Comments on the
Intersections of Particle* and Nuclear Physics

This is NOT a recent or NEW phenomenon !!

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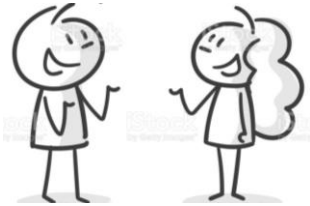
*** HEP is the DOE program, but it doesn't fully capture the mission**

"Hello, I'm funded by DOE HEP"

"Nice to meet you, I'm funded by DOE NP"

"Can we work together on something? Hmmm… "



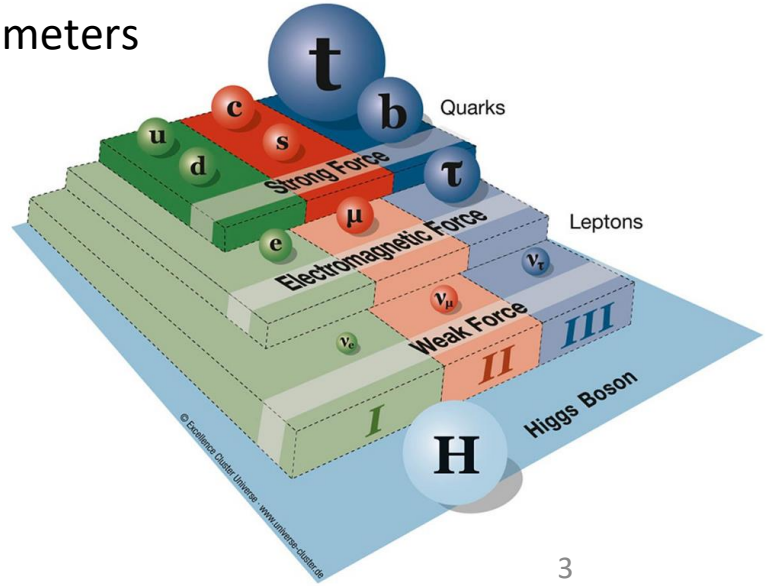
Many organizations deal with the <u>benefits</u> and <u>drawbacks</u> of "Silos". In U.S. HEP / NP there are generally rather clear distinctions of what each program supports. But, fortunately some boundaries are fuzzy

A common mission … “Discovery”

- **Completeness of the Standard Model** --
  - This passion largely drives the field
  - You know the deficiencies …
  - There are many “solutions” suggested, just none are proven

- ***Establishing* the Standard Model parameters**
  - Masses M_Z, M_W !!!, M_H, m_b, m_t, m_e, m_u, m_ν !! …
  - Couplings: a_{QED}, a_{Strong}, G_F, G_{grav}
  - Structure of interactions $SU(3)_C x SU(2)_L x U(1)_Y$
  - Neutrino properties
  - #Generations; Mixing angles, Lepton number and flavor, CP violation parameters

- **The structures of hadrons**
  - Exotic quark and gluon combinations
  - The proton mass and spin
  - The possible QCD phase transition and early universe physics



The Standard Model and Beyond

Tools

Examples

The main technique: Aim Collider at the Standard Model and try to crack it

Warning: evidence of the unbreachable castle …

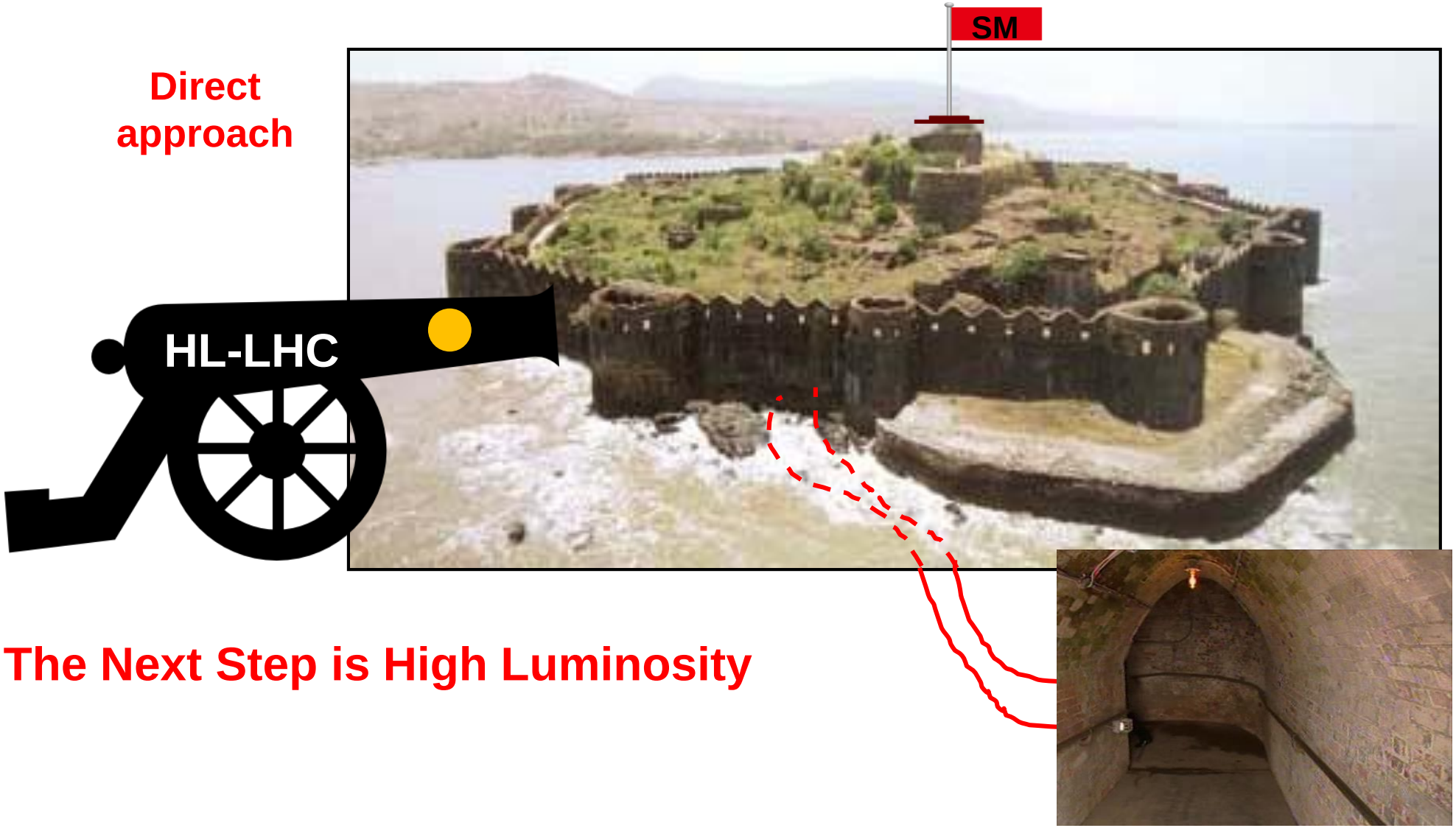
Direct approach

Coming up empty

With apologies, I created this for the 2013 Zurich Latsis Symposium on “The state of particle physics at the end of LHC's first run”

What else can we do?

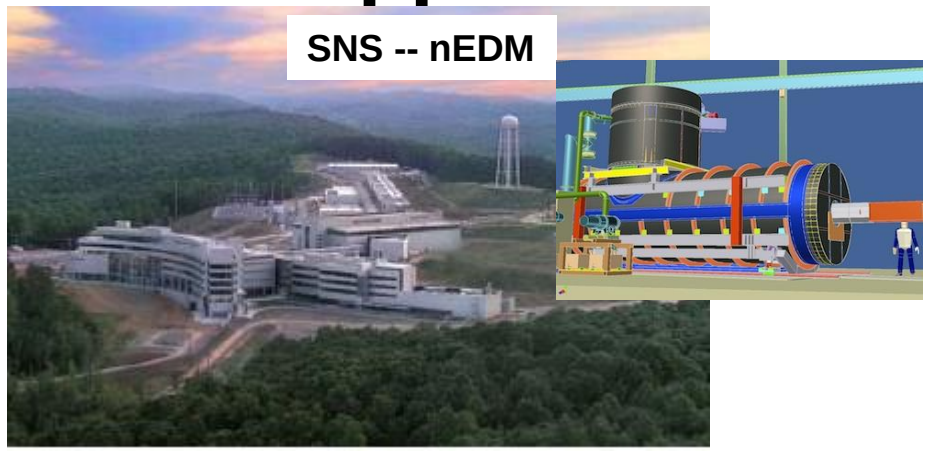
Direct approach

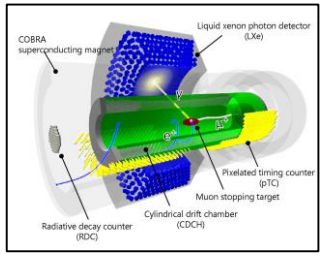


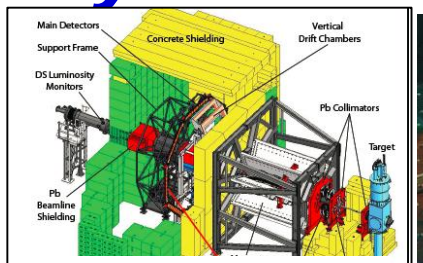
The Next Step is High Luminosity

But, there is also an indirect approach: "Quantum tunneling"

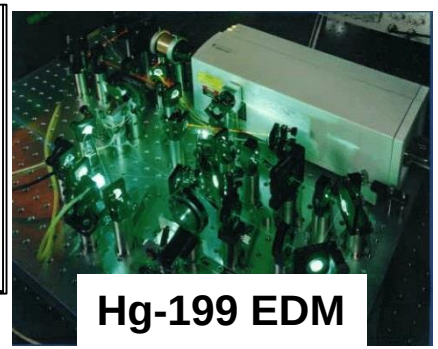
Indirect approach: *Precision and Intensity*





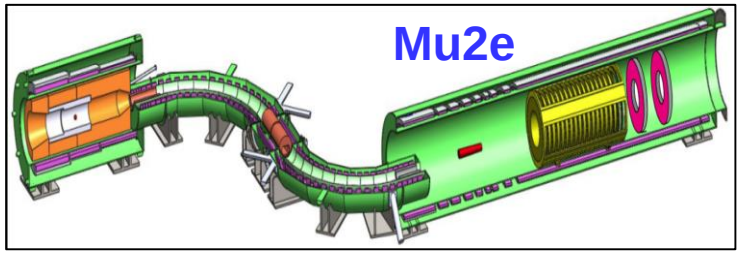


JLab - Qweak



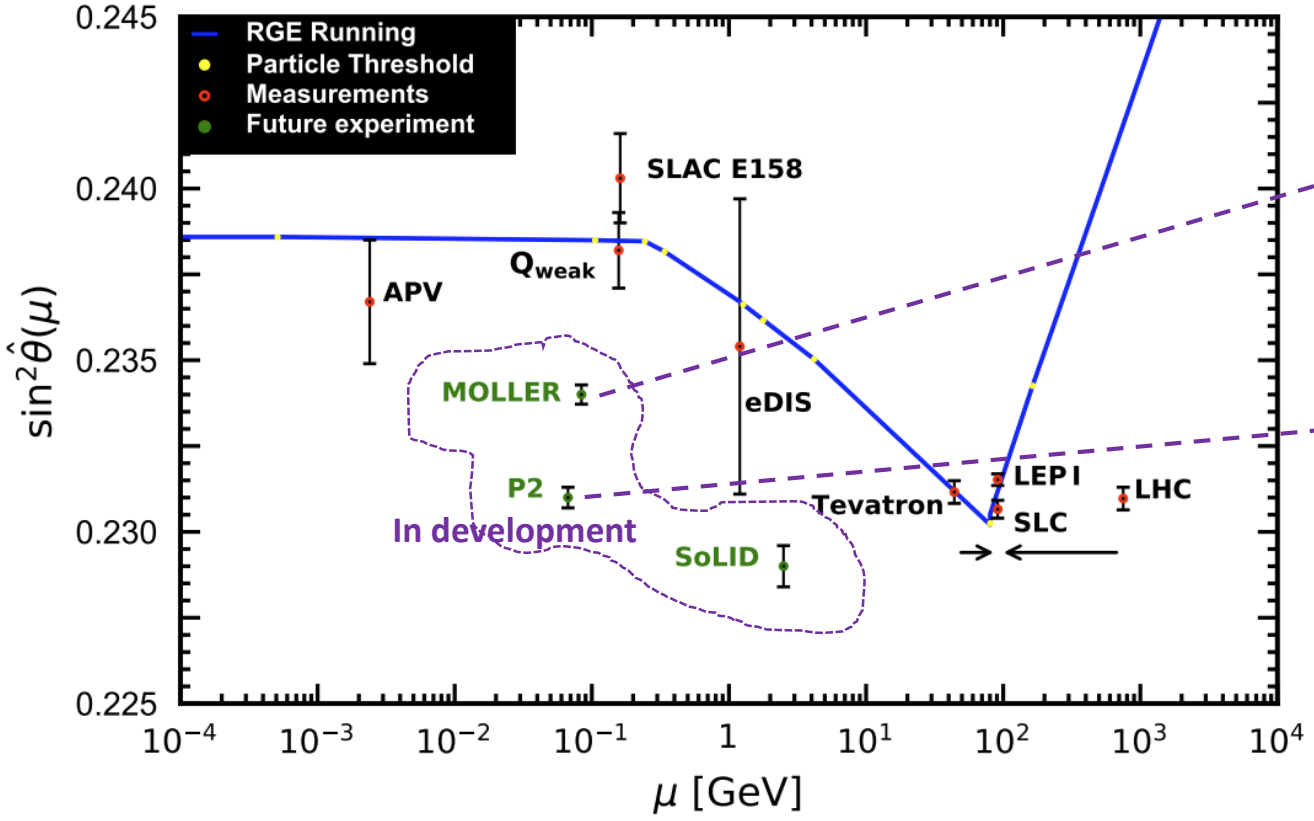
- Is lepton number conserved?
  - MEG, Mu2e, Mu3e
- Origin of the Matter – Antimatter asymmetry in the universe
  - EDMs of neutrons, atoms, molecules …
  - Are neutrinos their own antiparticles? $0\nu\beta\beta$ efforts
- What is Dark Matter !
  - WIMP searches
  - Axion searches
- Are there deviations from SM predictions?
  - Muon g-2
  - Parity Violating Electron Scattering … running of $\sin^2\theta_W$
  - Tests of the CKM mixing matrix for unitarity
  - Decay symmetries of leptons
- Atomic physics tests with incredible precision (too many to list)

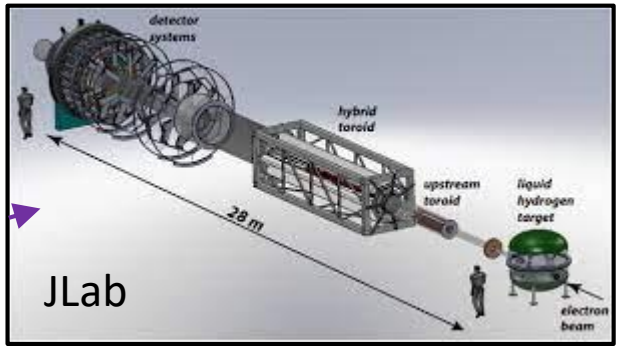
Underground - LUX

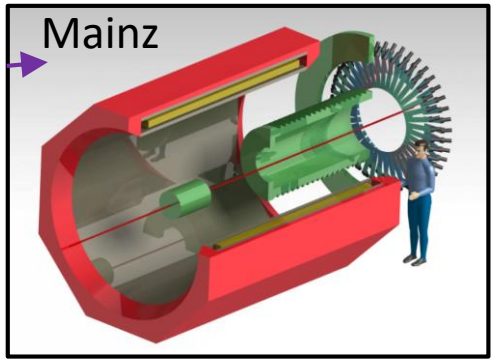


Where our communities contribute independently toward common goals.

Example 1: Running of $\sin^2\theta_W$





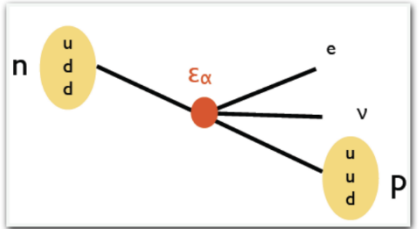


Example 2: Search for Weak Interaction chirality-flipping (Scalar / Tensor) currents

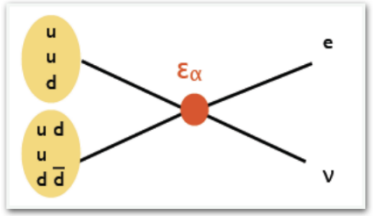
- Precision beta decays of 6-He, 19-Ne, 14-O using modern techniques like CRES (same as Project 8 ν mass)

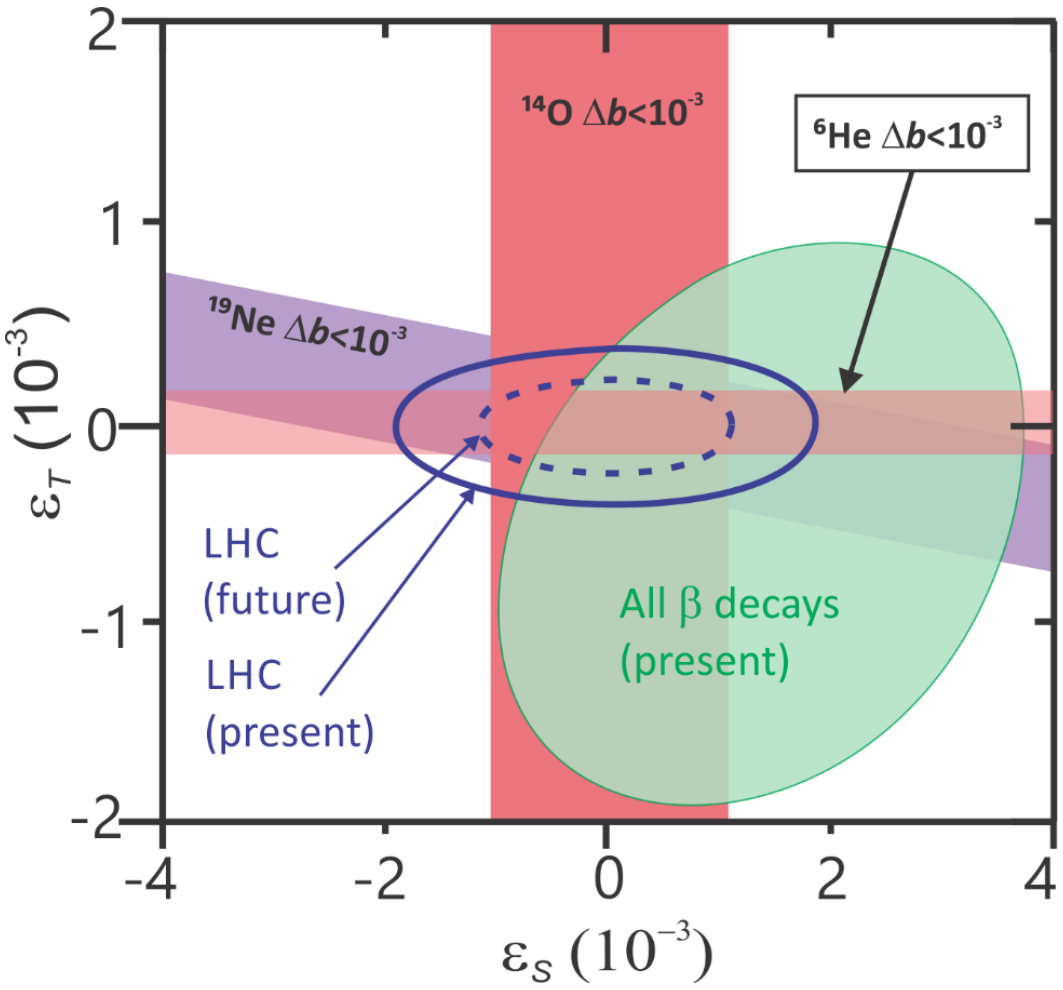
- If New Physics is at scale Λ > TeV, EFT framework at LHC can produce bounds on the effective couplings ε_α in the process pp → eν + X
  - No excess events in transverse mass distribution set bounds

n → p e ν



LHC: pp → e ν + X

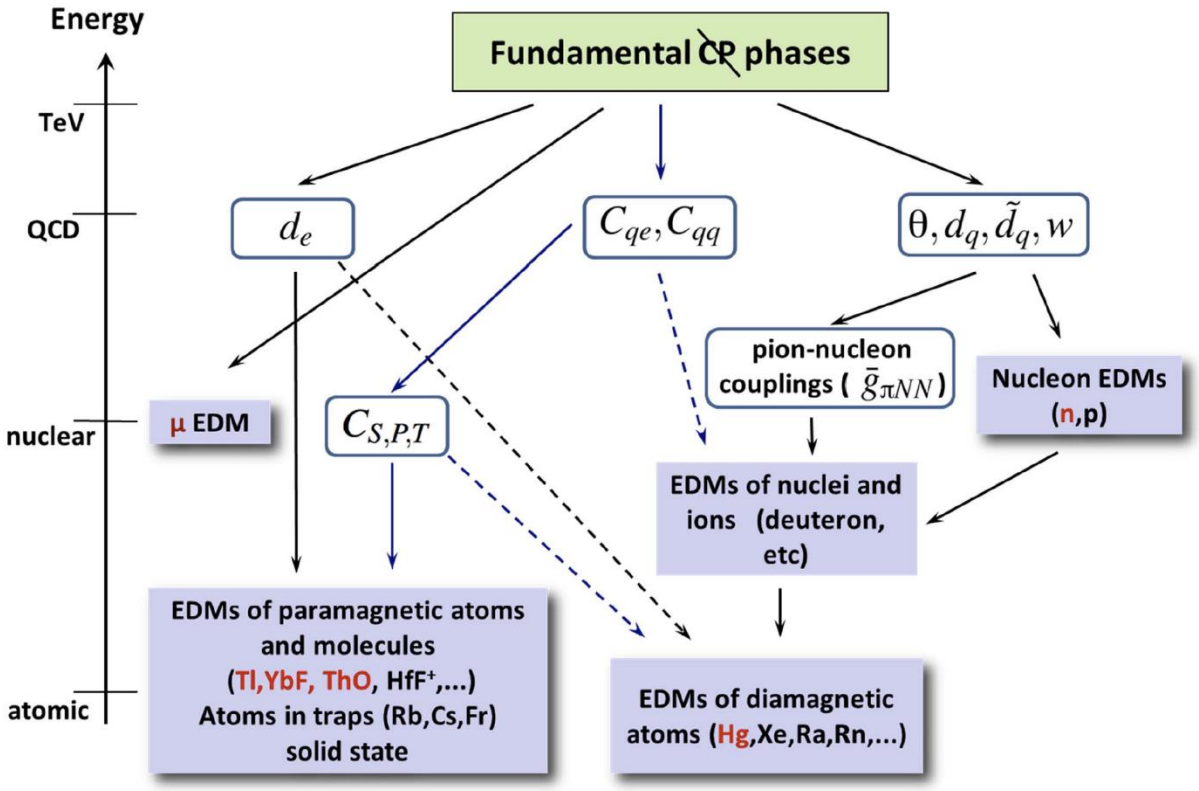


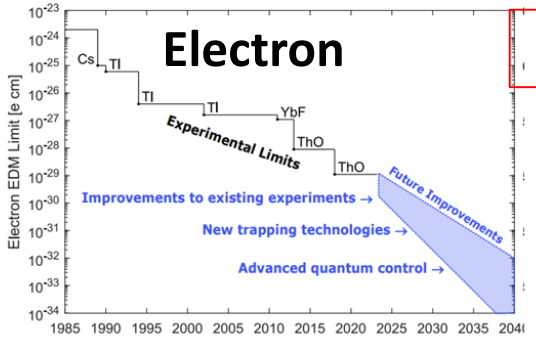


See, for example: V. Cirigliano, S. Gardner, and B. R. Holstein, Beta decays and non-standard interactions in the LHC era, Progress in Particle and Nuclear Physics 71, 93 (2013).

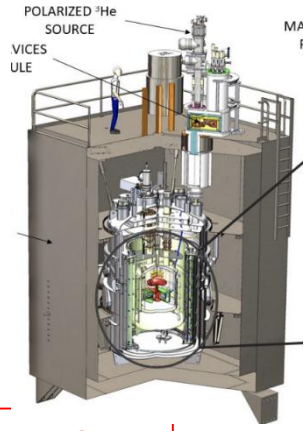
Example 3: EDMs and impact on CPV, and thus, baryogenesis

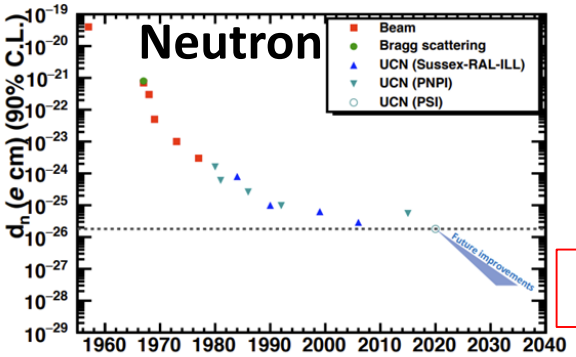
- Free of SM background
- Probes high scales ~ $10^{2\text{-}3}$ TeV
- Multiple systems required to uncover the fundamental physics



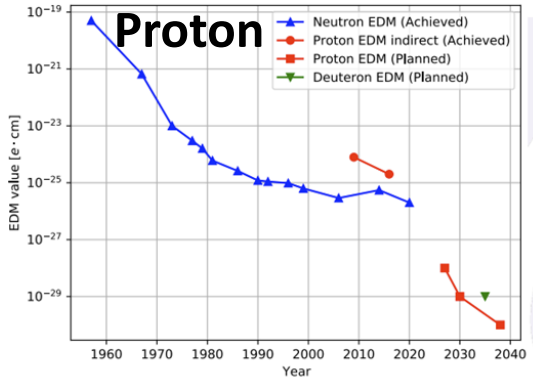


AMO





Nuclear



"HEP"

See also, slides by T. Bhattacharya, O. Kim, N. Hutzler, M. Safronova and others for progress and plans

Example 4: The new Neutrino properties

- "HEP" focus
  - Neutrinos from accelerators
    - Oscillation physics
    - Mass hierarchy
    - Sterile neutrinos
    - CP and electroweak physics
    - COHERENT *nuclear* scattering
  - Neutrinos from reactors
    - Oscillations
    - Sterile neutrinos
- "Nuclear" physics focus
  - Neutrinos from the sun
    - CNO cycle; oscillations
  - $0\nu\beta\beta$
    - **LEPTON NUMBER VIOLATION**
  - **Neutrino absolute mass**
  - Short baseline cross sections

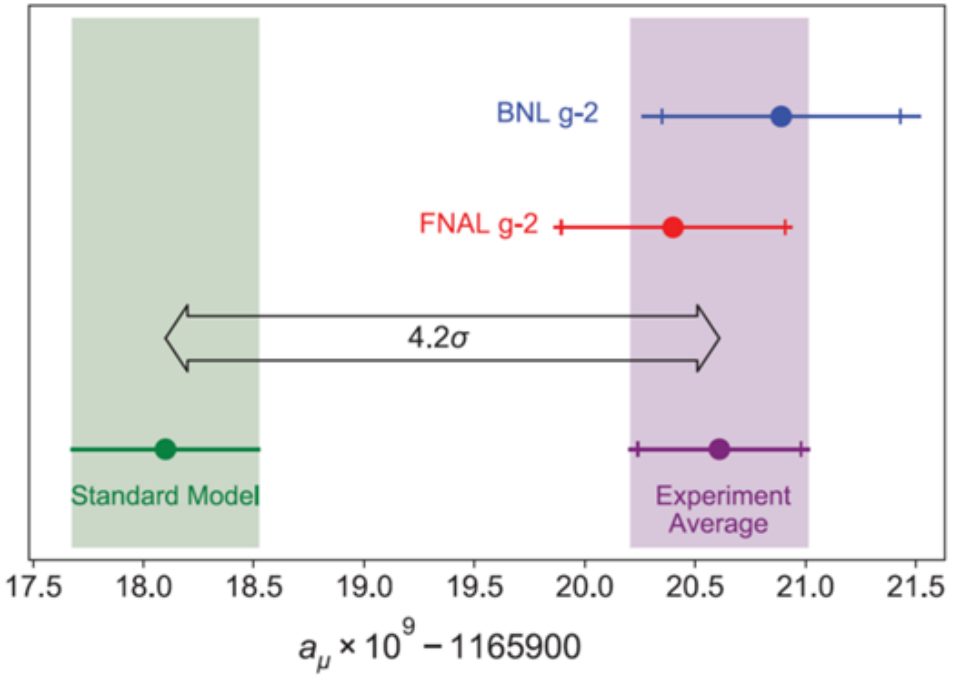
Who can work on what ?

- These are clearly some of the most compelling questions we know how to answer.
- They will "establish" the (new) SM (for ν)
- But also provide exciting opportunities for New Physics discovery

MANY Sessions here at Snowmass (215 occurrences of "neutrino" in the program) !

An Example having significant collaboration with a common goal: The Muon Anomalous Magnetic Moment

- When 200 physicists combine for 1 Number
  - U.S. DOE & International HEP groups
  - U.S. Nuclear Physics groups: DOE and NSF
  - U.S. "Atomic" physicists
  - U.S. Accelerator / Storage Ring physicists
  - Italian "Optical" physicists
- + Nuclear & particle theory collaboration
  - Lattice and hadronic models
- + e^+e^- absolute cross section data input from Babar, KLOE, BES, BELLE, SND, ...



The results published in 4 papers representing the field and communities

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 044002 (2021)

PR-AB Beam Dynamics Corrections

Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

T. Albahri,[38] A
E. Barlas-Yucel,
P. Bloom,[21] J.
B. C. K. Casey,[7]
R. Chislett
J. D. Crnkovic,[3,36,
R. Di Stefano,[10,
R. Fatemi,[37] C. Fer
E. Frlež,[45] N. S. F
A. Garcia,[46] J. G
W. Gohn,[37]
T. Halewoo
D. W. Hertzog,[4]
R. Hong,[1,37] M. Ia
J. Kaspar,[46] D.
Z. Khechadoori
B. King,[38,a] N. Ki
J. LaBounty
I. Logashenko,[4,g]
B. MacCoy,[46] R
S. Miozzi,[12] W. M
S. Park,[5] G. Pau
D. Počanić,[45] N. P
E. Ramberg,[7]
C. Schlesier,[36] A. S
D. Stöckinger,[27]
G. Sweetmor
A. E. Tewsle
E. Valetov,

[5]*Center for*

[5]*Center for A*

PHYSICAL REVIEW A **103,** 042208 (2021)

Featured in Physics

PRA Proton Precession

Magnetic-field measurement and analysis for the Muon $g-2$ Experiment at Fermilab

T. Albahri,[39] A. Anas
F. Bedeschi,[11] M. B
G. Cantatore,[13,34] R. M.
R. Chislett,[36] J. Ch
S. Dabagov,[9,‖] P.
V. N. Duginov,[17] M
A. Fioretti,[11,14] D. Flay,[4]
L. K. Gibbons,[6] A. C
F. Gray,[24] S. Haciomerog
G. Hesketh,[36] A. Hib
P. Kammel,[48] M. Karg
K. S. Khaw,[27,26,48,§] Z.
N. Kinnaird,[2] E. Kraegel
D. Li,[26,¶] L. Li,[26,§]
B. MacCoy,[48] R. Ma
J. Mott,[2,7] A. Nath,
K. T. Pitts,[37] B. Plaster
E. Ramberg,[7] J. L
Y. K. Semertzidis,[5,18]
D. Stratakis,[7] T. Stu
T. Teubner,[39] A. E.
D. Vasilkova,[36] G. Ve

PHYSICAL REVIEW D **103,** 072002 (2021)

Editors' Suggestion Featured in Physics

PRD Muon Precession

Measurement of the anomalous precession frequency of the muon in the Fermilab Muon $g-2$ Experiment

T. Albahri,[38] A. Anastasi,[11,a] A. Ani
T. Barrett,[6] A. Basti,[11,31] F. B
E. Bottalico,[11,31] T. Bowcock,[38]
S. P. Chang,[18,5] A. Chapelain,[6] S. C
J. D. Crnkovic,[3,36,42] S. Dabagov,[9]
A. Driutti,[34,13,37] V. N. Duginov,
A. T. Fienberg,[46] A. Fioretti,[11,14] D.
S. Ganguly,[36,7] A. Garcia,[46] J. Geo
T. Gorringe,[37] J. Grange,[1,41] S. G
J. Hempstead,[46] A. T. Herrod,[38,d] D.
R. Hong,[1,37] M. Iacovacci,[10,30] M. In
L. Kelton,[37] A. Keshavarzi,[39] D.
M. Kiburg,[7,21] O. Kim,[18,5] Y. I. Kin
K. R. Labe,[6] J. LaBounty,[46] M. Lar
A. Lorente Campos,[37] A. Lucà,[7]
F. Marignetti,[10,29] S. Mastroiann
R. Osofsky,[46] S. Park,[5] G.
D. Počanić,[45] N. Pohlman,[22]
J. L. Ritchie,[44] B. L. Roberts,[2] D. L
D. Shemyakin,[4] M. W. Smith,[46,11] M

PHYSICAL REVIEW LETTERS **126,** 141801 (2021)

Editors' Suggestion Featured in Physics

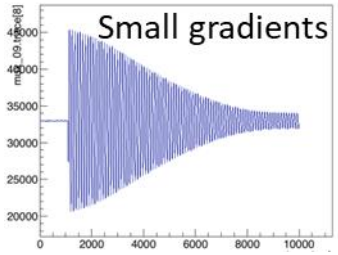
PRL

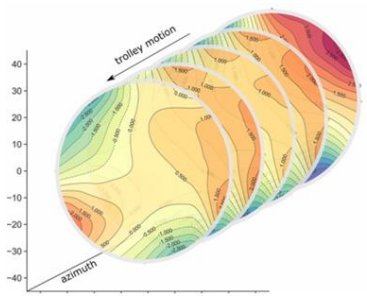
Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi,[44] T. Albahri,[39] S. Al-Kilani,[36] D. Allspach,[7] L. P. Alonzi,[48] A. Anastasi,[11,a] A. Anisenkov,[4,b] F. Azfar,[44] K. Badgley,[7] S. Baeßler,[47,c] I. Bailey,[19,d] V. A. Baranov,[17] E. Barlas-Yucel,[37] T. Barrett,[6] E. Barzi,[7] A. Basti,[11,32] F. Bedeschi,[11] A. Behnke,[22] M. Berz,[20] M. Bhattacharya,[43] H. P. Binney,[48] R. Bjorkquist,[6] P. Bloom,[21] J. Bono,[7] E. Bottalico,[11,32] T. Bowcock,[39] D. Boyden,[22] G. Cantatore,[13,34] R. M. Carey,[2] J. Carroll,[39] B. C. K. Casey,[7] D. Cauz,[35,8] S. Ceravolo,[9] R. Chakraborty,[38] S. P. Chang,[18,5] A. Chapelain,[6] S. Chappa,[7] S. Charity,[7] R. Chislett,[36] J. Choi,[5] Z. Chu,[26,e] T. E. Chupp,[42] M. E. Convery,[7] A. Conway,[41] G. Corradi,[9] S. Corrodi,[1] L. Cotrozzi,[11,32] J. D. Crnkovic,[3,37,43] S. Dabagov,[9,f] P. M. De Lurgio,[1] P. T. Debevec,[37] S. Di Falco,[11] P. Di Meo,[10] G. Di Sciascio,[12] R. Di Stefano,[10,30] B. Drendel,[7] A. Driutti,[35,13,38] V. N. Duginov,[17] M. Eads,[22] N. Eggert,[6] A. Epps,[22] J. Esquivel,[7] M. Farooq,[42] R. Fatemi,[38] C. Ferrari,[11,14] M. Fertl,[48,16] A. Fiedler,[22] A. T. Fienberg,[48] A. Fioretti,[11,14] D. Flay,[41] S. B. Foster,[2] H. Friedsam,[7] E. Frlež,[47] N. S. Froemming,[48,22] J. Fry,[47] C. Fu,[26,e] C. Gabbanini,[11,14] M. D. Galati,[11,32] S. Ganguly,[37,7] A. Garcia,[48] D. E. Gastler,[2] J. George,[41] L. K. Gibbons,[6] A. Gioiosa,[29,11] K. L. Giovanetti,[15] P. Girotti,[11,32] W. Gohn,[38] T. Gorringe,[38] J. Grange,[1,42] S. Grant,[36] F. Gray,[24] S. Haciomeroglu,[5] D. Hahn,[7] T. Halewood-Leagas,[39] D. Hampai,[9] F. Han,[38] E. Hazen,[2]

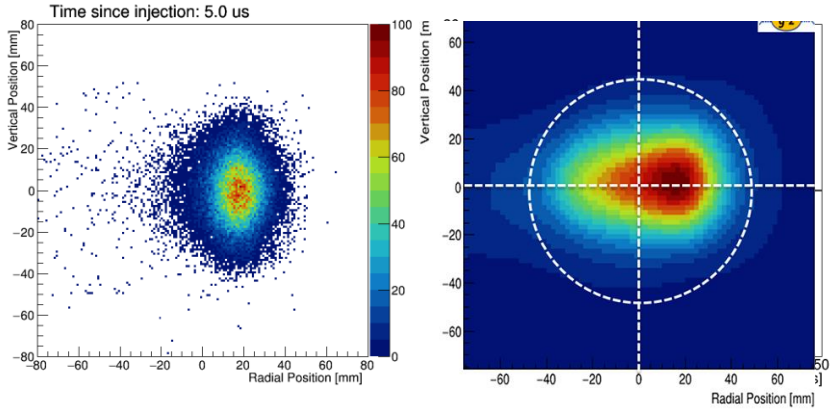
Technical expertise is drawn from different communities

- Precision magnetometry

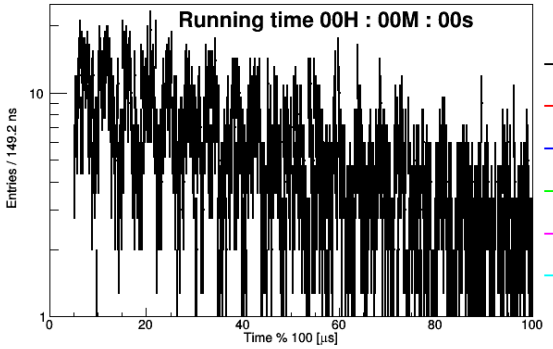




- Storage Ring Modeling and Measurement



- Muon precession frequency measurement



- *And fundamental values from CODATA*

$\frac{\mu_e(H)}{\mu'_p(T)}$	Measured to 10.5 ppb at T = 34.7°C Metrologia **13**, 179 (1977)	$\frac{m_\mu}{m_e}$	Known to 22 ppb from muonium hyperfine splitting Phys. Rev. Lett. **82**, 711 (1999)
$\frac{\mu_e}{\mu_e(H)}$	Bound-state QED (exact) Rev. Mod. Phys. **88** 035009 (2016)	$\frac{g_e}{2}$	Measured to 0.28 ppt Phys. Rev. A **83**, 052122 (2011)

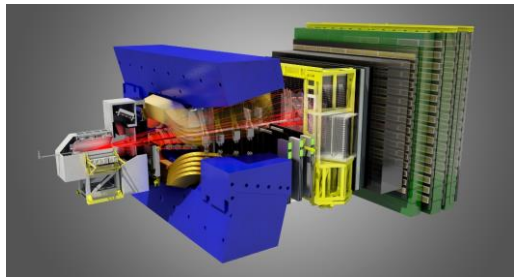
QCD and Hadronic Physics

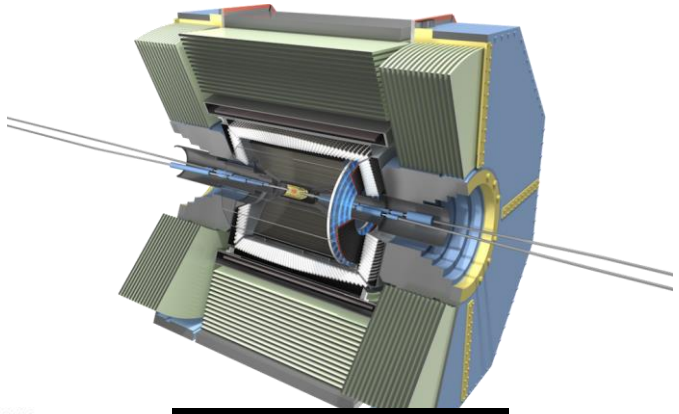
Tools

Examples

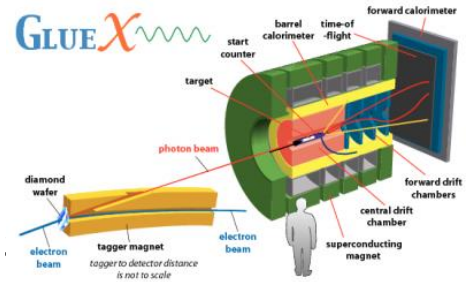
Facilities / Experiments (incomplete)

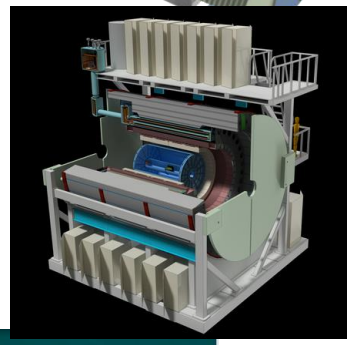
- LHC-heavy ion (all expts)
- LHCb & Belle II
  - Exotic hadrons with s, b, c quarks





- GlueX @ Jlab
  - Exotic hadron search in u,d,s system
  - CLAS

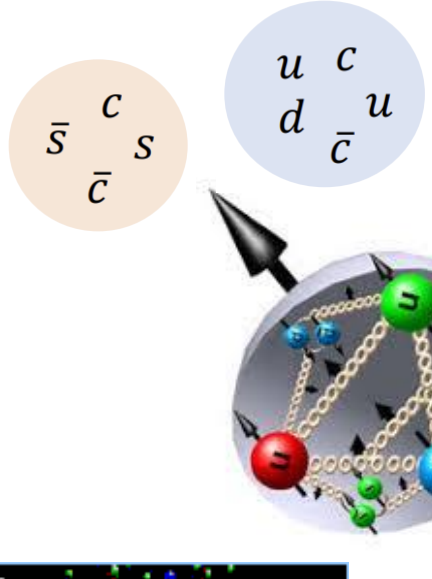


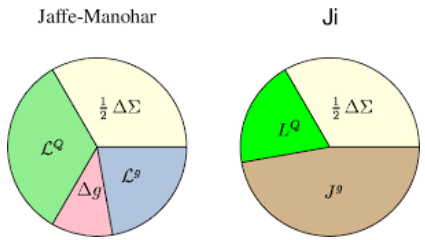


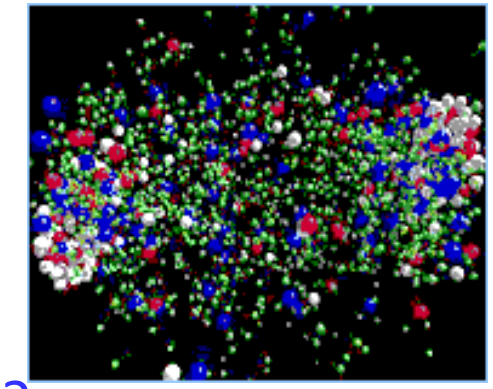
- RHIC - STAR, PHENIX, sPHENIX
  - Full heavy ion program entering final pha
- EIC – detector(s) TBD
  - Future ep, eA at high Luminosity
  - Proton mass, spin, nature of gluons in matter

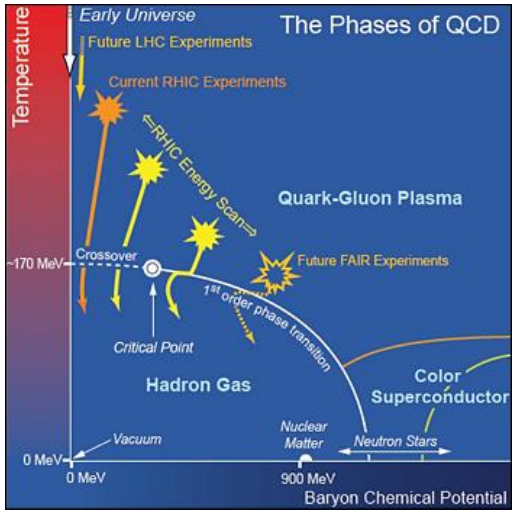
Some Physics Questions…

- Exotic hadrons .. beyond qqq and $q\bar{q}$
  - (18 “exotic” discovered at LHC)
- Spin decomposition of the nucleon
  - Beyond the sum rules
- Mass of the proton (not the trivial answer)
  - New mission of the EIC
- High-density QCD of the Early Universe
  - Most perfect liquid
- Is there a QCD 1st-order phase transition?
  - Beam energy scan to explore









The Technological Influence

(usually HEP → other communities)

(but occasionally the other way)

Detector Technology

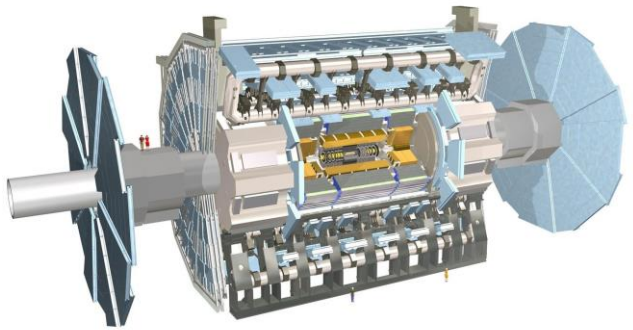
High-speed Electronics

Monte Carlo Modeling and Offline Analysis

Support for these developments is beneficial to all of us

Detectors & Electronics
(just a tiny few mentions)

- MWPC and Drift Chamber advances
- Silicon strips, pixels, …
- Scintillating fibers for tracking and more
- Calorimetry (EM and Hadronic)
- Photosensors (PMTs, SiPMs)
- TPCs
- Large, Superconducting Magnets
- Micro-electronics and ASIC readouts
- Fast digitization

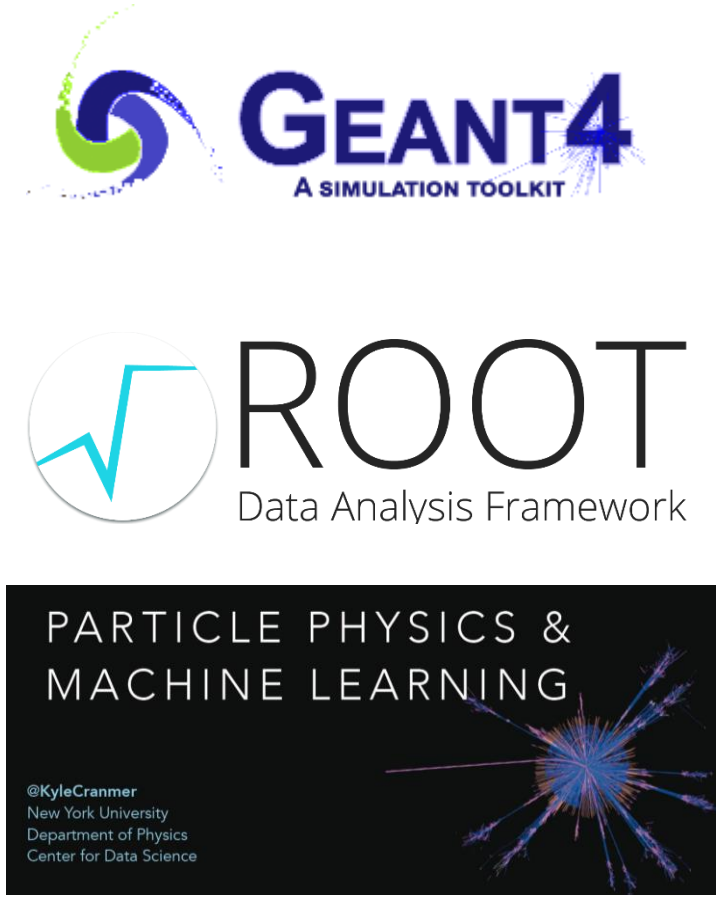


These developments, often over years, DO trickle down to the broader communities

(personal experience and often)

Modeling and Analysis
(just a tiny few mentions)

- GEANT 4 !!
  - being used down to the lowest energy scales one might imagine
- ROOT and its various futures
  - Again, used even in classrooms in modern physics courses (personal experience)
  - And is a “default” tool for most of the community
- Leading various ML techniques for event selection and analysis

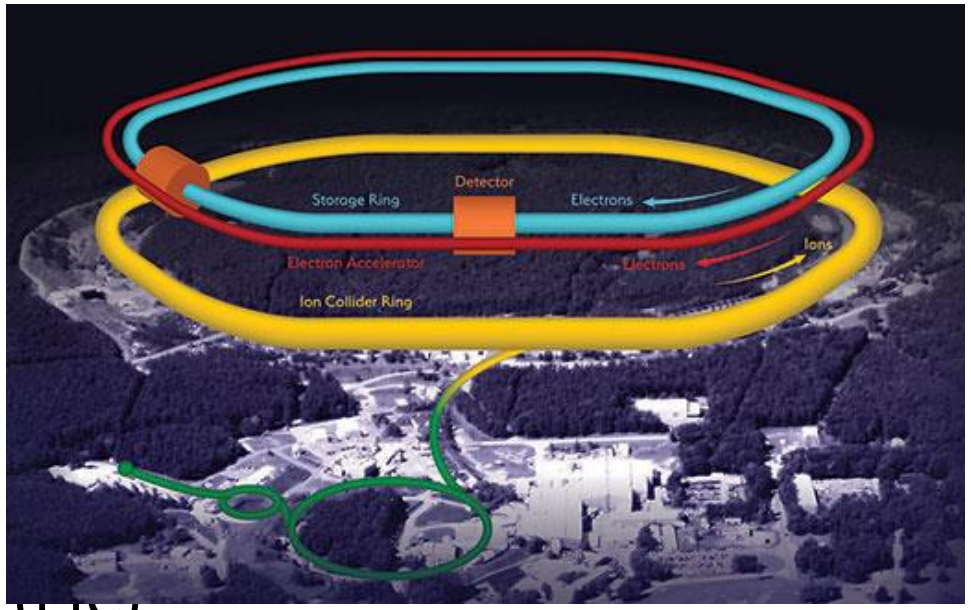


The Practical Intersections

Tools

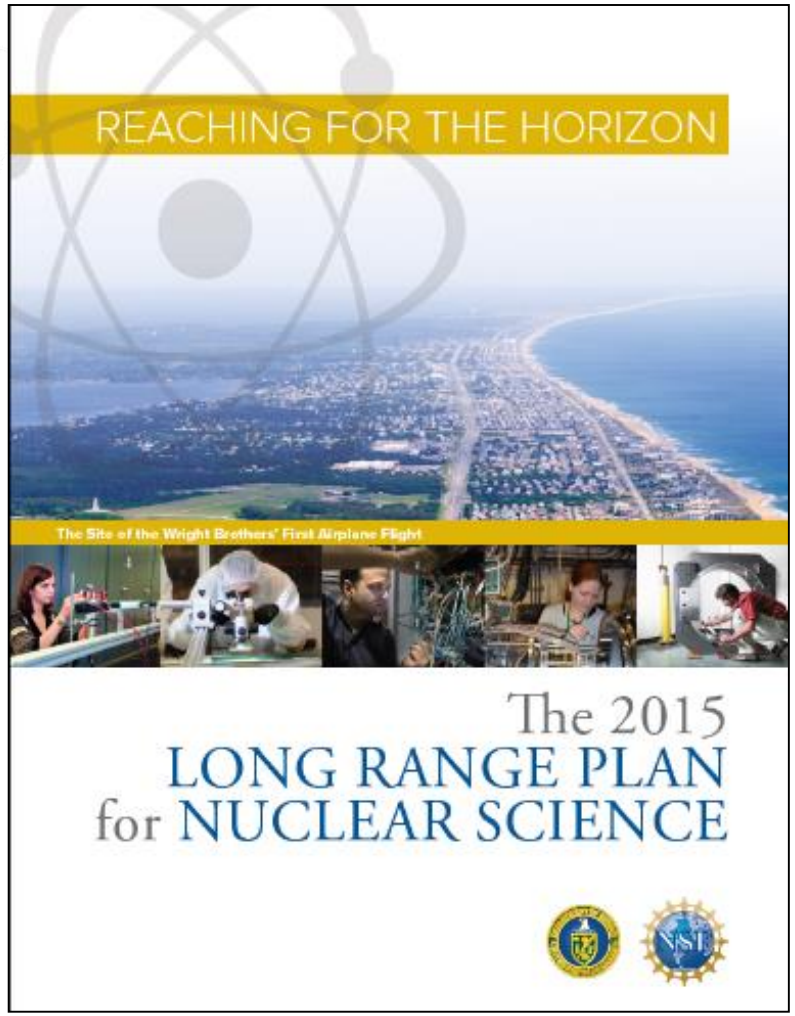
Vision for the future

Nuclear Physics Priorities:



- Accelerator based programs at
  - Jefferson Lab electron accelerator and 4 halls
  - BNL RHIC proton and HI collider
  - Facility for Rare Isotope Beams (FRIB)
  - ATLAS at ANL
- Future will see RHIC → the Electron Ion Collider (EIC)
- NP Program also supports a "target program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model"
  - nEDM, neutrino mass, $0\nu\beta\beta$, muon g-2, PVEW, n-tau, n-decay, "V_{ud}", ..

This year, Nuclear Physics is embarking on a new "Long Range Plan" (much like P5).



The LRPs have identified scientific opportunities and recommended priorities

They proceed from DNP sponsored Town Halls and White papers and are material is distilled by a Resolution Committee

What to expect in terms of Intersections with HEP?

- These are **PERSONAL guesses** ..
  - Strong endorsement for ton scale $0\nu\beta\beta$ program
  - Strong endorsement for vigorous pursuit of m_ν
  - Very strong endorsement for EIC and its Detectors*
  - Continued support for
    - Neutron lifetime! Beta decay asymmetry at higher sensitivity
    - Moller PVES
    - nEDM at SNS
    - Support selective muon/pion programs

- And what not to expect? (geez, really? I won't touch that one)
  - …

*Very strong HEP overlap here