Ordering Muons off the Collider Menu for Measurement & Discovery

Darin Acosta (Rice University)

Outline

- Introduction to particle physics and the muon
- Overview of the LHC and the CMS experiment
- Some results on searches for rare decays of the Higgs boson
- A few potentially anomalous measurements with muons
- Some possible future facilities beyond the LHC
  - Muon colliders
  - A muon-ion collider
- Summary & Outlook

The Muon…

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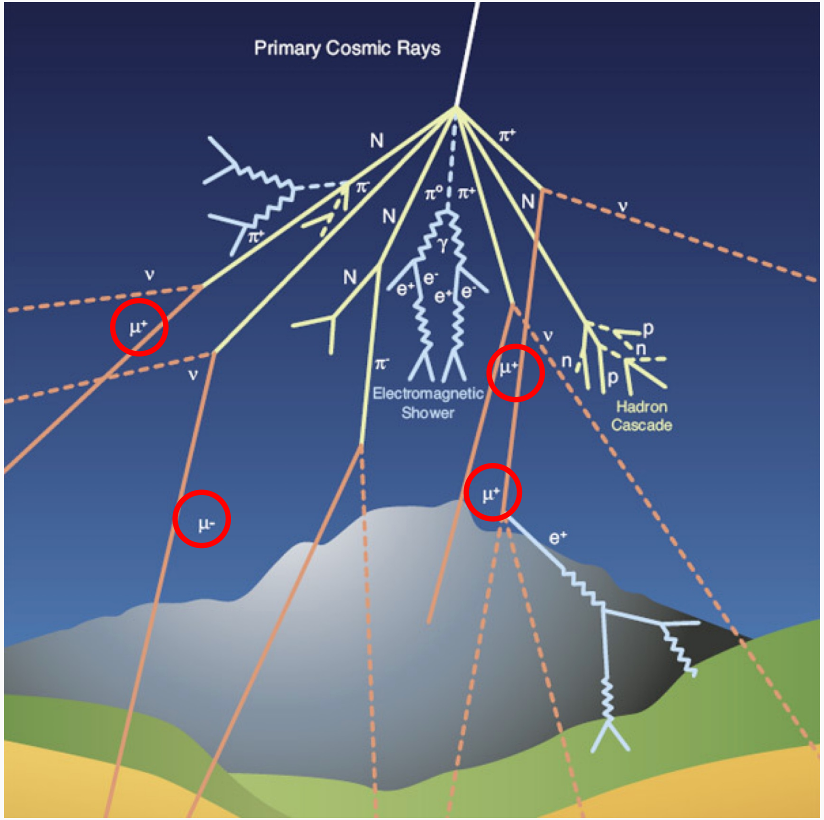
Cosmic Rays, Muons, & Relativity

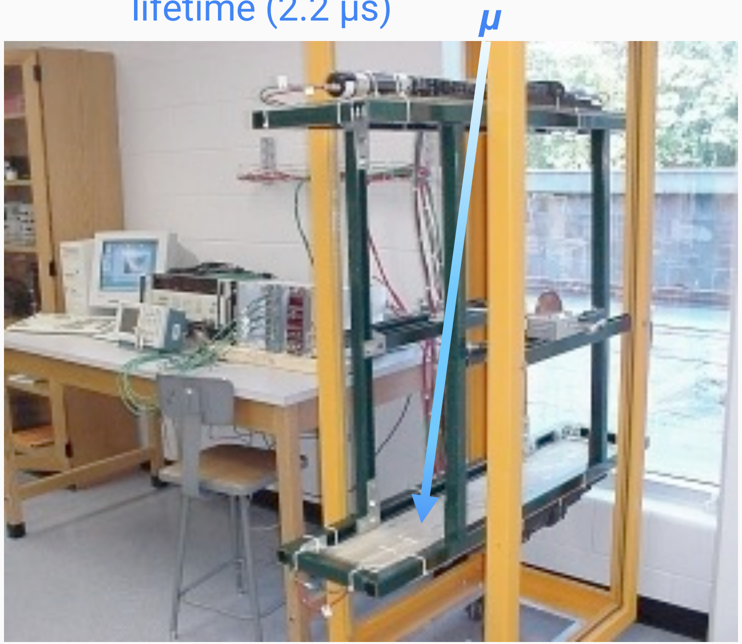


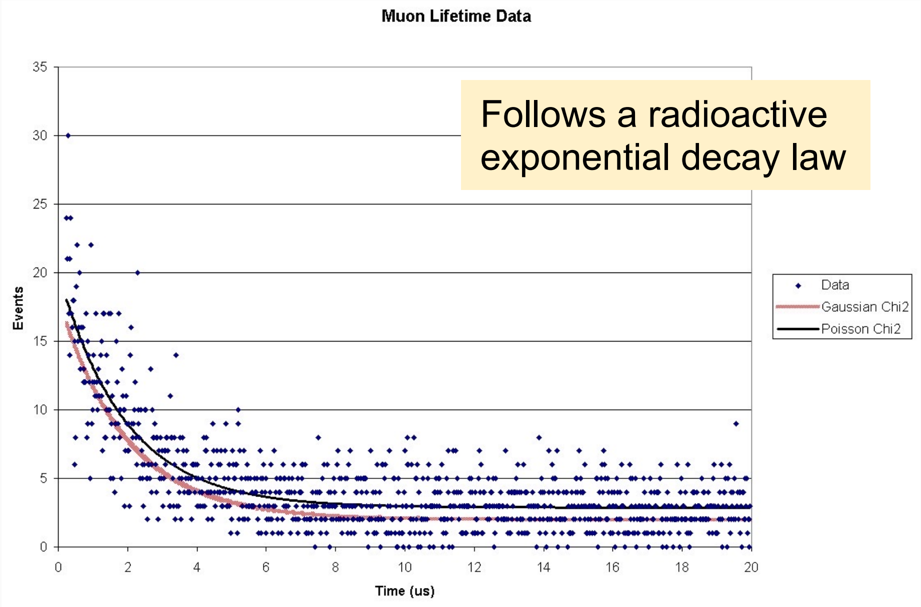
- Cosmic rays (protons, light nuclei) undergo nuclear collisions in the upper atmosphere to create showers of subatomic particles
- Longest-lived penetrating particle is the mu-meson (muon)
  - Discovered by Carl D. Anderson and Seth Neddermeyer in cosmic radiation
  - Average lifetime is 2.2 microseconds

- But without time dilation, average travel distance at the speed of light is
  - $d = ct = 660$ m
- With time dilation, the distance is
  - $d = ct/\sqrt{1 - v^2/c^2}$
- which can penetrate through the kilometers thick atmosphere and be detectable at the surface of the Earth

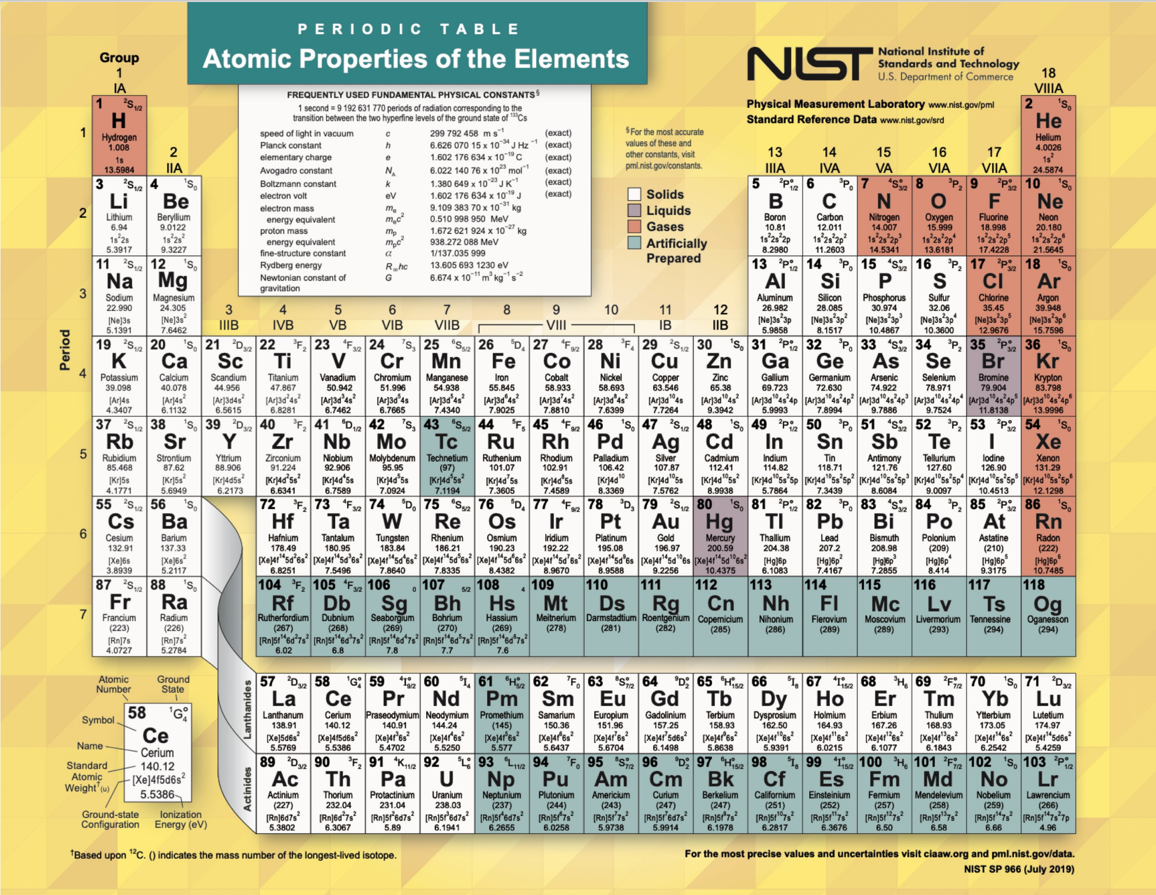
Measurement of Muon Lifetime

- Muons decay as $\mu^- \rightarrow e^- + \nu_e + \nu_\mu$
- Can be measured in an undergraduate modern physics lab!
  - Detect the signals from stopping muons and their decay electrons to measure the muon lifetime (2.2 μs)





The Periodic Table



- All of chemistry, from the structure of the periodic table, is explained by just 3 particles:
  - Electron
  - Proton
  - Neutron
- But deep inelastic scattering experiments in the 1950s-1960s showed that the nucleons are not fundamental
  - Comprised of quarks

Deep Inelastic Scattering

- Electron-proton scattering experiments at SLAC led by Hofstadter in the 1950s showed that the nucleon charge distribution had a size (~10^{-15} m)
  - Not a point, i.e. not fundamental
- For inelastic scattering, by Kendall and Taylor in the 1960s, the nucleon broke up, but point-like Coulomb scattering of charged particles could explain the data *if the nucleon was considered comprised of "partons" (quarks)*

203 6.2 Nucleon structure

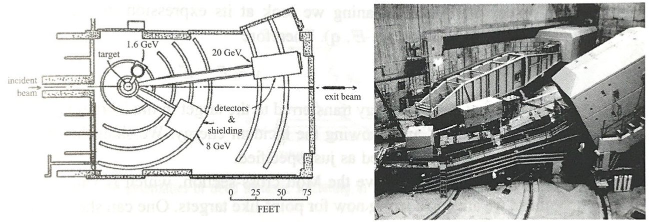
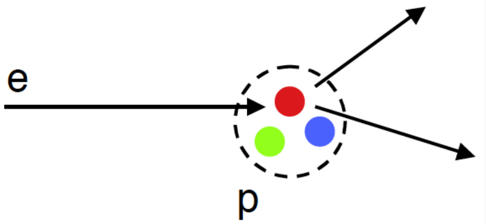
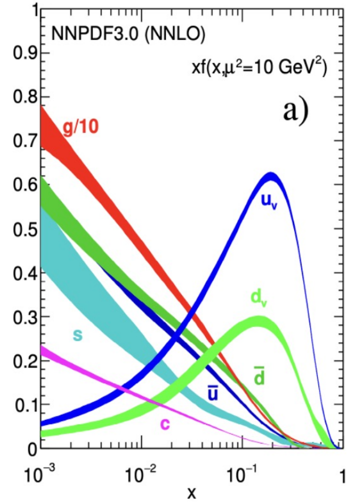


Fig. 6.8. SLAC: the spectrometers ride on rails and can be rotated about the target to change the angle of the detected electrons. The detectors are inside the heavy shielding structures visible at the ends of the spectrometers (Taylor 1991, courtesy of SLAC and © Nobel Foundation 1990).



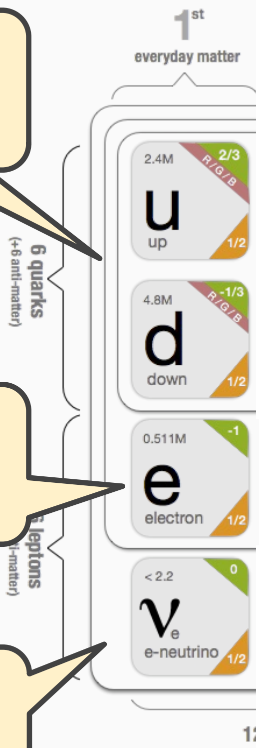
Modern inferred distribution of quark densities vs. momentum fraction inside the proton →



A Periodic Table for Fundamental Particles

Proton recipe: take 2u and a d

Quarks



hydrogen recipe: take 1p add 1 e⁻

Leptons

Neutrino: emitted in beta decay

But where does the muon fit?

I.Rabi: “Who ordered that?”

A Periodic Table for Fundamental Particles

Proton recipe: take 2u and a d

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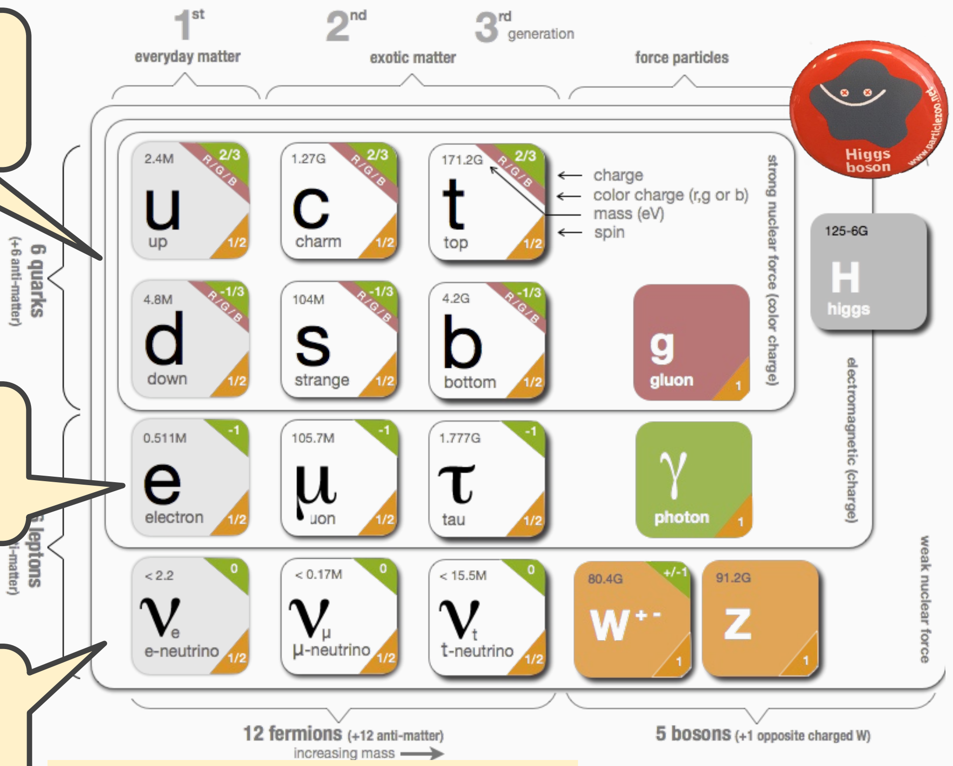


But where does the muon fit?

I.Rabi: “Who ordered that?”

- Matter families are replicated 3 times
  - Leptons and quarks are spin-1/2 particles → fermions
- Relativistic theories for forces quantize fields into particles (gauge bosons)
  - Quarks feel the strong force,
  - Leptons do not
- These quantum field theories and the quarks and leptons form the “Standard Model”
  - With a Higgs boson to provide mass

The Quark-Parton Model

- Even before the experimental evidence for quarks, they were postulated to exist in order to explain the zoo of particles

Quarks are necessary to explain the “Particle Zoo”

See the listings from the Particle Data Group:
http://pdg.lbl.gov

LIGHT UNFLAVORED MESONS (

Mini Reviews

- Form Factors for Radiative Pion and I
- Note on Scalar Mesons below 2 GeV
- The $\rho(770)$
- The Pseudoscalar and Pseudovector
- The $\rho(1450)$ and $\rho(1700)$ (rev.)

Particles

$\pi^{\pm}$
π^0
η
$f_0(500)$or $\sigma$was $f_0(600)$
$\rho(770)$
$\omega(782)$
$\eta'(958)$
$f_0(980)$
$a_0(980)$
$\phi(1020)$
$h_1(1170)$
$b_1(1235)$
$a_1(1260)$
$f_2(1270)$
$f_1(1285)$
$\eta(1295)$
$\pi(1300)$
$a_2(1320)$
$f_0(1370)$
$h_1(1380)$
$\pi_1(1400)$
$\eta(1405)$
$f_1(1420)$
$\omega(1420)$
$f_2(1430)$

STRANGE MESONS (S = :

Mini Reviews

- The Charged Kaon Mass
- Rare Kaon Decays (rev.)
- Dalitz Plot Parameters for K
- $K^{+-}_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors
- CPT Invariance Tests in Neu
- CP Violation in $K^0_S \to 3\pi$
- V_{ud}, V_{us} the Cabibbo Angle,
- CP Violation in K^0_L Decays
- $\Delta S = \Delta Q$ in K^0 Decays
- $K^*(892)$ Masses and Mass D

Particles

$K^{\pm}$
K^0
K^0_S
K^0_L
$K^*_0(800)$or κ
$K^*(892)$
$K_1(1270)$
$K_1(1400)$
$K^*(1410)$
$K^*_0(1430)$
$K^*_2(1430)$
$K(1460)$
$K_2(1580)$
$K(1630)$
$K_1(1650)$
$K^*(1680)$
$K_2(1770)$
$K^*_3(1780)$
$K_2(1820)$
$K(1830)$
$K^*_0(1950)$

CHARMED MESONS (

Mini Reviews

- $D^0 - \overline{D}^0$ Mixing (rev.)

Particles

$D^{\pm}$
D^0
$D^*(2007)^0$
$D^*(2010)^{\pm}$
$D^*_0(2400)^0$
$D^*_0(2400)^{\pm}$
$D_1(2420)^0$
$D_1(2420)^{\pm}$
$D_1(2430)^0$
$D^*_2(2460)^0$
$D^*_2(2460)^{\pm}$
$D(2550)^0$
$D^*_J(2600)$was $D(260$
$D^*(2640)^{\pm}$
$D(2740)^0$
$D(2750)$
$D(3000)^0$

BOTTOM MESONS ($B = \pm 1$)

Mini Reviews

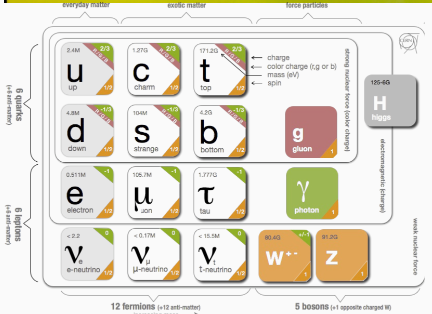
- Production and Decay of b-flavored Hadrons
- A Note on HFAG Activities (rev.)
- Polarization in B Decays (rev.)
- $B^0 - \overline{B}^0$ Mixing (rev.)
- Semileptonic B meson decays and the determination of V_{cb} and V_{ub} (rev.)

Particles

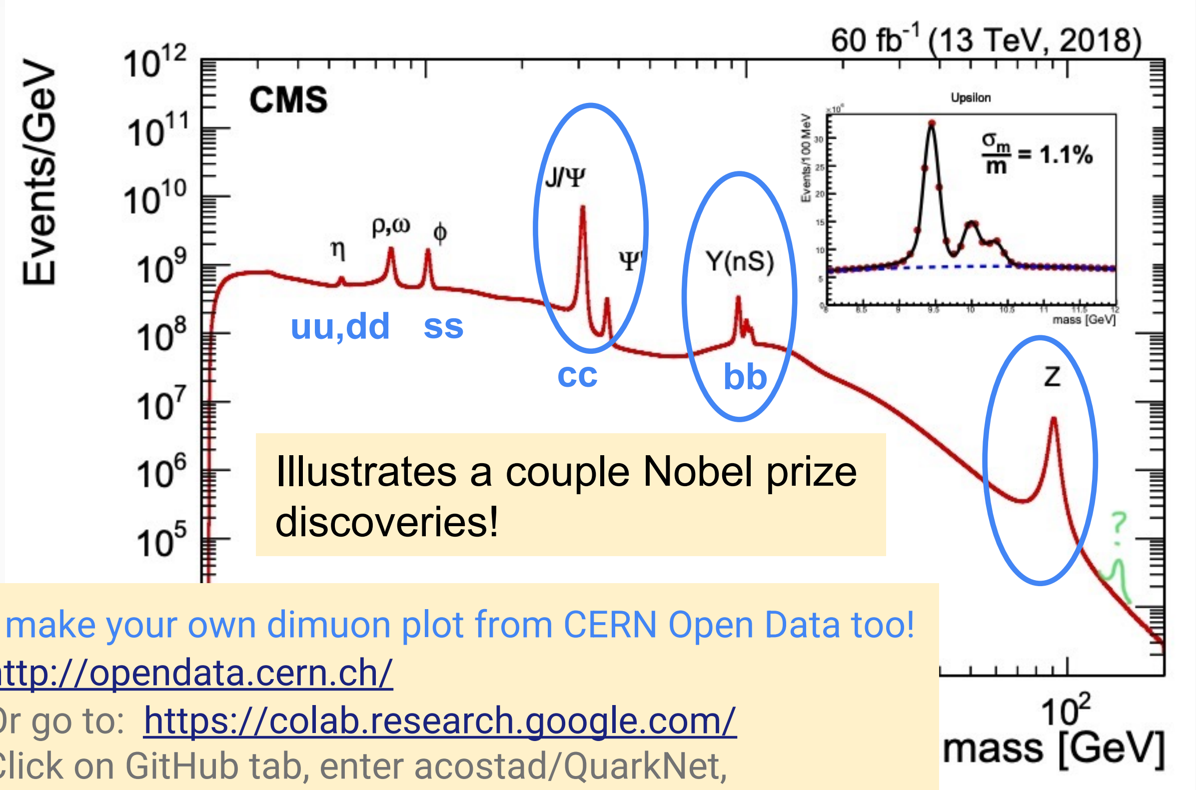
B-particle organization	
$B^{\pm}$	
B^0	
$B^{\pm}/B^0$ ADMIXTURE	
$B^{\pm}/B^0/B^0_s$/b-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
B^*	
$B_1(5721)^+$	**
$B_1(5721)^0$	***
$B^*_J(5732)$or B^{**}	
$B^*_2(5747)^+$	**
$B^*_2(5747)^0$	***
$B_J(5840)^+$	**
$B_J(5840)^0$	**
$B_J(5970)^+$	**
$B_J(5970)^0$	**

The Quark-Parton Model

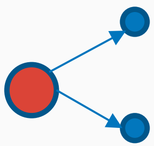
- Even before the experimental evidence for quarks, they were postulated to exist in order to explain the zoo of particles
    - Sorting particles by their electric charge, mass, and “strangeness” made some interesting patterns (multiplets)
        - “Eightfold way” of Murray Gell-Mann, and independently by Yuval Ne’eman
    - In 1964 for Gell-Mann and George Zweig propose that these particles are comprised of just 3 quarks: **u, d, s**
        - Which was extended to **6** by 1995
- Particles are just combinations of these quarks
- Many such particles can decay into muons!



(Composite) Particle Decays into Two Muons



Illustrates a couple Nobel prize discoveries!



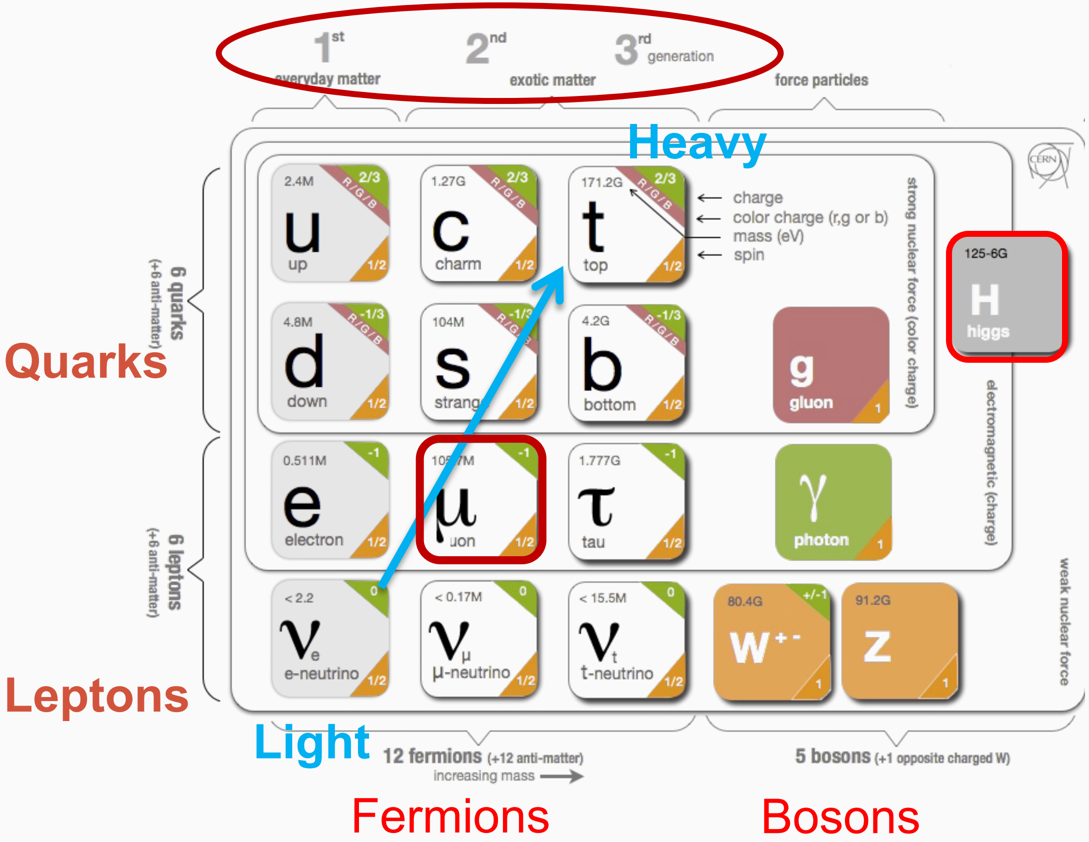
You can can make your own dimuon plot from CERN Open Data too!

- http://opendata.cern.ch/
- Or go to: https://colab.research.google.com/
- Click on GitHub tab, enter acostad/QuarkNet, choose Dimuon-Open-Data-with-CMS-outreach-and-education.ipynb

$m^2c^4 = E_{tot}^2 - p_{tot}^2c^2$

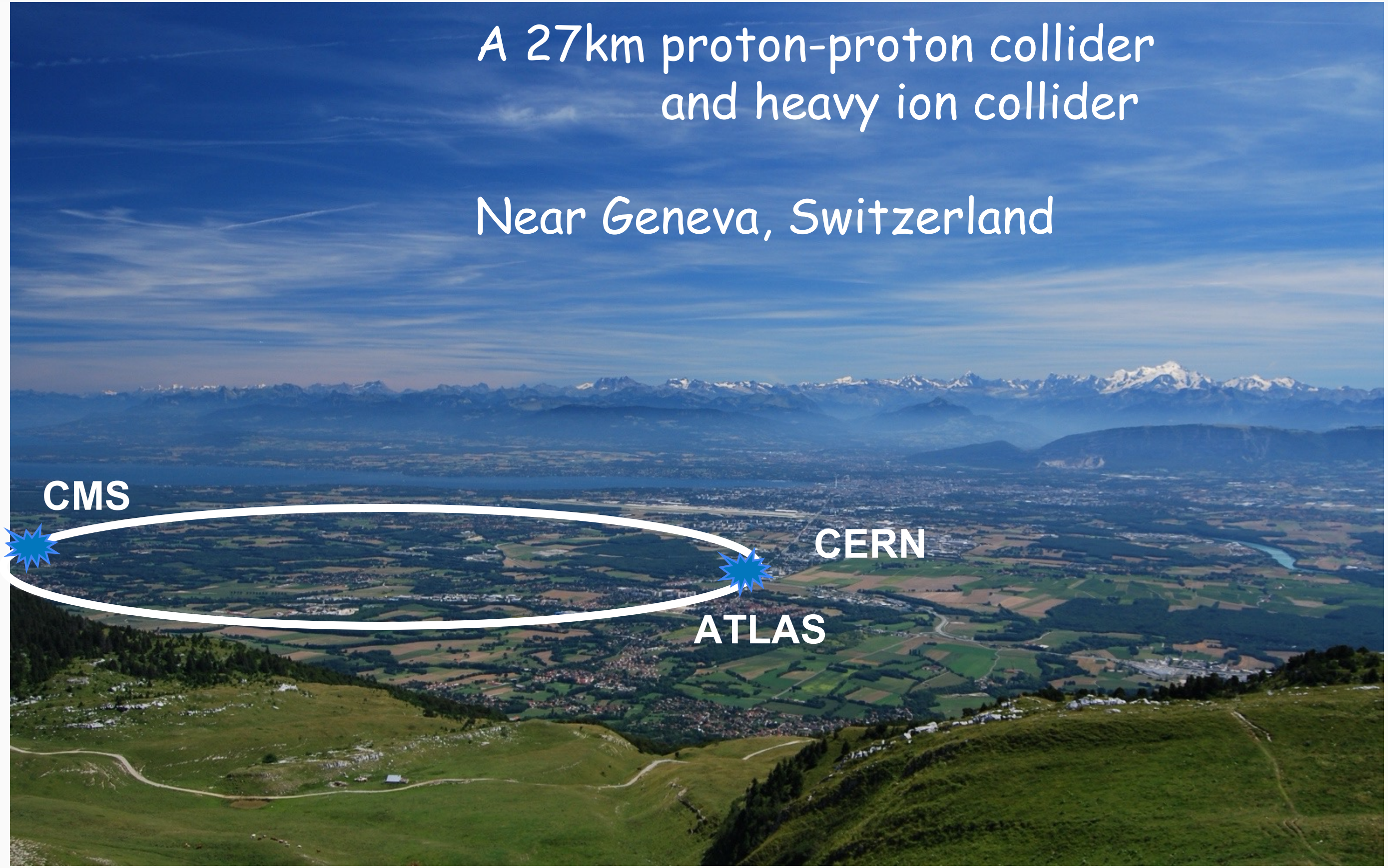
Resonances (bumps) indicative of production and decay of particles

But some unanswered questions remain…



- Fermionic matter is replicated 3 times
  - Who ordered that?
- Wide ranges of masses: sub-eV to 170 GeV
  - Flavor physics
- Quarks and leptons are related, but how?
  - Atoms are neutral…
- Are the strong and electroweak forces related?
  - Grand unified theories
- And does this comprise all forms of matter and forces?
  - Dark matter, dark sectors
- We need more experiments!

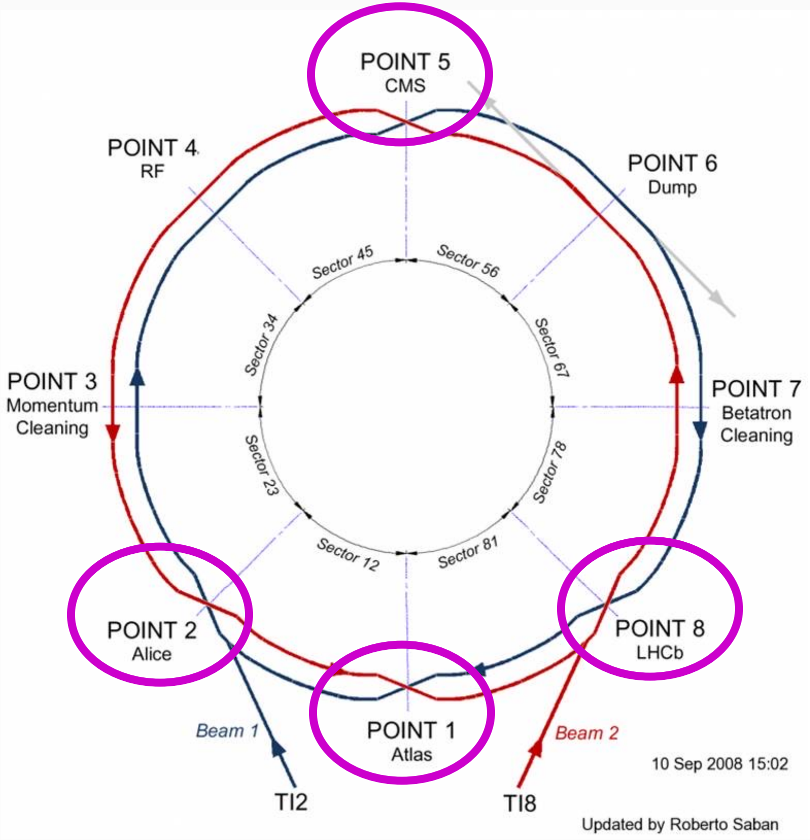
The CERN Large Hadron Collider (LHC)



The Large Hadron Collider (LHC)

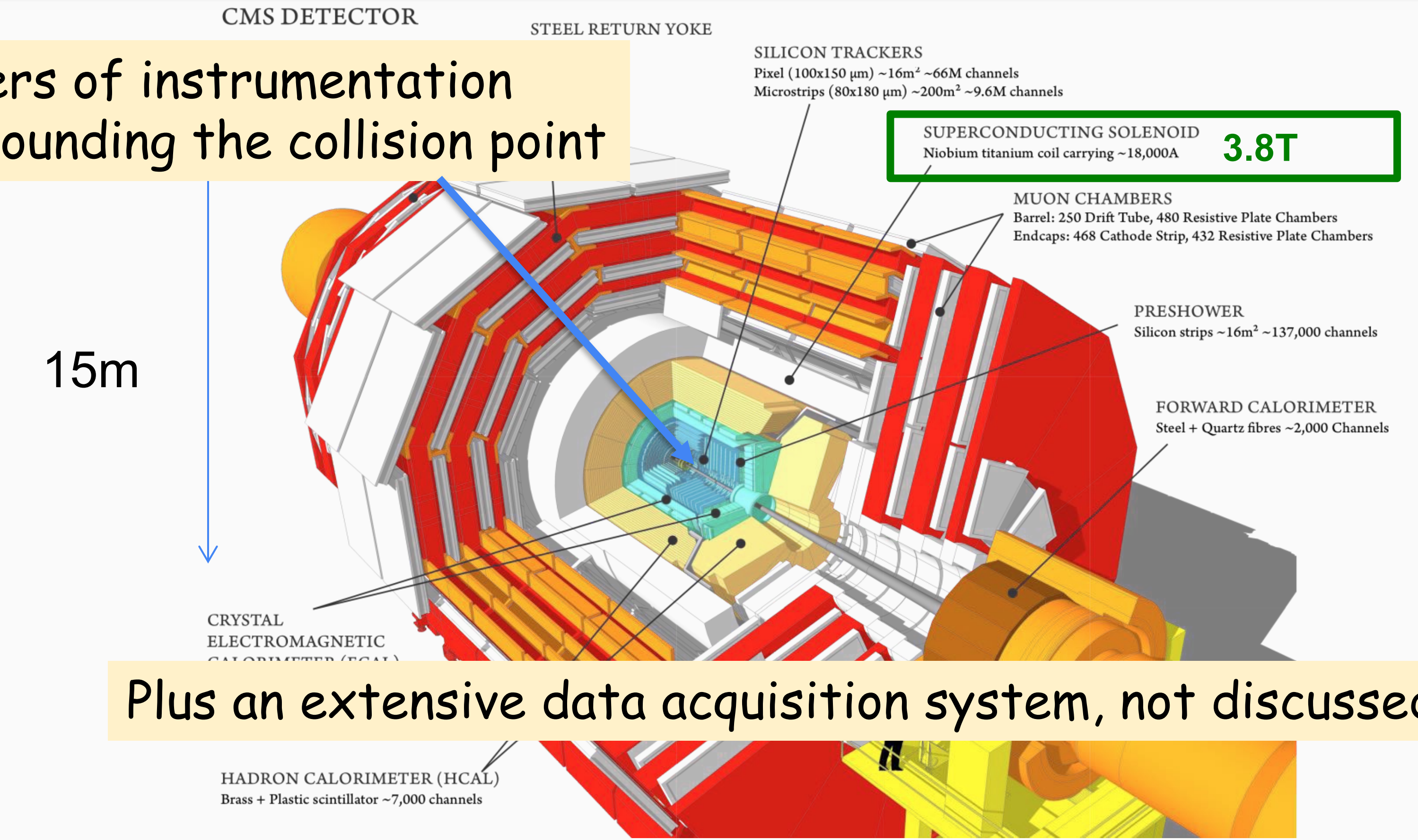
- Proton and ion collider
  - 27 km ring (17mi)
  - 6.5 TeV beam energy (7 TeV design)
- 1232 superconducting 8.4T dipole magnets @ T=1.9ºK
  - World's largest cryogenic structure

- 4 major experiments
  - ATLAS, CMS (both general purpose)
  - and ALICE, LHCb
- First collisions in 2009, last data run (Run 2) was 2015-18 at 13 TeV
  - Currently ending a 3 year maintenance+upgrade period, restarting now!



The "Compact" Muon Solenoid (CMS)

Layers of instrumentation surrounding the collision point



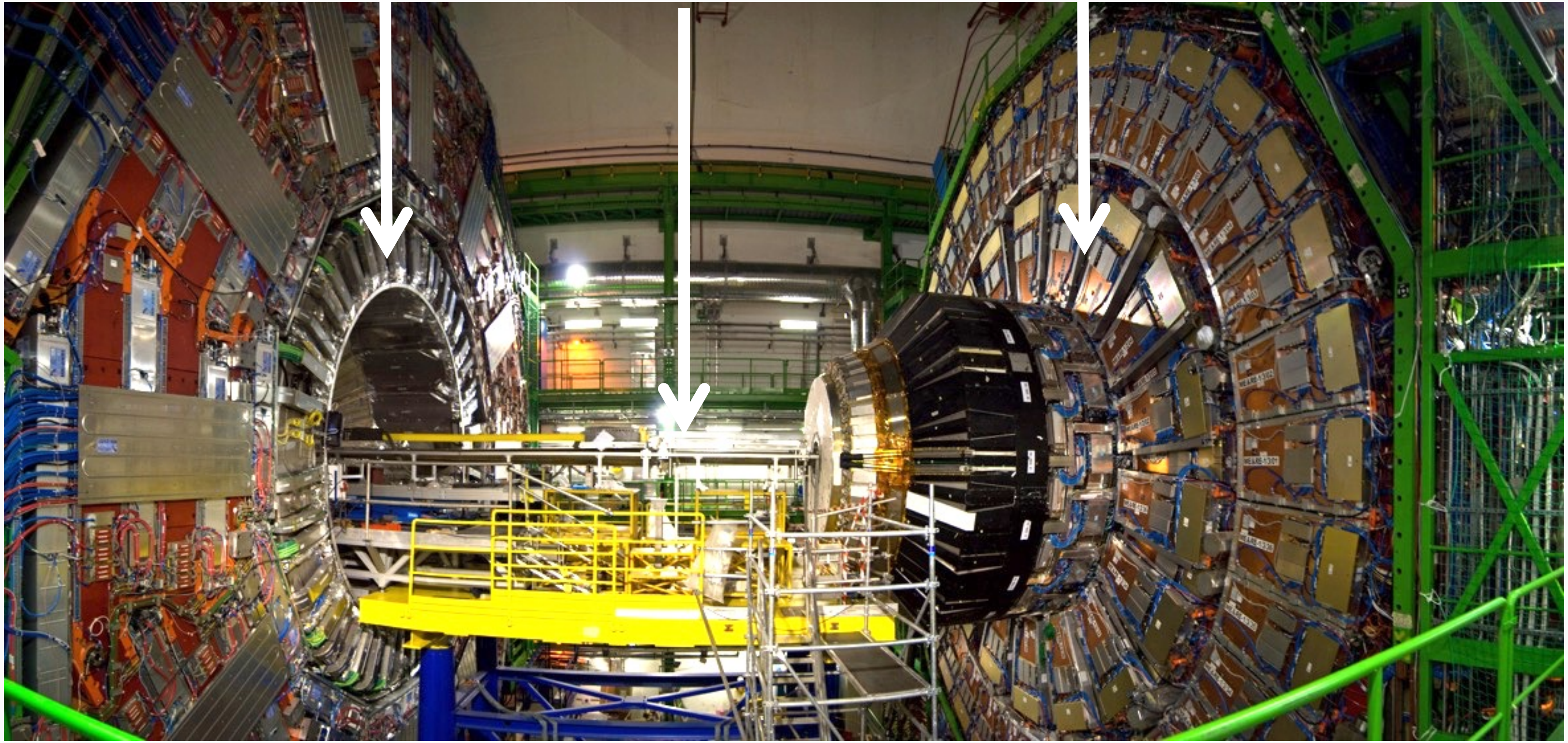
Plus an extensive data acquisition system, not discussed here

CMS Experiment Opened

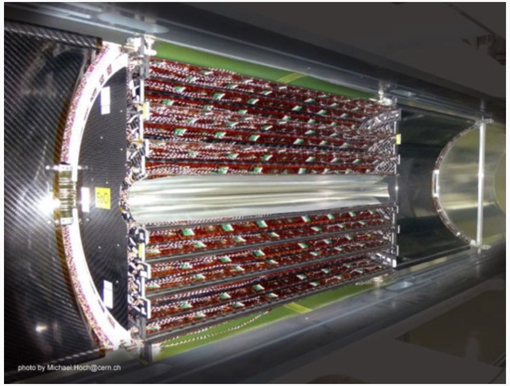
3.8T solenoid (2.7 GJ)

beampipe

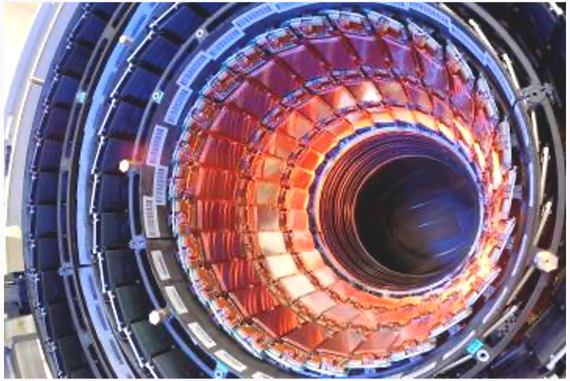
Muon detectors



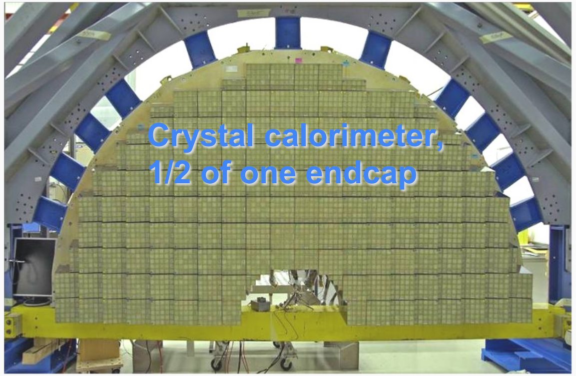
CMS Detector Subsystems



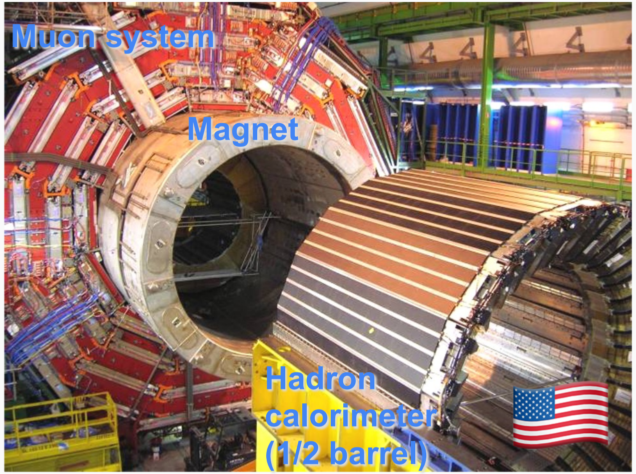
Barrel pixels



Silicon
strip modules



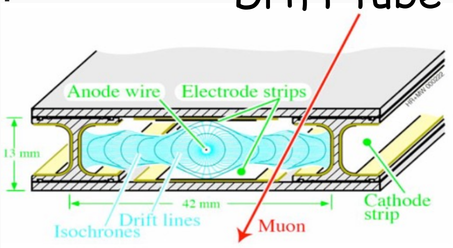
Forward
pixels

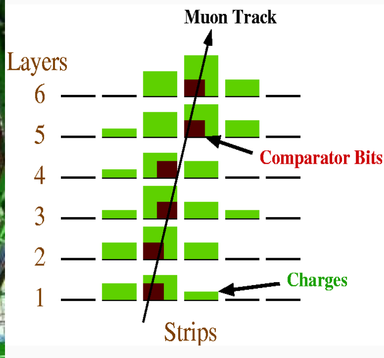


CMS Muon Systems

- 3 technologies to measure ionization of passing charged particles
  - drift-tubes, cathode strip chambers, resistive plate chambers
- 25000 m^2 of active detection planes
  - 100μm precision on position for DT and CSC
- About 1M electronic channels
- Coverage: DT: $|\eta|<1.2$, CSC: $0.9<|\eta|<2.4$, RPC: $|\eta|<1.6$

Drift tube





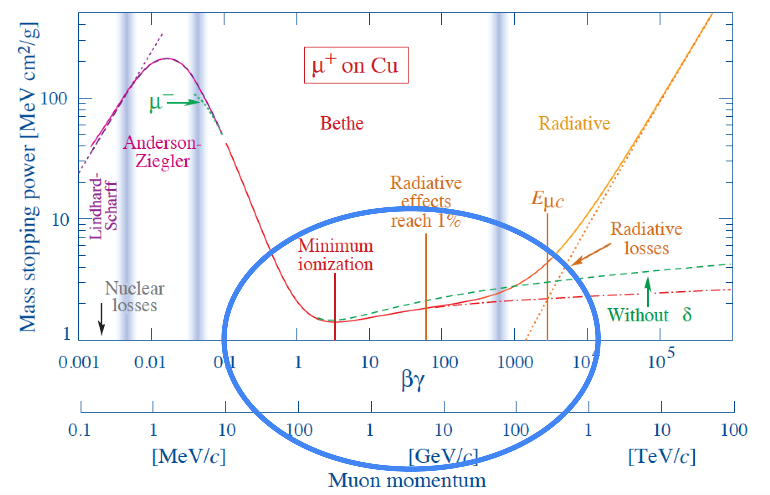
CSC

How muons interact…

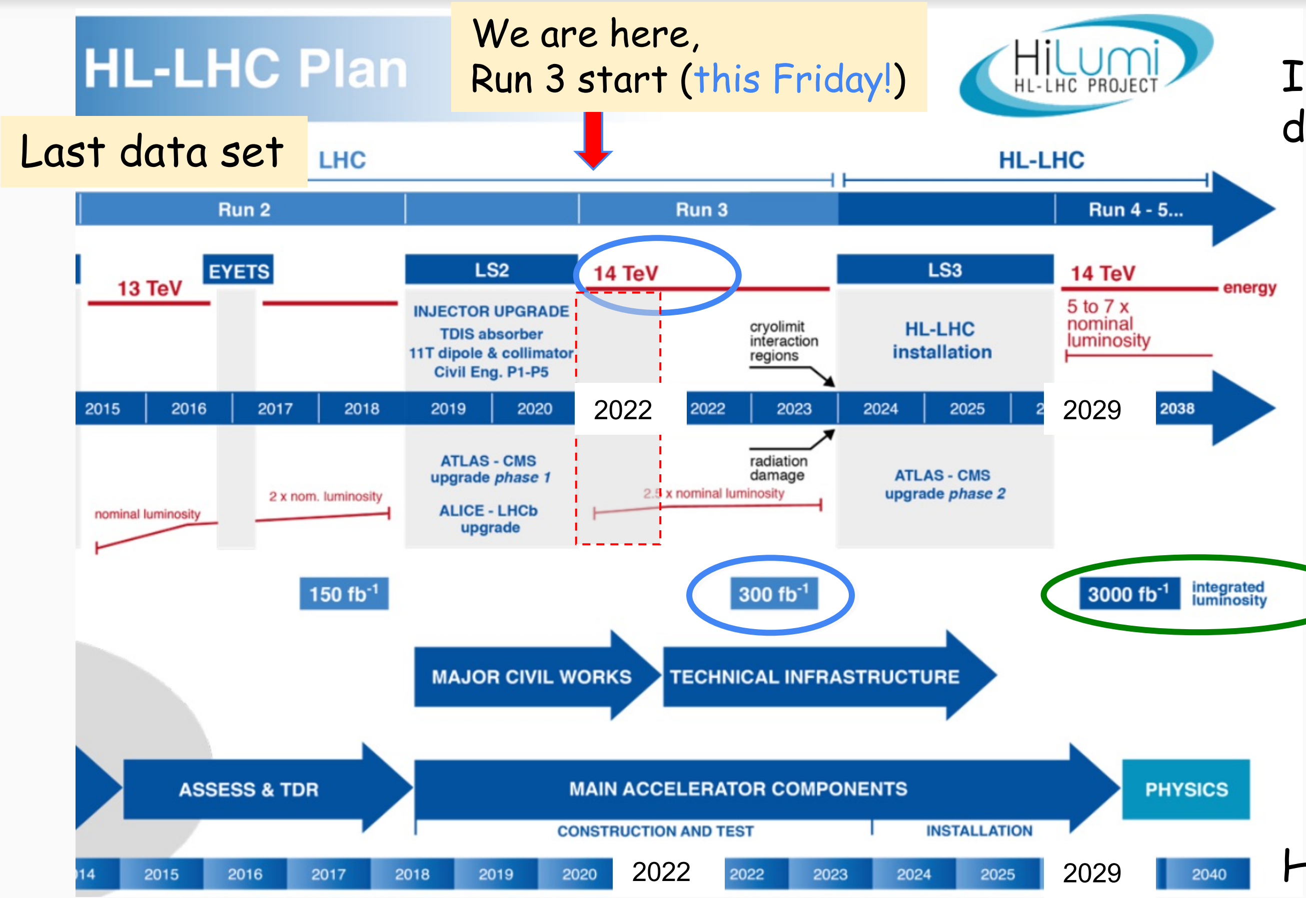
- But how do the muon detectors “know” they are measuring muons, and not electrons or protons, for example?
- Or put another way, why are the muon detectors on the outside of the experiment?
  - The muon is a lepton, and is blind to the strong nuclear force that binds quarks and nucleons in the nucleus
  - The muon is 200X heavier than the electron
- Thus, the muon interacts only minimally in matter, and is very penetrating

- This makes muons clean probes of the dynamics of the proton collisions
  - Little ambiguity

Bethe-Bloch equation:
muons are only minimally ionizing



LHC Run 3 and the HL LHC Upgrade Schedule



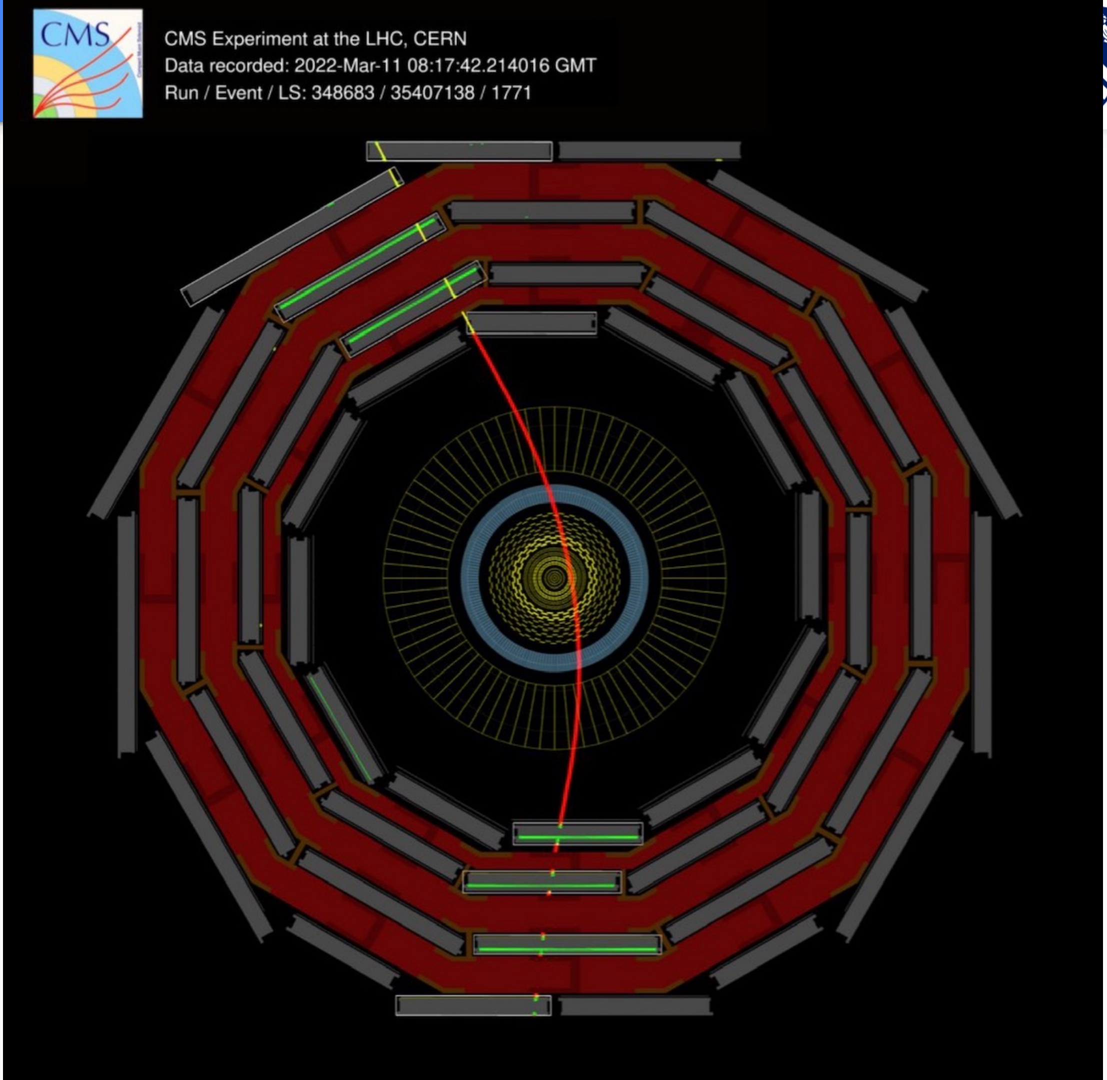
Initially, doubling of data set in next 4 years

Longer term, HL LHC luminosity and detector upgrades to start in 2029

20X more collected data than today with 4X busier collisions in detector by end

HL LHC starts in 2029

Cosmic Muon in CMS

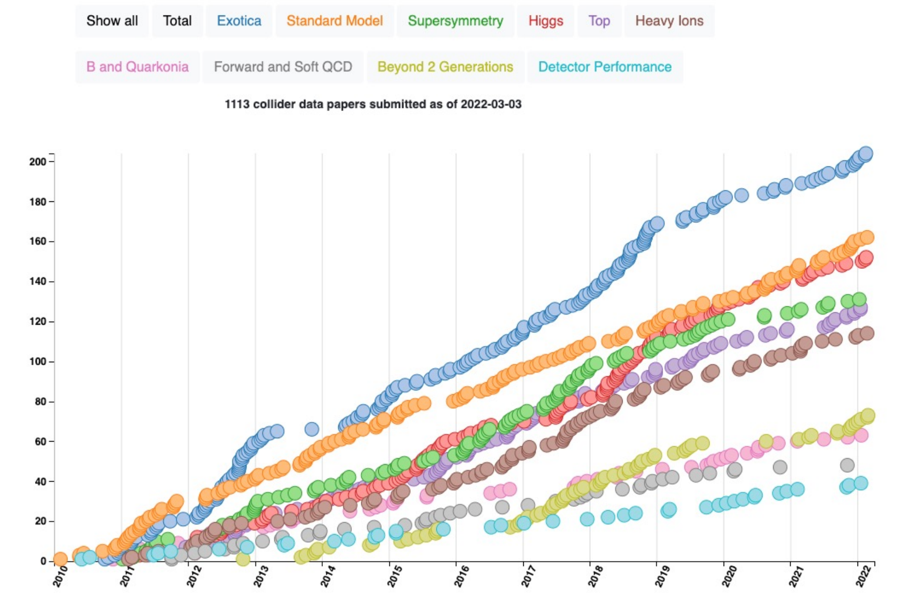


On to the Physics Menu…

- Leptoquarks
  - First-Generation Leptoquarks
  - Second-Generation Leptoquarks
  - Third-Generation Leptoquarks
- Randall--Sundrum Gravitons
- Heavy Gauge Bosons
  - Sequential Standard Model
  - Superstring-Inspired Models
- Long-Lived Particles
- Dark Matter
- Large Extra Dimensions
  - Arkani-Hamed--Dimopoulos--Dvali Model
  - Semiclassical and Quantum Black Holes
- Compositness
- Contact Interactions
- Excited Fermions
- Heavy Fermions, Heavy Righ-Handed Neutrinos
- Colorons, Axigluons, Diquarks
- Supersymmetry
- Resonances
  - Multijets
  - Dijets
  - Dileptons
  - $t\bar{t}$
  - Dibosons, VV and VH
  - Boosted Topologies

A Collider Experiment is like a (micro) Observatory

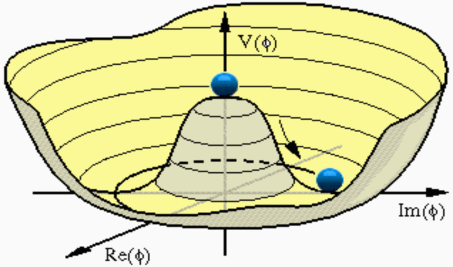
- Broad science program
- >1000 publications by the CMS Collaboration since 2009
- Broad coverage of physics areas
  - Higgs boson physics
  - Top quark physics
  - Other Standard Model
  - Searches for Beyond Standard Model
  - Heavy ion physics
- Only a tiny sampling here!
  - Essentially on the Higgs boson



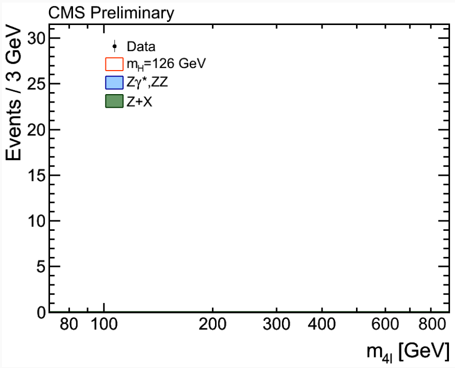
http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

Higgs Field and Boson

- Introduced to the Standard Model Lagrangian a complex scalar field Φ, a weak isospin doublet
- With spontaneous symmetry breaking, the potential V(Φ) takes an inverted shape
    - $V(\phi)=\mu^2|\phi(\mathbf{x},t)|^2+\lambda|\phi(\mathbf{x},t)|^4$ $\mu^2 < 0$



- → Field takes on a nonzero vacuum expectation value
    - Interactions with this field gives mass to the W and Z bosons of electroweak theory (Brout, Englert, Higgs mechanism)
    - Introduced trilinear couplings with fermions in proportion to their mass
    - Also gives rise to a scalar boson (found in 2012 after nearly 50 years!)
- Measured boson mass of 125 GeV is on the boundary between a stable and metastable electroweak vacuum state
    - Could indicate new physics at a scale below the Grand Unification (GUT) scale of 10^{16} GeV

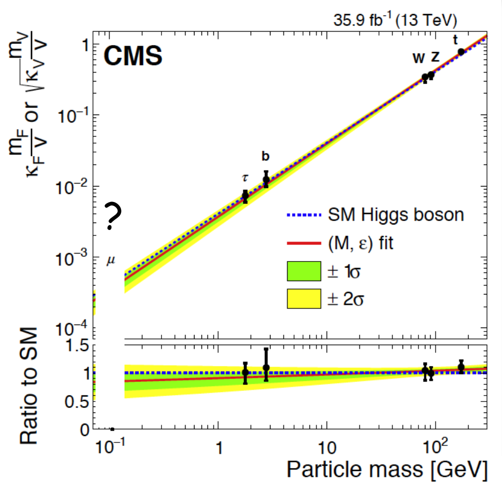


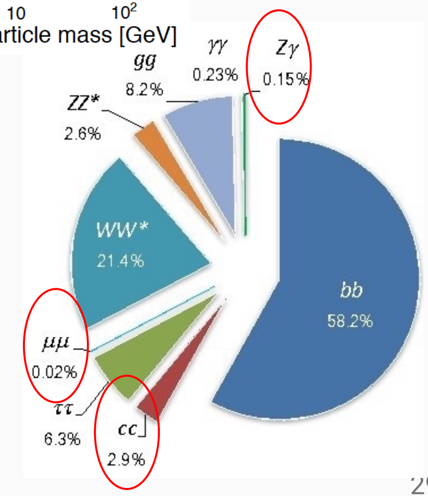
The Higgs Boson…

particlezoo.net

Search for Rare Higgs Decays (2^{nd} Gen. Fermions)

- The Higgs coupling to gauge bosons and to 3^{rd} generation fermions has been established
- Next: probe the coupling of the Higgs boson to 2^{nd} generation fermions
  - Should be in proportion to mass
- But the branching fractions are very small,
  - 2.2×10^{-4} for $H\rightarrow\mu\mu$
- Optimize selection of signal over background by Higgs productionchannel
  - VH, VBF, ttH, inclusive
- Use machine-learning to squeeze best discrimination





Associated VH→V(μμ) Leptonic Channel

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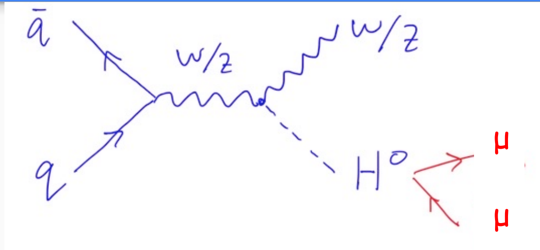
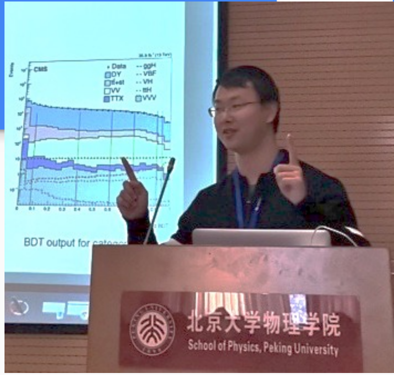


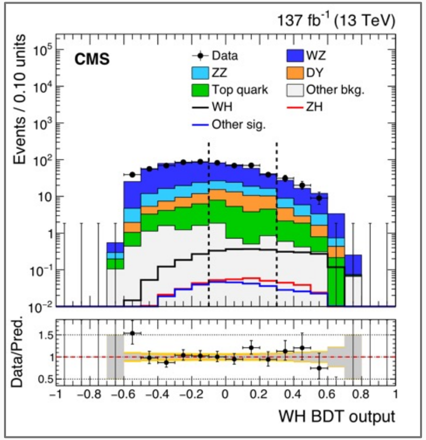


PhD topic of Xunwu Zuo

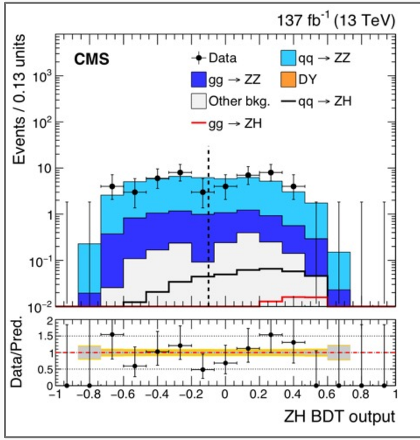
(And a major research area for Prof. Brinkerhoff)

- Selection
  - One extra lepton for WH category
  - Or extra pair of same-flavor, oppositely charged leptons for ZH category
  - No b-tagged jets
  - Main backgrounds: WZ, ZZ
- Analysis
  - Independent Boosted Decision Trees (machine learning) trained on lepton kinematics for the WH and the ZH categories
  - Use $1/\sigma(m_{\mu\mu})$ as weight for signal events
  - Divide into subcategories

WH BDT

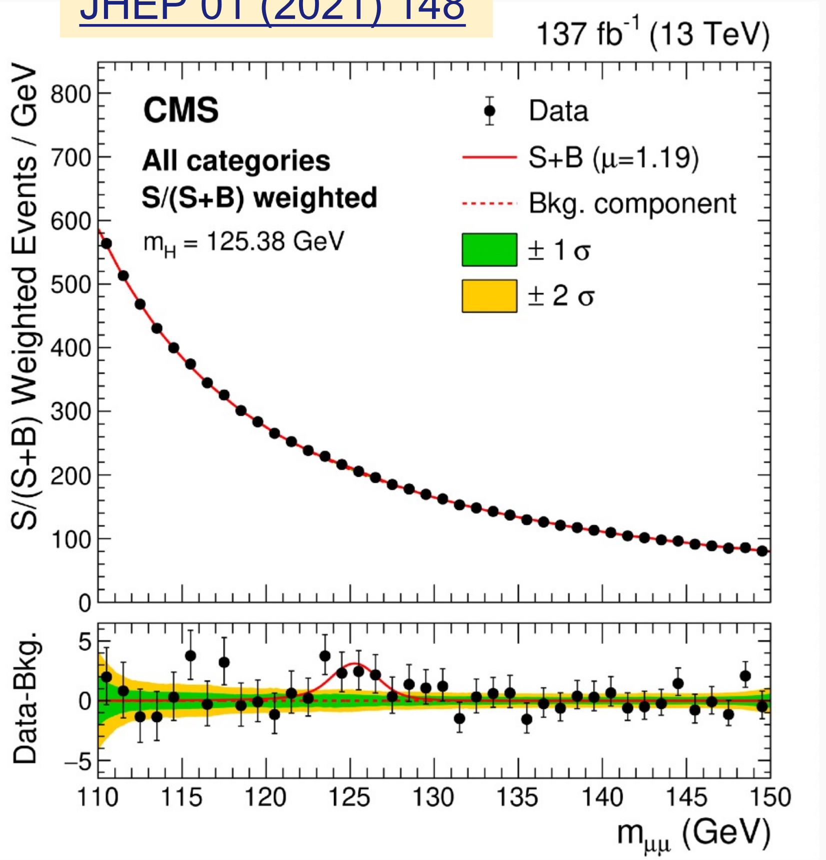


ZH BDT



H→$\mu\mu$ Search Result

- The plot shows the weighted combination, S/(S+B), for all production categories
- Data are well described by background shape over most of the range, but
- Signal fit at best Higgs mass measurement 125.38 GeV shows an excess



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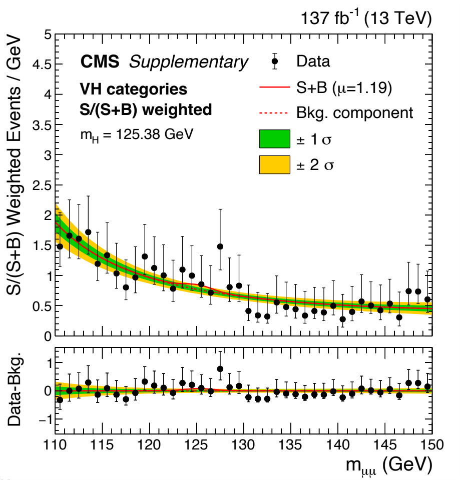
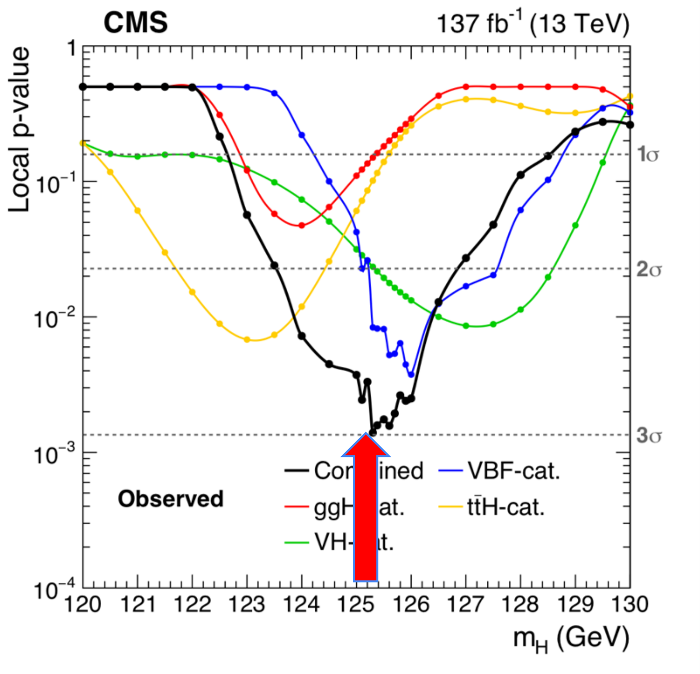
- VH only →



Statistical Significance vs. Mass

- P-value is the probability for pure background (no Higgs) to fluctuate above signal observed
- At the best Higgs mass measurement by CMS, 125.38 GeV, the observed significance is 3.0 σ (expected was 2.5 σ).
    - i.e. 3 standard deviation fluctuation for the background to mimic the signal
    - 3 σ is the accepted standard for evidence
    - 5 σ gets you a discovery



Best Fit Signal Strength μ (Ratio to SM prediction)

- Agrees with SM

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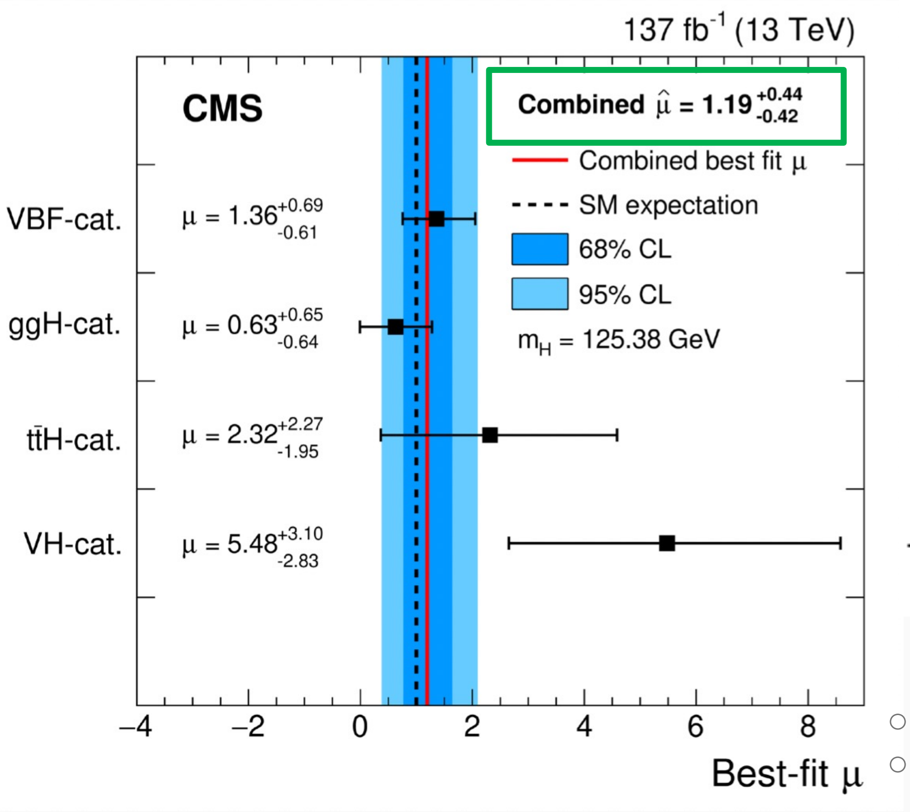
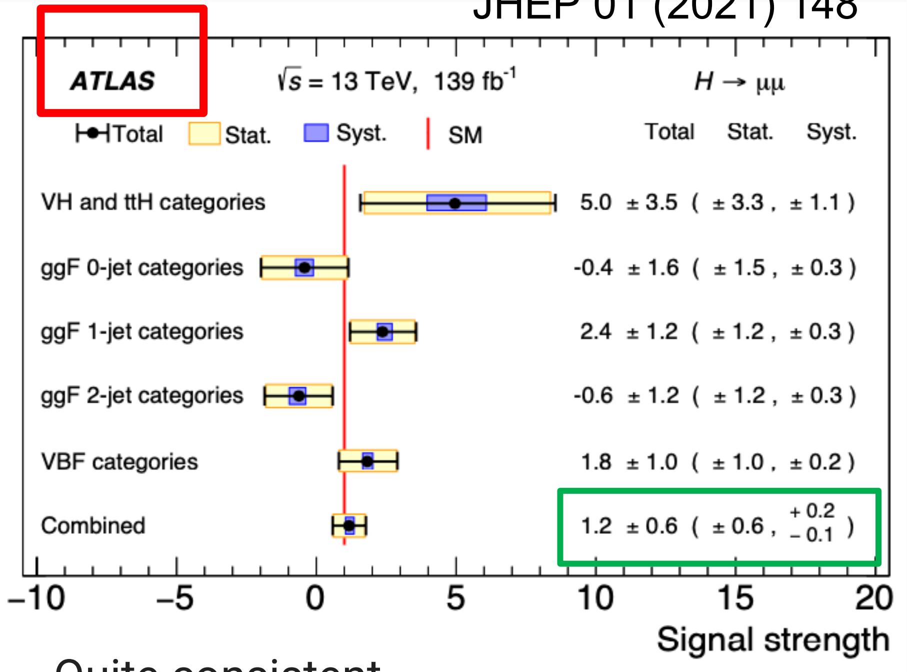


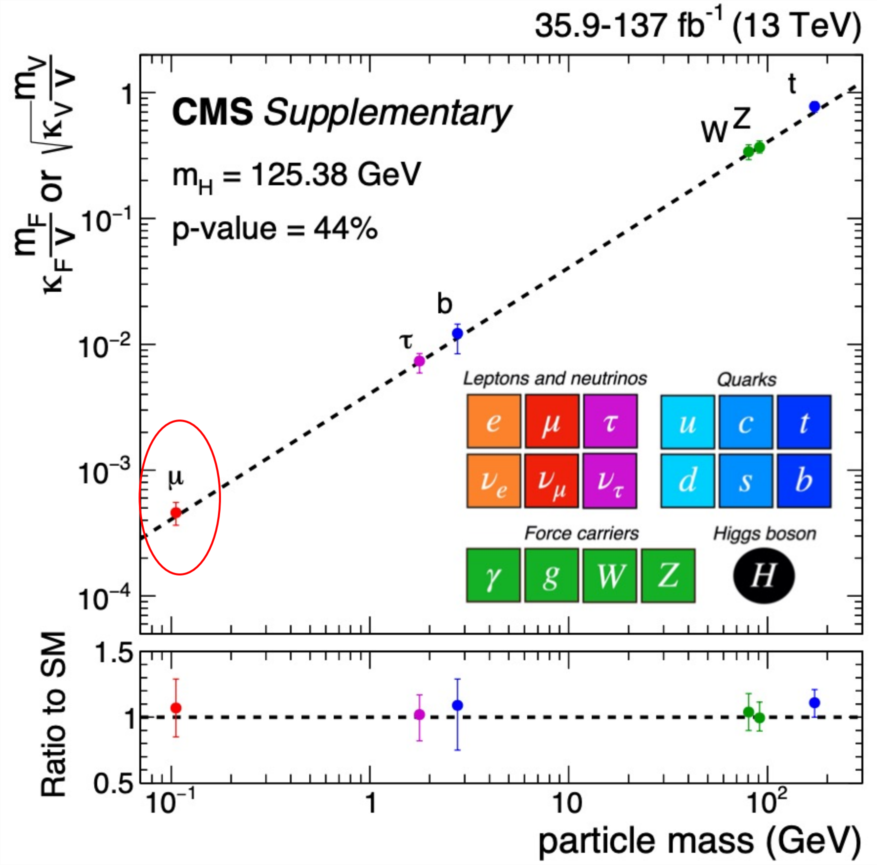


Quite consistent

- ATLAS significance: 2.0 σ (expected was 1.7 σ)
- Less than CMS, primarily from mass resolution
  - 2T vs. 4T solenoid magnet

Higgs Couplings

- The μμ result is also combined with the latest published results on other Higgs channel measurements [EPJC (2019) 79:412] to extract all Higgs-particle couplings
- Provides the most precise measurement on the κ_μ up to date
- Demonstrates the expected linear coupling with mass →



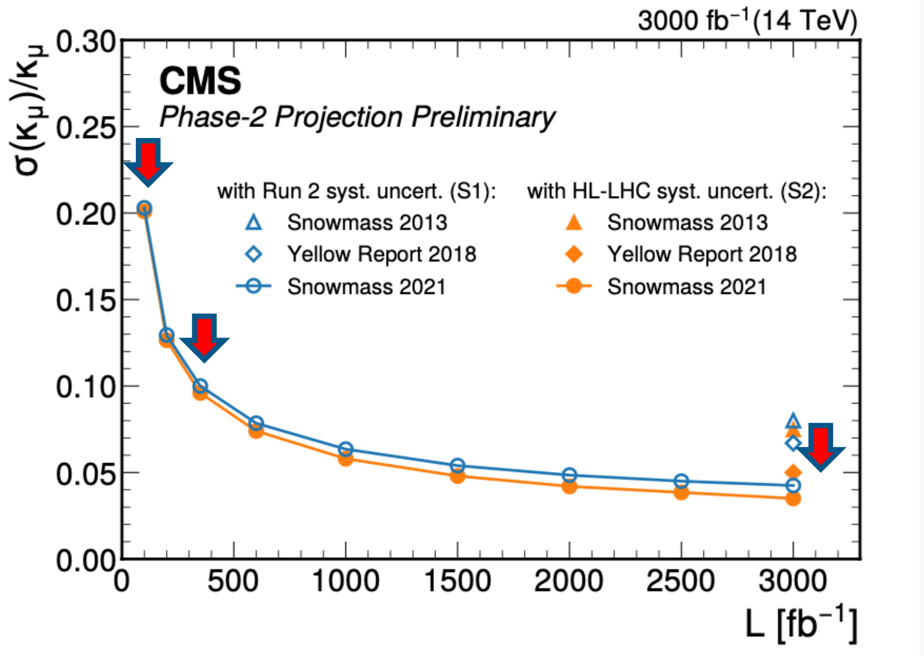
H→$\mu\mu$ Coupling Projections with Future CMS Data

CMS-PAS-FTR-21-006

- Projections of the uncertainty on the κ_μ coupling with additional data
- Based only on ggH and VBF production mechanisms
  - Most sensitive measurement channels

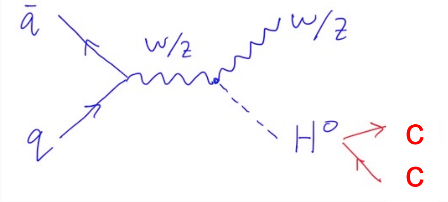
- 20% measurement as of today
- 10% with Run 3 data [coming up!]
- 4% ultimately with HL LHC upgrade

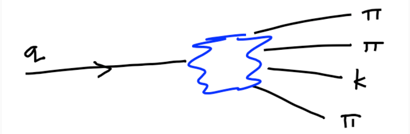
- 5σ discovery significance with ~400 fb^{-1}
  - Will need HL LHC upgrade for discovery



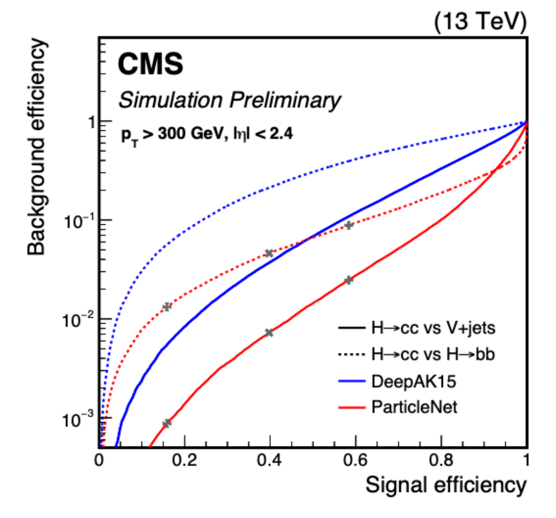
What about Higgs to Charm? (also 2nd Generation)

CMS-PAS-HIG-21-008





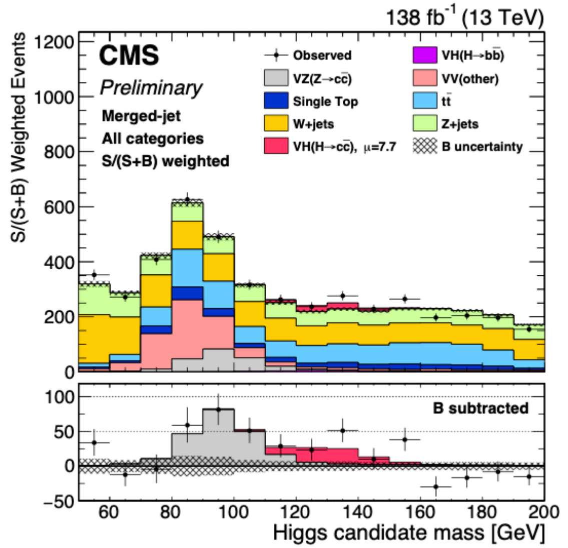
- Larger branching fraction, 2.9%, than μμ
- But more difficult experimentally:
  - We cannot measure a bare quark !
    - Property of the QCD theory of the strong nuclear force
  - Fragments into a collimated “jet” of particles
  - Particles containing a charm quark have a small, but finite lifetime
    - This leads to a tiny, but measurable displacement from the collision point
    - But it is even less than, and polluted with, particles containing b quarks
  - *So this channel is even more challenging than H→bb, which has been discovered*
- Again target the associated VH production mode
  - Use a Deep Neural Net to distinguish charm from b jets and light quarks
  - Can cross check on very similar VZ → Vcc signal !

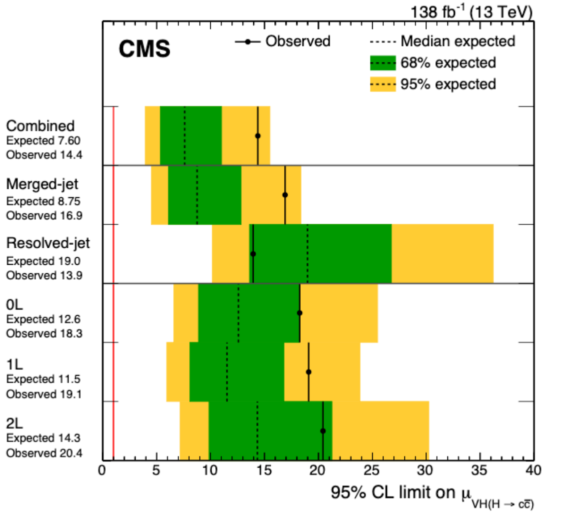


Higgs to Charm

CMS-PAS-HIG-21-008

- Conduct analysis on mutually exclusive channels targeting leptonic decays of the vector bosons:
    - $Z \rightarrow \nu\nu$ (0L) , $W \rightarrow l\nu$ (1L) ,and $Z \rightarrow ll$ (2L)
    - Also distinguish high P_T>300 GeV Higgs decays, which lead to merged jets
- Shown in the mass plot is the weighted combination, S/(S+B), for all categories
- VZ → Vcc signal cross check: $\mu = 1.01 \pm 0.22$
    - First observation of Z→cc in a hadron collider !
- VH→Vcc upper limit :
    - Expected sensitivity is $\mu = 7.6$
    - Observed limit is 14
- H→cc not yet observed, but constraint at 95% CL on Higgs coupling to charm is:
    - $1.1 < |\kappa_c| < 5.5$

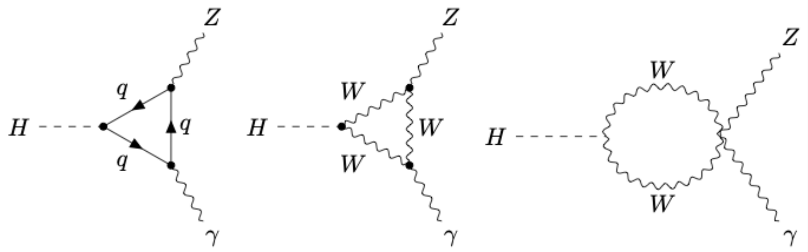




Search for H→Zγ

CMS-PAS-HIG-19-014

- Probes loop diagrams in Higgs decays, with Higgs coupling to quarks and gauge bosons

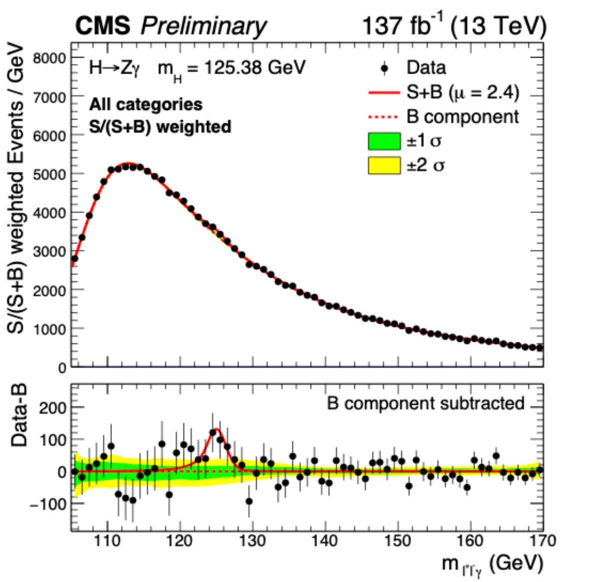


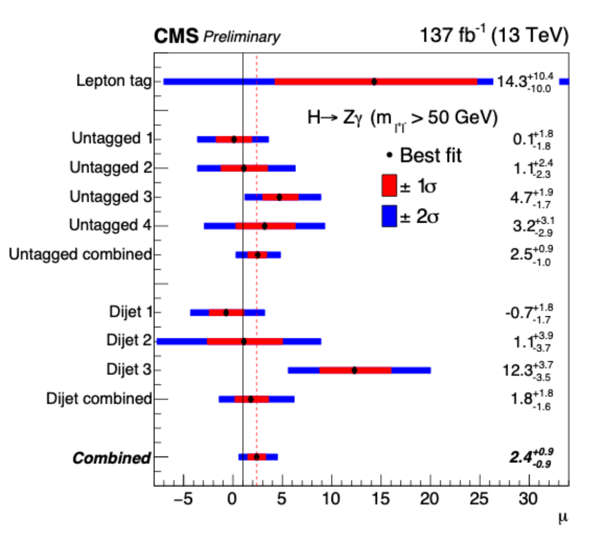
- Branching fraction is small, 0.16%
  - Smaller still if you consider only the clean lepton decays of Z → ee or μμ:
  - **1.0 x 10^{-4}**, half of H→μμ
- Analysis searches for Z→ ee or μμ in conjunction with a photon
- Categorization based on production mode
  - Lepton tag: additional lepton from associated VH production
  - Dijets from VH or VBF production: 3 categories
  - Untagged categories
- Machine learning (BDT) classifiers employed

Search for H→Zγ

CMS-PAS-HIG-19-014

- Intriguing excess in the weighted combination, S/(S+B), for all categories
- At the best Higgs mass measurement by CMS, 125.38 GeV, the observed significance is 2.7 σ (expected 1.2 σ)
    - Not quite 3 σ for evidence
- Combined measurement relative to the SM
    - 2.4 ± 0.9

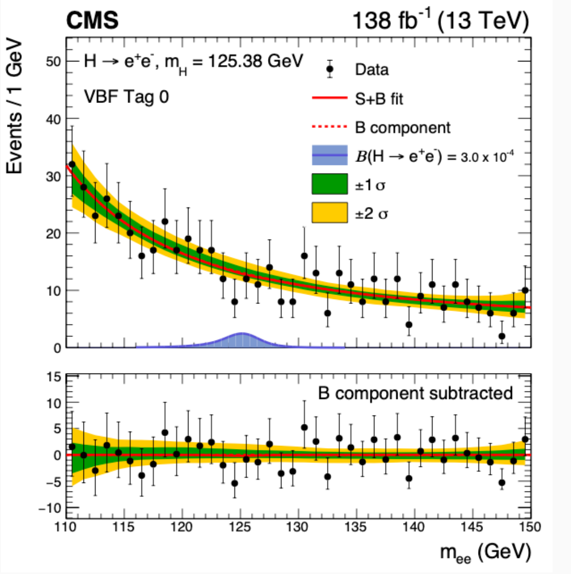




What about Higgs to Electrons? (1st Generation)

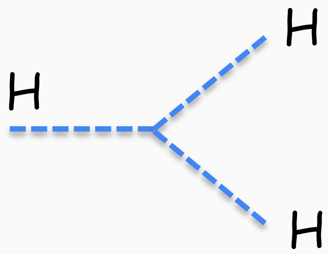
CMS-PAS-HIG-21-015

- Can we establish that the Higgs couples to first generation fermions?
  - i.e. normal matter such as electrons
- The SM Higgs coupling is proportional to mass (BF to mass^2)
  - Electron mass (0.511 MeV) is 207x smaller than the muon mass (105.7 MeV)
  - For H→ee, this implies BF = 5×10^{-9} , > 40,000X smaller than μμ BF
  - The LHC program is not going to provide 40,000X more data… 😞
- So why bother?
  - Be prepared for any surprises: “Who ordered that?!”
- CMS has recently performed a search
  - VBF and inclusive categories using machine learning to optimize discrimination
- No evidence of an excess…
  - Set upper limit: $B(H \rightarrow e^+e^-) < 3.0 \times 10^{-4}$
  - A long way from SM value, but close to constraining that it is less than that for muons



Higgs Self-Coupling Sensitivity

From CERN Yellow Report on (HE)HL LHC
https://arxiv.org/abs/1902.00134



- Aside from the Higgs coupling to other particles, it is also important to measure the shape of the electroweak potential
- Measurement of di-Higgs production probes the self coupling of this field (unique to Higgs)
  - But cross section much smaller than for single Higgs
- Can extract the λ parameter, which gets at the shape of the Higgs potential
  - $V(\phi) = \mu^2 |\phi(\mathbf{x},t)|^2 + \lambda |\phi(\mathbf{x},t)|^4$
- HL LHC can reach 4σ sensitivity, and probe cross section to 40% precision
- Improves further with the larger cross section at higher energy colliders
  - More about those at the end

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

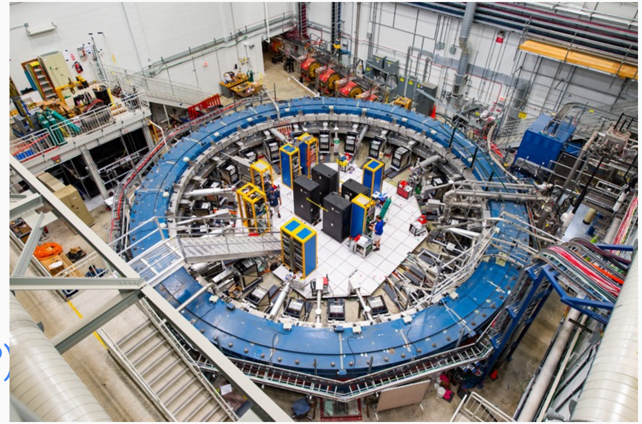
Some Recent Anomalies…

The muon anomalous magnetic moment g−2

Phys. Rev. Lett. 126, 141801

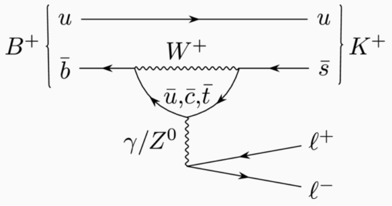
- The Dirac equation, from 1928, is a relativistic quantum mechanical equation for spin-1/2 particles like the electron or muon
  - **Predicted antimatter,** and predicts that the **gyromagnetic ratio *g*** for leptons is precisely 2
    - Where *g* is used, for example, for the potential energy in a magnetic field: $U = -g\mu_B B m_s$
- The quantum field theories of the Standard Model modify this, however, and in fact comprise the most precise theories to date:
  - The exact prediction is $a_\mu = \frac{g_\mu - 2}{2} = 116591810(43) \times 10^{-11}$
- A recent measurement at Fermilab (2021) of g-2 from muon precession confirmed earlier BNL result:
  - The average of these is $a_\mu = \frac{g_\mu - 2}{2} = 116592061(41) \times 10^{-11}$
- While numerically quite remarkable in agreement, they are 4 standard deviations apart!
  - A hint of new physics? (an error/uncertainty in the calculations?)

Muon storage ring at FNAL



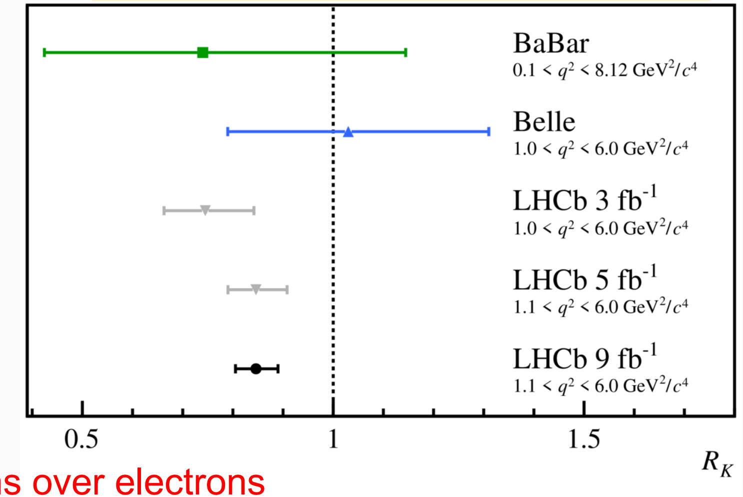
Lepton Flavor Universality (or not!)

- Electroweak interactions involving charged leptons are expected to be universal in the Standard Model
- Evidence has been accumulating that this may not be the case in rare B meson decays (so-called "penguin" diagrams of $b \to s\, \ell^+\ell^-$)
  - SM contributions are tiny and very precise



- Measure the ratio of B meson branching fractions to muons vs. electrons (and a kaon):
  - $R_K = BF(B^+ \to K^+\mu^+\mu^-) / BF(B^+ \to K^+e^+e^-)$
- The LHCb experiment is latest experiment to show some tension with predictions at the 3σ level →
  - Other K channels consistent with this and with SM
- What this implies, if true, may be additional forces or particles beyond those in the SM
  - e.g. leptoquark or Z'

LHCb, Nature Phys. 18 (2022) 3, 277

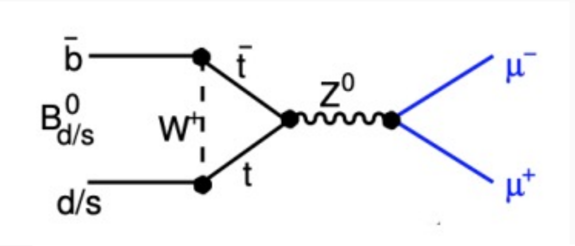


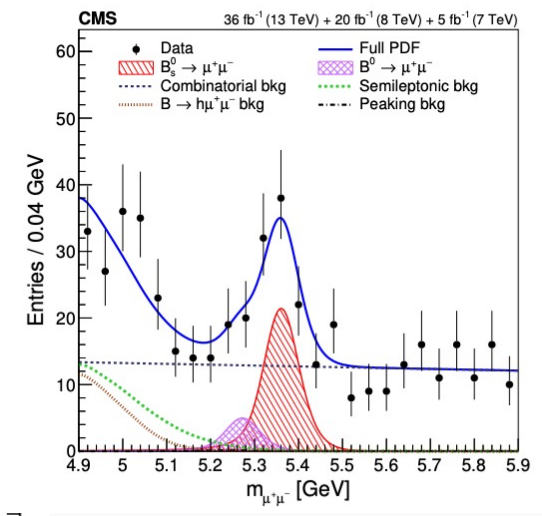
Less coupling to muons over electrons

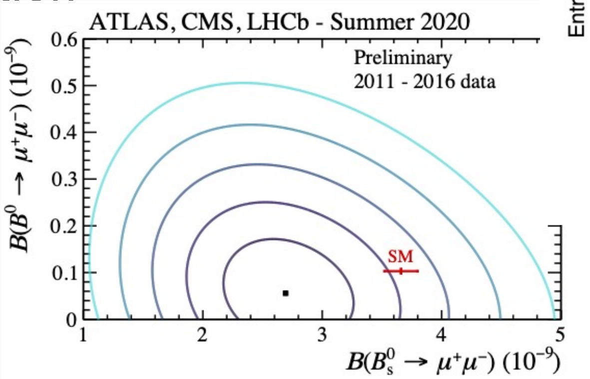
Rare $B_s^0 \to \mu\mu$ Decay

CMS-PAS-BPH-20-003
JHEP 04 (2020) 188

- The same penguin diagram, and physics sensitivity, also applies to other rare B meson decays
  - Just rotate your head… 😉
- The rare decay channel $B_s^0 \to \mu\mu$ has been observed by LHCb, CMS, and ATLAS
  - CMS: $B(B^0_s \to \mu^+\mu^-) = (2.69 \pm 0.36) \times 10^{-9}$
  - CMS significance is 5.6 σ
- Combination of LHCb, CMS, and ATLAS results shows 2.4 σ tension with the SM prediction
  - Smaller than expected to muons 🤔

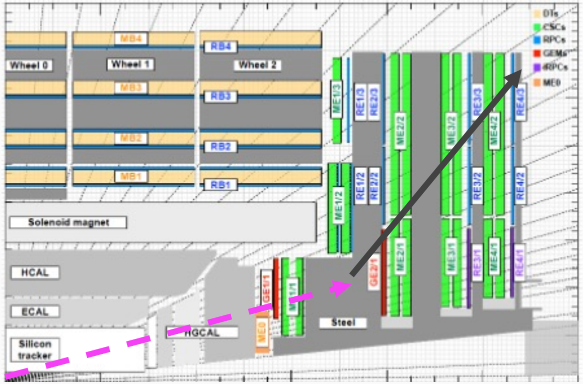




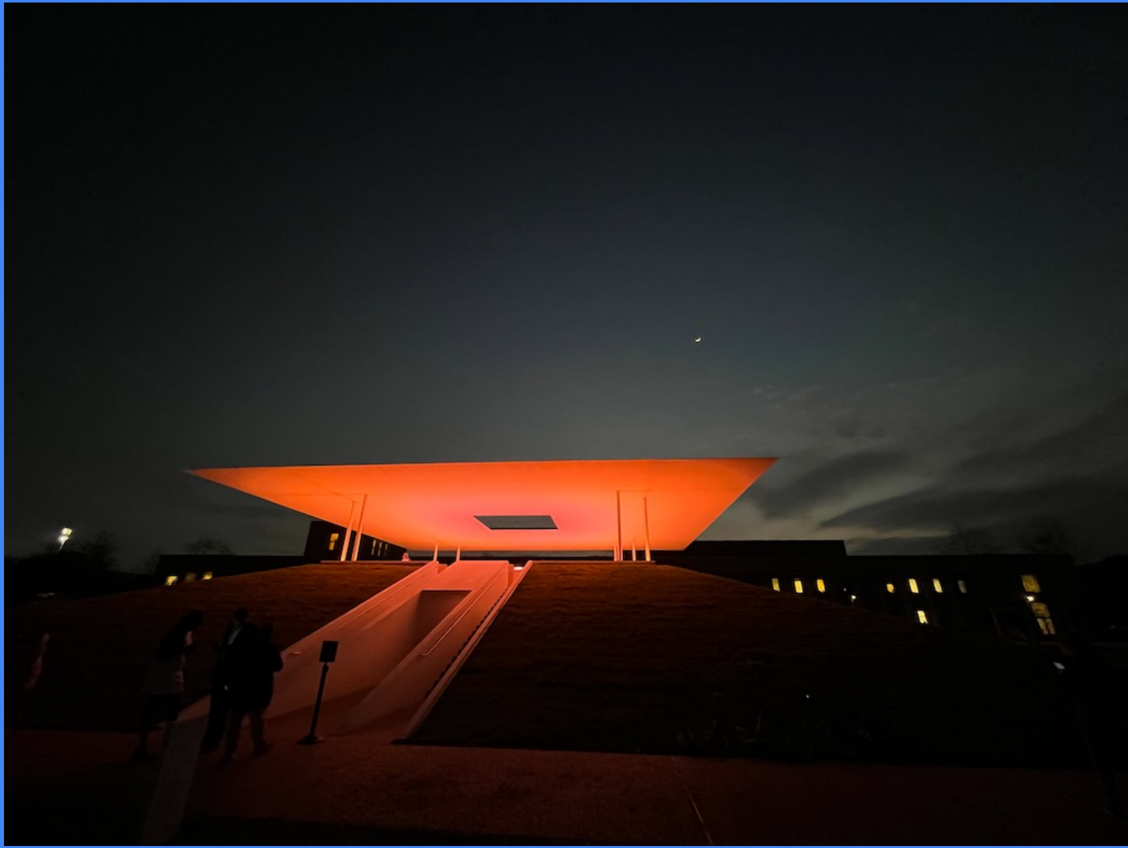


Searches for Long-Lived Particles

- Many extensions to the Standard Model predict new heavy particles with long lifetimes (> 1mm). Like a muon but not a muon…
  - Examples include new long-lived scalar particles coupling to the Higgs boson, and long-lived particles arising from R-parity violating Supersymmetry
- For the upcoming LHC Run 3, CMS will include the ability to identify any "muons" that arise from a decay highly displaced from the collision point (meters), whereas current sensitivity is of order cm's
  - This will open up new acceptance over previously recorded data
  - For the online muon trigger system, we will use for the first time a **neural network** embedded into the FPGAs of the electronic processors
    - Like GPUs, FPGAs have an architecture amenable to NN's



The Future...



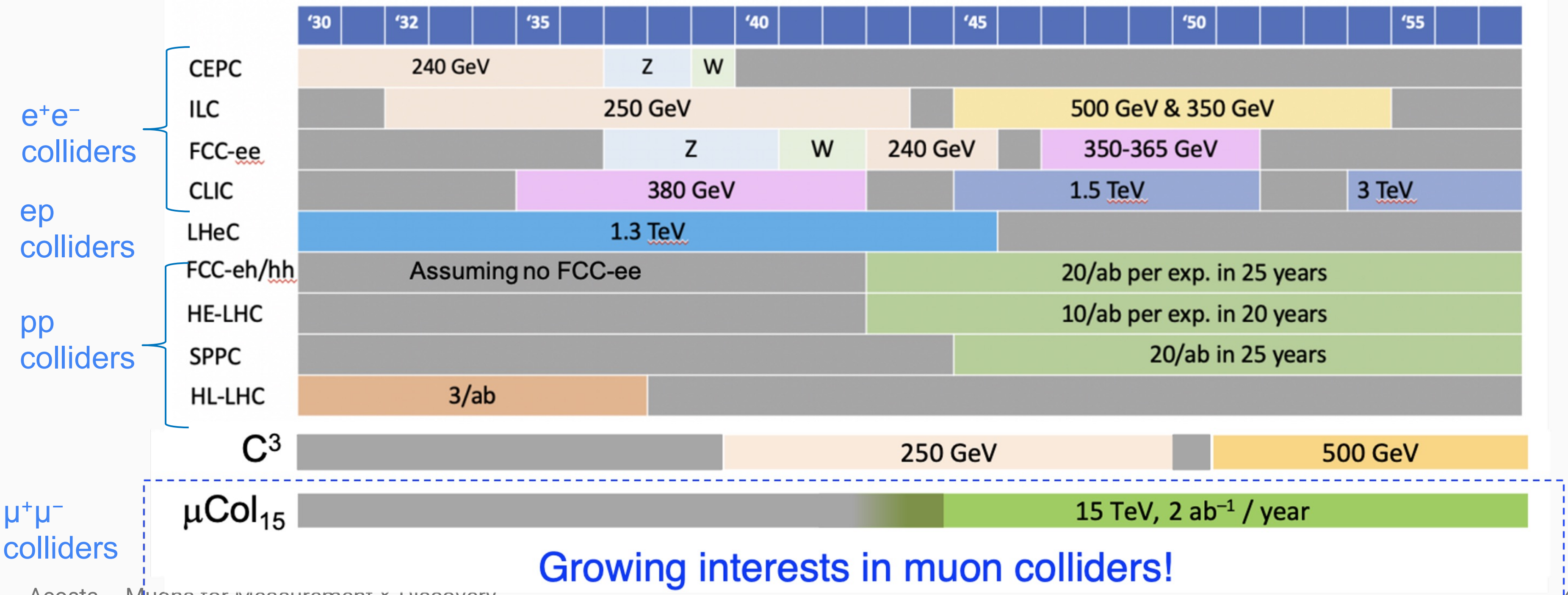
The Future of Particle Physics

- What are the next steps beyond the LHC program to address some of the open questions in particle physics?
  - Higher precision experiments
    - Measure quantities more precisely to test for deviations from theory through higher intensity beams and collisions
    - The indirect, finessed approach
  - Higher energy colliders
    - Pack more energy into collisions to produce more massive particles
    - The brute force, direct approach
  - Or both!
- There is currently an ongoing community exercise in the U.S. to help set the priorities for the future ("Snowmass" process)
  - In some ways we are at a branch point, with many possible directions
    - "Higgs factories" to study Higgs couplings more precisely
    - Energy frontier machines to produce new particles, probe Higgs potential shape

Future of High Energy Physics Energy Frontier

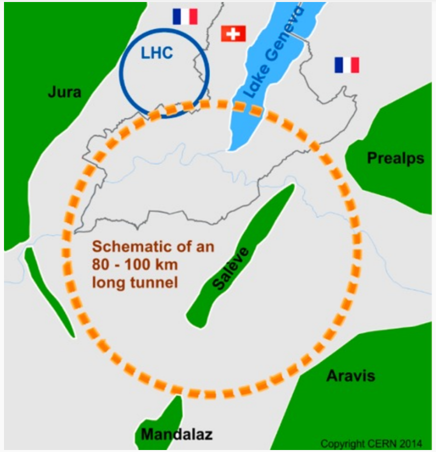
- Many options for Higgs factories and energy frontier machines
- What is an optimal and realistic path forward?

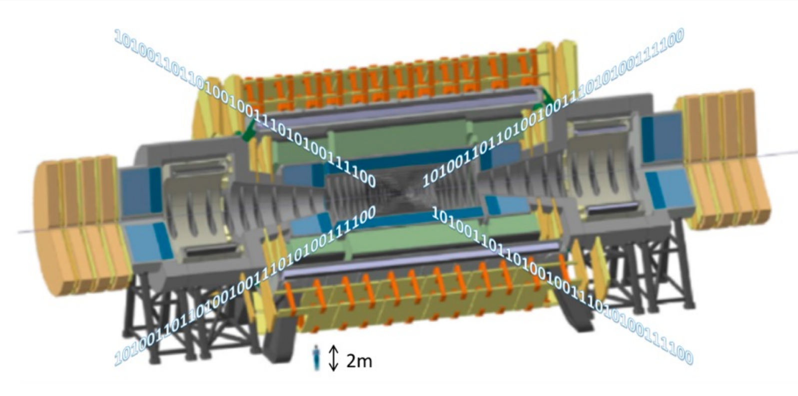
S. Dasu



A Future Circular Collider? (hadrons)

- Scale up the LHC by about a <u>factor 5 or more</u>
- Goals:
  - Higher energy: ~100 TeV
    - Explore the high energy frontier:
      → heavy new particles
  - Higher luminosity: 5–30 x 10^{34} Hz/cm^2
    - High precision, e.g. Higgs boson couplings
- Challenges:
  - 100 km ring
    - Though the SSC in Texas would have been that size...
  - 1000 pp collisions per beam crossing
  - Higher radiation levels in tracking volume
  - Huge data rates from detectors

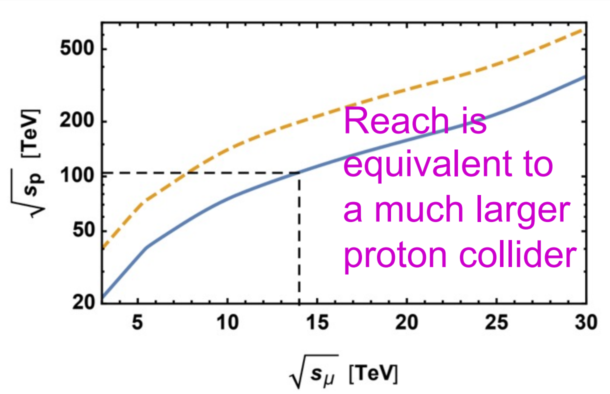


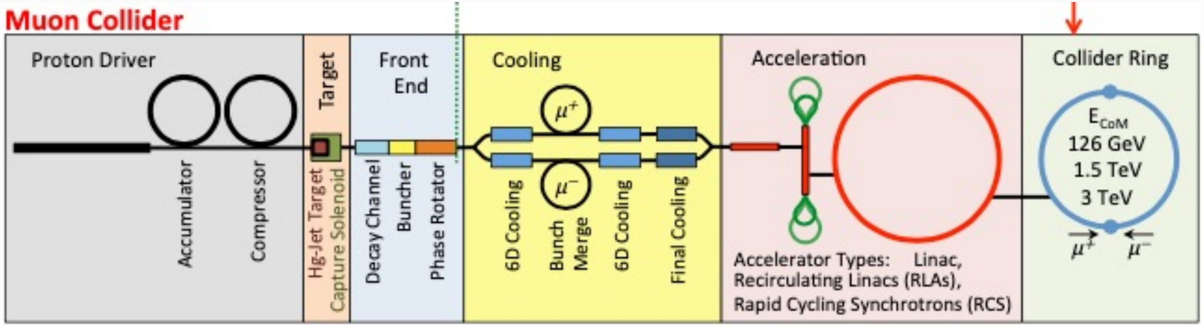


A Muon Collider?

- A more compact and innovative facility to incorporate the advantages of a high precision lepton collider and an energy frontier machine
  - $\mu^+\mu^-$ annihilation uses all of the beam energy in a collision, whereas quark/gluon collisions use only a fraction of the proton beam energies
  - Muons also radiate away much less energy than an e^+e^- collider, and can be smaller than proton colliders for equivalent reach
- But it's a race against time to produce, cool, and accelerate muons !
  - Recall that muons decay in 2.2μs
  - Significant extension to higher energy and intensity than g-2 storage ring

Needs R&D





Higgs Boson Sensitivity @ Muon Collider

arXiv:2203.07261

Table 2: 68% probability sensitivity to modifications on the Higgs coupling from the κ fit, assuming no BSM contributions to the Higgs width.

Coupling	HL-LHC	HL-LHC + 125 GeV μ-coll. 5 / 20 fb^{-1}	HL-LHC + 3 TeV μ-coll. 1 ab^{-1}	HL-LHC + 10 TeV μ-coll. 10 ab^{-1}	HL-LHC + 10 TeV μ-coll. + e^+e^- H fact (240/365 GeV)
κ_W [%]	1.7	1.3 / 0.9	0.4	0.1	0.1
κ_Z [%]	1.5	1.3 / 1.0	0.9	0.4	0.1
κ_g [%]	2.3	1.7 / 1.4	1.4	0.7	0.6
κ_γ [%]	1.9	1.6 / 1.5	1.3	0.8	0.8
κ_c [%]	-	12 / 5.9	7.4	2.3	1.1
κ_b [%]	3.6	1.6 / 1.0	0.9	0.4	0.4
κ_μ [%]	4.6	0.6 / 0.3	4.3	3.4	3.2
κ_τ [%]	1.9	1.4 / 1.1	1.2	0.6	0.4
$\kappa_t^\dagger$ [%]	3.3	3.1 / 3.1	3.1	3.1	3.1
$\kappa_{Z\gamma}^\dagger$ [%]	10	10 / 10	10	10	10
$\Gamma_H^\ddagger$ [%]	5.3	2.7 / 1.7	1.5	0.5	0.4

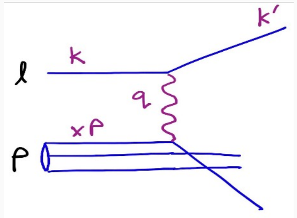
† No input used for μ collider.
‡ Prediction assuming only SM Higgs decay channels. Not a free parameter in the fits.

- International Muon Collider Collaboration study
- Need a lepton collider to measure Higgs coupling to charm quarks
  - Not really possible at LHC !
- Improves precision of many measurements to sub-percent
- Higgs self coupling also possible to measure
  - $>10^4$ HH pairs in 10 ab^{-1}

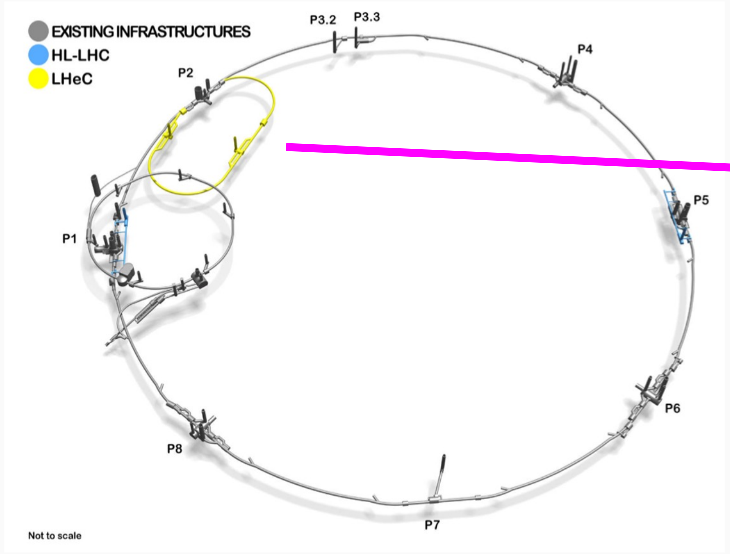
PRD 103, 013002 (2021)

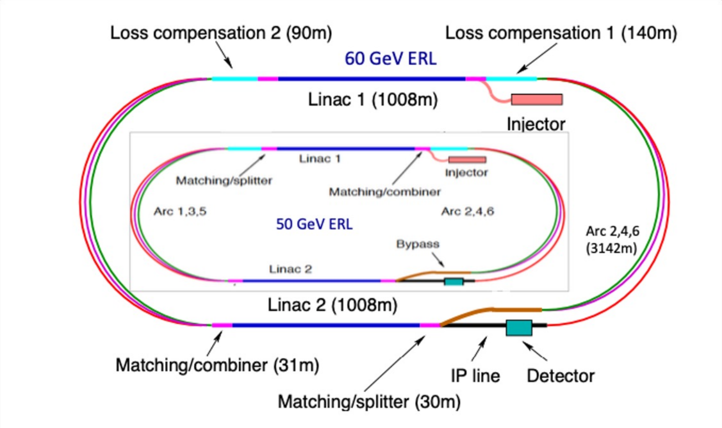
A Hybrid Collider: The Large Hadron-Electron Collider at CERN

LHeC: arXiv:2007.14491

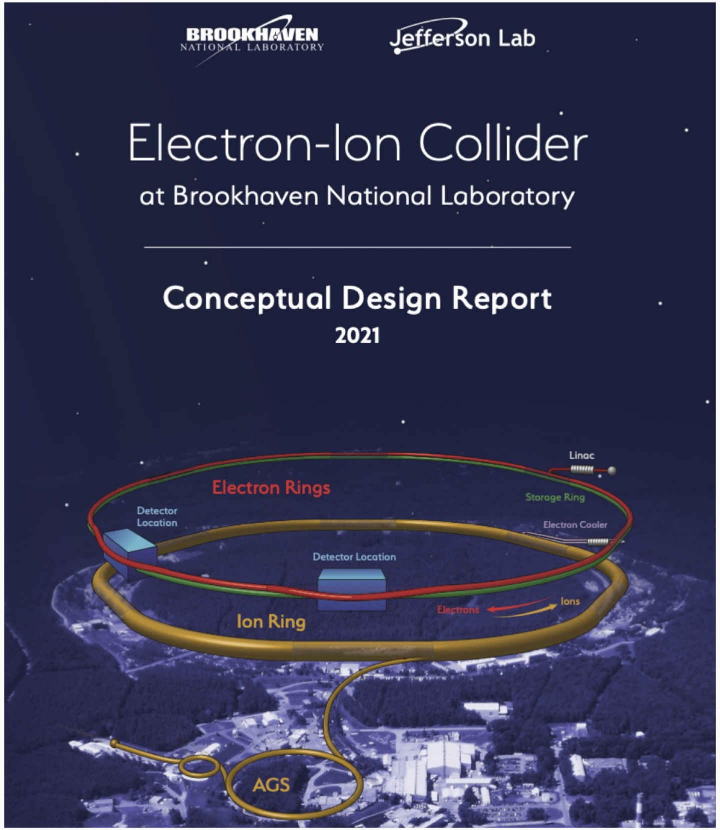


- A proposed next generation Deep Inelastic Scattering experiment to study nuclear structure and more
- LHeC: 50 – 60 GeV e^- on 7 TeV p ($\sqrt{s}$ = 1.2–1.3 TeV)
    - Two oppositely directed linacs and 3 arcs
    - Two design options: 50 GeV (smaller) vs. 60 GeV (larger, more expensive)





The Electron-Ion Collider (EIC) at BNL



A similar, but lower energy facility approved by the U.S. nuclear physics program. Science to begin in 2030s

EIC Conceptual Design Report recently released and project approved. Initial detector design also selected.

Salient points:

- Electron beam energy up to 18 GeV
- Hadron beam energy up to 275 GeV
- $\sqrt{s}$ = 20 -- 140 GeV
- Luminosity 10^{33} -- 10^{34} Hz/cm^2
- Polarized electron, proton and ion beams (any)

But what if we changed leptons? 🤔

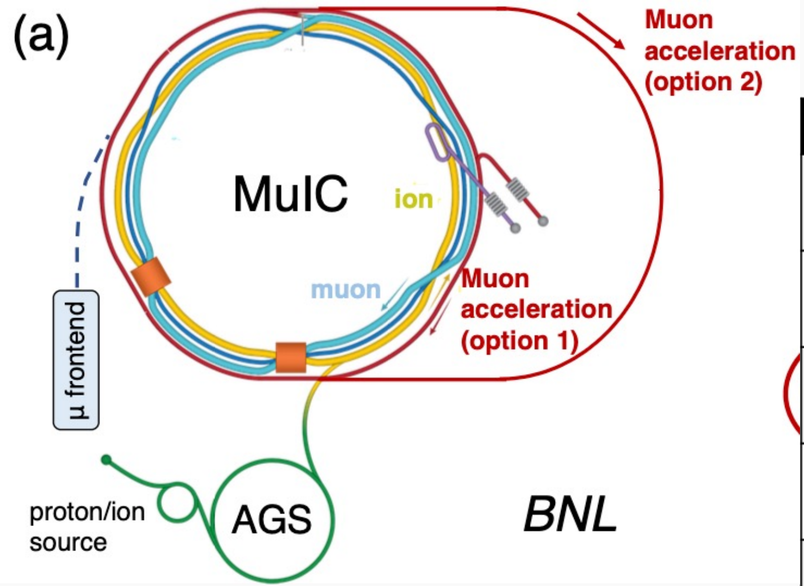
Physics goals:

- ep and eN deep inelastic scattering
- Nucleon spin structure
- Gluon saturation scale (Q_S)

A Muon-Ion Collider at BNL?

Acosta and Li, NIM A 1027 (2022) 166334

→ Replace e by μ beam at EIC



Bending radius of RHIC tunnel: **r = 290m**

Achievable muon beam energy: **0.3Br**

Parameter	1 (aggressive)	2 (realistic)	3 (conservative)
Muon energy (TeV)	1.39	0.96	0.73
Muon bending magnets (T)	16 (FCC)	11 (HL-LHC)	8.4 (LHC)
Muon bending radius (m)		290	
Proton (Au) energy (TeV)		0.275 (0.11/nucleon)	
CoM energy (TeV)	1.24 (0.78)	1.03 (0.65)	0.9 (0.57)

$\sqrt{s}$ = 1 TeV !

7-8X increase over EIC energy

A Muon-Ion Collider? Who Ordered That?

Probe a **new energy scale** and nucleon momentum fraction in Deep Inelastic Scattering using a relatively compact machine

- $\sqrt{s} \sim 1$ TeV or more
- Q^2 up to 10^6 GeV^2
- x as low as 10^{-6}

Well beyond the EIC, matches that of the proposed LHeC

Provides a science case for a TeV muon storage ring as a demonstrator toward a multi-TeV μ+μ- collider

- QCD and hadron/nucleon structure in new regimes
- Higgs, Top, and Beyond Standard Model (particularly with LFV with muons)

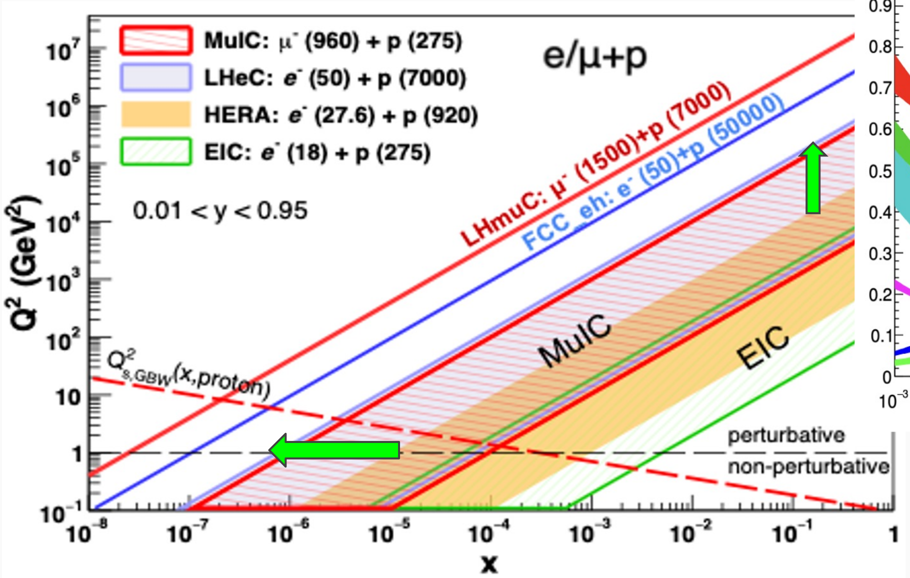
Facilitate the **collaboration of the nuclear and particle physics communities** around an innovative and forward-looking machine

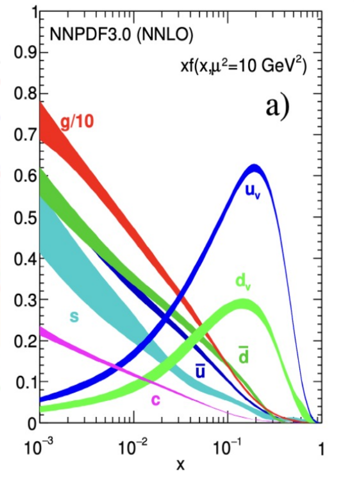
Re-use existing facilities at BNL (MuIC as an upgrade to the EIC)

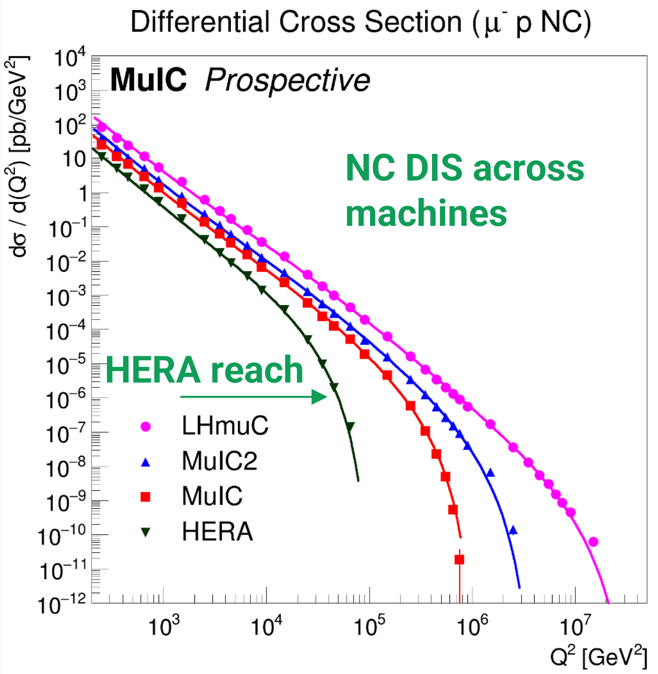
Broad science program helps share costs, and re-use helps economize

DIS Reach in x and Q^2 with MuIC

Acosta, Barberis, Hurley, Li, Miguel, Wood, Zuo
arXiv:2203.06258 (2022)





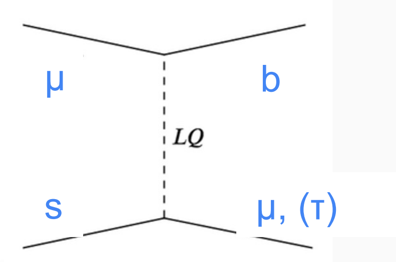


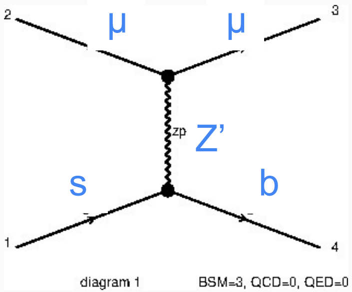
- Everything above gold (HERA) region is unexplored
- Measure expected gluon saturation at low momentum fractions x
- Test if quarks have any substructure at highest Q^2 (resolving power)
- Data useful also for precision physics at a future large hadron collider (FCC-hh)

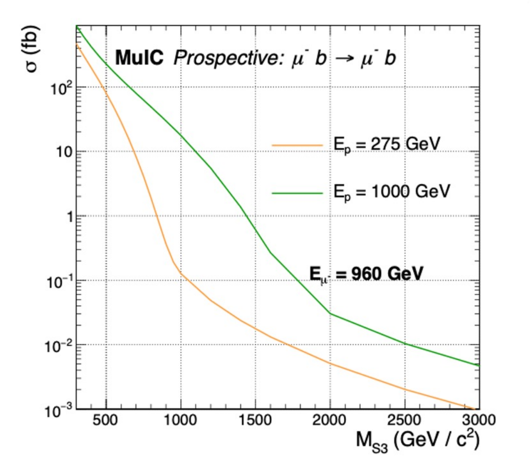
MuIC: Leptoquarks & Z’ Sensitivity

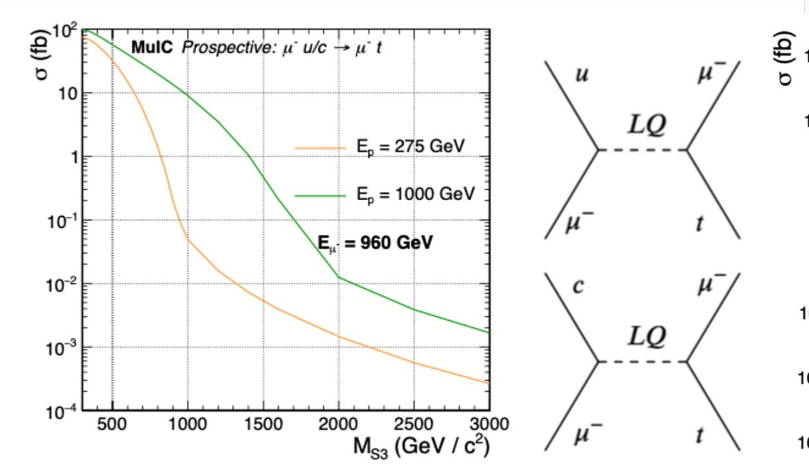
Acosta, Barberis, Hurley, Li, Miguel, Wood, Zuo
arXiv:2203.06258 (2022)

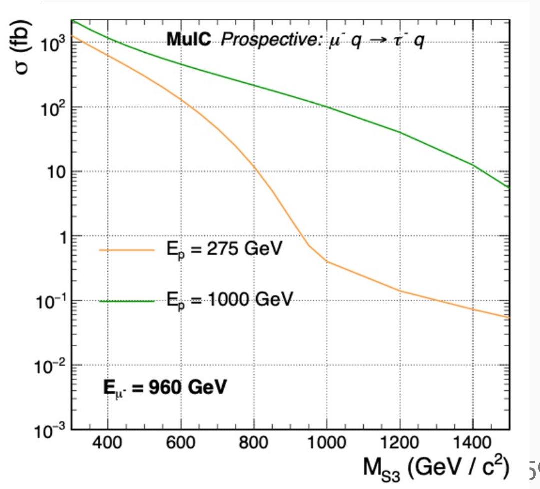
- Studies focusing on LQ and Z’ models inspired by B and μ anomalies
- Including a LFV case μ→τ





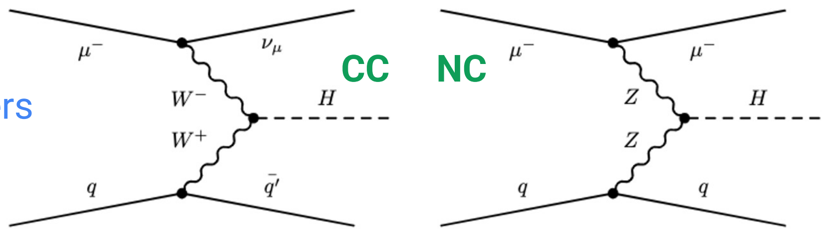




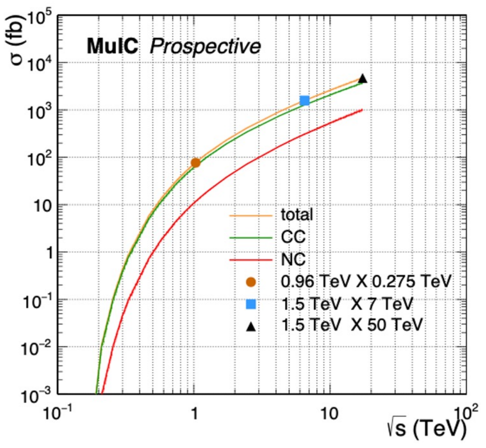


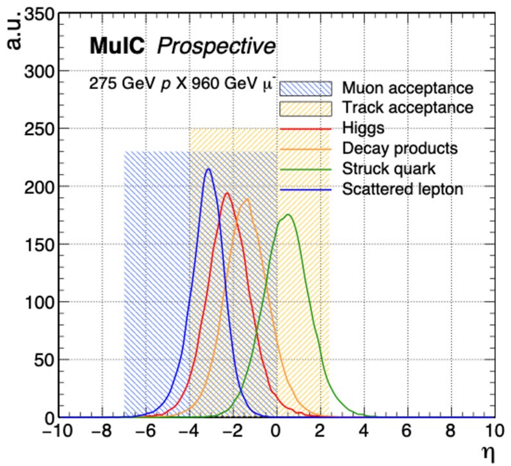
Higgs Physics with MuIC

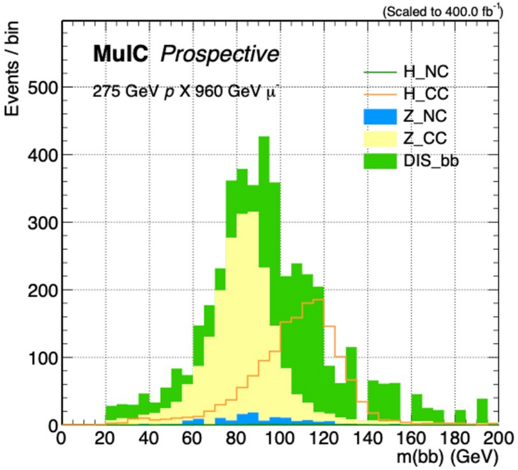
Acosta, Barberis, Hurley, Li, Miguel, Wood, Zuo
arXiv:2203.06258 (2022)



- VBF mode
  - Cross section comparable to LHeC and $\mu^+\mu^-$ colliders
- Acceptance
  - All final state objects, other than muon, are **in central region of detector** (in contrast to LHeC)
  - 3 jets, muon veto, MET, Higgs p_T all help reduce DIS bb bkgnd
  - **H→bb: S/B ~ 1, expect ~900 Hbb in 400 fb^{-1} (10y) @ 1TeV MuIC** (expect 10x more at LHmuC)







Summary & Outlook

- Higgs boson
  - Evidence for the rare decay to muons
  - On the verge for the Zγ channel
  - Constraints on couplings to the charm quark and to electrons
  - Measurements of the Higgs self coupling requires HI LHC
- CMS and other experiments show some potential anomalous couplings involving muons
- A high energy muon collider and/or muon-ion collider have interesting science programs
- Future novel collider and detector facilities, no matter which way we go, will have challenges that need the next generation of scientists (i.e. you!)

Acknowledgements

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