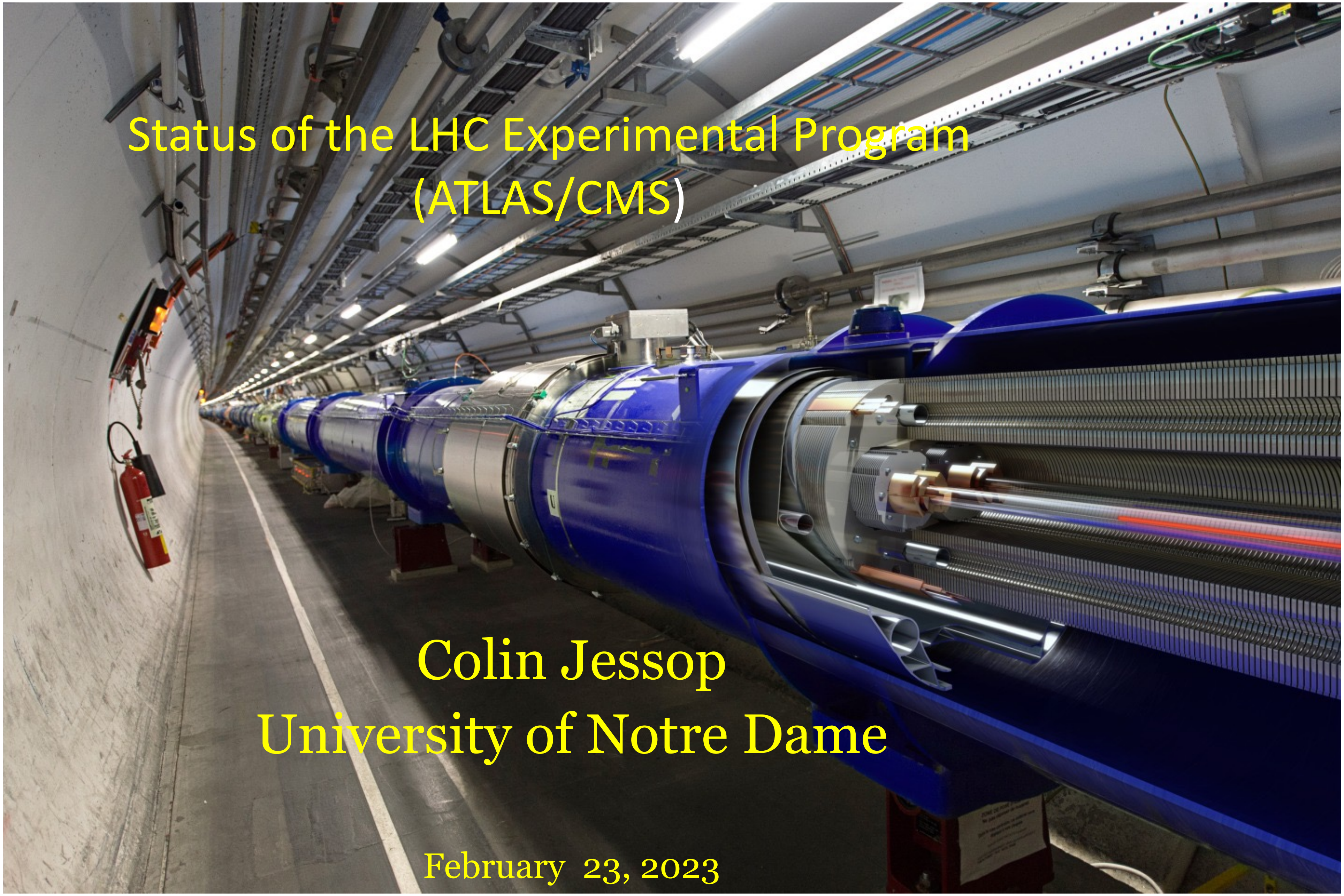
UNIVERSITY OF NOTRE DAME

CMS



Status of the LHC Experimental Program (ATLAS/CMS)

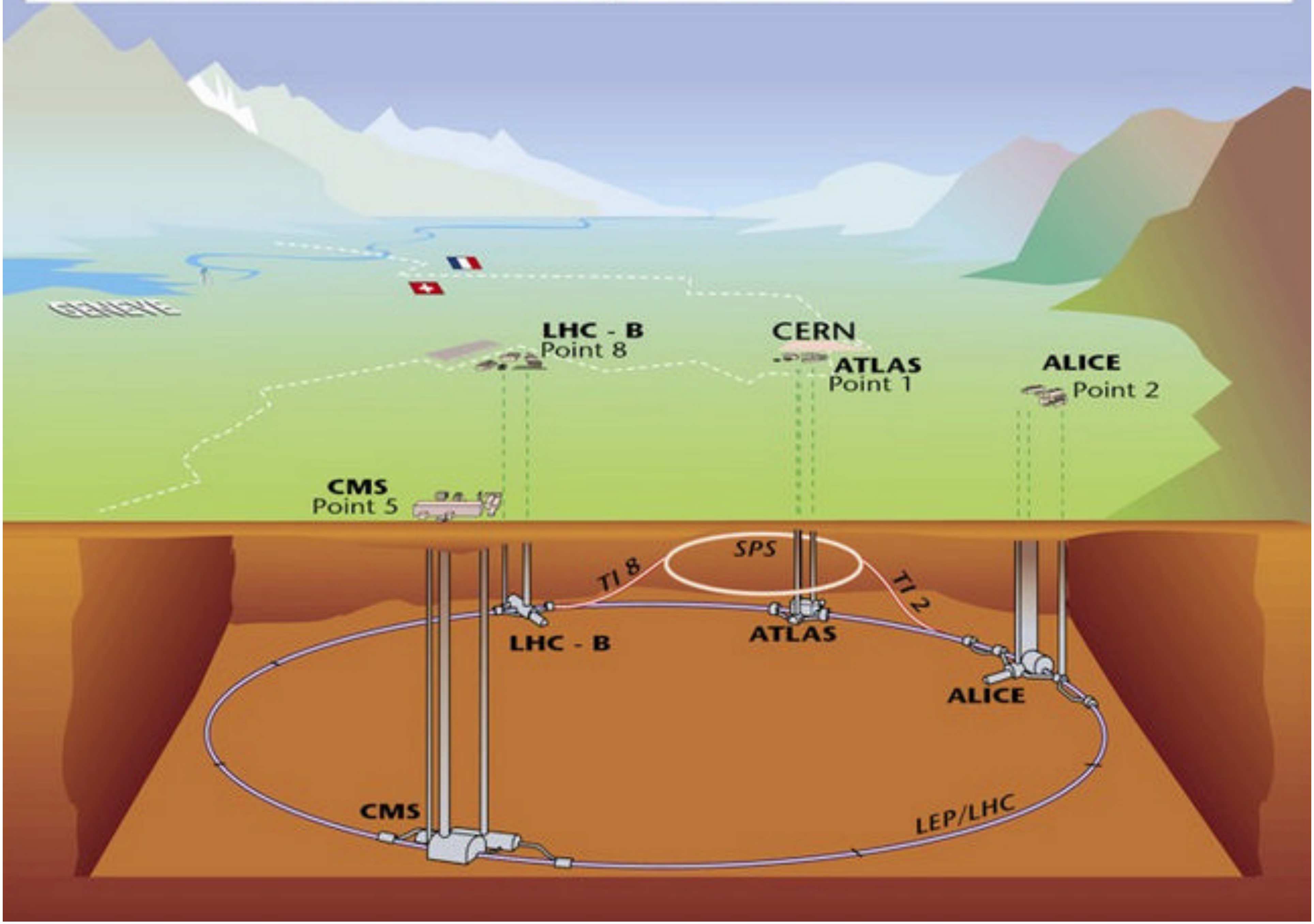
Colin Jessop
University of Notre Dame

February 23, 2023

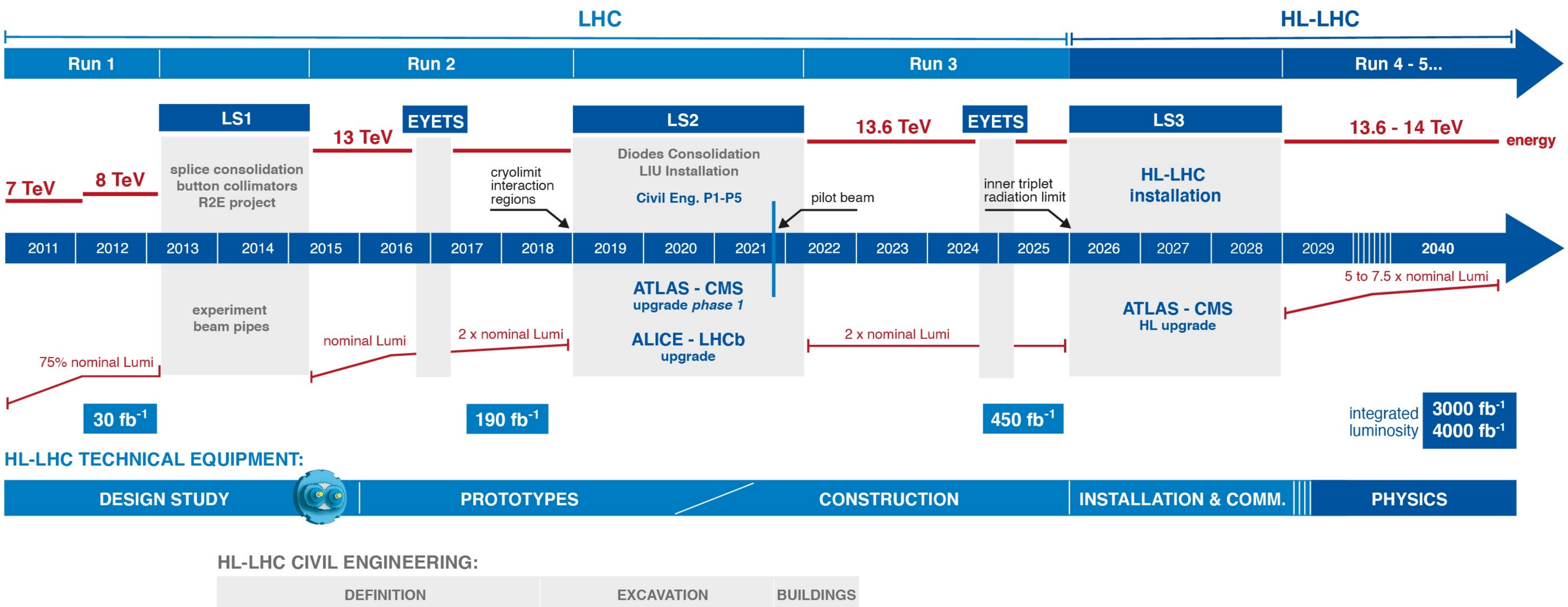
Contents

- LHC Status
- ATLAS/CMS status
- Physics Highlights
- HL-LHC upgrade status
- Conclusion

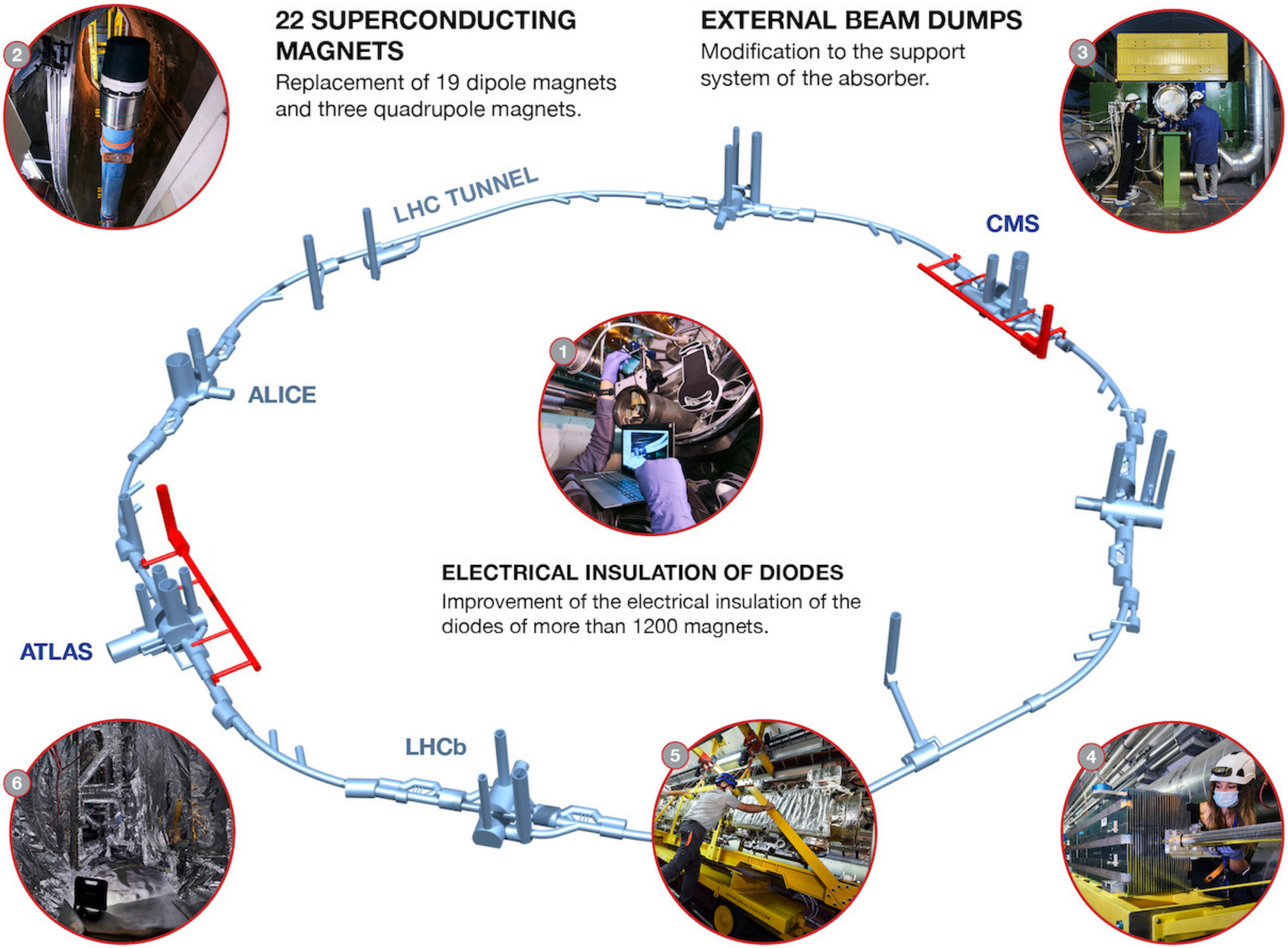
Overall view of the LHC experiments.



The LHC Plan


LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
inner triplet
radiation limit
HL-LHC
installation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
5 to 7.5 x nominal Lumi
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1
HL-LHC TECHNICAL EQUIPMENT:
DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS
HL-LHC CIVIL ENGINEERING:
DEFINITION
EXCAVATION
BUILDINGS

LHC UPGRADES DURING LS2



1 ELECTRICAL INSULATION OF DIODES
Improvement of the electrical insulation of the diodes of more than 1200 magnets.

2 22 SUPERCONDUCTING MAGNETS
Replacement of 19 dipole magnets and three quadrupole magnets.

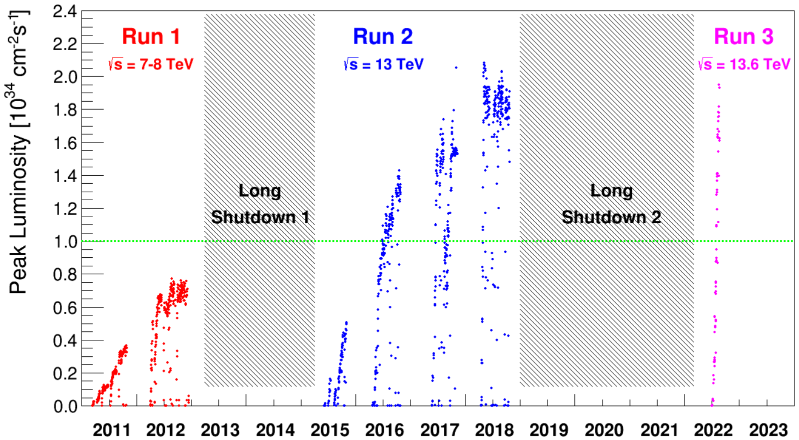
3 EXTERNAL BEAM DUMPS
Modification to the support system of the absorber.

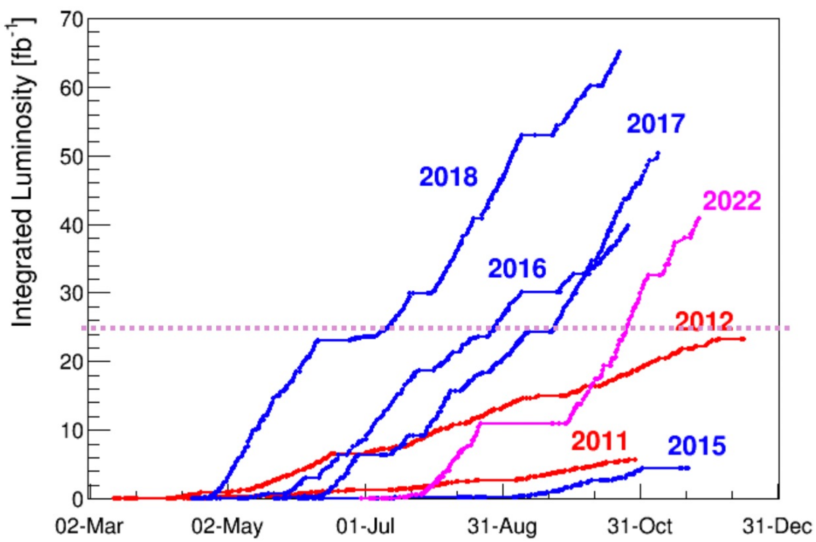
4 COLLIMATORS
Installation of 16 new collimators.

5 BEAM ABSORBERS
Installation of a new internal beam absorber and two new neutral beam

6 INCREASED CRYOGENIC POWER
Installation of high-performance cold boxes at Point 4.

LHC Operation in Run 3 and beyond





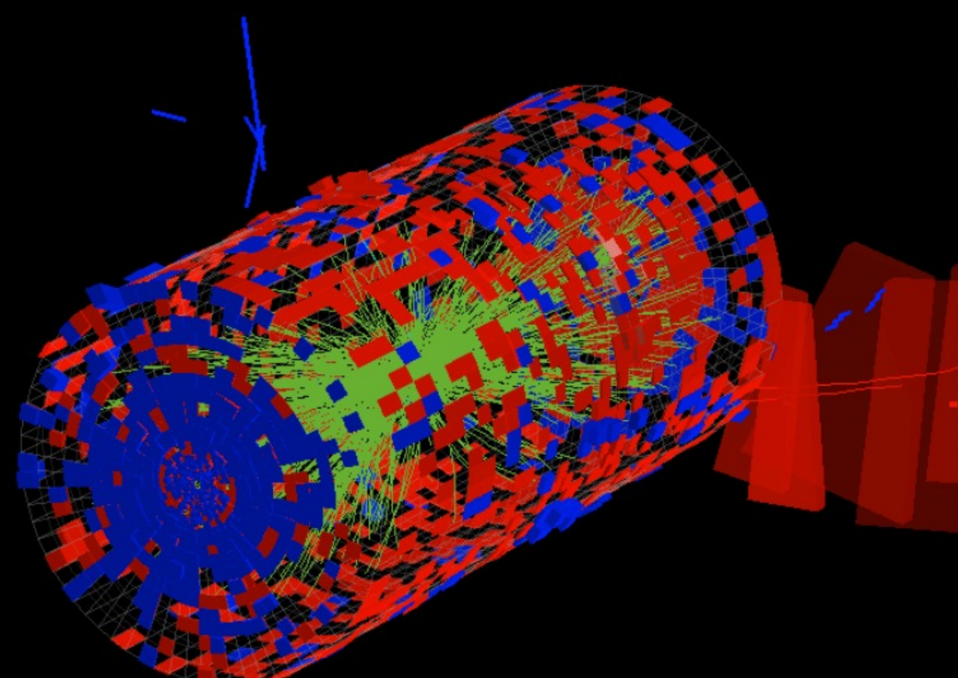
- Rapid ramp up to $L = 2{\times}10^{34} cm^2 s^{-1}$ (Twice original design luminosity)

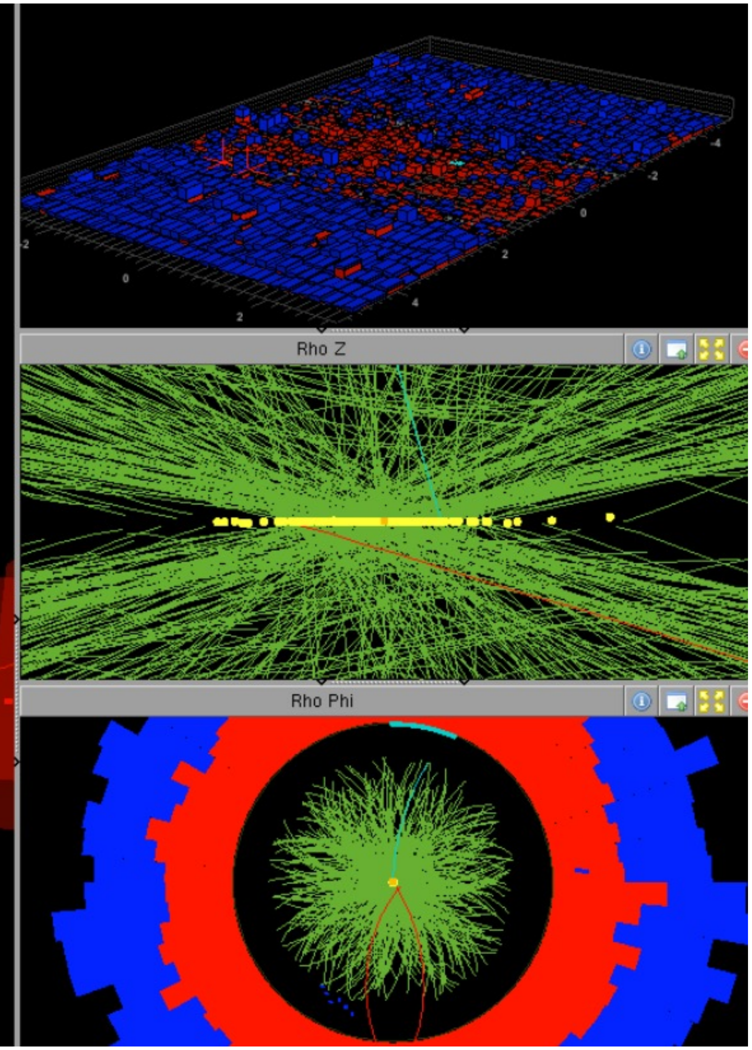
		$\sqrt{s}$ (TeV)	$\int Ldt$ (fb-1)
Run 1	2010-13	7/8	5/20
Run 2	2015-18	13.1	138
Run 3	2022	13.6	40
Run 3	2023-25	13.6	210
Run 4	2028-38	14.0	3000

20% less running time in Run 3 due to European energy crisis

Pileup at higher luminosity

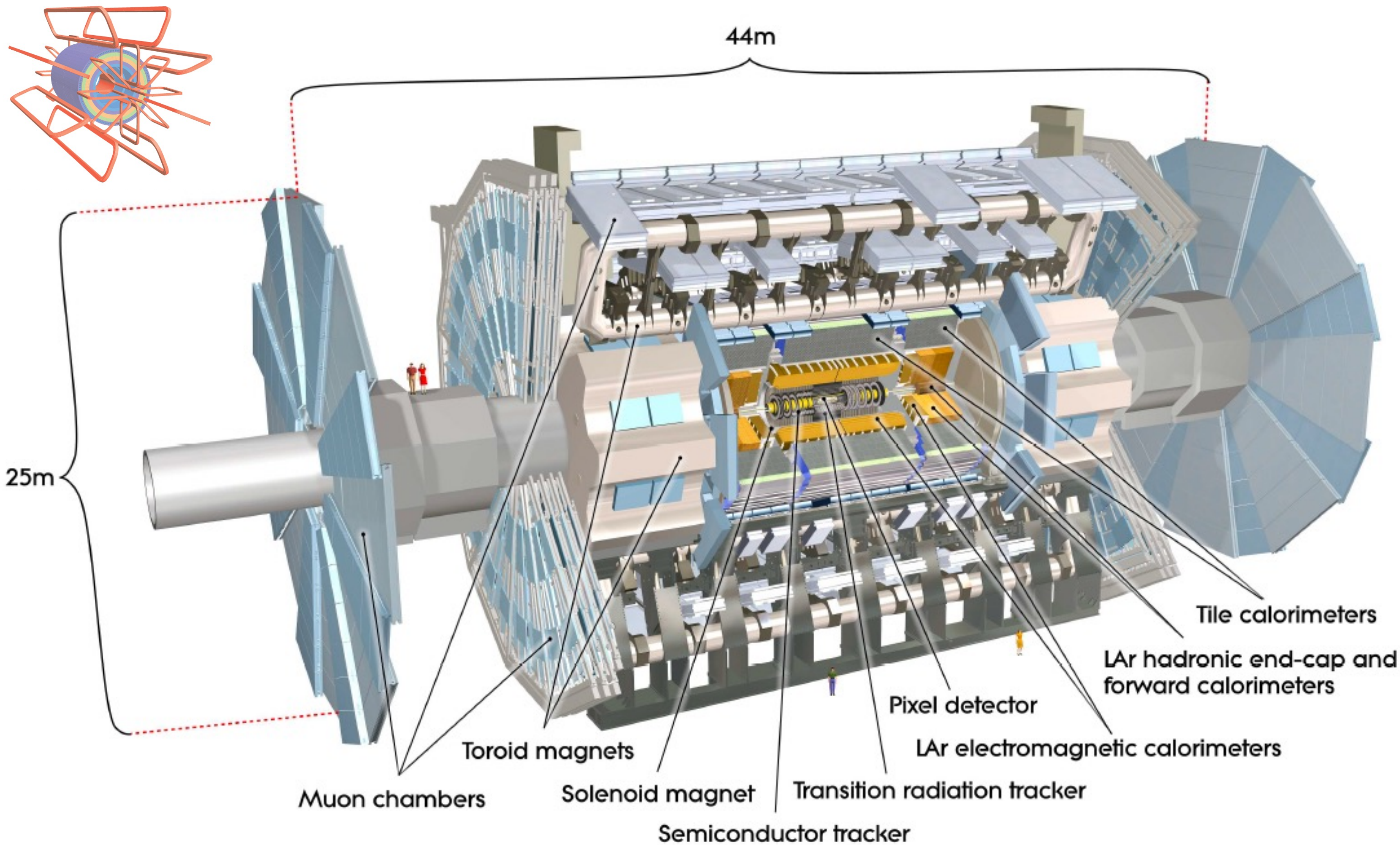
Higher luminosity means more multiple interactions per event creating challenges for the detectors





A CMS event with 78 interactions

ATLAS Detector

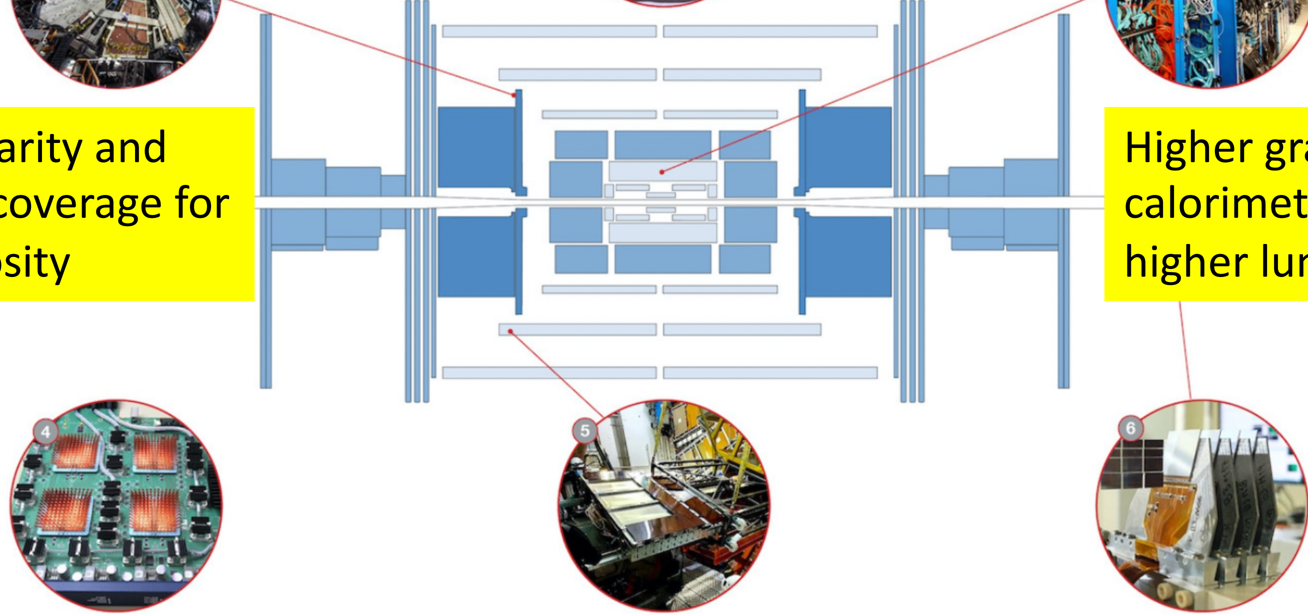


ATLAS Upgrades for Run 3

MUON NEW SMALL WHEELS (NSW)
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

NEW READOUT SYSTEM FOR THE NSWs
The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.

LIQUID ARGON CALORIMETER
New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.



Higher granularity and better muon coverage for higher luminosity

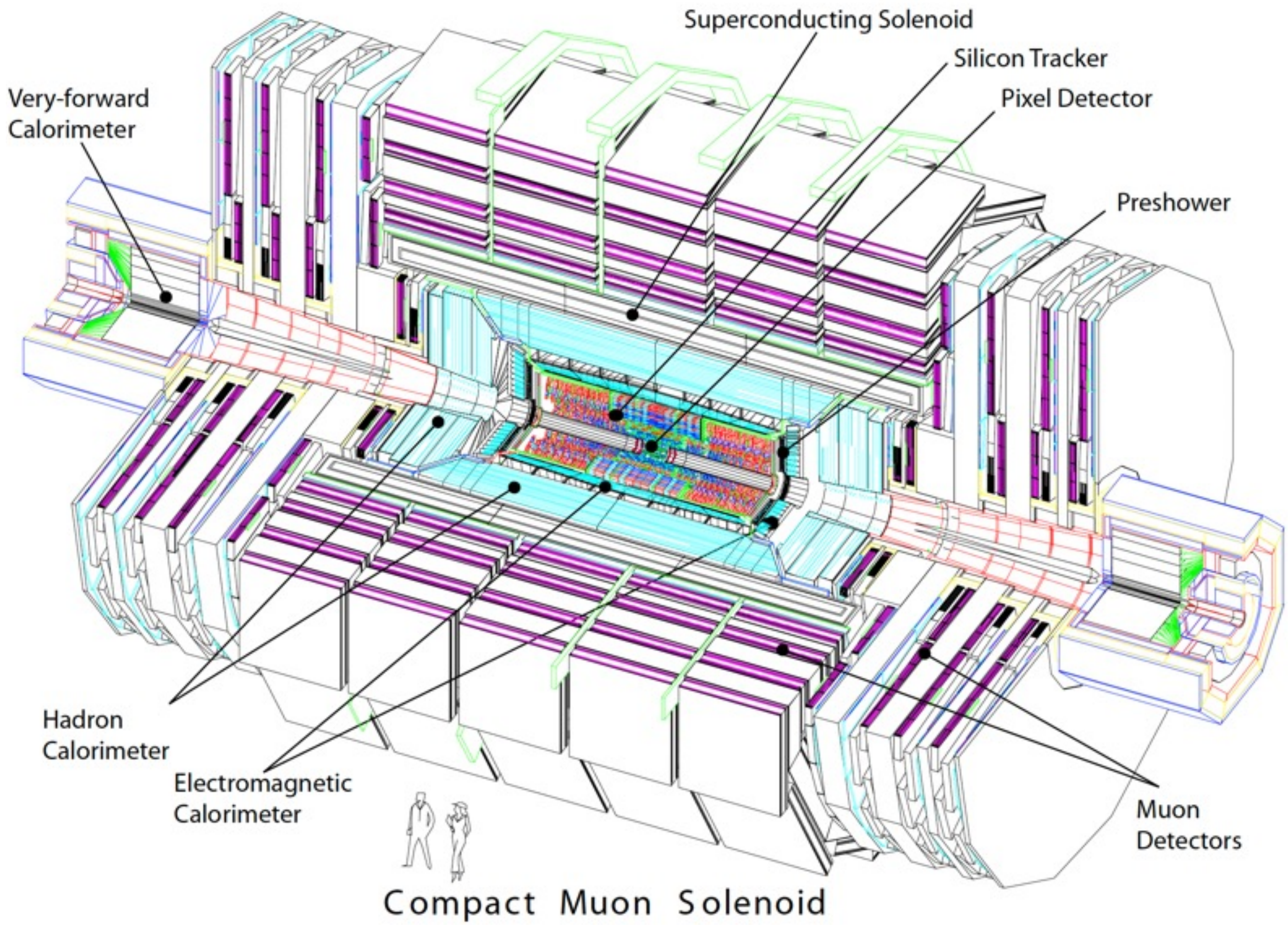
Higher granularity calorimetry readout for higher luminosity

TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)
Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.

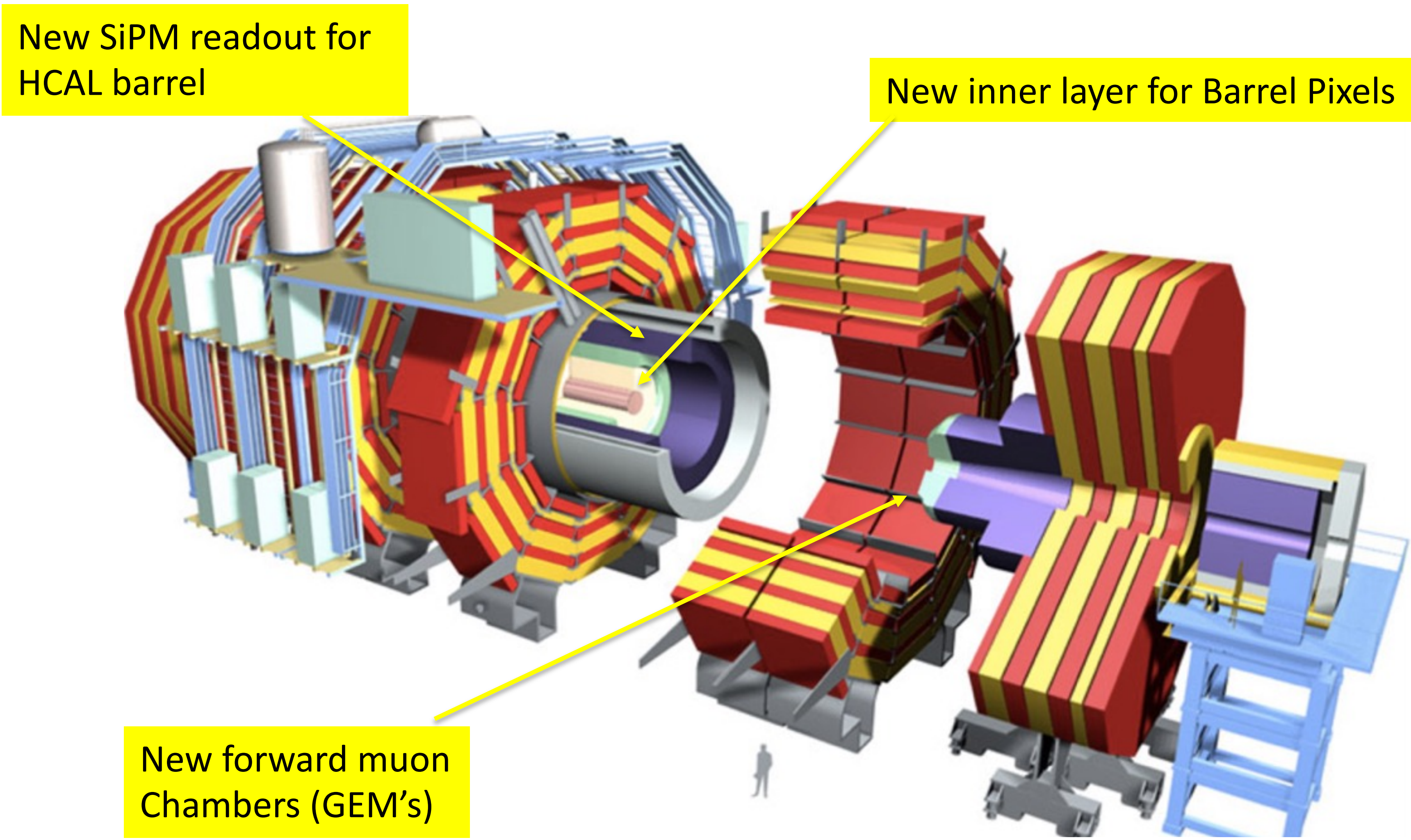
NEW MUON CHAMBERS IN THE CENTRE OF ATLAS
Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.

ATLAS FORWARD PROTON (AFP)
Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new “out-of-vacuum” solution.

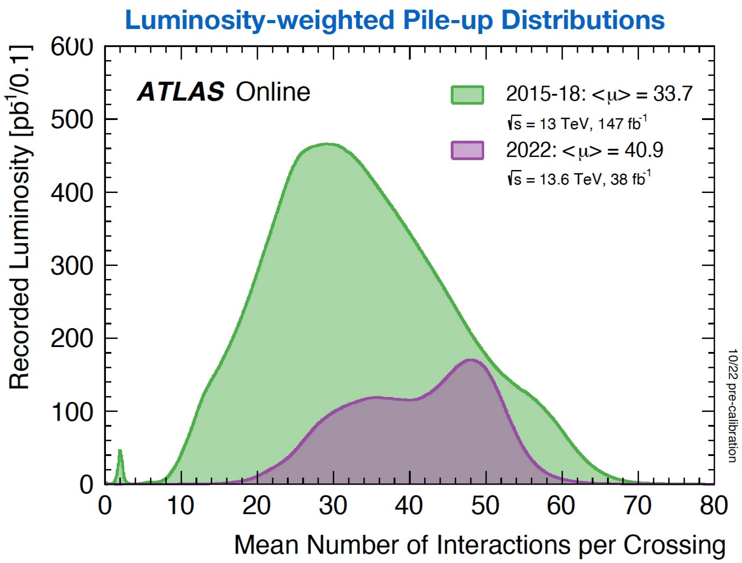
The CMS detector

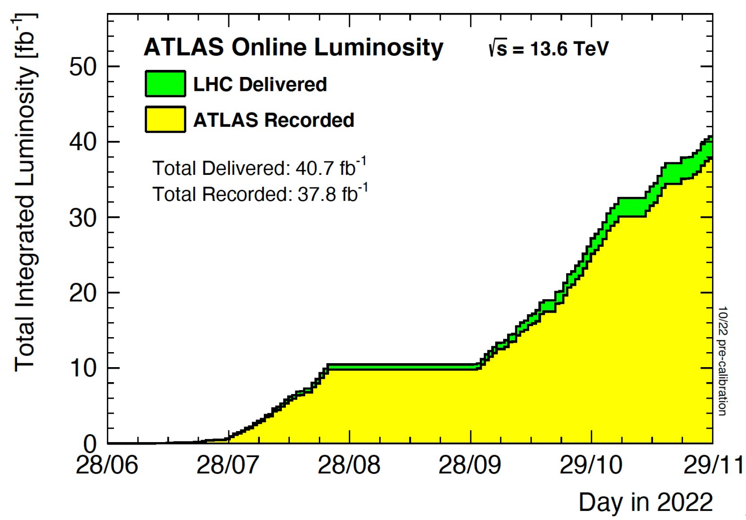


The CMS detector for Run 3

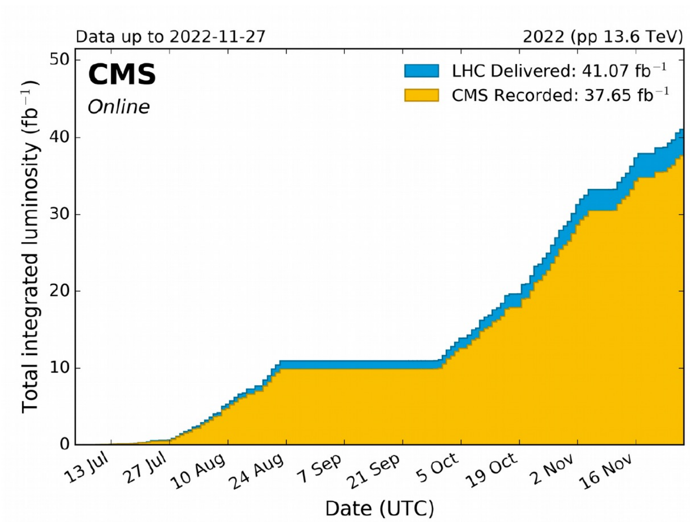


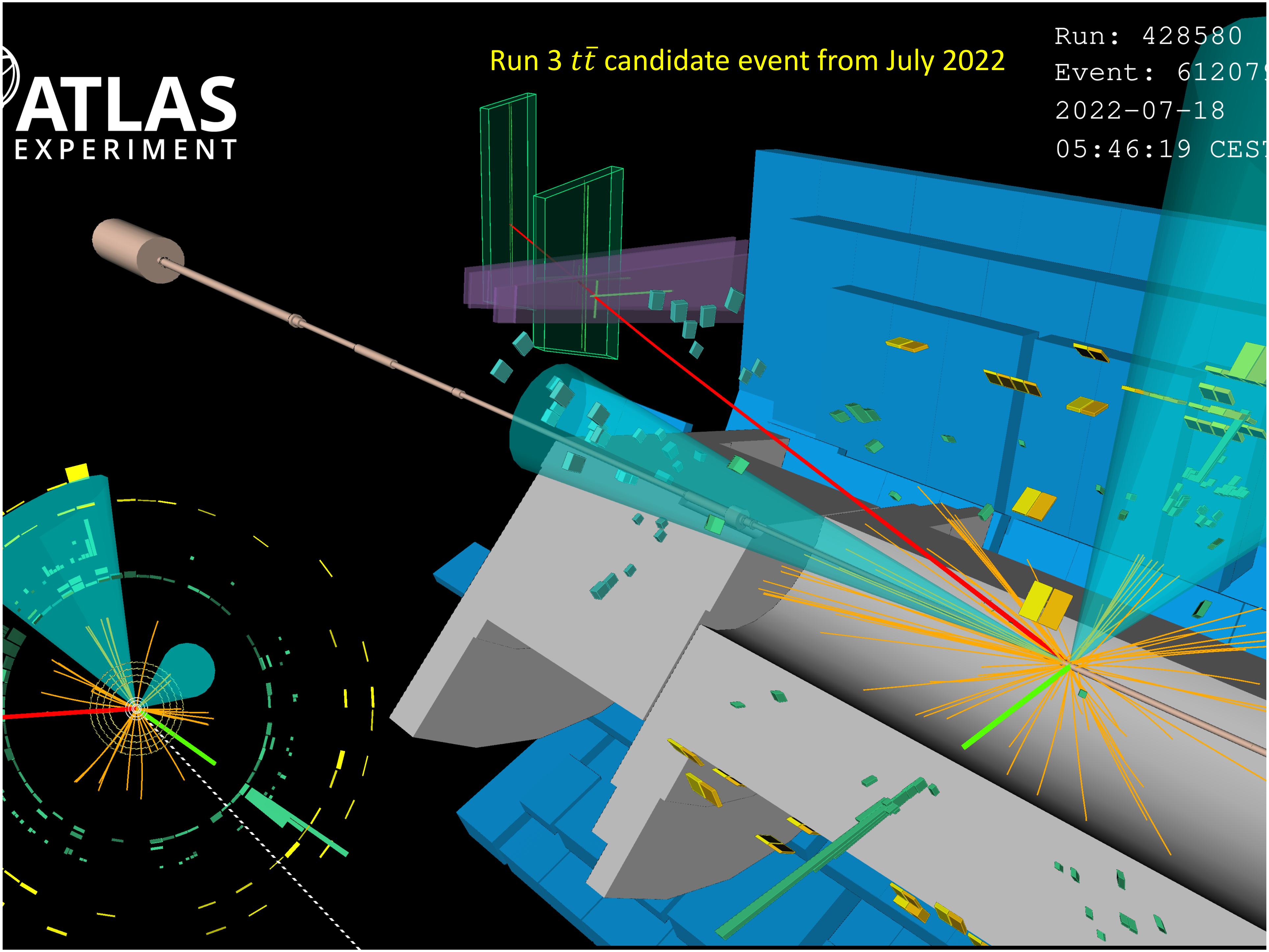
ATLAS/CMS Run 3 Data taking





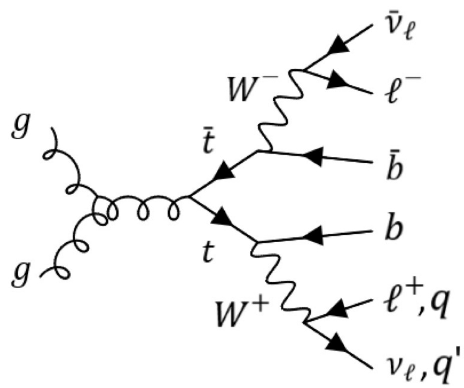
- Good startup of both ATLAS/CMS for Run 3
- Upgrades all working well in both experiments
- Higher pileup (multiple collisions per event)

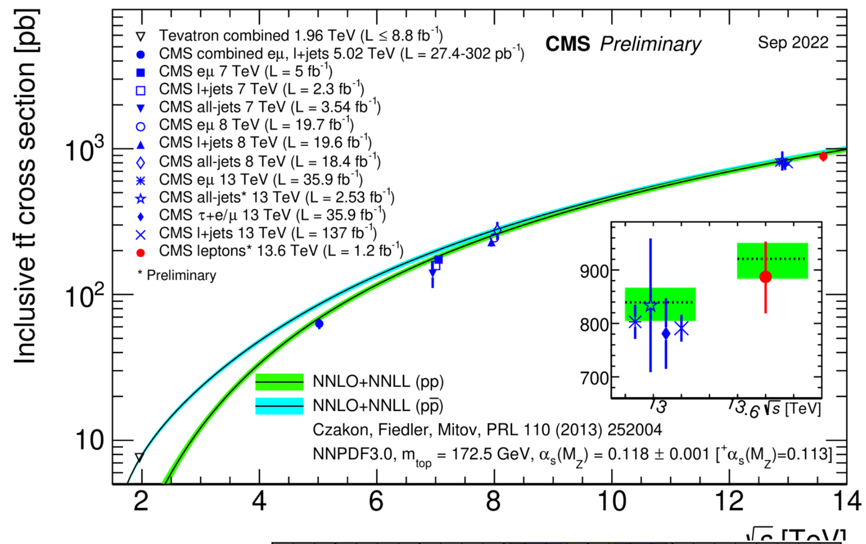


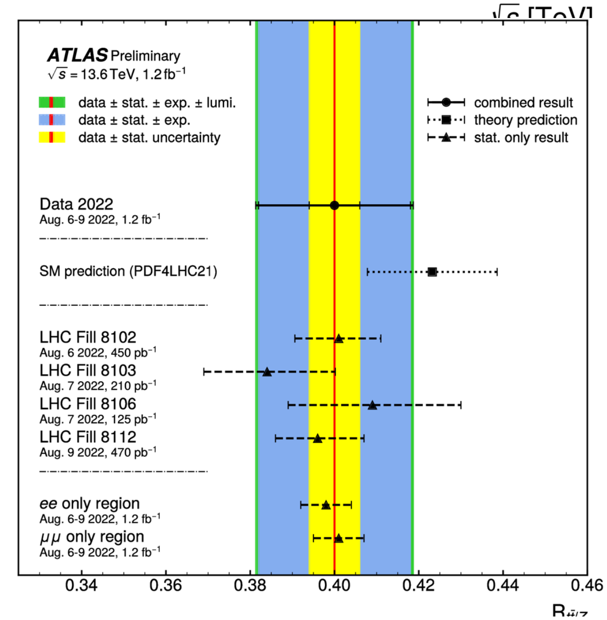

Run 3 $t\bar{t}$ candidate event from July 2022
ATLAS
EXPERIMENT
Run: 428580
Event: 61207
2022-07-18
05:46:19 CES

First Results from Run 3

$t\bar{t}$ cross-section measurements from a few days of data (1.2 fb^{-1})







- 10% rise in $\sigma_{t\bar{t}}$ for $\sqrt{s}$ from 13 → 13.6 TeV

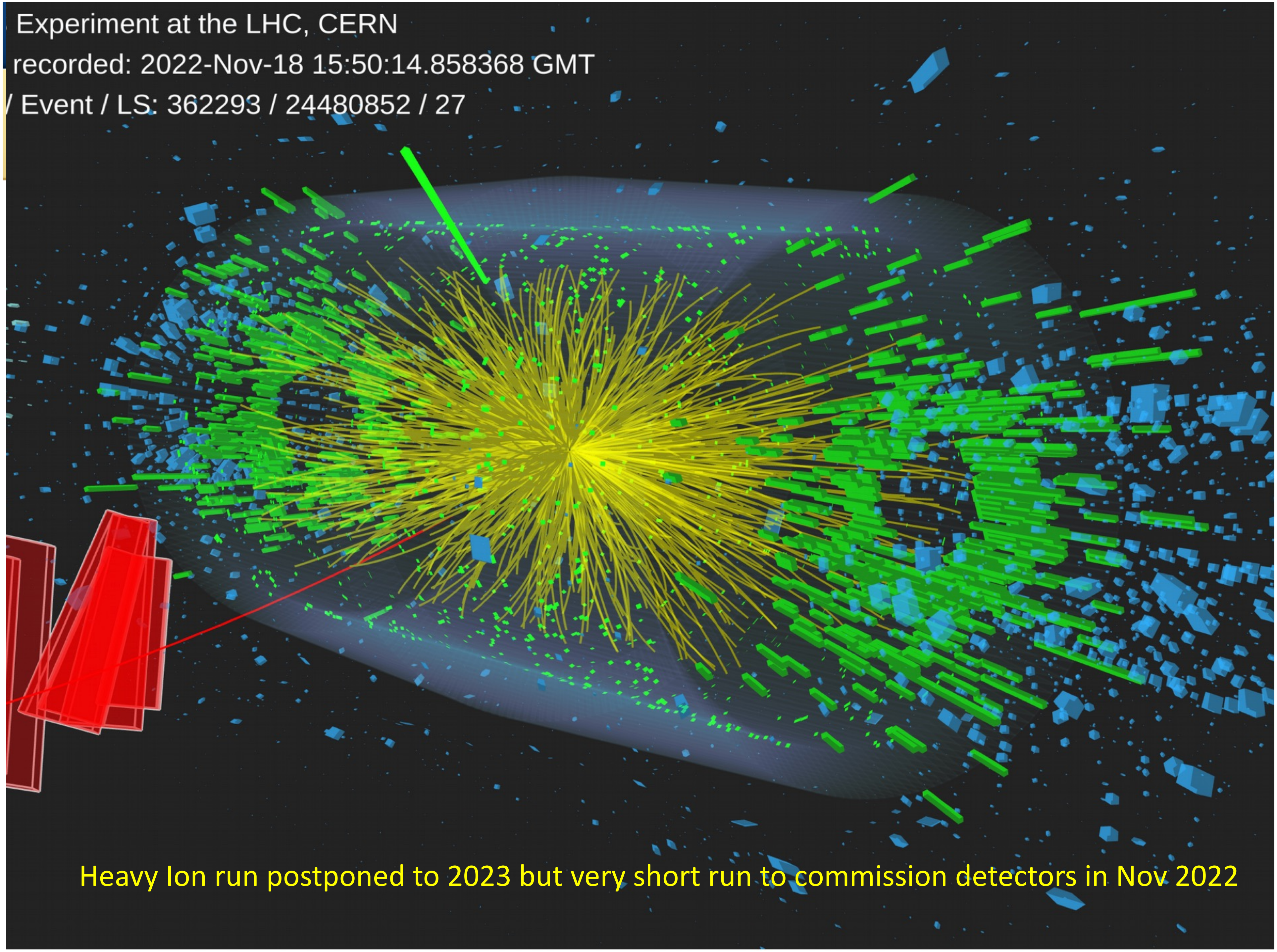
$$\sigma_{t\bar{t}}(Theory) = 921^{+29}_{-37} pb$$ @ NNLO

CMS (*CMS-PAS-TOP-22-012*)

$$\sigma_{t\bar{t}} = 887^{+43}_{-41}(stat.+sys.) \pm 53(lumi) pb$$

ATLAS (ATLAS-CONF-2022-070)

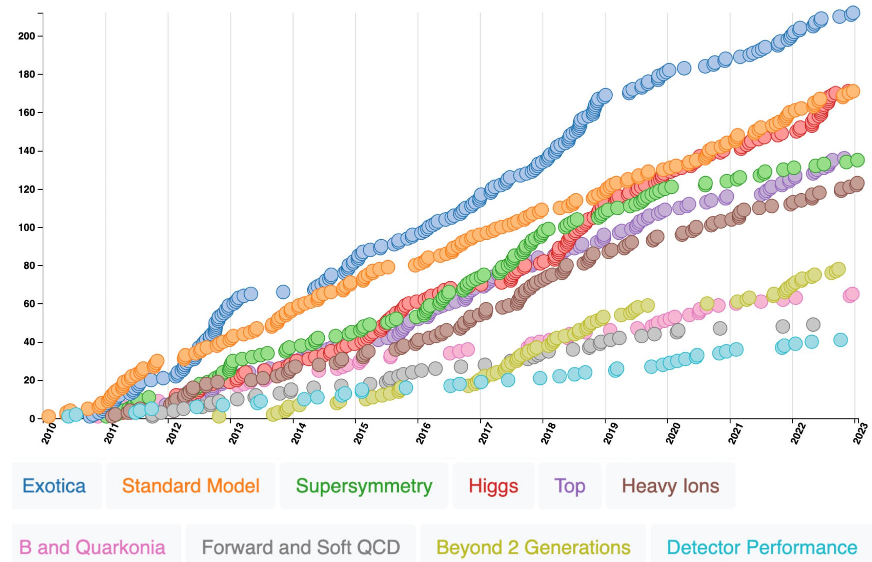
$$\sigma_{t\bar{t}} = 830 \pm 12\ (stat.) \pm 26(syst.) \pm 83(lumi) pb$$



Heavy Ion run postponed to 2023 but very short run to commission detectors in Nov 2022

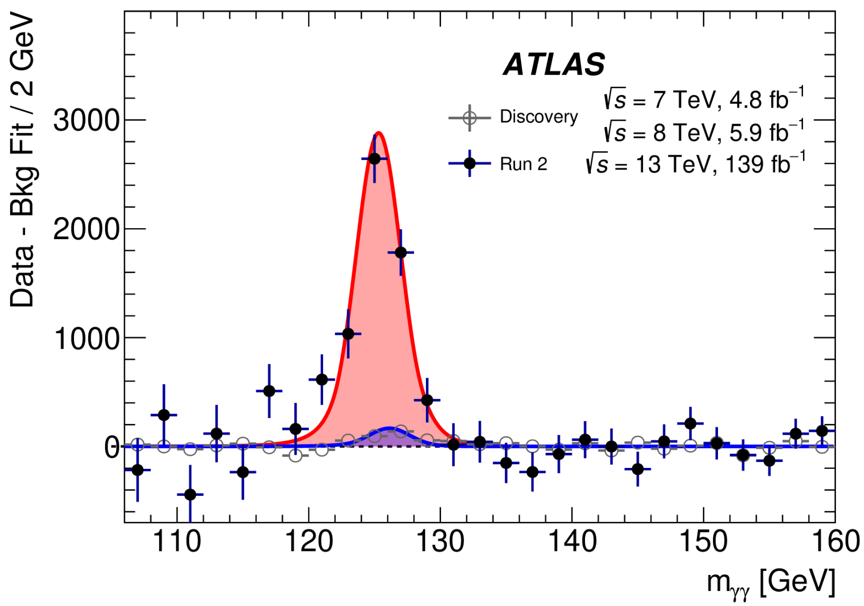
Recent Physics Highlights

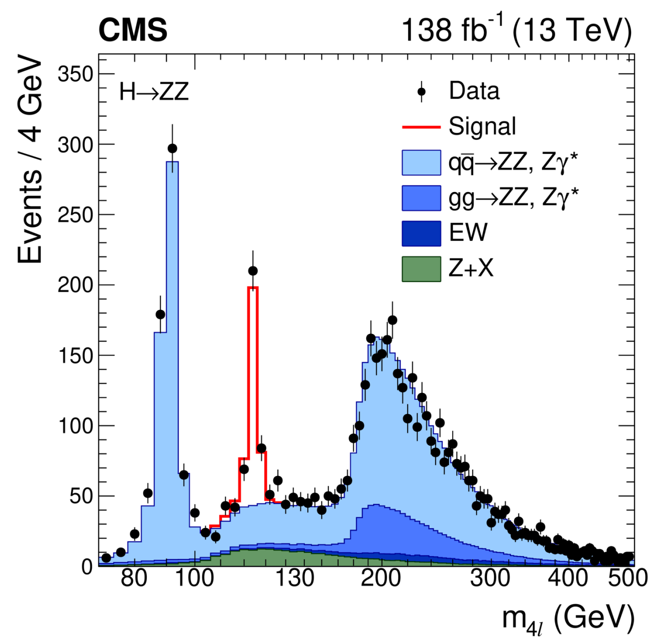
- First batch of full Run 3 results targeted for summer. Possibly some at Moriond
- Recent papers are all from Run 2 dataset
- Many papers produced in past year
- Pick a few highlights.



The Higgs @ 10 years

In July 2022 two papers published in Nature to summarize the understanding of the Higgs Boson 10 years after the discovery.

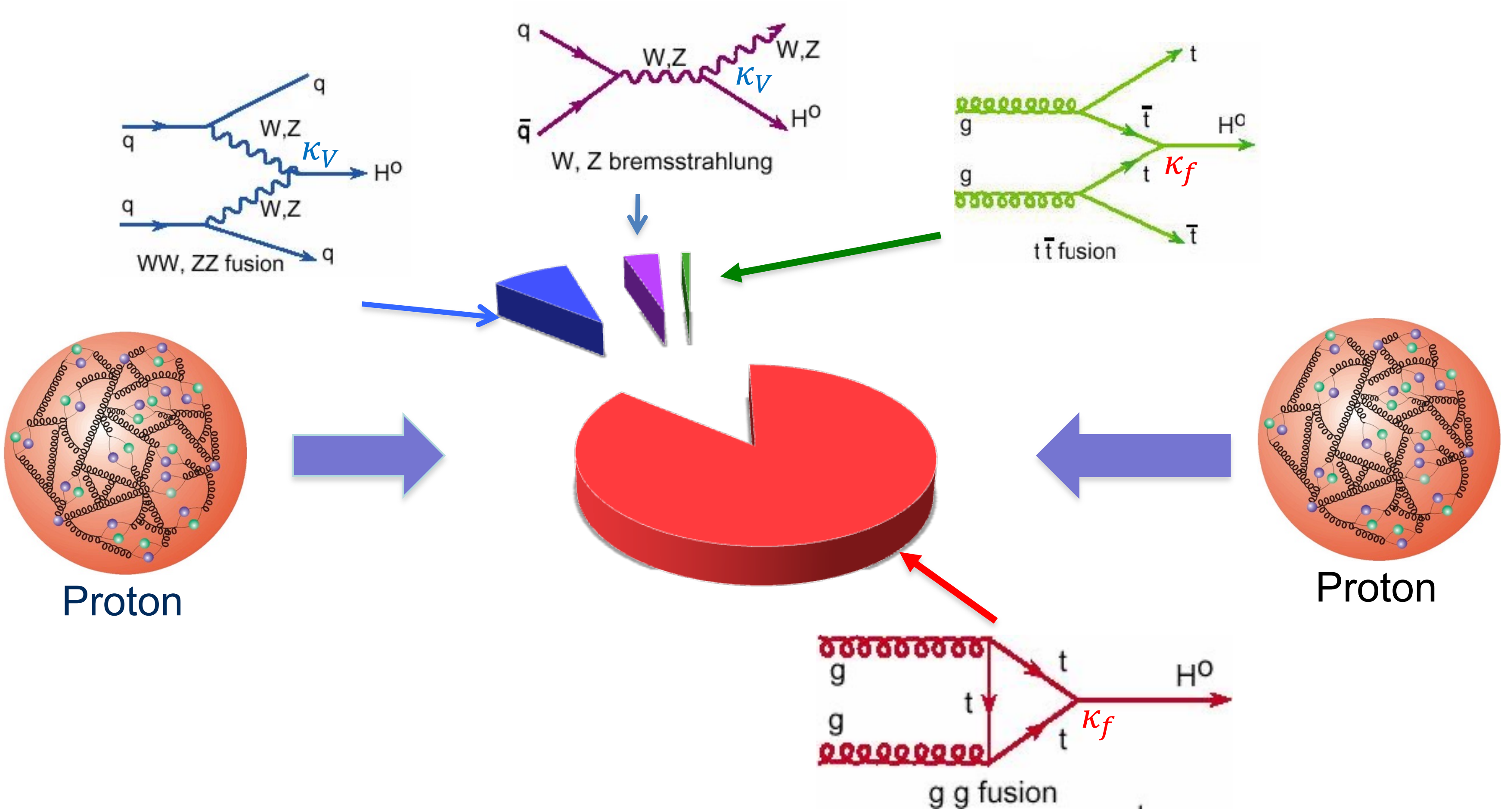




Approximately 8 Million Higgs Bosons produced in Run 2 allowing a full program of studies

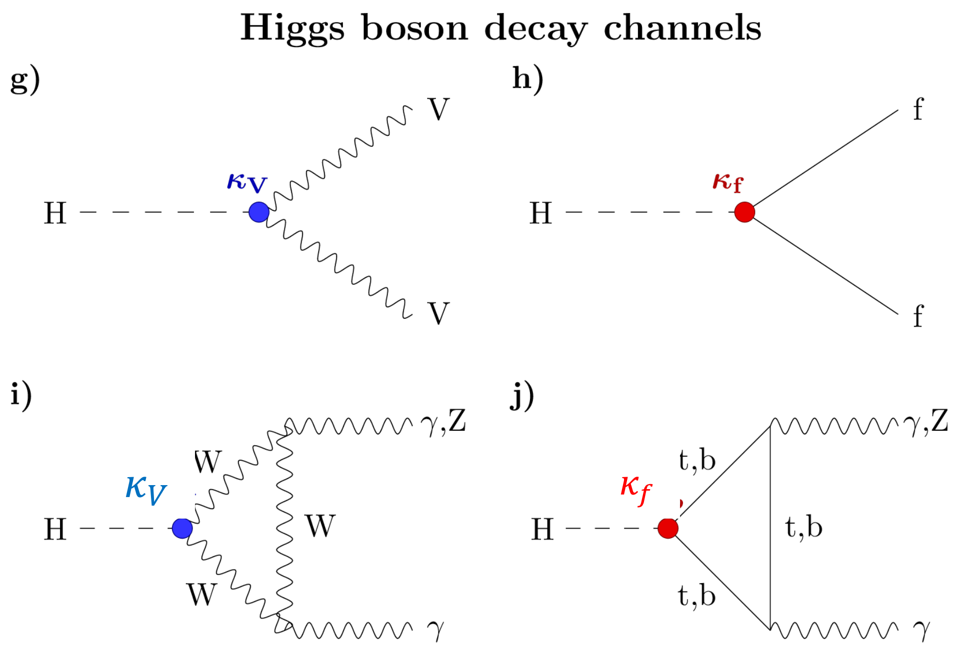
Nature 607, pages 52-59 (ATLAS)/60-68(CMS) 2022

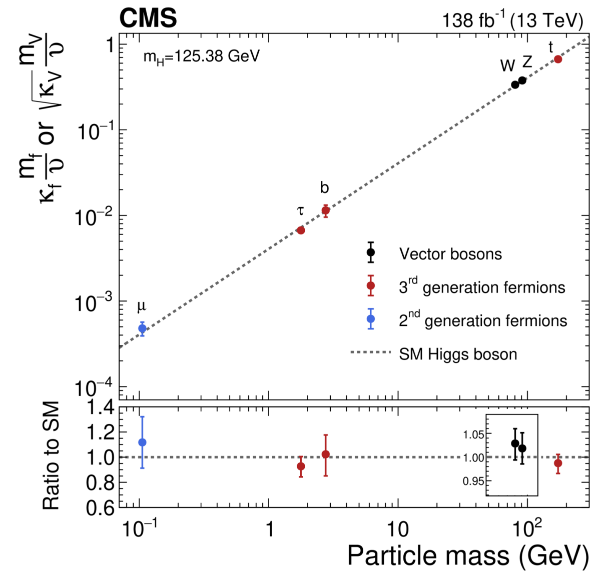
Higgs Production Mechanisms

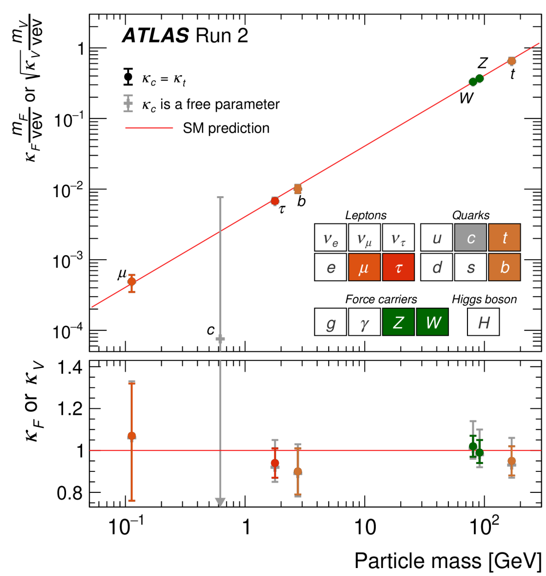


κ_V and κ_f parameterize new physics contributions. In the SM they are both =1

Higgs Decay Modes



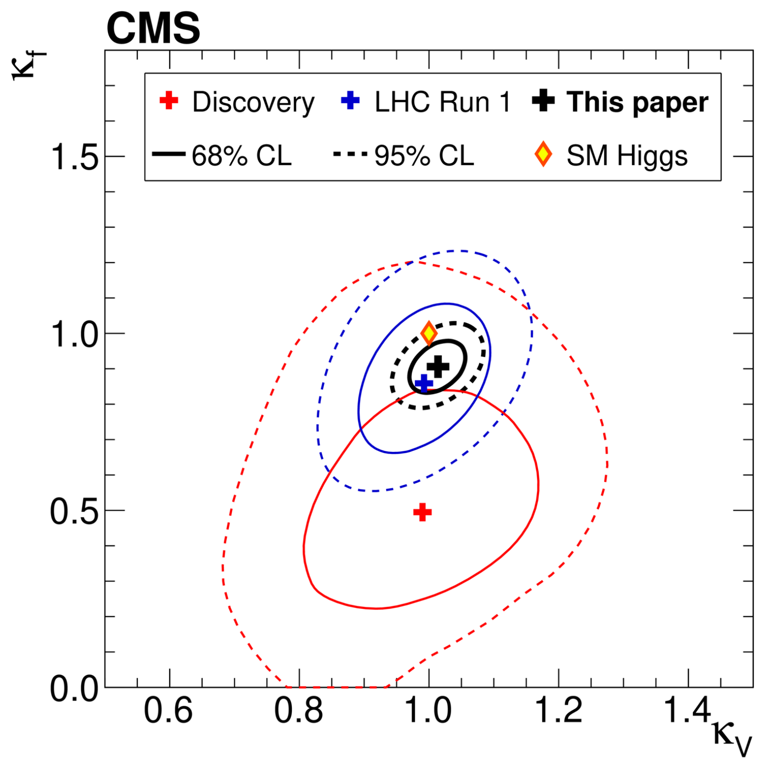


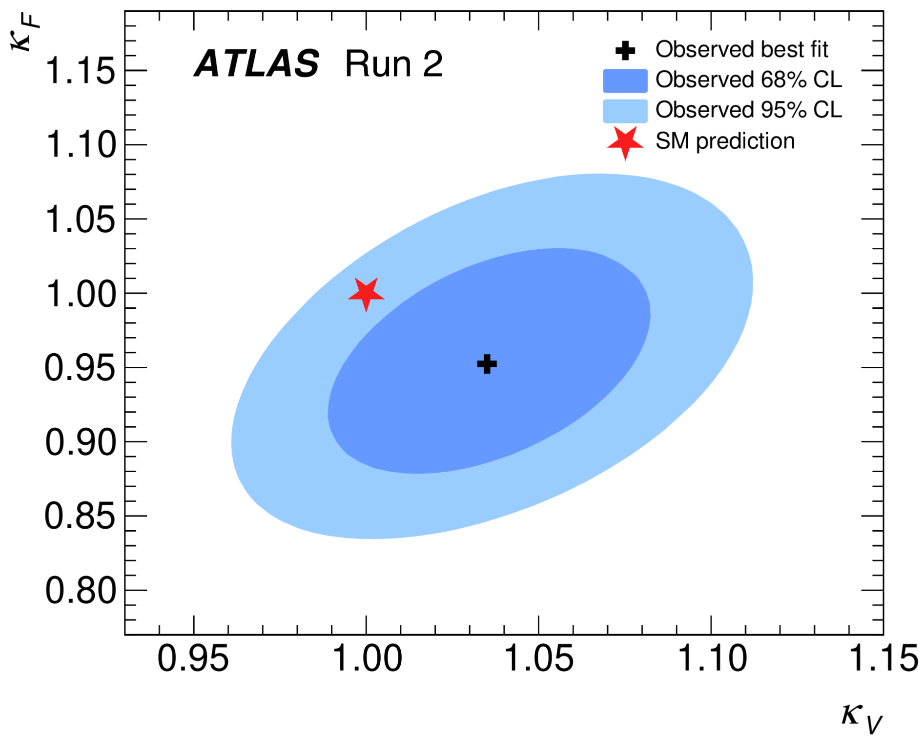


κ_V and κ_f parameterize new physics contributions.

In the SM they are both =1

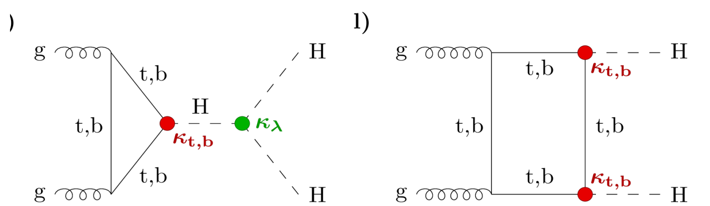
Constraints on κ_V and κ_f





No signs yet of deviations from the SM in the Higgs sector

HH production

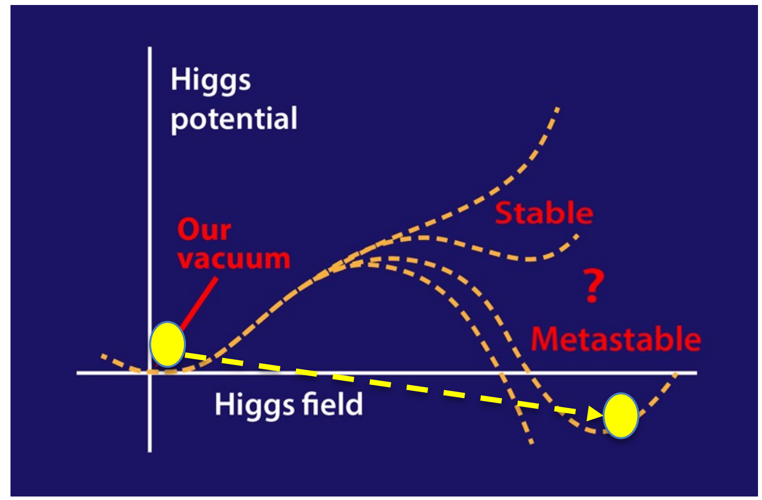


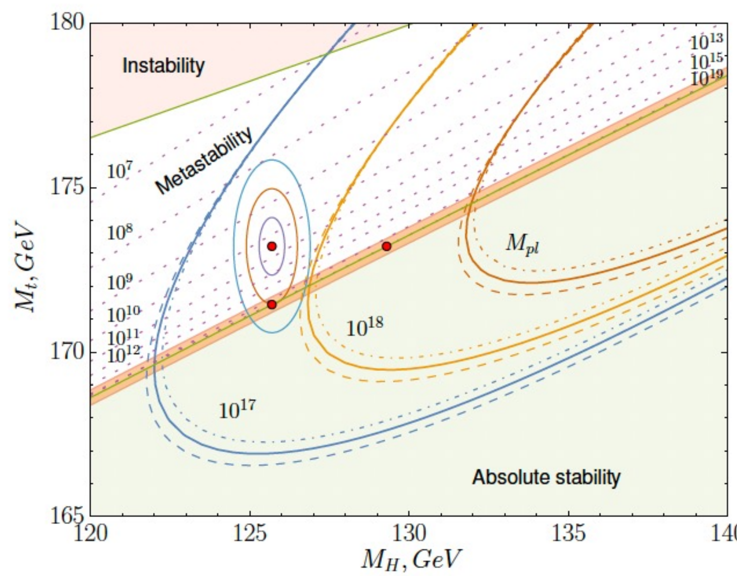
HH production probes Higgs self interaction λ

Help constrain the vacuum potential which may be meta-stable

σ_{HH}^{SM} expected to be ~ 10^{-3} σ_{H}^{SM}

Major goal of HL-LHC but LHC searches are surprisingly sensitive

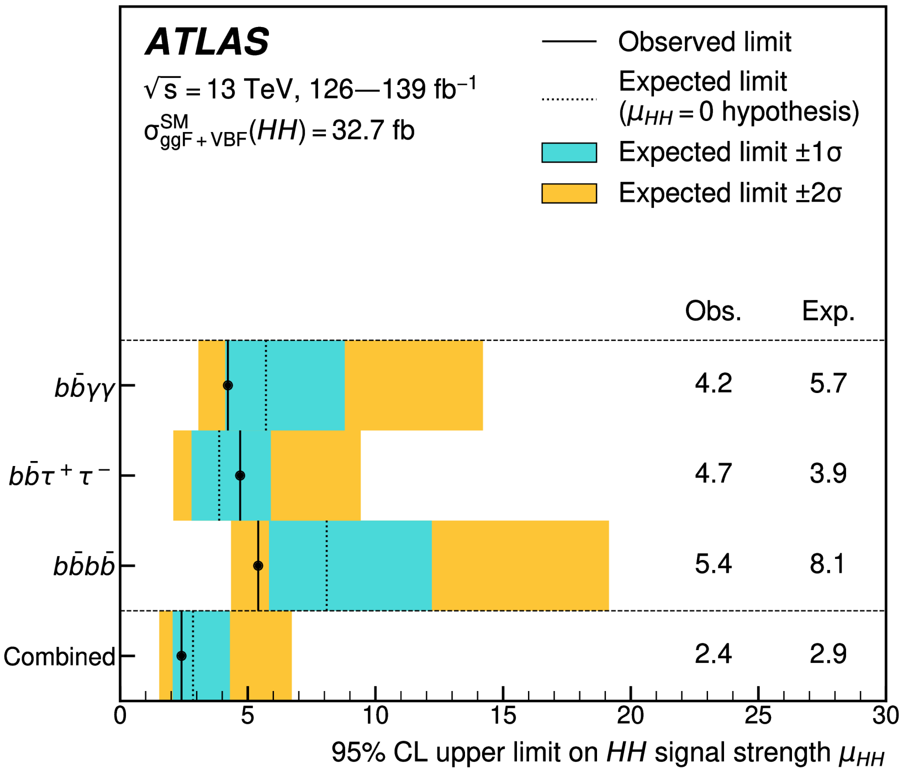


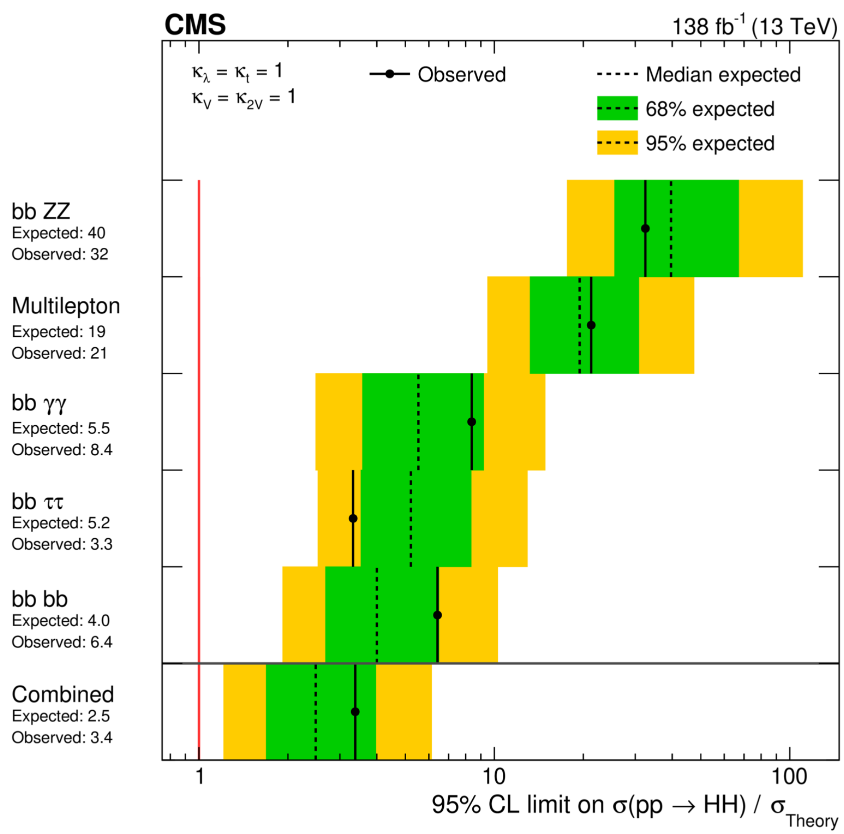


Bednyakov et. al. Phys. Rev. Lett. 115, 201802 (2015))

HH production limits

https://arxiv.org/abs/2211.01216
(new H+HH combination)

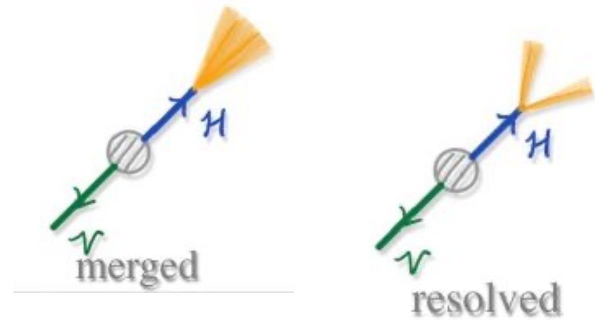


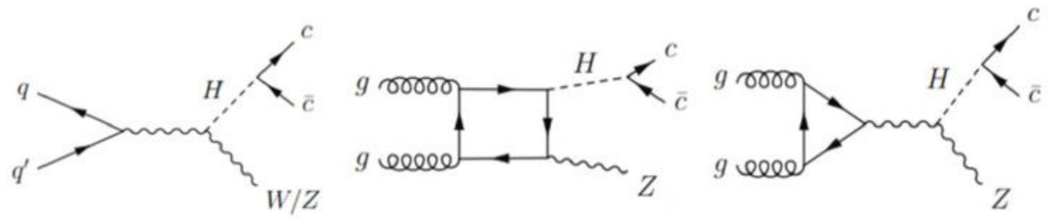


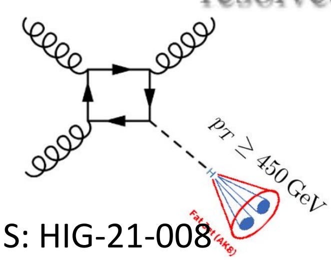
No sign yet but intriguing possibility for Run 3 (LHC) and seems in range for SLHC

Search for $\mathrm{H} \rightarrow c\bar{c}$

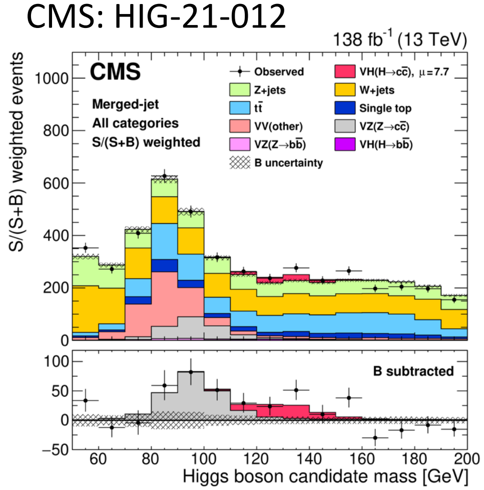
- Search for second generation quark decay of H.
- Very challenging due to high back grounds
- Machine learning to identify charm jets
- Using both merged and resolved cc signatures
- No observation yet. Limits @95% C.L.





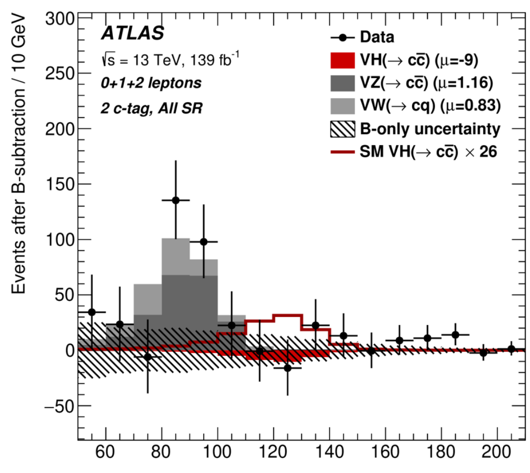


CMS: HIG-21-012



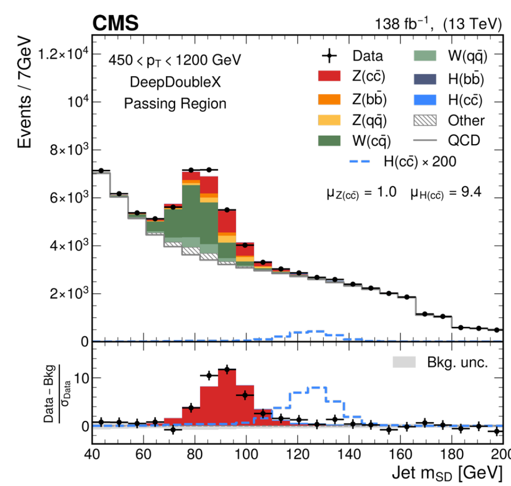
$\sigma_{obs}(\mathrm{H} \rightarrow c\bar{c}) < 14\sigma_{SM}$

ATLAS: [Eur. Phys. J. C 82 (2022) 717]



$\sigma_{obs}(\mathrm{H} \rightarrow c\bar{c}) < 26\sigma_{SM}$

CMS: HIG-21-008

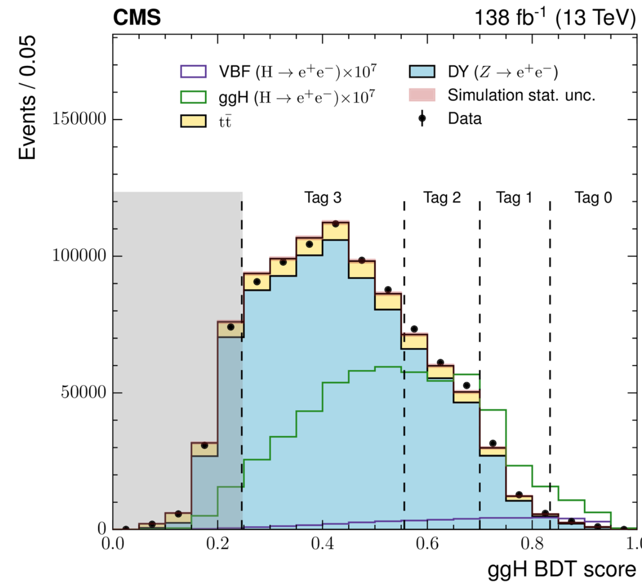


$\sigma_{obs}(\mathrm{H} \rightarrow c\bar{c}) < 47\sigma_{SM}$

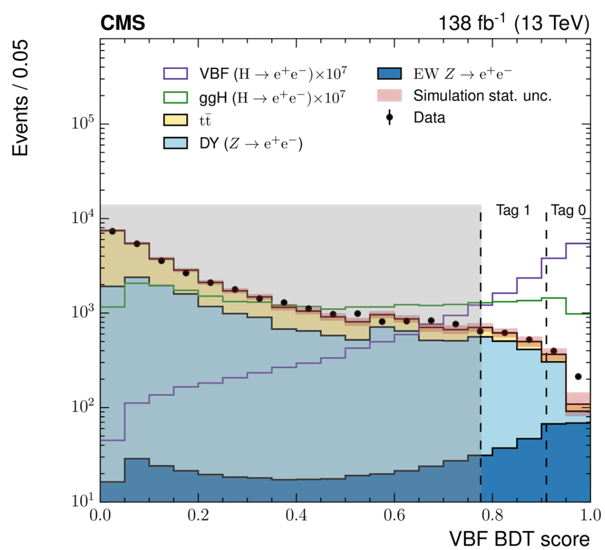
Search for $H \rightarrow e^+e^-$

- Very rare decay in SM. $B_{SM}(H \rightarrow e^+e^-) \sim 5\times10^{-9}$
- Only direct probe of H-ee Yukawa coupling.
- Could be enhanced by BSM e.g 2HDM models
- Analysis strategy similar to $H \rightarrow \gamma\gamma$ but $\gamma \rightarrow e$

ggF H production



VBF H production

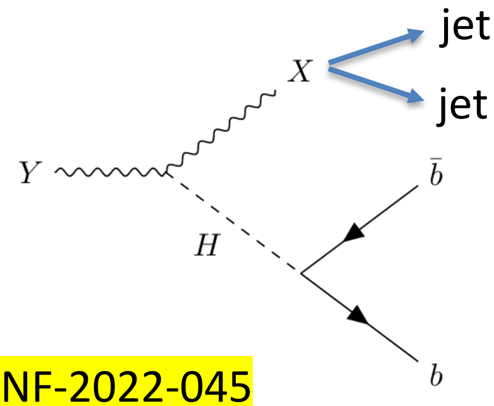


CMS: HIG-21-015

$B(H \rightarrow e^+e^-) < 3\times10^{-4}$ @ 95% C. L

ATLAS: Search for New Physics with Higgs

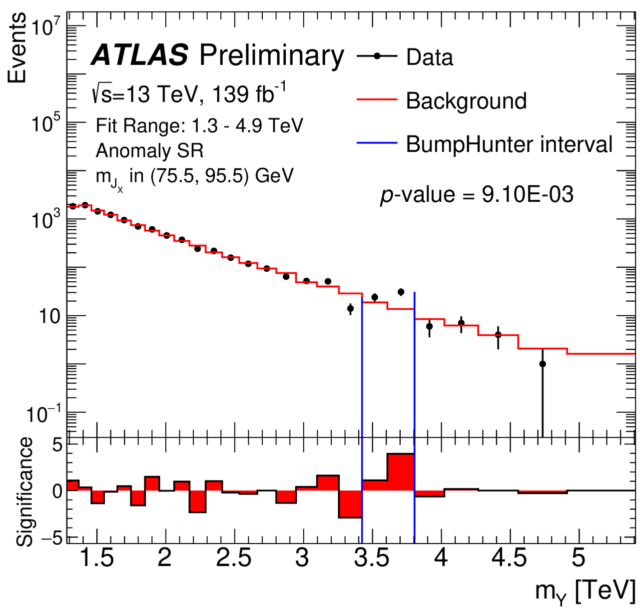
- Search for heavy resonance Y → XH

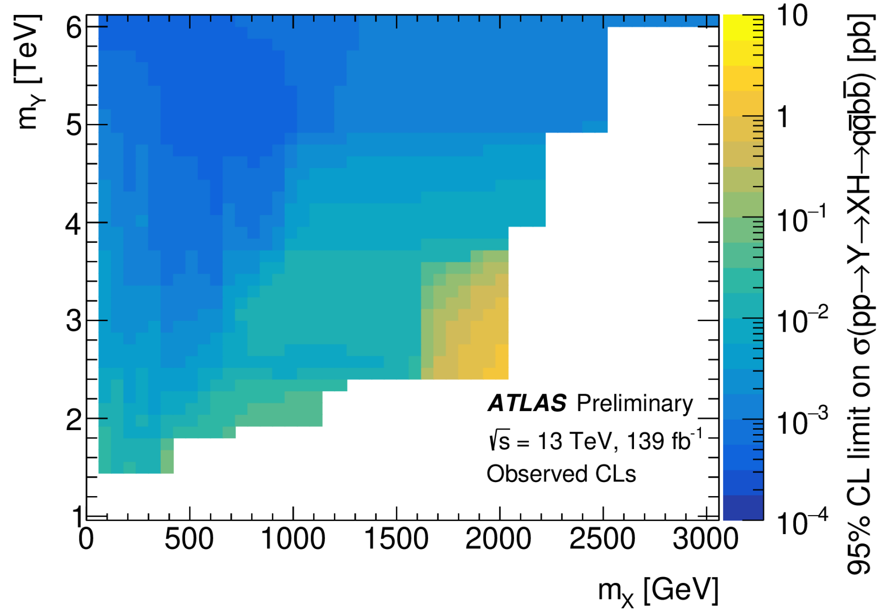


- Identify X in merged and non merged topologies using machine learning anomaly detection (i.e the anomaly is inconsistency with SM background)

- Look for bumps in M_Y for bins of M_X

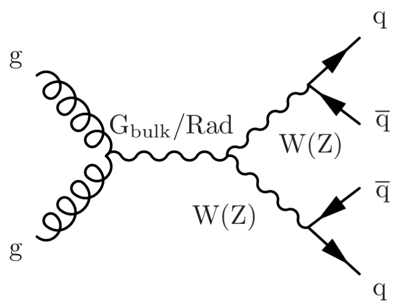
ATLAS –CONF-2022-045

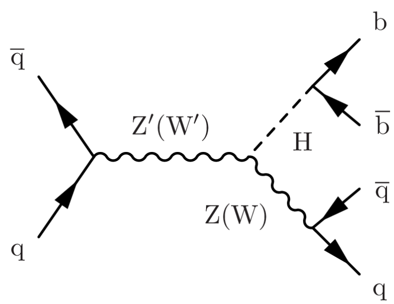




No significant excess observed and limits set in M_y - M_x plane

CMS: Search for Y→ to VV/VH





Here Y is a Z' or Graviton/Radion

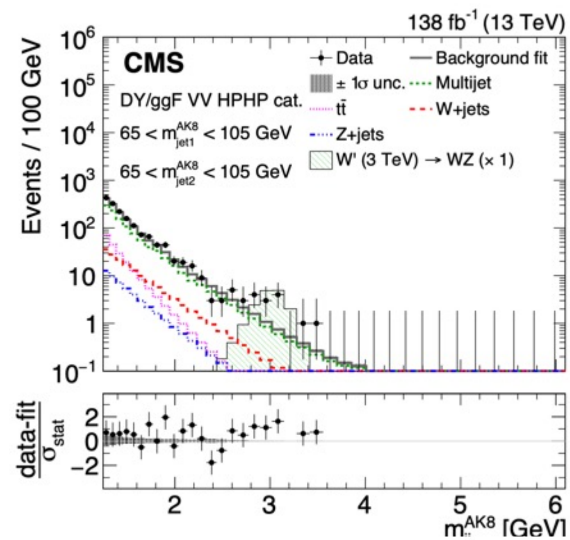
All hadronic merged topologies with machine learning algorithms applied to jet substructure

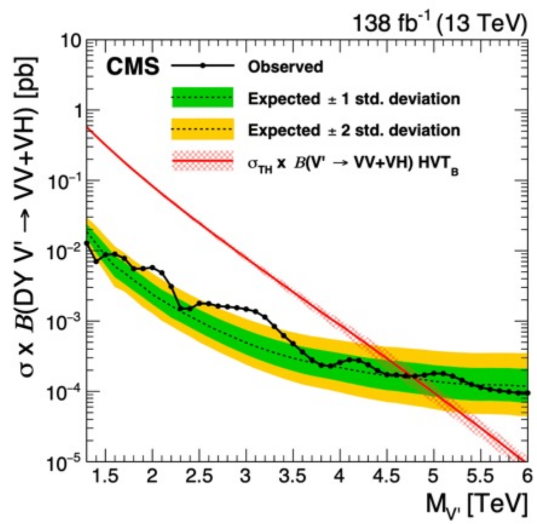
Final discriminating observable:
3D(m_{JJ}, m_{J1}, m_{J2})

Z' → VV+VH: $m_{V'}$ > 4.8 TeV
Radion → VV: $m_{V'}$ > 2.7 TeV
Graviton → VV: $m_{V'}$ > 1.4 TeV

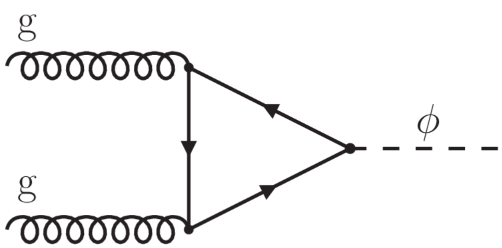
Max. excess at 2.9 TeV (local 3.6 σ, global 2.3σ)

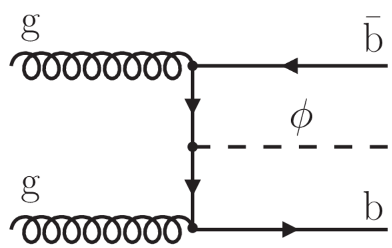
https://arxiv.org/abs/2210.00043

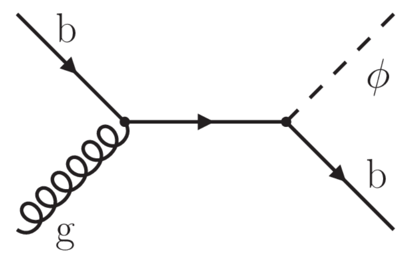




CMS: $\phi \rightarrow \tau\tau$ search







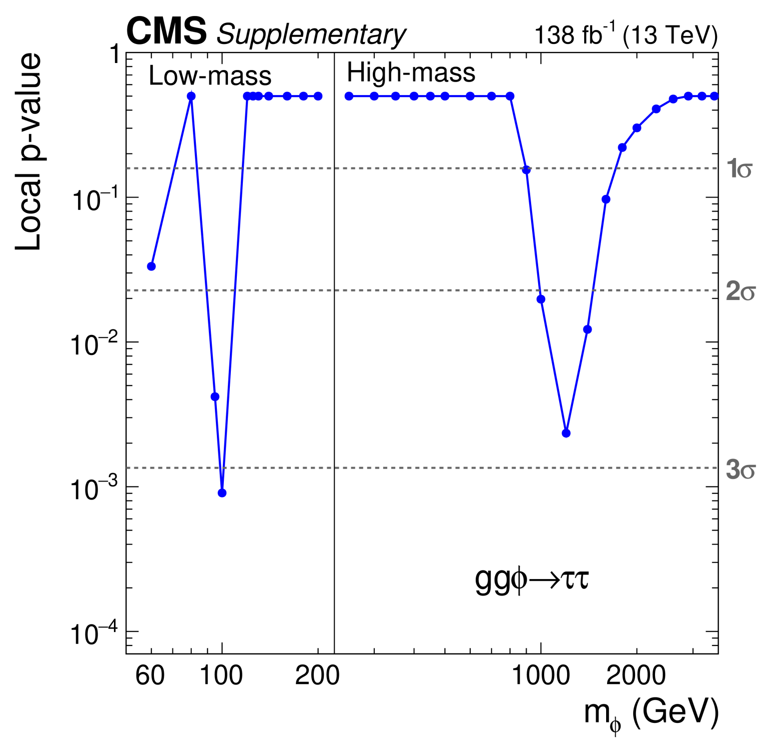
https://arxiv.org/abs/2208.02717

$\tau \rightarrow e, \mu \; or \; hadrons$ signature

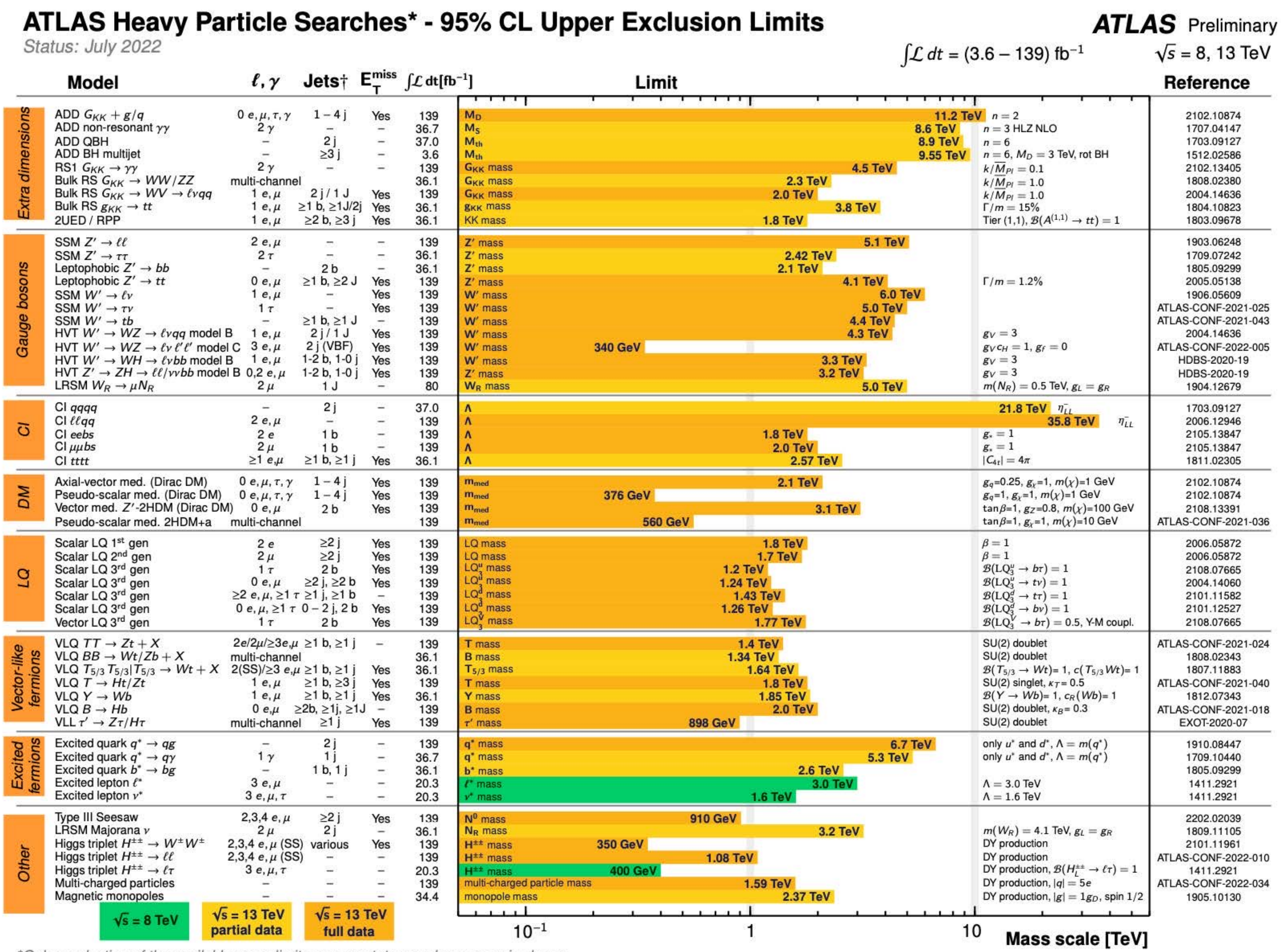
Machine learning DEEPTAU algorithm used for

Search for additional neutral Higgs (Φ)

Local excesses of 3σ at M_{Φ}=0.1,1.2 TeV



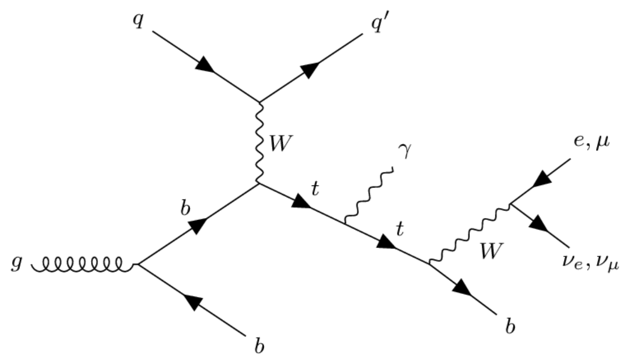
Many Searches for Heavy Resonances !



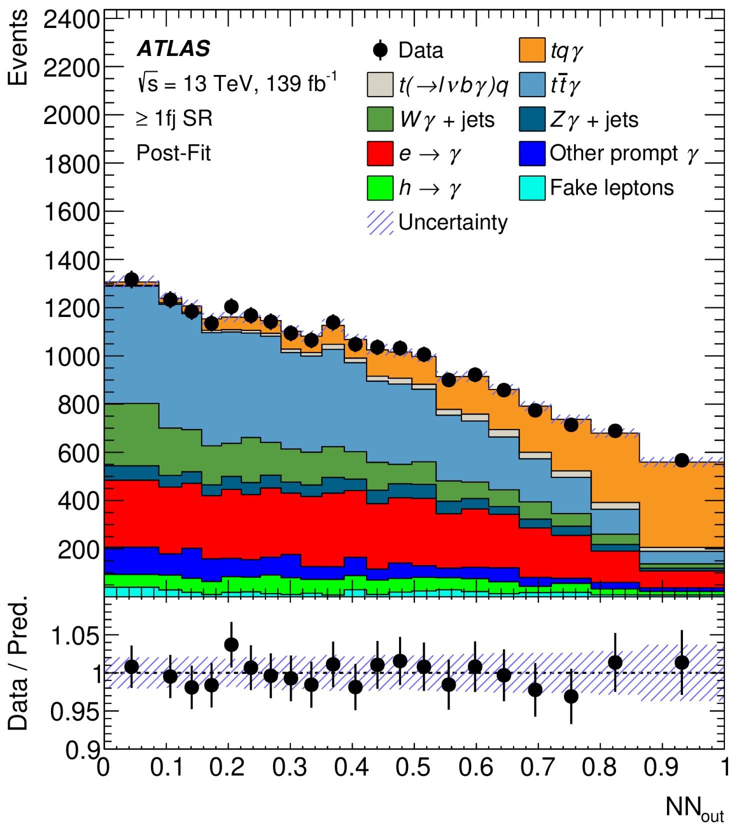
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS: Observation of single top +photon



https://arxiv.org/abs/2302.01283



- t-channel production with forward jet
- Neural Net background discriminant

σ_{obs} = 688 ± 23 (stat.) +75 (syst.) fb

$\sigma_{SM\ theory} = 515^{+36}_{-42}$ fb. @ NLO

Earlier evidence for with CMS (36 fb^{-1})
Phys. Rev. Lett. **121** (2018) 221802

CMS: Top quark Mass from boosted Top

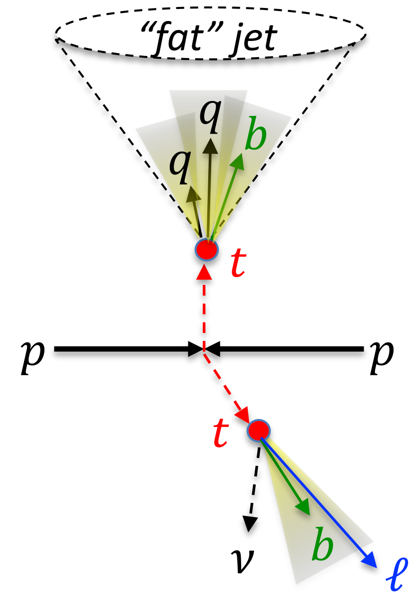
$tt \rightarrow (bjj) + b\ell\nu$

https://arxiv.org/abs/2211.01456

- Boosted top (p_T>400 GeV)
- one top decays hadronically and forms a merged "fat" jet with sub-structure (jet p_T>400 GeV)
- another top decays leptonically (due to boost, the lepton may not be isolated)

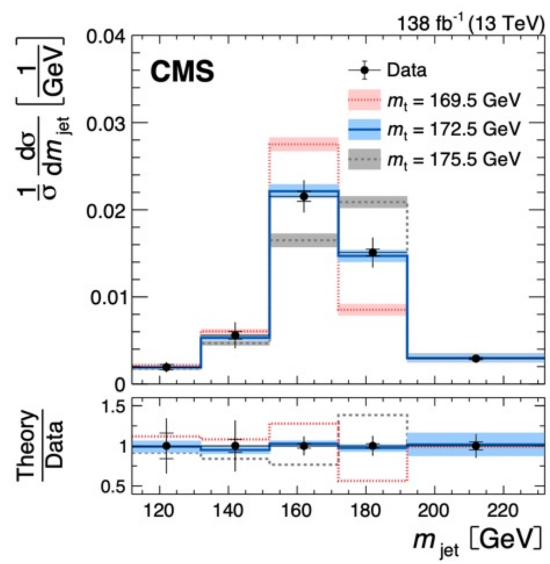
•

• "fat" jet mass (m_{jet})



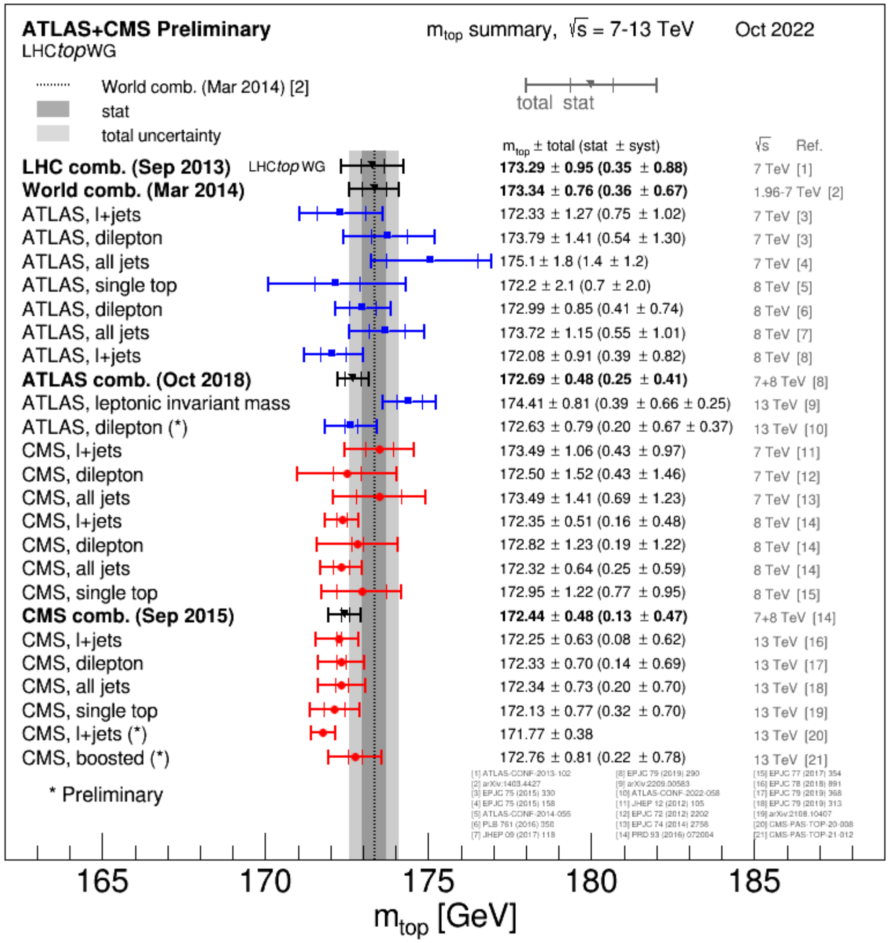
$\boldsymbol{m_t = 172.76 \pm 0.81}$ **GeV**
$= 172.76 \pm 0.22(stat) \pm 0.57(exp) \pm 0.48(model) \pm 0.24(theo)$GeV

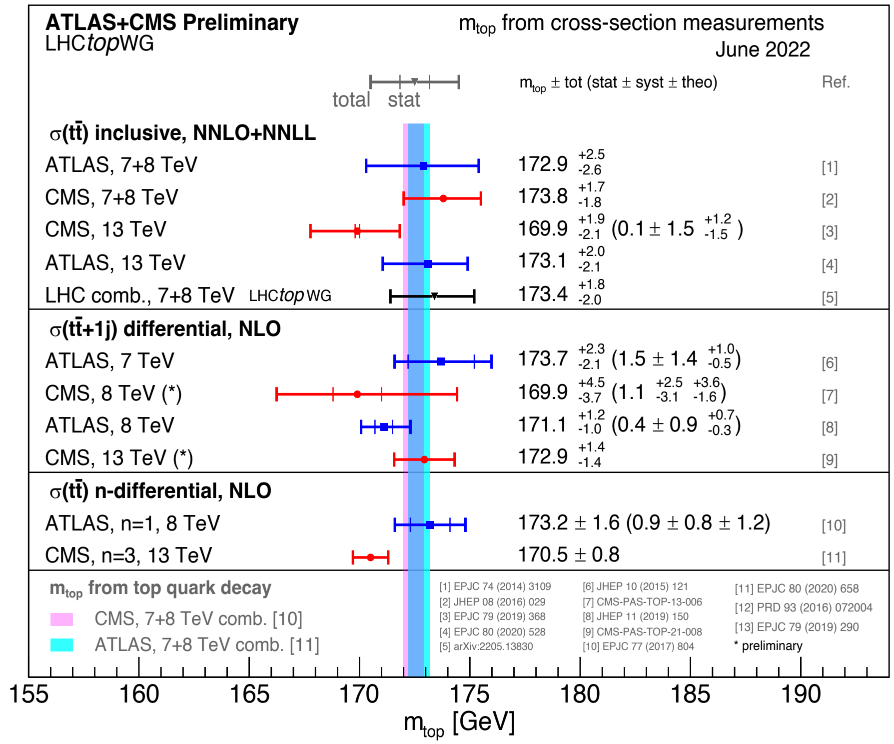
First top quark mass measurement with the full Run 2 dataset
(precision is improved by a factor of 3 w.r.t. the 2016 dataset analysis)



Many Top Mass Measurements !

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots#Top_Quark_Mass





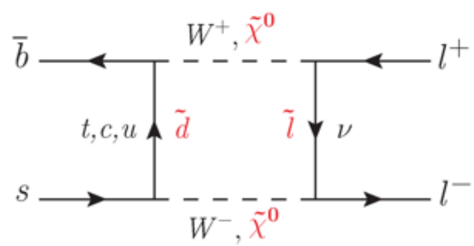
CMS: $B \to \mu\mu$

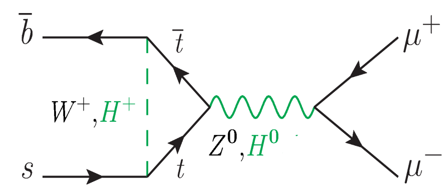
https://arxiv.org/abs/2212.10311

- B→ μμ is highly suppressed in SM, which ca make BSM-induced decays more visible

- Two muons, forming a common displaced vertex MVA to suppress backgrounds.

- Main bkgs:
  muons from different heavy-flavor mesons
  muons from B-meson cascade decays
  $B \to K\pi, B_s \to KK$ (mis-id)



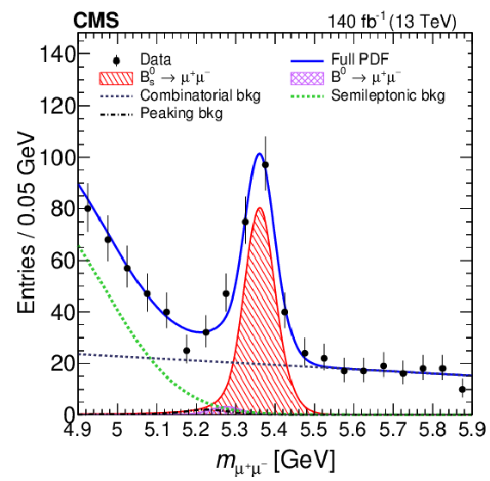


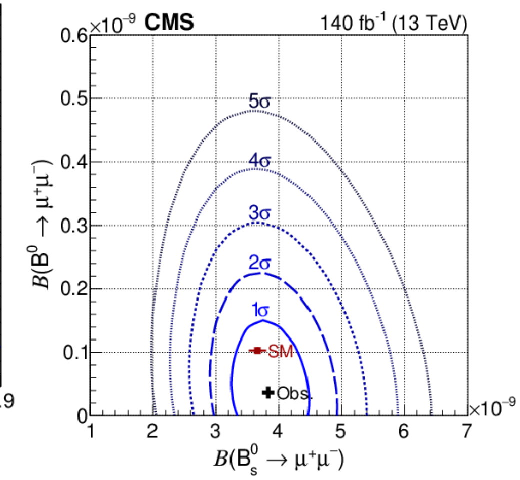
Examples of Feynman diagrams: black – SM particles
red/green - BSM

F$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[4.02^{+0.40}_{-0.38}\,(\text{stat})\,^{+0.28}_{-0.23}\,(\text{syst})\,^{+0.18}_{-0.15}\,(\mathcal{B})\right] \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-10}$ at 90% CL

Consistent with SM

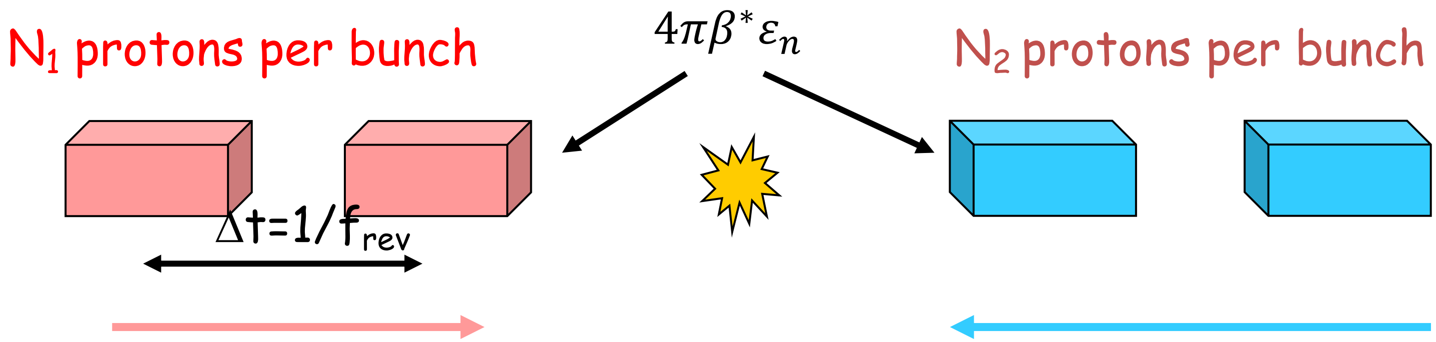




Luminosity at the LHC/HL-LHC

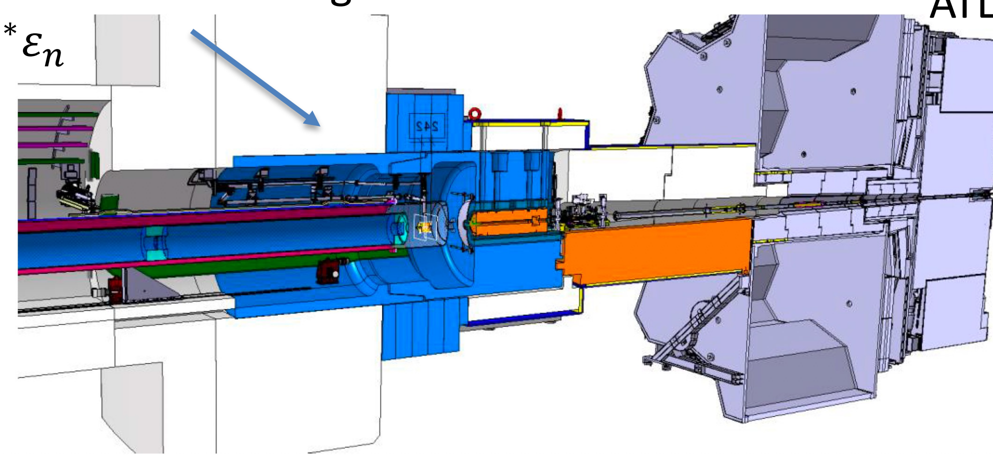
$$L = \frac{N_{bunchs} N_1 N_2 f_{rev}}{4\pi\beta^* \varepsilon_n} \gamma R$$

R is a geometric factor from beams crossing at an angle



Quad focusing for interaction region minimizes $4\pi\beta^* \varepsilon_n$

ATLAS endcap



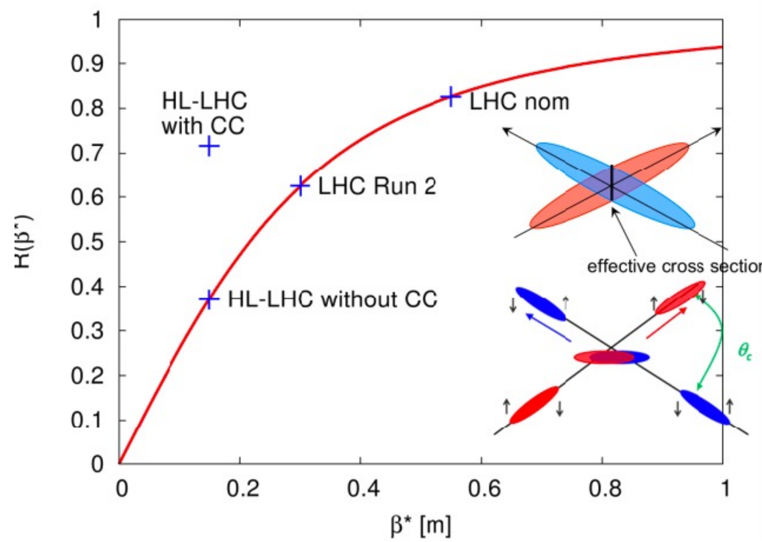
LHC luminosity is limited primiarily by heat dissipation in quad focusing to $2{\times}10^{34} cm^2 s^{-1}$

The HL-LHC – Key developments

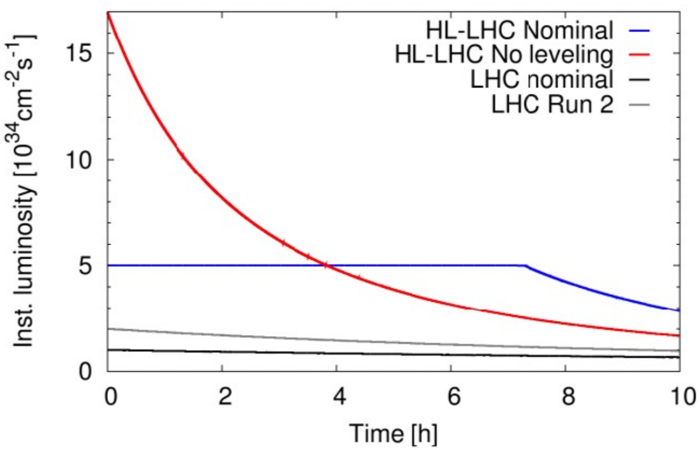
Superconducting Nb_3Sn focusing quadrupole

1. Stronger focusing for smaller β^*. Key technology is the use of Nb_3Sn (Niobium Tin) magnets developed in USA. NbTi used now limited to 8T. Nb_3Sn can go to 12-16T

2. Crab crossing cavities that rotate beam at interaction point to increase R

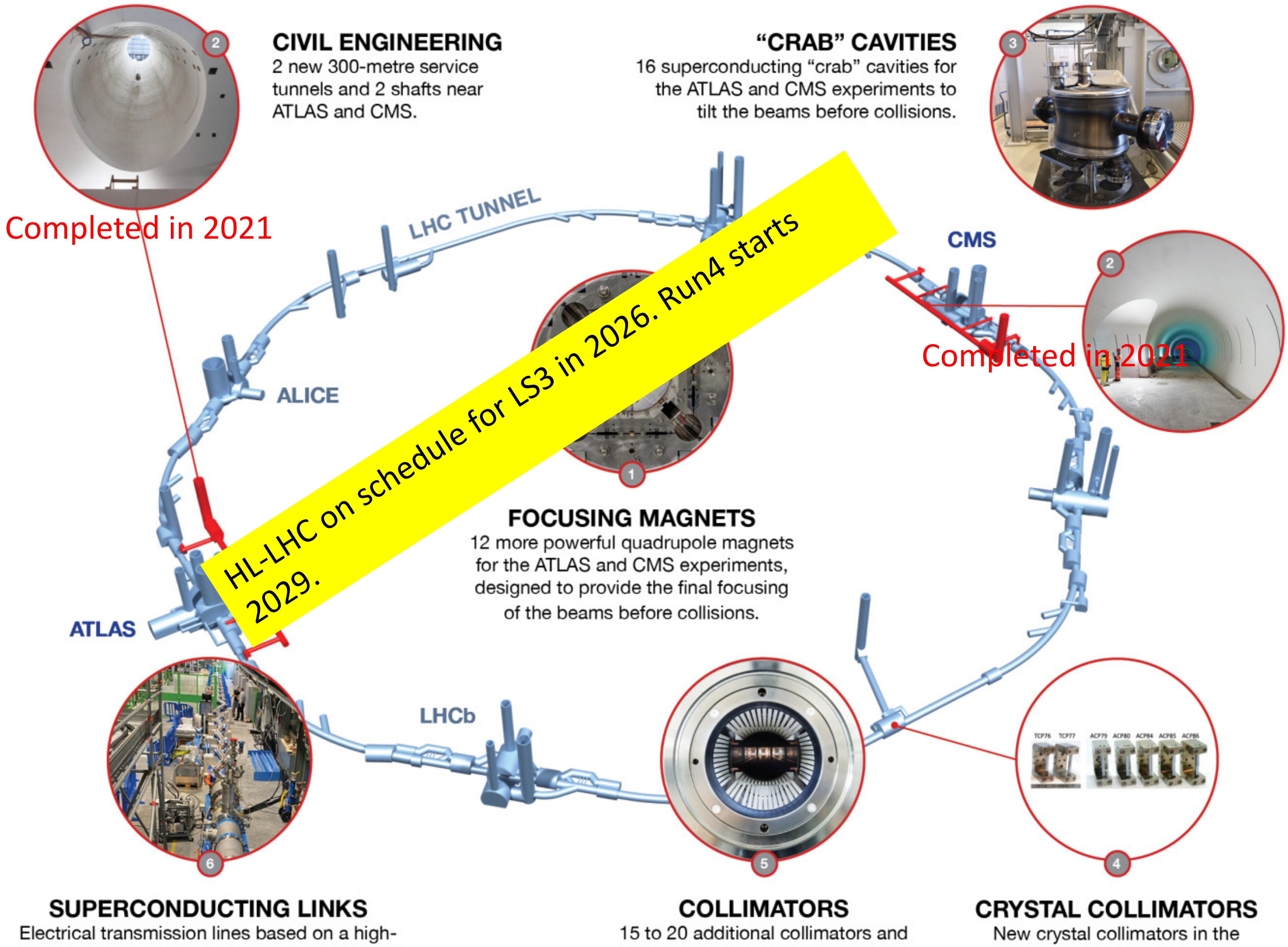


3. Luminosity leveling (by adjusting β^*) to control pileup and quad heating



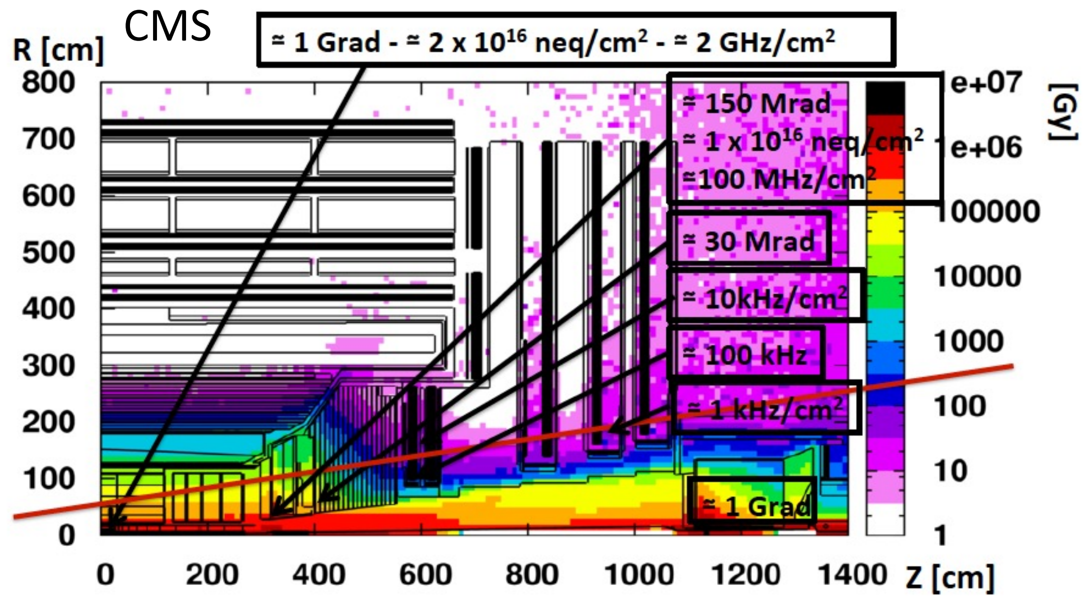
4. Double number of protons per bunch

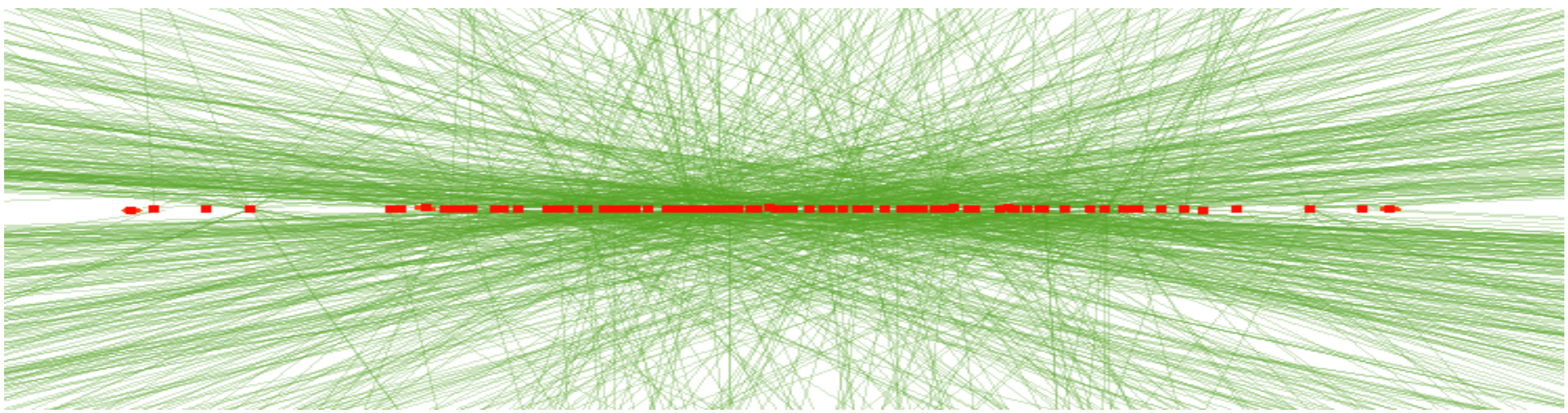
NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC



Challenges of the Detector Upgrade

- High Luminosity means
  - Many collisions (Pileup) (140 to 200 per event)
  - High irradiation (up to 1 GigaRad in forward region or close to collision point)





A top pair event with 140 collisions

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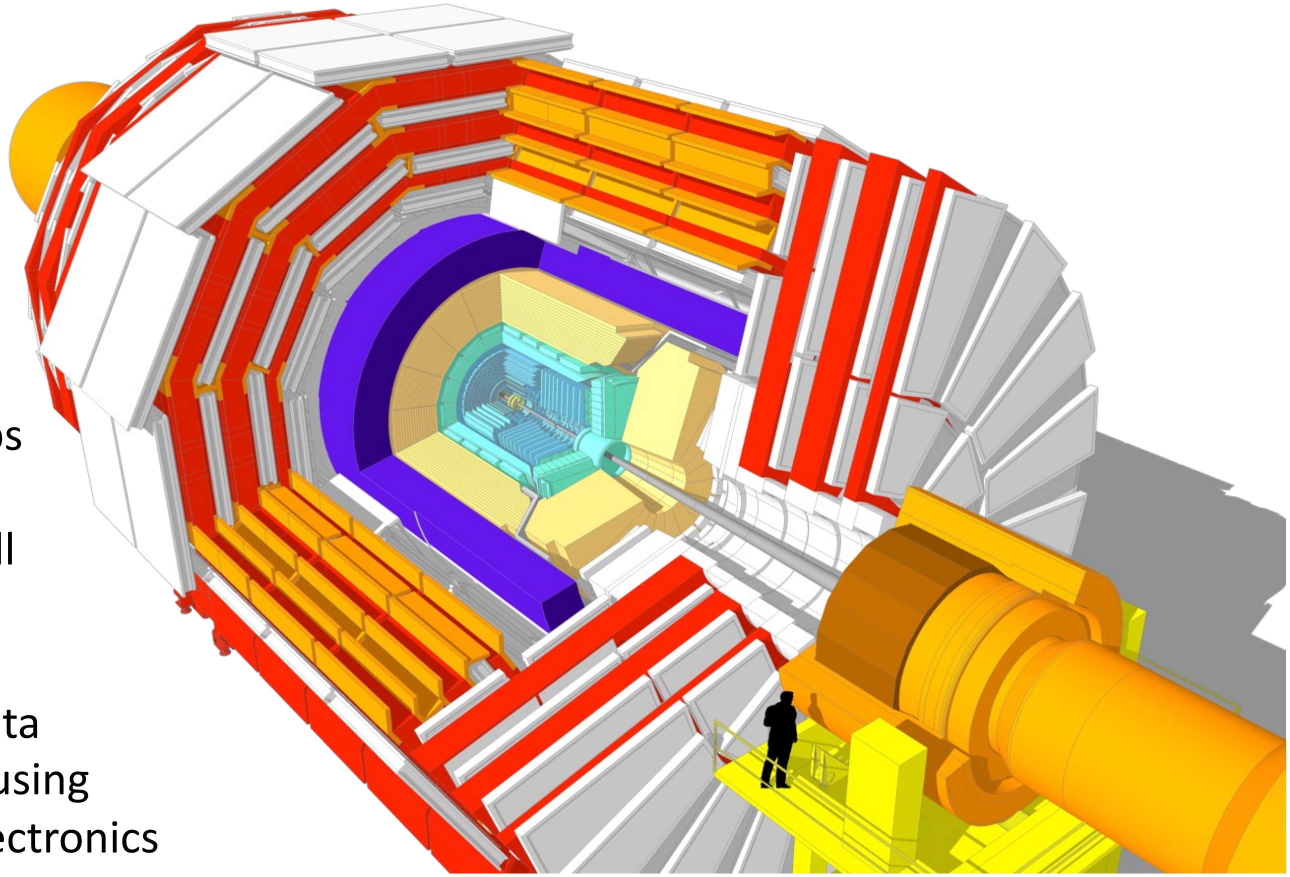
Strategies to Deal with the Challenges

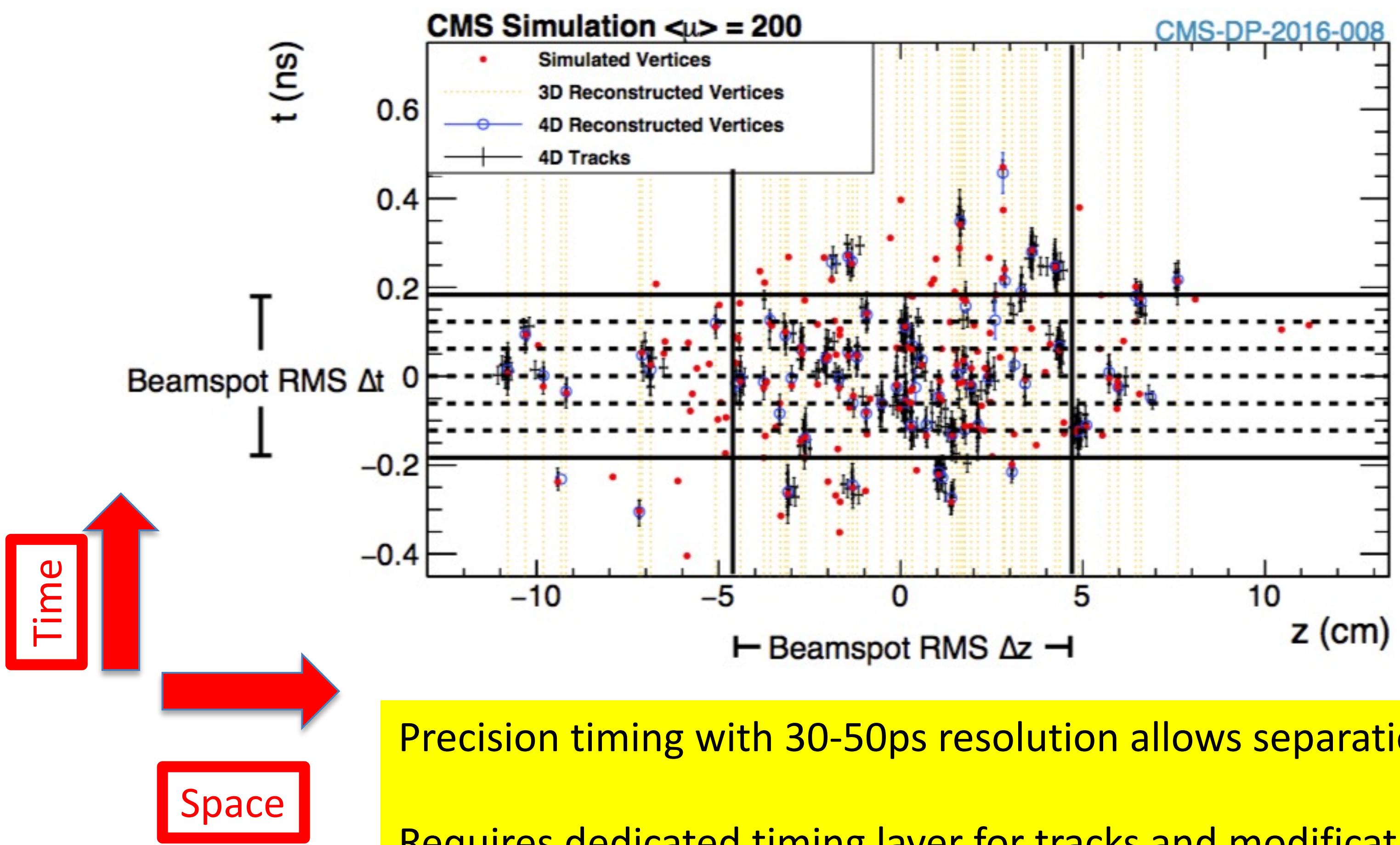
- **Increased use of silicon sensors** (high radiation tolerance)
- **More granularity in the silicon** to deal with the high pileup
- **Precision timing** (< 50ps resolution) to separate collisions in time as well as space
- **Faster processing** of data in real time for trigger using modern high speed electronics



Essentially try to maintain or improve the legacy LHC performance in HL-LHC conditions

Precision Timing

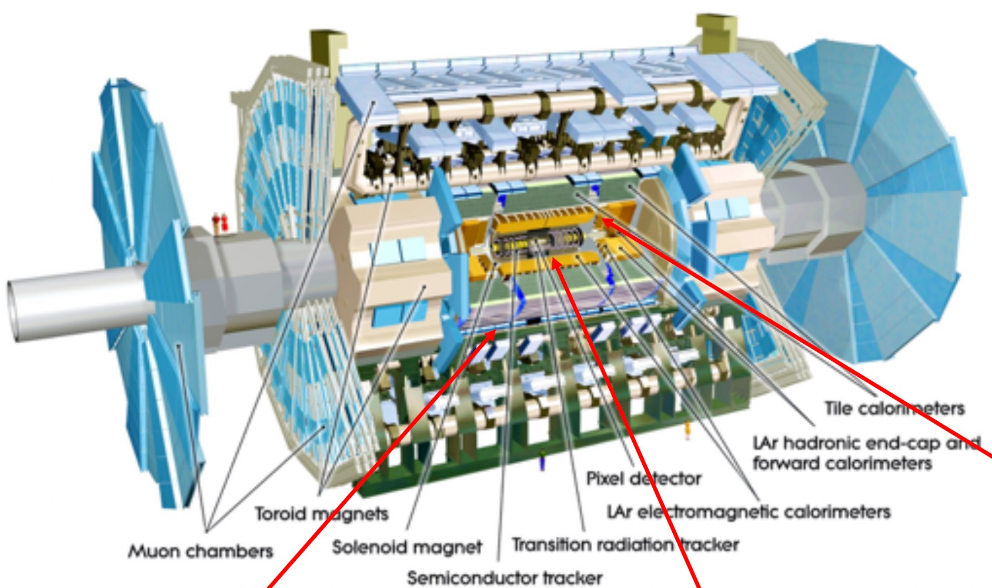
Collision Vertices in the CMS interaction region with 200 Pileup



Precision timing with 30-50ps resolution allows separation of pileup

Requires dedicated timing layer for tracks and modification of readout for Barrel Calorimeter in CMS. Dedicated endcap timing in ATLAS

ATLAS Detector Upgrade



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz

Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4$

Additional small upgrades

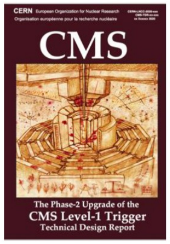
Luminosity detectors (1% precision goal)

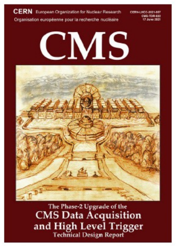
HL-ZDC

Detailed scope described in 7 TDRs approved by the CERN Research Board in 2017, 2018, 2020

Detector upgrades on schedule. Moving from proto-type to pre-production stage now

CMS Detector Upgrade





L1-Trigger HLT/DAQ

https://cds.cern.ch/record/2714892

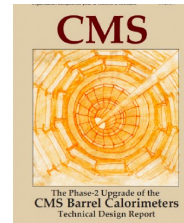
https://cds.cern.ch/record/2759072

- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

Barrel Calorimeters

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

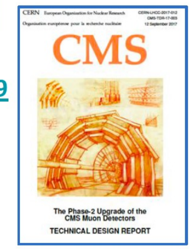
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

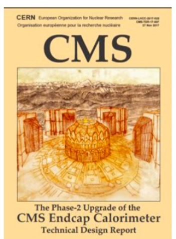


Muon systems

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 $\eta \approx 3$

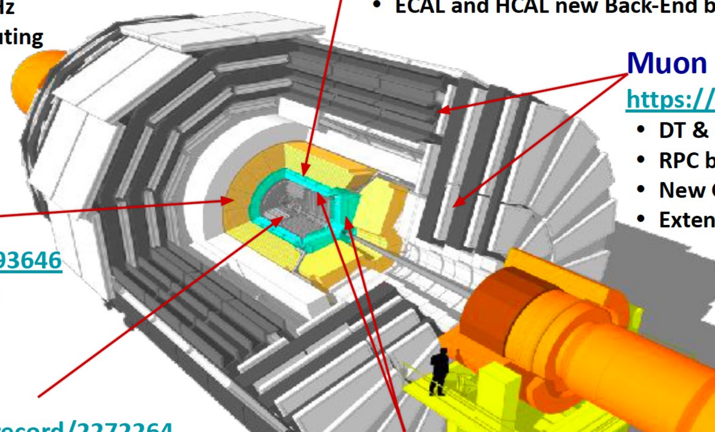




Calorimeter Endcap

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

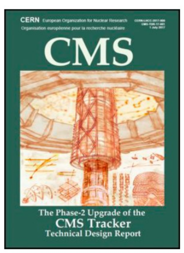
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Bunch-by-bunch luminosity measurement: 1% offline, 2% online



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

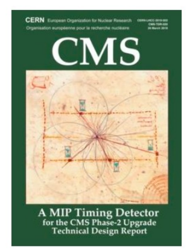
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$

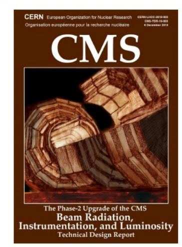
MIP Timing Detector

https://cds.cern.ch/record/2667167

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes





Detector upgrades on schedule. Moving from proto-type to pre-production stage now

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Summary and Conclusions

- Excellent startup to Run 3 from LHC and ATLAS/CMS. First round of results due this summer
- ATLAS/CMS continue to mine Run 2 with new and innovative analysis techniques on key measurements and searches
- A number of 2-3σ excesses to keep an eye on
- High Luminosity LHC and ATLAS/CMS upgrades on schedule
- The following talks will expand on these and present many more new results