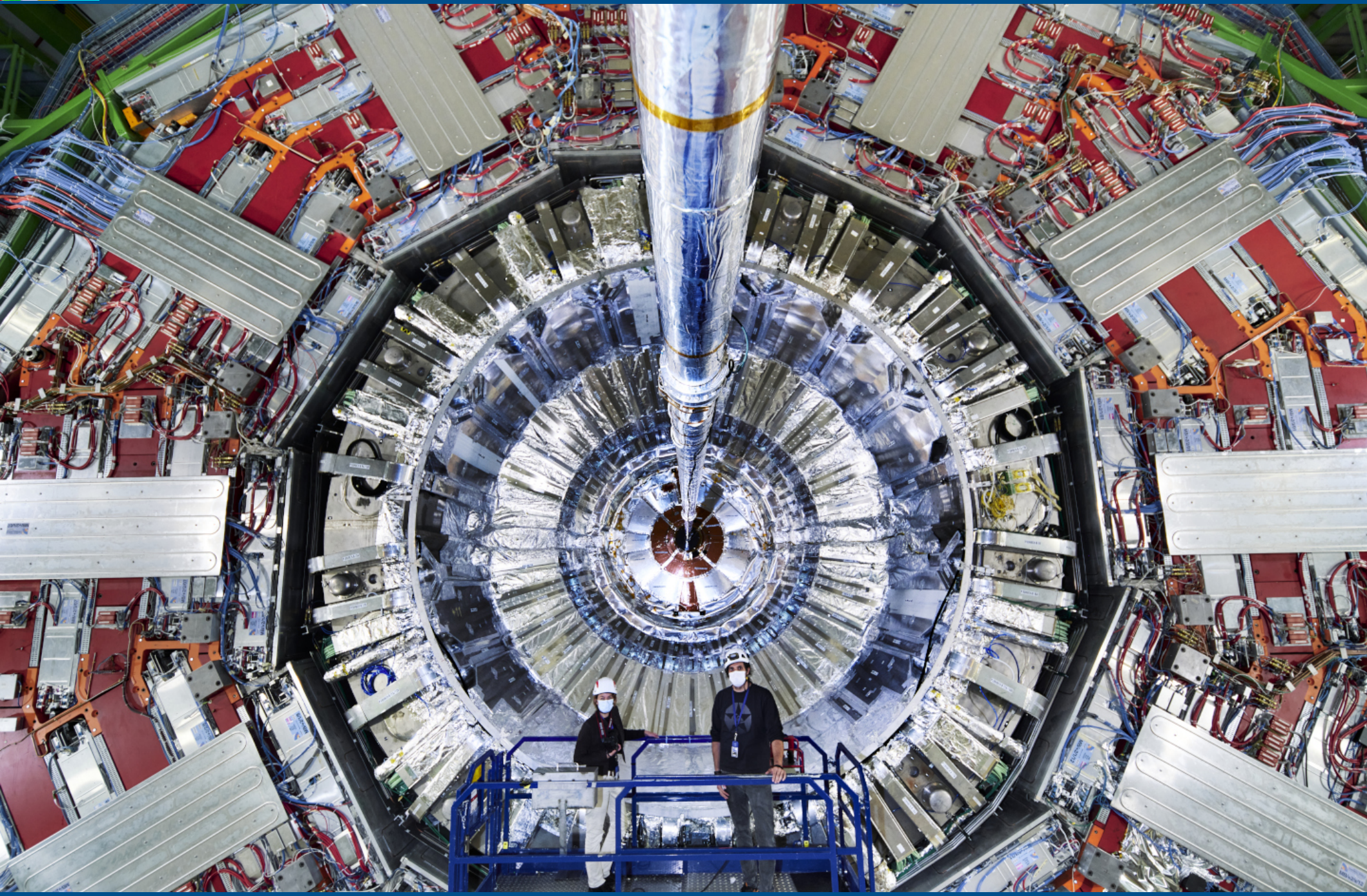
CMS — current and future

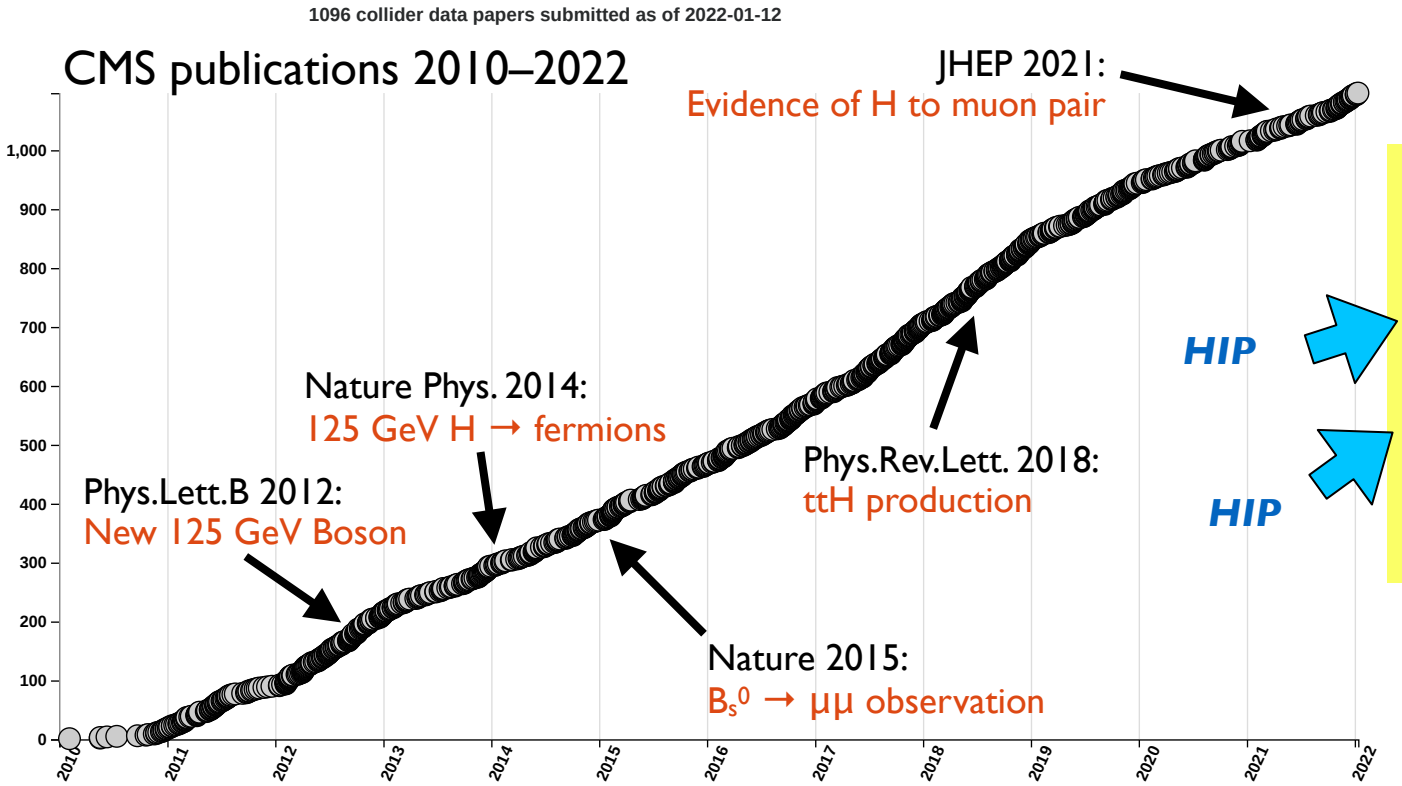


Where we are today

- 1000 published papers as first collaboration in history
- Beautiful results fully confirming Standard Model
- Discovery of **Higgs boson** and studies of its properties
- HIP a powerhouse in **Particle Flow and Jets**

Video published for 1000th CMS paper (19 Jul 2020)

"Observation of a New Boson at a mass of 125 GeV…" in Phys.Lett.B. from 2012 (>12k citations)



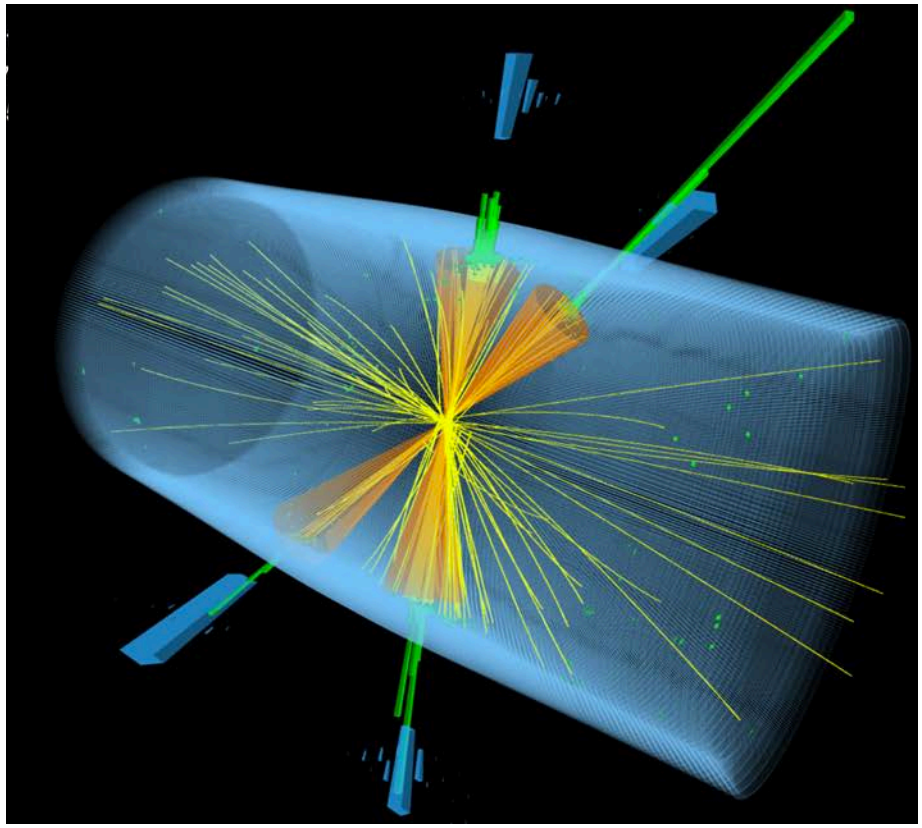
Strong PI contribution in high-impact CMS papers (after 3 Higgs papers and 2 TDRs):

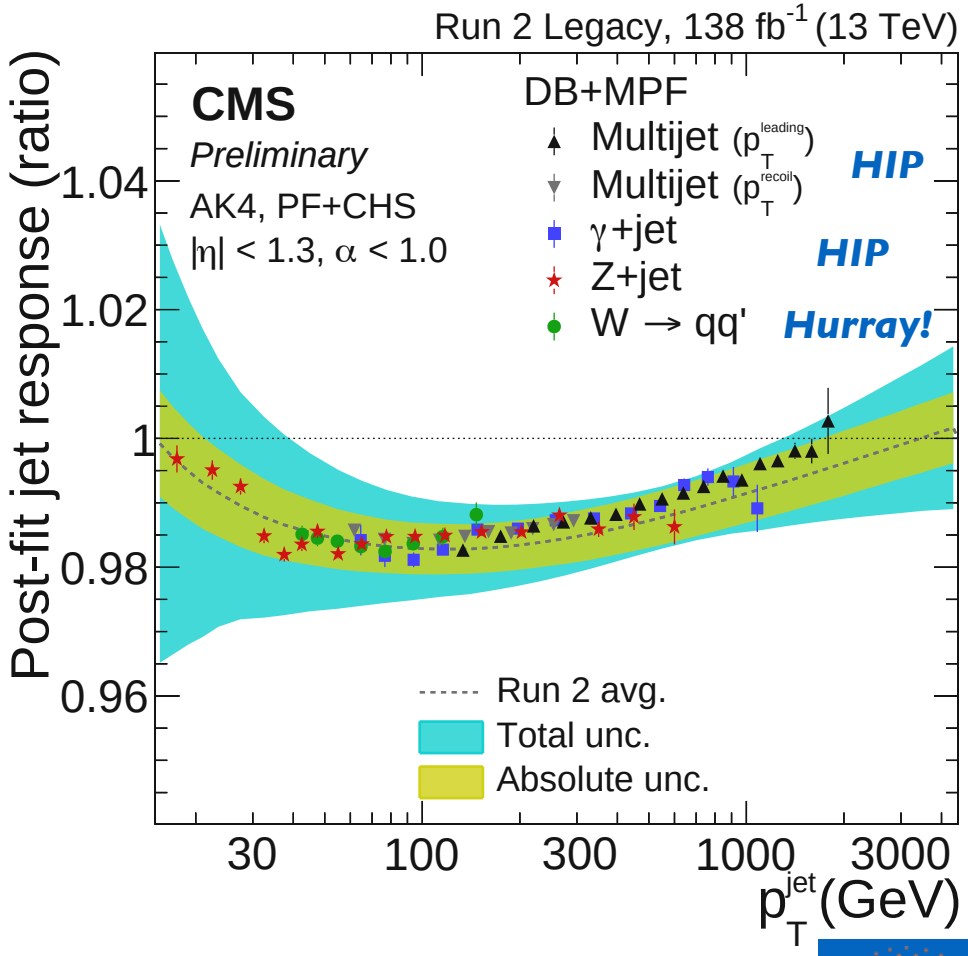
- Jet Energy corrections paper (#6, 1300 citations, 2011) — ***HIP***
- Particle-flow algorithm paper (#8, 1150 citations, 2017) — ***HIP***
- Jet energy scale & resolution (#19, 790 citations, 2017)

Hurray!

Jet powerhouse

- LHC is a hadron collider, so jets are at the very core of LHC physics:
  - *anything* that can be produced with hadrons, must be able to decay back to hadrons => **jets**
  - new particles may be discovered at high energy, possibly explaining **dark matter**
  - precision measurements with jets probe Standard Model even up to **Planck scale**

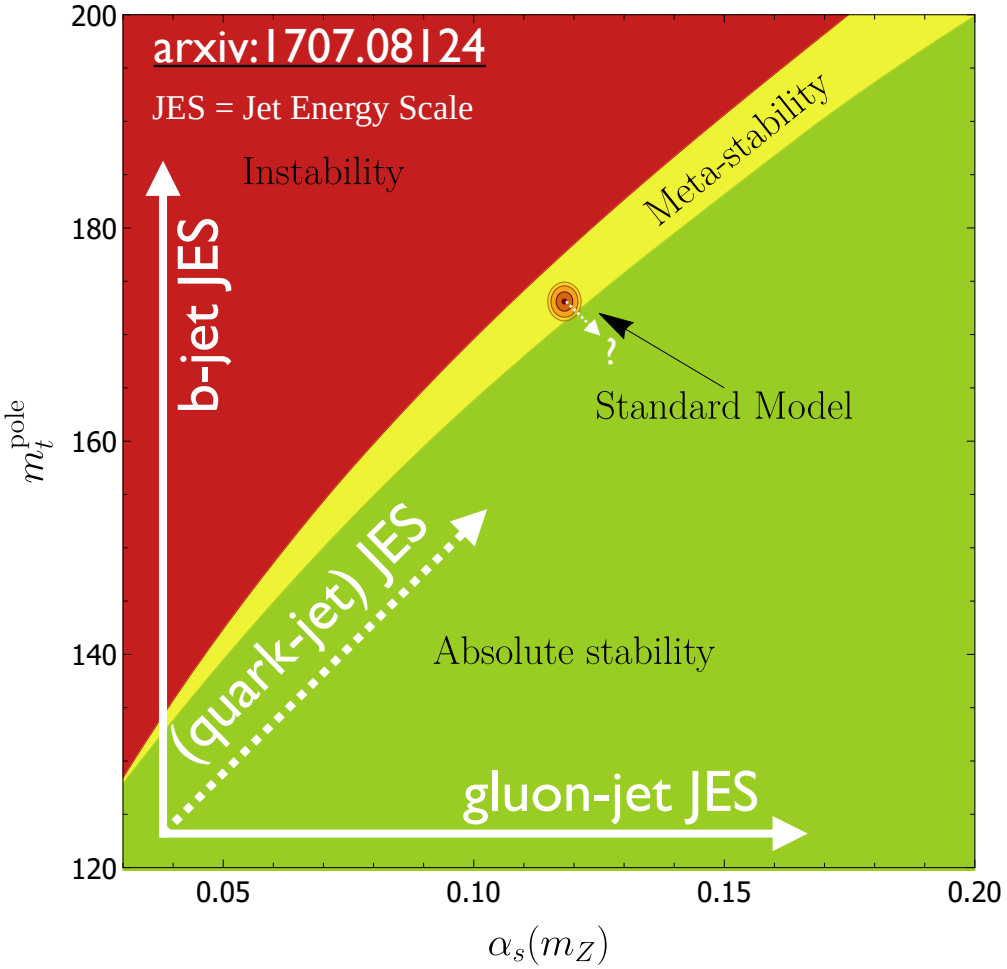


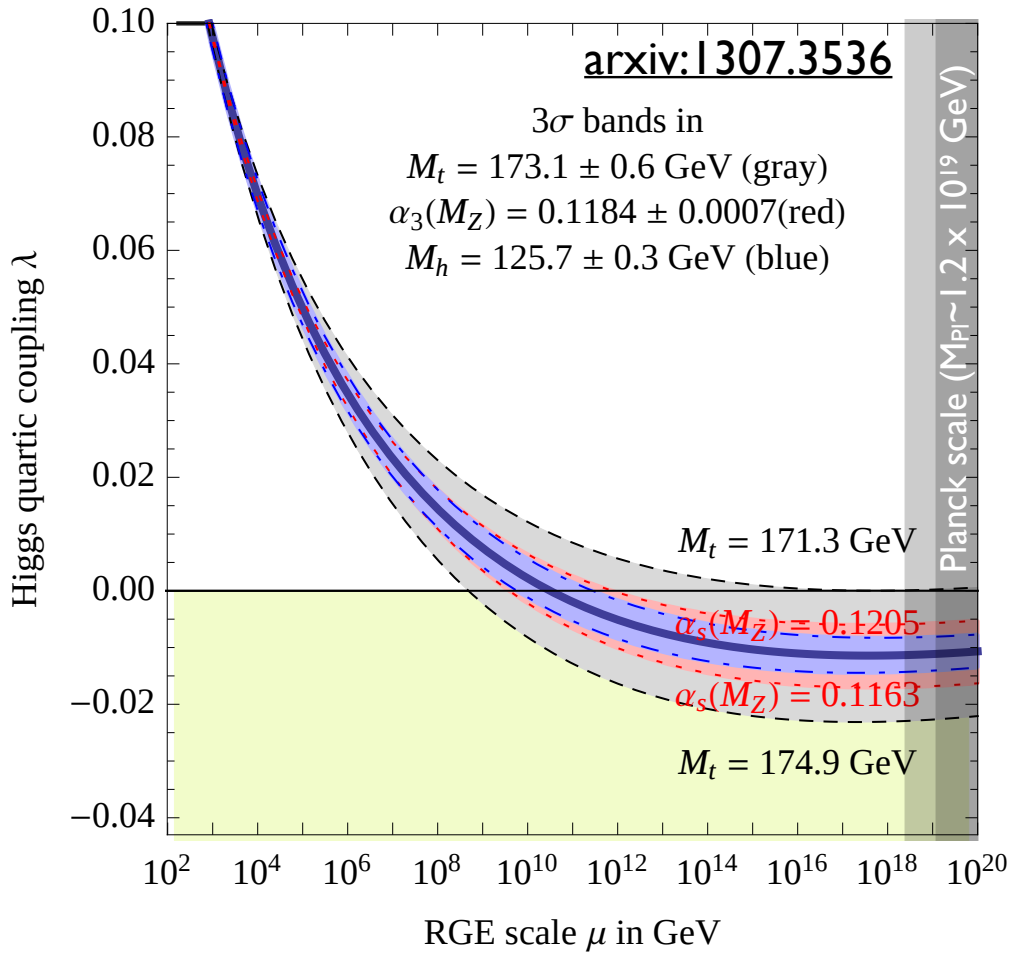


Project goal: ***breakthrough 0.1% precision*** on jet energy, having potential for insight on ***physics up to Planck scale***

Probing up to Planck scale

- Top quark mass m_t and strong coupling constant α_s can potentially probe physics up to *Planck scale* — with constraints on cosmological history
- Latest from CMS (2016 data) are world's most precise measurements at hadron colliders:
  - m_t = 171.77 ± 0.38 GeV => expect full Run 2 with 0.19 GeV uncertainty
  - $\alpha_s(m_Z)$ = 0.1170 ± 0.0019 => expect full Run 2 to approach lattice QCD precision of 0.0010





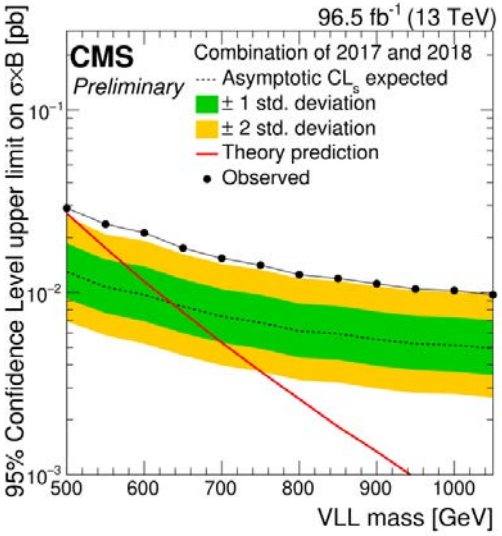
Cliffhangers from Run 2

- CMS ≳3σ excesses: vector-like leptons, dijet pairs, Higgs-like ττ
- These could turn into discoveries in Run 3, if real. Most others need HL-LHC

Jim's LHCP talk on May 16

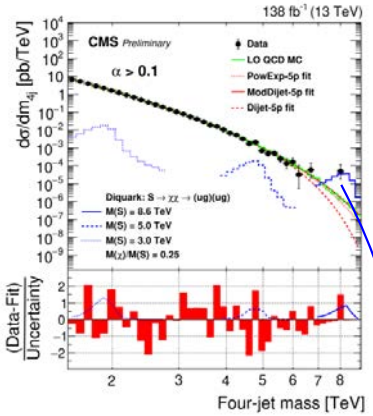
Vector-like Leptons (VLLs) B2G-21-004

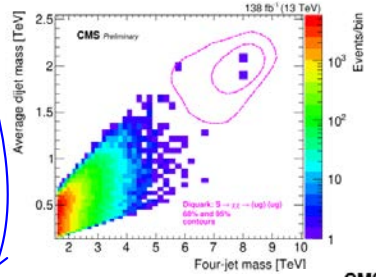
- Targeting pair-produced VLLs in final states with ≥ 3 b jets and up to 2 tau leptons
- In the context of 4321 model, UV-complete and relevant to describe flavor anomalies
- Mild excess at seen in 1τ and 2τ in both 2017 and 2018, combined global 2.8σ

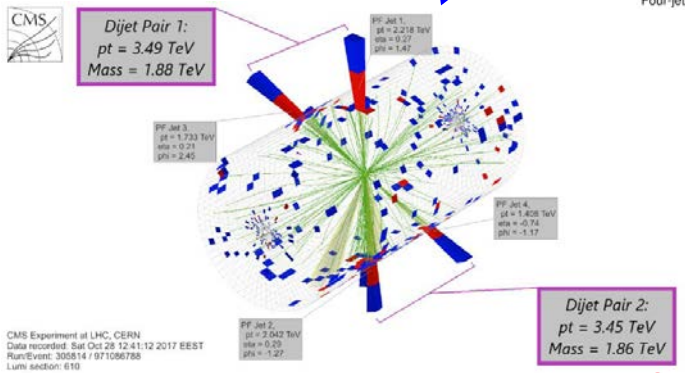


Pairs of dijets EXO-21-010

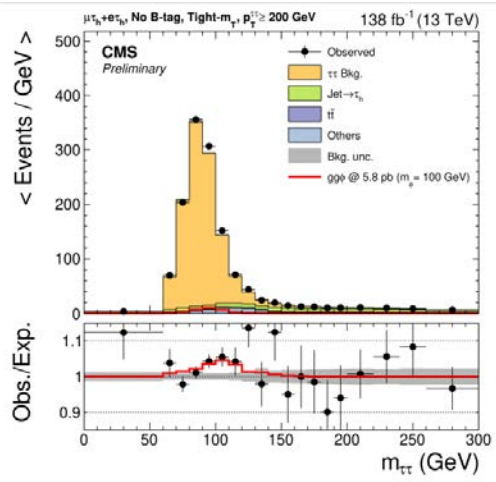
- Search for resonant and non-resonant pairs of dijets
- Excess at 8 TeV with local (global) sig of 3.9σ (1.6σ)

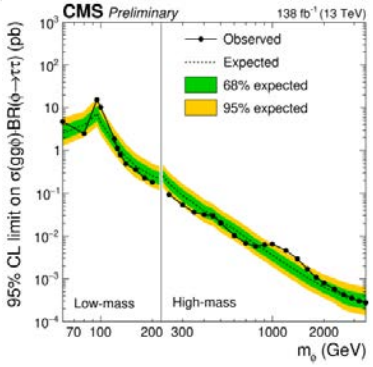






Higgs-like decay to ττ HIG-21-001



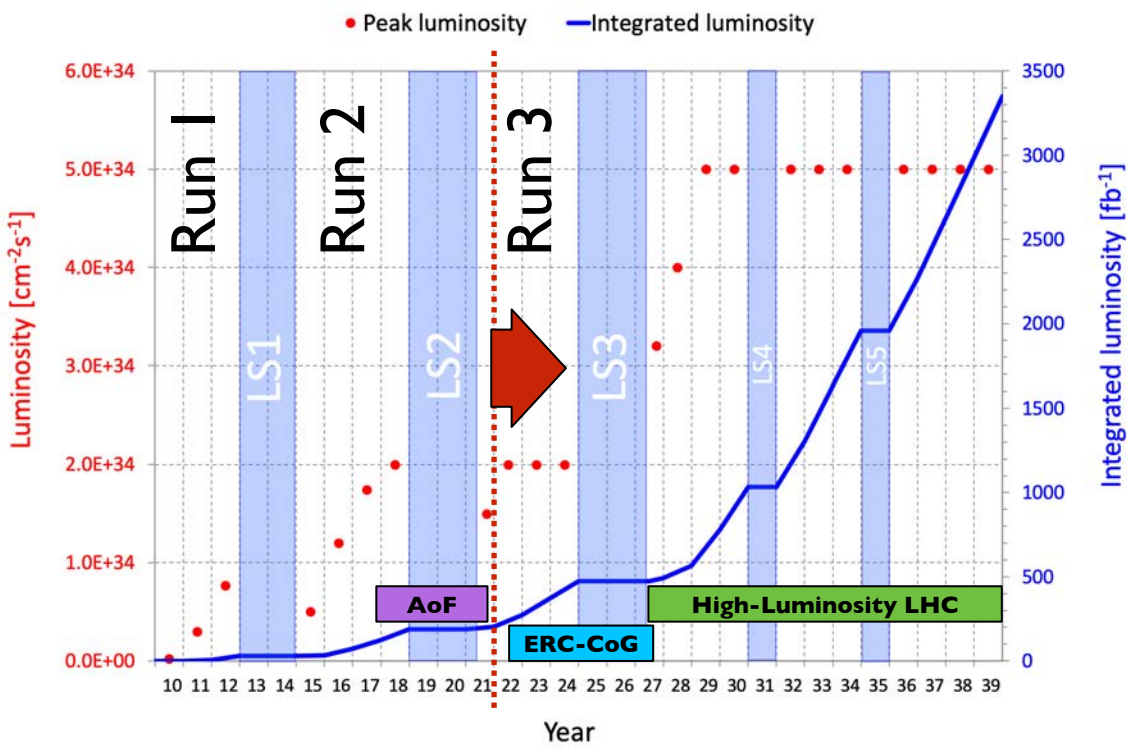


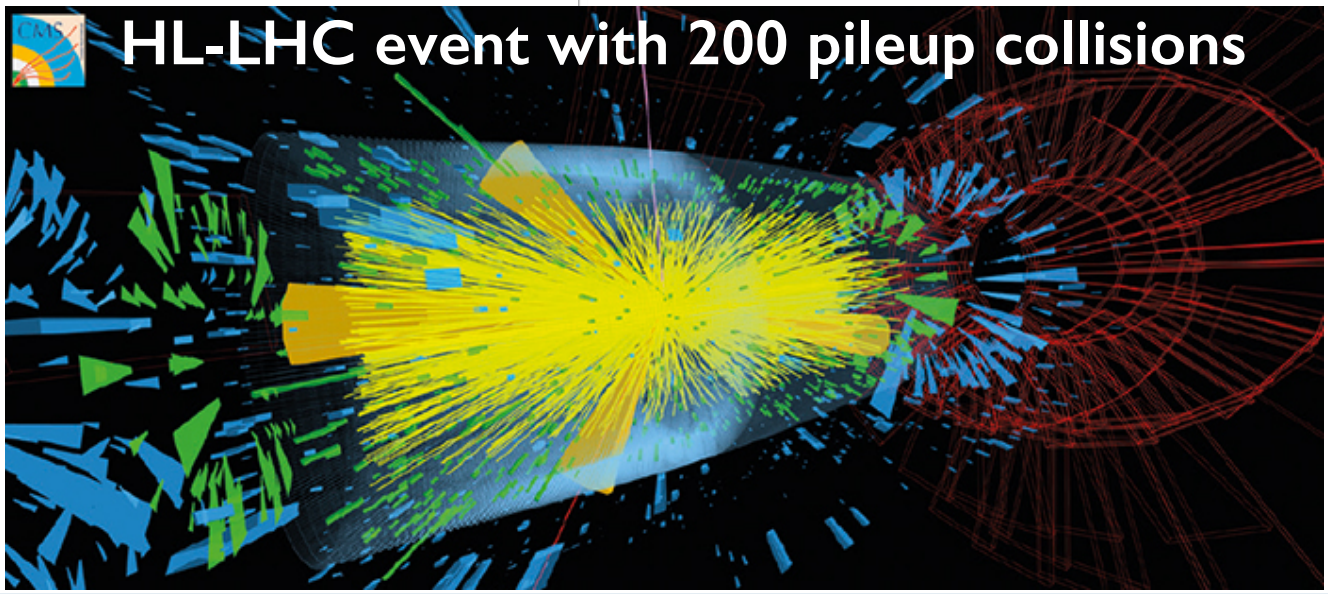
- Spin-0 decaying to tau pairs in the context of extra Higgs (e.g. MSSM) and vector lepto-quarks
- In the Higgs-like search, two excess with local 3σ observed near 100 and 1000 GeV

Several enticing excesses to watch in Run 3!

High-luminosity LHC

- HL-LHC is *focal point of HEP future*
  - Need *unprecedented* experimental uncertainties to fully exploit the data
- Run 3 ideal opportunity to improve in methods for HL-LHC
- <u>European Strategy for Particle Physics</u> calls for *"continued innovation in experimental techniques"*
  => precision and pileup robustness



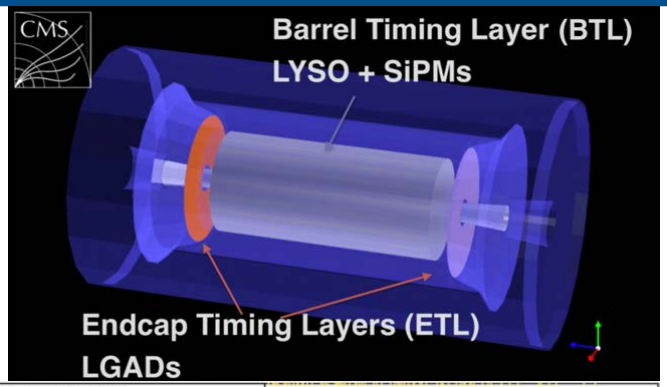


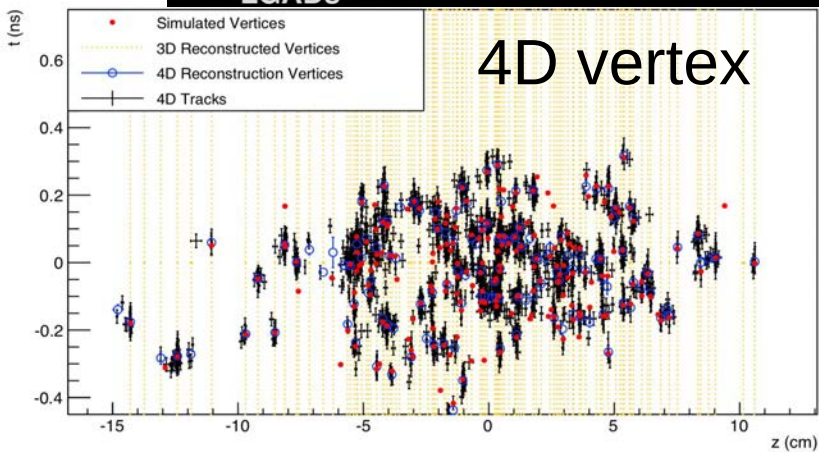
Detector upgrades

- Tracker extension (|η|<2.4 to |η|<3.8)
  - larger reach, less dead material
  - large Particle Flow performance gains in endcap

- MIP timing detector (MTD)
  - 4D interaction vertex reconstruction
  - precision timing to filter out pileup interactions

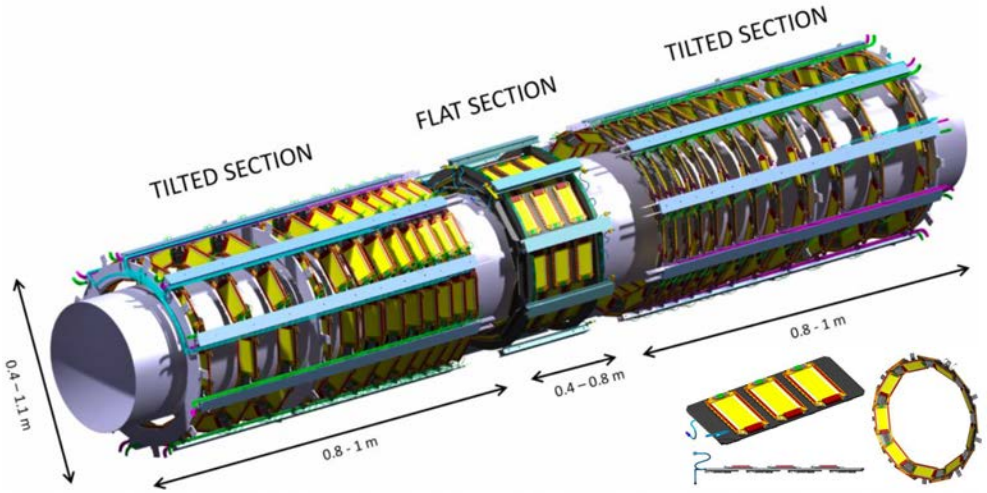
Timing detector

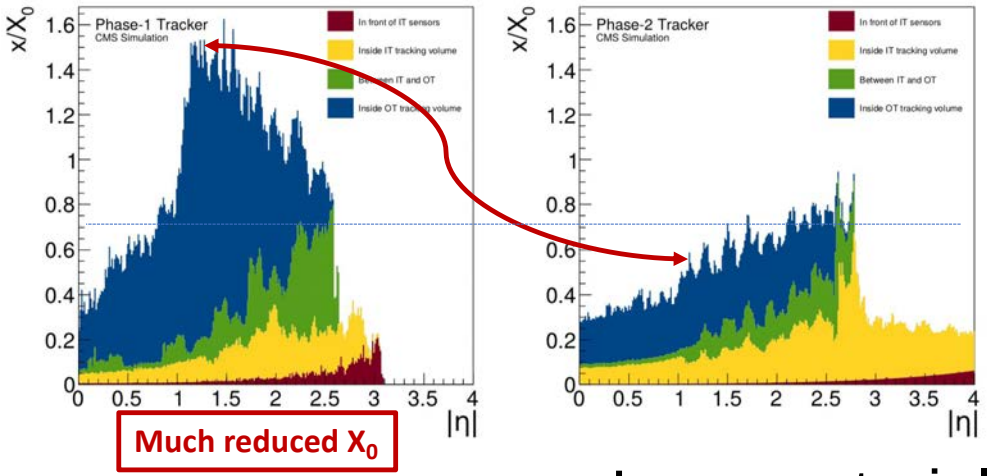




4D vertex

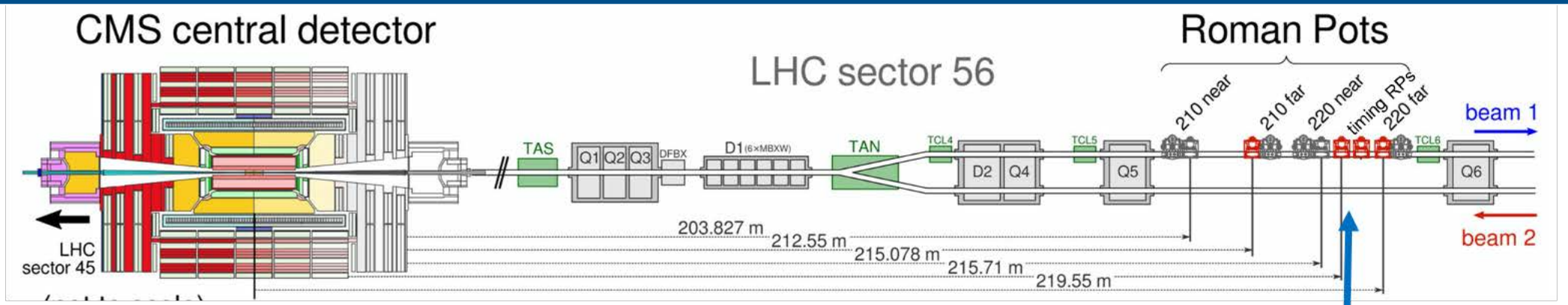
Tracker extension



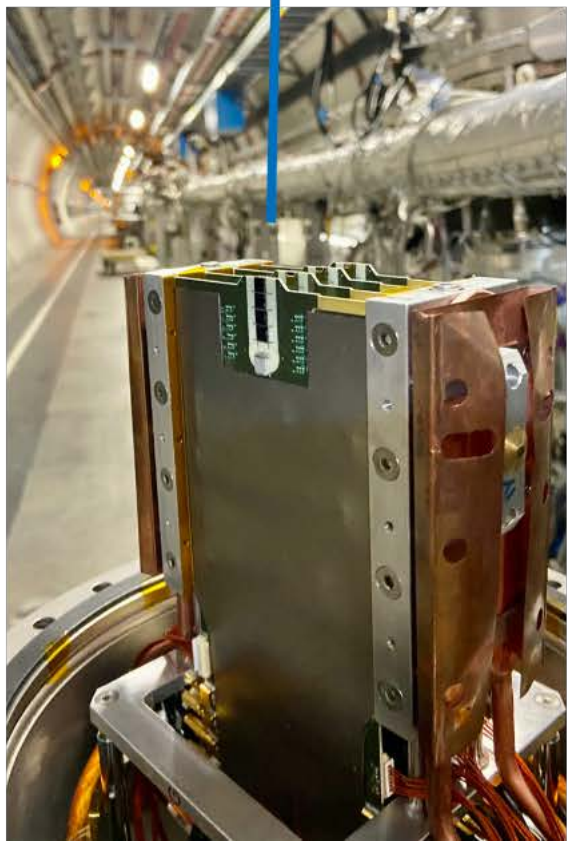


Less material

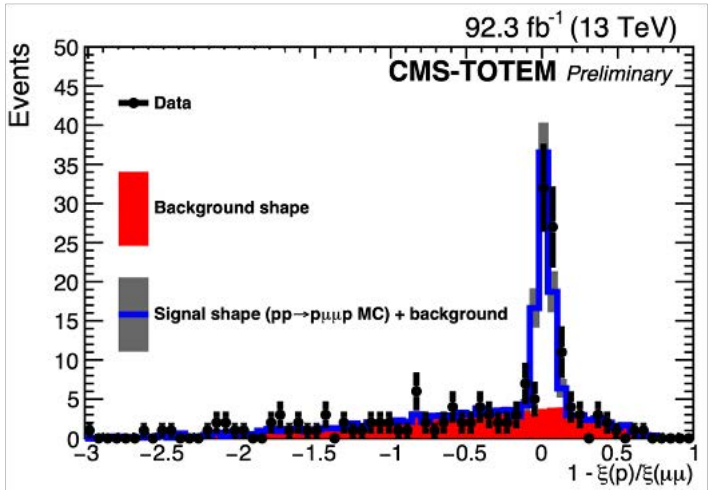
Precision proton spectrometer

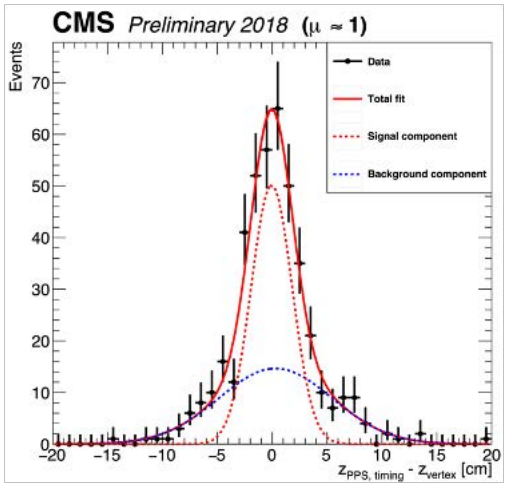


- Detects protons from central exclusive processes @200m at a few mm distance from the outgoing beam
- Tracking and time-of-flight (TOF) in Roman Pots (RP)
  - replaced tracking and upgraded TOF for Run 3
  - refurbished RP systems and new detectors for HL-LHC
  - HIP contribution: diamond based TOF detectors



CMS and TOTEM collaborations, CMS-PAS-PRO-21-001

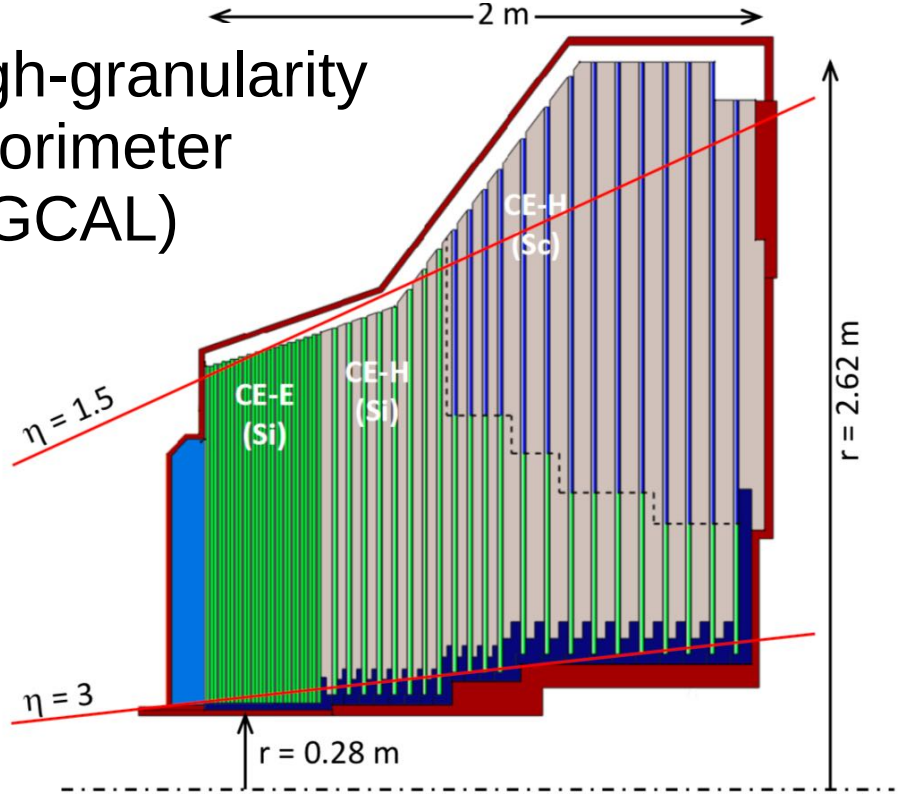




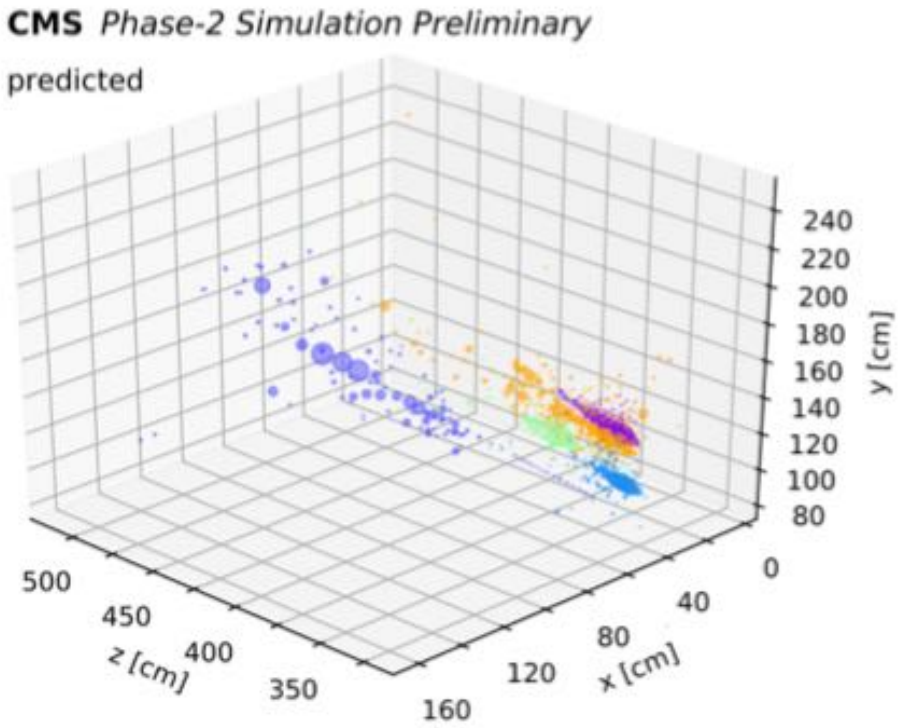
High-Granularity calorimeter

- All-silicon electromagnetic calorimeter
  - very radiation hard inner parts
  - low radiation hadronic part: Si & scintillator
- 3D shower imaging in calorimeter endcap
  - very accurate, but very high data rates
  - machine learning used for reconstruction

High-granularity calorimeter (HGCAL)

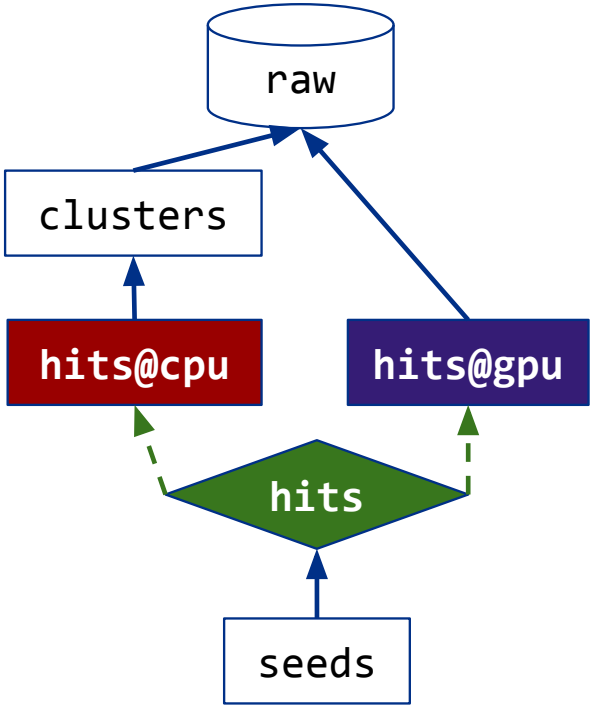


3D shower + Machine learning



Machine learning

- From novelty to everyday tool:
  - CMS Open Data for Machine Learning
  - Real-time analysis with ML (SMARTHEP)
  - Heterogeneous computing (CPU + GPU)
- Deep learning algorithms now widely used
  - W polarisation tagging
  - quark / gluon discrimination
  - ML-based JEC



arXiv:2004.04334

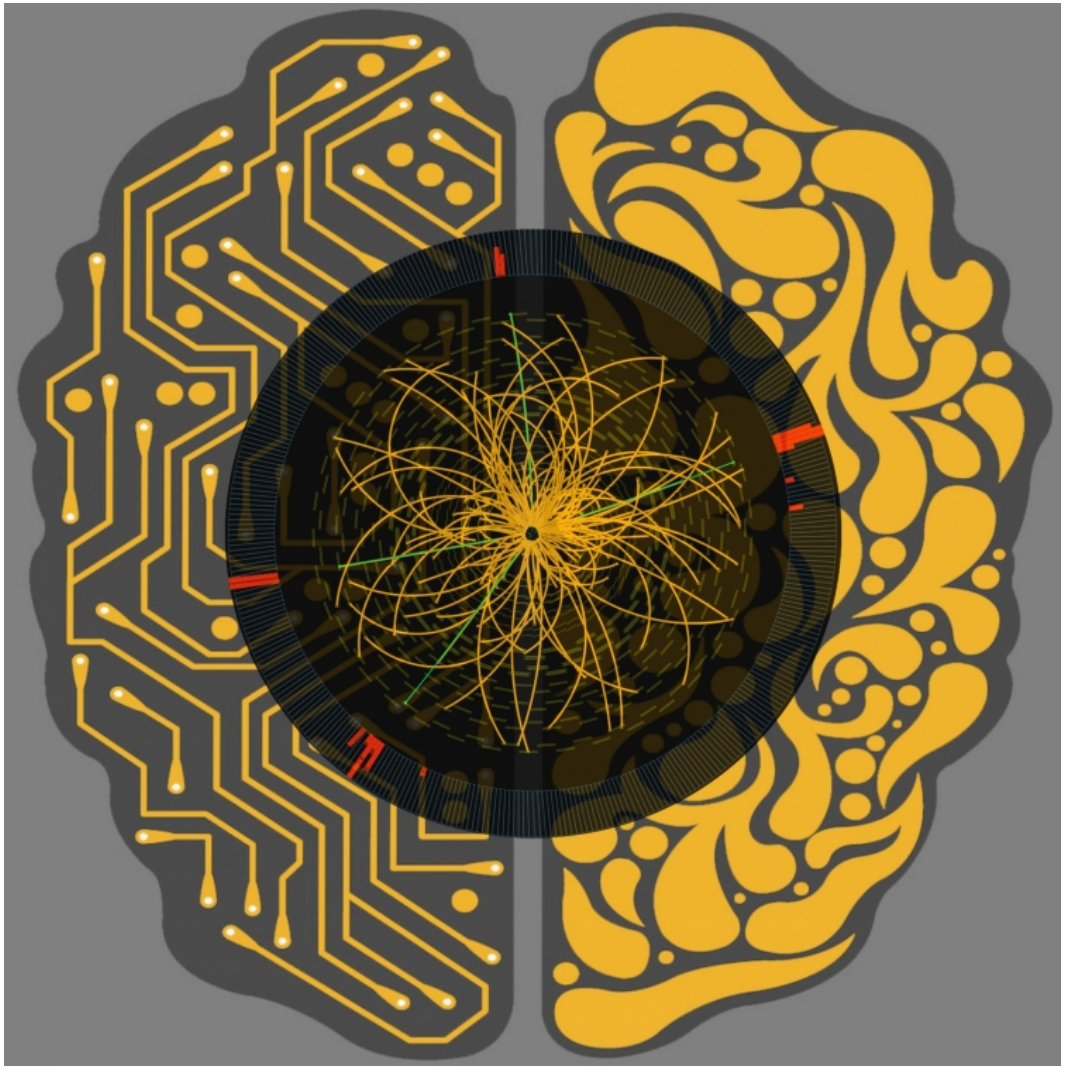


Image: Fermilab/CERN

https://cms.cern/news/cms-releases-open-data-machine-learning

Quantum computing?

- Quantum technologies could mature in next 5-10 years
- CERN Quantum Technology Initiative:
  - quantum machine learning
  - direct simulation of quantum systems (e.g. lattice QCD)
- Finland's first quantum computer at VTT made by IQM
  - first commercial 54-cubit computer being built
  - ERC-AdG 2021 highlight: ConceptQ, a new qubit concept

Visiting quantum computer at IQM in Espoo in 2019

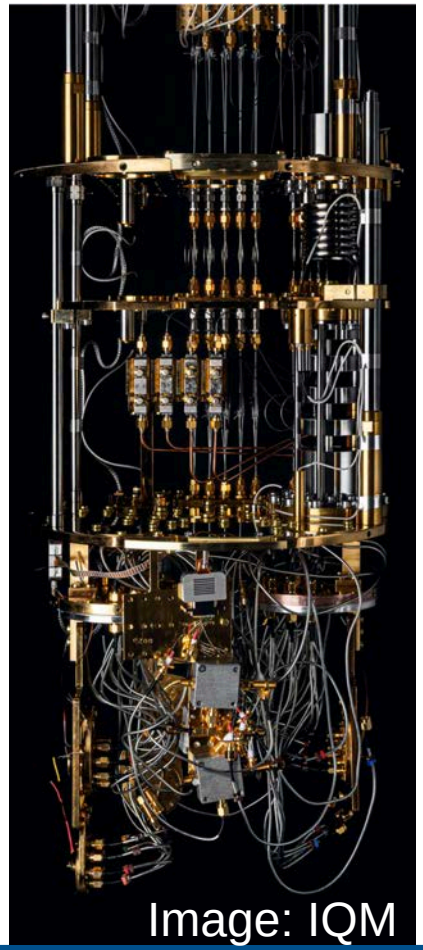
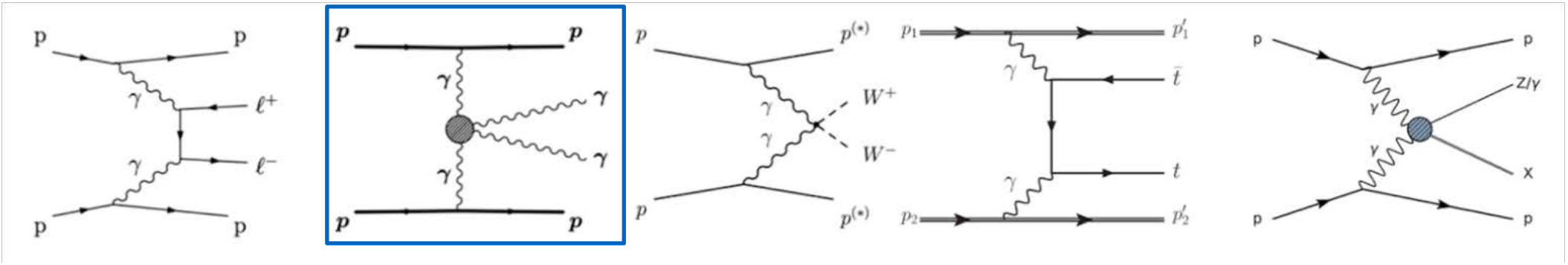


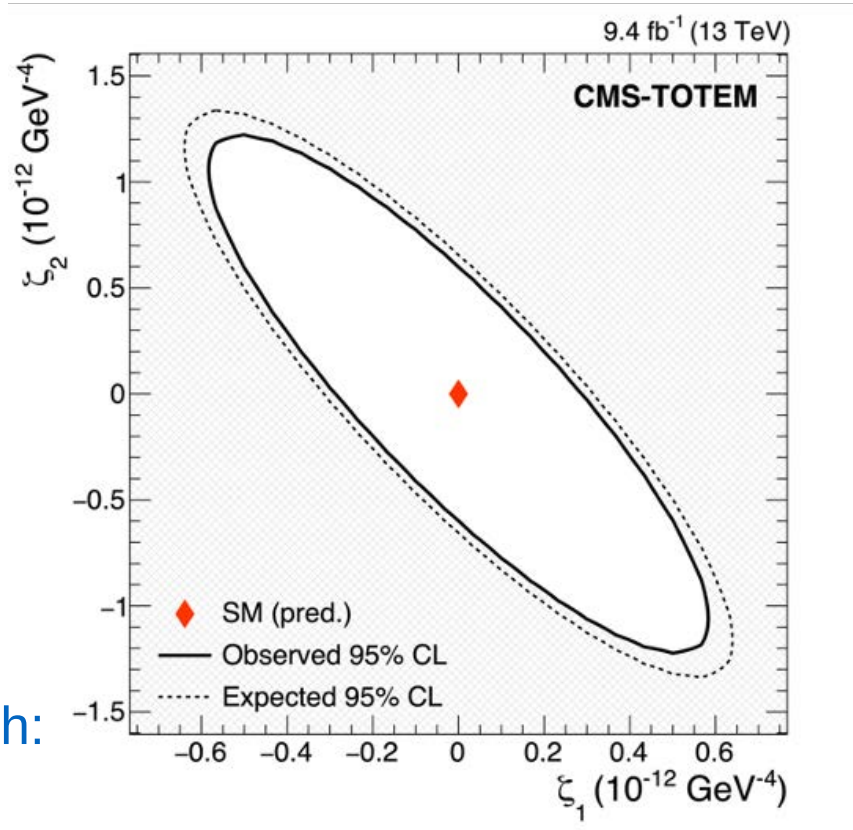
Image: IQM

Central exclusive production



- Central exclusive production: LHC turned into photon-photon (or gluon-gluon) collider!
- Interacting protons remain intact and can be measured by precision proton spectrometer (PPS)
- Background much reduced by mass & rapidity matching between central & forward systems
- Sensitive to beyond-standard-model physics through loops (anomalous gauge couplings)
  - or direct new particle production

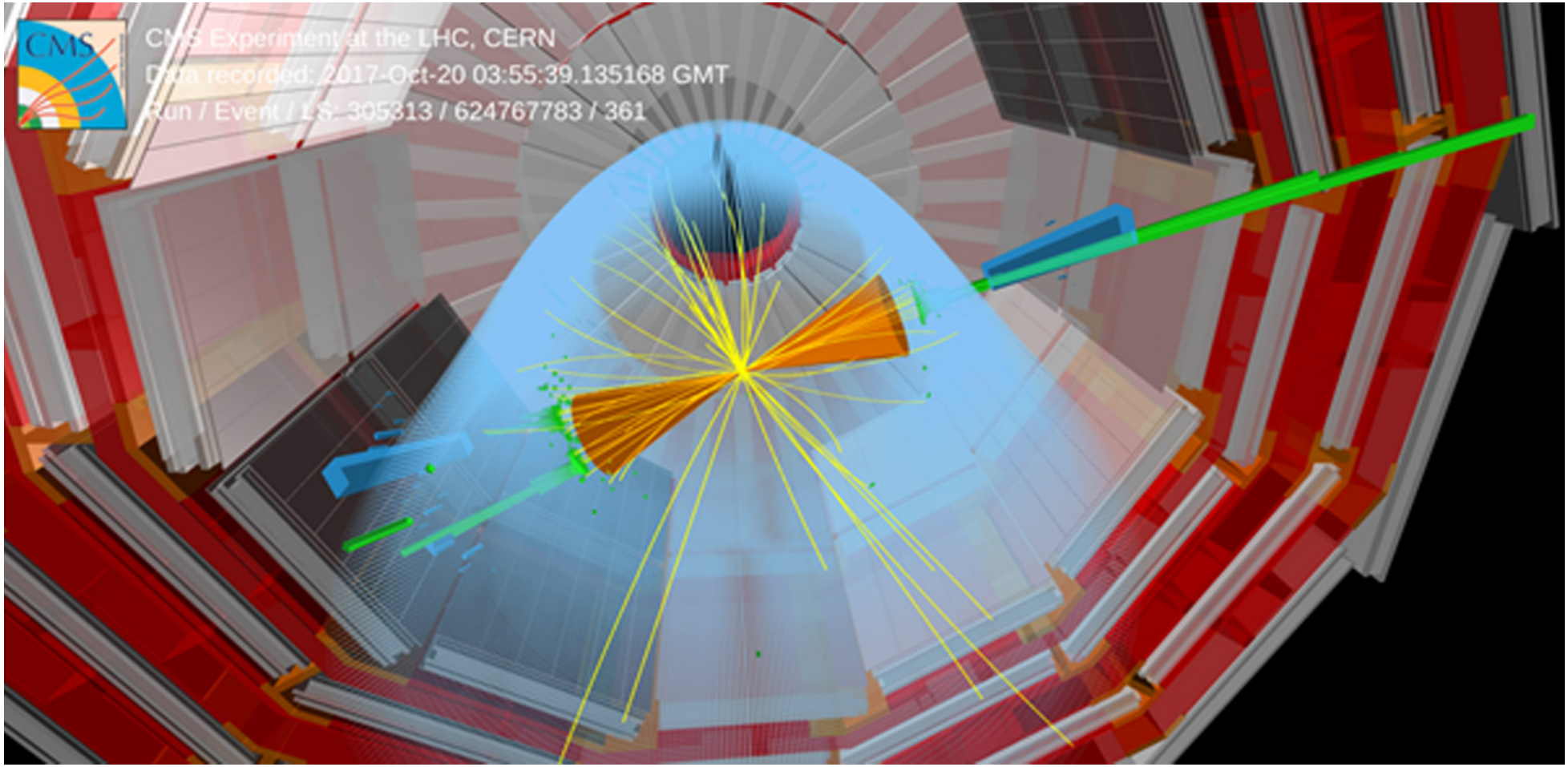
CMS and TOTEM collaborations, arXiv: 2110.05916, accepted by Phys. Rev. Lett.



e.g. high mass (> 800 GeV) exclusive diphoton search: sensitive to anomalous 4-photon couplings (ς_1, ς_2)

Higgs to bb

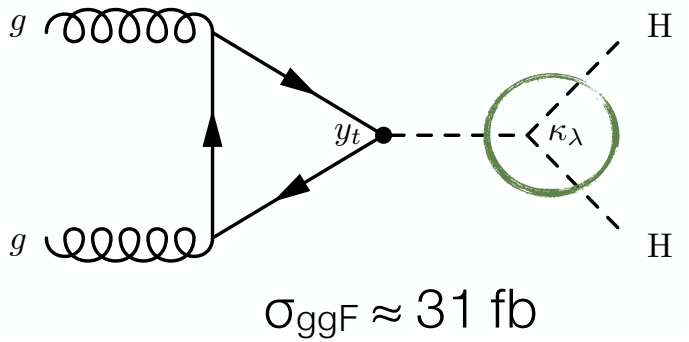
- Project supported by SMARTHEP European Training Network
- Real-time machine-learning analysis of Z-to-bb and H-to-bb in Run 3
- Establish general-purpose real-time-analysis stream for the High-Luminosity LHC
  - exploiting extended capabilities of the new detector



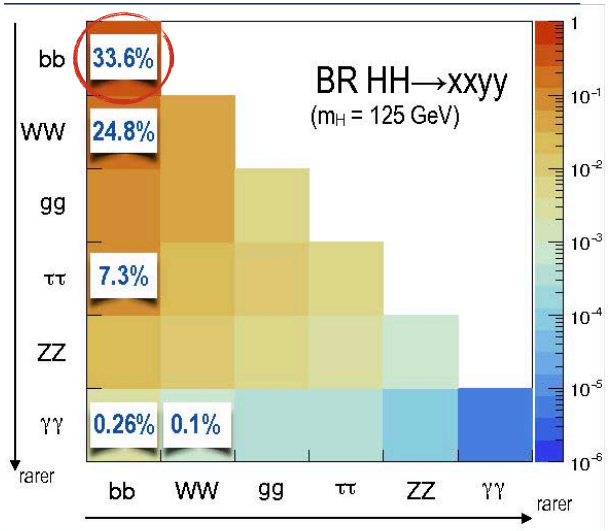
Di-Higgs

- HH production is among the main priorities of the LHC physics program
- Very rare process in the SM — forces the analysts to innovate to push sensitivity higher
- Self-coupling most obvious way to understand the Higgs field

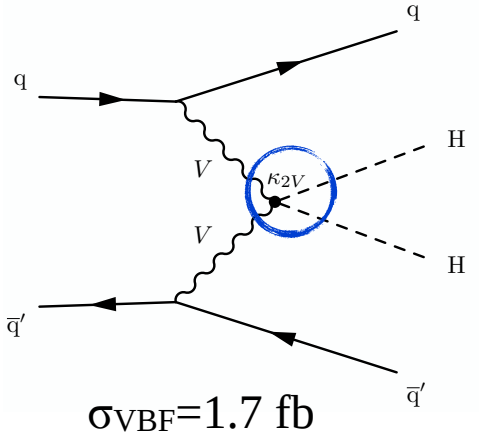
gluon-gluon fusion (ggF)



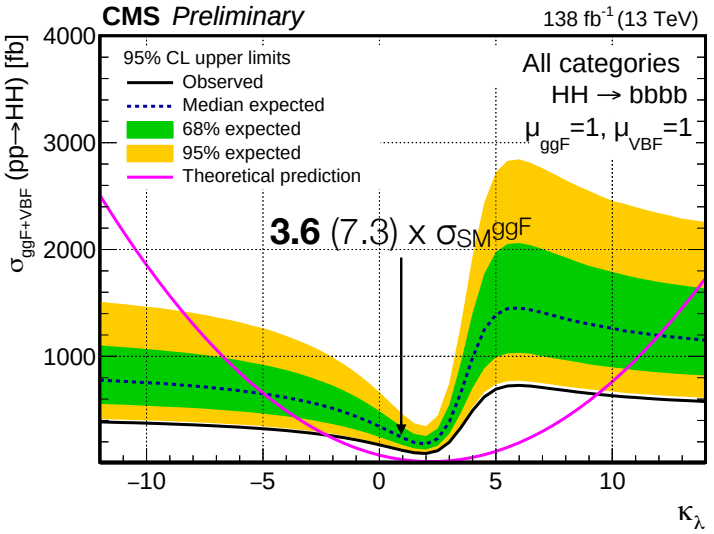
$\sigma_{ggF} \approx 31$ fb



vector boson fusion (VBF)

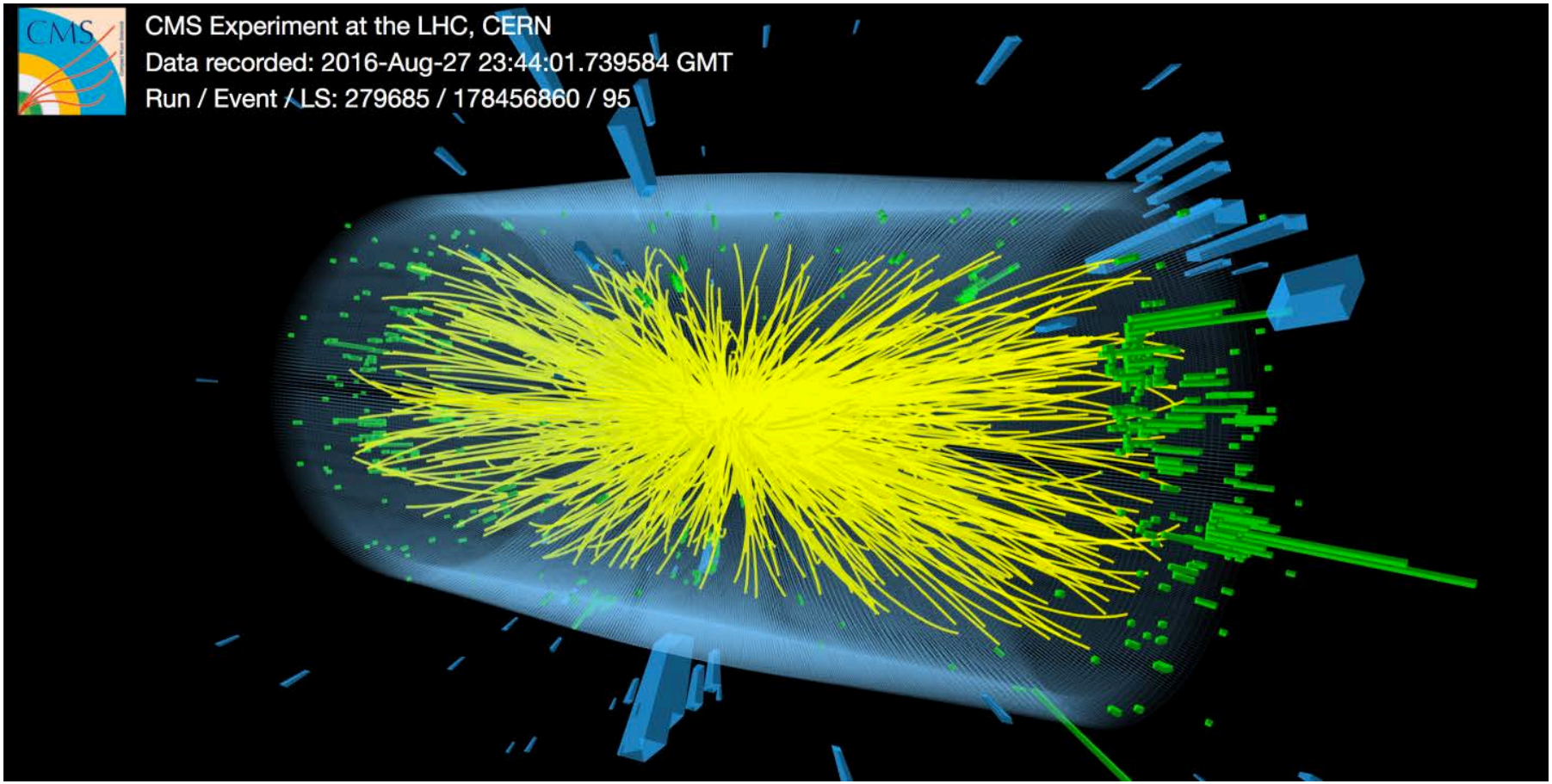


σ_{VBF}=1.7 fb



Summary

- **Jet powerhouse:** top quark mass, strong coupling constant, dijet resonances, Higgs to bb
  - new physics or Standard Model up to the Planck scale?
- **Exciting upgrades** for High-Luminosity LHC: tracking, timing, high-granularity calorimeter
  - supercharging CMS with precision proton spectrometer and machine learning
- **Exploration ahead:** vacuum stability, dark matter, Higgs potential
  - High-Luminosity LHC as the focal point

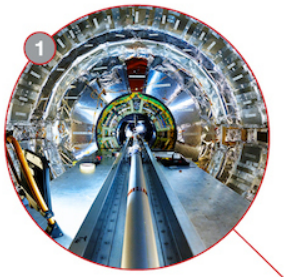


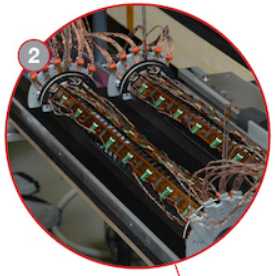
Thanks to the team!

Backup slides

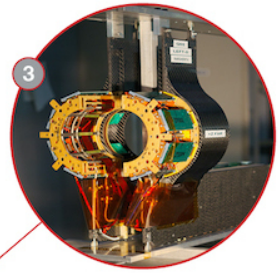
LS2 upgrades

BEAM PIPE
Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.

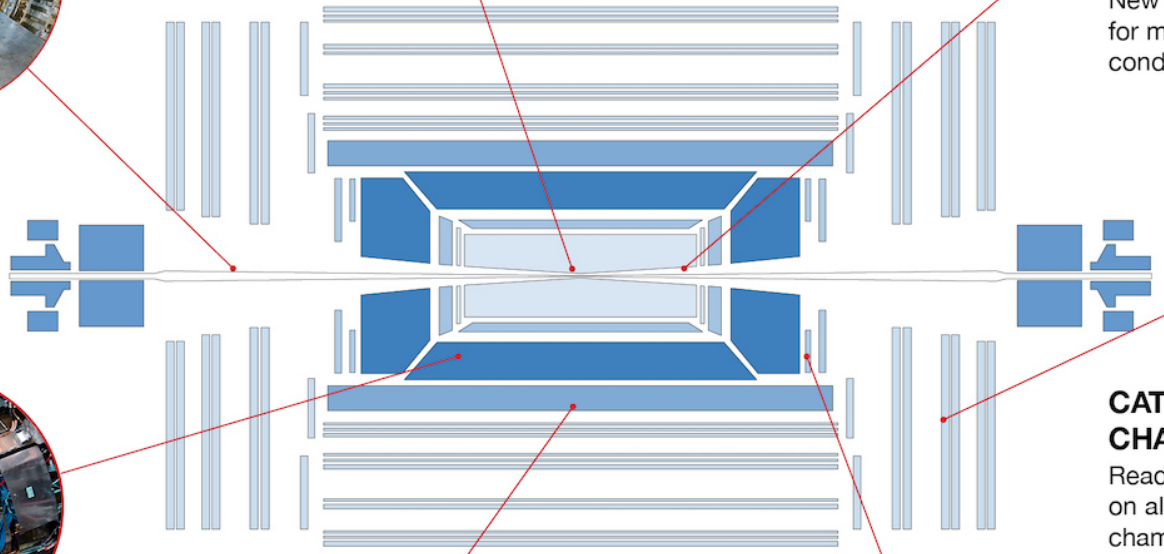




PIXEL TRACKER
All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.

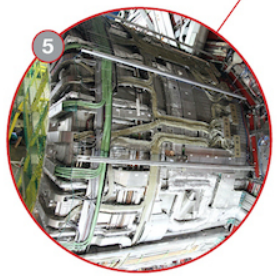


BRIL
New generation of detectors for monitoring LHC beam conditions and luminosity.

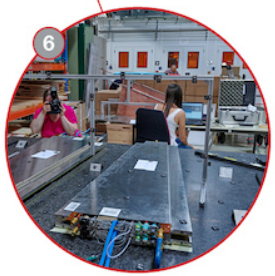


CATHODE STRIP CHAMBERS (CSC)
Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.

HADRON CALORIMETER
New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.



SOLENOID MAGNET
New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.



GAS ELECTRON MULTIPLIER (GEM) DETECTORS
An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.

https://home.cern/press/2022/CMS-upgrades-LS2

Higgs bosons

AoF v2 in Sept.

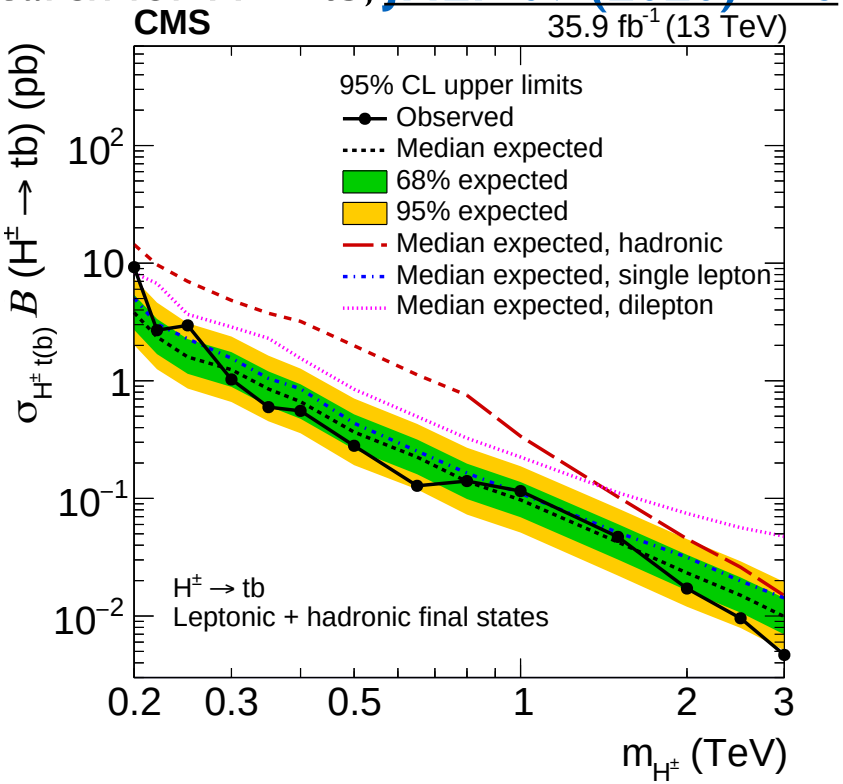
- Additional Higgs bosons predicted in many BSM models — Lehti

Singly-charged Higgs bosons

- Analyses on-going with full Run 2 data on $H^+ \to \tau\nu$ and $H^+ \to tb$ with Cyprus
- Trigger development for Run 3 started

Havukainen, Lotti, Lehti

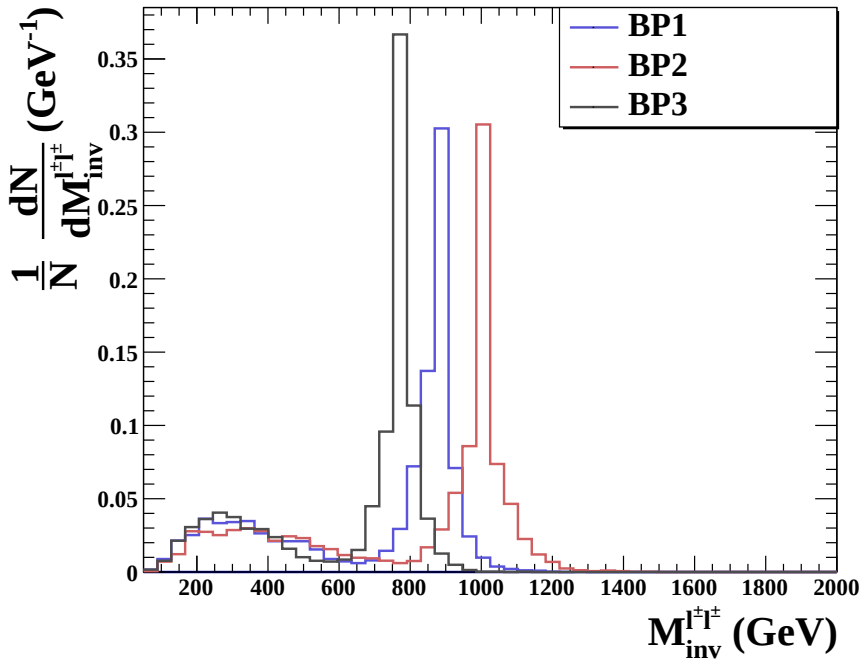
- Search for $H^\pm \to tb$, JHEP 07 (2020) 116



Doubly-charged Higgs bosons

- Minimal left-right symmetric SUSY allows high scale and favours H^{++} always in the lightest part
- Explains neutrino masses, has DM candidate
- Dominant decay into $H^{++} \to \tau^+\tau^+$, HIP expertise
- Paper by HIP phenomenology group [1]

Potential analysis for starting in Run 3



[1] PHYS. REV. D 101, 115014 (2020)