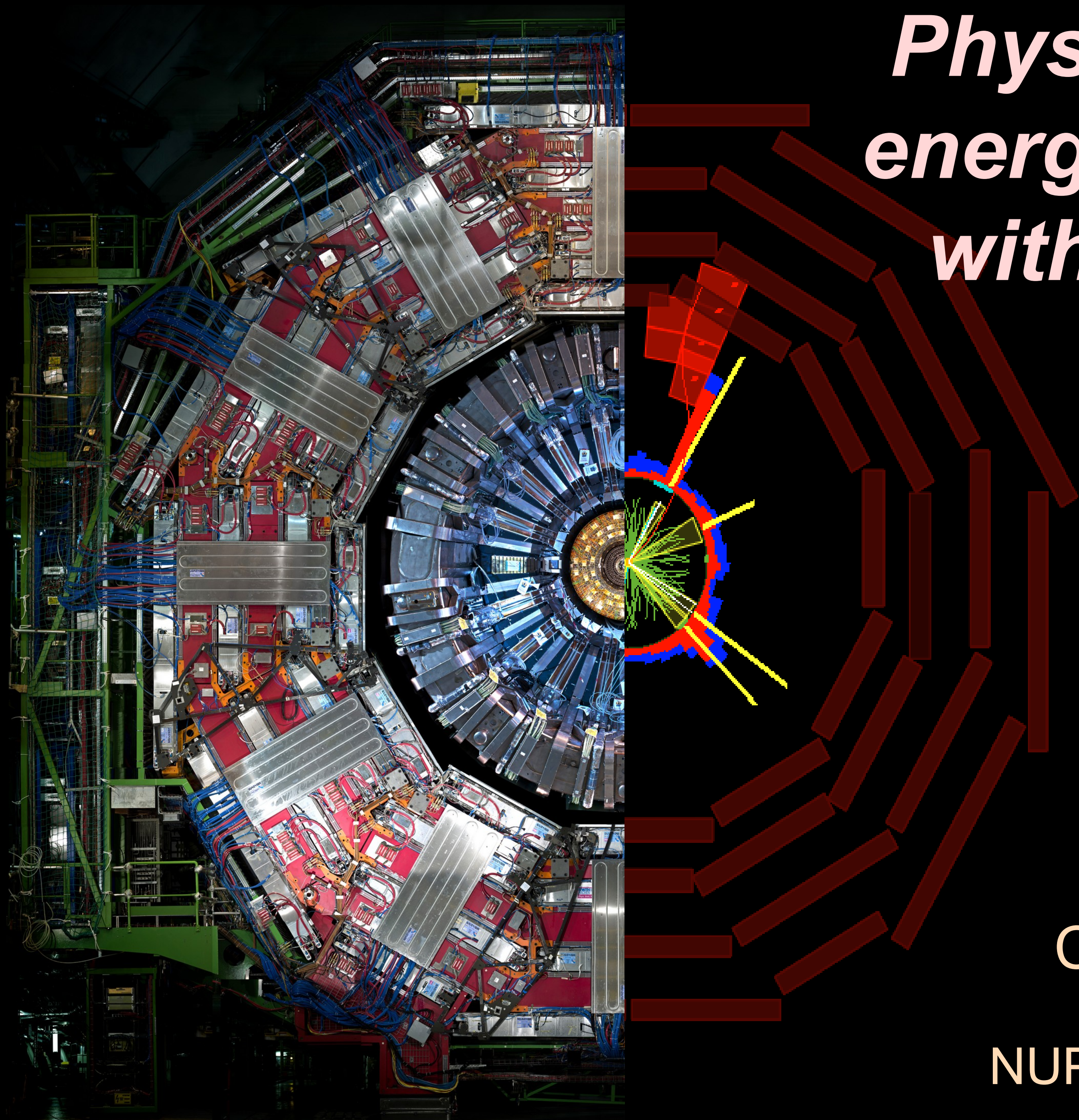


Physics at the energy frontier with the CMS Detector

Christoph Paus

April 3, 2025

NUPAX Open House

Particle Physics Collaboration (PPC)

Faculty

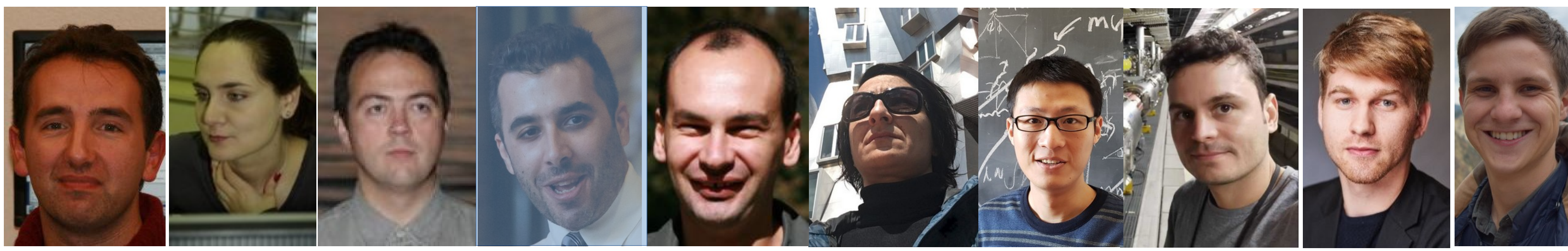
Christoph Paus

PPC web site: https://ppc.mit.edu/

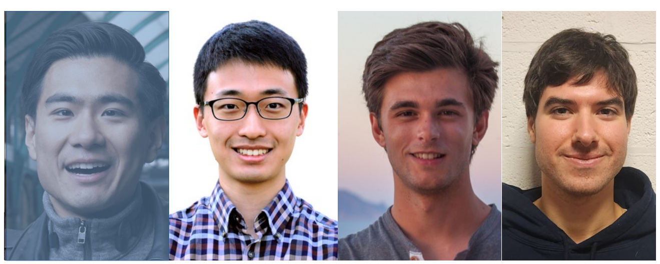
A number of crucial operational responsibilities

- **~ half of the people are at CERN**

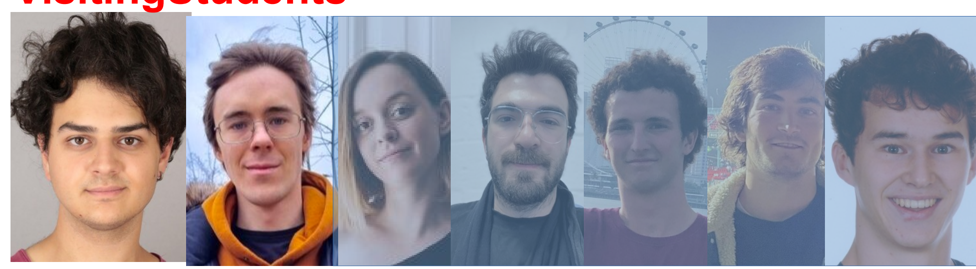
Research Scientists, Postdocs



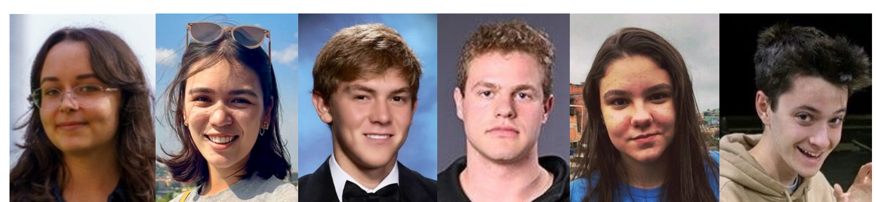
Graduate Students



VisitingStudents



Undergrads many many many



more

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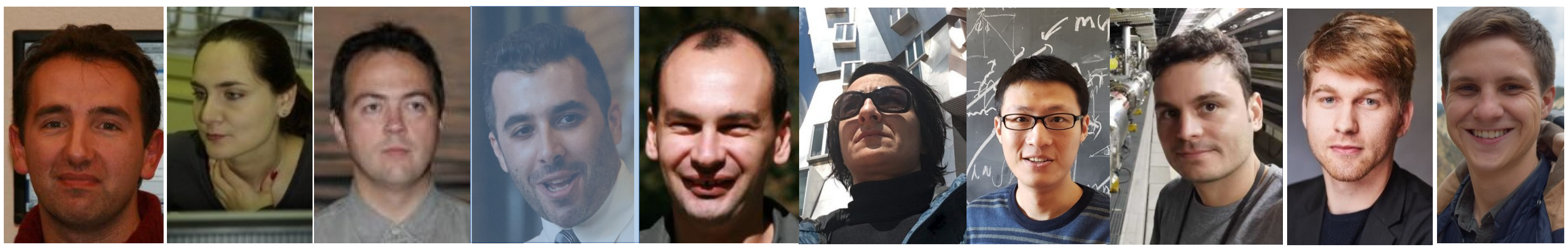

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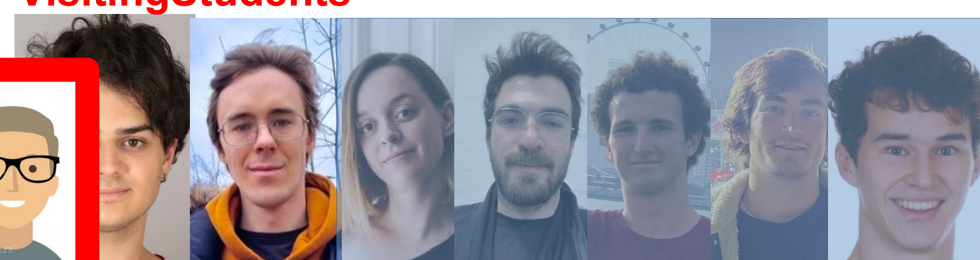
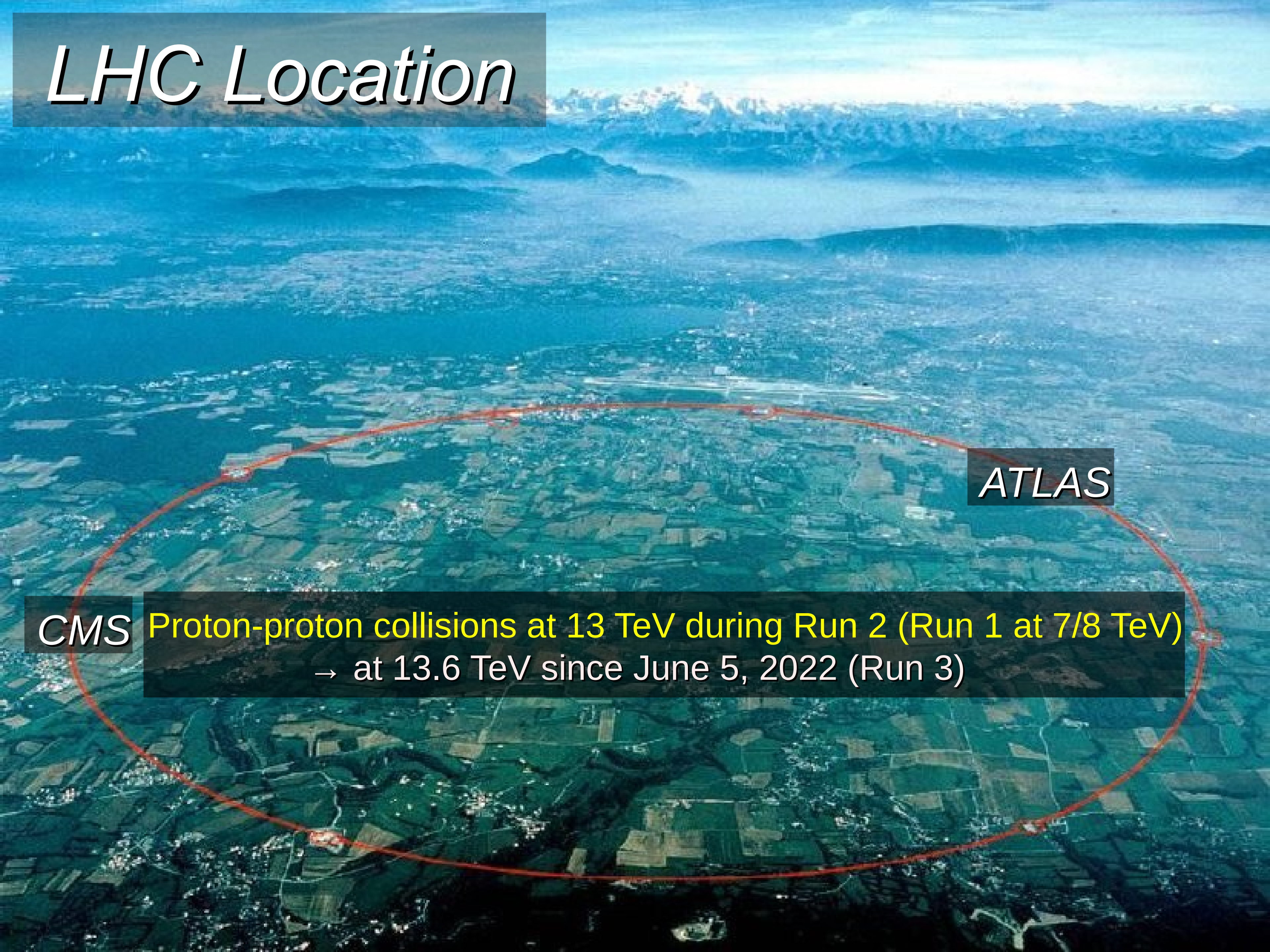


Join in 2025
Perfect for
Run 3.

Undergrads many many many

more

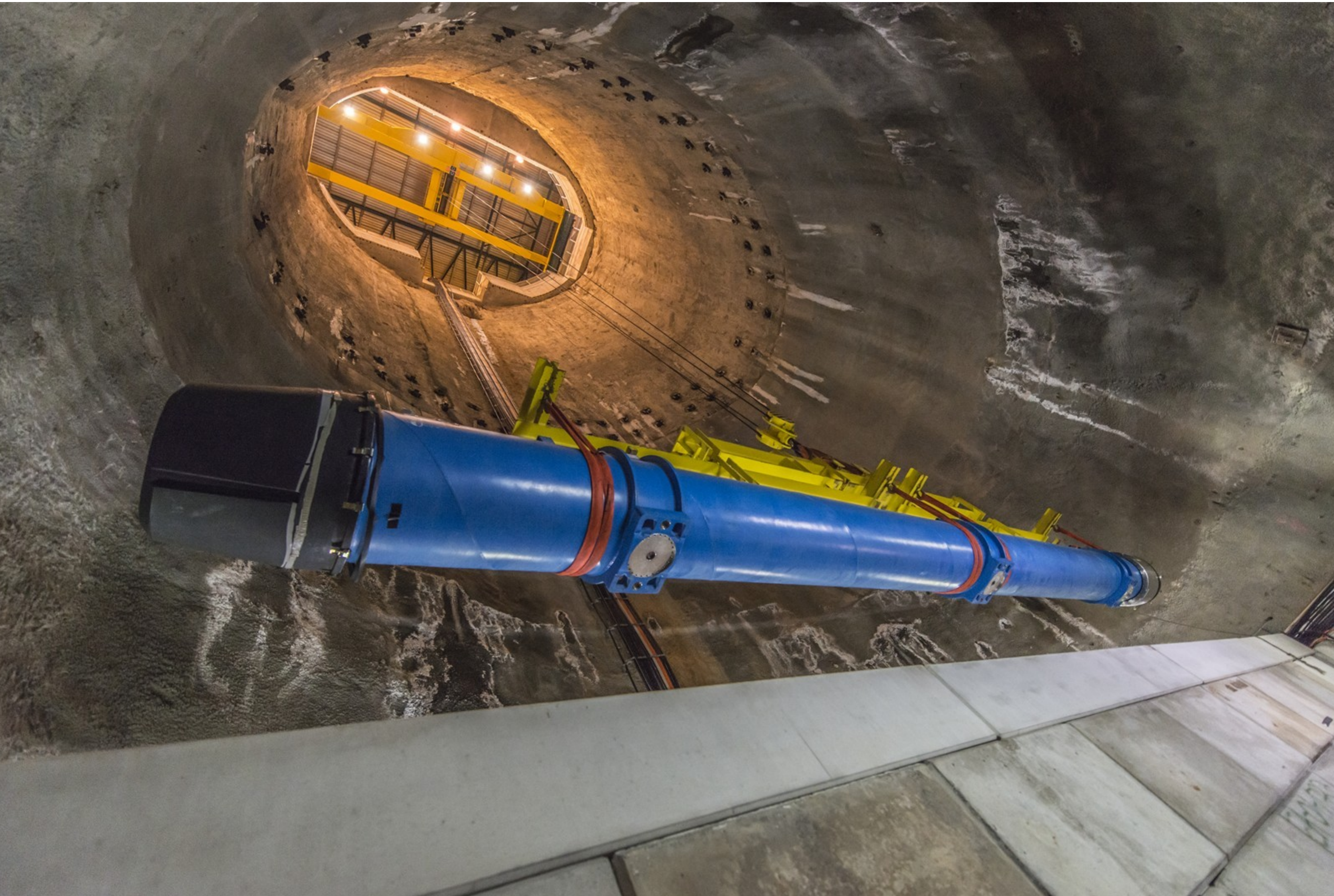
LHC Location



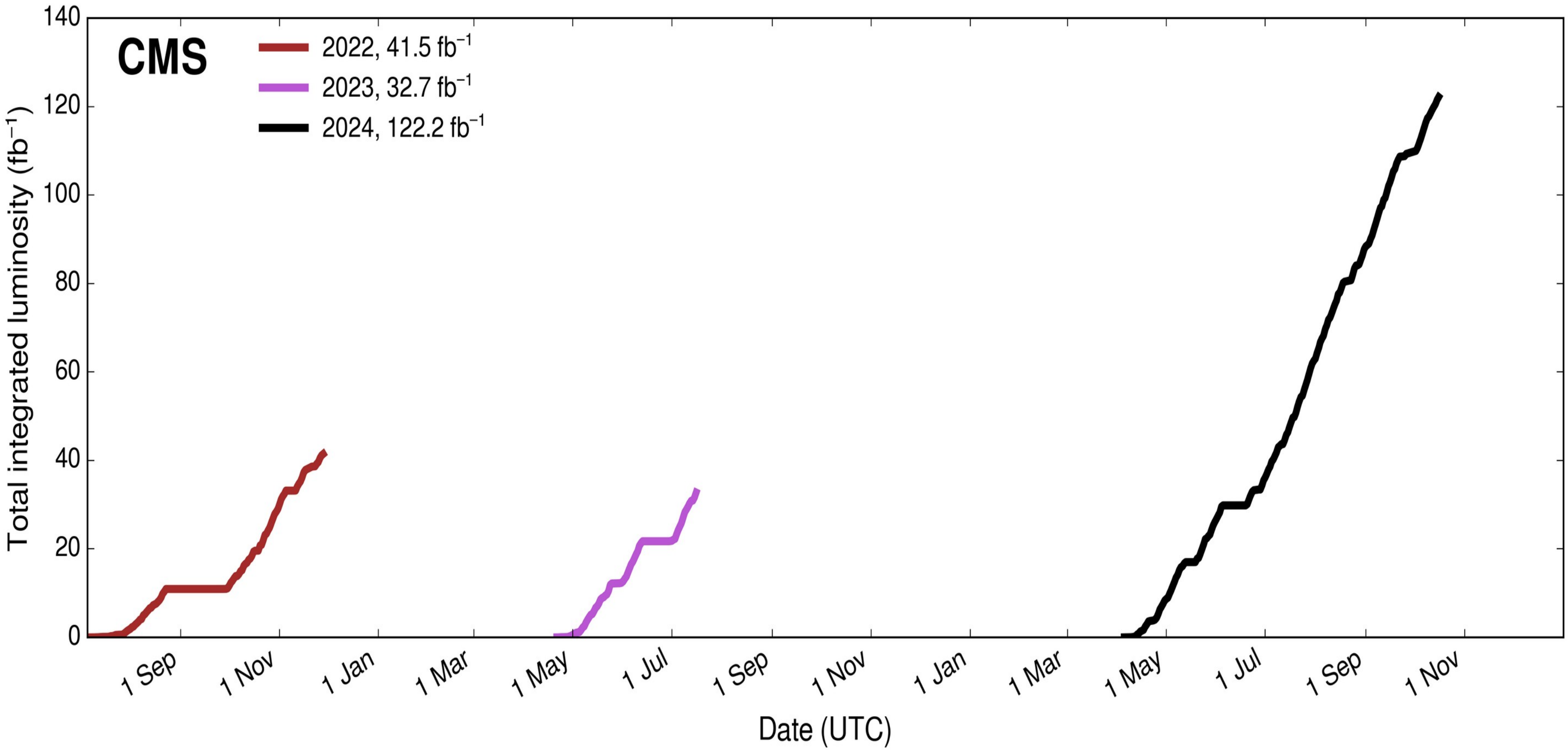
Proton-proton collisions at 13 TeV during Run 2 (Run 1 at 7/8 TeV)

→ at 13.6 TeV since June 5, 2022 (Run 3)

Long Shutdown 2 finished 2019-2022



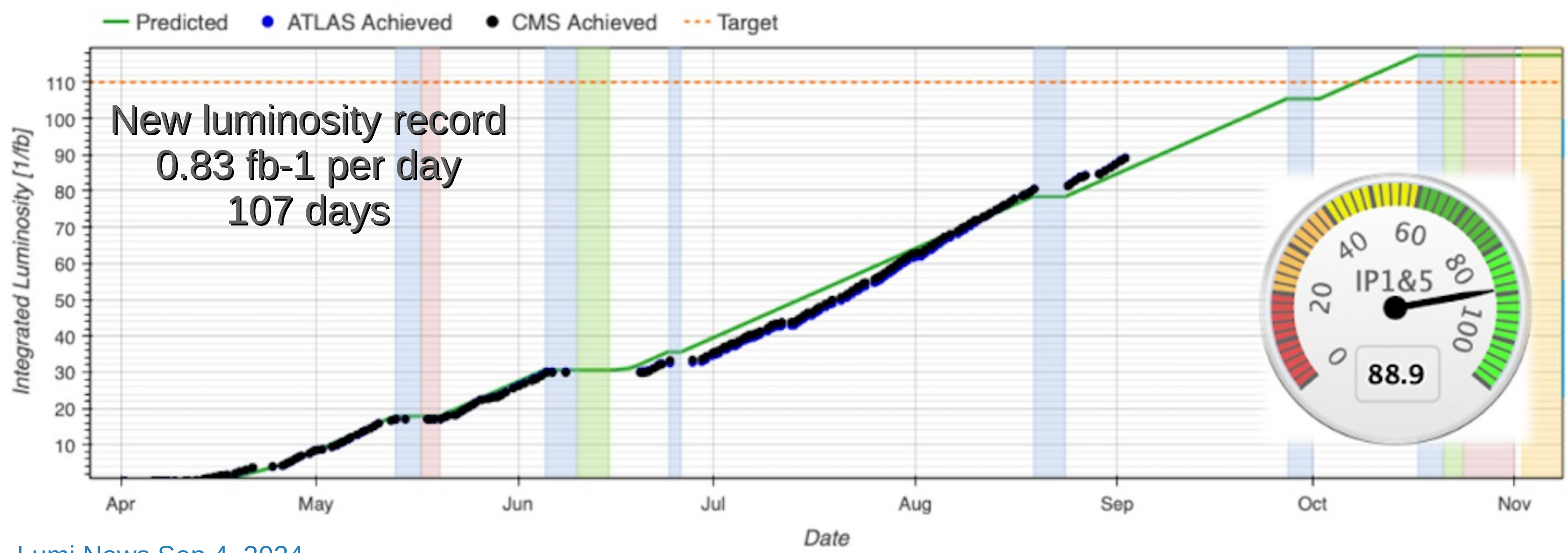
LHC Data – Newest 2022/3/4



Mixed years

- Start went well, big quench and other repairs followed
- Great year 2024!
- Excellent continuation: 13.6 TeV

LHC Data – Newest 2024

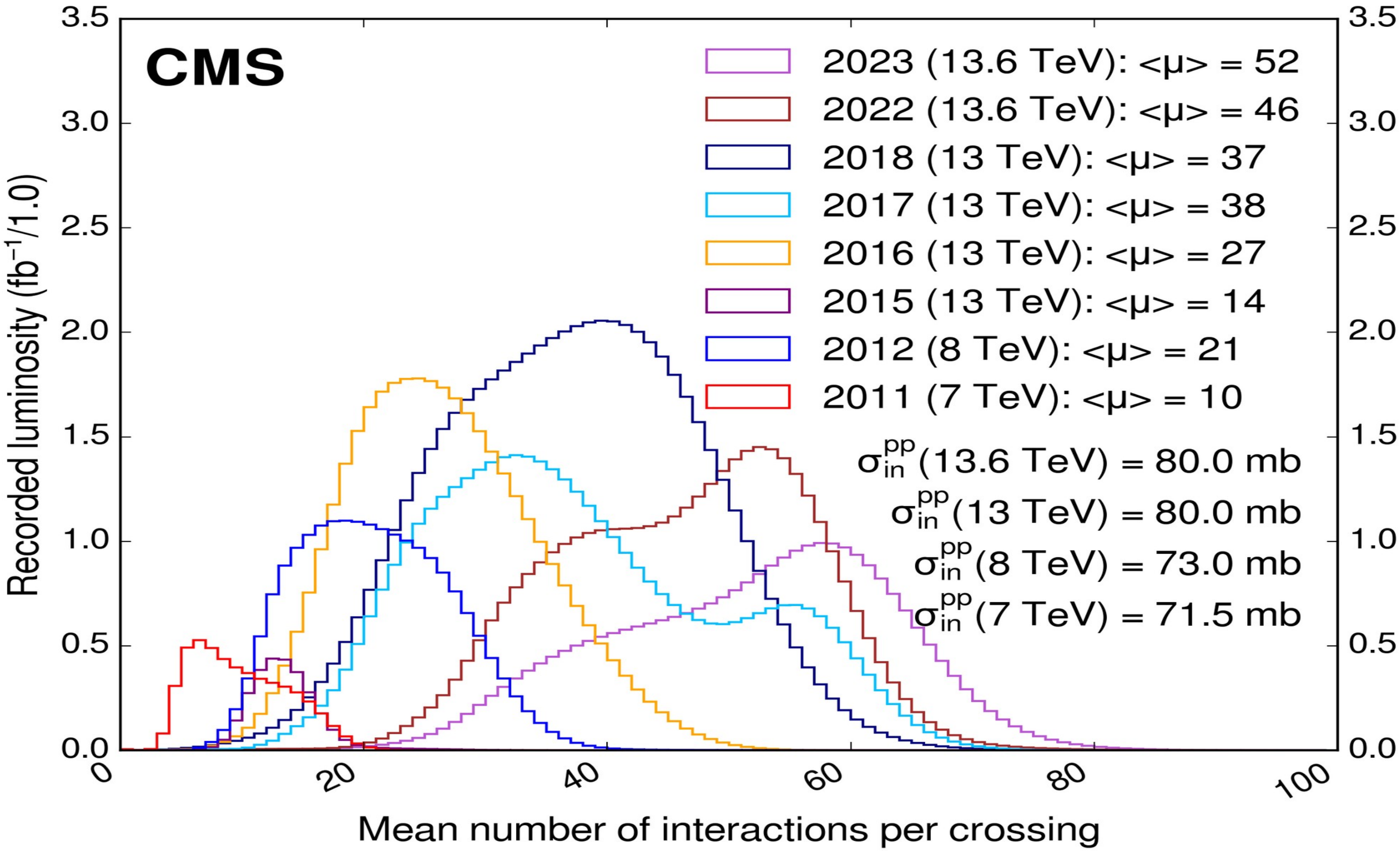


Lumi News Sep 4, 2024

Record breaking 2024

- LHC provided CMS with more int. luminosity than anticipated: 122/fb (110/fb was projected)
- The run had its issues but excellent planning and dedicated work keeps this machine performing extremely well

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.

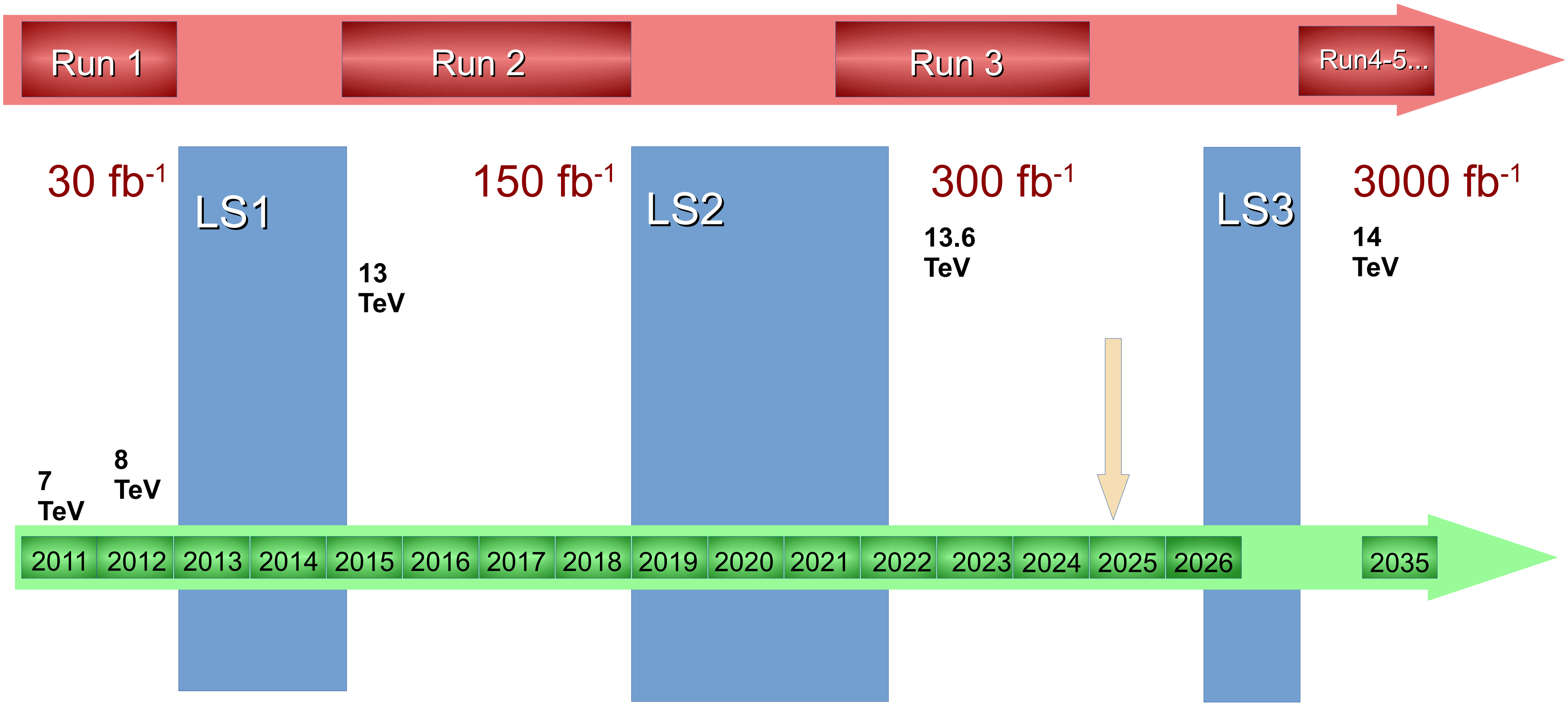
Standard Model analyses

- Precision measurement: *W*, Z masses, p_T spectra, α_S and $\sin^2\theta_W$?
- 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



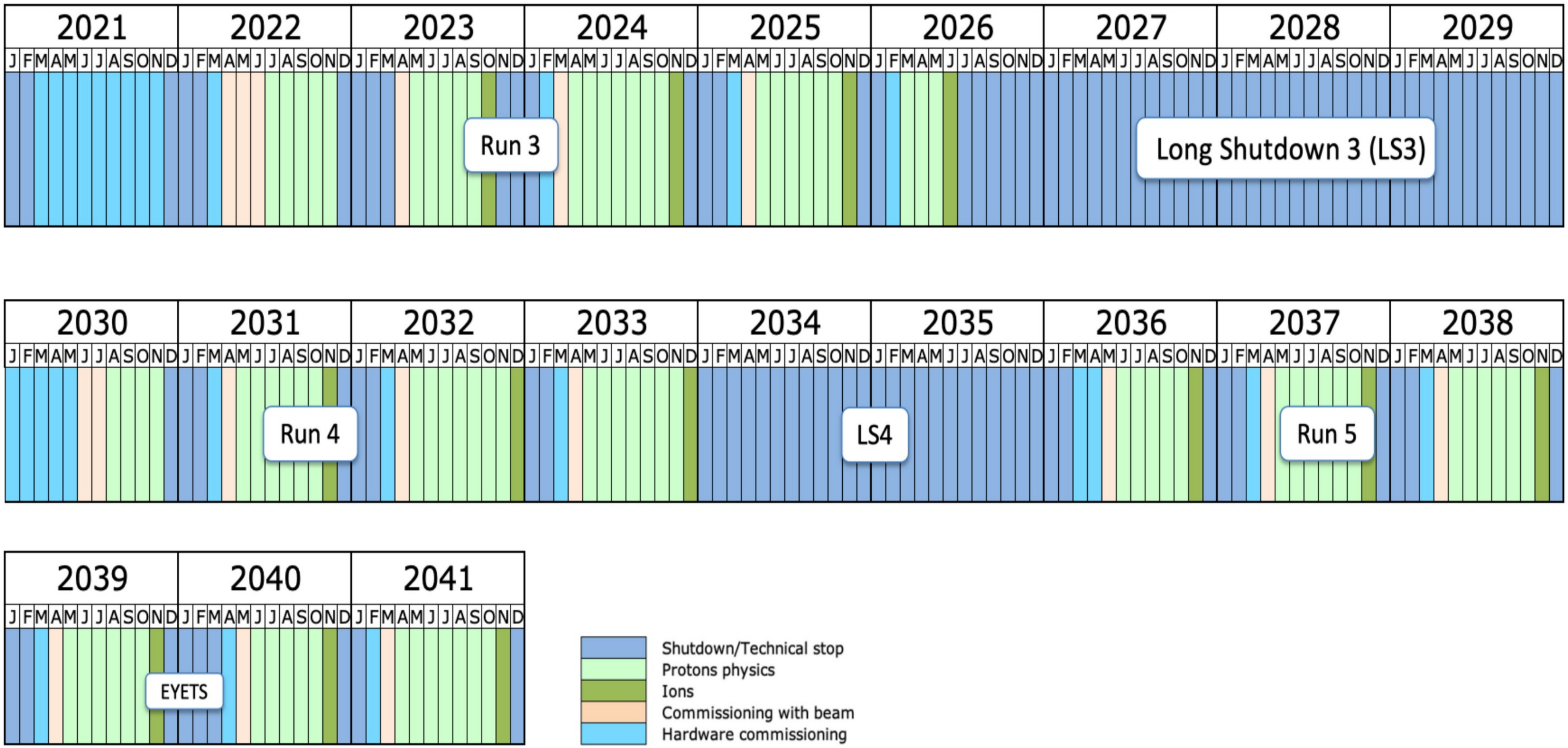
LHC Physics is highest priority for P5 HEPAP panel

→ fantastic opportunities for excellent physics right now

→ with existing data, Run 3 started, and beyond

LHC Schedule – Long Term

We are here,
right before the run starts



Last update: November 24

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
- **Expanded writing rate from 7 GB/sec → almost 40 GB/sec**

Computing Operations – Tier-0 and Processing

- Tier-0 completely revised: new data management
- Tier-0 application can now run at Tier-1 or Tier-2 centers

Tier-2 Computing center and Tier-3 center

- Major hardware upgrades for Run 3 including GPU servers
- Upgraded Tier-3 storage technology

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 (cephFS)
- Massive hardware expansion needed: CPU, GPU, networking

Tape Pilot project

- Established tape storage at MIT: need to move to production
- The NESE tape facility in Holyoke is fully integrated into the CMS storage system – network upgrades under way

Future Analysis Facility concept development

- New concept to support HL-LHC-and-beyond analysis is being developed (we have a prototype: SubMIT)

PPC Leadership

CMS Physics Coordinator (L1)

- **Guillelmo Gomez Ceballos**

CMS B Physics convener (L2)

- Dmytro Kovalskyi

CMS Computing Operations (L2)

- Dmytro Kovalskyi

CMS Particle Flow (L2)

- Kenneth Long

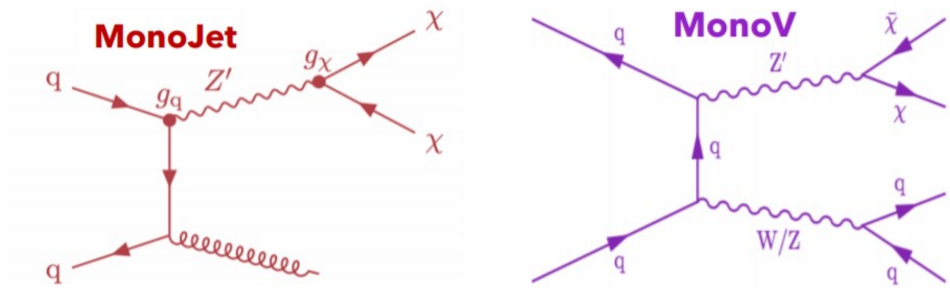
FCC project

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

Mono-Jet and mono-V dark matter search

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

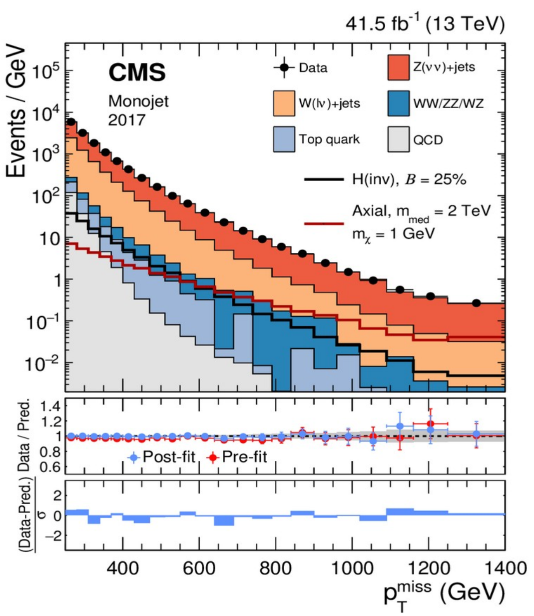
- performed in Mono-Jet and Mono-V categories and combined

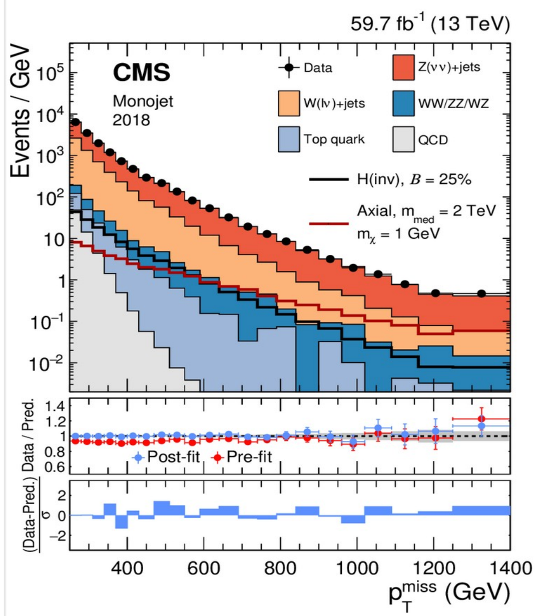


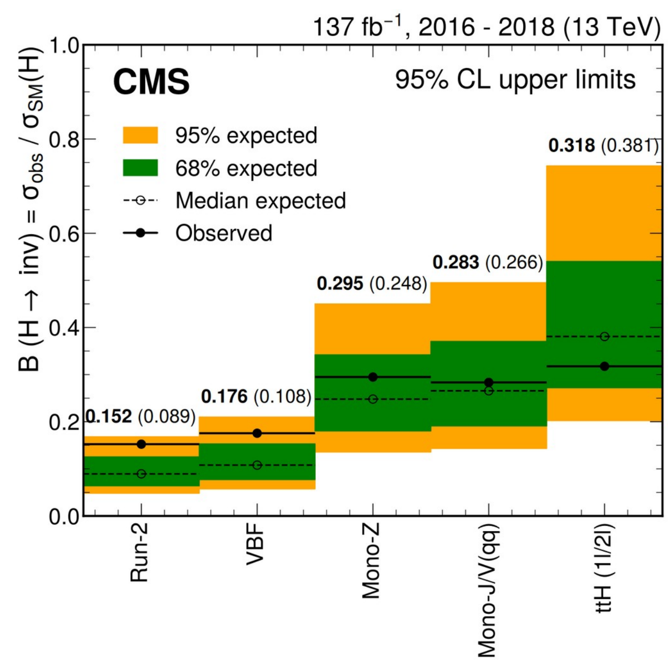
Full Run 3 data
Analysis planned

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.



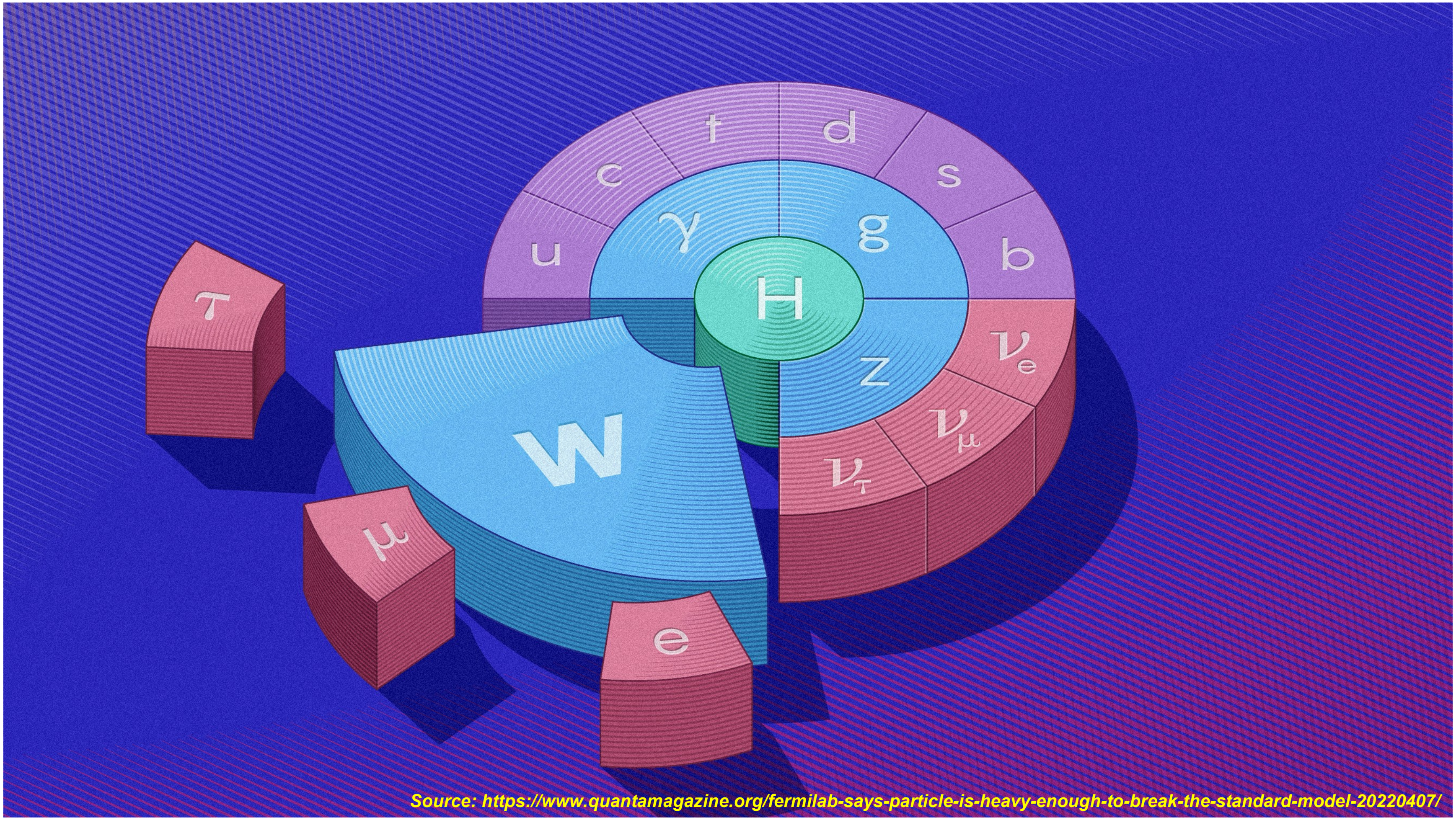




Status W Mass

CDF experiments last word

- W mass too heavy by seven standard deviations !



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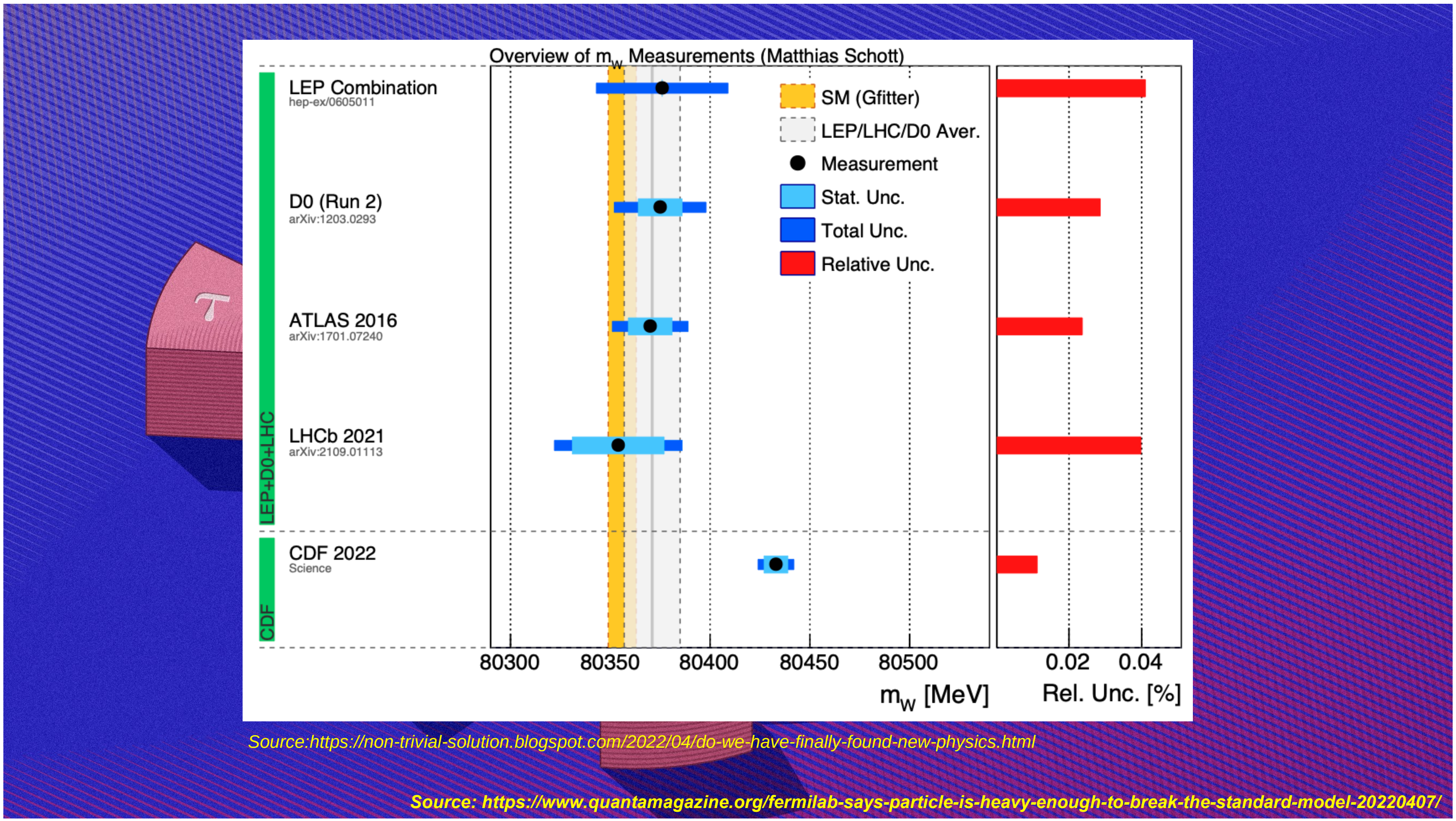
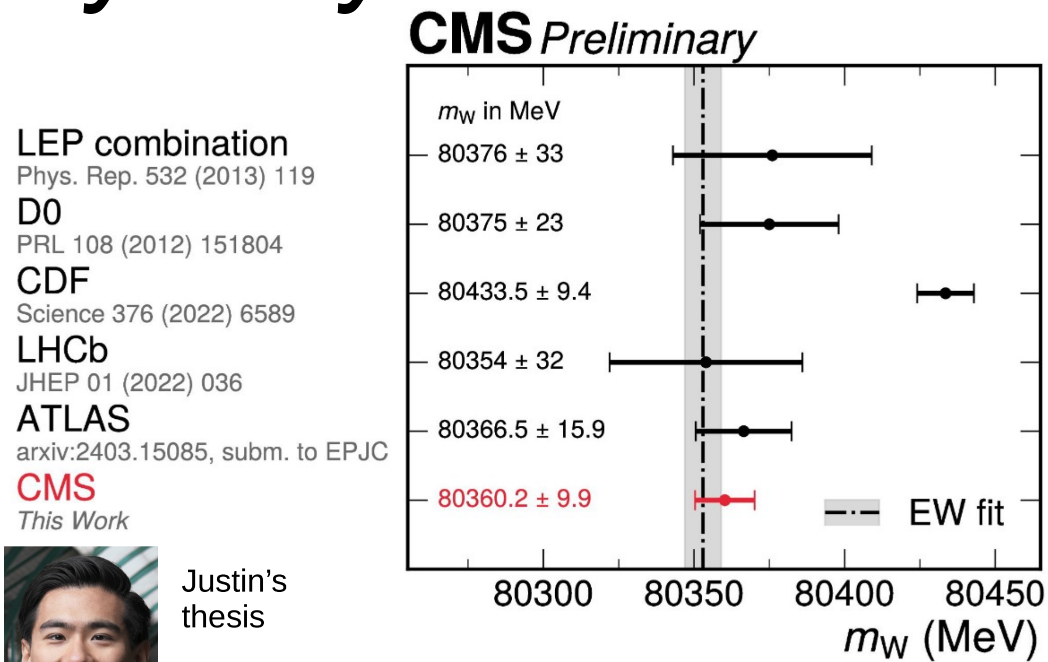


W boson mass mystery resolved

Work of a decade

- CMS finally finished
- Most complex analysis in CMS (arguably!)
- Excellent collaboration by many people
- PPC led the way to the finish line
- An extraordinary result
- Precision unexpected



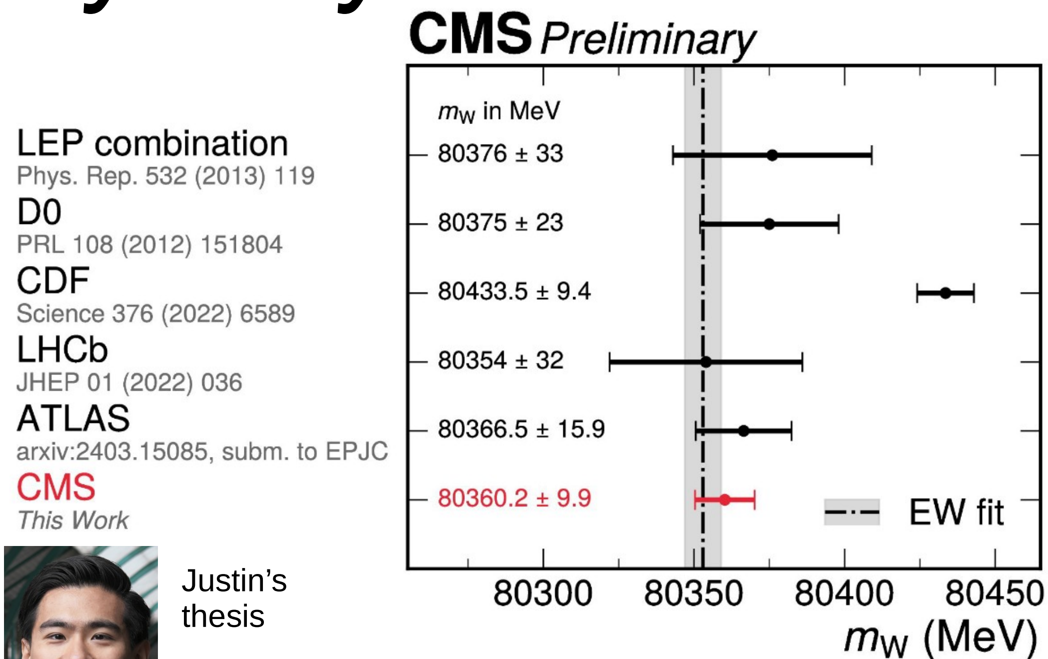
Justin's thesis

What does it all mean?

- Tests self-consistency of the SM
- Resolved tension of CDF measurement
- MIT next step is to further reduce uncertainty, and measure m_Z and α_S
- **New precision era at hadron colliders**

Source of uncertainty	Nominal in m_Z	Nominal in m_W
Muon momentum scale	5.6	4.8
Muon reco. efficiency	3.8	3.0
W and Z angular coeffs.	4.9	3.3
Higher-order EW	2.2	2.0
p_T^V modeling	1.7	2.0
PDF	2.4	4.4
Nonprompt background	–	3.2
Integrated luminosity	0.3	0.1
MC sample size	2.5	1.5
Data sample size	6.9	2.4
Total uncertainty	13.5	9.9

W boson mass mystery resolved



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PDF	2.4	4.4

Δm_Z < 2 MeV ?

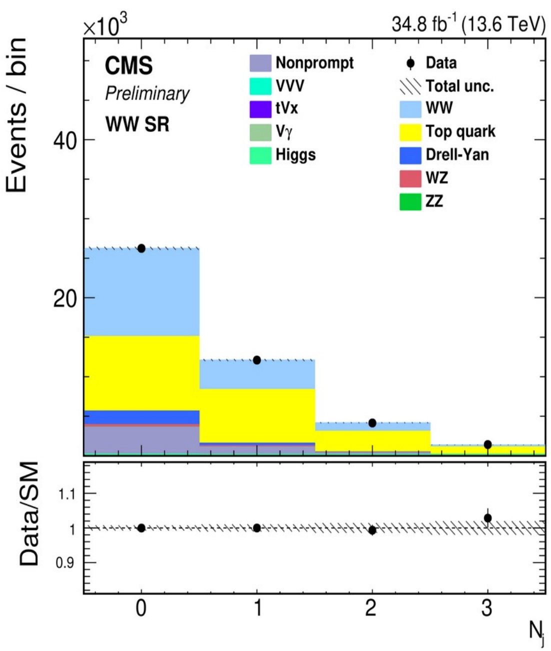
Δm_W<5 MeV

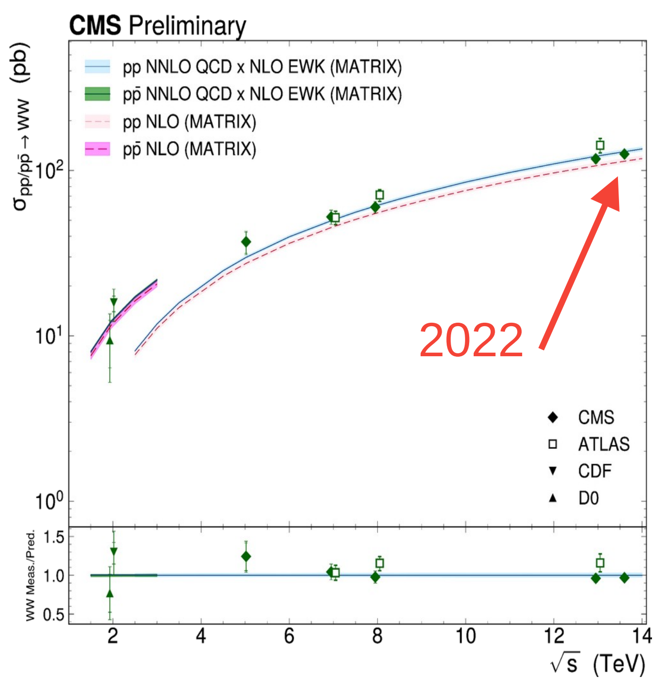
First Run 3 analyses from PPC

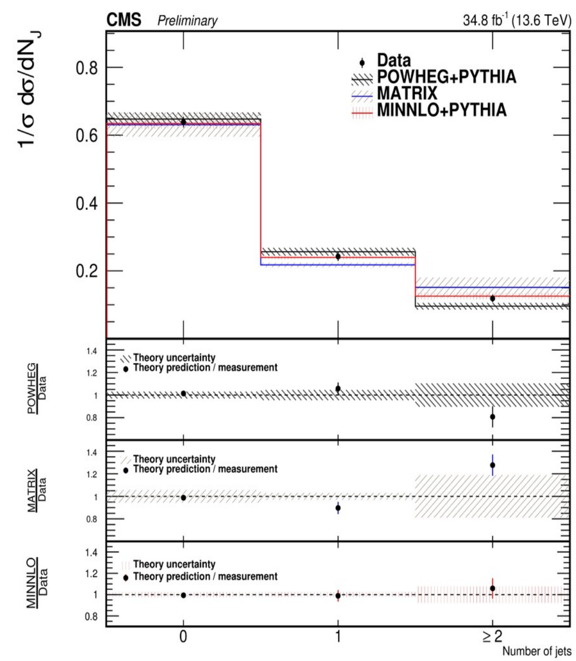
First diboson measurements at LHC in Run 3: $W^+W^- \rightarrow e\nu\mu\nu$

- ~35 fb^{-1} of CMS data collected in 2022, and publ. in PLB → **record time**
- electron-muon events split by lepton charges, the number of jets, and number of jets identified as originating from b quarks
- **PPC low level contribution: Essential to debug the Run 3 CMS detector**

Inclusive cross section: 125.7 ± 5.6 pb agrees with predictions







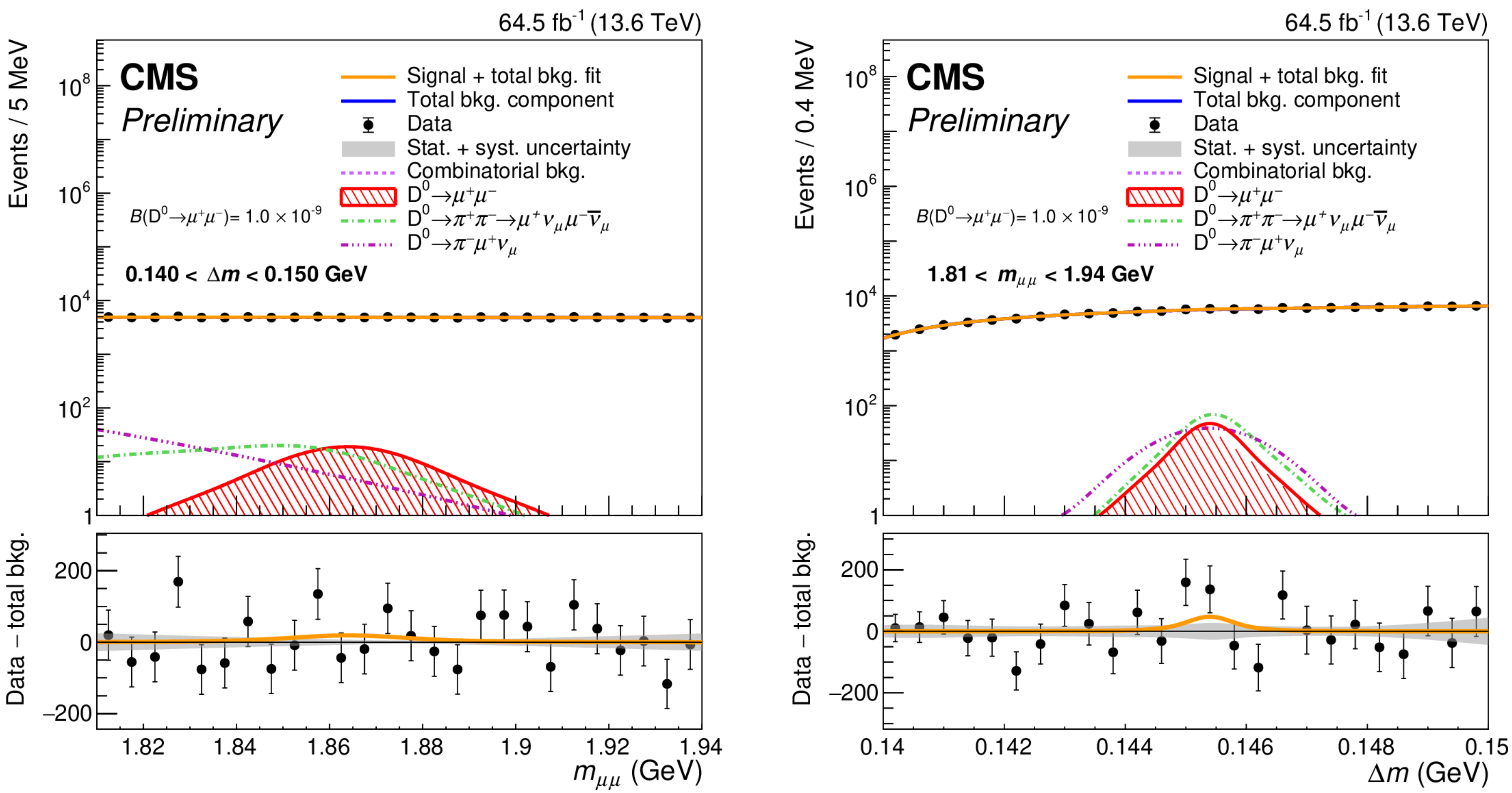
First Run 3 analyses from PPC

World best limit

$$(D^0 \to \mu + \mu -)) < 2.6 \times 10^{-9} \text{ at } 95\% \text{ C.L.}$$

Most stringent limit on flavor-changing neutral currents in charm sector, set additional constraints on new physics models that modify the decay branching fraction of *D0→μ⁺μ⁻*.

Low level PPC work: overhauled low momentum muon trigger and reconstruction



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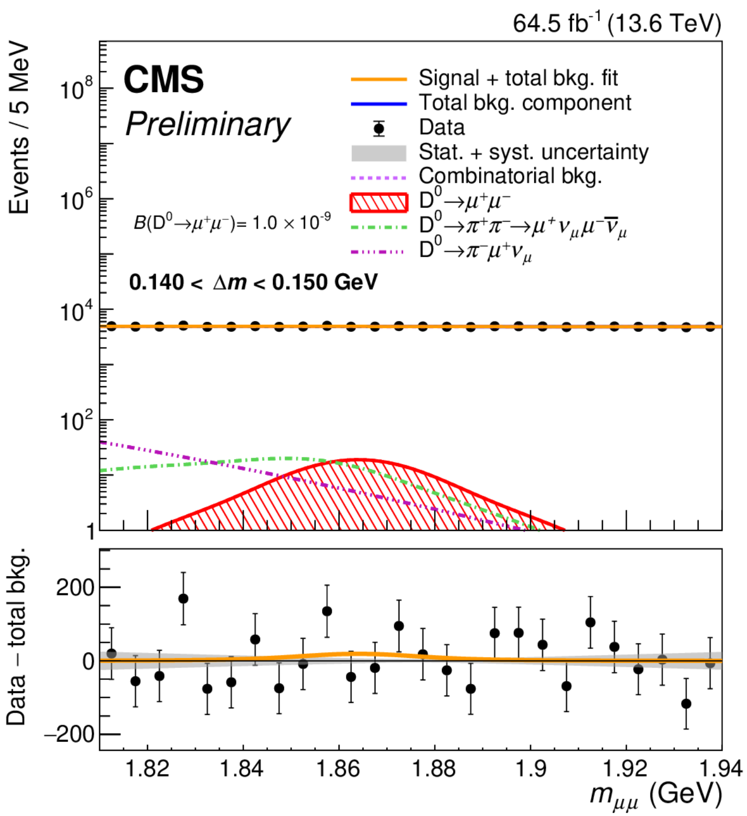
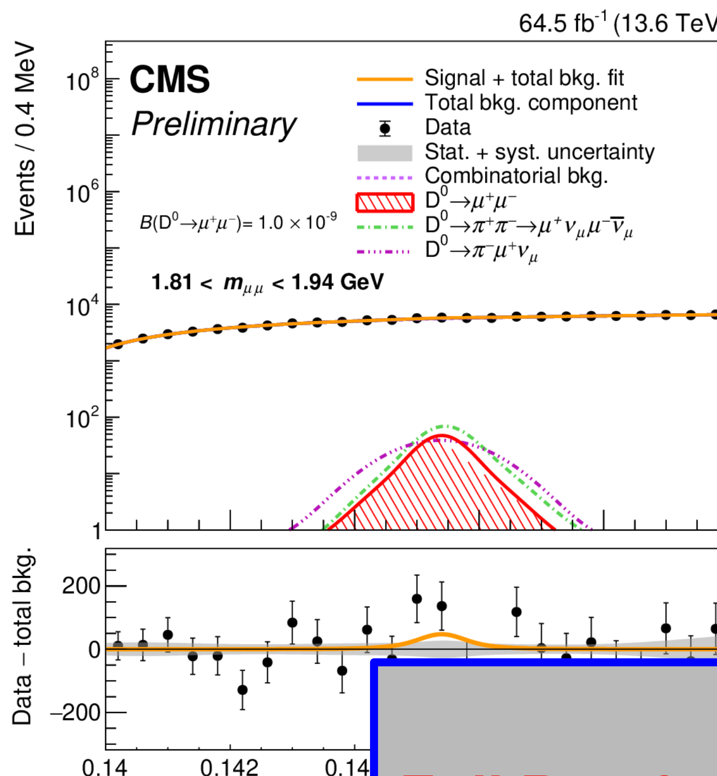




Full Run 3 data

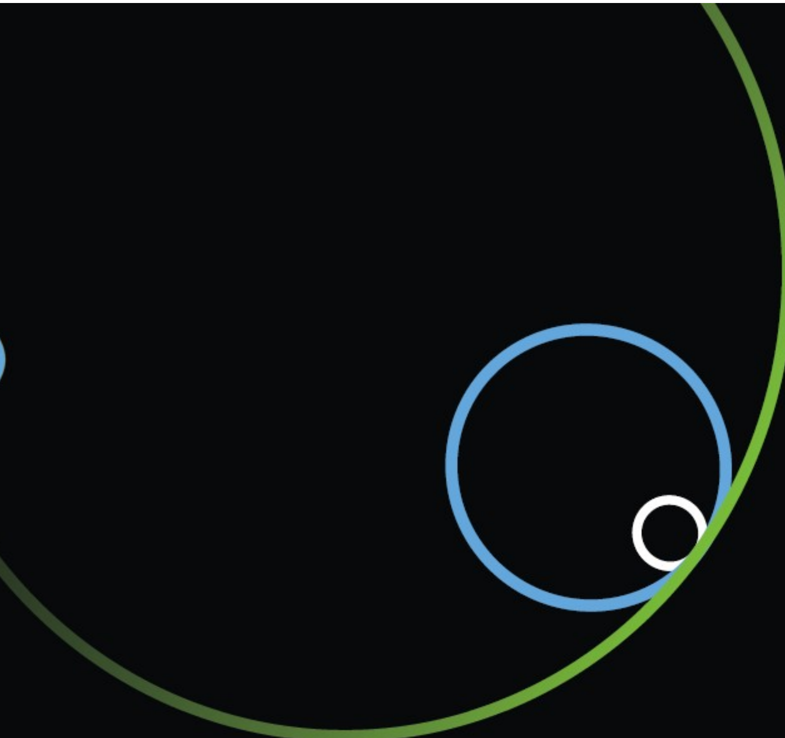
BPH-23-008, submitted to PLB

Future of The Energy Frontier

- **Future Circular Collider (FCC)**
  Circumference: 90 -100 km
  Energy: 100 TeV (pp) 90-350 GeV (e^+e^-)

- **Large Hadron Collider (LHC)**
  Large Electron-Positron Collider (LEP)
  Circumference: 27 km
  Energy: 14 TeV (pp) 209 GeV (e^+e^-)

- **Tevatron**
  Circumference: 6.2 km
  Energy: 2 TeV ($p\bar{p}$)



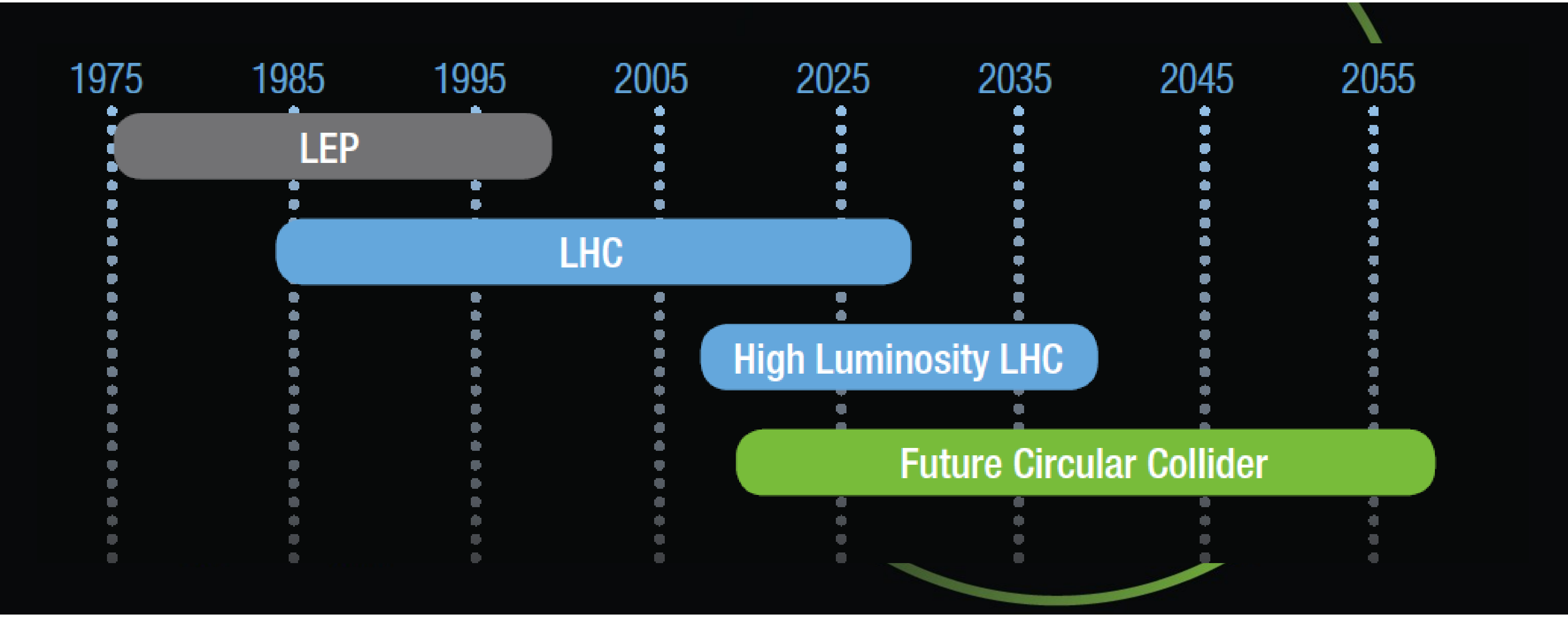
Precision measurements of Z, W, Higgs boson & top quark physics

- 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

- Will work with Gian Michele Innocenti who is constructing a lab for the EIC and beyond *(see next presentation)*

Future of The Energy Frontier



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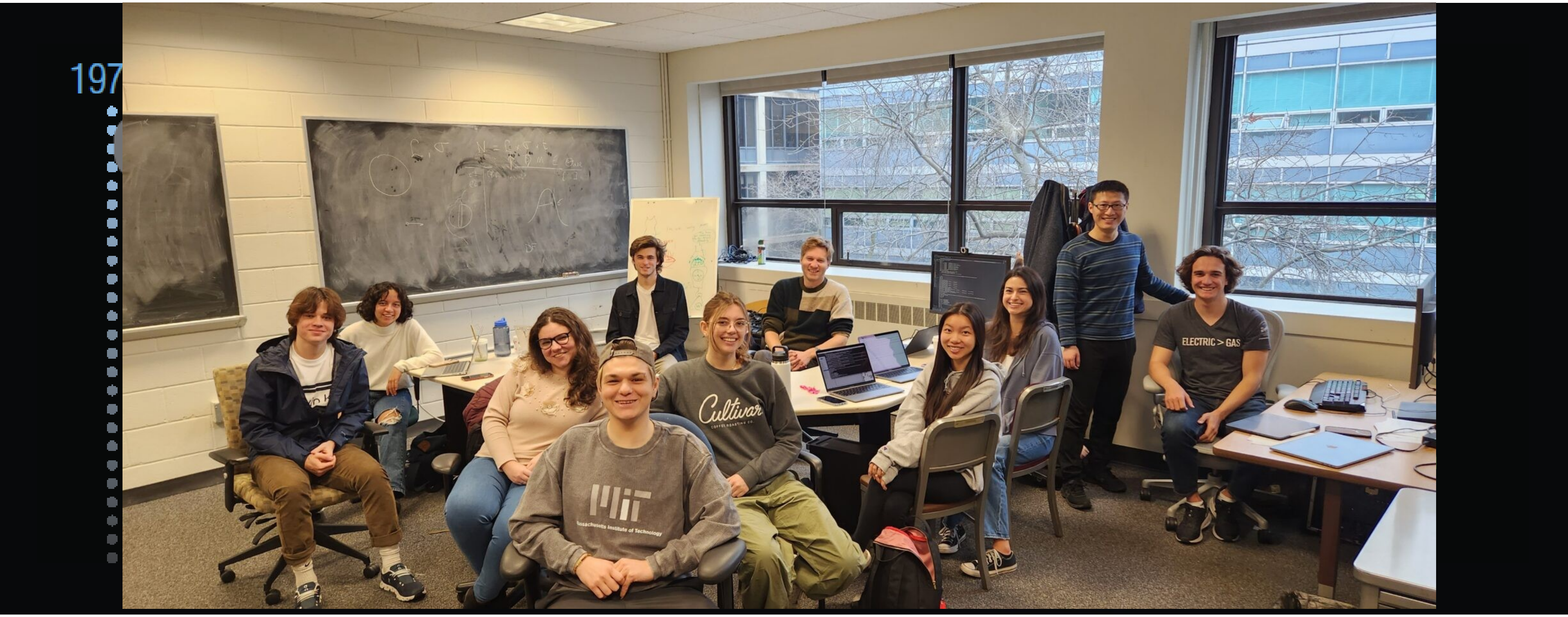

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Higgs Rare Decays

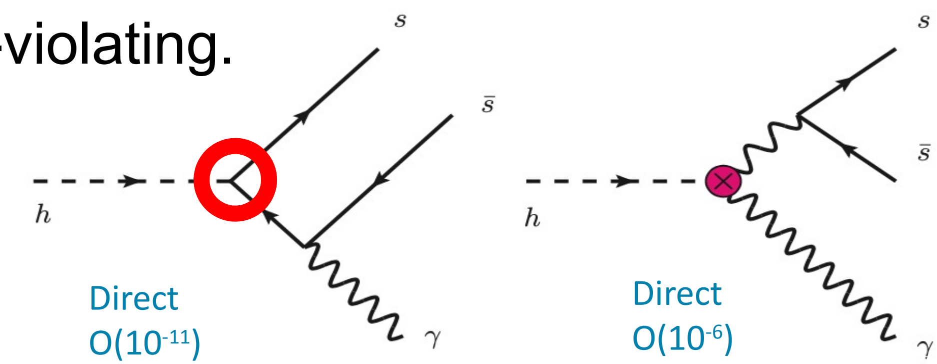
The exclusive hadronic decays $H \to$ ***Mγ***, (also $H\to$***MZ*** and $h\to$***MW***)

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.

$\mathcal{B}$ ($H \to M\gamma$) ~ $10^{-6} - 10^{-10}$

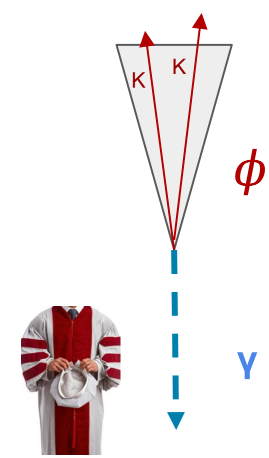
in comparison $\mathcal{B}(H \to \mu\mu) \approx 2.2 \times 10^{-4}$



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

First public results just published a few month ago

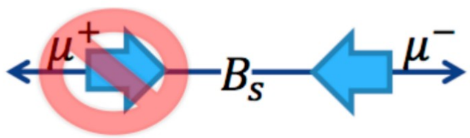
- Run 3: implement quasi real time analysis with new HLT capabilities
- Meson reconstruction with new ML techniques to increase efficiency are a must
- Any other channels?

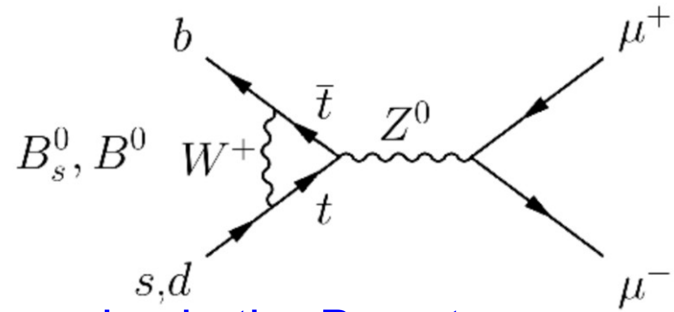


Search for $B_{s,d} \to \mu^+\mu^-$

B decay through effective FCNC in Standard Model → rare

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





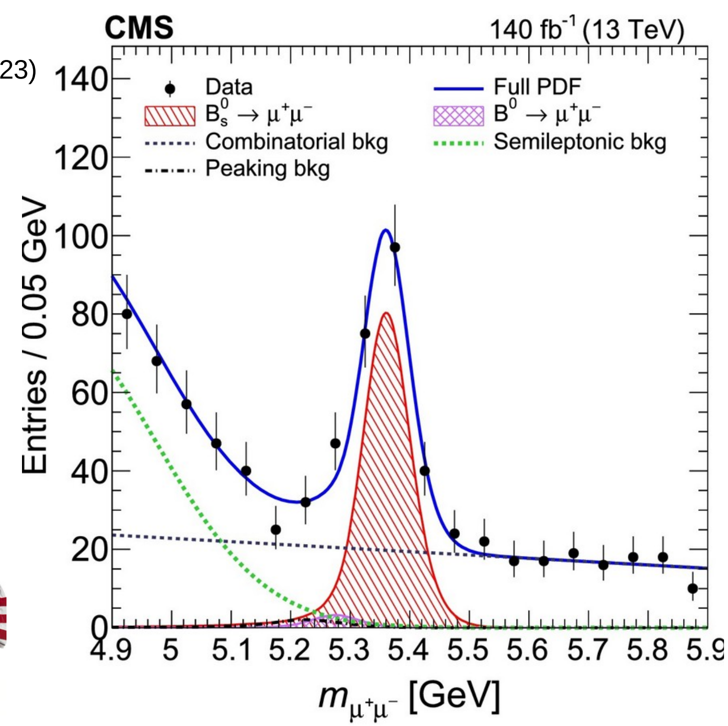
- Could cast some light on the present discrepancies in the B sector
  - 3 std LFU violation in R(K) and R(D*), 2-3 std discrepancies in branching ratios

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 K_S search are on their way, B_d might be in reach



Dark Photon → μ μ Search

Search for a prompt dark photon resonance in dimuon final state

- scouting data: 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 developed: improved sensitivity at low mass / scouting

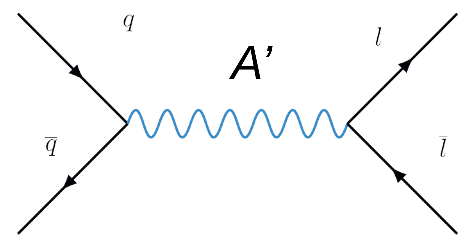
Result interpreted in Hidden Abelian Higgs Model and 2HDM+S.

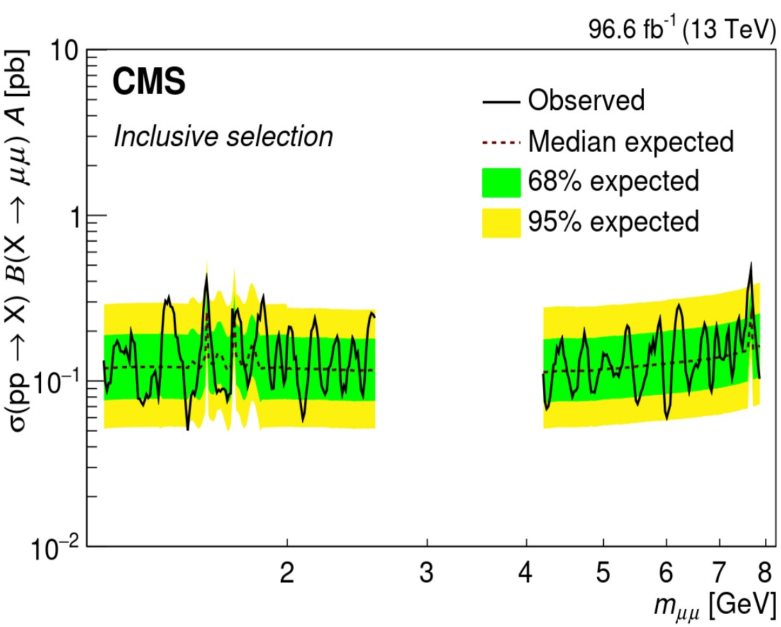
- Sensitivity exceeds Babar/LHCb results, just a little

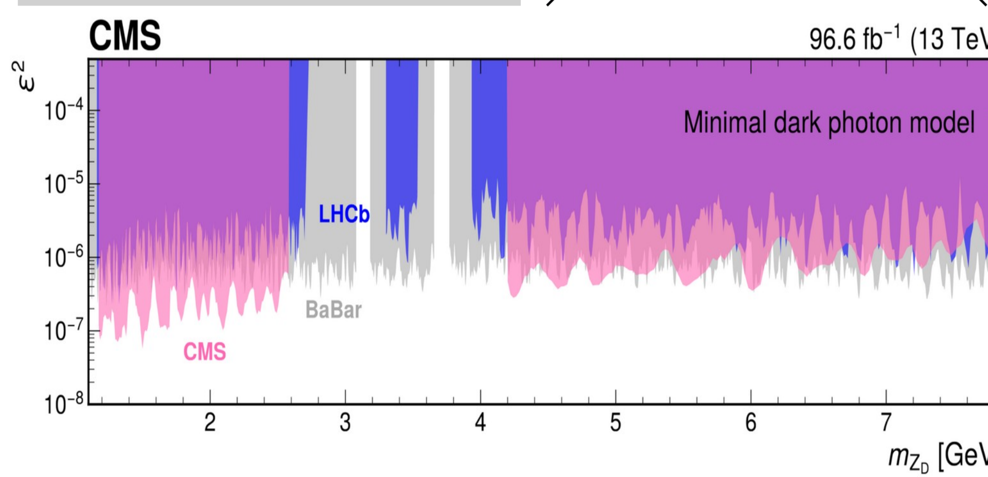
For Run 3

- Substantial improvements in trigger, no more scouting

Full Run 3 data







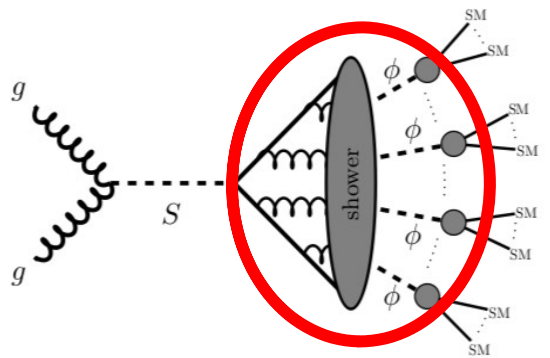
Soft Unclustered Energy Patterns (SUEPs)

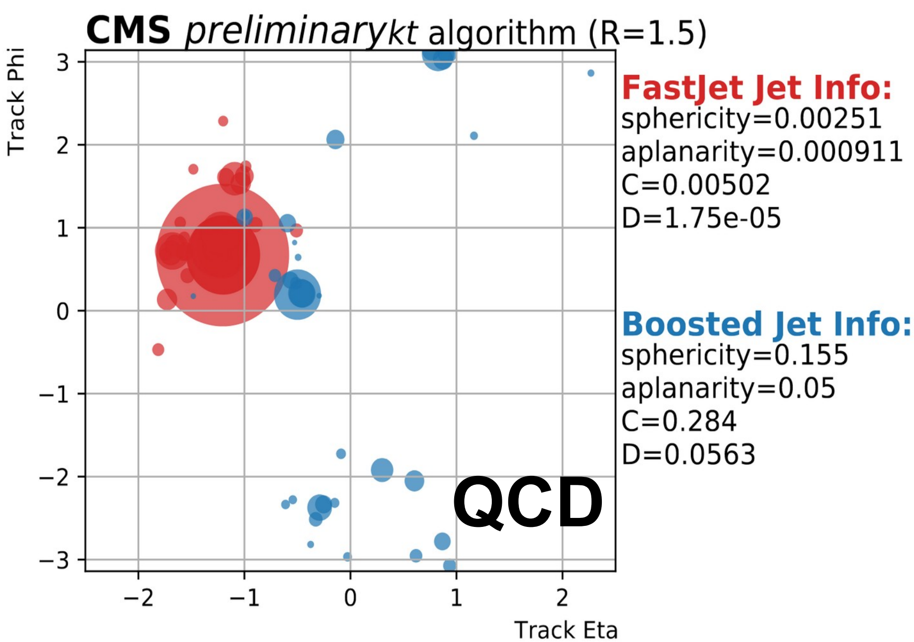
No WIMP at LHC → explore more complex DM scenarios: e.g. dark strong dynamics

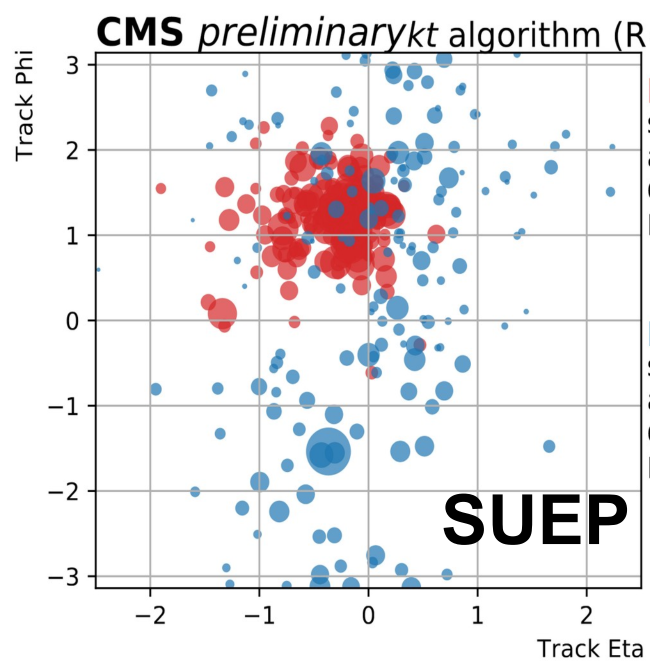
Strongly coupled hidden valleys through high-multiplicity decays of new heavy scalar mediators

- 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



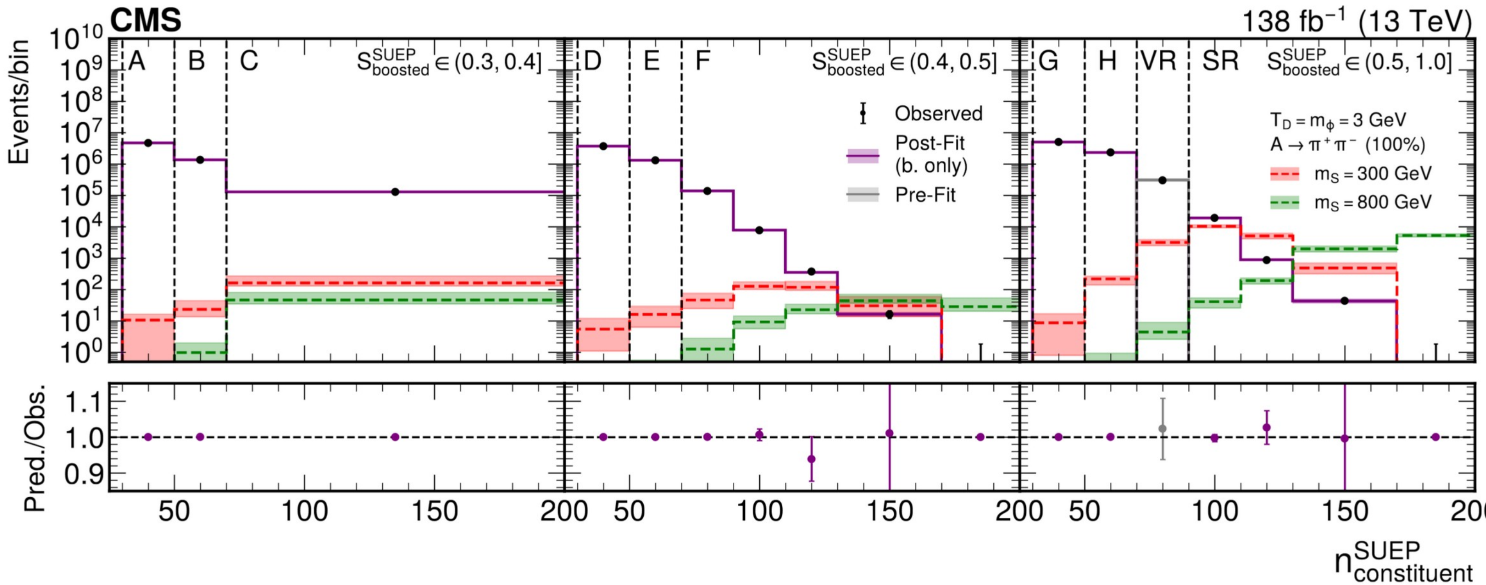




Full Run 3

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



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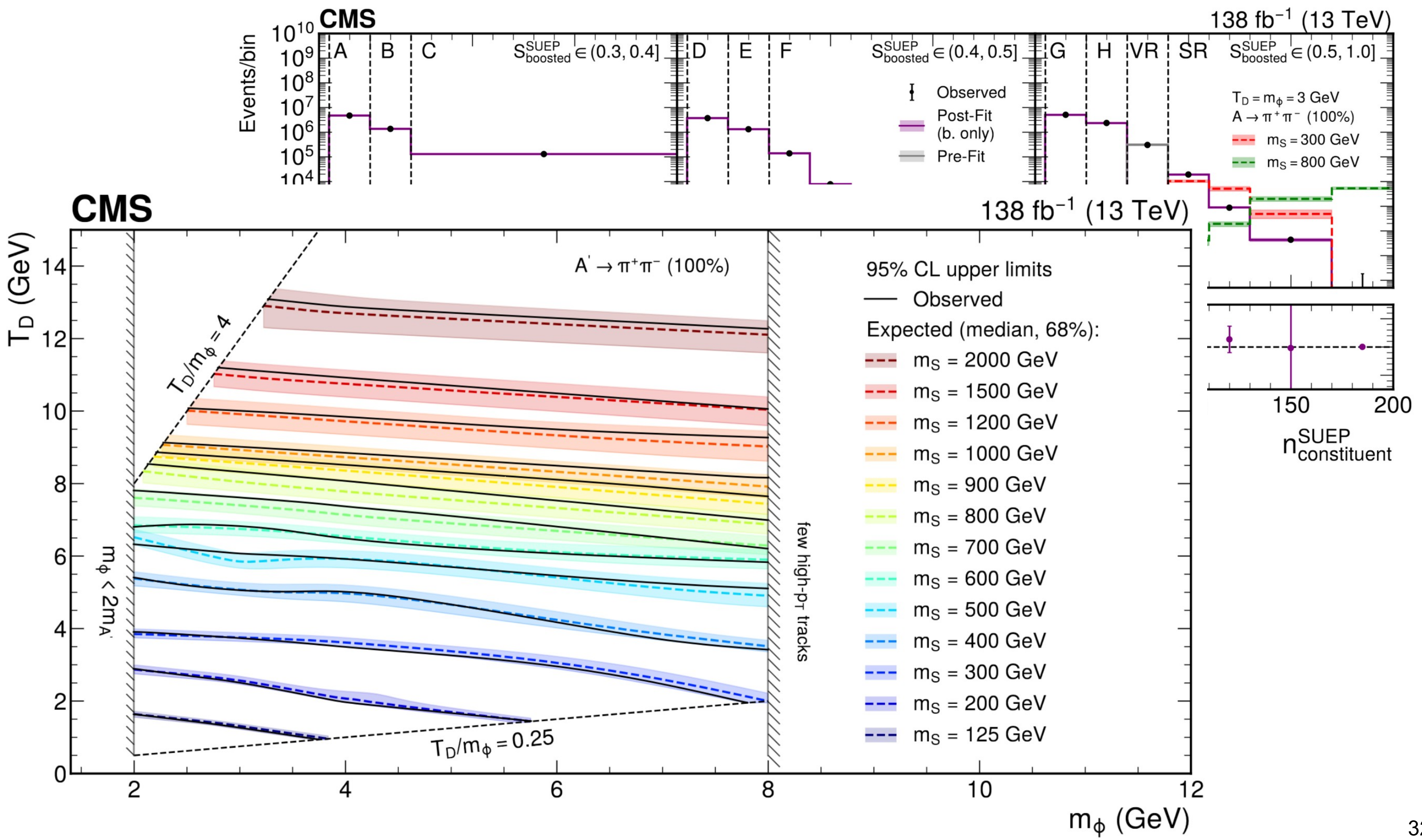

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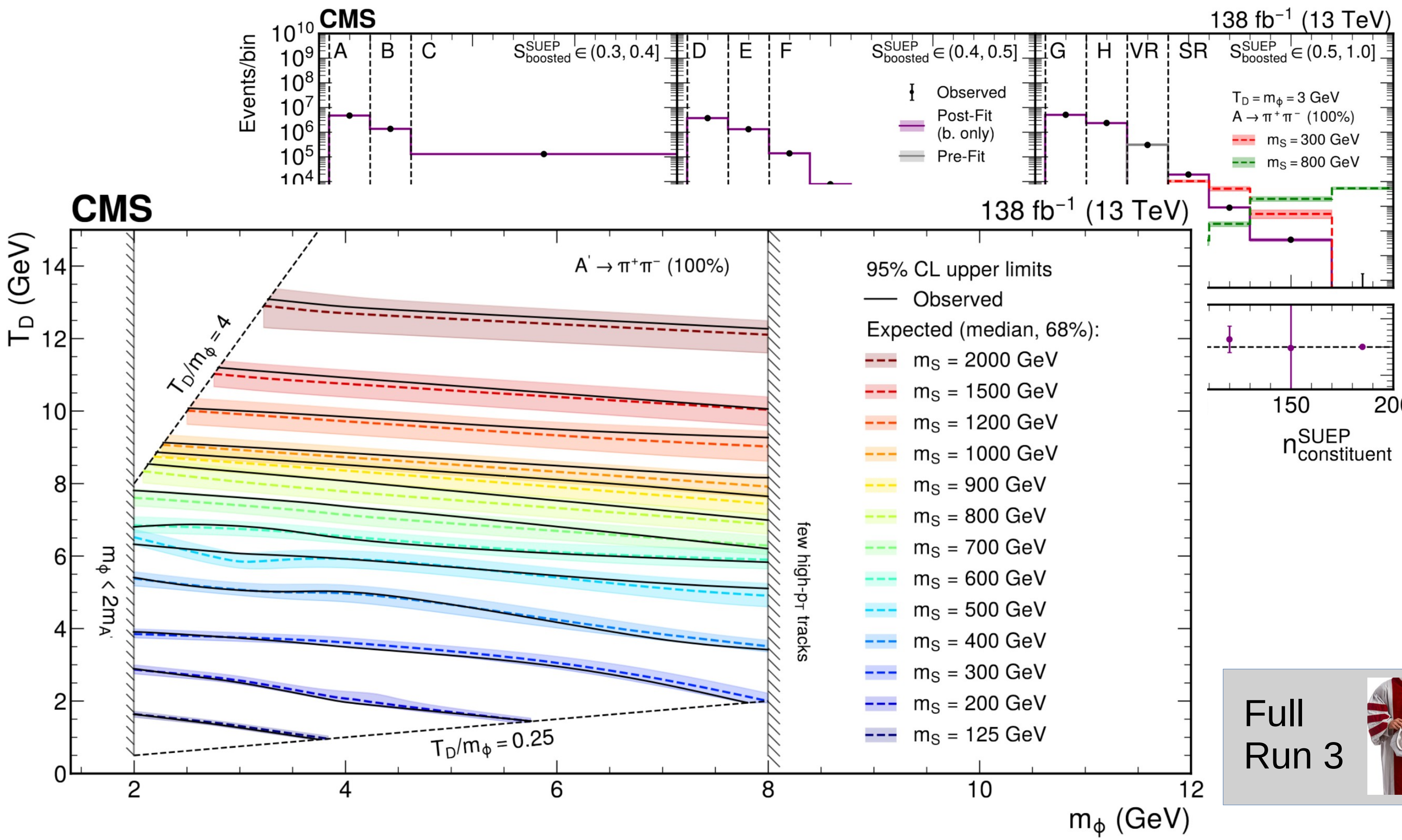

Full Run 3

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
- Invent your own thesis on CMS data
- Software, Computing, Trigger, DAQ, and Detector projects offer a lot valuable experience

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

PPC has strong leadership in CMS detector and physics organization

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

8% **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