Looking Forward

Projects Tend To Be Long

- LHC (the longest yet)
  - Inception in 1980s
  - Experiments confirmed mid-1990s
  - Operation start 2007
  - Major upgrade 2025
  - End of operations planned ~2037
- A full career!
- Worldwide planning is a must

Future Projects

- Energy Frontier
  - HE-LHC, FCC
  - ILC, CEPC
- Baryon number violation
  - DUNE, Hyper-K
  - NNbar

High Luminosity LHC

- ❖ 2025: High Luminosity LHC upgrade
  - Go to 5-7.5 x 10^{34}, pile-up of 200
  - New interaction region focusing magnets and crab cavities
  - Significant detector "upgrades"
    - Replace inner trackers, detector readout and trigger and data acquisition systems
      - Basically, only keep magnets, calorimeters and muon chambers
  - Overall, 1 GCHF construction project
  - Then run until ~2037 to collect 3000-4000 fb^{-1}
    - Still not enough to measure di-Higgs production (if it's SM strength!)
      - Who knows, we may get smarter

High-Energy LHC

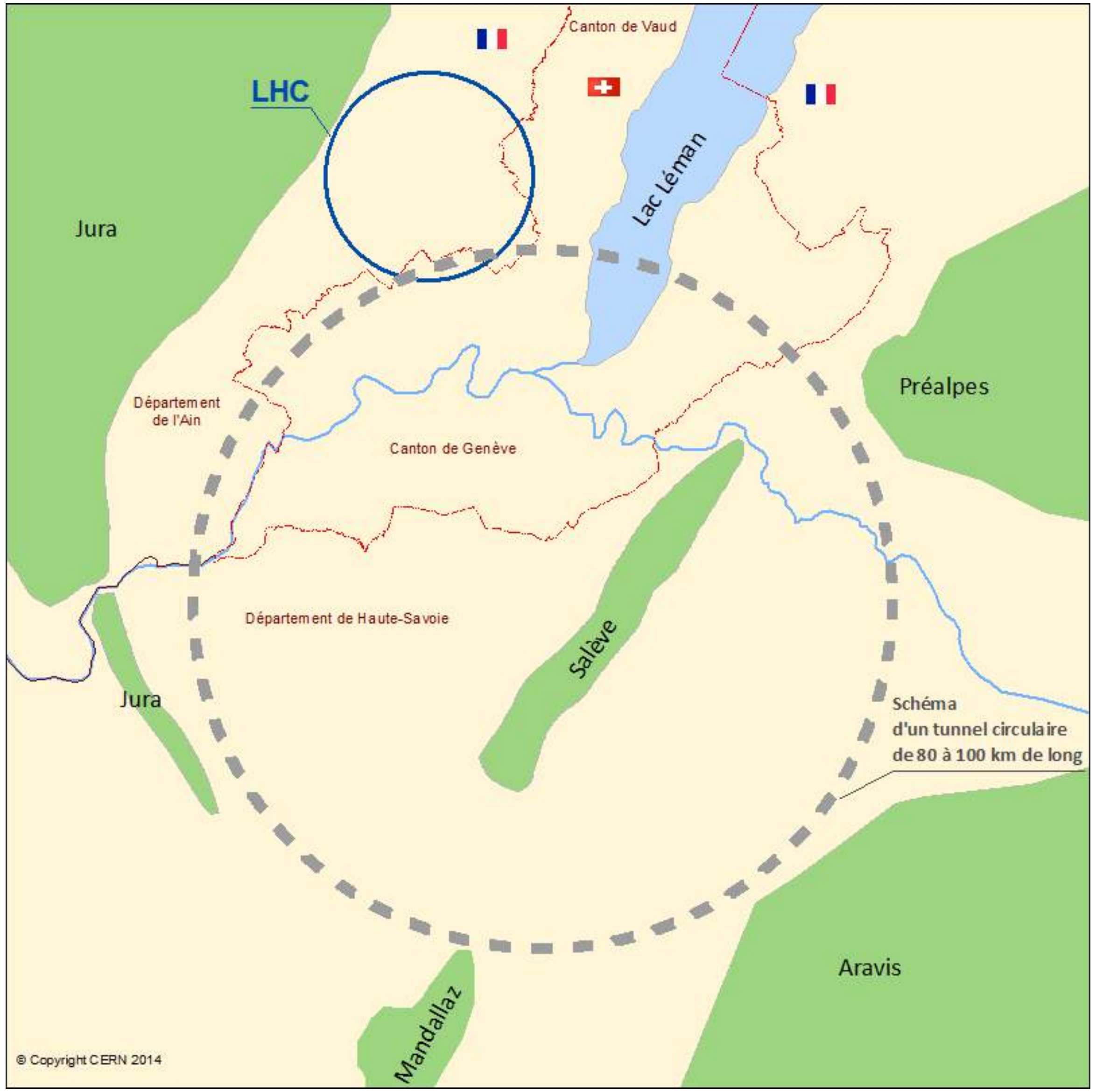
- Replace current 8.33 T dipoles with 16 T dipoles
  - 27 TeV center-of-mass energy
  - 4x LHC luminosity: to keep same relative mass reach (wrt com energy), luminosity needs to scale by ~(com energy)^2

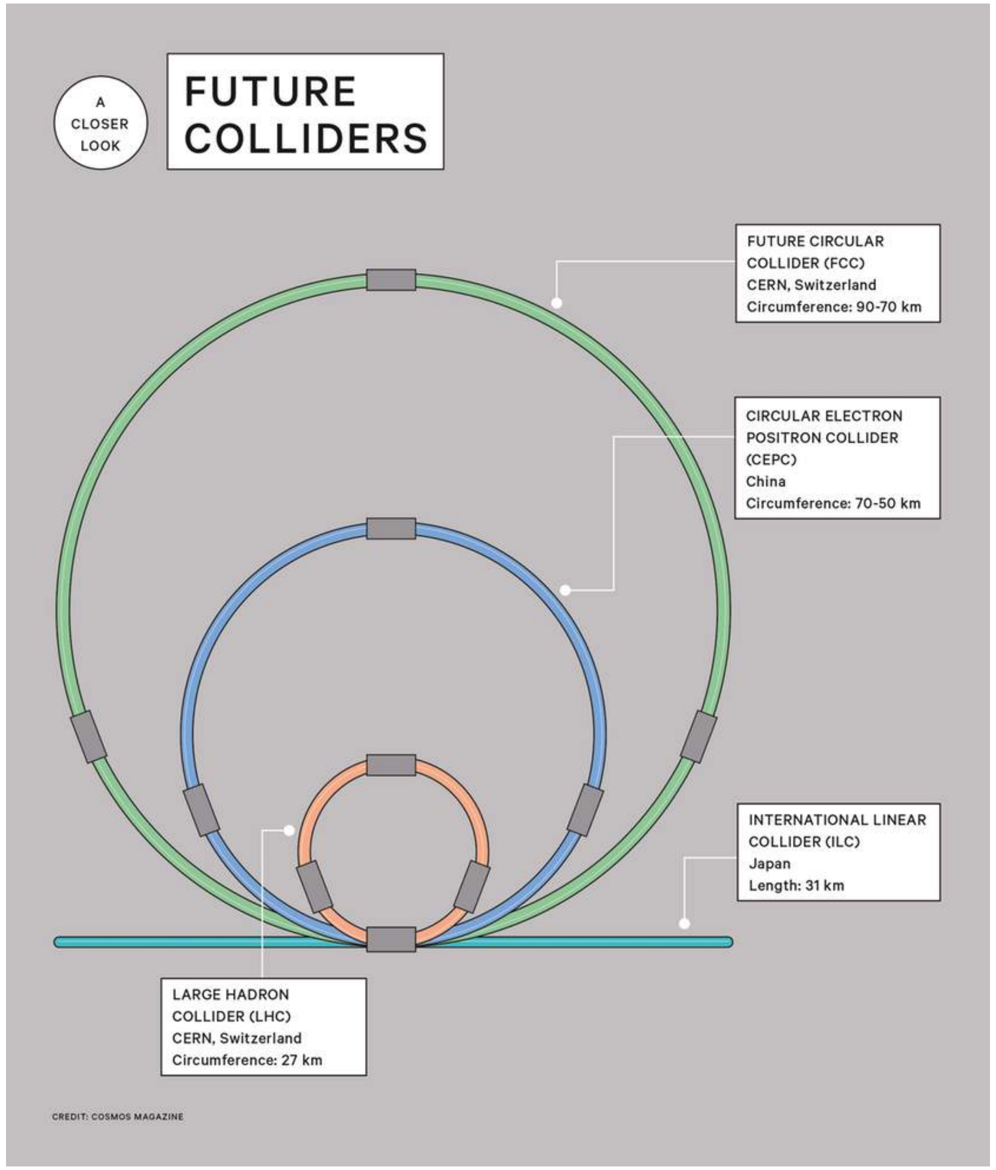
Rizzo, arXiv:1501.05583

- But no new tunnel needed!
  - Just 27 km of 16 T magnets
    - (Technology exists, but current production yield too low to build 27 km of magnets)
- Double the mass reach ⇒ x4 in fine-tuning
  - And can measure di-Higgs production!

Future Circular Collider

❖ New 100 km ring, 100 TeV center-of-mass energy (16 T magnets)



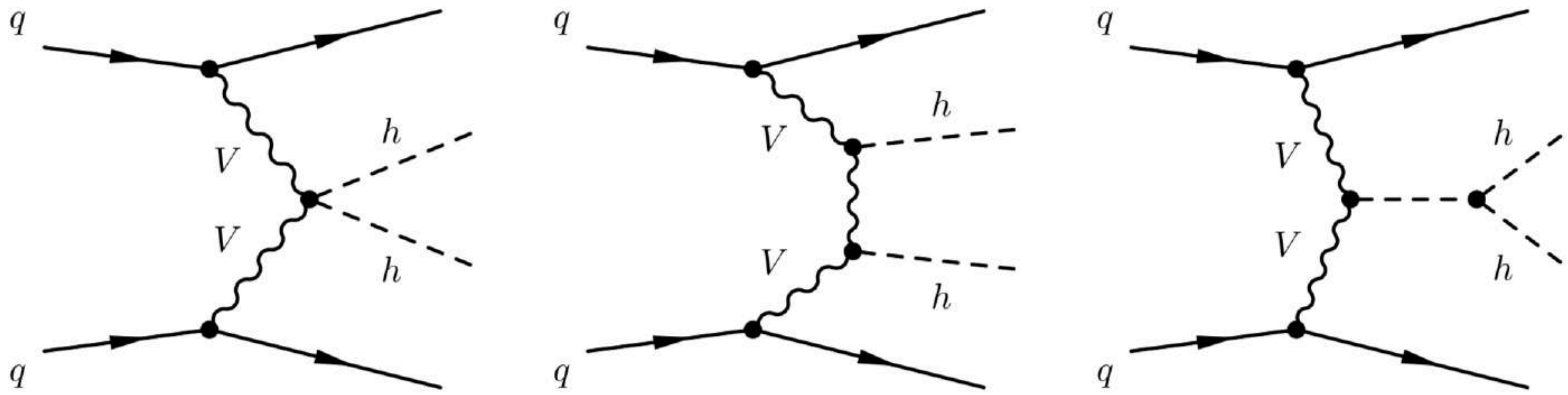


Parameters

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity $[10^{11}]$	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity $[10^{34}\ cm^{-2}s^{-1}]$	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

Why 100 TeV?

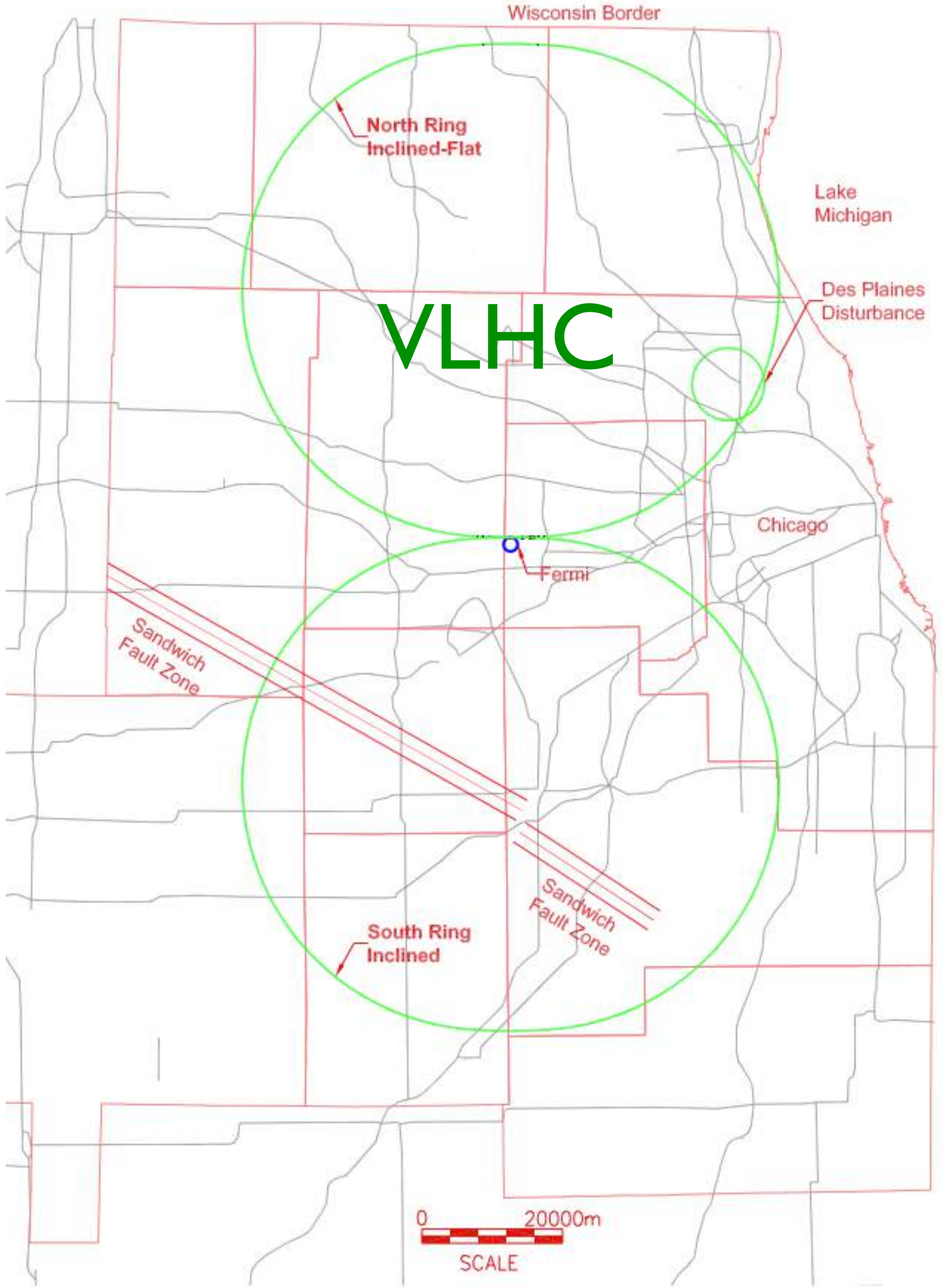
- At CERN, bigger ring cannot avoid significant geological features
- If can deliver the luminosity ($3x10^{35}$), mass reach ~7x LHC
  - Measure Higgs quartic coupling!



  - Discover new physics, or push fine-tuning x50
  - But no no-lose theorem…

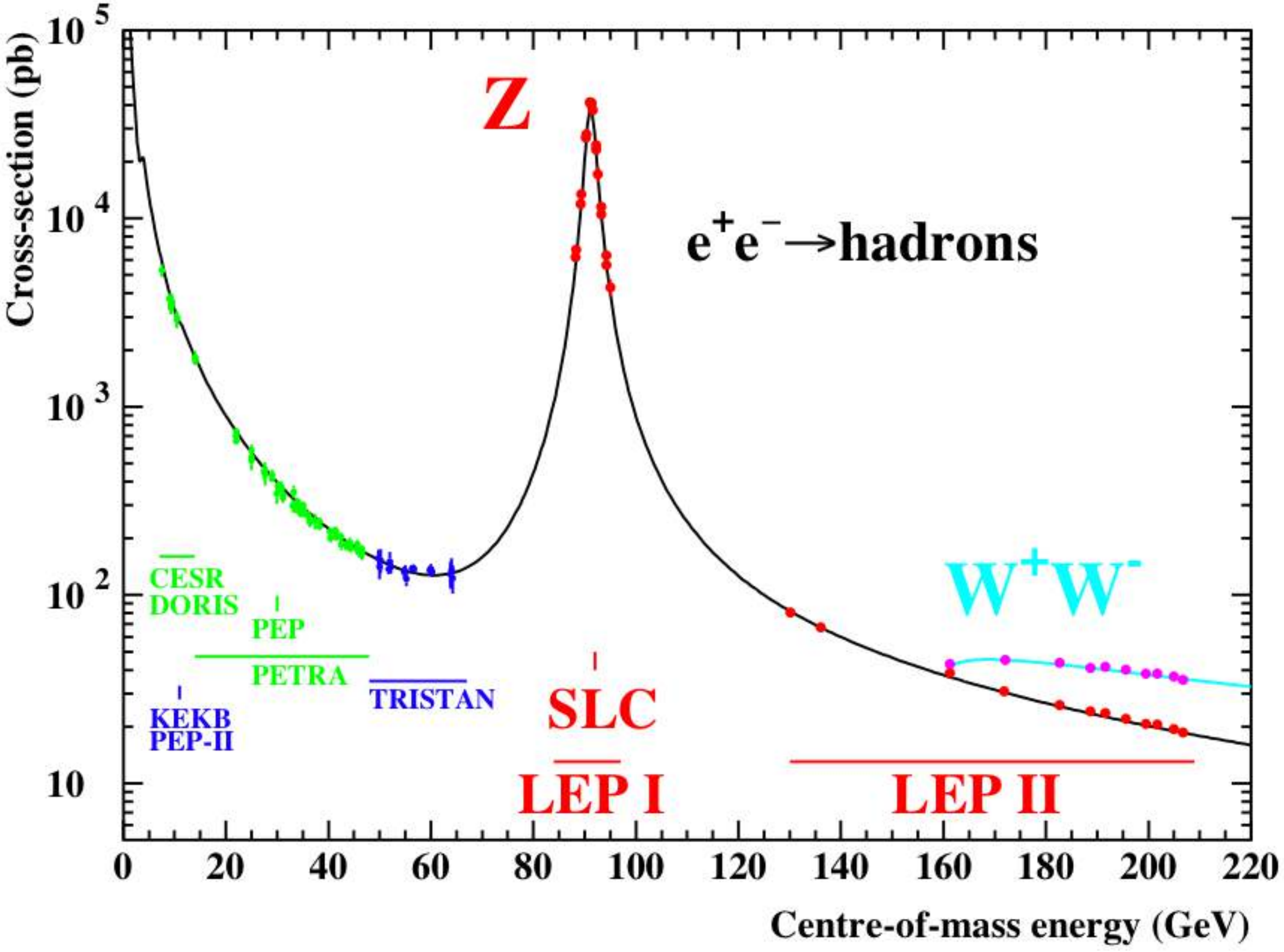
So Bigger Would Be Better

- VLHC
  - 200 km ring
  - With permanent magnets, 40 TeV center-of-mass
  - With superconducting magnets, 200 TeV…



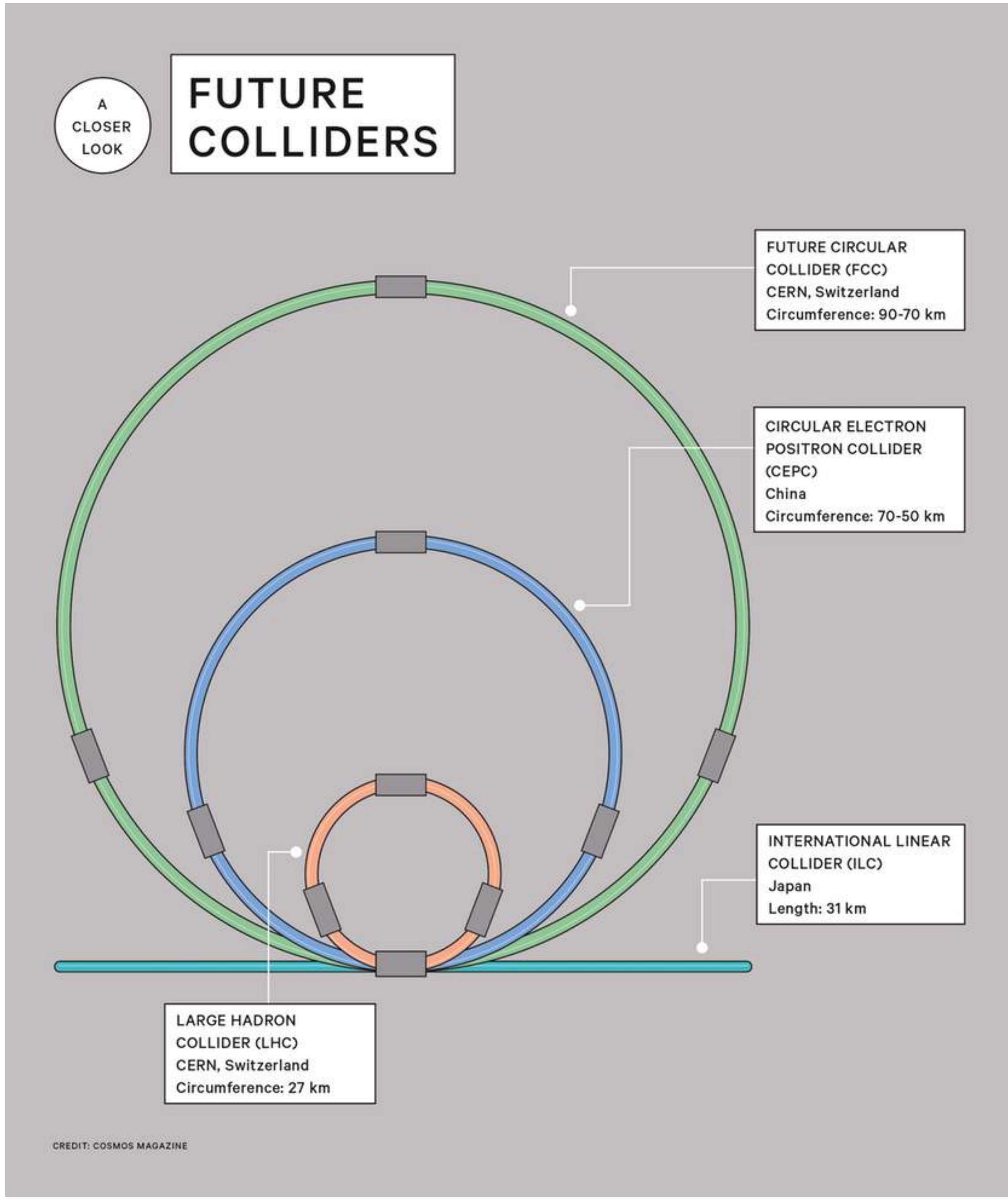
e^+e^- Colliders

- Precision machines
  - At LEP and SLC, total cross-section = signal!
  - But cross-section drops quickly, so at higher energy, need more luminosity
  - Energy limited by length (for linear collider) or synchrotron radiation (for circular collider)



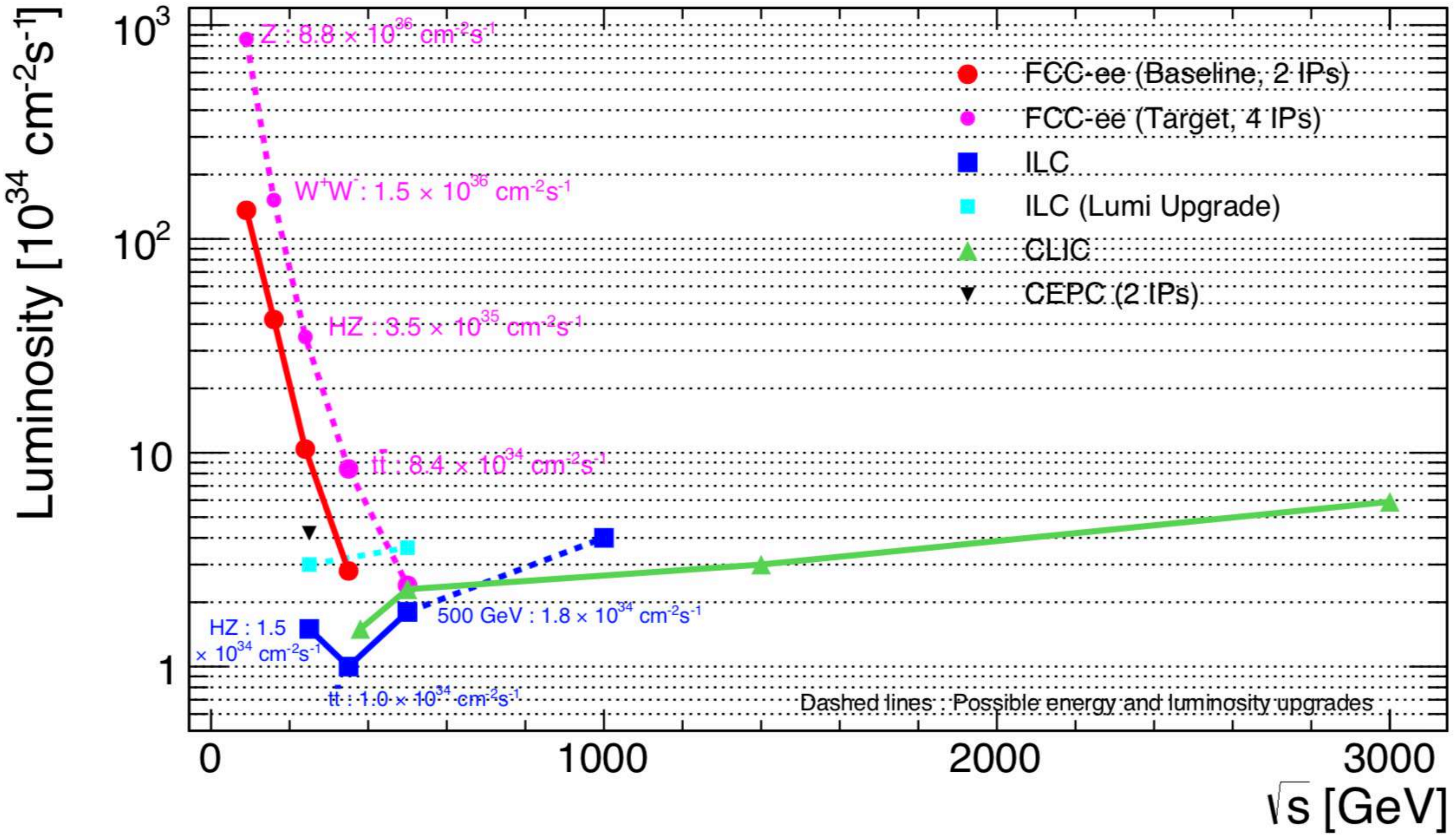
Linear vs Circular

- ❖ Circular:
  - Limited by synchrotron radiation: for FCC-ee, at $\sqrt{s}$ = 250 GeV, deposit 5 kW/m (over ~100 km!)
  - But good luminosity, as beam goes around many times
- ❖ Linear:
  - Limited by accelerating gradient: O(50 MeV/m) achievable, so 1 TeV machine is ~20 km long
  - Limited luminosity: each accelerated beam used only once
- ❖ Either way, huge power consumption: > 200 MW (!)

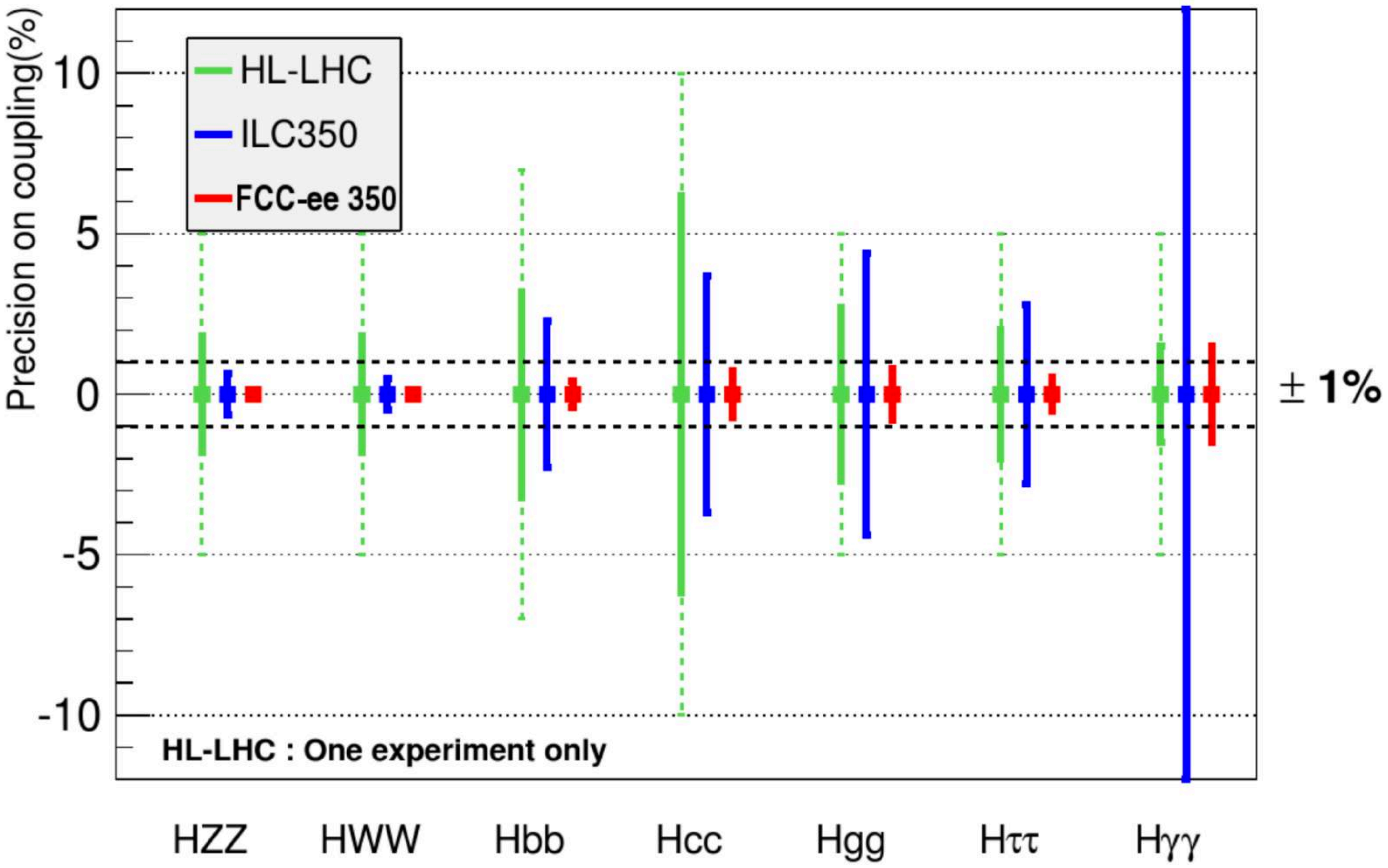


e^+e^- Collider Physics

- Higgs factory
  - Not more Higgses than at LHC, but clean environment allows access to more couplings
- New Physics difficult to probe at LHC
  - E.g. pair production of weakly interacting particles decaying to soft leptons
- Top quark mass



Higgs Couplings



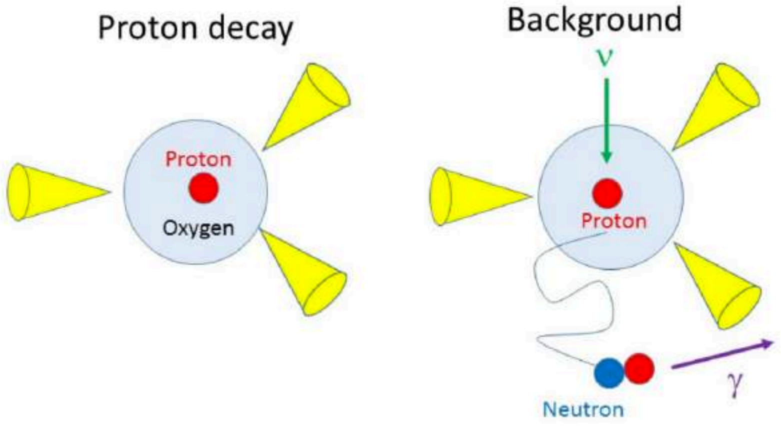
Non-Collider

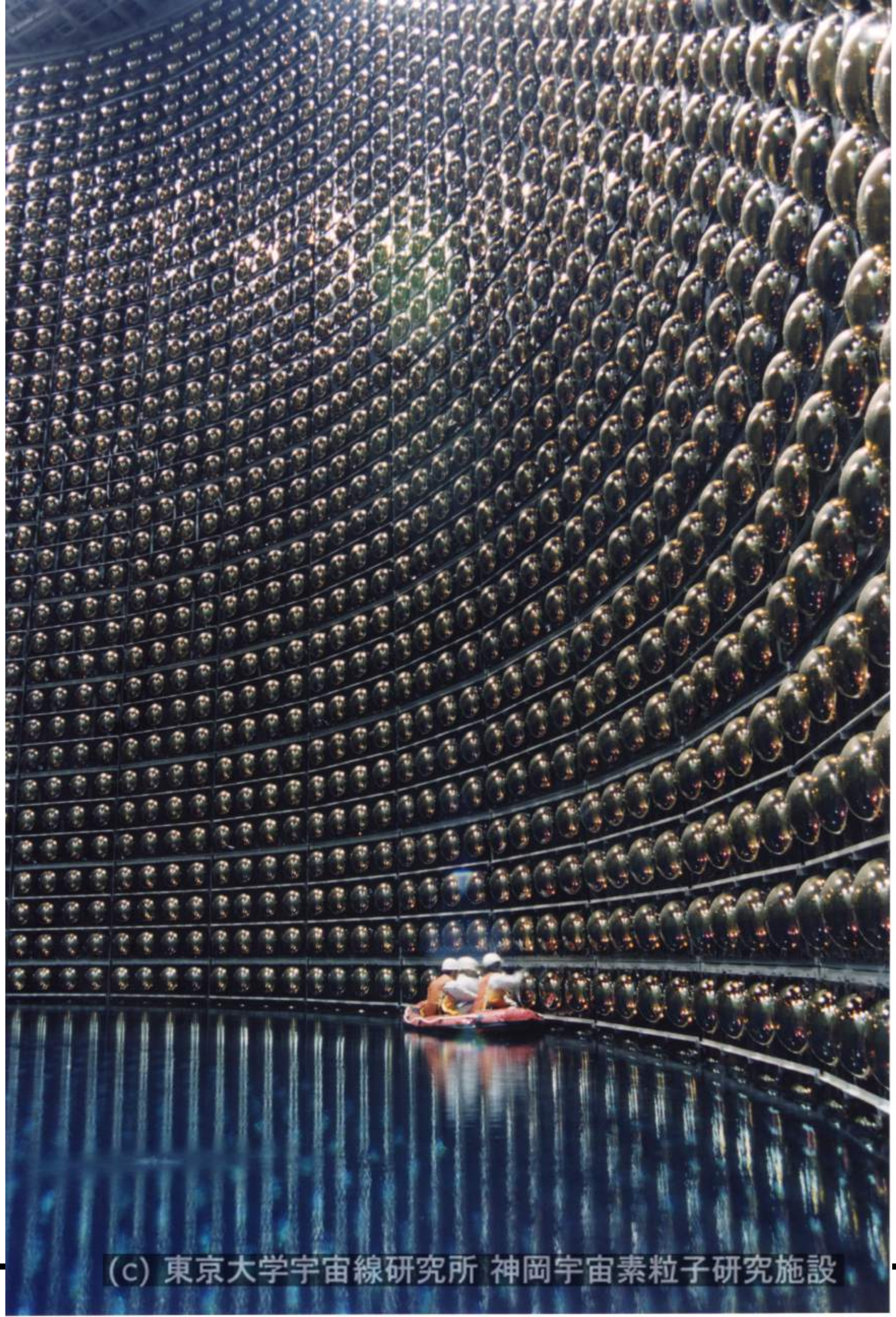
- Baryon number violation key to our existence, but not observed
  - (Almost) an accidental symmetry in the SM
    - The accidental symmetry is really B-L
- Probe through proton decay, or neutron-anti-neutron oscillations
  - Proton decay predicted by grand unification: if quarks and leptons part of a multiplet, “rotation” can turn a quark into a lepton: $p \rightarrow \pi\, e,\ K\, \nu, \ldots$
    - Mediating boson is a leptoquark
  - Neutron-anti-neutron oscillation motivated by neutrino oscillations

Proton Decay

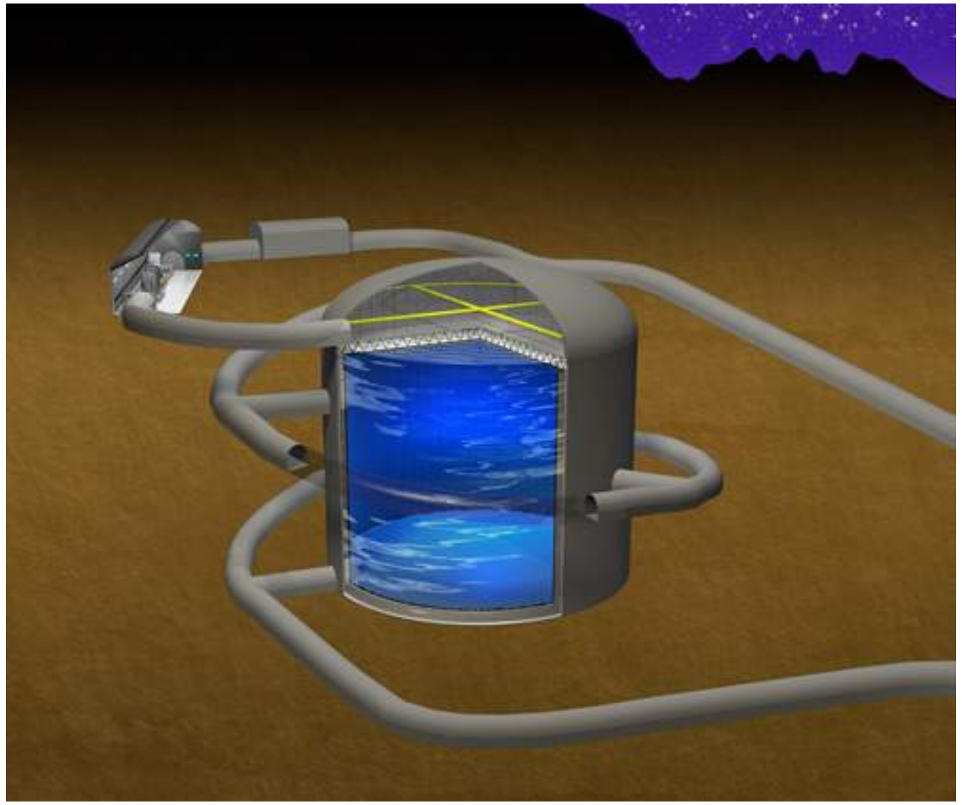
❖ Direct probe of quark-lepton unification scale

- Next generation large neutrino detectors well-suited to probe proton decay
  - Kamiokande = Kamioka Nucleon Decay Experiment
- Current limits ~10^{34} years (super-Kamiokande, 220 kton-years)

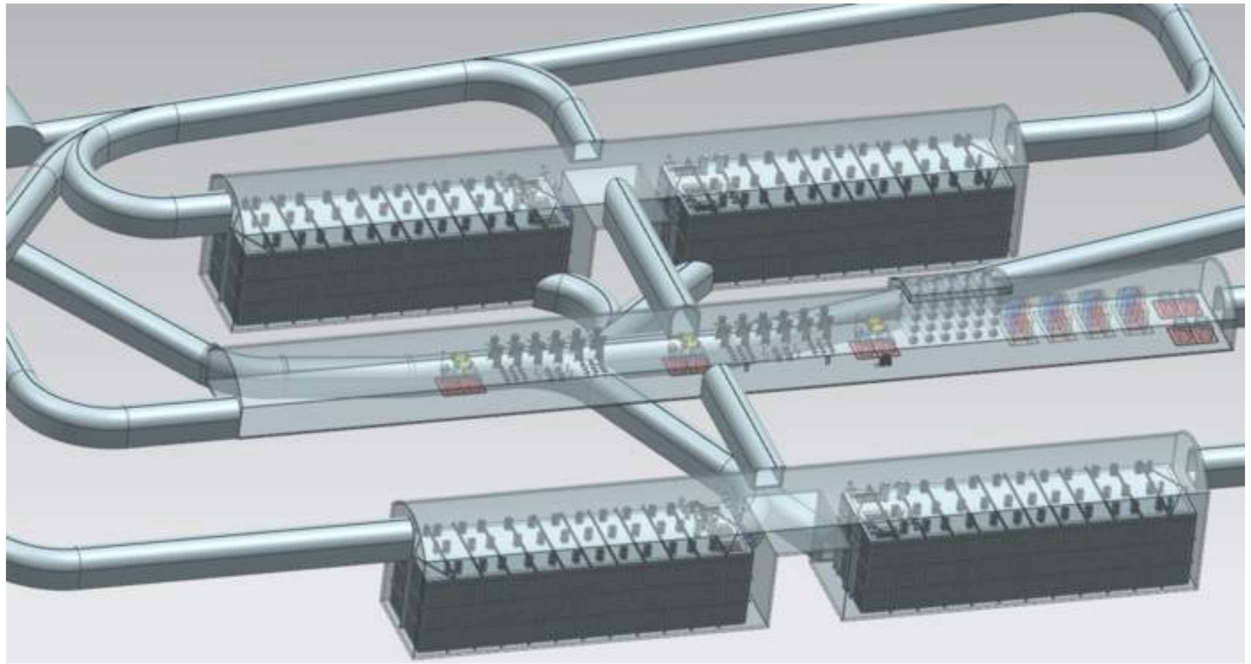




DUNE and Hyper-K

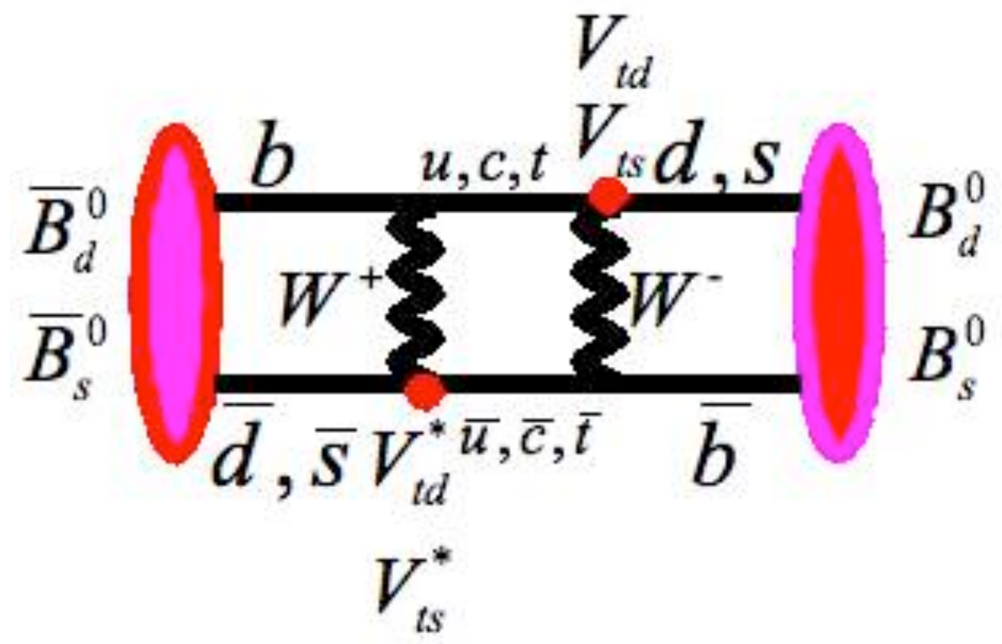


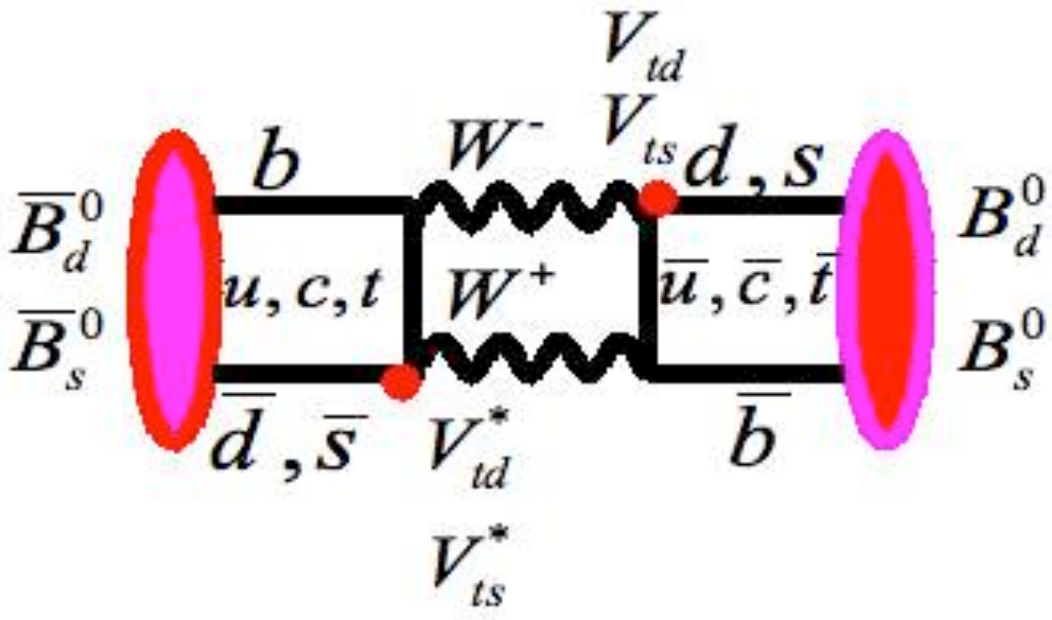
- Hyper-K is still water cherenkov
  - ~250 kton vs 50 kton for super-K
  - But 10x the fiducial volume (only ~20 kton for super-K)
    - 3-10x the Super-K sensitivity, depending on background suppression
- DUNE is 4 x 10 kton LAr TPC
  - Good sensitivity to p → K ν
    - Complementary to water cherenkov



Neutral Particle Oscillations

- HUGE role in particle physics
  - Kaon-anti-kaon oscillations allowed us to discover CP violation
    - Another necessary condition to our existence…
  - B mesons-anti-B meson oscillations now CP violation "workhorse"
    - Also first indication top quark mass was so large (~10 years before top quark discovery)
    - Low energy process that probes much higher energy scales

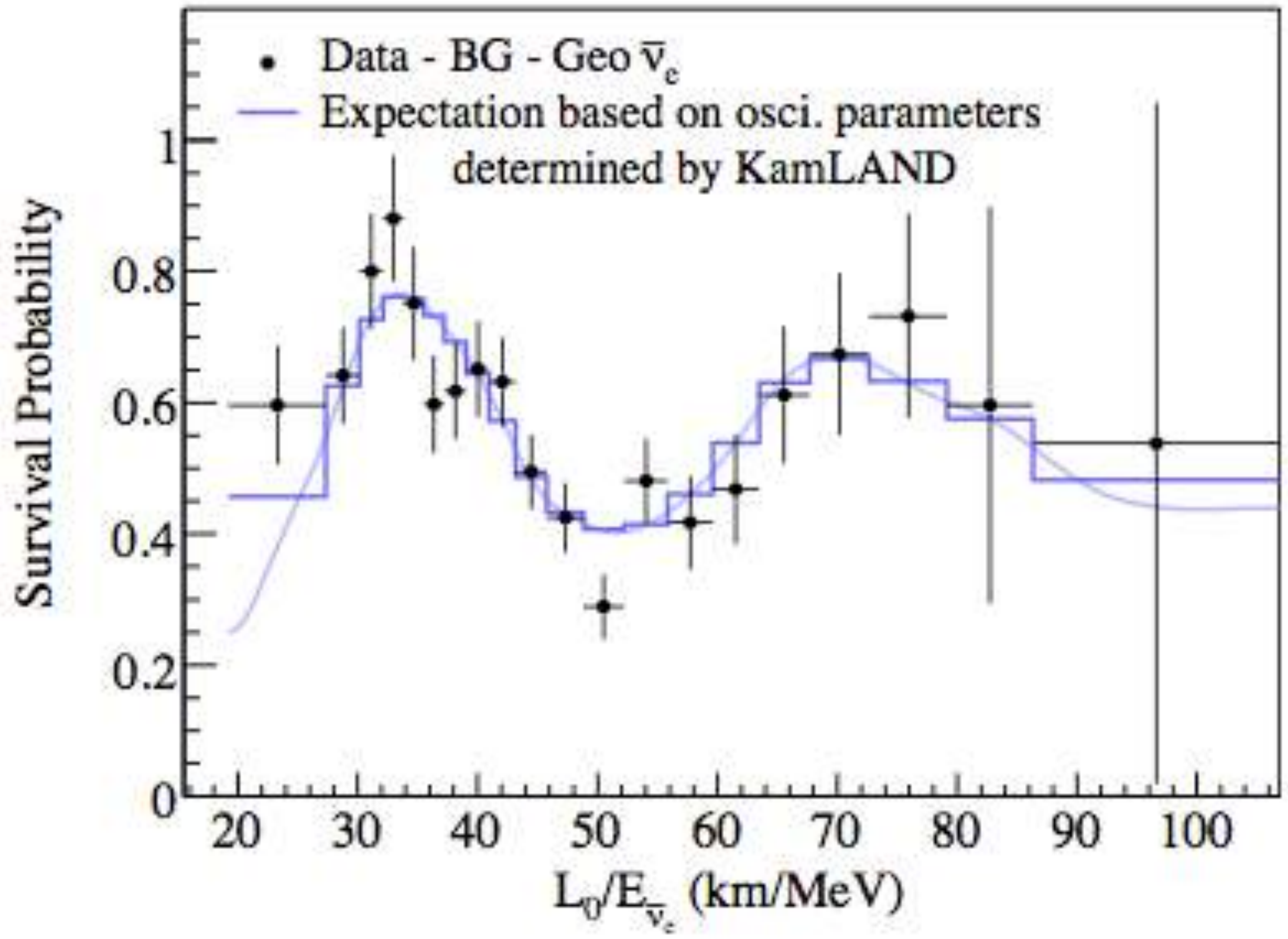




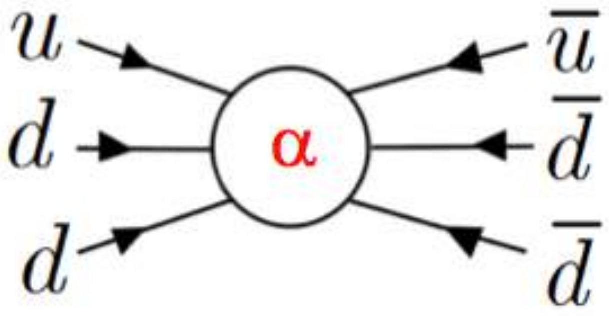
Neutral Particle Oscillations

❖ HUGE role in particle physics

- Neutrino oscillations
  - Establish neutrinos have mass
  - Suggest the existence of a mass scale between Higgs and unification scales where lepton number is violated by 2 units
- If link between quarks and leptons real, natural to expect baryon number violation by 2 units at similar scale
  - Opens the door to neutron-anti-neutron oscillations



Neutron-Anti-Neutron



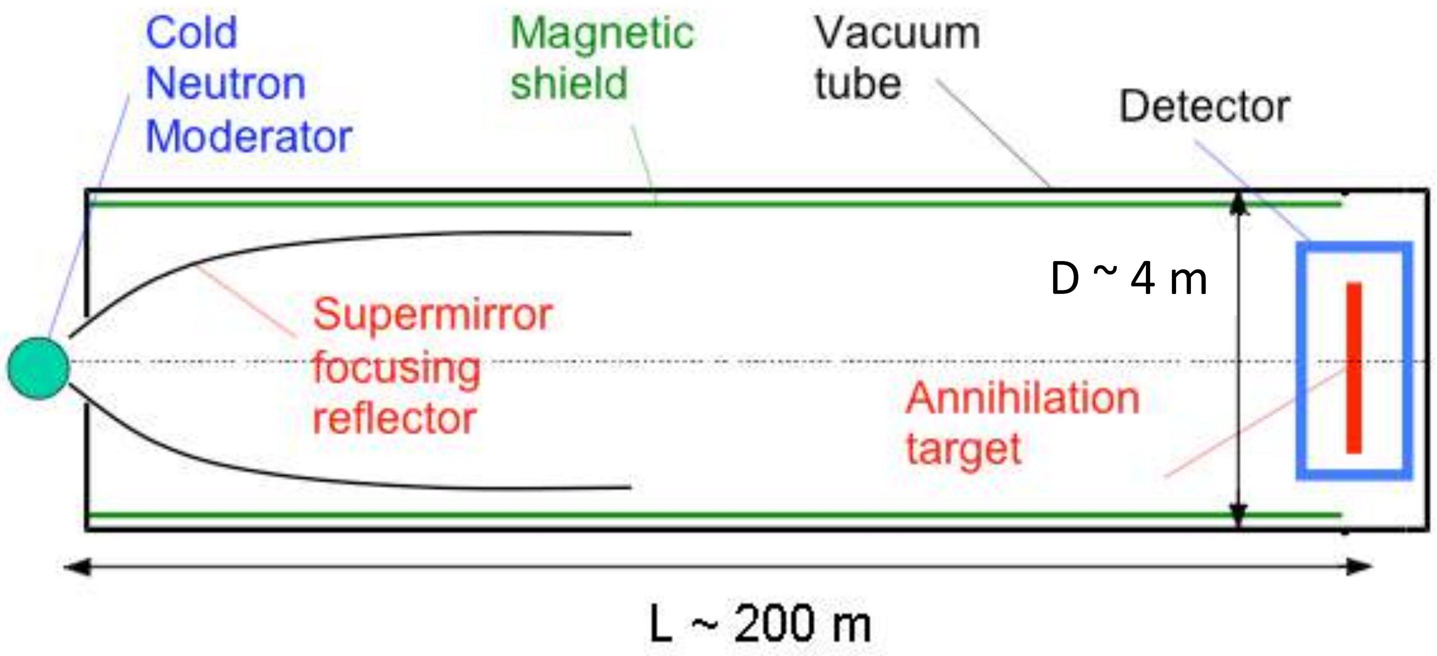
$$P_{n\to\bar{n}}(t)=\frac{\alpha^2}{\alpha^2+V^2}\cdot\sin^2\left(\frac{\sqrt{\alpha^2+V^2}}{\hbar}\cdot t\right)$$

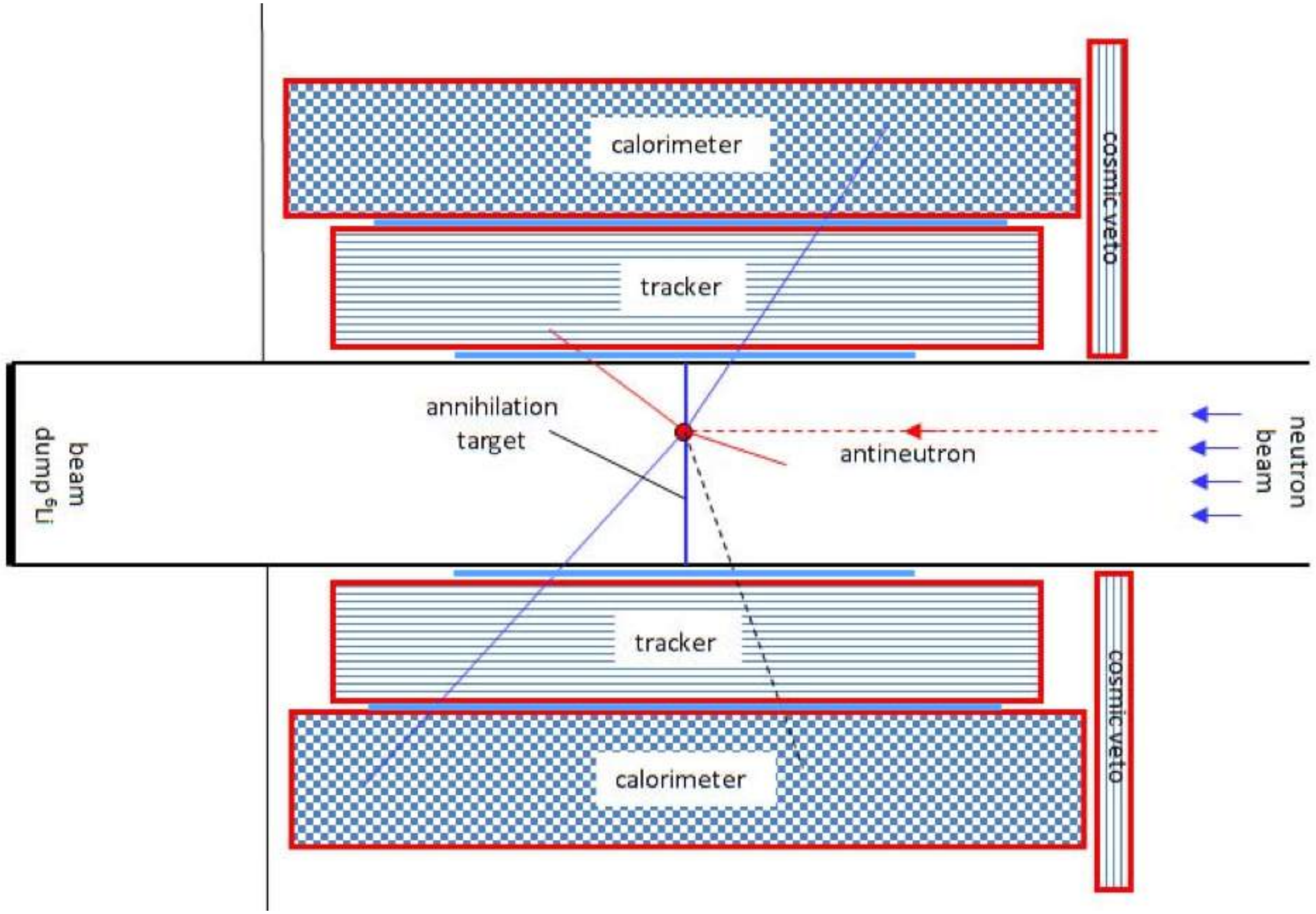
- Potential V (if antisymmetric for n vs n̄)
  - Nuclear potential ~100 MeV
  - $\mu_n.B_{Earth}$ ~ 10^{-18} MeV
  - Current limit: α < ~ 10^{-30} MeV
- Leads to strong suppression
  - Free neutron experiment requires substantial cancellation of Earth magnetic field, then:
  - For free neutron experiment, magnetic field can be used to check result if signal is seen

$$P_{n\to\bar{n}}=\left(\frac{\alpha}{\hbar}\times t\right)^2=\left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

Neutron-Anti-Neutron Oscillations

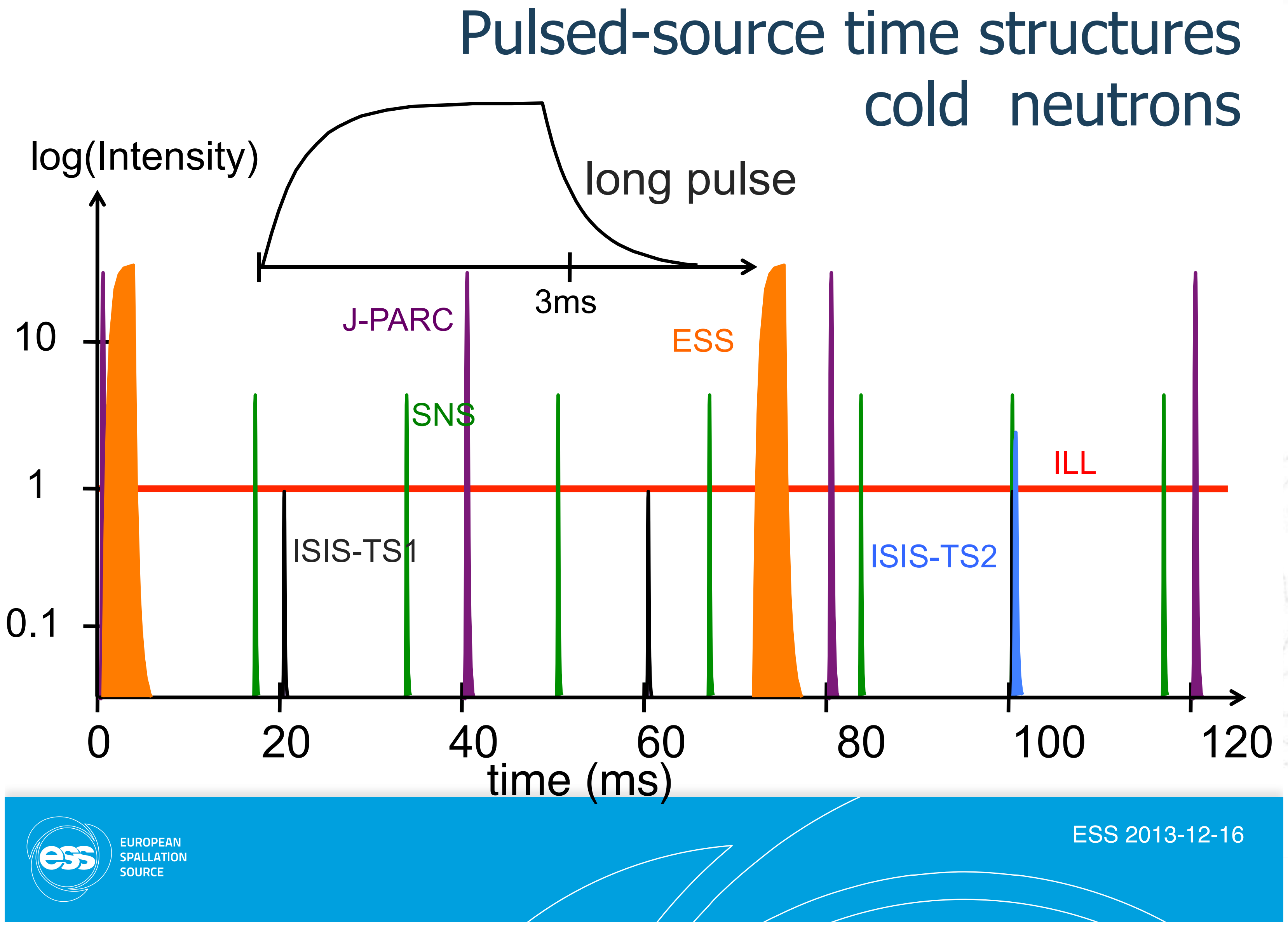
- Make a lot of neutrons, let them fly as long as possible, look for an anti-neutron

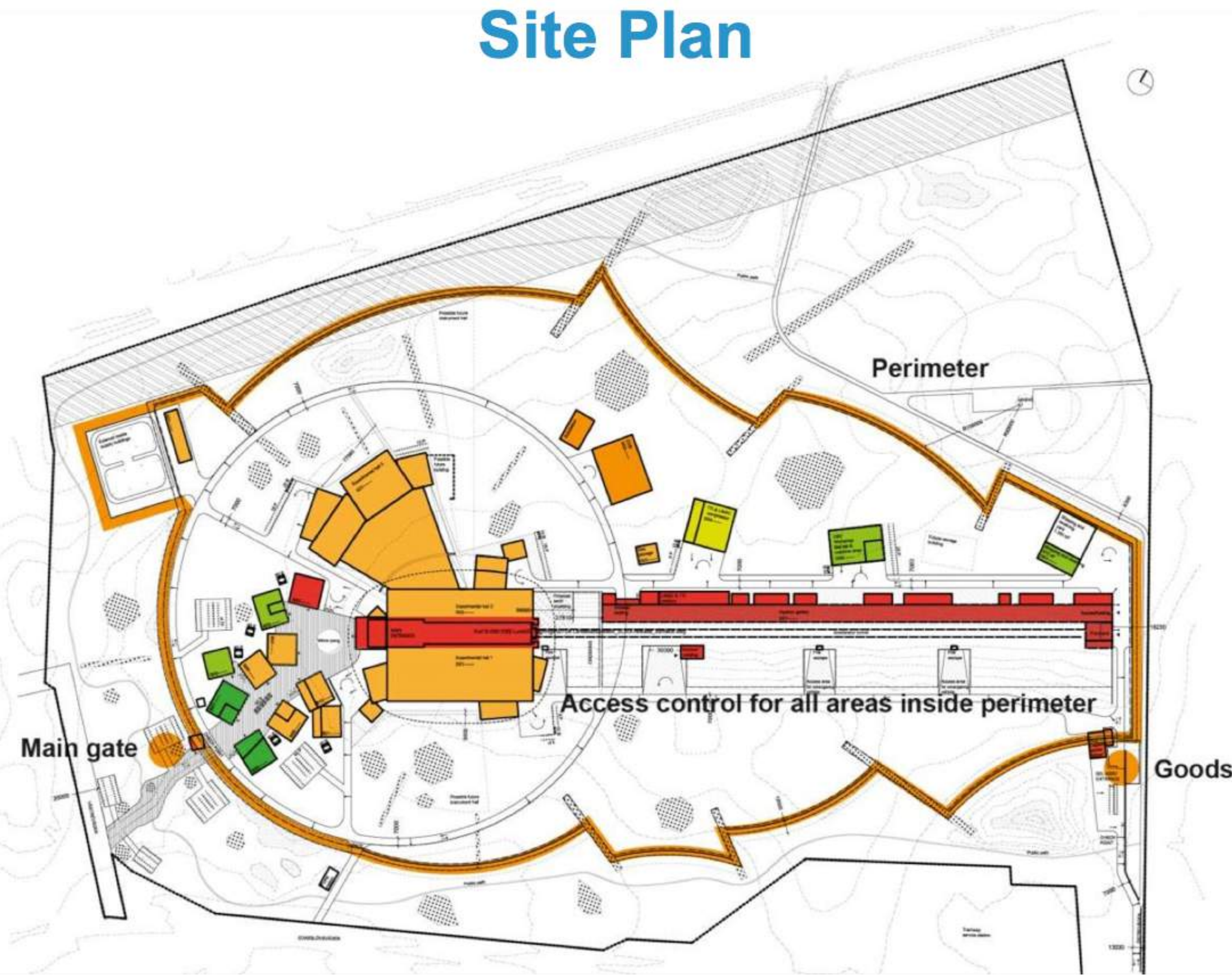




European Spallation Source

❖ Under construction…



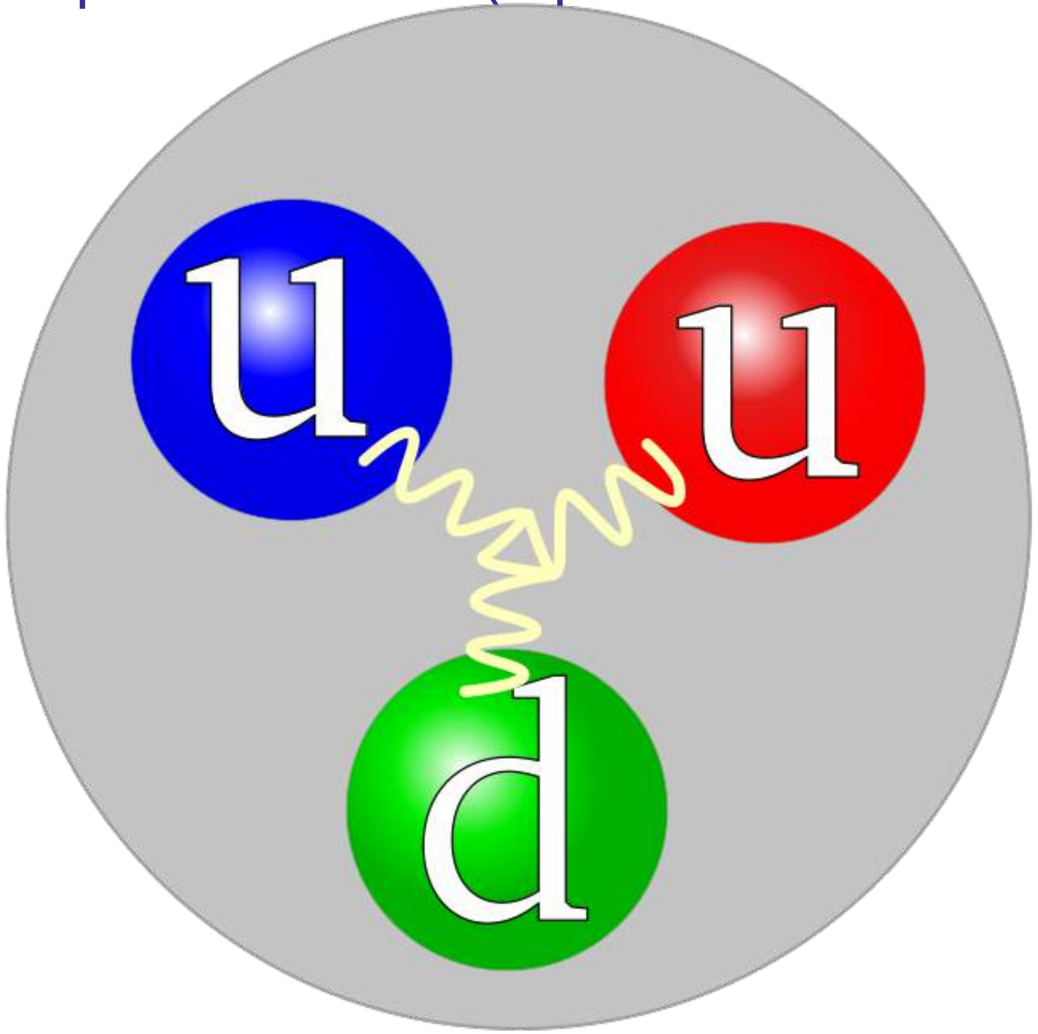


NNbar@ESS

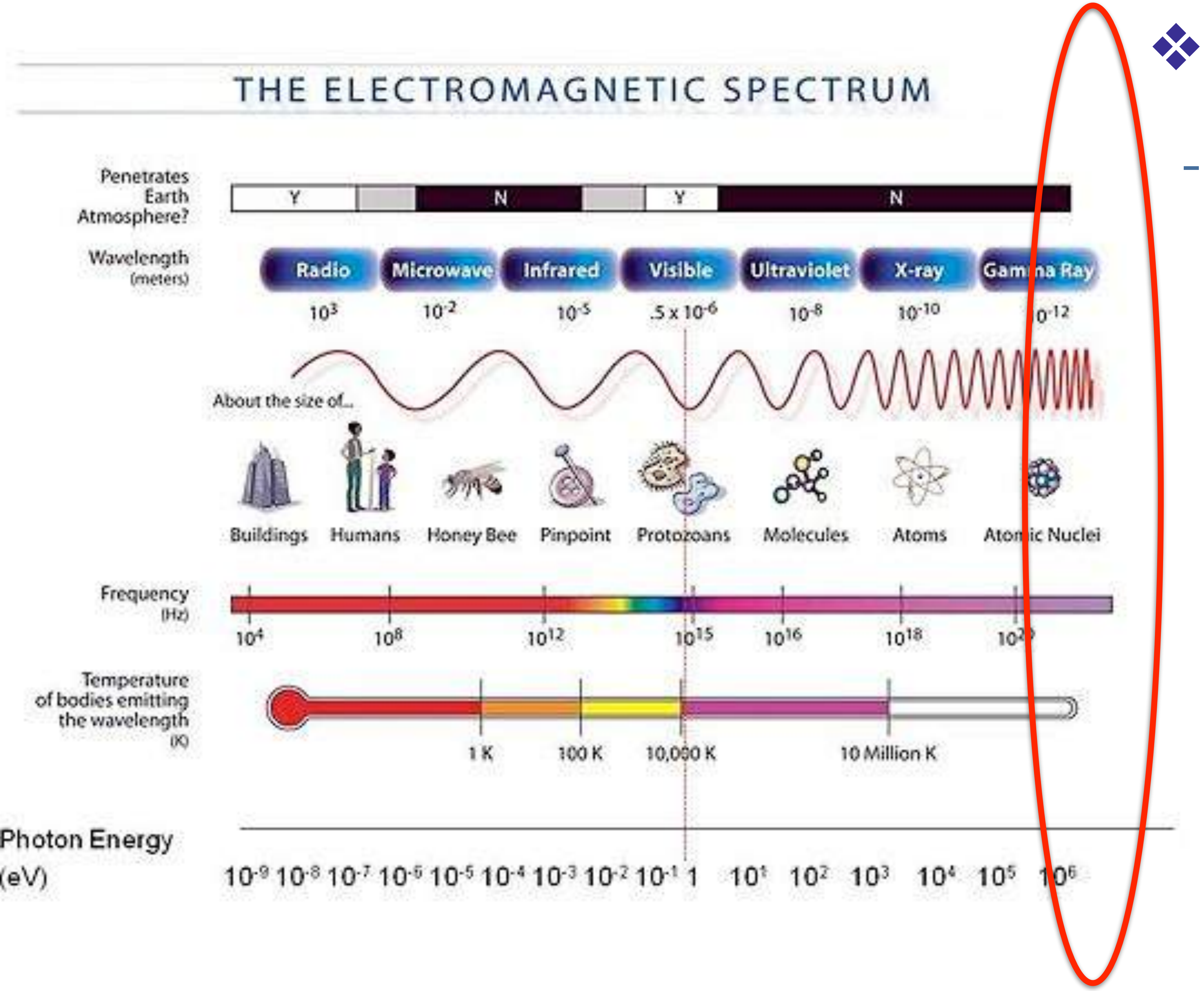
- ❖ Maximize flux of cold neutrons
  - Very low energy: travel at ~1000m/s
- ❖ State-of-the-art techniques
  - Last experiment was done in late 1980's
- ❖ Expect to get a **factor 1000 improvement** in sensitivity!
  - An opportunity not to be missed
- ❖ Hope to start experiment in late 2020's

The Proton Spin

- For a long time, it was assumed the proton spin = sum(spins of constituent quarks)

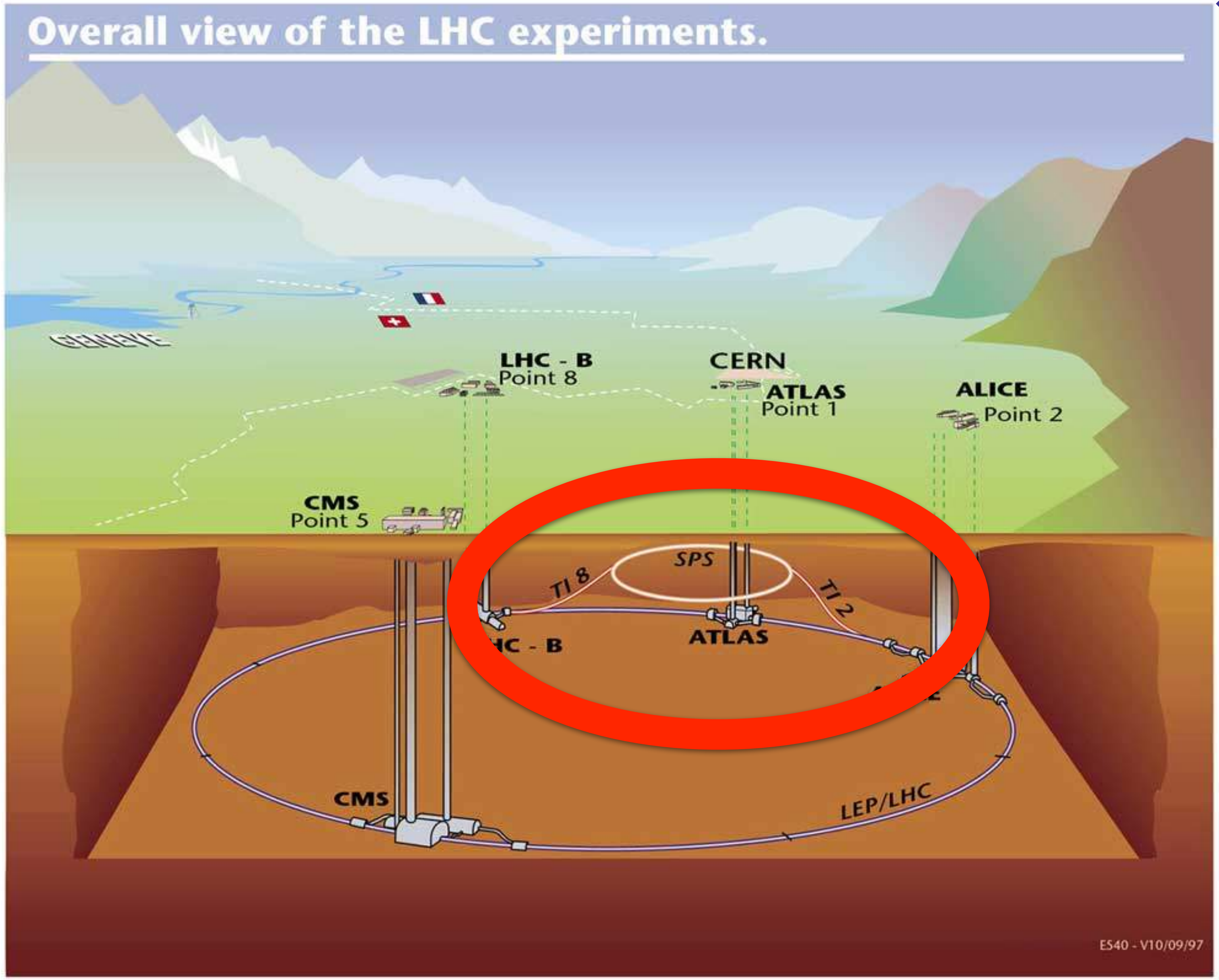


Measuring Quark Spins



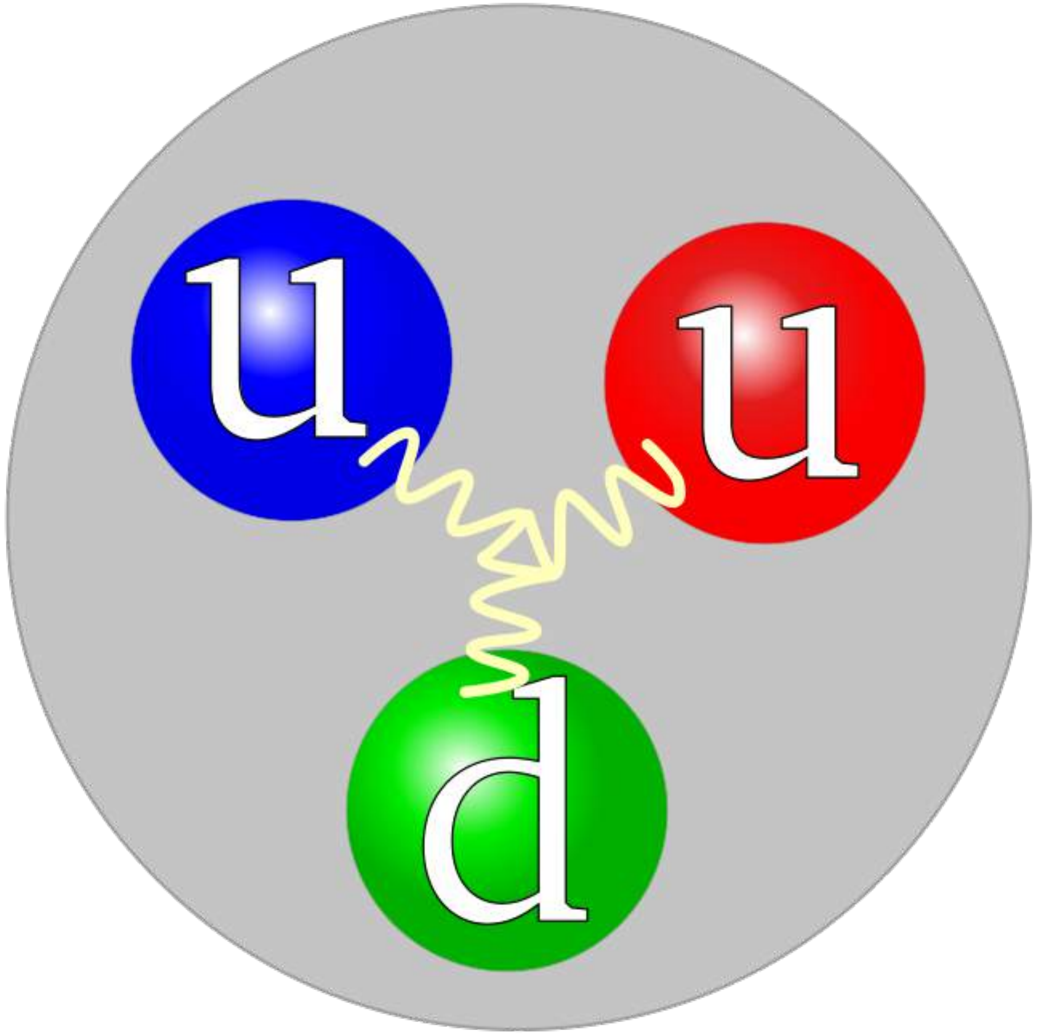
- Need to poke inside protons
  - Photons with wavelength < proton radius
    - Proton radius ~ 1 femto-meter, 10^{-15} m
    - That's a 1 GeV photon

Measuring Quark Spins



- ❖ Need to poke inside protons
  - Photons with wavelength < proton radius
    - Proton radius ~ 1 femto-meter, 10^{-15} m
    - That's a 1 GeV photon
  - SPS: accelerate protons to 450 GeV
    - Use those to make photons 1-100 GeV

Measuring Quark Spin Orientations

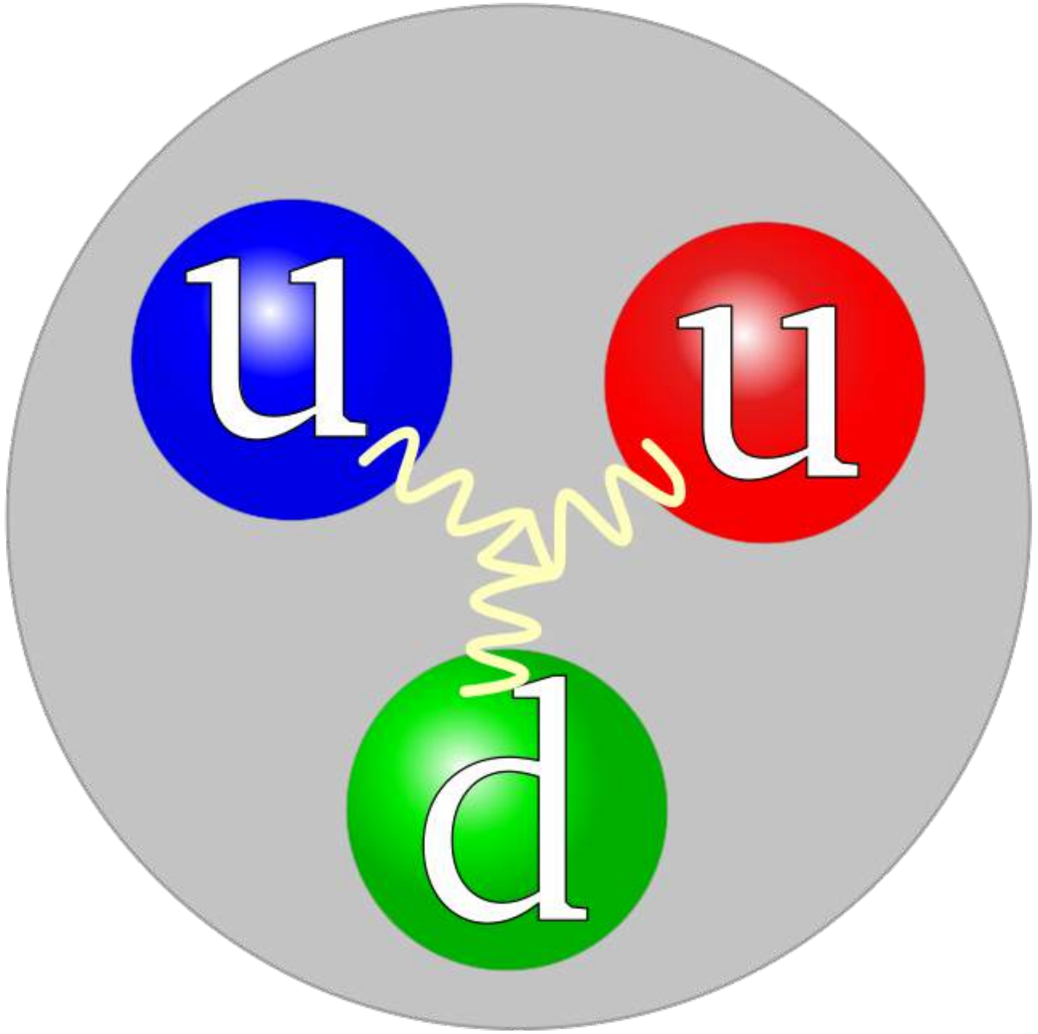


❖ Need to poke inside protons

- Photons with wavelength < proton radius
  - Proton radius ~ 1 femto-meter, 10^{-15} m
  - That's a 1 GeV photon
- SPS: accelerate protons to 450 GeV
  - Use those to make photons 1-100 GeV
- Scatter these off *polarized* protons
  - I.e. protons with spins aligned in specific direction

The Proton Spin

- For a long time, it was assumed the proton spin = sum(spins of constituent quarks)
  - In 1987, the contribution of constituent quarks to the proton spin was measured to be ~0! "Proton spin crisis"
  - Many measurements since
    - Basically, proton spin appears due to dynamics of constituents, quarks ***and*** gluons

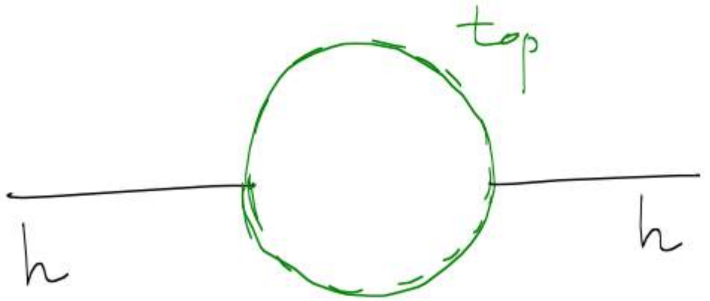


So

- Why is the proton spin 1/2?
  - Quantized: some form of boundary condition
  - There are "excited proton states" of spin 3/2, 5/2, 7/2, …
  - No integer spin "proton" though, presumably violates boundary conditions
- Key message: proton spin **originates in dynamics**
  - Does that say something about quark/lepton spins?
- Or, are we misinterpreting and is this the equivalent of a 2-slit experiment?

The Future

- Convergence on “thoughts for the next machine”
  - Substantial investment ⇒ careful weighing of goals and potential for return on investment
  - Quoting Nima: https://indico.bnl.gov/getFile.py/access?sessionId=9&resId=6&materialId=0&confId=571



$$\left(\frac{\delta m_h^2}{m_h^2}\right) = \left(\frac{\Lambda}{350\,\text{GeV}}\right)^2$$

What is Λ?

How will we Know?

- Higher Energy, Most Obviously!!
  - * Find Something! → End of discussion!
  - * Find Nothing → Tuning $\propto E^2_{machine}$
- Rare processes
- Precision measurements

} Indirect, Linear gain in tuning

LHC @ 13 TeV : Few % tuning

LHC @ 33 TeV : Sub-% tuning!

* Best for finding heavy particles
* Best + most direct quantifier of tuning

Precision Higgs Couplings

"LHC will get to 10%, Higgs factory to 1%"

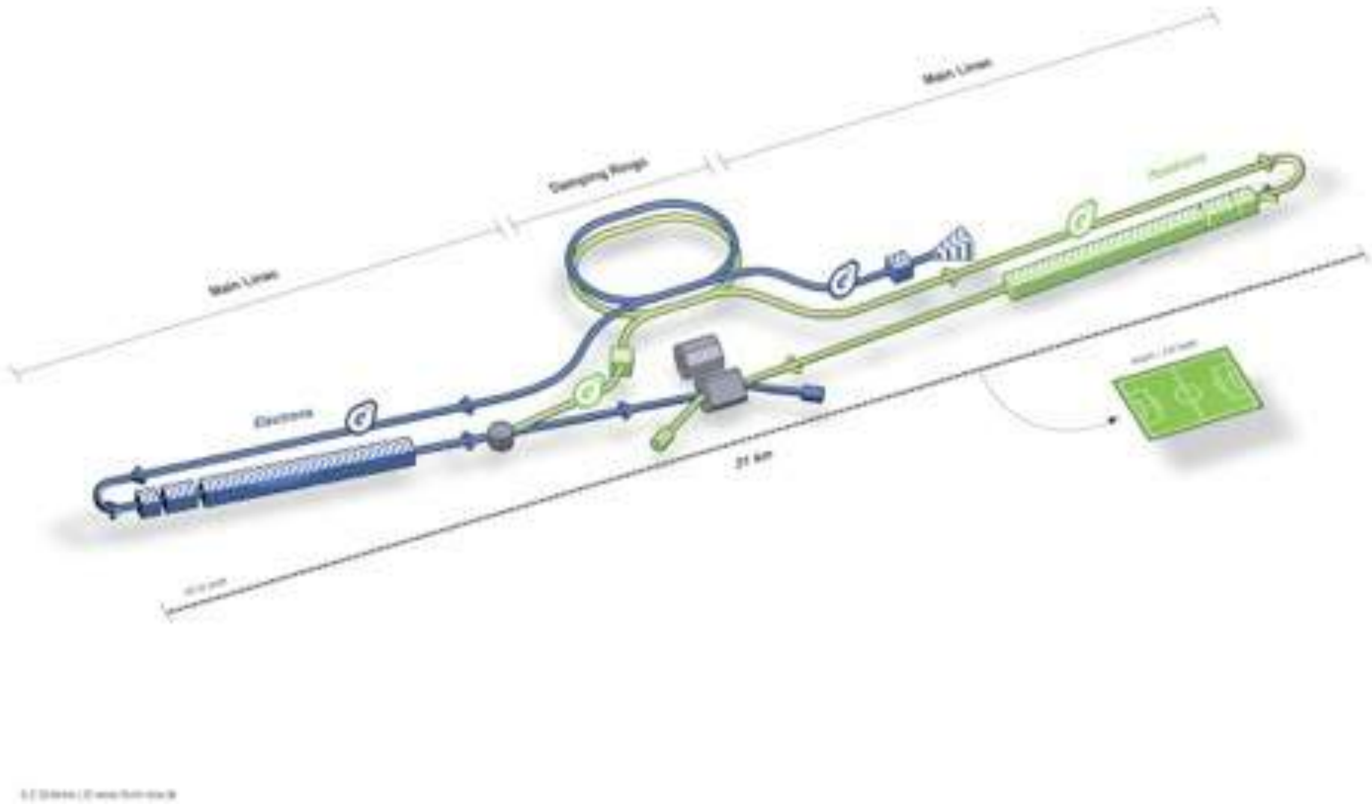
☆ Can a deviation of 1% be solidly established?

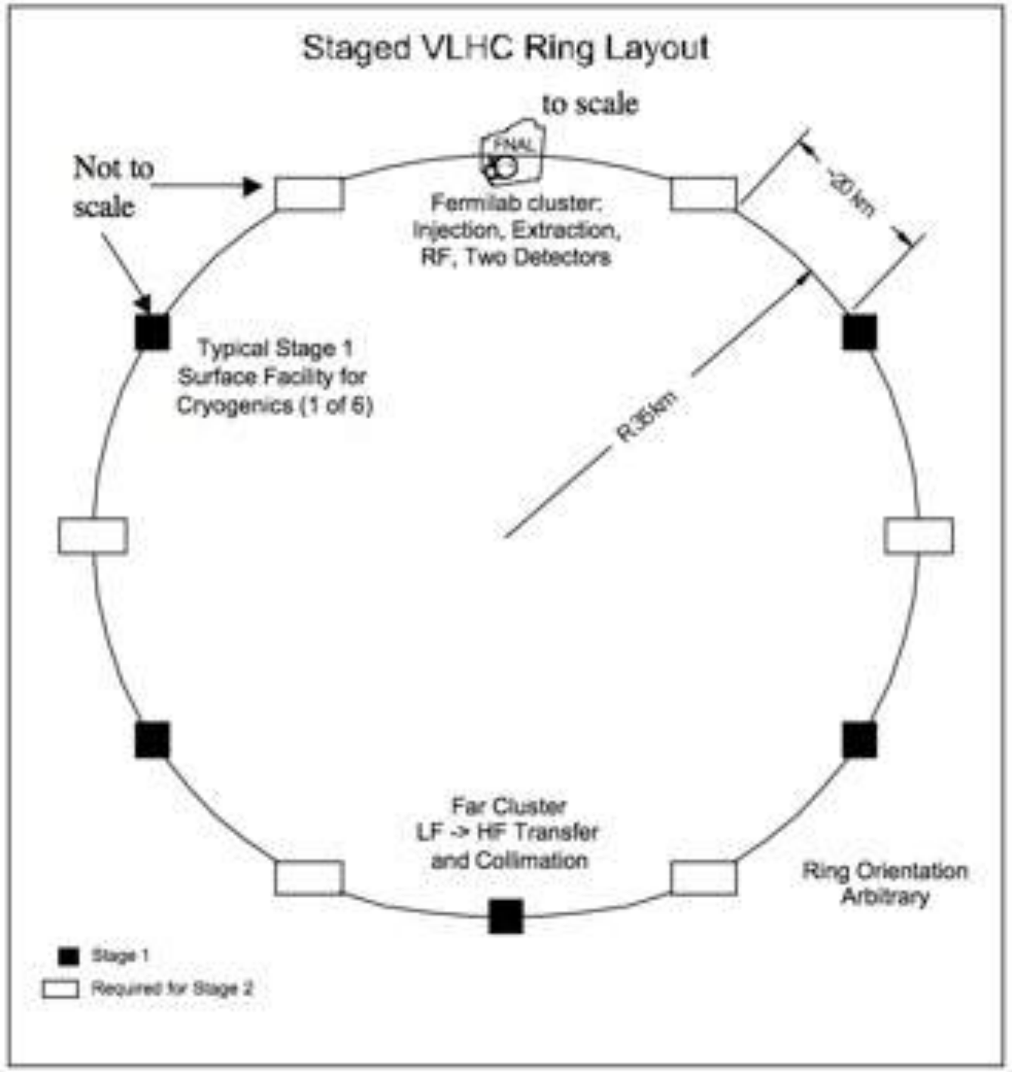
☆ Doesn't LHC see underlying NP anyway?

To Close

- Proton stability, couplings suggest ~10^{16} GeV is an important scale
  - Can probe through EDMs, n-n̄, μ → e, ... *important!*
  - Implies fine-tuning, so, new physics nearby?
- New physics at 3 TeV?

?





Thanks

(and mainly: stay critical of what you're told!)