The search for new physics at the energy and lifetime frontiers

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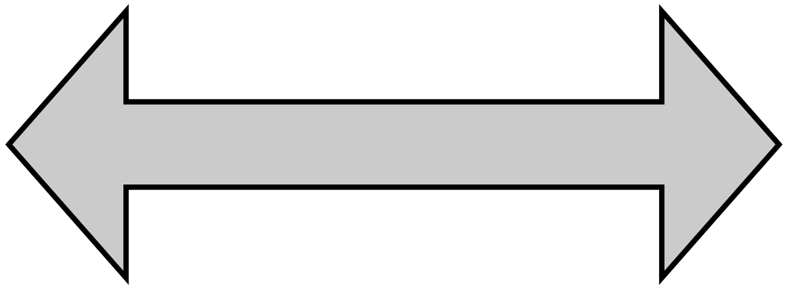
NEWTON

Celestial Gravity



$$\mathbf{F} = -\frac{G_{\mathrm{N}} m_1 m_2}{\mathbf{r}^2}\hat{\mathbf{r}}$$

Terrestrial Gravity

CAVENDISH

- In 1797-98, 110 years after Newton published *Principia*, Cavendish performed his famous torsion experiment

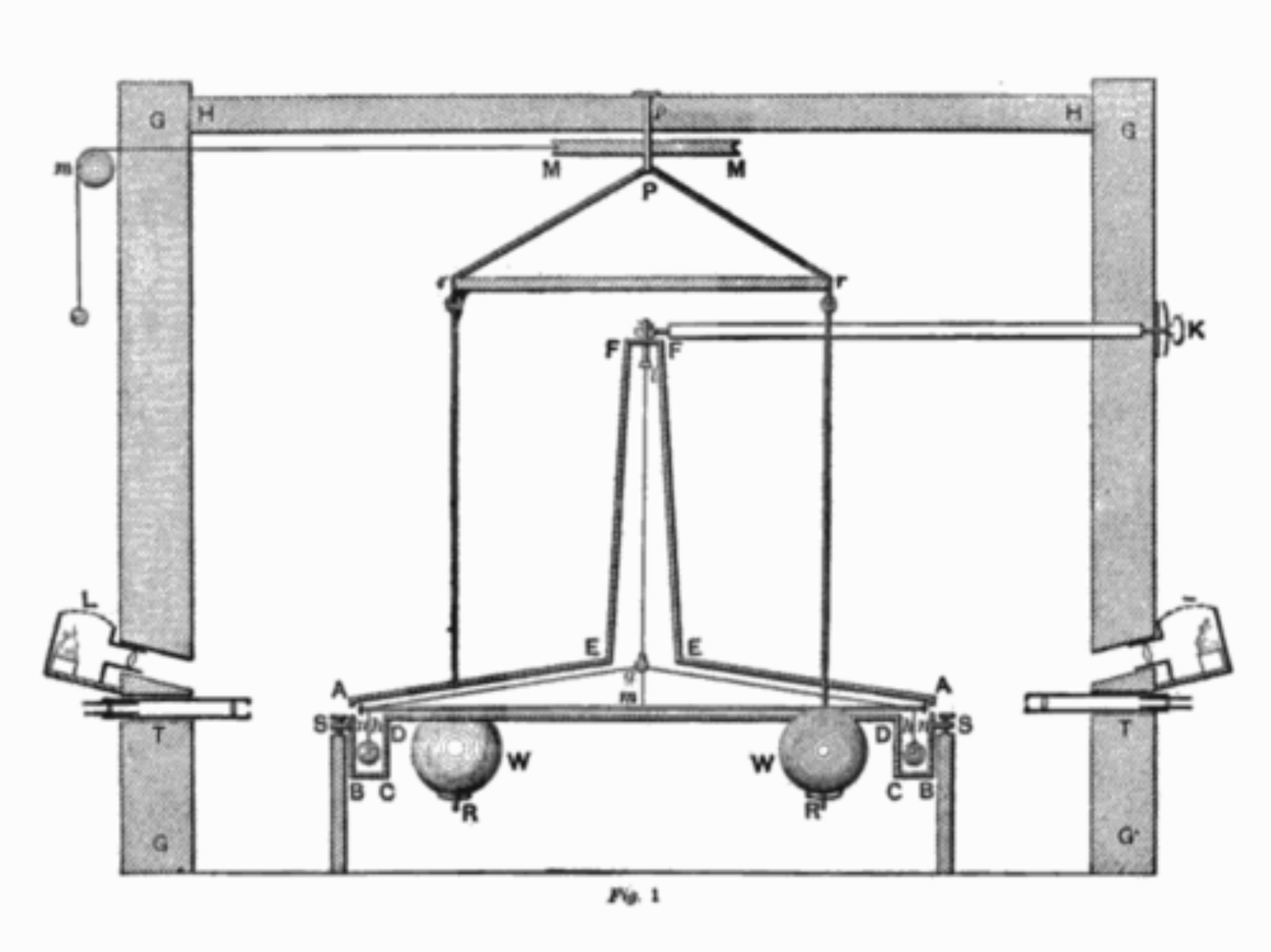
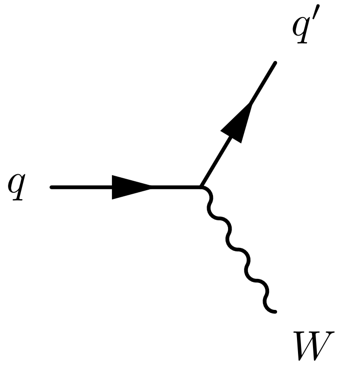


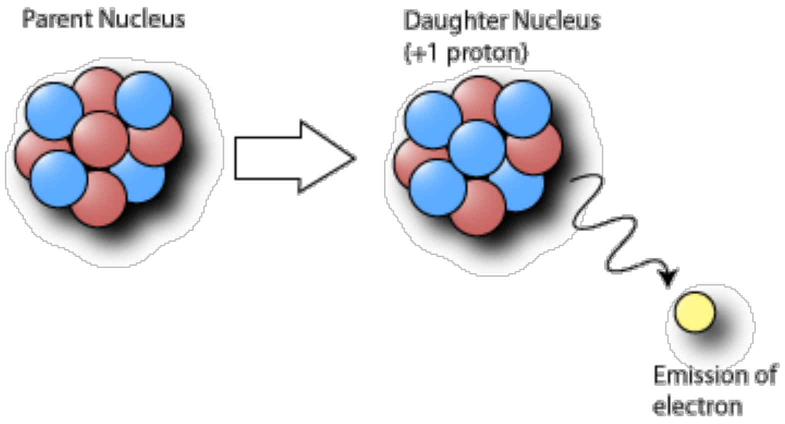
Fig. 1

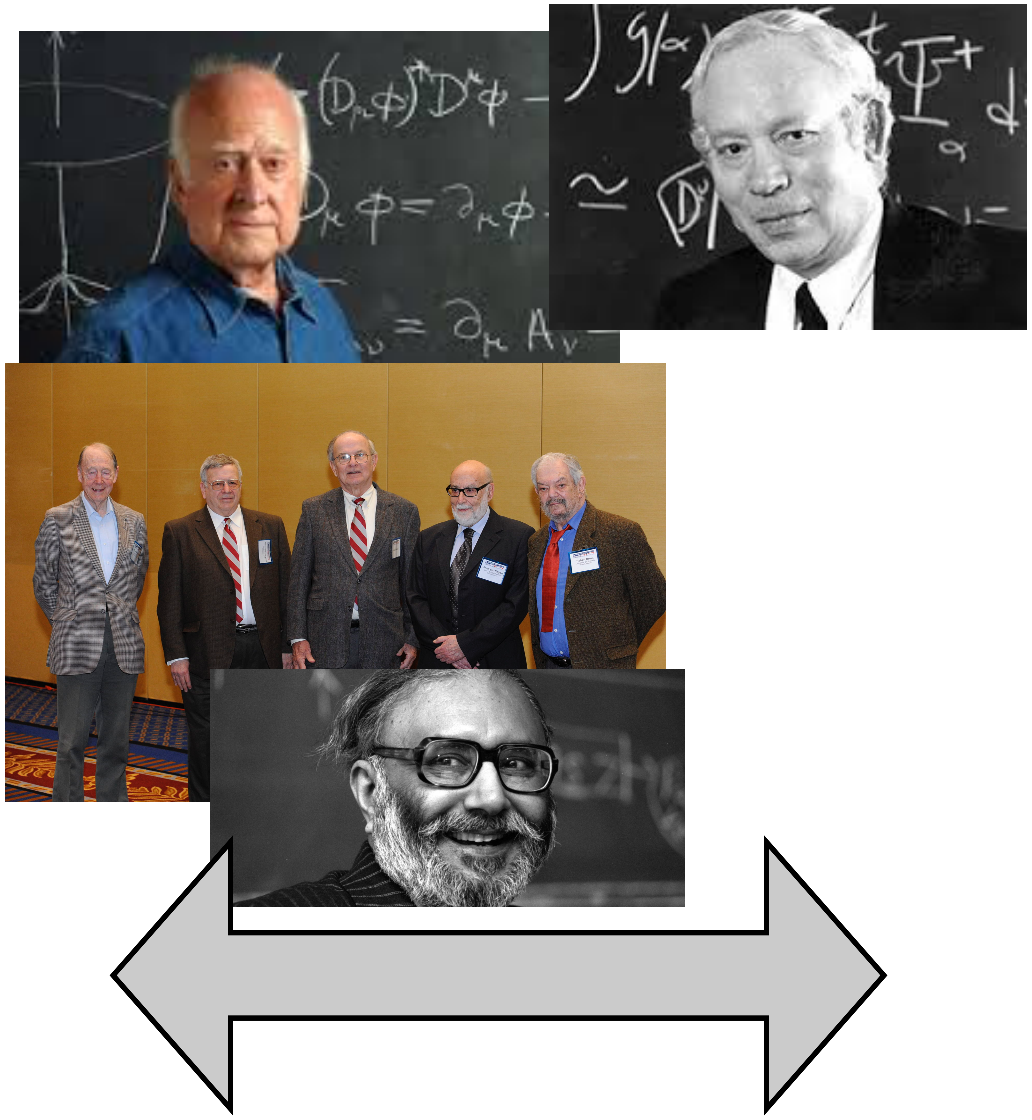
  - this confirmed the principle of Universal gravitation and determined Newton’s constant

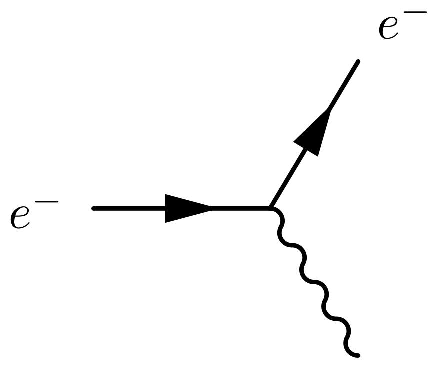
HIGGS



Weak Force



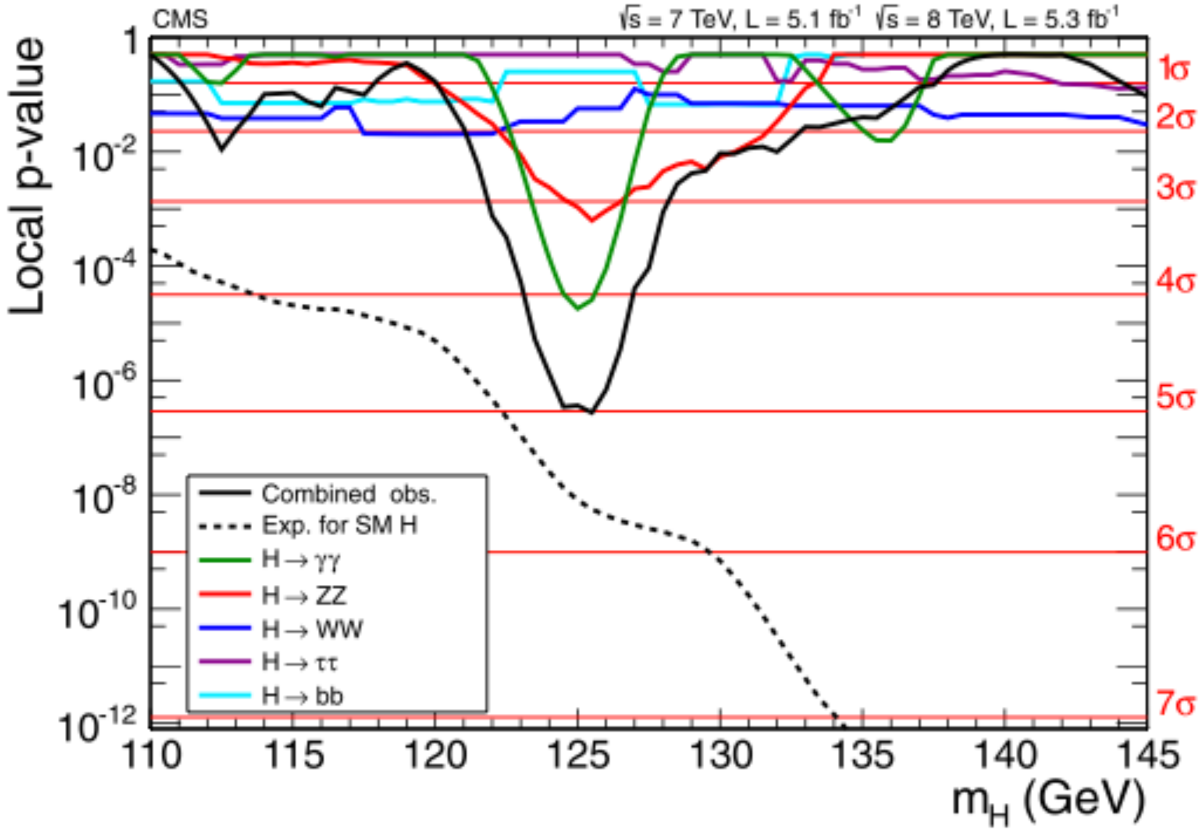


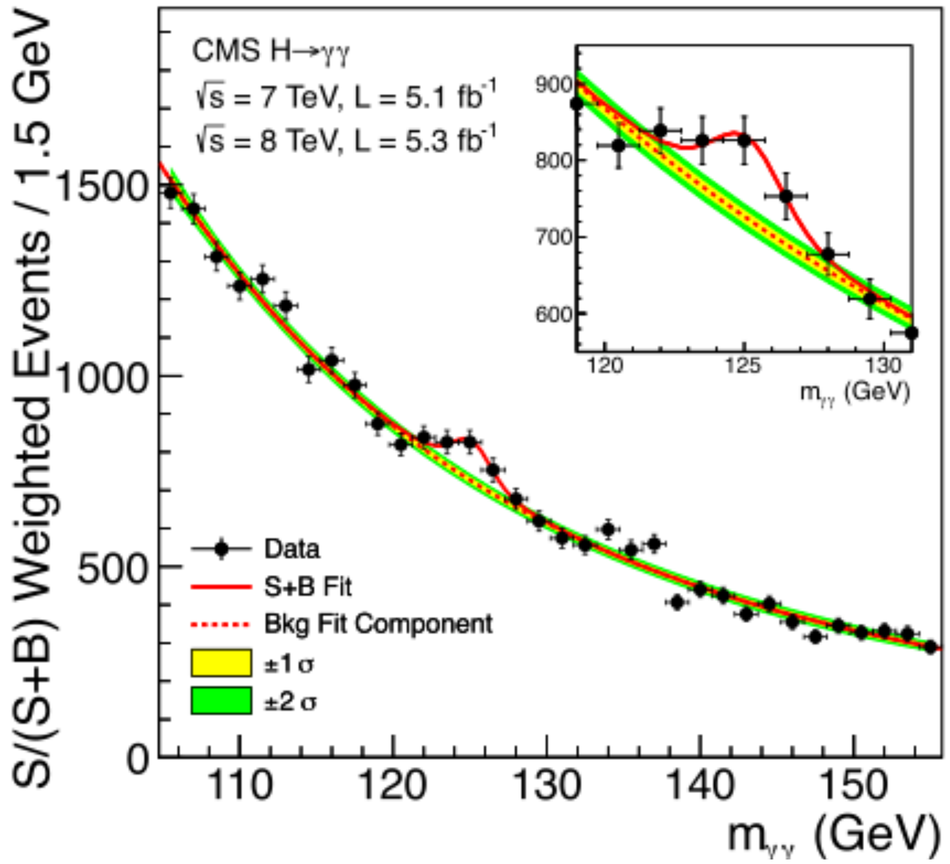


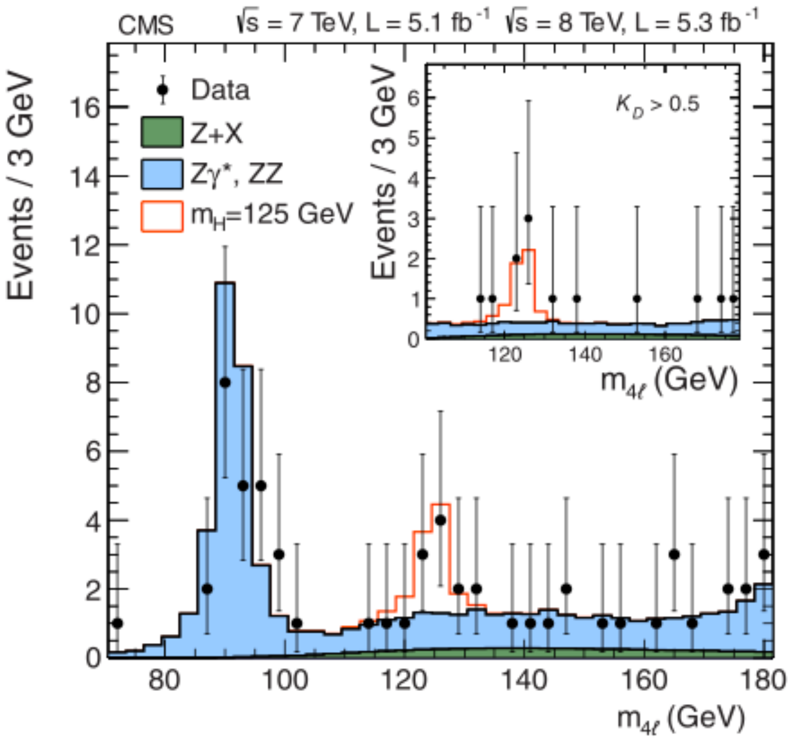
Electromagnetic Force

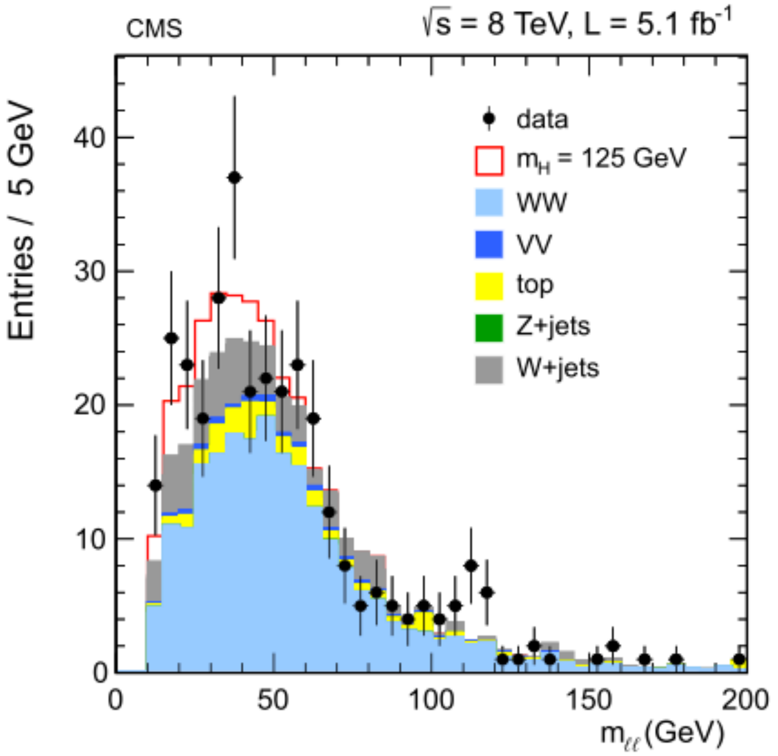
$$S(\phi, A) = \int -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + |(\partial - iqA)\phi|^2 - \lambda(|\phi|^2 - \Phi^2)^2.$$

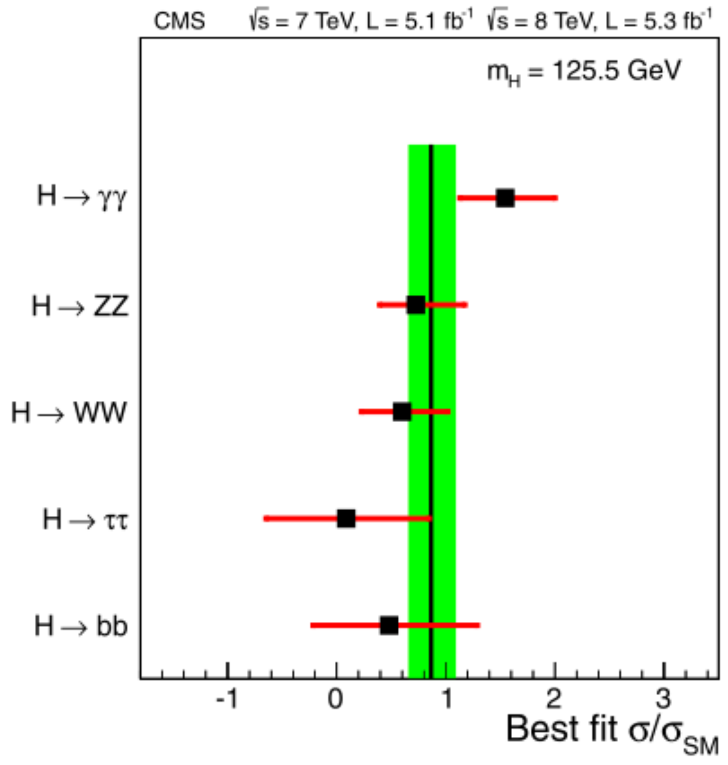
DISCOVERY ~50 YEARS LATER







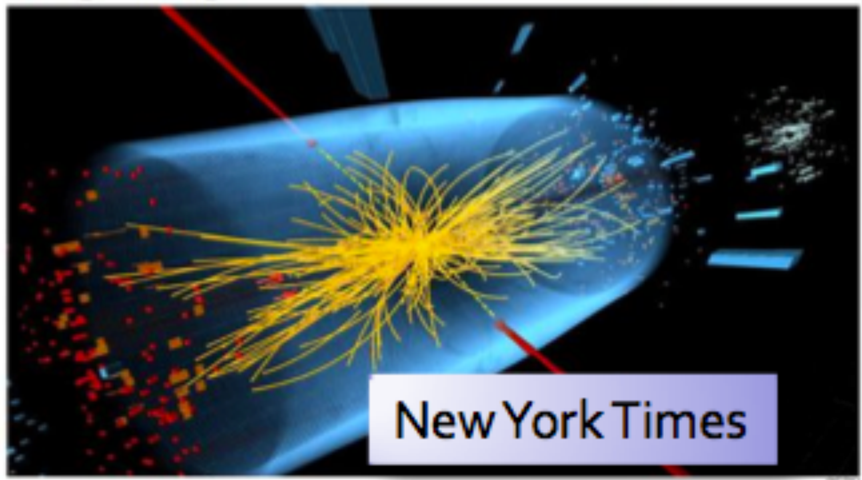




DISCOVERY ~50 YEARS LATER


CERN Press Conference

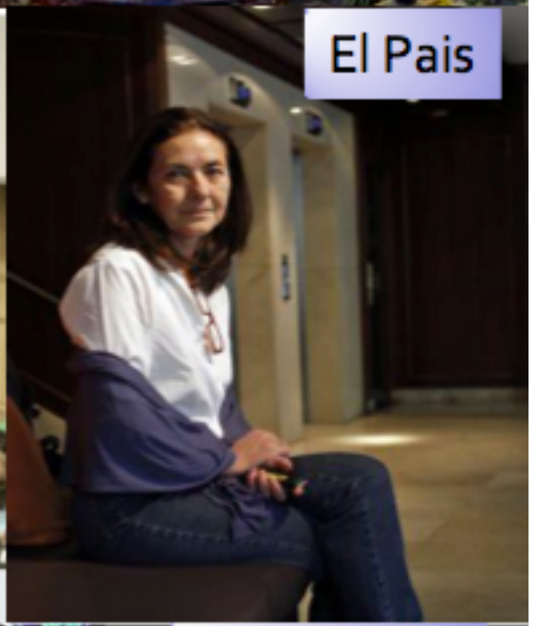
A Blip That Speaks of Our Place in the Universe


New York Times


La Republicca


ABC Breakfast News, Aus.


The Economist


El Pais


CERN Press Conference


CERN Press Conference

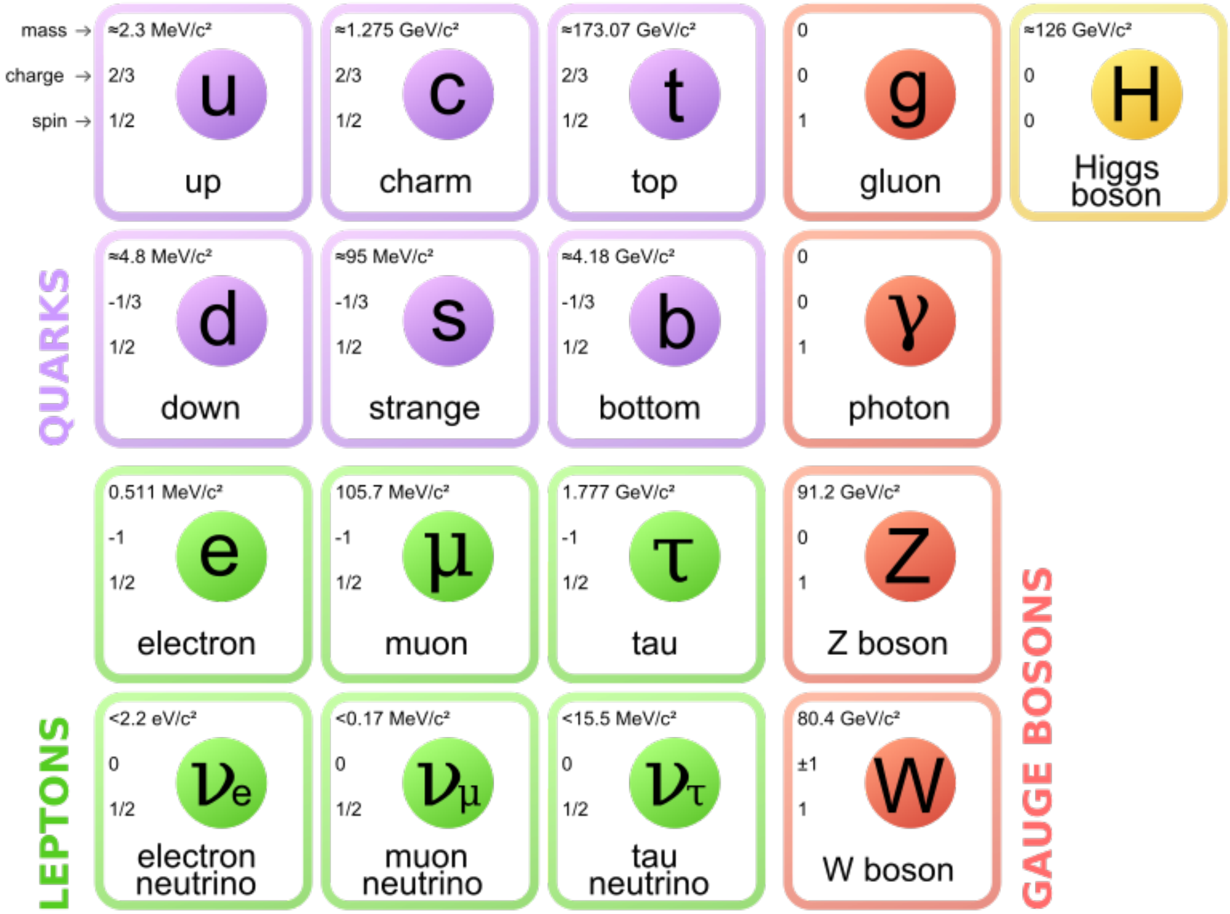

Paris Match

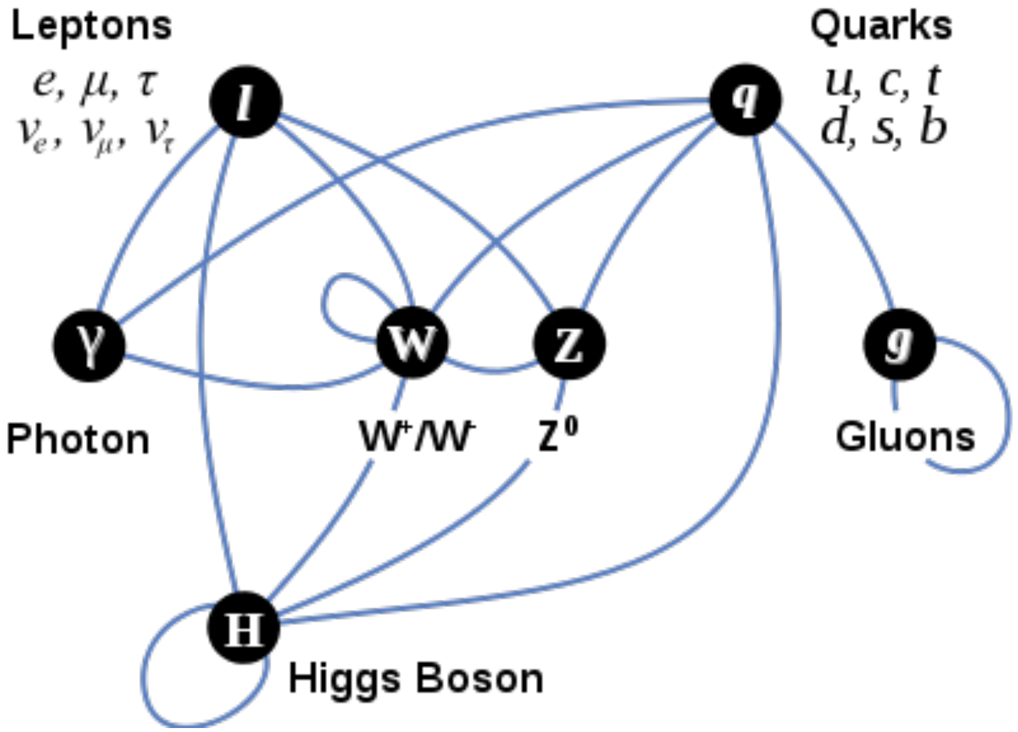
La salle de contrôle du Large Hadron Collider au Cern. | Photo REUTERS/Denis Balibouse

What are the Big Questions of Particle Physics?

PARTICLE PHYSICS

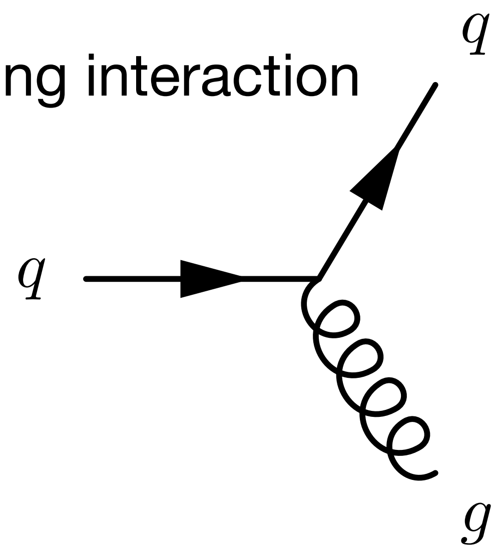
- The standard model of particle physics describes a remarkable range of phenomena
  - The interactions of particles are described by Quantum Field Theory (i.e. Quantum Mechanics + Special Relativity)
  - Matter and energy, at the lowest level of organization, is composed of some combination of quarks and leptons interacting via force carrying bosons



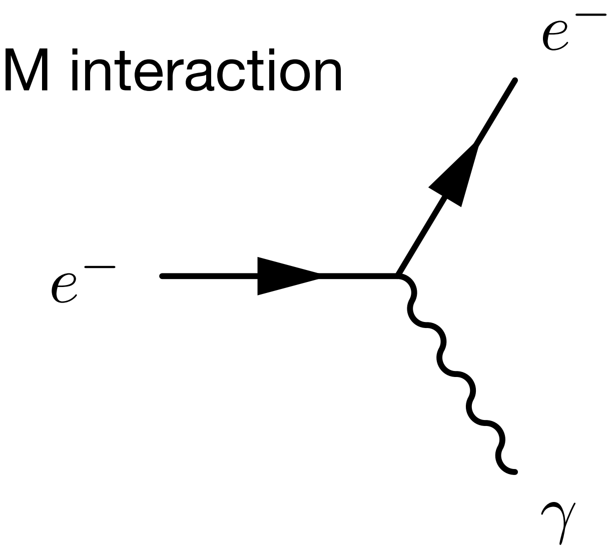


FOUR FORCES OF NATURE

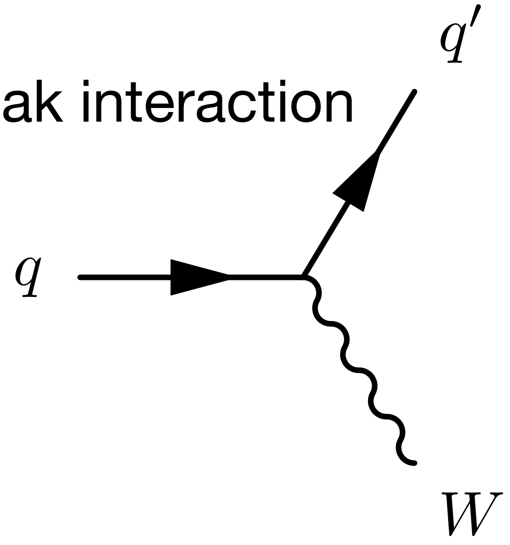
- Strong Force (~10)
  - Keeps the nucleons in the atom together
  - All “colored” particles (e.g. quarks/gluons) interact via strong force
  - Force is mediated by the gluon
- Electromagnetic Force (~10^{-2})
  - All “charged” particles interact under this force
  - Field description discovered by Maxwell
  - Force is mediated by the photon
- Weak Force (~10^{-13})
  - Governs many radioactive decays ($n \rightarrow p^{+} e^{-} v$)
  - Both leptons and quarks interact under this force
  - Force is mediated by “heavy photons” ($W^{\pm}$ and Z^{0})
- Gravitational Force (~10^{-42})
  - Not a part of the standard model
  - non-renormalizable quantum theory
  - Force is mediated by the graviton



strong interaction



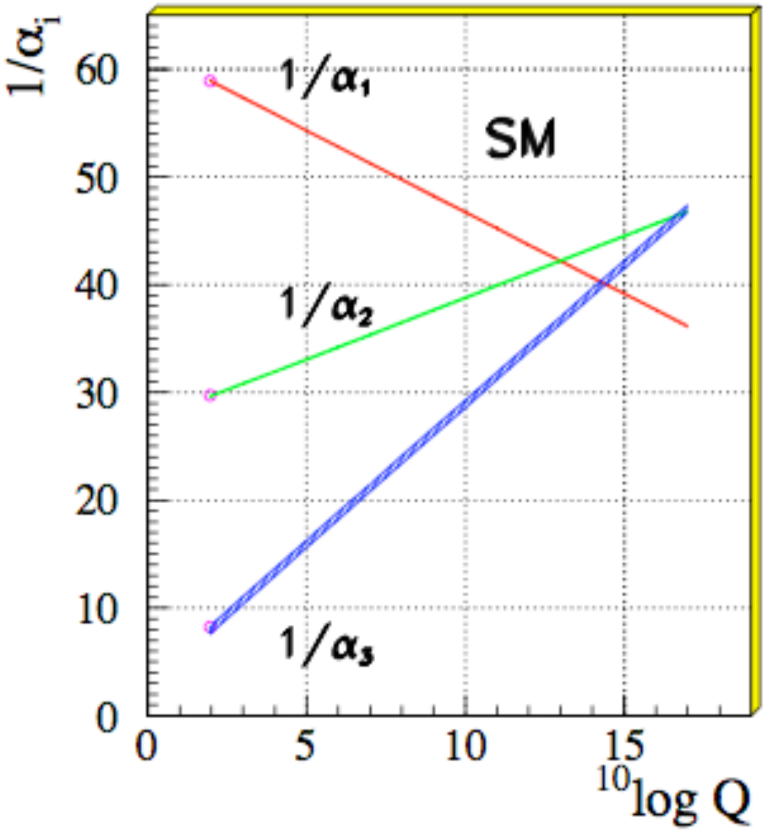
EM interaction

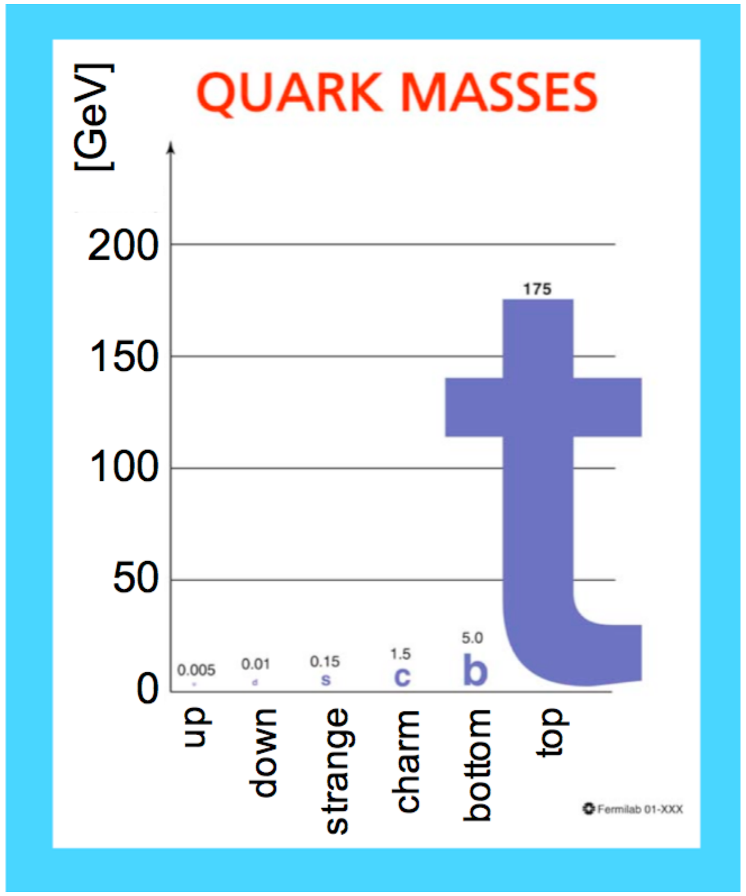


Weak interaction

PROBLEMS WITHIN THE STANDARD MODEL

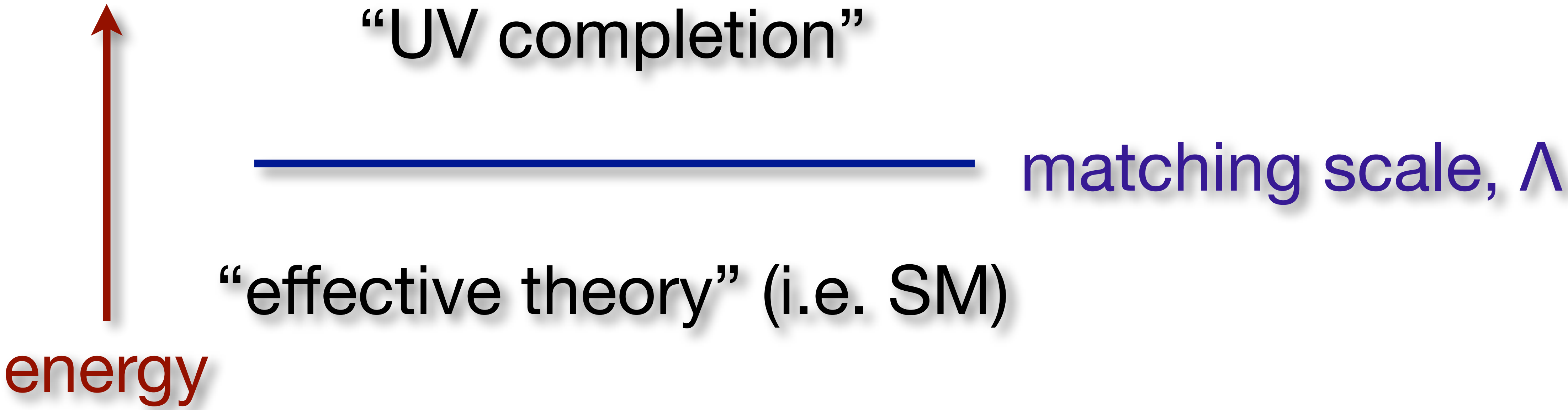
- The standard model doesn't explain a lot of things...
  - There are many free parameters (CKM phases, fermion masses)
  - Why is there a generational structure? Why three generations?
  - Why is the top quark so massive?
  - The gravitational force is neglected entirely from the SM
  - No coupling constant unification





THE HIERARCHY PROBLEM

- The SM is really *just an effective theory* which is completed in the UV by a new theory that takes over



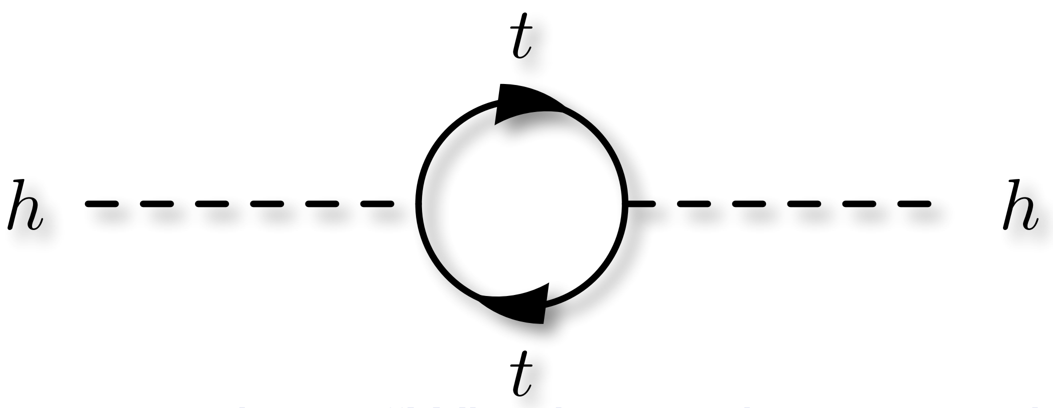
“UV completion”

matching scale, Λ

“effective theory” (i.e. SM)

energy

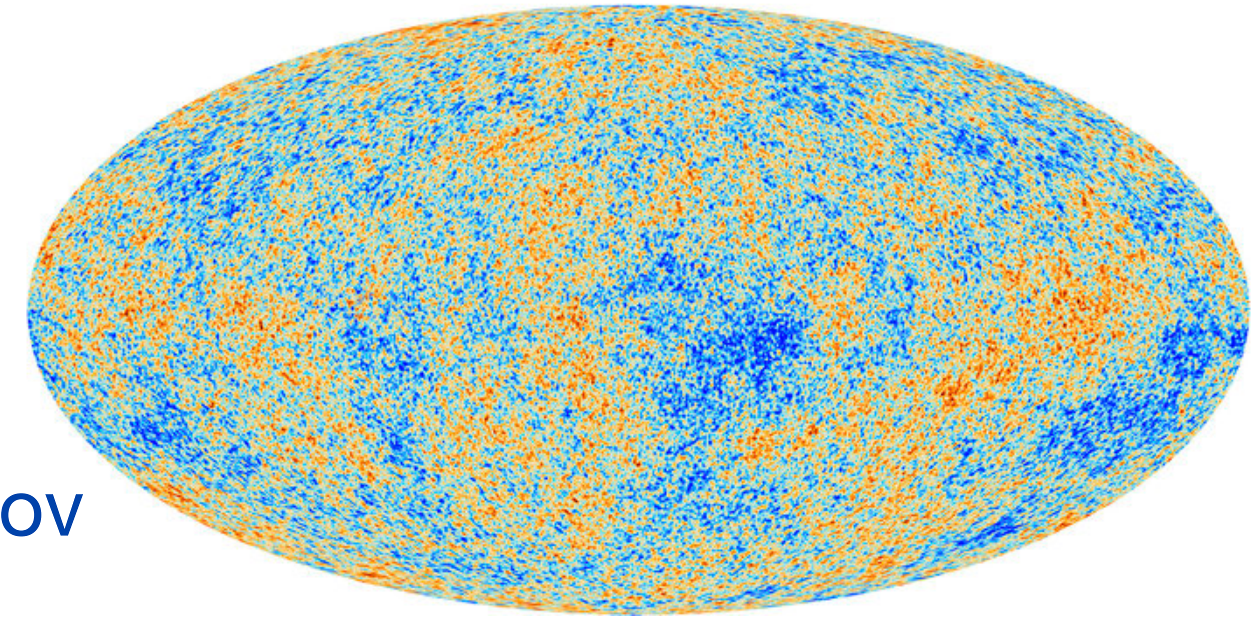
- as a fundamental scalar, the Higgs mass acquires quantum mechanical corrections to it’s mass, proportional to the matching scale: $m^2_h \approx m^2_0 + k\Lambda^2$
  - if the scale is the Planck scale, the corrections are ~10^{34} times larger than the Higgs mass itself



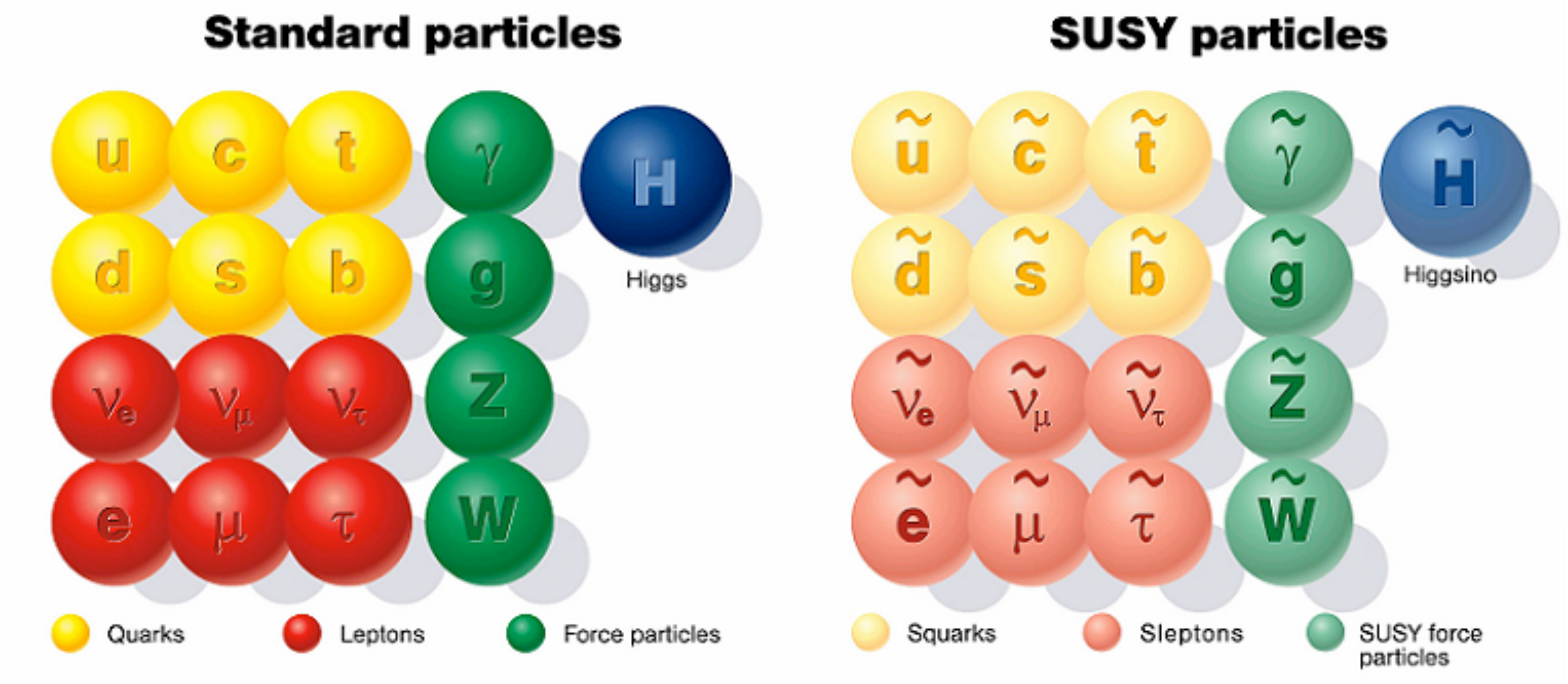
- The Hierarchy problem, colloquially: “Why is gravity so weak?”

PROBLEMS FROM COSMOLOGY

- Dark Matter
  - From studying microwave background:
    - ~70% of the universe is dark energy
    - ~5% is baryonic matter
    - ~25% is some non-baryonic cold dark matter
  - Confirmation from galactic rotation curves and gravitational lensing
- Baryon (matter/antimatter) Asymmetry
  - More CP violation (and phase transition) need to satisfy Sakharov conditions

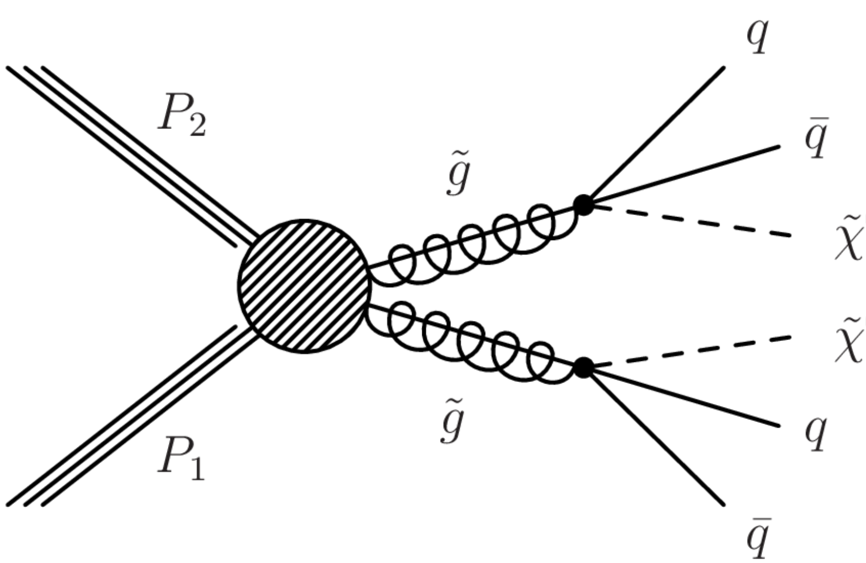


SUPERSYMMETRY

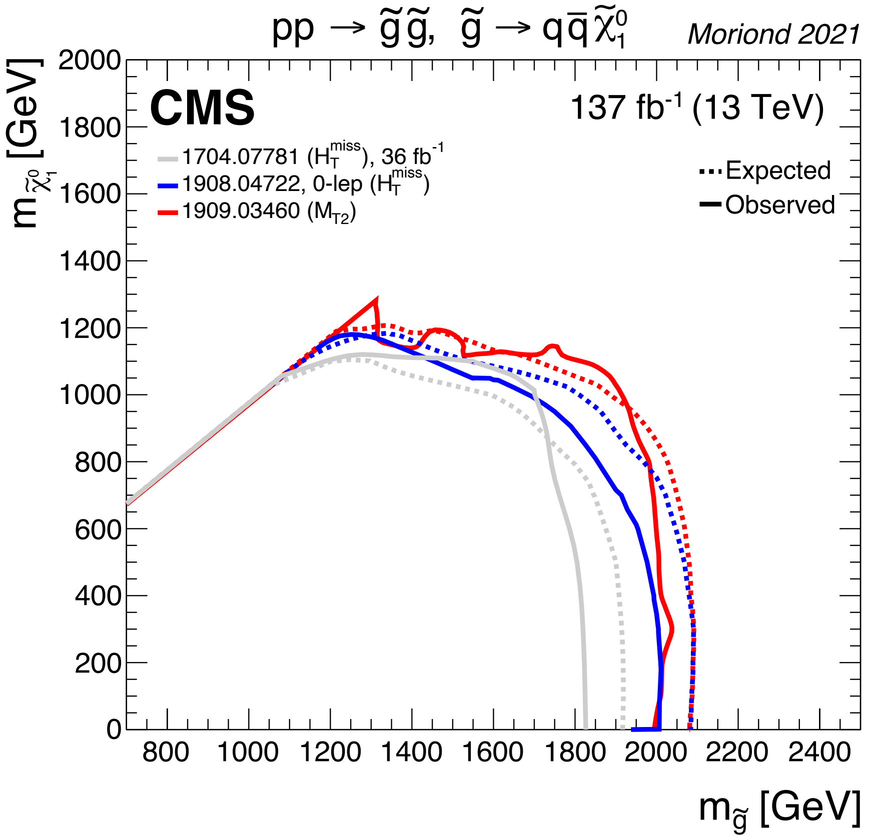


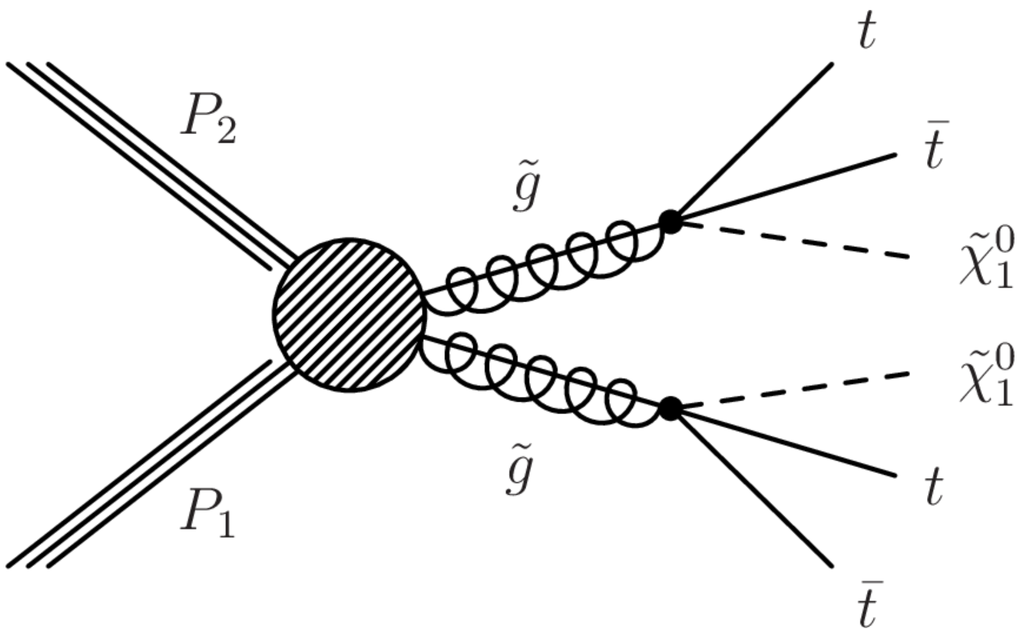
- The leading Beyond the SM (BSM) theory
  - provides gauge-coupling unification
  - natural dark matter candidate (if lightest super-particle is neutral and stable)
  - solves the Hierarchy problem
    - Only problem is that we haven't seen it yet..

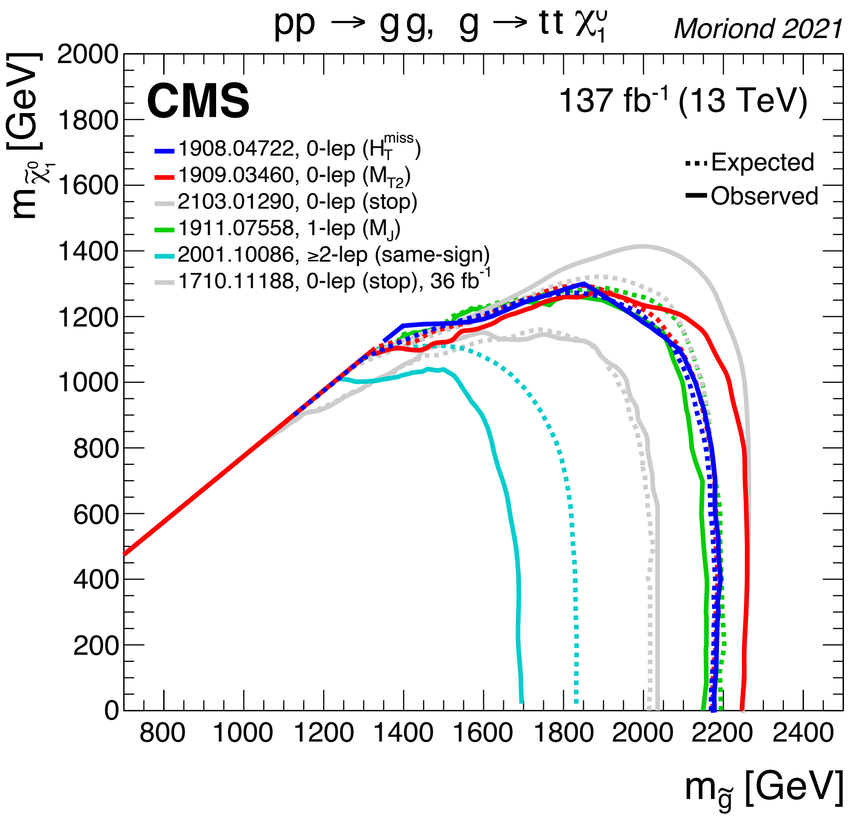
GLUINO LIMITS



- CMS and ATLAS have together conducted *hundreds* of searches for gluinos, stops, sbottoms, sleptons, electroweakinos, …

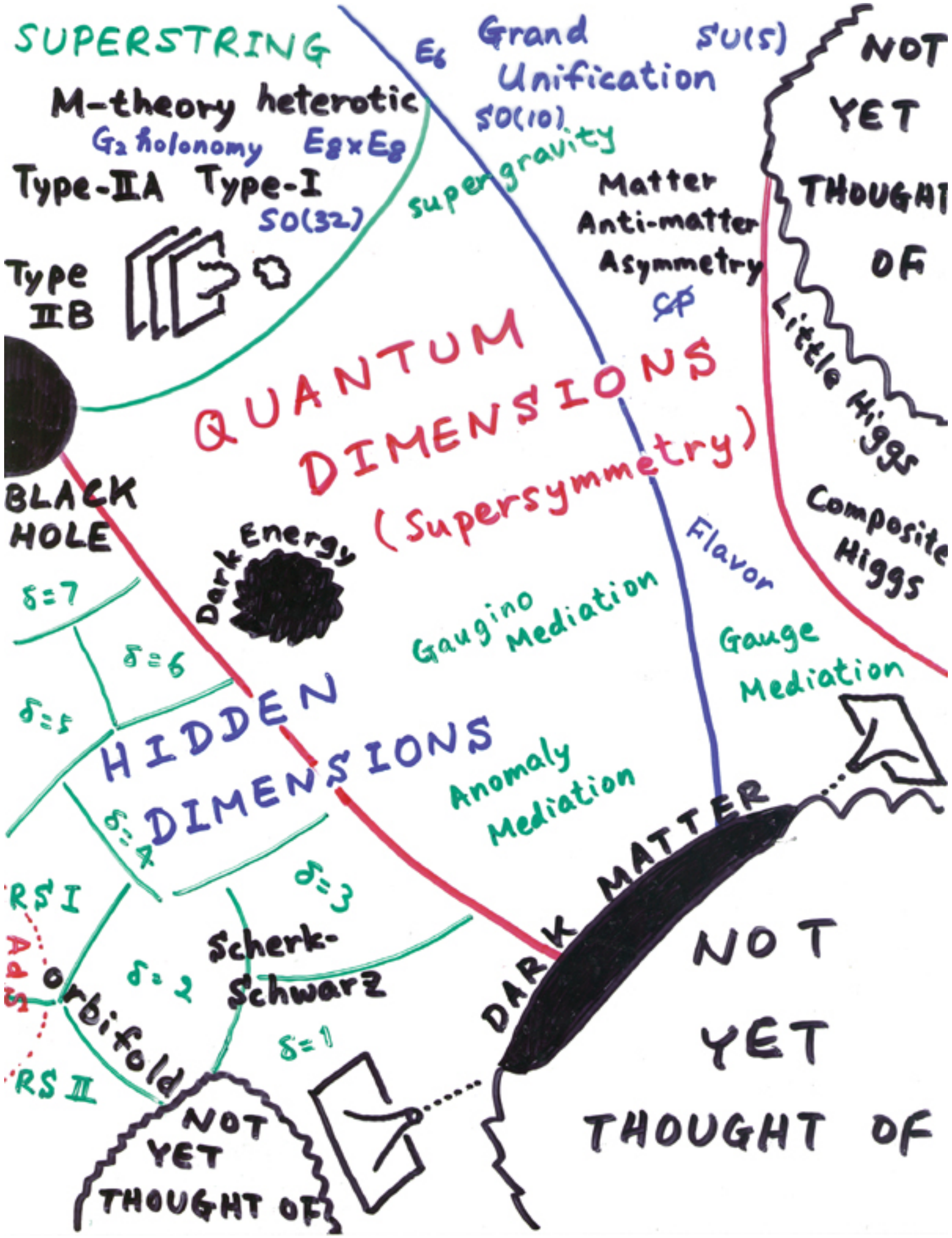




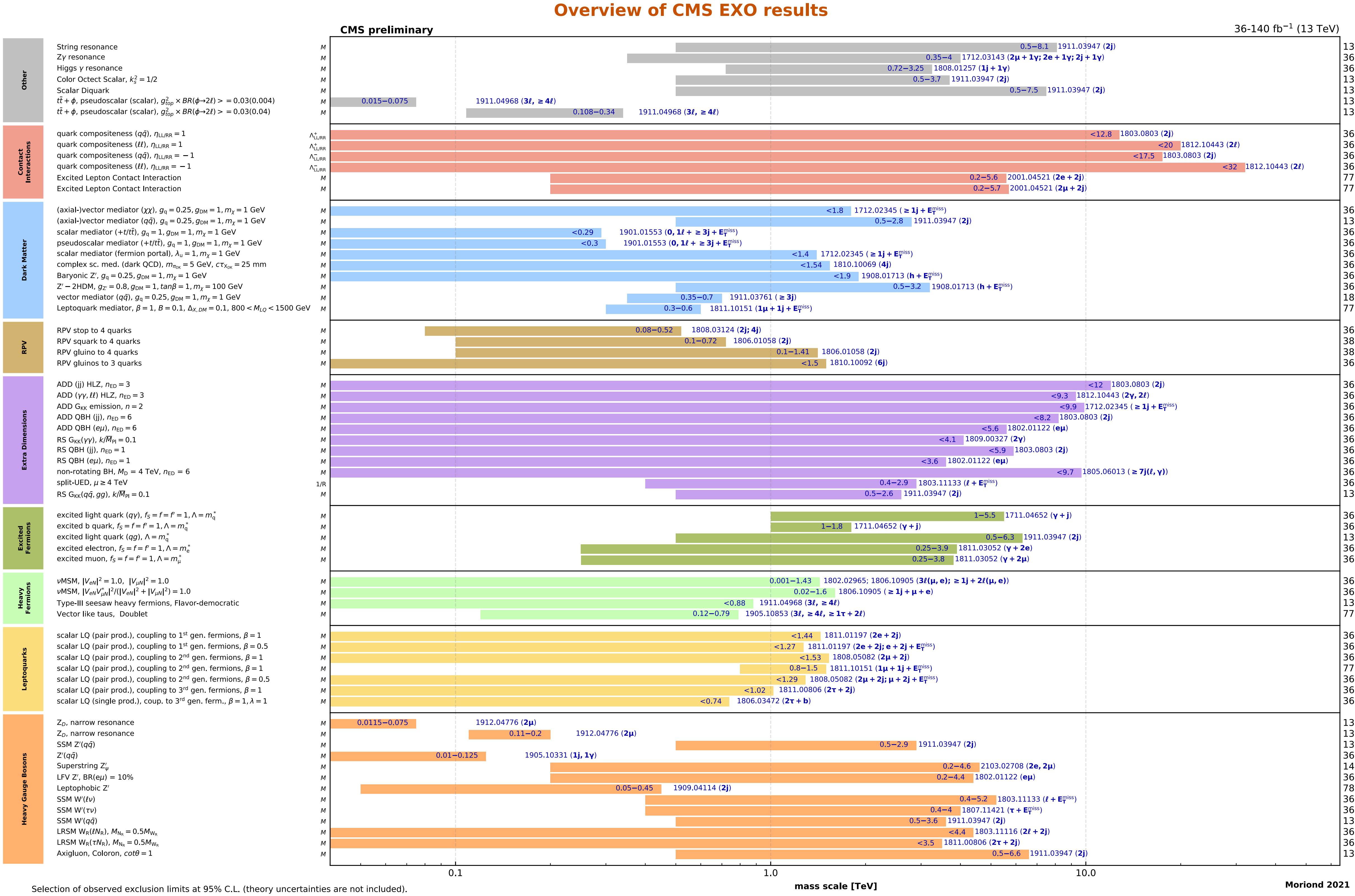


MODELS, MODELS, EVERYWHERE…

- Of course, SUSY is just one prominent example of a model
  - There are many other models that can solve some, all, or none of the problems I've already mentioned
    - maybe the most likely model is "not yet thought of"…



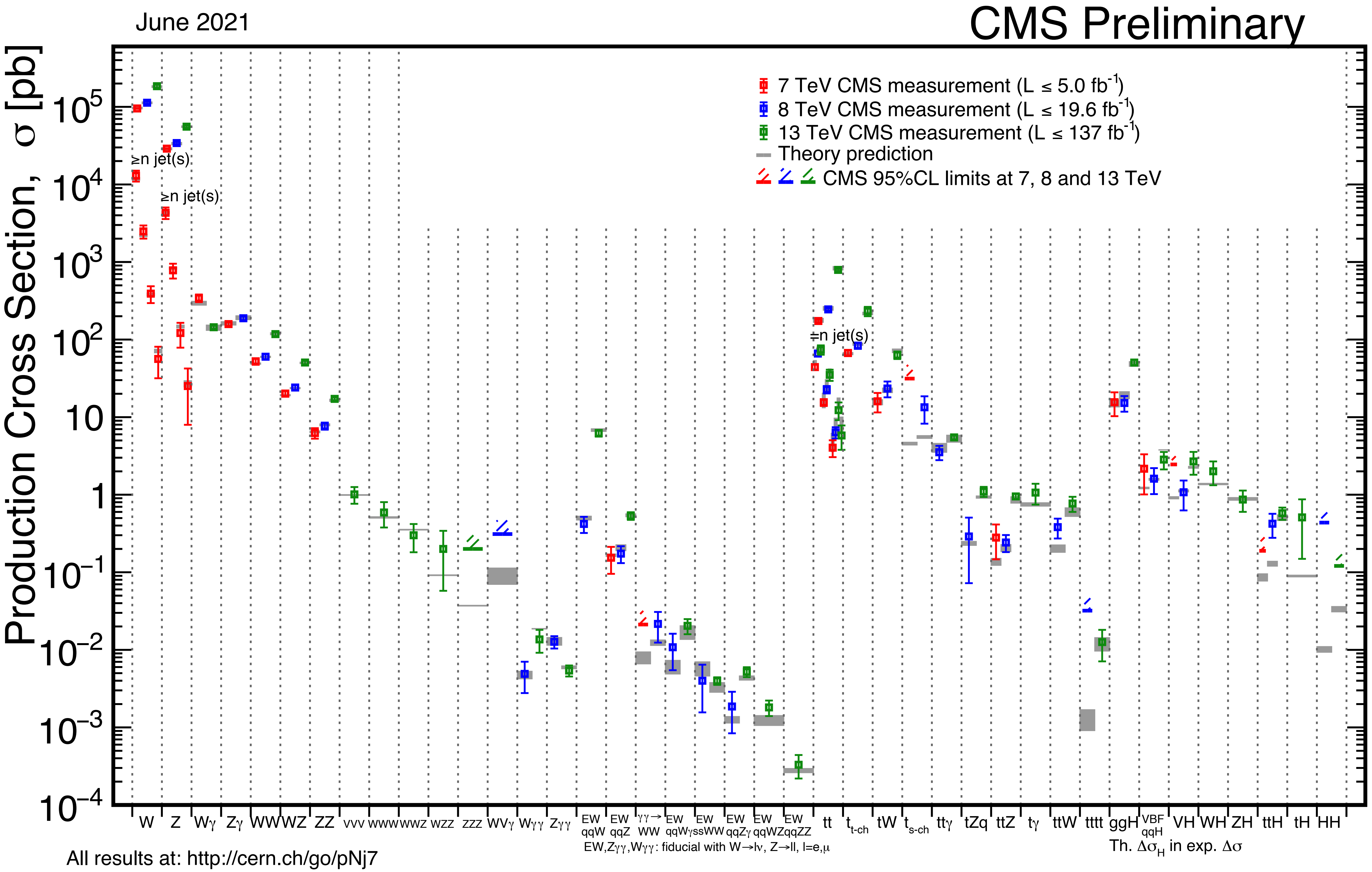
SEARCHES FOR NEW PHYSICS



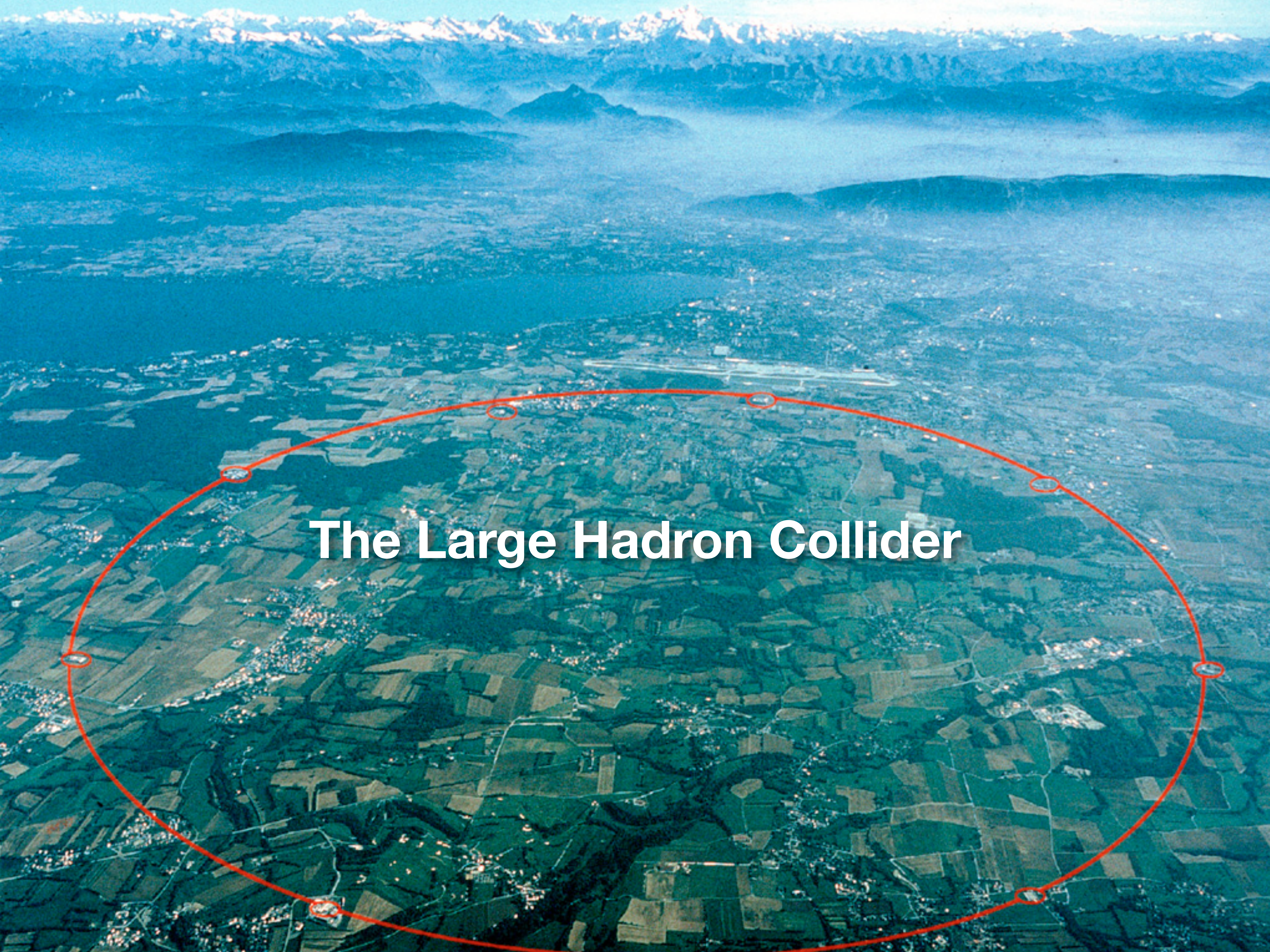
Overview of CMS EXO results

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

STANDARD MODEL EXCELLENCE



The Large Hadron Collider



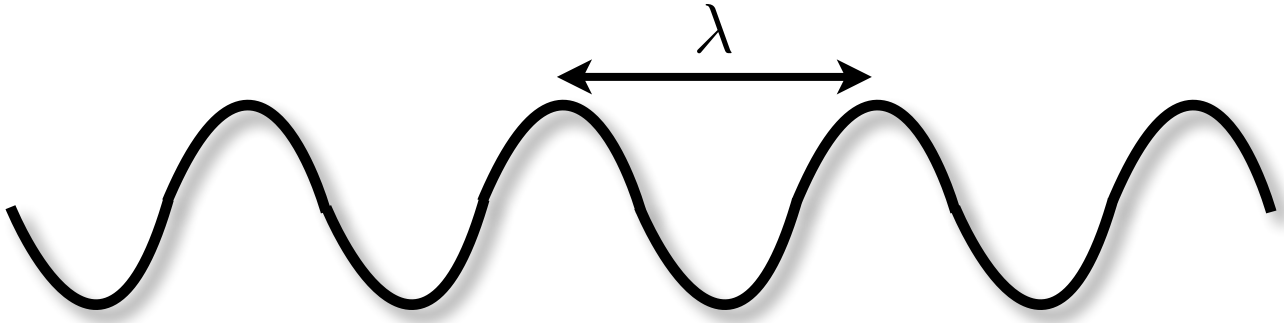
PARTICLE COLLIDERS AS MICROSCOPES

- Wave-particle duality: particles exhibit both particle- and wave-like behavior

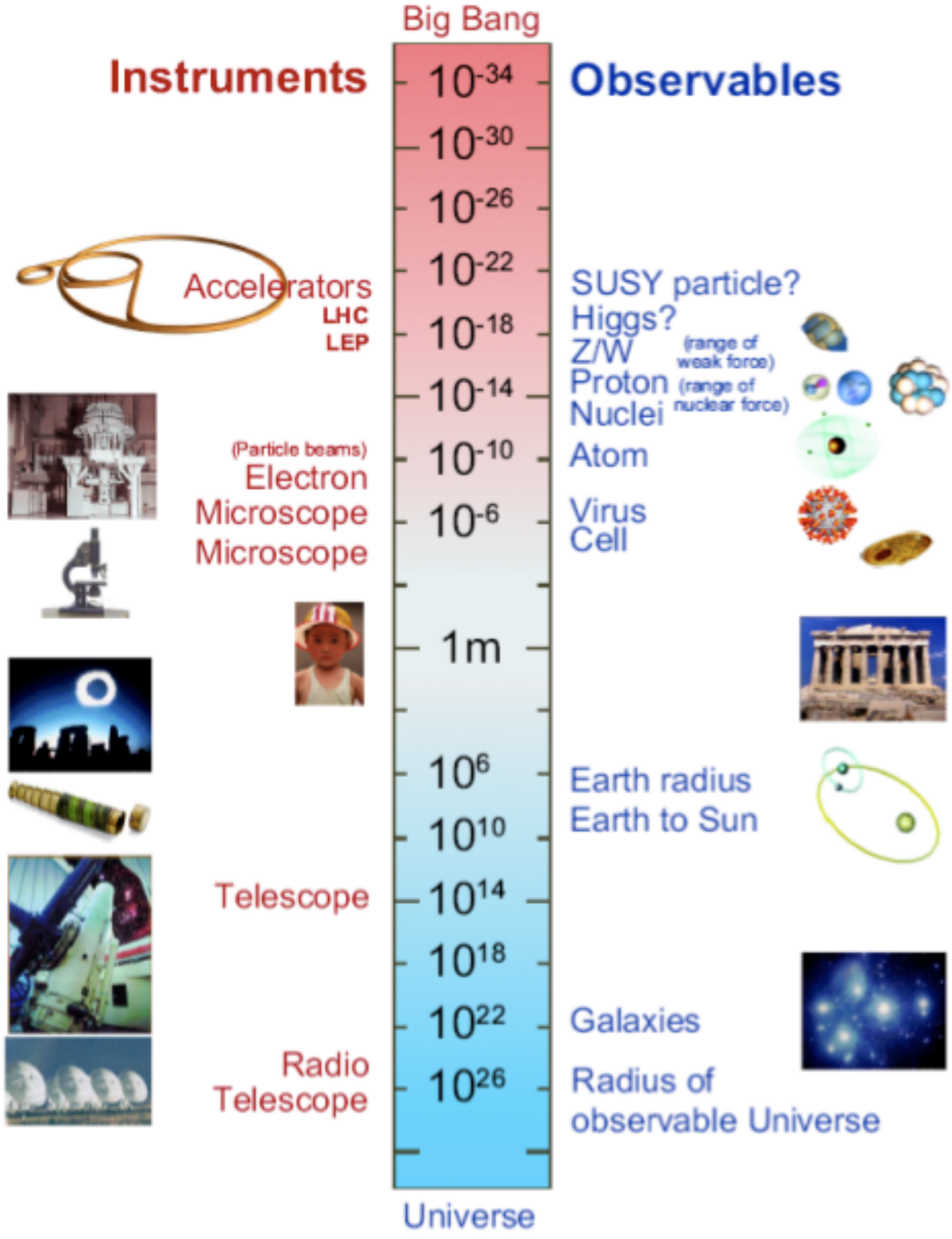
Planck's constant

particle momentum → $p = \frac{h}{\lambda}$ ← wavelength

- If you want to probe short length scales, use high momenta particles!

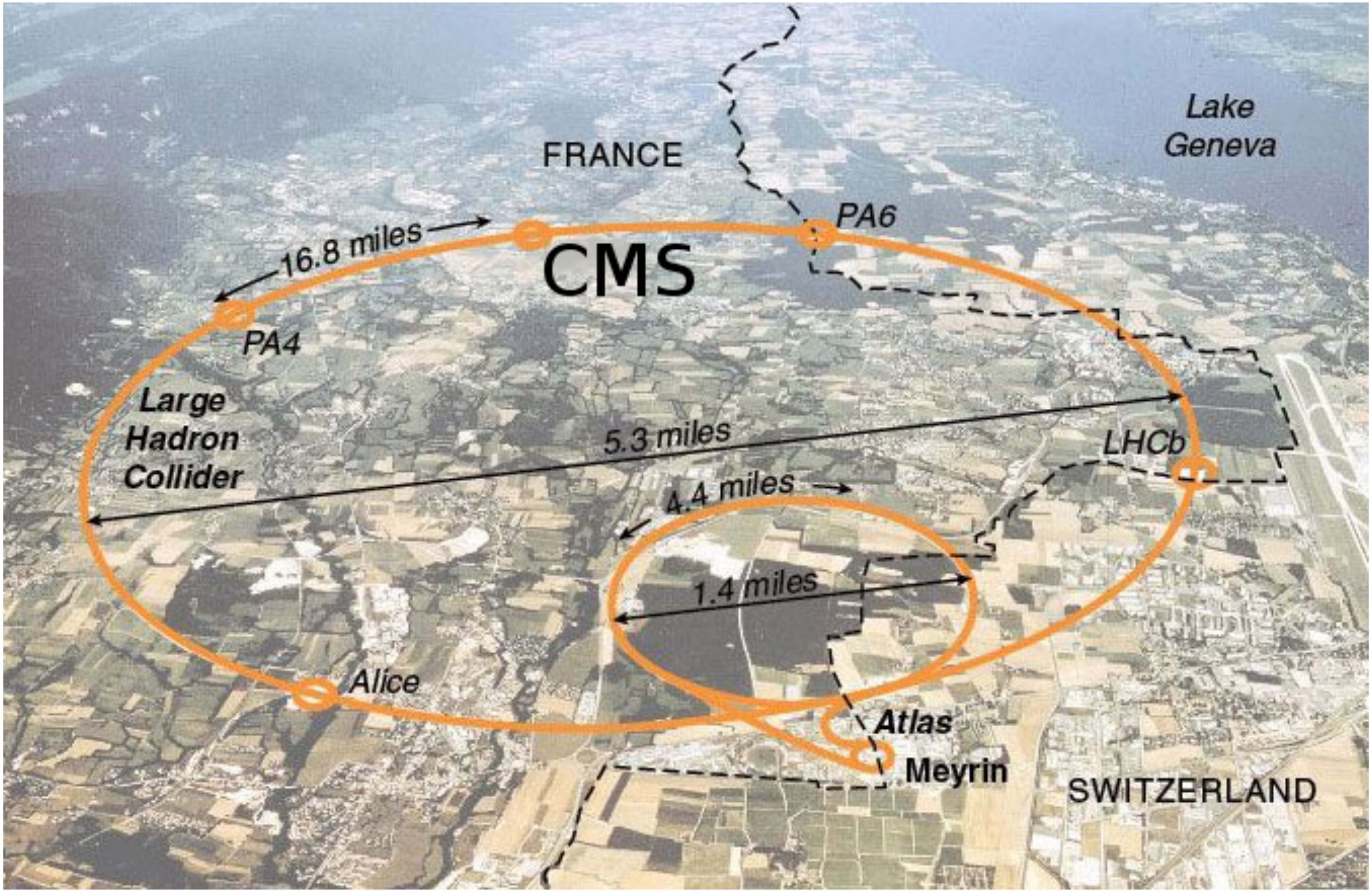


- We collide high energy protons to study the smallest length scales (particles)

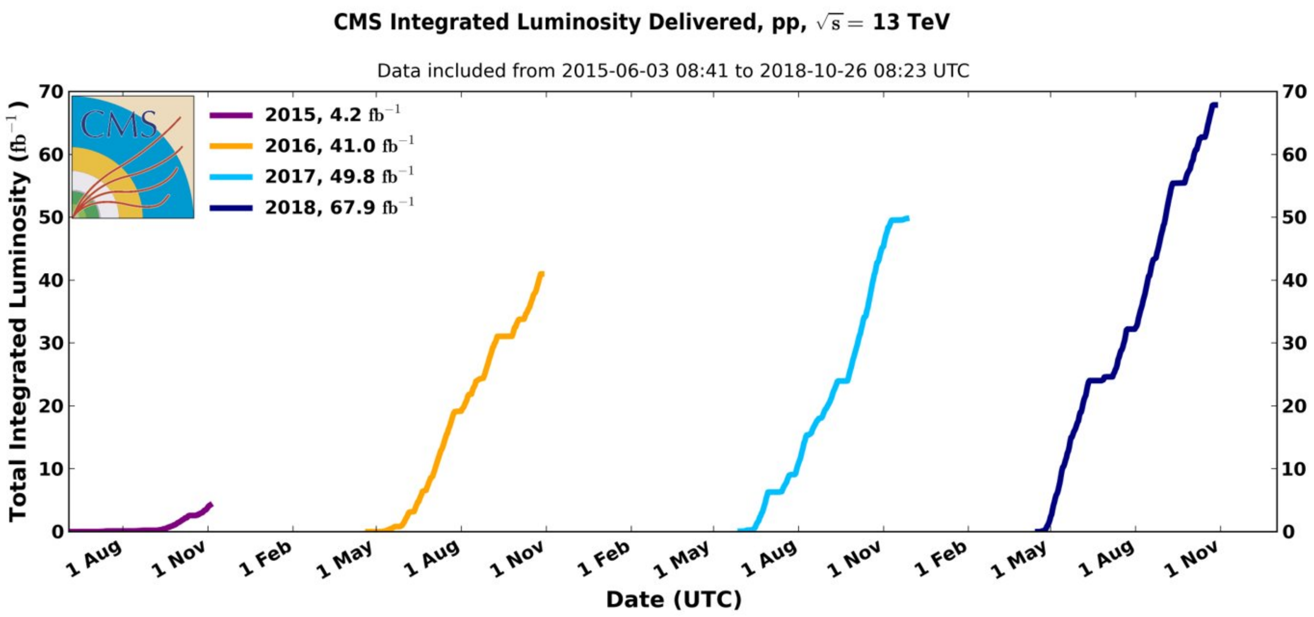


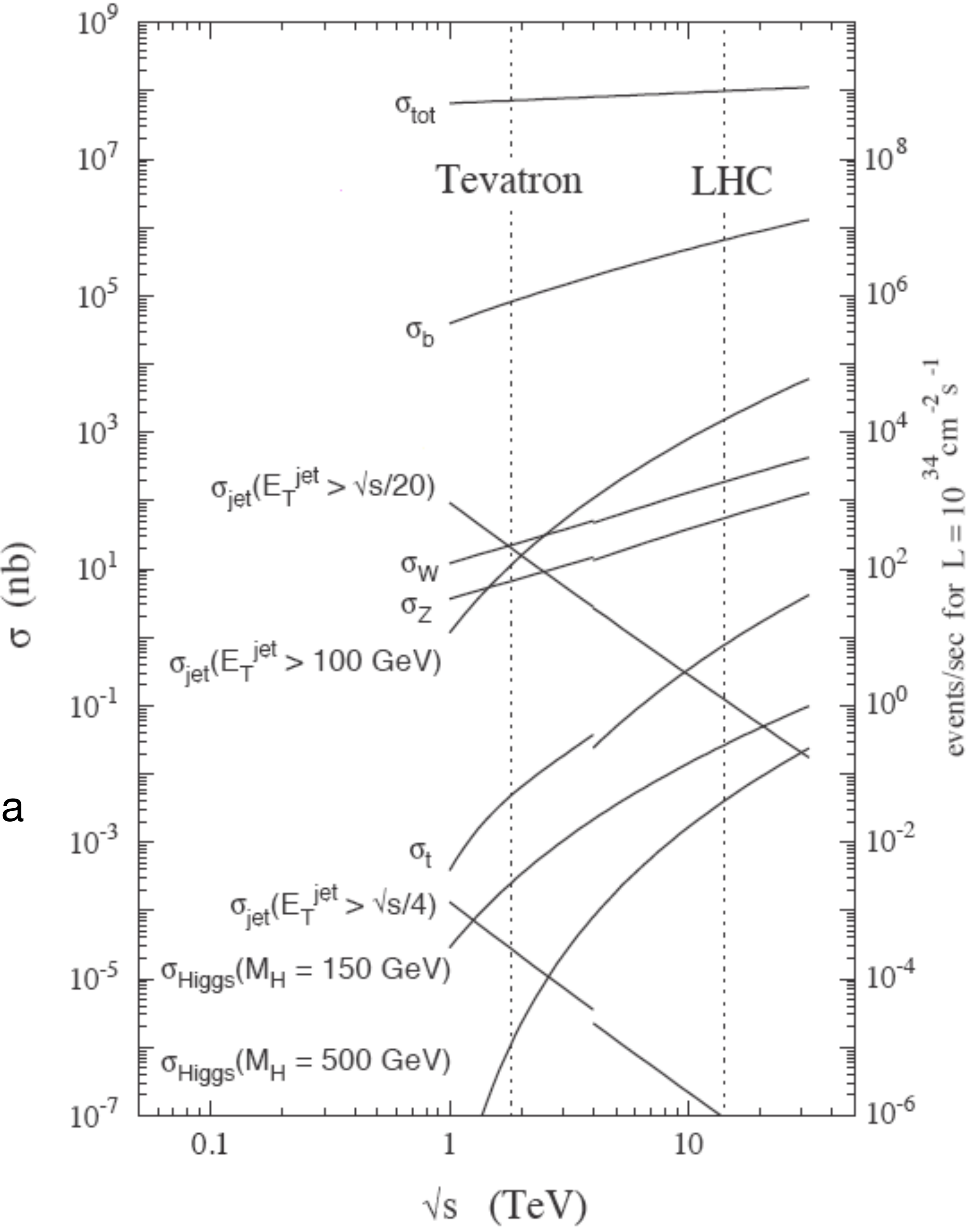
THE LARGE HADRON COLLIDER

- The LHC is the world's highest energy particle collider



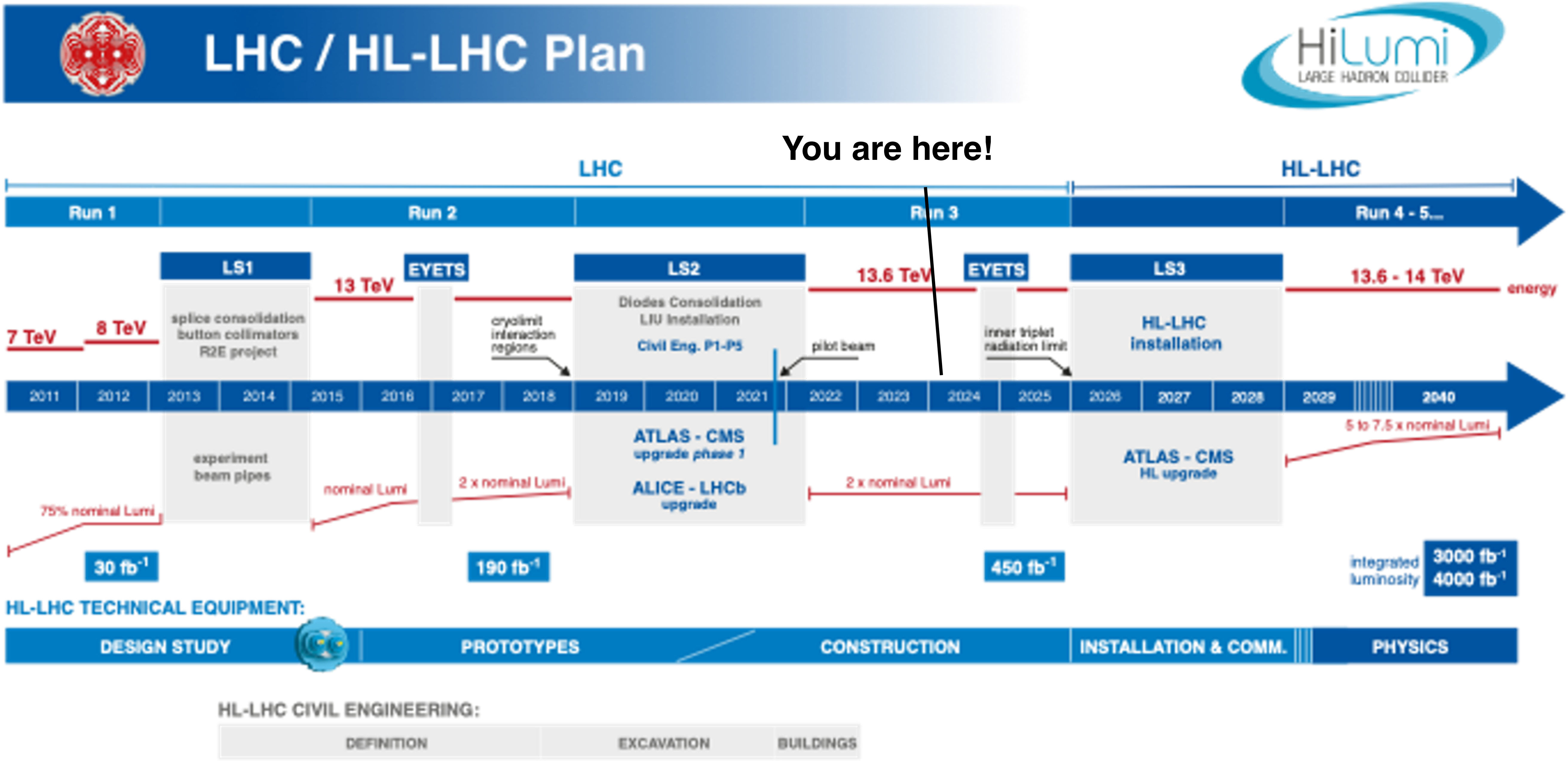
LUMINOSITY AND CROSS SECTION





- Data is quantified by the integrated rate of collisions or the luminosity
  - unit of 1/cross section = cm^{-2} or inverse-barns, where 1 barn = 10^{-24} cm^{2}
- ATLAS and CMS experiments collected ~140 fb^{-1} data luminosity for analysis in Run 2
- Run 3 proton collisions at higher collision energy of 13.6 TeV have just begin

SCHEDULE


LHC / HL-LHC Plan
HiLumi
LARGE HADRON COLLIDER
You are here!
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
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2016
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2021
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2024
2025
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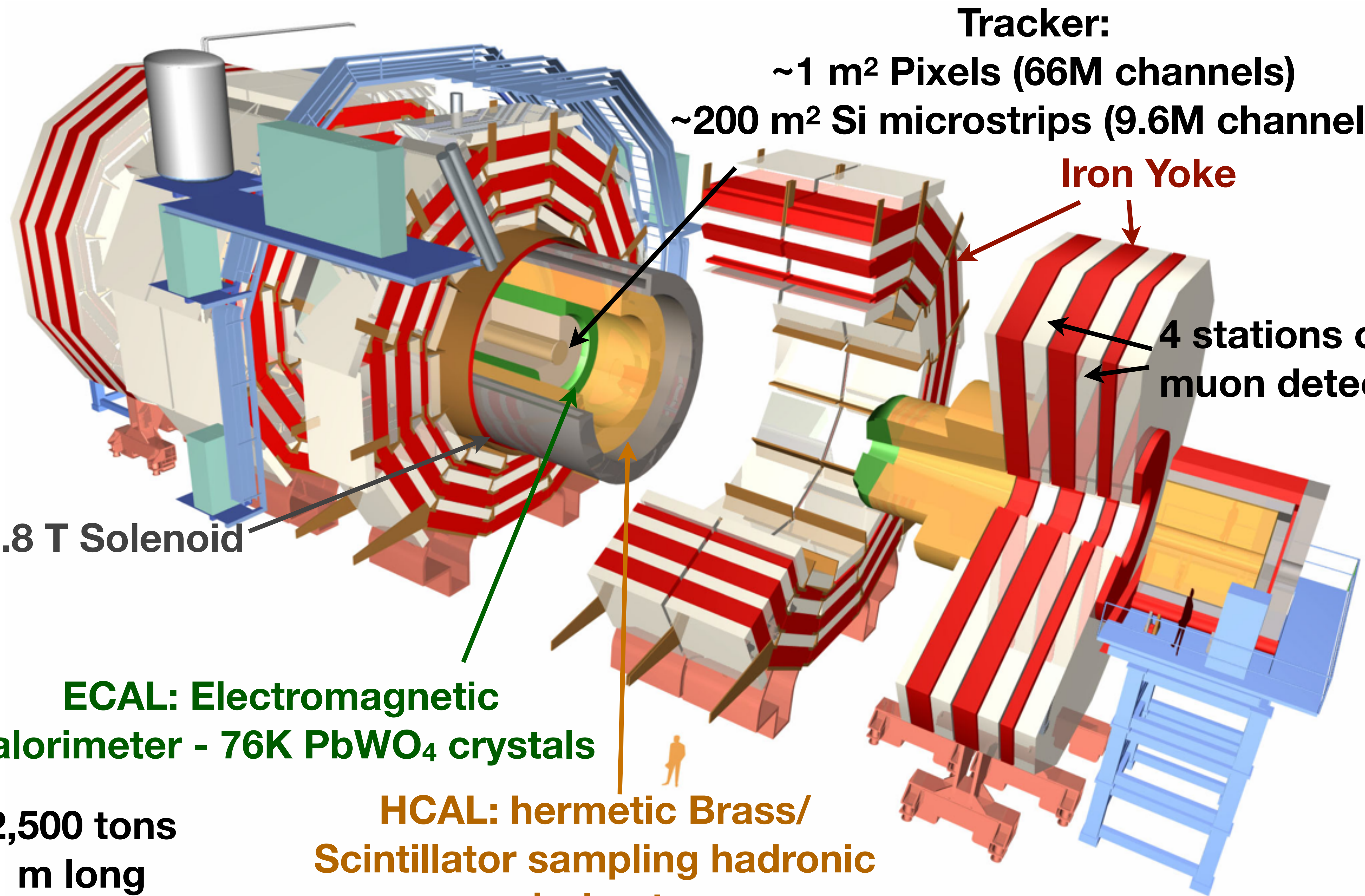
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
5 to 7.5 x nominal Lumi
30 fb⁻¹
190 fb⁻¹
450 fb⁻¹
integrated
luminosity
3000 fb⁻¹
4000 fb⁻¹
HL-LHC TECHNICAL EQUIPMENT:
DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS
HL-LHC CIVIL ENGINEERING:
DEFINITION
EXCAVATION
BUILDINGS

THE CMS EXPERIMENT



Tracker:
~1 m² Pixels (66M channels)
~200 m² Si microstrips (9.6M channels)

Iron Yoke

4 stations of muon detectors

3.8 T Solenoid

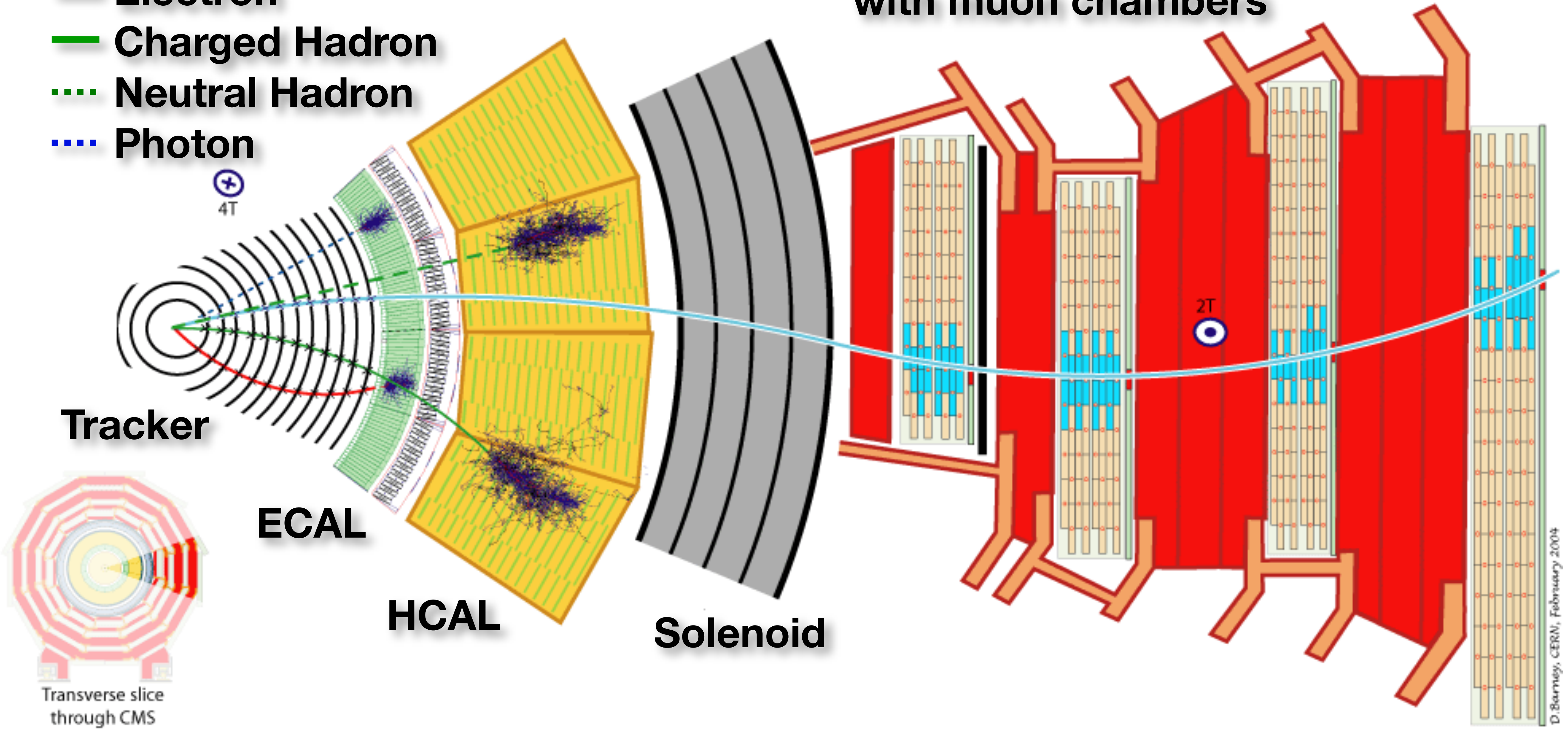
ECAL: Electromagnetic calorimeter - 76K $PbWO_4$ crystals

HCAL: hermetic Brass/ Scintillator sampling hadronic calorimeter

12,500 tons
21 m long
15 m diameter

PARTICLE DETECTION (AT CMS)

Key:
- — **Muon**
- — **Electron**
- — **Charged Hadron**
- ···· **Neutral Hadron**
- ···· **Photon**



Iron return yoke interspersed with muon chambers

Tracker

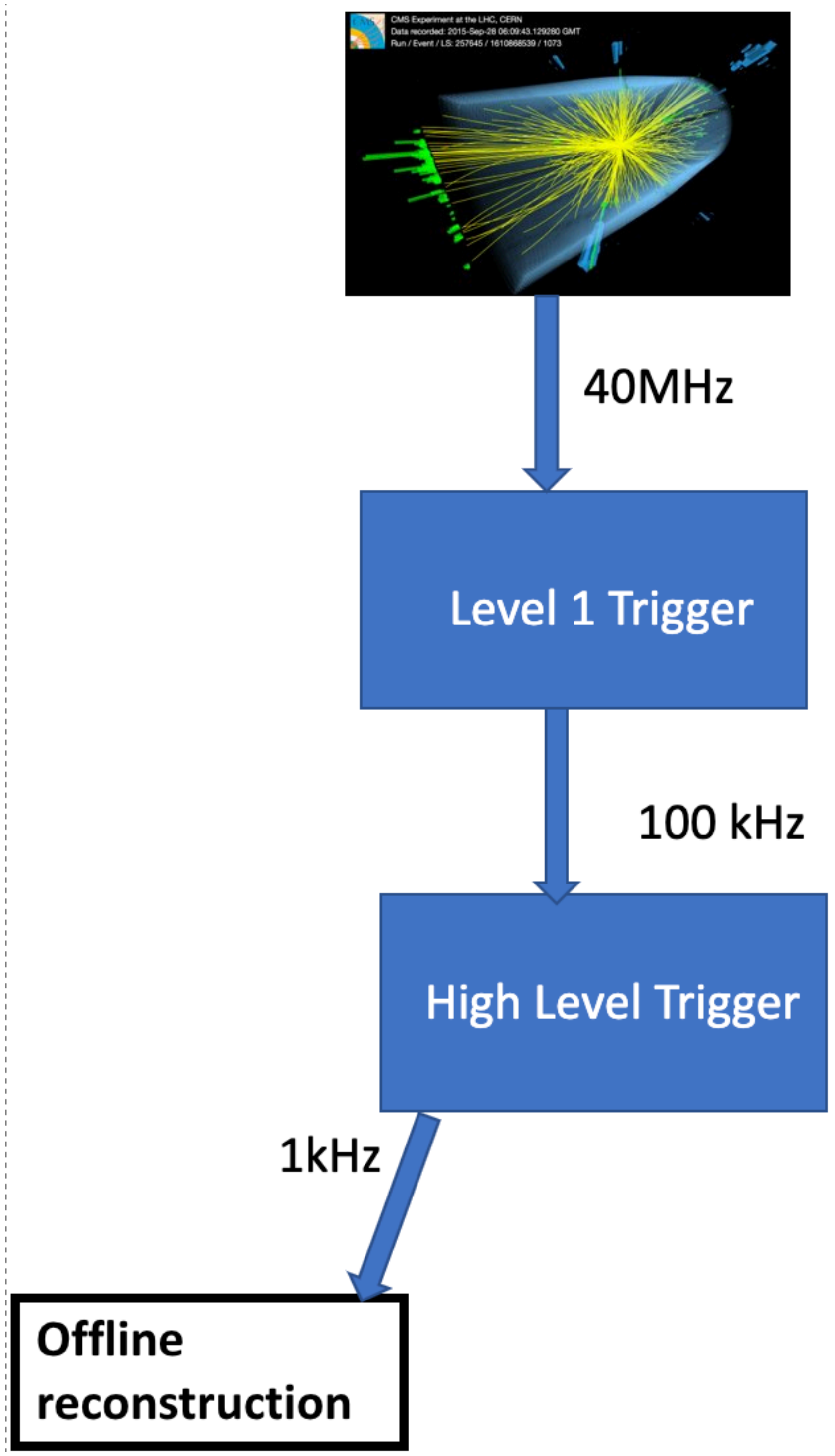
ECAL

HCAL

Solenoid

TRIGGER WARNINGS

- Need to decide which events to keep
  - Event filtering: the trigger system
- The event trigger is one of the biggest challenges at the LHC
  - Proton beams cross 40 million times per second (every 25 ns)
  - Multiple overlapping proton collisions for every beam crossing
- Interesting collisions are very rare
  - We can only record about 1000 per second
    Data not selected by trigger are lost forever!



40MHz

Level 1 Trigger

100 kHz

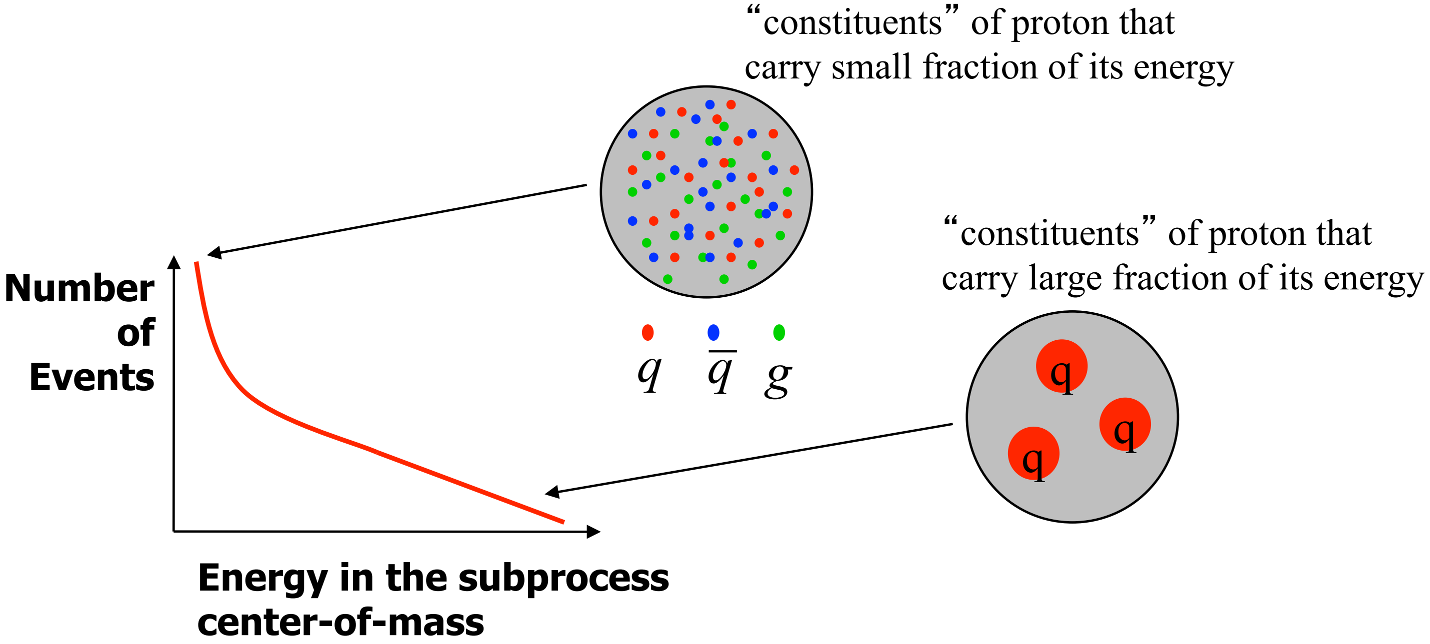
High Level Trigger

1kHz

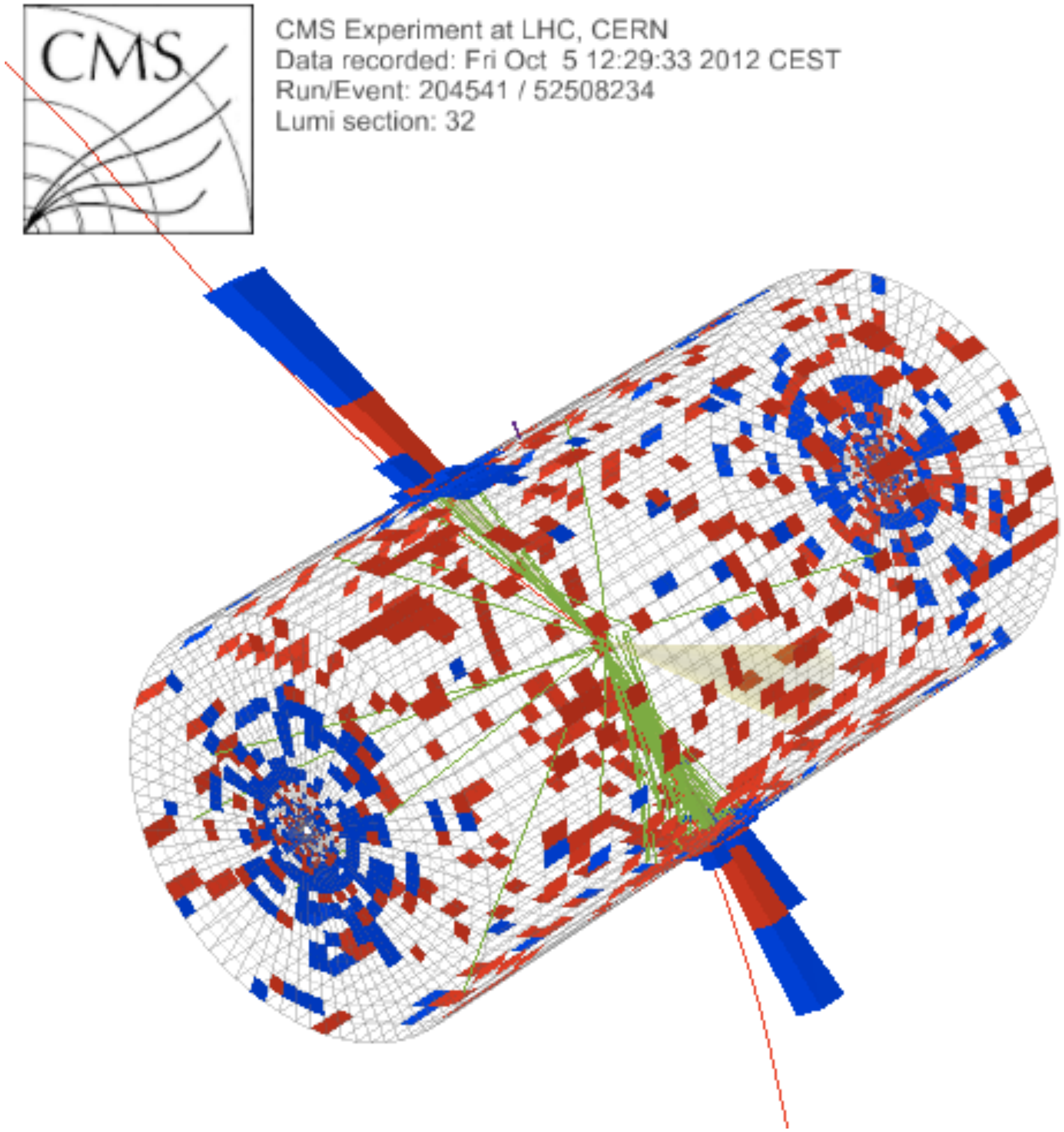
Offline reconstruction

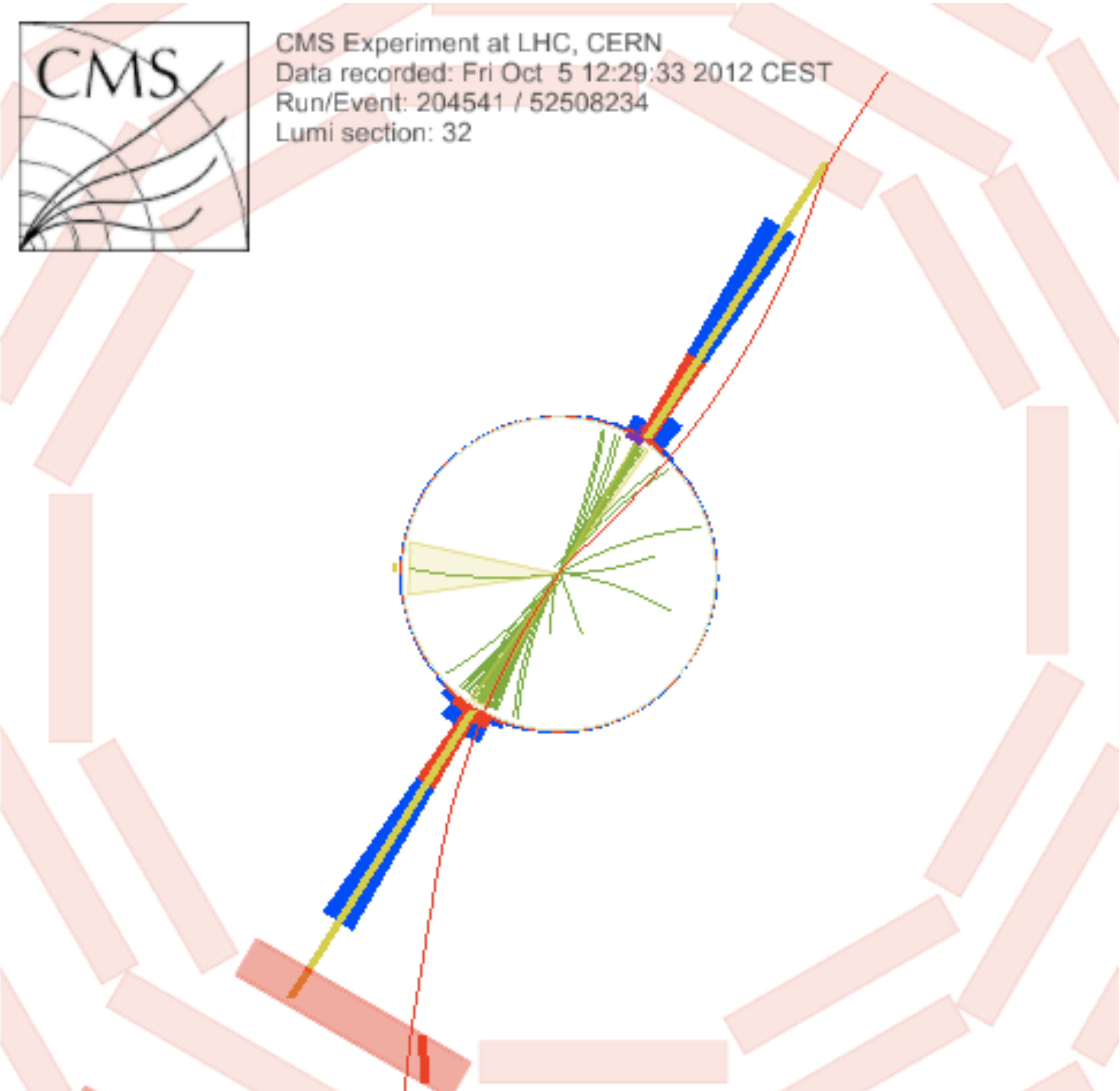
HADRON COLLIDERS

- Easiest way to achieve high center-of-mass energy is colliding beams of protons or anti-protons
  - heavy, so little synchrotron radiation
  - stable, so can take time accelerating
- But: messy!
  - hadron colliders are really quark/gluon colliders
  - The center of energy of a pp collision is not known
- Transverse momentum (p_T), rather than momentum itself, characterizes the energy scale of events
- rely on transverse momentum conservation to identify undetected particles



JETS



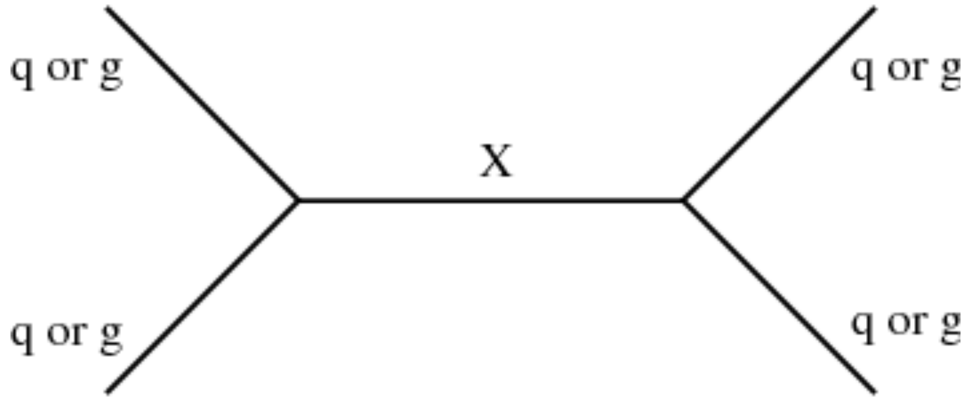


- When **quarks and gluons** are produced, they shower and hadronize to form “jets”, collimated streams of pions, kaons, protons, etc.

The Mass and Multiplicity Challenges

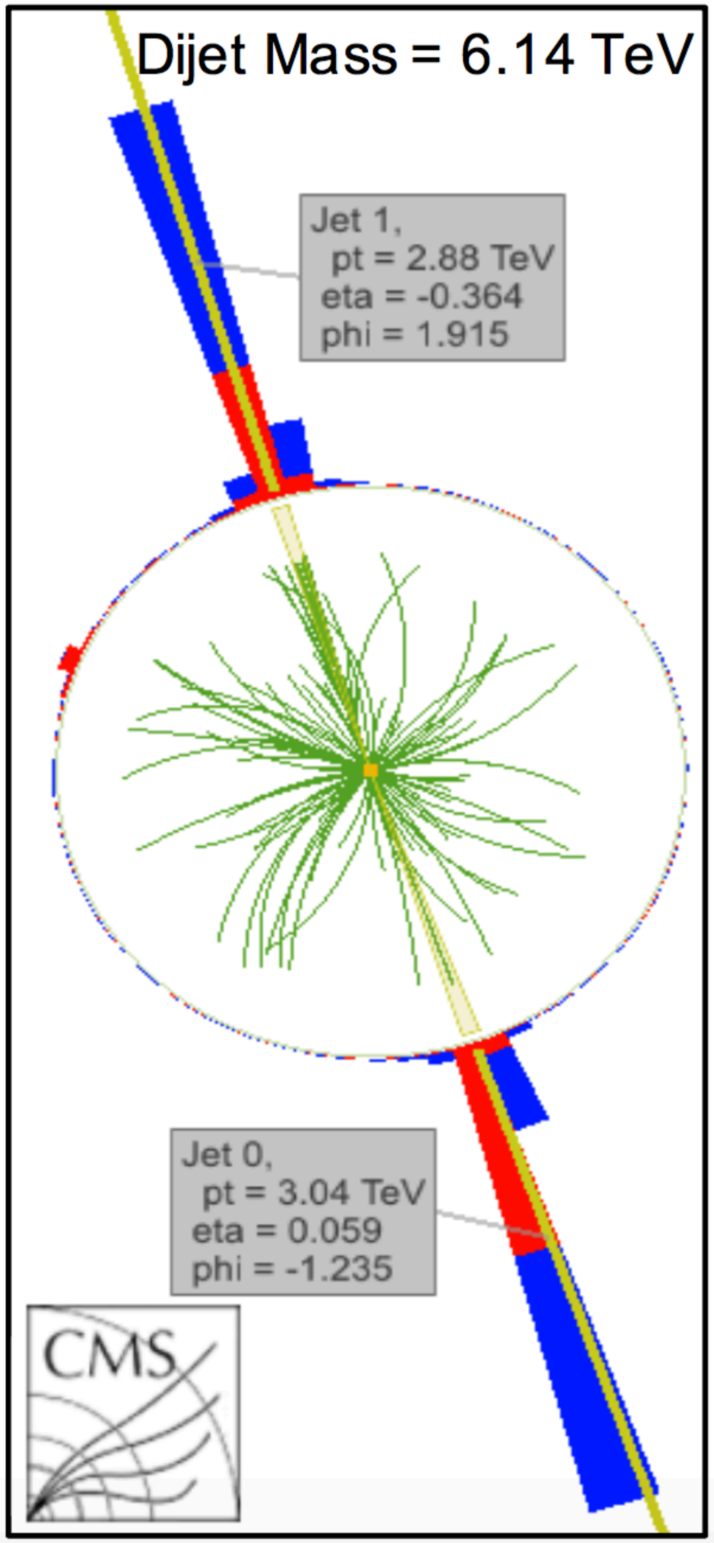
DIJET RESONANCES

- Paradigmatic search for s-channel resonances



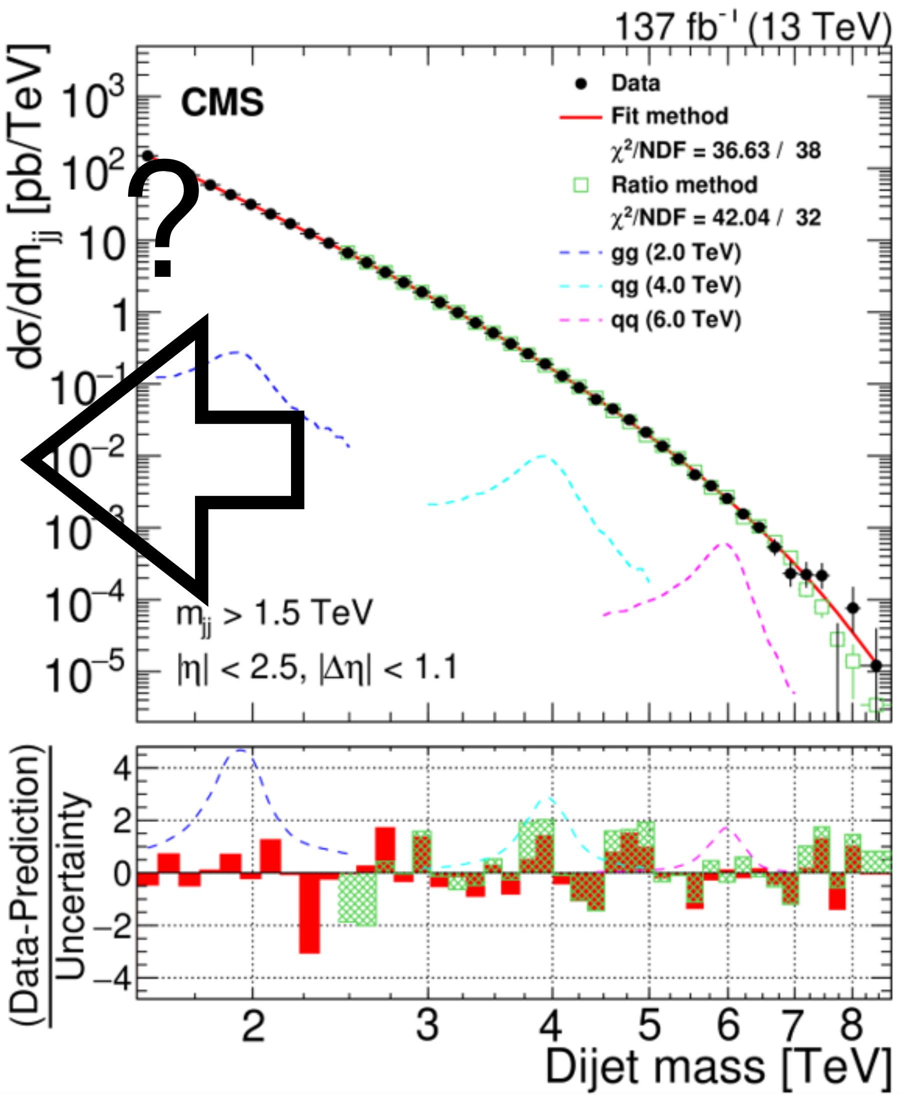
  - If a particle can be produced through two quarks (or gluons), it will decay back into them
    - bump-hunt strategy: look for a back-to-back dijet resonance on top of a falling background
    - long history of this search dating back to UA2

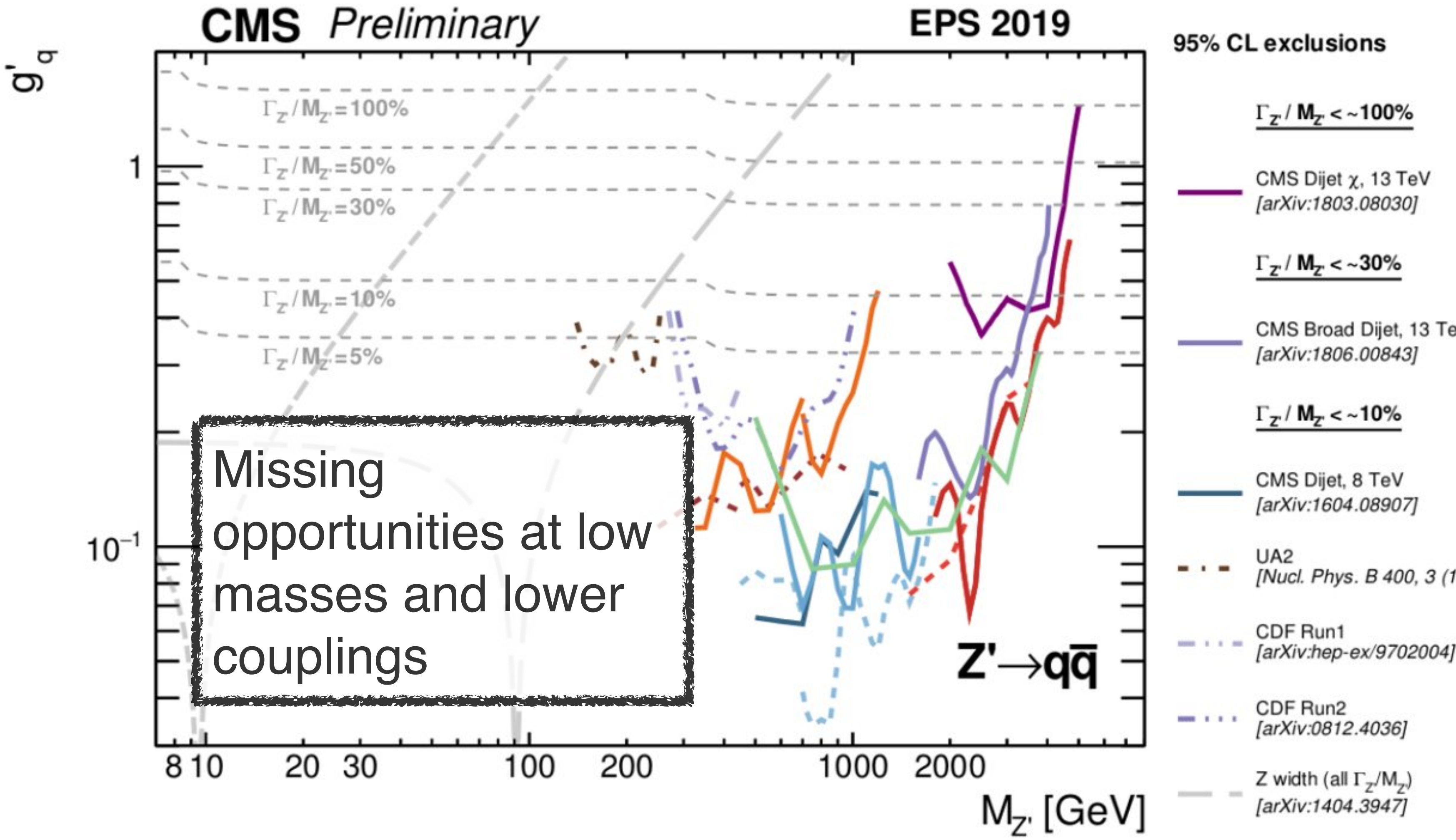
$$M^2 = (E_1 + E_2)^2 + (\vec{p_1} + \vec{p_2})^2$$



THE MASS CHALLENGE

- Focus has historically been on increasing sensitivity to higher masses
  - The trigger constrains the lowest reconstructable invariant mass
  - Is it possible that we missed something along the way?
- The hierarchy problem is an electroweak scale problem: **we should look for solutions at the electroweak scale**
  -

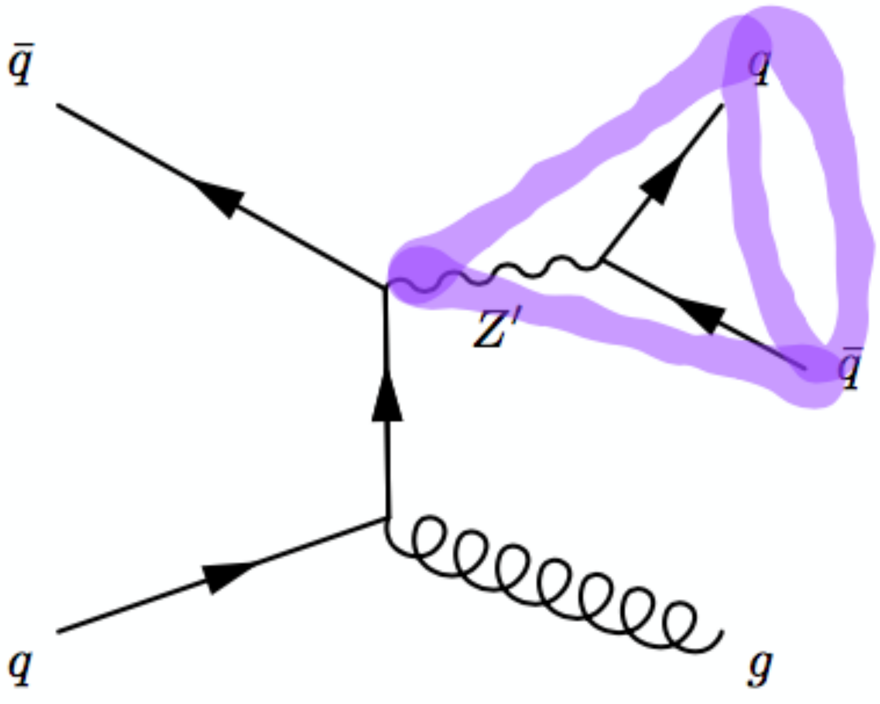


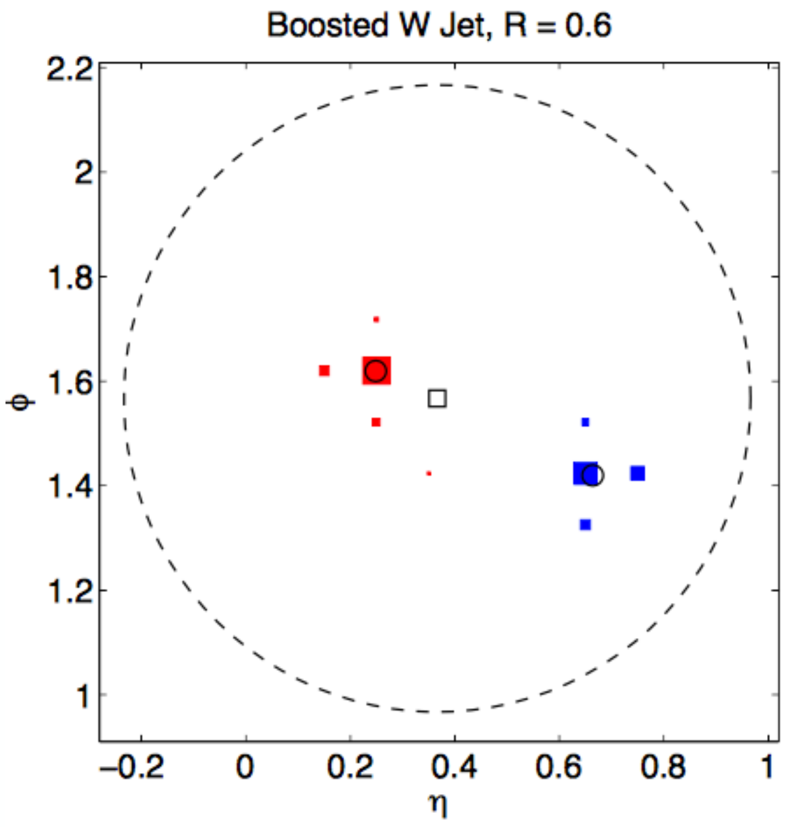


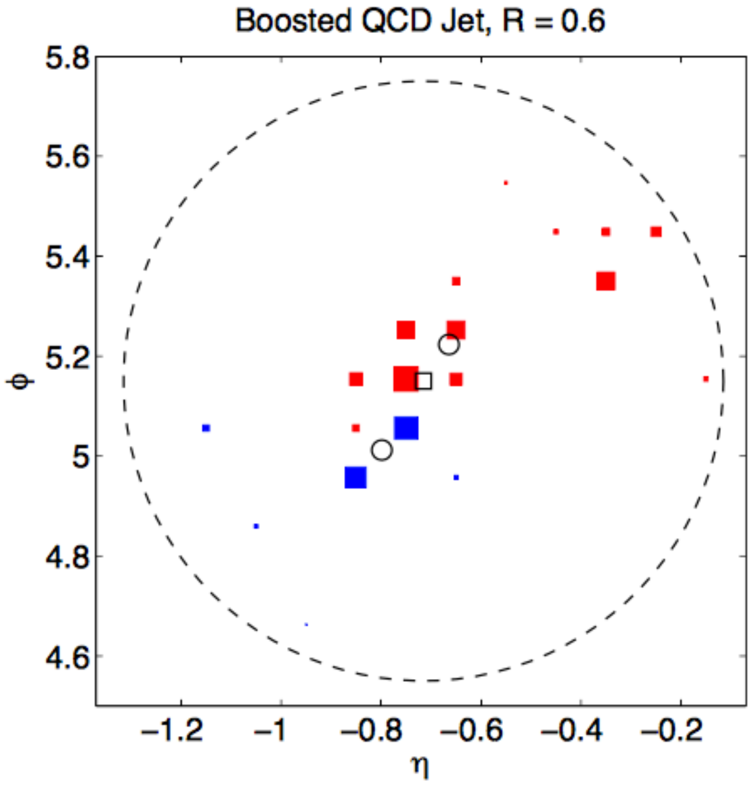
Missing opportunities at low masses and lower couplings

BOOSTED TOPOLOGIES

- One technique to find low-mass resonances is to move into a boosted topology
  - Use recoil of another particle (e.g. gluon) to get the event enough total transverse energy that it is recorded by the trigger system
  - But this collimates the massive particle (e.g. Z'), merging its decay products together
    - Use variables dedicated to identifying substructure to distinguish it from other jets

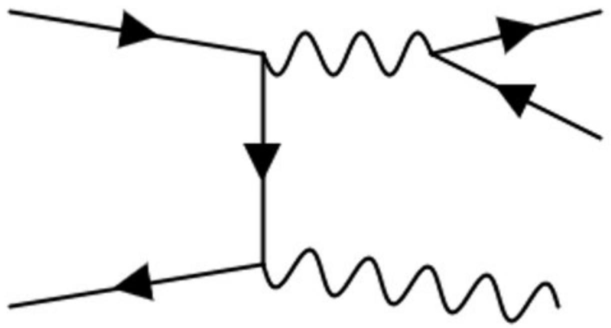




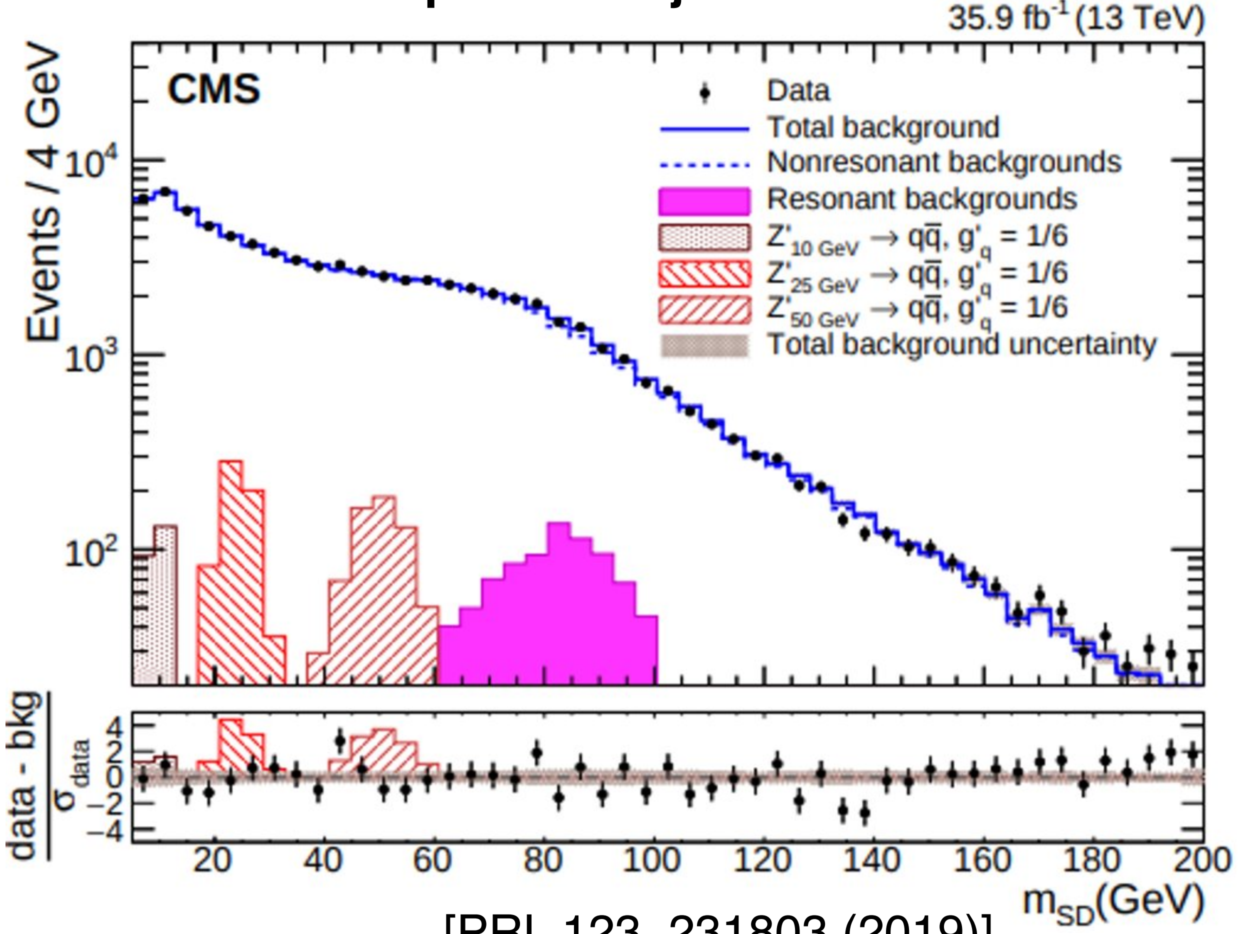


PHOTON/JET ISR

- Use a photon or jet to recoil against the dijet system
  - Scan the mass of the recoiling dijet system

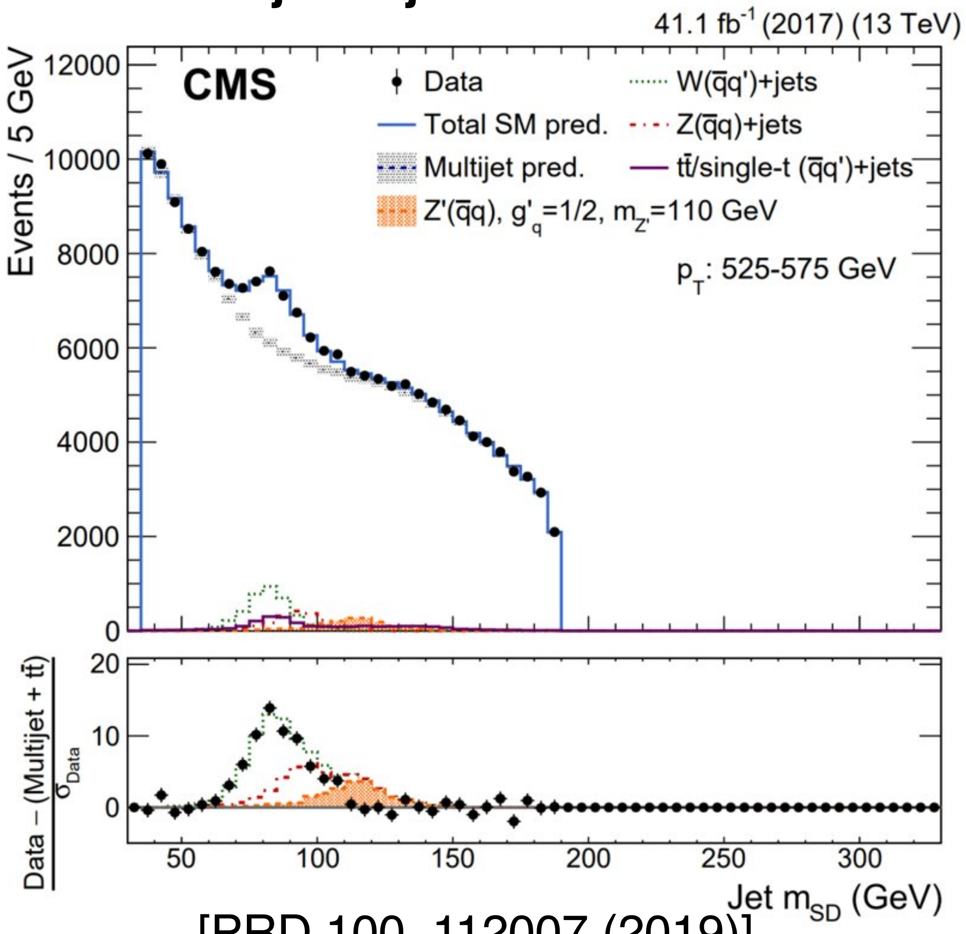


photon+dijet



[PRL 123, 231803 (2019)]

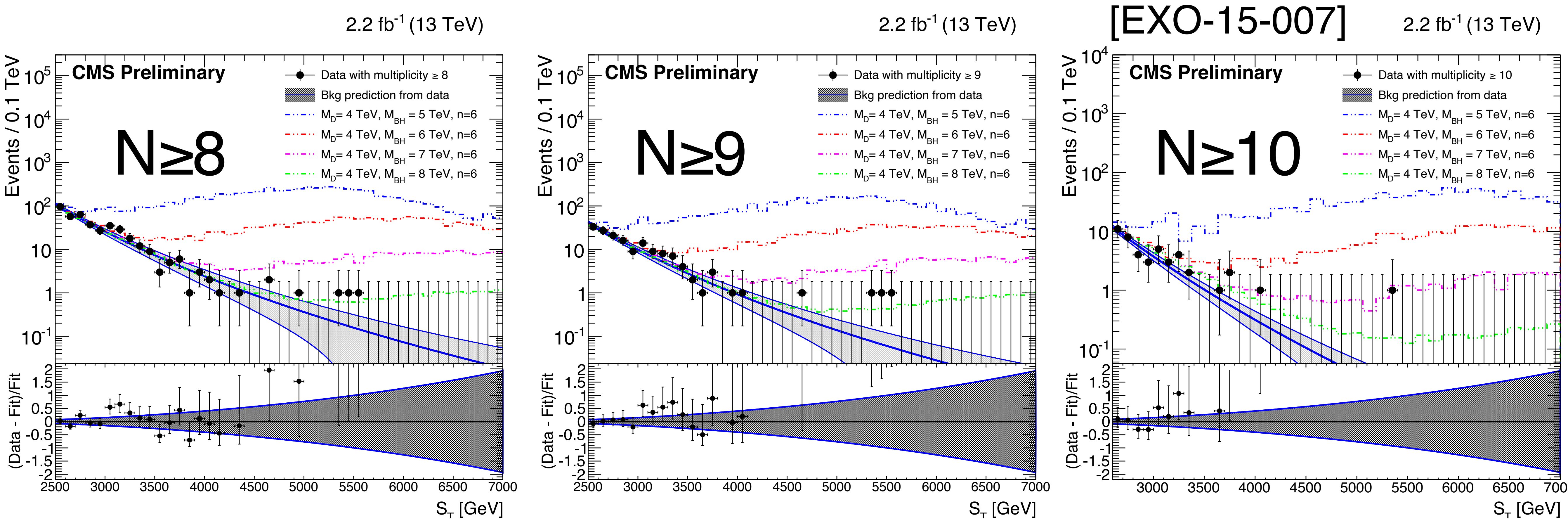
jet+dijet



[PRD 100, 112007 (2019)]

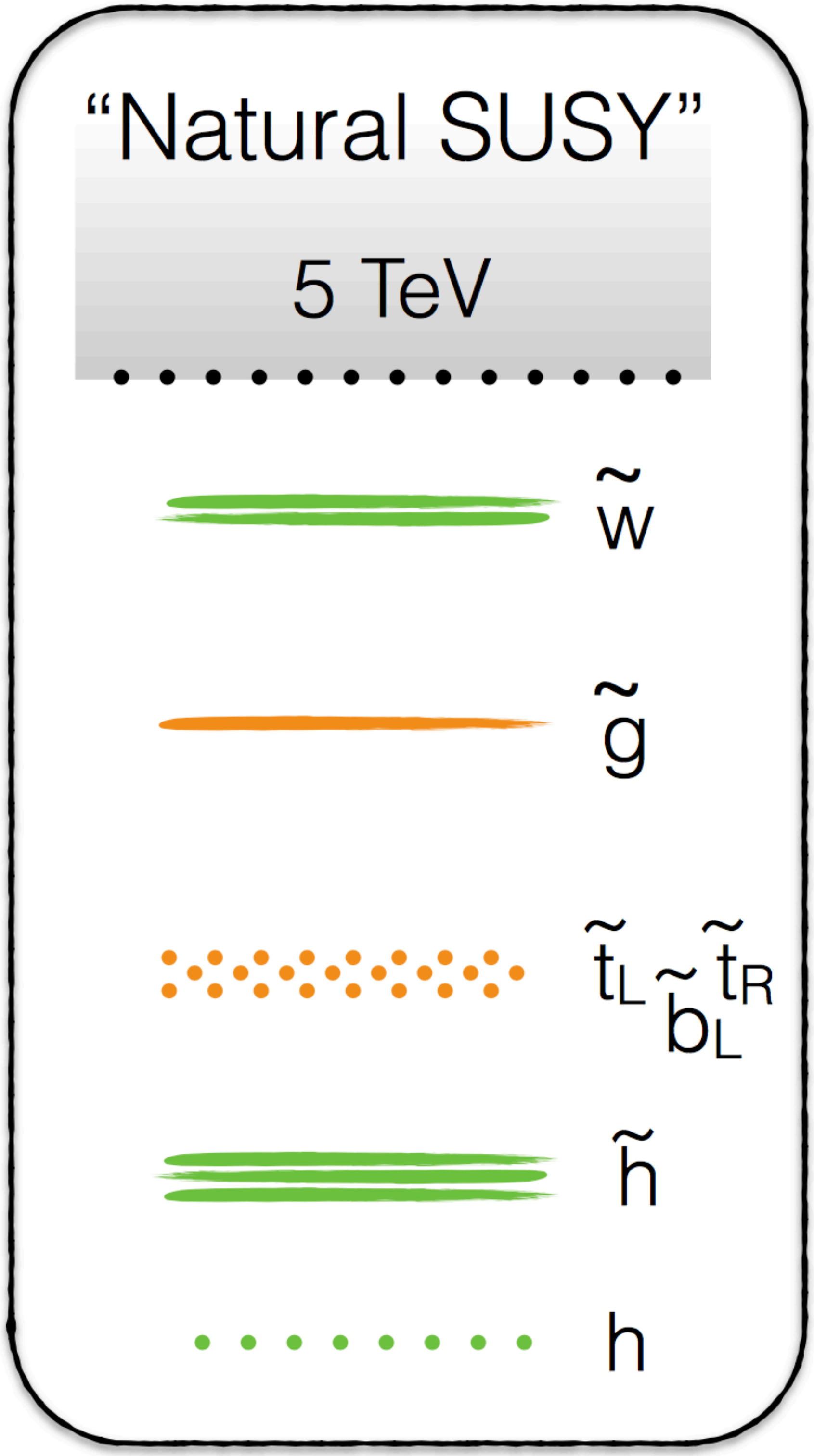
THE MULTIPLICITY CHALLENGE

- Multijet physics is difficult to constrain experimentally, **but it is an easy way to hide an beyond-the-Standard-Model excess**
  - Looks a lot like generic QCD production of jets
  - Monte Carlo simulations are not reliable. How do you predict backgrounds?
- Black Hole search takes scalar sum of pT of all objects in the event and looks for an excess in the tail as a function of the number of objects
  - Notice the search begins at S_T=2.5 TeV for N~8



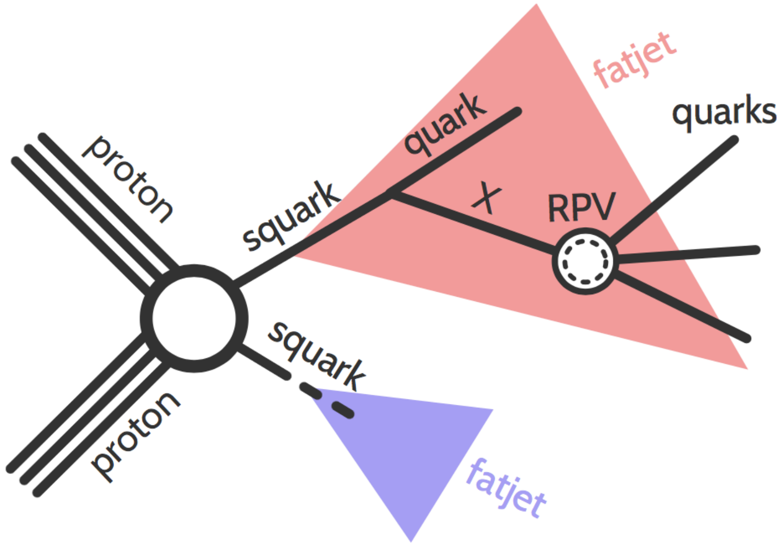
[EXO-15-007]

MOTIVATING LIGHT, LARGE-N JET RESONANCES



Natural SUSY anticipates light (100-500 GeV) 3rd generation squarks above the Higgsinos

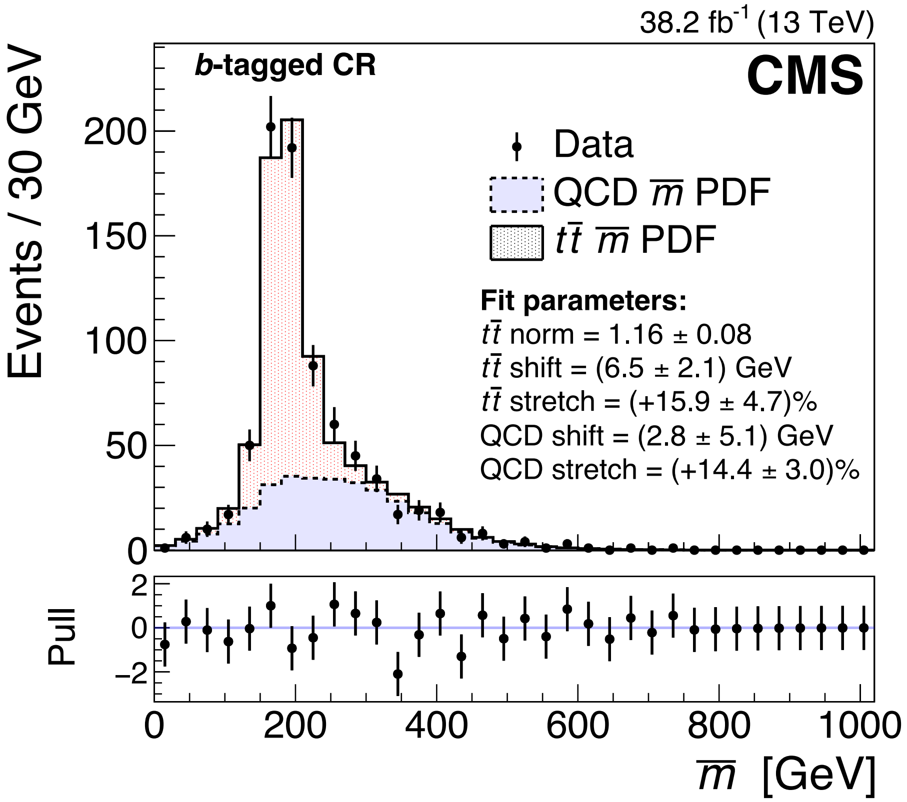
- A hadronic R-parity violating coupling would result in squarks decaying into 4 quarks (8 quarks in the final state)

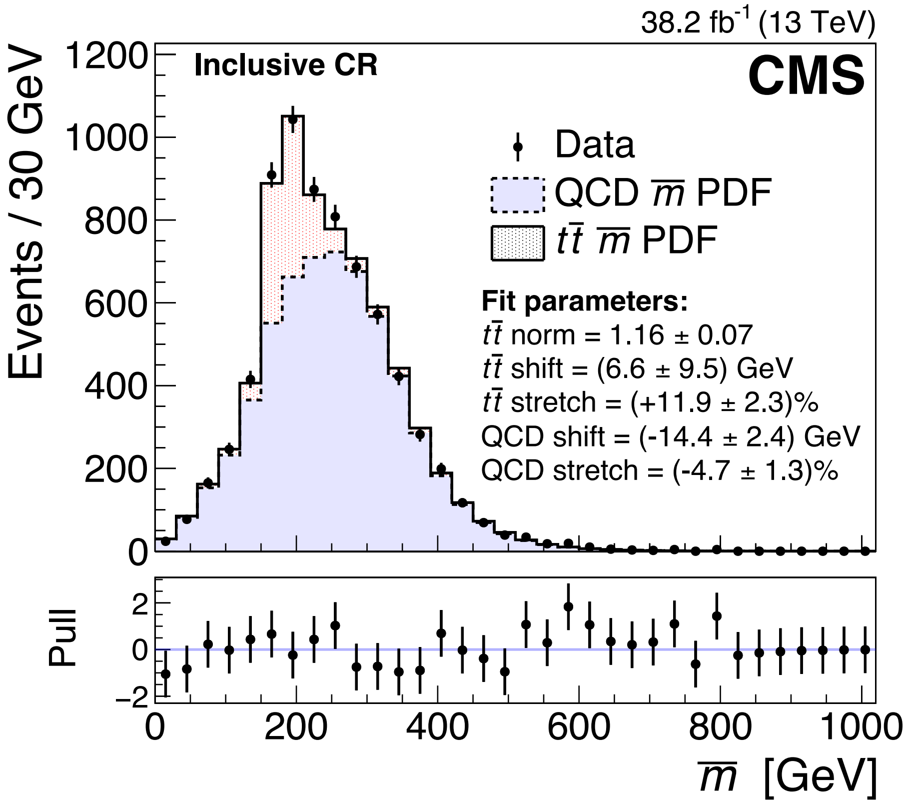


- Let's see if we can't tackle **the most challenging scenario** first: no b quarks, top quarks, soft leptons, or intermediate resonances

EVENT SELECTION

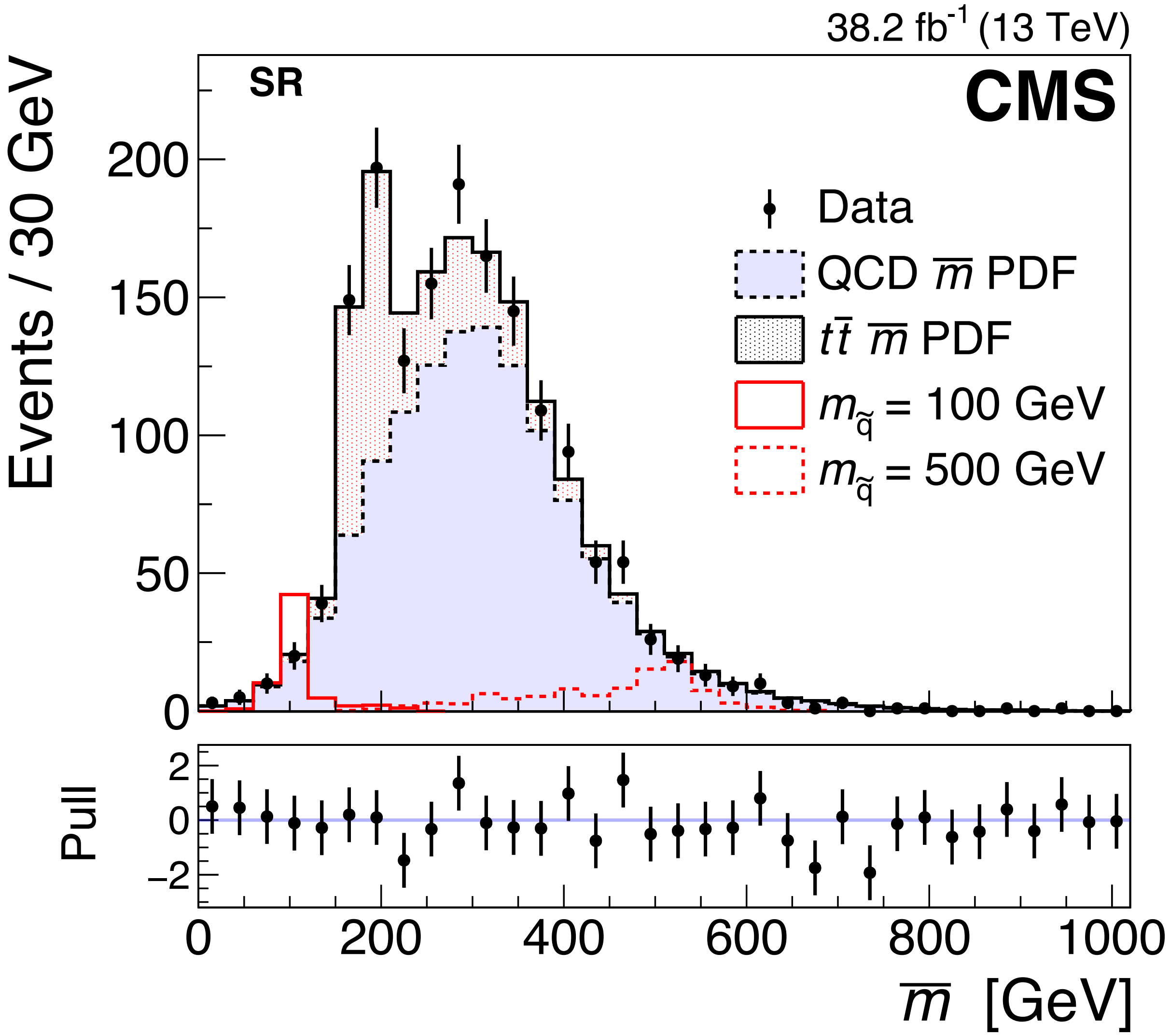
- Look for two high-p_T, **large-radius** (R=1.2) jets
  - $H_T>900$ GeV (to pass trigger threshold)
  - Each jet has substructure (N-subjetiness) consistent with at 4 least for “prongs”
  - Scan in the average mass of the two jets
- Top quark events is a standard candle (3-prong control region):
  - Controls understanding of the jet energy scale and resolution

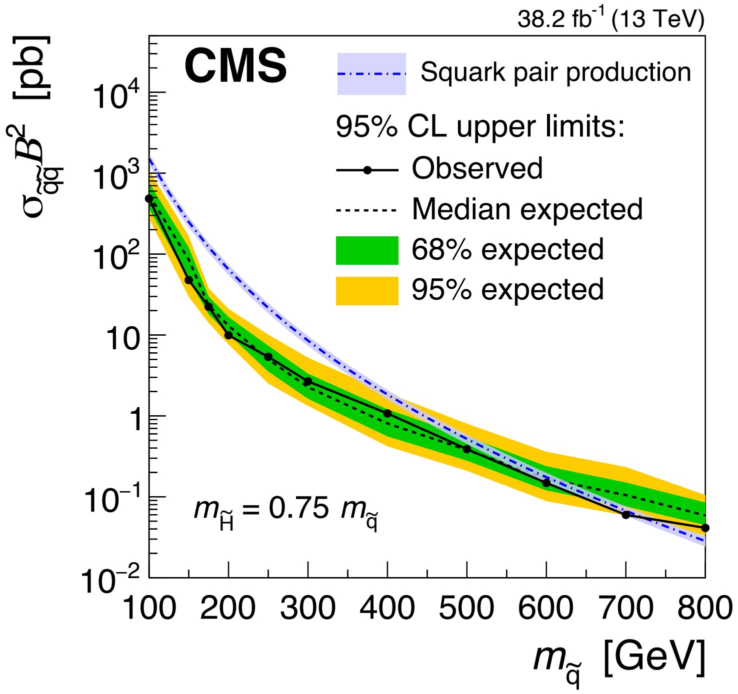


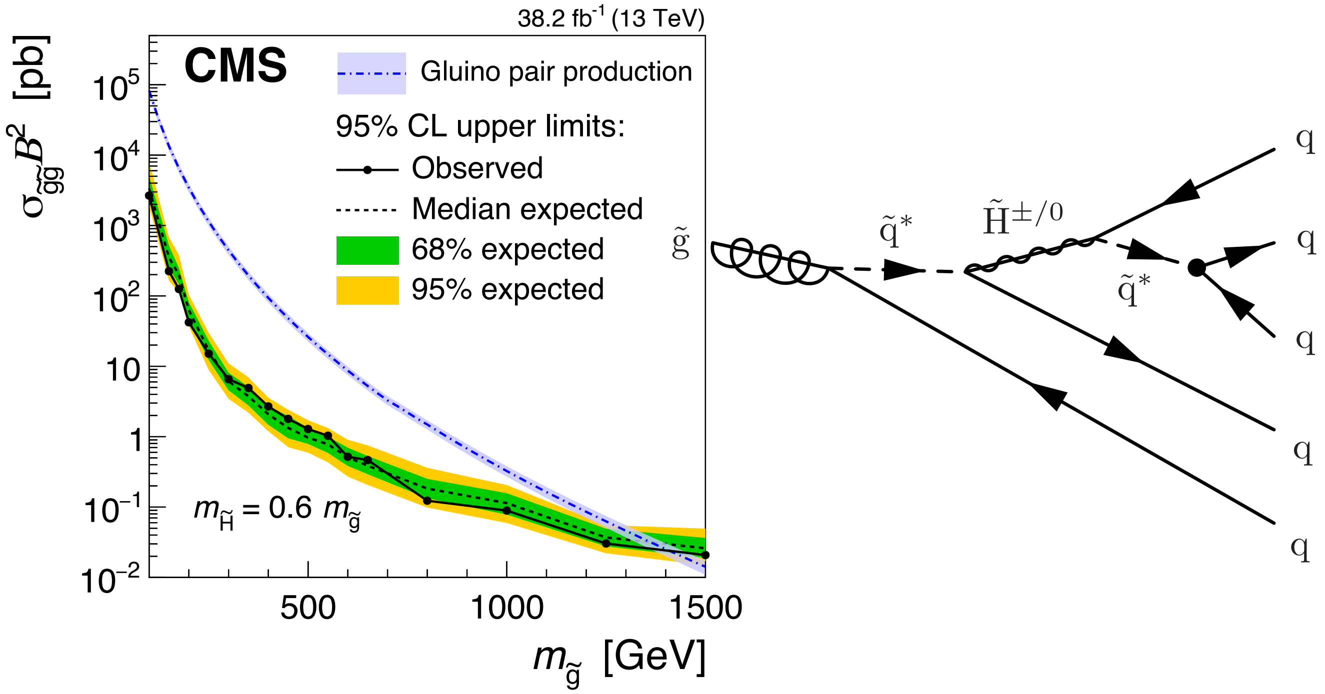


CONSTRAINTS ON 4 AND 5-JET RESONANCES

- Signal region analysis constrains **strong** production of pair-produced resonances decaying into **4 or more objects** as light as 100 GeV!





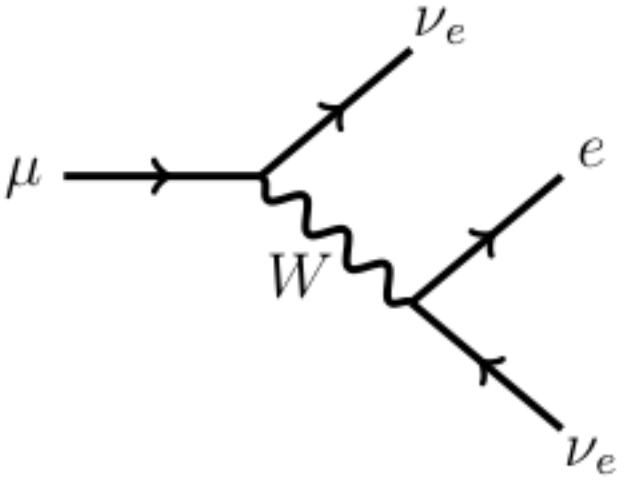


The Lifetime Challenge

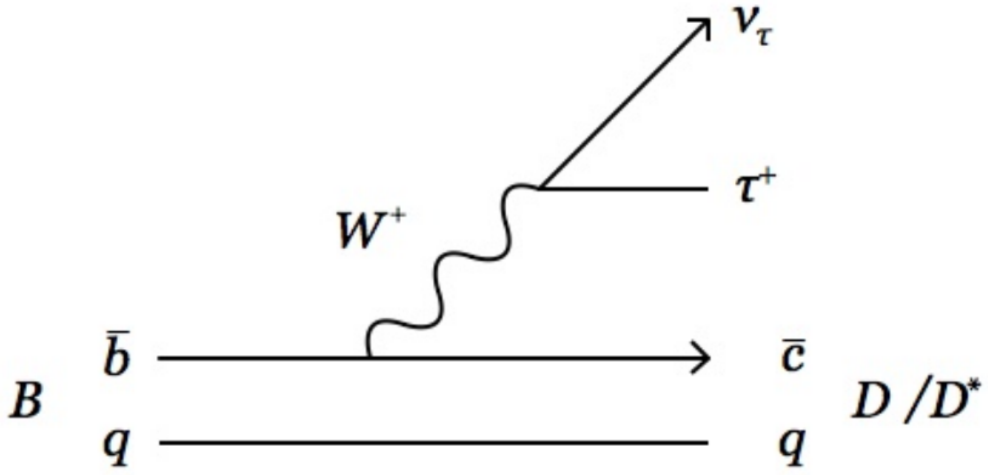
LONG-LIVED PARTICLES IN THE SM

- Common Mechanisms
  - Approximate symmetry
  - Heavy mediator
  - compressed phase space
  - small couplings

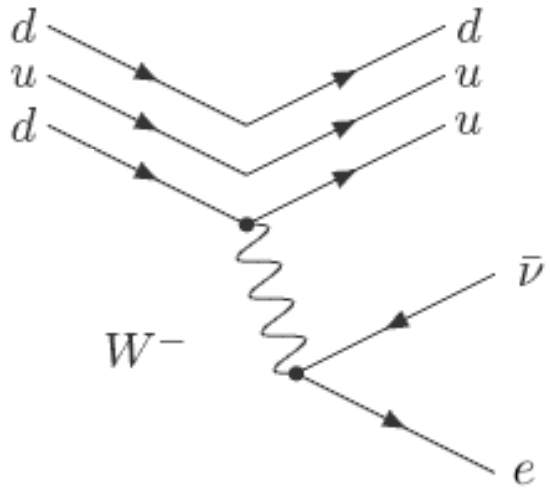
muon
(2 μs)



b-quarks
(~ps)



neutron
(15 mins)



- The same mechanisms that give rise to long-lived particles in the SM can also result in such particles in BSM theories
- Finding these particles at the LHC requires us to use the detectors—that were designed largely with ~prompt physics in mind—in novel ways

MANY EXPERIMENTS

- The last 8 years has seen a renaissance of new detector proposals to look for long-lived particles at the LHC

THE MILLIQAN EXPERIMENT

FASER

SND@ LHC

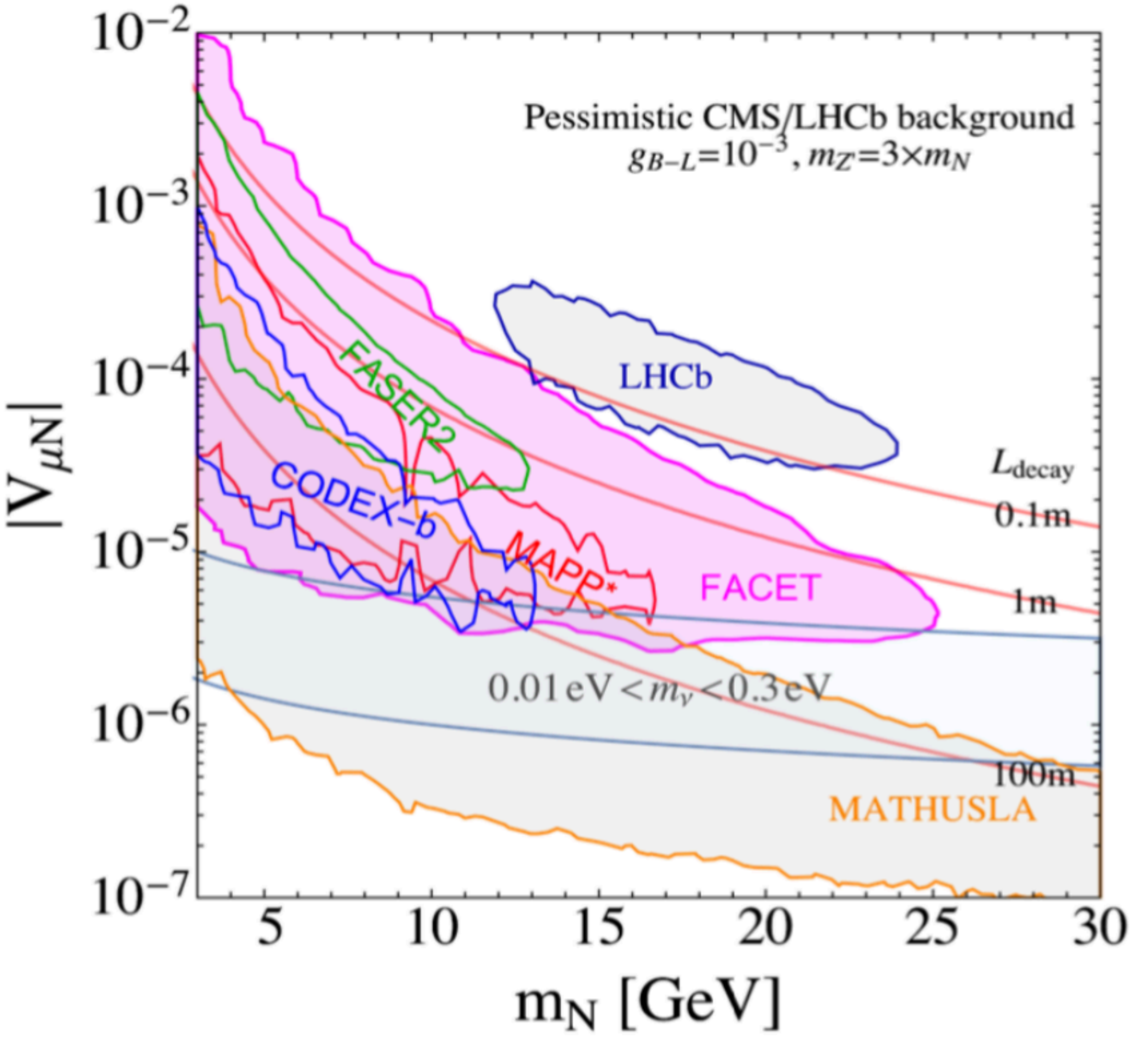
SHiP
Search for Hidden Particles

CODEX-b

MATHUSLA

ANUBIS

FACET

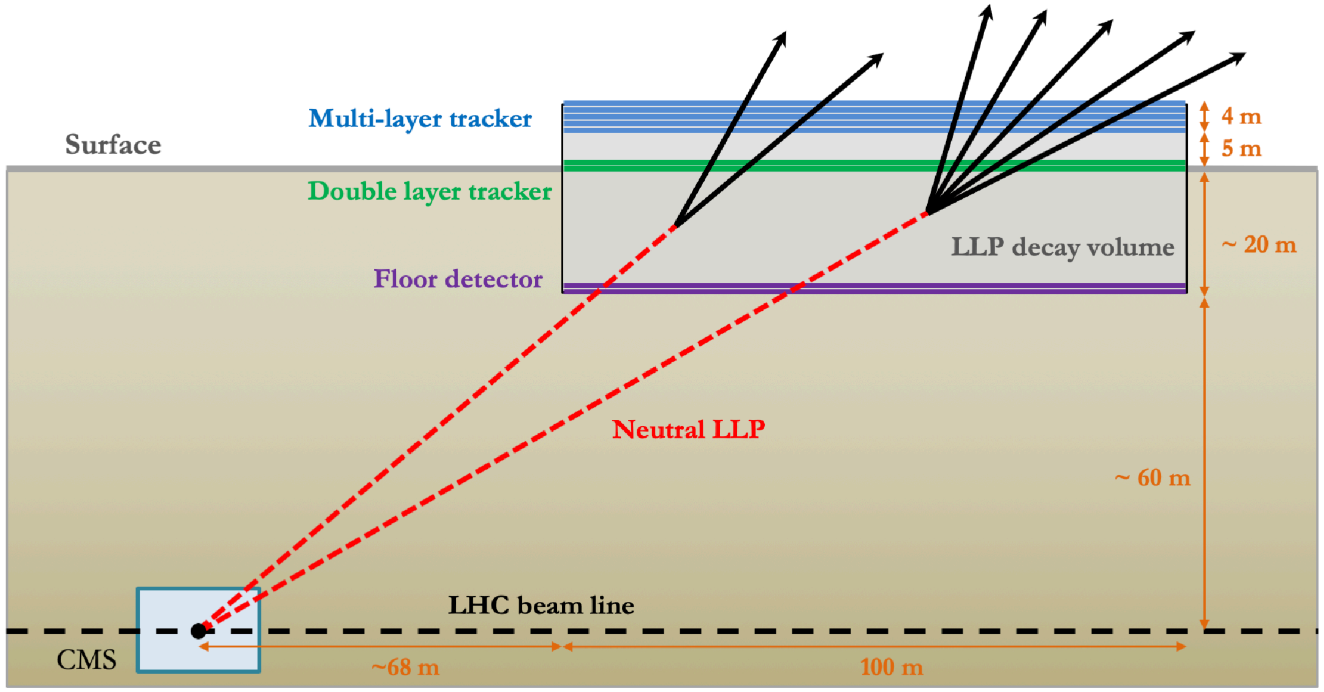


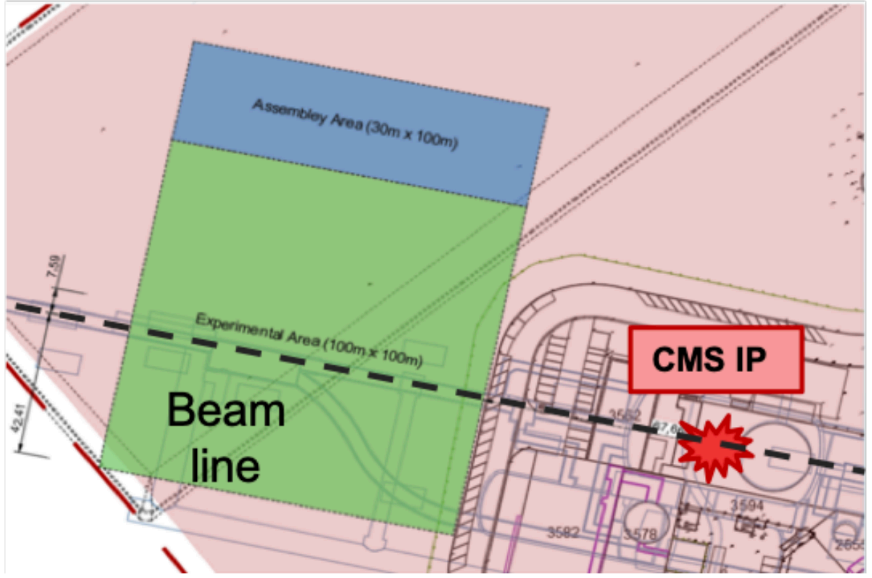
- Vastly different sensitivities as a function of mass and lifetime

MATHUSLA

[PLB (2017) 01 043]

- **MA**ssive **T**iming **H**odoscope for **U**ltra-**S**table **N**eutra**L** P**A**rticles
- MATHUSLA is a dedicated detector for long-lived particles
  - Designed to have applicability across a broad range of potential final states
  - Conceptually simple: build a big empty box with trackers on CERN-owned land near CMS
    - LLPs that decay inside will be reconstructed as displaced vertices
    - Backgrounds can be ~O(1) because 80+ m rock shielding suppresses IP backgrounds and 4D tracking from ~ns timing are distinct criteria for signal identification





MATHUSLA COLLABORATION

- International collaboration including members & institutions from US, Canada, Chile, Bolivia, Mexico, Italy, Switzerland, …
  - TDR draft to be released in the coming weeks
  - Begin MATHUSLA operation with HL-LHC!
- Physics justification detailed in ~200 page report [1806.07396]

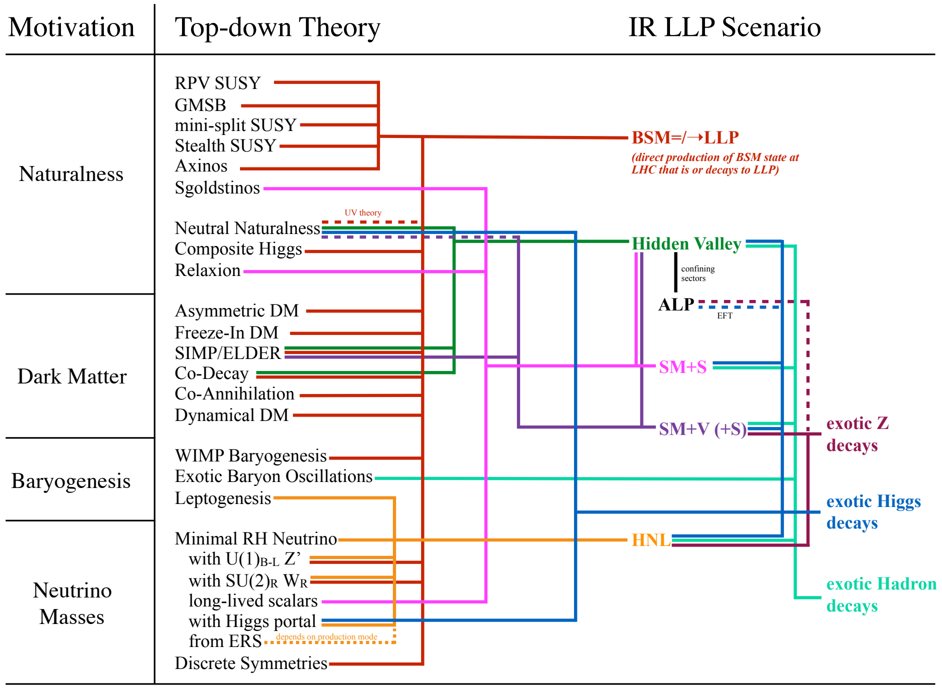
A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

1811.00927
LHCC-I-031

Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

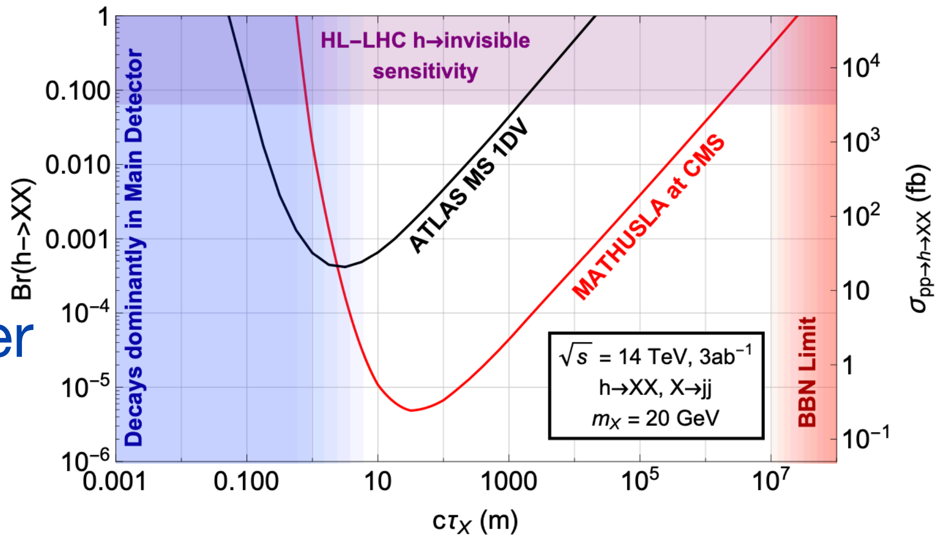
**Long-Lived Particles at the Energy Frontier:
The MATHUSLA Physics Case**

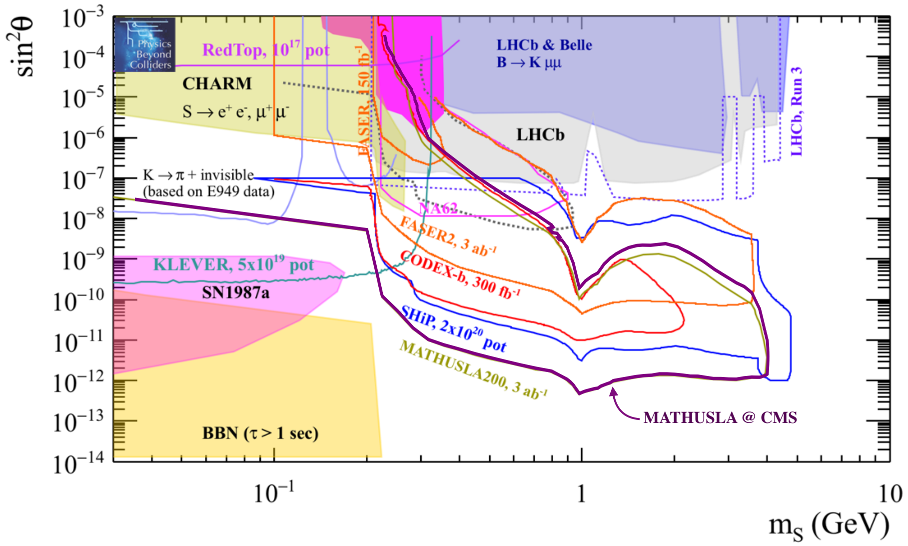
1806.07396

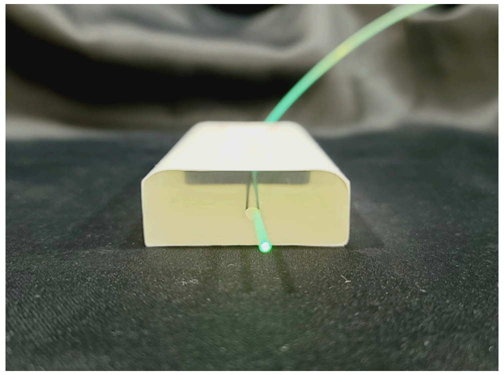


DESIGN PRINCIPLES

- In the long lifetime regime > 100m, MATHUSLA has roughly same chance of “catching” an LLP decay in its decay volume as the main detectors
  - Greater depth of decay volume compensates for smaller solid angle coverage
  - For LLP searches, MATHUSLA’s greater sensitivity than ATLAS/CMS is due to
    - near-zero backgrounds
    - no trigger limitations
- Therefore, MATHUSLA will beat the main detectors for LLP signals where main detector searches are significantly impeded by background and trigger considerations (up to 1000x better reach)
- Targets (in order of priority)
  - Hadronically decaying LLPs from few GeV to TeV
  - LLPs with mass < few GeV (any decay mode)
  - Cosmic Ray Physics



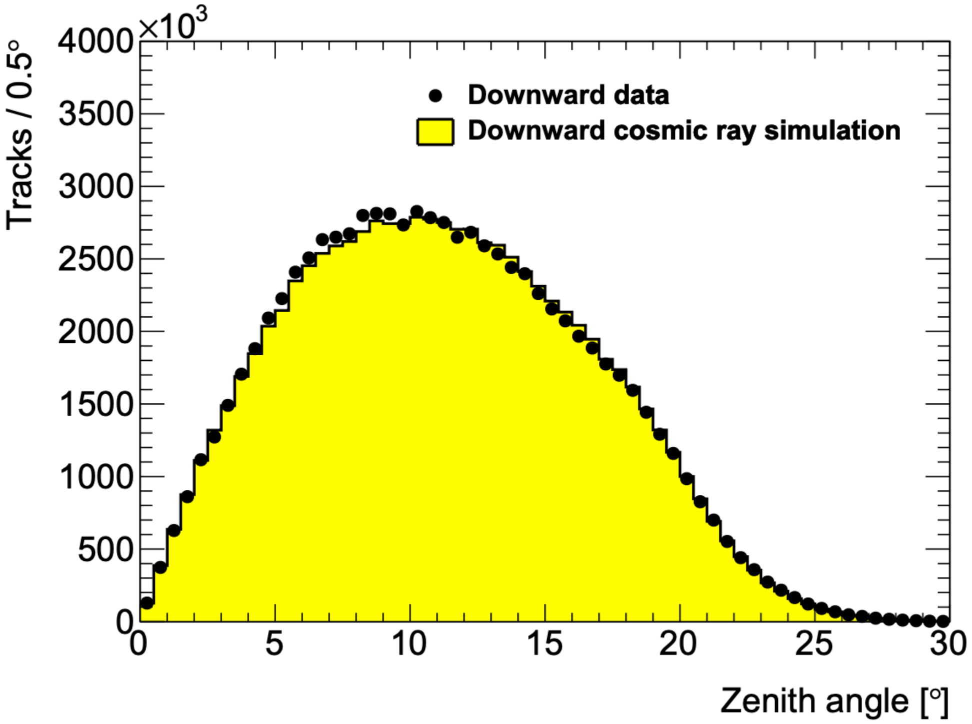


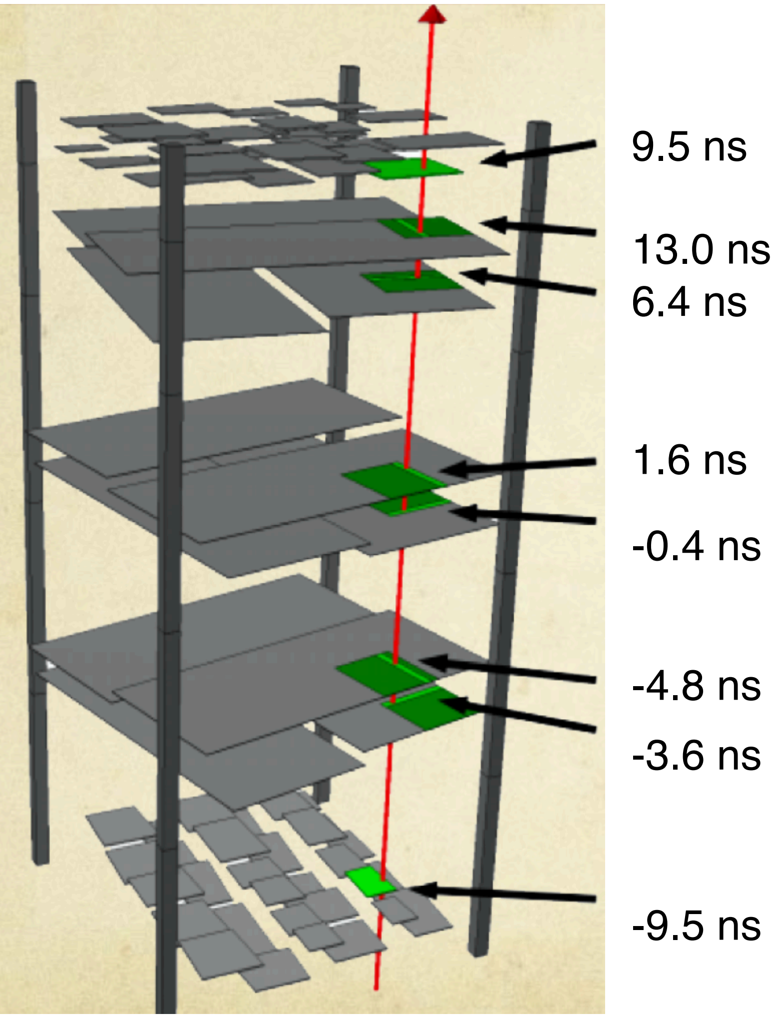


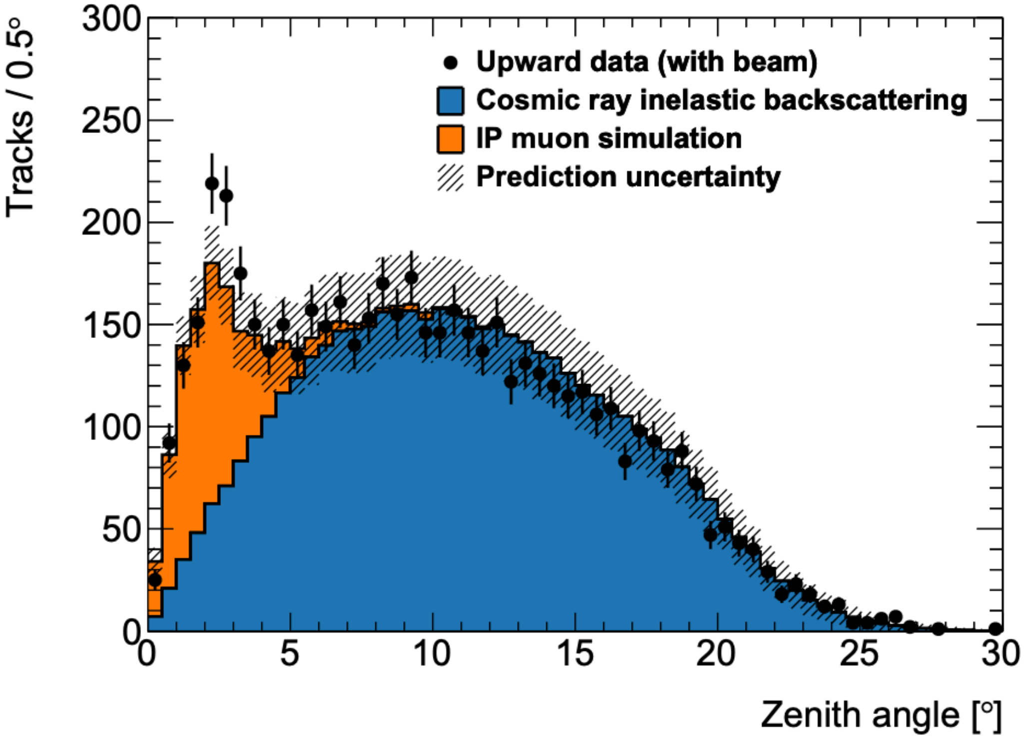
TEST STAND RESULTS

[NIM A (2020) 164661]

- Test stand operated above ATLAS in 2018 — combination of plastic scintillator and RPCs
  - Both downward and upward rates/angular distributions well predicted by simulation O(~10%)







CONCLUSIONS

- The LHC is performing marvelously
  - We are just well into a new run at 13.6 TeV that will integrate ~400 fb^{-1} of data
    - Any discovery of new physics, whether it addresses the problems I mentioned at the beginning or not, will bring with it a whole host of questions:
      - How does it relate to the other particles of the Standard Model?
      - Does it solve the dark matter problem? The Hierarchy problem? Something else? Who ordered it?
- Whatever happens, the next decade promises to be a challenging and exciting time in particle physics