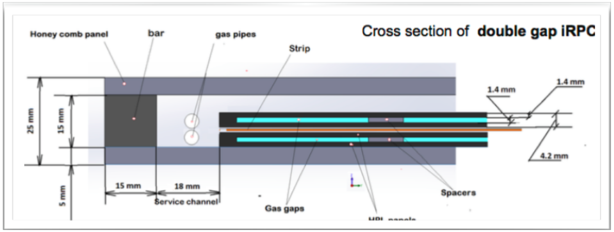


Spike rate vs E_T threshold at HL-LHC
(with no spike mitigation applied)

APD spikes already a severe problem now, mandatory to improve in HL-LHC

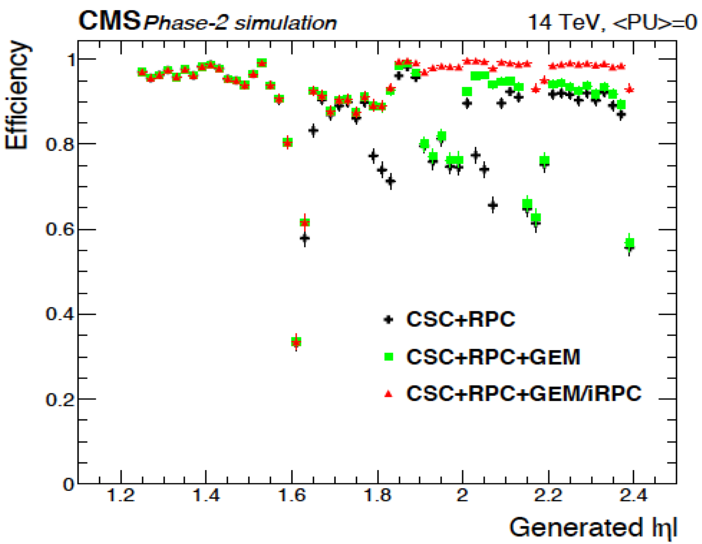
New RPC stations RE3/1 RE4/1





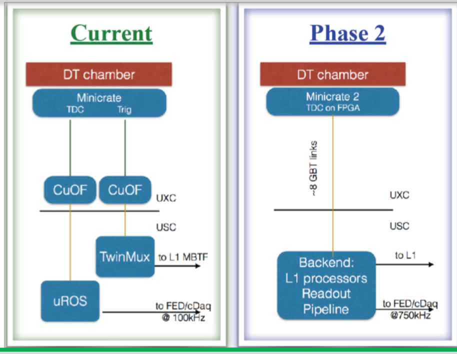
- Goal: more redundancy at 1.8<|η|<2.4, better timing resolution, better ability to trigger muon stand-alone
- New thinner gaps improved RPC and electronics, able to cope with the higher occupancy

Improvements-iRPC

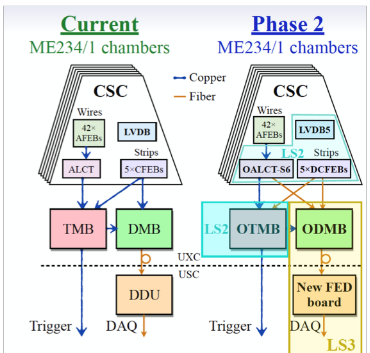


- iRPC hits improve CSC segment finding efficiency as we have already seen in the present data at lower η
- iRPCs will provide true 2D hits with O(1) cm resolution in both dimensions, which will help resolve combinatorial background in CSCs

DT, CSC, RPC electronics



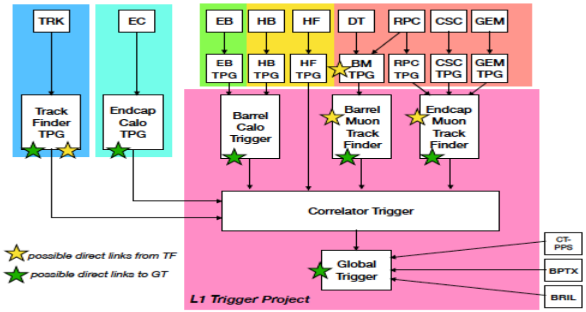
DT electronics: read full information (1ns drift resolution) at 40MHz and move complexity and L1 interface to backend (merging DT and RPC information)



RPC: upgrade of the link system, higher bandwidth and improved time resolution (25→1.6 ns)

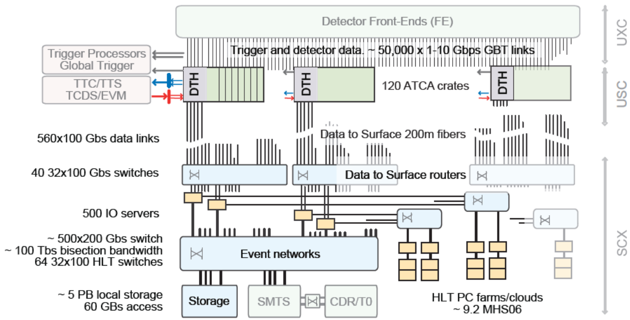
L1 trigger

- Increased latency to 12.5μs (from 5μs) and rate up to 750kHz (from the present 100kHz)
  - So more time to decide (latency) and more bandwidth available
  - All detector electronics needs to be updated to cope with these parameters
- **Will use also input from the Si outer tracker detector**
  - This will allow to port Particle Flow algorithms already at L1 trigger



DAQ

Baseline: HLT output at 7.5 kHz



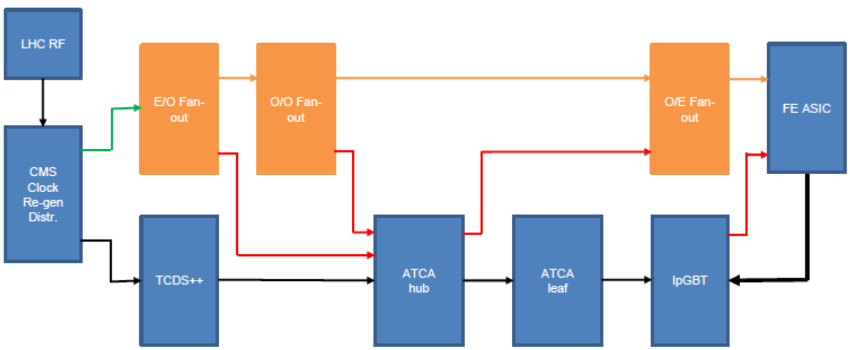
Is it possible a "triggerless" readout at 40 Mhz, using tracker trigger primitive and full information from (some) other subdetectors?

- "Triggerless" means no L1 trigger, fast targeted data analyses on alternative processors (e.g. GPUs
- Being investigated
- A test beam with triggerless 40 MHz readout, with the new HL-LHC electronics for the DT minicrates, has been successful few weeks ago

Precise Clock Distribution

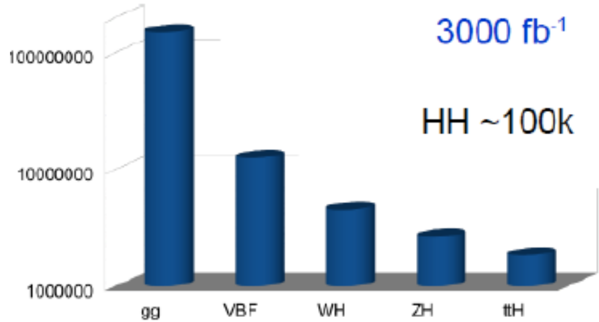
DAQ has also to provide precise Clock distribution for Calorimeters and MTD

- Target ≃ 10 ps resolution - two path investigated
- Through BE boards and GBT or Through additional OL directly to FE



HL-LHC as Higgs factory

- HL-LHC is (also) a Higgs factory, will produce > 150M Higgs bosons
  - Including ~120k of pair produced events



- Enables a broad program:
  - Precision O(1-10%) measurements of coupling across broad kinematics
    - can reveal new particles in loops or non-fundamental nature of Higgs
  - Exploration of Higgs potential (**HH production**)
  - BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays…)