# The Next Big Thing:
# Future Particle Colliders Now Coming into Focus – Their Physics Goals and Detector Technology Challenges

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Sonora Workshop on Medical and High Energy Physics

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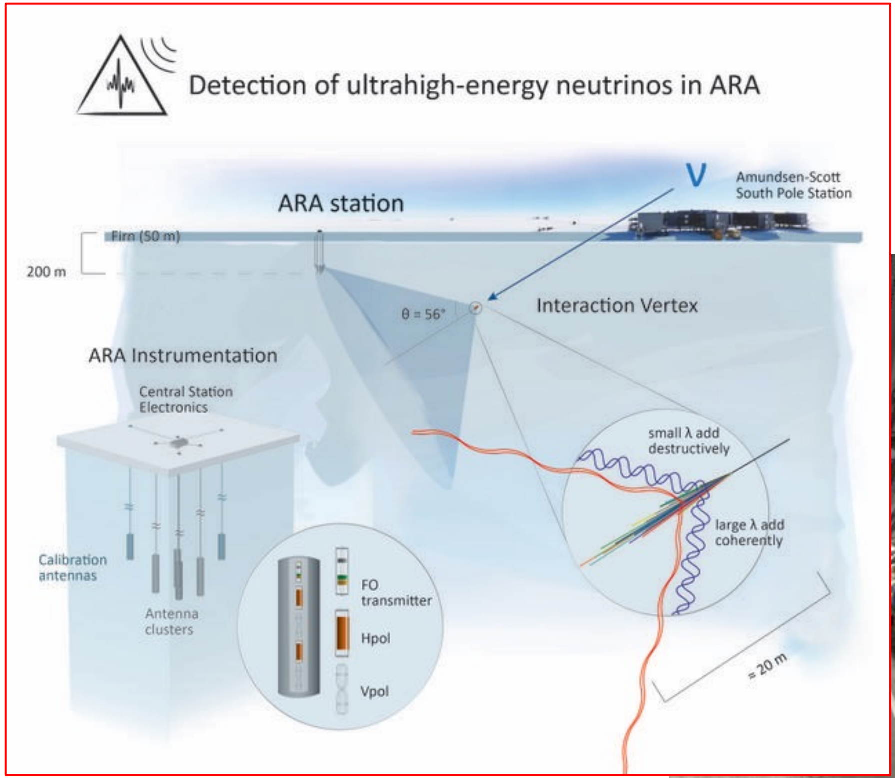
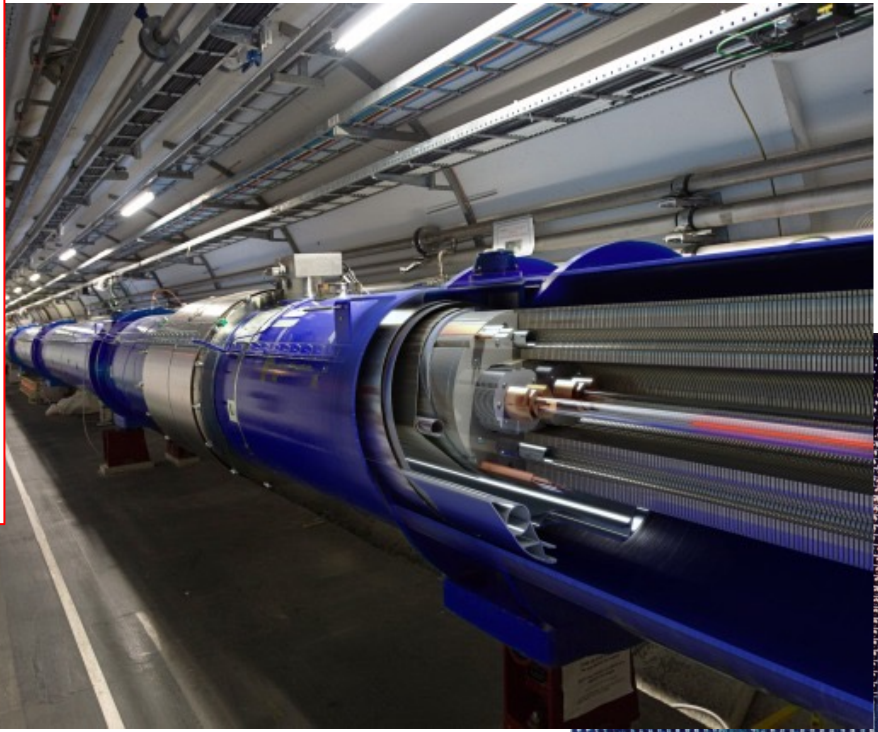
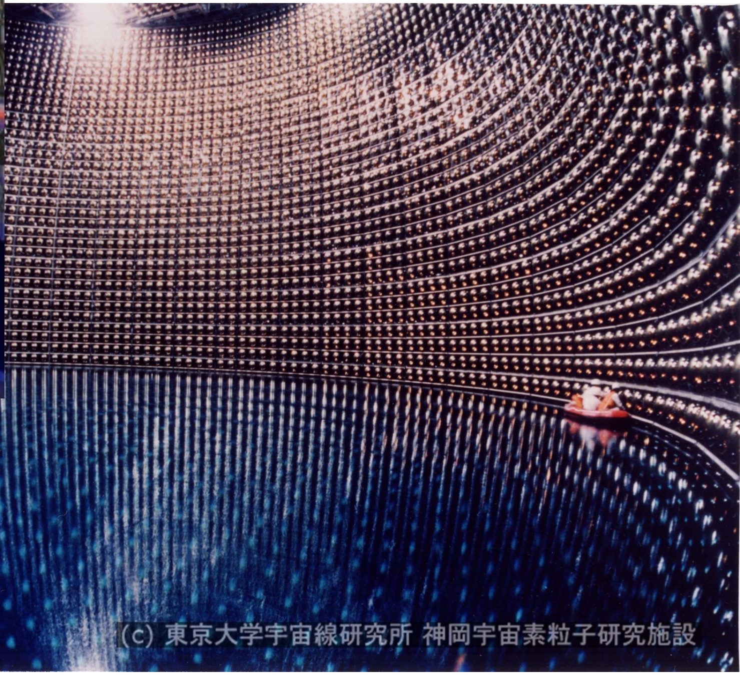
# There are many ways to explore the properties of elementary particles and fields, for example...

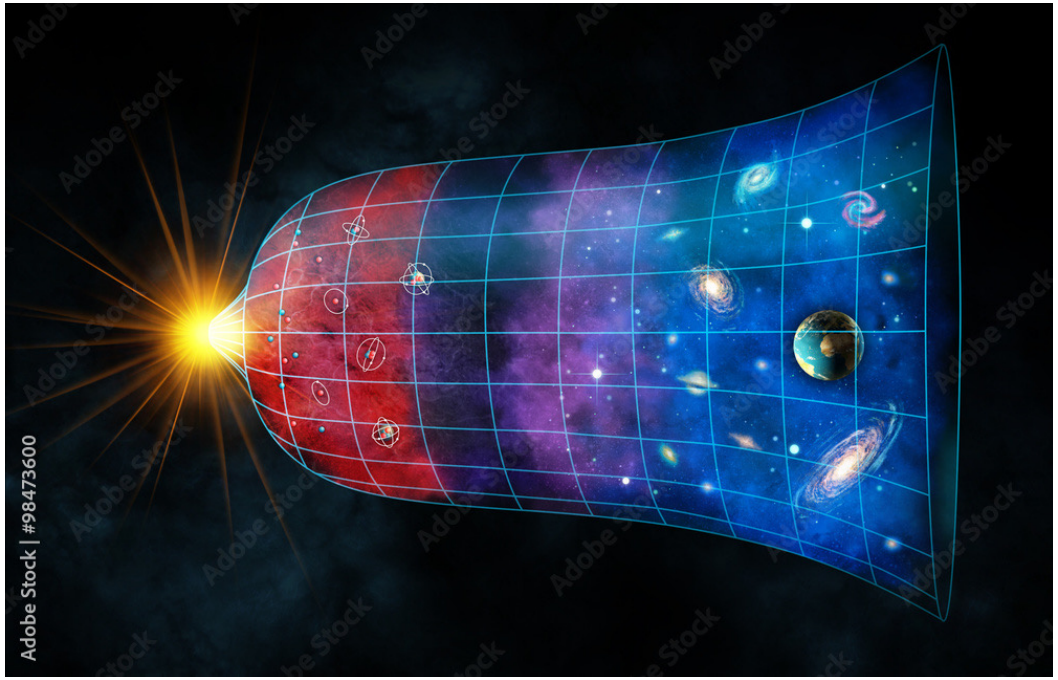






- ***Focus here on particle colliders***....facilities with counter-circulating bunches of particles that are brought into collision at one or more points, where detectors are installed to image the events initiated at the crossing.

- The accelerated particles are "energy carriers" (part of the energy is in their mass, and part is in their momentum). When 2 collide, the energy of both is concentrated into nearly a point. We can think of this as **a tiny replica of something like the Big Bang**. Give Nature all the energy it wants, and see what Nature will make of it.



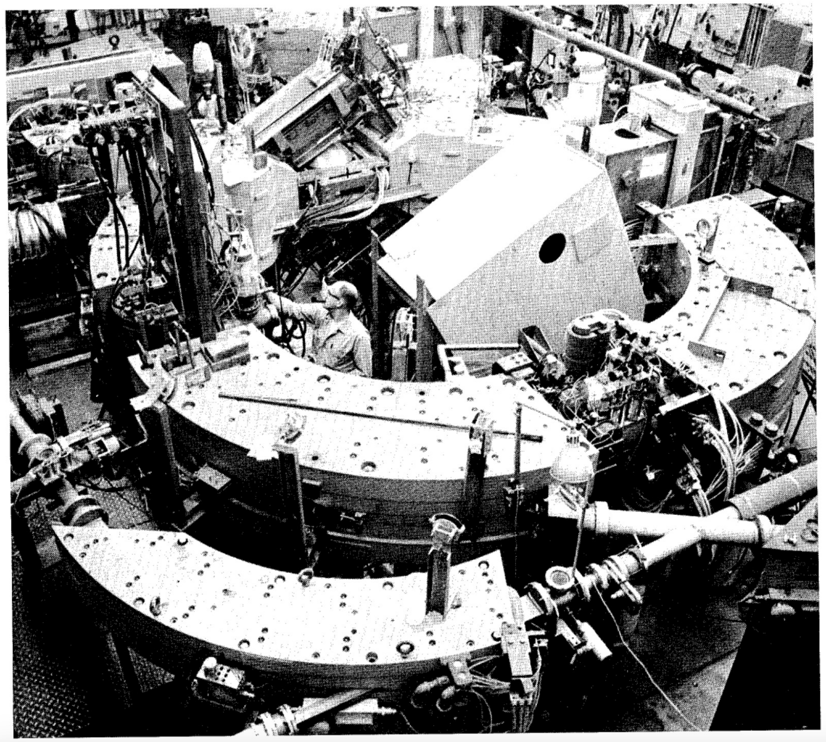
- Murray Gell-Mann quoted the "totalitarian principle of physics" in 1956:
  - ***"Everything not forbidden is compulsory."***
  - Energy can transform into mass. **We look at the characteristics of the collision products to see – new particles** (like the Higgs) that are implicated in how things work; **new conservation laws** that prevent or permit certain final states; **new symmetries** that enhance or suppress processes; evidence for **short-lived or invisible particles** to explain gaps in the record, and so forth.


M. Gell-Mann

The interactions that can produce the highest mass particles, or can probe the most deeply into a system, are obtained at the highest energy collisions – and these are achieved by **colliding counter-rotating beams**.

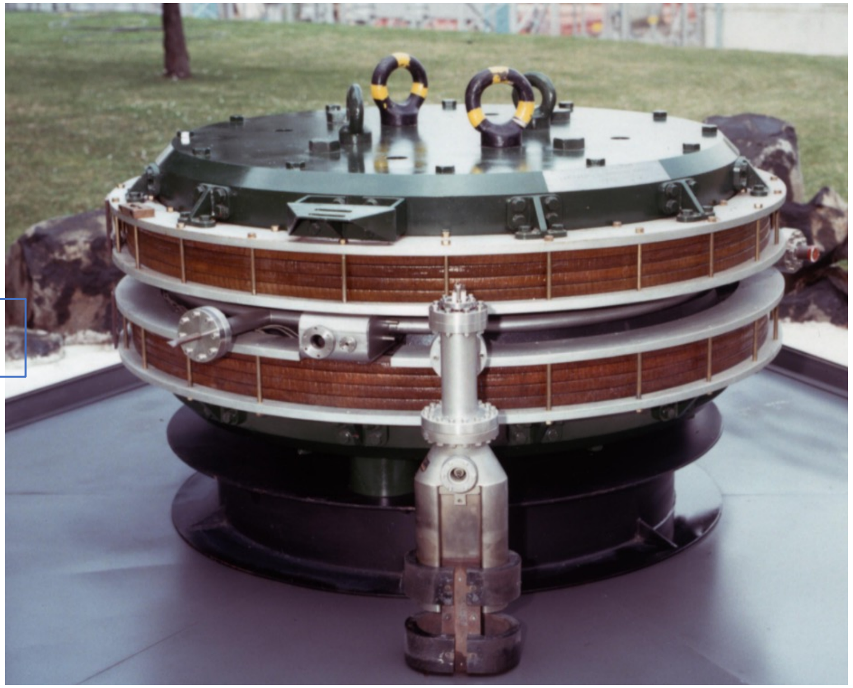
First thoughts about particle colliders were published by Burton Richter and collaborators at Stanford/Princeton. Electron-electron machine concept in 1957, stored beam in 1962.

*The Stanford-Princeton Storage Rings*



*B. Richter*

*AdA*

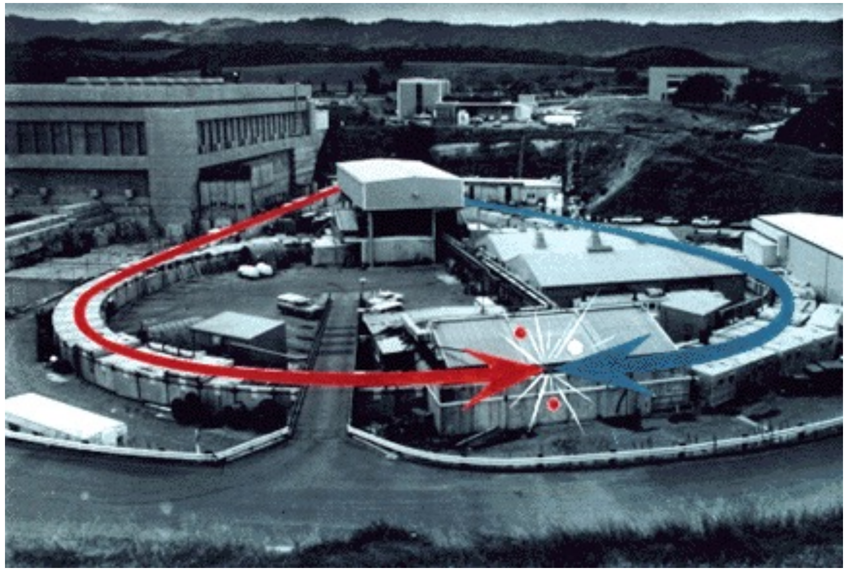


The first collider – electron or positron stored beam in the AdA at Frascati, 1961

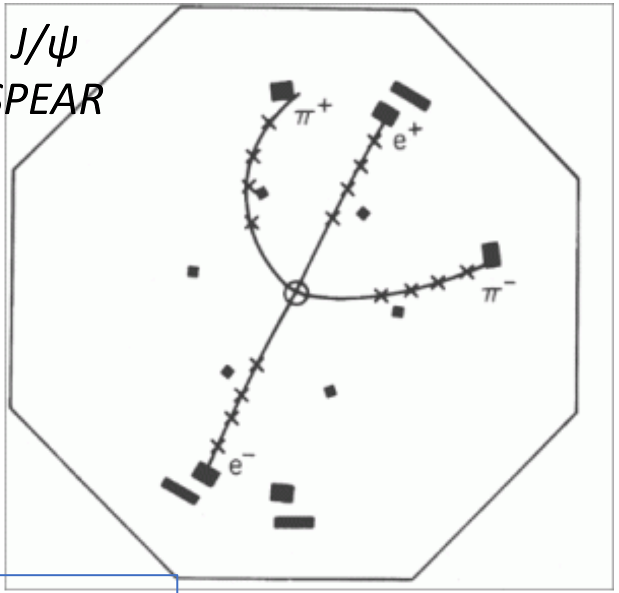
AdA transferred to Orsay to increase energy with a linac, 1962. Achieved luminosity $10^{25}$ collisions/cm$^2$/sec

Many electron/positron storage rings were commissioned around the world beginning in the 1970’s, including:

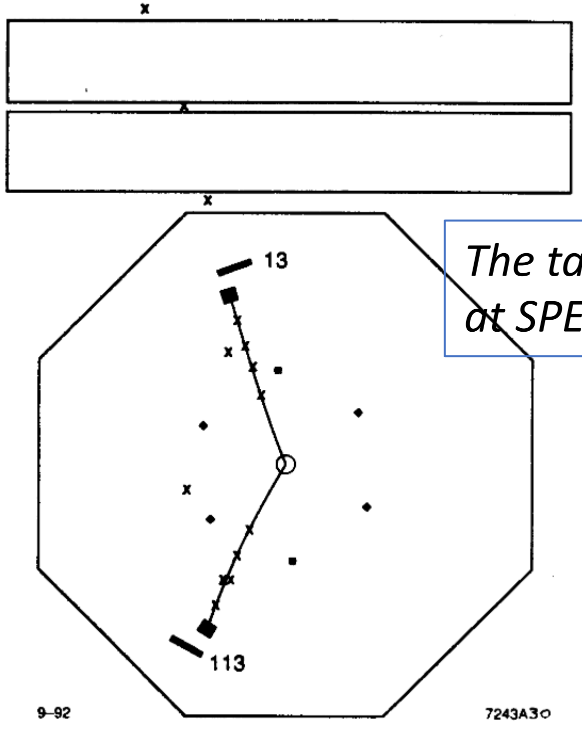
- VEP (Novosibirsk) – confirmation of QED radiative effects
- SPEAR (Stanford) – discovery of the J/ψ meson [discovery of charm] and discovery of the tau lepton



*The J/ψ at SPEAR*



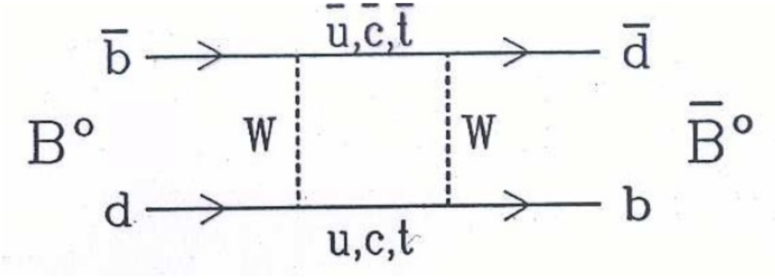
*The tau at SPEAR*

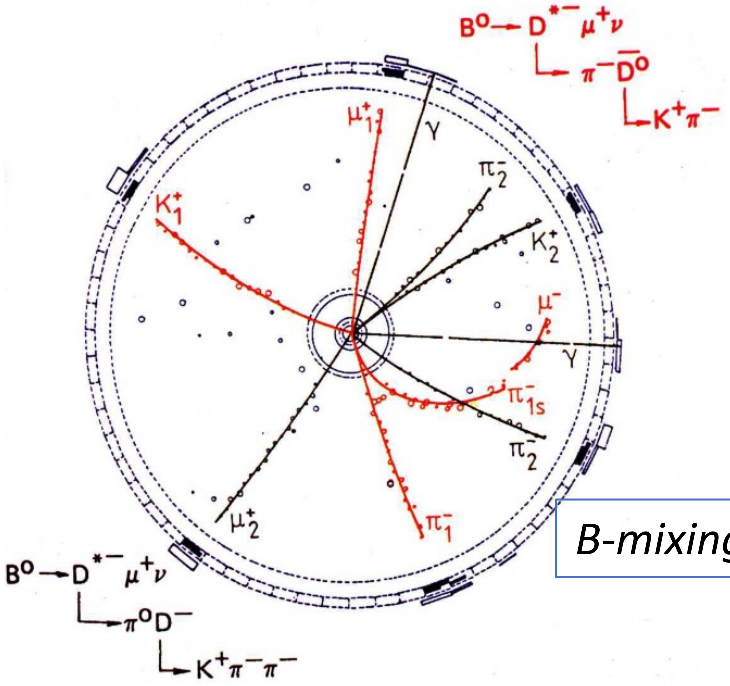


In these discovery events, you are looking along the axis of one beam, at the point where it collided with the oncoming beam.

# Those groundbreaking electron/positron storage rings, continued...

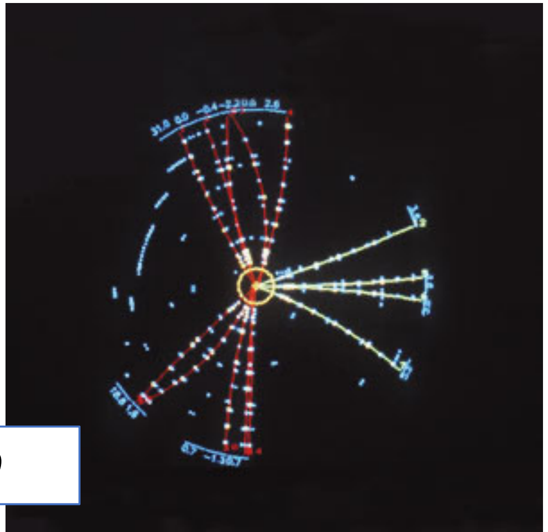
- DORIS (Hamburg) – discovery of B-meson mixing and excited charmonium states





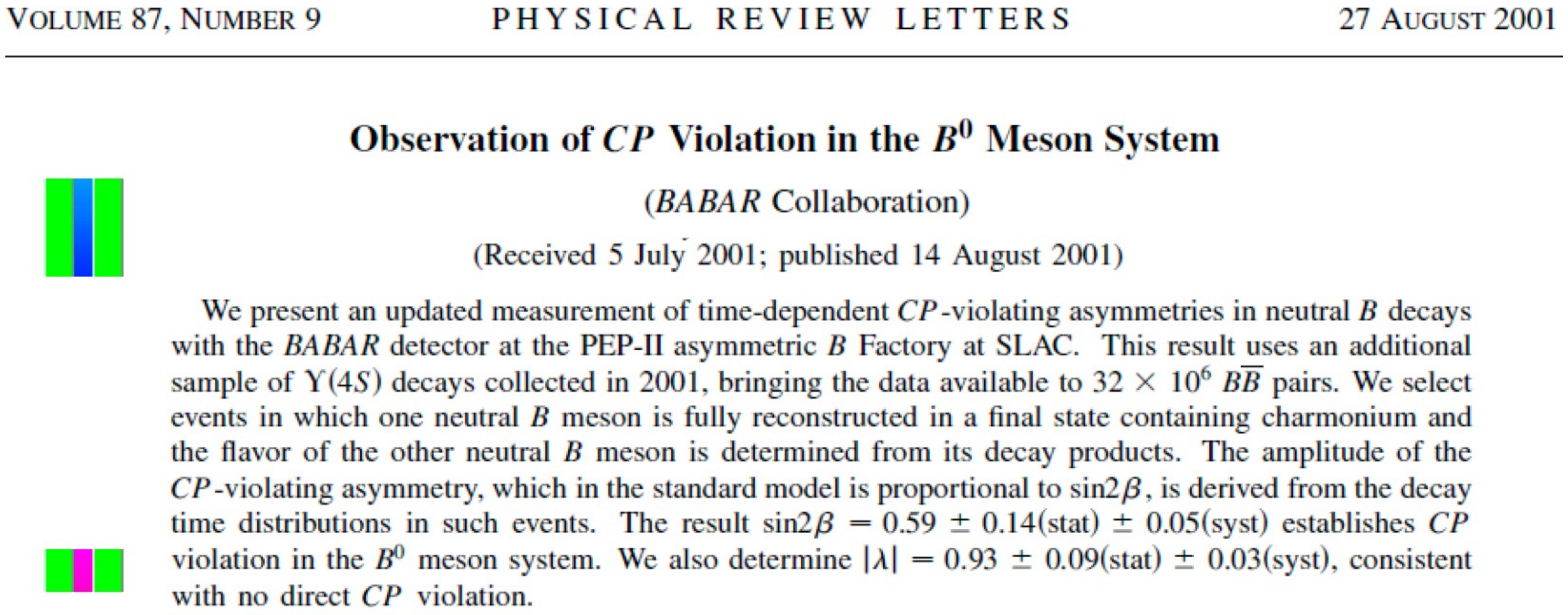
*B-mixing at ARGUS*

- PETRA (Hamburg) – discovery of the gluon, the mediator of the strong interaction



*The gluon at TASSO*

- PEP-II (Stanford) and KEKB (Tsukuba) – discovery of CP violation in B-meson systems



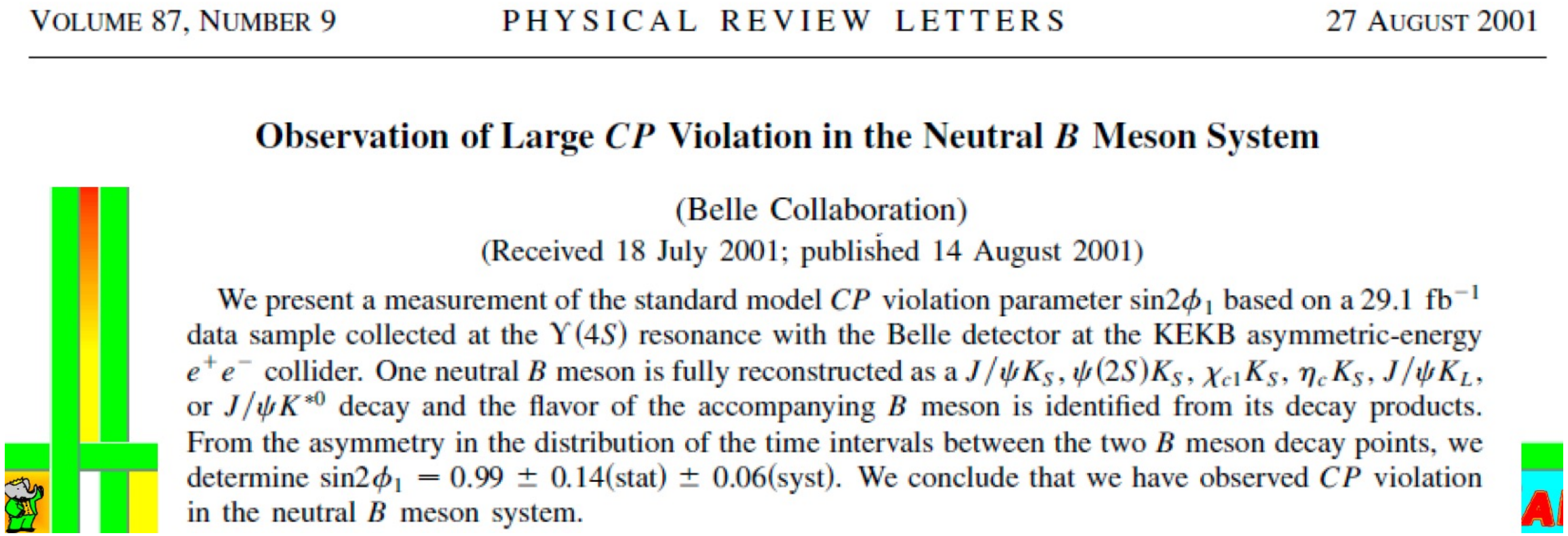
VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

# Observation of *CP* Violation in the $B^0$ Meson System

(*BABAR* Collaboration)

(Received 5 July 2001; published 14 August 2001)

We present an updated measurement of time-dependent *CP*-violating asymmetries in neutral *B* decays with the *BABAR* detector at the PEP-II asymmetric *B* Factory at SLAC. This result uses an additional sample of $\Upsilon(4S)$ decays collected in 2001, bringing the data available to $32 \times 10^6$ $B\overline{B}$ pairs. We select events in which one neutral *B* meson is fully reconstructed in a final state containing charmonium and the flavor of the other neutral *B* meson is determined from its decay products. The amplitude of the *CP*-violating asymmetry, which in the standard model is proportional to $\sin 2\beta$, is derived from the decay time distributions in such events. The result $\sin 2\beta = 0.59 \pm 0.14(\text{stat}) \pm 0.05(\text{syst})$ establishes *CP* violation in the $B^0$ meson system. We also determine $|\lambda| = 0.93 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$, consistent with no direct *CP* violation.



VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

# Observation of Large *CP* Violation in the Neutral *B* Meson System

(Belle Collaboration)

(Received 18 July 2001; published 14 August 2001)

We present a measurement of the standard model *CP* violation parameter $\sin 2\phi_1$ based on a 29.1 $\text{fb}^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. One neutral *B* meson is fully reconstructed as a $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$, or $J/\psi K^{*0}$ decay and the flavor of the accompanying *B* meson is identified from its decay products. From the asymmetry in the distribution of the time intervals between the two *B* meson decay points, we determine $\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst})$. We conclude that we have observed *CP* violation in the neutral *B* meson system.

These colliders were all clearly ***discovery machines***. In addition to the results mentioned, they made hundreds of other “bread and butter” measurements that **validated and extended the precision** of the Standard Model of particle physics.

***Precision*** derives directly from the fact that the colliding electrons are **pointlike**, so the vertex of the collision is unambiguously known.

But to continue toward higher energies, the rings were getting larger, civil construction more expensive. Would a different approach make sense?

## Circular or linear?

- A challenge with ***circular*** electron colliders arises because circulating charged particles of mass m, traversing radius of curvature R, radiate energy ΔE as

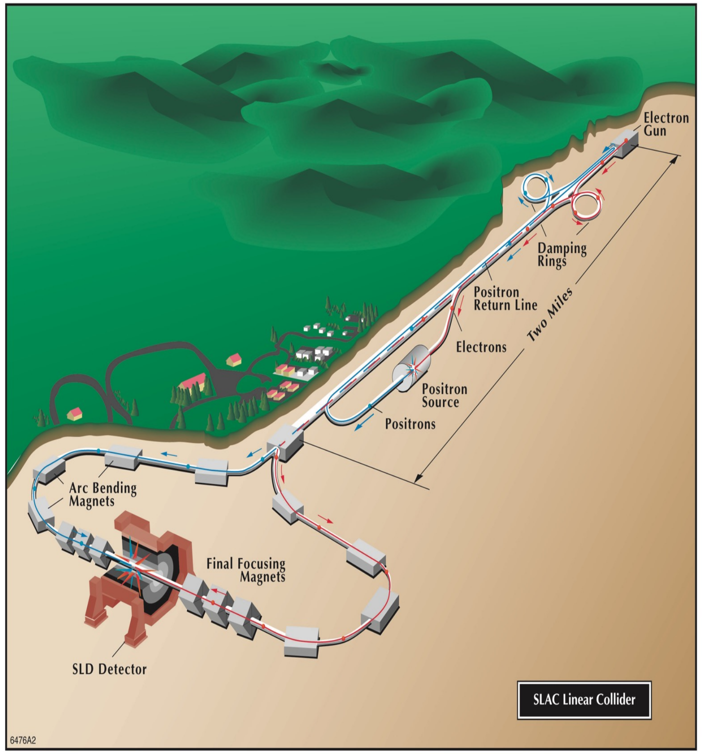
$$\Delta E = \frac{4\pi}{3\epsilon_0}\frac{q^2}{R}\left(\frac{E}{m}\right)^4$$

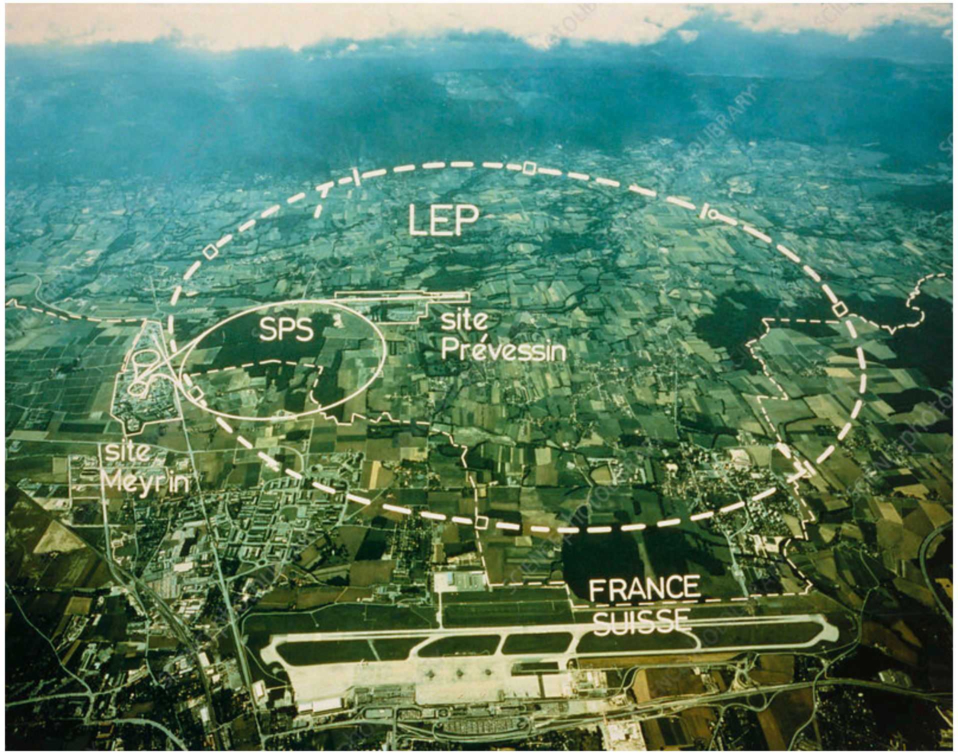
- But charged particles accelerated ***linearly*** emit negligible radiation. But in a linear collider luminosity is depleted if the beam is dumped after every crossing

Beginning 1998/1999, both approaches were explored:

- **SLC: Stanford Linear Collider**
  – peak luminosity approximately $2 \times 10^{30}/cm^2/sec$
  - generated 350,000 Z particles

- **Large Electron Positron (LEP) Collider**, CERN
  - peak luminosity $10^{32}/cm^2/sec$
  - generated 17,000,000 Z particles.

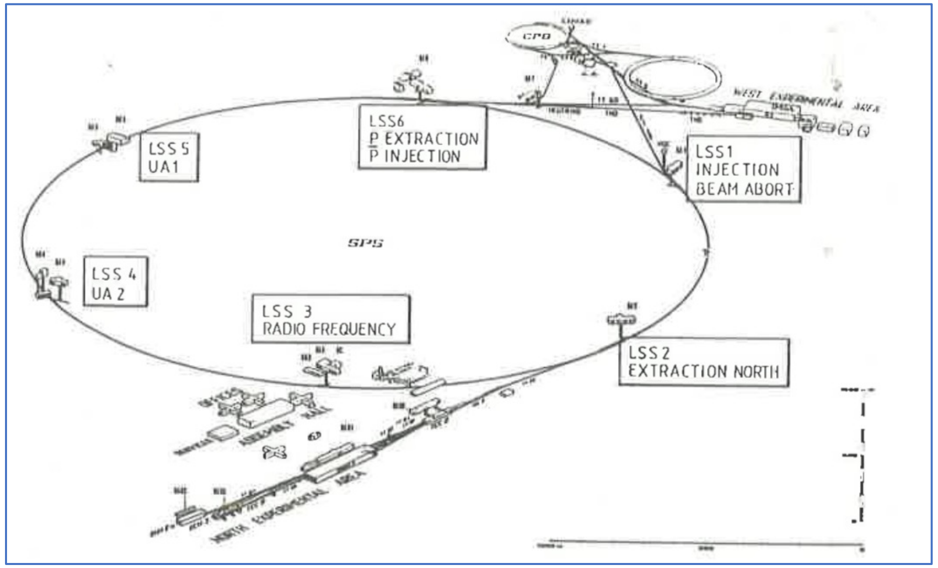




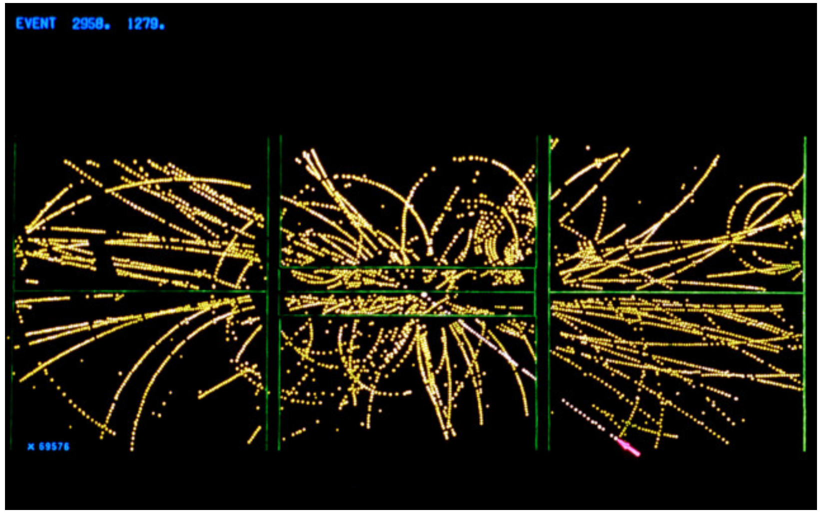
***SLC was a successful demonstration of a groundbreaking technique***, but it did not compete with LEP in *luminosity.* By measuring the width of the Z-boson to very high precision, LEP demonstrated that there are only 3 light neutrinos, and thus 3 generations leptons. ***LEP was the state of the art in lepton (pointlike, electron-type) colliders when it was turned off in 2001.***

Contemporaneously, people were thinking about ***colliding protons***. These higher mass particles ($m_p = 1837 \times m_e$) give access to higher energies, with less synchrotron radiation loss.

At CERN, the **ISR (Intersecting Storage Rings)** collided protons at 62 GeV center of mass energy, at currents up to 57 amp per beam, and luminosity of $1.4 \times 10^{32}/\text{cm}^2/\text{sec}$. It was approved in 1965 and started operation in 1971.



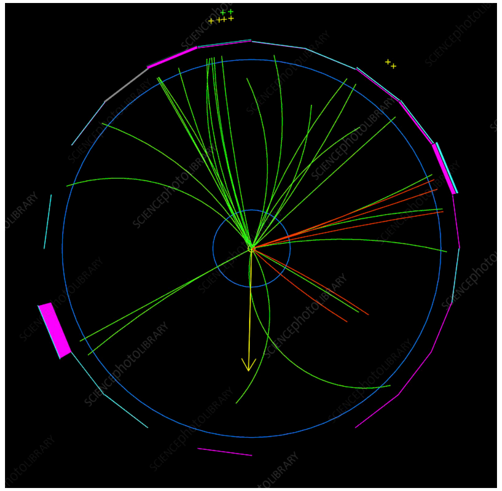
Technologies developed there (including – first use of stochastic cooling, Van der Meer Nobel 1984) led to the **S-p-pbar-S (Super proton antiproton Synchrotron)** which was completed in 1981. The W and Z bosons, carriers of the weak force were discovered here.



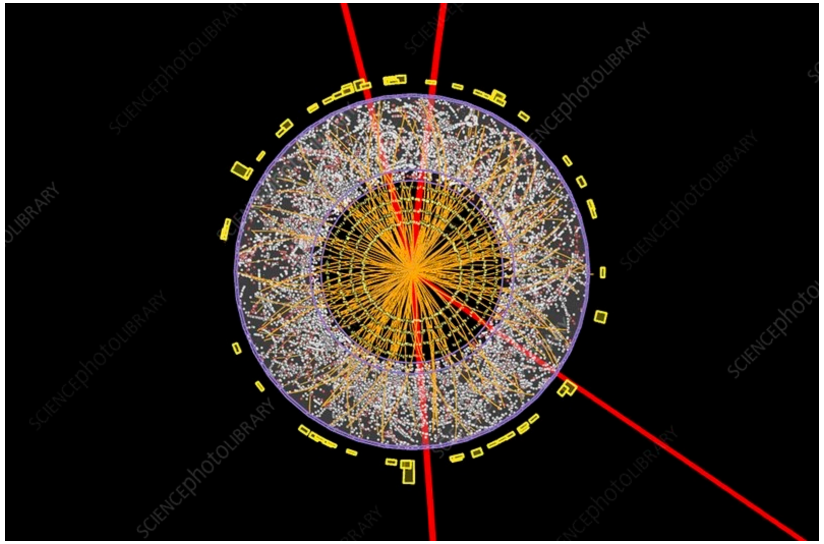
*The first W event, in UA1*

# *Evolution continues in high energy discovery machines:*

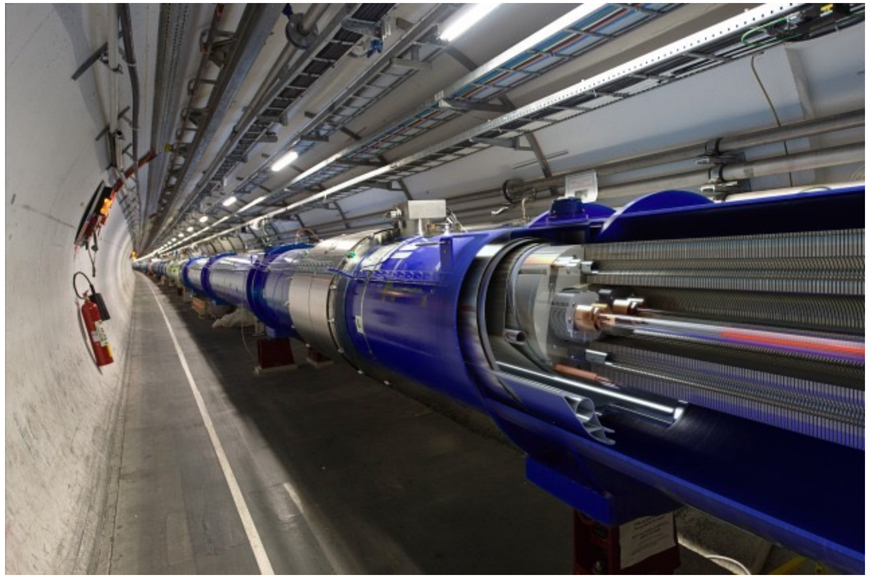
- **Tevatron at Fermilab:** p-pbar with energy ~3x higher than SppbarS: discovery of the **top quark**



*top at CDF*



*Higgs at ATLAS*



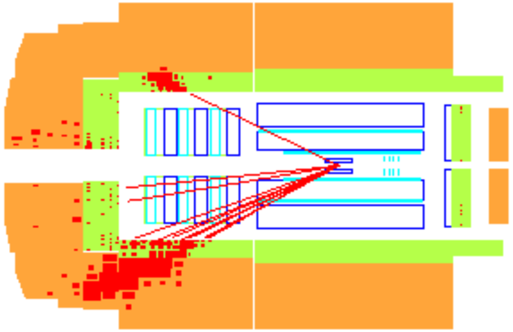
**LHC at CERN**: proton-proton [or Pb-Pb] – discovery of the **Higgs boson**

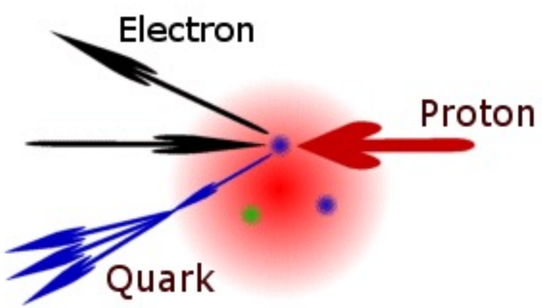
# *Two other unique colliders,*

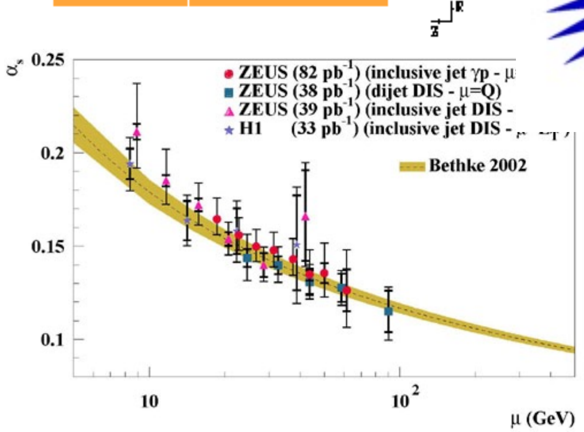
- **HERA** (Hamburg): electron-proton collider for studies of **proton structure and quark properties**

proton ring

electron ring

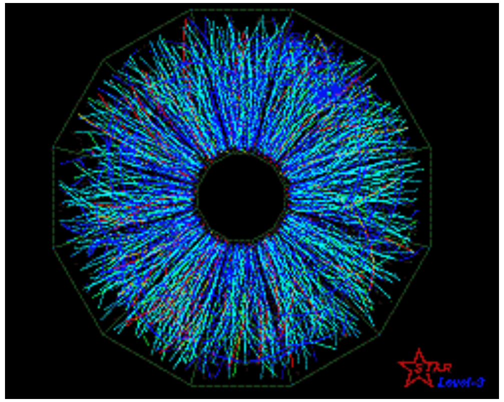


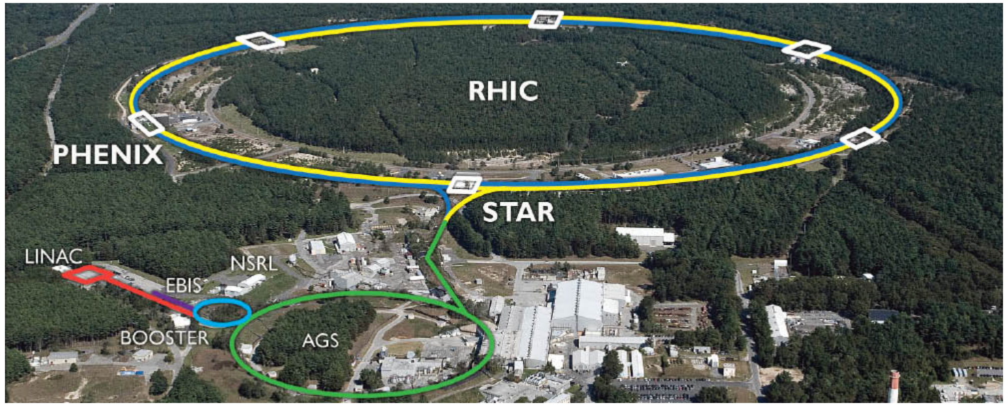




- **RHIC** (Brookhaven): polarized protons for spin studies, and heavy ions to create and probe the quark-gluon plasma

*Au-Au event at STAR*





## What’s next?

Electrons, protons, or something else?

Where?  What energy makes sense?  What luminosity is possible?

***What are the physics goals?***

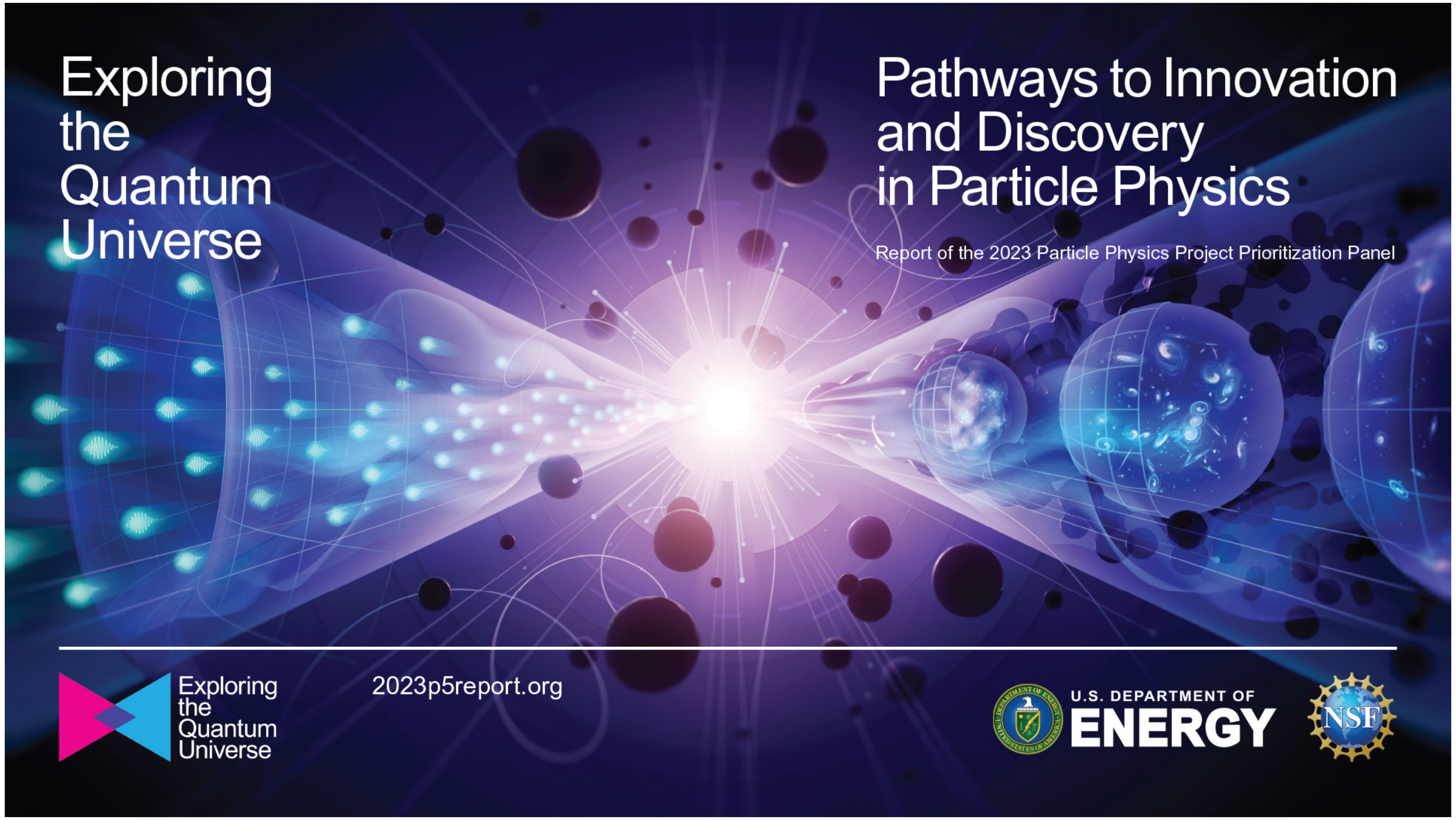
During 2021-2023, **the US particle physics community conducted a planning process to set its research directions for the next 10 – 20 years**. This involved 2 steps:

- the ***"Snowmass" process*** – white papers on any and all topics (theory, experiment, instrumentation...) were written, presented at workshops, and published by hundreds of researchers

➢ The full Snowmass proceedings are here: https://www.slac.stanford.edu/econf/C210711/

- the ***Particle Physics Project Prioritization Process (P5)*** – a committee of 30 experts drawn from the community used Snowmass process information and other resources to produce recommendations.

➢ **The complete P5 recommendations** are here: [https://science.osti.gov/-/media/hep/hepap/pdf/Reports/P5Report2023_120123-DRAFT-to-HEPAP.pdf](https://science.osti.gov/-/media/hep/hepap/pdf/Reports/P5Report2023_120123-DRAFT-to-HEPAP.pdf)



Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

Exploring the Quantum Universe

2023p5report.org

U.S. DEPARTMENT OF ENERGY

NSF

**The recommendations are EXTENSIVE and cover the full scope of particle physics and cosmology. This talk examines *only* recommendations about future colliders.**

*Recommendations from the P5 report that reference colliders:*

- Complete construction projects and support operations at the **High-Luminosity (HL) LHC**.
- Plan and start major initiatives including an off-shore **Higgs factory**....the current designs of **FCC-ee and ILC** meet our scientific requirements
- Support the Belle-II upgrade...including contributions toward the **Super-KEKB accelerator**
- Support vigorous R&D toward a cost-effective **10 TeV parton center-of-mass (pCM) collider** based on proton, muon, or possible wakefield technologies.

*The next slides examine these future colliders.*

## An argument for prioritizing electrons (precision) at this time*

Historically, lower energy precision measurements have established road maps for higher energy machines.

- 1970’s, precision neutral current studies indirectly indicated the W and Z; these were then found in the expected mass range by UA1/UA2 at S p pbar S.
- precision measurements at LEP and SLC, combined with the FNAL top mass, provided the Higgs mass range, subsequently discovered at LHC.

*What will precision measurements at an e+e- Higgs factory predict?*

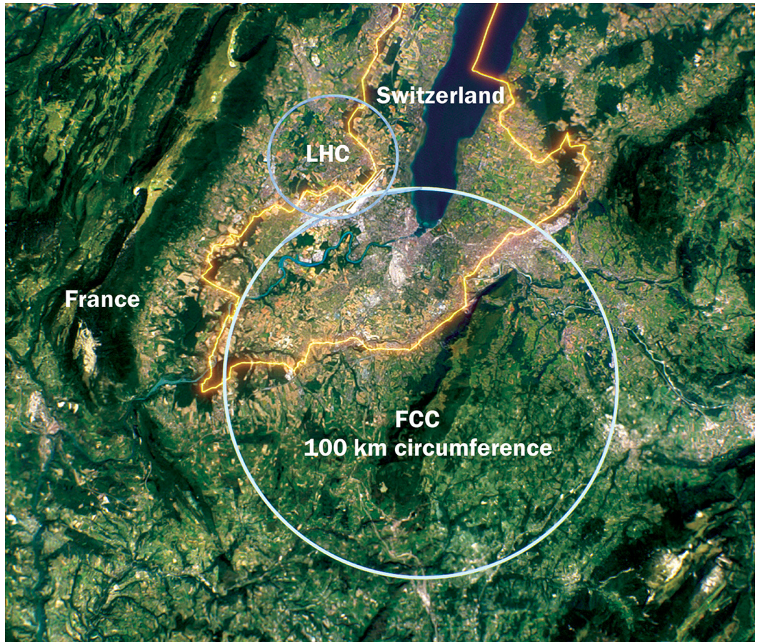
A. Abada et al., https://doi.org/10.1140/epjst/e2019-900045-4, page 291.

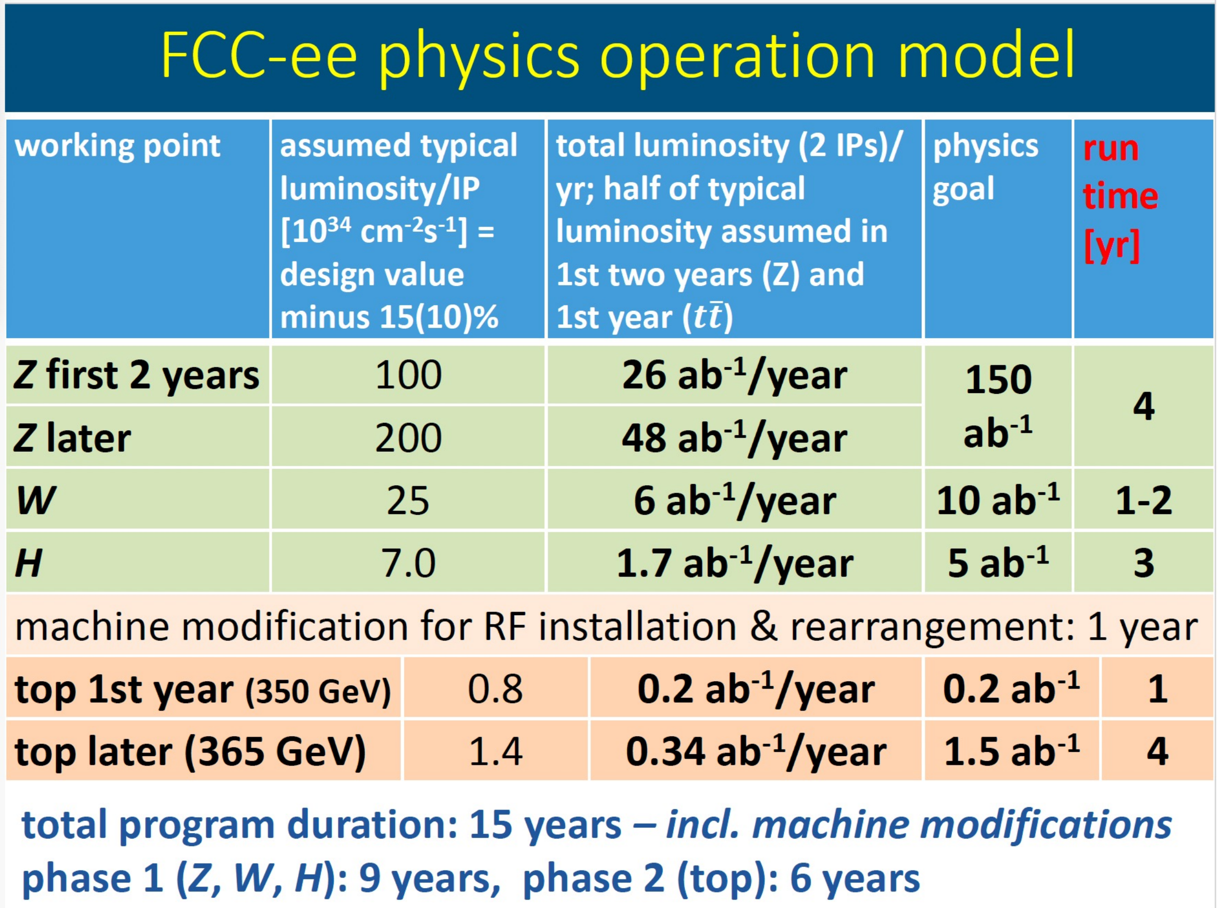
# A Higgs Factory.....potentially FCC-ee†

- Invoked in the European Strategy document of 2013, a post-LHC forefront accelerator project at CERN
- Staged implementation, at collision energies from 88 to 365 GeV
- 97.75 km circumference
- potentially 4 interaction points
- double ring to store maximum # of bunches
- crab waist collision scheme for extremely small $\beta_y^*$, goal ~ 1mm, in use since 2008 at Dafne
- high precision center of mass energy calibration uses a scheme unique to circular colliders – transverse beam polarization.

$\beta^* = \sigma^2/\varepsilon$, beam size /emittance, at the interaction point

Emittance: beam area in phase space





## FCC-ee physics operation model

| working point | assumed typical luminosity/IP [$10^{34}$ cm$^{-2}$s$^{-1}$] = design value minus 15(10)% | total luminosity (2 IPs)/ yr; half of typical luminosity assumed in 1st two years (Z) and 1st year ($t\bar{t}$) | physics goal | run time [yr] |
|---|---|---|---|---|
| ***Z* first 2 years** | 100 | **26 ab$^{-1}$/year** | **150 ab$^{-1}$** | **4** |
| ***Z* later** | 200 | **48 ab$^{-1}$/year** | | |
| ***W*** | 25 | **6 ab$^{-1}$/year** | **10 ab$^{-1}$** | **1-2** |
| ***H*** | 7.0 | **1.7 ab$^{-1}$/year** | **5 ab$^{-1}$** | **3** |
| machine modification for RF installation & rearrangement: 1 year | | | | |
| **top 1st year (350 GeV)** | 0.8 | **0.2 ab$^{-1}$/year** | **0.2 ab$^{-1}$** | **1** |
| **top later (365 GeV)** | 1.4 | **0.34 ab$^{-1}$/year** | **1.5 ab$^{-1}$** | **4** |

**total program duration: 15 years – *incl. machine modifications***
**phase 1 (*Z*, *W*, *H*): 9 years, phase 2 (top): 6 years**

+ Periodically return to Z-pole for detector calibrations.

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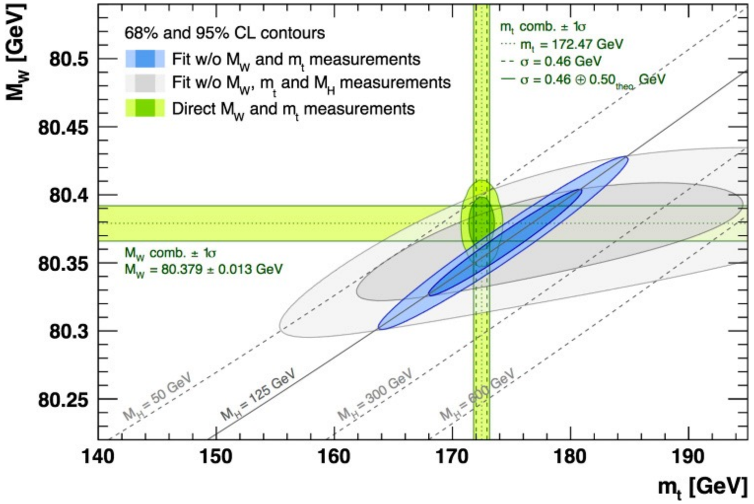
†FCC-ee: The Lepton Collider, Eur. Phys. J. Special Topics 228, 261-623 (2019), https://fccis.web.cern.ch/conceptual-design-report-volumes#

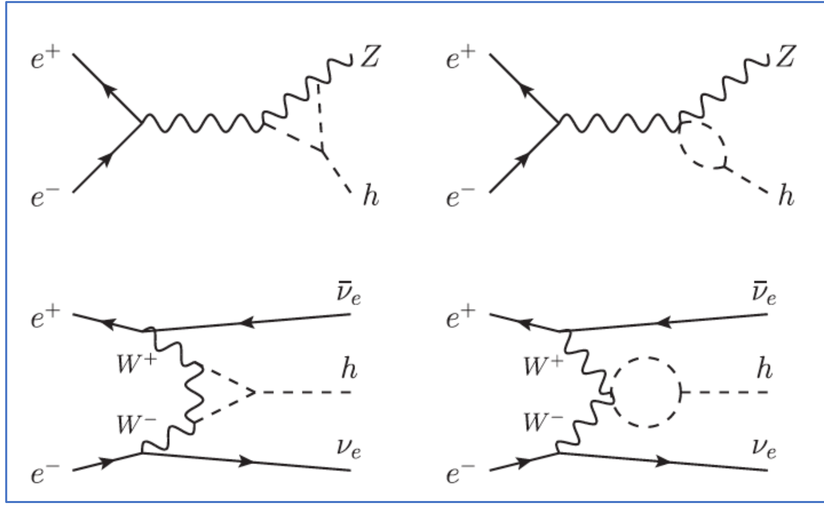
**The FCC-ee design parameters** are driven by numerous **physics goals** including:

- comprehensive study the full electroweak sector, including W/Z, Higgs, and top, with high precision.

  Motivation: EW quantum corrections are sensitive to (New Physics) particles with EW couplings and masses higher than directly accessible**

  ➢ **Higgs self-coupling** characterizes the Higgs potential, impacting the questions of naturalness and stability of the EW vacuum, and controlling the EW phase transition, possibly impacting baryogenesis.





*More about this on the next slides….*

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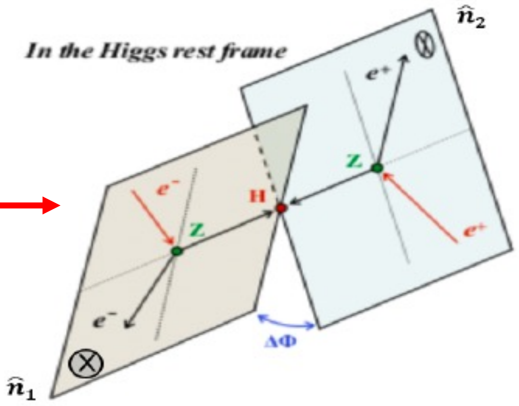
**M.J.G. Veltman, Nucl. Phys. B 123 89 (1977).

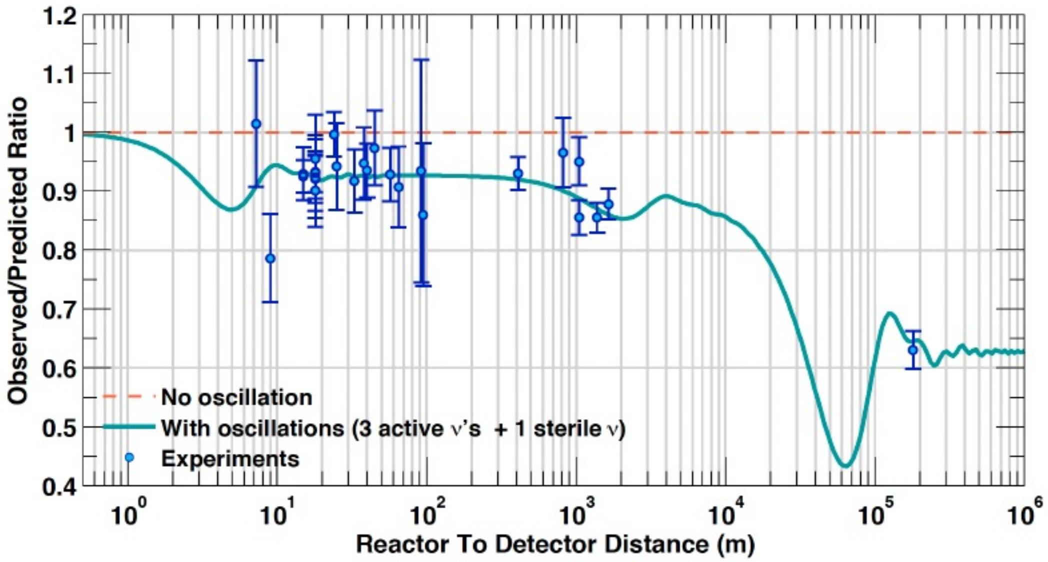
# FCC-ee physics motivation, continued...

- **CP violation in Higgs** interactions?
- 5 x $10^{12}$ Z-bosons can uncover **dark matter** that couples with strength as low as $10^{-11}$ x EW coupling.



Definition of the CPV sensitive angle Φ in the Higgs boson production in ZZ-fusion.

- **Unveil small but significant deviations between data and Standard Model.** Current agreement between the Standard Model and direct data means that any New Physics effect must be smaller than current uncertainties.
  - Delivering $10^5$ times the luminosity accumulated at LEP at the Z pole produces ~$10^{11}$ leptonic and ~$10^{12}$ hadronic Z decays, reduces statistical uncertainty by factor 300 (few mil per $10^5$).
- Observe **rare new processes**
  - Heavy right-handed **(sterile) neutrinos**?



Based on a figure from G. Mention et al., PRD 83 (2011) 073006, updated in arXiv:2106.05913.

# The importance of measuring the Higgs self-coupling

The *qualitative* image of the Higgs potential looks like some kind of hat.

But we don't know the shape *quantitatively*, and it determines whether the vacuum of our present universe is stable or not.

The Standard Model Higgs potential looks like

$$V_H = \mu^2\phi^\dagger\phi + \frac{1}{2}\lambda\left(\phi^\dagger\phi\right)^2$$

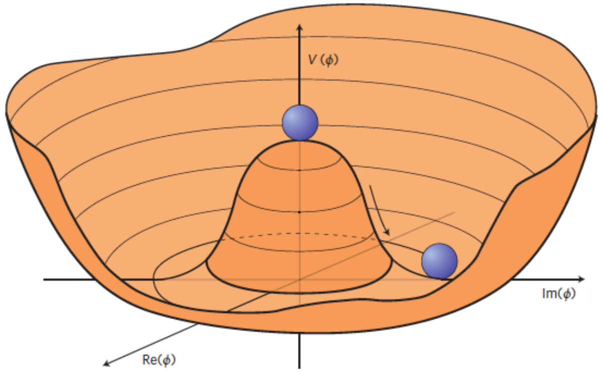
where $\lambda = \frac{M_H^2}{v^2}$ and $\mu^2 = -\frac{1}{2}M_H^2$

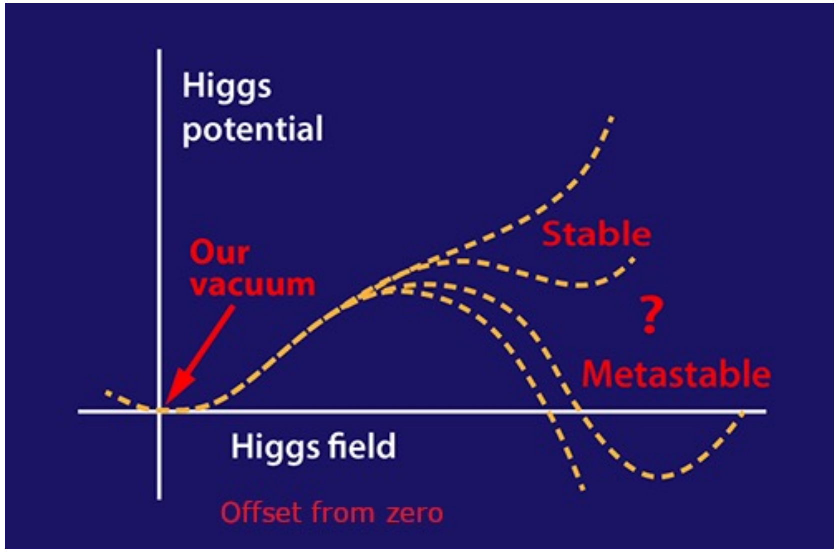
But if the Standard Model is an effective theory, $\lambda$ can be extended to include additional free parameters:

$$\lambda_{HHH} = \frac{3M_H^2}{V}$$

and

$$\lambda_{HHHH} = \frac{3M_H^2}{V^2}$$





In Beyond the Standard Model scenarios, $\lambda_{HHH}$ and $\lambda_{HHHH}$ can be large.

# The motivation for the search for CP-violating elements of the Higgs sector

Andrei **Sakharov identified 3 conditions** that would lead to a cosmological matter-antimatter asymmetry:

- Baryon number B violation
- C- and CP-violation, and
- an era of thermal interactions out of equilibrium.

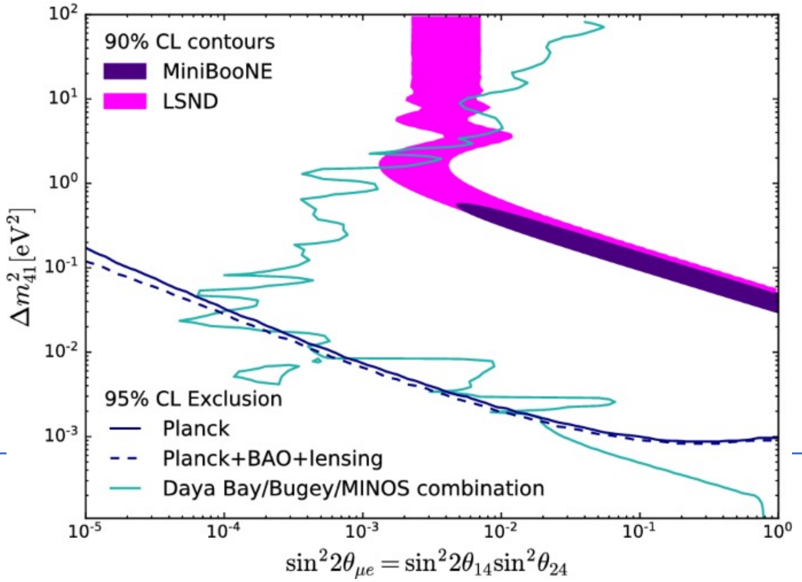
**Existing data on CP-violation in weak interactions of quarks are not sufficient** to explain the existing matter-antimatter asymmetry. Could there be additional violation in the Higgs sector?

**Current constraints** from ATLAS and CMS on Higgs interactions still **allow coupling deviations of 10% or more from Standard Model predictions.**

Andrei Sakharov

## Motivation for the search for Heavy Sterile Neutrinos,†

**i.e., charge-neutral singlet fermions that do not interact via the weak interaction – interact with SM particles only through mixing with neutrinos**



***Puzzles in the existing neutrino oscillation data:***

- the “LSND anomaly” [1993-98] - a 3.8 σ excess of antineutrino - electron interactions over standard backgrounds
- the “MiniBooNE anomaly” [ 2009-2021] - 4.8 σ excess of electron-like events at 4.8σ
- reactor anti neutrino flux anomalies [2011] – 3 σ deficit of electron antineutrinos observed, relative to model
- Gallium experiment anomalies (GALLEX, SAGE) [2008] – electron-neutrino disappearance: measurements of charged-current capture rate of neutrinos on $^{71}$Ga from strong radioactive sources below expectation - < 3 σ

***Interesting feature in theory:***

- singlet fermions appear naturally in theories of the dark sector. Could the dark matter be sterile neutrinos?
- sterile neutrinos generically appear in models that explain the smallness of neutrino masses (for example the “seesaw mechanism”)

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† B. Dasgupta and J. Kopp, Phys. Rep. 928 (2021) 1; arXiv:2106.05913.

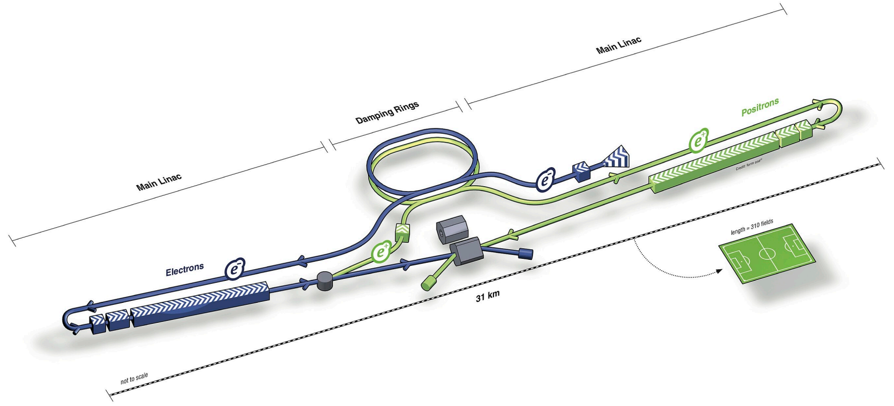
**Motivations for FCC-ee dedicated energy runs:**

- on both sides of the Z-boson peak - measures $\alpha$, Z width (# light neutrinos)
- at the Z-pole – measures weak mixing/Weinberg angle, $\alpha_s$
- at the WW production threshold – measures W mass and decay width, # neutrino species, and $\alpha_s$
- at 240 GeV – measures Higgs couplings and HZ production
- at t-tbar threshold – measures top mass, top decay width, top coupling to Higgs
- above the t-tbar threshold – measures top EW couplings and Higgs width

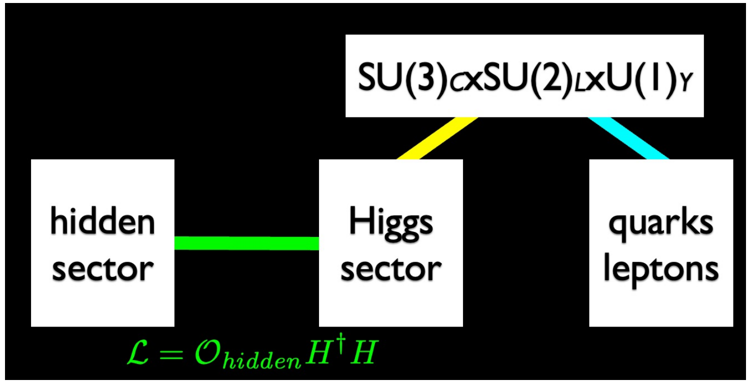
**Constraints on the detectors:**

- interaction rates (~100 kHz at the Z pole) limit event size and readout speed.
- beam crossing angle – limits solenoid to 2 T
- measurement of COM energy – requires 100 microrad resolution of muon trajectories

# A different proposed Higgs factory – the International Linear Collider (ILC)[‡]



- ***Goals: precision study of the Higgs, searches for new particles, constraints on new interactions***
- Could the Higgs be a **"portal"** to a sector of phenomena that do not interact via Standard Model processes?



*from H. Murayama*

**Features and advantages:**

- For cost savings, initial run at 250 GeV ($e^+e^- \rightarrow Zh$) with length ~20 km. Note $m_h$ = 125 GeV, so *observation of the recoiling Z tags the presences of the Higgs, even in cases where the Higgs decays invisibly.*
- Detectors are *not limited by radiation hardness constraints* and thus may be placed close to the collision point.
- *Absence of strong interaction backgrounds*
- Theoretical models provide *predictions to very high precision.*

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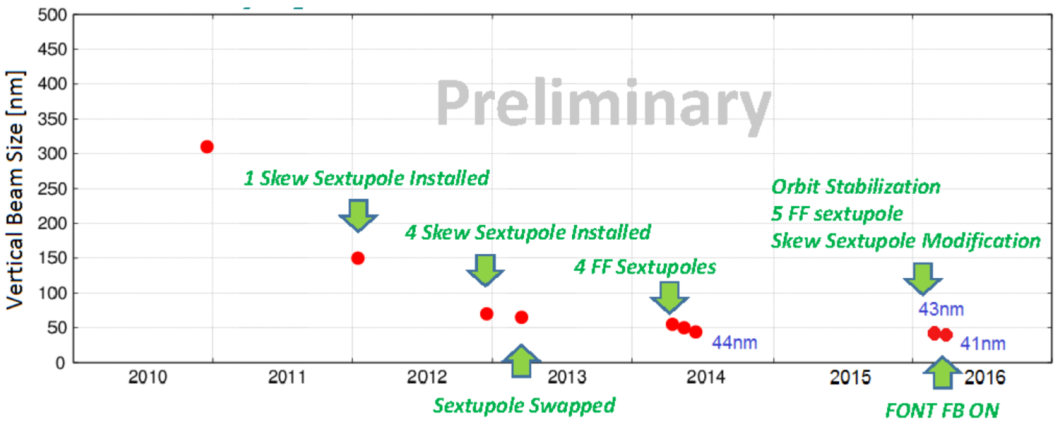
[‡] https://linearcollider.org/technical-design-report/

## Strengths of a linear configuration:

- Later extension to 500 GeV (tunnel length ~30 km), the full design energy. *Linear tunnel is extendable, and can accommodate new technology*
- Linac preserves *longitudinal polarization*, so polarized beams (30% for $e^+$, 80% for $e^-$) are possible, then complete reconstruction of initial and final states.
- *Nano-beam technology* achieving 41 nm vertical dimension in tests at KEK (goal for ILC is 37 nm)



**But political considerations:**

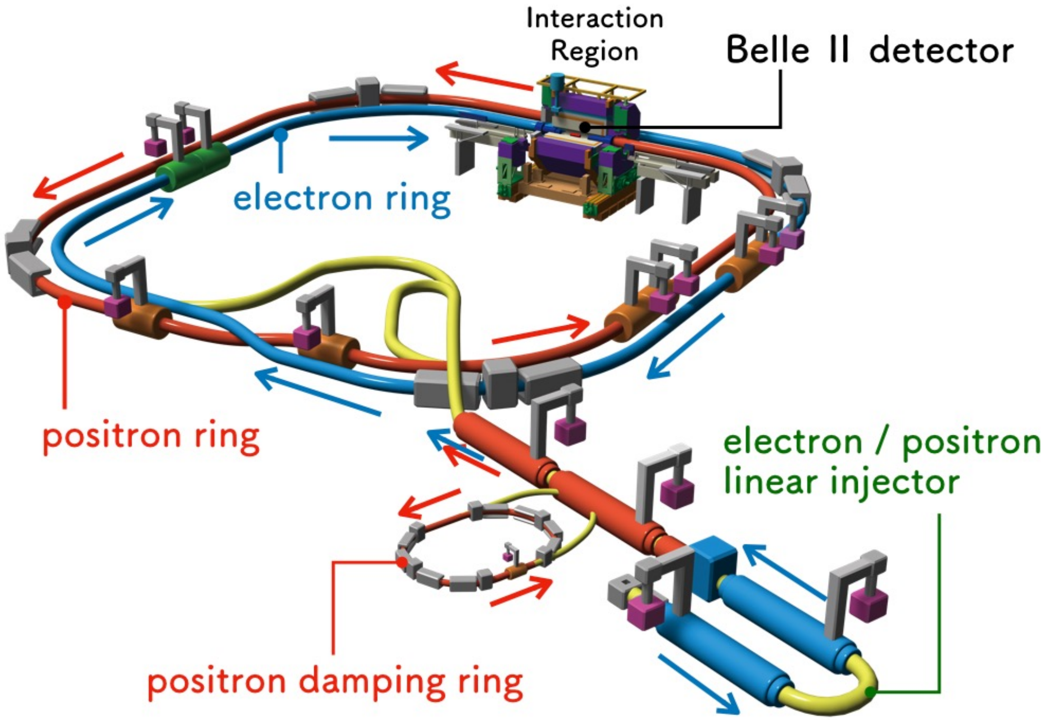
- In 2013, 20% of the Japanese Diet signed support for the ILC. Possible location proposed in the Tohoku region 400 km north of Tokyo
- Also supported by the Japanese physics community, industry, and regional governments
- In 2014, govt committee concluded that decision postponed until the end of LHC Run II – that was 2018
- 2019 – a new committee of the Science Council of Japan did not recommend support without additional international backing.
- Idea for a “pre-lab” for detector studies was proposed in 2021– but labeled “premature” by committee in 2022
- The international community may now be reopening the search for locations outside Japan.

# “Support the Belle-II upgrade…including contributions toward the Super-KEKB accelerator”

- an electron-positron collider located at the KEK national laboratory in Tsukuba, Japan
- combines a high energy (7 GeV) electron storage ring and a lower energy (4 GeV) positron storage ring. Energies are tuned to the mass of the Υ(4S) resonance, which decays promptly to B-mesons. Thus: it is a B-factory.
- Because of the energy asymmetry, the B-mesons are Lorentz-boosted.
- Continues to break the world record for collider instantaneous luminosity: now at 4.70×$10^{34}$ $cm^{-2}s^{-1}$

**An exceptional high integrated luminosity requirement is applied:**

- Integrated luminosity > 30 times the combined datasets of the previous 2 B-factory experiments, Belle (at KEK) and BaBar (at SLAC)
- Required instantaneous luminosity for SuperKEKB is 6.5×$10^{35}$ $cm^{-2}s^{-1}$ in order to achieve science goals within a decade



**The large dataset is linked to the primary goals of Belle-II:**

- seek evidence of deviations from Standard Model expectations, either through
  - **extremely high precision** (must be matched to precision in theory), or
    - Example, *CP violation studies, measurement of the CKM angles*
  - in **extremely rare/forbidden processes**.
    - *B-decays, involving potentially exotic particles in loop processes*, for example the null test of $B^0 \rightarrow K^0\pi^0$

- *explore processes for which LHCb is hampered by hadron bkg*, ex. decays involving neutral particles or missing energy
- *complement LHCb* on modes to which both are sensitive

  - ➢ SuperKEKB has been operating since 2016.

  - ➢ **Design luminosity depends on increasing beam current and decreasing beam size** at the interaction point.

  - ➢ Technology: low emittance colliding beams in the **"nano-beam scheme"***. Goal: $\beta_y^* = 0.3\ mm$. (Presently at 1.0 mm)

  - ➢ The challenge: **beam backgrounds**: particles that deviate from orbit and strike the beam pipe inner wall. These produce showers of particles that penetrate the Belle II particle identification and drift chamber systems.

  - ➢ Extensive work is underway to model the background processes.**

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*A. Piwinski, "The Touschek Effect in Strong Focusing Storage Rings," arXiv:physics/9903034 [physics.ac-ph]

** A. Natochii et al., "Measured and projected beam backgrounds in the Belle II experiment at the SuperKEKB collider, arXiv:2302.01566

## "Complete construction projects and support operations at the High-Luminosity (HL) LHC"

*Some physics motivations:*

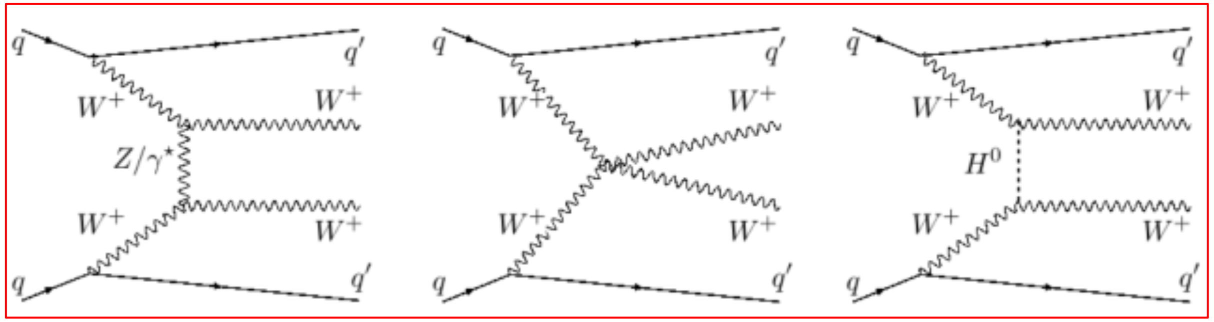
- **The hierarchy problem**: Gravity is $10^{17}$ times weaker than the other forces. In the SM this requires precision cancellation of numerous immense contributions to Higgs mass.
  - Solutions propose new particles that cancel the largest (positive and negative) contributions. Problem solved if those new particles have mass ~ 1 TeV.
  - Strength of gravity may be an issue of extra dimensions. HL-LHC will be sensitive to Kaluza-Klein gluons of mass up to 5.7 TeV.

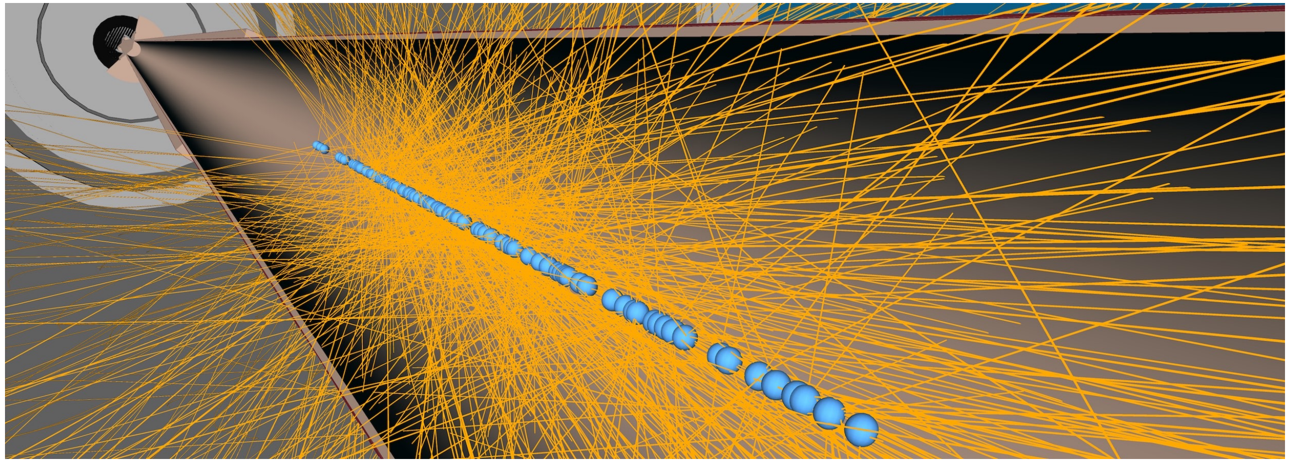
- **Dark matter**, obviously exists. Mass unconstrained below ~hundreds of TeV. HL-LHC will be sensitive into the TeV range.

- Precision studies of **ultra-rare processes**, as signals of deviation from the SM.

- Supersymmetry – can resolve the hierarchy problem, unify couplings at high energy, be the dark matter.

- Measurement of longitudinal **vector boson scattering – very rare process**. Rate will appear to violate unitarity if the Higgs is *not* a SM particle.





## *HL-LHC collider parameters:*

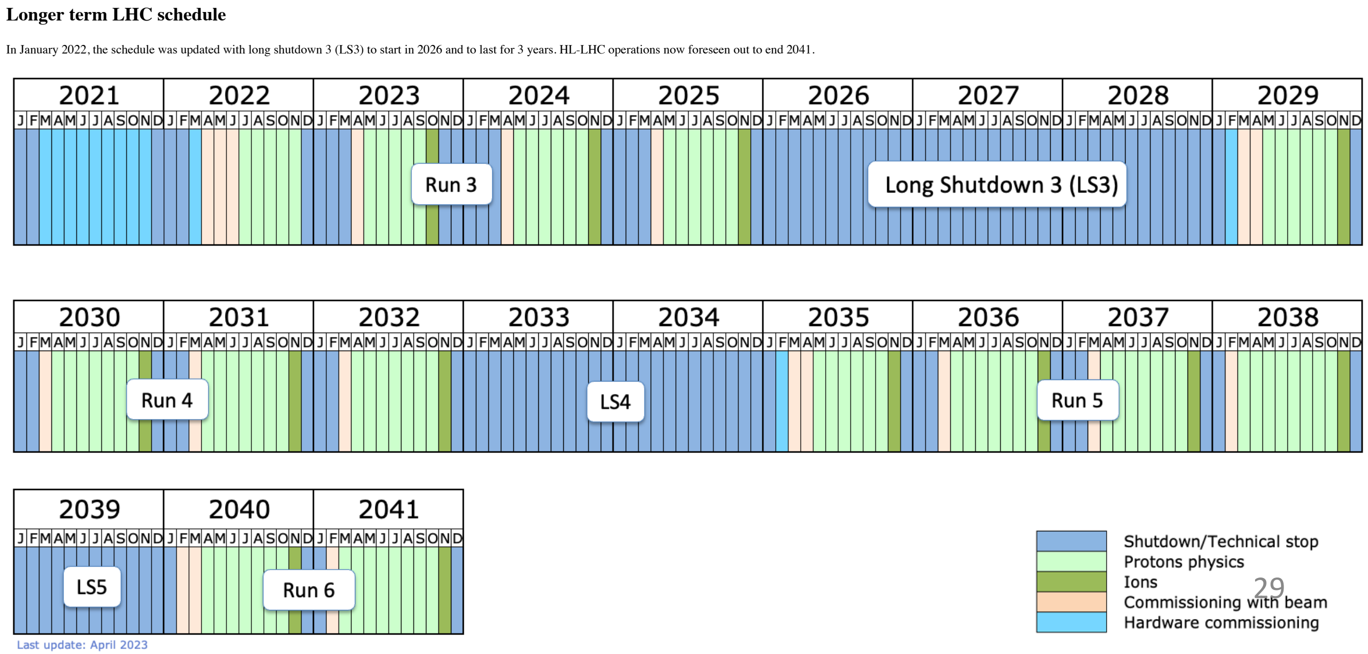
- 14 TeV [compare 13.6 TeV at LHC]
- 5 x LHC instantaneous luminosity
    - more protons per bunch, smaller β*
- integrated luminosity (dataset size) 3000 $fb^{-1}$, 10 times larger than at LHC
- Limit #of simultaneous interactions (“pileup”) per crossing to 140: restrict peak luminosity to 5e34 $cm^{-2}s^{-1}$.

## *Instrumentation challenges:*

- **Radiation tolerance.** Detectors within a few cm of the beamline will receive > $10^{16}$ hadrons/$cm^2$.*
- **Timing.** Distinguishing collision vertices from the same crossing requires ~picosecond resolution on their outgoing tracks.

An interesting comparison even if not quite fair: the fluence at ground zero of Hiroshima was ~6 x $10^{11}$/$cm^2$.

LHC long term schedule http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm



**Longer term LHC schedule**

In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years. HL-LHC operations now foreseen out to end 2041.

🟦 Shutdown/Technical stop
🟩 Protons physics
🟩 Ions
🟧 Commissioning with beam
🟦 Hardware commissioning

# "R&D toward a 10 TeV pCM collider...maybe a muon collider[‡] "

The idea was first introduced in 1969,* and reactivated when the Muon Collider Collaboration formed (1997) and then the International Muon Collider Collaboration (2021).

**Motivation:**

- Circular mode allows reuse of the beams – *maximum luminosity and multiple simultaneous experiments* enabled.
- Point-like particles – *precision position resolution*
- Muon mass is 206 x electron mass: *synchrotron radiation suppressed, and muon-Higgs coupling* is $10^4$ x greater than electron-Higgs coupling

**Energy goal**: 10 TeV parton COM energy
**Luminosity goal**: 10 $ab^{-1}$.

Thus: ***A precision machine and a discovery machine, combined.***

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[‡] C. Accettura et al., "Towards a Muon Collider," arXiv:2303.08533 [physics.acc-ph].

* G. Budker, Proc. 7th Int. Conf. High Energy Accel., Yerevan (1969) 33.

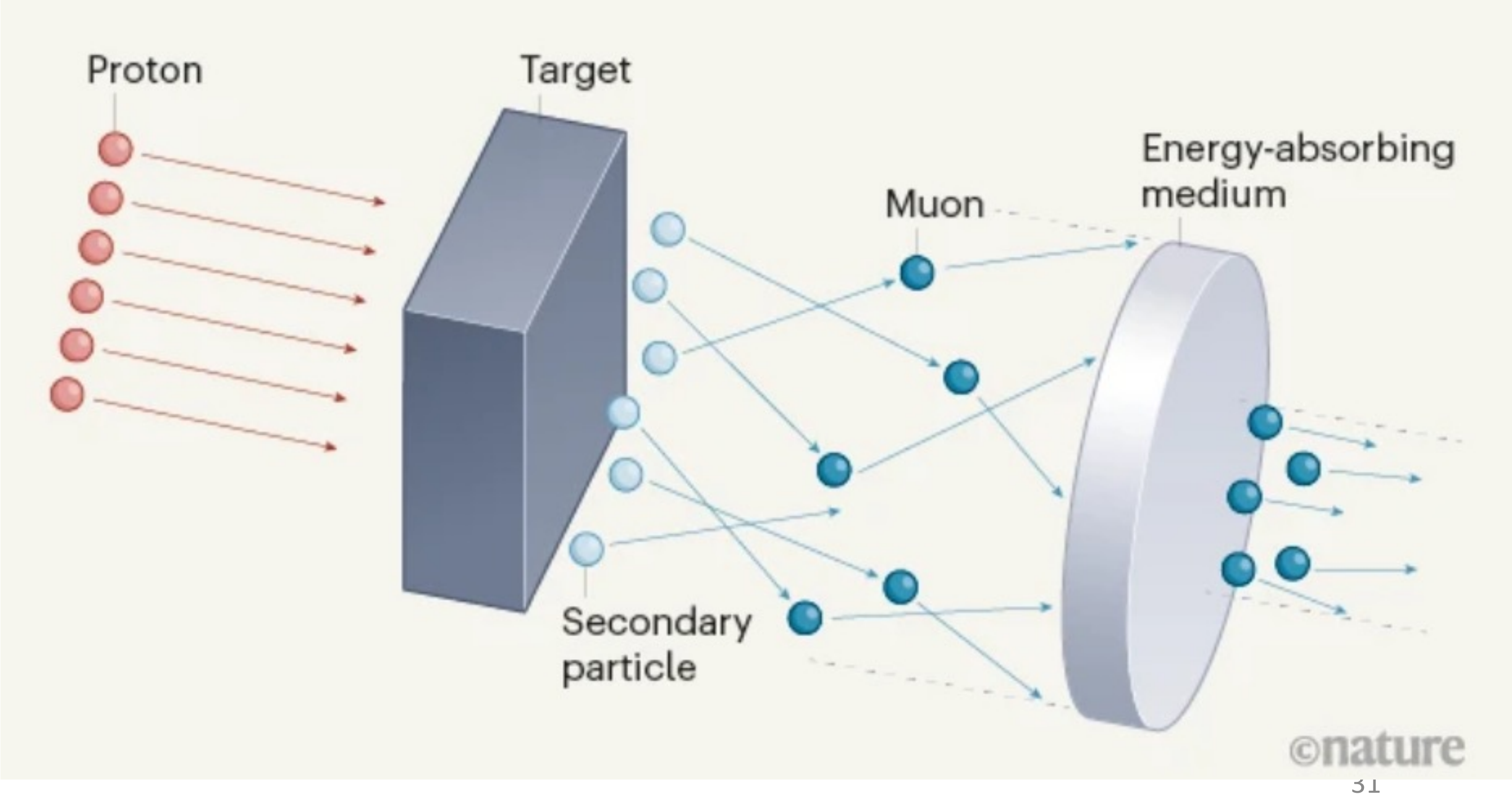
## Muon collider challenges:

- **Muon lifetime 2.2 μsec** reduces # muons by ~factor 10 before they enter the storage ring. So: increase their energy to use time dilation. Dipole magnets with field 10.5 T can circulate a muon 2000 turns in 10 km circumference ring, before decay.

- This technology requires ***muon cooling: reducing the phase space volume.*** Direct a proton beam onto a target to produce pions. Pions decay to muons. The muon cloud is captured, and an ionization system cools the muons into a beam.

- ***The cooling***: a chain of low-Z absorbers in which the muons lose energy by ionizing the matter. Replace the lost energy by acceleration.

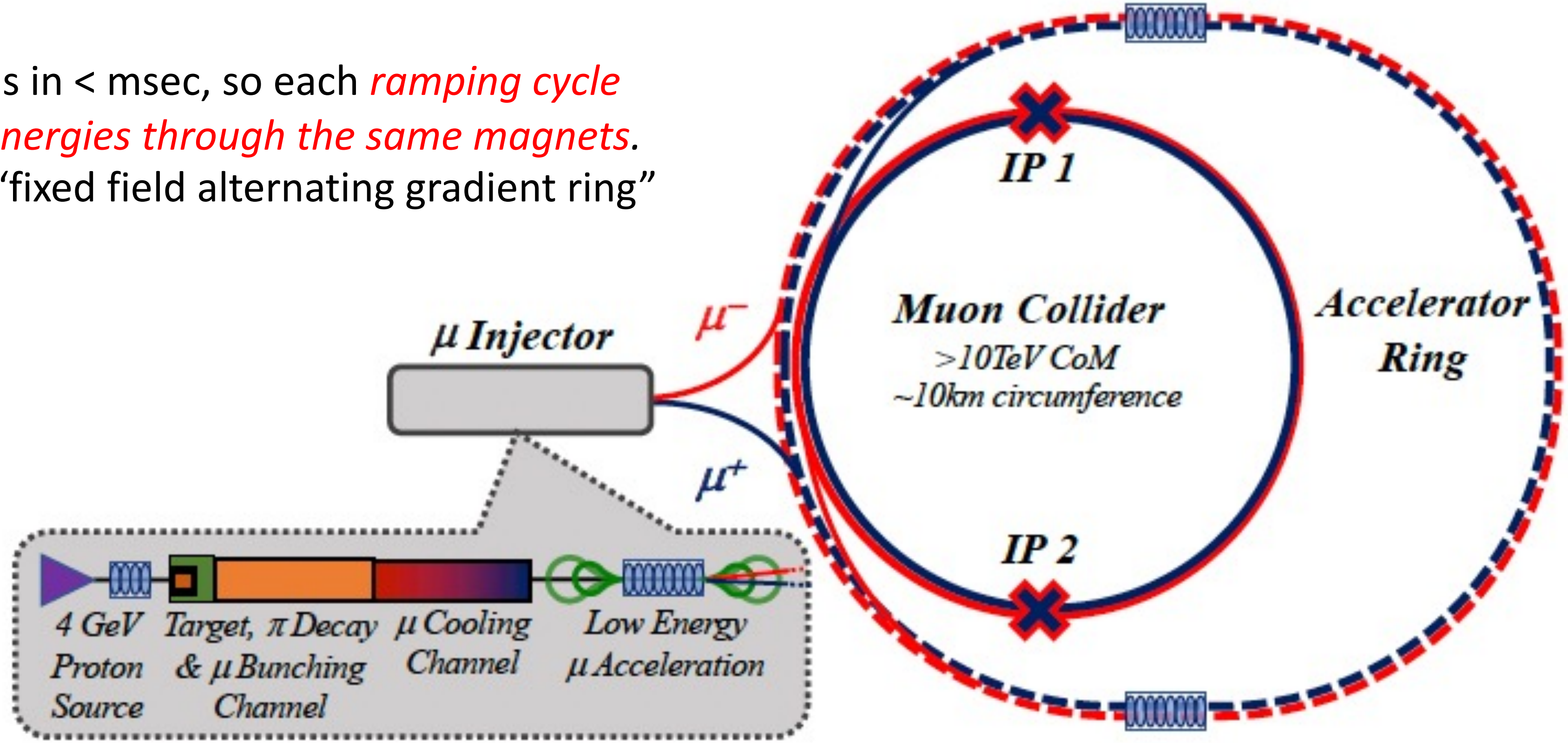
*This is the concept of the Muon Ionization Cooling Experiment (MICE) in combination with the Muon Acceleration Program (MAP).*

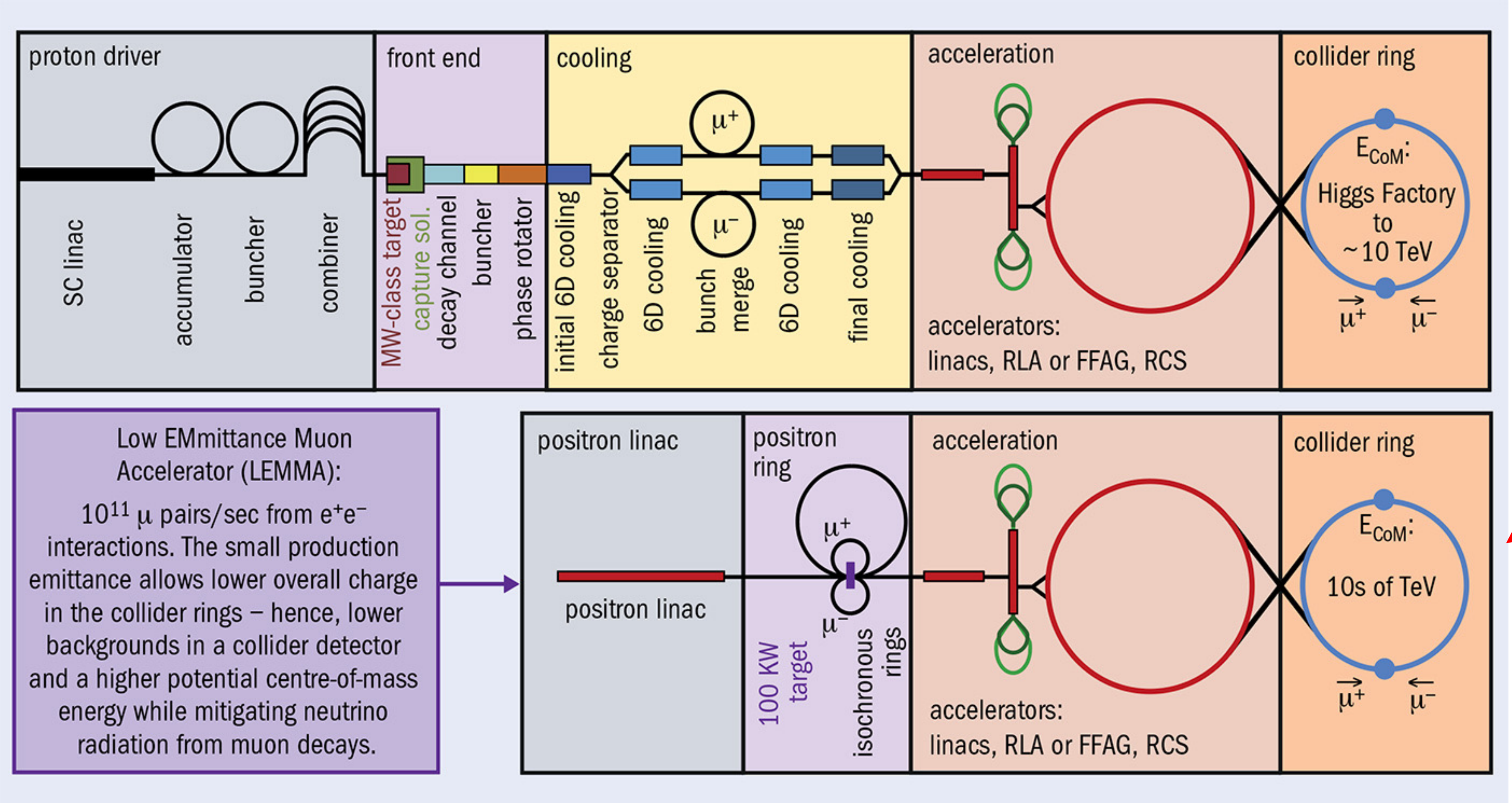


https://www.nature.com/articles/d41586-020-00212-3

# Muon Collider Challenges, continued...

- The cooling (squeezing the beam phase space) by *ionization loss must outweigh the heating* due to Coulomb scattering within the absorber.
- Muons decay to electrons + positrons. If these strike the magnets, they can lead to a quench. *Protect the magnets or exclude superconductor* from the plane of the beam.
- Ring has to accelerate the muons in < msec, so each *ramping cycle passes muons of very different energies through the same magnets.* "Fast ramping synchroton" and "fixed field alternating gradient ring" are options.





Low EMmittance Muon Accelerator (LEMMA):

$10^{11}$ $\mu$ pairs/sec from $e^+e^-$ interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential centre-of-mass energy while mitigating neutrino radiation from muon decays.

**two muon collider concepts:***

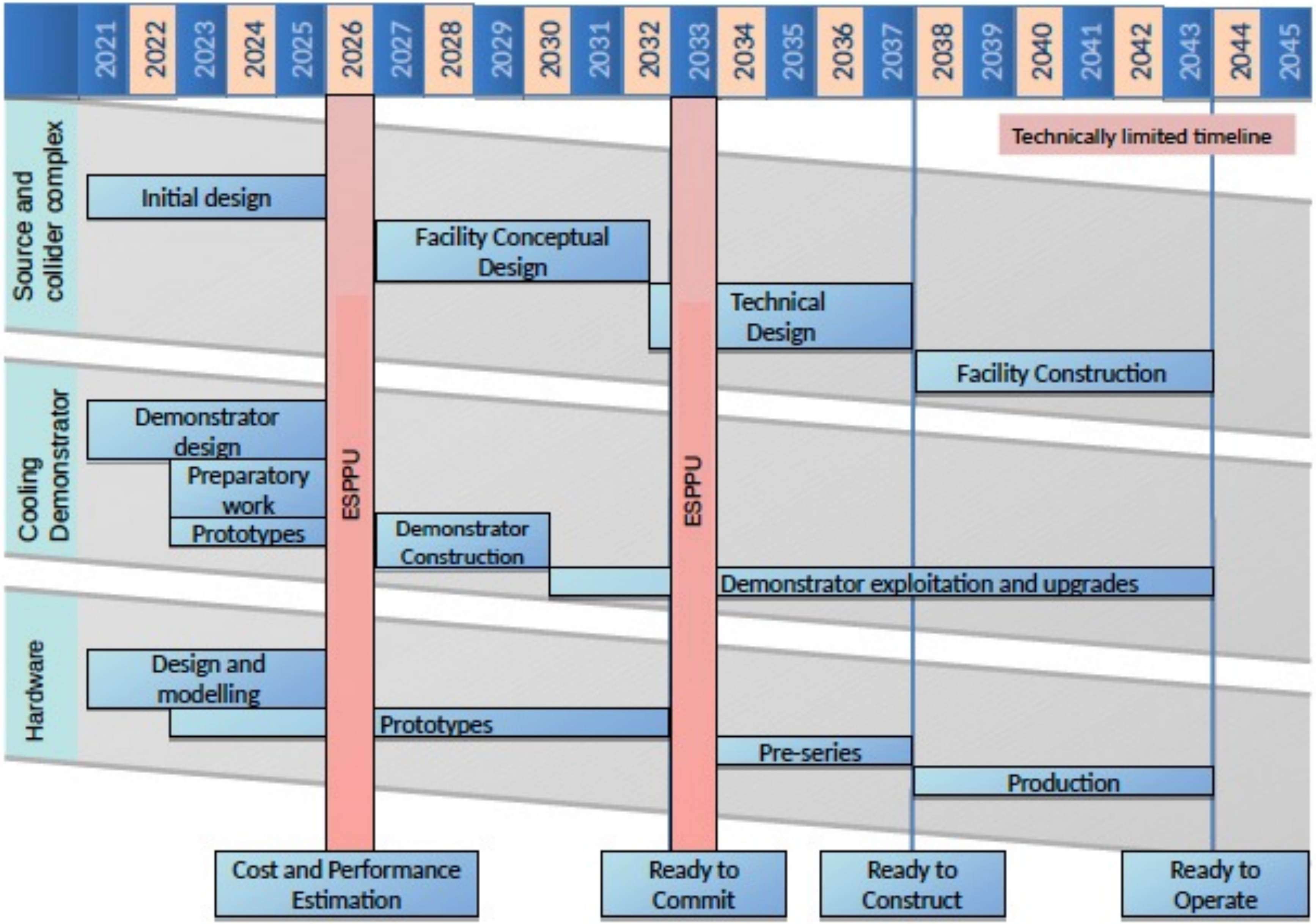
MAP starts with protons

and LEMMA starts with positrons

* arXiv:1901.06150

From the P5 report (page 23): “**This is our Muon Shot.**”

***Muon collider technically limited timeline, for a 2043 start:***



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Source and collider complex
- Initial design
- Facility Conceptual Design
- Technical Design
- Facility Construction

Cooling Demonstrator
- Demonstrator design
- Preparatory work
- Prototypes
- Demonstrator Construction
- Demonstrator exploitation and upgrades

Hardware
- Design and modelling
- Prototypes
- Pre-series
- Production

ESPPU

ESPPU

Cost and Performance Estimation

Ready to Commit

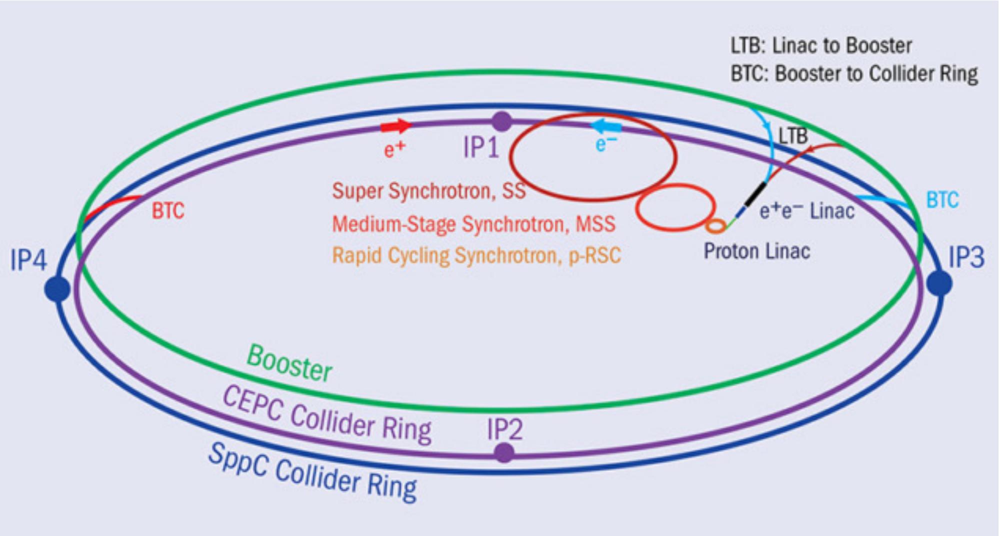
Ready to Construct

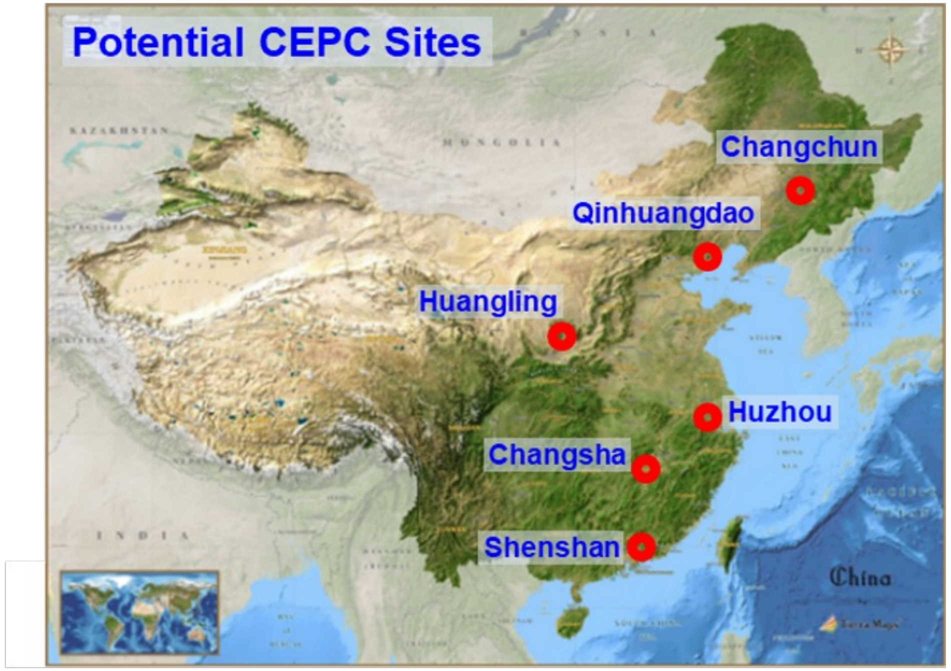
Ready to Operate

Other colliders, not in the P5 recommendations for various reasons, yet very much on the research horizon

# The Circular Electron Positron Collider (CEPC)*

- Proposed by China in 2012
- Motivation parallel to that of the FCC, leading to similar run plan:
  - Operate in energy stages from the Z-pole (2 yr), WW threshold (1 yr), 240 GeV (Higgs factory, 10 yr), 360 GeV (t tbar threshold, 5 yr)
  - tunnel could subsequently host the Super Proton-Proton Collider (SPPC)
- Anticipate $10^7$ improvement in Higgs S/N relative to HL-LHC
- Construction originally intended to begin in 2022, now delayed to 2027, with collisions approx 8 years later.





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*CEPC Study Group, “CEPC Conceptual Design Report” Volume 1 (arXiv:1809.00285) and Volume 2 (arXiv:1811.10545)

# FCC-hh, the Hadron Collider*

- Center of mass energy **100 TeV**, integrated luminosity = 20 $ab^{-1}$ in each of 2 detectors, combined to yield >30 $ab^{-1}$ total, i.e. 5 x HL-LHC

***Why 100 TeV?*** Would provide *5% precision on the Higgs cubic self coupling. Related to the EW phase transition* in which EW gauge symmetry was reduced from $SU(2)_L x U(1)_Y$ to $U(1)_{EM}$. *Was the phase transition first order* or second order? *Baryogenesis (leading to the matter/antimatter asymmetry) can only occur if first-order.***

- Mass reach for direct observation of new particles: 10's of TeV. [The heaviest currently known elementary particle is the top quark: $m_{top}$ = 172.52 *GeV*]
- can include heavy ion collisions, and modification to allow electron-proton or electron-ion collisions.
- Instantaneous luminosity ramp from 5E34 to 3E35 $cm^{-2}s^{-1}$.
- After the conclusion of FCC-ee: 10 years of construction then 25 years running.
- Higgs self-coupling to ultimate precision
- thermal dark matter candidates discovered or ruled out

**Instrumentation challenges**

- New refrigeration technique (He-Ne) would reduce electrical consumption by 20%
- New vacuum techniques
- Precision timing needed to separate ~1000 pileup events per crossing
- Radiation exposure ~6E17 at the first layer, unprecedented, no current technology for this.

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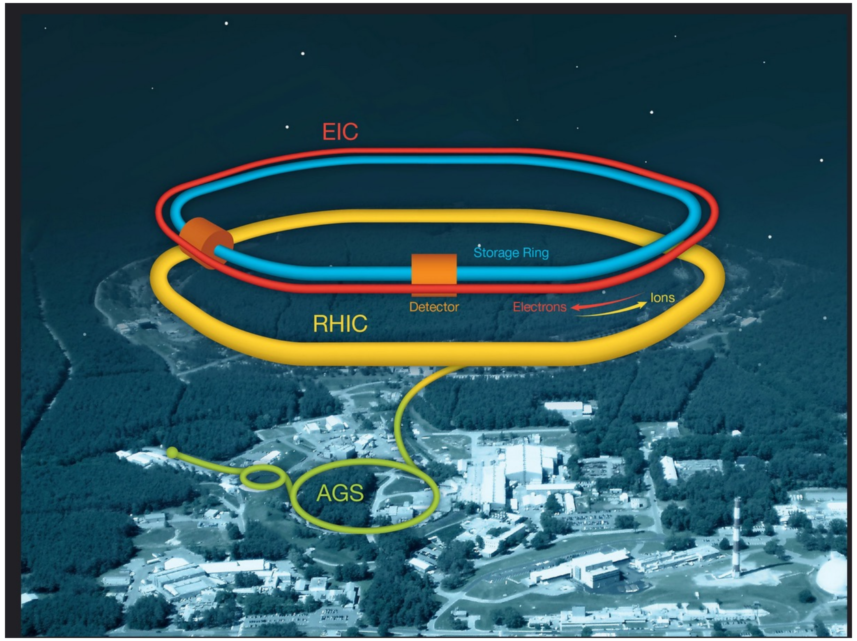
* FCC-hh: The Hadron Collider, Eur. Phys. J. Special Topics 228 (2019) 755-1107, https://fccis.web.cern.ch/conceptual-design-report-volumes#

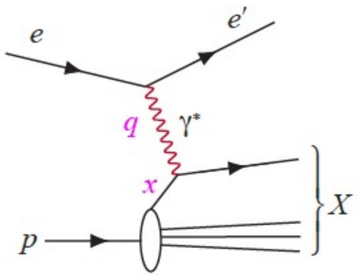
** A. Noble and M. Perelstein, PRD 78.063518 (2008)

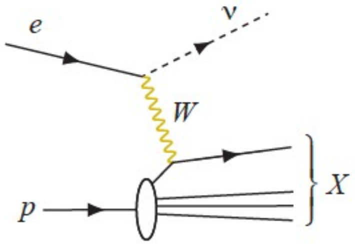
# EIC: The Electron-Ion Collider

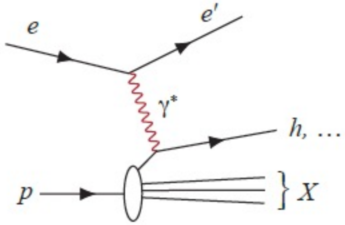
- A collider in development, **top priority by the Nuclear Physics Community**, not in the scope of P5
- ***Physics goals***: high precision QCD, beyond the scope of HERA, “modern nuclear physics”: understanding the structure of p and n directly from their quark and gluon dynamics

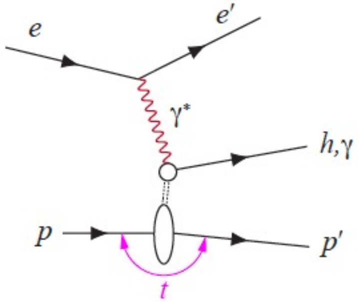


EIC construction will begin when RHIC ceases in 2025. EIC start of operations ~2031.









***Collider configuration:***

- Re-uses the RHIC accelerator complex, 2.4 mile circumference at Brookhaven Lab on Long Island
- Solokov-Ternov effect: high energy lepton beams become naturally transversely polarized in a storage ring.
- World’s first ***spin-polarized proton collider***
- Species: polarized protons, $^2$H, $^3$He, and heavy ions such as Au, U
- Energies
  - 3.85 – 110 GeV/u for heavy ions, up to 255 GeV for p, up to 166 GeV/u for $^3$He
  - 5– 18 GeV ***polarized electrons***

# Conclusions

Colliders have provided unique access to fundamental knowledge for over 60 years, in some cases revealing features of nature that would not be obtainable any other way.

The questions that are within our reach now are amazing.  Colliders can access them.

The future of particle physics looks ... breathtaking.

***Students thinking about what direction to take...please join us!***