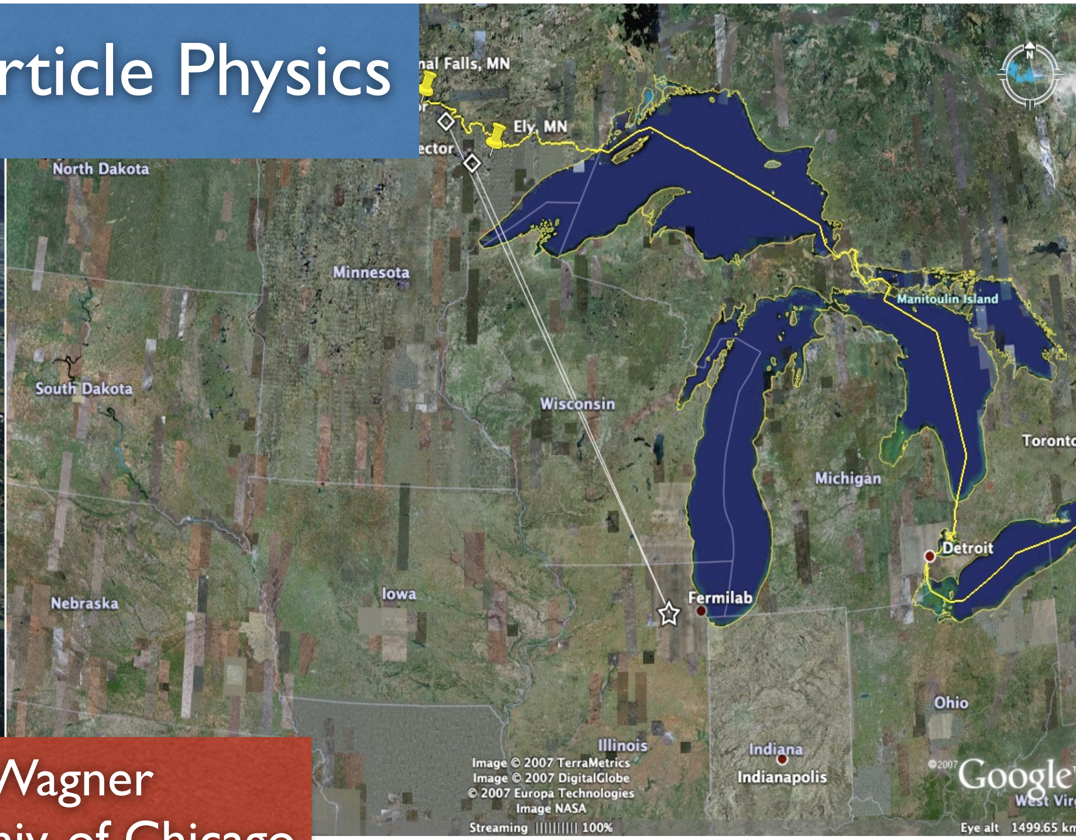
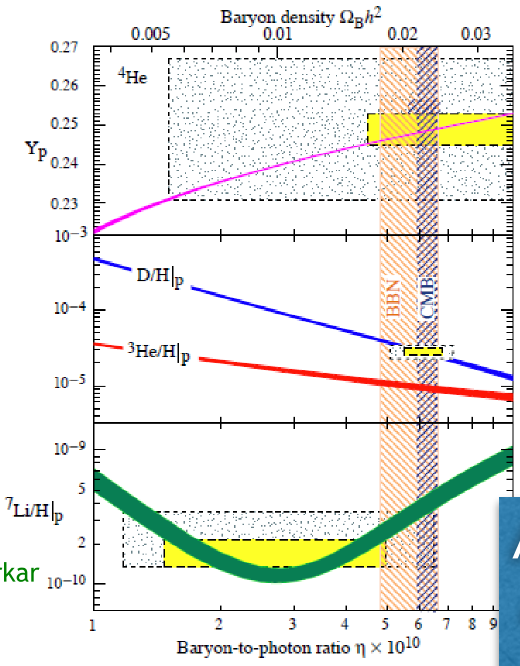
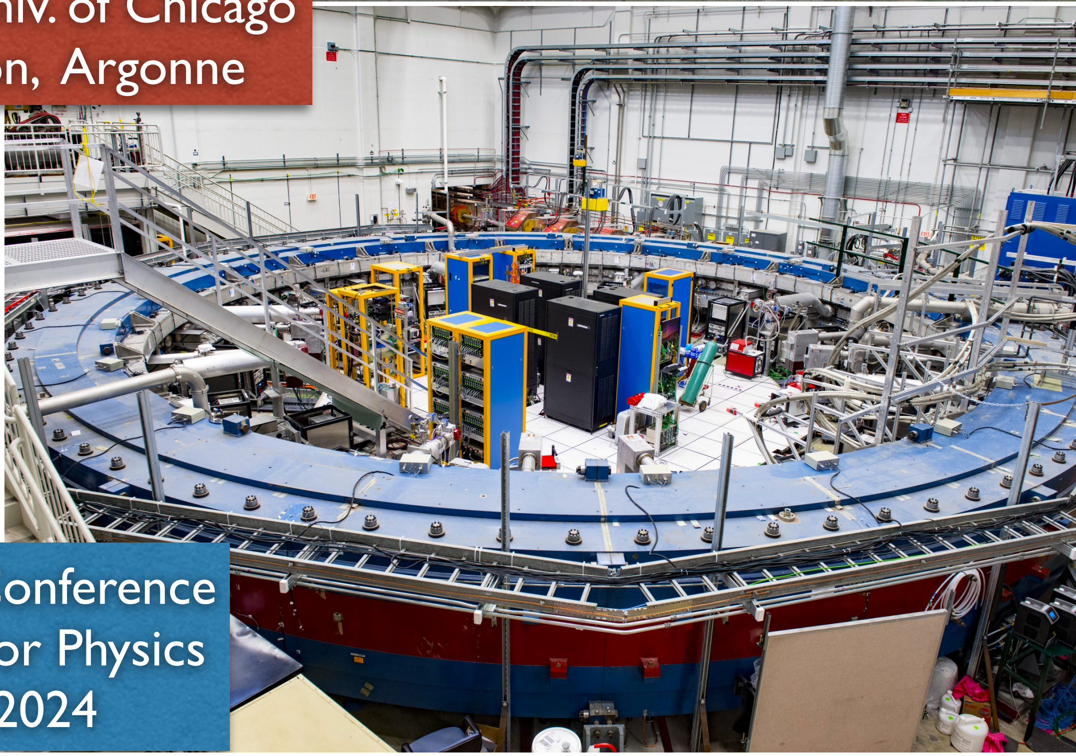
The Future of Particle Physics

C.E.M. Wagner
EFI & KICP, Univ. of Chicago
HEP Division, Argonne





Fields, Sarkar



Aspen Winter Conference
Aspen Center for Physics
March 29, 2024

Disclaimer

This is not supposed to be a summary talk.
It is just a personal view of what will happen.

Many of the subjects I'll discuss have been covered
in much better detail during this conference.

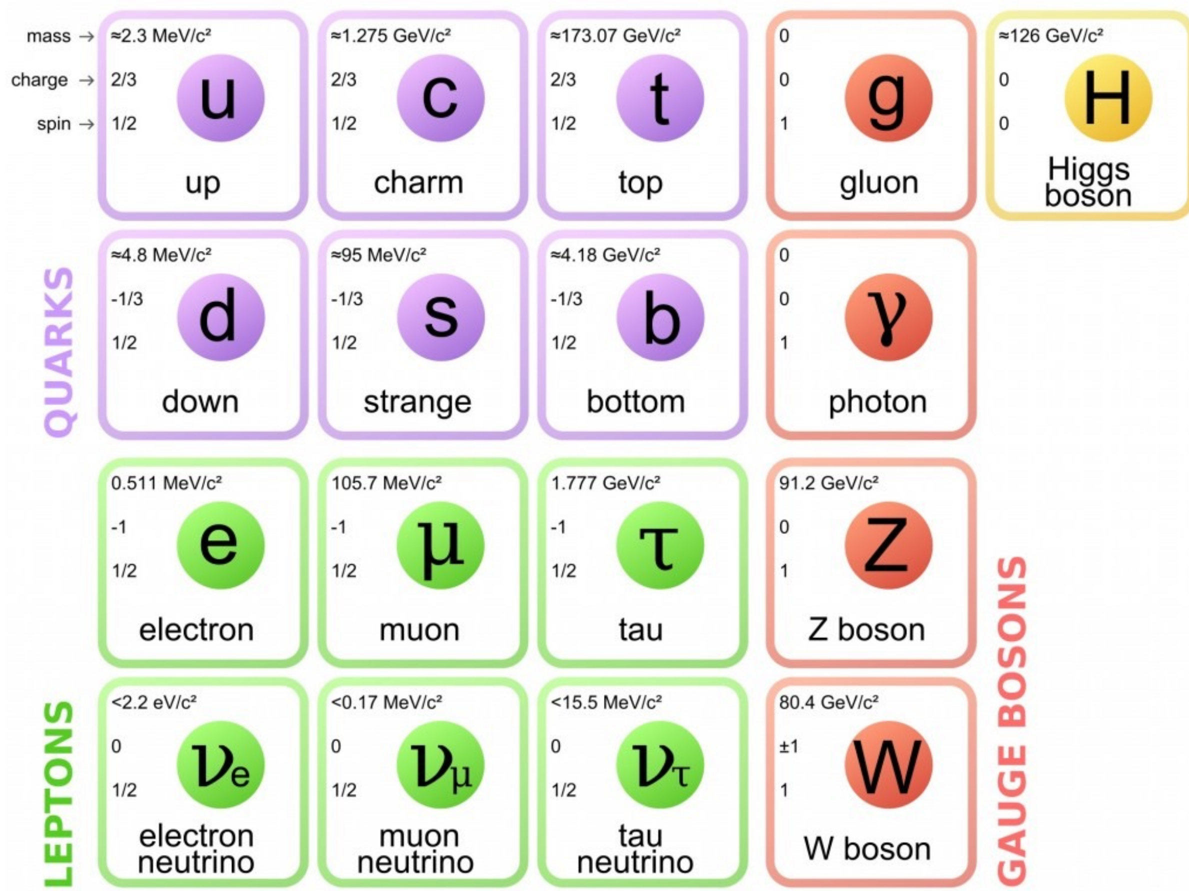
Look, in particular, to the many vision talks presented
in this conference.

The Standard Model

Is an extremely successful Theory that describes interactions between the known elementary particles.

3 generations of fermions (mattter)

Gauge and Higgs Fields



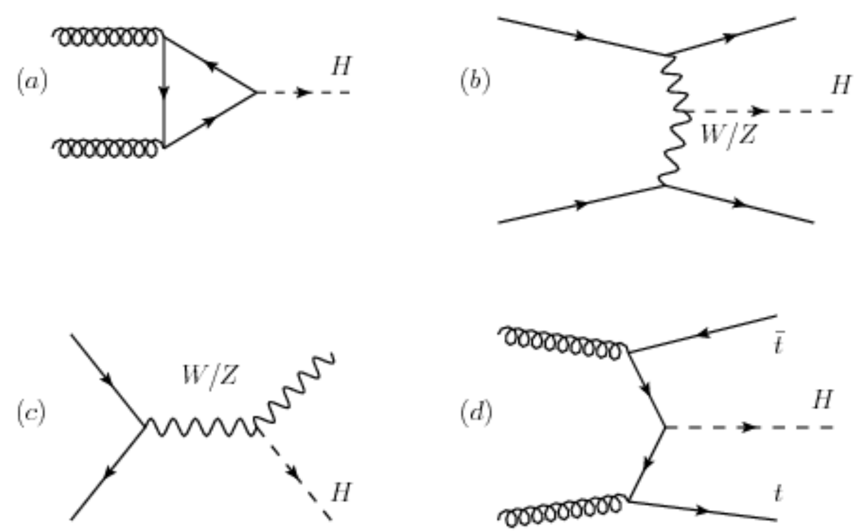
Well known, Open Question in HEP (not addressed satisfactoraly by the SM)

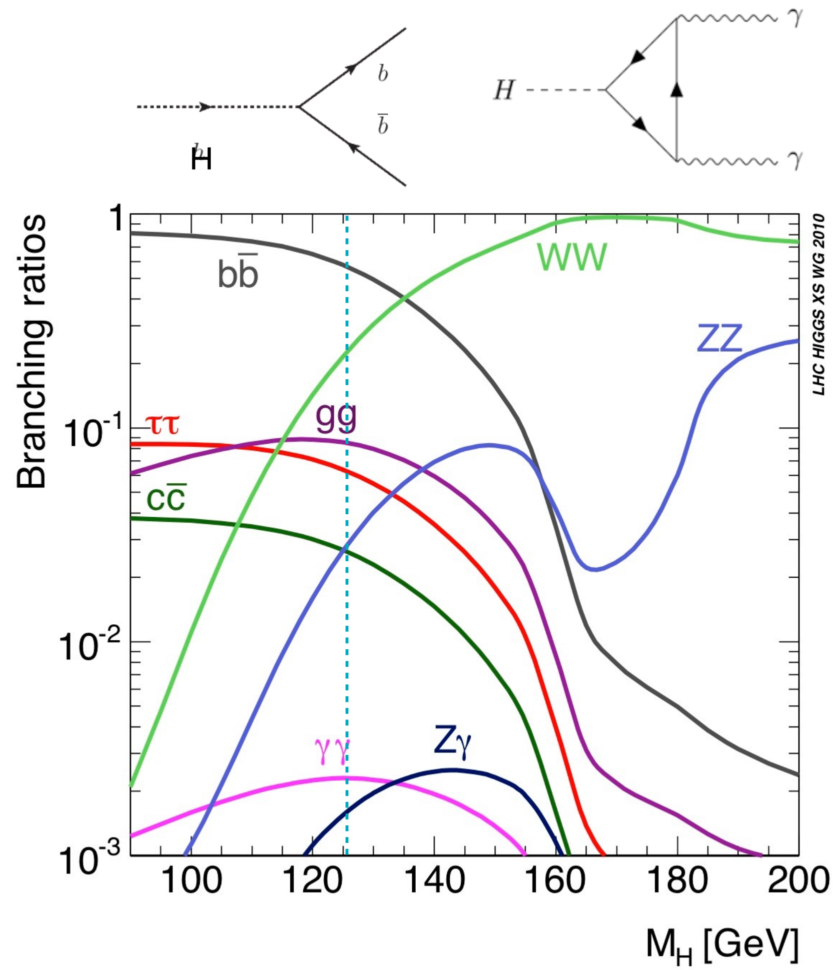
- The Nature of **Dark Matter**
- The cause of the Universe's accelerated expansion **- Dark Energy**
- The origin of the **Matter-Antimatter Asymmetry**
- The generation of **Neutrino Masses**
- The reason for the **Hierarchy in Fermion Masses and their Flavor Structure**
- Why Electroweak Symmetry Breaking occurs?
  What is the history of the Electroweak Phase Transition ?
- What are the quantum properties of Gravity?
- What caused Cosmic Inflation after the Big Bang?

The Mass Mystery

LHC Higgs Production Channels and Decay Branching Ratios

Gluon Fusion is the Main Production Channel



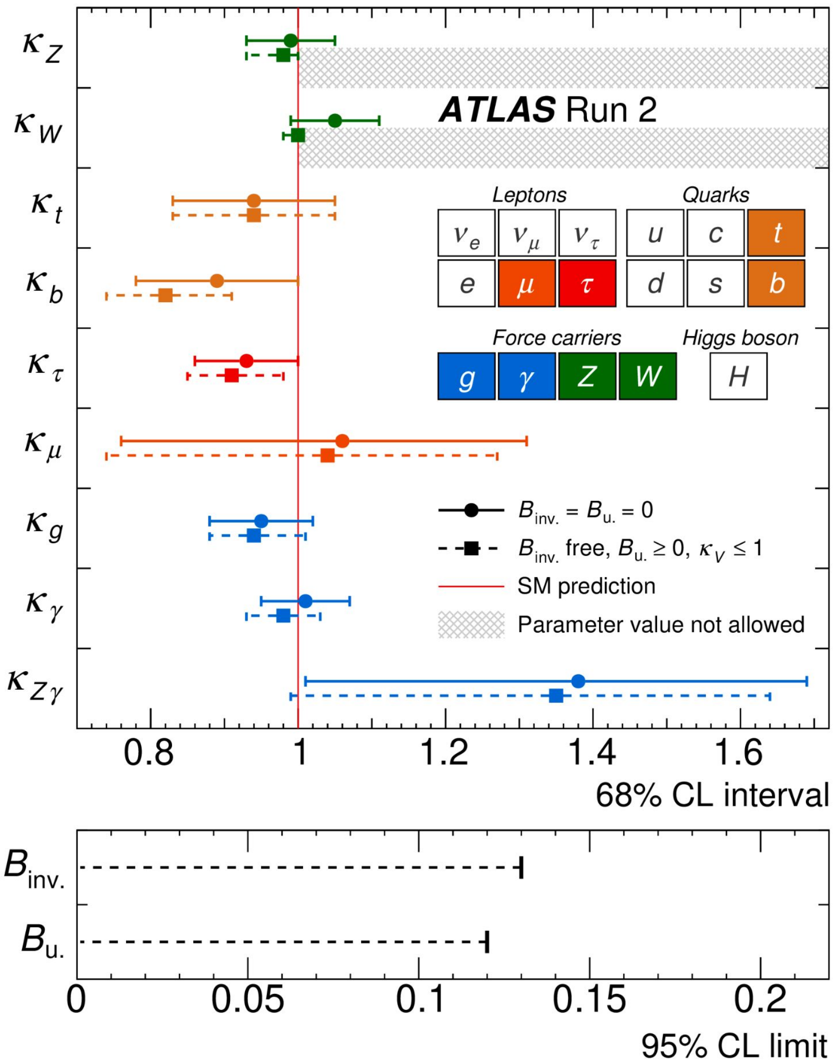


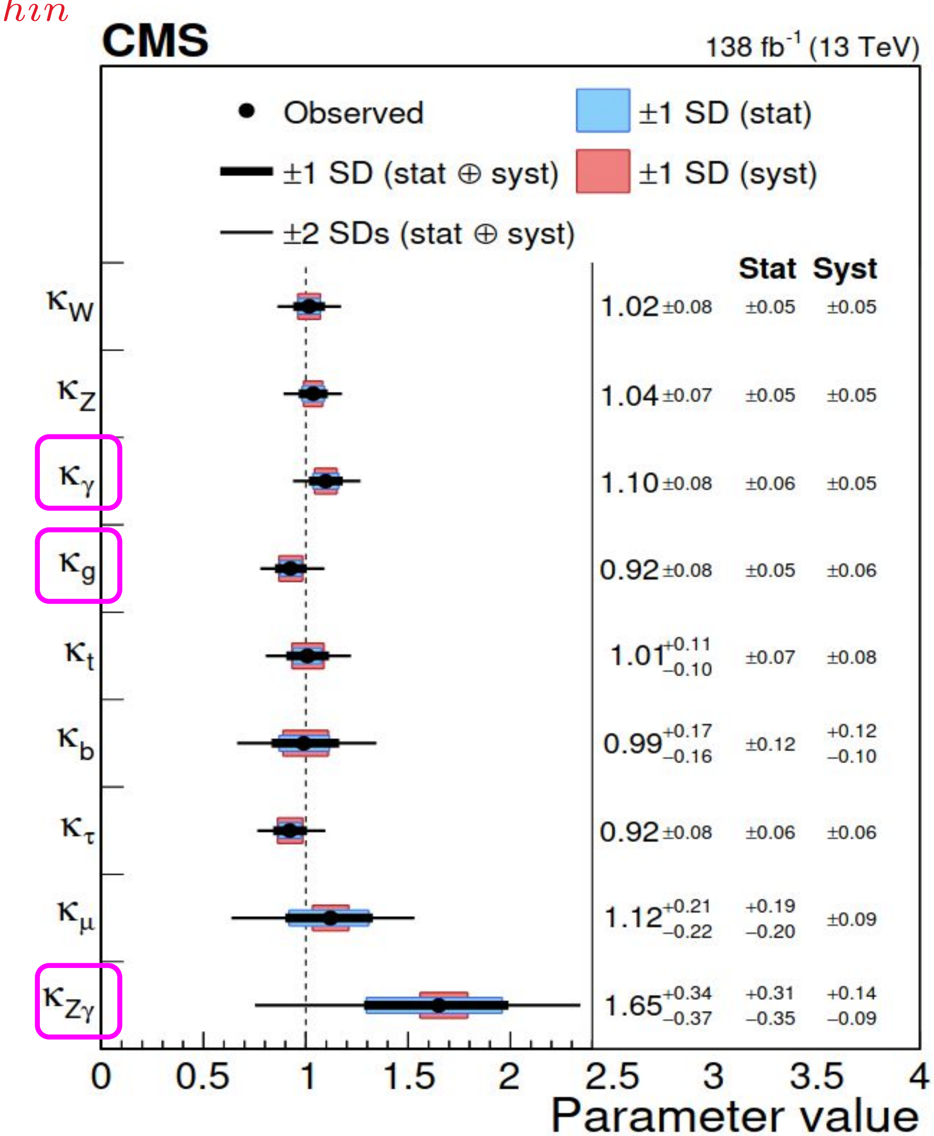
A Higgs with a mass of about 125 GeV allows to study many decay channels

ATLAS and CMS Fit to Higgs Couplings

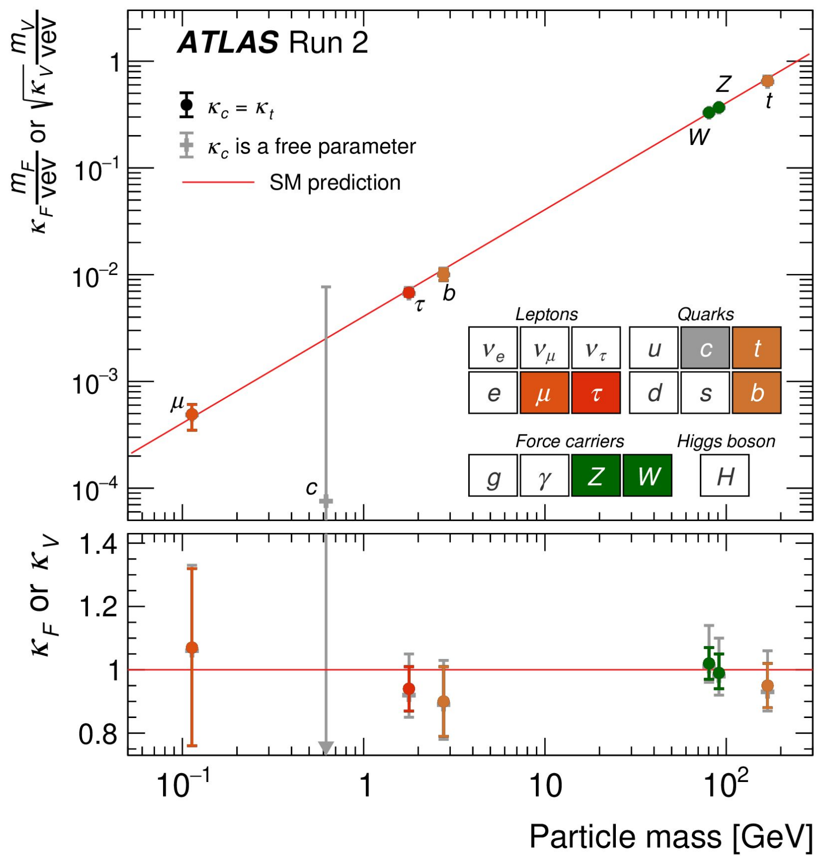
Departure from SM predictions of the order of few tens of percent allowed at this point.

$$\kappa_i = \frac{g_{hii}}{g^{\mathrm{SM}}_{hin}}$$

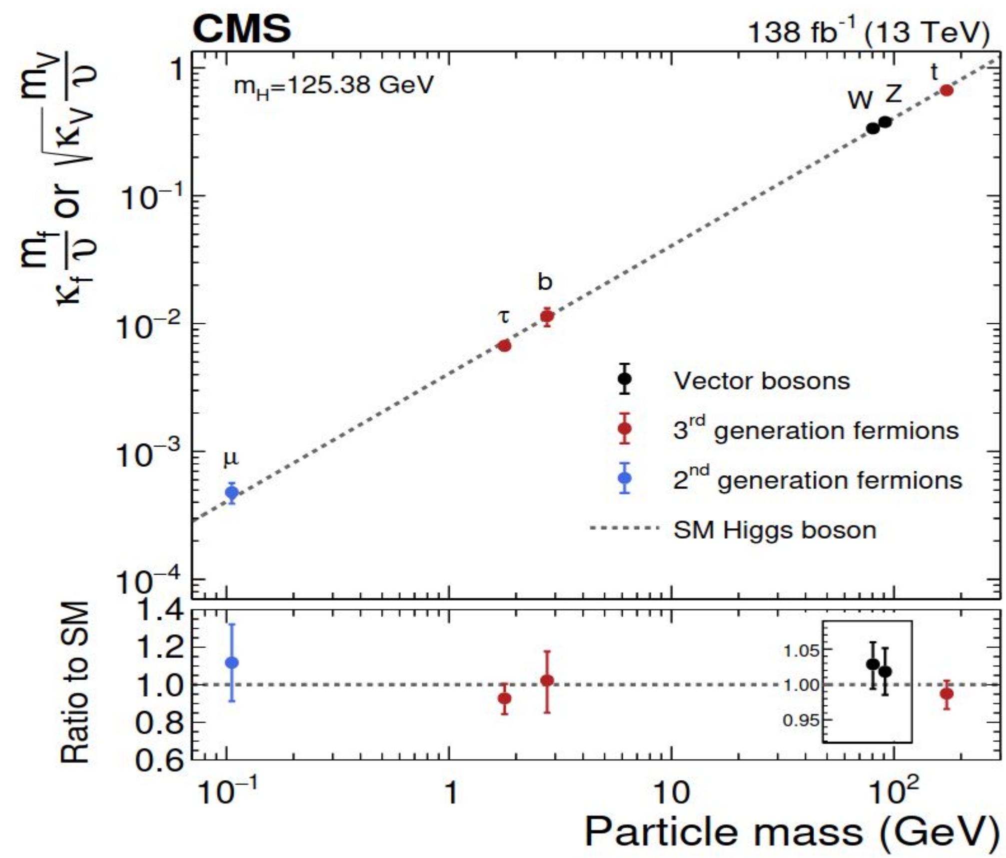




Correlation between masses and couplings consistent with the Standard Model expectations



H couplings vs particle mass



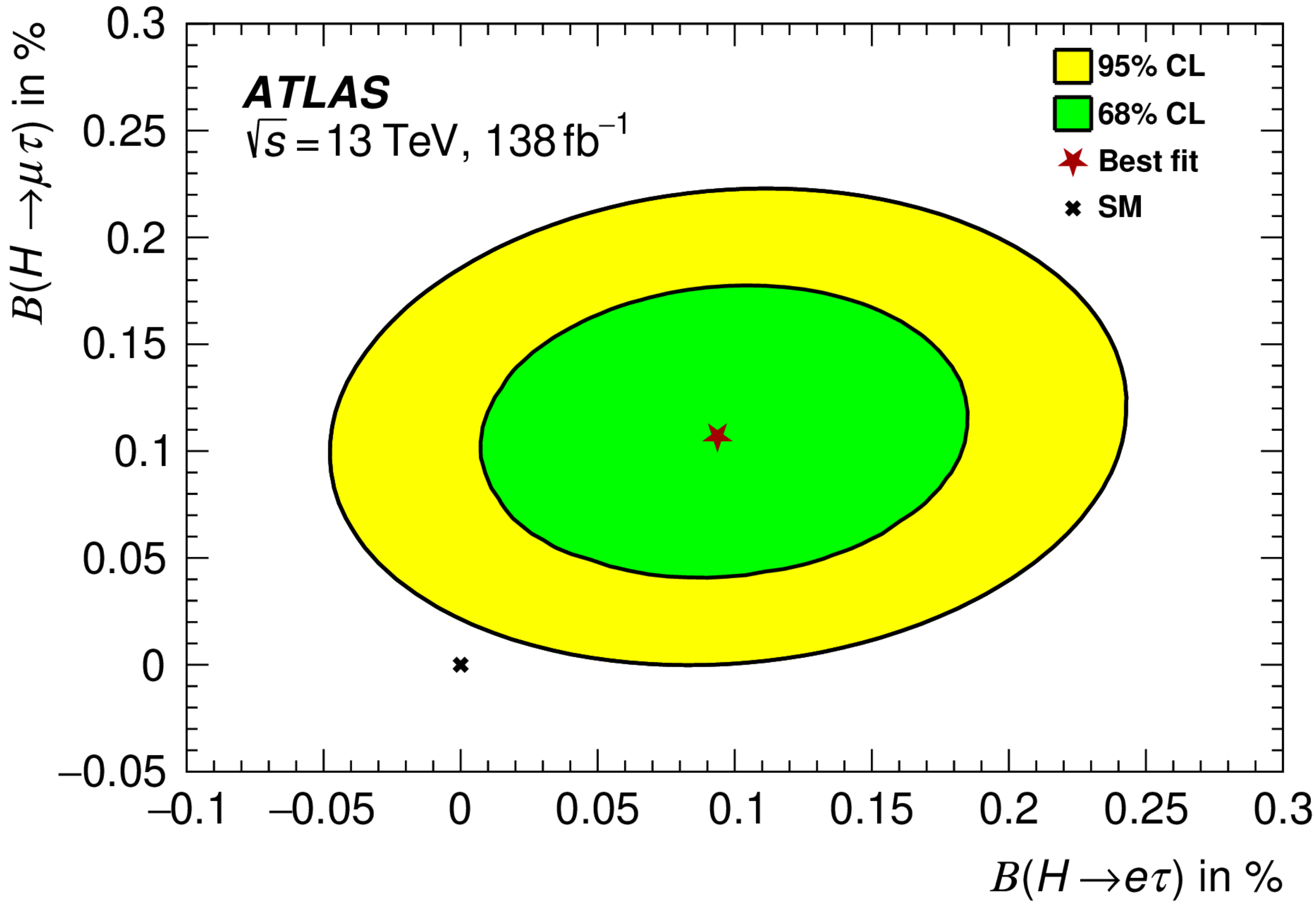
11

$$g_{hf\bar{f}} = \frac{m_f}{v}, \qquad g_{hVV} = \frac{m_V^2}{v}$$

We are starting to get information on the second generation couplings !!

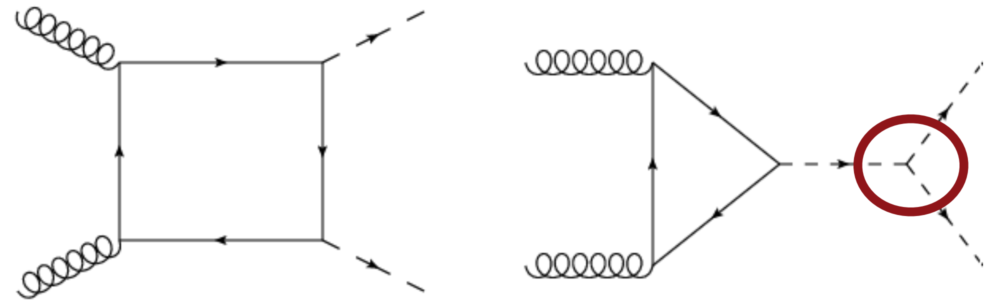
There may be, of course, surprises

Possible flavor violation in Higgs decays

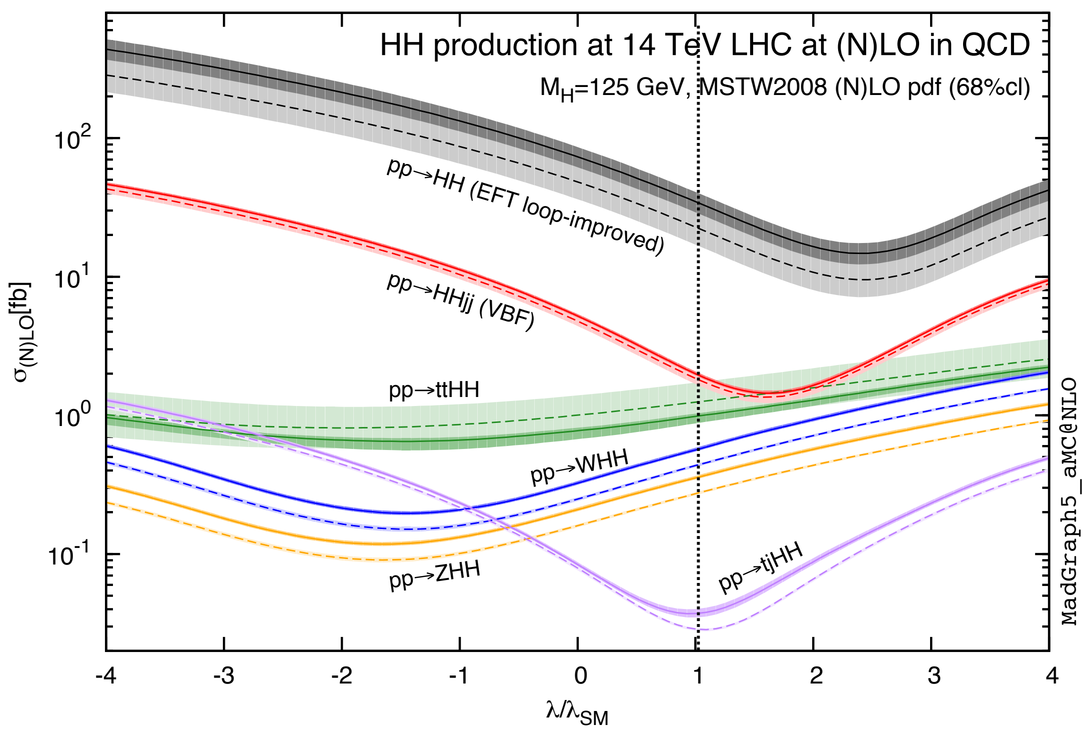


No hint from CMS, though : $BR(H \to \tau\mu, e) < 0.15\%$

Di-Higgs Production dependence on the Higgs self coupling



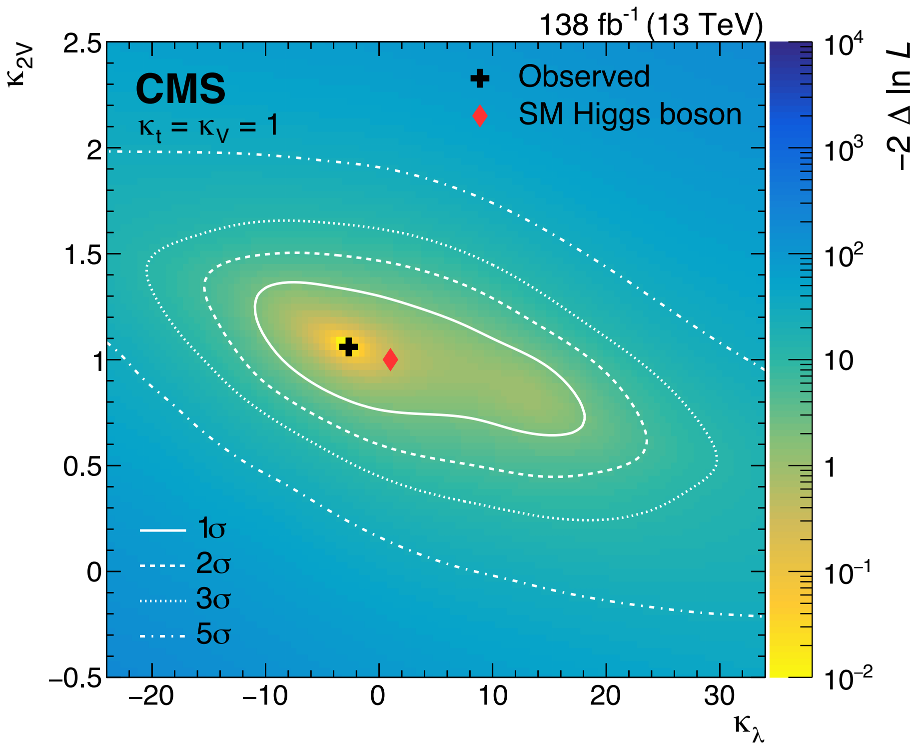
Top Coupling Fixed to the SM value.

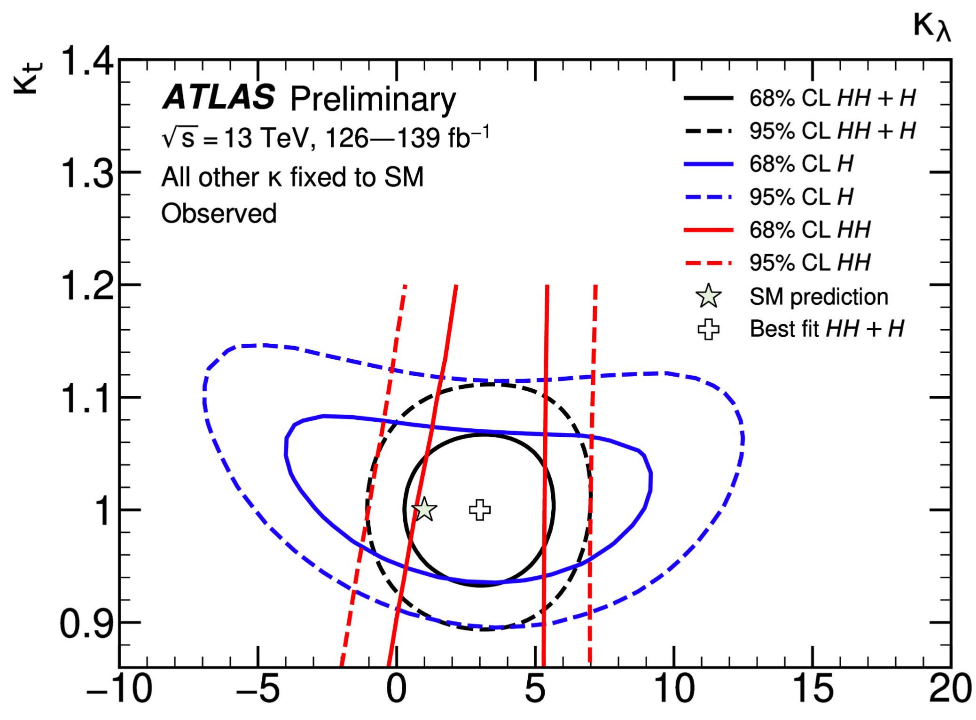


Frederix et al'14

Box Diagram is dominant, and hence interference in the gluon fusion channel tends to be enhanced for larger values of the coupling. At sufficiently large values of the coupling, or negative values, the production cross section is enhanced.

Amazing Experimental Progress





ATLAS-CONF-2022-050

HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination (2019)	$-2.3 < \kappa_\lambda < 10.3$	$-5.1 < \kappa_\lambda < 11.2$	$\kappa_\lambda = 4.6^{+3.2}_{-3.8}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$
HH+H combination (2019), κ_t, κ_V, κ_b, κ_ℓ floating	$-3.7 < \kappa_\lambda < 11.5$	$-6.2 < \kappa_\lambda < 11.6$	$\kappa_\lambda = 5.5^{+3.5}_{-5.2}$

HL-LHC may improve these bounds to the order of 50 %

May be connected with Electroweak Baryogenesis
Models; for a short review, C.W. , arxiv:2311.06949

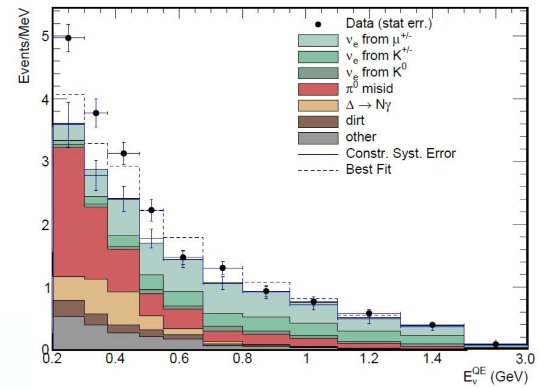
Symmetries and Neutrinos:

❖ The SM is build based on symmetries: What if the gauge symmetries and the fermion content get unified? One could expect:

- Gauge coupling unification modulo effects from heavier stuff
- Proton decay
- 3-Neutrino see-saw mass generation with possibility of leptogenesis

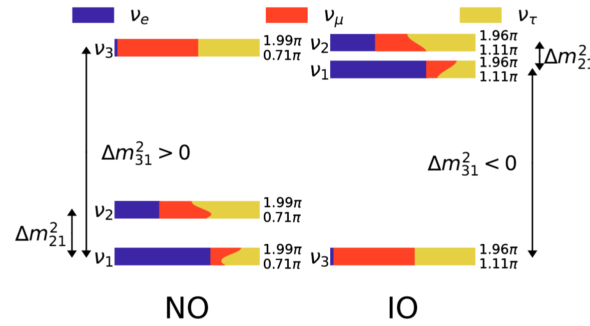
Neutrinos are also suggesting opportunities beyond their mass generation:

- Neutrinos, being weakly interacting neutral fermions, can mix with steriles with many possible origins, e.g., the dark matter
- Possible exotic properties of neutrinos less constrained than other SM particles
- Can provide a window to new physics at very high energies



In fact, there are currently several very puzzling neutrinos anomalies, in particular the MiniBooNE low energy excess, following on LSND results -

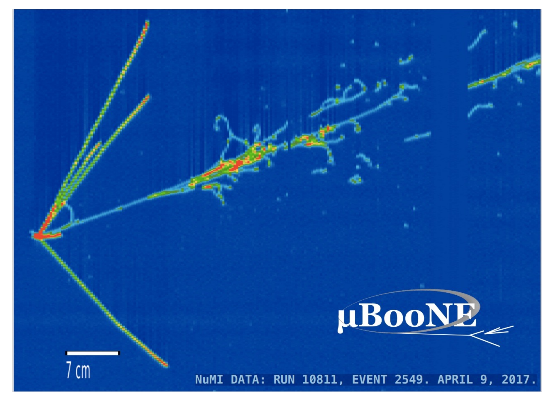
Neutrinos at many energy scales



- The origin of the tiny neutrino masses and of neutrino mixings is a great mystery
- The dominant paradigm for explaining neutrino masses requires the existence of new heavy electroweak singlet leptons

But the energy scale of these heavy neutral leptons is not specified

- Neutrino CP violation could be the origin of the matter-antimatter asymmetry through leptogenesis
- Low-scale leptogenesis is a viable possibility
- Heavy neutral leptons more generally could be connected to other mysteries, e.g. can be portals to the dark sector



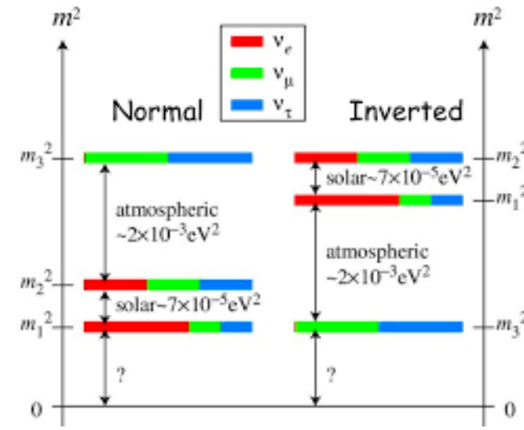
T2K and NoVa working towards the question of CP-violation.
Neutrino mass hierarchy and CP-violation will be one of the science goals of the future long baseline neutrino program of DUNE and HyperK, starting in the next decade.

Is CP violated in the neutrino sector ?

Best test : $\nu_\mu \to \nu_e$ oscillations.

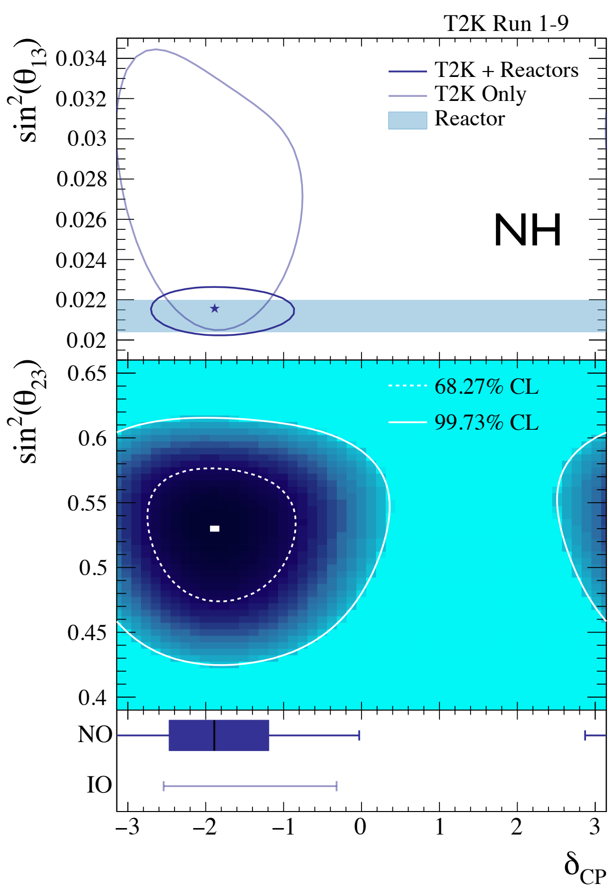
$$P_{\mu e} = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} + 4c_{13}^2 c_{23}^2 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}$$

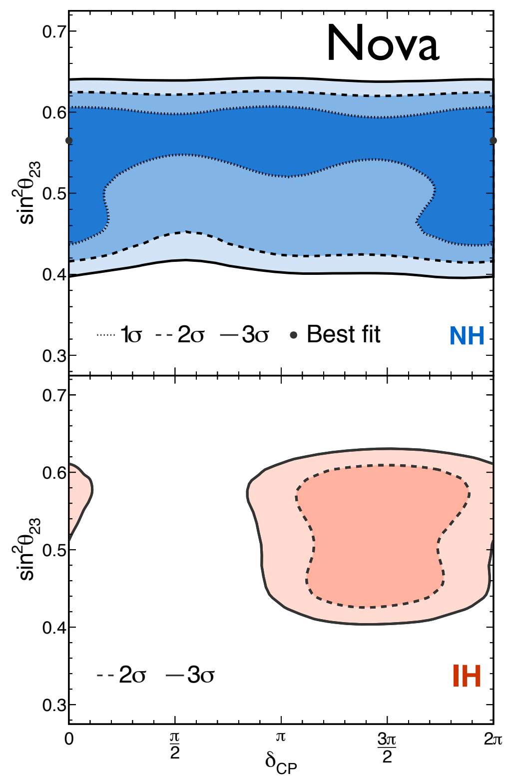
$$+ 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \Delta_{31} \sin \Delta_{21} \cos(\Delta_{32} + \delta_{13}).$$



$$\Delta_{ij} = \frac{(m_i^2 - m_j^2)L}{4E}$$

Hints of sizable CP-violation





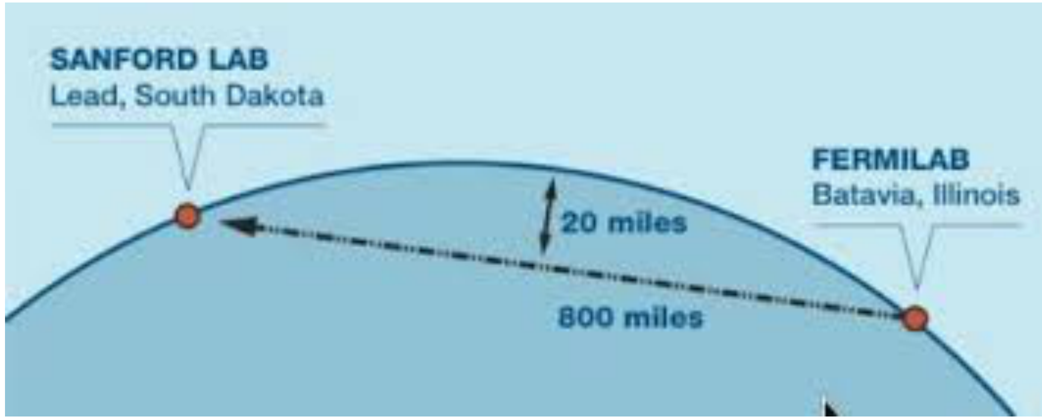
C.W. rule

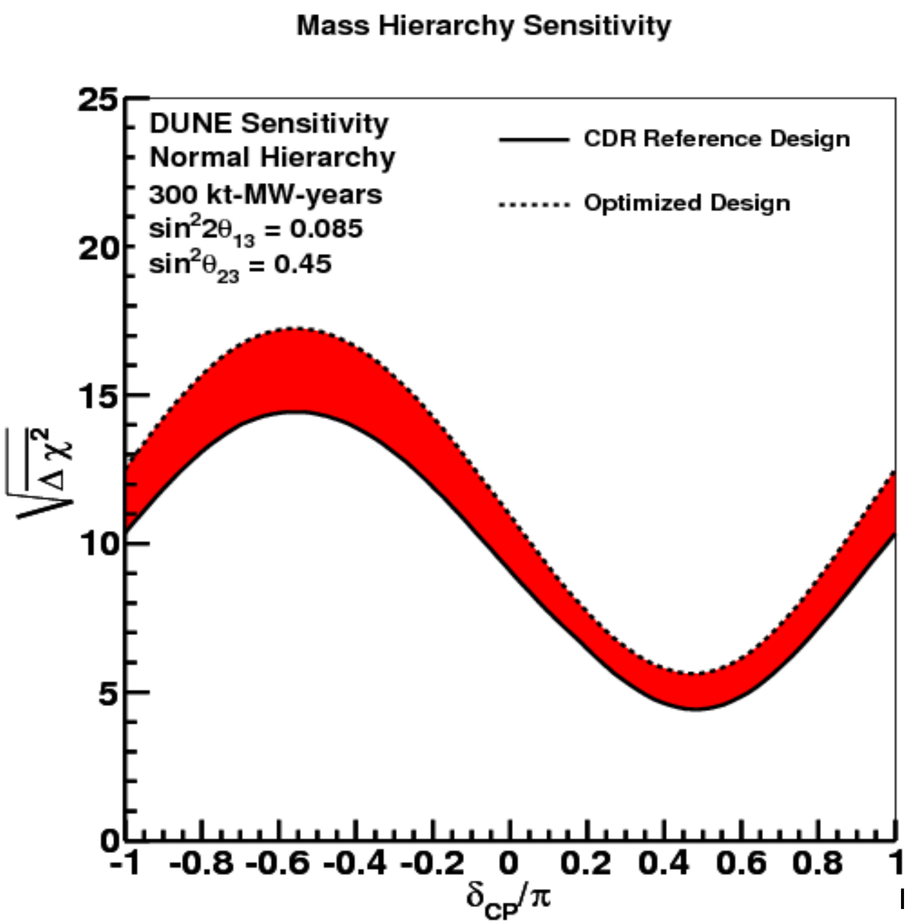
$$\theta_{12} \sim 34^o$$

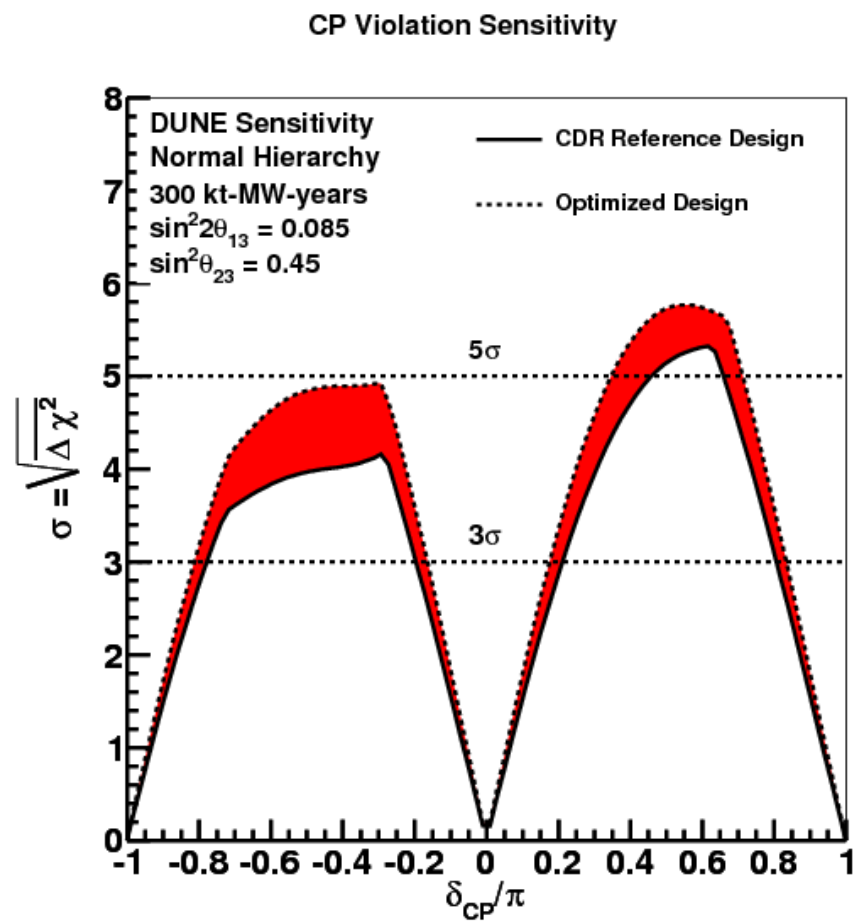
$$\theta_{23} \sim 45^o$$

$$\theta_{13} \sim 9^o$$

Future long baseline facilities : DUNE and HyperK







Lepton flavor opportunities

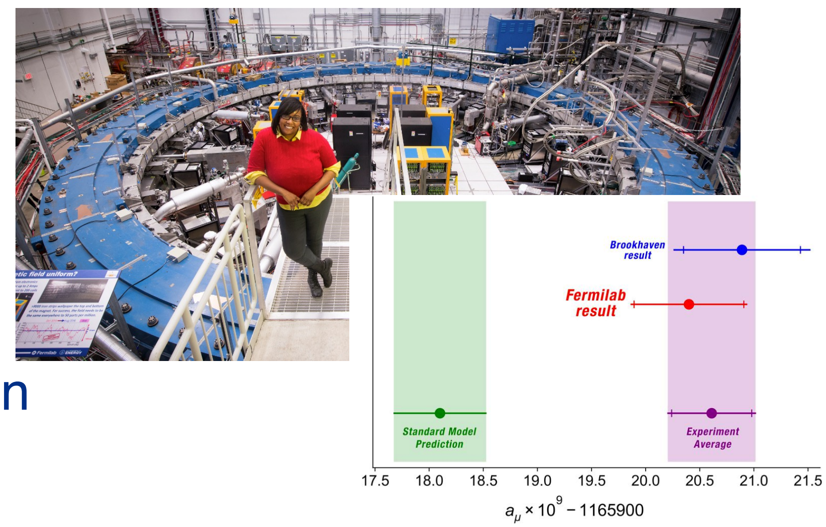
In the quark sector no compelling evidence for flavor effects beyond CKM

What about LFV in the charged lepton sector?
Could be new particles that couple differently to electrons/muons/taus

- new gauge bosons, new scalars, leptoquarks - new type of particles appearing in extended symmetries of nature- or squarks in special types of supersymmetry

Have we already seen such effects?

- The muon g-2 anomaly :
  4.2 standard deviation from SM expectation
  Lattice theory calculations under scrutiny

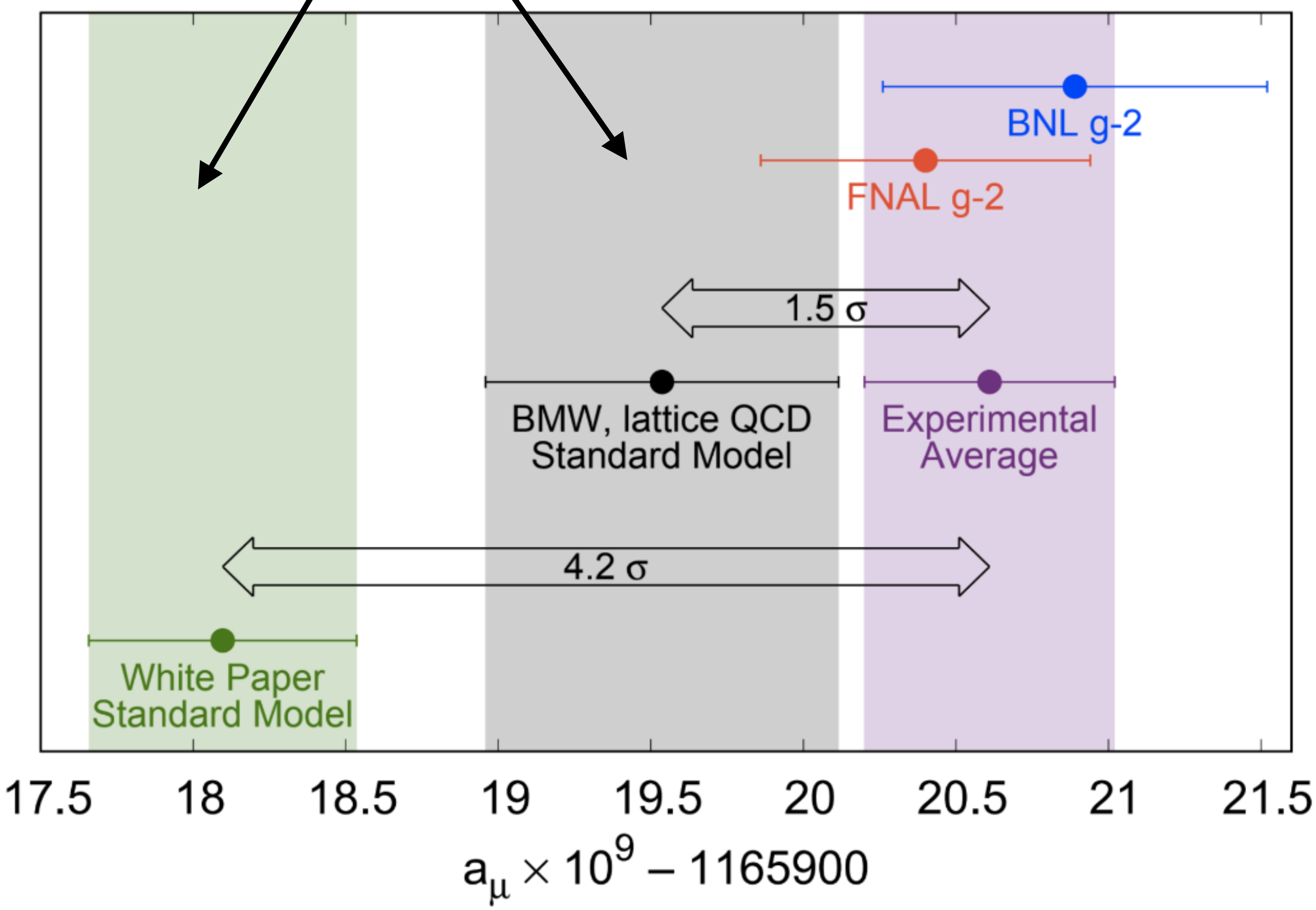


- LHCb R_K anomaly: 3 Sigma evidence of lepton universality violation in b-quark decays

Mu2e Fermilab experiment will provide a huge jump in sensitivity to some possible effects

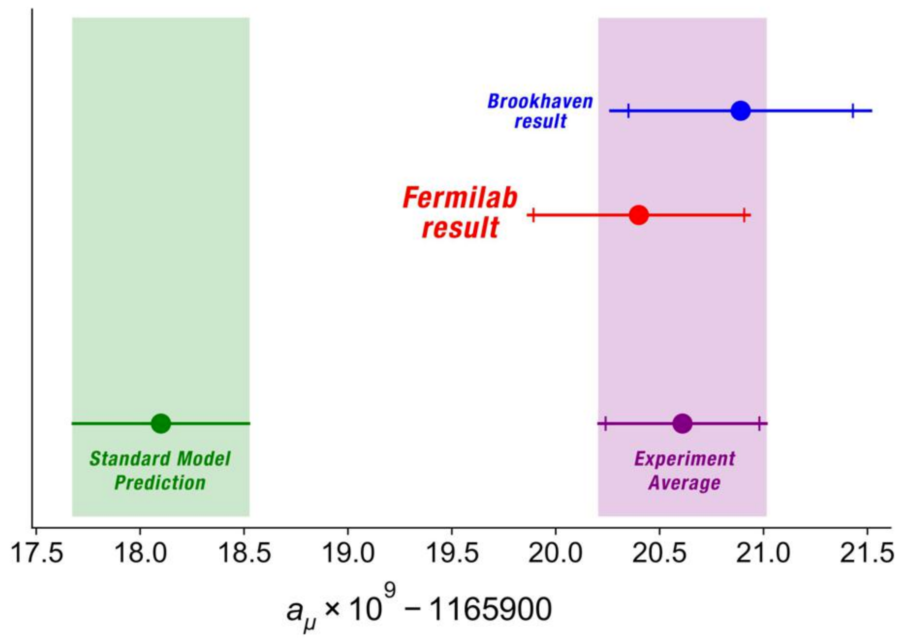
Comparison of BMW lattice computation with data driven method to fix hadronic contributions

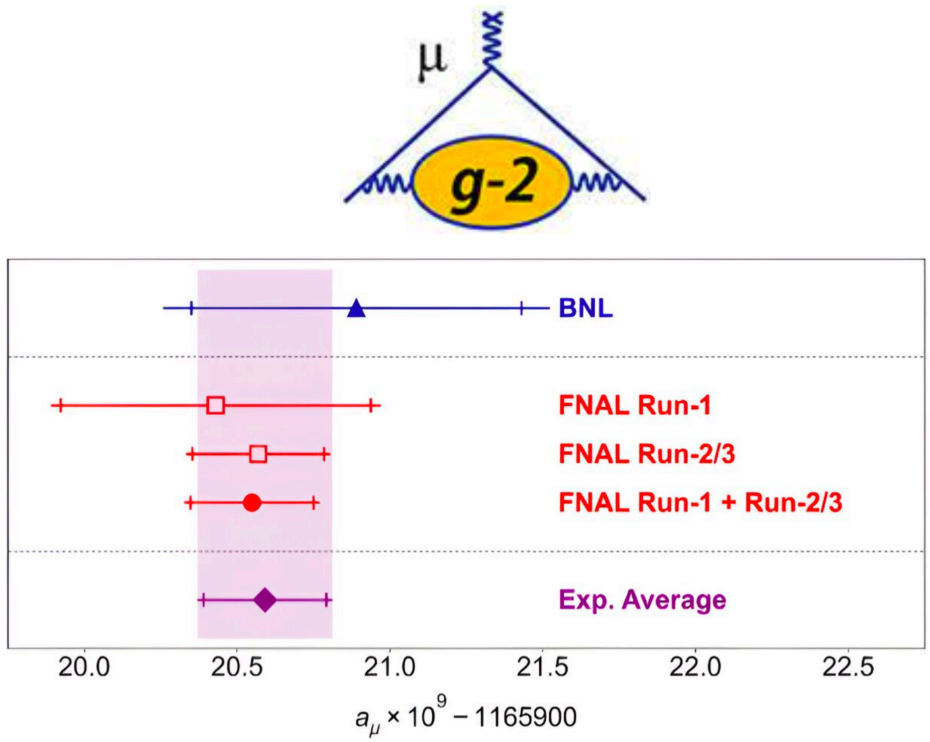
N. Coyle, C.W.'23 | Can they be reconciled ? | Z. Fodor ' 21 | arXiv:2002.12347



In the following, I will take the 4.2 sigma discrepancy seriously.
This question will be clarified within the next few years.

Updated result in 2023





arXiv:2104.03281

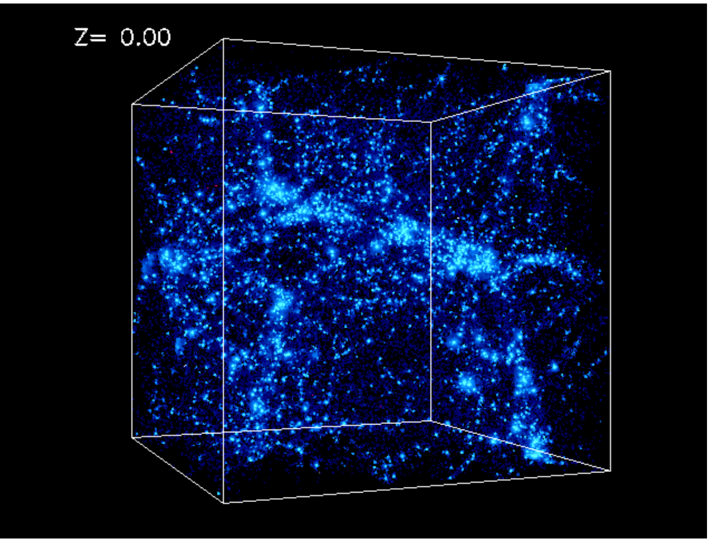
arXiv:2308.06320

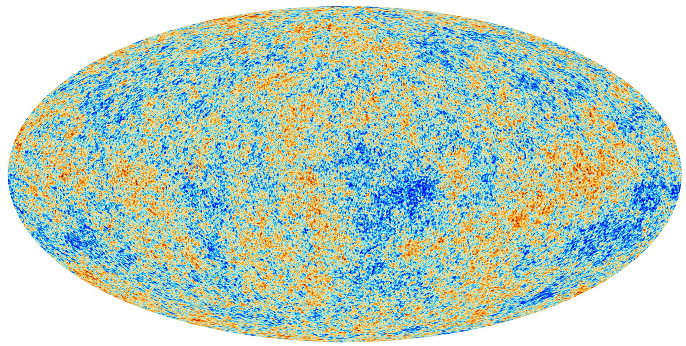
Central Value did not change, experimental error decrease by a factor 1.6.
Taken at face value, discrepancy increased to 5.1 sigma.

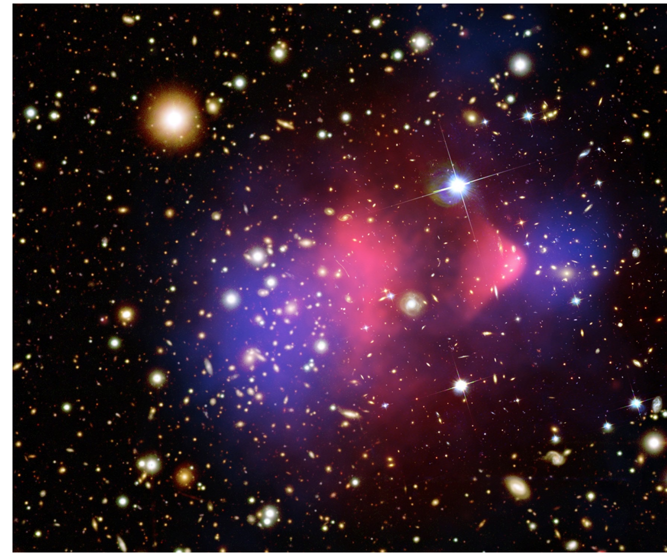
Dark Matter Mystery

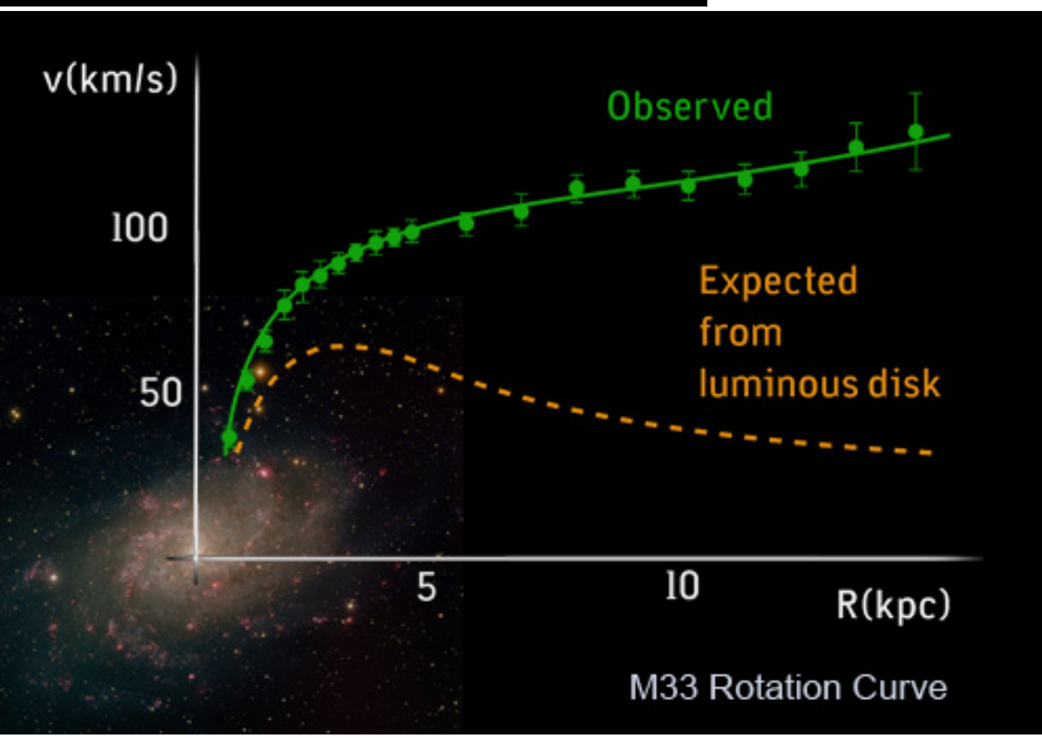
What is the Dark Matter ?

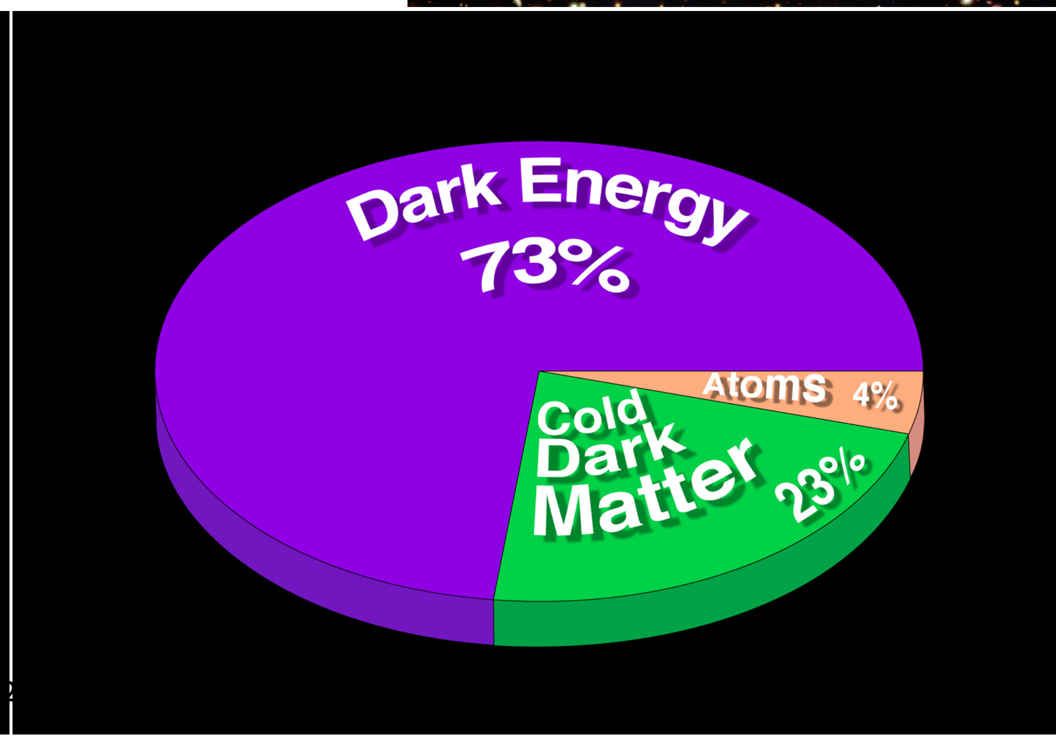
Existence of Dark Matter Supported by overwhelming indirect evidence







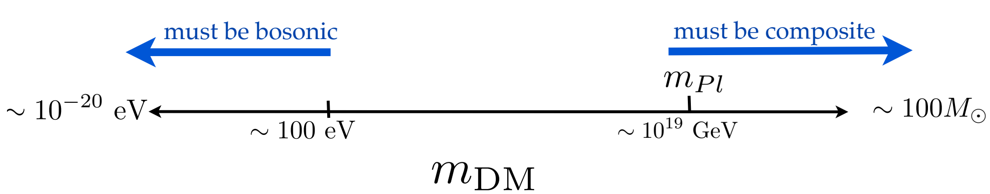


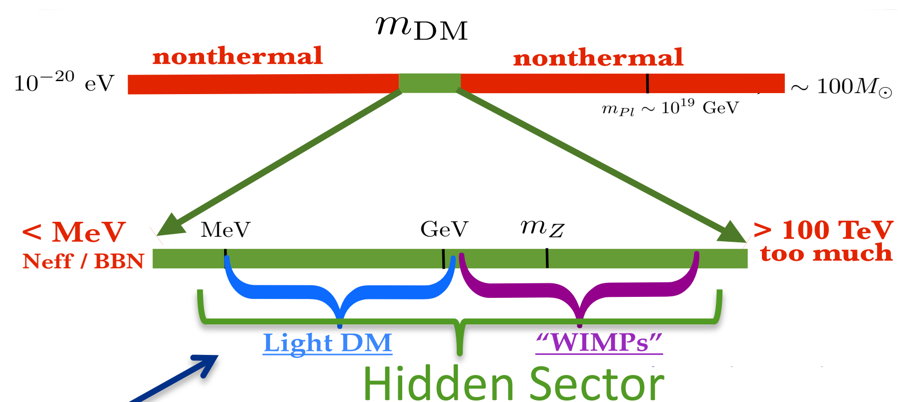


What do we know about Dark Matter ?

- very little -

- Couples gravitationally
- It is the most abundant form of matter
- It can be part of a larger invisible/dark sector with new dark forces
- It must be made of something different that all the particles we know, it can be made of particles or compact objects, or better described as wavelike disturbances
- Its mass can be anything from as light as 10^{-22} eV to as heavy as primordial black holes of tens of solar masses





Folding in assumptions about early Universe cosmology can provide some guidance

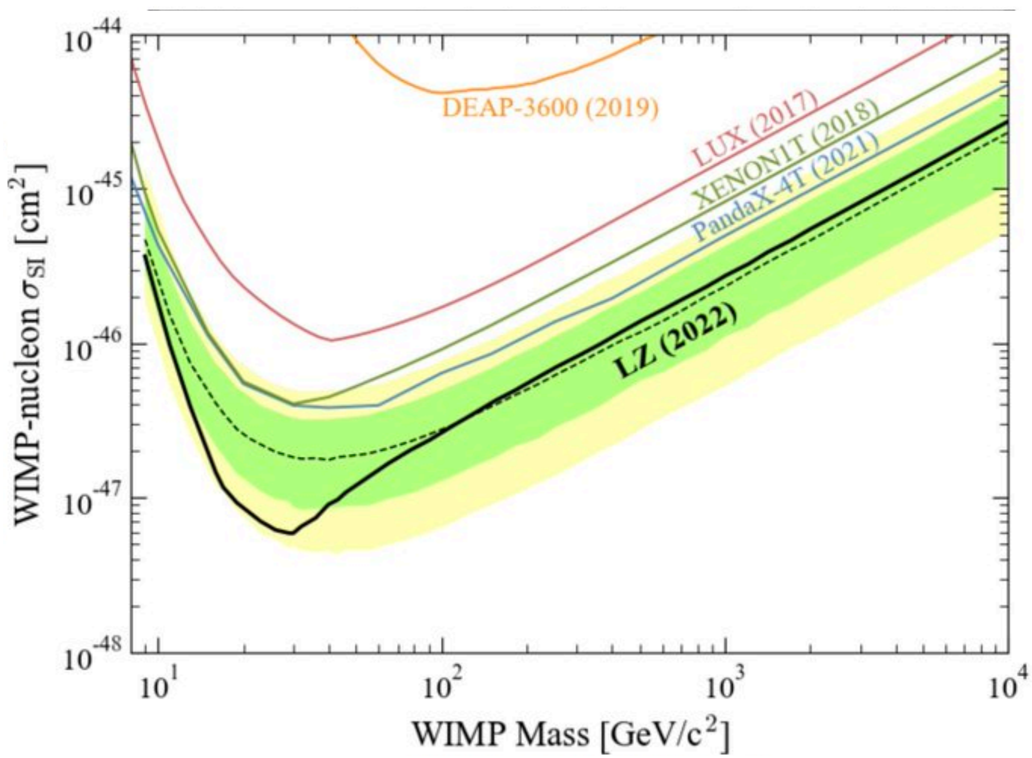
Theories abound. Some of them embedded in theories proposed to solve other problems !

T. Tait

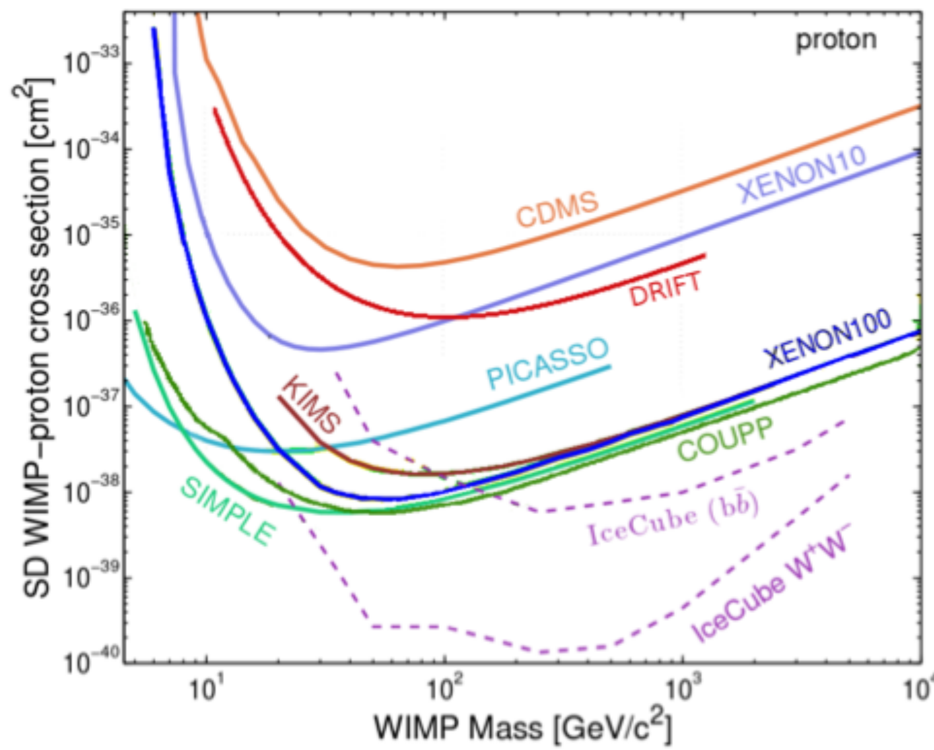
Current Bounds from Direct Dark Matter Detection

Current Limits

$$1\ \text{pb} = 10^{-36}\ \text{cm}^2, \qquad 1\ \text{zb} = 10^{-45}\ \text{cm}^2$$

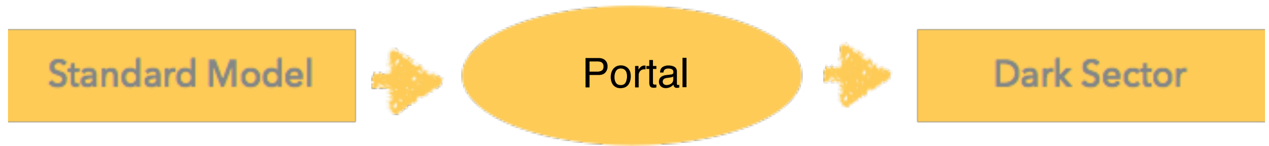


Spin Independent Interactions



Spin Dependent Interactions

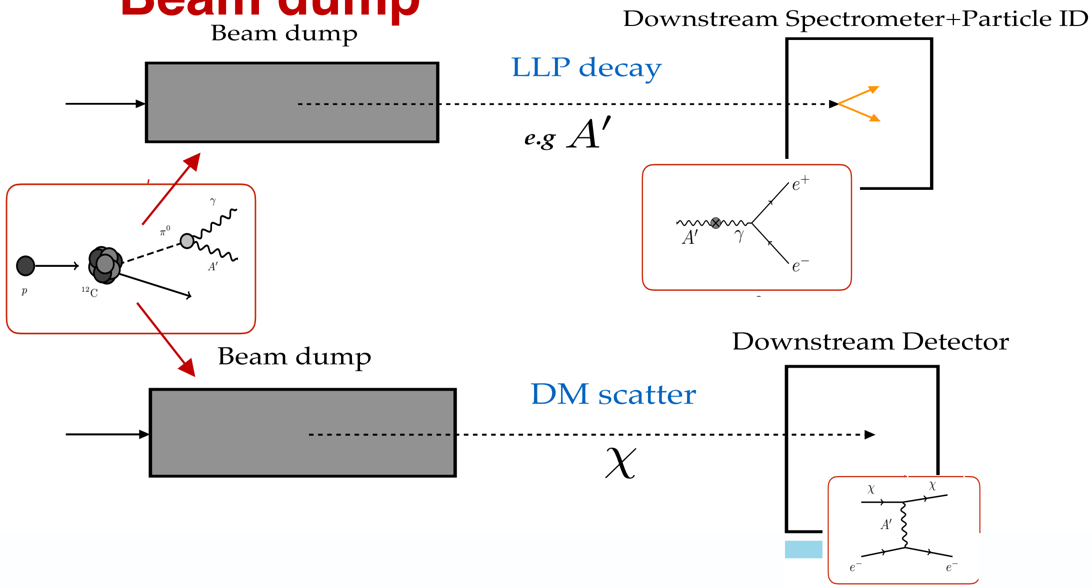
Entering a new era in exploring the Dark Sector:



Portals can be the Higgs itself or Feeble Interacting Particles (FIPs):
Dark photon, Dark Higgs, Heavy Neutral Leptons, Axion-like particles, Millicharged particles

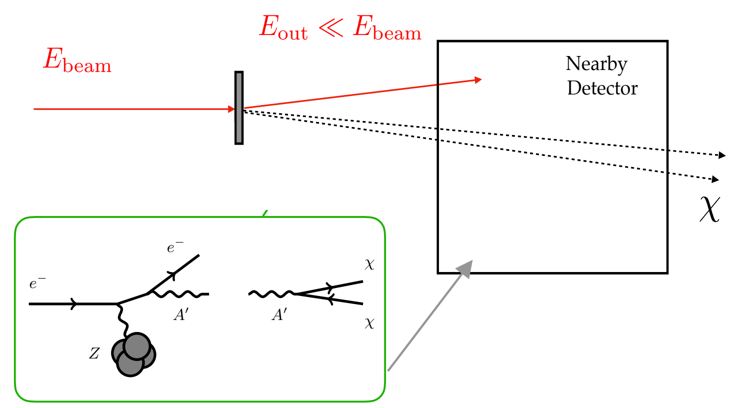
Accelerator based searches for MeV-GeV dark matter with lepton or proton beams

Beam dump



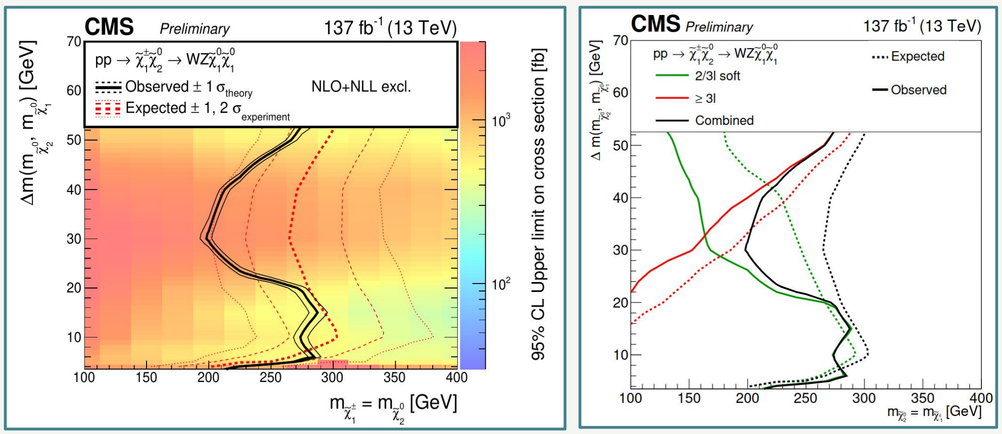
Fixed target: Missing Energy/Momentum

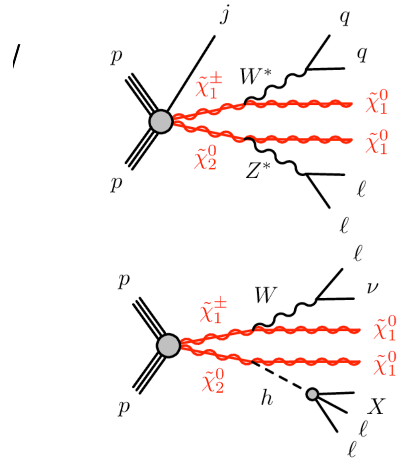
The electron or muon beam is the signal

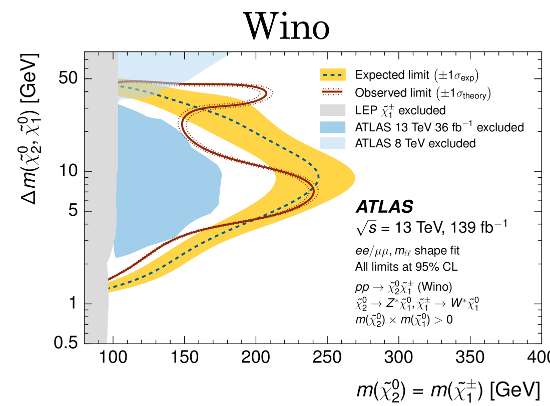


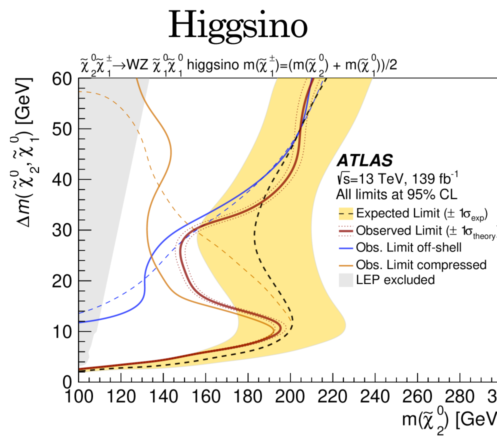
There may be surprises, like in collider searches

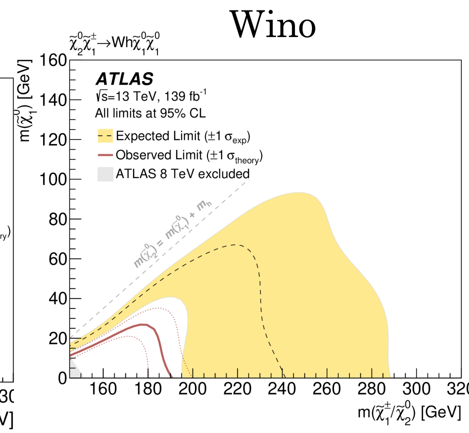
- The 2/3l soft and ≥3l analyses complement each other in the compressed region
  - Orthogonal lepton p_T ranges but different selections (e.g. MET for 2/3l soft) → Challenging to be fully optimal in the crossover regime







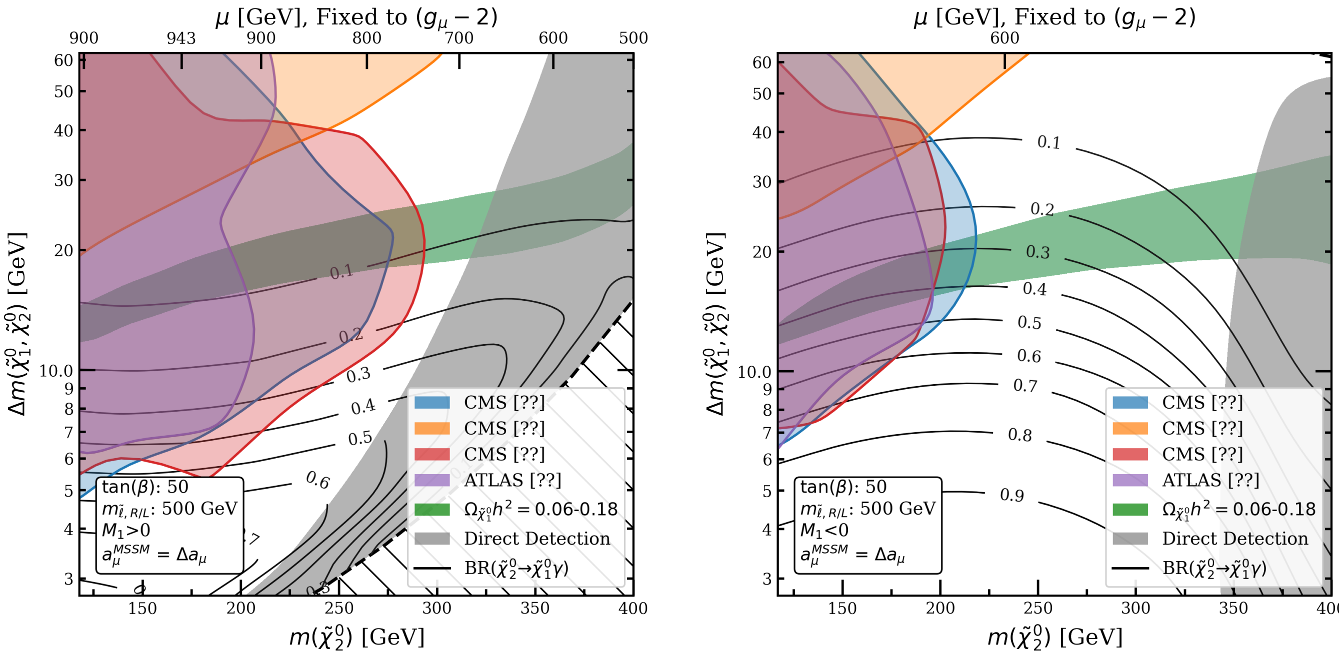




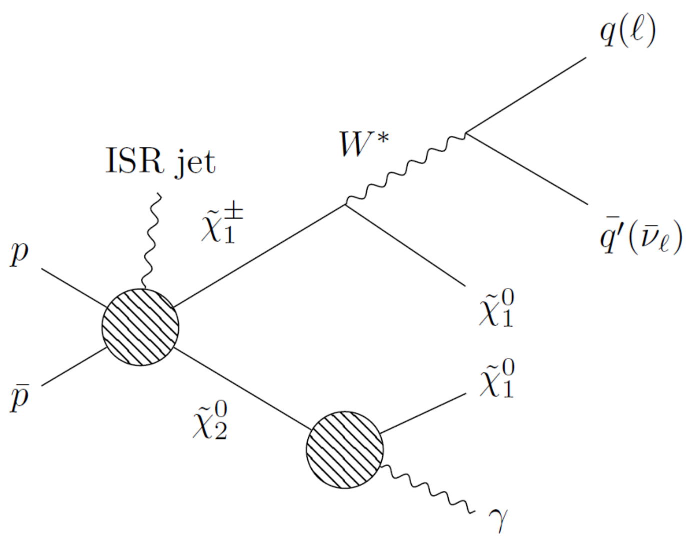
Excesses in regions consistent with co-annihilating Dark Matter

Same region of Parameters

S. Baum, M. Carena, N. Shah, C. Wagner'21
D. Rocha, T. Ou, 2305.02354,
S. Roy, C.W., 2401.08917



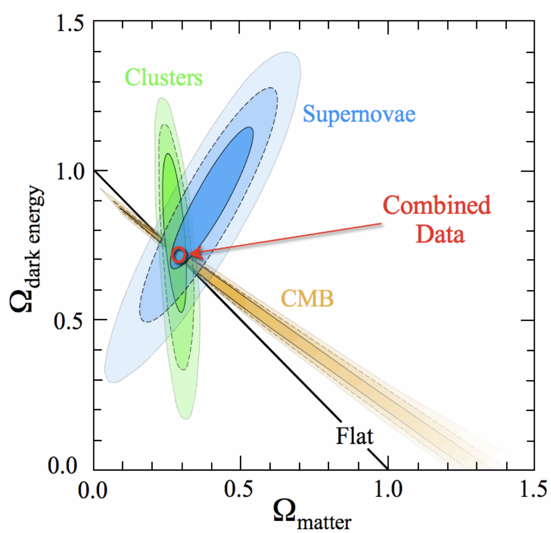
Large regions of parameter space that can be probed at the LHC for negative M_1

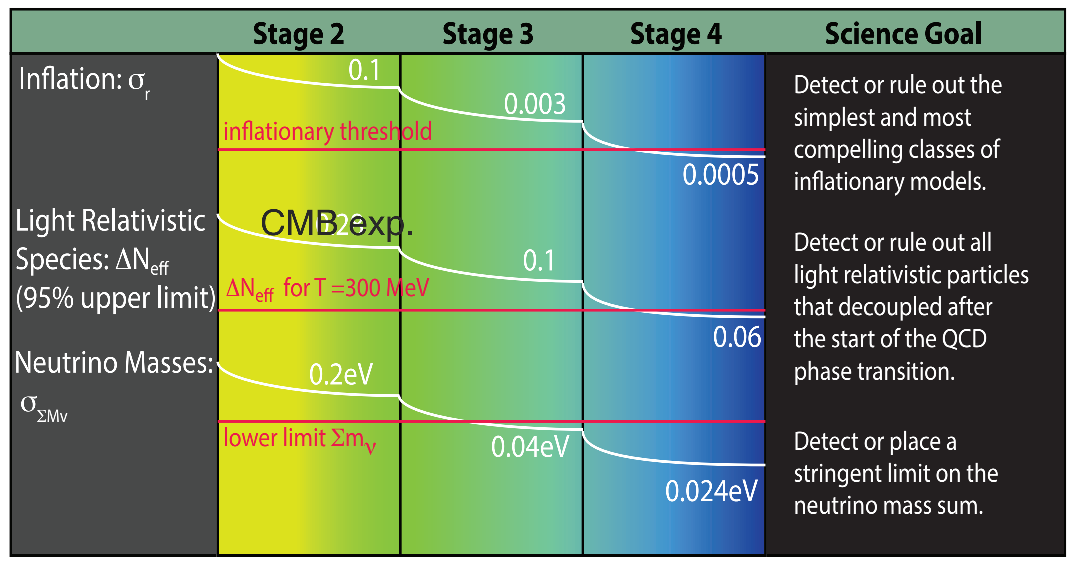


Enhanced radiative decays into photons provide a novel signature

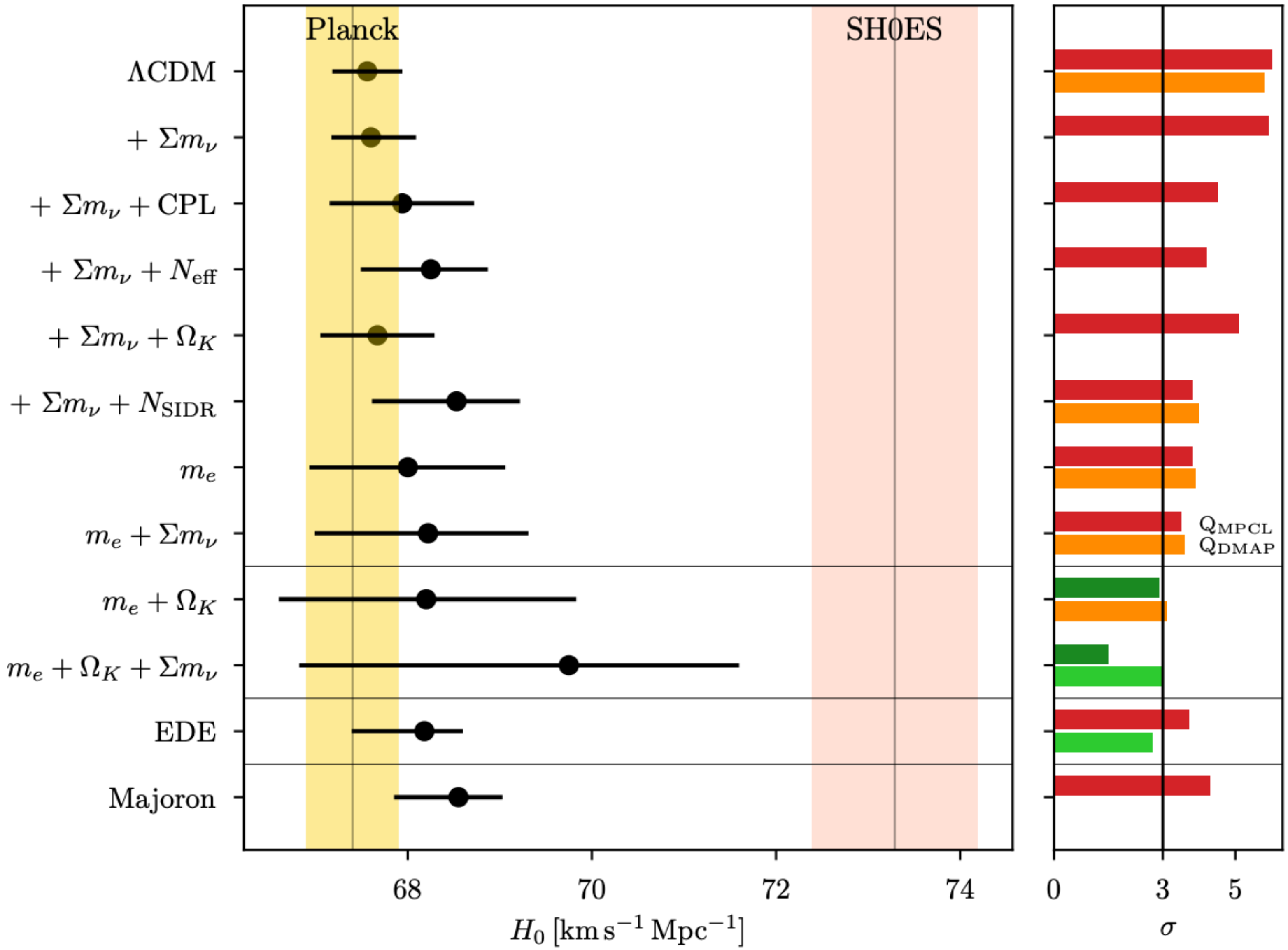
Cosmological probes

- CMB observations provide the most direct access to inflation, and also inform us about neutrino mass, N_{eff} (light relics), dark energy and the Hubble constant
- Cosmic surveys study dark energy/modify gravity, dark matter (gravitational and non-gravitational interactions), neutrinos and inflation through various probes of the geometry, expansion history and structure of the universe. They also tell us where to look for indirect dark matter signals



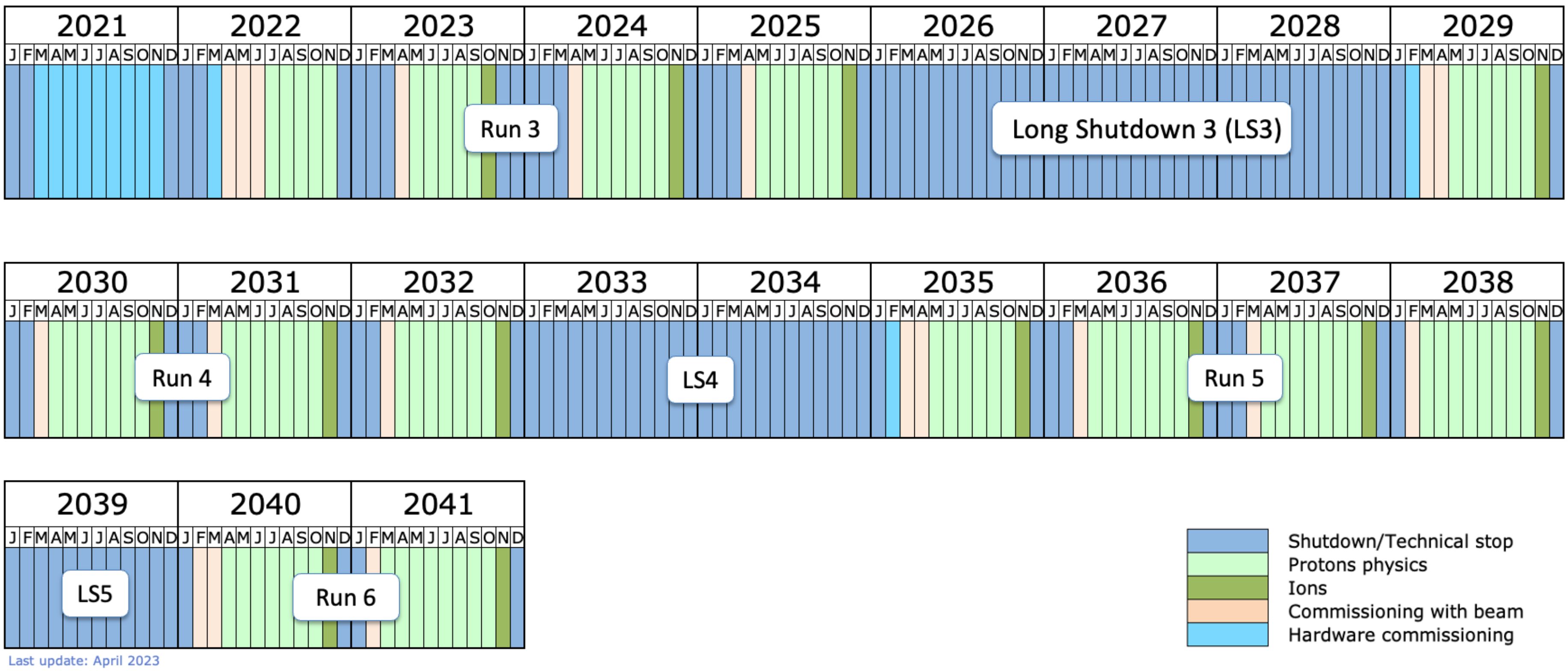


Hubble Tension still unexplained



The Future of Particle Physics

Current LHC Schedule



I personally believe that, even ignoring delays, this schedule is uncertain after 2032

HEP landscape in 2032: LHC

HL-LHC will have been running for a few years with upgraded detectors

Many discoveries possible by this time from the mature LHC dataset:

- Higgs cousins of many types (like in SUSY) with many possible implications
- Dark matter, dark sector, feebly-interacting particles, long-lived particles
- New forces (gauge bosons)
- New kinds of fermions
- Higgs boson is composite
- Higgs flavor violation, Higgs CP violation
- Etc.

HEP landscape in 2032: Neutrinos

NOvA, SBN, JUNO, T2K, experiments all complete:

- SBN results will make a definite statement about the MiniBooNE anomaly and its many possible BSM interpretations – a variety of discoveries possible
- Mass ordering may be known at 5 sigma from global fits including NOvA, T2K, JUNO.
- CP violation will still be uncertain

DUNE will have started (also HyperK?), with dozens of DUNE analyses looking for:

CP violation, mass hierarchy, light and boosted dark matter, dark neutrinos and neutrino magnetic moments, tau neutrino physics, heavy neutral leptons, supernova neutrinos,

HEP landscape in 2032: Muons

Muon g-2 unambiguous endgame:

- The experimental value already is in solid grounds and will be even more precise
- The J-PARC muon g-2/EDM experiment will have an independent measurement
- The theory prediction will not be in doubt
- If the current large discrepancy holds:
  - This is a Nobel Prize
  - Will require new particles and/or forces
  - Other experiments, e.g., LHC, beam dump (NA62) and missing momentum exp., Belle2, CMB-S4, etc, will have narrowed down many of the possibilities

Mu2e will be running and could have an emerging discovery of lepton flavor violation

HEP landscape in 2032: Dark Matter

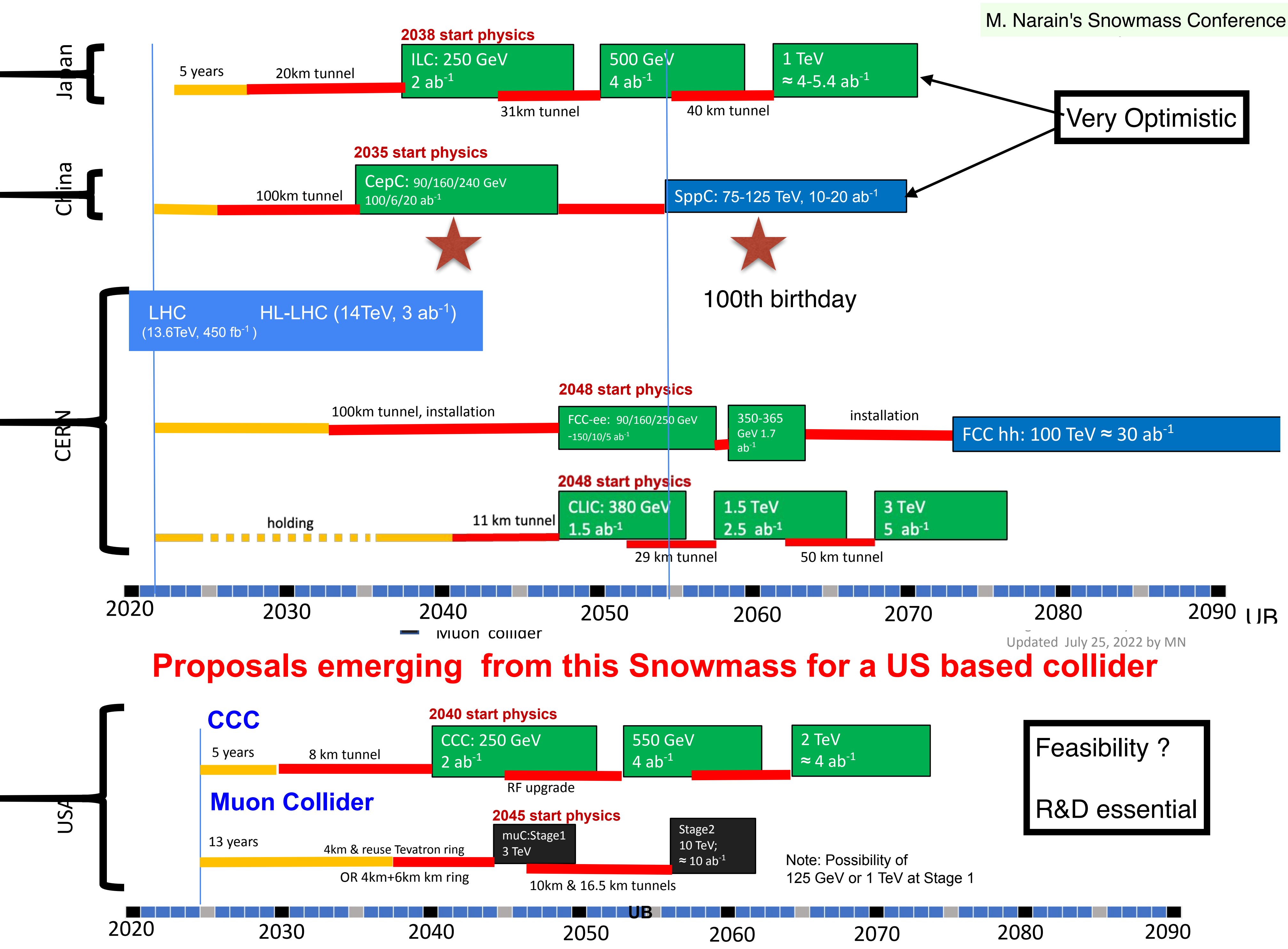
- Current direct dark matter searches LZ, ADMX, SuperCDMS, XENON-nT, PandaX-4T, ALPS II, SENSEI will be done: could have discovered one or more kinds of DM particles
- One or more very large G3 Xenon/Argon experiments may have launched (e.g., DARWIN/DarkSide-20k).
- A full and varied slate of dark matter new initiatives for light DM will be in mature stages (including ADMX-EFR, OSCURA, MAGIS-100, Dark SRF++): any discovery?
- New concepts for direct detection under development now (some leveraging synergies with the quantum initiative and accelerators) could be deployed before 2032.
- Some fixed target accelerator-based experiments running or complete: NA62 and NA64 (CERN), LDMX (SLAC), HPS and BDX (JLAB): did we discover anything?
- A discovery in direct detection experiments, LHC, SBN, DUNE, other accelerator-based searches, indirect dark matter searches, cosmic probes of DM will have immediate implications for all other techniques. Applies both to DM and dark sector mediators/forces

HEP landscape 2032: Cosmic

- SPT-3G – Currently in operation. Data will be analyzed
- CMB-S4 - Currently in the design phase. Scheduled to start in ~ 2030
- DES – Final cosmology results will be done; best measurements of dark energy
- DESI - Currently operating 5-year program; final results will be out, possible extended run
- Rubin/LSST – Several years of operation

By 2032 we could have learned about

- Primordial B-modes either observed or better constrained
- Dark energy is dynamical
- Something new about dark matter properties
- Solidify the Hubble tension
- Measure or constrain neutrino masses
- Better measurement of N_{eff} (relevant for light relics)



M. Narain's Snowmass Conference
Japan
2038 start physics
5 years
20km tunnel
ILC: 250 GeV
2 ab^{-1}
31km tunnel
500 GeV
4 ab^{-1}
40 km tunnel
1 TeV
≈ 4-5.4 ab^{-1}
Very Optimistic
China
2035 start physics
100km tunnel
CepC: 90/160/240 GeV
100/6/20 ab^{-1}
SppC: 75-125 TeV, 10-20 ab^{-1}
100th birthday
CERN
LHC
(13.6TeV, 450 fb^{-1})
HL-LHC (14TeV, 3 ab^{-1})
2048 start physics
100km tunnel, installation
FCC-ee: 90/160/250 GeV
~150/10/5 ab^{-1}
350-365
GeV 1.7
ab^{-1}
installation
FCC hh: 100 TeV ≈ 30 ab^{-1}
2048 start physics
holding
11 km tunnel
CLIC: 380 GeV
1.5 ab^{-1}
29 km tunnel
1.5 TeV
2.5 ab^{-1}
50 km tunnel
3 TeV
5 ab^{-1}
2020
2030
2040
2050
2060
2070
2080
2090
Updated July 25, 2022 by MN
Proposals emerging from this Snowmass for a US based collider
USA
CCC
2040 start physics
5 years
8 km tunnel
CCC: 250 GeV
2 ab^{-1}
RF upgrade
550 GeV
4 ab^{-1}
2 TeV
≈ 4 ab^{-1}
Feasibility ?
R&D essential
Muon Collider
2045 start physics
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
muC:Stage1
3 TeV
10km & 16.5 km tunnels
Stage2
10 TeV;
≈ 10 ab^{-1}
Note: Possibility of
125 GeV or 1 TeV at Stage 1
2020
2030
2040
2050
2060
2070
2080
2090

A word on the Muon Collider

It looks quite challenging…
But it is gathering momentum

A word on the Muon Collider

It looks quite challenging…
But it is gathering momentum

There is great enthusiasm from the young HEP community

A word on the Muon Collider

It looks quite challenging…
But it is gathering momentum

There is great enthusiasm from the young HEP community

It will happen, hopefully soon !

Great Future Experiment Planning

- Based on previous experience, we can hope for the realization of at least one of these collider projects
- CERN, for instance has an annual budget provided by the member countries for the sole purpose of doing basic research in particle physics !
- I don't have to tell you have amazing this is.
- Beyond colliders, many of the projects I mentioned before may be revolutionary, leading to a new era in our understanding of Particle Physics and Cosmology
- Let me finish by emphasizing that the fields of particle physics and cosmology have advanced through great theoretical ideas and amazing experimental results.
- Let me state some of what happened during my thirty five year long career in this field :

Advances in the last thirty five years

- 1991 : LEP measures precisely the weak couplings, solidifying the SM description and confirming the idea of unification of gauge couplings (with Supersymmetry)
- 1995 : Tevatron discovers the top quark. Its mass consistent with the idea of unification of (bottom and top) Yukawa couplings.
- 1998 : Super-Kamiokande confirms neutrino oscillations, consistent with neutrino masses.
- 1998/1999 : Accelerated expansion of the Universe observed.
- 2003/2009 : Planck (2009) CMB measurements improves WMAP (2003) ones and lead to results that a high level of precision is consistent with the existence of DM, DE and with what is today the SM of cosmology.
- 2012 : Higgs Particle discovered at the LHC. Its properties are being explored by the CMS and ATLAS collaborations.
- 2015 : Gravitational Waves detected. GW detectors may one day not only measure mergers, but also waves from violent phase transitions in the early Universe.
- 2021 : Confirmation of muon g-2 anomaly ??
- 2023 : PTAs signals consistent with the ones of supermassive blackhole mergers.

The Future of our Field is Uncertain, but it is certainly Bright

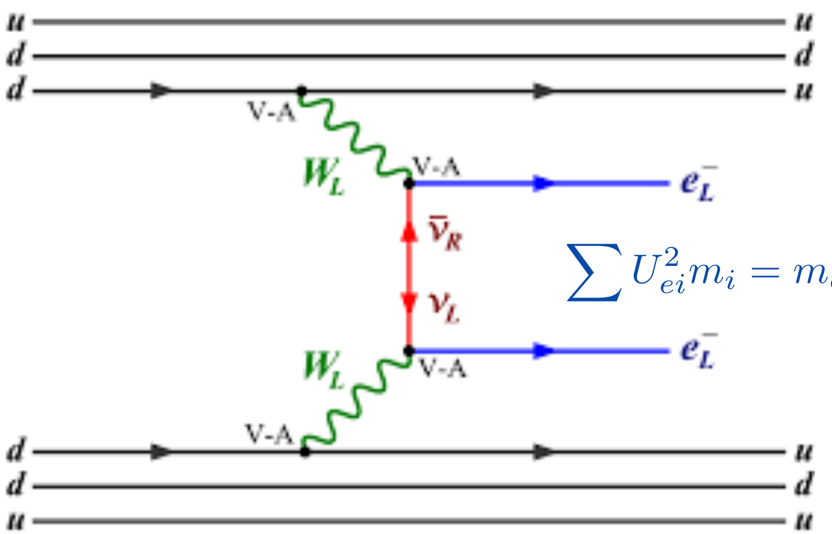
I wish all the young people in the audience as many advances in their career as the ones I witnessed.

History tells us that it will happen, but it will demand great ideas, hard work and of course financial resources

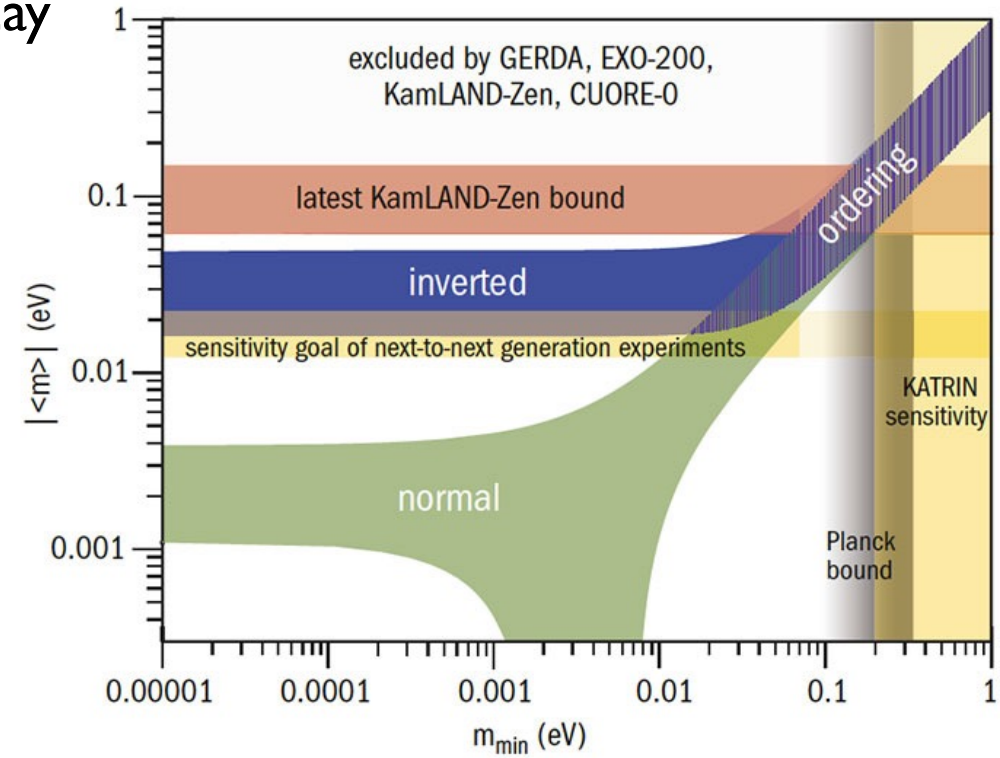
Thanks to the Organizers for this Great Conference !

Neutrino Oscillations demonstrate that neutrinos have mass and mix.
Are neutrinos there own antiparticle (Majorana)

Best test : Neutrino-less double beta decay



$$\sum U_{ei}^2 m_i = m_{ee}$$



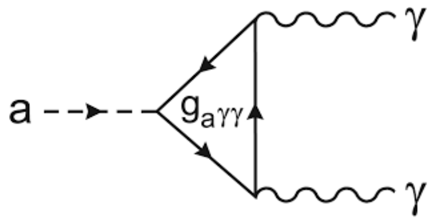
Half-Life Limits

EXO: $T_{1/2} > 1.1 \times 10^{25}$ yr (90% CL) ^{136}Xe WIPP
Nature, **510**, 229 (2014)

KamLAND-Zen: $T_{1/2} > 3.1 \times 10^{25}$ yr (90%CL) ^{136}Xe Kamioka
very preliminary

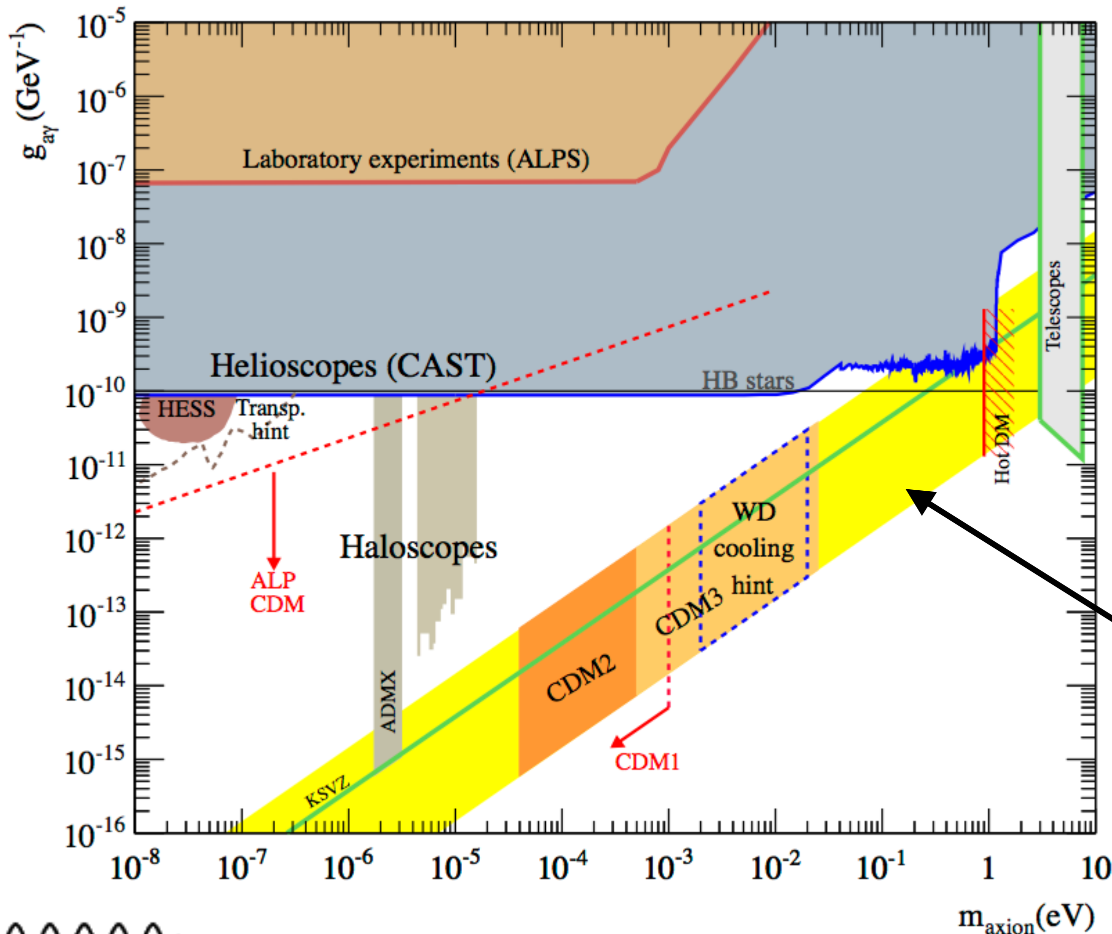
GERDA: $T_{1/2} > 2.1 \times 10^{25}$yr (90% CL) ^{76}Ge LNGS
PRL, 111, 122 (2013)

Standard Solution : Promote θ to be a field, a (axion), whose v.e.v is zero

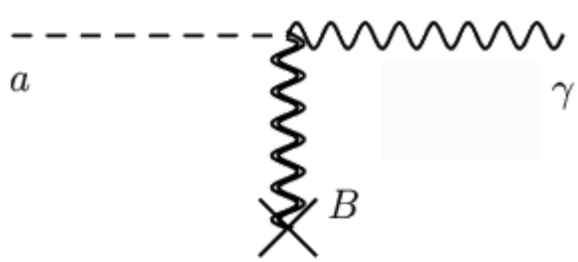


Axions : Solve the strong CP Problem
They are also a good CDM candidate

Axions produced in solar core (conversion to X Rays) : J. Collar



QCD Axion



Hallo Axions : Resonant Magnetic Cavity Searches