The LHC and the CMS experiment at CERN

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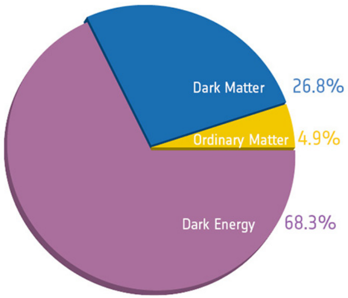
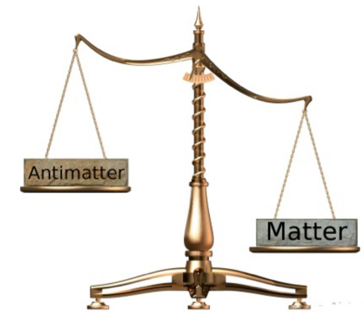
57th Fermilab Annual Users Meeting

July 2024

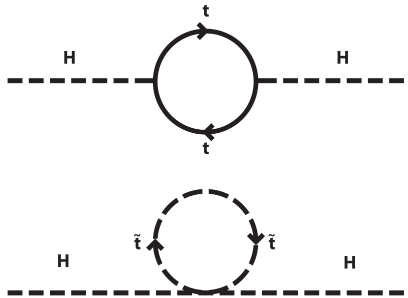
The big open questions in Particle Physics

- Experiment – driven
  - Dark Matter
  - Dark energy
  - Matter-Antimatter asymmetry
  - …



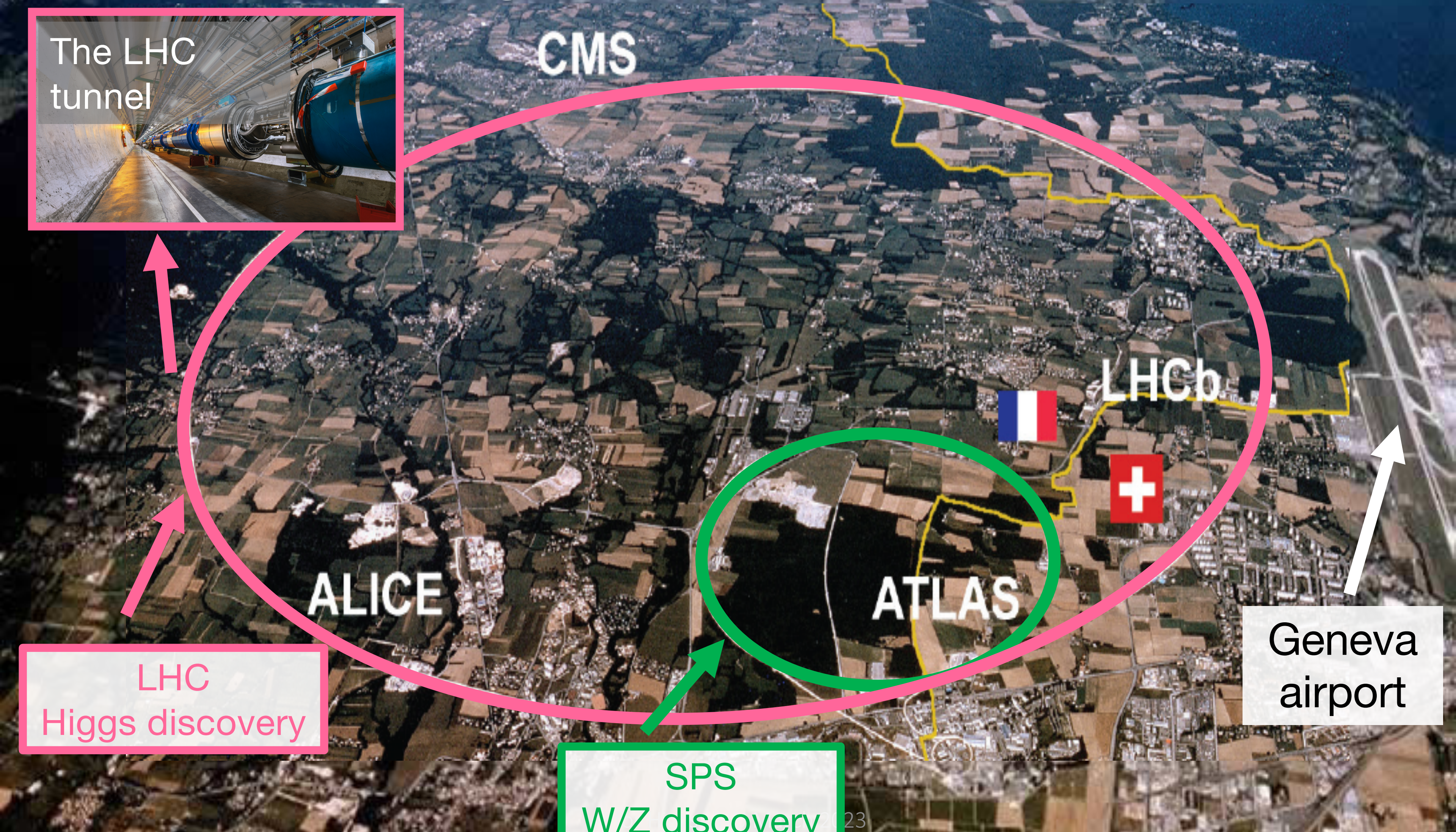


- Theory – driven
  - Hierarchy problem & naturalness
  - Number of generations
  - Origin of fermion families
  - …



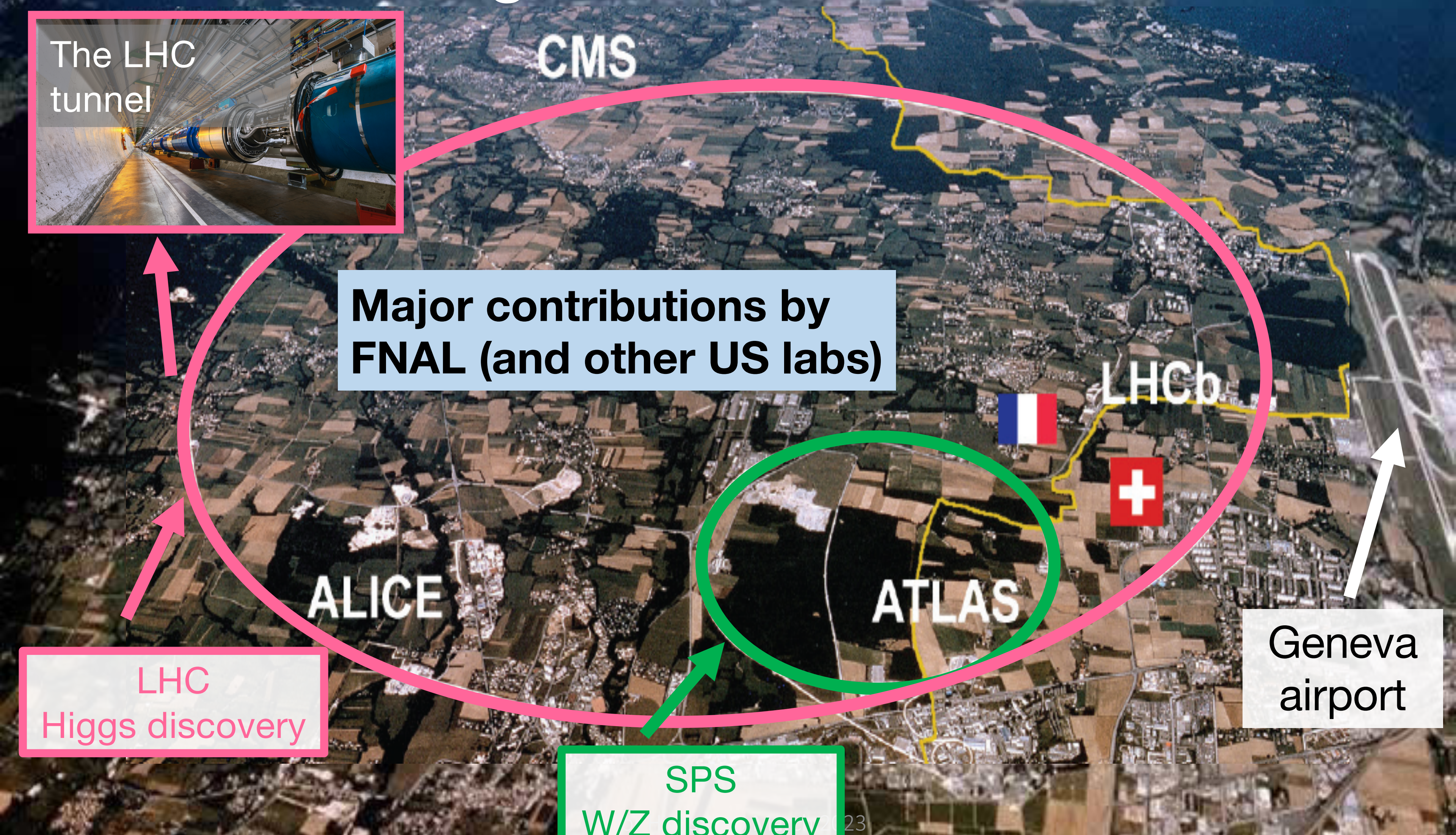
All beg for New Physics
At which Scale?

The tool: Large Hadron Collider at CERN



The tool: Large Hadron Collider at CERN

Major contributions by FNAL (and other US labs)



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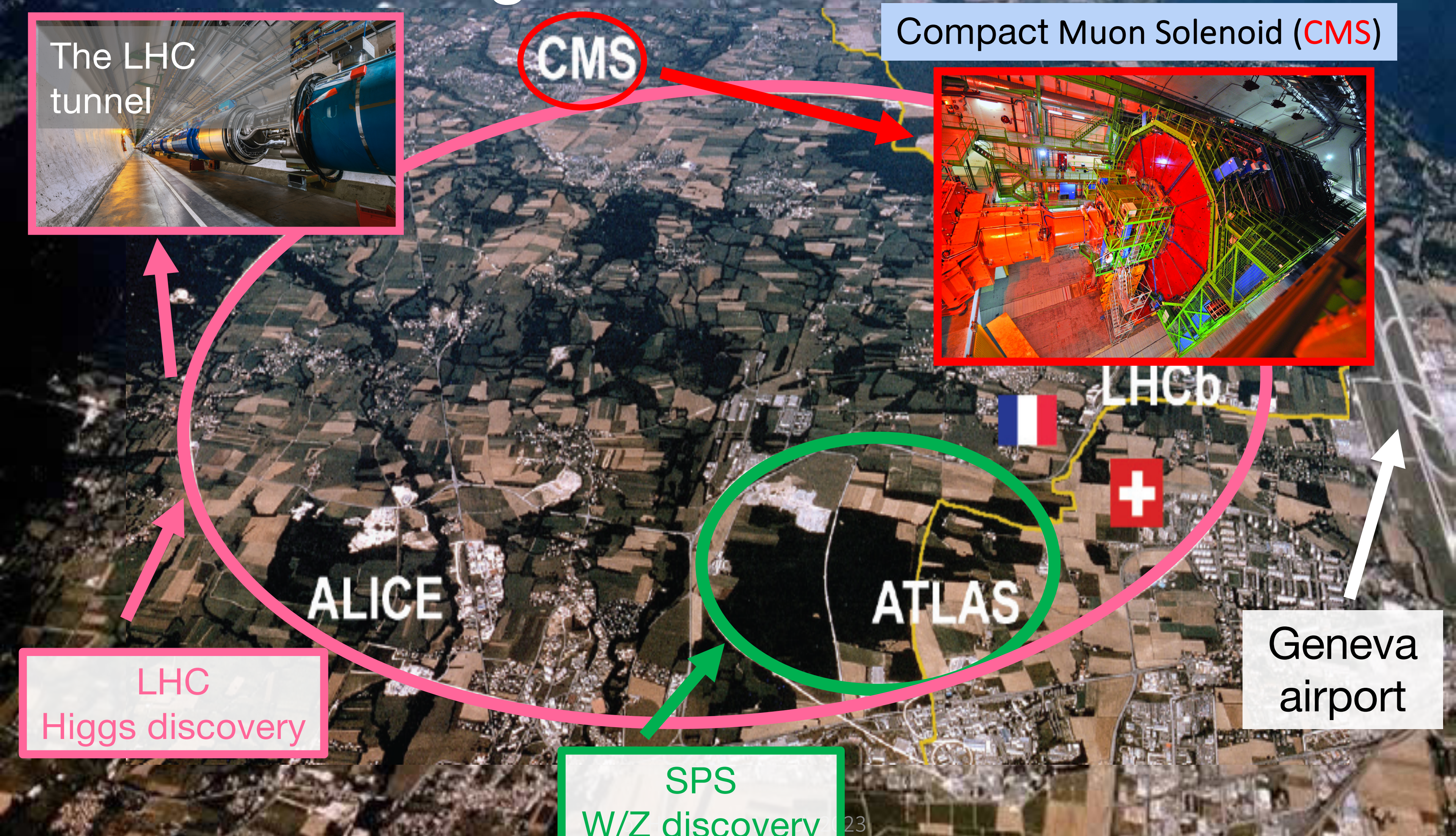
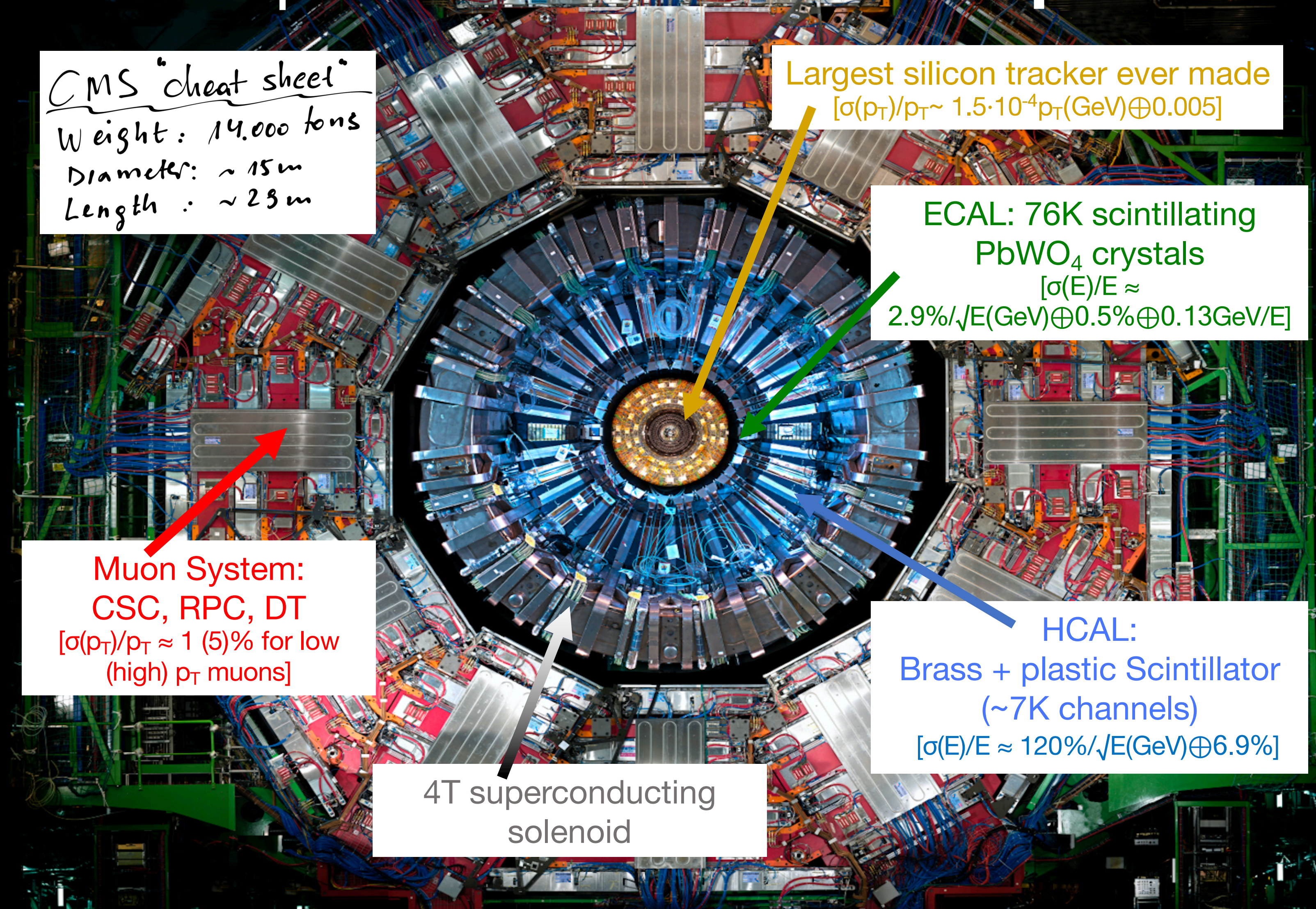


The Compact Muon Solenoid experiment

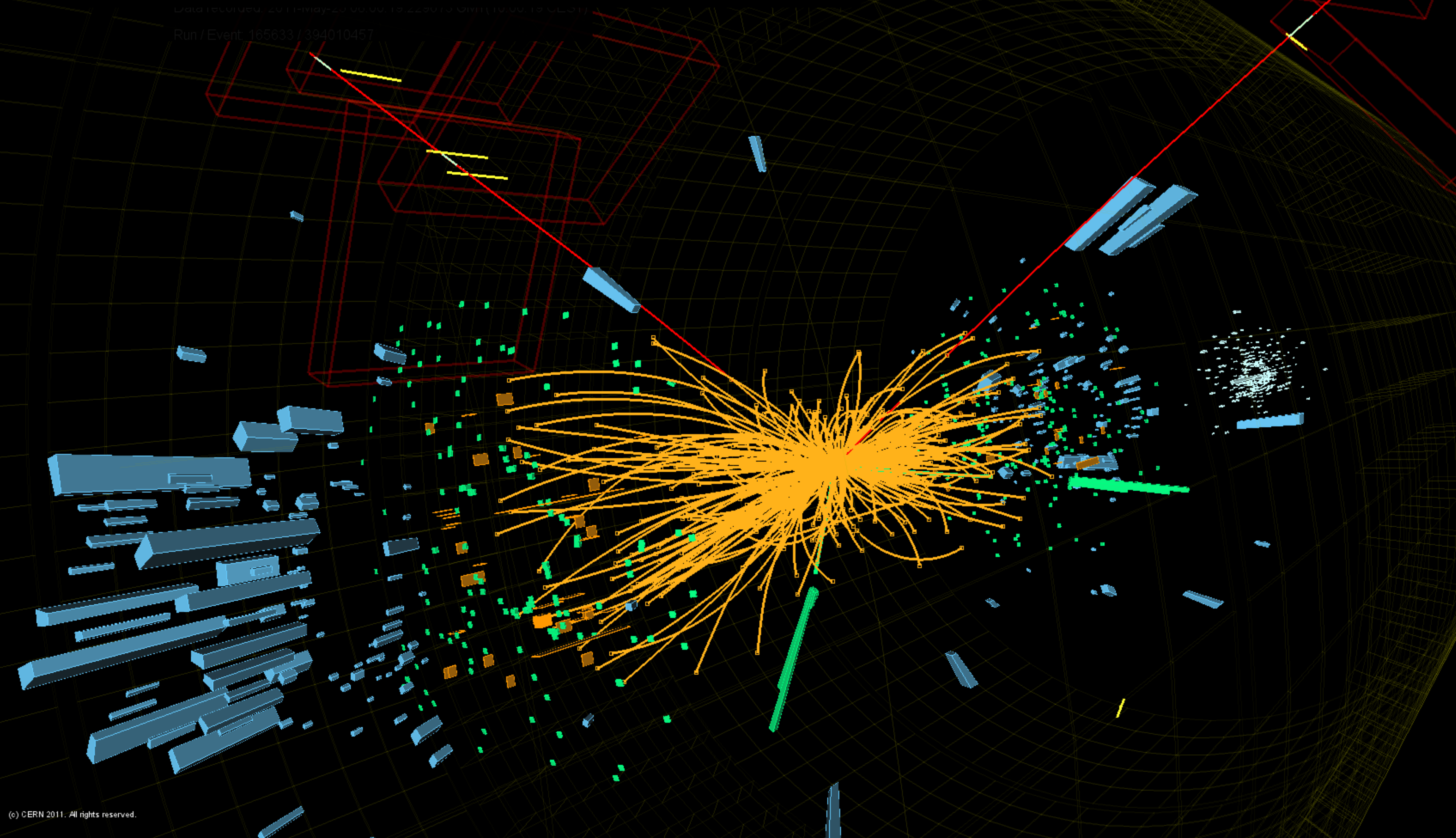


The Compact Muon Solenoid experiment

- **CMS Collaboration:** >3K members (scientists, engineers, students, ..) from more than 200 (60) institutes (countries)
- **US CMS:** >30% of the collaboration
- **Fermilab:** only US-lab in CMS

Fermilab (and US institutes in general) have been playing a leading role in all aspects of the experiment
[detector, computing, operations, data analysis..]

A collision event at CMS



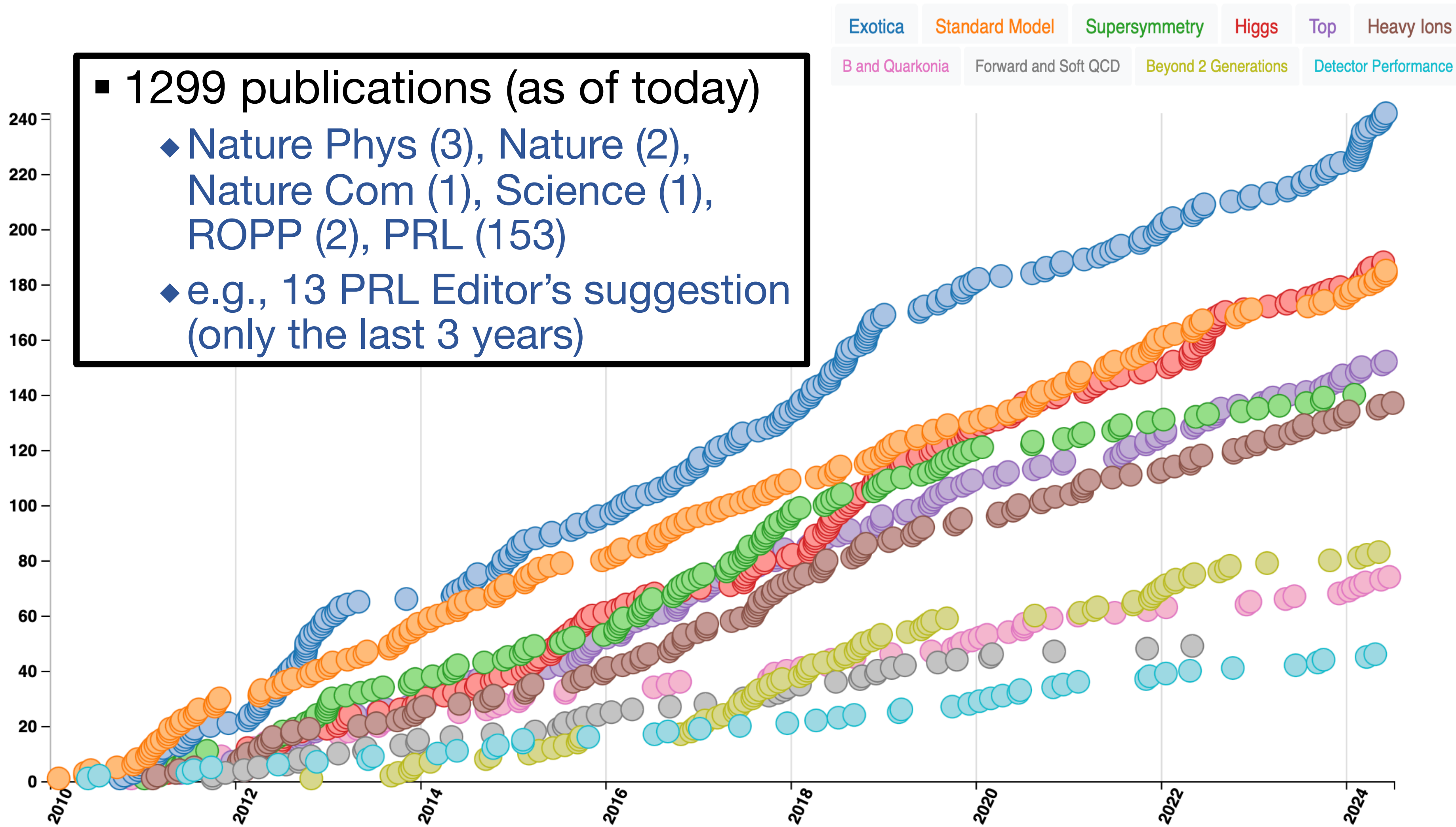
A collision event at CMS

Looking for New Physics

- Two complementary approaches
  - **Direct searches** for new particles/interactions
  - **Sensitive tests of the SM** and look for deviations

Very reach physics program

- 1299 publications (as of today)
  - Nature Phys (3), Nature (2), Nature Com (1), Science (1), ROPP (2), PRL (153)
  - e.g., 13 PRL Editor's suggestion (only the last 3 years)



This year's theme: Inspirations from P5

- Priorities in particle physics:

Elucidate the Mysteries of Neutrinos	Search for Direct Evidence of New Particles	Determine the Nature of Dark Matter
Reveal the Secrets of the Higgs Boson	Pursue Quantum Imprints of New Phenomena	Understand What Drives Cosmic Evolution

- Ingenuity and innovation:

> New detectors, such as picosecond-precision timing detectors, and forward tracking and extended trigger systems, will enable searches to better target new physics with challenging signatures. Alternative data-taking strategies and novel analysis techniques leveraging advances in AI/ML (for example, anomaly detection) will provide access to parameter space that is currently unexplored.

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LHC and it's upgrades extremely well-placed

- Ingenuity and innovation:

CMS upgrade for HL-LHC

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Run2, Run 3 and HL-LHC

Ingenuity and innovation

- i.e., How to maximize:

$$\mathcal{N} = \sigma \times \mathcal{L} \times \mathcal{A} \times \epsilon$$

- **Cross-section:** of a given process [∝ collision energy]
- **Luminosity:** ~linear increase vs. time
  →sensitivity ~ sqrt{L}; Help rare processes
- **Acceptance:** improvement mainly from new/upgraded detectors
- **Efficiency:** Trigger, Phys. Object reconstruction & ID, Sig-vs-BKGs, …

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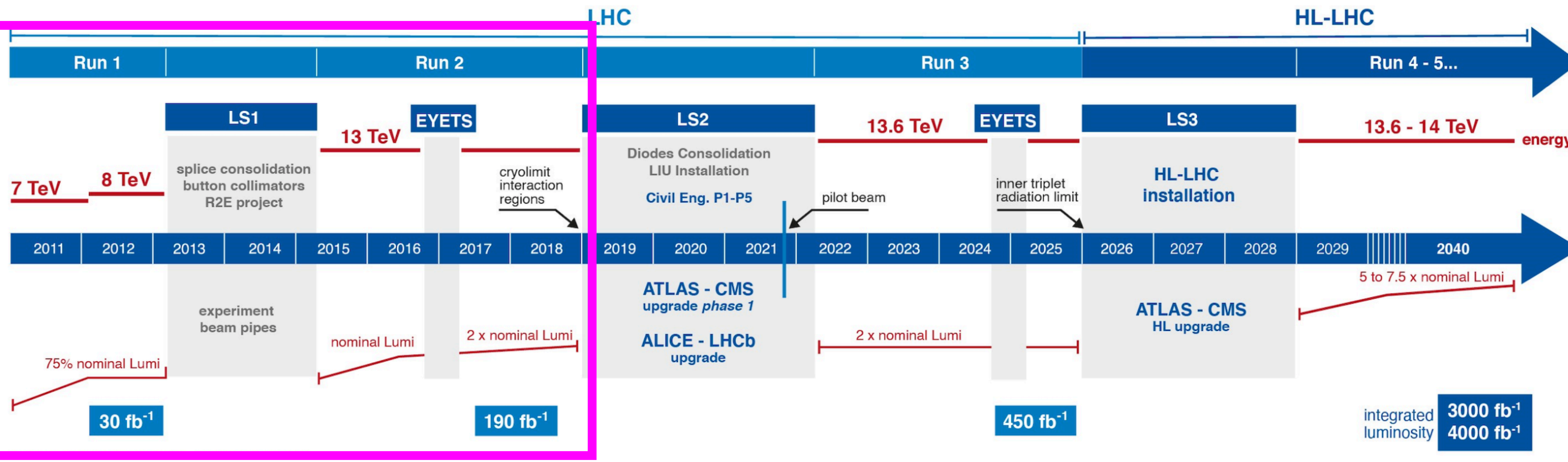
Requires breakthroughs in both
the **accelerator** and **experiments** fronts [and theory]

- Today’s talk
  - Cherry-pick areas/topics that we went “above-and-beyond”
    - and FNAL/US communities played a major role
  - Physics landscape after LHC Run 2
  - Run 3 expectations and new results [LHC & CMS]
  - Short-term future: HL-LHC

The past: Highlights from LHC Runs 1& 2

Highlights: Runs 1& 2

- Remarkable success



Highlights: Runs 1& 2

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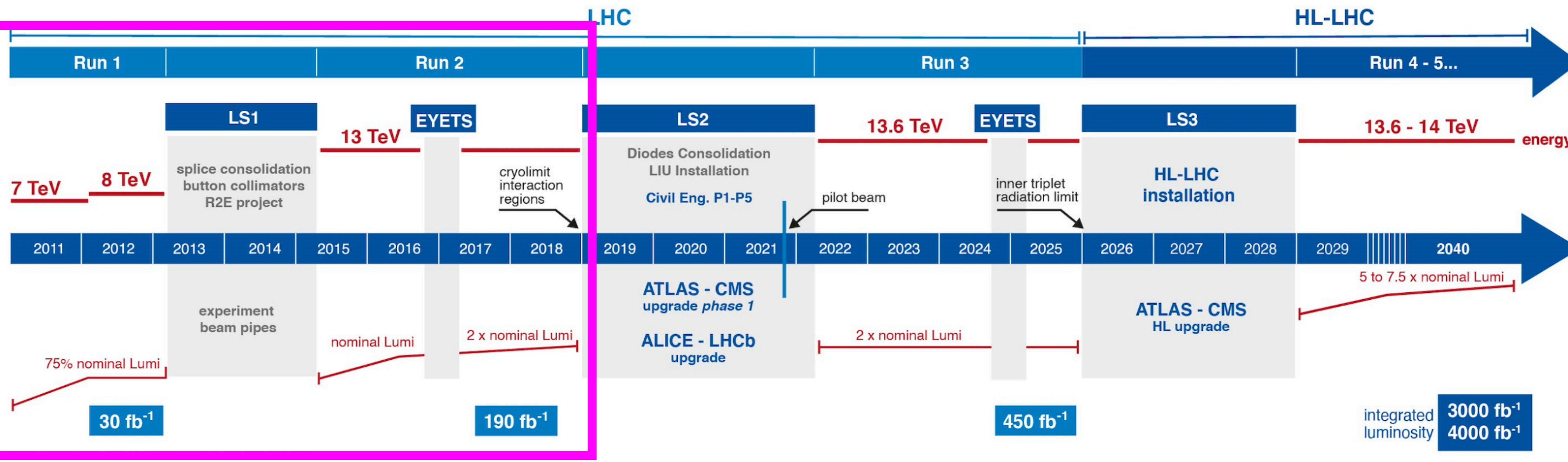

- FNAL/US: major contributions
  - In several areas (particularly focusing magnets)

Highlights: Runs 1& 2

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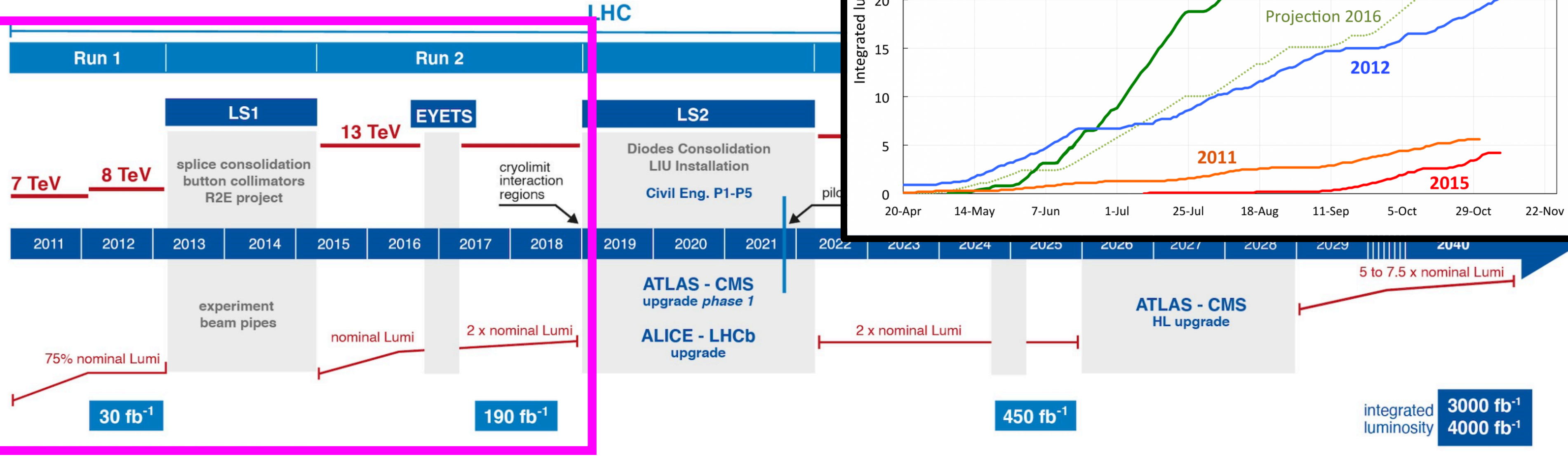
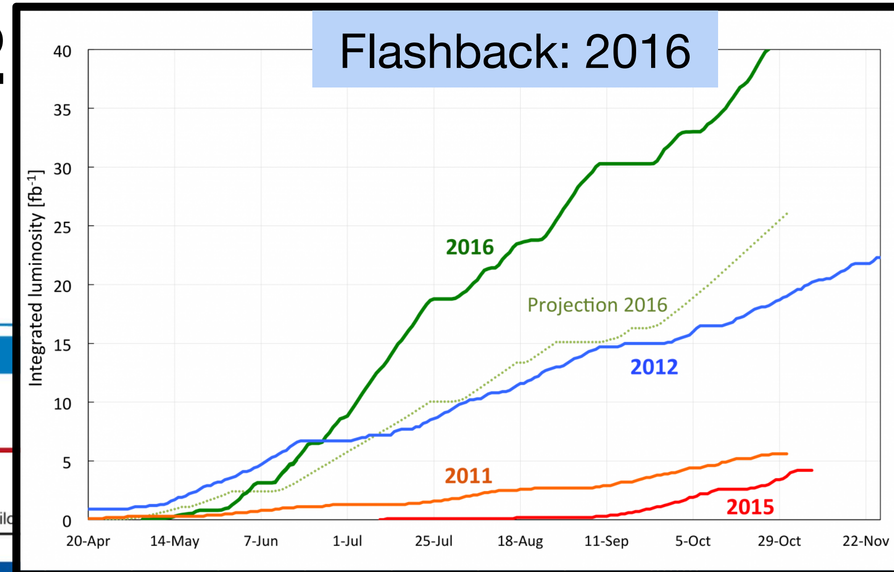
  - often exceeding expectations





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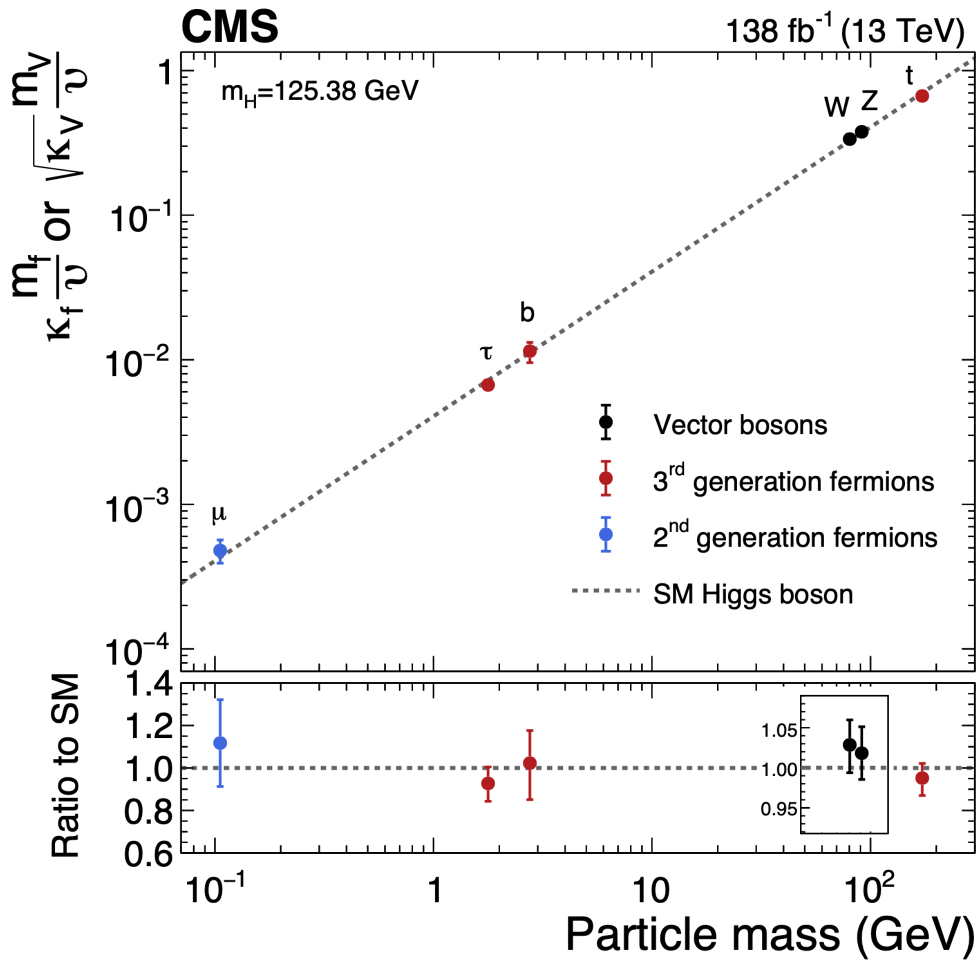
LHC Run 2:
20x more Int. Lumi than all previous hadron colliders

Highlights: The Higgs as exploration tool



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  - 3rd-Gen charged fermions

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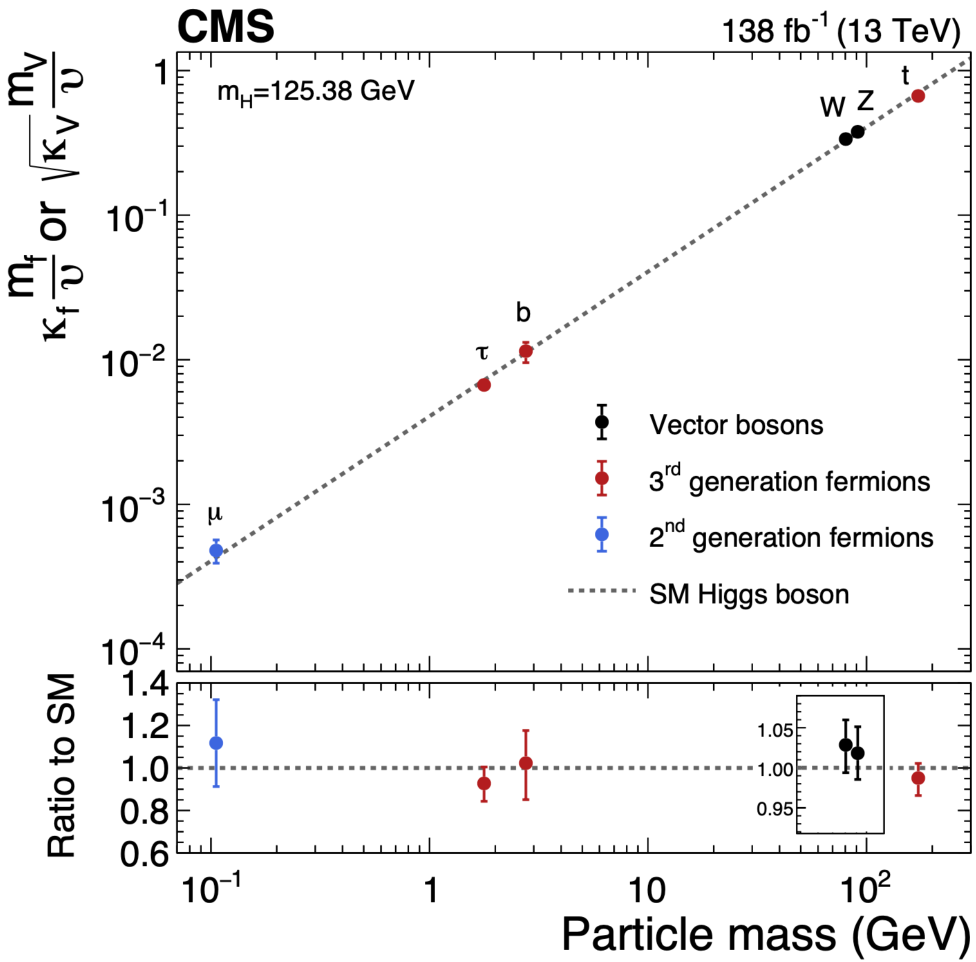

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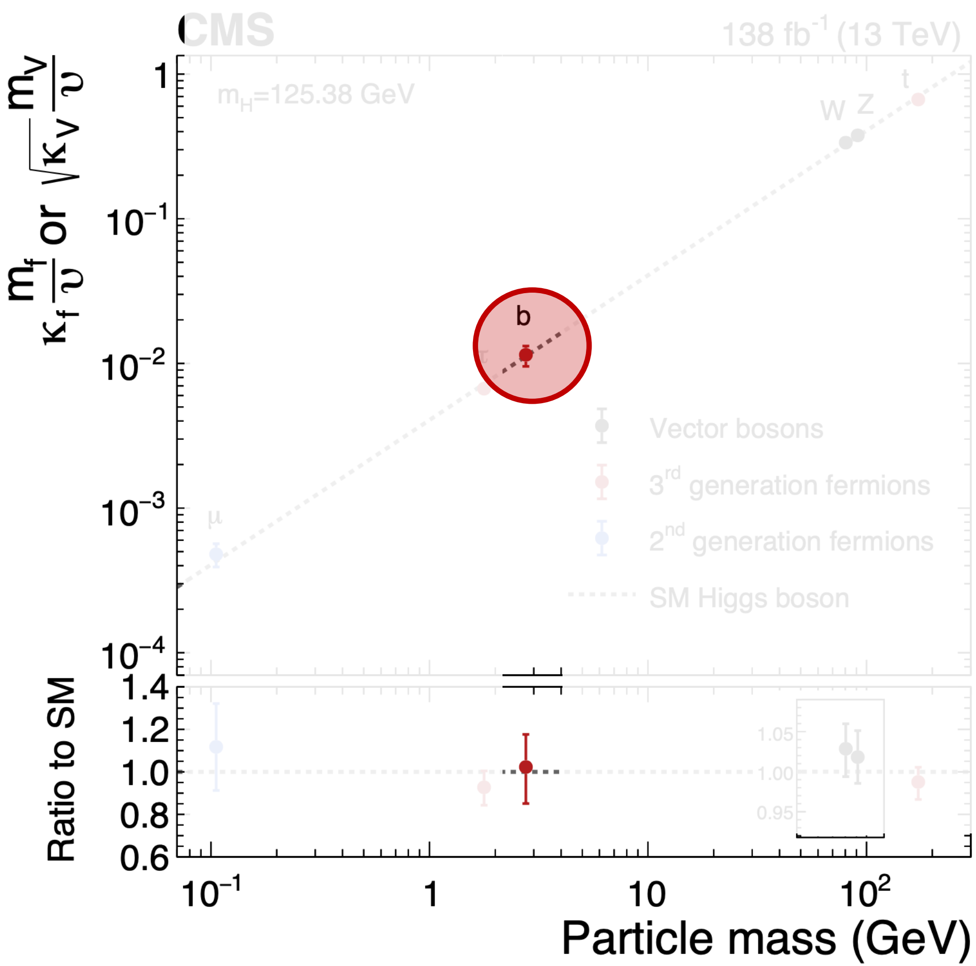
- **Evidence** for 2nd-Gen charged leptons
- + CP, differential measurements, STXS, EFT,..

Novel tools & techniques (e.g., AI/ML) played major role to reach this stage

Reminder: Far from trivial



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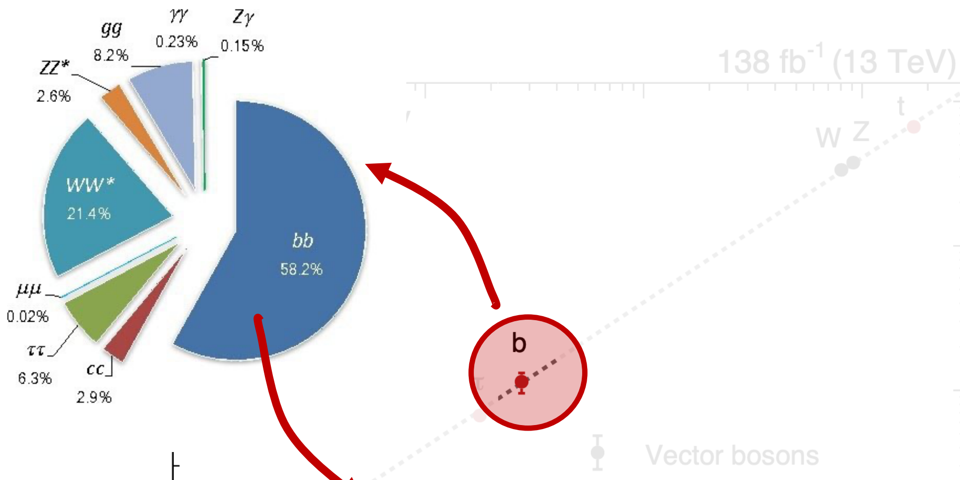

ATLAS Technical Design report (1999)
- feeling not different in CMS

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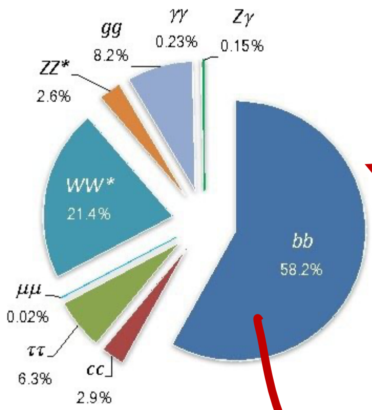

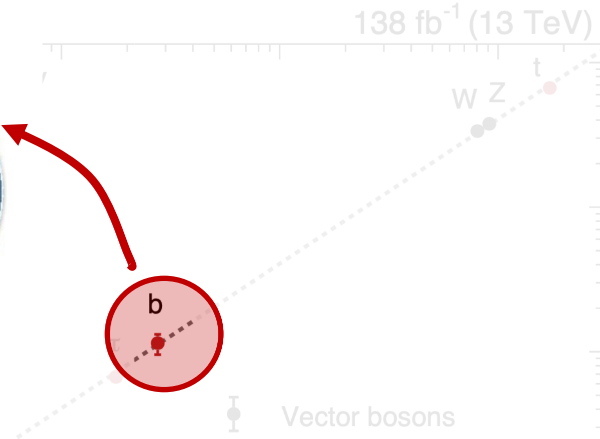

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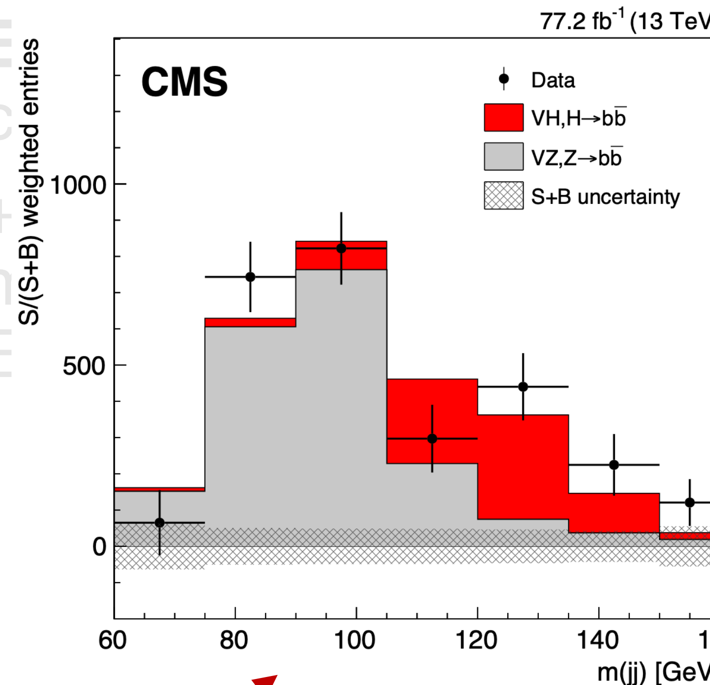
Exceed expectations: H→bb observation



Higgs-charm: Mission impossible (?)

- Similar concept to H→bb but two big challenges
  - **Small BR (H→cc):** ~20x smaller than BR(H→bb)
  - **Charm tagging** much more challenging than **bottom** tagging

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Major effort in improving jet identification
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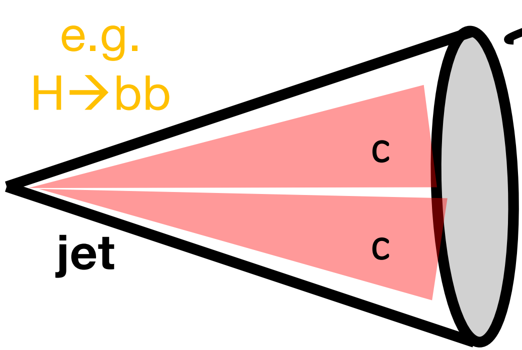
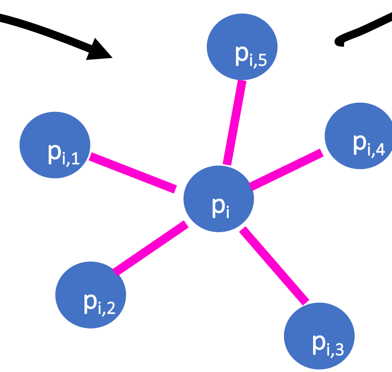
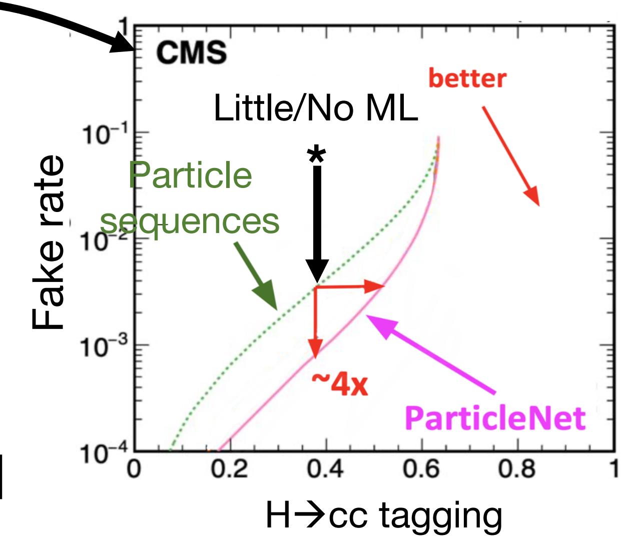




Cutting edge DL algorithms
[e.g., Graph Neural Networks]



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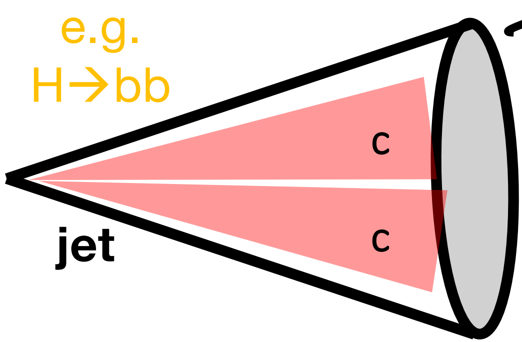

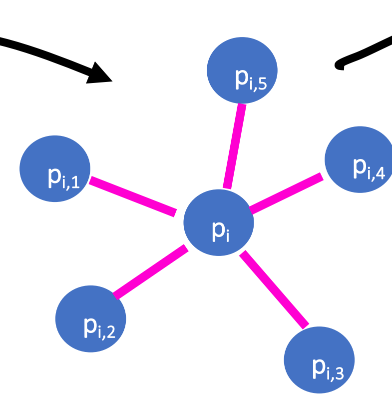

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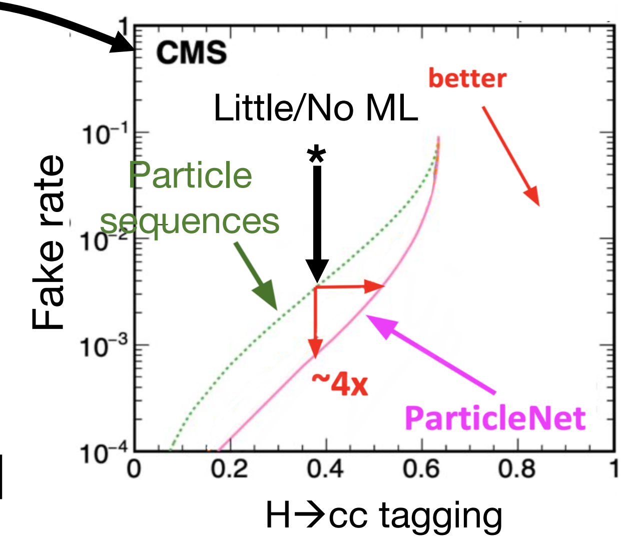

Obtained gains: ~equivalent to run twice the Full LHC Runs 1+2

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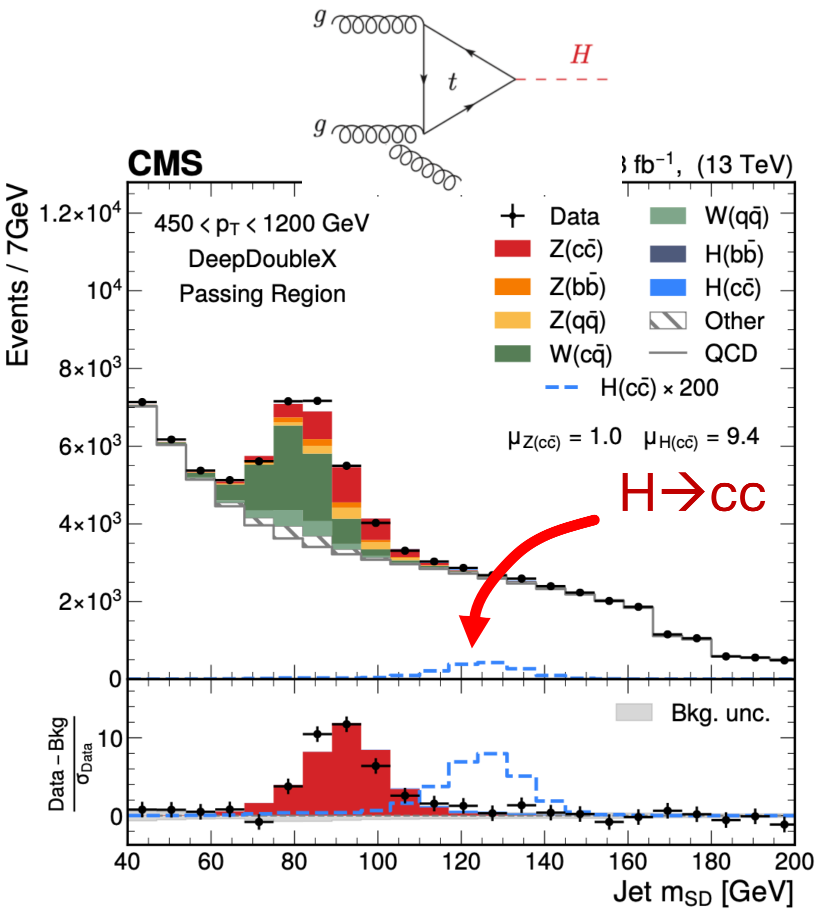
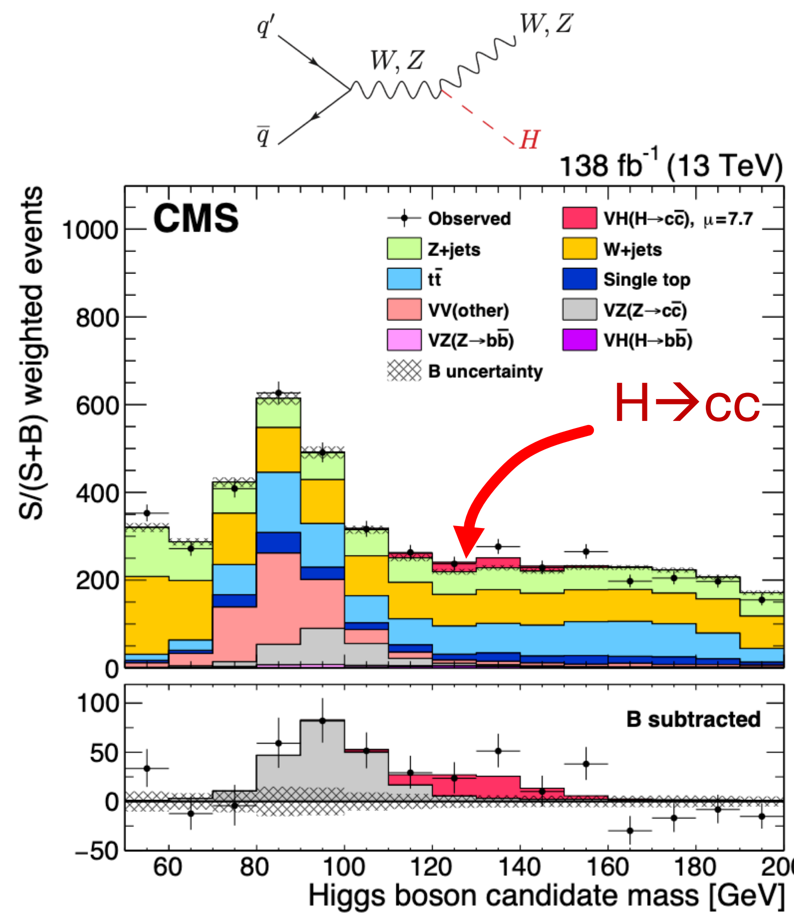




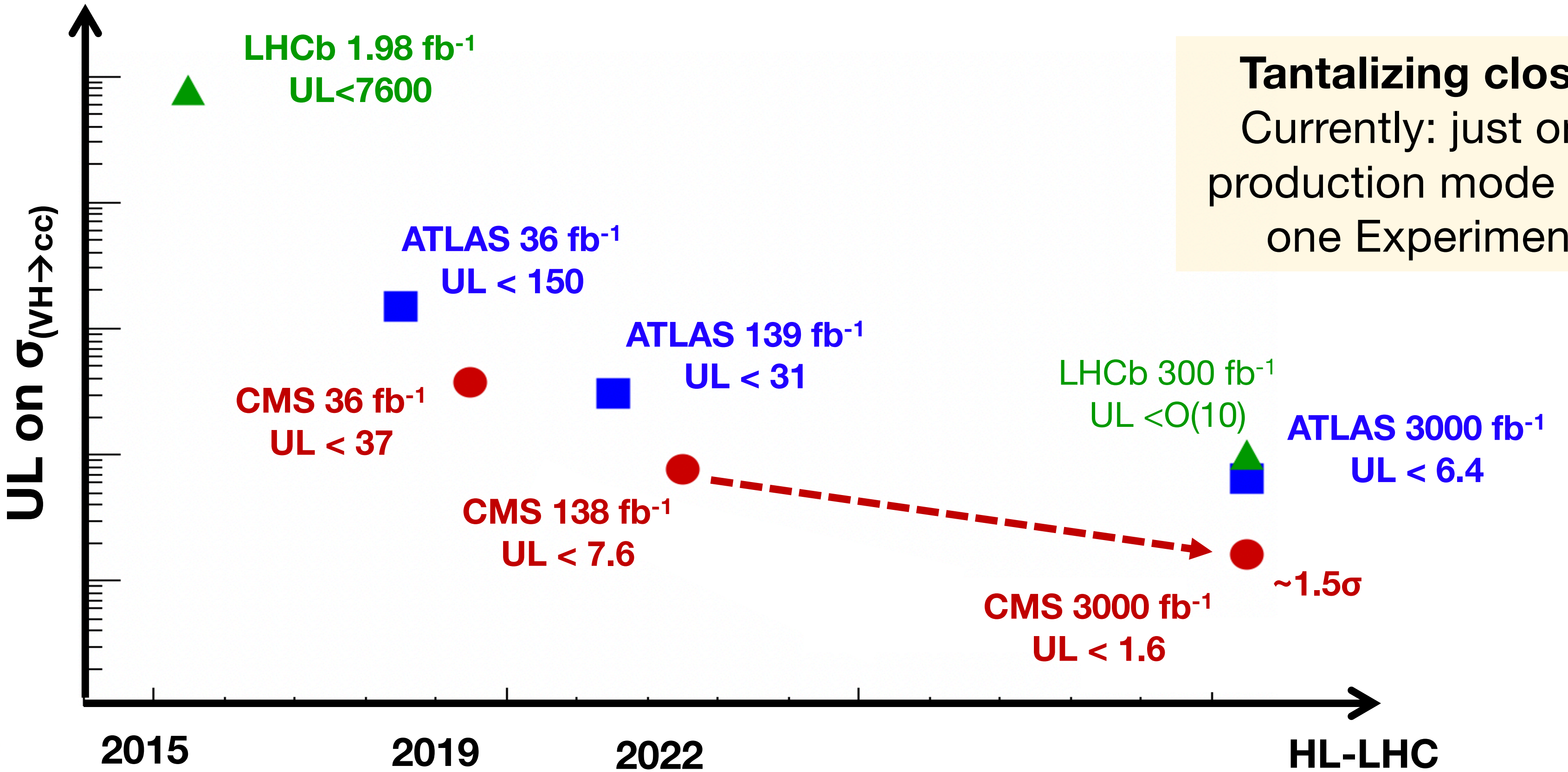
Obs. (Exp.): 47 (39) x SM

Obs. (Exp.): 13 (7) x SM

Major contributions: FNAL/LPC/US

Most sensitive results to date

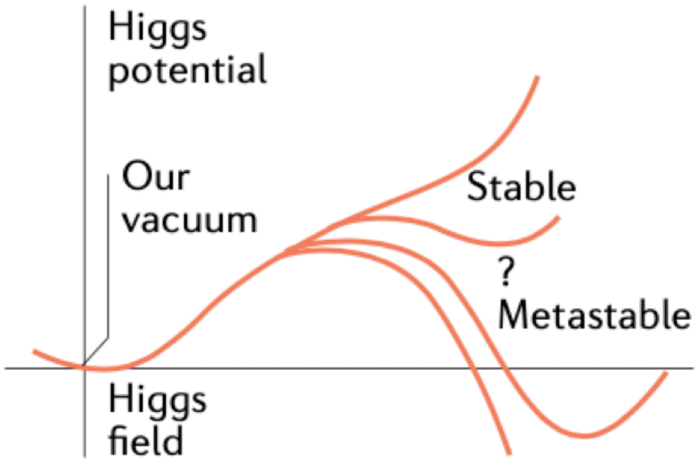
Towards 2nd-Gen Higgs-quark couplings



Tantalizing close!
Currently: just one production mode and one Experiment

O(10000)→….→ O(10) in ~5 years
Lot's of effort & ingenuity in multiple areas

The nature of the Higgs potential



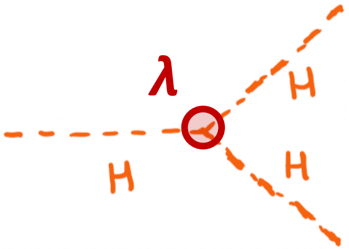
Ultimate goal:

$$V(h) = \frac{1}{2} M_H^2 H^2 + \frac{1}{3!}\sqrt{3\lambda_H} M_H H^3 + \frac{1}{4!}\lambda_H H^4$$

Higgs mass

Shape of potential

Measure Higgs self-coupling



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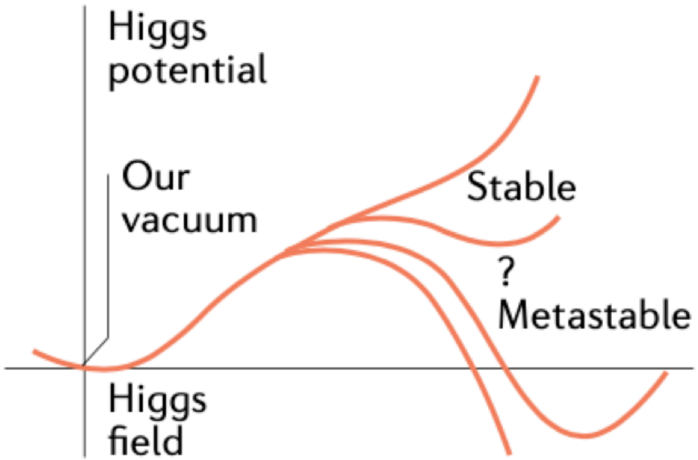

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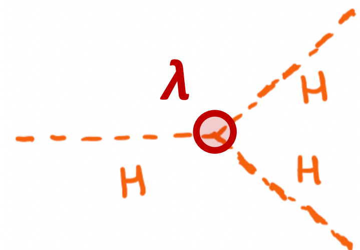
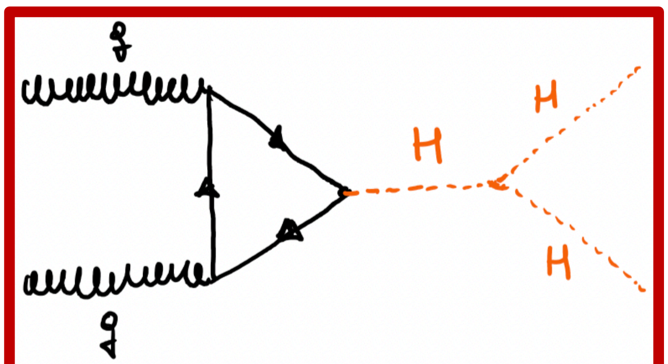


- Direct access: HH production

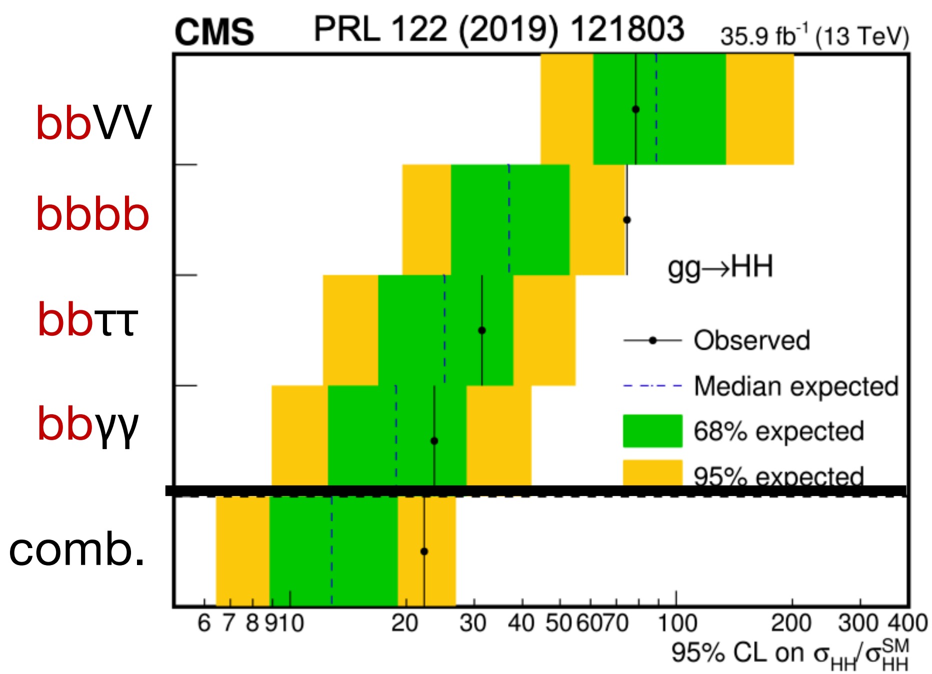


- Very rare process (σ~31fb); **1/1000 of Single-H**
- Run 2: ~4K HH events
- No golden channel

Needs innovation (and the HL-LHC)

Higgs pair production

Main drivers (Early Run 2)



Beyond reach even with HL-LHC ☹

Higgs pair production

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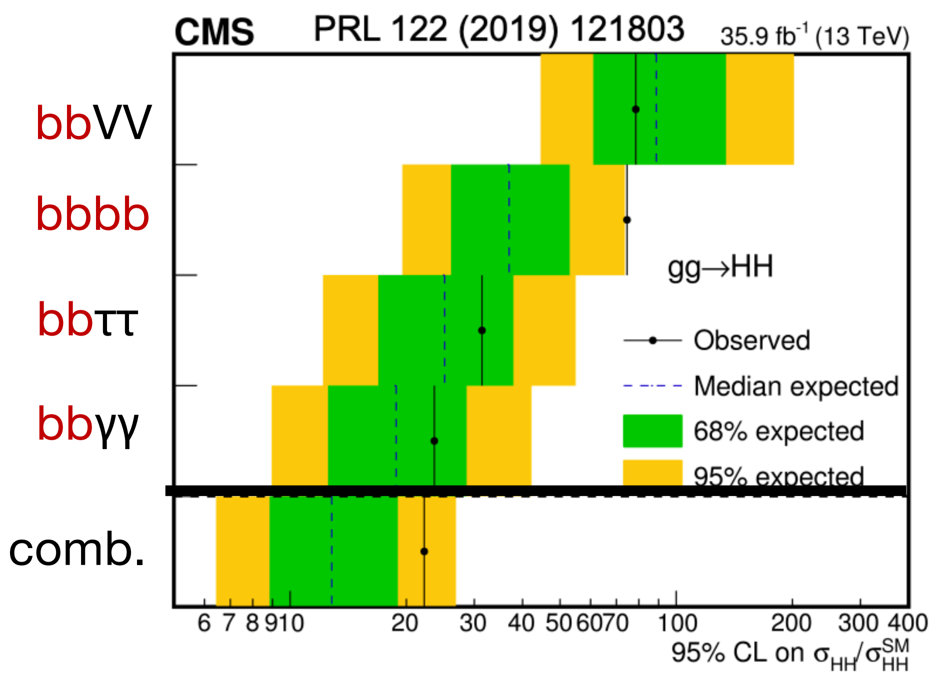

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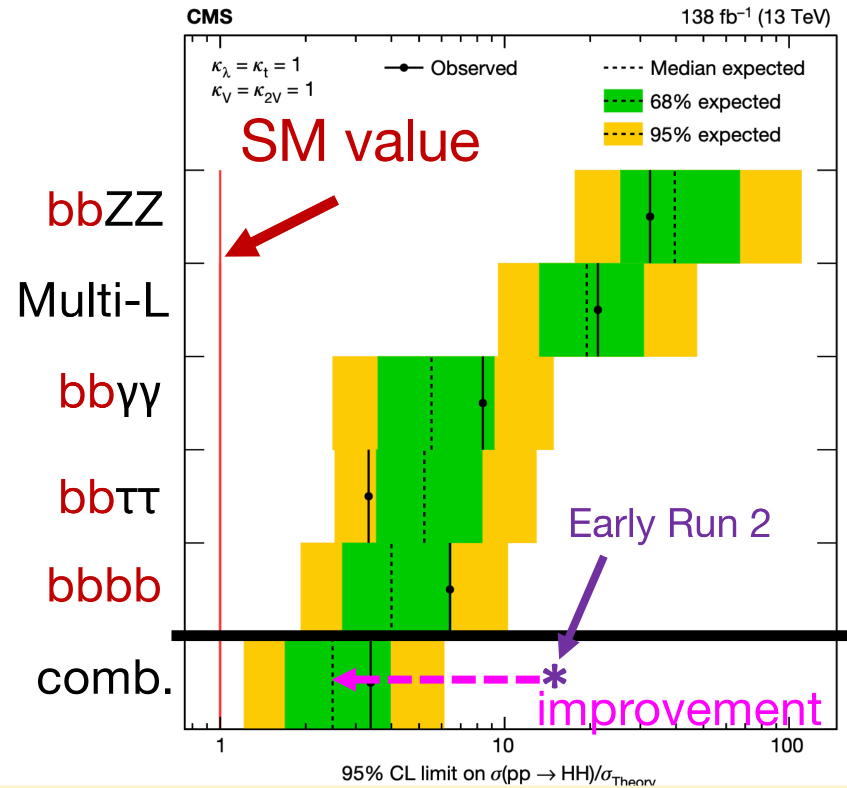
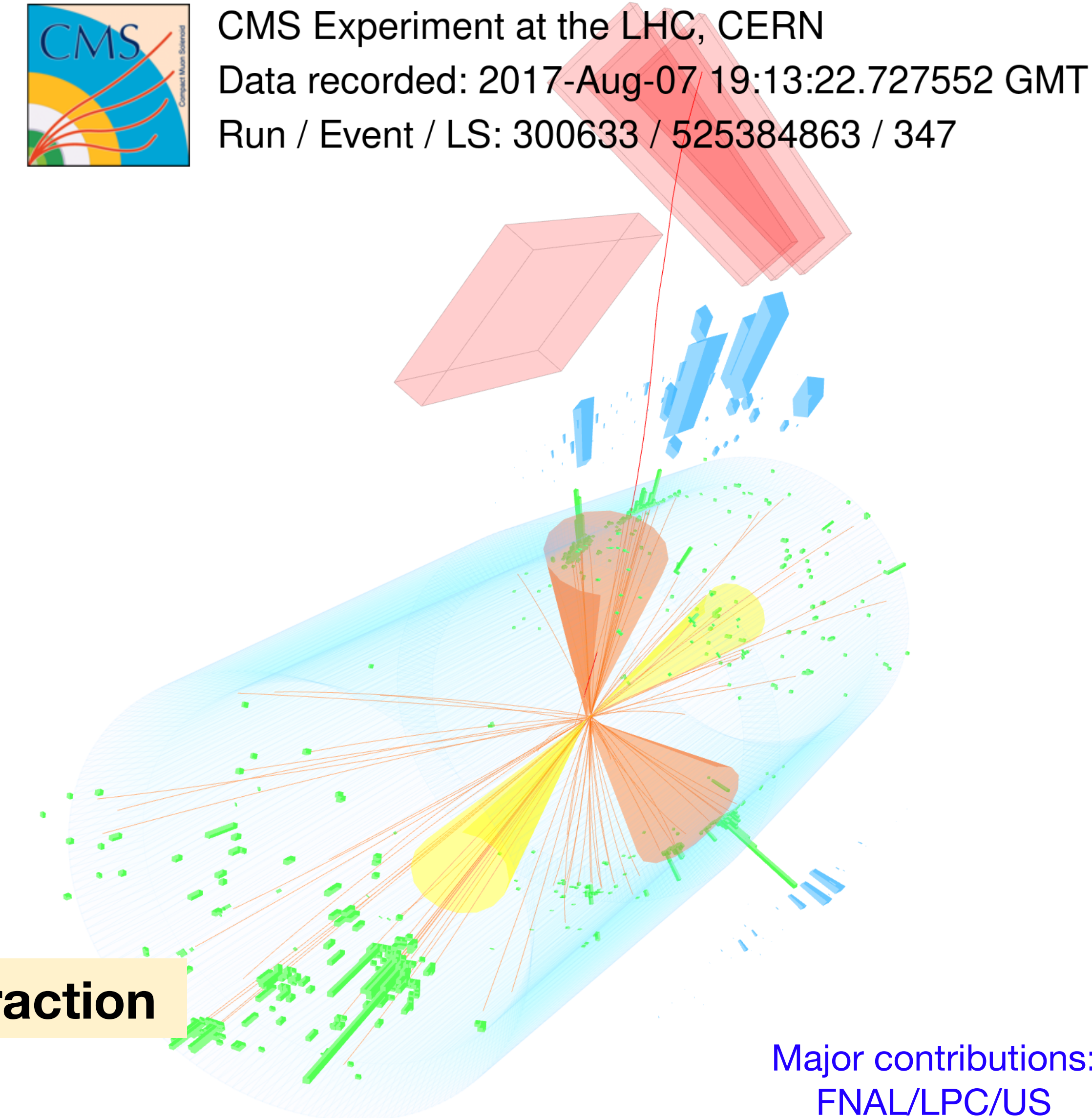
Major contributions:
FNAL/LPC/US

Full Run 2 (4x More data)

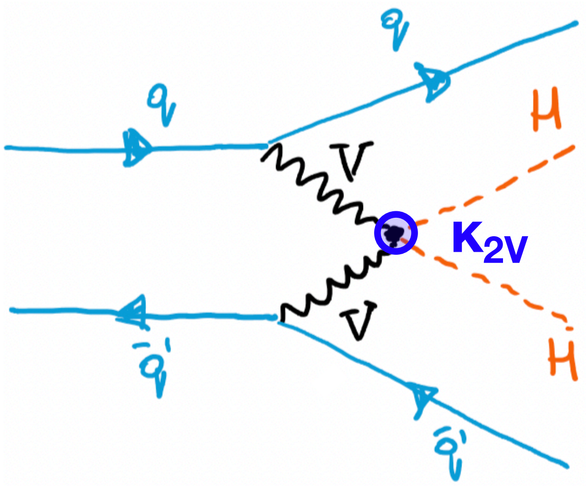


Improvements:
- **2x** from additional data
- **3x** from novel techniques and tools

En route to λ



- We turned the LHC to a VV collider:

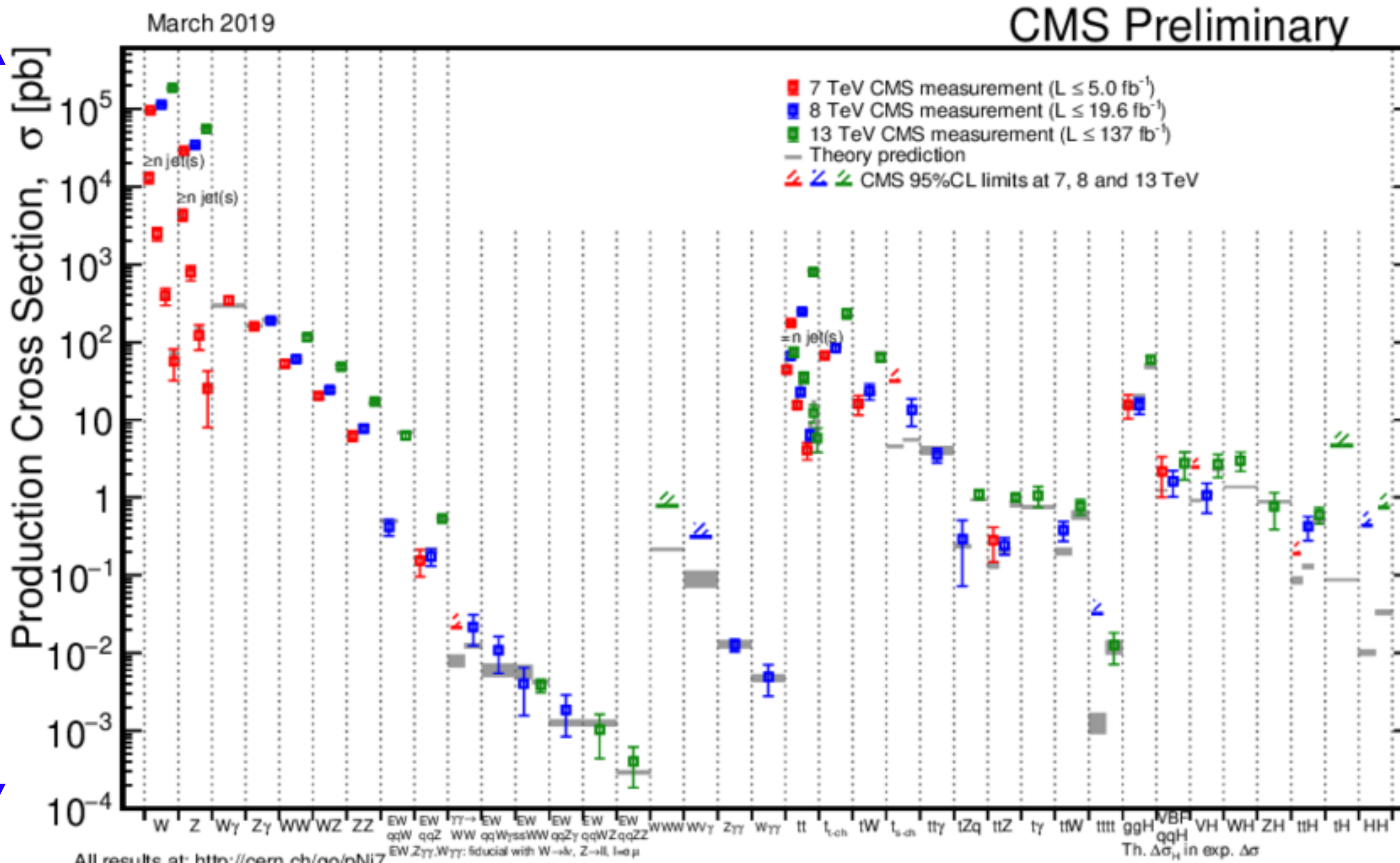


CMS established HHVV interaction

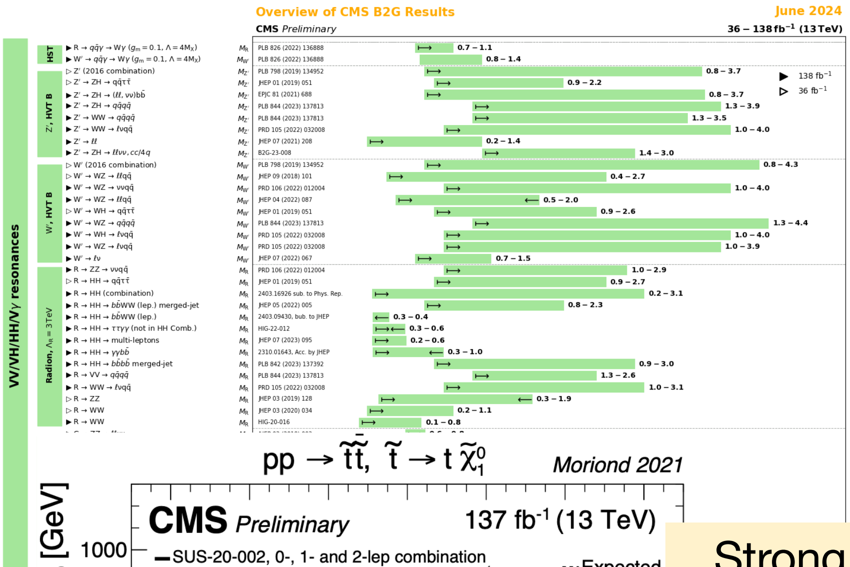
Major contributions:
FNAL/LPC/US

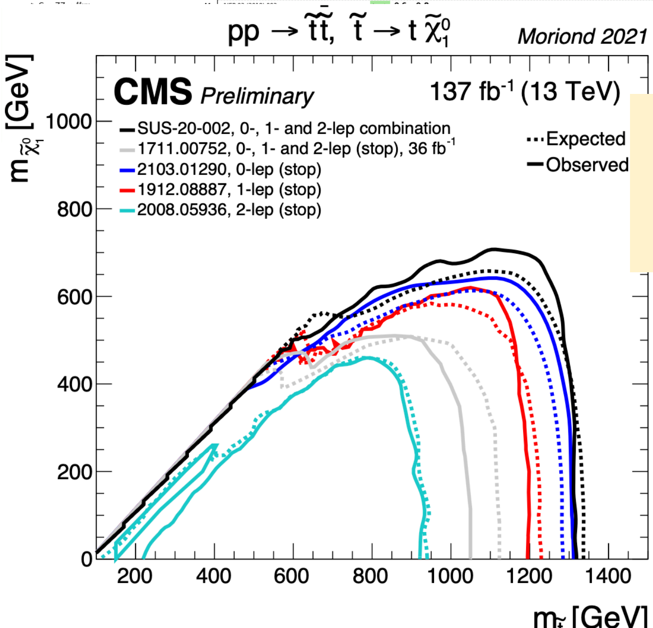
Constantly challenging SM

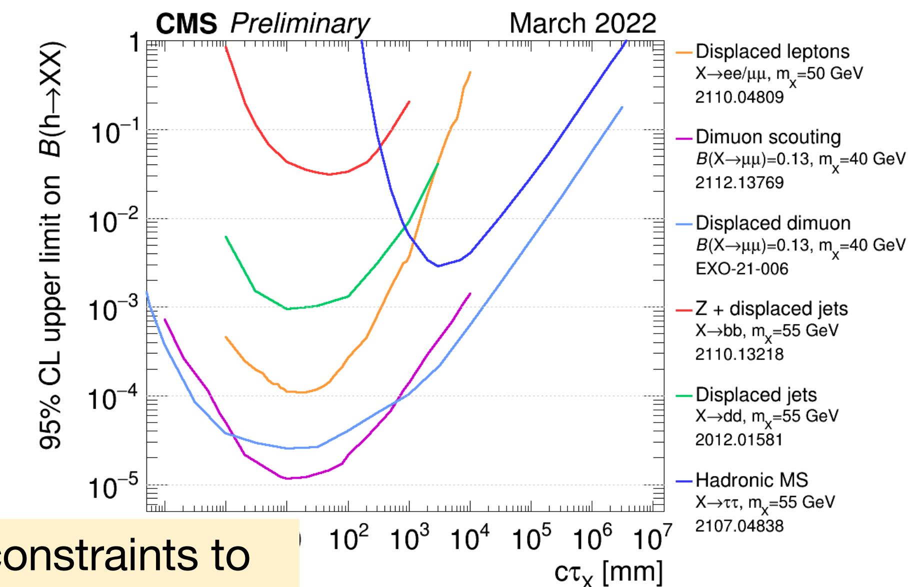
13 orders of magnitude



Clearly: Direct searches







Strong constraints to several appealing BSM models

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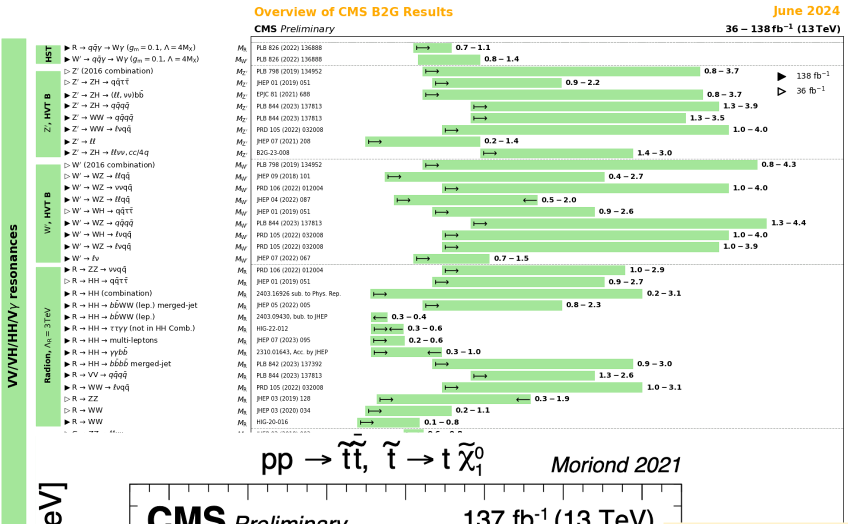

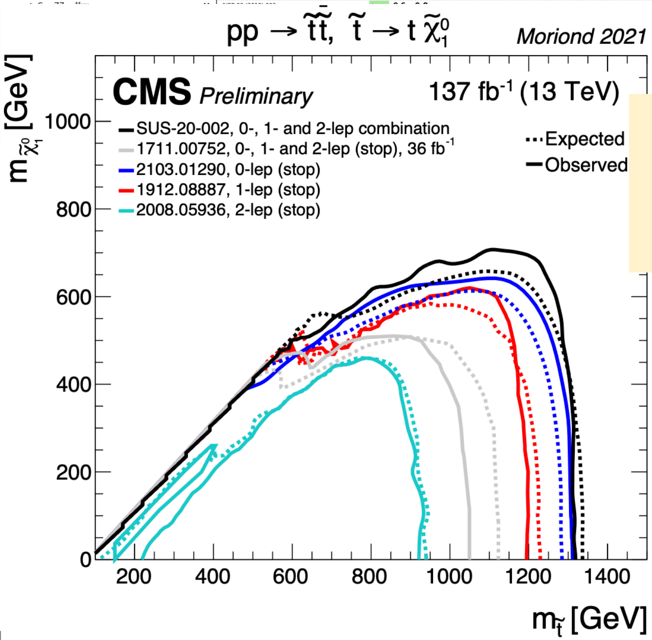

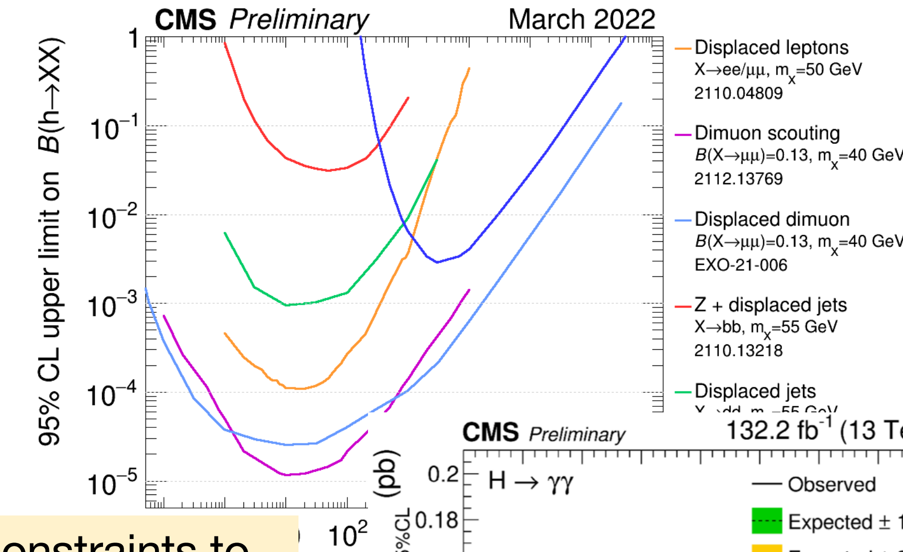

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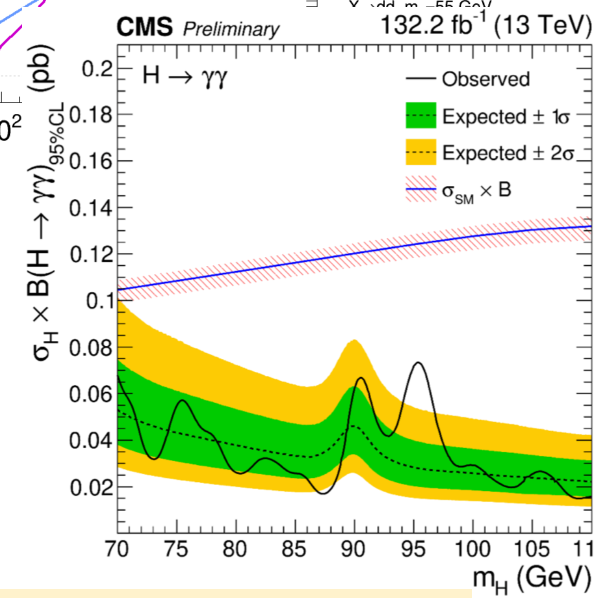
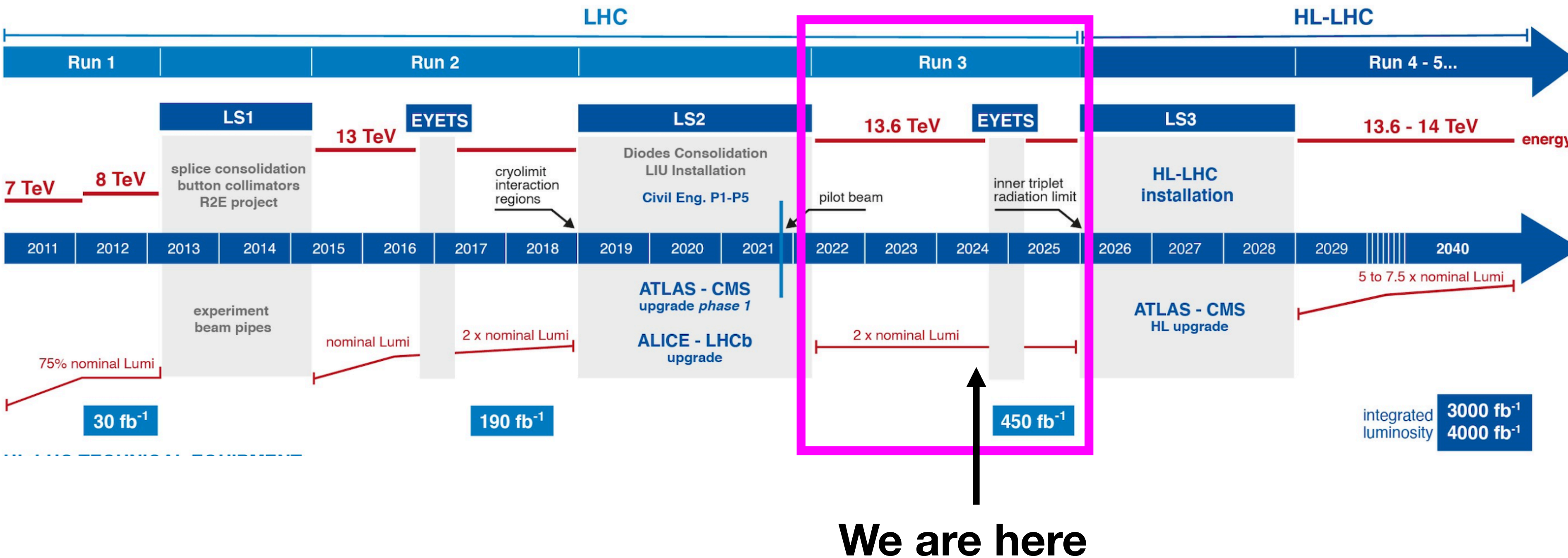


and some excesses…

The present: LHC Run 3 (and some Run 2)

LHC Run 3


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
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
5 to 7.5 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1
We are here

LHC Run 3: Accelerator front

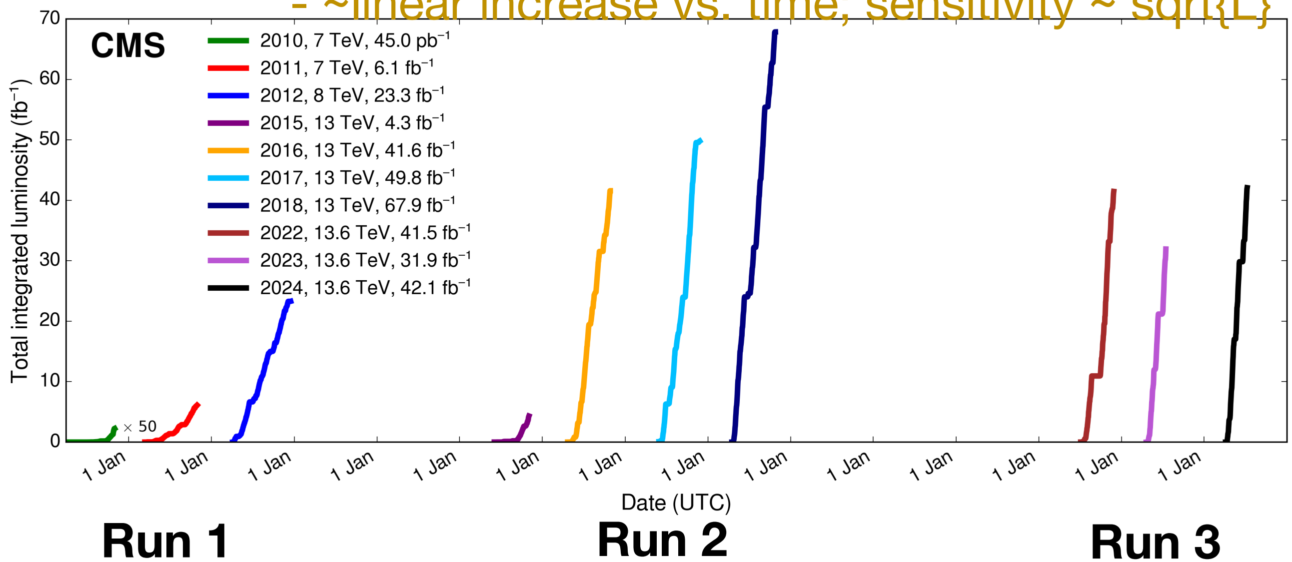
$$\mathcal{N} = \boxed{\sigma} \times \mathcal{L} \times \mathcal{A} \times \epsilon$$

cross-section:
13 → 13.6 TeV

process	σ(13.6 TeV) / σ(13 TeV)
W/Z	~1.1
ggF H	~1.10
ttbar	~1.15
m_X=1 TeV	~1.2
m_X=8 TeV	~2

Modest gain for the bulk of CMS physics program

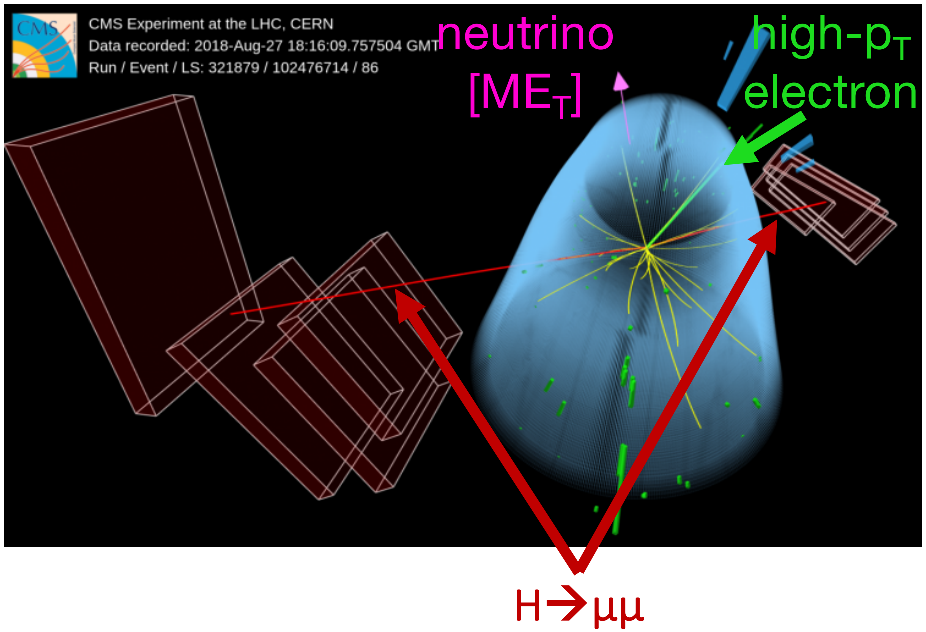
Int. Luminosity:
- similar instantaneous lumi with Run 2
- ~linear increase vs. time; sensitivity ~ sqrt{L}

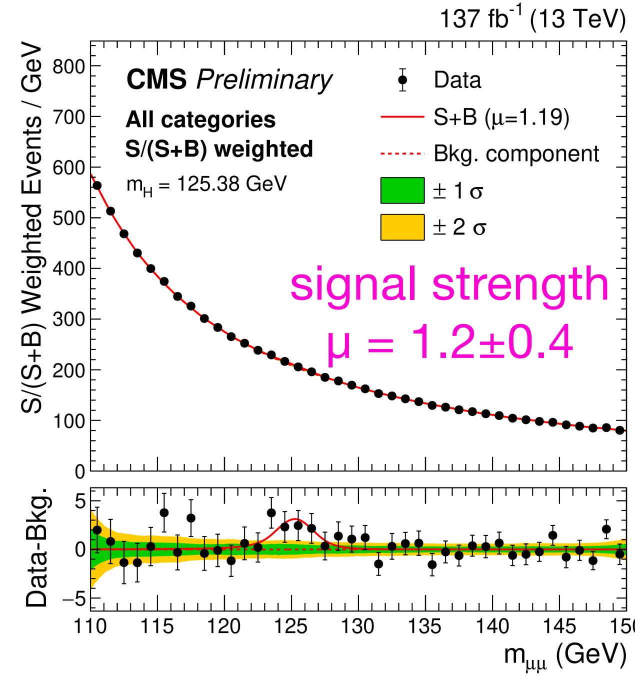


- Some hick-ups but **2024** looks good
- Run 3 to extended until 2026 (?) → ~300/fb (i.e., 2x Run 2)

"Bread and butter": Establish Higgs→μμ

W(→eν)H(→μμ) @13 TeV





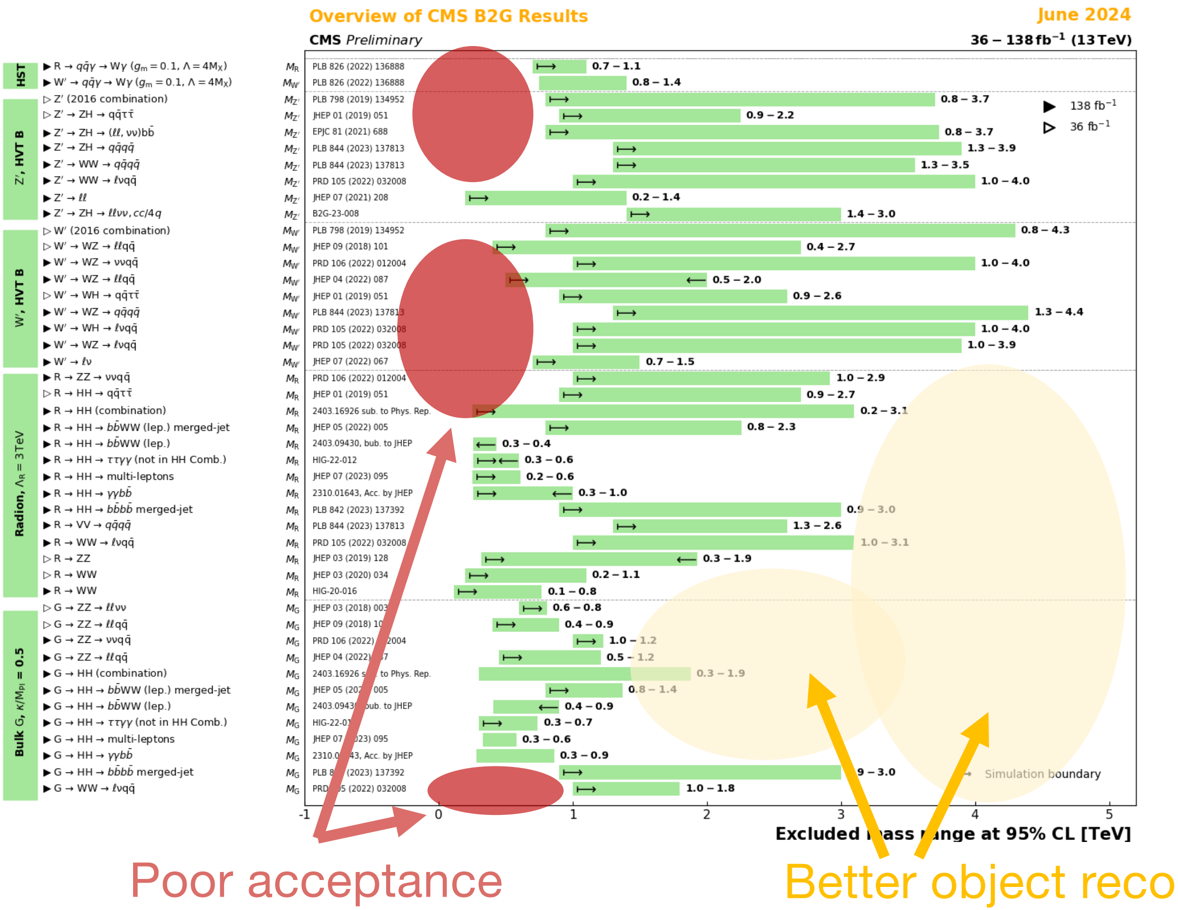
CMS: obs: 3σ (exp: 2.5 σ)
ATLAS: obs: 2σ (exp: 1.7 σ)

Evidence of Higgs coupling to 2nd-Gen charged leptons

- Run 3 (assuming ~300fb^{-1}):
  - Getting there: Expect ~4σ [CMS only]
  - + ATLAS (*sqrt2): Observation guaranteed (?)

Going beyond SQRT{L}

- New era: No big jumps in E_{CM} → Needs time to increase stats



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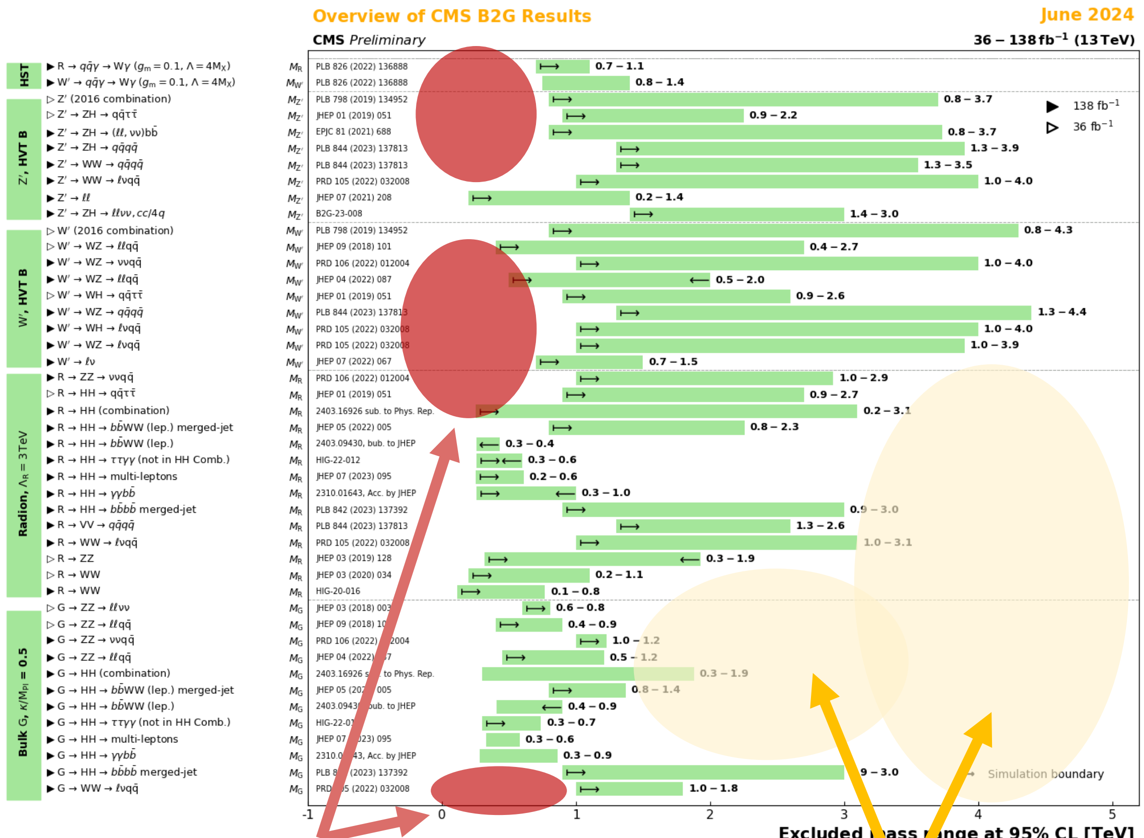

Poor acceptance

Better object reco

More data

- Baseline: Run 2 success story
  - More cutting-edge tools in more areas
- Main goals:
  - Extend acceptance (i.e., improved online selection (“triggering”)
  - “Exotic” topologies
  - Continue pursuing the “traditional program

Run 3: HL-LHC Prototype

LHC Run 3: CMS front

$$\mathcal{N} = \sigma \times \mathcal{L} \times \boxed{\mathcal{A} \times \epsilon}$$

Acceptance:
Smaller-scale improvements mainly @trigger system
- **HL-LHC:** Major improvement

Efficiency:
More sophisticated AI/ML @Trigger, and analysis level

LHC Run 3: CMS front

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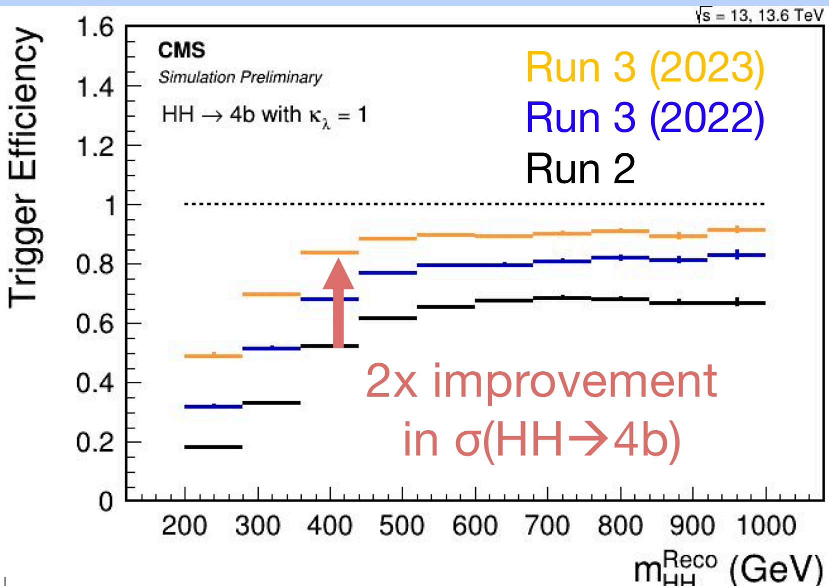
Efficiency:
More sophisticated AI/ML @Trigger, and analysis level

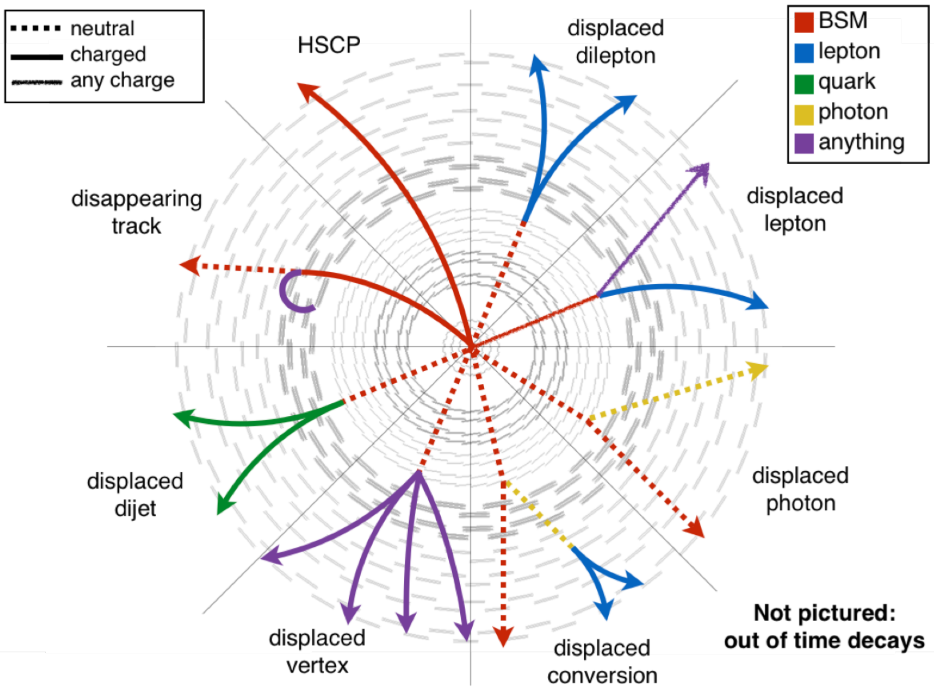
Cutting edge AI/ML for triggering



2x increase HH→4b acceptance
- preliminary results: reach Full Run 2 sensitivity with just 2022+23 (< half of Run2)
- Other channels HH(H) channels benefit
- More developments in the pipeline (bbττ, bbWW,…)

Leave no stone unturned

- e.g., Long-lived particles (LLPs)

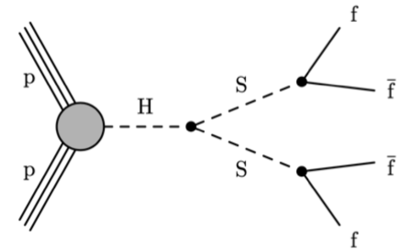


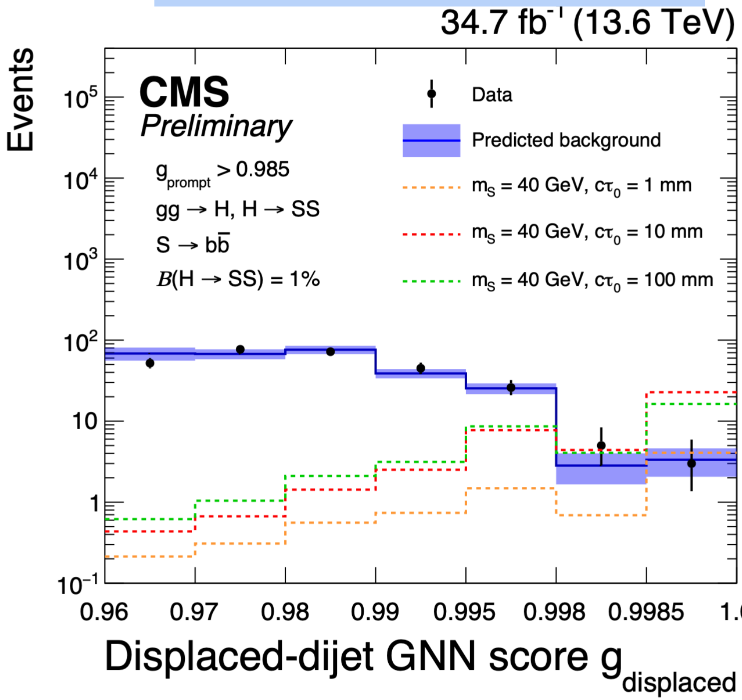
- Need dedicated RECO techniques
  - Effort started in Run 2
- Run 3: Target many more signatures with more sophisticated tools
  - Extend to online selection (triggering)

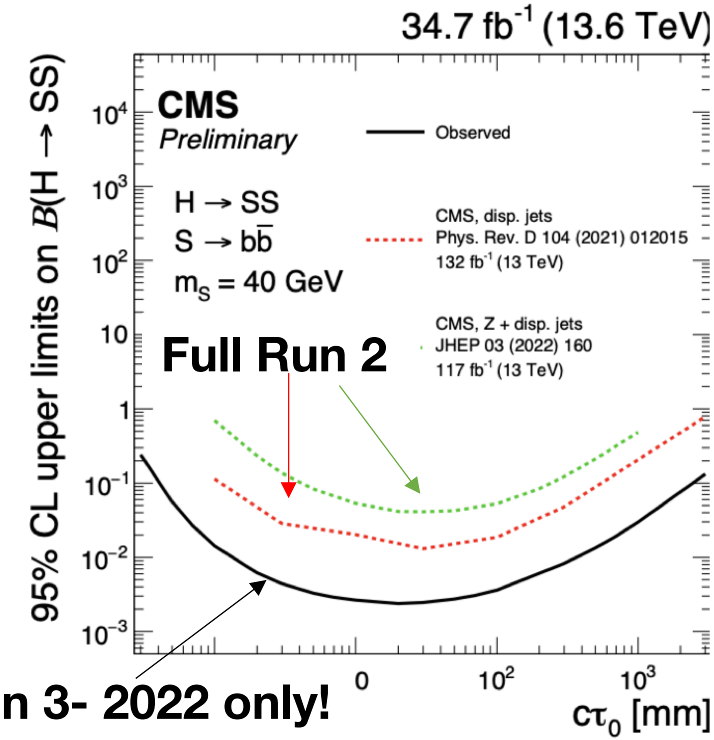
Leave no stone unturned

- e.g., New physics with displaced jets

Displaced-jet algo (online+offline)







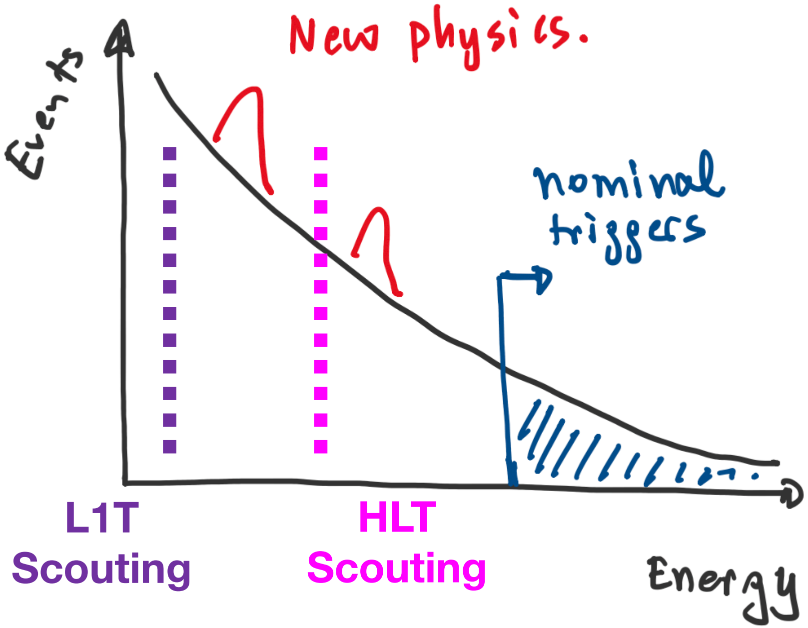
CMS-EXO-21-010

O(10) improved sensitivity wrt to Full Run 2 with ¼ of Run 3 data

FNAL/LPC/US led

Data Scouting

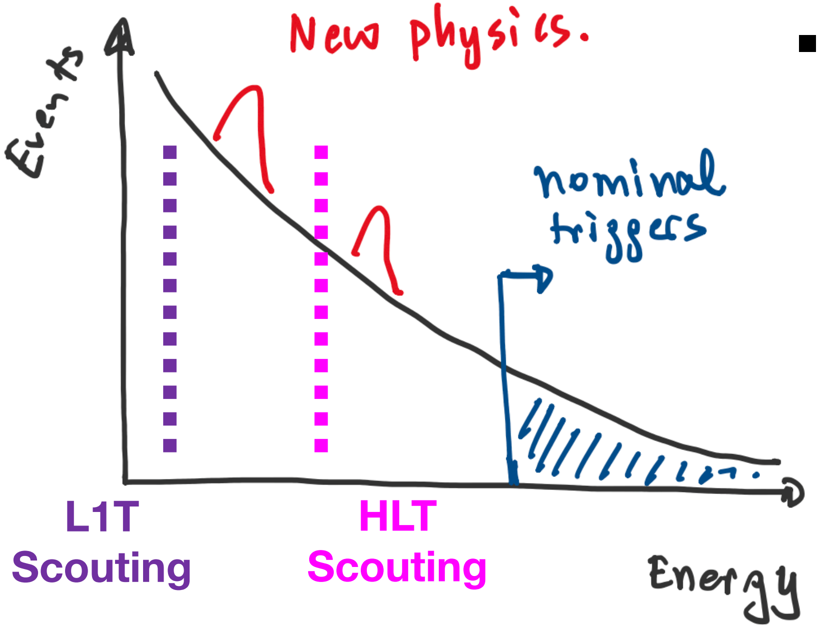
The problem



- Bottleneck of nominal triggers
  - Output bandwidth of DAQ

Data Scouting

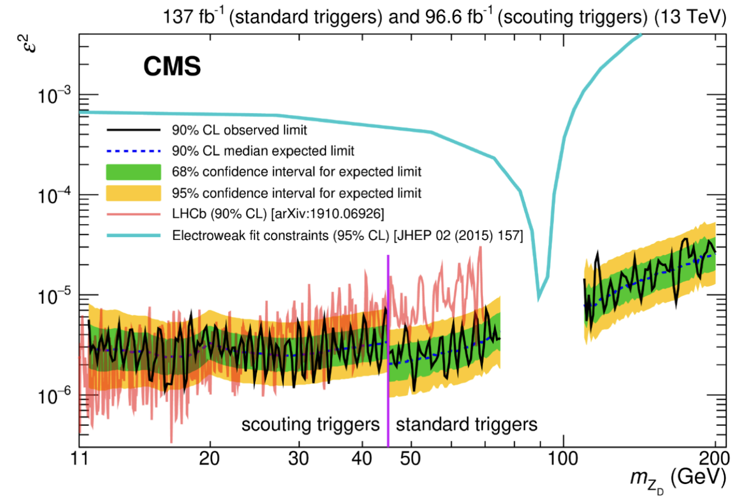
The problem



- Bottleneck of nominal triggers
  - Output bandwidth of DAQ

The solution: **Data Scouting**

- **Do more** [physics] **with less** [event-size]
  - Store minimal set of TRG-level info
  - Caveat: no offline reco, no raw data



Already since Run 1; Run 3 & beyond:
- improved performance & user friendliness
- extended to L1T

Full potential yet to be explored!

Searching for the unknowns

- Typical analysis workflow:
  - Starting point: signal hypothesis
  - Design triggers and analysis strategy
  - Extract signal from data → Interpretation

Great!
IFF we know what you are looking for..

Searching for the unknowns

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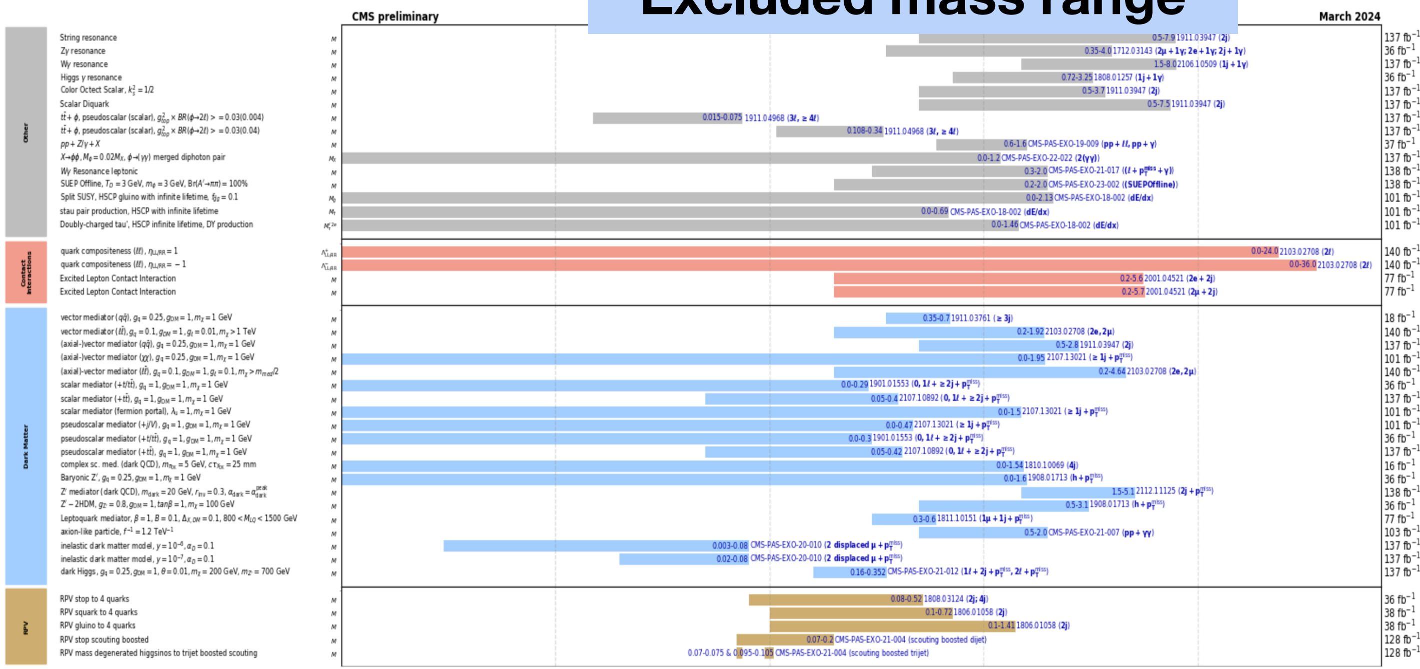
Excluded mass range



Null results so far

Anomaly detection @LHC

- From **fully supervised → un/less supervised** methods
  - **Learn** as well as possible known physics [i.e., the SM]
    - Using directly collision data
  - **Test** in collision data and look for deviations

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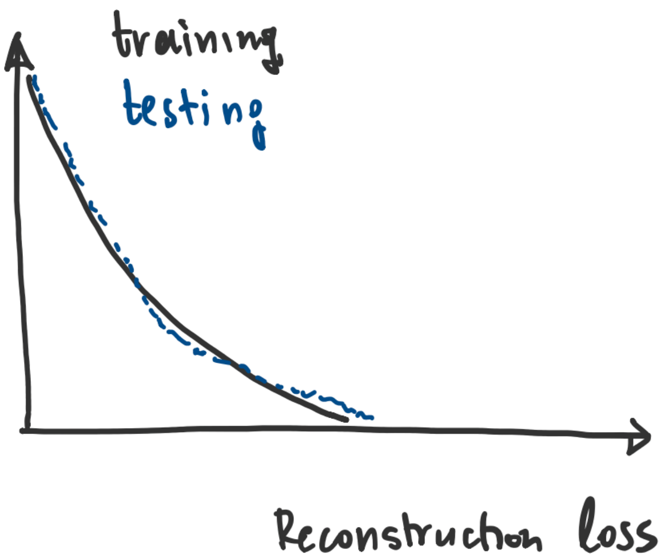
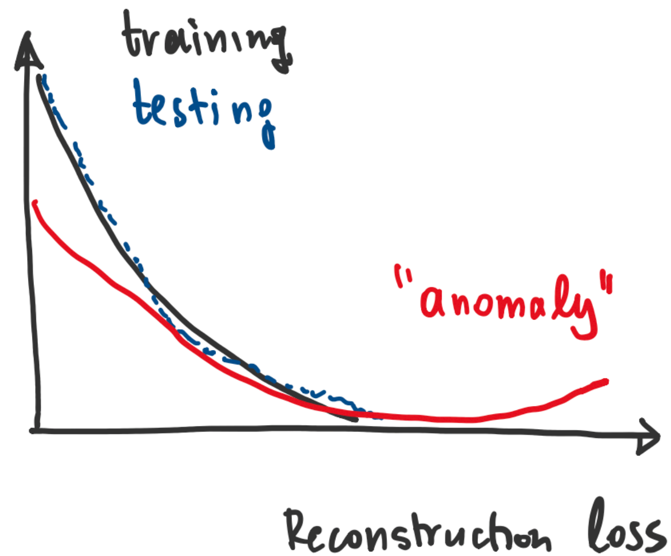
No new physics

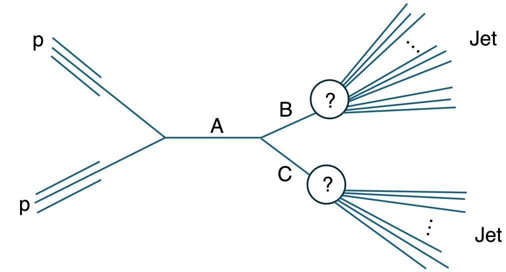


With new physics

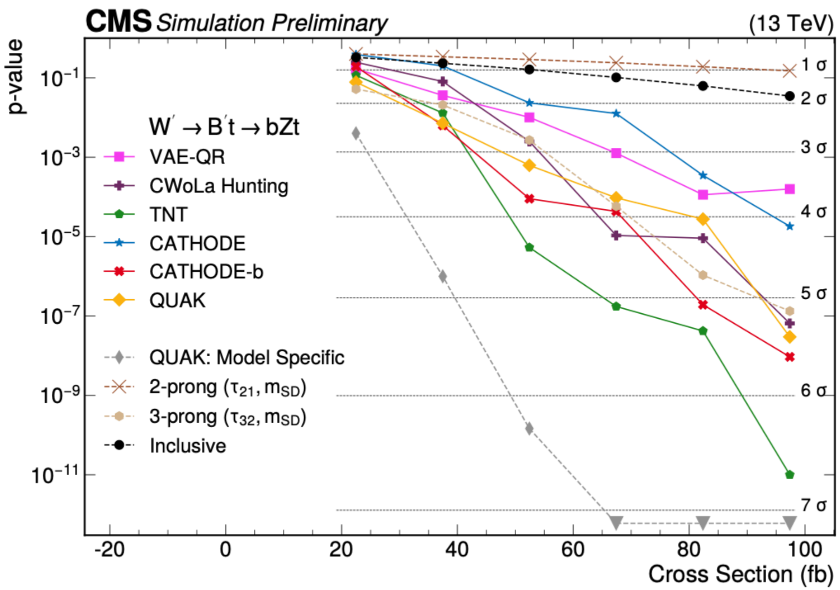


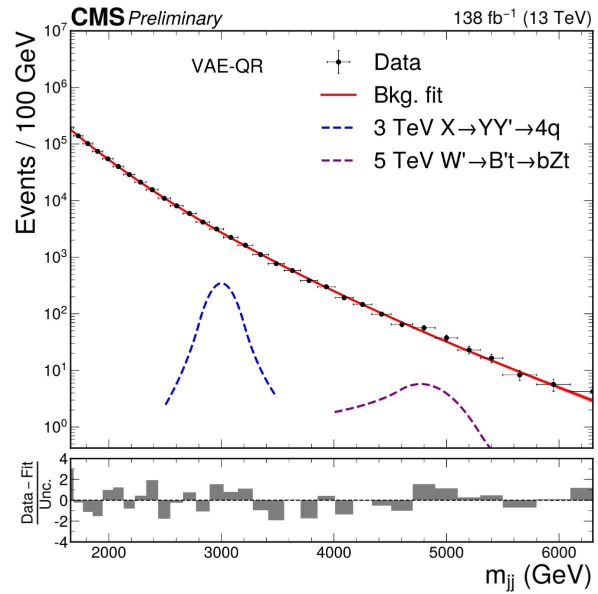
Anomaly detection @LHC

FNAL/LPC/US led



- Developed and demonstrated that it works using LHC Run 2
  - well.. without seen "anomalies" ☹





Implemented at trigger Level for Run 3 and beyond

The (near-term) future: HL-LHC

The HL–LHC project

- P5 recommendation (2015):
  - Continue strong participation at LHC
  - Full participation in HL-LHC upgrade + detectors

The HL–LHC project

- P5 recommendation (2015):
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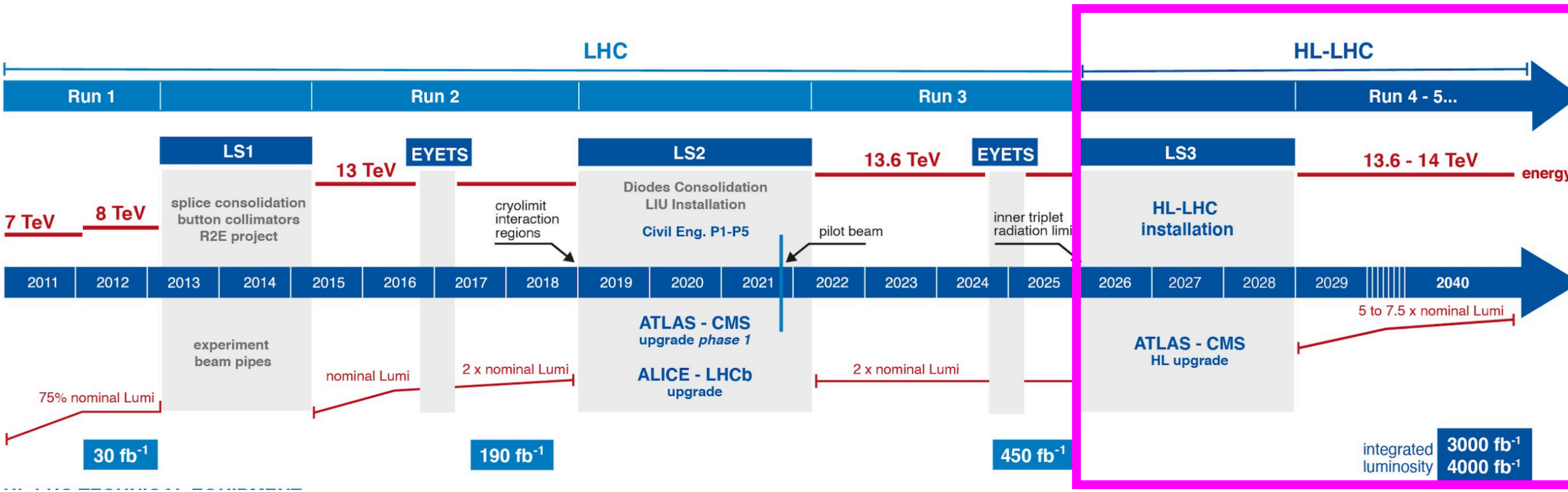
  - Full participation in HL-LHC upgrade + detectors

- P5 recommendations (2023):

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

A significant consideration in the prioritization process was the execution of projects begun in the past decade. In addition to operating facilities producing excellent science, three major facilities are currently under construction: the **High-Luminosity Large Hadron Collider (HL-LHC)**, the **Deep Underground Neutrino Experiment (DUNE)**, and the **Vera C. Rubin Observatory (Rubin)**. Each plays a crucial role

The HL–LHC project

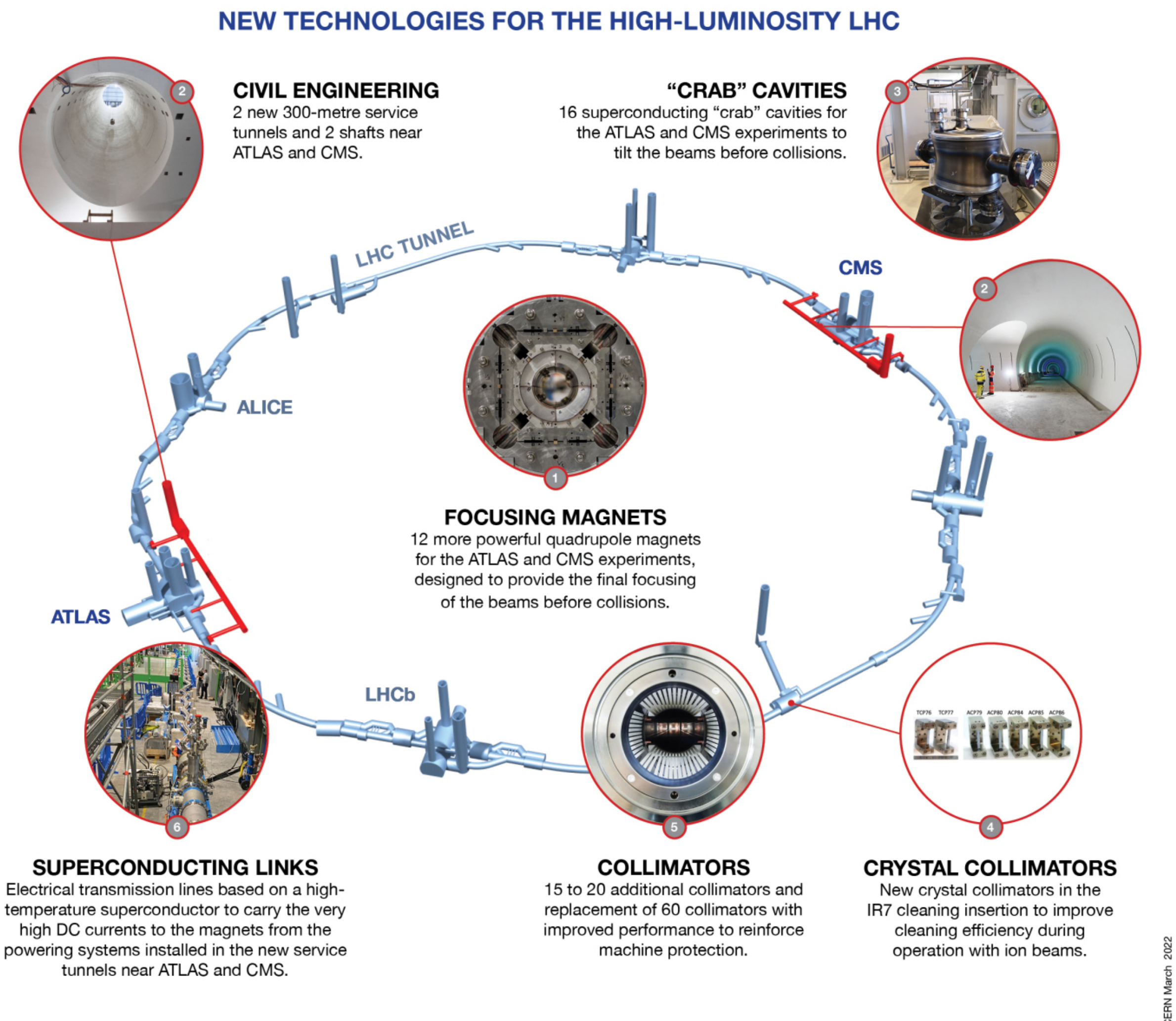


- 5-7x instantaneous collision rate
- O(10) larger dataset

Key for rare processes:
H(H), VBF/VBS, EWK SUSY, ..

A major project

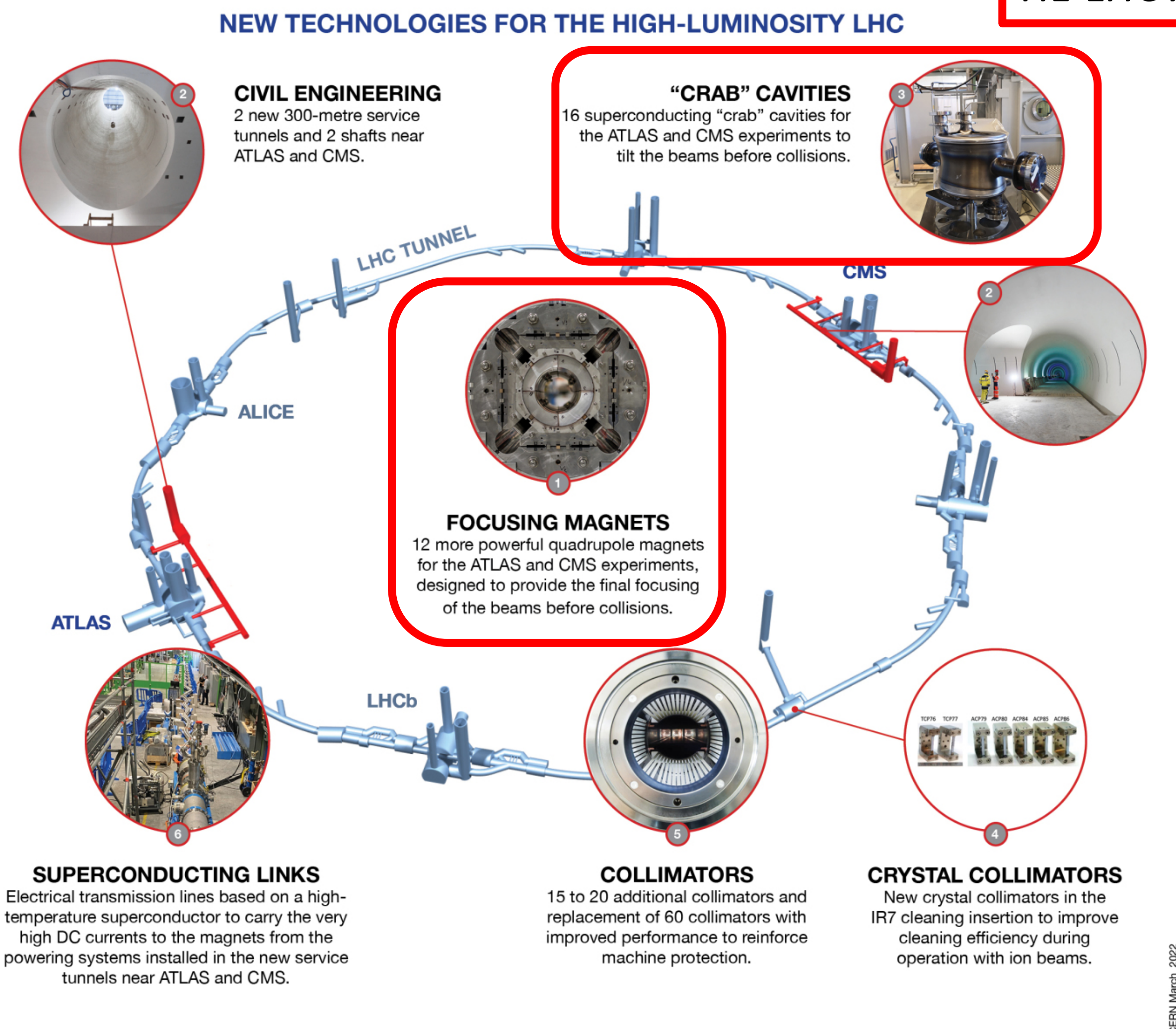
From:
G. Apollinari and O. Bruning



A major project

HL-LHC AUP

From:
G. Apollinari and O. Bruning



FNAL (& US): Leading role on critical technologies :
- Focusing Magnets
- "Crab" cavities

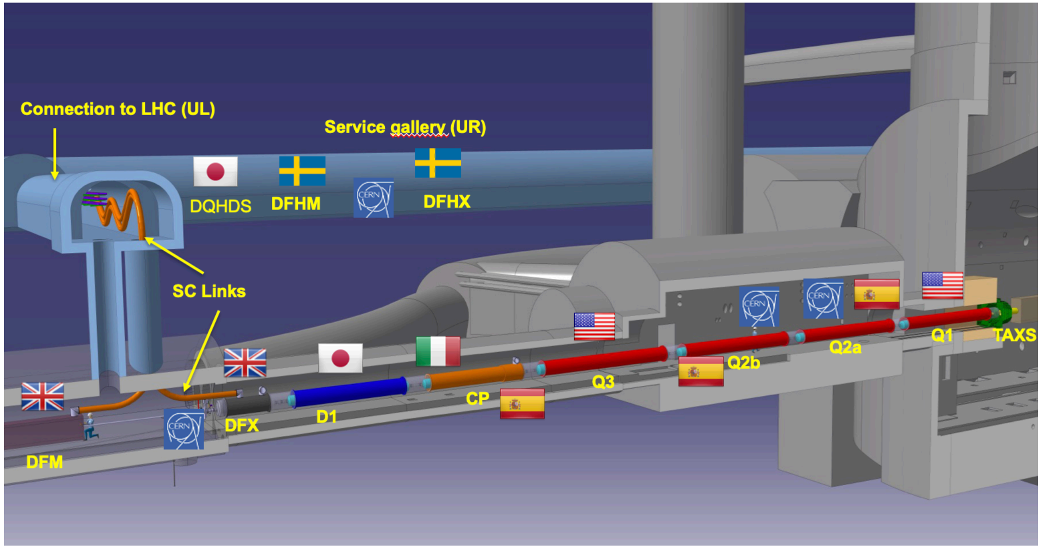
Quadrupole magnets

- Beam focusing (small transverse size):

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

Need to be as dense as possible
- LHC: ~50cm
- HL-LHC: ~10cm

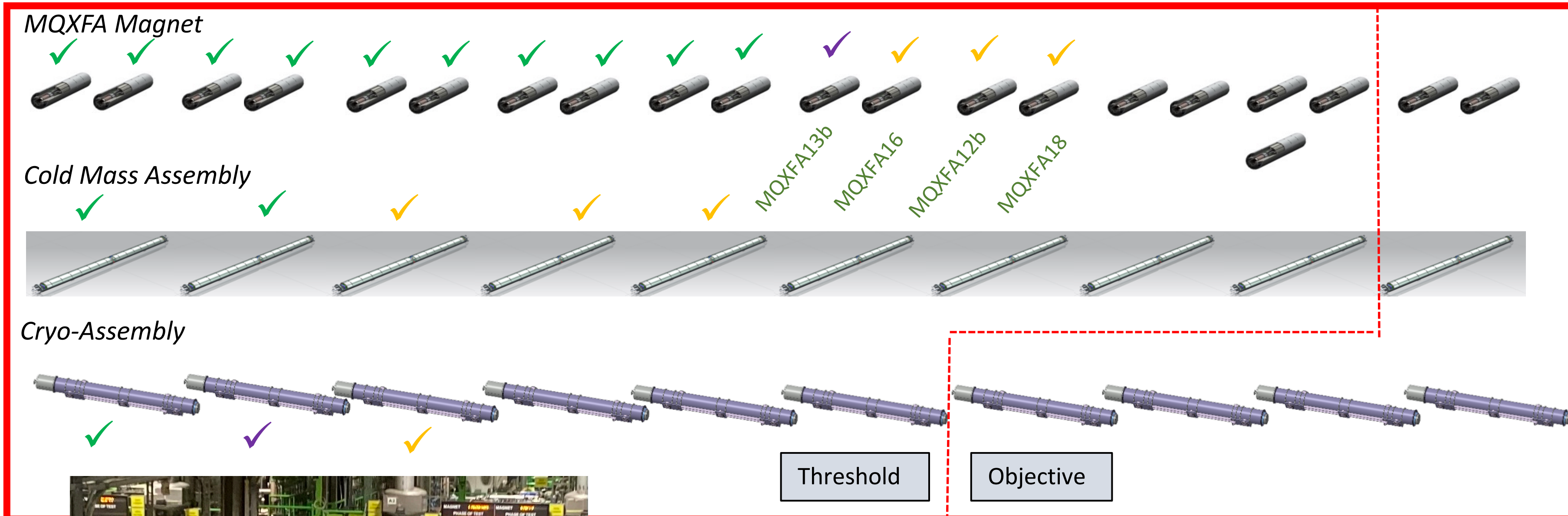
- β*: controlled by focusing magnets
  - FNAL is leading the efforts in developing Niobium–tin (Nb3Sn) quadrupoles



From: G. Apollinari

Quadrupole magnets: Status

From: G. Apollinari



Test at CERN - Jun. '24

- ✓ Completed, sitting on a shelf or delivered to CERN
- ✓ Under Fabrication
- ✓ Under Test

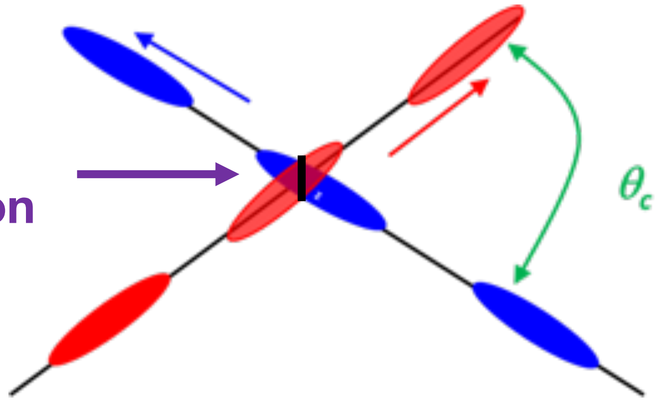
Key developments for the future (100 TeV pp) collider

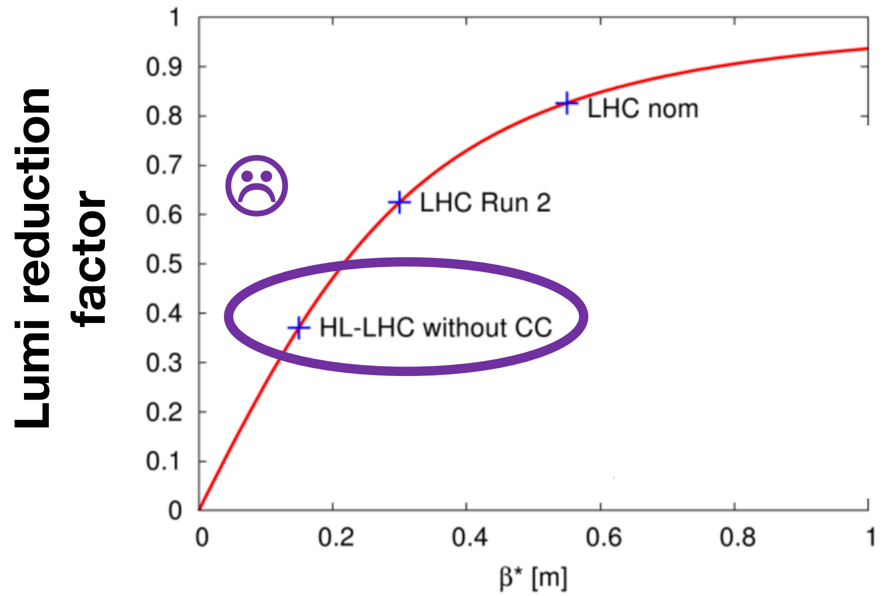
"Crab" cavities

- But: Small β → larger crossing angle. (θ_c)

LHC

Effective cross-section





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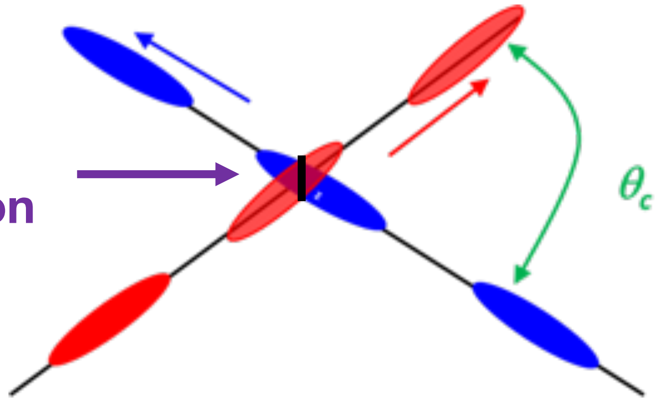
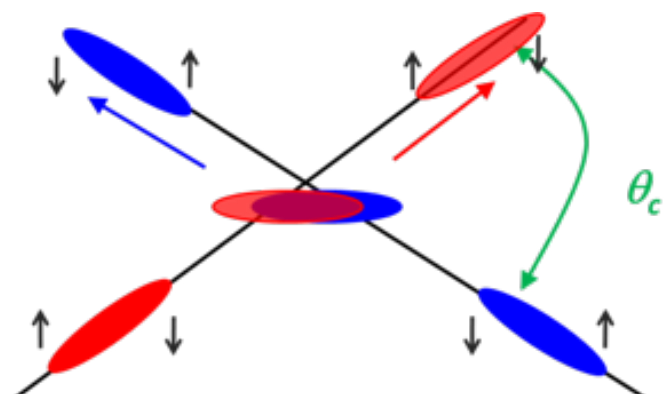
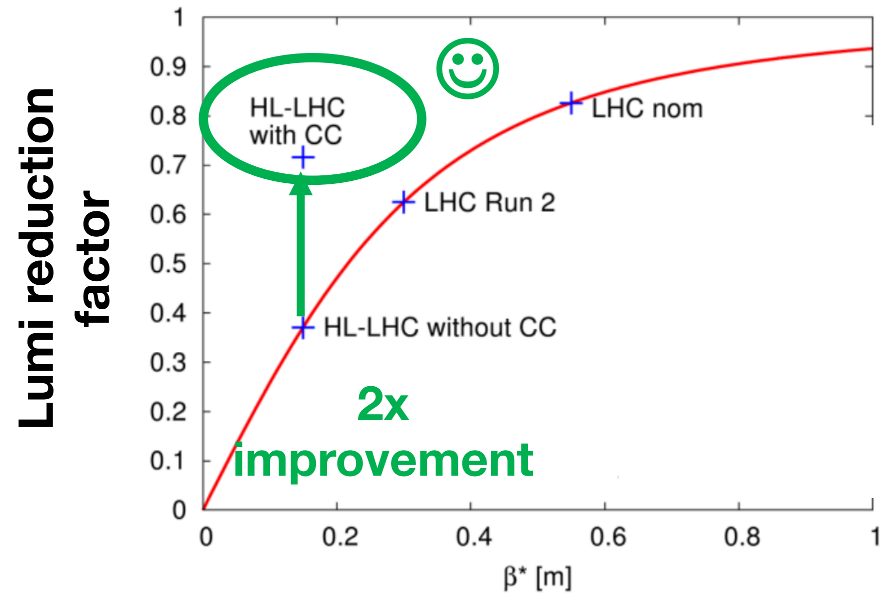
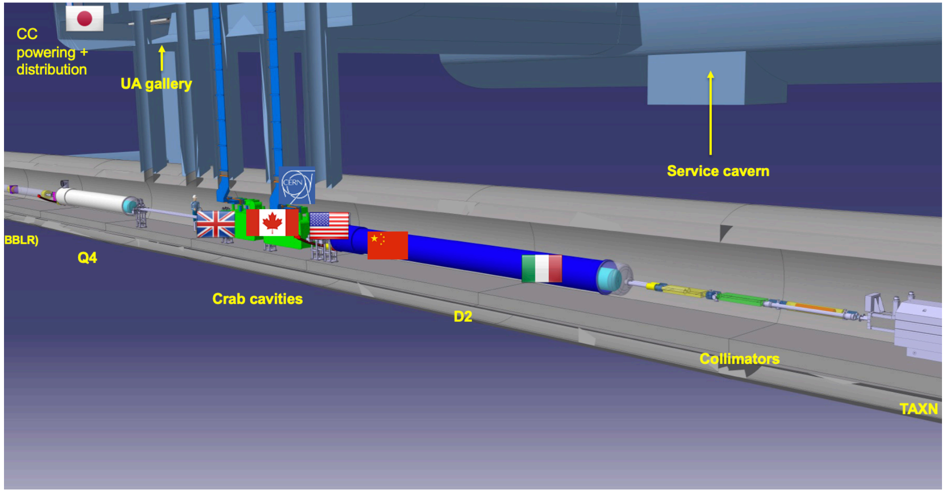


HL-LHC

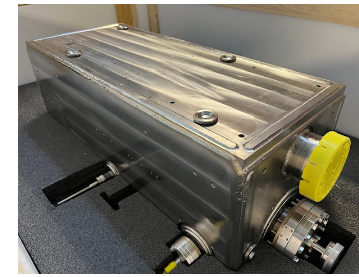


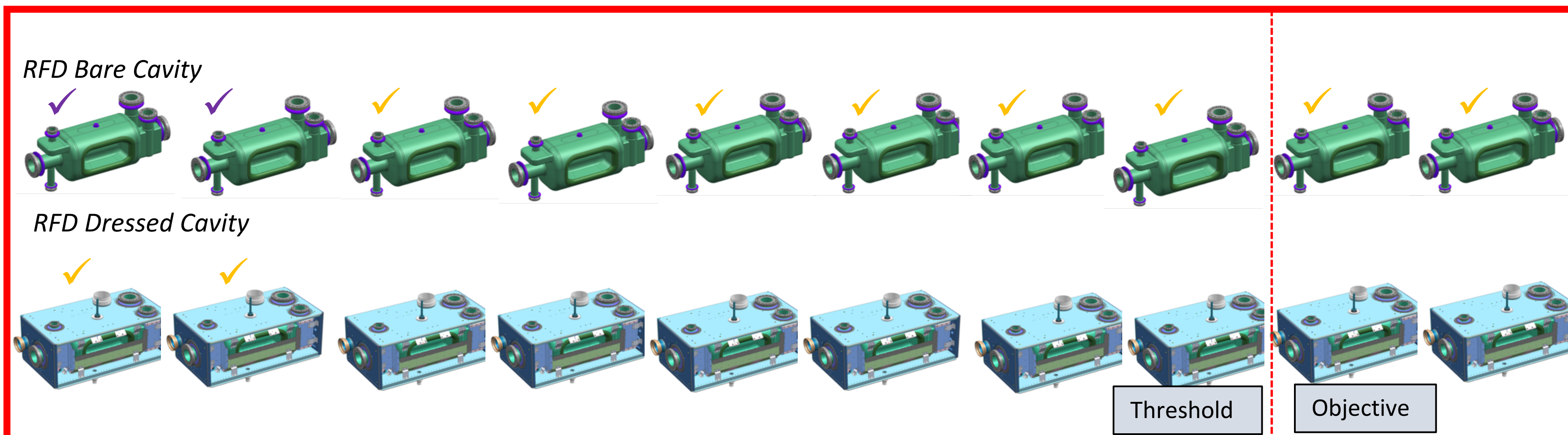


“Crab” cavities



Assembly in full swing





The CMS HL-LHC detector

- P5 2023:

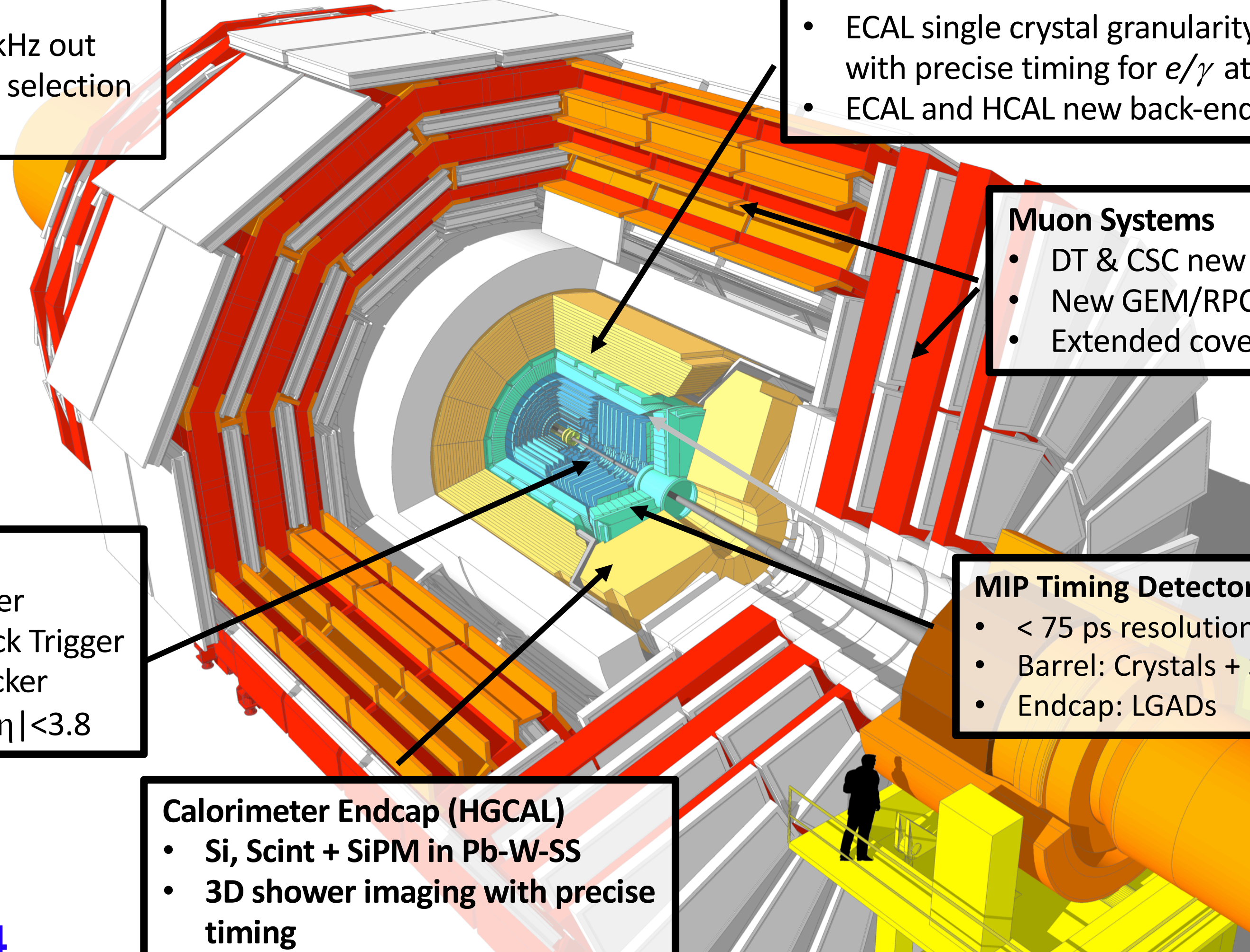
> New detectors, such as picosecond-precision timing detectors, and forward tracking and extended trigger systems, will enable searches to better target new physics with challenging signatures. Alternative data-taking strategies and novel analysis techniques leveraging advances in AI/ML (for example, anomaly detection) will provide access to parameter space that is currently unexplored.

The CMS HL-LHC detector

L1 Trigger/HLT/DAQ
- L1 40 MHz in/750 kHz out
- Tracking for PF-like selection
- HLT 7.5 kHz out

Barrel Calorimeters
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Muon Systems
- DT & CSC new FE/BE readout
- New GEM/RPC
- Extended coverage |η|<3



Tracker
- Si Strip **O**uter **T**racker designed for L1 Track Trigger
- Pixelated **I**nner **T**racker extends coverage |η|<3.8

MIP Timing Detector
- < 75 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

Calorimeter Endcap (HGCAL)
- **Si, Scint + SiPM in Pb-W-SS**
- **3D shower imaging with precise timing**

From: A. Ryd
US CMS 2024

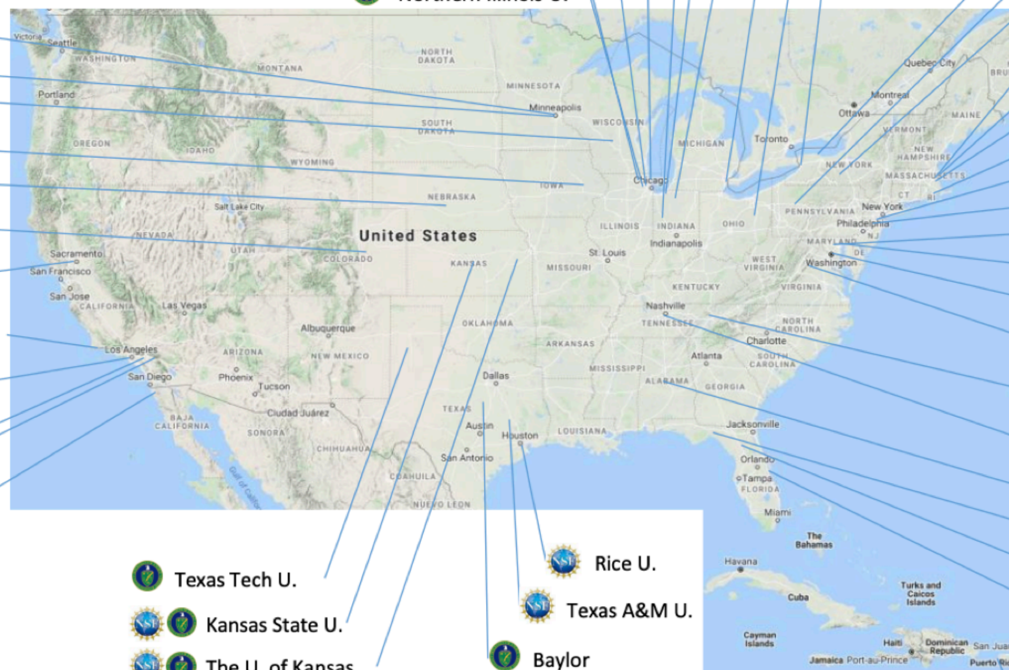
Major effort in the US

Work supported by NSF MREFC

Work supported by the U.S. DOE

- U. of Minnesota
- Bethel U.
- U. of Wisconsin - Madison
- U. of Iowa
- U. of Nebraska - Lincoln
- U. of Colorado Boulder
- U. of California Davis
- U. of California Santa Barbara
- U. of California Los Angeles
- California Inst. of Technology
- U. of California Riverside
- U. of California San Diego

- Purdue U. West Lafayette
- U. of Illinois at Chicago
- Northwestern U.
- Fermilab
- Northern Illinois U.
- Purdue U. Northwest
- U. of Notre Dame
- Wayne State U.
- The Ohio State U.
- SUNY Buffalo



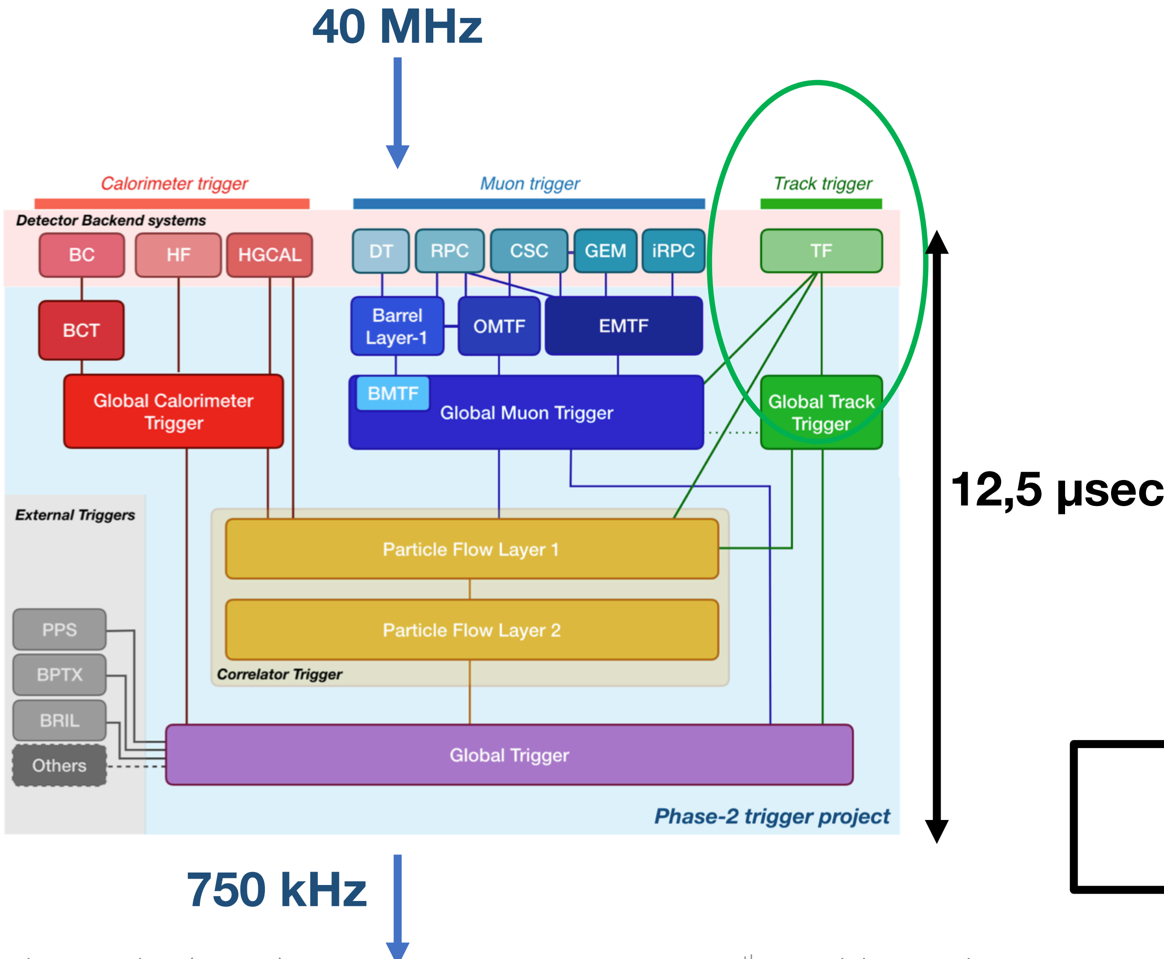
- Texas Tech U.
- Kansas State U.
- The U. of Kansas
- Rice U.
- Texas A&M U.
- Baylor
- U. of Puerto Rico - Mayaguez

- U. of Rochester
- Carnegie Mellon U.
- Cornell U.
- Northeastern U.
- Massachusetts Inst. of Technology
- Boston U.
- Brown U.
- Rutgers U.
- Princeton U.
- Johns Hopkins U.
- U. of Maryland
- The Catholic U. of America
- U. of Virginia
- The U. of Tennessee, Knoxville
- Vanderbilt U.
- U. of Alabama
- Florida State U.
- U. of Florida
- Florida Inst. of Technology

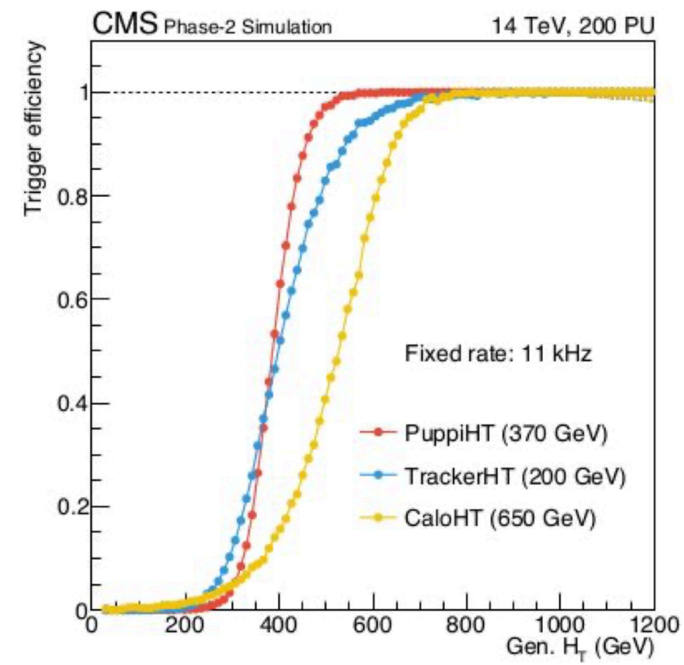
HL-LHC: “Offline-like” reco @ L1T

FNAL/LPC/US led

- 1st time: Tracking @L1T



Huge Physics potential

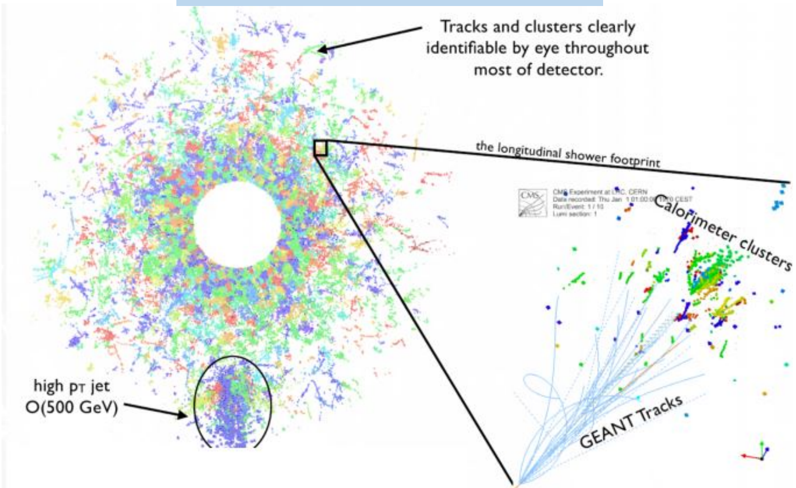


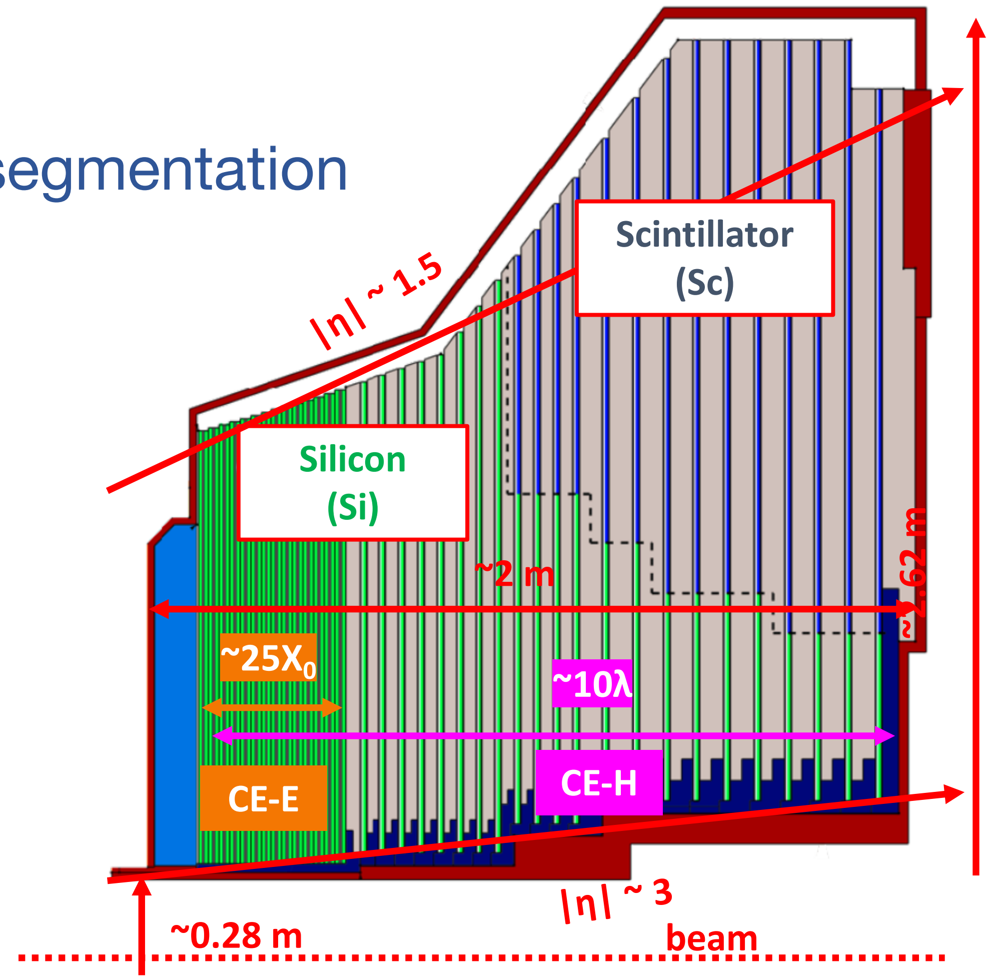
AI/ML on the edge [see Abhijith’s talk yesterday]

HGCAL

- Physics-driven design
  - Fine lateral and longitudinal segmentation
  - precision timing capabilities

Lot's of potential





- Major challenge: R&D, construction, as well as exploit its potential (particle reconstruction)
- FNAL/US: In the frontline of all aspects of the project

Last but not least: The LPC center

- The **L**arge Hadron Collider **P**hysics **C**enter: “**LPC**”
  - Located: 10^{th} and 11^{th} floor of Wilson Hall
  - Very vibrant community
    - AI Fellows, Distinguish researchers, Graduate Fellows,
    - Guest & Visitors (& Friends)
  - Learning hub for younger and more senior scientists
    - Several schools, meetings, forums

CMS DAS 2024

Outlook

- The LHC (and the experiments) is our best tool to provide insights to many of the big open questions

- We are at the beginning: <10% of total expected data
  - We discovered the Higgs
  - Exhaustively searching for direct evidence of New Physics
  - We are challenging SM probing processes in a range of $O(10^{13})$

- Oftentimes **exceed initial expectations**
  - Huge effort to exploit the **true** potential of LHC and CMS

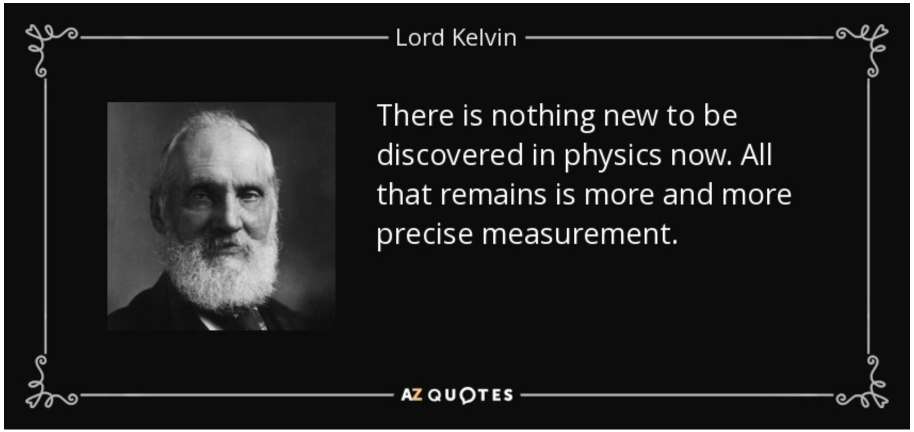
- NB: We cannot guarantee **“discoveries”**
  We can guarantee **“deliverables”**

Outlook

- Still: Everything looks very SM like, but…

Outlook

- Still: Everything looks very SM like, but…



Outlook

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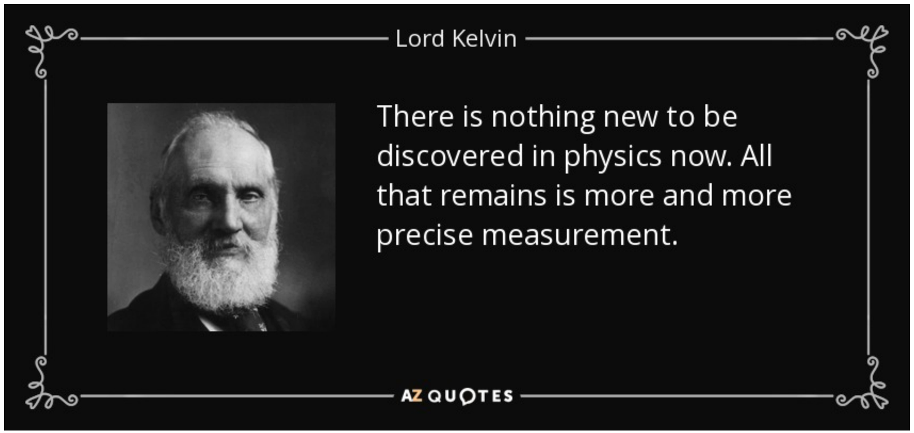

.. and we all know what followed after this statement