Physics with CMS at Large Hadron Collider

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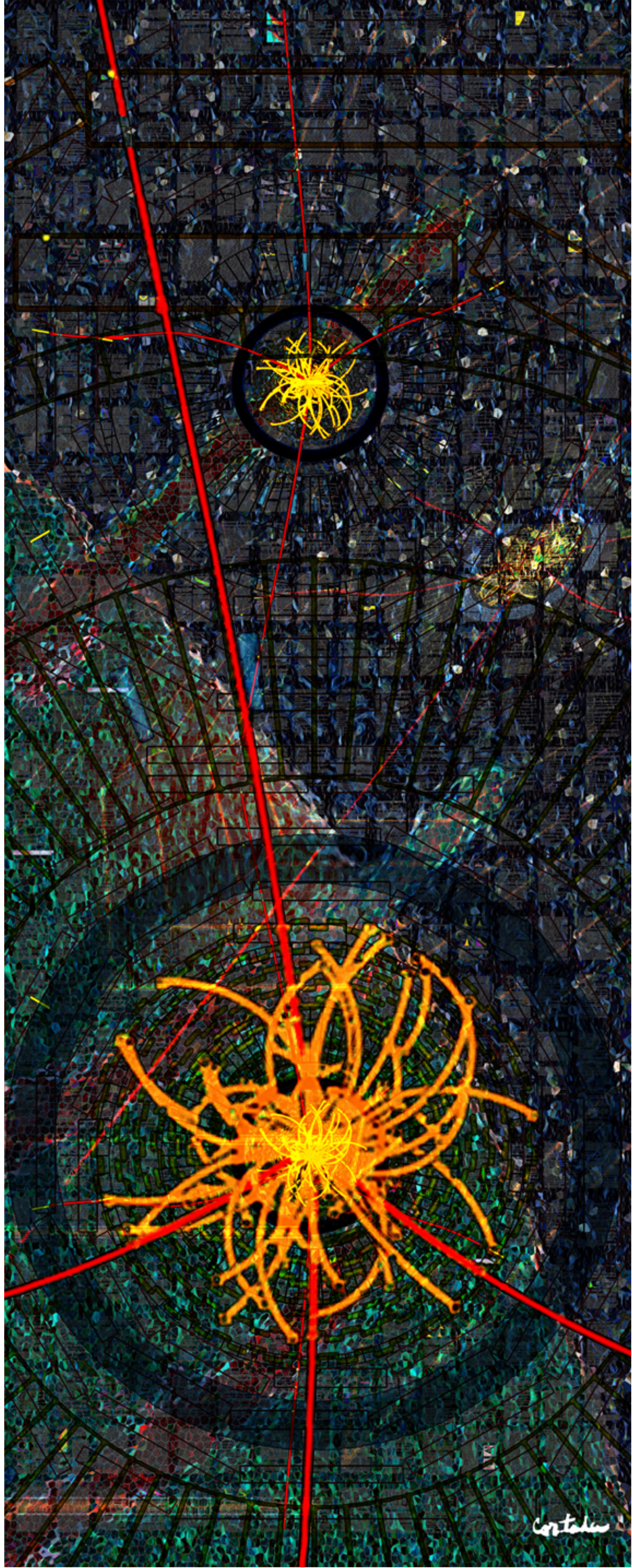
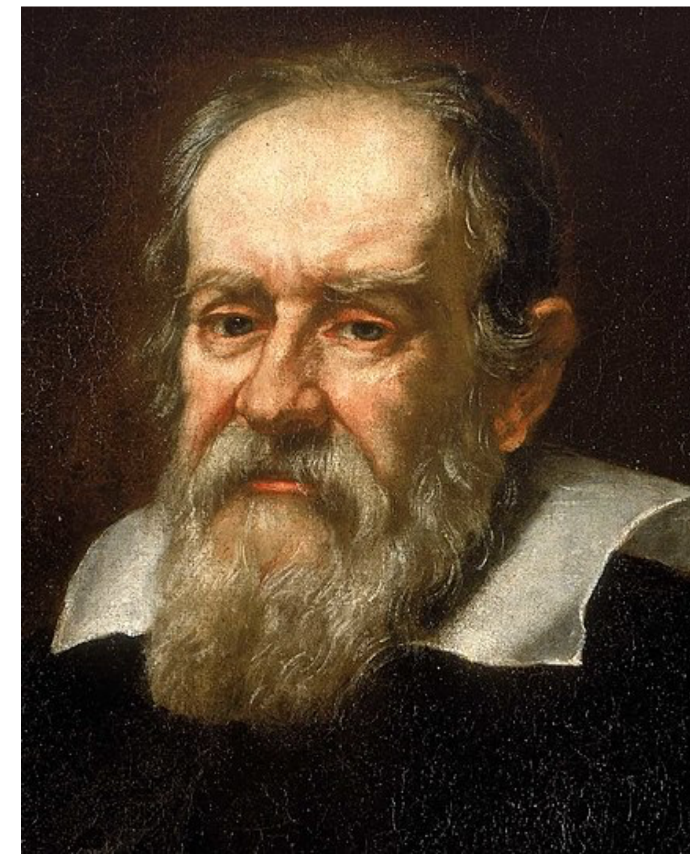


Scientific Method

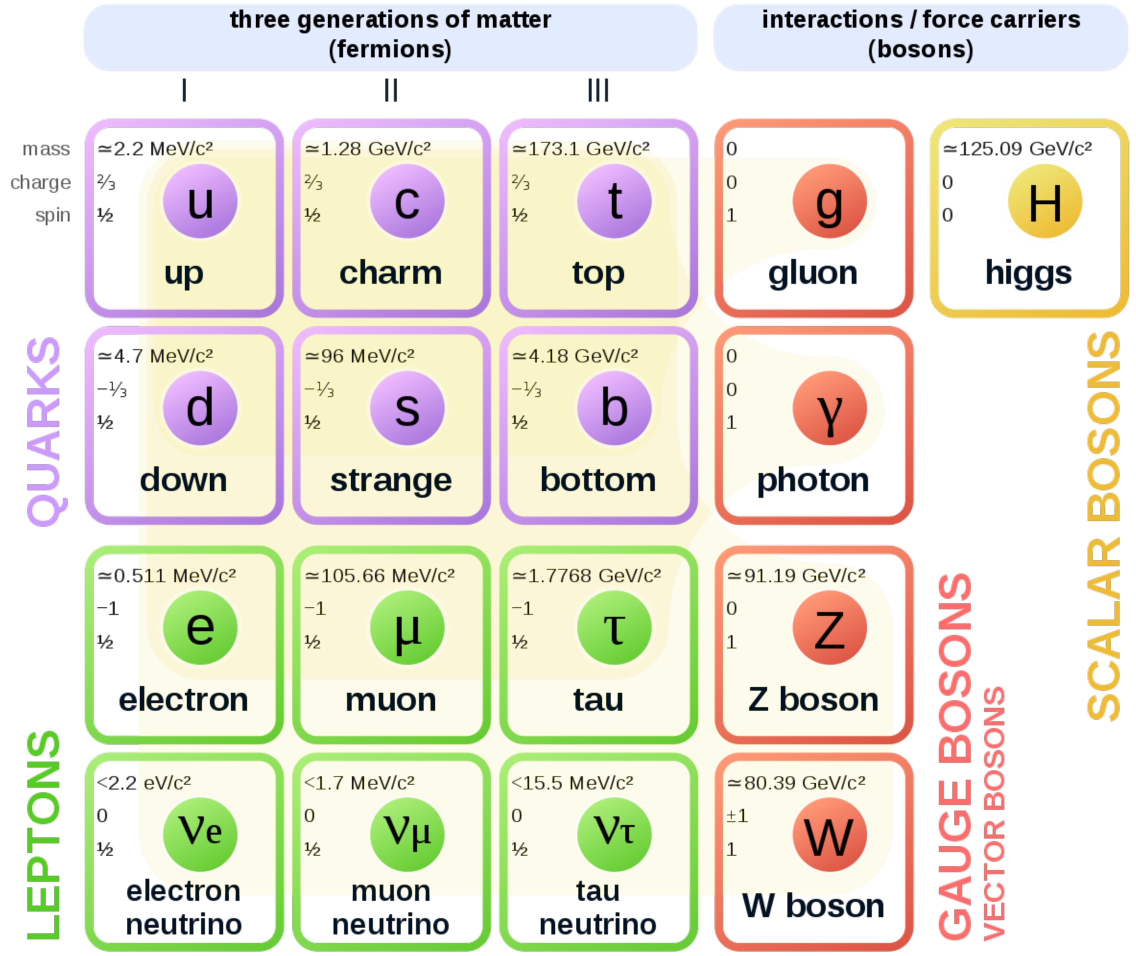
- Galileo was the father of the scientific method
  - Observe **phenomena** in Nature with experiments
  - Make **hypothesis** about laws of Nature (models)
  - Make quantitative **predictions**
  - Verify predictions with new **experiments**
  - Successful predictive models promoted to be a new **theory**
  - Never stop **verification and falsification** of existing theories
    - taking advantage of theoretical and technological advancements



XVI Century

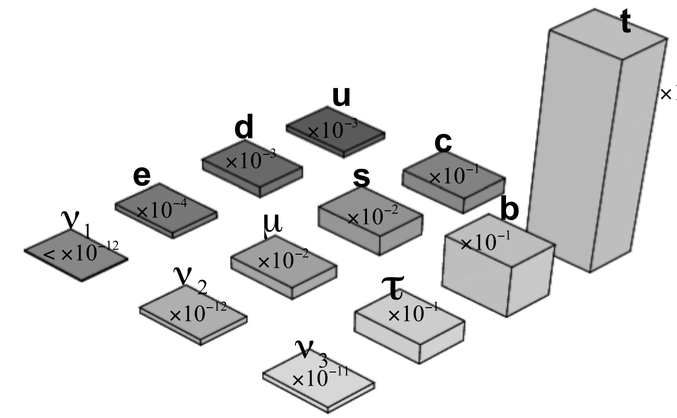
Standard Model

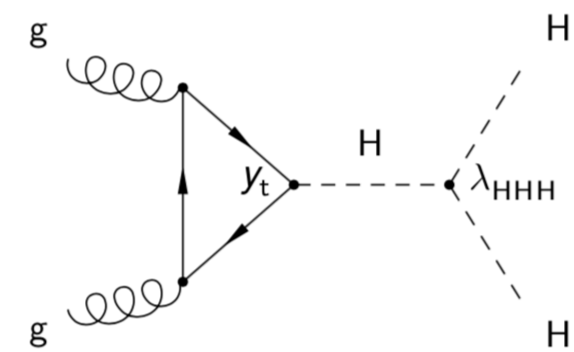
- ▻ Extremely predictive theory since its inception
- ▻ Last missing piece discovered almost 10 years ago
  - – Compare to gravitational waves and general relativity
- ▻ Has successfully resisted 50 years of falsification
- ▻ *We already know it is incomplete*
  - – e.g. neutrinos are massive
- ▻ It cannot address some basic curiosities and questions about our Universe

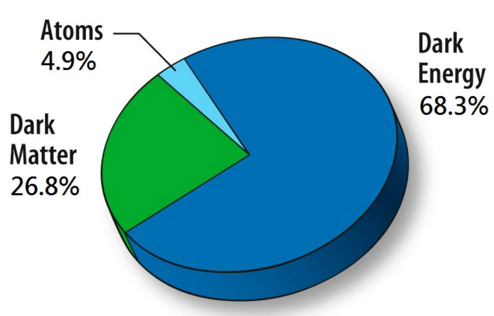


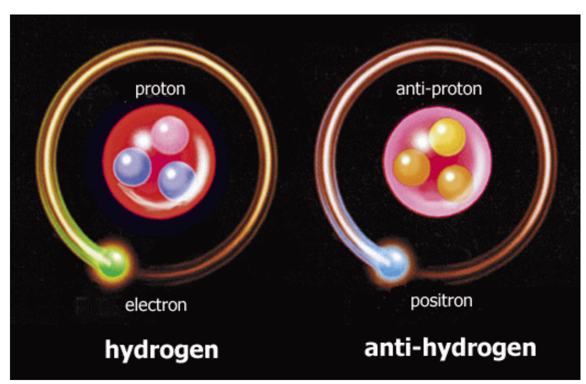
Questions and Curiosities

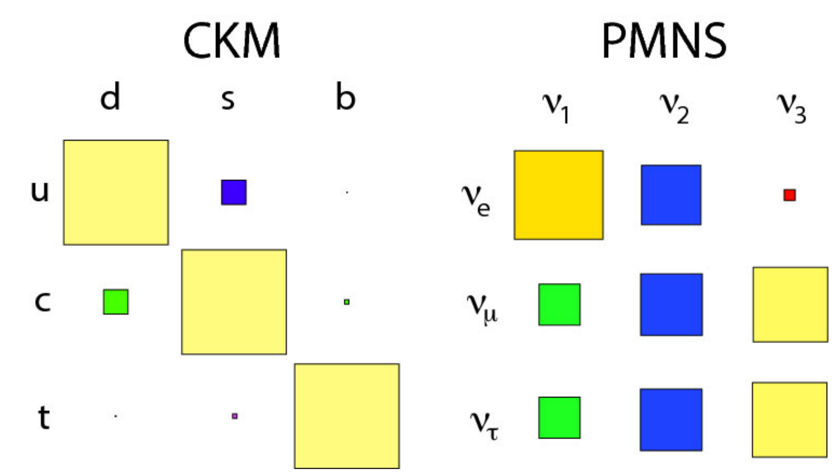
- ▻ What is the origin of mass?
- ▻ Have we found ***the*** Higgs boson?
- ▻ What is the origin of mass hierarchy?
- ▻ Do all leptons behave equally?
- ▻ Where is all the anti-matter in *our* Universe?
- ▻ What is Dark Matter?





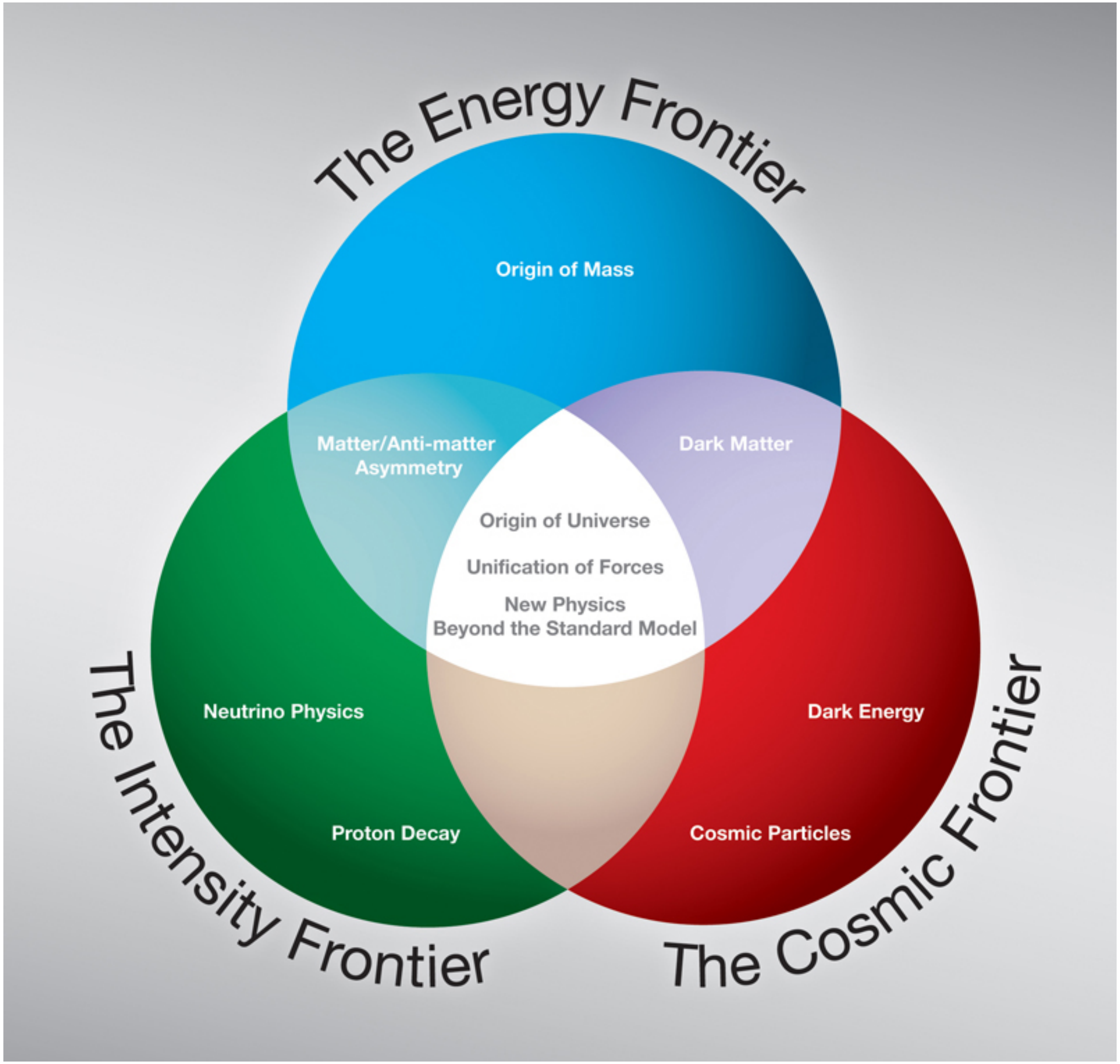




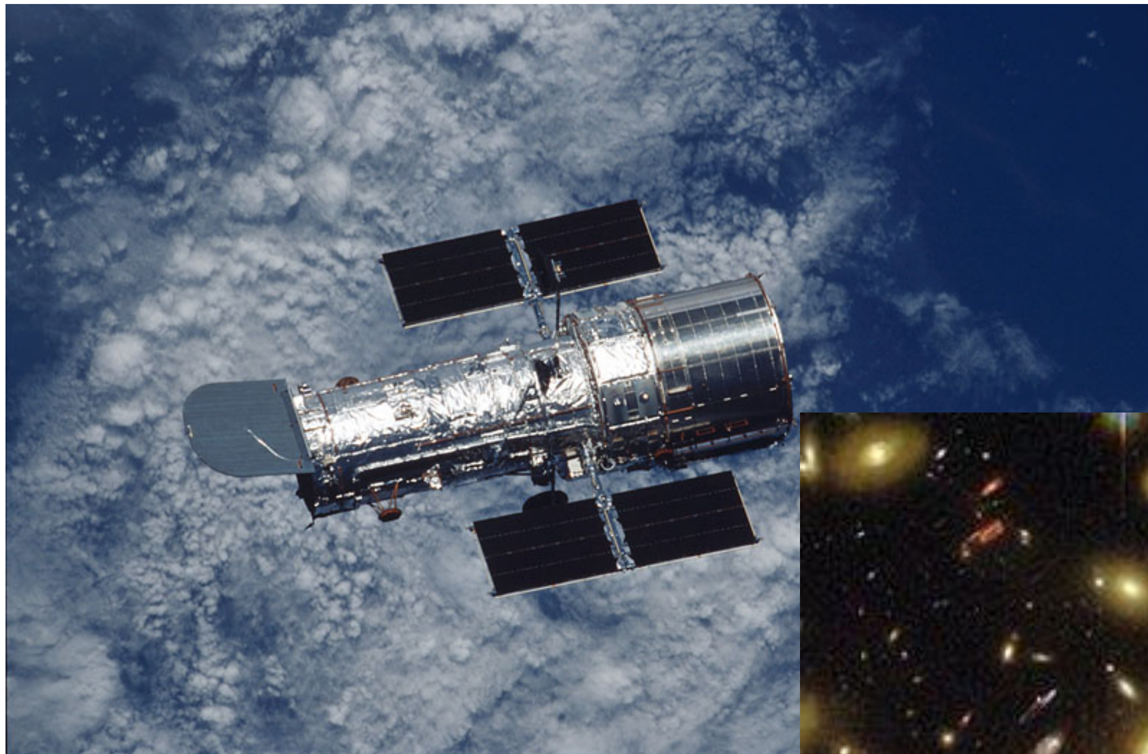


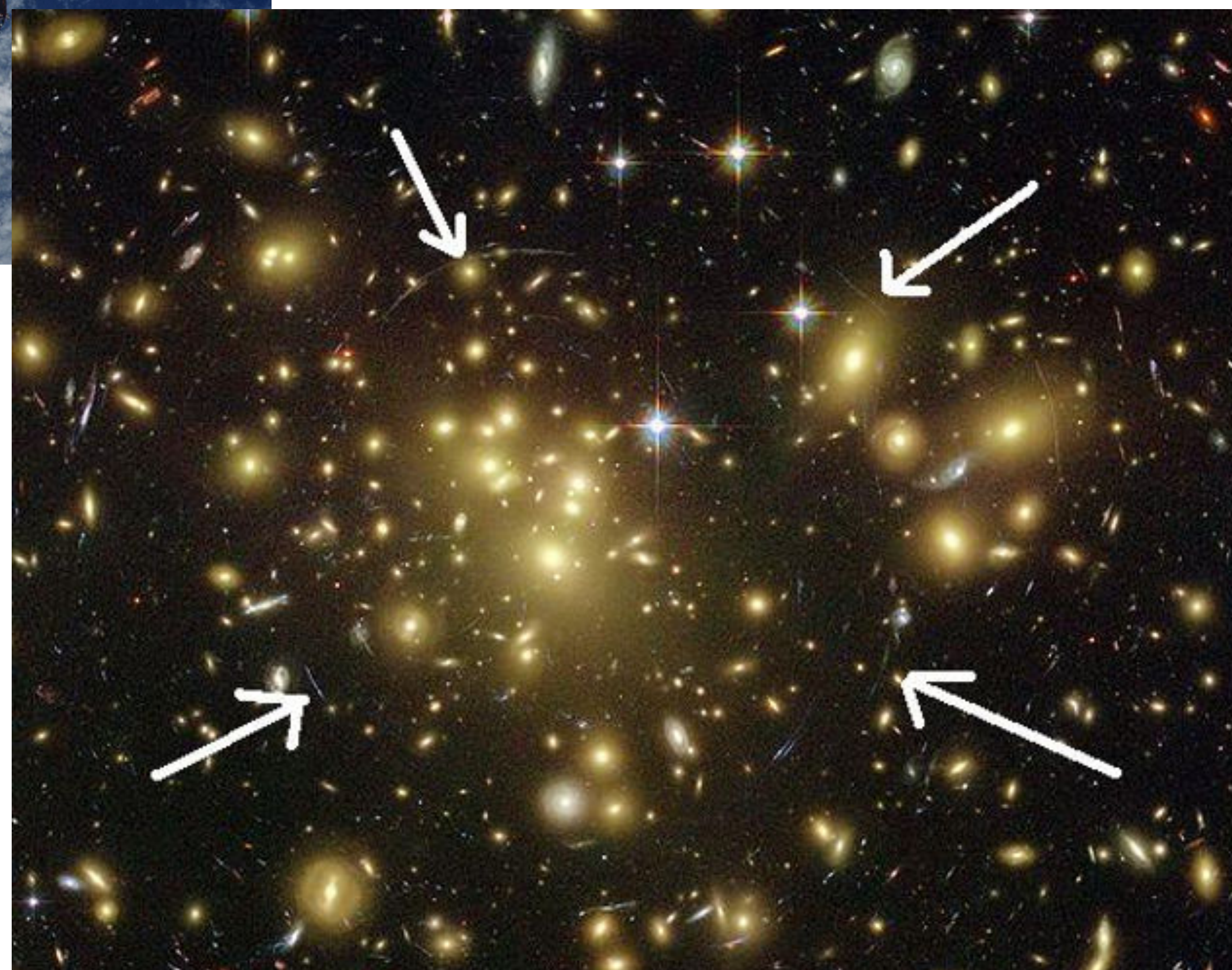
LHC provides broad spectrum of measurements to tackle almost all these questions!

Multi-prong Approach

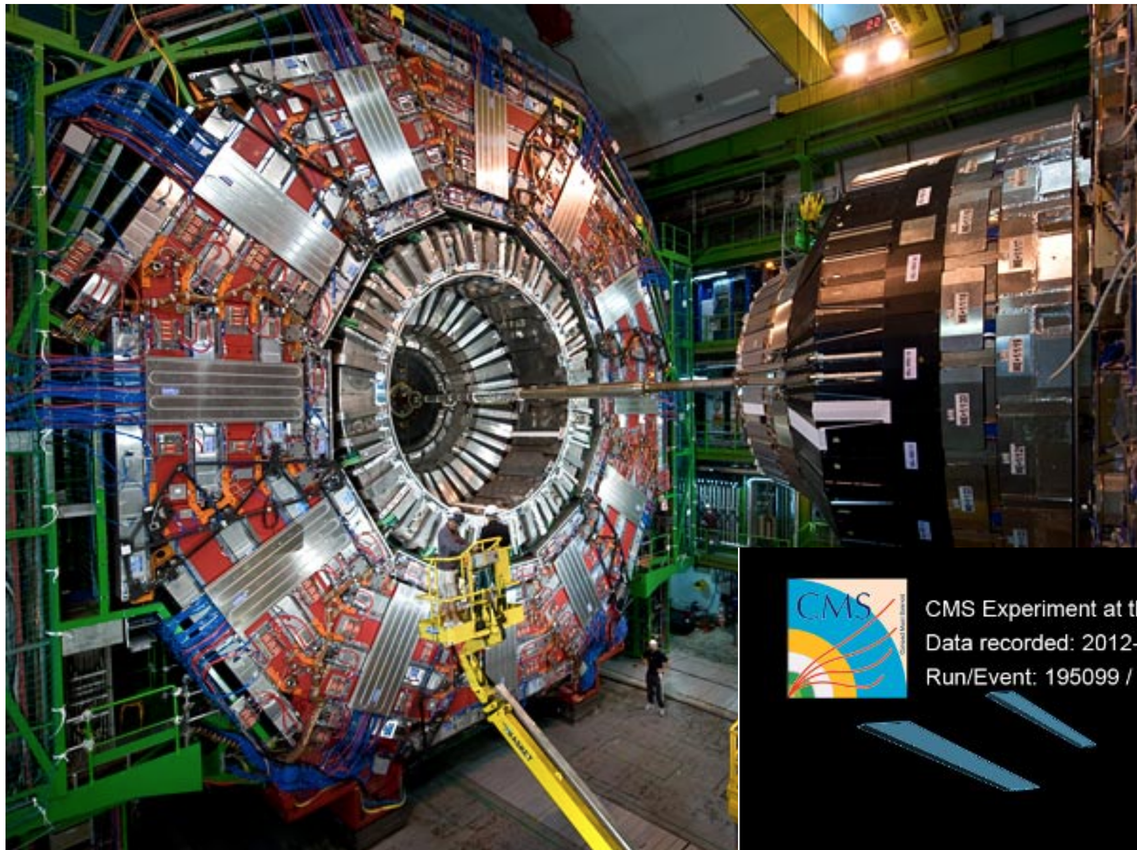


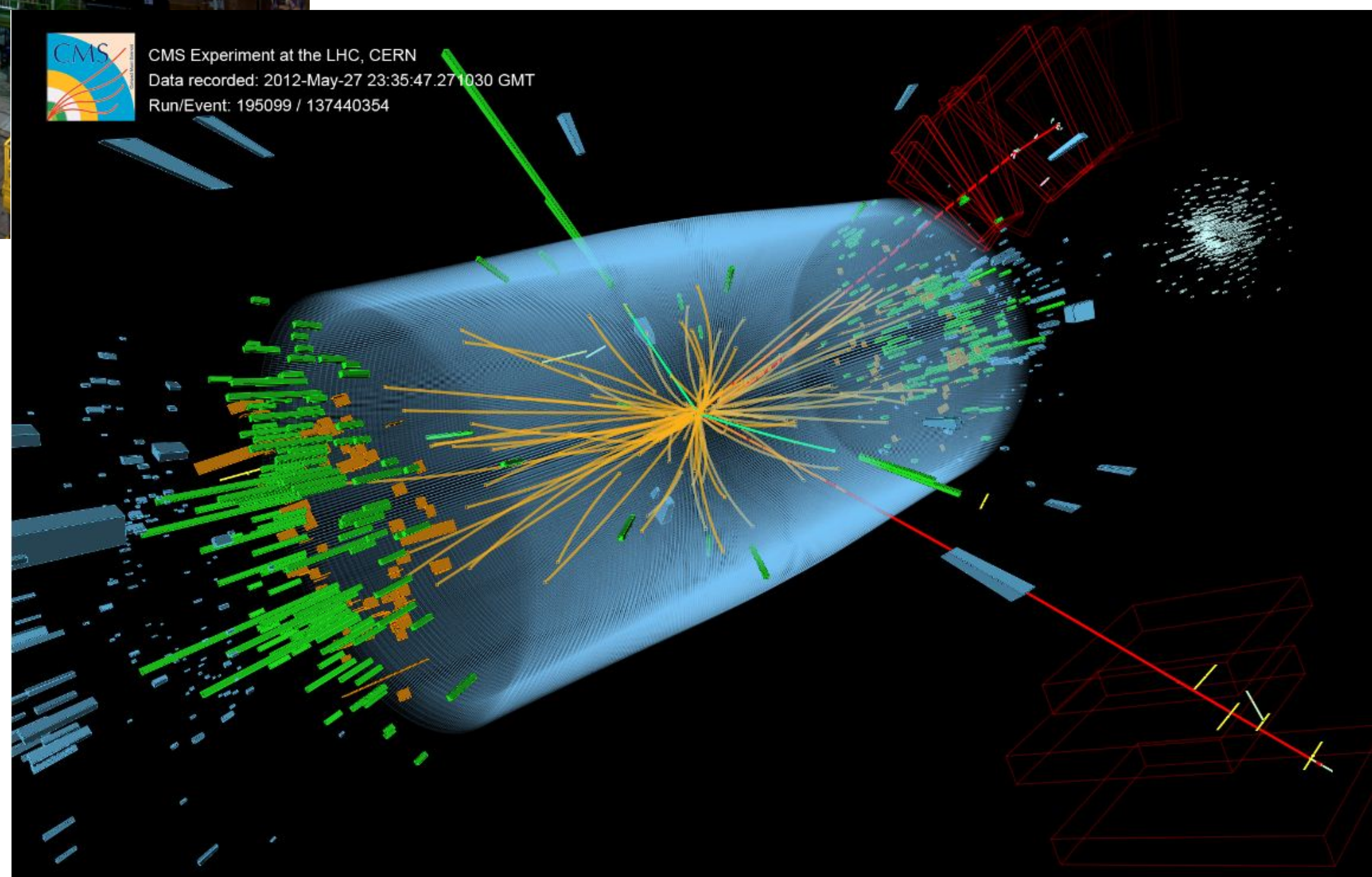
From Telescopes...



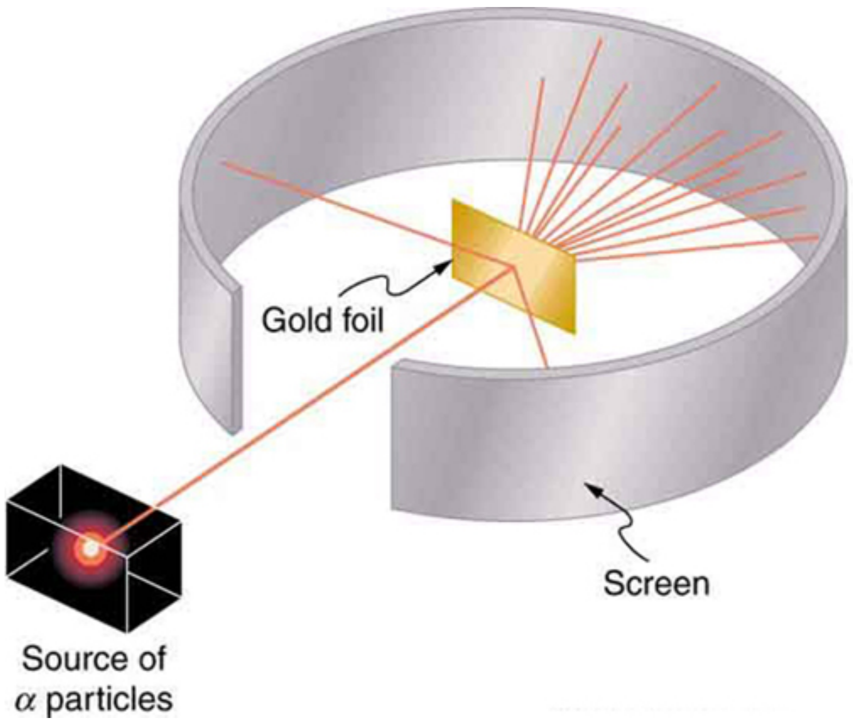


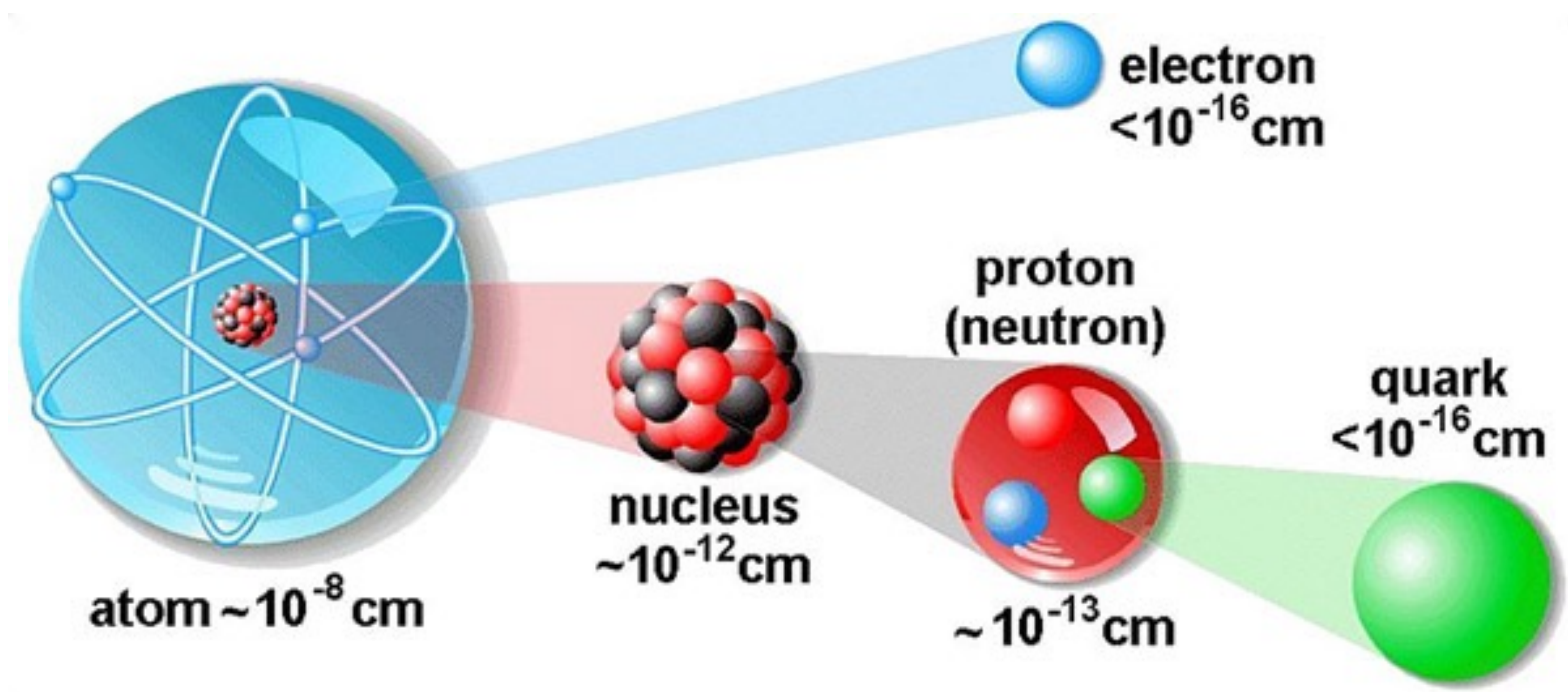
… To Particle Detectors



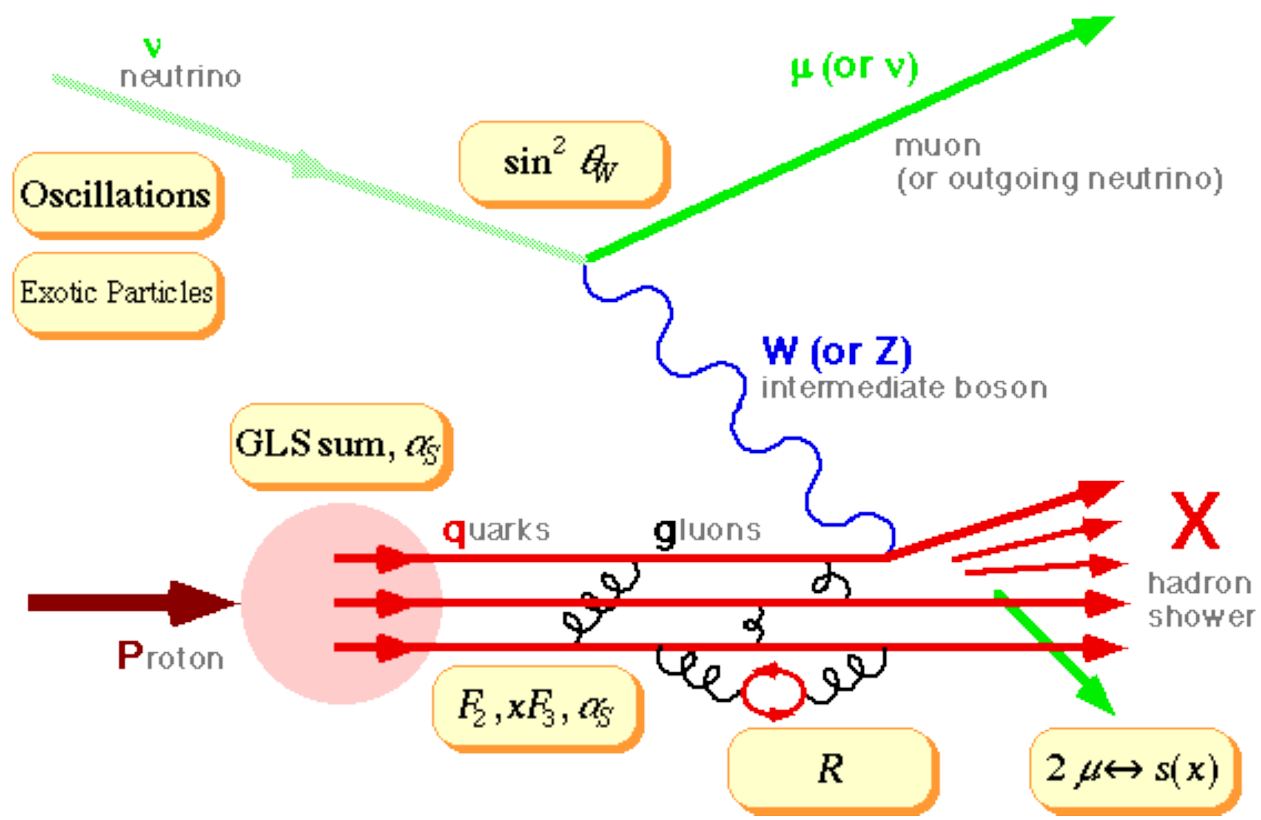


Frontier of Energy



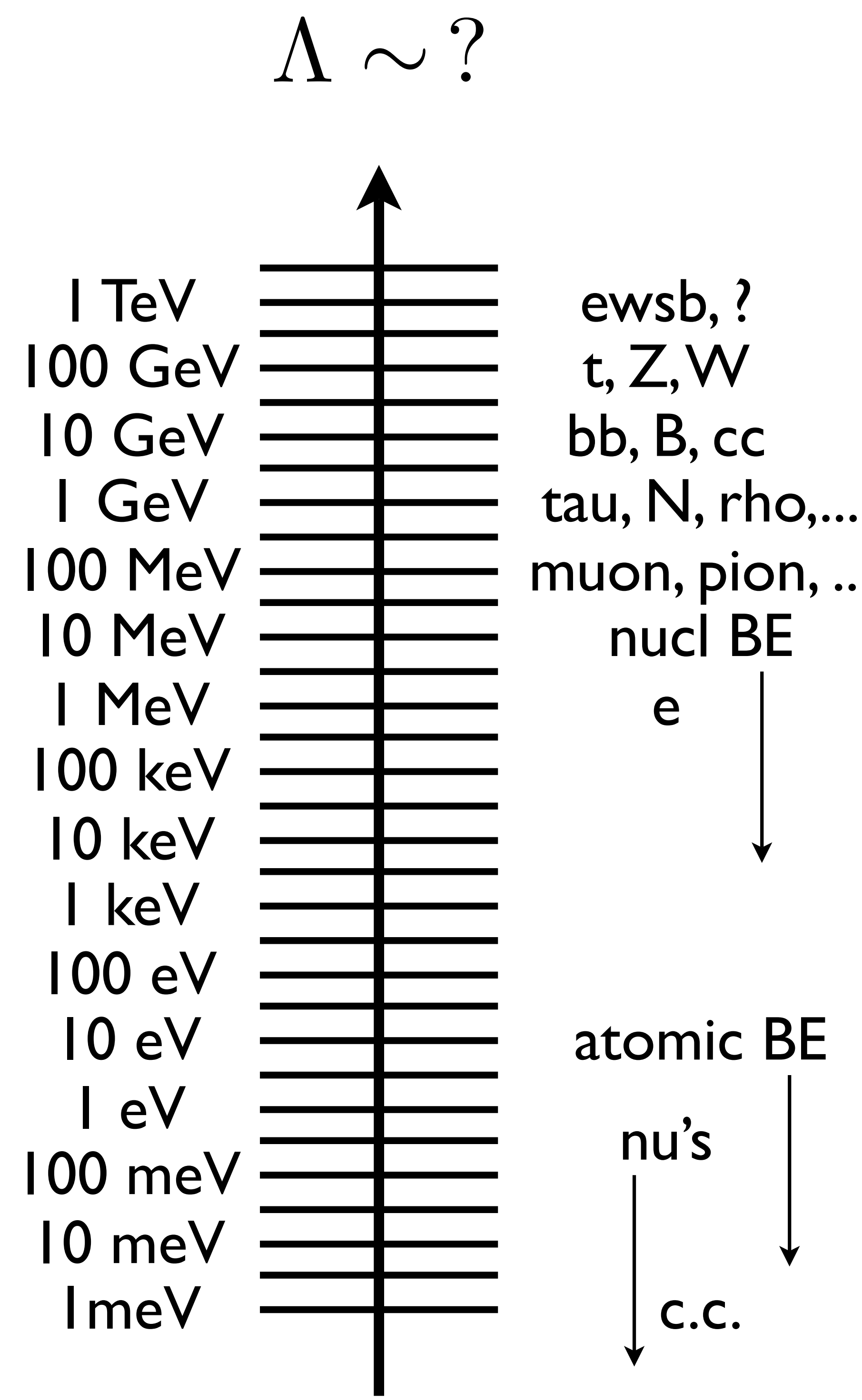


- Particle-Wave duality key to probe structure of matter
- Higher energy means
  - smaller wave length $E \approx 1/\lambda$
    - probe smaller constituents
  - higher temperature $E = kT$
    - recreate conditions closer to big bang



Scale of New Phenomena

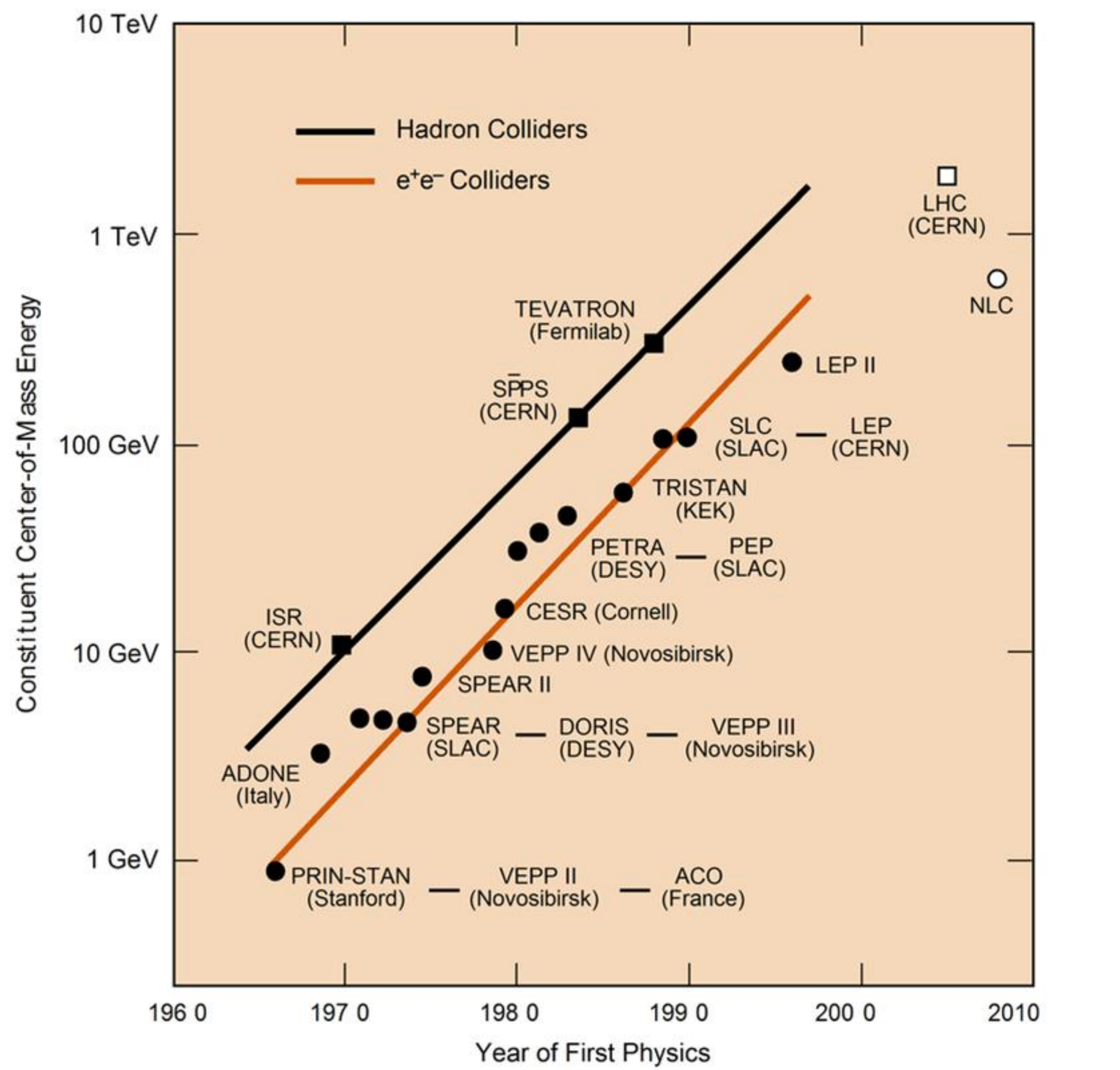
- Since birth of particle physics, experiments have explored many orders of magnitude in energy
- *New phenomena* appeared at *higher energy* scales
- Standard Model and Electroweak symmetry breaking occurs up to TeV scale
- How to determine scale of new physics beyond Standard Model?



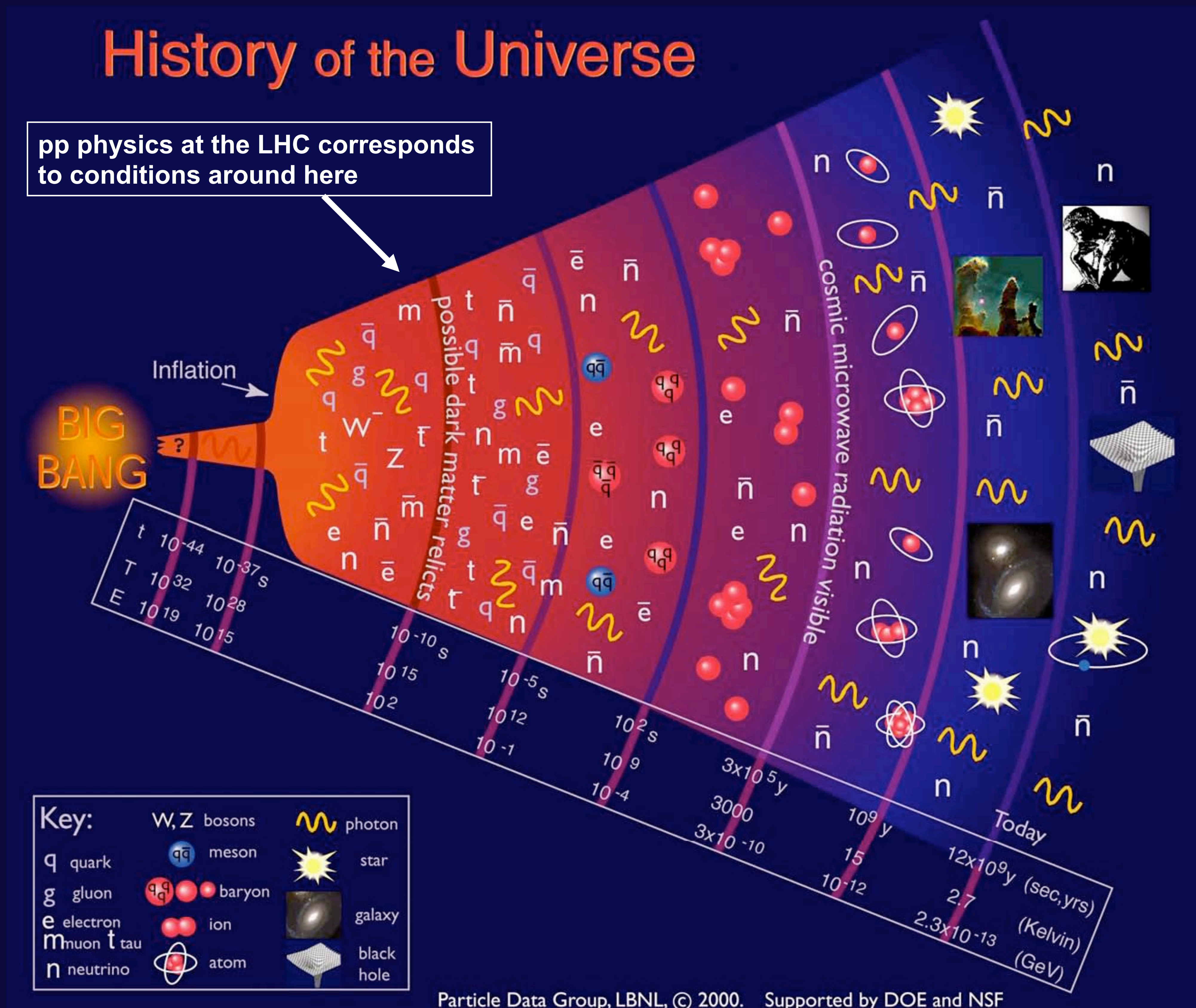
Evolution of Particle Colliders

- Direct production of new particles typically searched at hadron colliders
  - Increase of energy to access new production channels
    - Lack of discovery implies new particles are heavier
  - Accumulating data to probe weakly interacting particles
    - Particles are produced but with small cross section
- Alternatives
  - Lepton colliders if we know *where* to look for

LHC (CERN)
13 TeV (2015)

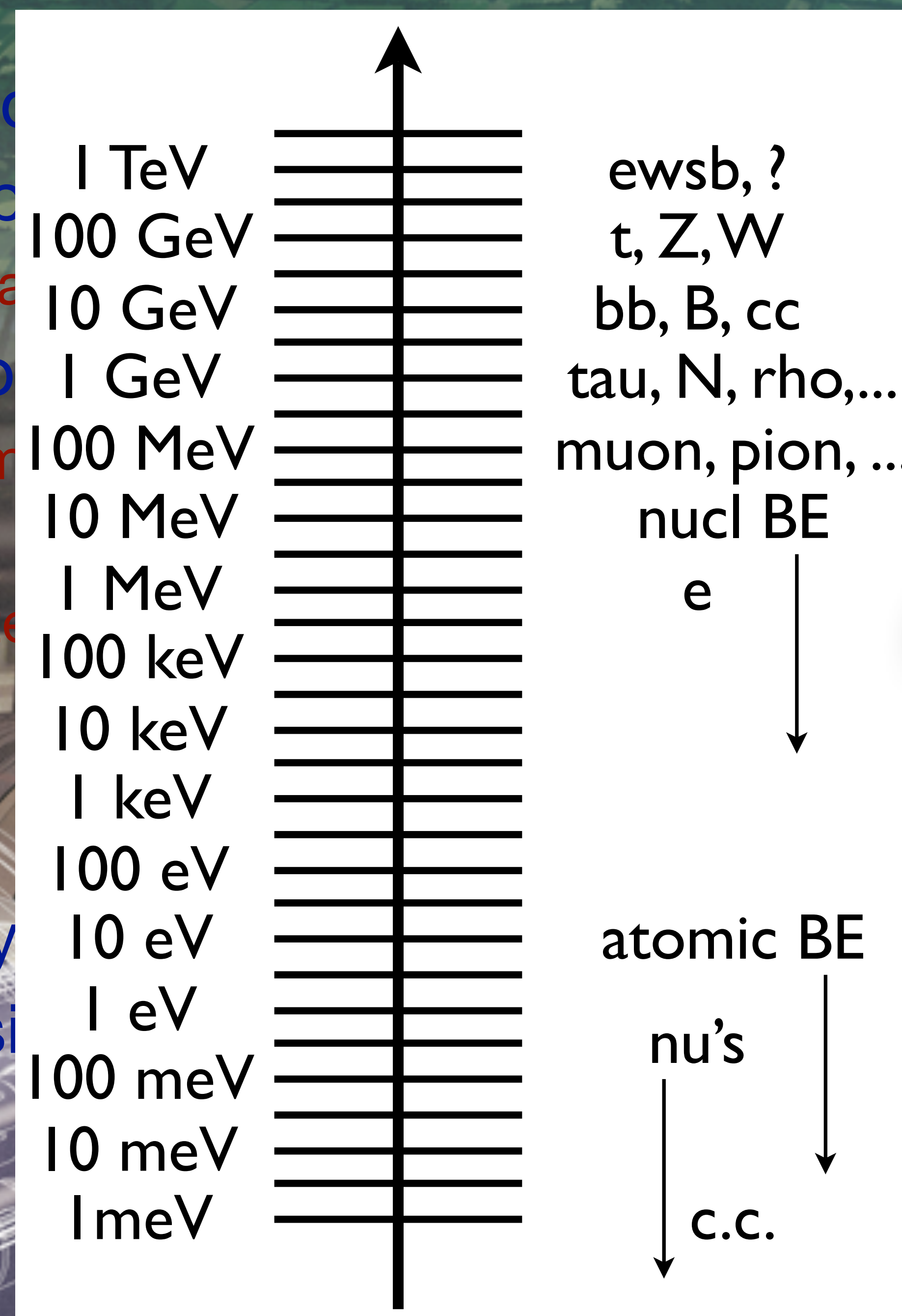


Probing The Universe



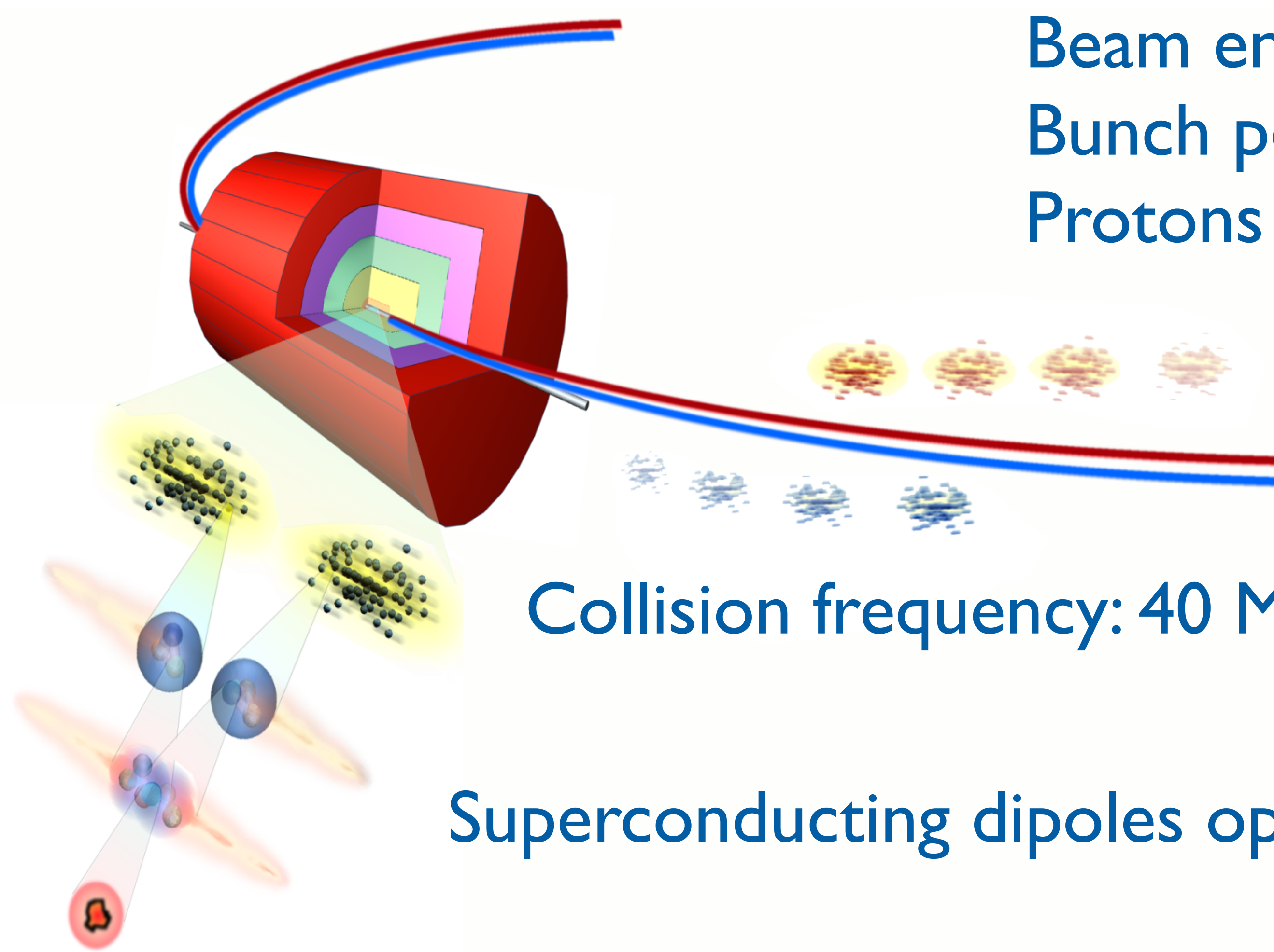
Large Hadron Collider

- Provide ultimate test of our understanding of the universe
- A new machine at the frontier of energy
  - Unexplored territory, not just precision test
- Primary objectives
  - Find Higgs boson prec
  - If found, measure its p
    - decay rates, spin, qua
  - Search for new pheno
    - New bosons and ferm
    - Compositeness
    - Dark matter candidate
- Many questions arise
  - Why so large?
  - Why such high energy
  - How to discriminate si

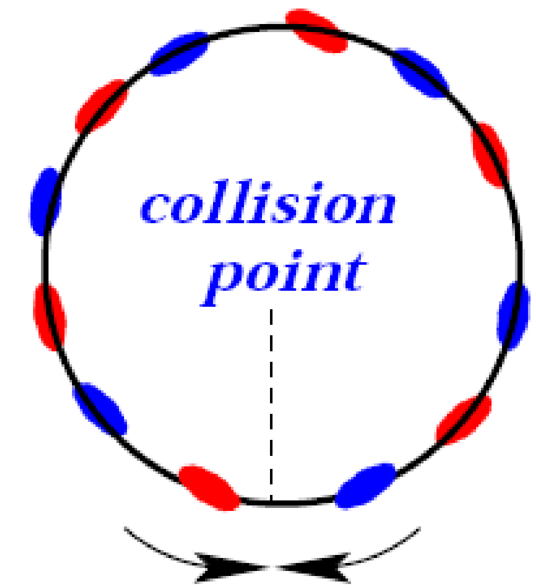


Four Experiments at LHC

Facts About LHC



Beam energy: 7 TeV
Bunch per beam: 2835
Protons per beam: 10^{11}



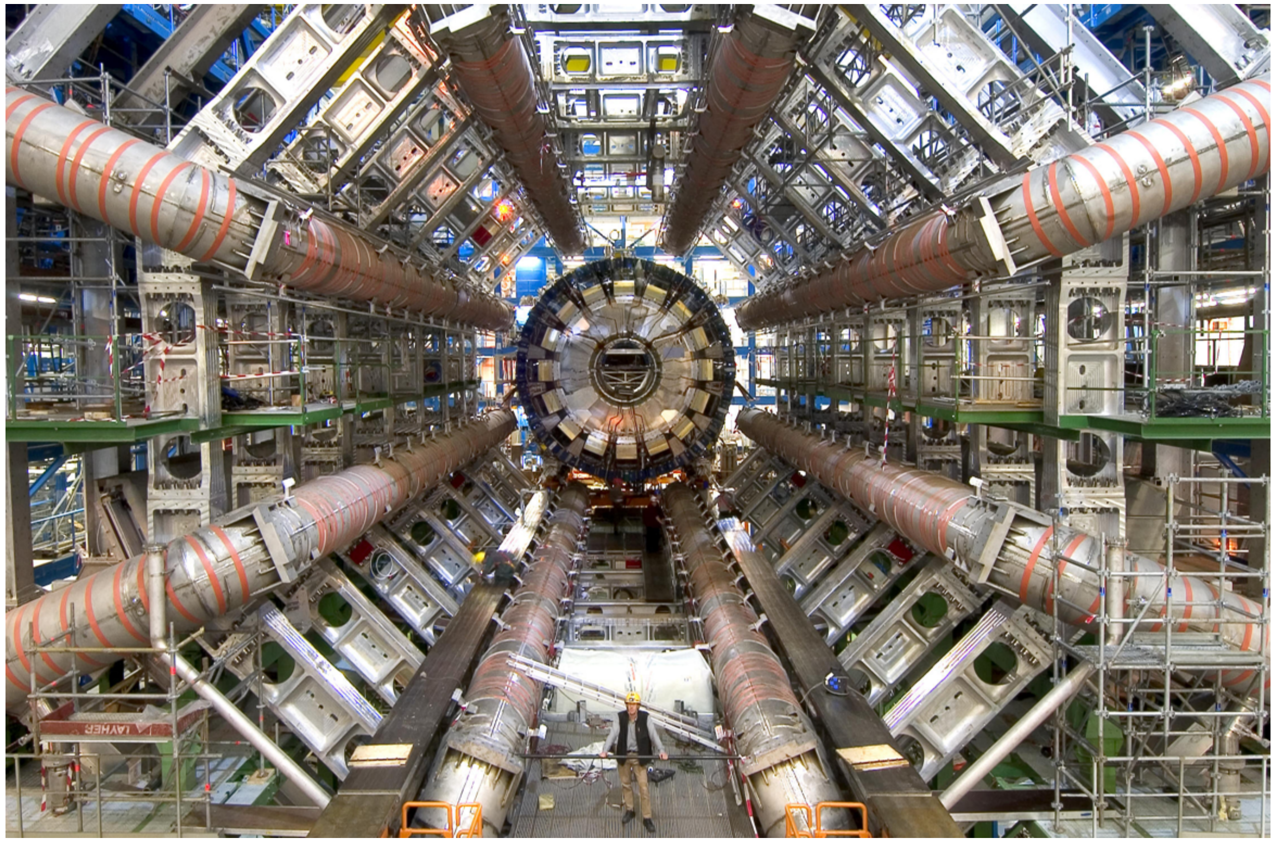
Collision frequency: 40 MHz

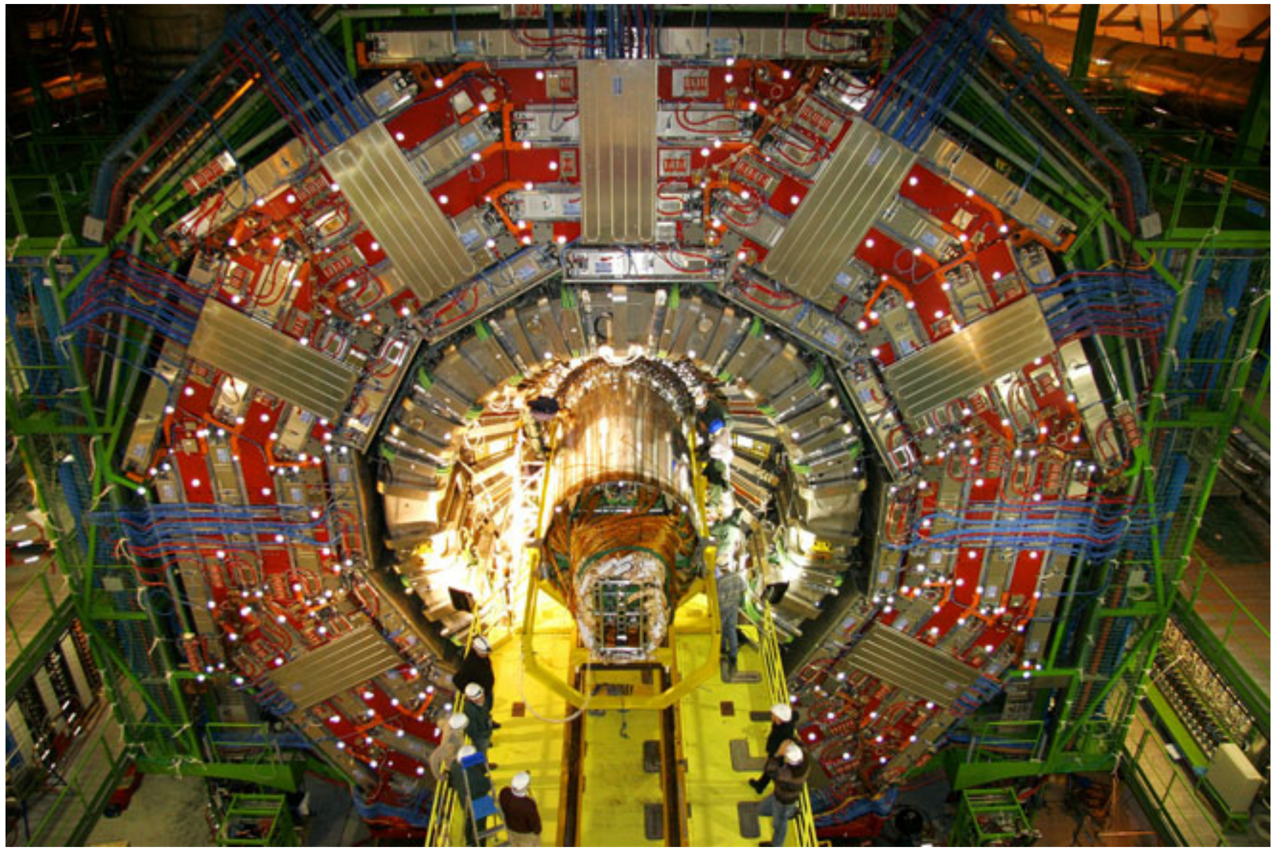
Superconducting dipoles operated at 1.9 K

- ▻ Energy stored in LHC magnets when operating at 14 TeV: 10.4 GJ
  - – Enough to melt 12 tons of Copper!
  - – The kinetic energy of an A380 at 700 km/hour
- ▻ Kinetic energy of 1 proton bunch: 129 kJ
- ▻ Kinetic energy of beam: 362 MJ

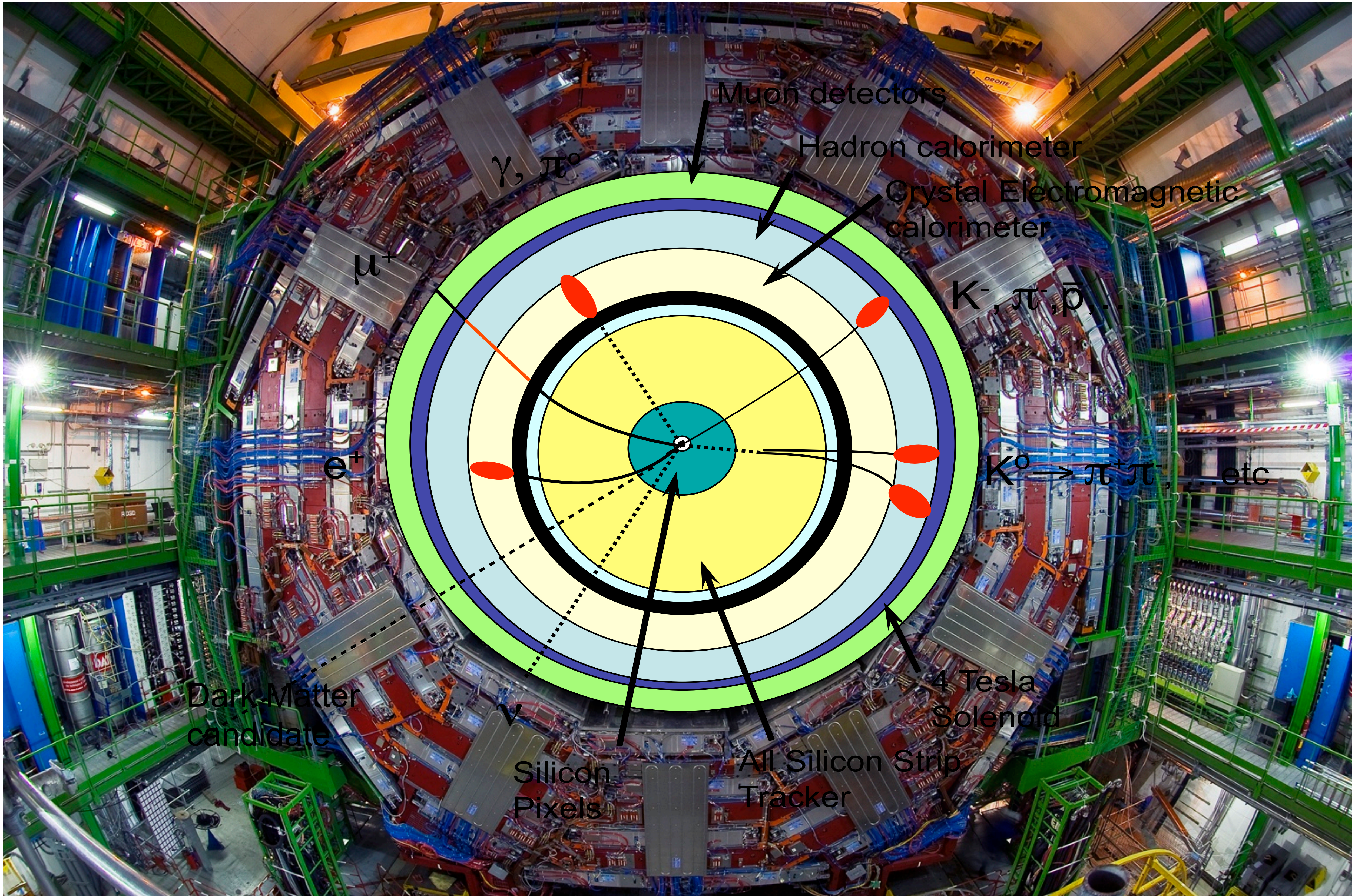
Gigantic Digital Camera

- Very heavy digital camera
  - 40 million pictures per second
  - Almost 100 million pixels
  - 3D pictures
- >100’000 of CPUs used to quickly filter data
  - 10’000 pictures selected each second
- Only 1000 pictures stored on disk
  - pictures selected within 100 ms
- 22 million GigaByte of data each year (>1 million DVD)
  - Data hosted and analysed at computing centers worldwide

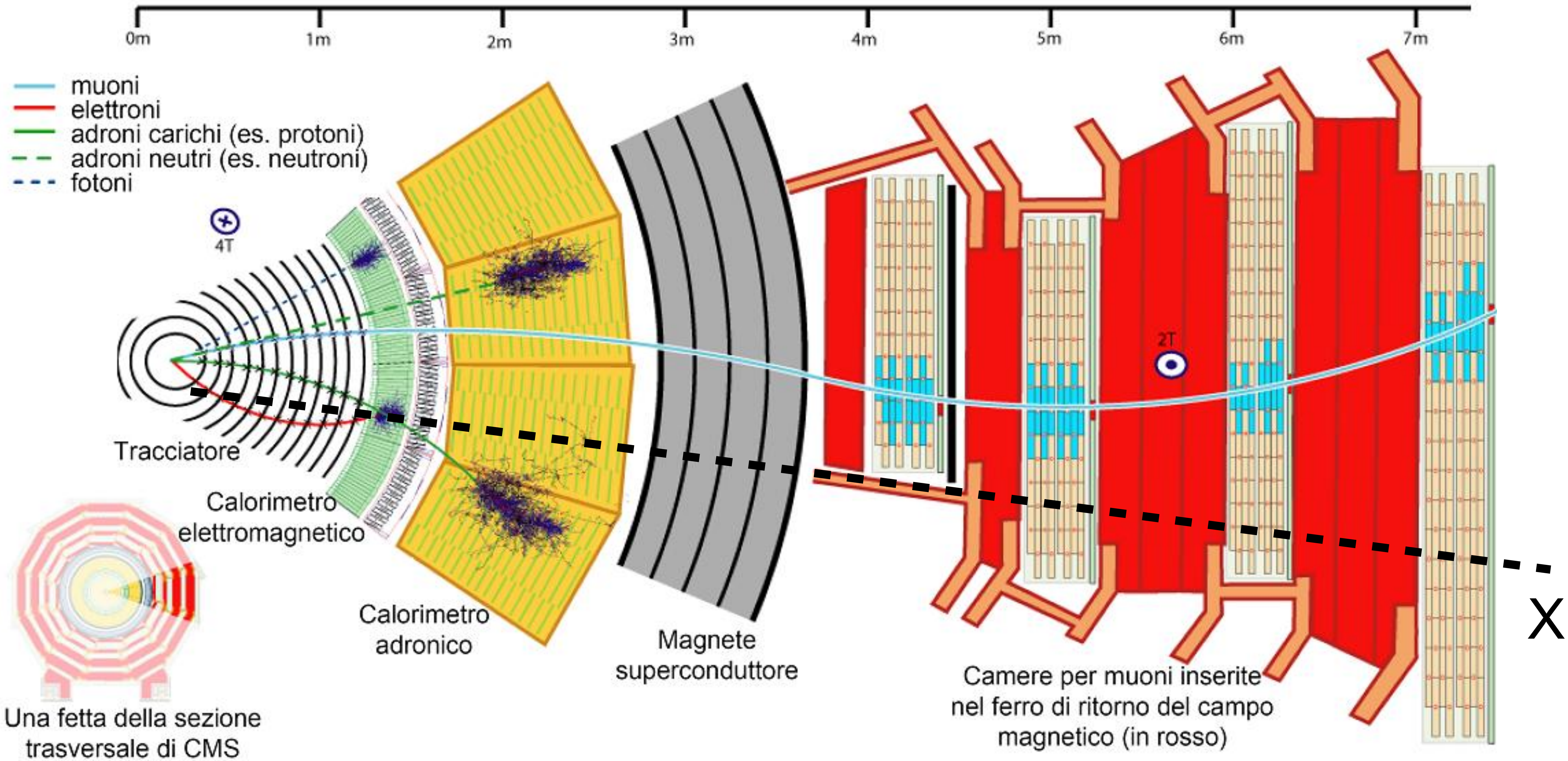




Compact Muon Solenoid



Particle Identification



- Detectors record signals from hadrons, charged leptons, and photons
- Relativistic kinematics with energy and momentum conservation

Energy Frontier after Higgs Discovery

- Intense scrutiny of Higgs and Yukawa sector

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

Precision Electroweak and QCD

$$+|D_\mu\phi|^2 - V(H)$$

Higgs properties
Higgs self interaction

$$+Y_{ij}\psi_i\psi_j\phi + \text{h.c.}$$

Higgs coupling to bosons and fermions
CKM matrix and CP Violation

- While keeping a wide open eye on new phenomena

$$+\mathcal{L}_{\text{New}}$$

New light and heavy particles
Lepton flavour universality violation
Leptoquarks
SUSY
Long-lived particles
Dark matter

Means of Falsification

- ▻ Multiple and redundant measurements of well known quantities
  - – different methods
  - – different contexts
  - – different technologies

The Known Knowns

- ▻ Measurement of very small and precise predictions
  - – variety of such observables across the spectrum
  - – typically referred to as indirect search for New Physics
  - – At LHC now merging with standard Physics thanks to amount of data

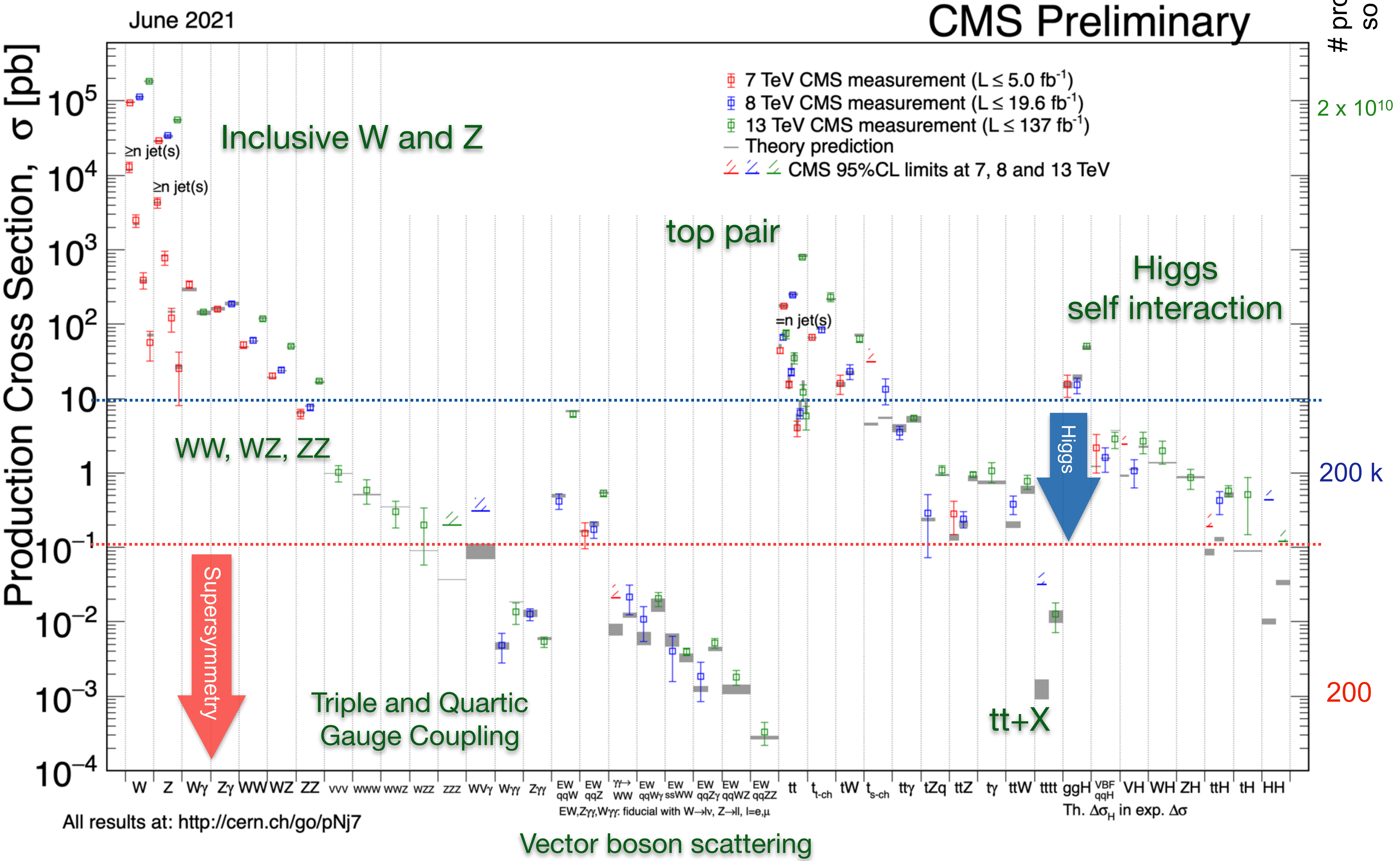
The Known Unknowns

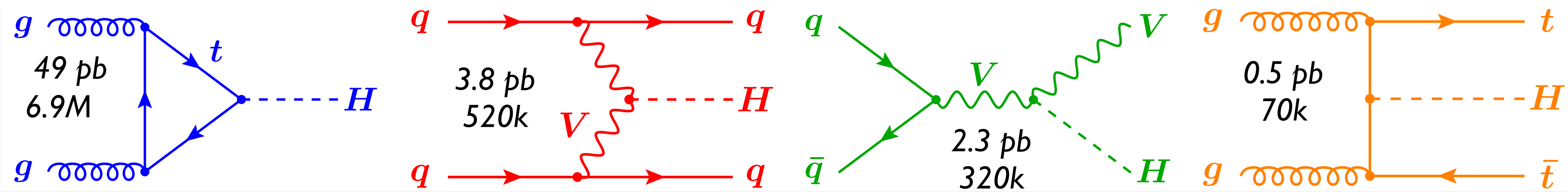
- ▻ Search for the exotic
  - – chasing more or less crazy ideas by theory friends
    - ○ often motivated by some big question
  - – Taking advantage of capabilities of detectors for unconventional signatures

The Unknown Unknowns

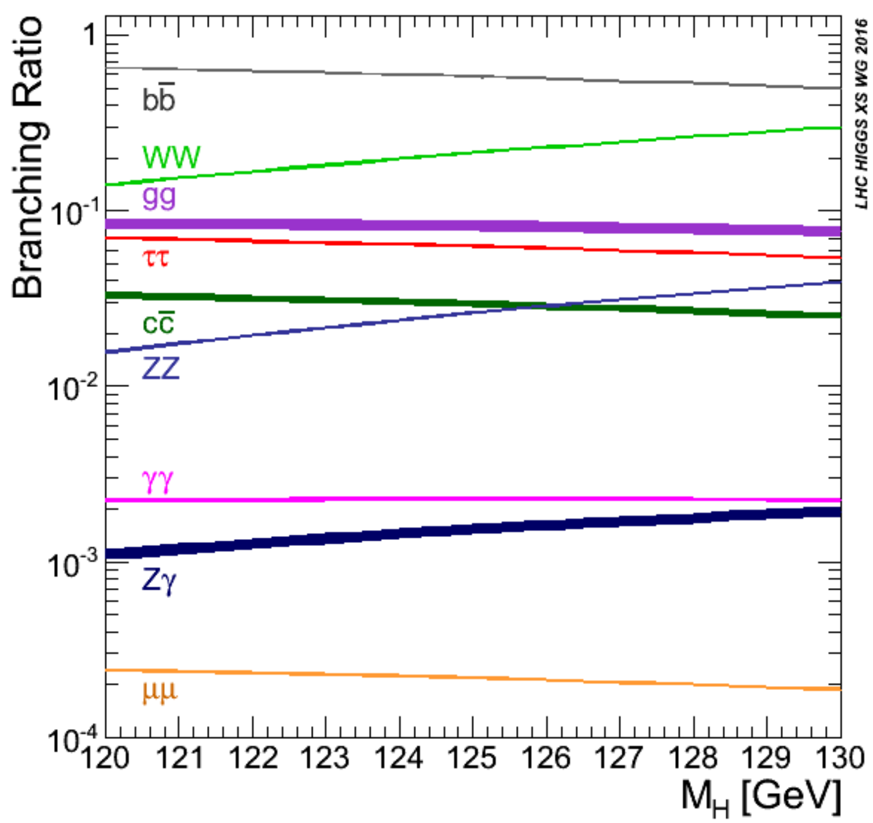
- ▻ New computational tools for more efficient data mining and increasing sensitivity
- ▻ New technologies to improve detection techniques and try new avenues

New Physics through Precision





σ [pb]
#Higgs produced during Run-2



Production

Decay

	ggF	VBF	VH	ttH
H→ZZ→4l	●	●	●	●
H→γγ	●	●	●	●
H→WW	●	●	●	●
H→bb	●	●	●	●
H→ττ	●	●		●
H→μμ	●	●	●	●
H→inv	●	●	●	

More than 250 event categories

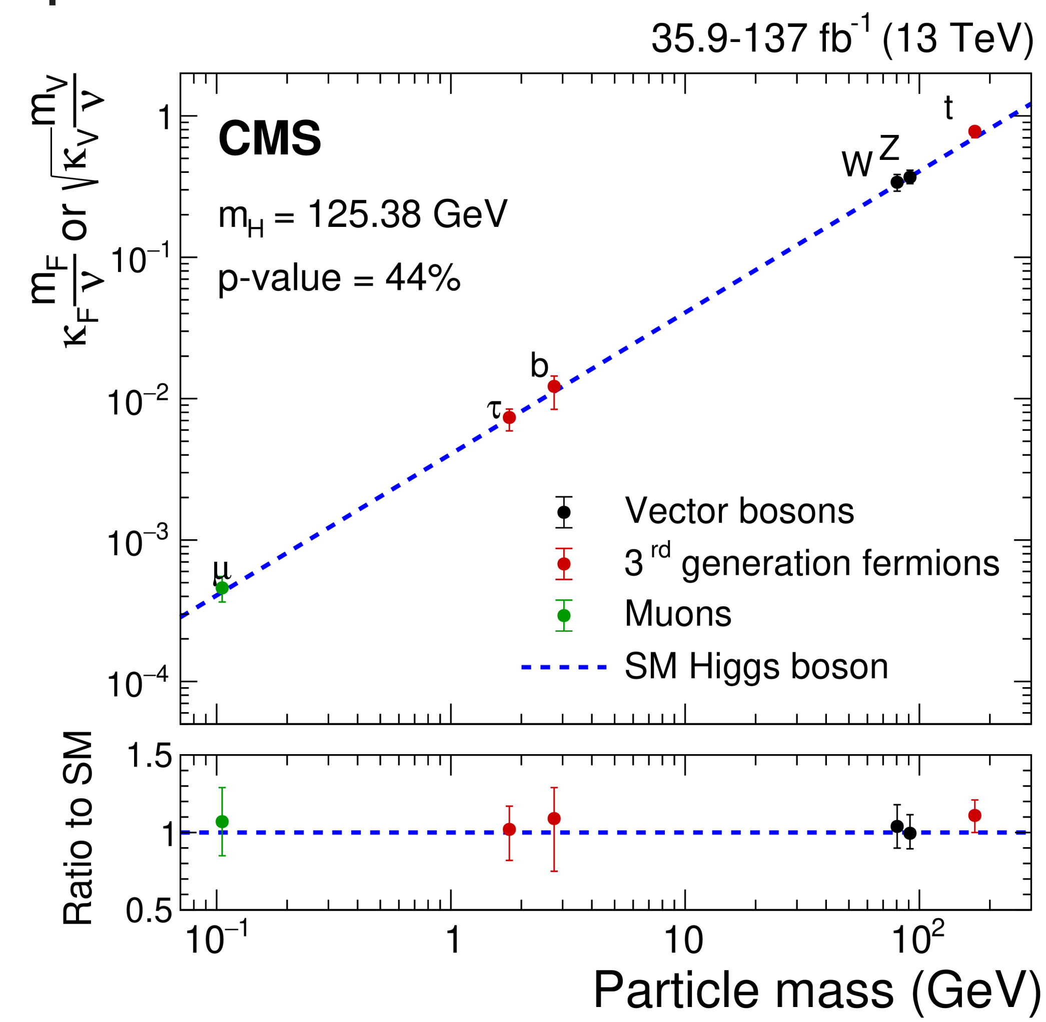
Higgs

From Discovery to Precision

$Y_{ij}\psi_i\psi_j\phi$

Higgs Physics

- A standard candle of Standard Model in just a decade since its discovery
  - compare to top, W, and Z
- Higgs now used as a probe in searches for new phenomena
  - FCNC in top decays
  - Search for Supersymmetry
  - Search for Dark Matter WIMP candidates
  - Decay of heavy new particles to H+X
- Couplings to 3rd generation established
  - taus in 2017, top and b in 2018
- Coupling to 2nd generation under way!
  - evidence for muons, tackling also charm



- So far it walks and talks like the Standard Model Higgs
- *Falsification of the Higgs mechanism a critical component of High Energy Frontier program*

Means of Falsification

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  - different contexts
  - different technologies

The Known Knowns

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The Known Unknowns

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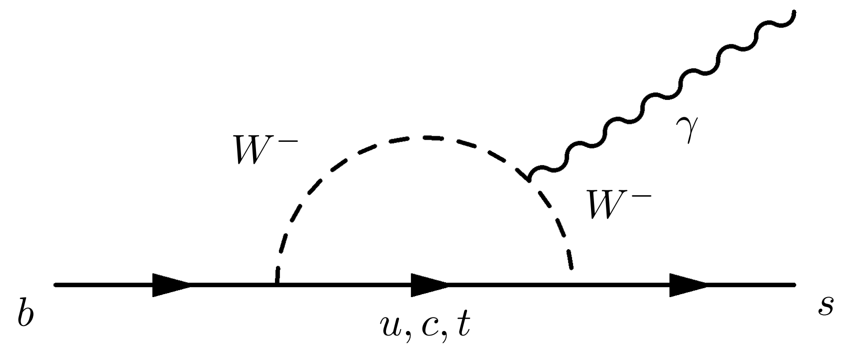
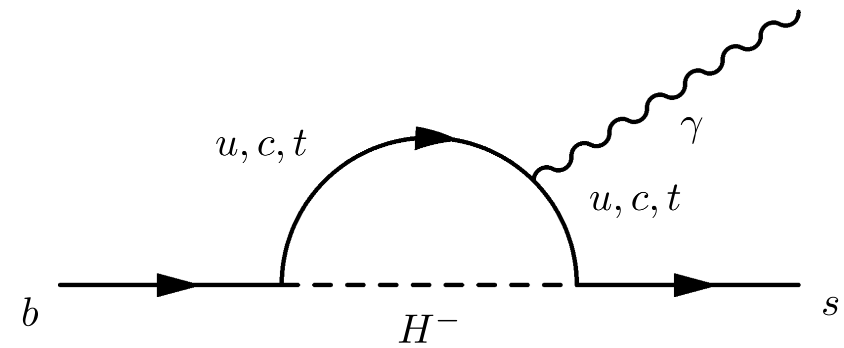
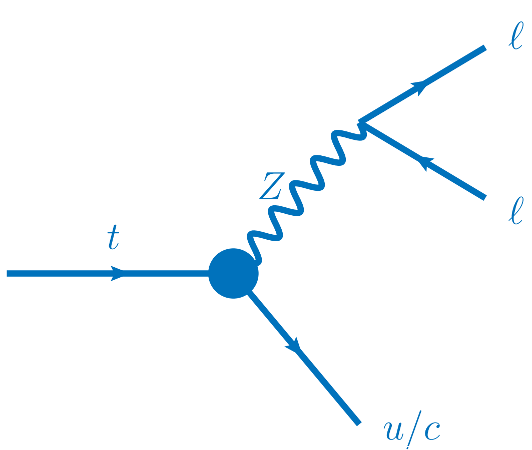
The Unknown Unknowns

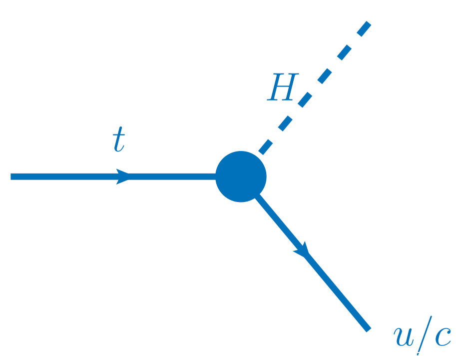
Flavor Changing Neutral Currents





- Forbidden in Standard Model at tree level
- Typically small predicated rates and hence sensitive to new particles in strong and electroweak penguin loops
- Rich area of probe in b, c, s, and now also top decays using Higgs!

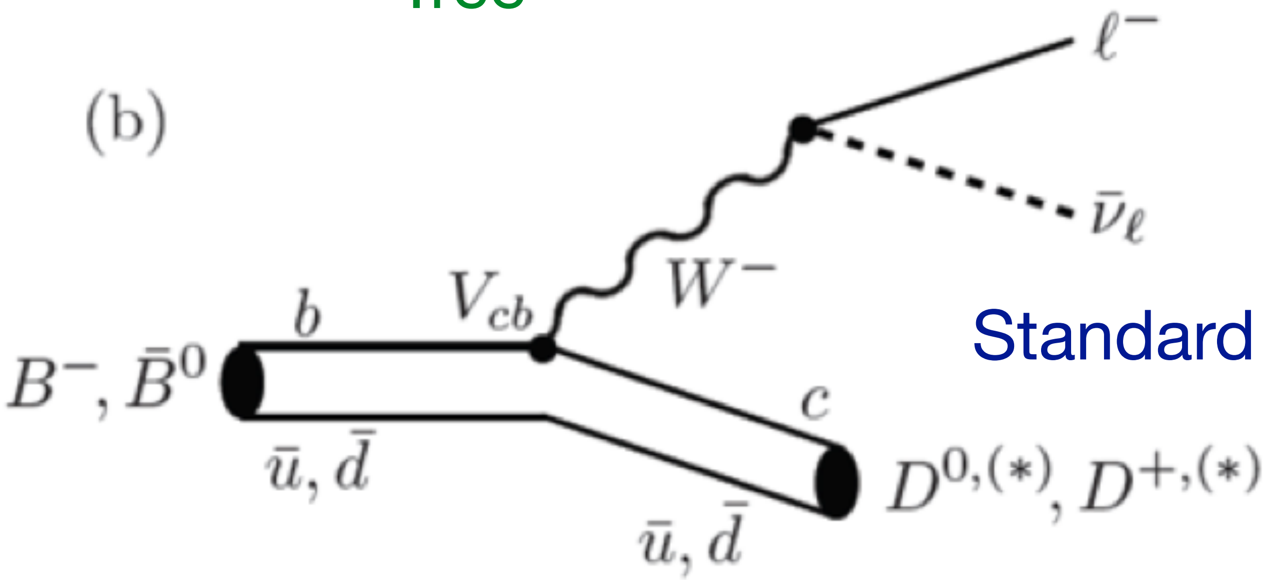




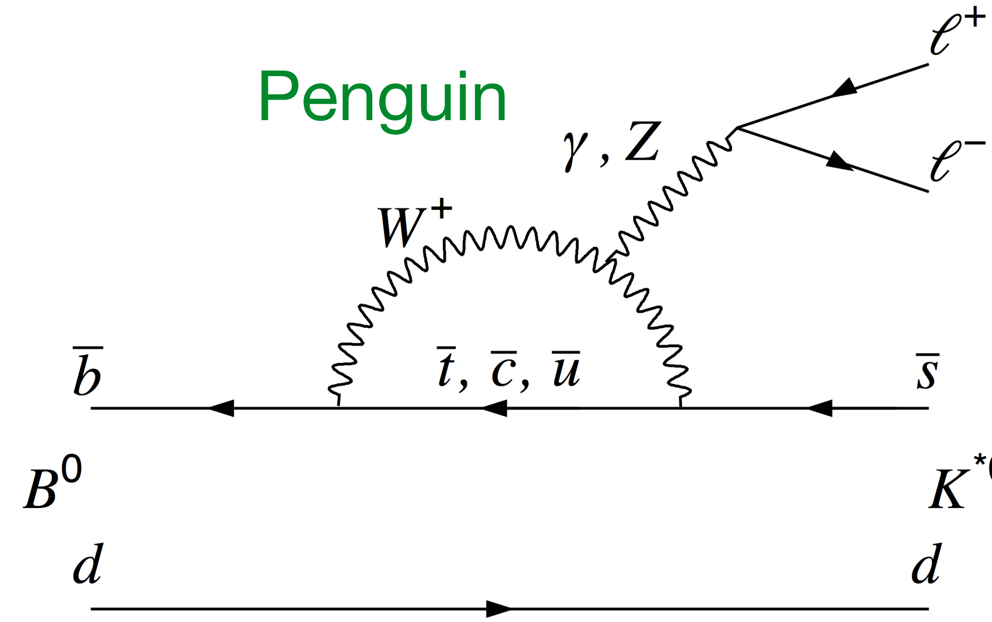
SM
BR($t \to qH$) ~ 10^{-15}
BR($t \to qZ$) ~ 10^{-14}

New CMS-PAS-TOP-20-007
B($t \to Hu$) < 1.9×10^{-4}
B($t \to Hc$) < 7.3×10^{-4}

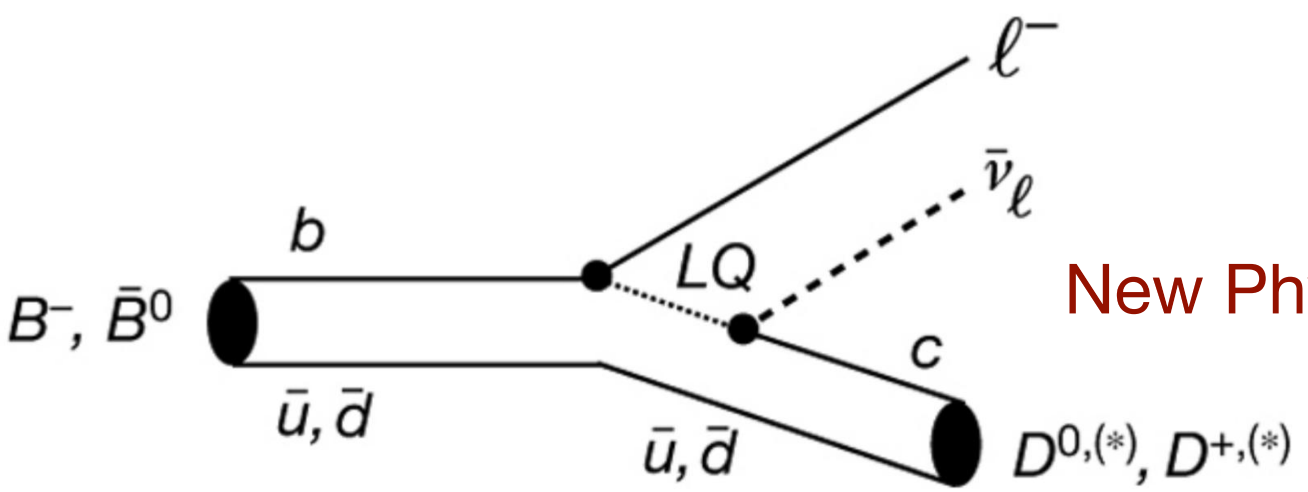
Tree



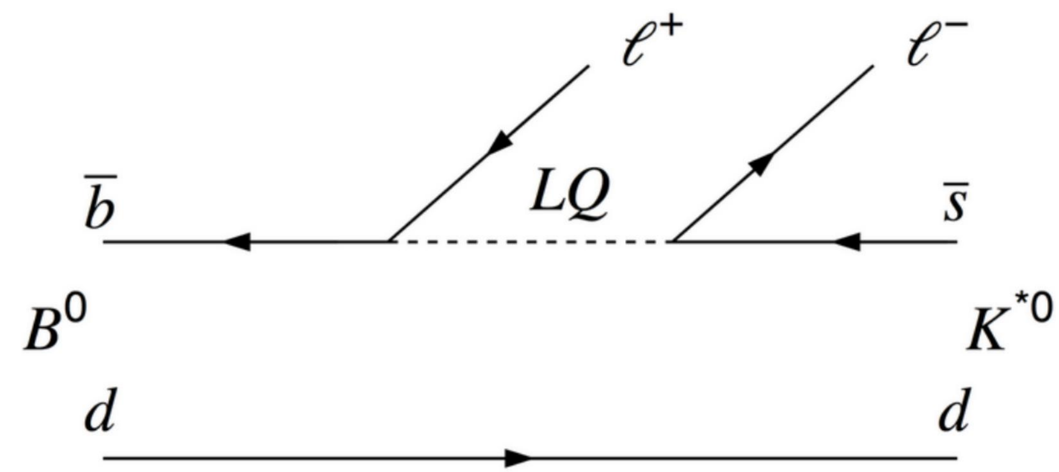
Penguin



Standard Model

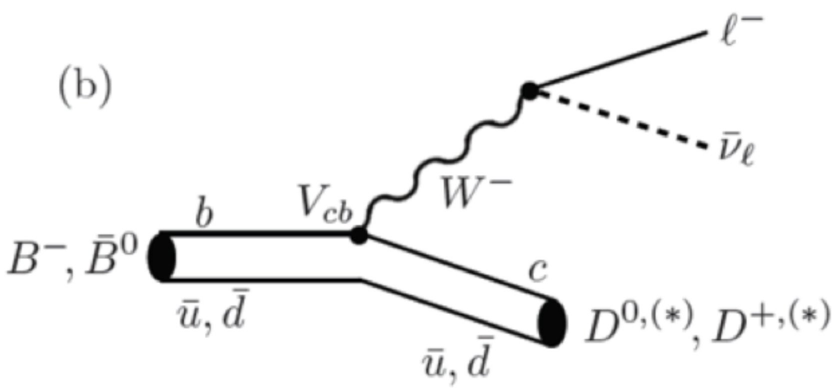


New Physics

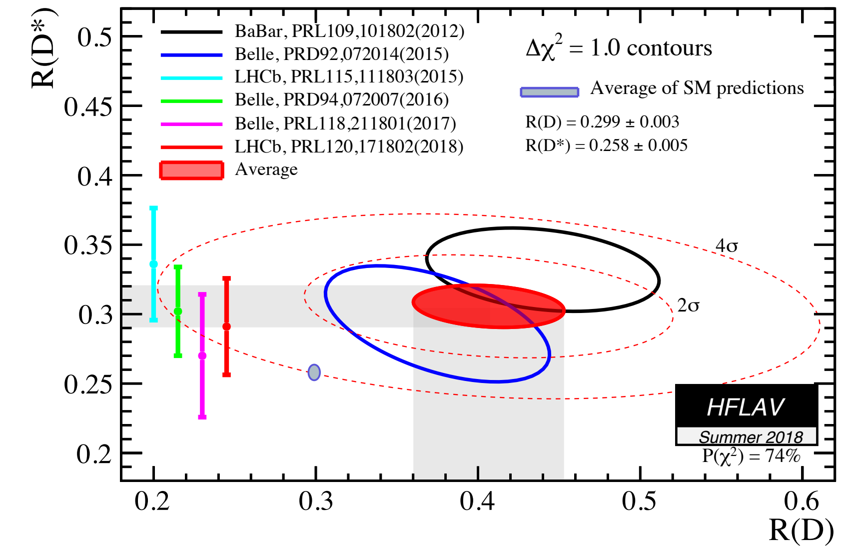


Lepton Flavor Universality

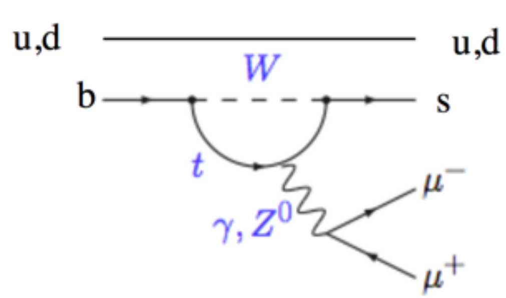
Long Standing Anomalies



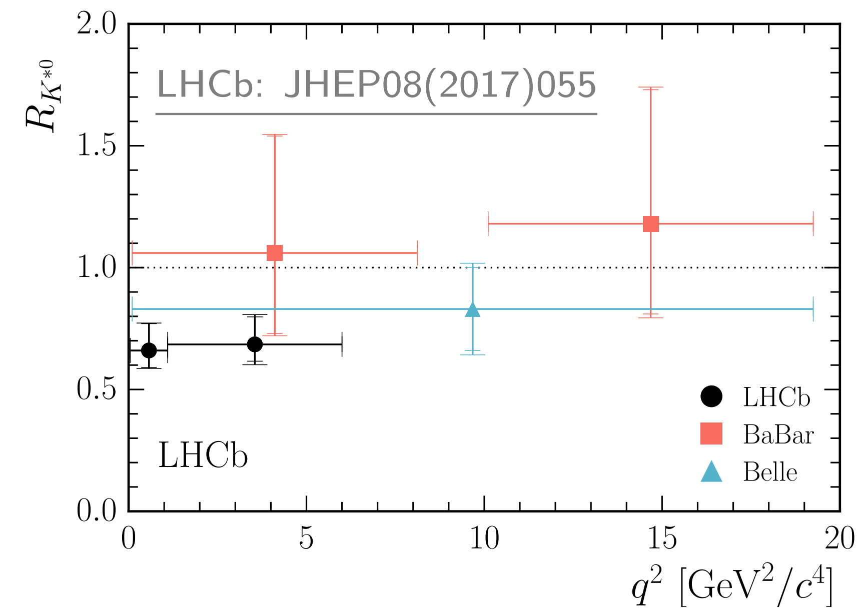
$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)}$$



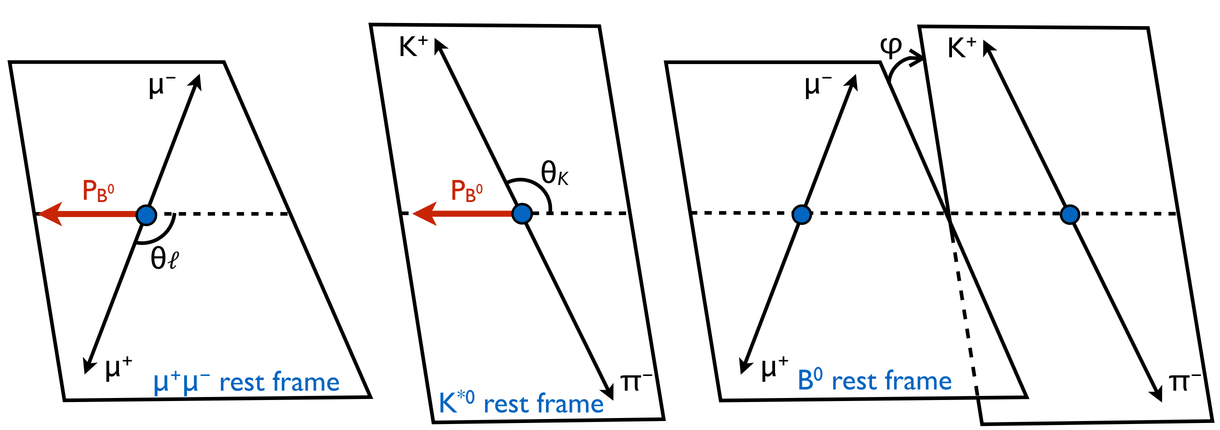
<u>muons / electrons [b → s]</u>

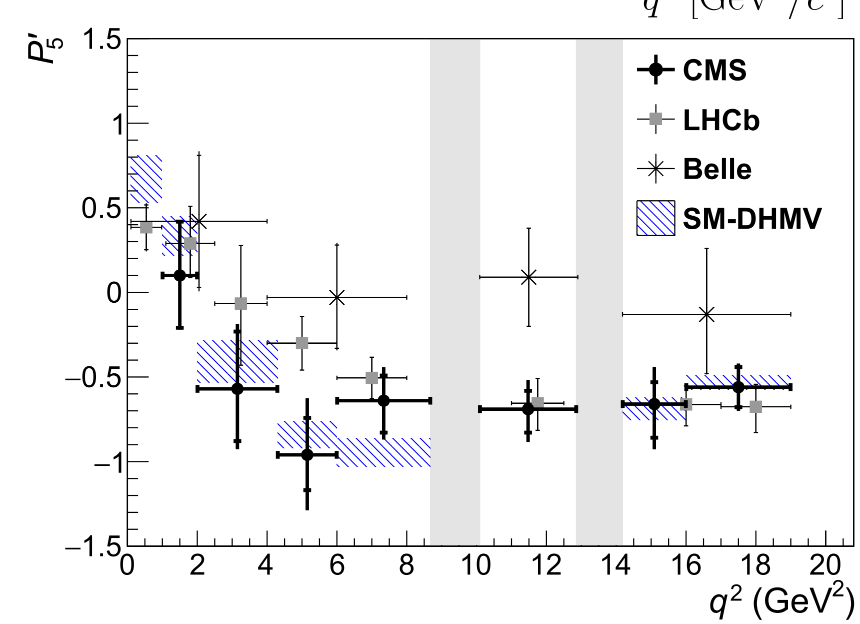


$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

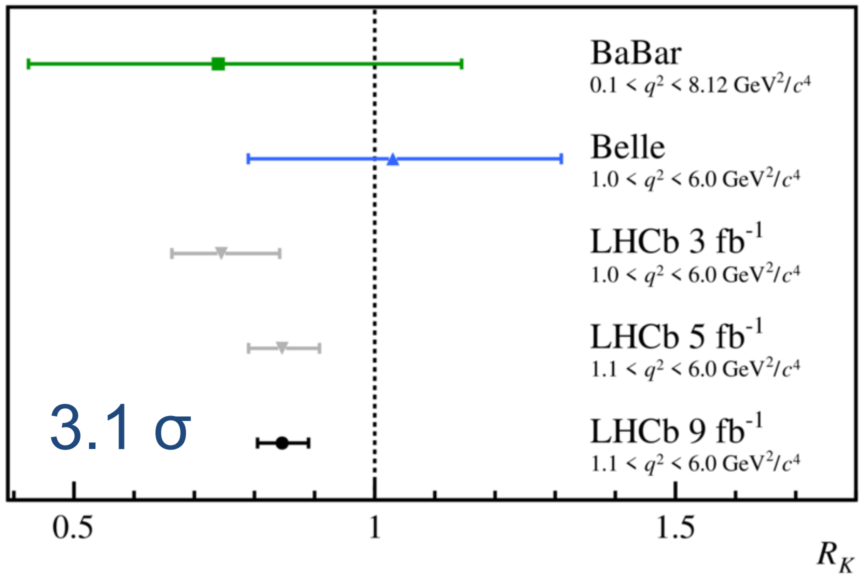


$$B^0 \to K^{*0}(K^+ \pi^-) \mu^+ \mu^-$$





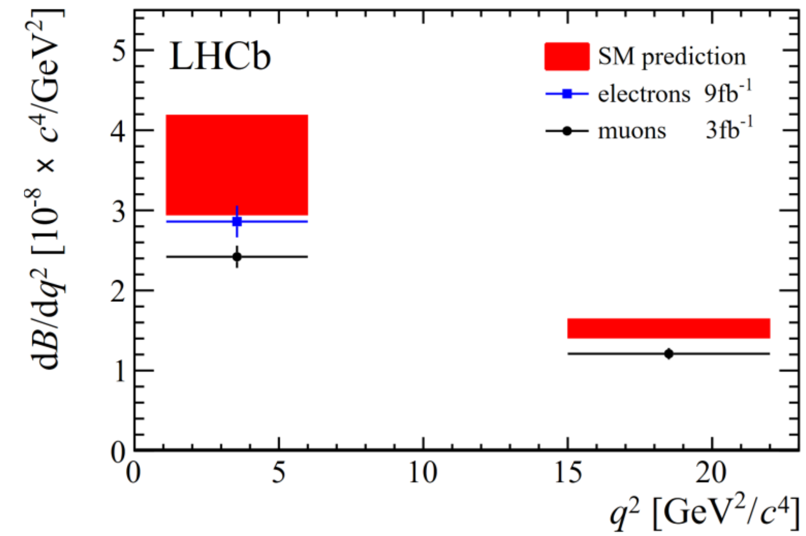
Anomaly stands still



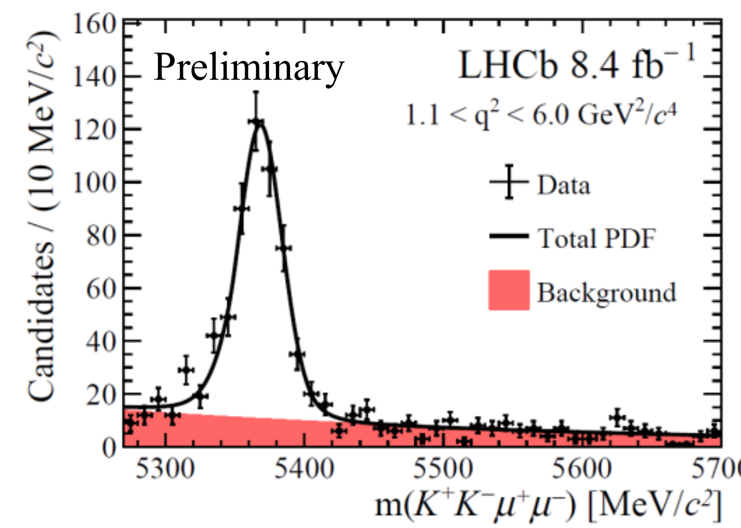
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ ee)} \Big/ \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+ J/\psi(ee))}$$

$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

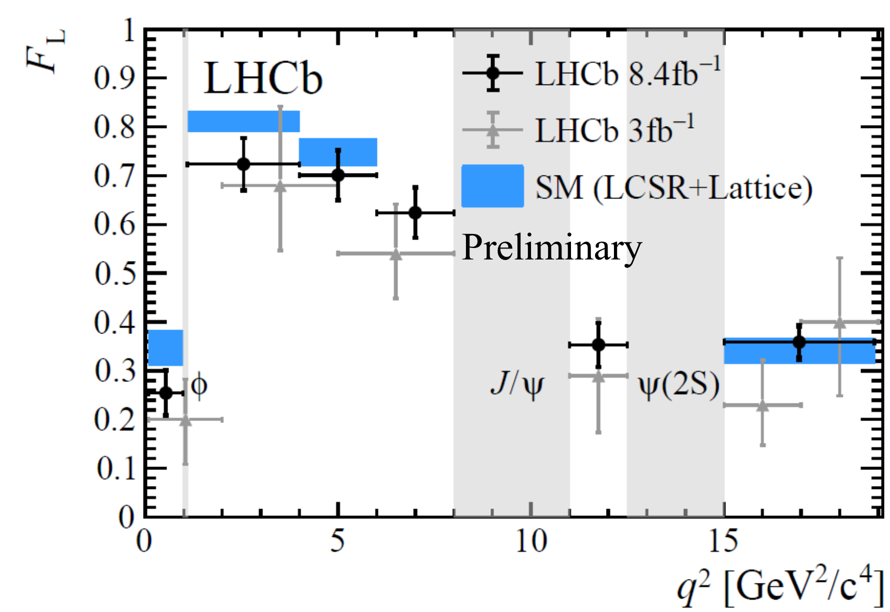
$$R_K = 0.846\,^{+0.044}_{-0.041}$$



- ▻ New angular analysis in $B_s^0 \to \phi\mu^+\mu^-$
  - Discrepancy wrt predictions similar to $K^{*0}\mu^+\mu^-$
  - CP Asymmetries and averages compatible with SM

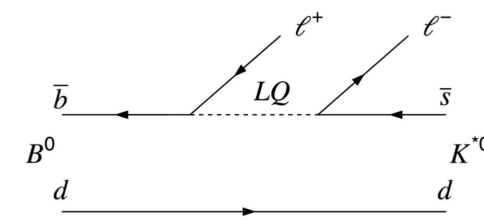


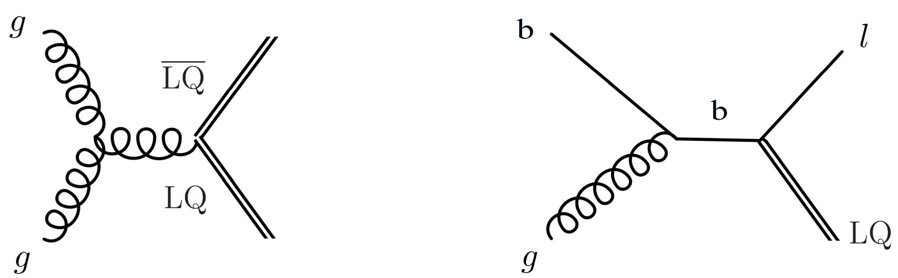
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\rm L}})\sin^2\theta_K(1+\tfrac{1}{3}\cos 2\theta_l)$$
$$+\boxed{F_{\rm L}}\cos^2\theta_K(1-\cos 2\theta_l)$$
$$+\boxed{S_3}\sin^2\theta_K\sin^2\theta_l\cos 2\phi+\boxed{S_4}\sin 2\theta_K\sin 2\theta_l\cos\phi$$
$$+\boxed{A_5}\sin 2\theta_K\sin\theta_l\cos\phi+\tfrac{4}{3}\boxed{A_{\rm FB}^{CP}}\sin^2\theta_K\cos\theta_l$$
$$+\boxed{S_7}\sin 2\theta_K\sin\theta_l\sin\phi+\boxed{A_8}\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+\boxed{A_9}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

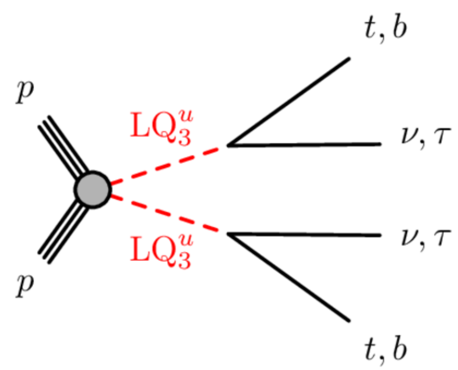


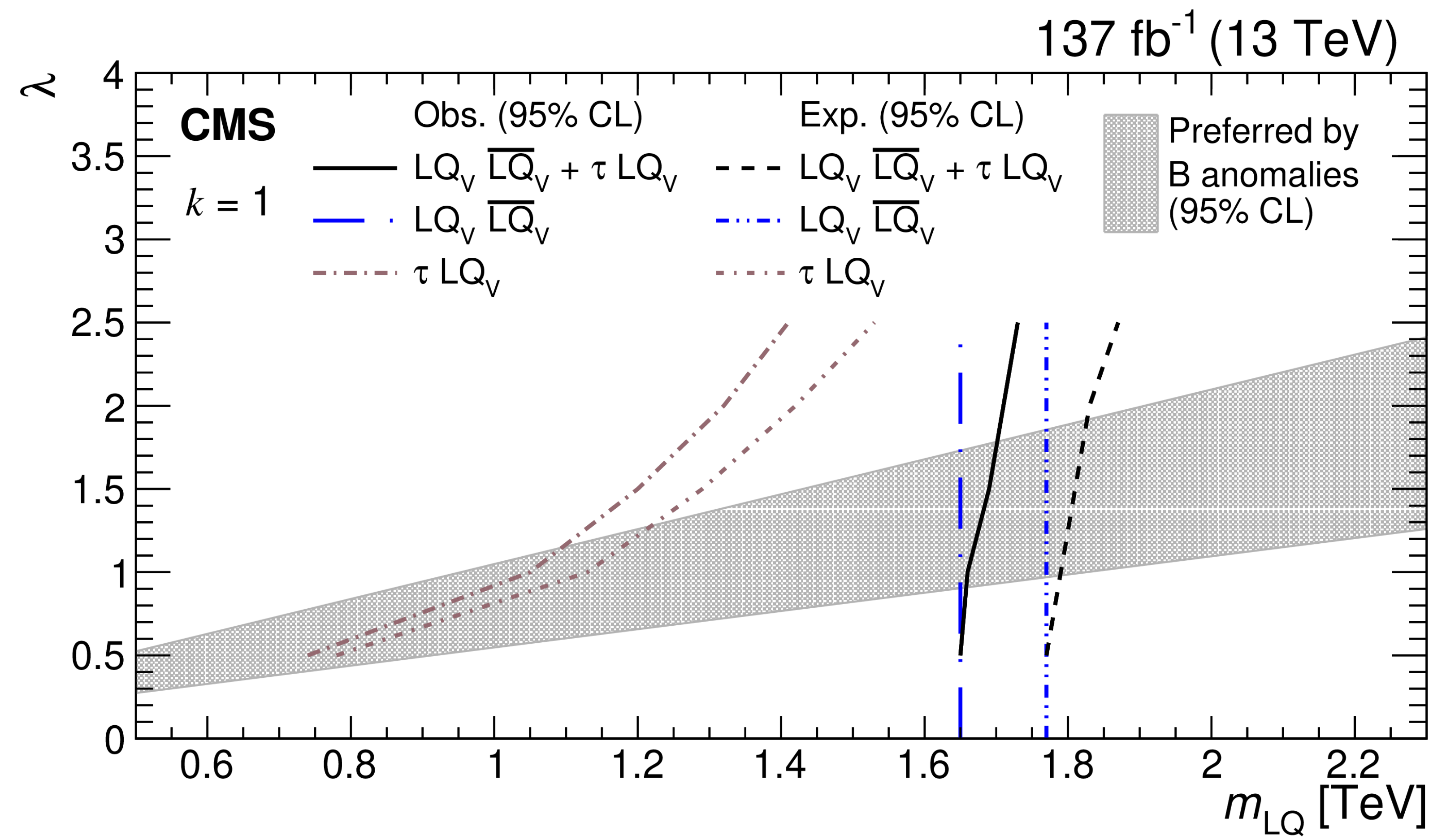
Tackling Anomalies at High Mass

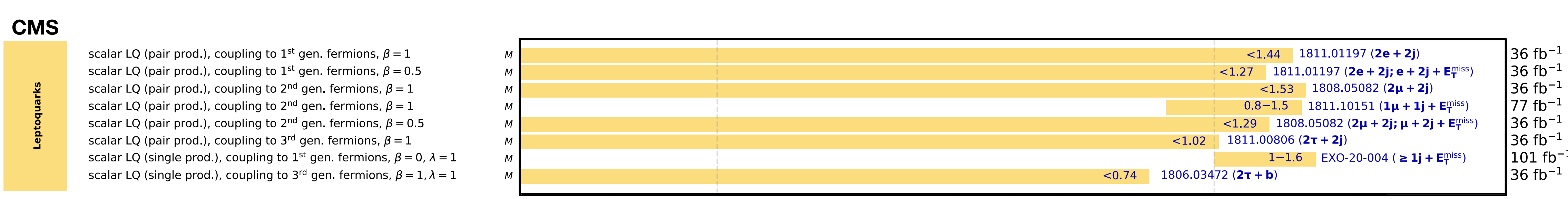
- Tree-level explanation of B anomalies with preferred coupling to 2nd and 3rd generations
  - Pair- and single-production of leptoquarks









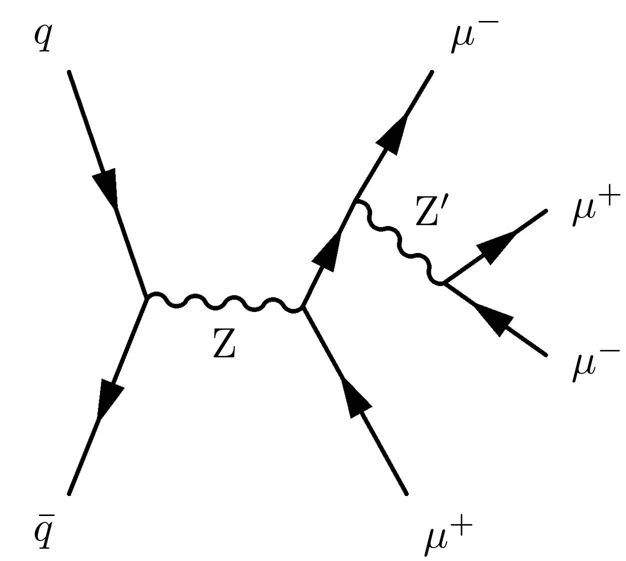


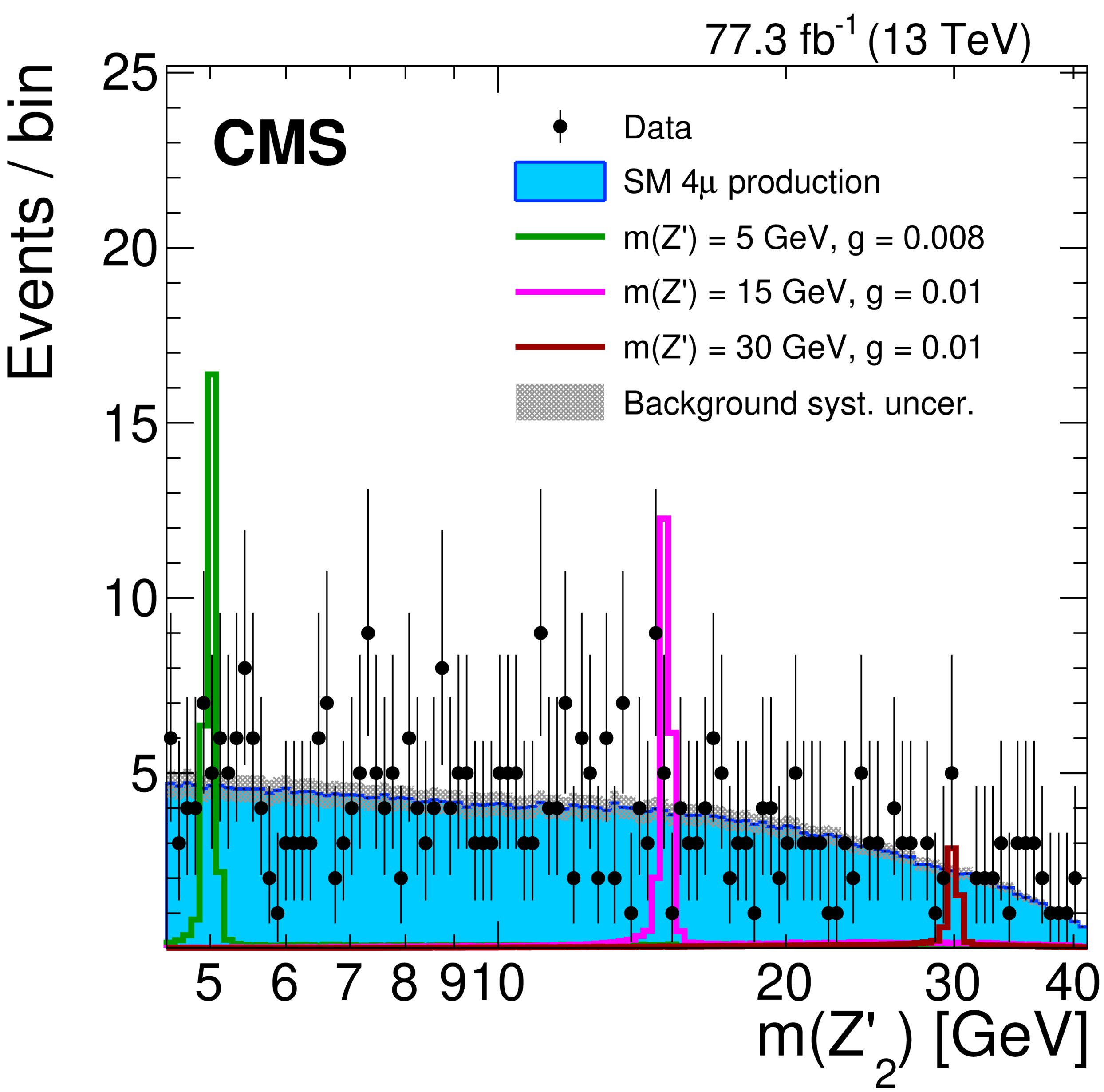
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

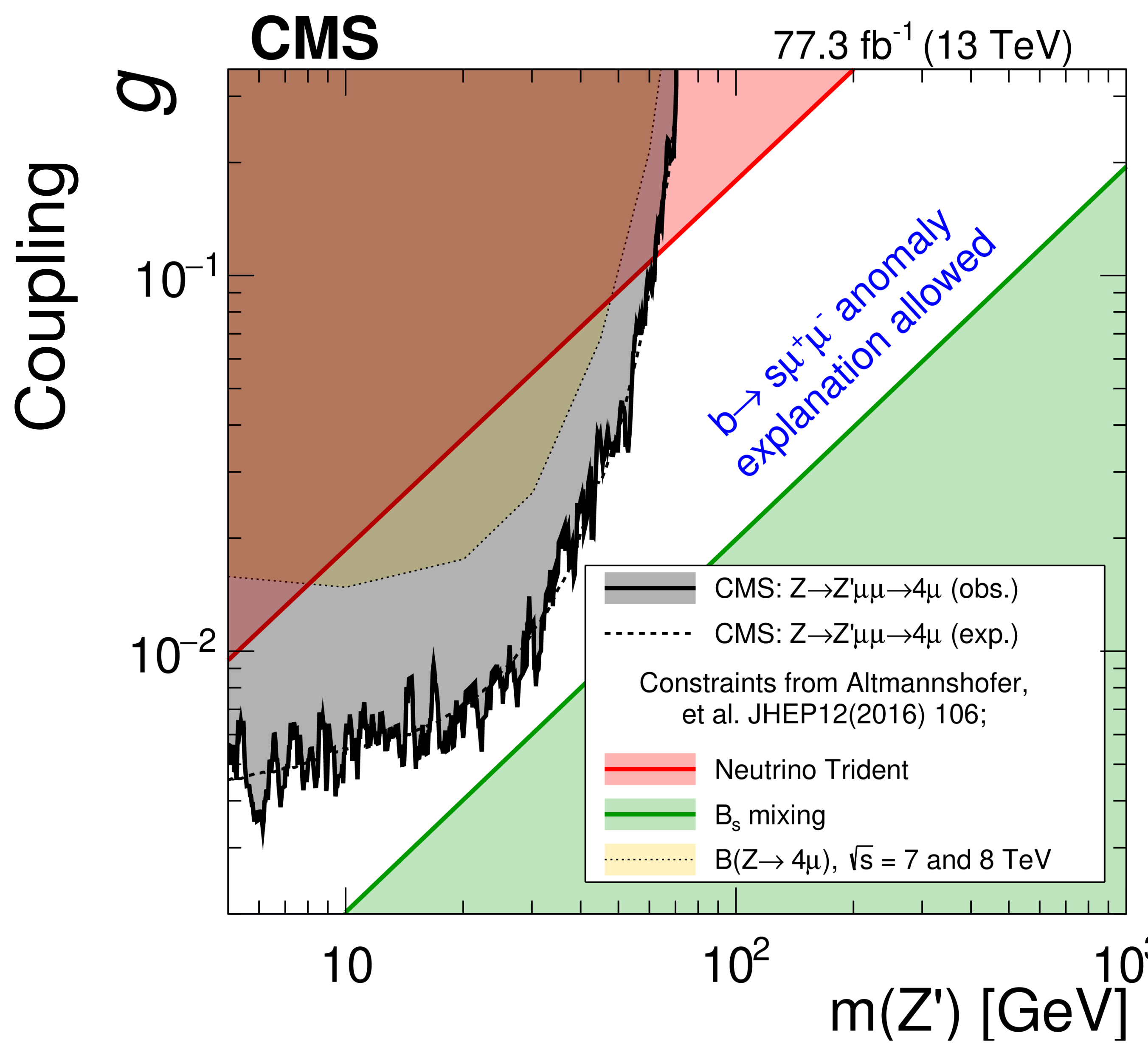
Light Z′ boson

- Search for new gauge boson below the Z mass
  - New ideas taking advantage of 2017 data

EXO-18-008

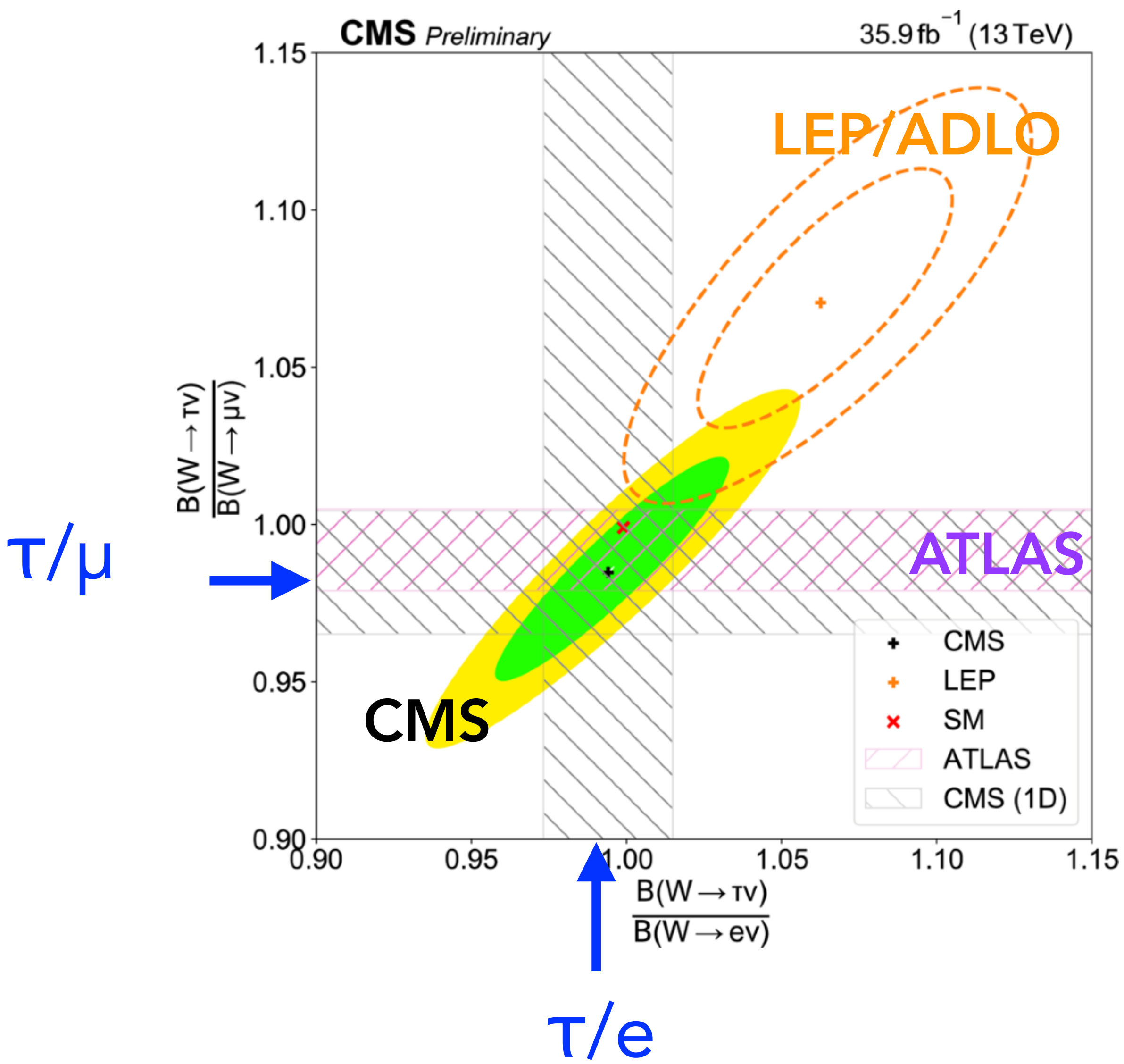




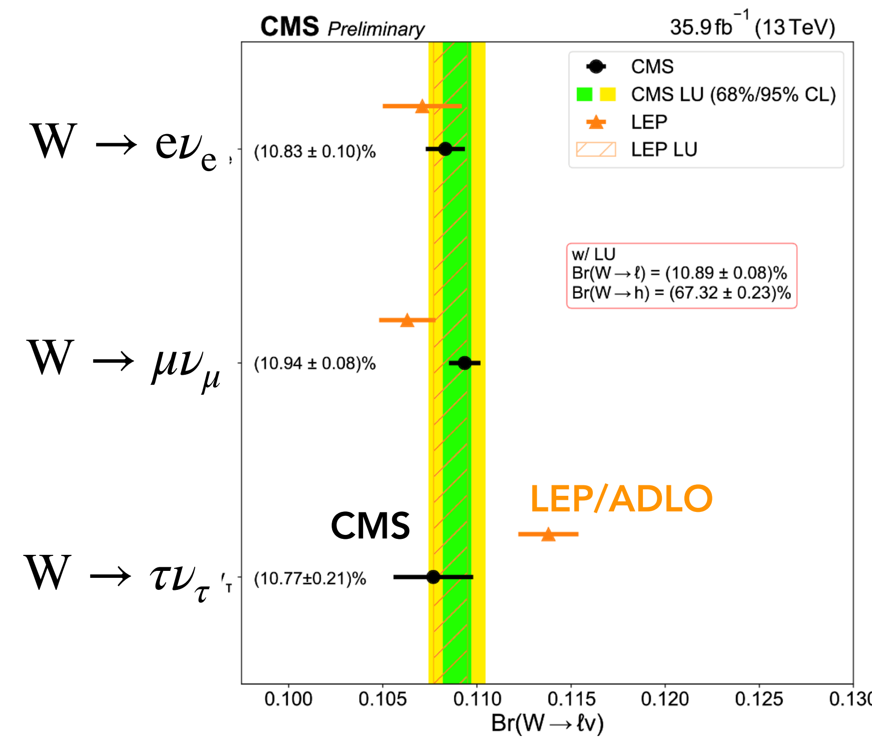


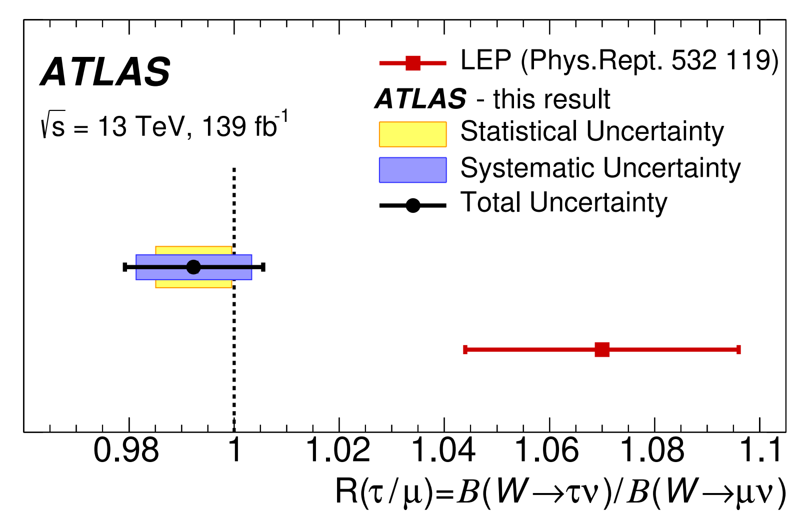
Lepton Universality in W decays

- ▻ Compare W branching fraction in e, μ, τ

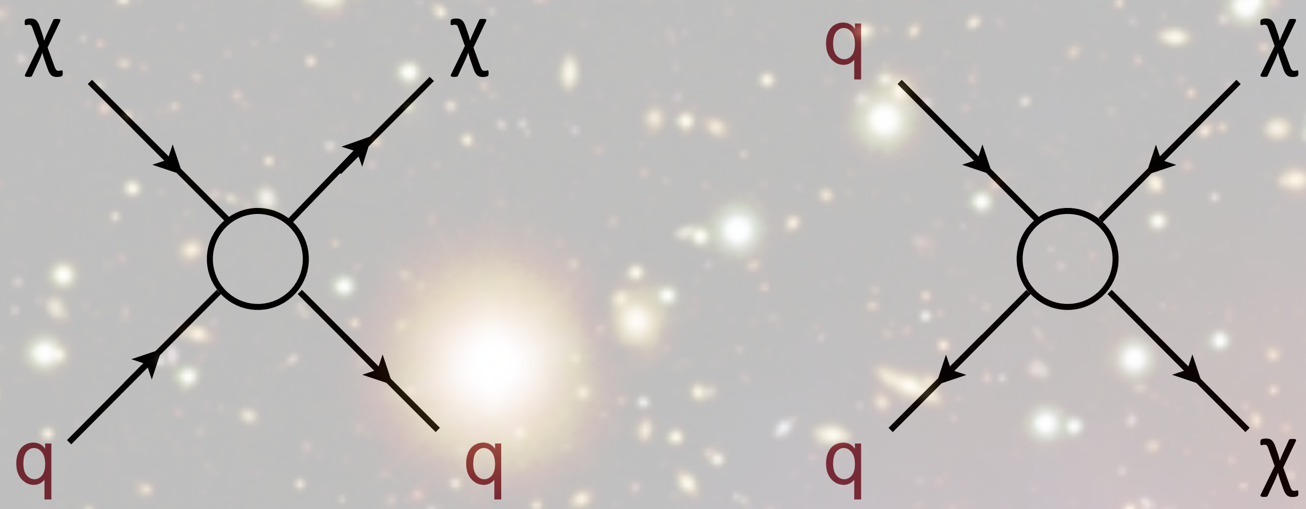


Branching fractions W → e, μ, τ

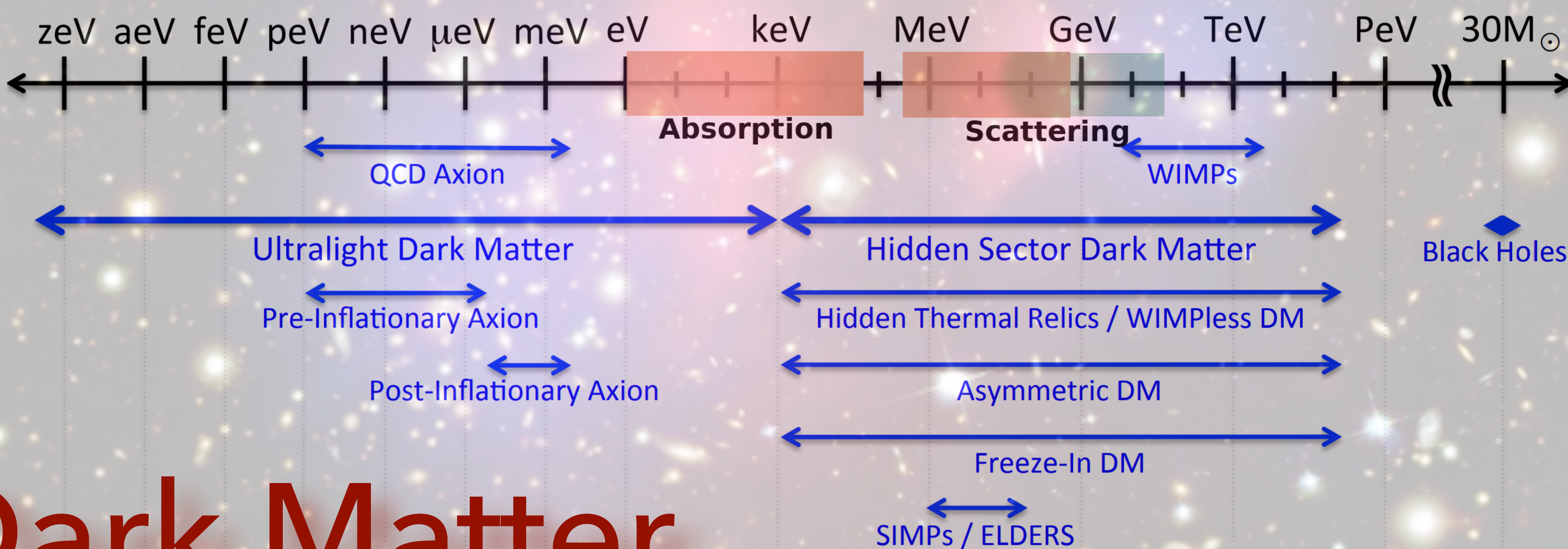




- ▻ Very good agreement between LHC and Standard Model



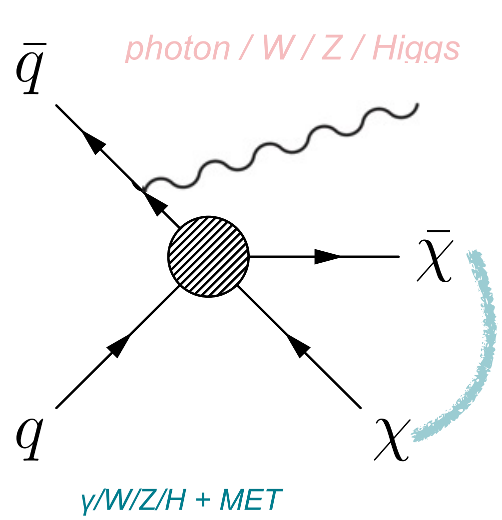
Direct Detection　　*Production at Colliders*

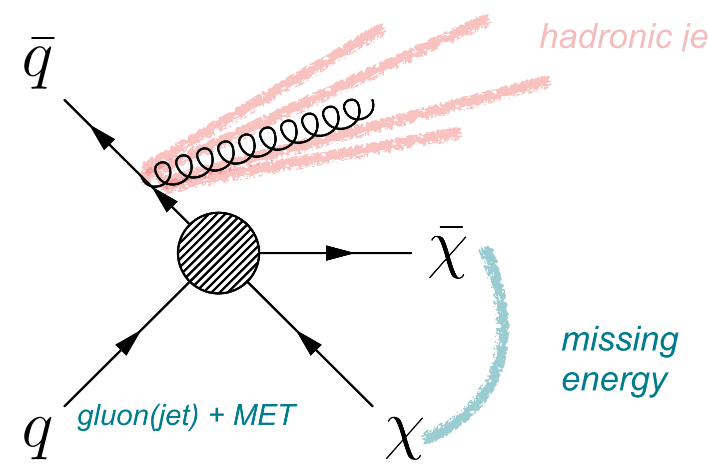


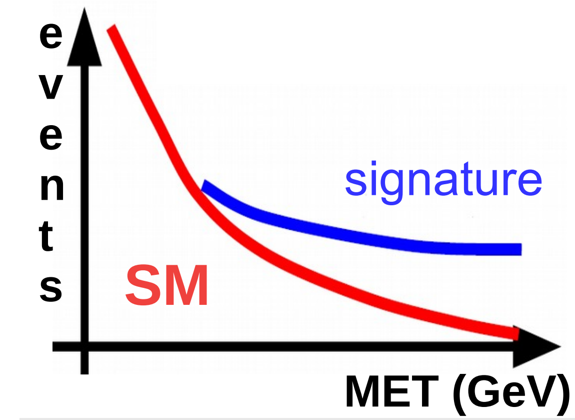
Dark Matter

The known unknown

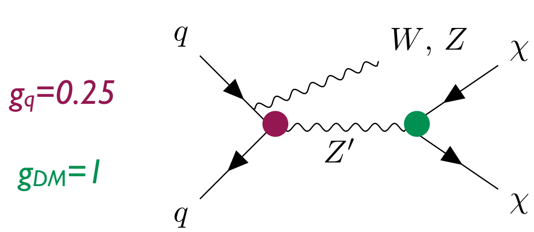
Dark candidates at LHC







- In addition to classic MET + SM-object(s) search, also constraining mediator mass and coupling in simplified models

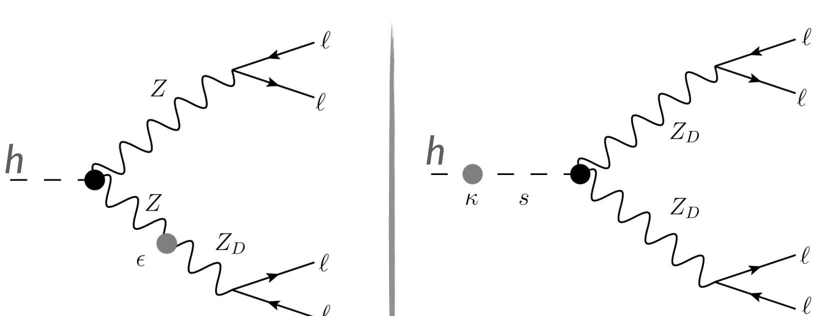


also visible decays

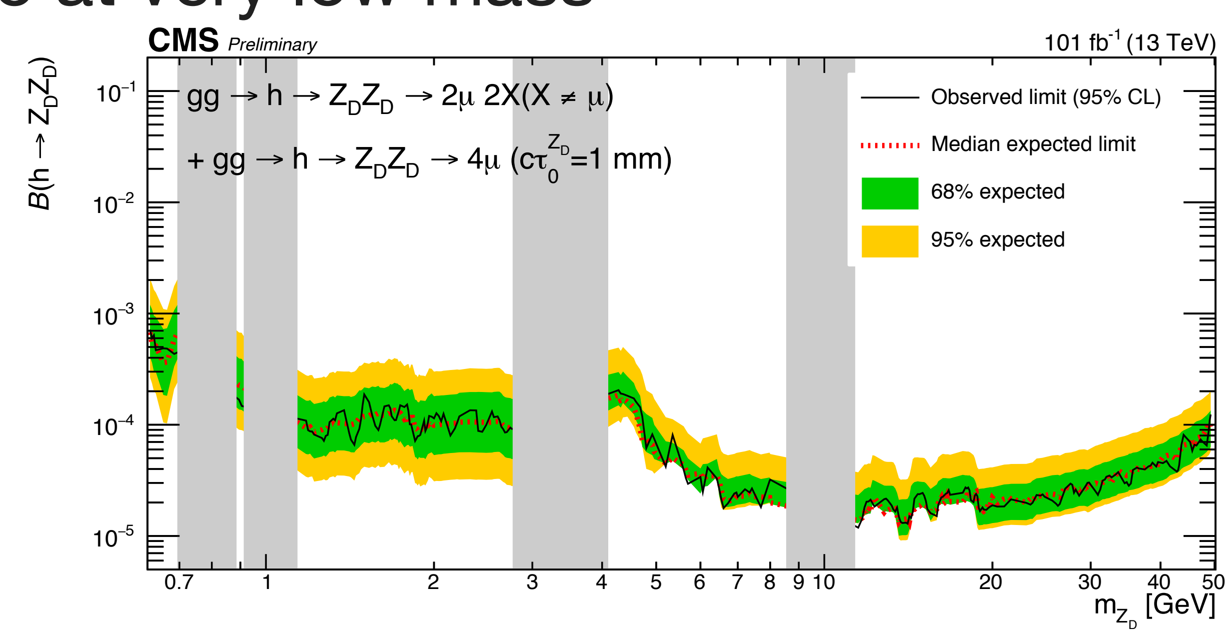
- Search for hidden sector also at very low mass

Hidden dark sector

dark/SM sectors interaction through dark photon Z_D, which can decay into SM particles



hypercharge portal *Higgs portal*



Means of Falsification

- Multiple and redundant measurements of well known quantities
  - different methods
  - different contexts
  - different technologies

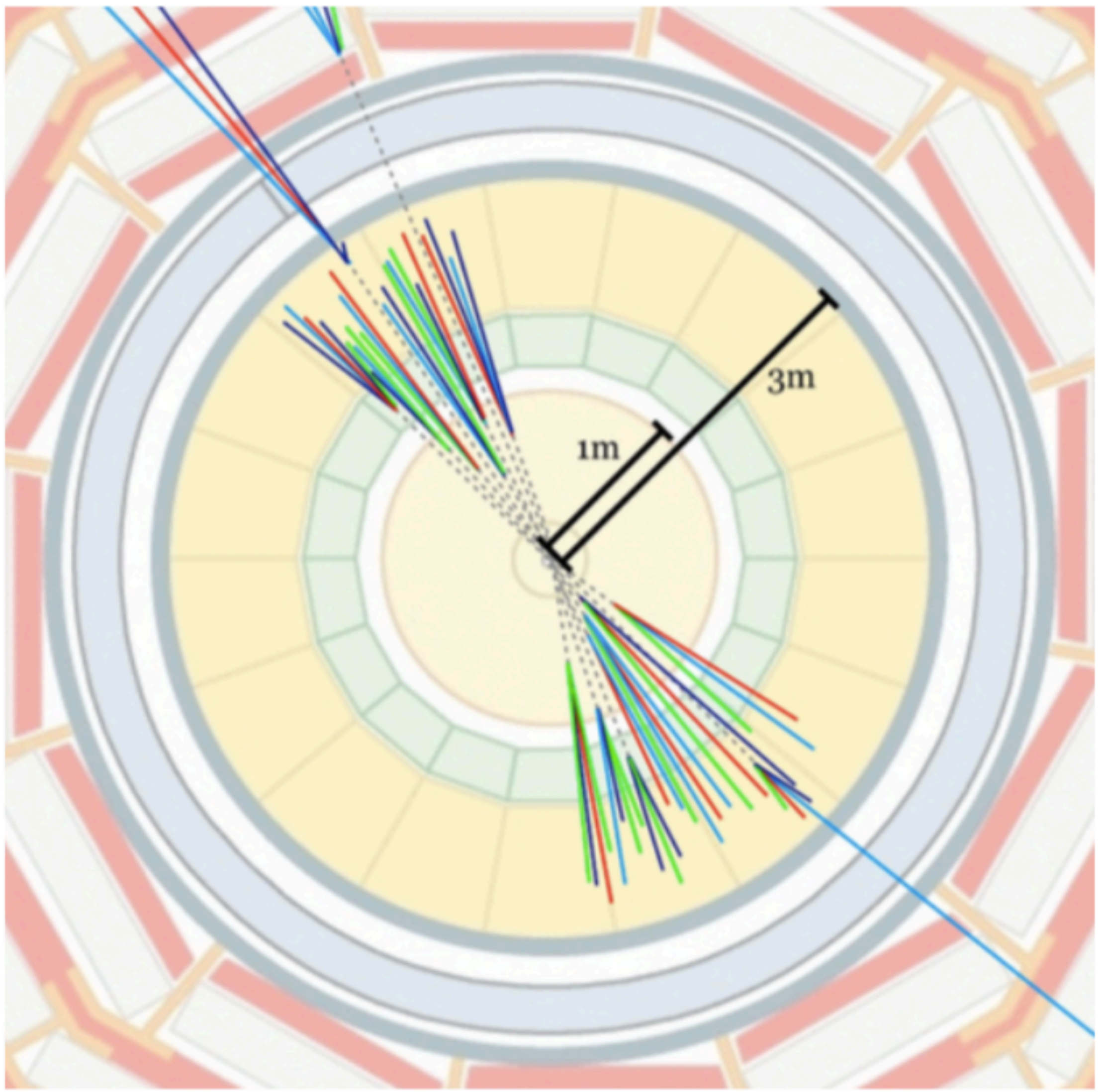
The Known Knowns

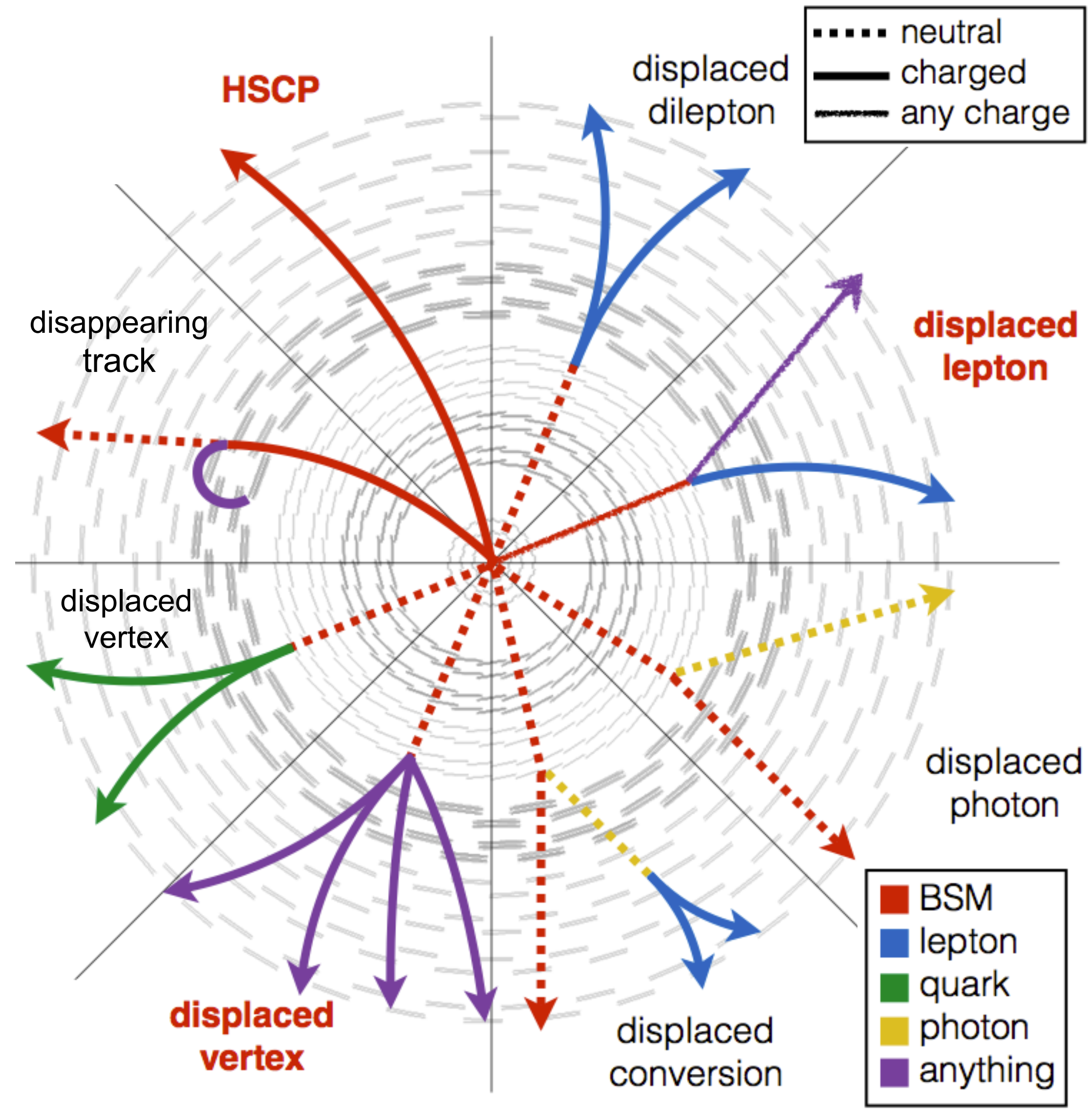
- Measurement of very small and precise predictions
  - variety of such observables across the spectrum
  - typically referred to as indirect search for New Physics
  - At LHC now merging with standard Physics thanks to amount of data

The Known Unknowns

- Search for the exotic
  - chasing more or less crazy ideas by theory friends
    - often motivated by some big question
  - Taking advantage of capabilities of detectors for unconventional signatures

The Unknown Unknowns





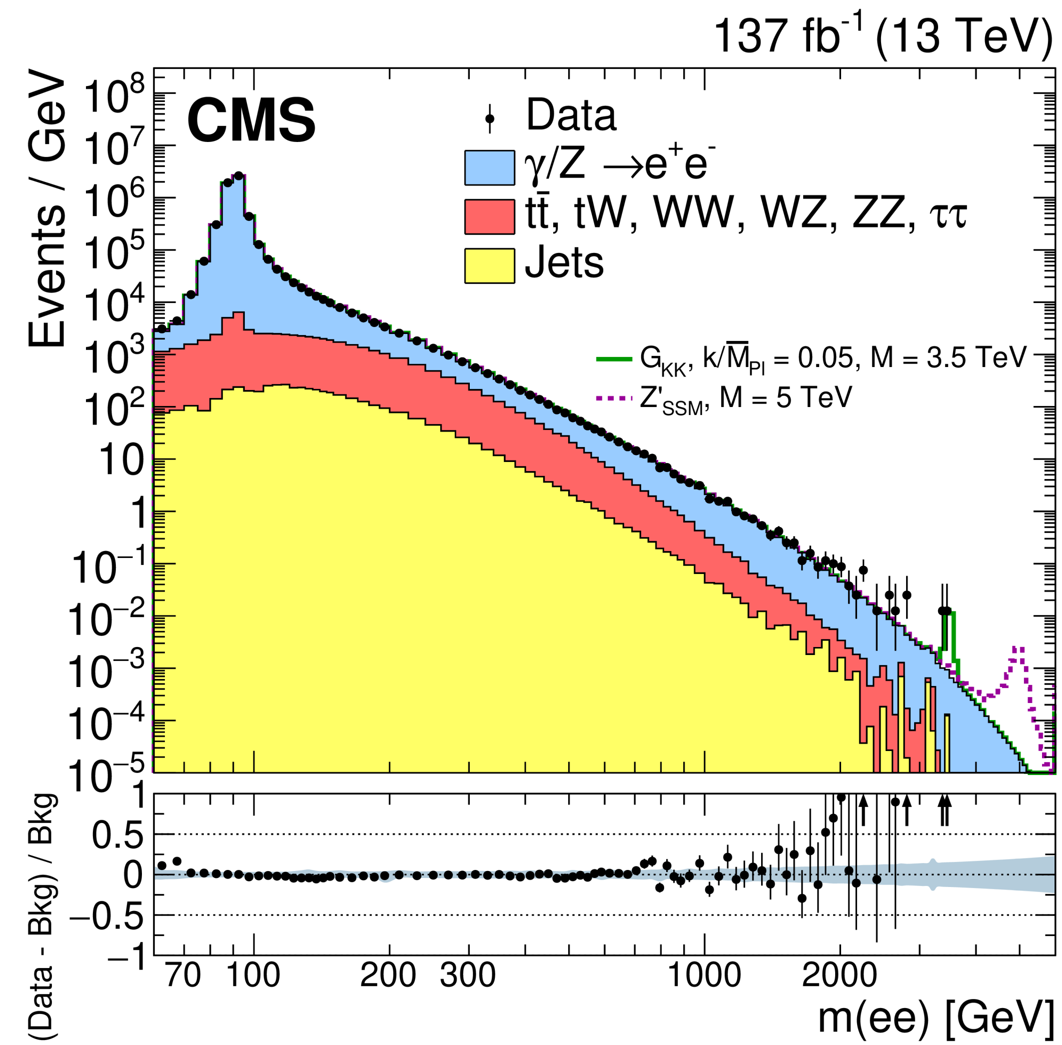
Credits: J. Antonelli

Exotic Phenomena

Exotica Timeline

Detector Understanding (time)

- Two-body resonances from day one: leptons, photons, jets
  - detector effects not critical
  - sensitive to bumps right away
- Increase complexity and multiplicity of final state
  - better understanding and calibration of detector
- Final states with X + MET
- Really exotic signatures such as long-lived particles
  - control of detector conditions over longer period
  - ultimate calibration and alignment
  - optimisation of dedicated algorithms

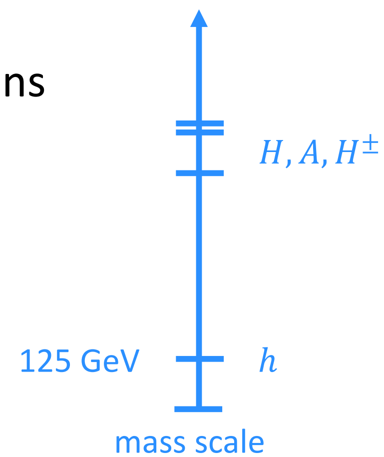


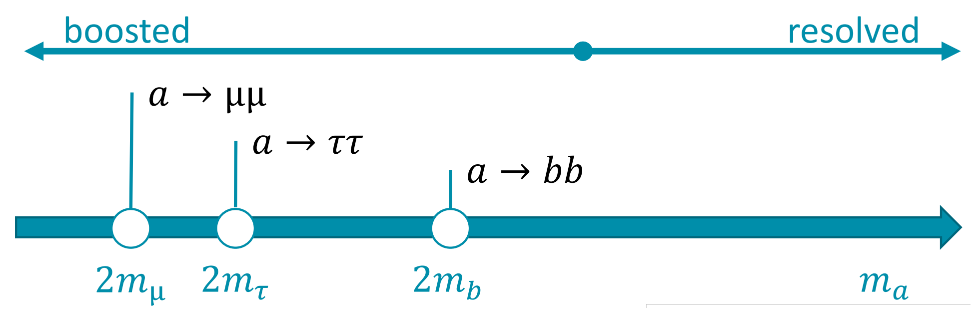
The Higgs or *A* Higgs?

- In BSM models with more Higgs bosons, some can resemble *the* Higgs
- Direct search for additional light and heavy Higgs bosons

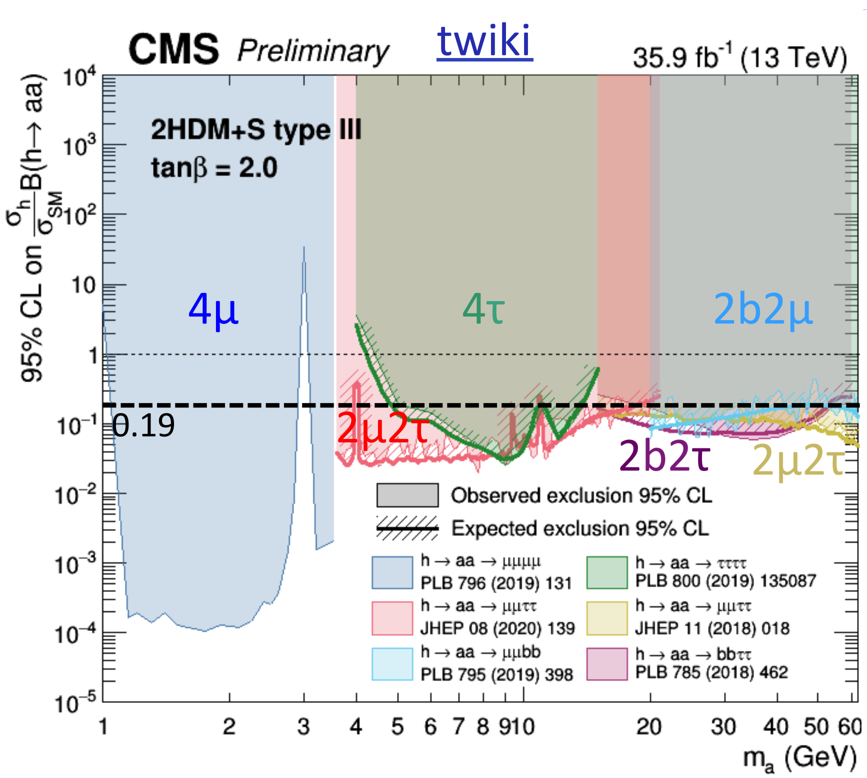
2HDM has 5 Higgs bosons

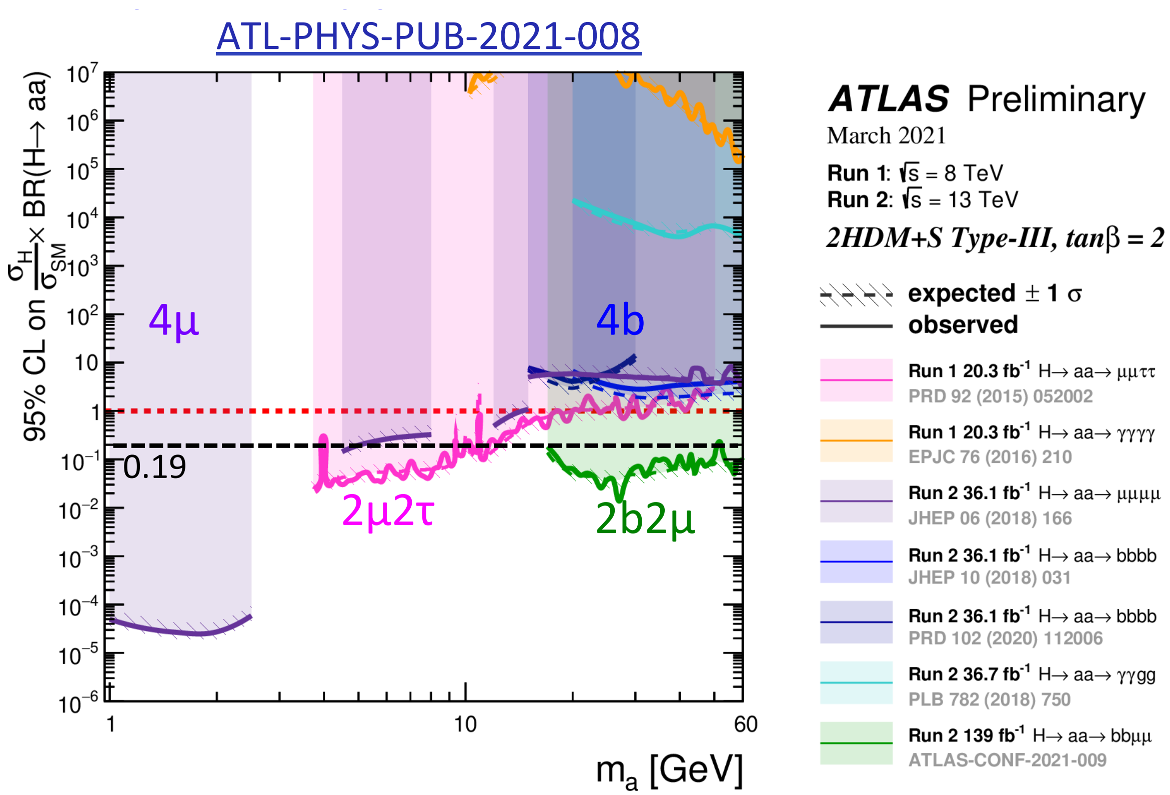
- h: "SM" Higgs
- H: heavy Higgs
- A: pseudoscalar
- $H^{\pm}$: charged Higgs





2HDM+S

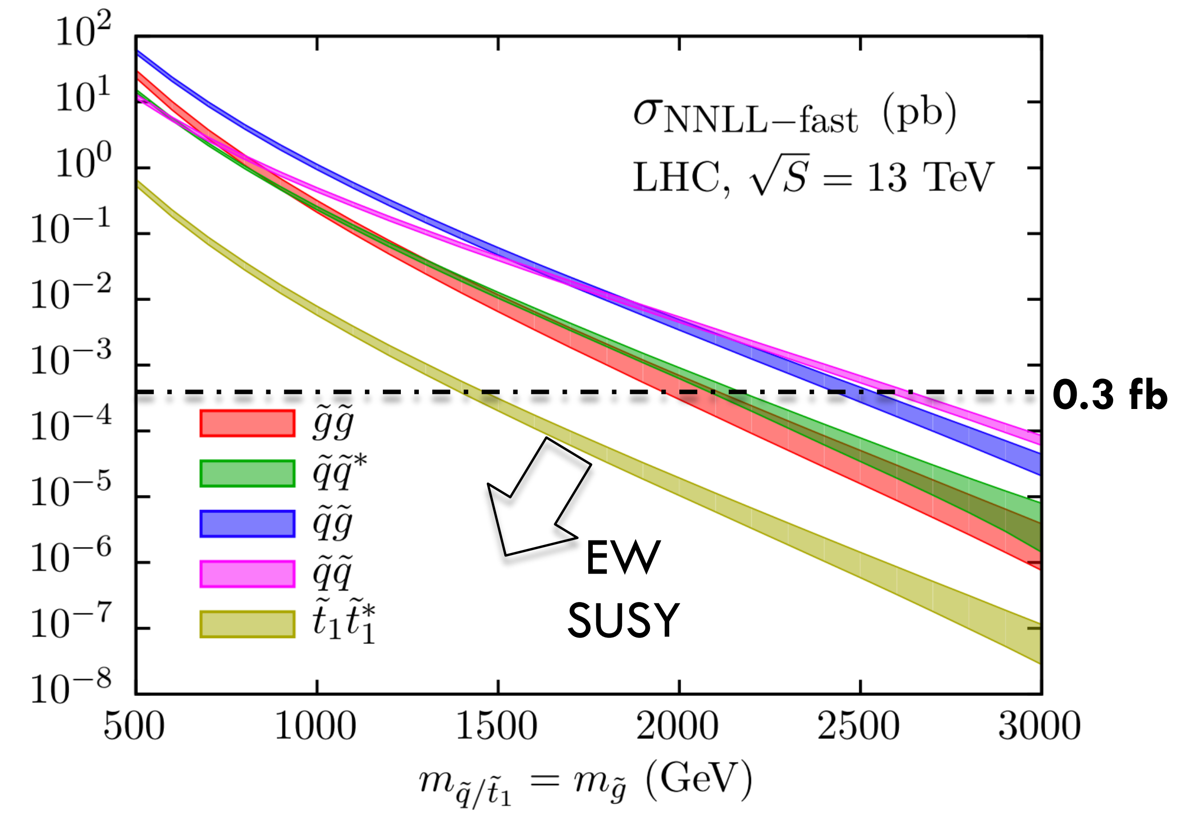


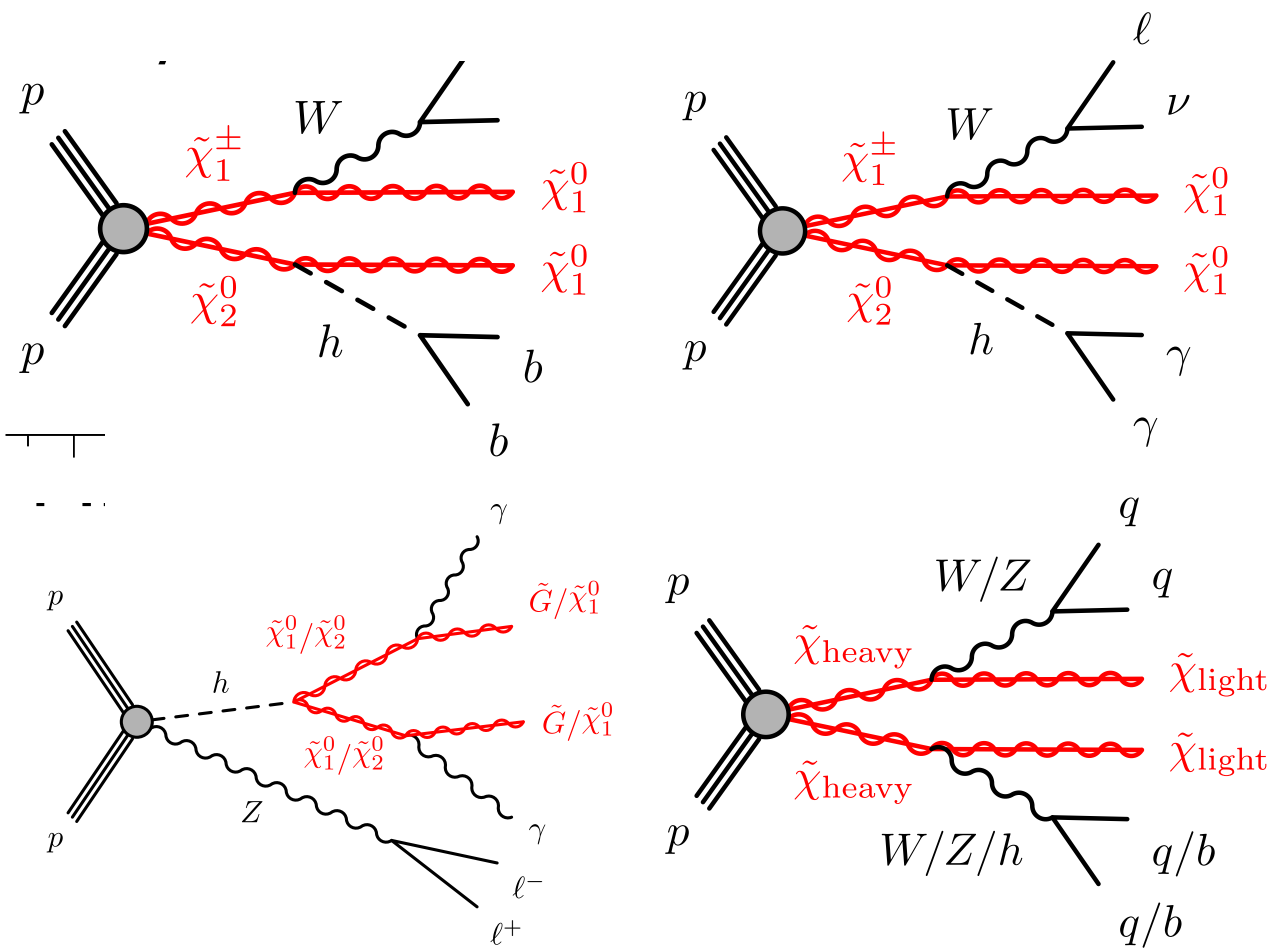


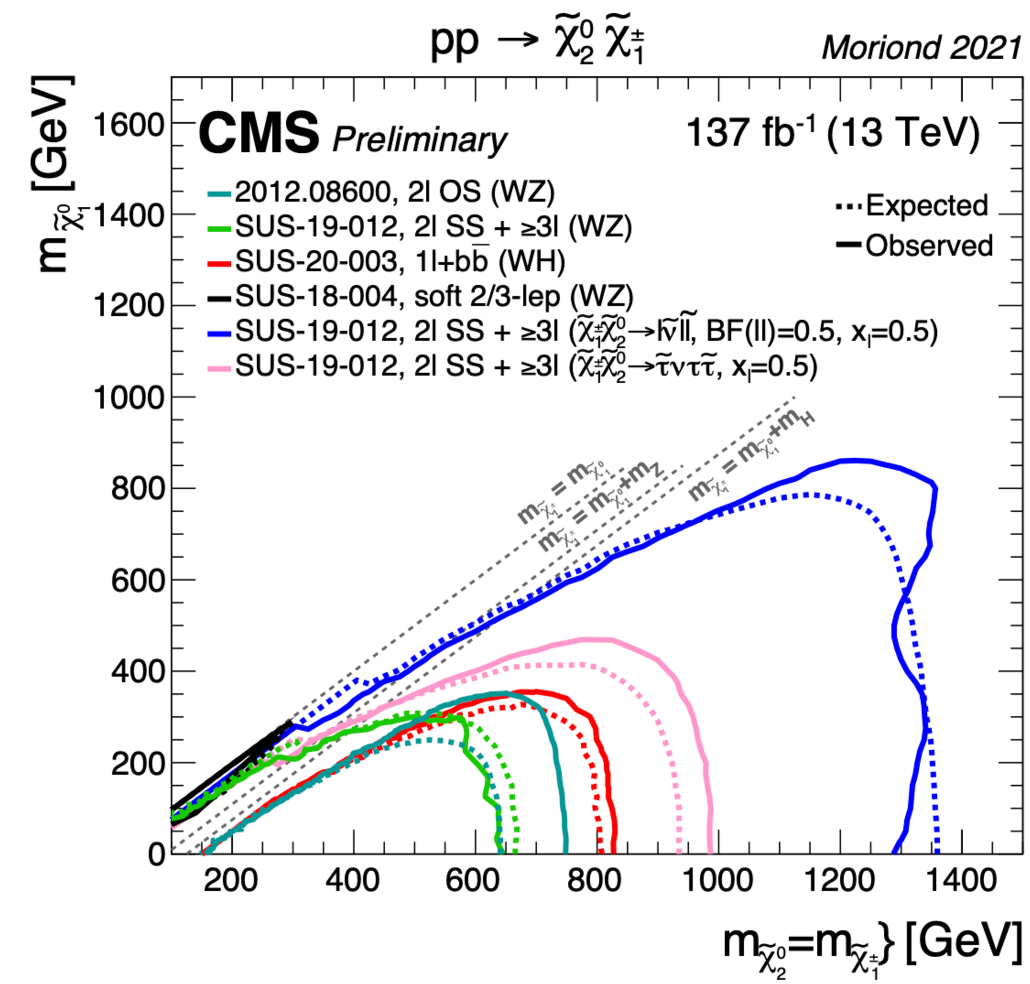
- So far no excess or evidence and only exclusion in theory parameter space
- High-Luminosity LHC two provide x20 increase in statistics

Supersymmetry

- Many new searches targeting both strong and electroweak production
  - No significant excess observed so far
- Strong SUSY searches targeting masses ~ 2 TeV
- Searches now using also H→γγ and exotic Higgs decays in electroweak production



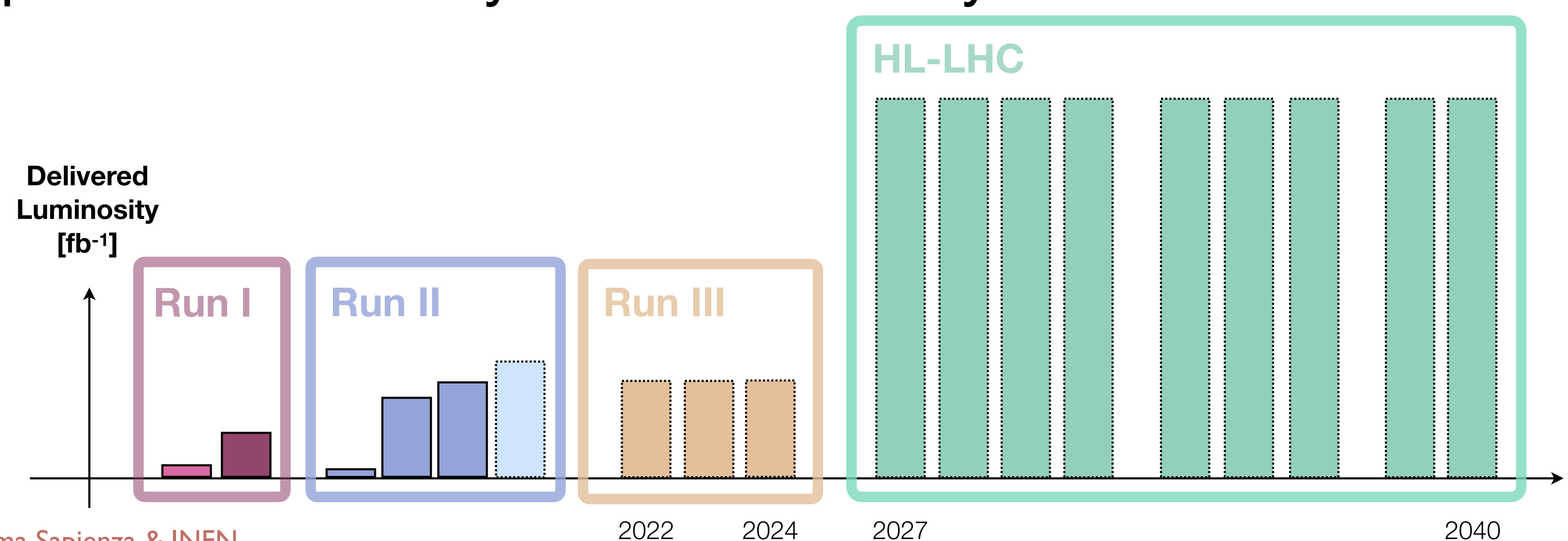




Towards High Luminosity

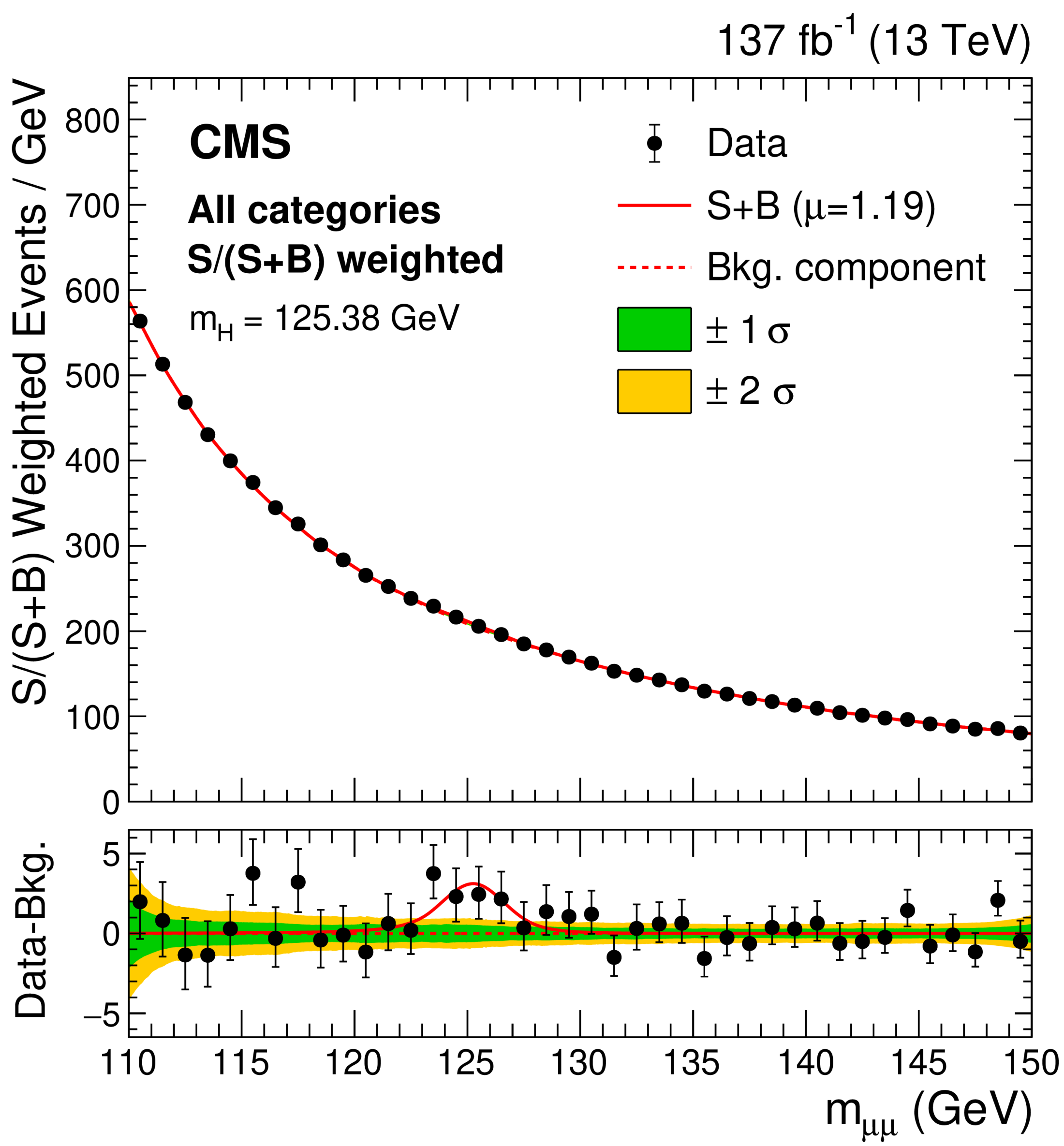
x5 Run1 x2 Run2 x10 Run3

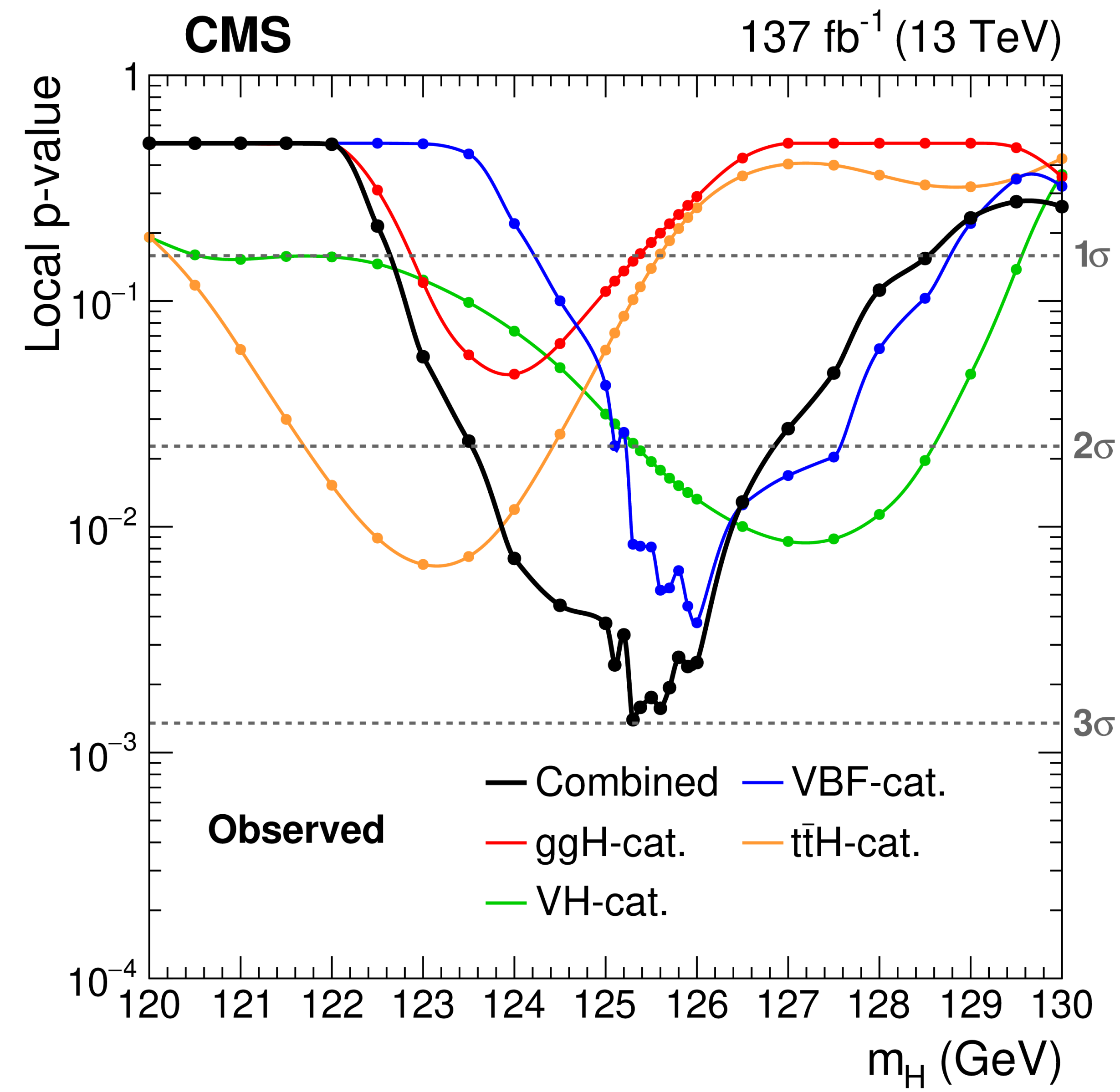
Data sample to increase by x20 in next 20 years



Rare Higgs Decays

- First evidence for H →μμ thanks to excellent detector performance

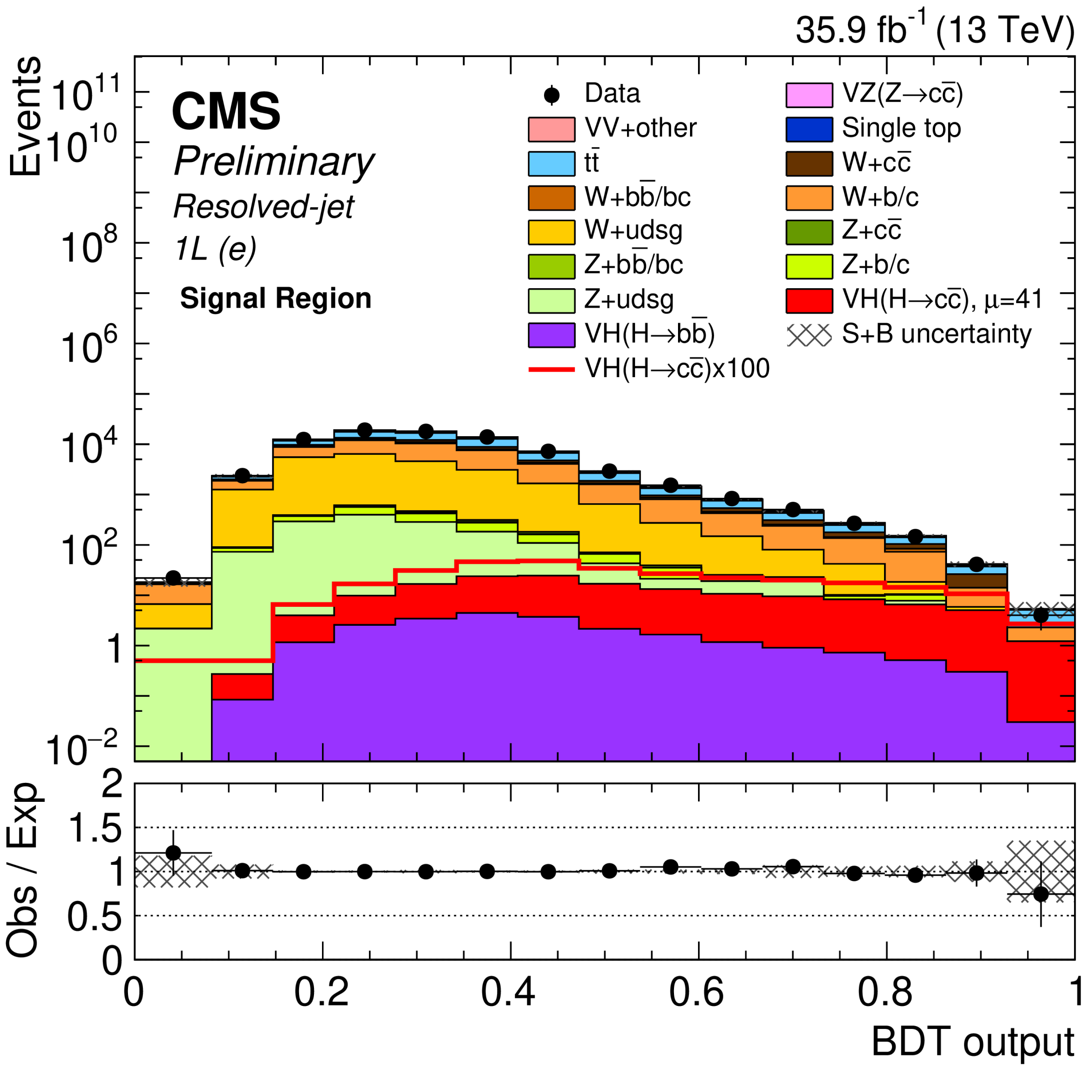


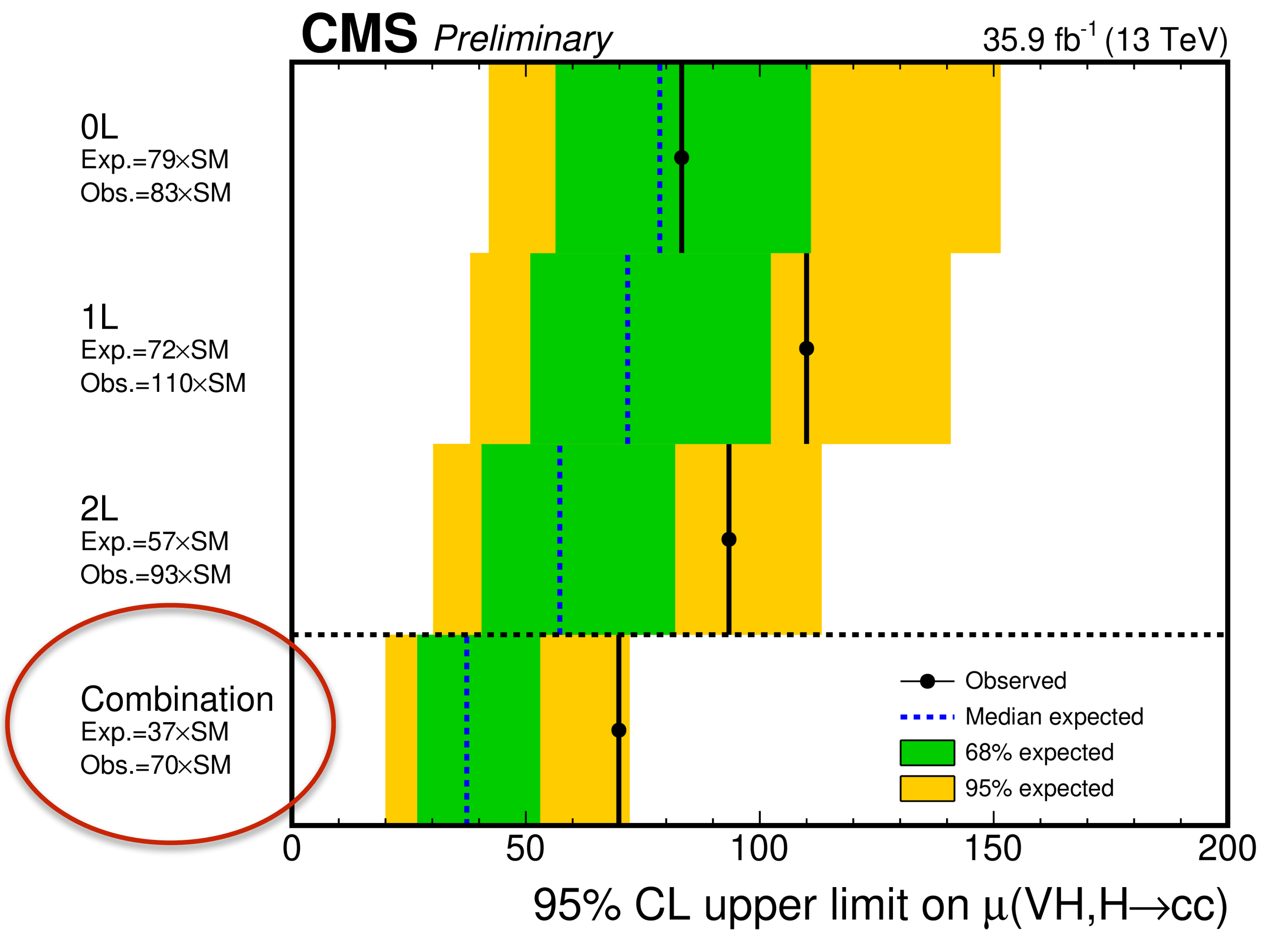


- First results now also on more challenging decay modes
  - Higgs to Zγ

Sensitivity to charm coupling

- ▻ First CMS analysis for $H(c\bar{c}) + W/Z$



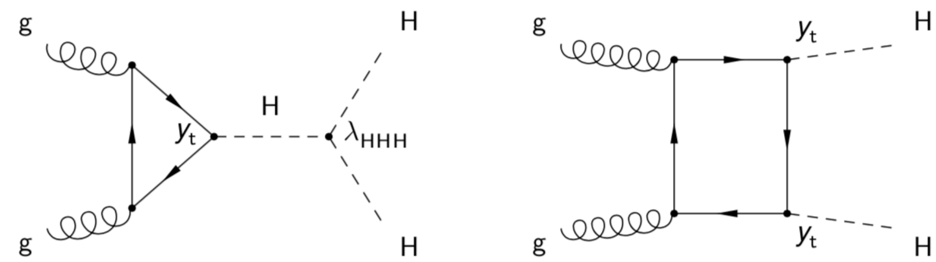


- ▻ Run3 and HL-LHC needed for first evidence of this challenging decay

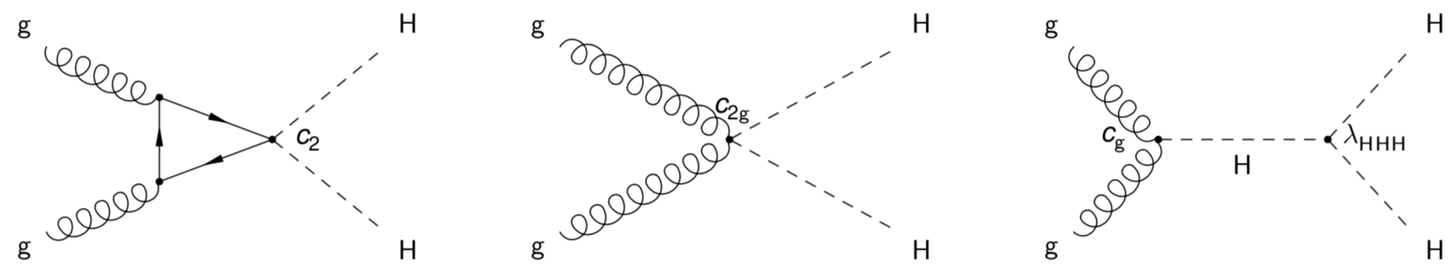
Higgs Self-Interaction

- Understanding Higgs sector requires measurement of its self-interaction

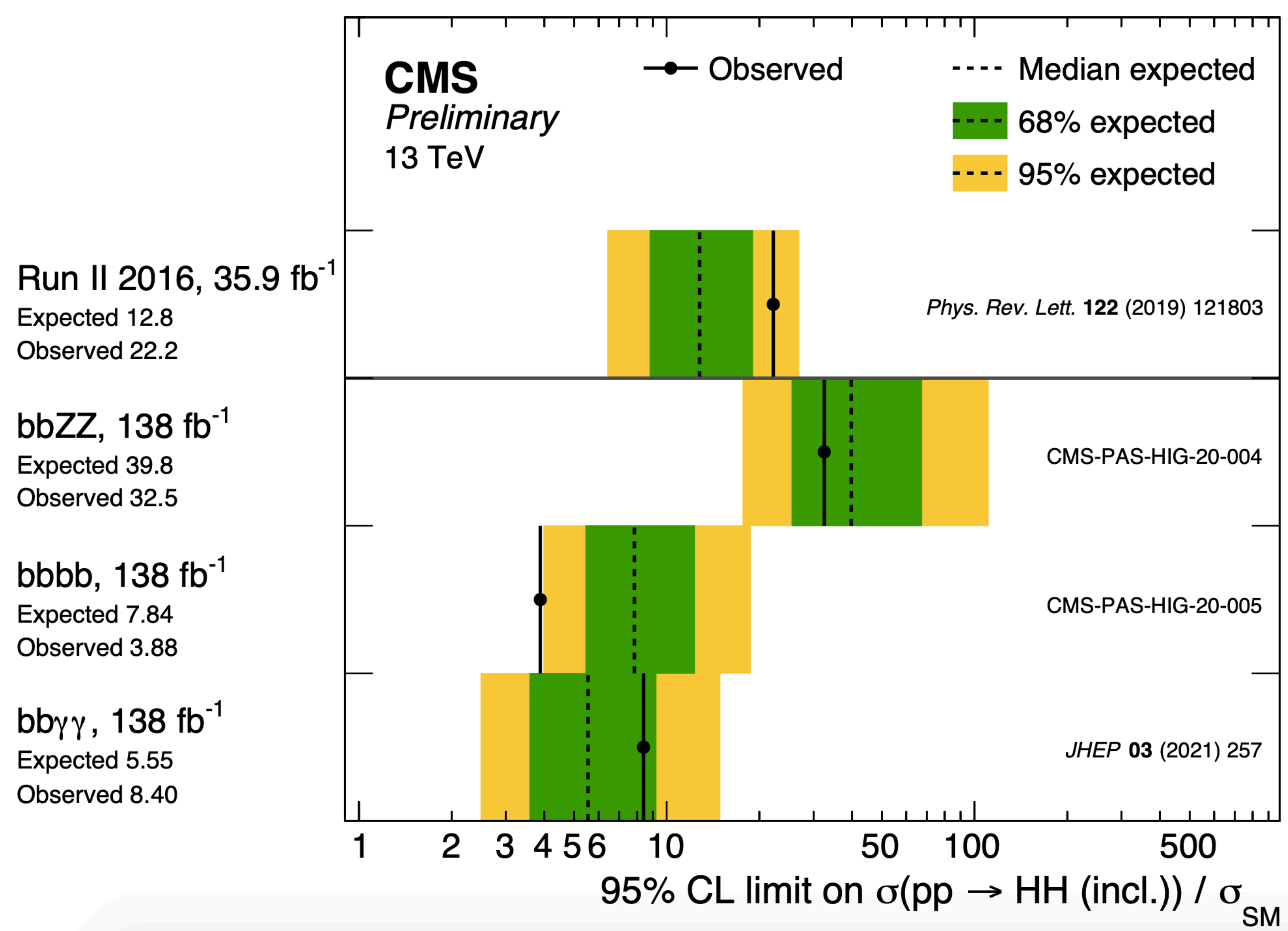
Standard Model



New Physics

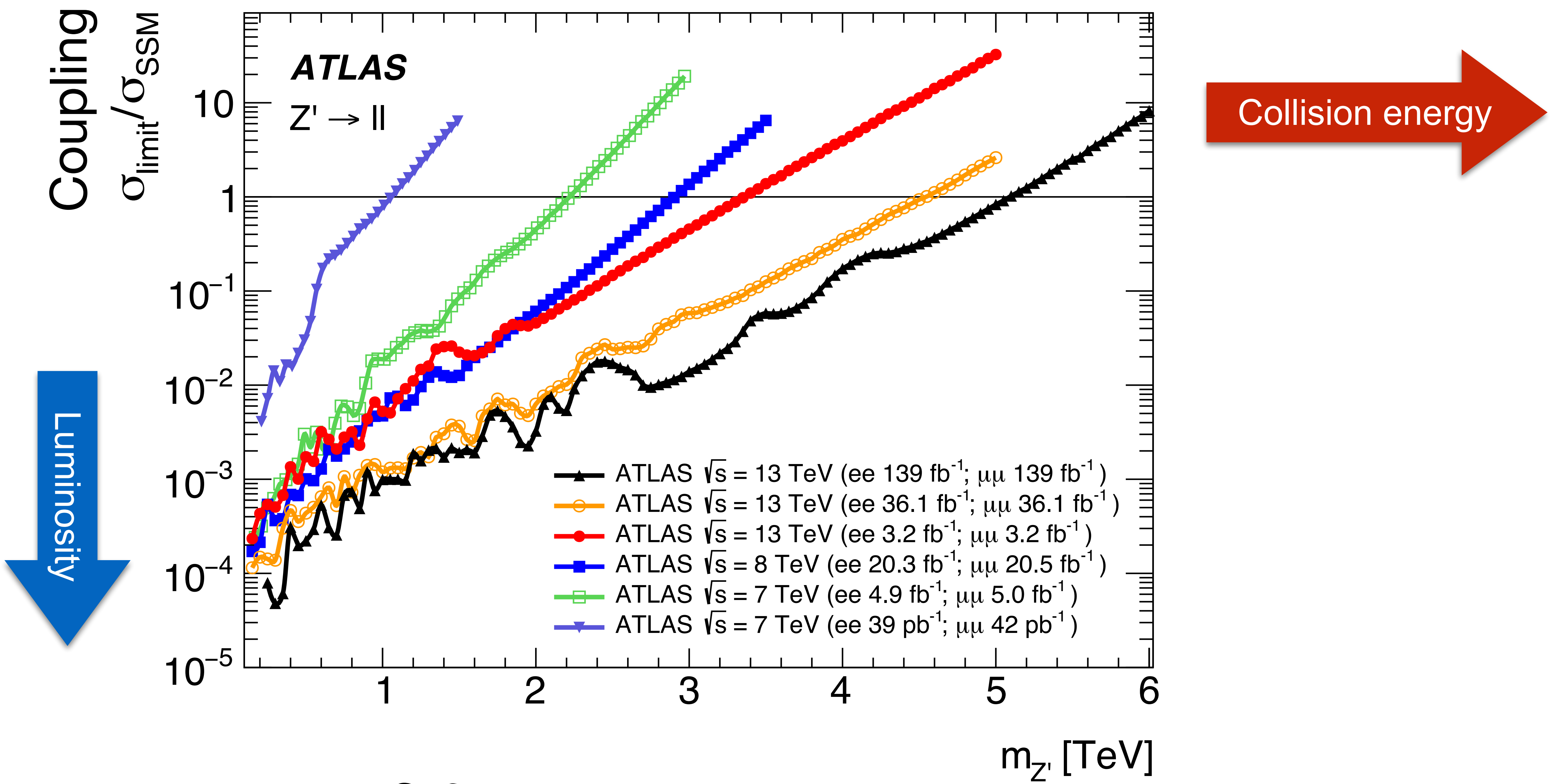


- Promising for next phase of LHC operation
  - currently limited by statistics
  - room for even more sophisticated data analysis techniques with machine learning



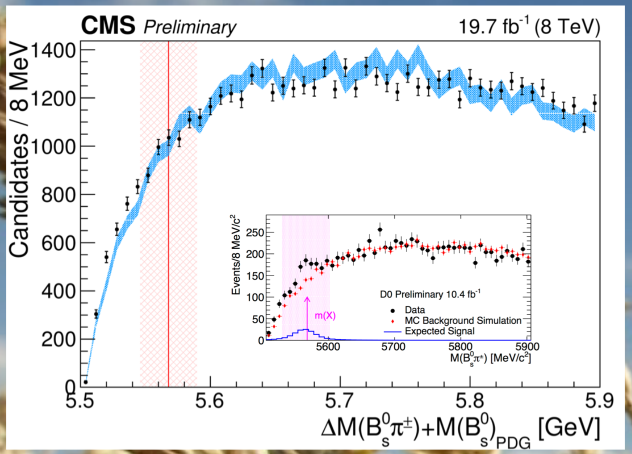
Energy vs Luminosity

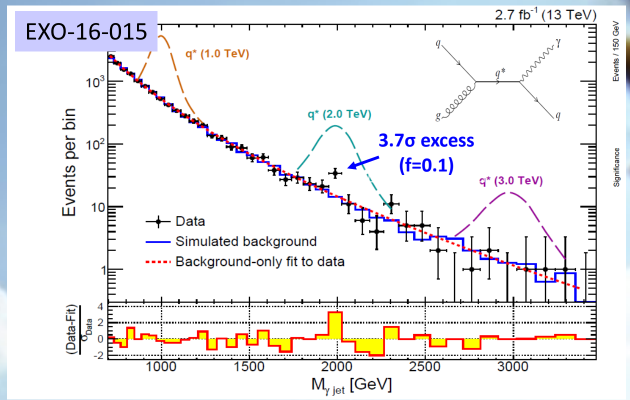
- Biggest jump in mass limits with increased energy at start of Run2
  - Assuming maximal coupling to SM particles
  - Most searches published with 36 fb^{-1} of data
- With Run3 data focus on exploring weakly coupled phenomena

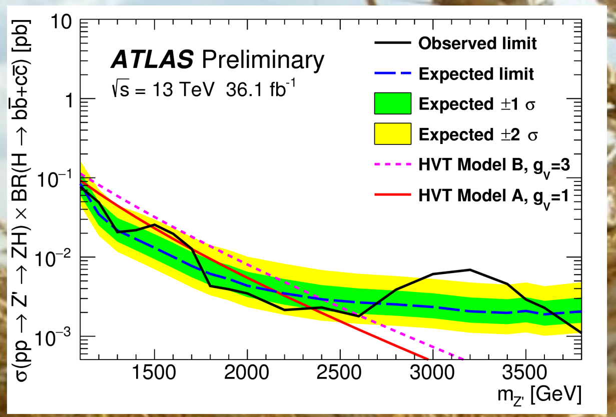


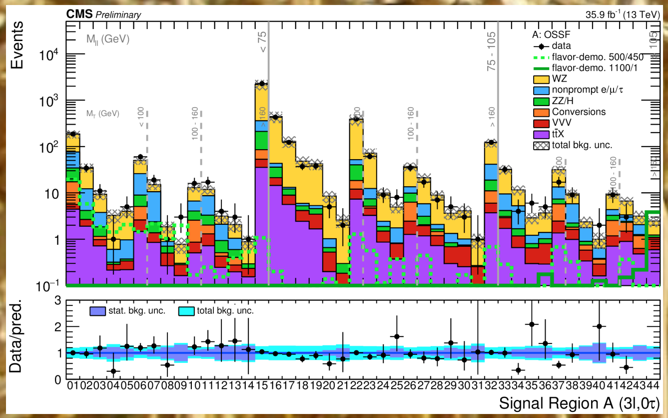
HIGH LUMINOSITY PROGRAM

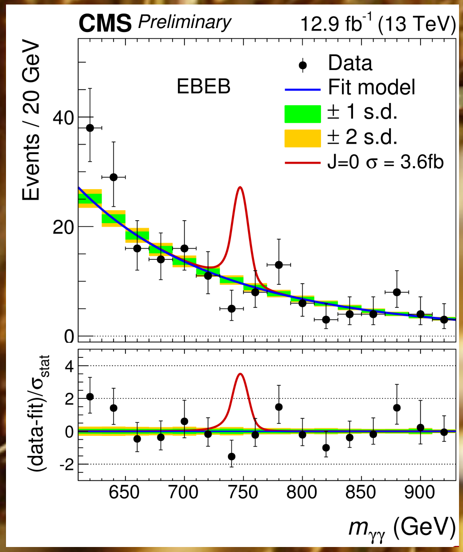
Hints and Fluctuations

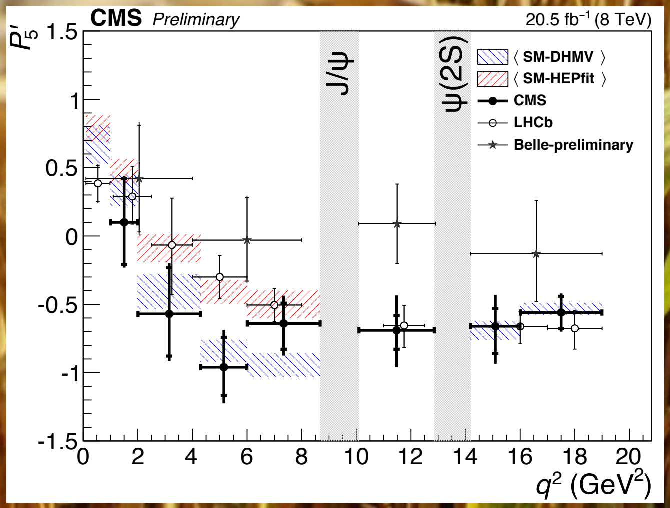


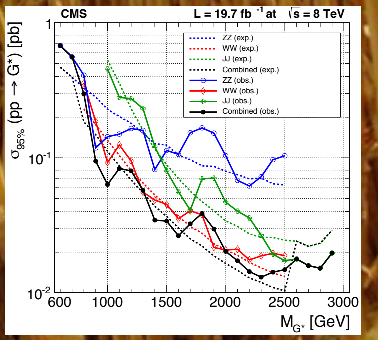




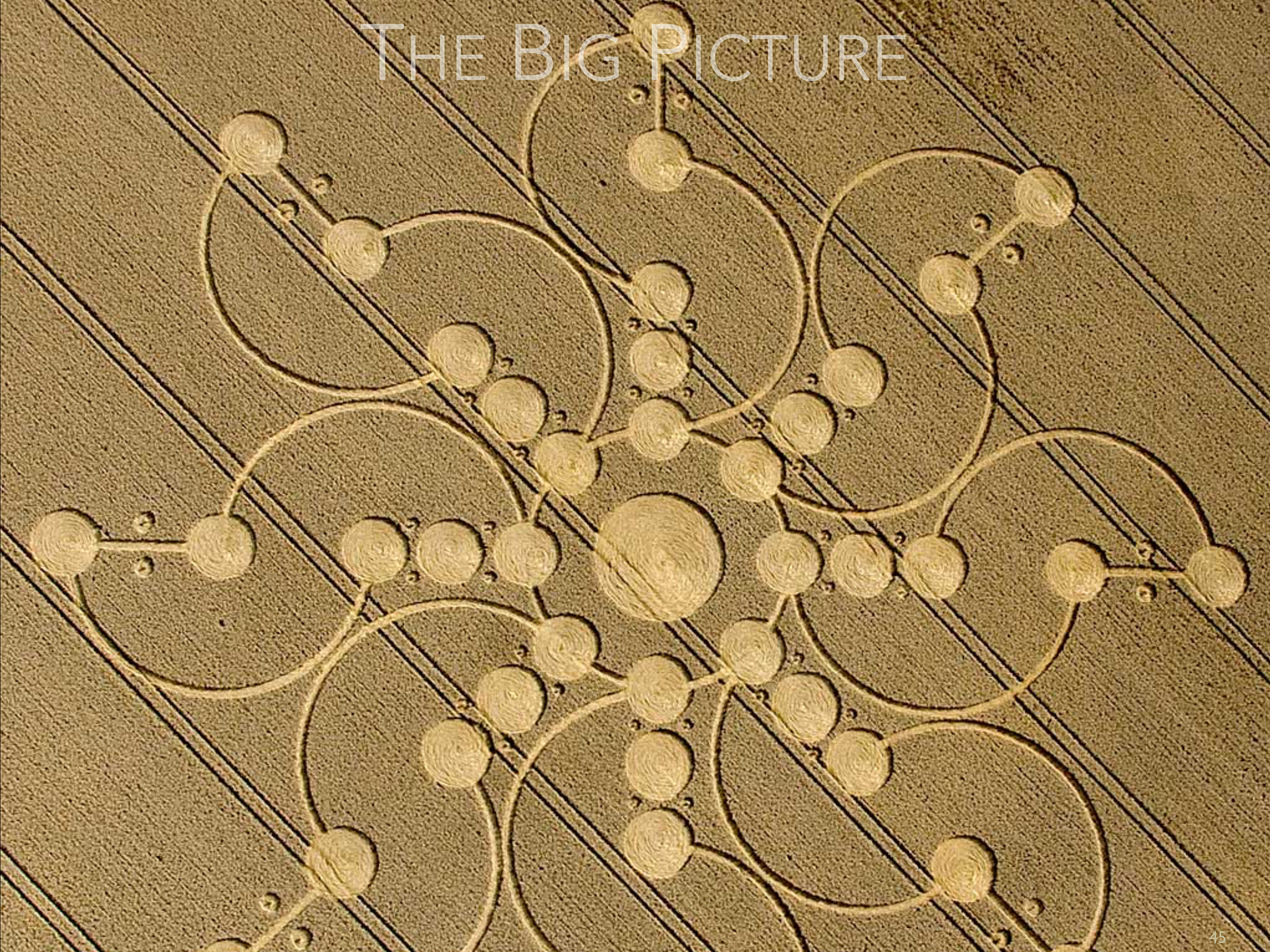








The Big Picture



Outlook

- Standard Model continues to stand strong
- Higgs coupling to 2nd generation fermion ahead of schedule
  - Take a look at physics TDRs released 15 years ago
- Flavor anomaly still there and to be pursued at low and high mass
  - Redundant measurements and revamped interest for Z' and LQ
- Bridging the gap between Searches and Standard Model physics
  - Top, W, Z, Higgs entering precision era in pp and constraining new physics
- *Upgraded detectors key for a successful physics program at high luminosity*
- *Human ingenuity assisted by Artificial Intelligence putting us further ahead of statistics-only pace*
- *Exploration of new territory for the first time without solid theoretical guidance*