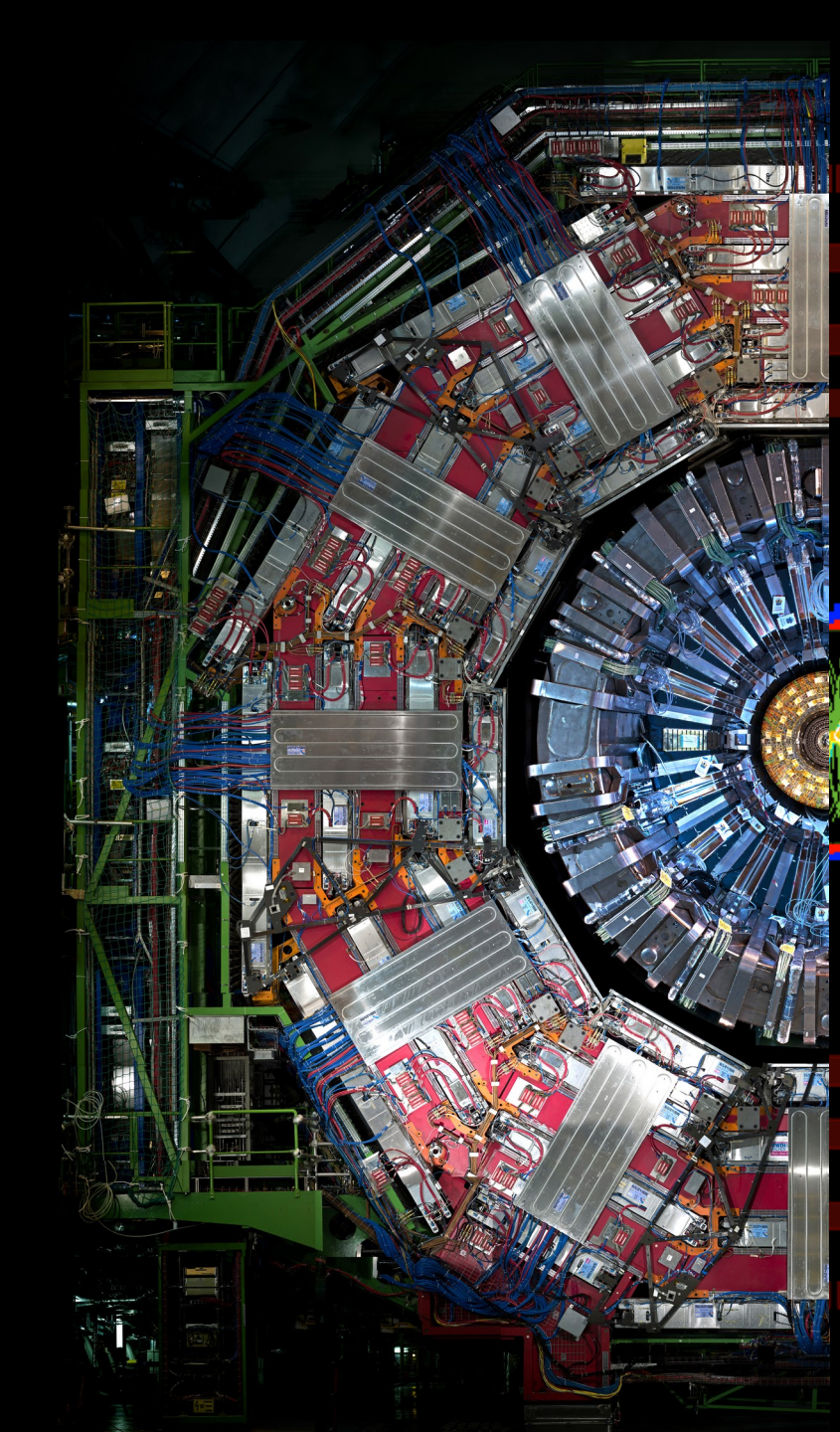


Physics at the energy frontier with the CMS Detector

Christoph Paus

April 4, 2024

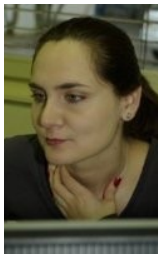
NUPAX Open House

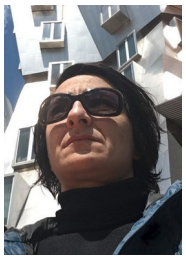
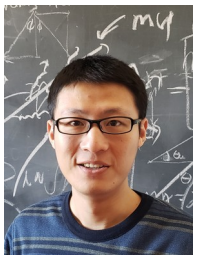
Particle Physics Collaboration (PPC)

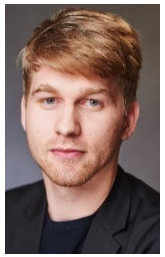
Faculty

Christoph Paus

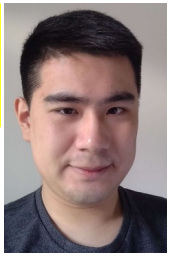
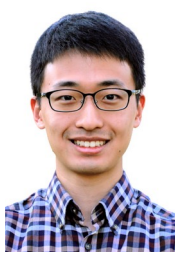
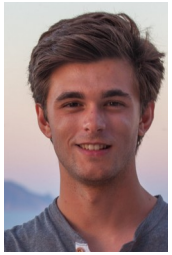
Research Scientists, Postdocs



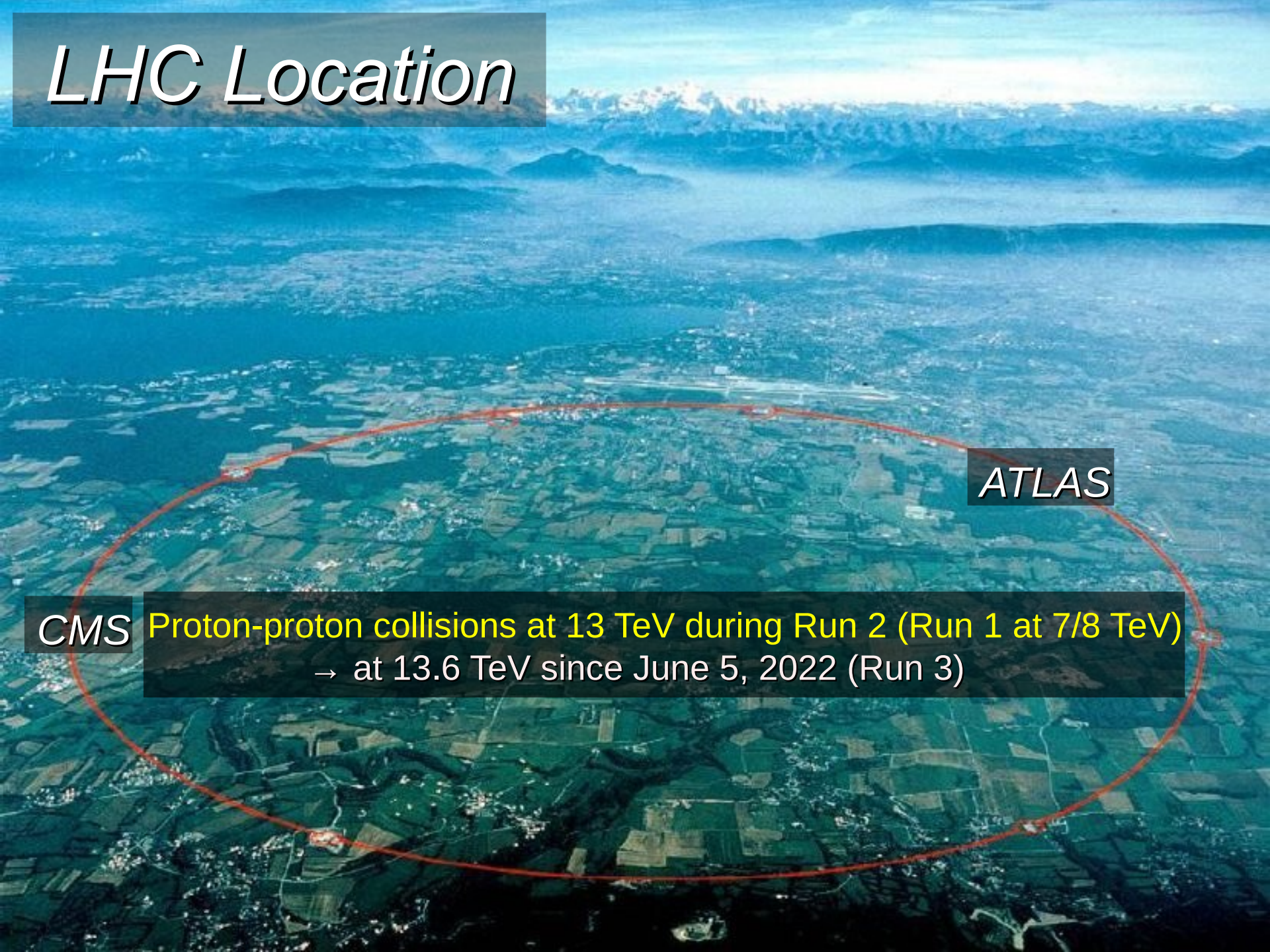

Graduate Students


Undergrads many many many

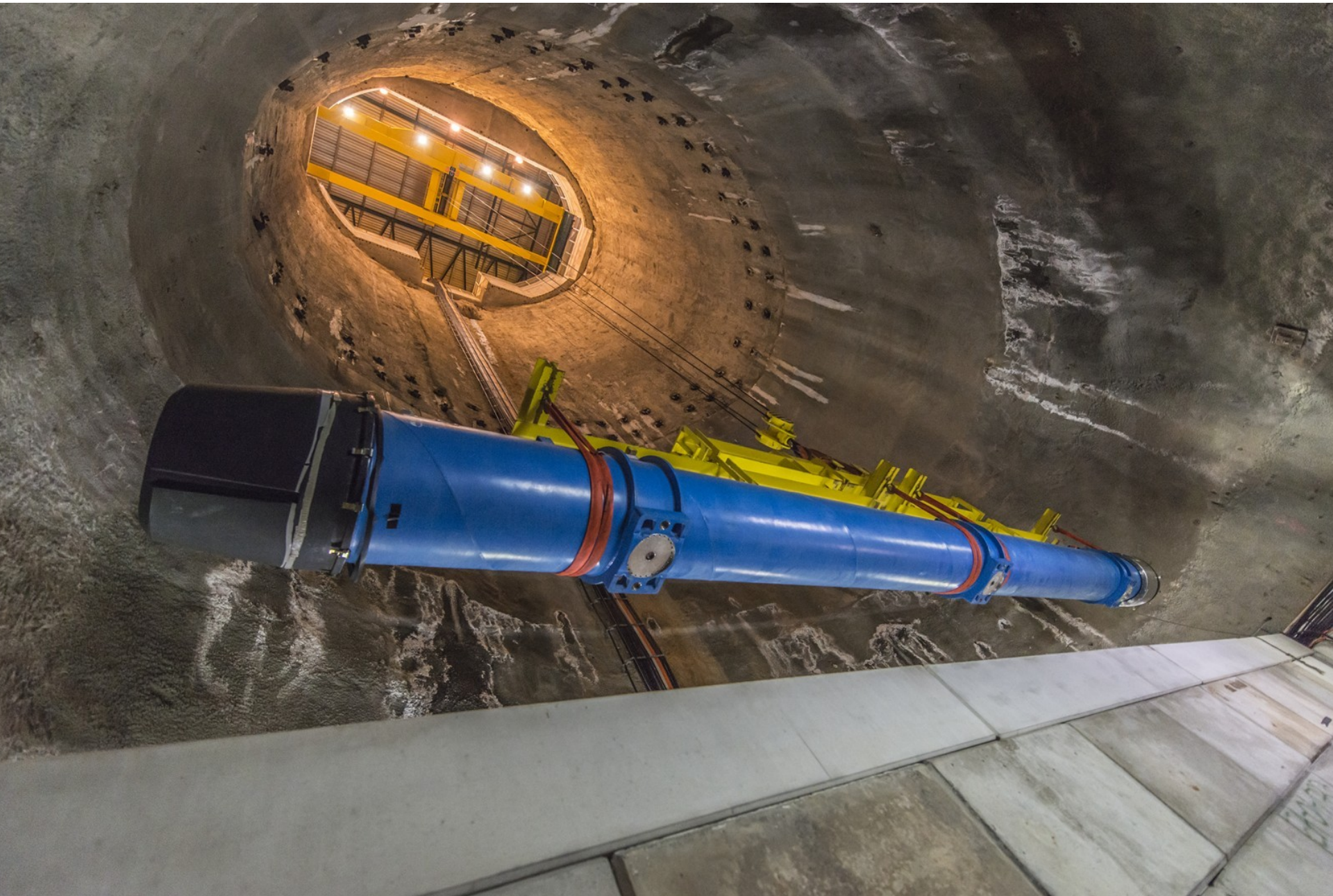
Join in 2024
Just in time
for Run 3.

LHC Location

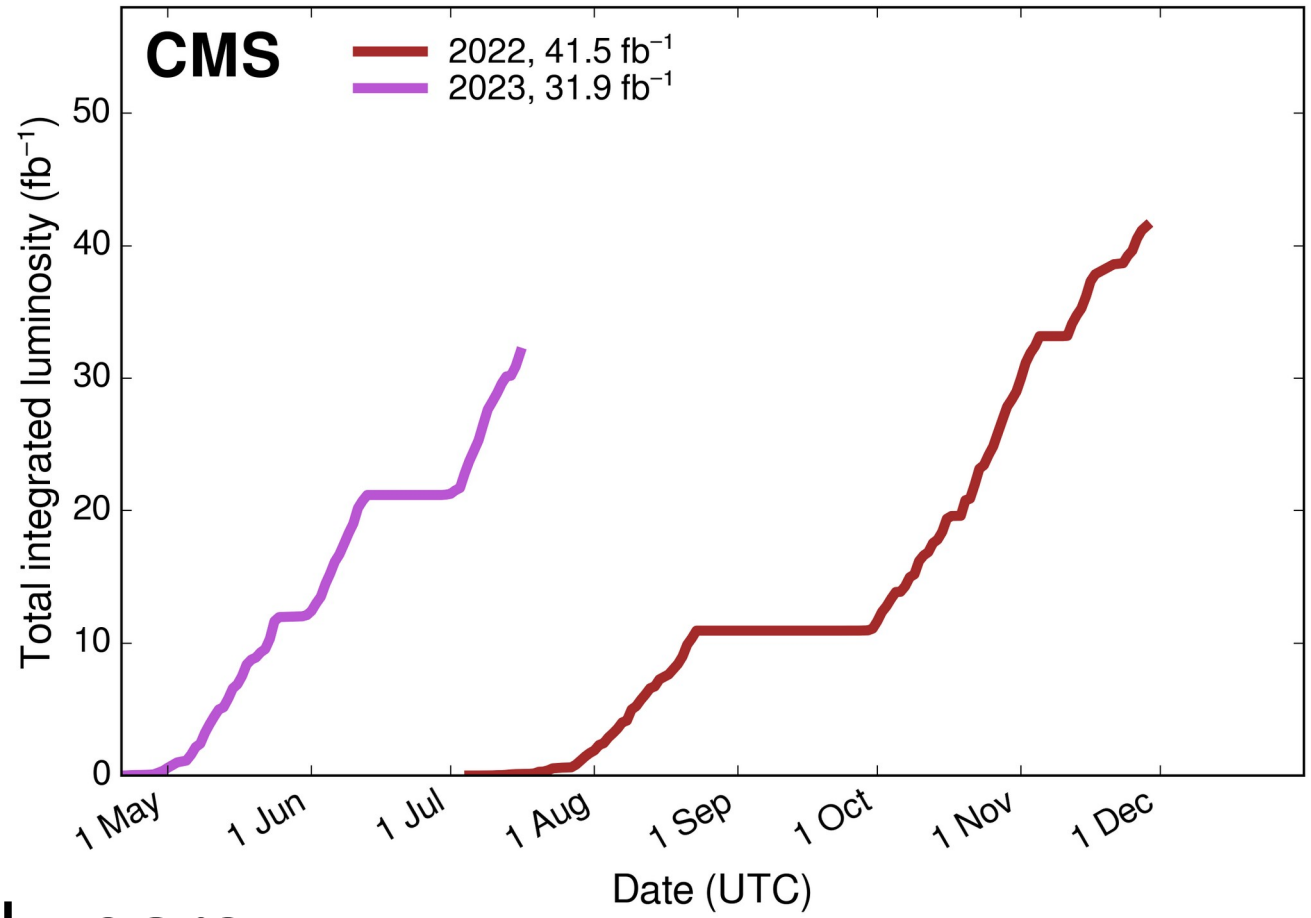


Proton-proton collisions at 13 TeV during Run 2 (Run 1 at 7/8 TeV)
→ at 13.6 TeV since June 5, 2022 (Run 3)

Long Shutdown 2 finished 2019-2022



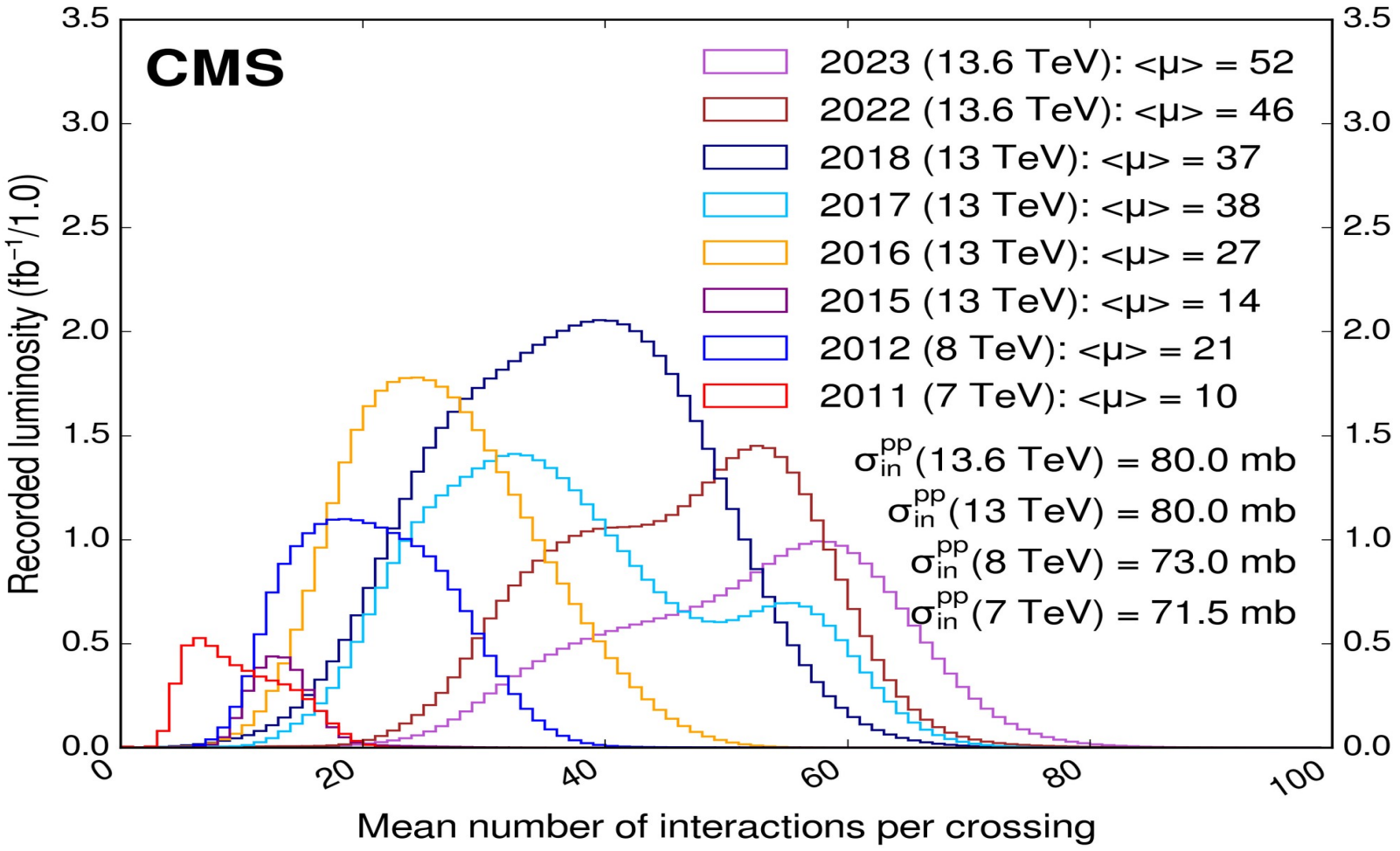
LHC Data – Newest 2022/2023



Mixed years

- Start went well, with commissioning ramp
- Big quench and other repairs
- Excellent continuation: **13.6 TeV**

LHC Steady Increase



Pileup expresses instantaneous lumi

- Event complexity also increasing: towards PU 200 at HL-LHC

Finishing Run 2 Analyses

Dark Matter searches

- Mono-*X* signatures (completed Mono-Jet, will come back after Run 3)
- Dark Photon searches
- Dark showers (Soft Unclustered Energy Patterns, SUEPs)

Higgs Physics

- Charged Higgs searches
- Invisible Higgs
- Higgs rare decays ($H \rightarrow M\gamma$, $M = \varphi, \rho, \omega, \ldots$)
- Higgs to dimuon and *bb*

Analyses in blue started or planned with Run 3 data.

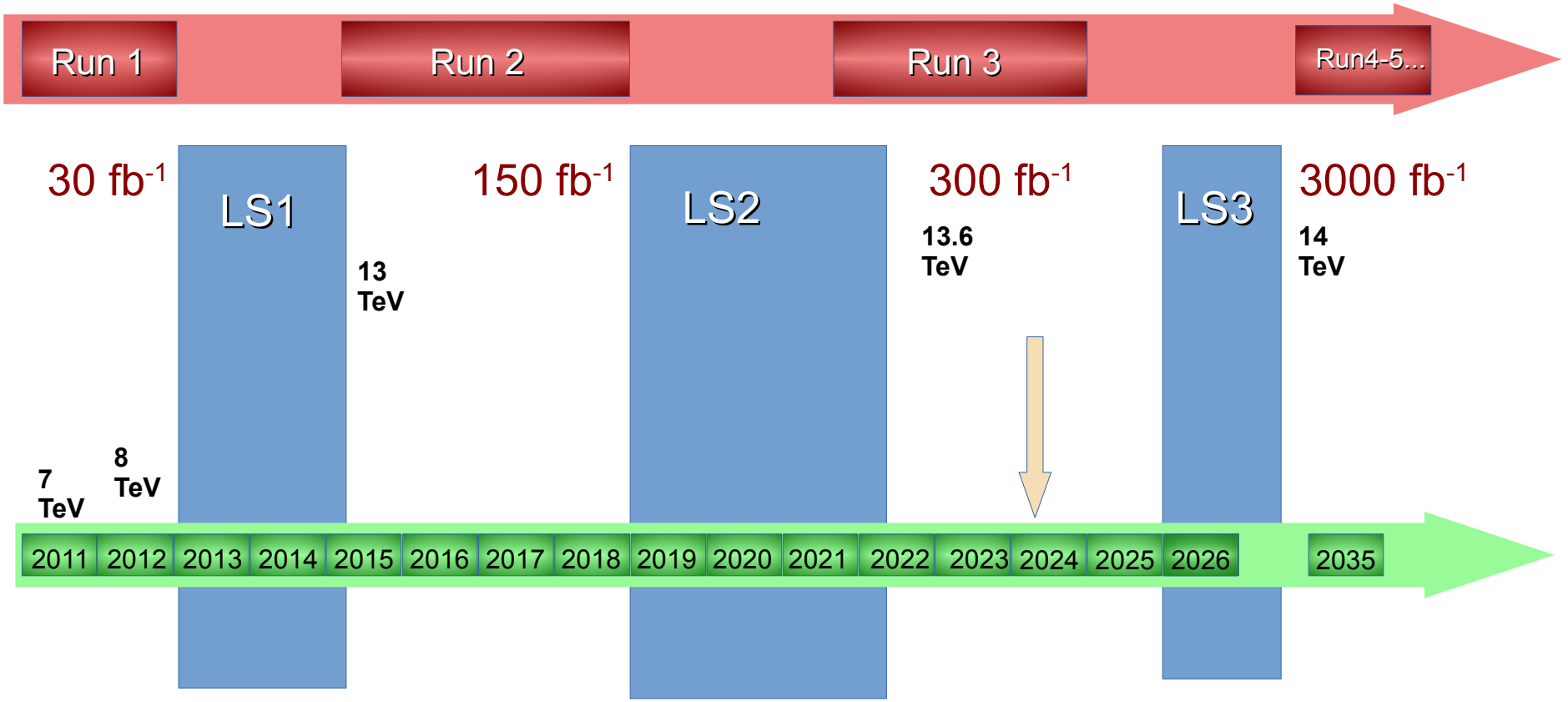
Standard Model analyses

- Precision measurement: *W* and Z masses and p_T spectrum, and α_S?
- cross sections: *Z* p_T, *WZ*, *WW*, VBS cross section

B Physics

- Rare decays: $B \rightarrow \mu\mu$, $D \rightarrow \mu\mu$

LHC Schedule – Long Term

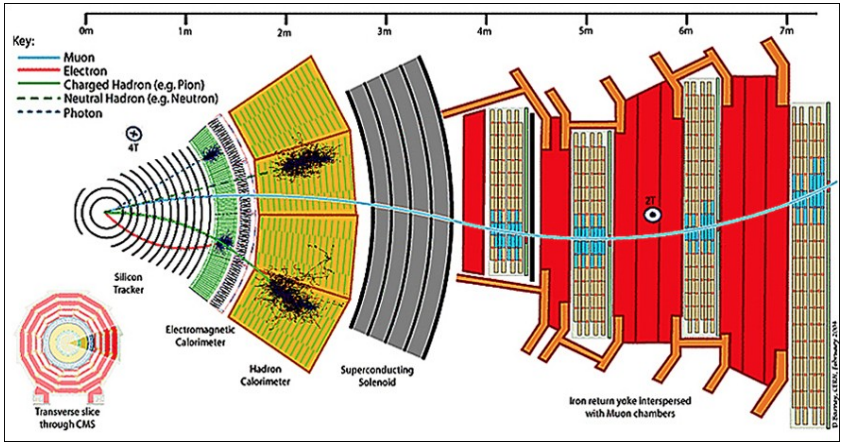


LHC Physics is highest priority for P5 HEPAP panel

→ fantastic opportunities for excellent physics right now

→ with existing data, Run 3 started, and beyond

Data flow in CMS

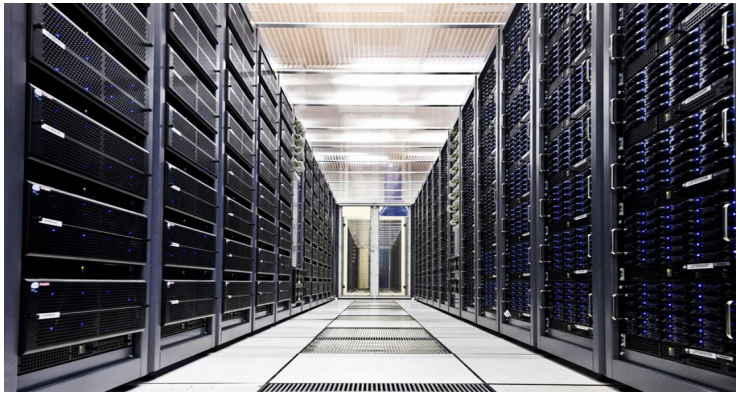


10 TB/s

Level One Trigger system

100 GB/s

High Level Trigger

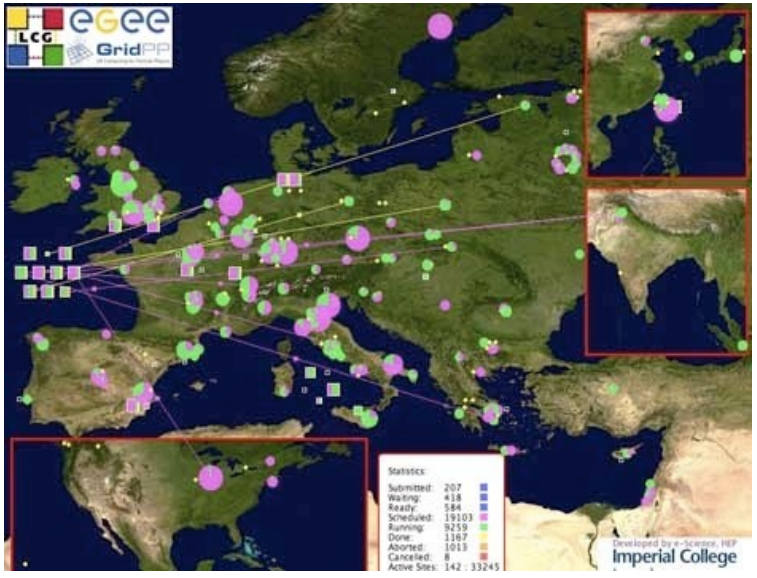


5 GB/s

Storage Manager

CMS HCAL

Computing & Software



Work Completed for Run 3

HCAL

- Transported the MAHI hit reconstruction to GPU
- Re-tuned and commissioned it

Storage Manager and Data Transfer system

- Designed, purchased,built and commissioned new Storage Manager hardware
- Data movement software, overhauled and transitioned to python 3

Computing Operations – Tier-0 and Processing

- Tier-0 was overhauled, adjusted to Rucio and ported to python 3
- Production and re-processing transition to Rucio

Tier-2 Computing center and Analysis Facility R&D

- Major hardware upgrades for Run 3 including GPU servers
- Local tape robot, and Analysis Facility prototype

Upgrade Projects

Storage Manager and Data Transfer system

- HL-LHC will need significantly larger system: design studies in progress

Tier-2 Computing center

- Needs to transition to new storage concept
- Massive hardware expansion needed: CPU, GPU, networking

Tape Pilot project

- Started demonstration project to establish tape storage at MIT
- The NESE tape facility in Holyoke is fully integrated into the CMS storage system but not yet commissioned, tests ongoing

Future Analysis Facility concept development

- New concept to support HL-LHC-and-beyond analysis is being developed

PPC Leadership

CMS Cross Physics Object Group organization (L2)

- Mariarosaria D'Alfonso

CMS Standard Model Physics convener (L2)

- Guillelmo Gomez-Ceballos

CMS Computing Operations (L2)

- Dmytro Kovalskyi

CMS Particle Flow (L2)

- Kenneth Long

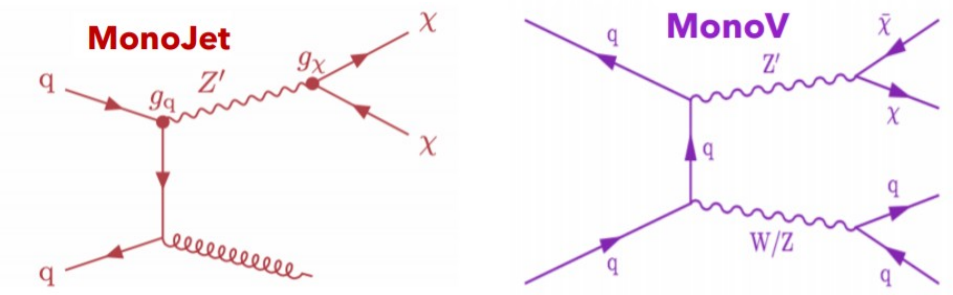
FCC project

- FCC-ee Higgs convener: Jan Eysermans
- FCC-ee Precision Electroweak: Christoph Paus

Mono-Jet and mono-V dark matter search

Search for physics with particles that decay invisibly in association with a jet

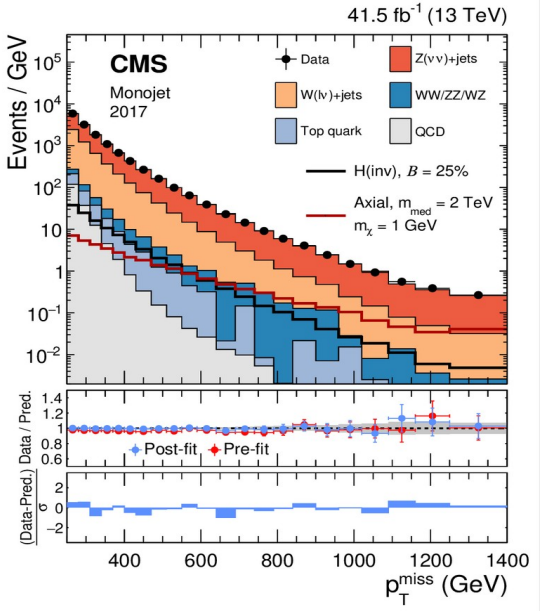
- performed in Mono-Jet and Mono-V categories and combined

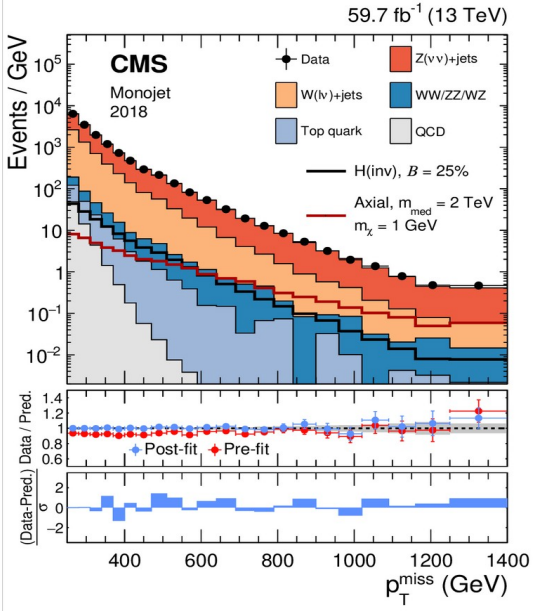


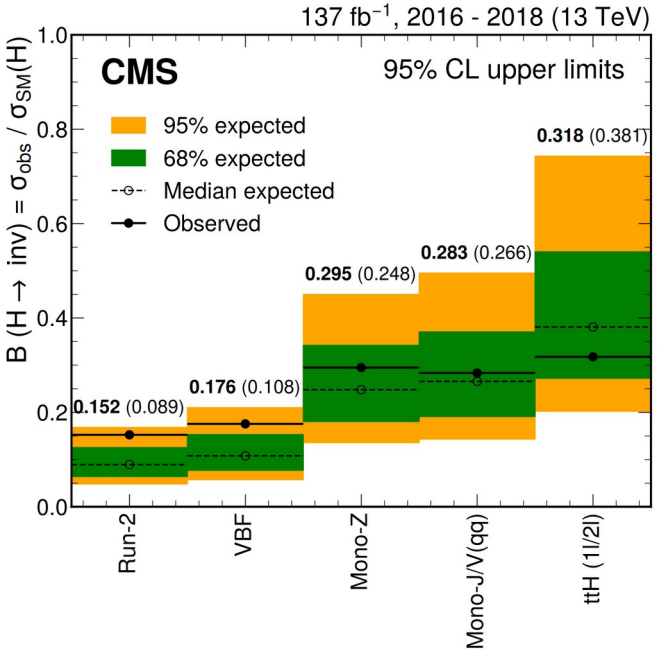
Full Run 3 data
Analysis planned

No significant excess of events is observed in data.

Several of the new limits, specifically for spin-1 dark matter mediators, pseudoscalar mediators, colored mediators, and leptoquarks.



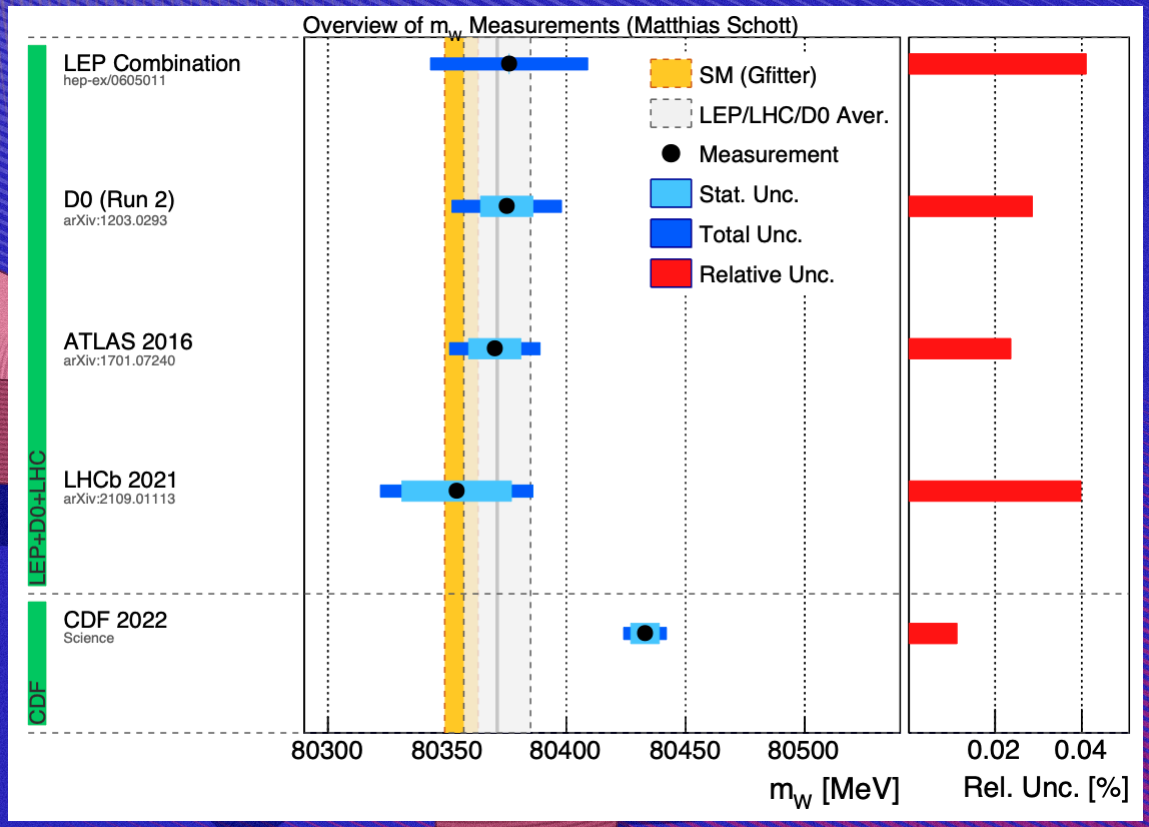




Status W Mass

CDF experiments last word

- W mass too heavy by seven standard deviations !



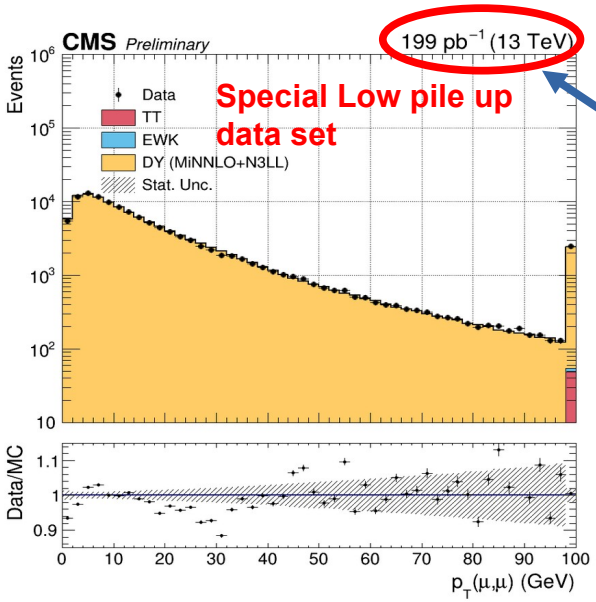
Source:https://non-trivial-solution.blogspot.com/2022/04/do-we-have-finally-found-new-physics.html

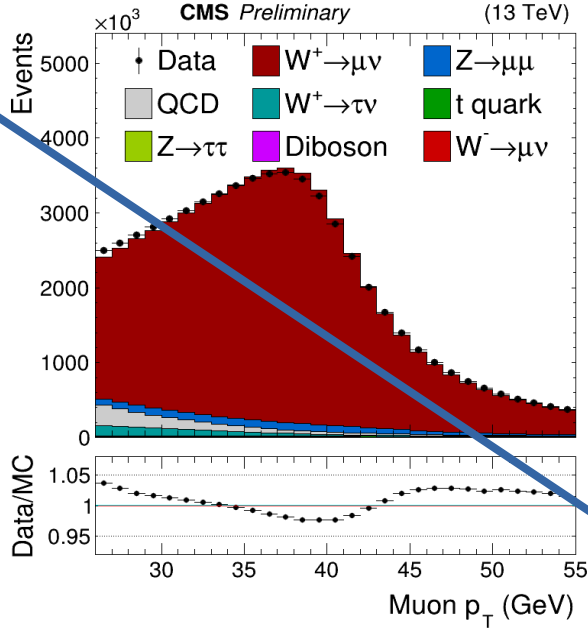
Source: https://www.quantamagazine.org/fermilab-says-particle-is-heavy-enough-to-break-the-standard-model-20220407/

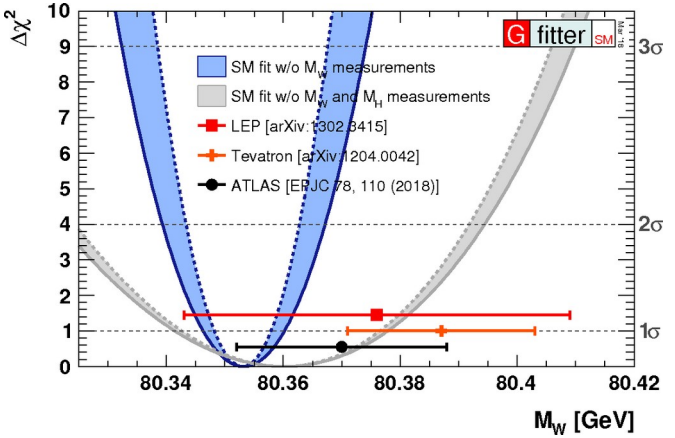
CMS W Mass Measurement

Precision measurement of W boson mass: Δm_W<15 MeV

- Direct measurements of observables over-constrain the SM







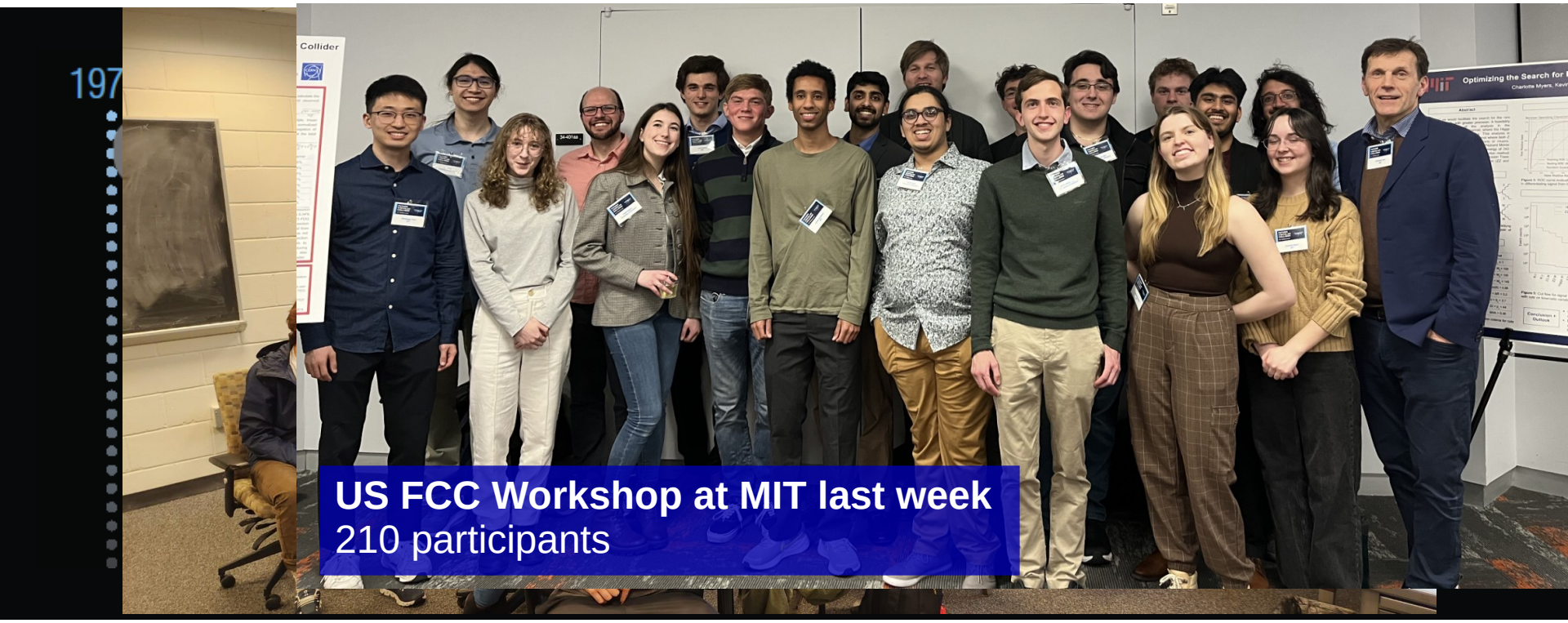
- Infer mass from muon p_T
- Improve predictions using low pileup data taking

Mass measurement using muon transverse momentum (p_T)

- Requires < percent level measurement of muon reconstruction efficiency, scale, and resolution
- Accurate detector material, particle interaction models, detection, efficiency, magnetic field
- Exploit state-of-the-art predictions Monte Carlo predictions to minimize modelling uncertainties
- Improve predictions with direct measurement of W boson p_T in special LHC runs at low pile up

Δm_W<5 MeV

Future of The Energy Frontier



Precision measurements of Z, W, Higgs boson & top quark physics

- Δm_Z ~ 4 keV == improve uncertainty by factor of 500 (almost 3 order of magn.)
- Δm_W~ some tens of keV
- Higgs boson couplings to percent levels, independent full width measurement

Starting to work on R&D for CMOS MAPS vertex detector

Higgs Rare Decays

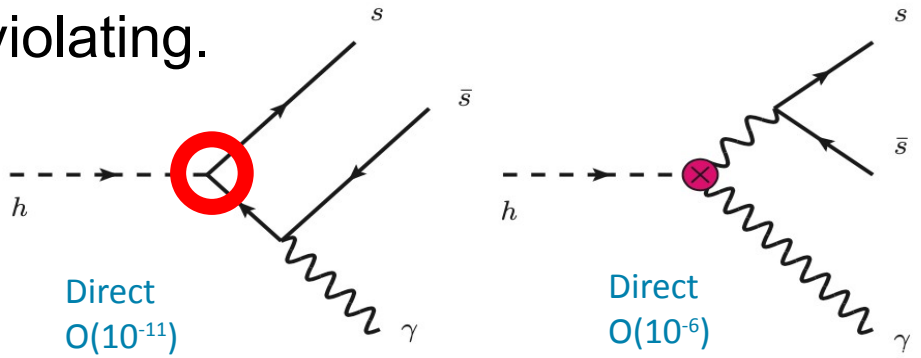
The exclusive hadronic decays H → ***M*γ**, (also H→***MZ*** and *h*→***MW***)

M is a meson such as ϕ, ω, ρ_{770}.....

Probe several different couplings of the Higgs boson to SM fermions both flavor-conserving and flavor-violating.

$\mathcal{B}$ (H → *M*γ) ~ 10^{-6} – 10^{-10}

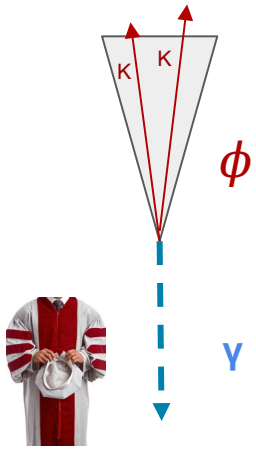
in comparison $\mathcal{B}$(H → $\mu\mu$) ≈ 2.2 × 10^{-4}



Increased branching ratio with respect to SM is <u>sign of new physics</u>.

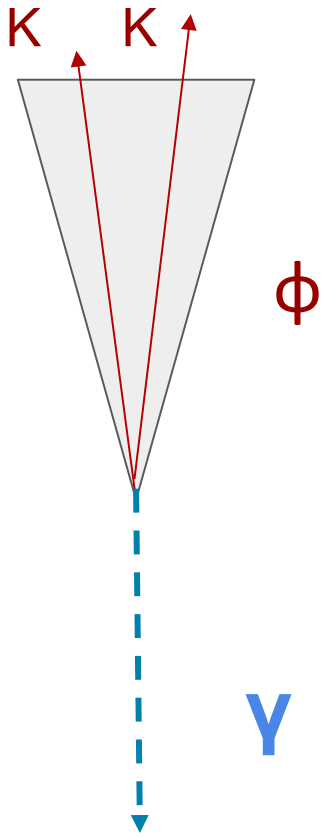
First public results expected for summer conferences

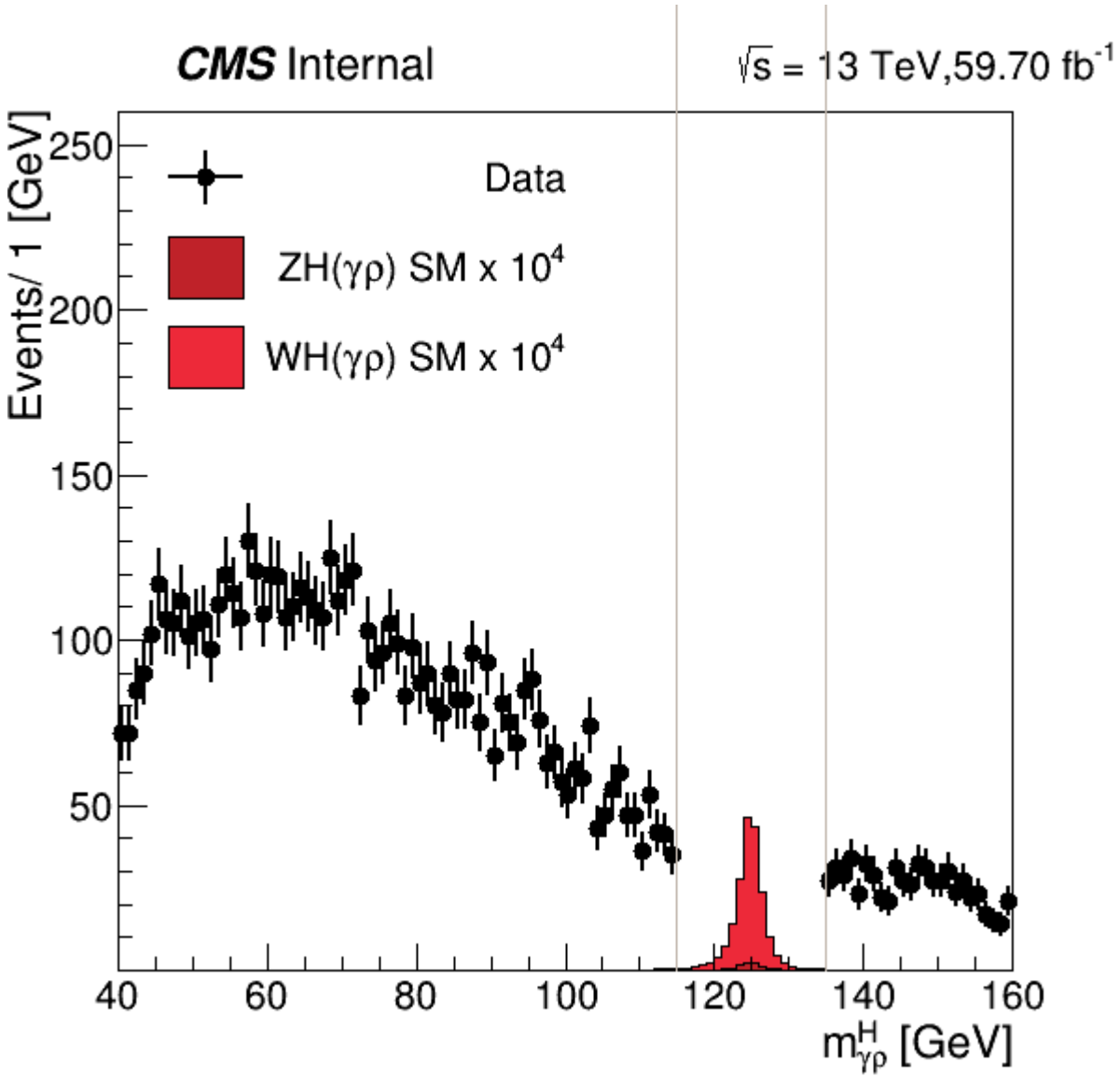
- Run 2: look for H boson production in association to Vector Bosons
- Run 3: implement quasi real time analysis with new HLT capabilities
- Meson reconstruction with new ML techniques to increase efficiency are a must



Higgs rare decays

First studies show that we can understand the backgrounds well.

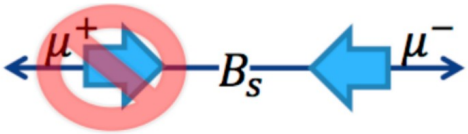


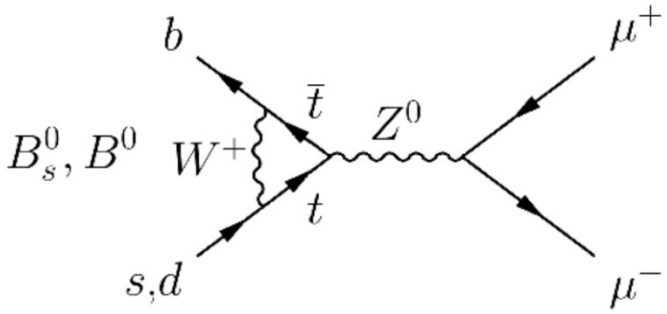


Search for $B_{s,d} \rightarrow \mu^+\mu^-$

B decay through effective FCNC in Standard Model → rare

- Stringently helicity surpressed
- And CKM subpression from B_s to B_d





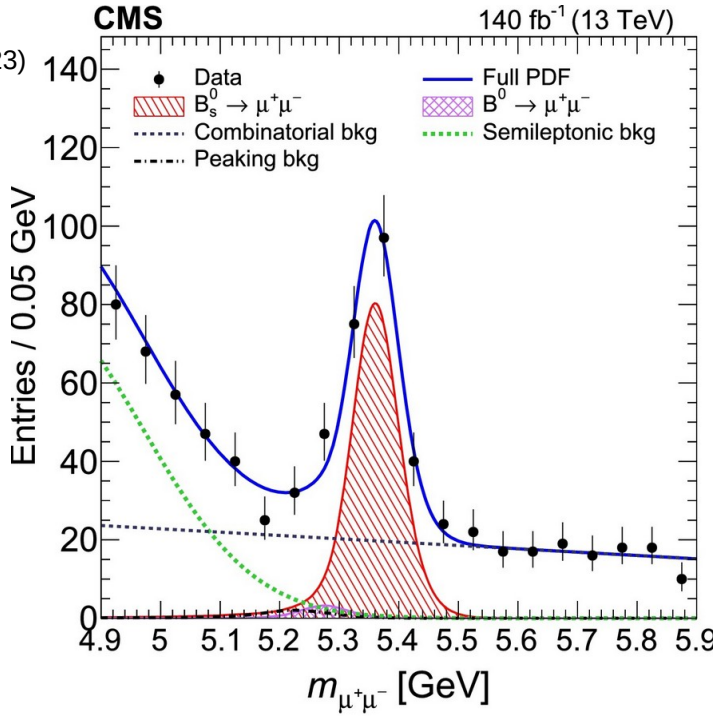
- Could cast some light on the present discrepancies in the B sector
  - 3 std LFU violation in R(K) and R(D*), 2-3 std discrepancies in branching ratios

Disappeared in CERN seminar (12/20/2022)

Confirmed in CERN seminar (3/21/2023)

Powerful test of theory prediction and indirect search for new mediator

- Legacy Run 2 analysis was a highlight at ICHEP 2022 and is published
- Substantially expanded trigger for Run 3
- B_d and D^0 search are on their way, B_d might be in reach



Dark Photon → μ μ Search

A search for a prompt dark photon resonance in the dimuon final state

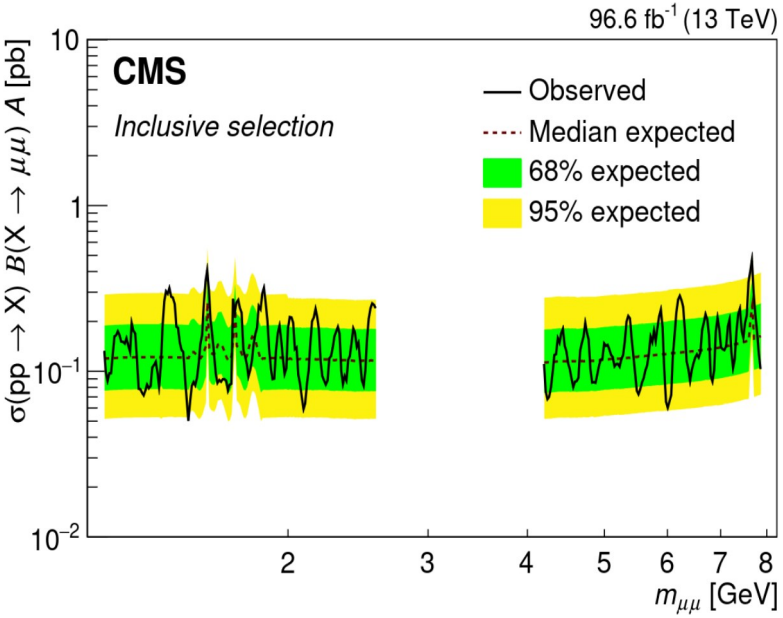
- using the scouting data collected in 2017 and 2018.
- probe dark photon masses from 1.00–2.63 GeV and 4.2–8.18 GeV

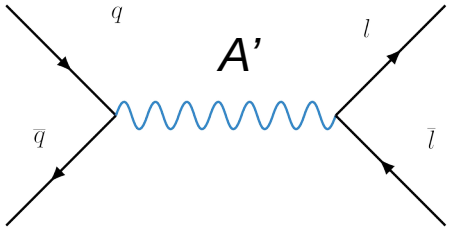
Looking for a narrow resonance peak in the dimuon mass continuum.

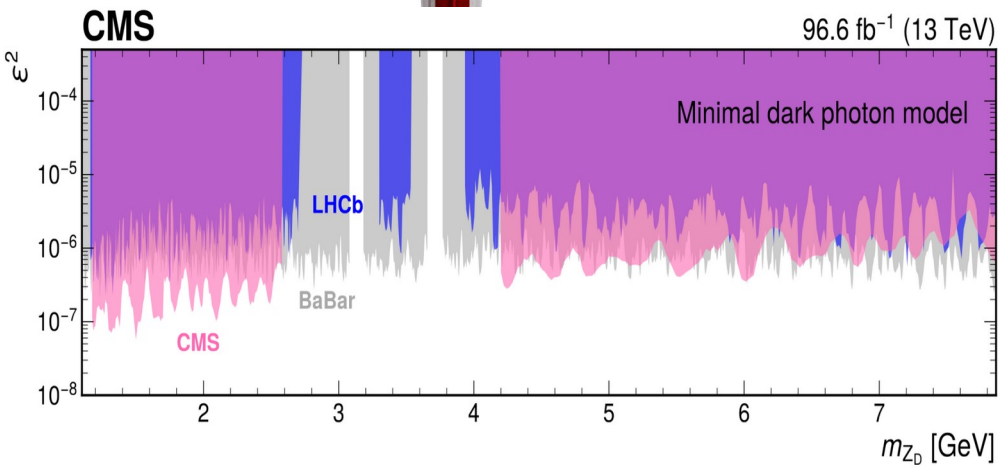
- New muon MVA IDs were developed to improve the sensitivity at low mass and for scouting data variables

Result interpreted in Hidden Abelian Higgs Model and 2HDM+S.

- Sensitivity exceeds Babar/LHCb results, just a little







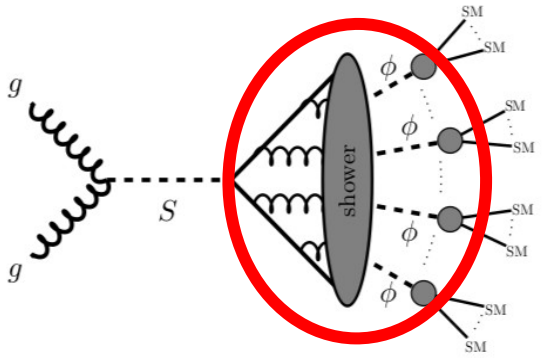
Soft Unclustered Energy Patterns (SUEPs)

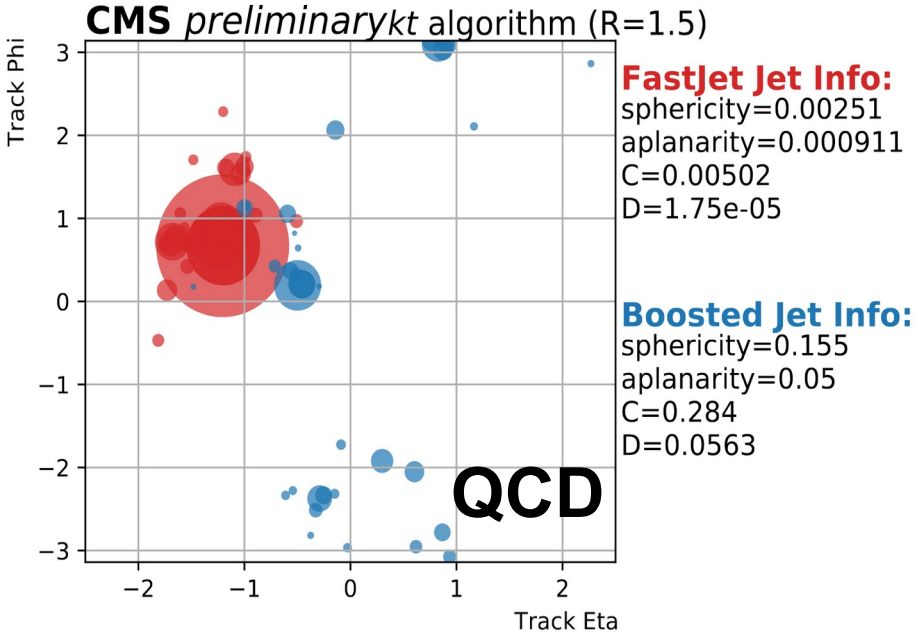
No WIMP at LHC → explore more complex DM scenarios: e.g. dark strong dynamics

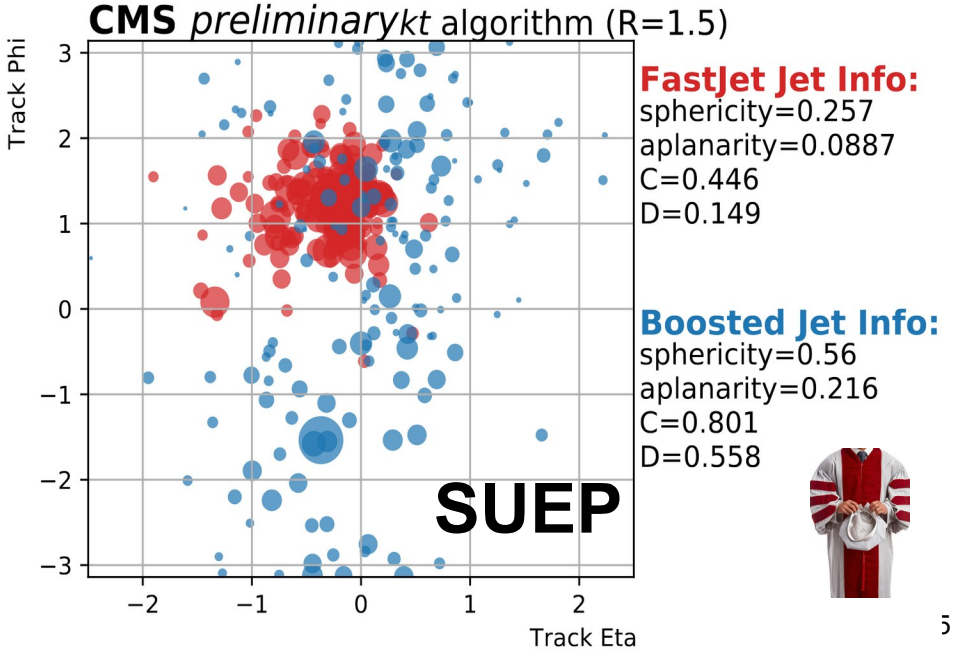
Strongly coupled hidden valleys through high-multiplicity decays of new heavy scalar mediators

- Searching for “belt of fire”, spherically symmetric distribution of tracks → exploit event shape variables to discriminate against QCD background
- Extremely difficult to trigger on soft sprays – two ways:
  - Explore data scouting techniques or,
  - Require Initial State Radiation (ISR) and look at SUEP rest frame
- Snowmass proposal was submitted, first analysis just came out

Dark shower → hidden valley

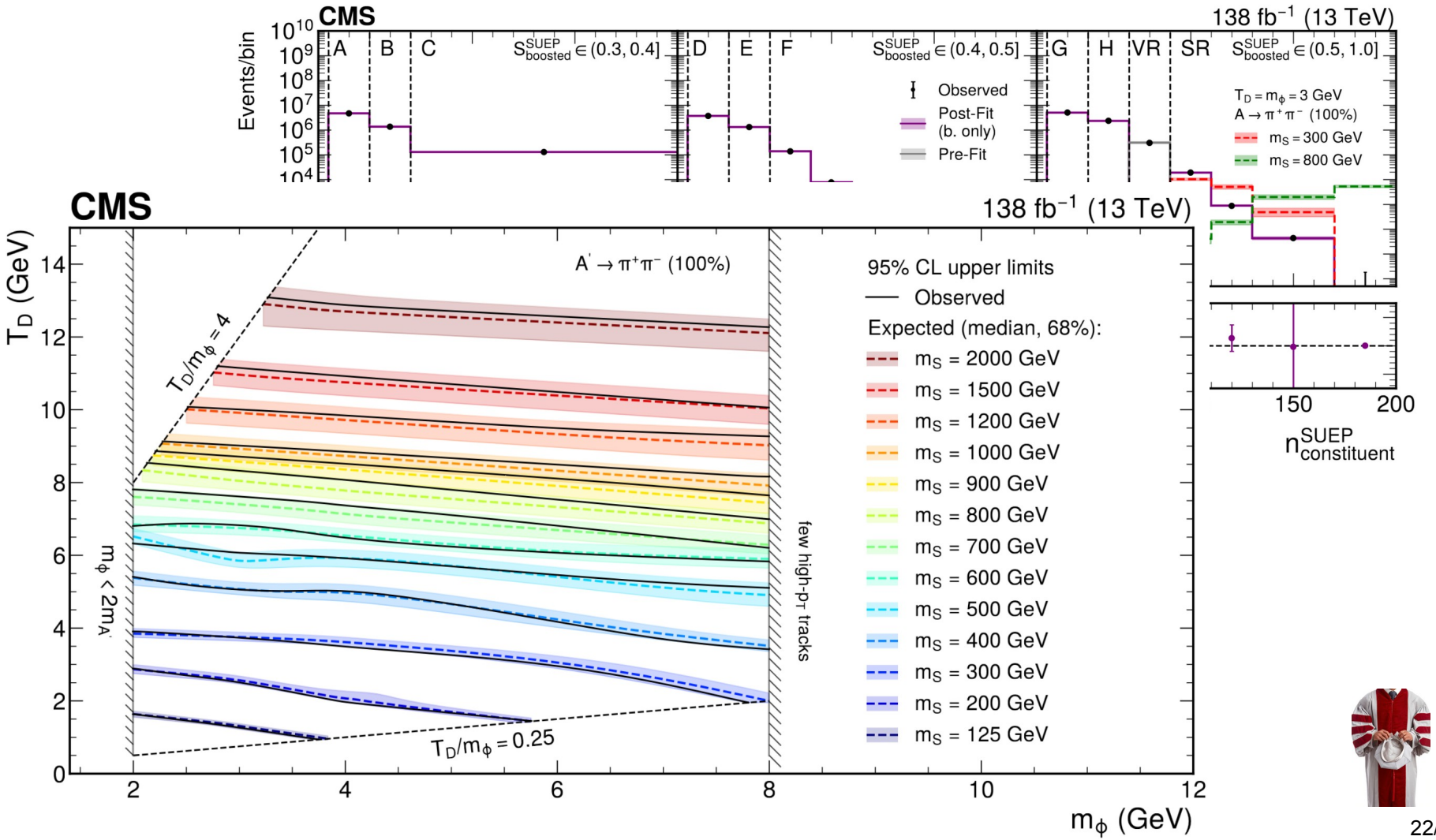






Soft Unclustered Energy Patterns (SUEPs)

Two parameters to describe dark showers: mass of the lowest state particle m_Φ and the temparature T_D, which describes how the energy is distributed in the shower



Conclusion

Broad physics and detector programs

- Higgs, New Physics (inc. dark matter) and sensitive precision tests
- Promising analyses for Run 3 with great team and theses topics
- Software, Computing, Trigger, DAQ, and Detector projects offer a lot valuable experience

Contribution to future collider projects (FCC, C^3) possible and encouraged

PPC has strong leadership in CMS detector and physics organization

It is an amazing time to join and stay in the field!

7% **LHC Status:** **Restarting end of April**

MIT is member of the CMS Collaboration

~50 Countries, ~250 institutes *[US makes up ~30%]*

~3000 Authors including ~1800 PhD's and ~950 PhD students

Research Computing Support

High **P**erformance **R**esearch **C**omputing **F**acility at BATES

- Build in 2009 with help from School of Science / MIT: ~ $8M
- Largest shares at the time: CMS Tier-2, LIGO, EAPS, Chemistry
- Today: CMS Tier-2, HI Simulation center, LHCb Tier-2, CLAS12
- But also others: CTP (HPC cluster), Chemistry, EAPS …

Major successes and plans, *examples*

- 1st CMS publication on pp-collisions was performed on HPRCF
- MIT was prominent in Higgs discovery analysis and most of the analysis was done on HPRCF
- LHCb decided to integrate its only US Tier-2 into the HPRCF
- NSF proposal for large HPC center (CTP) was granted a
- NSF proposal for large AI center also relies on this spacend is integrated in the HPRCF