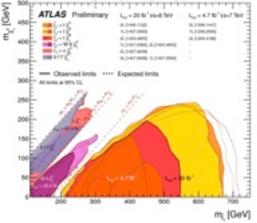
UNIVERSITÄT BONN

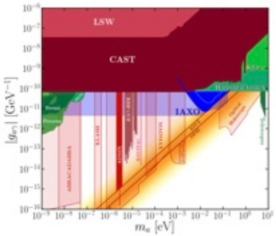
Matthias Schott

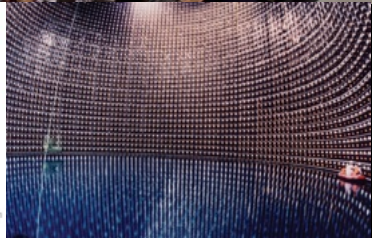
Particle Physics Is Not Over: It’s Just Getting Harder

www.jasonweissphotography.com

Predictions and Observations







- 1964: Prediction of the Higgs Mechanism
- 1973: Clear that top-quark should exist
- 1973/74: Supersymmetric Models
- 1974: Grand Unified Theories SU(5)
- 1977/78: First Axion Models
- 1983-85: WIMP Miracle
- 1990: Models with large extra dimensions

The Crisis of Particle Physics

- My main problems of the SM
  - Dark matter
  - Neutrino masses
  - Baryogenesis
  - Gravity
  - Fine-Tuning?
- SM can be consistently extrapolated to energies close to the Planck Scale without internal contradictions
  - So far no sign that the naturalness argument led to a validated theory
  - No reason to assume that the known problems need to be solved within the reach of the next collider

Do our critics have a point?

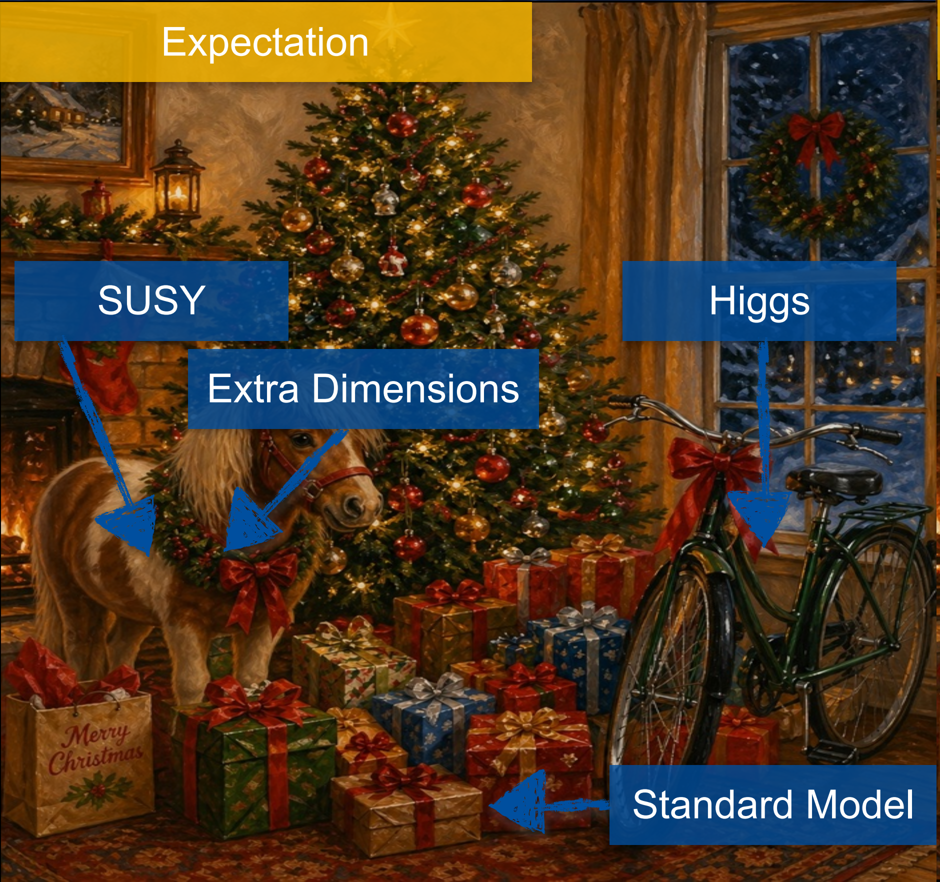
We promised too much!

Expectation

Christmas

Kids are sooo happy!

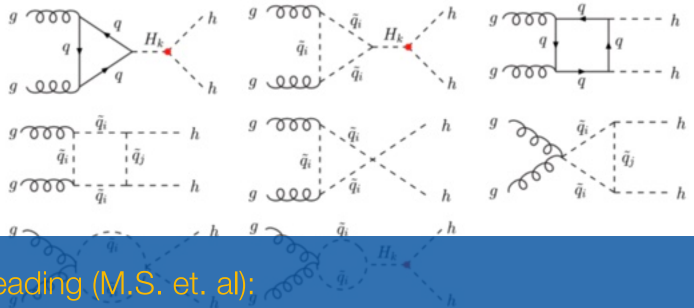
We promised too much!



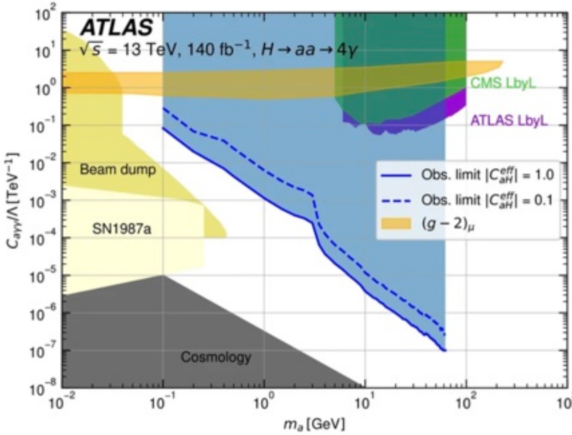
Worst Christmas ever

The Higgs as portal to new physics

- The Higgs is unique because it is a scalar:
  - It can couple to new, neutral states without charge constraints
    - Invisible decays (→ dark sector)
    - Exotic decays (long-lived particles, ALPs, …)
  - Is the Higgs a fundamental scalar? Or a bound state of new strong dynamics?



Further Reading (M.S. et. al):
https://arxiv.org/abs/2008.05355, https://arxiv.org/abs/2312.03306, https://arxiv.org/abs/2410.10363



Conso-
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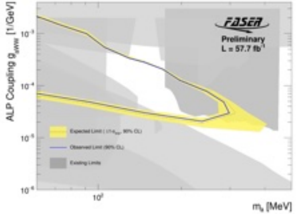
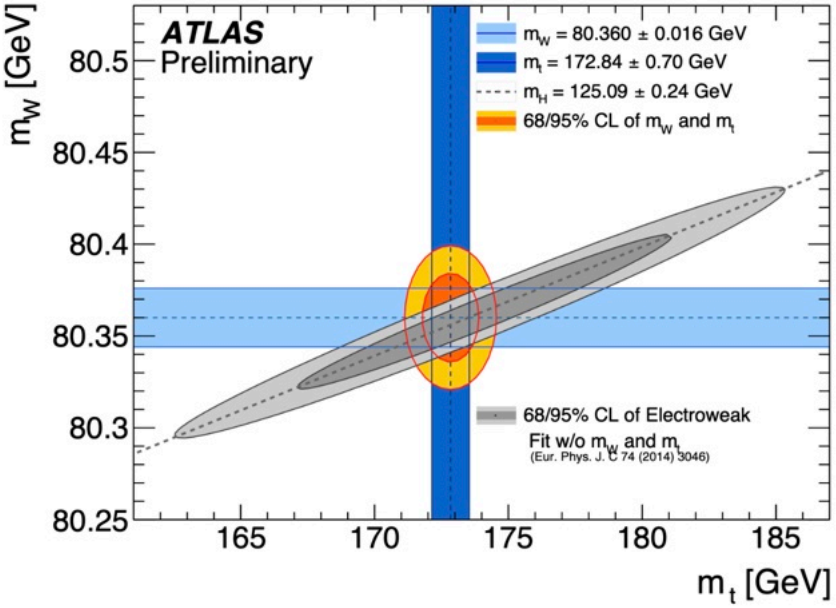


- Electroweak phase transition and cosmology
  - Is our vacuum is stable, metastable, or modified by new physics
  - Higgs potential governs early universe:
    - Determines the EW phase transition
    - Deviations from the SM Higgs potential enable electroweak baryogenesis

Model Agnostic High Precision Measurements



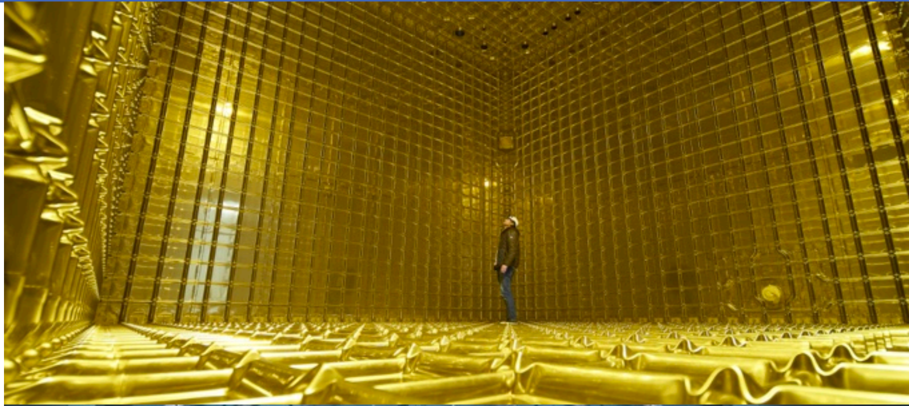
- Heavy BSM particles contribute to observables via quantum loops even if they cannot be produced on-shell

- Measuring an observable at the per-mille level can probe scales far above the collider energy

- Examples
  - W Boson mass: few MeV precision but lever arm in the TeV regime
  - Flavor-Physics Observables: Constraints often reach 10–100 TeV scales

Neutrinos are certainly new physics

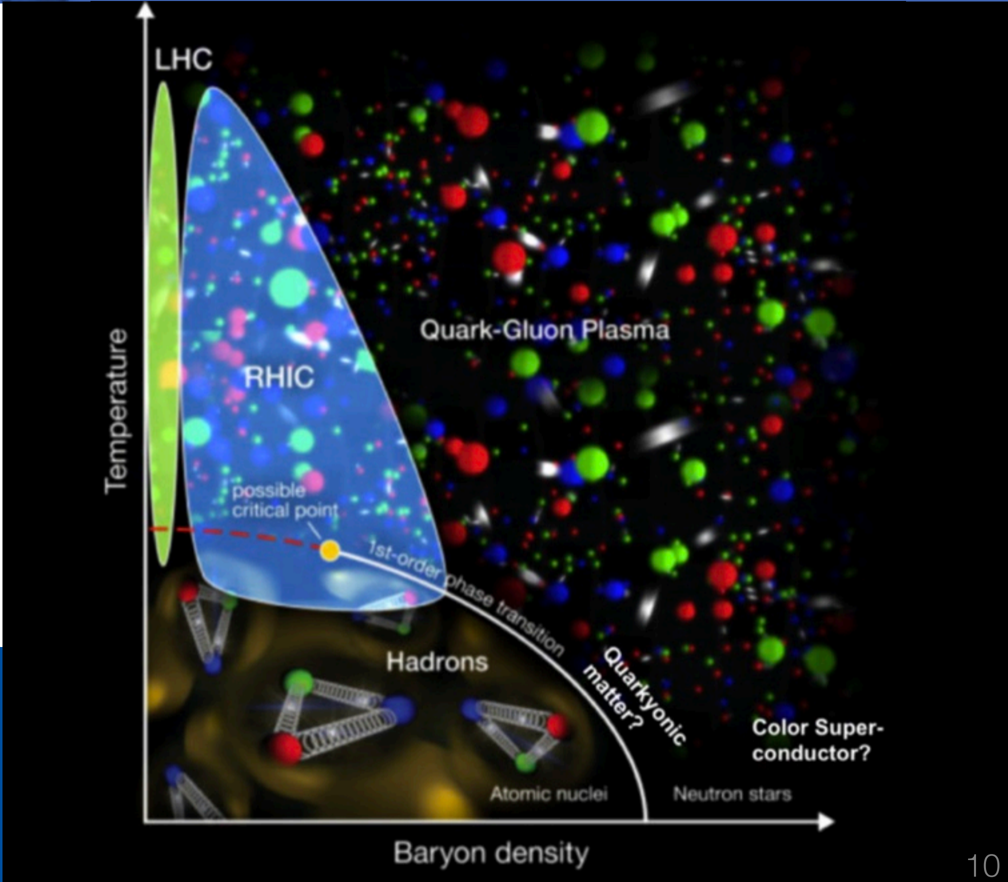
- Masses break the Standard Model
    - neutrino oscillation shows neutrinos have mass, which the SM cannot explain.
- Mass scale implies new mechanisms
    - tiny masses point to ideas like the seesaw mechanism and new heavy particles.
- New symmetries & cosmology links
    - Majorana neutrinos and leptogenesis connect to matter–antimatter asymmetry beyond the SM.

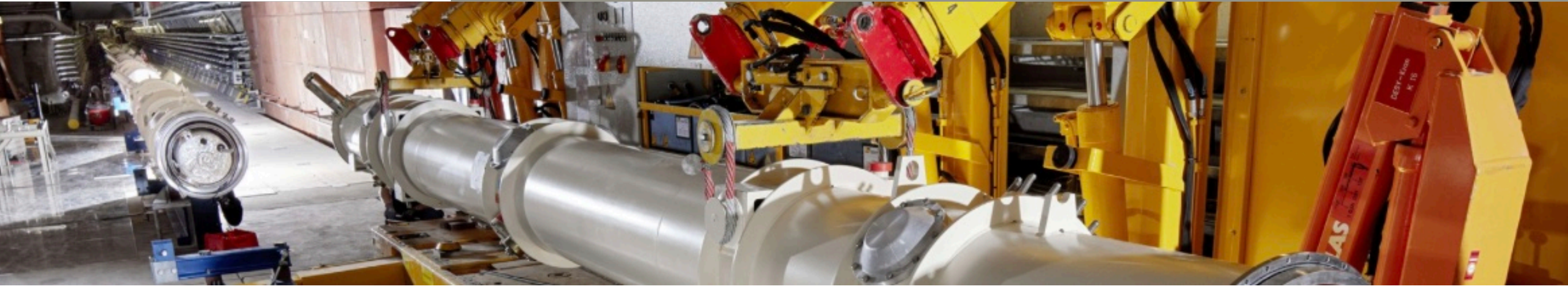


We don’t even understand Quantum Chromodynamics!

- conceptually well-defined and experimentally successful, but still deeply unresolved in its strongly coupled regime
    - Confinement
    - Strong CP problem
    - Non-perturbative dynamics
    - Hadron structure
    - QCD phase diagram
    - Jet formation and hadronization
    - …

- Particle physics is not over!
- Plenty of adventures and discoveries ahead of us
- It does not have to be extra dimensions …

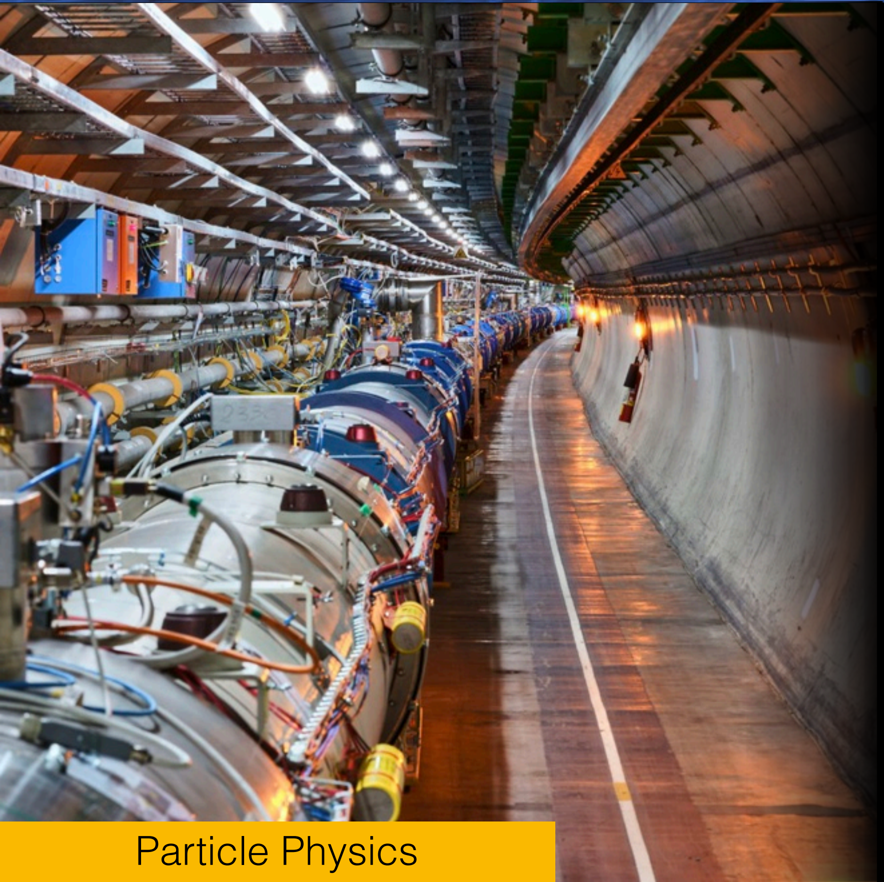




My Research

My Research Group in Bonn

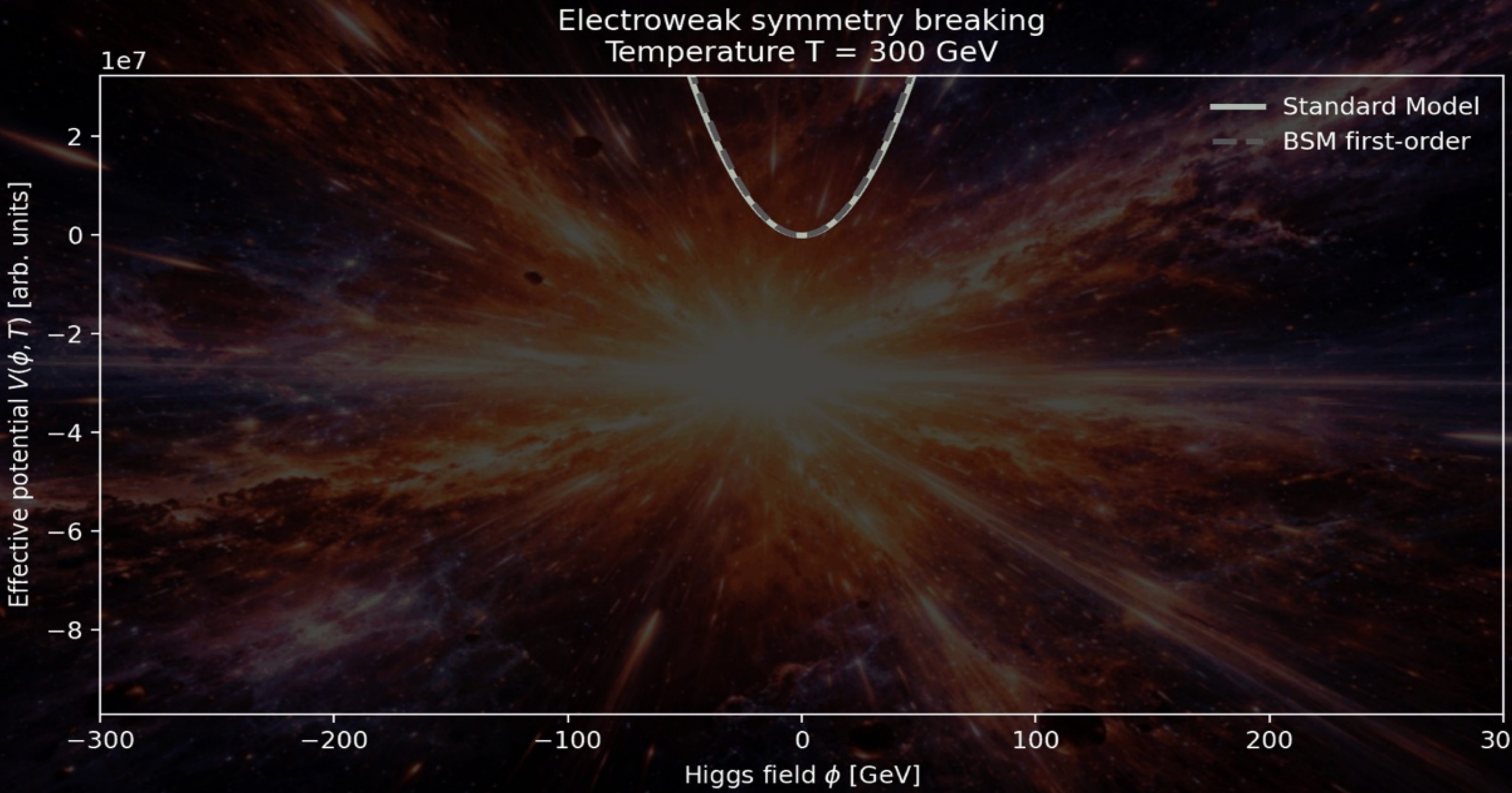
Between Particle Physics and Gravitational Waves



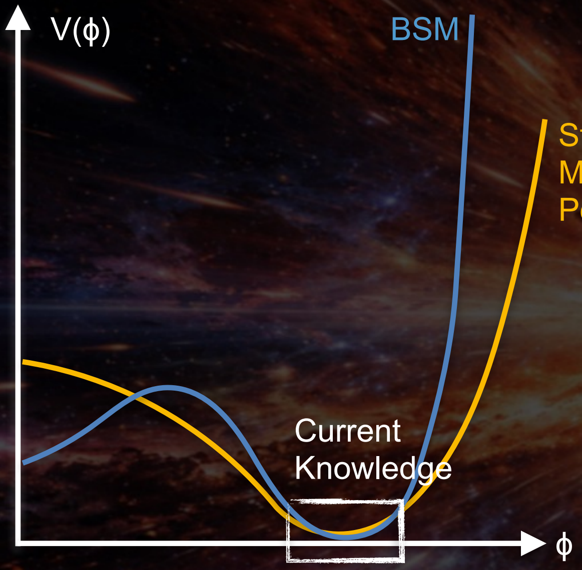
Particle Physics

Gravitational Waves

Electroweak Symmetry Breaking

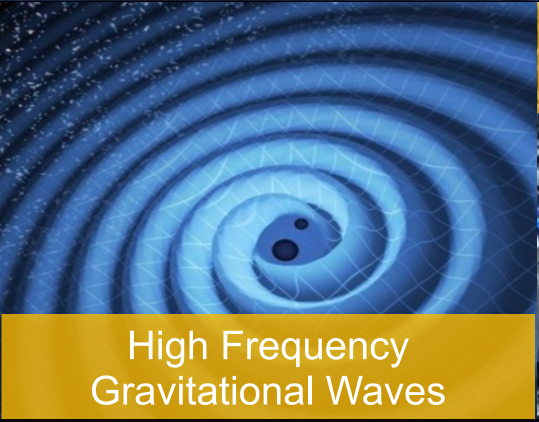


Electroweak Symmetry Breaking



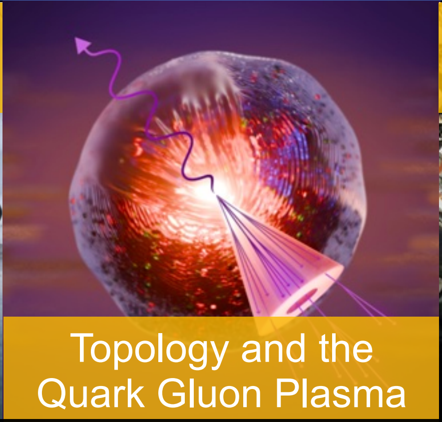
Higgs field value in our Universe

My Research in one Slide



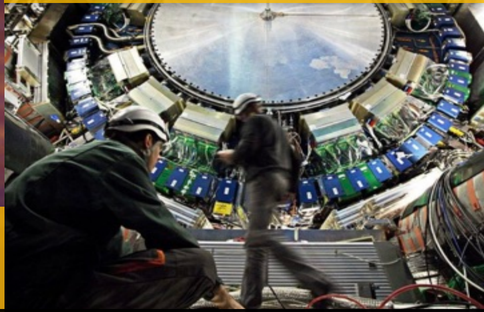
High Frequency Gravitational Waves

Neutrino Physics at Colliders



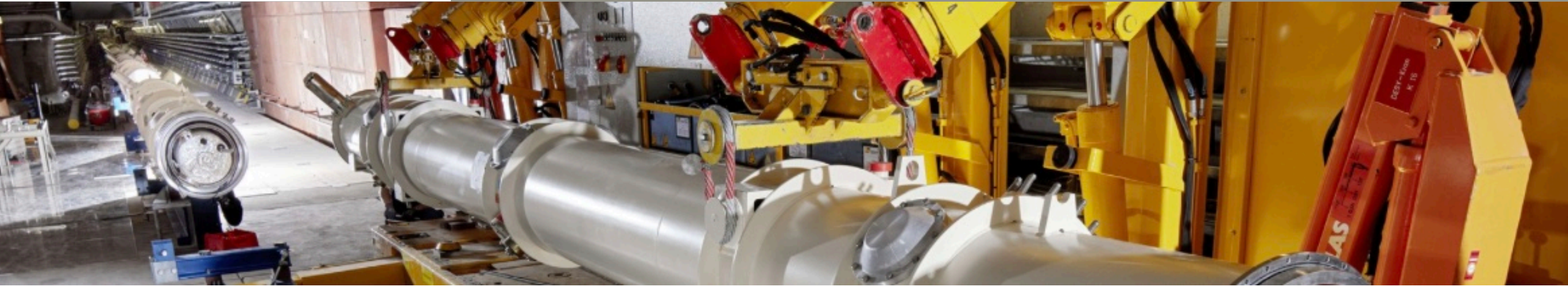
Topology and the Quark Gluon Plasma

(Electroweak) Precision Physics with ATLAS



I decide

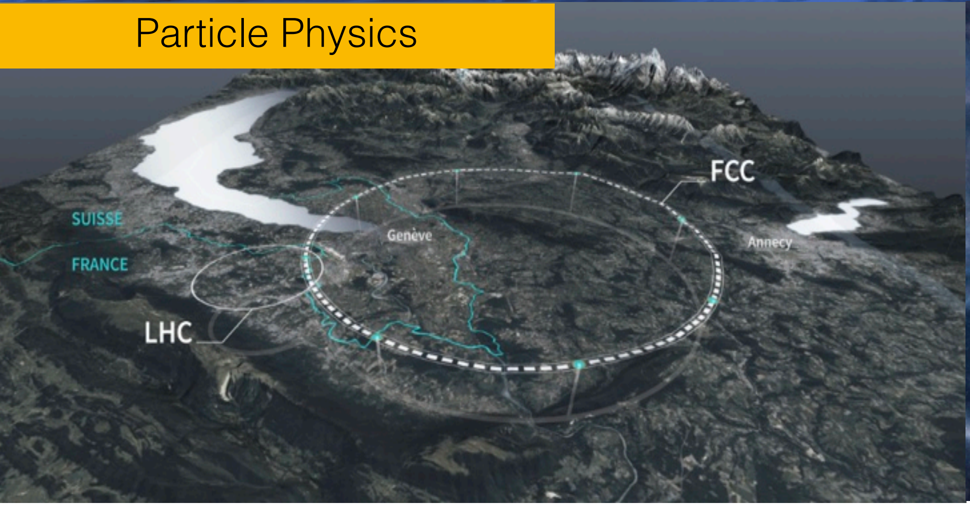
You decide



Searching for Gravitational Waves with Quantum Technologies

Probing the Higgs Potential

Particle Physics



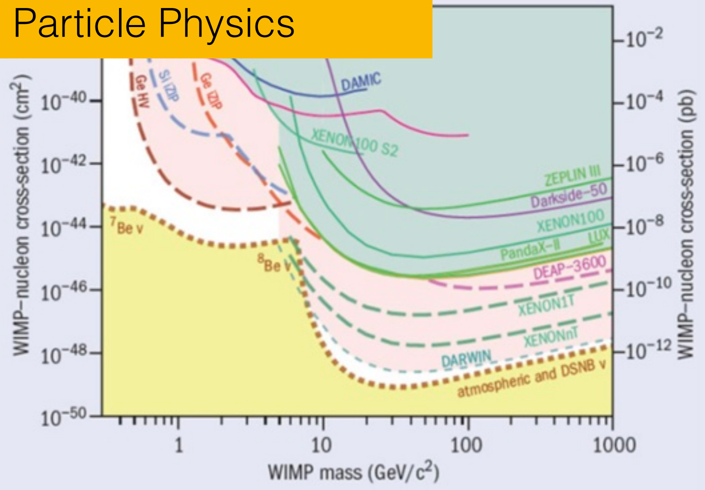
Gravitational Waves

- Build a new collider and measure the Higgs Boson self coupling

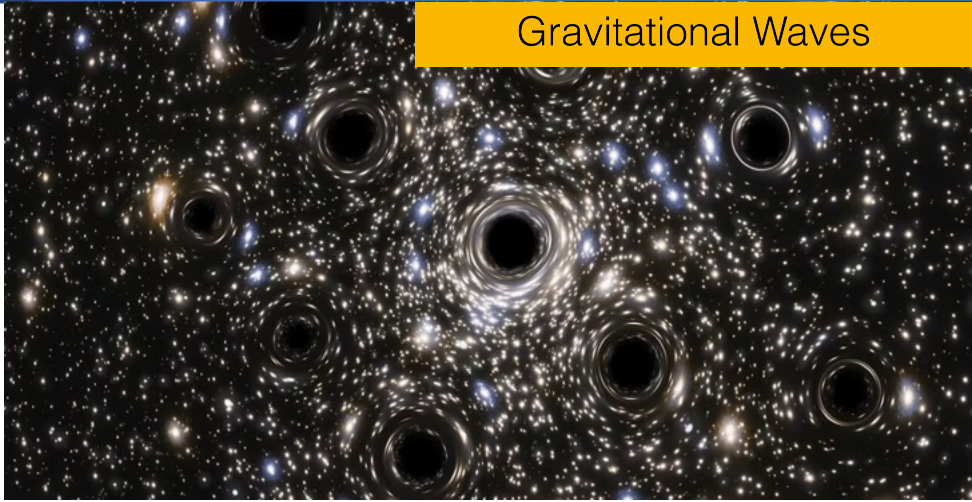
- The Higgs field changes rapidly at the wall of bubbles
  - Vacuum energy is converted into kinetic energy. This makes the wall an efficient GW radiator

Dark Matter

Particle Physics

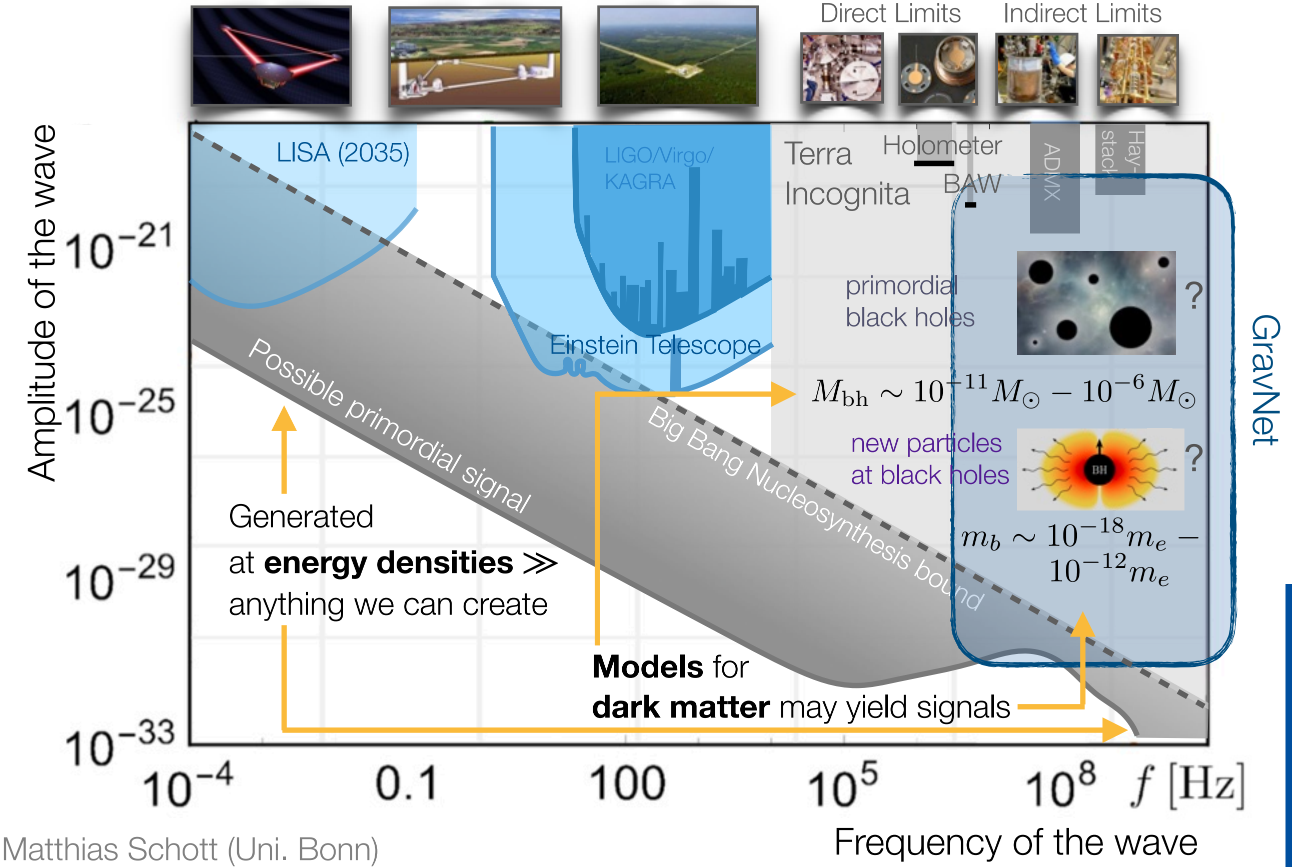


Gravitational Waves



- Dark Matter might be WIMPs
  - No indication of any WIMPs at the LHC nor at any other Experiment
- New Idea: Primordial black holes!
  - should be formed in the early universe
  - Small masses $10^{-20}\ M_\odot$ to $\geq 10^4\ M_\odot$!
  - Merges of primordial black holes emit High Frequency Gravitational Waves

Gravitational Wave Soundscape



Generated at **energy densities** ≫ anything we can create

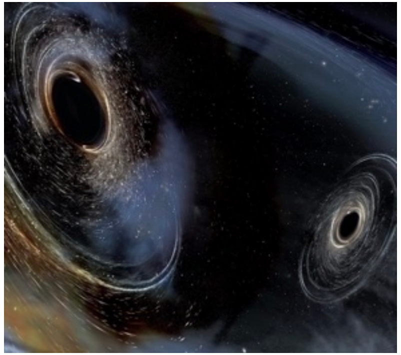
Models for **dark matter** may yield signals

- Interesting observations below 1kHz
- Very mild limits for
  - f =1 MHz - 10 GHz

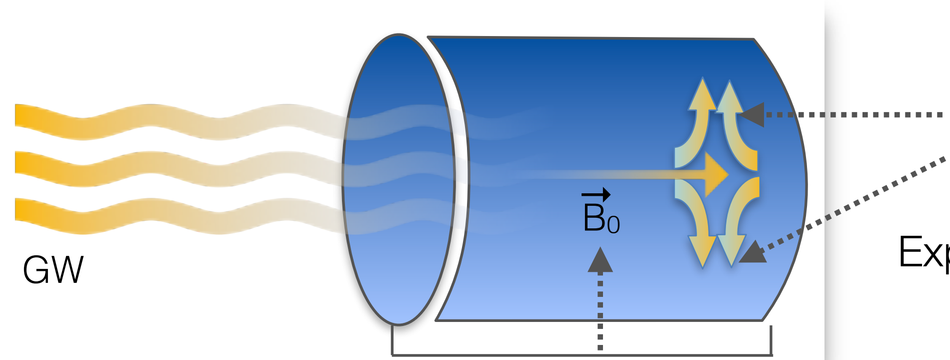
GravNet:
dedicated effort probing high-frequency gravitational waves with cavities

How to Detect High Frequency Gravitational Waves

- Gravitational waves convert to photons in presence of magnetic fields



Source

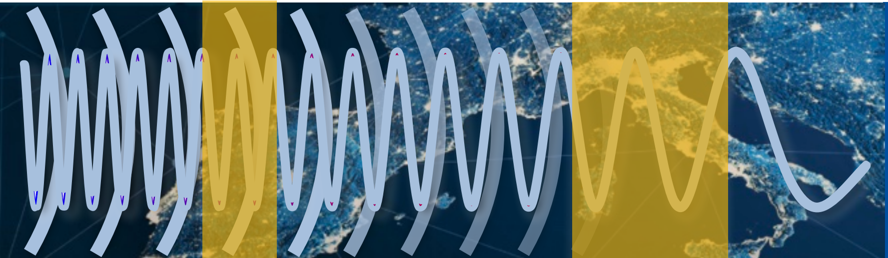


Photons generated at $f = f_{\mathrm{GW}}$

Expected signal power: $\ll 10^{-24}$ W

Strong static magnetic field

- If photon matches **resonance** frequency of cavity, signal is enhanced and **detectable**

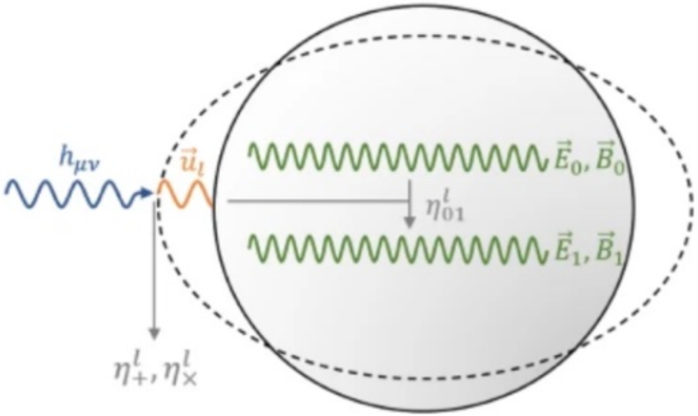


GravNet approach

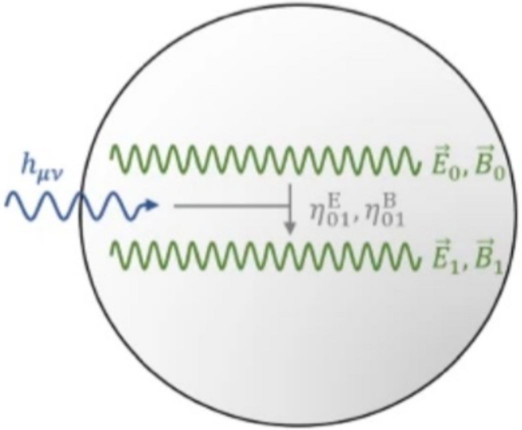
- HFGWs may sweep through frequency space
  - Focus on frequencies with best sensitivity!
- HFGWs yield coherent signals across Earth

GW Signals in electromagnetic cavities

- Mechanical coupling: GW leads to deformation of cavity boundaries
  - induces overlap between the initial eigenmodes.



- Direct coupling via the inverse Gertsenshtein effect: Conversion of GWs to EM waves in an external magnetic field



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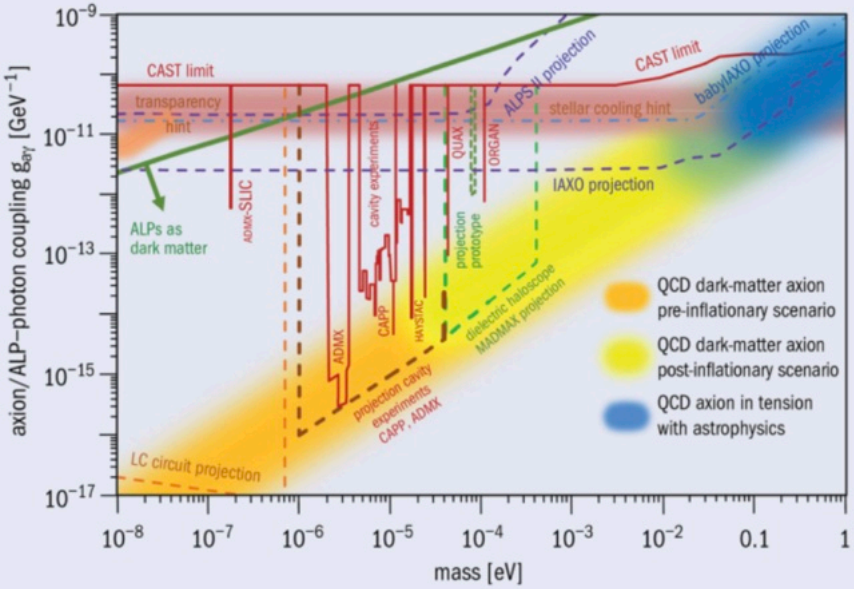
- EM coupling much weaker than mechanical coupling at low frequencies but dominant >1 GHz

Interplay: Searches for Axionic Dark Matter

- Axions could not only solve the strong CP Problem, but also good candidate for DM

- Several detection ideas
  - Light-through-Wall
  - Helioscopes
  - Colliders
  - …

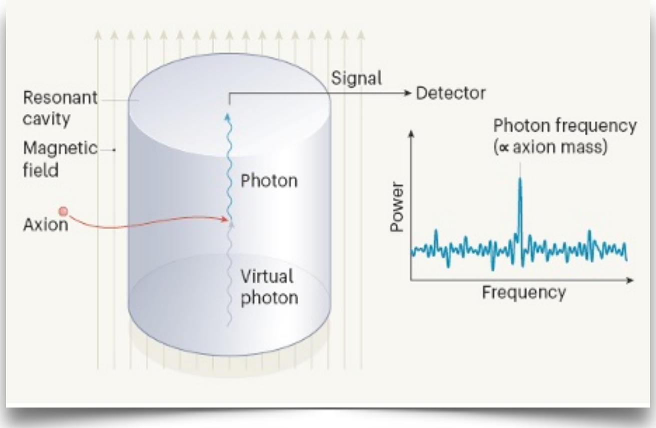
- Haloscope Experiments
  - Well-known approach: Cavity-based searches (among others: lumped circuits, spin-based haloscopes, antennas, …)
  - But also new broadband search concepts

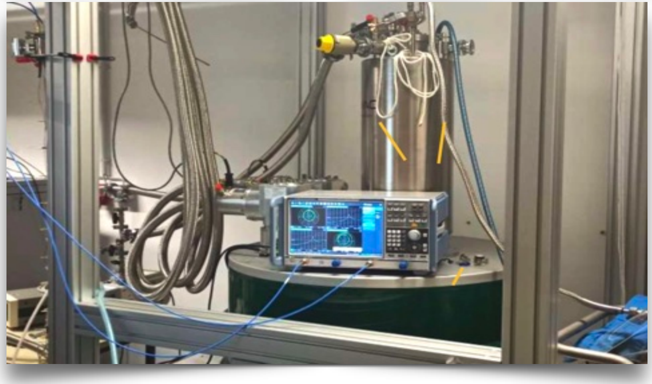


Cavity Based Searches

- Axion can convert into photon in a magnetic field within an EM-cavity
  - If axion mass corresponds to resonance frequency of the cavity
- Cavities transverse axion-field in galaxy
- Challenges
  - only sensitive at one frequency, i.e. need to make cavity tunable
  - Very small signal power (<10^{-24} W)

… well-established experimental method

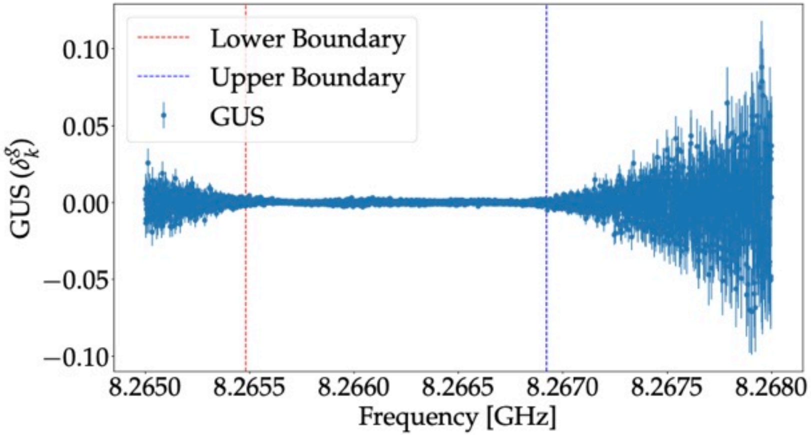


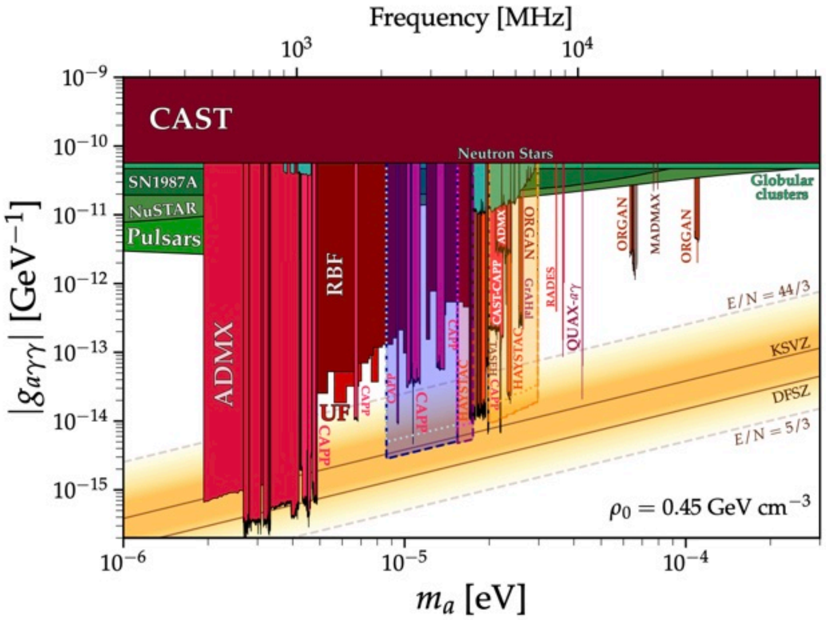


First Results from SUPAX

- SUPAX is our first experiment in Mainz
  - Search for ALPs between 2 GHz to 7.2 GHz
  - Moving to Bonn in winter 2026

- First Results: Exclusion of 8μeV and 30μeV.





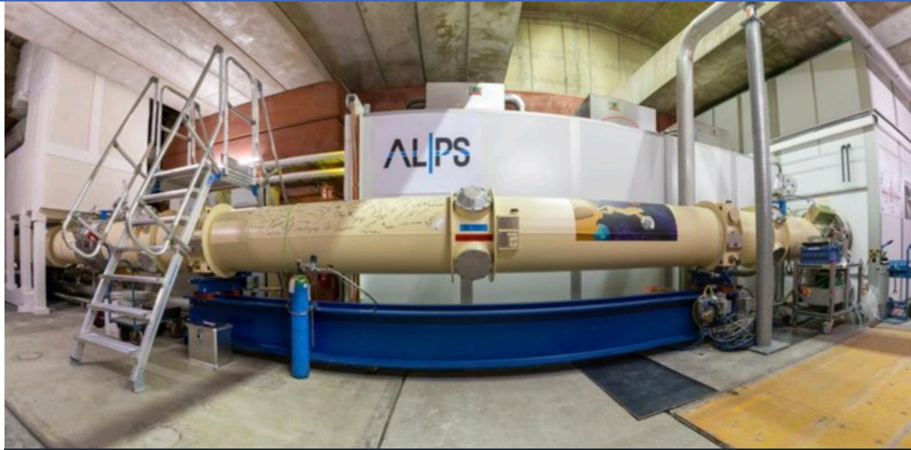
Further Reading (M.S. et. al):
https://arxiv.org/abs/2308.08337, https://arxiv.org/abs/2505.07541
https://arxiv.org/abs/2603.10943

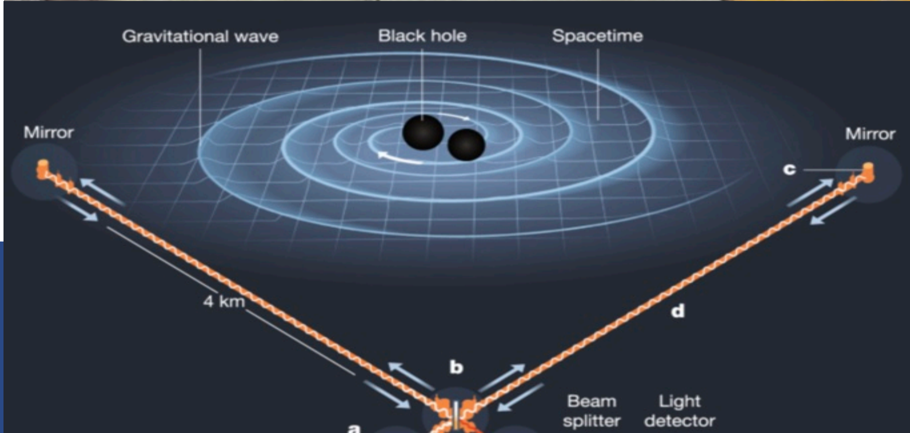
Going from Axions to Gravitational Waves

- Axion signal is different from HFGW signal
  - Duration
  - Coupling to the cavity and the magnetic field: orientation of the GW w.r.t. to B and cavity shape

- However, same technological challenges
  - High field magnets
  - Ultra low noise amplifier
  - Highly sensitive readout systems

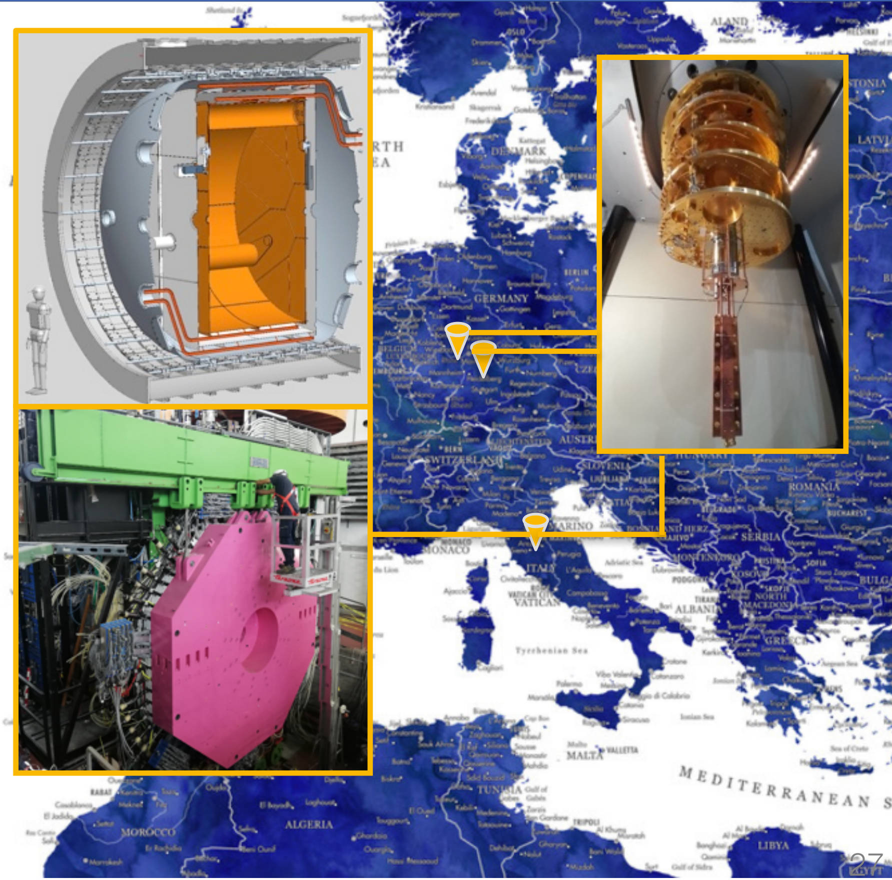
Everybody who searches for axions, typically can also search for HFGW





A Global Network of HFGW Detectors

- Starting point of GravNet
  - Initial sites: Bonn, Mainz, Rome
  - Technical synergies: magnets and local infrastructure already available
- GPS based data-acquisition scheme
  - Experience from GNOME Network
- Nine small resonant cavities (5-9 GHz)
  - operation of three cavities in one magnet
- One large resonant cavities (100 MHz)



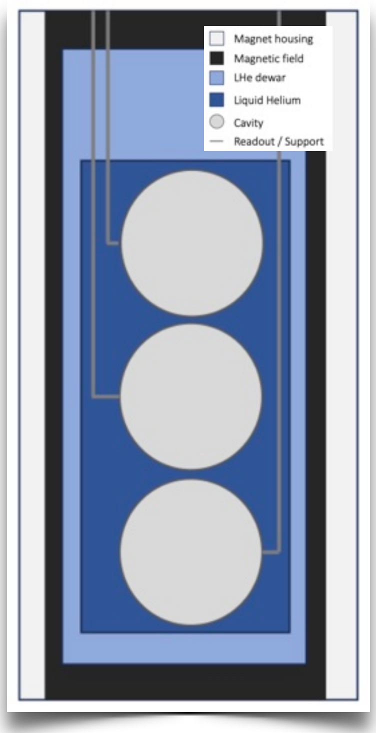
5-8 GHz Cavities

- High frequencies typically correspond to small volumes
  - Example: 8 GHz corresponds to a sphere of r≈5cm

- Challenge: Signal power depends nearly quadratically on V

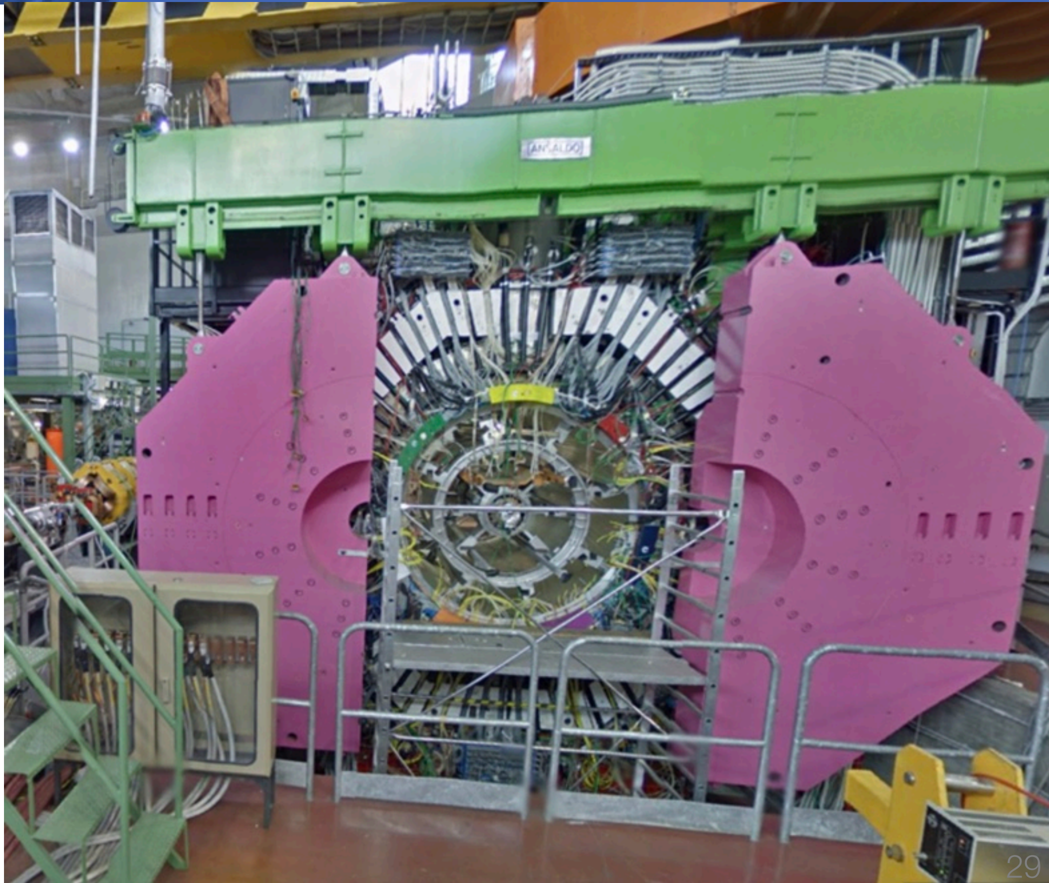
$$P_{sig} = \frac{1}{2} Q \omega_g^3 V^{5/3} (\eta_n h_0 B_0)^2 \frac{1}{\mu_0 c^2}$$

- Advantages
  - Higher Magnetic Fields
  - Single Photon Readout
  - Operation of several cavities in parallel



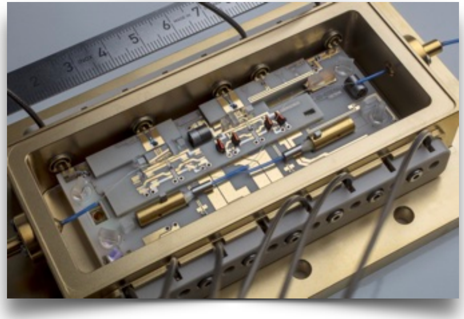
The FLASH Cavity

- Reuse of the FIDUNA magnet system at INFN Frascati within the FLASH Experiment
    - Axion Search (0.49-1.49 µeV)
    - Res. Frequency: 100-300 MHz
- Magnet Properties
    - $V = 4.15\ m^3$, $B=1.1T$
    - $Q_L = 1.4x10^5$,$T_{sys} = 4.9K$
- Readout
    - SQUID Readout
    - Limited by thermal noise



R&D Efforts

Drastically reduce noise in readout

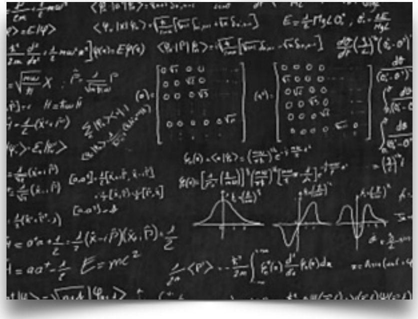


- Use of quantum sensing revolution
- Quantum non-demolition measurements
- Entanglement in two-qubit devices

Optimize Cavity

- Shape to improve coupling
- Enhance quality factor with superconductors

Optimize Data Analysis

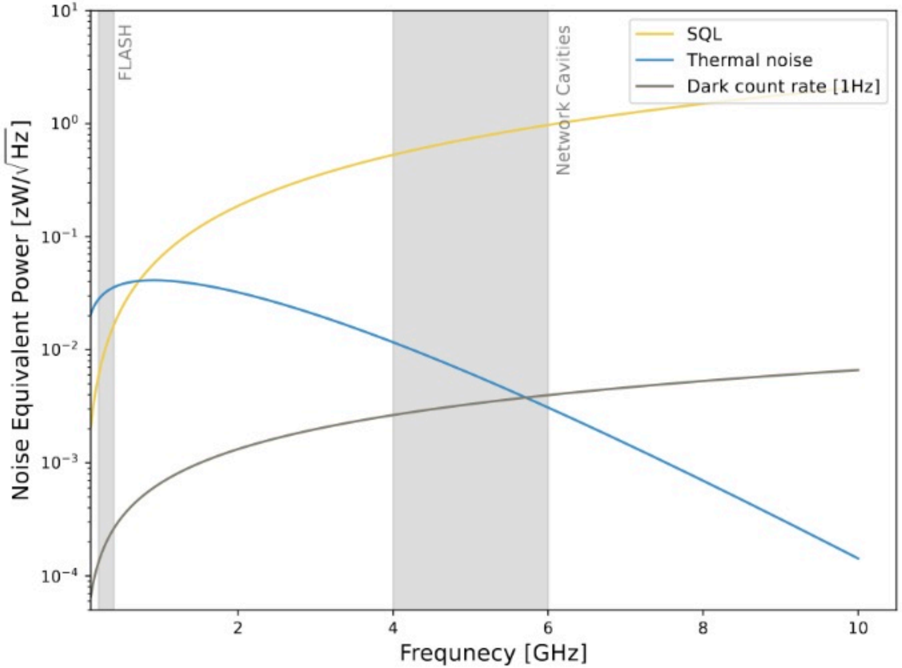


- Precise signal modelling
- Advanced neural networks for combined data analyses

GravNet Goal: gain in sensitivity to amplitude by O(100) - O(1000)

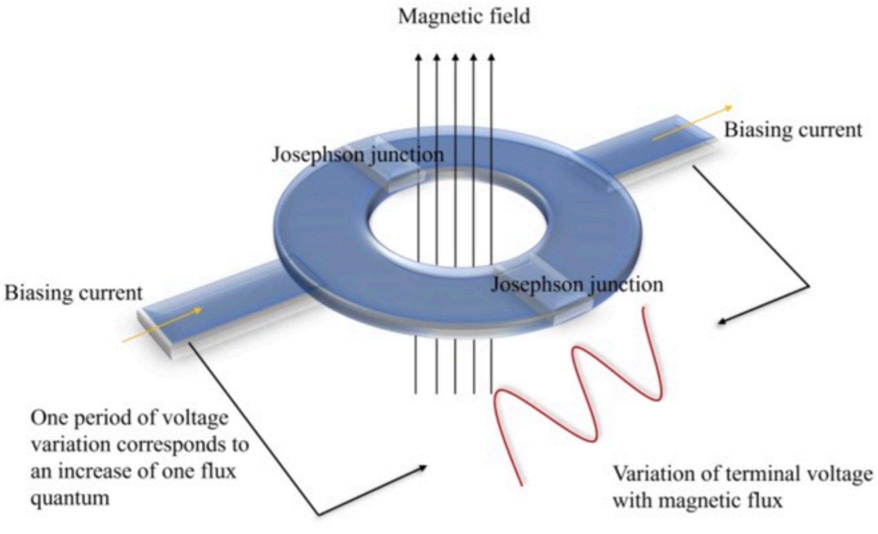
Noise at the Readout

- Quantum amplifiers (SQUIDs or JPAs)
  - Optimal for f < 1 GHz
  - Quantum noise (SQL) < 50 mK
- Quantum sensors based on superconducting qubits
  - Optimal for f > 1 GHz
  - Quantum noise (SQL) > 50 mK
- QS get dark counts to thermal limit
  - Quantum non-demolition measurements
  - Entanglement in two-qubit device



SQUID Readout

- A SQUID (Superconducting Quantum Interference Device) consists of:
    - A superconducting loop
    - Two Josephson junctions in parallel
    - A magnetic flux Φ passes through the loop.
- Signal flow
    - Input current or magnetic field
    - Converted into magnetic flux in SQUID loop
    - Flux changes junction phase
    - Phase changes critical current
    - Critical current change modifies voltage
    - Voltage variation is amplified output



- Where the Gain Comes From
    - Nonlinear Josephson relation I=Ic sinϕ
    - Flux-dependent interference between the two junctions
    - Steep voltage–flux slope at optimal bias point
- Microwave SQUID: 15–25 dB with input current of nA–100 nA

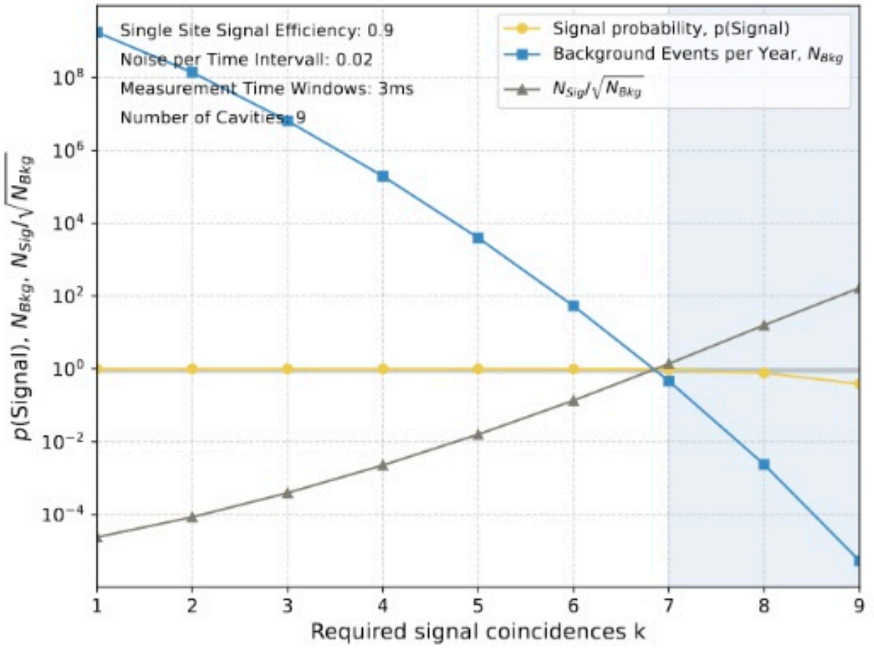
Expectations

- We expect about 1 transient signal per year with a duration of 3 ms

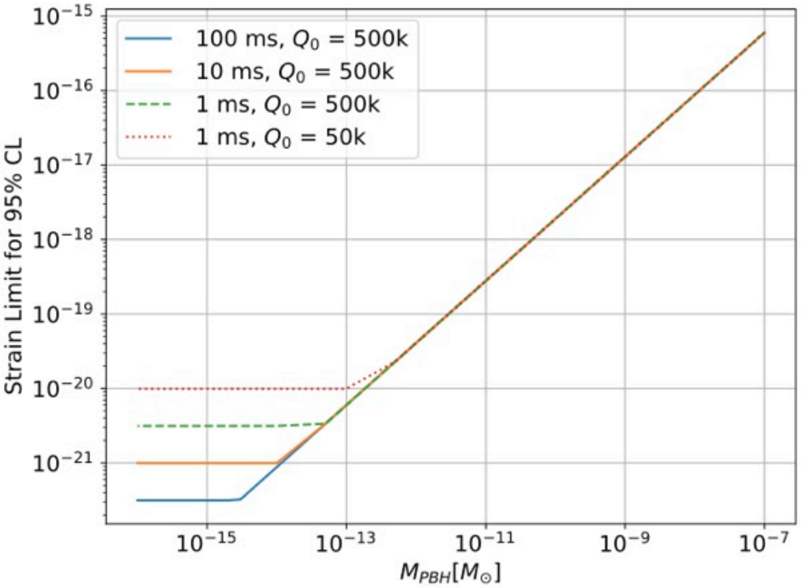
- Interpret situation as counting experiment
  - Thermal/quantum noise yields a certain number of photons per time-interval

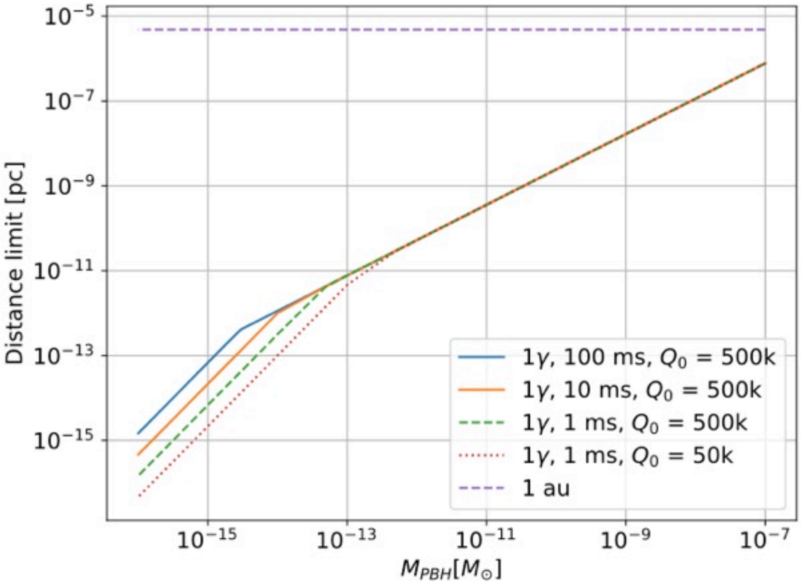
- Gain combinatorially in background rejection when combining sites
  - No background problem as long as $p_{signal} > p_{background}$

- Relevant quantity: Induced power should be in the order of O(1) photon



GravNet: Expected Sensitivities





- Limit for Primodial Black Hole Mergers
  - Only a few orders of magnitude missing

Further Reading (M.S. et. al):
https://arxiv.org/abs/2412.14958, https://arxiv.org/abs/2603.24645
https://arxiv.org/abs/2511.17817, 10.1016/j.nima.2024.169721

Going beyond the 1-photon limit

- We can measure also sub-photon energy deposits when connecting/entangling our Cavities with QuBit Systems
    - The EM-wave in the cavity changes the frequency of the quBit
        - Commuting with the photon-number operator
        - Quantum Non-Demolition Measurements
    - 0.1 photons→small qubit frequency shift

- Hamiltonian for a coupled cavity and QuBit System

$$H = h\omega_c a^\dagger a + \frac{h\omega_q}{2}\sigma_z + hg(a\sigma_+ + a^\dagger\sigma_-)$$

- In the limit of highly different frequencies, we get

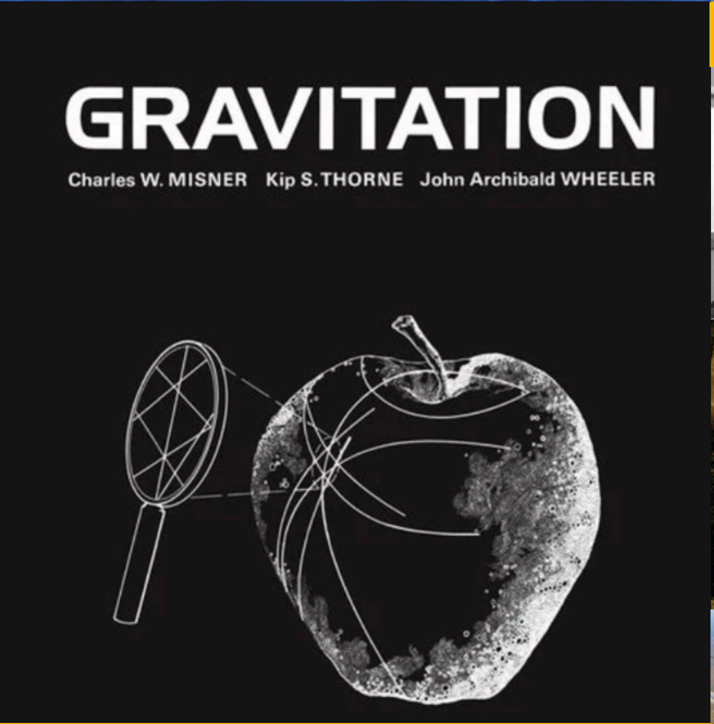
$$H_{disk} = h\omega_c a^\dagger a + \frac{h\omega_q}{2}\sigma_z + \frac{h}{2}(2\chi a^\dagger a)\sigma_z$$

with

$$\chi = \frac{g^2}{\Delta}, \Delta = \omega_q - \omega_c \qquad [a^\dagger a, H_{disp}] = 0$$

- This has not been technically realised. Lots of R&D in the coming years!

Isn’t this depressive?

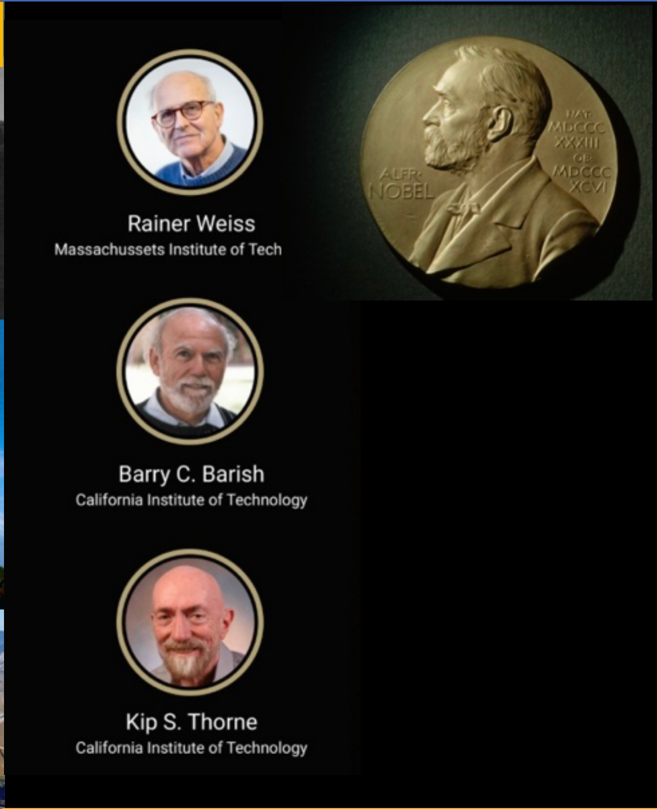


GRAVITATION

Charles W. MISNER Kip S. THORNE John Archibald WHEELER

“[interferometers] have so low sensitivity that they are of little experimental interest”

50 years of work



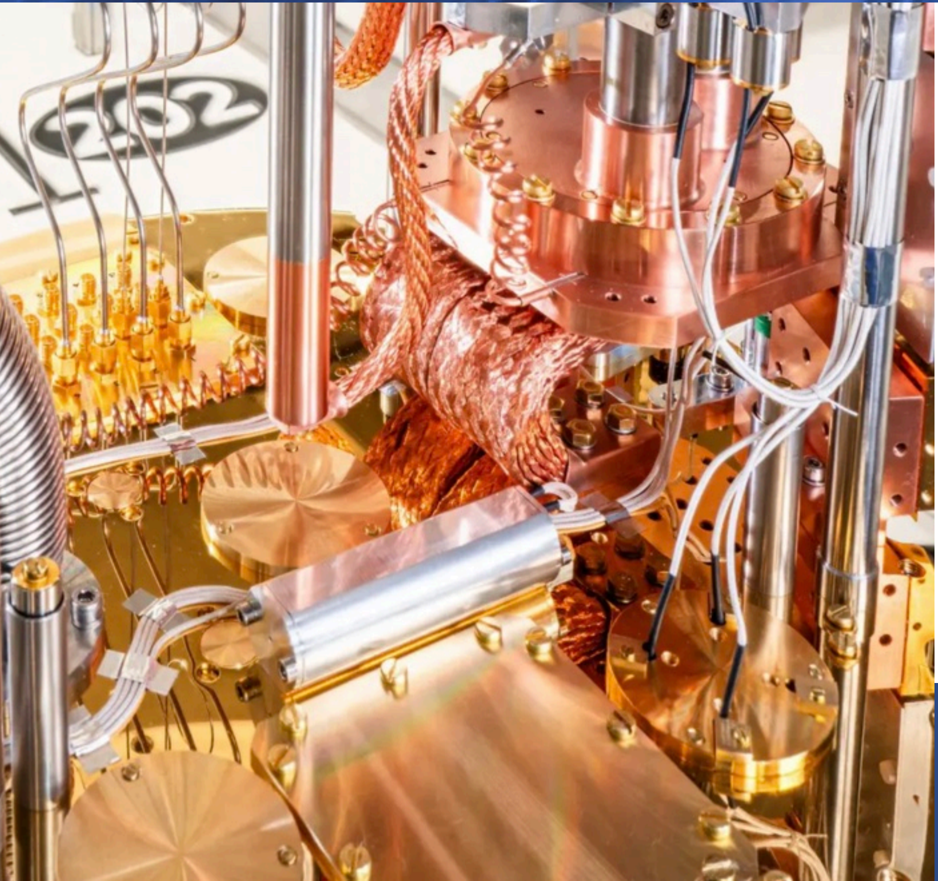
Rainer Weiss
Massachussets Institute of Tech

Barry C. Barish
California Institute of Technology

Kip S. Thorne
California Institute of Technology

Nobel Prize 2017

Which Technologies to Choose?



- GravNet will start with cavities since their technology is mature
- Most interesting HFGW sources are transient
  - Any HFGW search will profit from combining signals
  - Most developments (Quantum sensing, Superconducting cavities, analysis) is from generic use
  - Magnetic fields and ultra cold volumes are used in most approaches

We will switch to the most promising experimental approach in the next years

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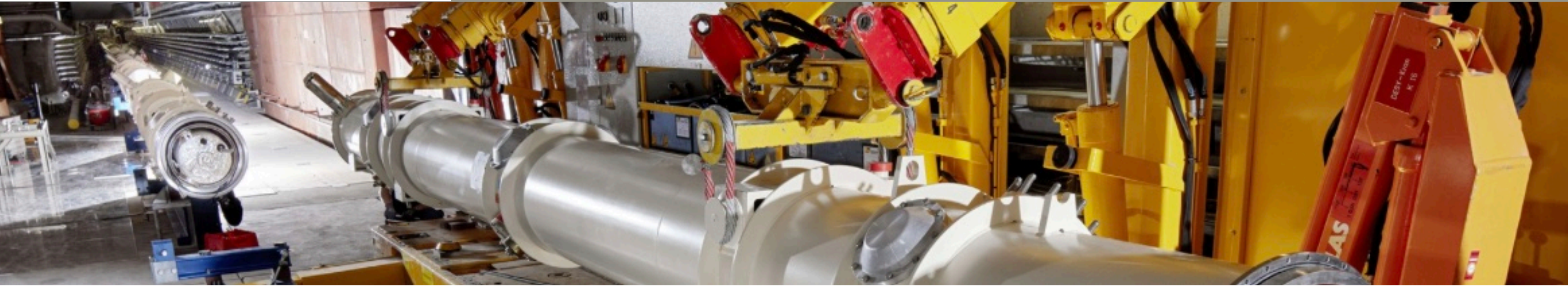
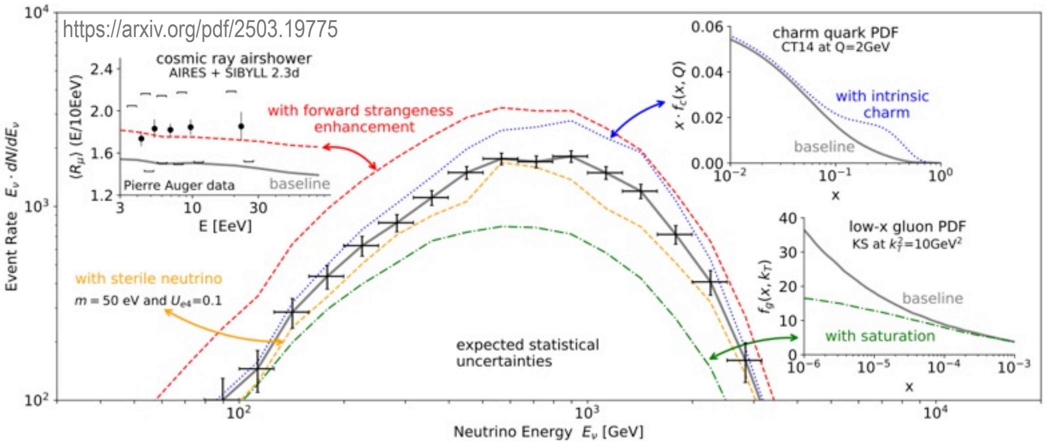
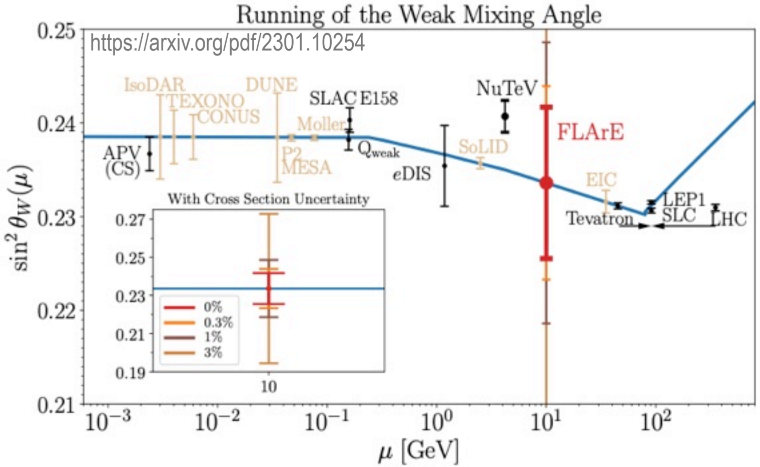


New Approaches in Neutrino Physics with Pixel Detectors

Neutrinos at the LHC

Why Neutrino Physics at FASER?


https://arxiv.org/pdf/2503.19775


https://arxiv.org/pdf/2301.10254

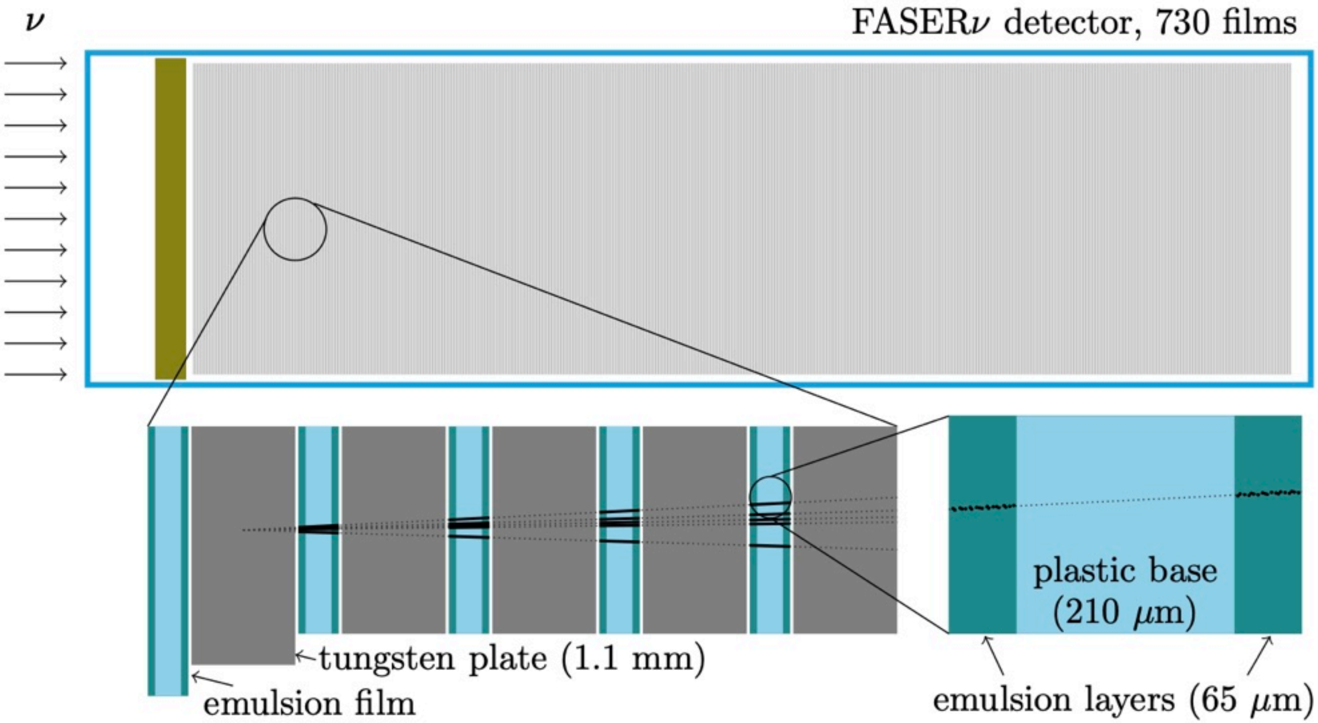
- Neutrino cross sections at TeV energies probes PDFs (muonic interactions also help)

- Neutrino flux measurements
  - constraints on forward QCD and hadron production models, crucial astroparticle physics

- Measurement of neutral current neutrino interactions allow to test the energy dependence of the weak mixing angle

How do we detect neutrinos?

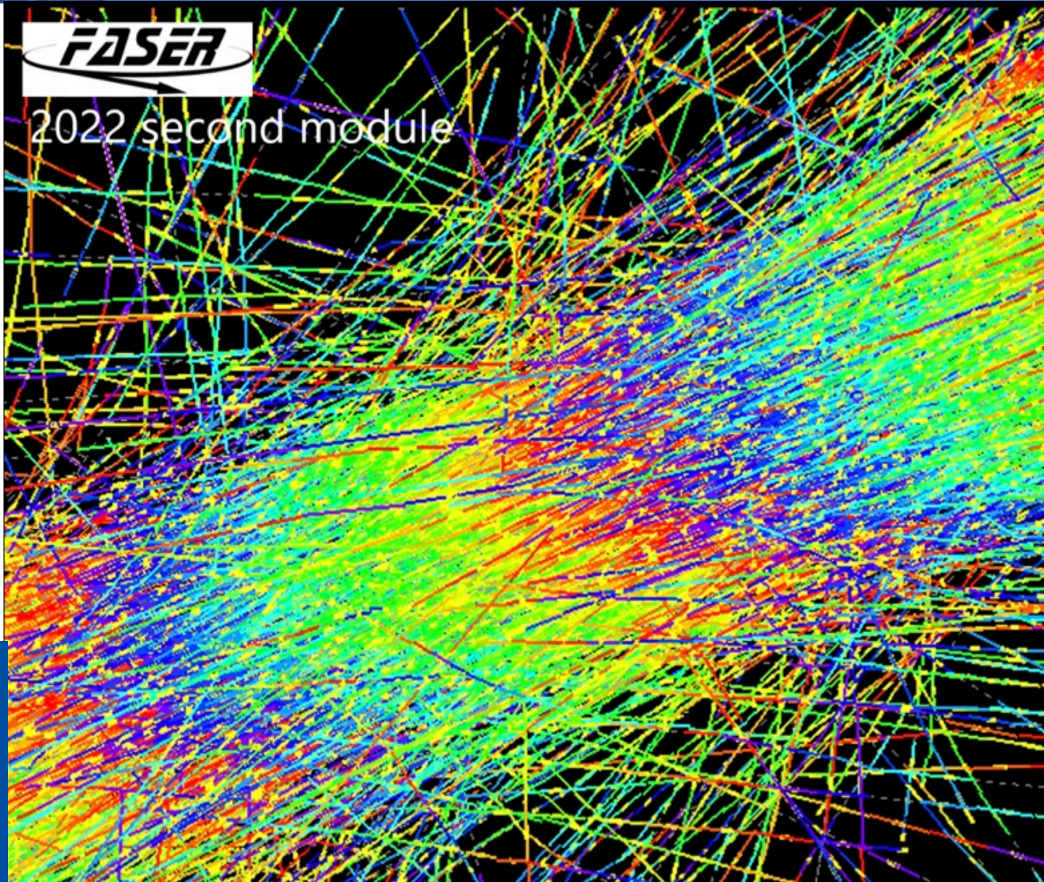
- Large Target Mass for neutrino interactions
  - Tungsten
- Emulsion-Layers as „photographic“ films
  - Recording for several months
  - no time information
  - Each layer has nm-resolution
- Allows for the reconstruction of trackless per layer



An active neutrino detector for Run-4

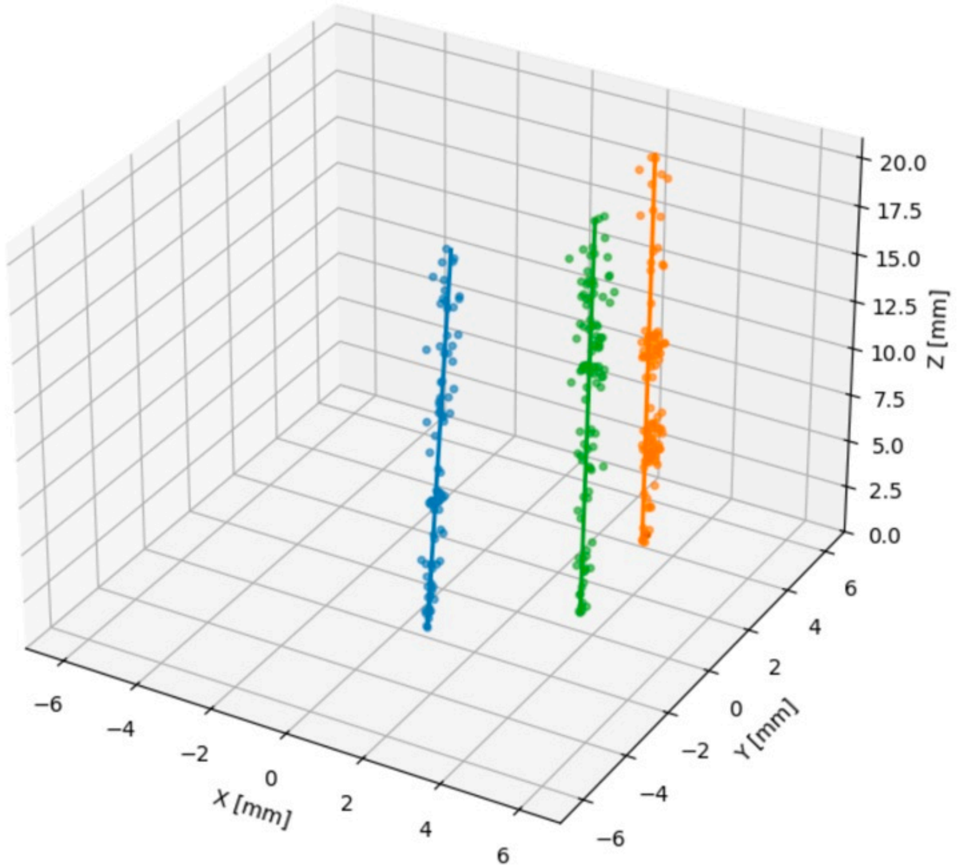
- Problem: millions of muons passing through during recording time
  - Reconstruction can handle 10^6 muon tracks per cm^2

- Conditions during Run-4
  - >2-3 times more muons
  - Need to replace emulsion films every few weeks



- Solution: Active neutrino detector with allows to reconstruct the full event information in real-time

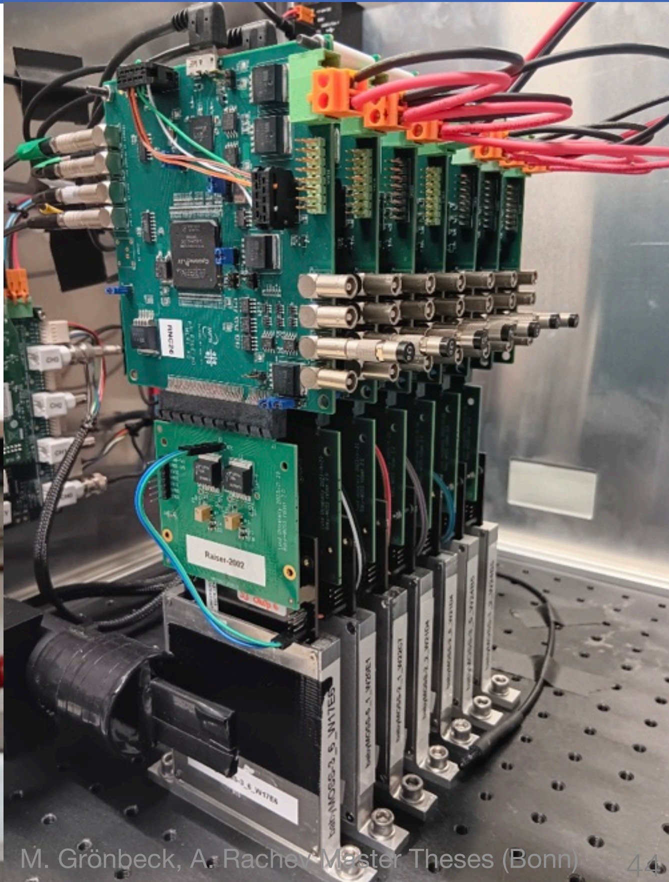
My idea: From Micromegas to Pixels



- 2014: Construction of the ATLAS NSW prototype based on Micromegas
  - construction of 100 m² drift-panels
- Idea: Use GridPix detectors as active layers
- Test-beam measurements showed promising results
- Simulation implies too large hadronic activities: GridPix NOT feasible
- „Trostpreis“: This triggered a new idea for a medical application (patent+ERC Proof of Concept Grant applications ongoing)

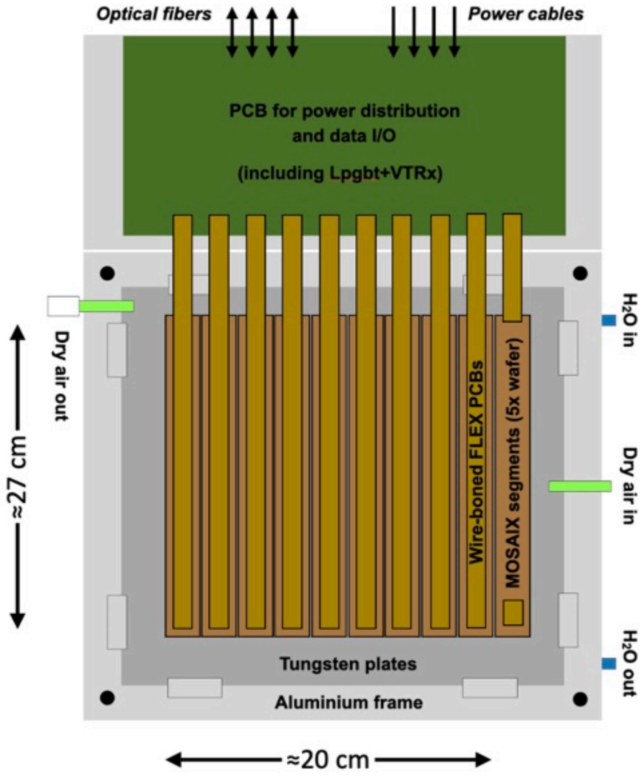
BabyMOSS Laboratory Tests

- MOSS (i.e. full-scale prototype) good chip yield thoroughly examined over 14 wafer
  - Measured yield >84%
- Laboratory tests on BabyMOSS chips including test-beam studies ongoing in Bonn



M. Grönbeck, A. Rachev Master Theses (Bonn)

Powering & Readout Electronics

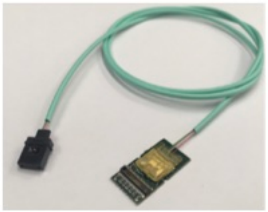


- Slow control, data out and power provided to short sides of MOSAIX via wire-bonded PCBs
  - Connected to power boards and Lpgbp+VTRx transceivers via power cables and optical fibers
  - DAQ FPGAs (e.g. Altera Cyclone IV)
  - AISCs equipped with 2/4 serialisers @1.28 GB/s

Lpgbt

→

VTRx transceivers



→

Electrical to optical signal conversion
2 links per plane

- Adaptation / Development of Boards in ’27
- Production & testing in ’28

… and an additional textbook result!

	three generations of matter (elementary fermions) I	II	III	three generations of antimatter (elementary antifermions) I	II	III	interactions / force carriers (elementary bosons)	
mass charge spin	≈2.2 MeV/c^2 ⅔ ½ u up ✓	≈1.28 GeV/c^2 ⅔ ½ c char ✓	≈173.1 GeV/c^2 ⅔ ½ t top ✓	≈2.2 MeV/c^2 −⅔ ½ ū antiu ✓	≈1.28 GeV/c^2 −⅔ ½ c̄ anticha ✓	≈173.1 GeV/c^2 −⅔ ½ t̄ antito ✓	0 0 1 g gluo ✓	≈124.97 GeV/c^2 0 0 H higgs
QUARKS	≈4.7 MeV/c^2 −⅓ ½ d dow ✓	≈96 MeV/c^2 −⅓ ½ s strang ✓	≈4.18 GeV/c^2 −⅓ ½ b botto ✓	≈4.7 MeV/c^2 ⅓ ½ d̄ antido ✓	≈96 MeV/c^2 ⅓ ½ s̄ antistra ✓	≈4.18 GeV/c^2 ⅓ ½ b̄ antibott ✓	0 0 1 γ photo ✓	
	≈0.511 MeV/c^2 −1 ½ e electr ✓	≈105.66 MeV/c^2 −1 ½ μ muo ✓	≈1.7768 GeV/c^2 −1 ½ τ tau ✓	≈0.511 MeV/c^2 1 ½ e^+ positr ✓	≈105.66 MeV/c^2 1 ½ μ̄ antimu ✓	≈1.7768 GeV/c^2 1 ½ τ̄ antita ✓	≈91.19 GeV/c^2 0 1 Z Z^0 bos ✓	
LEPTONS	<2.2 eV/c^2 0 ν_e electron neutri ✓	<0.17 MeV/c^2 0 ν_μ muon neutri ✓	<18.2 MeV/c^2 0 ν_τ tau neutrin ✓	<2.2 eV/c^2 0 $\bar{\nu}_e$ electron antineut ✓	<0.17 MeV/c^2 0 $\bar{\nu}_\mu$ muon antineut ✓	<18.2 MeV/c^2 0 ½ $\bar{\nu}_\tau$ tau antineutrino	≈80.39 GeV/c^2 1 1 W^+ W^+ bos ✓	≈80.39 GeV/c^2 −1 1 W^- W^- bos ✓

- Common Story: Higgs Discovery in 2012 as the last missing piece of the SM

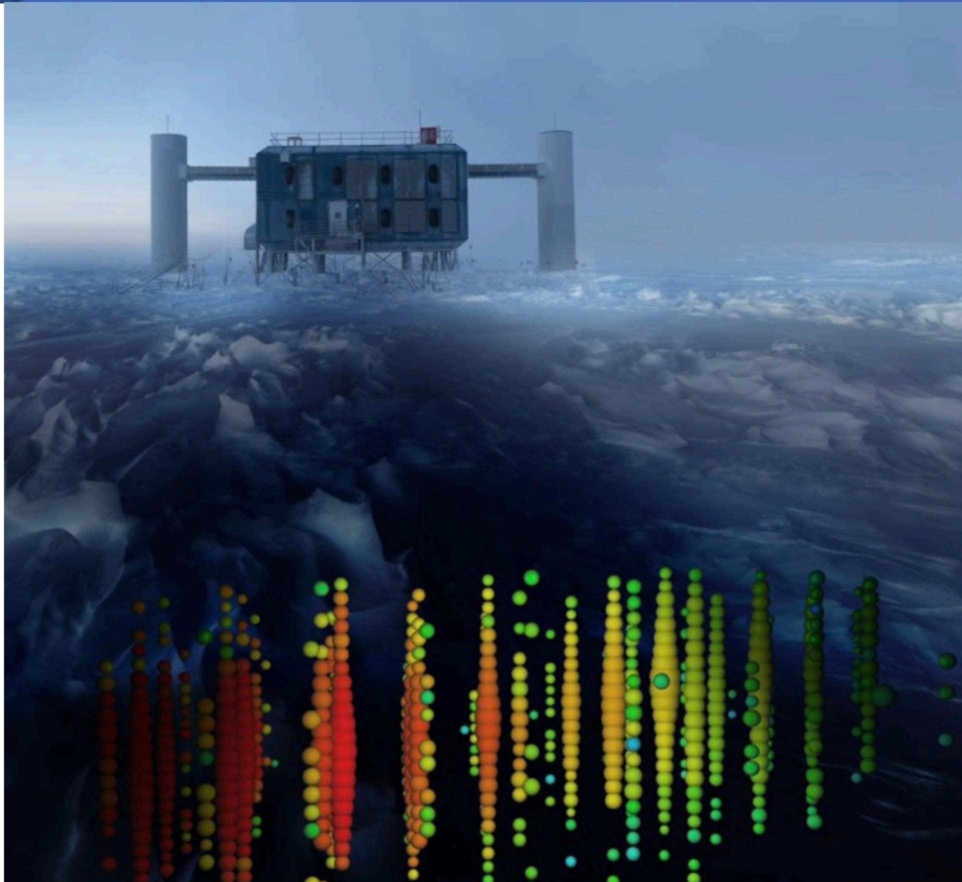
- The existence of an Anti-Tau Neutrino was actually never experimentally confirmed
- FASER can discover the last missing SM particle

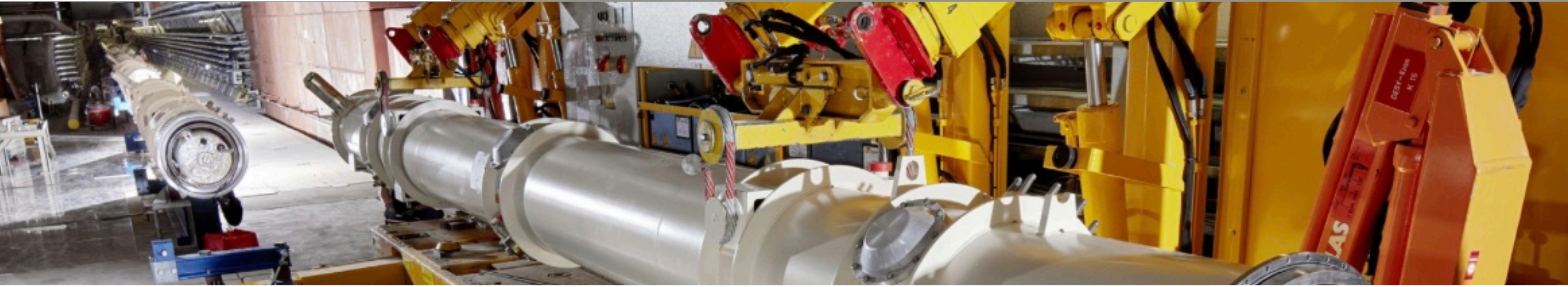
Further Reading (M.S. et. al):
https://arxiv.org/abs/2210.15532, https://arxiv.org/abs/2303.14185, https://arxiv.org/abs/2503.19775,

Working Together in Neutrino Physics

- Neutrino–nucleon cross-section, QCD models, models of cosmic-ray air showers are required by several neutrino experiments
  - DUNE, Icecube, MINERvA, …

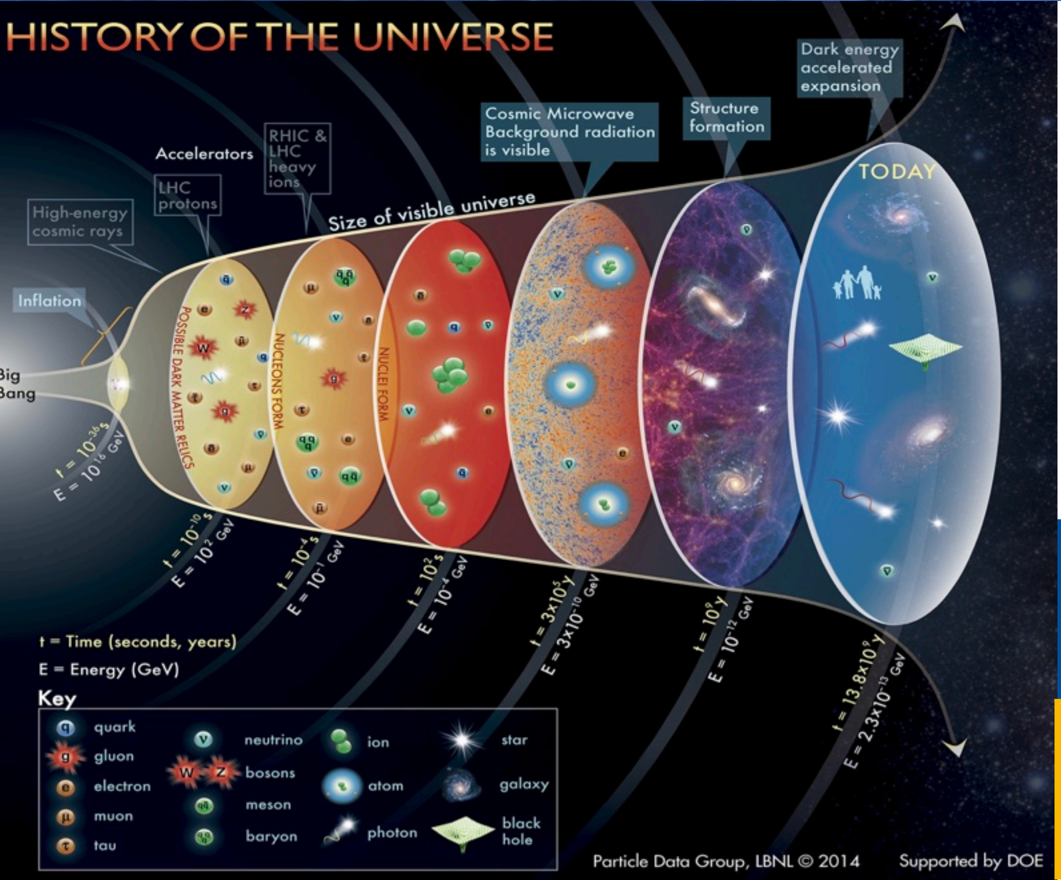
- Particle physics can help
  - Dedicated measurements of neutrino cross-sections at colliders e.g. by FASER
  - Development of hadronic models, …
  - Forward particle production at colliders
  - proton-oxygen measurements





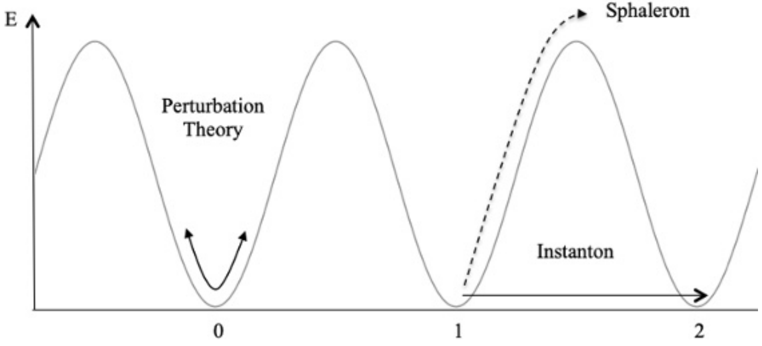
From Topological Effects to the Quark Gluon Plasma

From Sphalerons to Instantons



Particle Data Group, LBNL © 2014

Supported by DOE

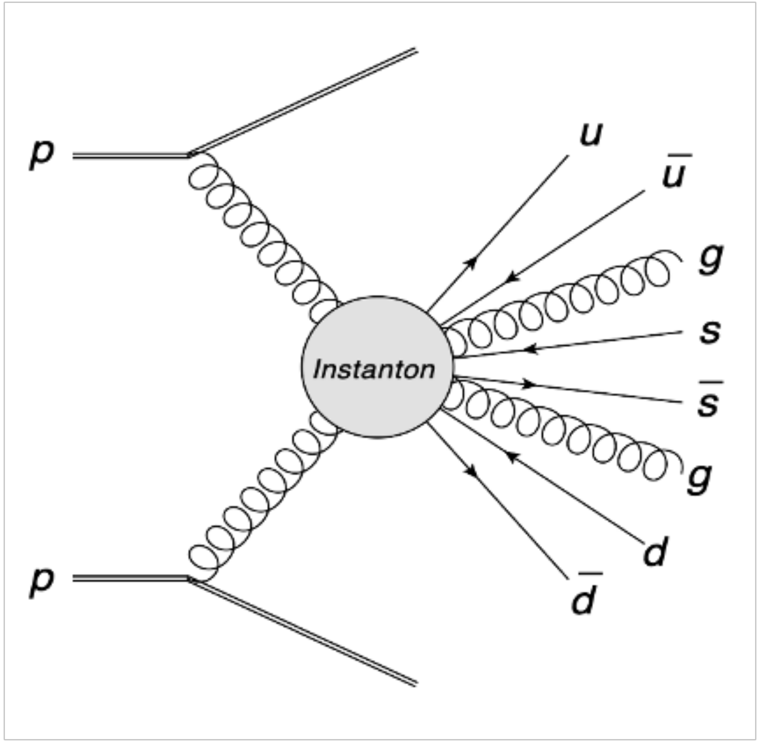


- Collider energies to observe EWK Sphaleron Processes far too low
- Need (heavy ion) collision of >100 TeV

- … any other idea to probe the topology of the vacuum?
  - Instanton Processes in QCD!

Searching for QCD Instantons

- Potential wall between two vacua governed by α_s
  - Low energies, low potential wall, instanton processes
- Signature
  - Creation of all kinematically accessible quark/anti-quark pairs (with the same chirality) + gluons
- Problem 1: for a long time there was calculation nor event generator available for such signatures
- Problem 2: Signal looks pretty much like multiple-parton interactions and we don't know the background shape

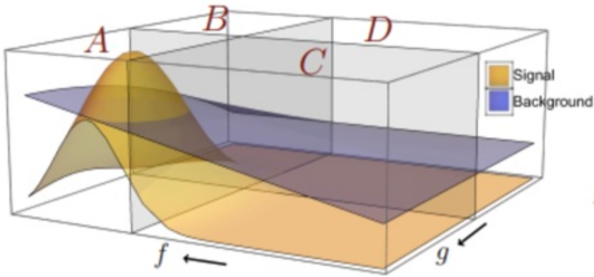


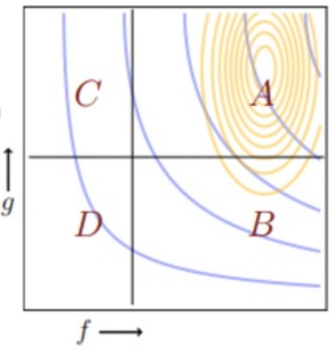
Searching for QCD Instantons

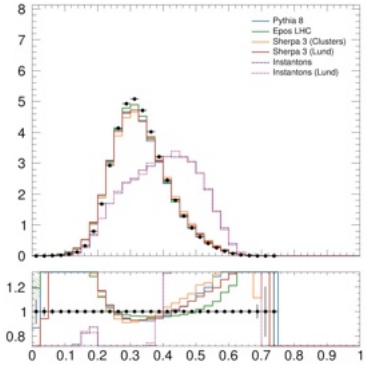
- Most important separating observables between signal and background
  - <η> and <|Δη|>
  - In fact already known since HERA

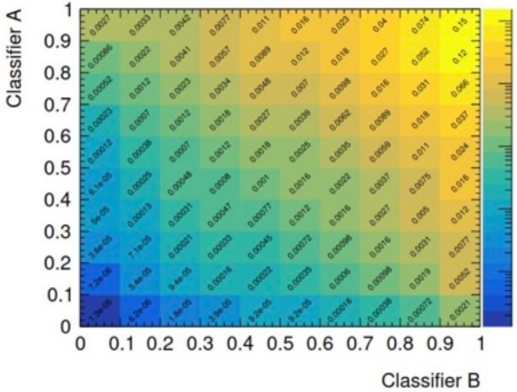
- Dedicated data-driven background estimation techniques
  - ABCDisco method based on two NN-based classifiers
  - We noticed that a modified version of a Rosenblatt transform is more efficient
  - https://arxiv.org/abs/2509.25521

- High hopes to publish a first limit/ observation this summer
- Then focus on non-diffractive events

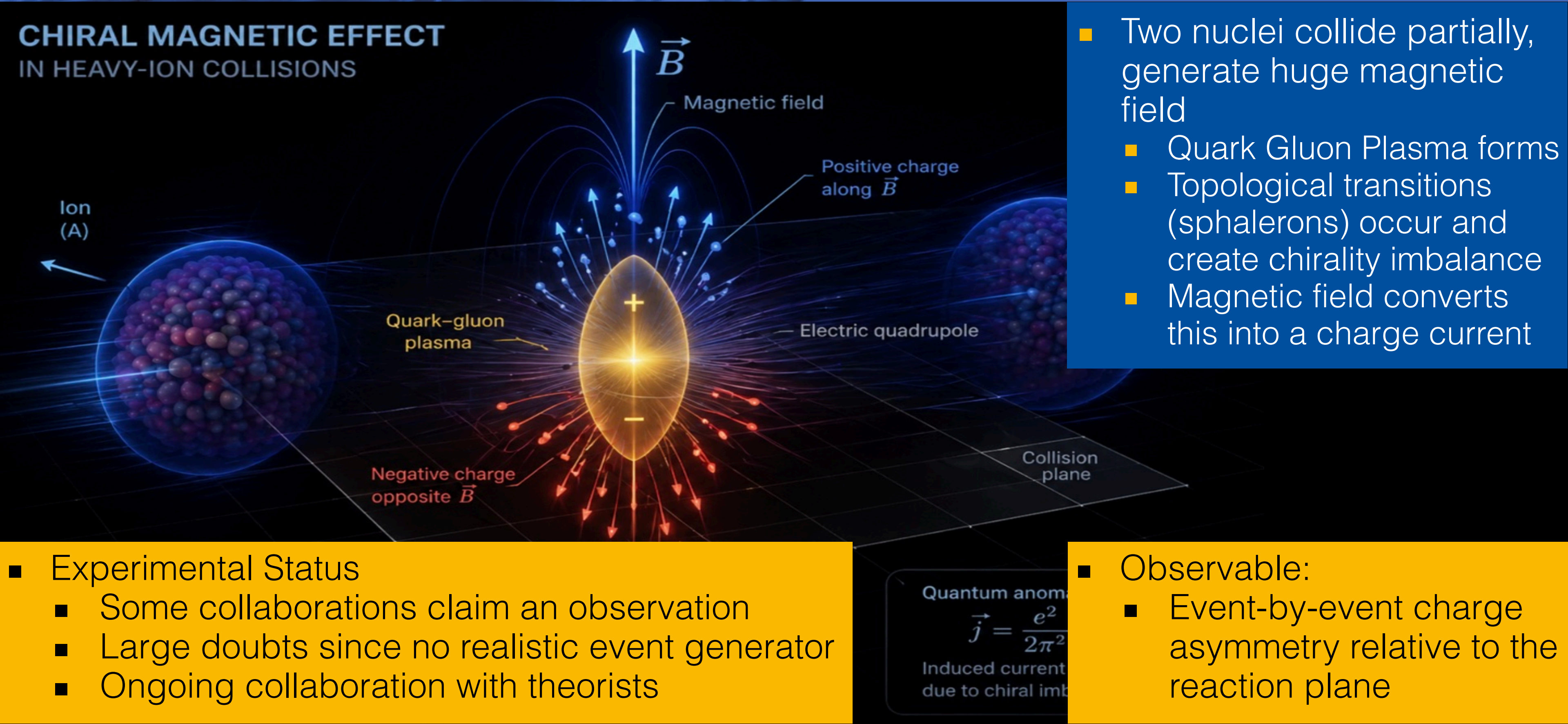








Chiral Magnetic Effect



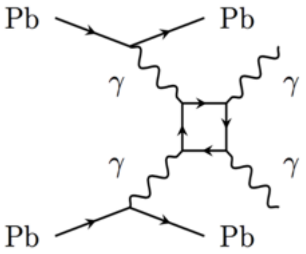
- Two nuclei collide partially, generate huge magnetic field
  - Quark Gluon Plasma forms
  - Topological transitions (sphalerons) occur and create chirality imbalance
  - Magnetic field converts this into a charge current

- Experimental Status
  - Some collaborations claim an observation
  - Large doubts since no realistic event generator
  - Ongoing collaboration with theorists

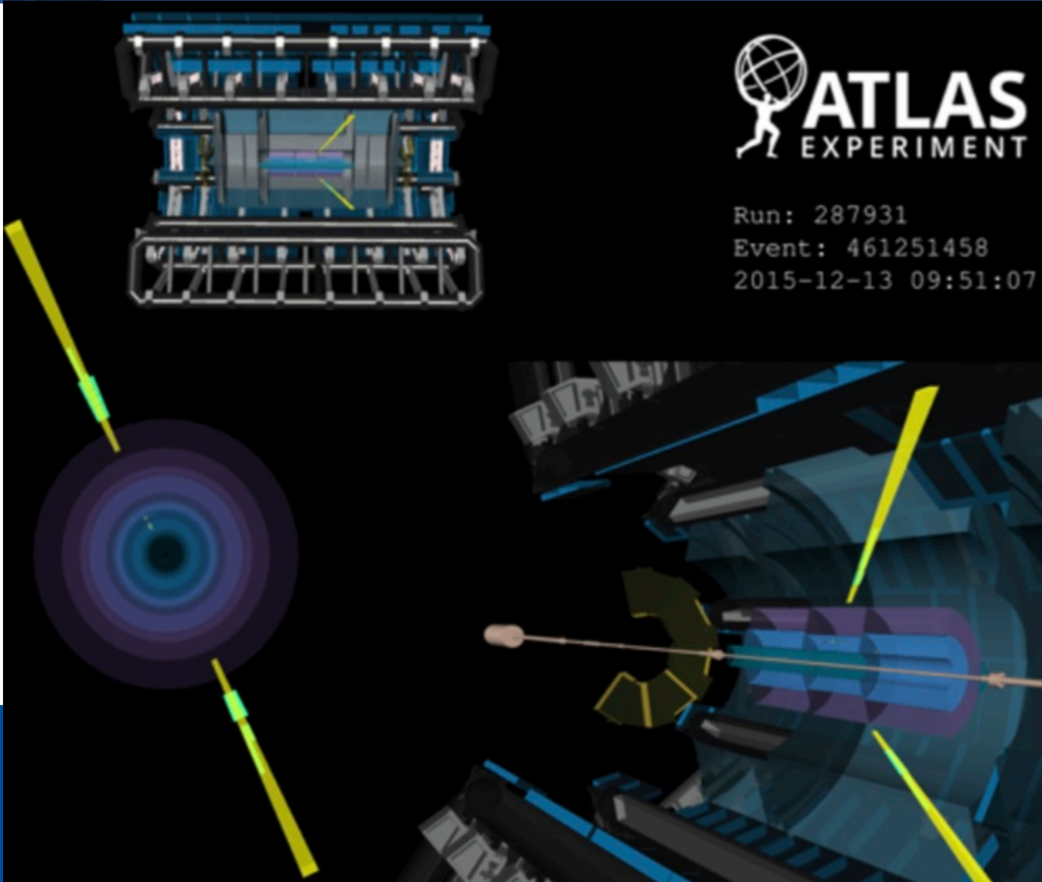
- Observable:
  - Event-by-event charge asymmetry relative to the reaction plane

Getting Used to Heavy Ion Collisions

- To search for the chiral magnetic effect, one needs to understand Heavy Ion collisions
- My starting point: The most not-heavy ion collisions environment in heavy ion collisions: ultra-peripheral collisions

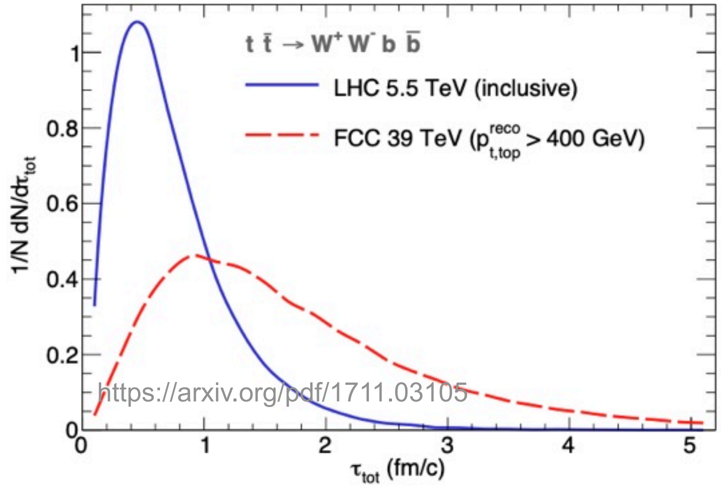


- 2018: First observation of light-by-light scattering
- See my last Oxford Seminar

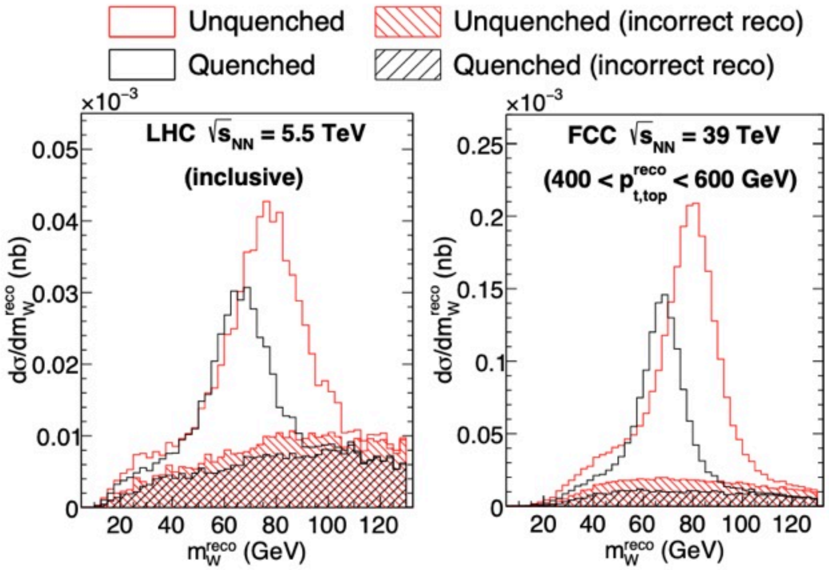


Top-Quarks in a Quark Gluon Plasma

- Going more towards Heavy-Ion Collisions: Top-Quarks
- Idea of G. Salam et. al.: Probing the time structure of the QGP with top quarks
  - Something only ATLAS/CMS can do



https://arxiv.org/pdf/1711.03105



https://arxiv.org/pdf/1711.03105

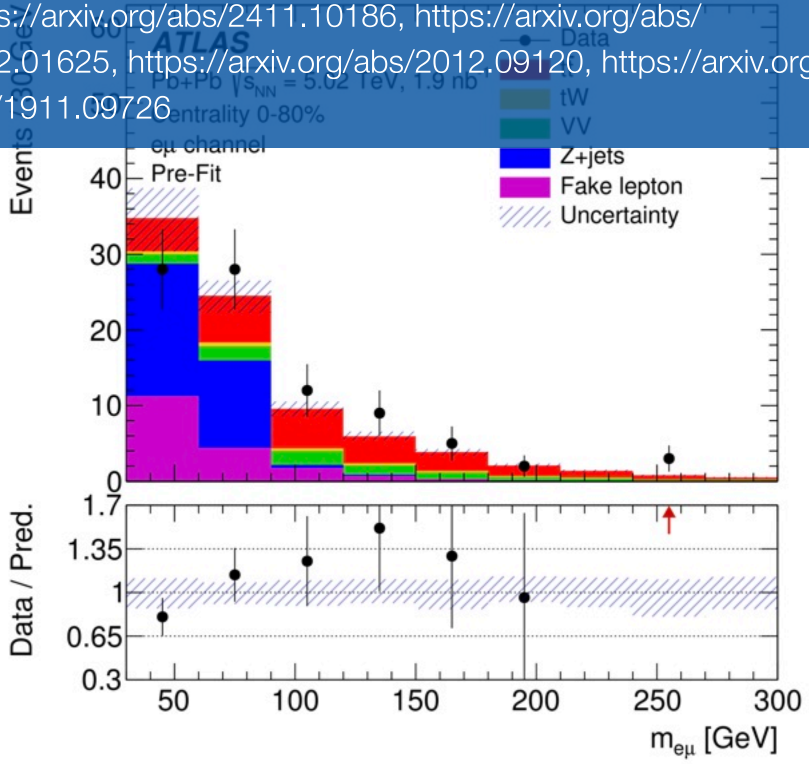
First Step: Observation of Top Events in Heavy Ion Collisions

- 2015 and 2018, 5 TeV Pb-Pb data with 1.9nb^{-1}
  - Electron-Muon decay channel to suppress background

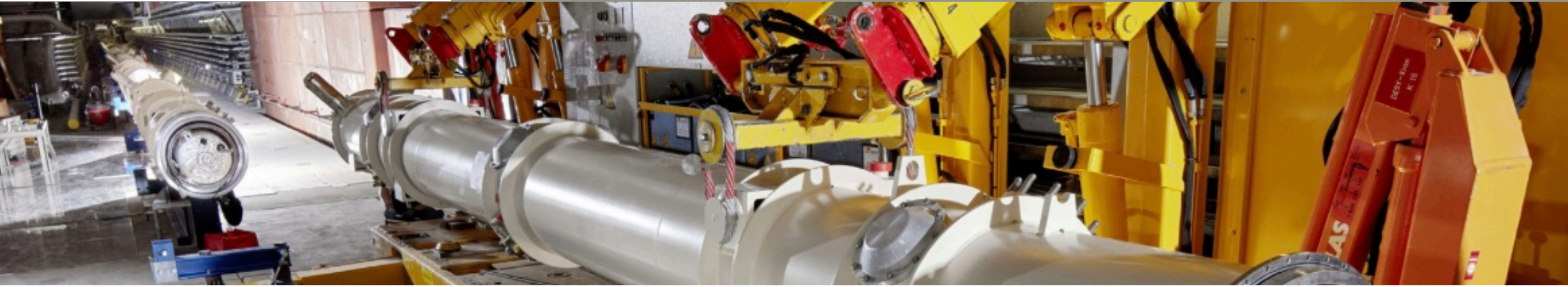
- Largest experimental challenge
  - Understanding the jet-energy scale and fake-jet rate in heavy ion collision

- Observed (expected) significance 5.0 (4.1)σ

Further Reading (M.S. et. al): Phys. Rev. Lett. 134 (2025) 142301 https://arxiv.org/abs/2411.10186, https://arxiv.org/abs/1702.01625, https://arxiv.org/abs/2012.09120, https://arxiv.org/abs/1911.09726



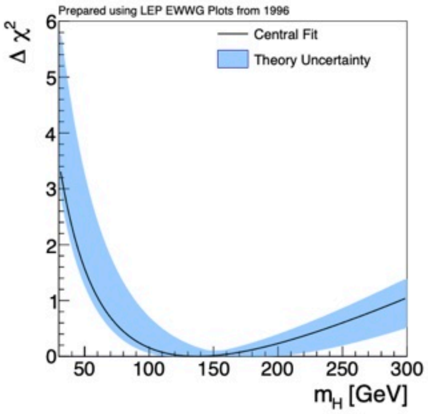
- Currently ongoing to develop b-tagging in heavy ion collisions using a transformer based model
- Midterm goal: Foundation model for heavy ion collisions, which can the be used for the CME

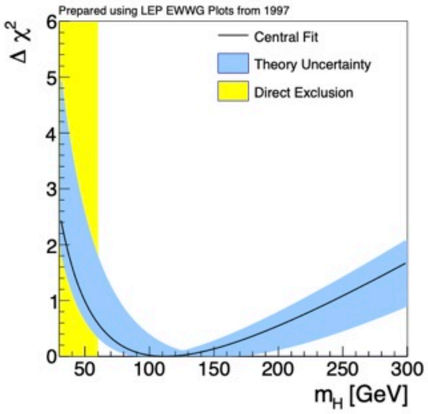


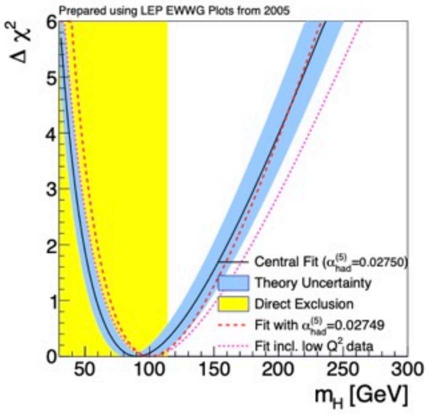
Electroweak Precision and the Running of Couplings

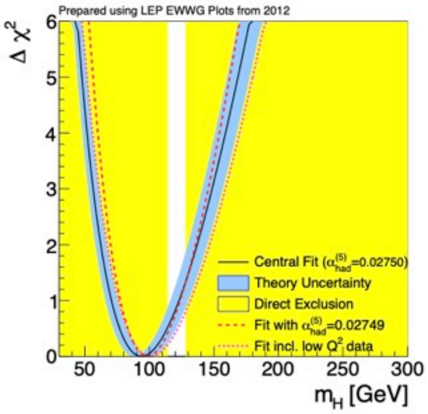
The Global Electroweak Fit

- Quantum loops yield corrections to the W boson mass (and other observables)
  - By comparing precision measurements of electroweak precision observables with predictions allow to constrain SM parameters / probe the SM consistency


Prepared using LEP EWWG Plots from 1996

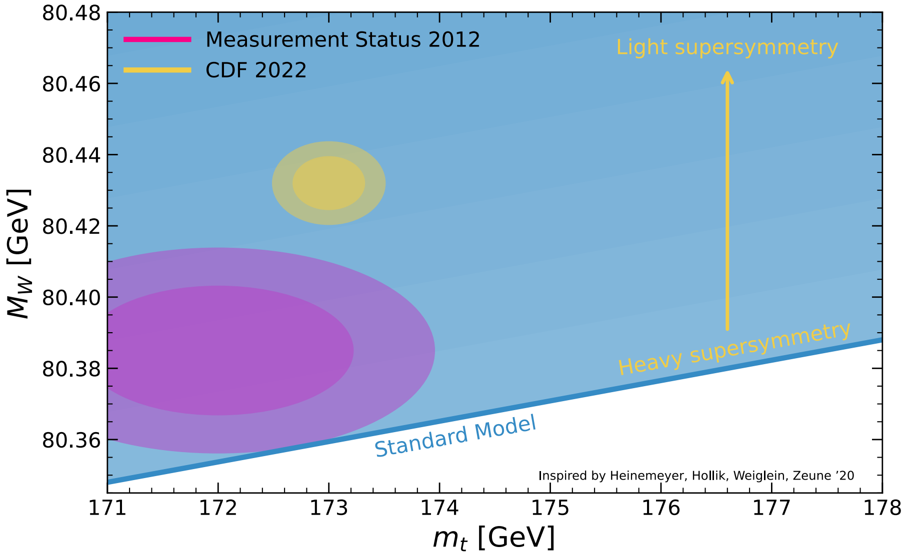

Prepared using LEP EWWG Plots from 1997


Prepared using LEP EWWG Plots from 2005

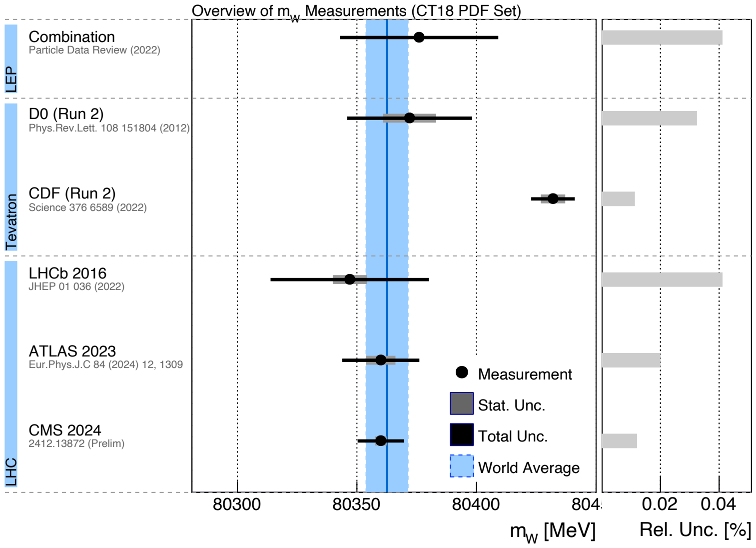

Prepared using LEP EWWG Plots from 2012

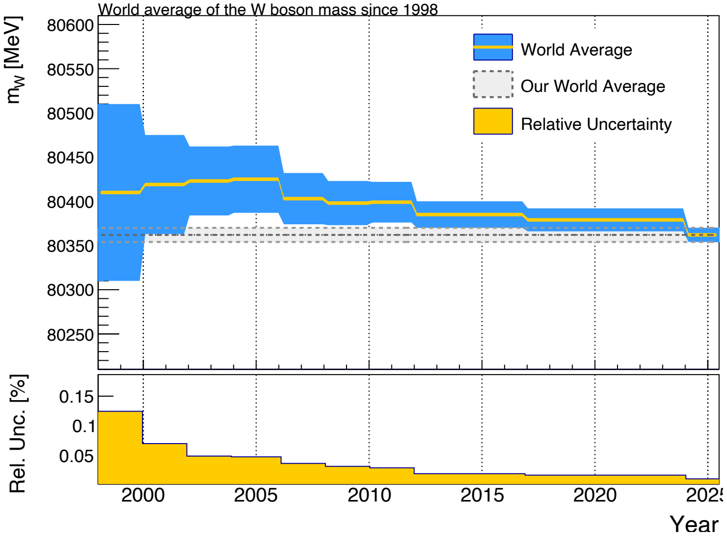
Where it all started for me

- W boson mass in 2012
  - prediction was significantly more precise than the measurement
  - a slight tension between the SM prediction and the measurement



A Preliminary W Boson Mass Combination

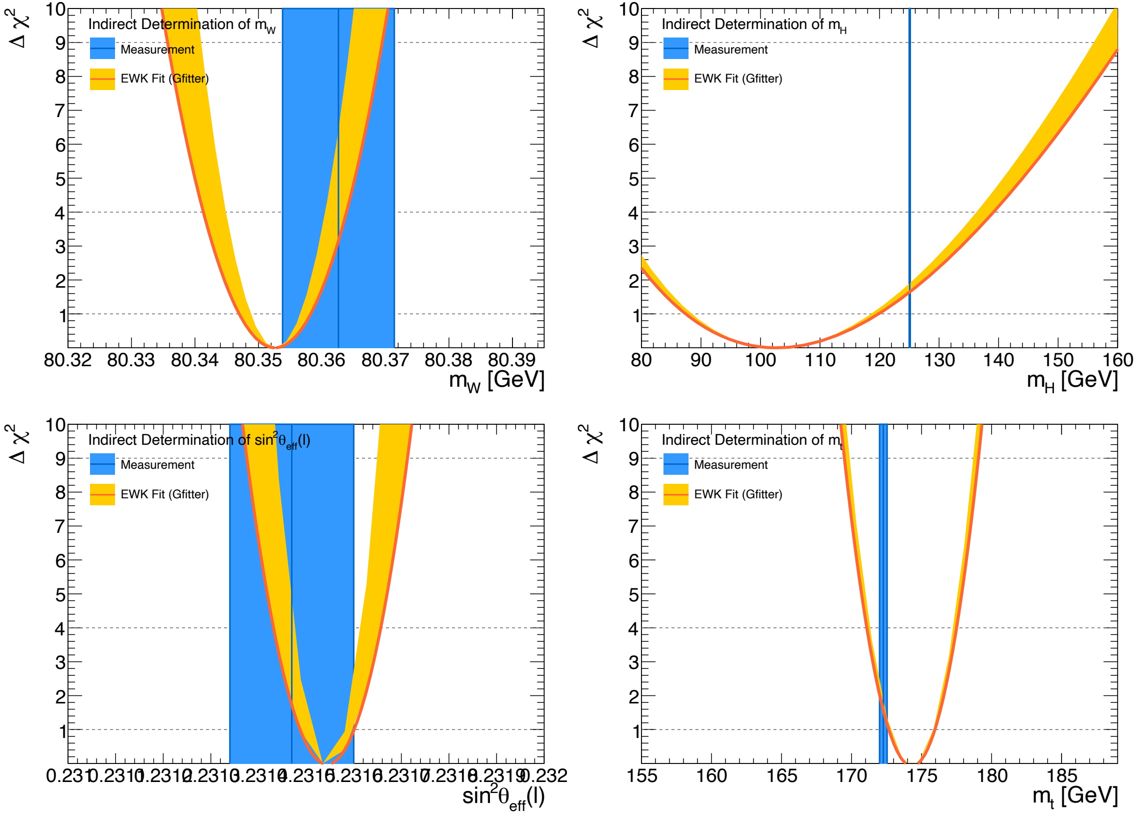




- W Boson mass combination perfectly consistent when ignoring the CDF result
  - m_W= 80362.6±8.8 MeV (p-value of 0.83)
  - Result consistent under different assumptions on correlation scenarios
  - When including CDF, the p-value drops below 0.001

Update of the Global Electroweak Fit

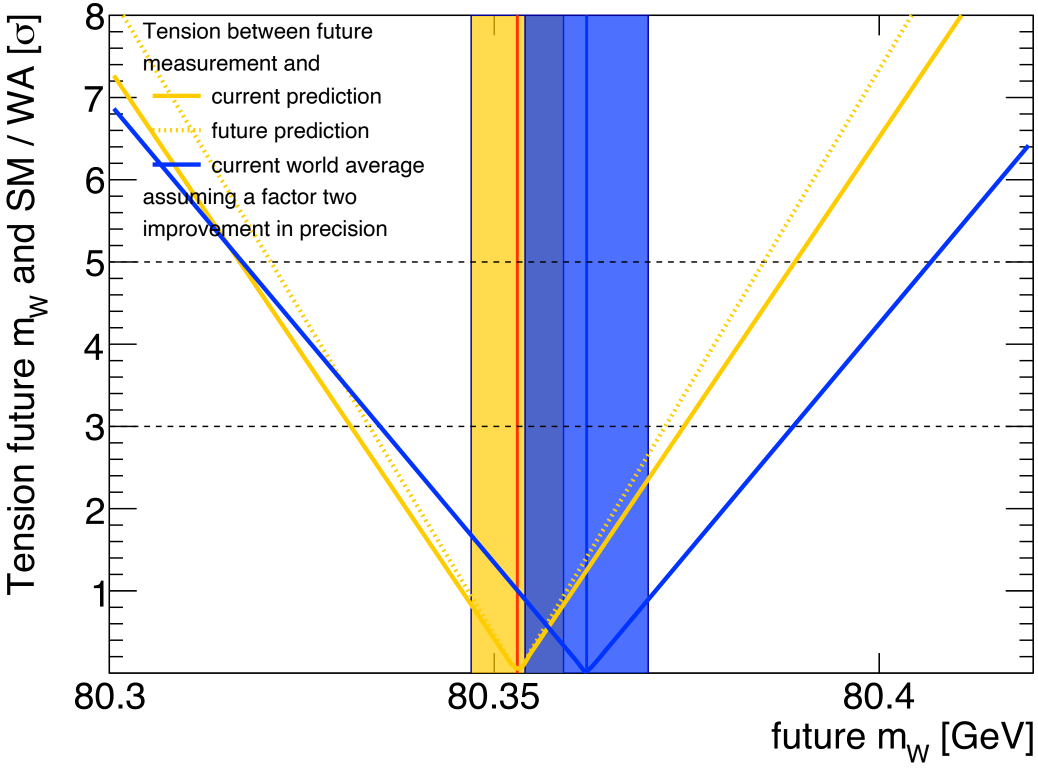
- Fitting-Framework Gfitter
- Main Input observables
  - m_W = 80362.6±8.8 MeV (p-value=0.83)
  - m_T = 172.27±0.27 GeV (p-value=0.4)
  - m_H = 125.1±0.1 GeV (p-value=0.9)
  - $\sin^2\theta_W$ =0.231433±0.00013 (p-value=0.1)
- Indirect predictions for main observables
  - m_W = 80353±5.6 MeV
  - m_Z = 91195±7 MeV
  - m_T = 174.3±1.6 GeV
  - m_H = 102.7±16 GeV
  - $\sin^2\theta_W$ = 0.231544±0.000056
- Overall consistency of the SM Global Electroweak Fit
  - χ^2/ndf=17.1/14 (p-value 0.25)



The Future of the W Boson Mass

- Assumes experimental precisions after HL-LHC
  - Δm_W =4 MeV
  - Δm_Z = 1 MeV
  - Δm_T = 150 MeV (unrealistic?)
  - Δm_H = 50 MeV
  - $\Delta \sin^2\theta_W$ = 0.00007

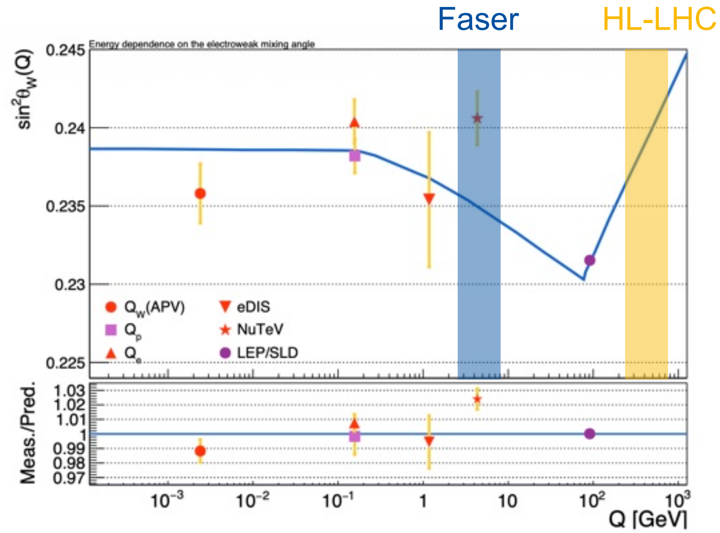
- Realistic future single measurements of m_W that are incompatible with the SM are also incompatible with the current WA



The Future of Electroweak Precision Observables at the LHC

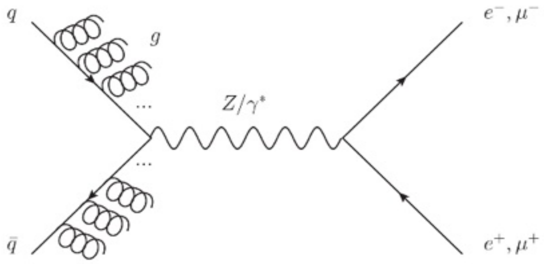
- Standard EWPO likely not a direct gate to NP, rather important input to SMEFT-Fits
    - but, Λ scales with (precision)$^{1/2}$

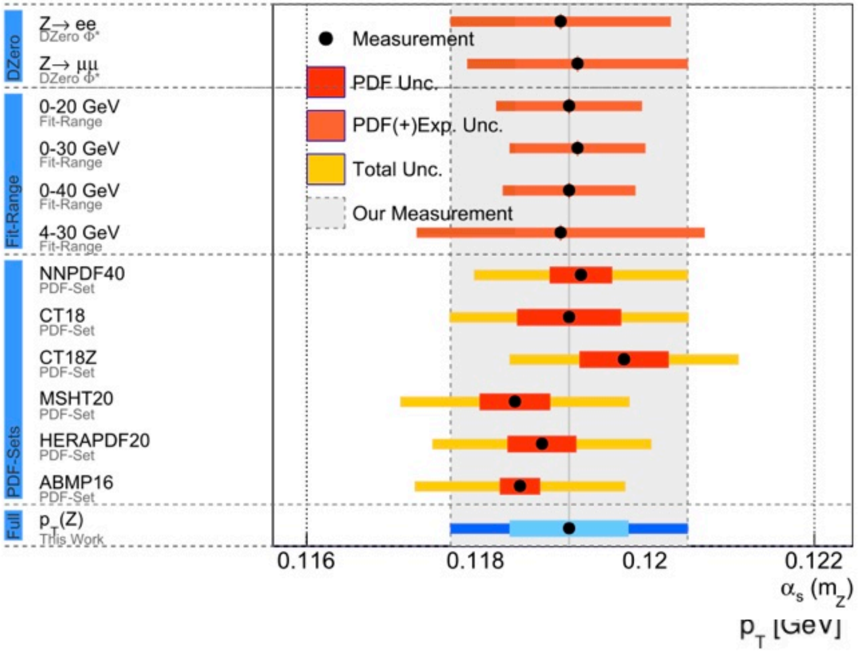
- Focus on running of couplings
    - Unique opportunity at HL-LHC



The Strong Coupling Constant

- Z bosons produced in hadron collisions recoil against QCD initial-state radiation

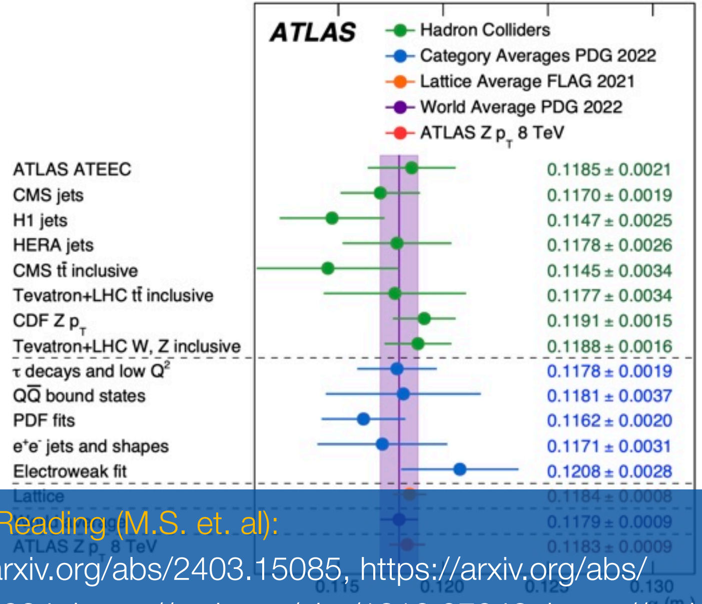




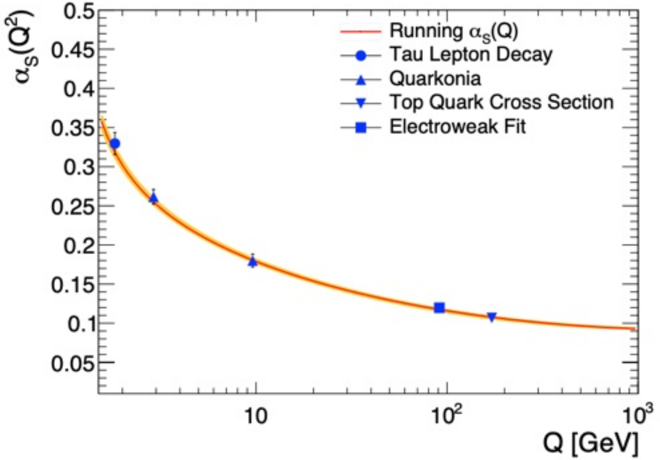
- The position of the „ Sudakov“ peak is sensitive to $\alpha_s(m_Z)$
- Advantage
  - $p_T(Z)$ spectrum can be described at N^3LO/N^3LL
  - Experimentally well defined

A unified approach to study the running of α_S

- ATLAS followed up on this idea, with the most precise measurement …

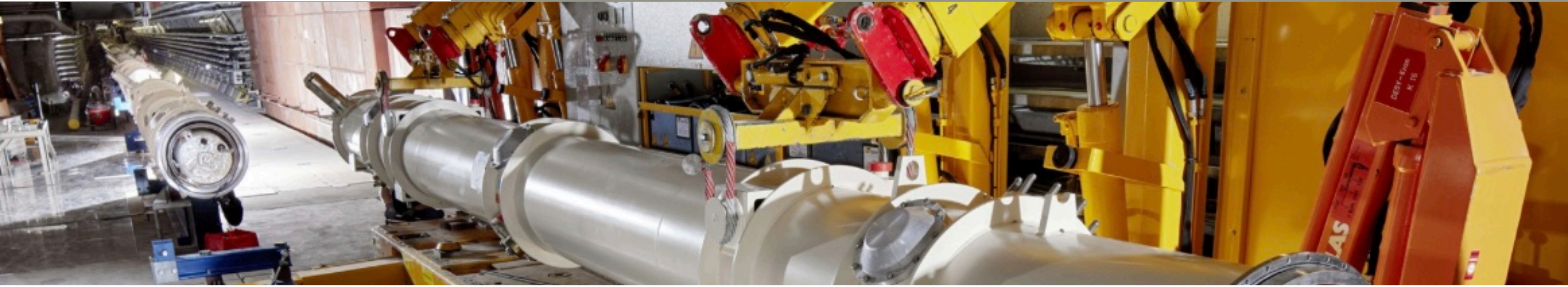


- High Luminosity measurements allow to contain NP parameters and PDFs with off-shell measurements

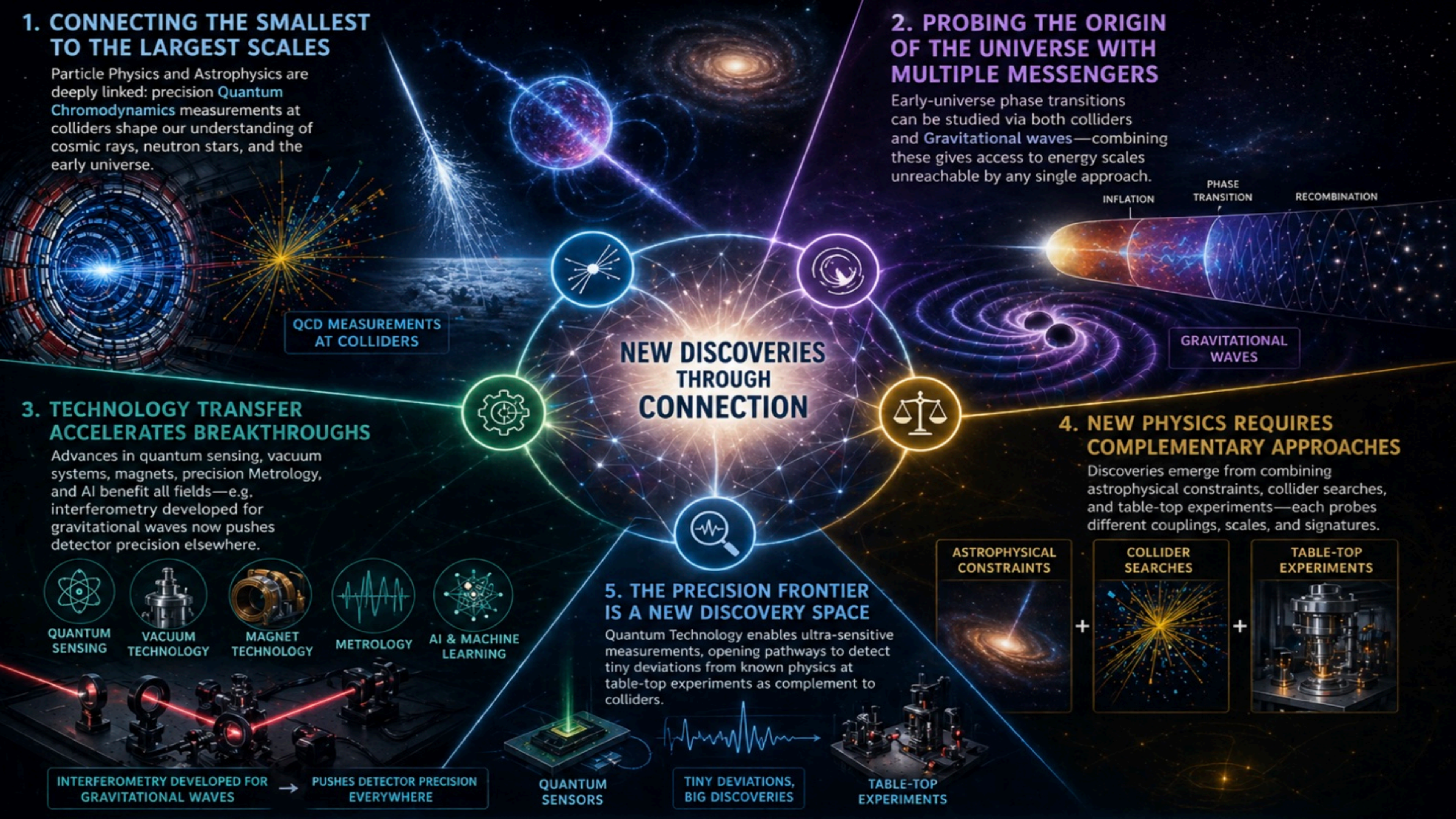


Further Reading (M.S. et. al):
https://arxiv.org/abs/2403.15085, https://arxiv.org/abs/2203.05394, https://arxiv.org/abs/1910.07049, https://arxiv.org/abs/1407.3792

- Unified approach to study the running of α_S
- … if I wouldn't have an ERC Grant, then this would be my next proposal



A common effort across domains



NEW DISCOVERIES THROUGH CONNECTION

1. CONNECTING THE SMALLEST TO THE LARGEST SCALES

Particle Physics and Astrophysics are deeply linked: precision Quantum Chromodynamics measurements at colliders shape our understanding of cosmic rays, neutron stars, and the early universe.

2. PROBING THE ORIGIN OF THE UNIVERSE WITH MULTIPLE MESSENGERS

Early-universe phase transitions can be studied via both colliders and Gravitational waves—combining these gives access to energy scales unreachable by any single approach.

3. TECHNOLOGY TRANSFER ACCELERATES BREAKTHROUGHS

Advances in quantum sensing, vacuum systems, magnets, precision Metrology, and AI benefit all fields—e.g. interferometry developed for gravitational waves now pushes detector precision elsewhere.

4. NEW PHYSICS REQUIRES COMPLEMENTARY APPROACHES

Discoveries emerge from combining astrophysical constraints, collider searches, and table-top experiments—each probes different couplings, scales, and signatures.

5. THE PRECISION FRONTIER IS A NEW DISCOVERY SPACE

Quantum Technology enables ultra-sensitive measurements, opening pathways to detect tiny deviations from known physics at table-top experiments as complement to colliders.

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Take Away Messages

- Don’t promise things which you can’t keep
  - True for kids and true for science
- Particle Physics isn’t over - it is just getting harder
- We have to combine our strength across disciplines
- FunFact: Bonn and Oxford have a city partnership since more than 75 years