Hva skjer etter LHC?

Fremtidige partikkelknusere

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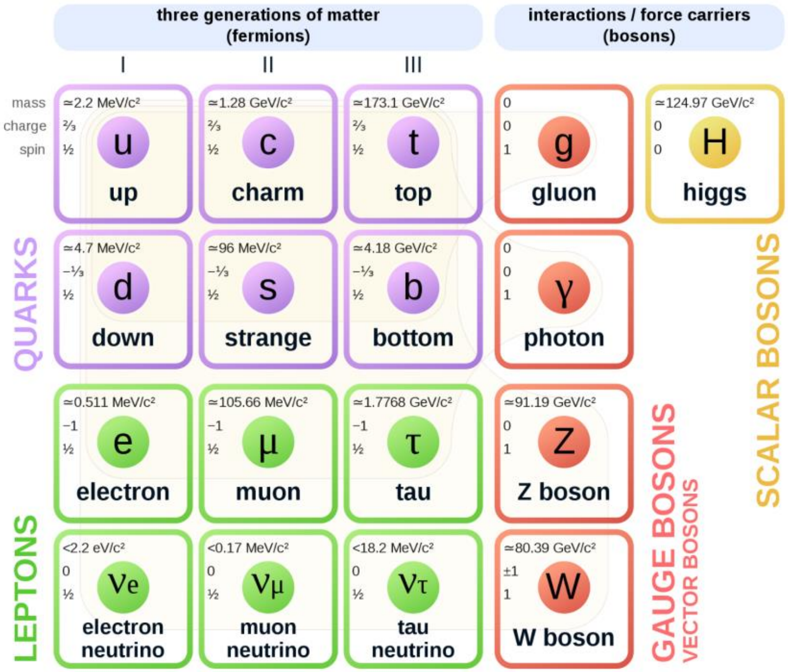
Fysikermøtet 2019
Oslo, Norway

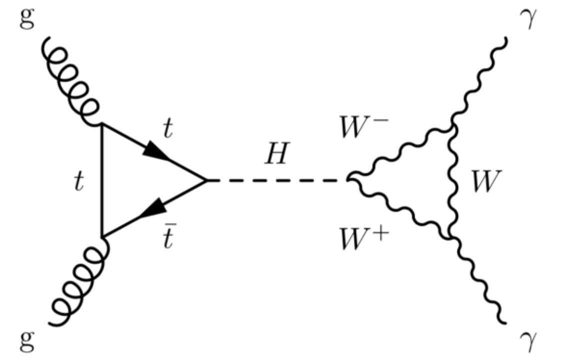
Strategioppdateringen 2018-2020:
[Update of The European Strategy for Particle Physics.]

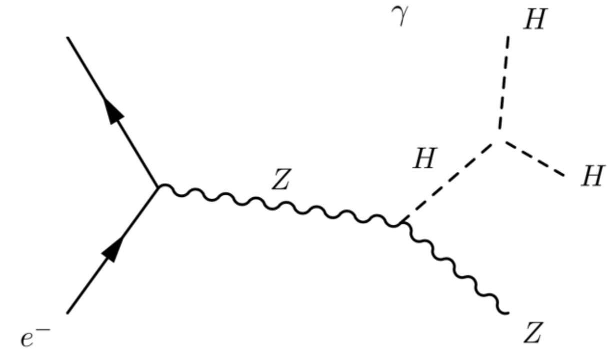
The Standard Model

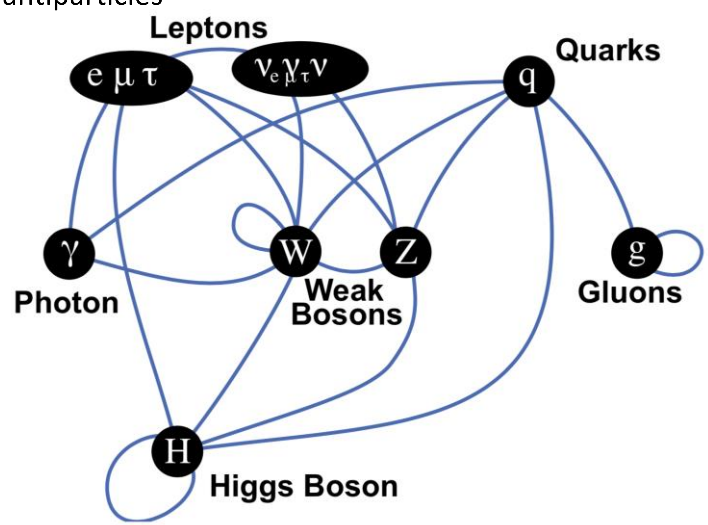


+ antiparticles

Wikipedia







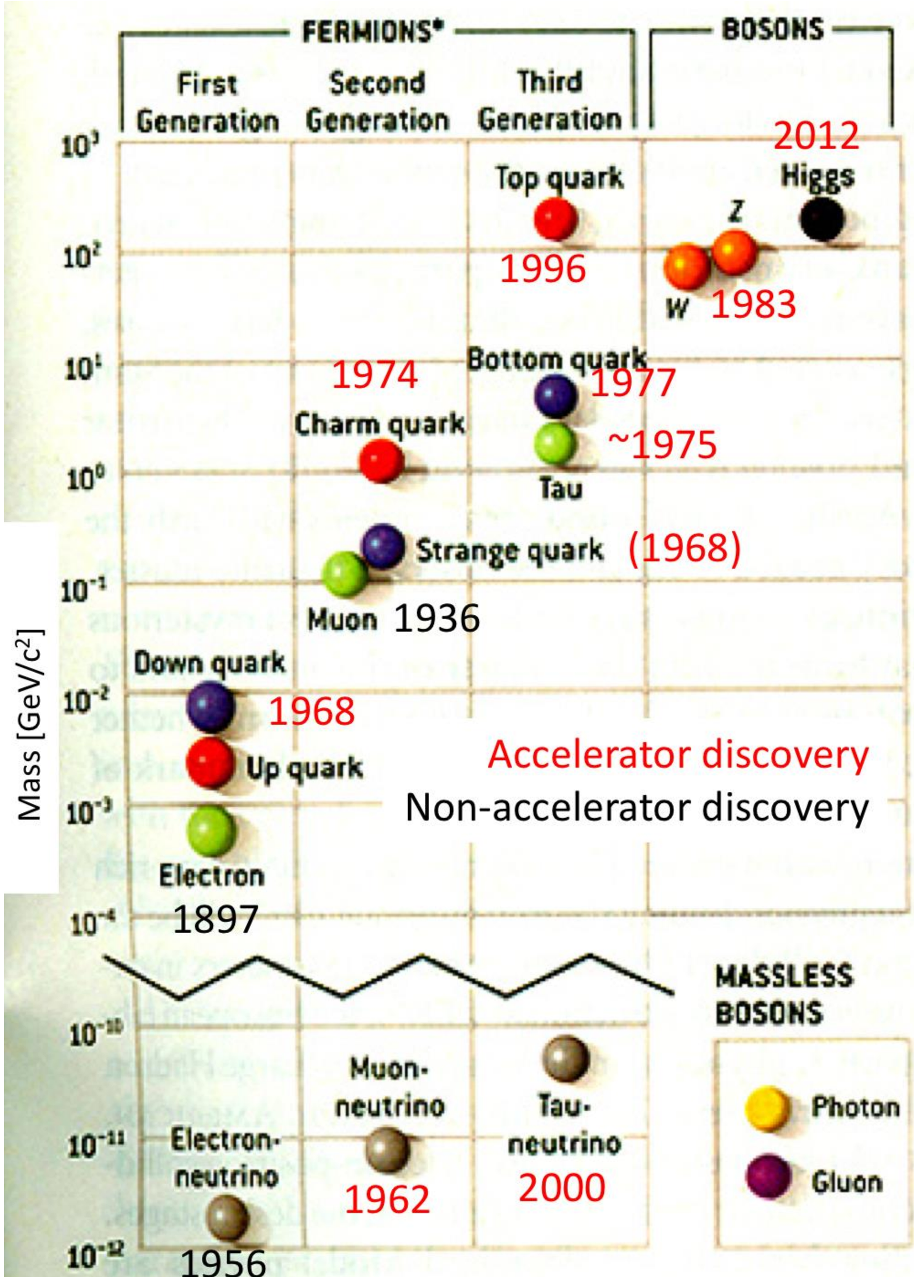
Unanswered questions:

- **Three families? 19+7 free parameters?**
- **Nature of the Higgs field?**
- Anti-matter
- Dark matter
- ...

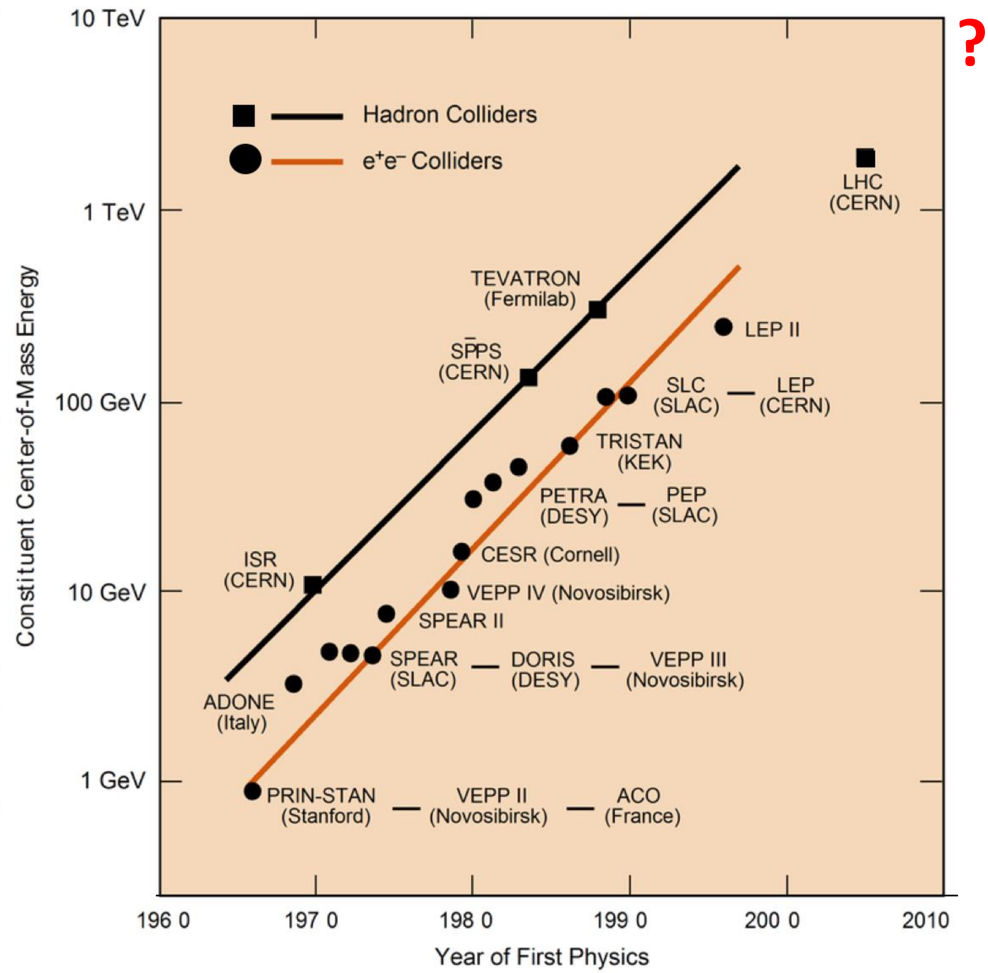
Experimental results required to guide us!

The Standard Model is a relativistic quantum-field theory, consistent and predictive.
It describes all phenomena accessible at colliders.

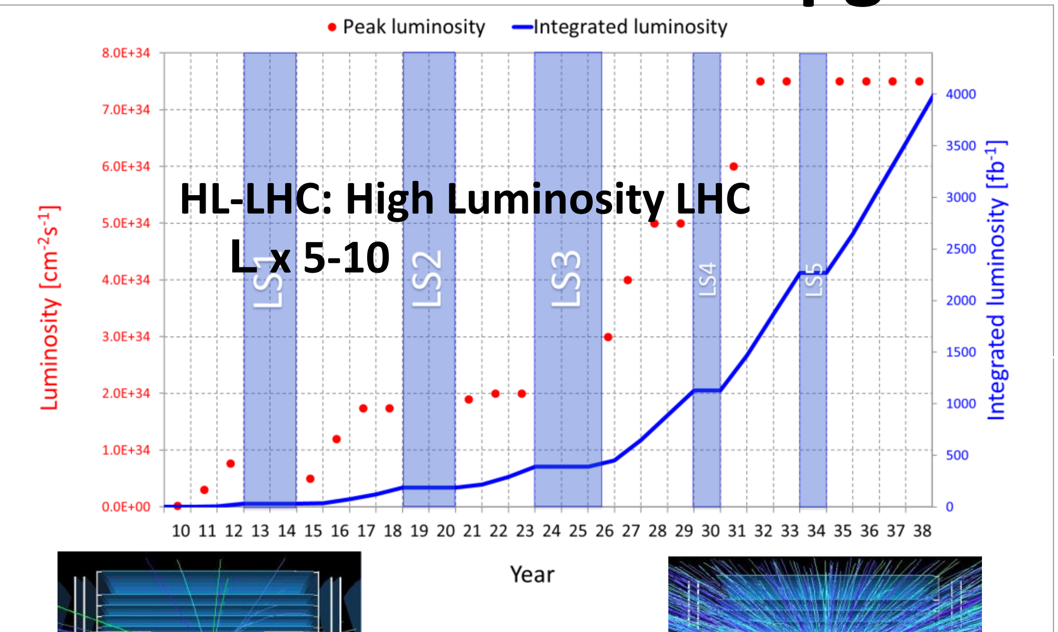
The role of particle accelerators

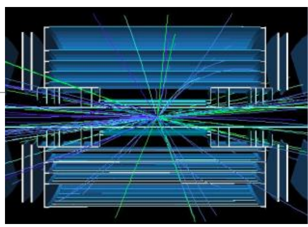


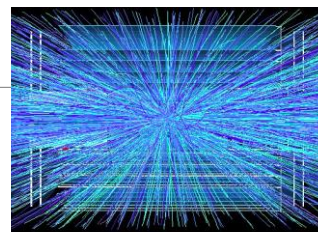
The last particle predicted by the standard model, discovered at the LHC in 2012.



"Near" future: LHC upgrades







Large Hadron Collider

- **proton**-proton collisions (Pb, Au)
- **collision energy of** 14 TeV
- 10^{11} protons at 40 MHz, squeezed to a width of 10 μm, yielding a **luminosity =** rate/cross-section of 10^{34} cm^{-2} s^{-1}

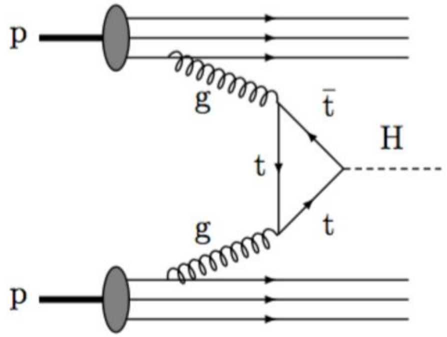
What defines a collider :

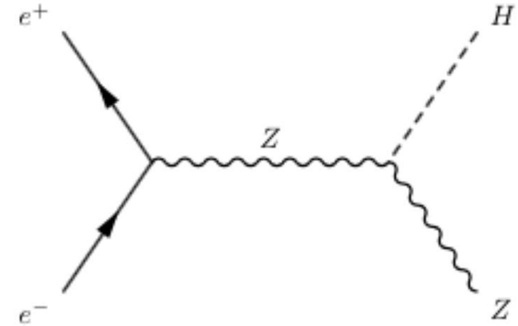
- particle type
- collision energy
- luminosity

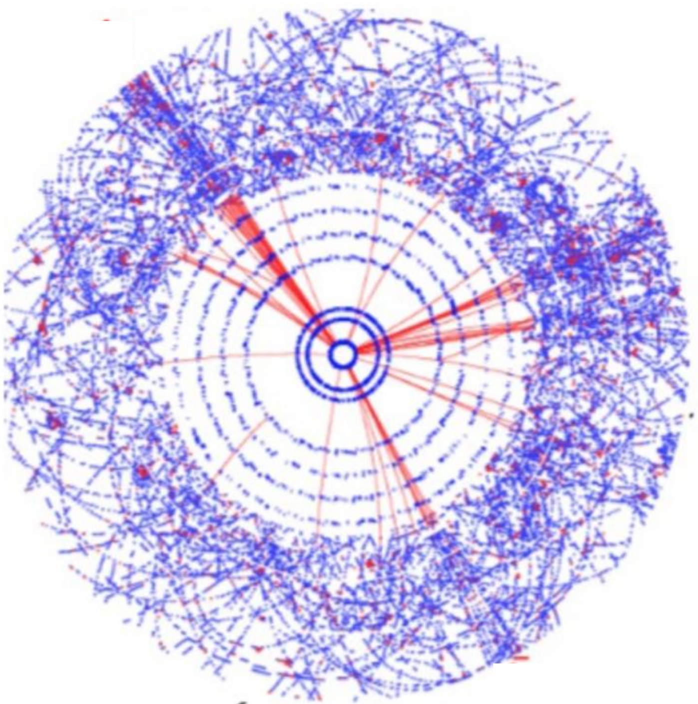
"Timeline plot" – as used in the strategy discussions:

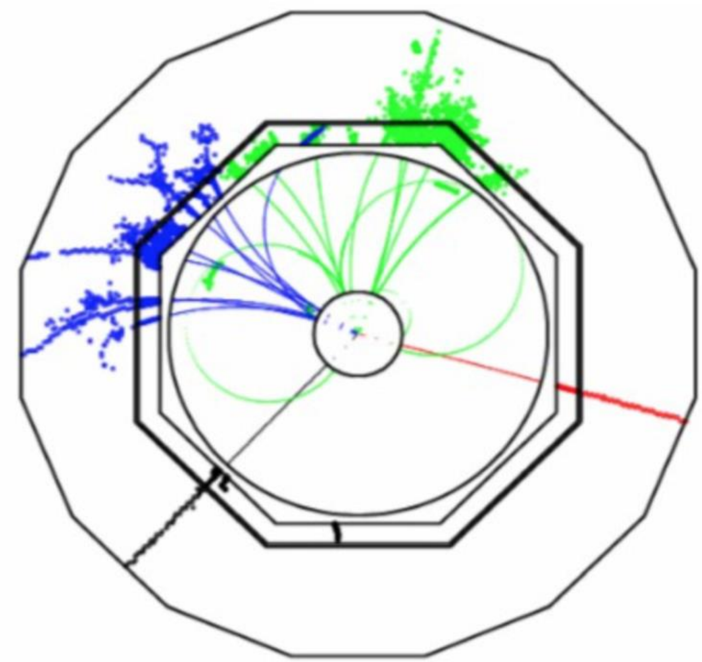
- Beyond HL-LHC we need to either **change to e- e+**, or **to increase the collision energy**, while retaining a high luminosity
- **LHC was 25 years in the making**, decision to **fund in 1995**. **Urgen**t to plan new project for the future
- **Proposed projects on the energy frontier:** proton-proton or e- e+? Circular or linear?

proton-proton versus e- e+ colliders





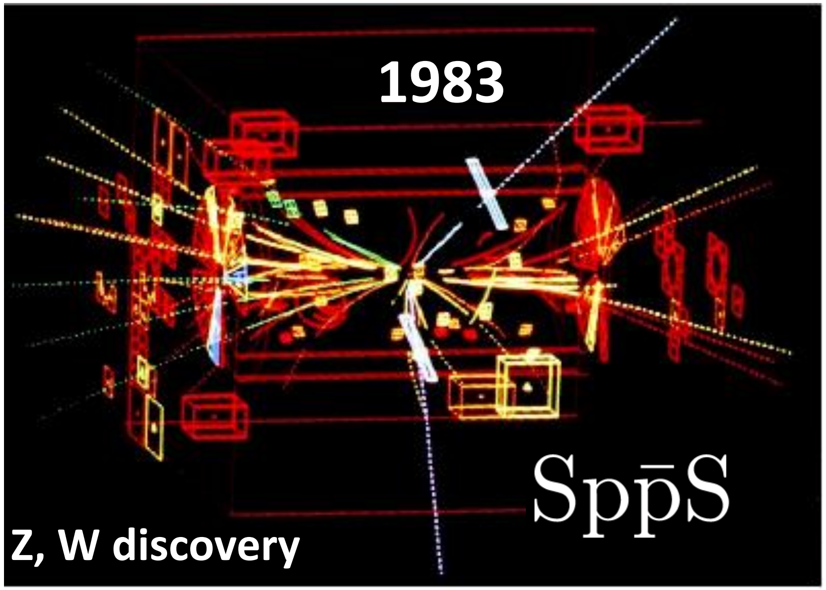


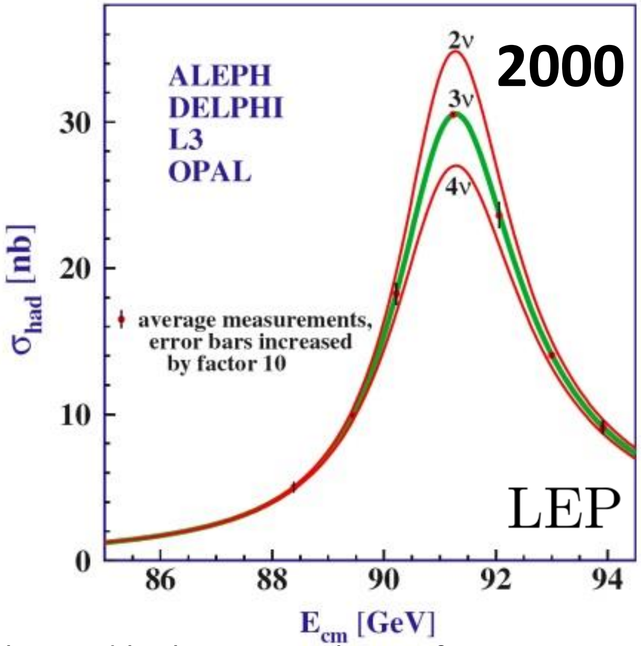


- Initial state not available
- Strong background, busy events, filtering, triggers

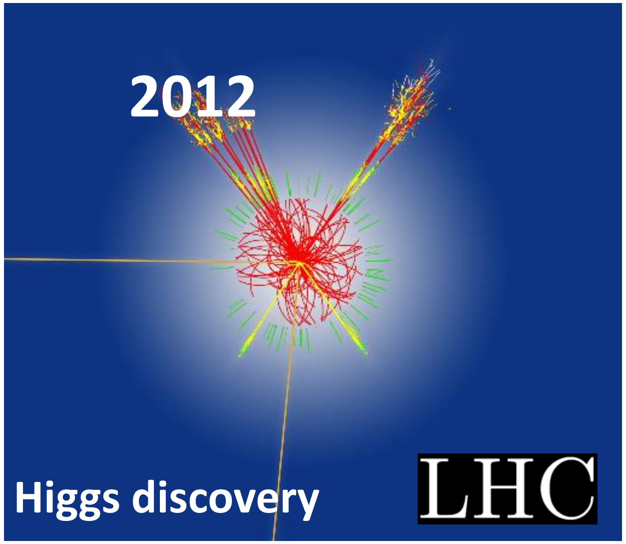
- High signal-to-noise; cleaner events
- Well defined initial stage
    - Higgs decay width can be established. > model independent measurements

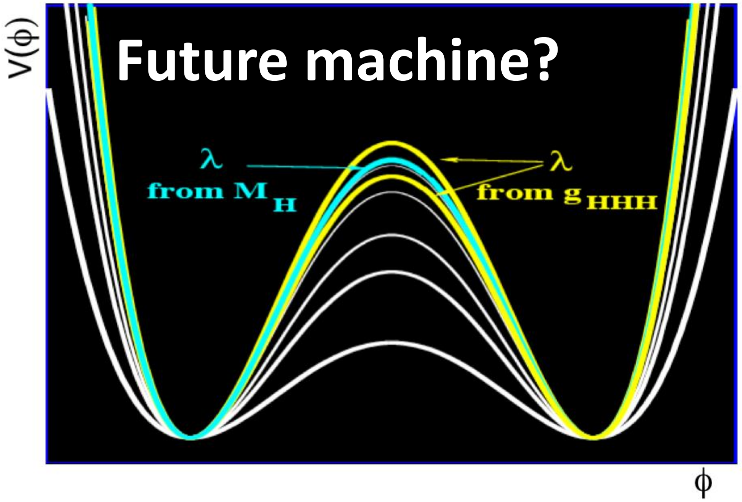
Example: recent colliders at CERN





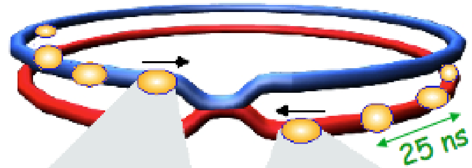
"LEP changed high-energy physics from a 10% to a 1% science."





Future machine: **per mille precision**, model independence

Energy and luminosity limitations, for rings and linacs

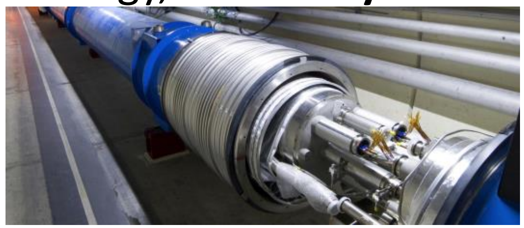


Energy challenges | **Luminosity challenges (examples)**

Circular proton-proton colliders

LHC: 14 TeV collision energy, **limited by 8T** SC magnet field

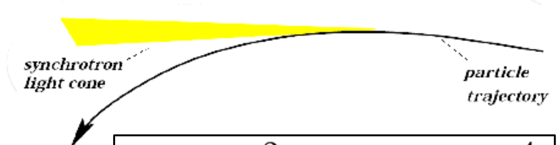
$$p = eB\rho$$



Collective electromagnetic effects constrain charge

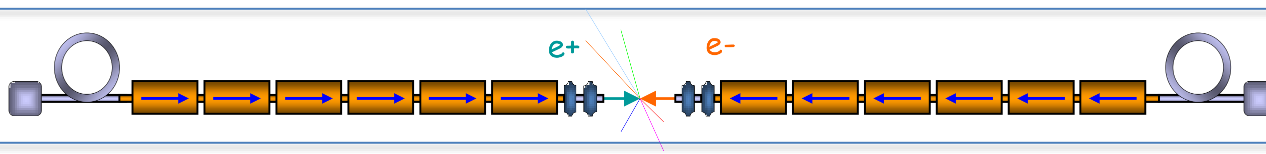
Circular e- e+ colliders

Synchrotron radiation loss limited LEP collision energy to 209 GeV.



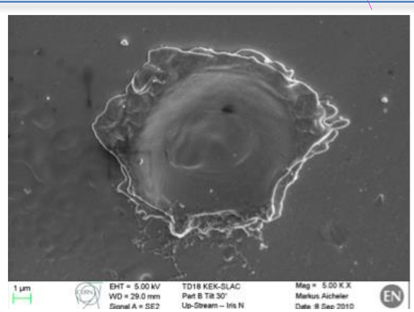
$$P_e = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

Synchrotron radiation loss constrains charge



Linear e- e+ colliders

Reaching high accelerating RF fields. **100 MV/m** is the state of the art. 10 km <= 1 TeV.



Colliding beams with nm width**,** as opposed to µm width for LHC, required for the same luminosity.

Progress on the Energy Frontier relies on the evolution – or revolution – of **particle accelerators**

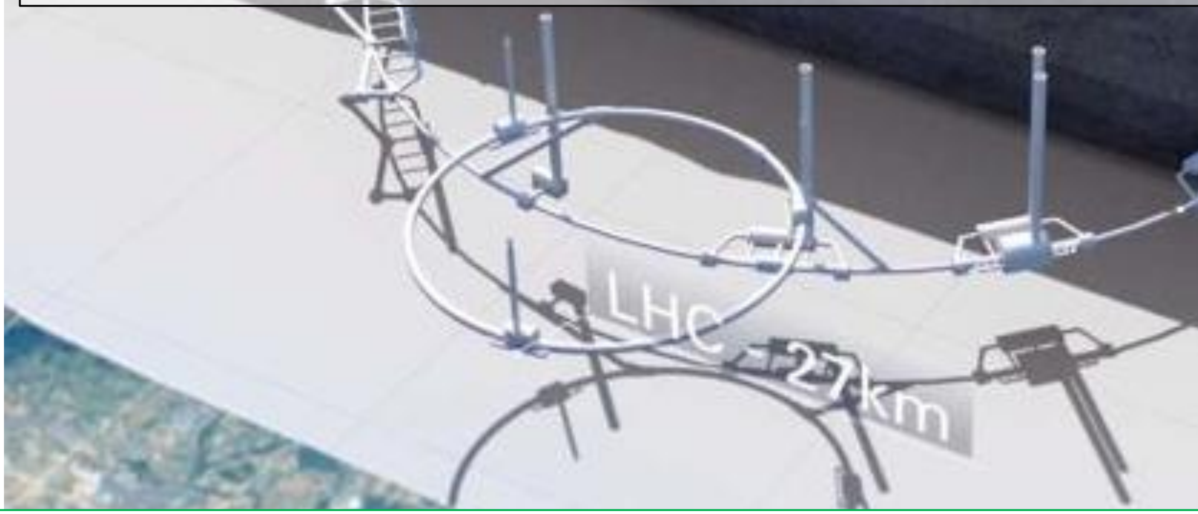
The Future Circular Collider - **FCC**

Idea: Increase energy to **7 times that of LHC** . Tunnel of **98 km**. **16T Nb_3Sn magnets** at 2K. **Re-use of LHC** for 3.3 TeV injection.

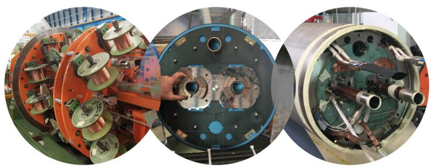
Main challenge: magnet development. 15-20 years R&D, first possible start T0+23 years (8+15). Cost: **tunnel 6 BCHF**, total **24 BCHF (+/- 30%).**

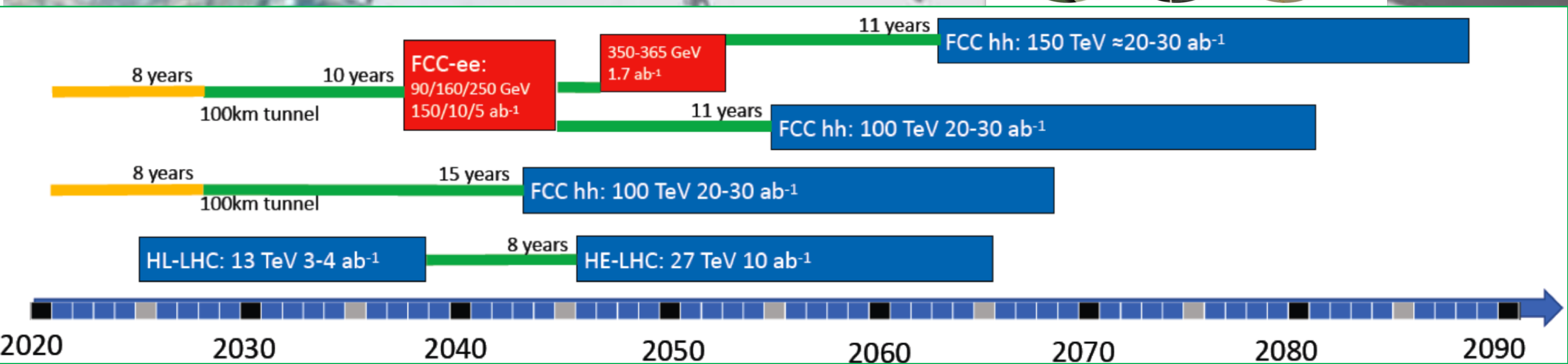
Option: use the tunnel for **e- e+ collisions first**, up to 365 GeV (1.7 x LEP energy). Charge adjusted to keep **synchrotron radiation loss at 100 MW** for all energies.

- **For FCC-ee: no technological show stoppers**. Cost: **total 11.5 BCHF** (+/- 30%**).** FCC magnet development in parallel.



Main challenge:
16T Nb_3Sn magnets

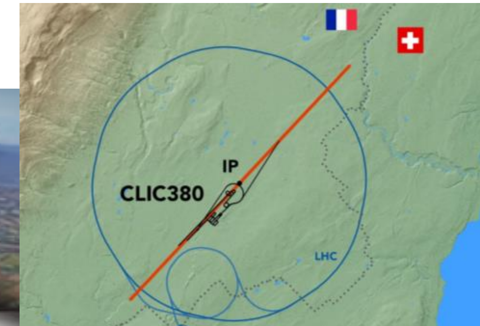


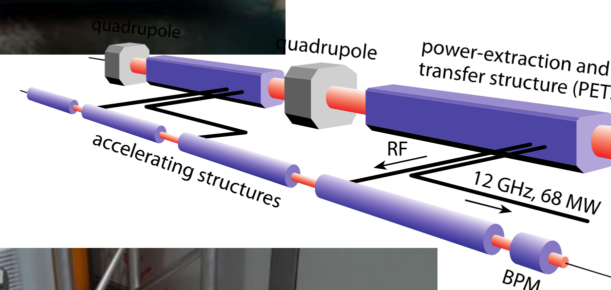


Linear Electron Positron Colliders: **CLIC**

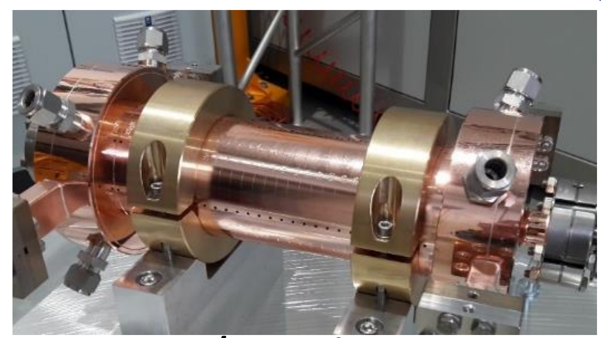
The Compact Linear Collider, CLIC

Normal conducting 12 GHz, two-beam acceleration, 100 MV/m.
First stage 380 GeV, 11 km. Upgradable to 3 TeV, 50 km.

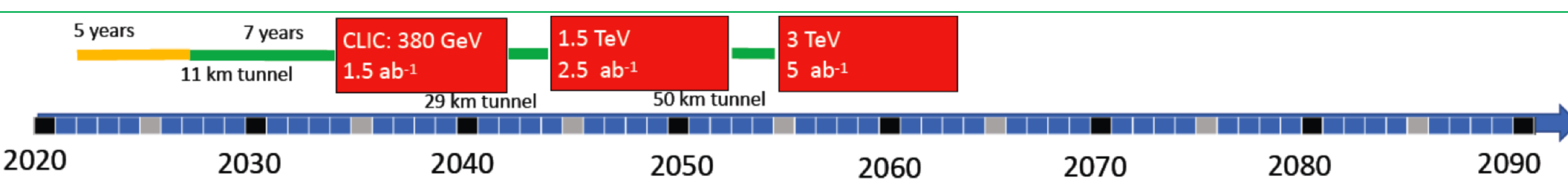




- Two-beam acceleration with **100 MV/m demonstrated** at CERN
- **Conceptual Design done** – about 5 years of technical design required before construction
- Cost: **5.9 BCHF** (380 GeV) + 5.1 BCHF (1.5 TeV) + 7.3 BCHF (3 TeV) = **18.3 BCHF total**
- Also Japanese site option: "ILC"



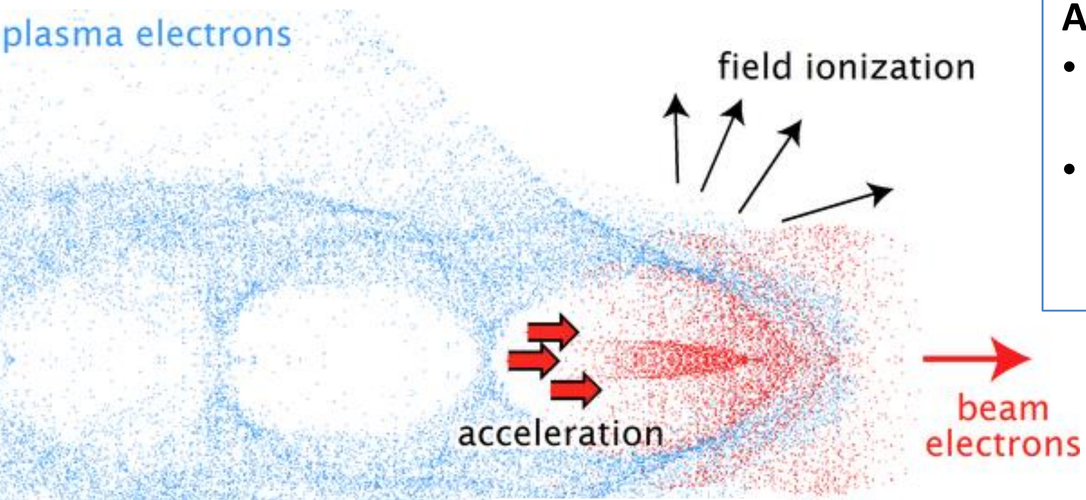
CLIC 100 MV/m accelerating structure



Novel accelerator concepts: **plasma acceleration**

RF cavities: limited by metal surface break down
Alternative: high fields inside plasmas:

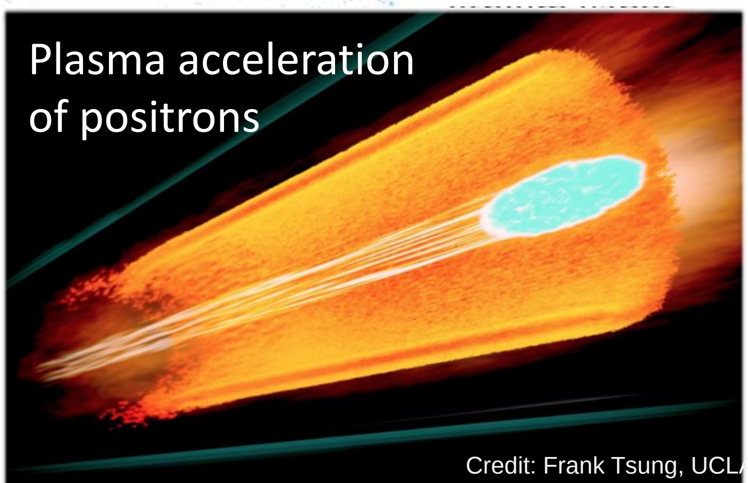
- Plasmas are already broken down; can **sustain the very high fields.**
- **100 GV/m** accelerating fields, as opposed to 100 MV/m

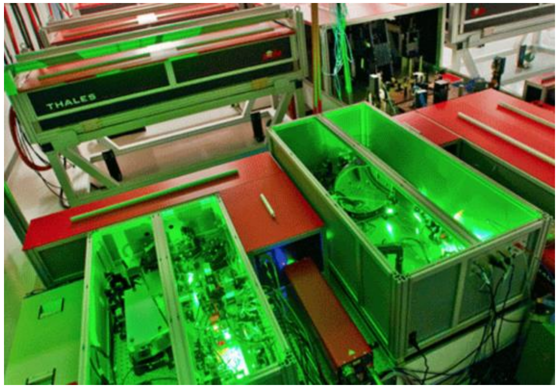


Principle: *drive a wave in plasma with particle or laser beams*

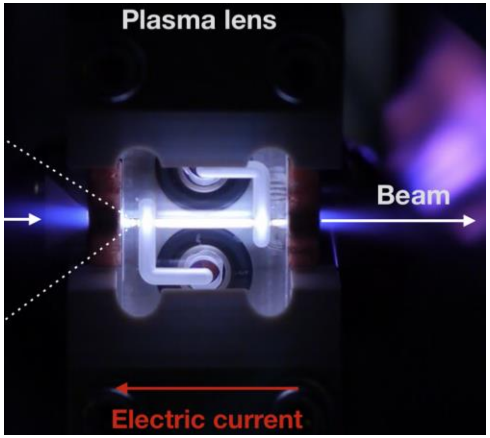
Typical numbers :

Plasma density ~ **10^{16-18}/cm^3**
Field scale: 10-100 GV/m
Length scale : $\lambda_p/2\pi$=**10-100 μm**





TW-PW laser technology



Plasma lenses for particle beams

CLEAR visit !

Novel accelerator concepts: **muon collider**

Novel concepts: boost accelerator performance with **radical change in technology**

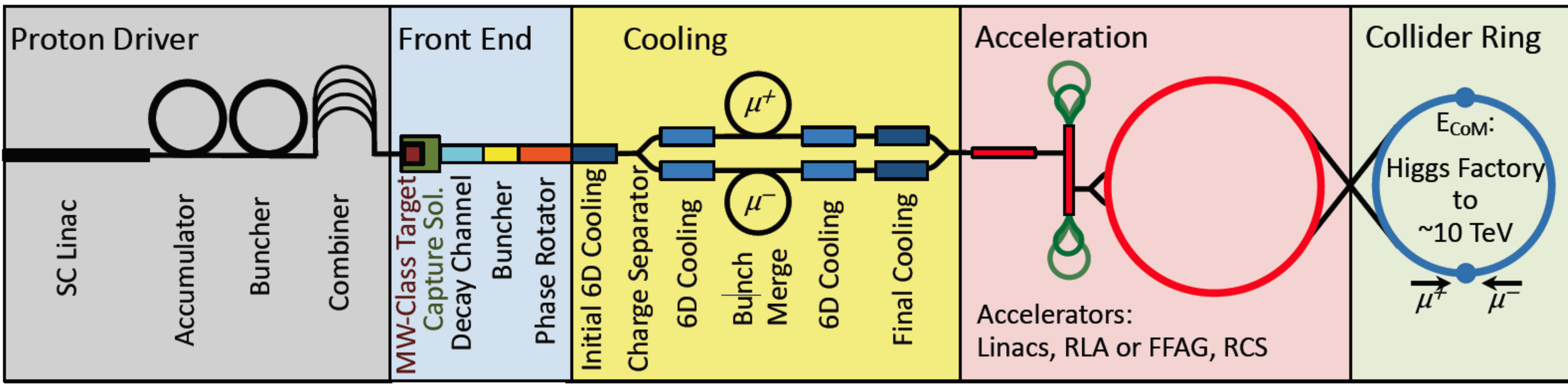
Very promising and interesting research, many hurdles to overcome before use in a collider.

Muon collider pros and cons

Negligible synchrotron radiation

Main challenge: τ_μ = 2.2 μs

- Produce sufficiently dense muon beams
- Rapid acceleration
- Mitigate radiation hazards



Protons on target hadronic showers, Pions decay into muons

Muon are captured, bunched and then cooled.

Rapid acceleration to collision energy

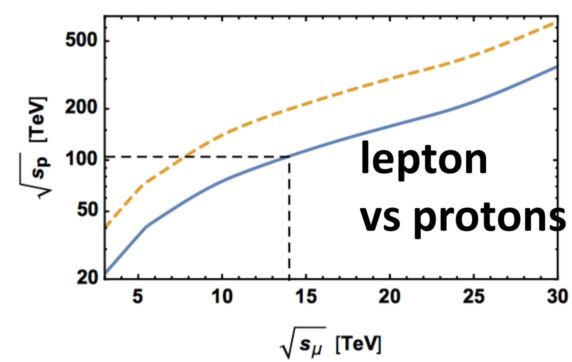
Collision

Precision, plus discovery potential!

3 TeV ~ LHC

14 TeV ~ FCC-hh;

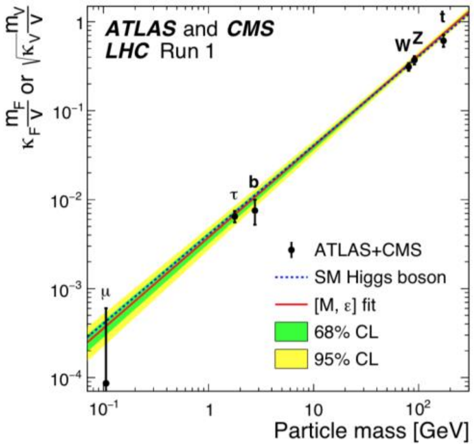
30 TeV ~ "amazing"

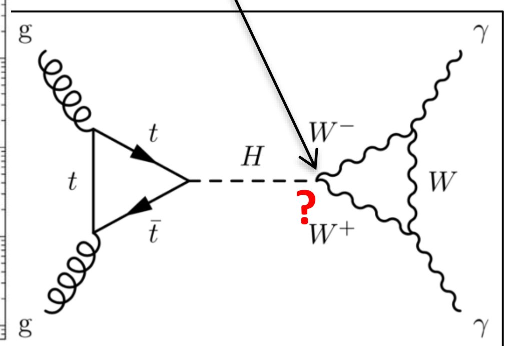


Comparison of machine physics potential: examples

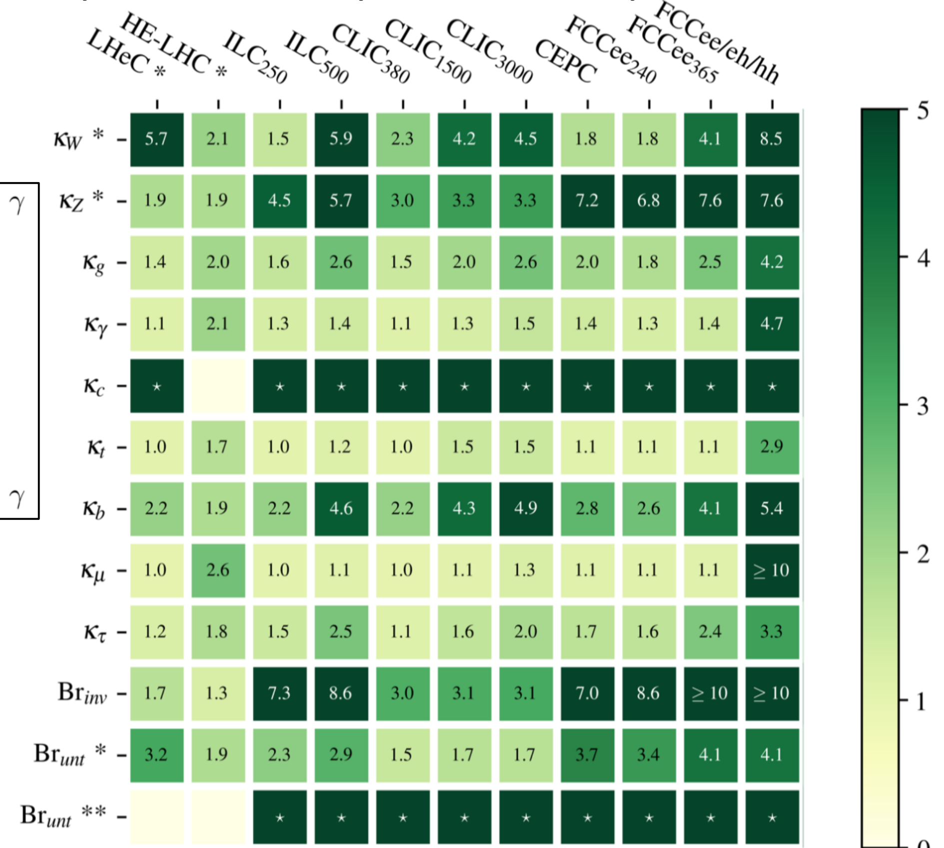
Precision measurements of Higgs couplings

$$g_{hXX} = \kappa_X \, g_{hXX}^{\mathrm{SM}}$$





Improvement of precision compared to HL-LHC



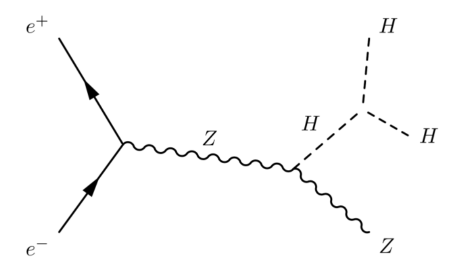
	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

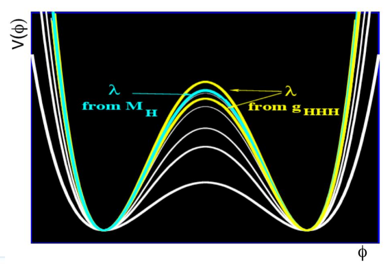
(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC

M. Cepeda, ESU meeting, Granada, 2019 arXiv:1905.03764 [hep-ph]

Probing the Higgs potential

$$V(\phi)$$





$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Measurements of the Higgs potential could be done at a FCC-hh, or at a Multi-TeV e- e+ collider

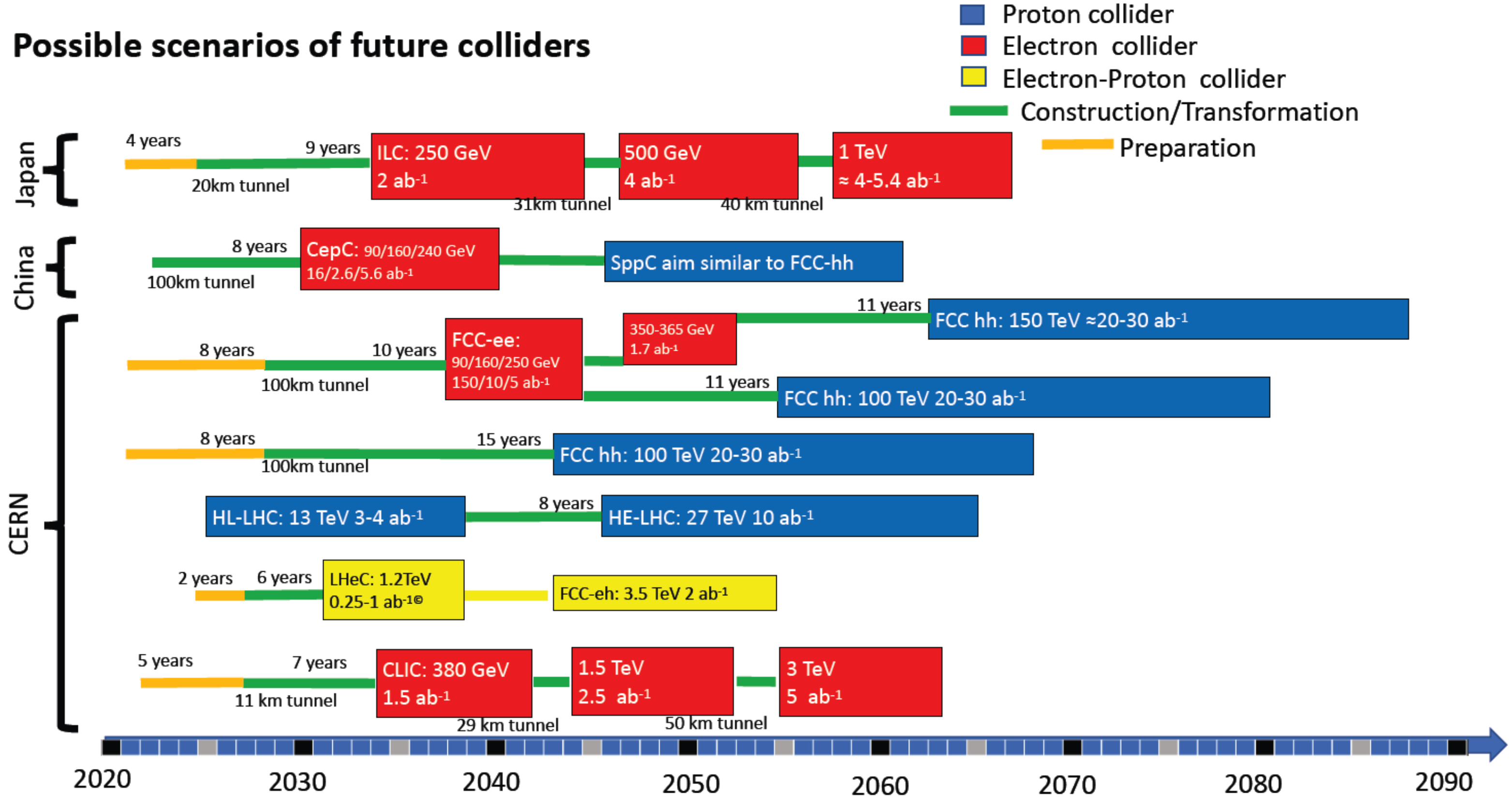
Current opinions seem to be: an e-e+ Higgs factory desired as first machine

"The guaranteed physics of new machines is centered on revealing **the deeper nature of the Higgs**."

Nima Arkani-Hamed

Summary

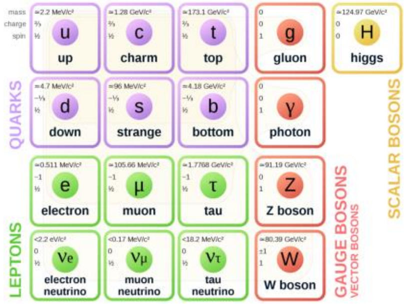
- LHC will continue ~20 years, HL-LHC upgrade from ~2026
- Several future projects suggested, FCC and linear colliders, to address open questions. Novel technology being developed, great promise, not yet ready to consider for a collider
- Best option? Depends on time scale, and budget. Strong potential for future upgrades and reuses are important considerations
- Exiting future for the field ahead!



Acknowledgements: much material taken from the European Strategy Update meeting, May 2019

Link to input from the Norwegian CERN community to the European Strategy Update

Extra

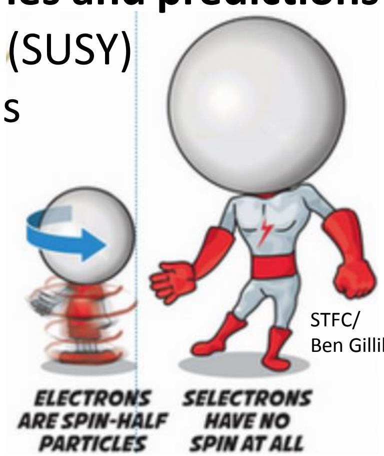


Unanswered questions

- Three families? 19+7 free parameters?
- Nature of the Higgs field?
- Difference matter-antimatter?
- 95% of universe non-baryonic matter? Dark matter?
- .. See talk by A. Kvellestad

Theories and predictions

- Supersymmetry (SUSY)
- Extra dimensions
- String Theory
- ..

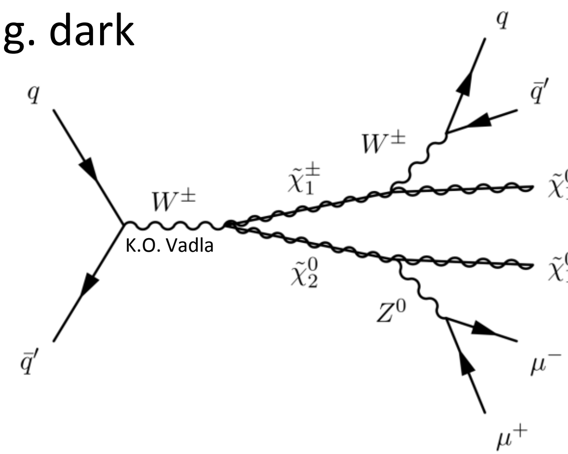


STFC/
Ben Gilliland

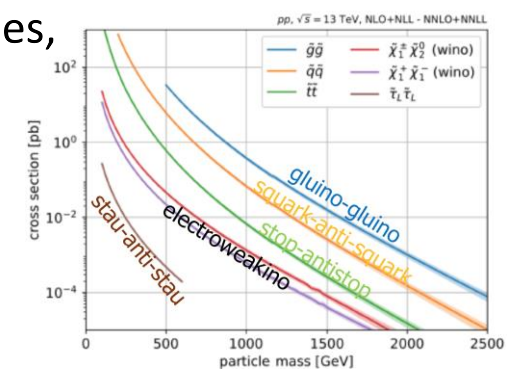
Experimental results required to guide us!

Searches and analyses

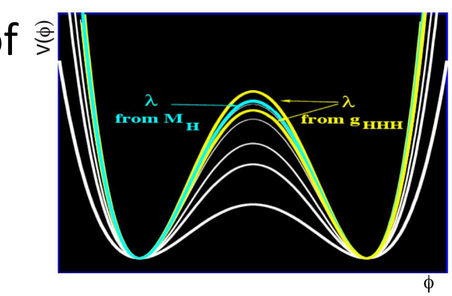
- Direct discovery of new physics. e.g. dark matter particle



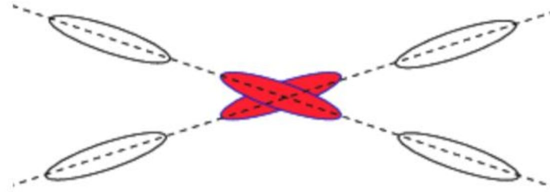
- Constraining theories, e.g. exclude SUSY parameter space

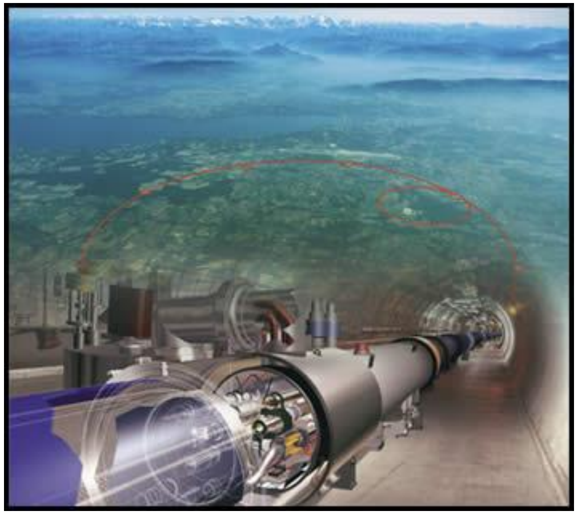


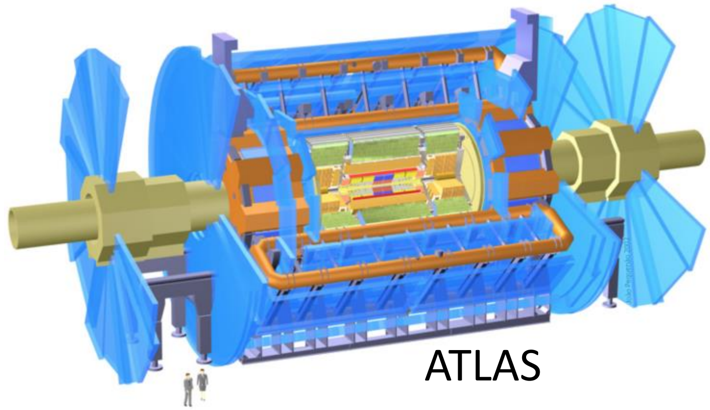
- Precision measurement as proof for new physics, e.g. deviation from coupling parameters



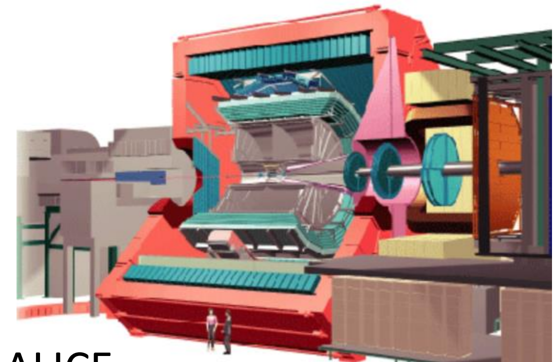
Where are we now?



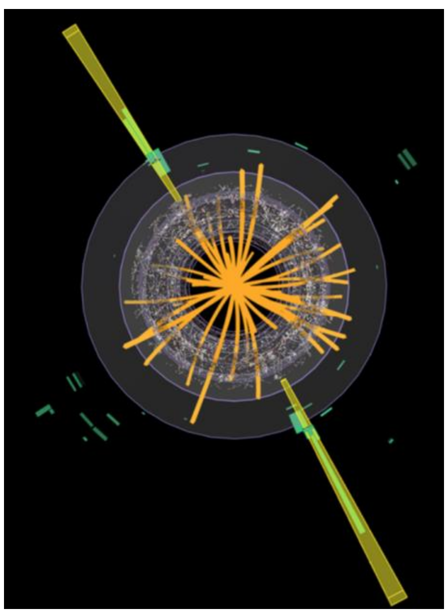


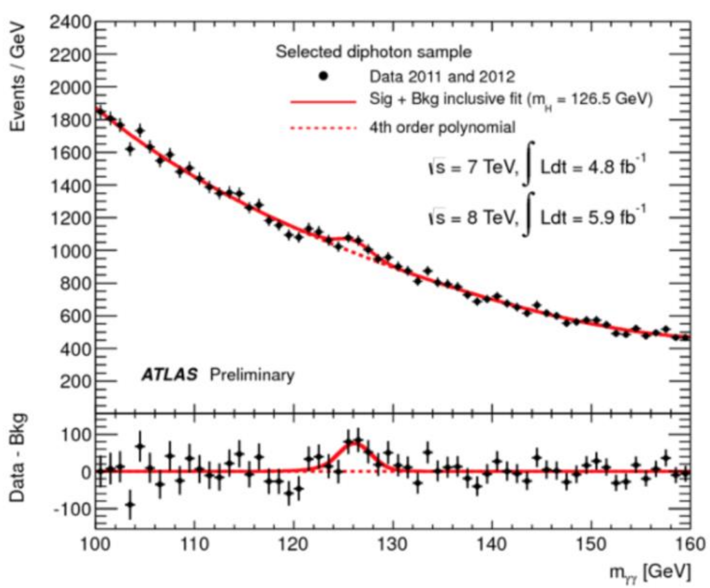


ATLAS



ALICE





Higgs discovery at the LHC, 2012

The ***Large Hadron Collider, LHC***

- **proton**-proton collisions (Pb, Au)
- **collision energy of** 14 TeV
- 10^{11} protons at 40 MHz, squeezed to a width of 10 μm, yielding a **luminosity =** rate/cross-section of 10^{34} cm^{-2} s^{-1}

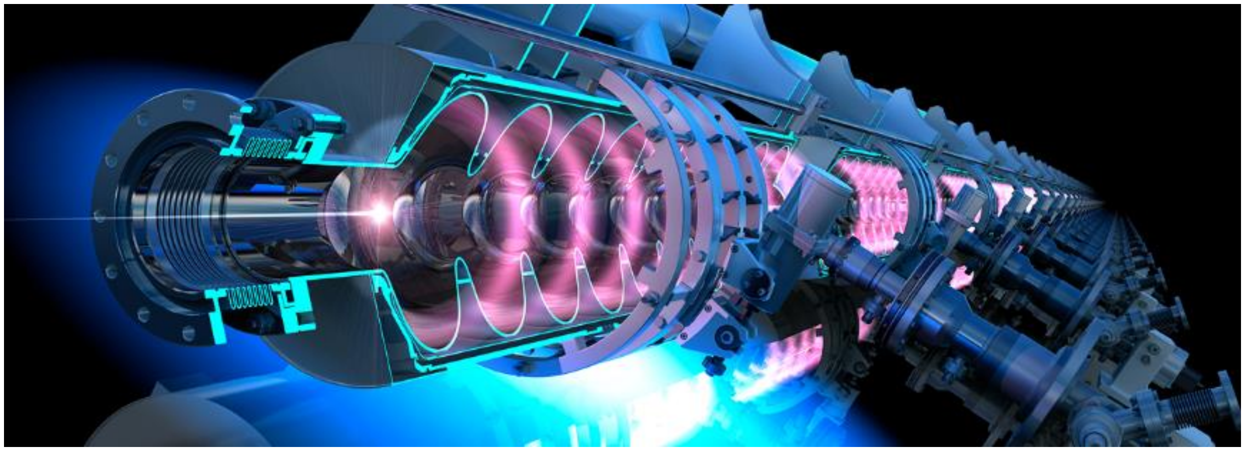
What defines a collider :

- particle type
- collision energy
- luminosity

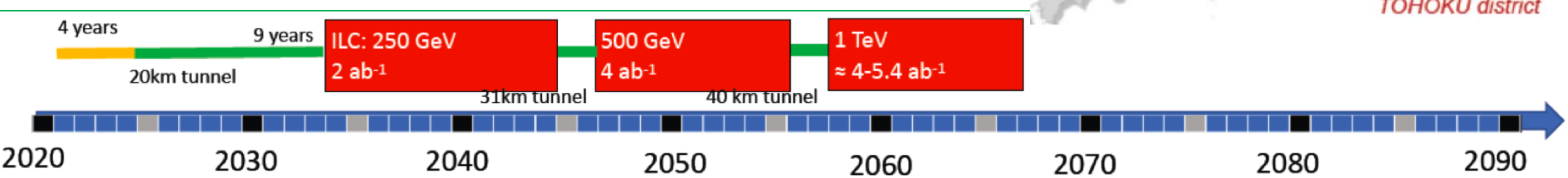
Linear Electron Positron Colliders: **ILC**

The International Linear Collider, ILC - Japan potential host

Superconducting 1.3 GHz cavities, 31.5 MV/m,
First stage 250 GeV, 31 km. Upgradable to 1 TeV, ~50 km.

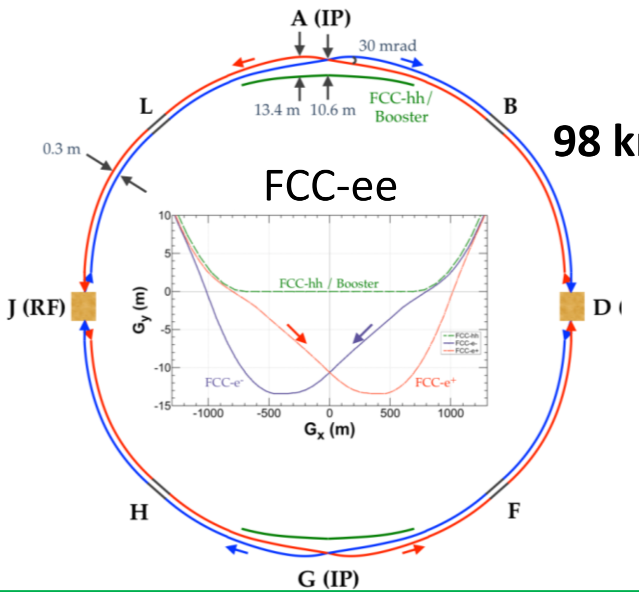


- Development of SCRF cavities with 31.5 MV/m, mostly done. Technology proven (XFEL).
- Technical Design done – almost ready for construction
- Cost: **4.8-6.3B 2012$** (250 GeV)
- May go forward if the Japanese government agrees to pay the bulk, and with sufficient support from Europe and USA. decision process has taken a long time



FCC-ee – an e- e+ collider as first step

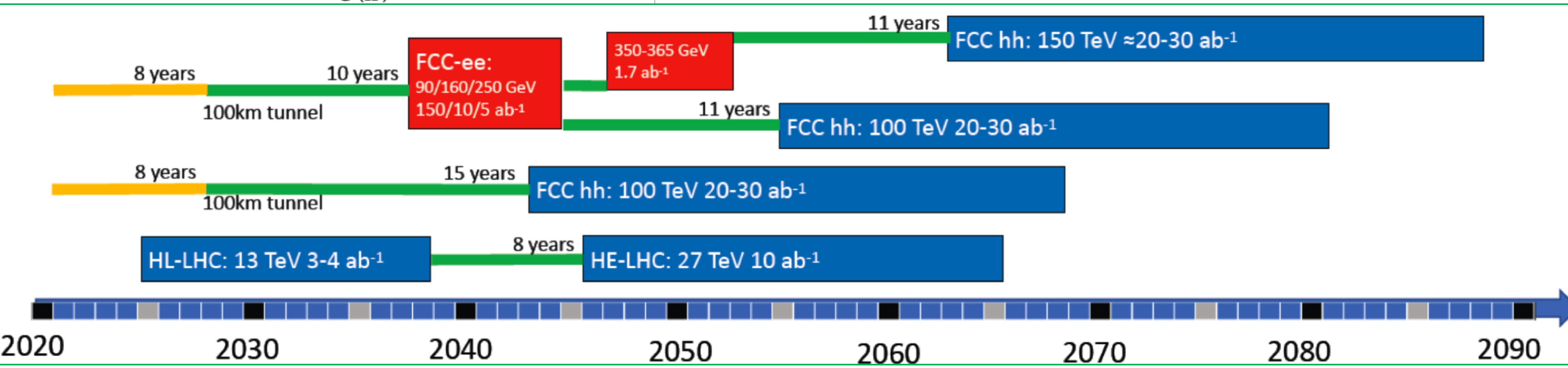
Idea: Use the FCC tunnel first for **e- e+ collisions**, up to 365 GeV (1.7 x LEP energy). Charge adjusted to keep **synchrotron radiation loss at 100 MW** for all energies.
No technological show stoppers. Cost: **total 11.5 BCHF** (+/- 30**%).** FCC magnet development in parallel.



98 km tunnel

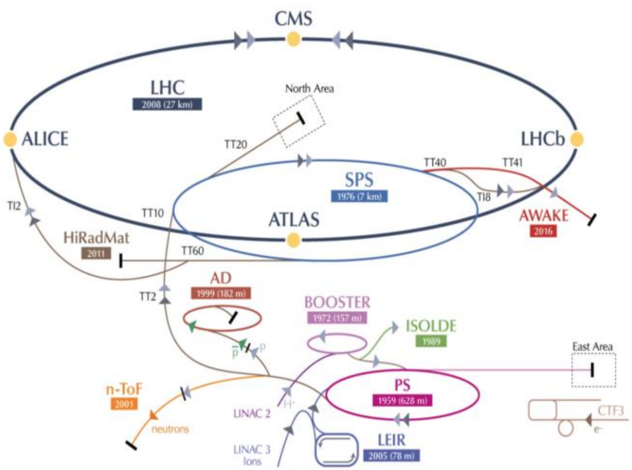
Chinese "FCC" studies

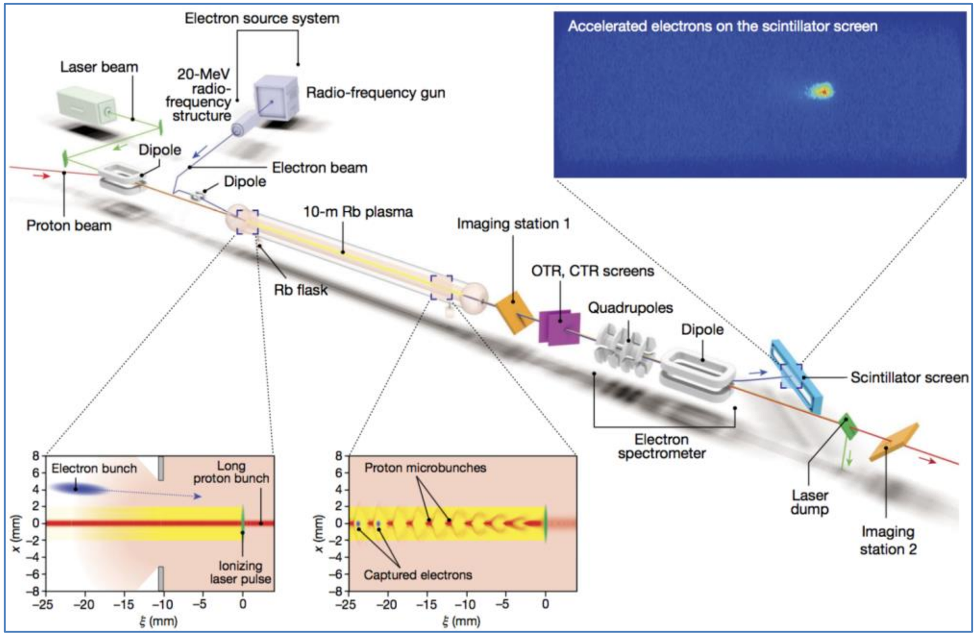
- Chinese has proposed a "FCC-ee" (CEPC) and a "FCC-hh" (SppS), to be built in China (2012)
- Would be very similar to the FCCs
- CEPC CDR finalized (2018)
- Funding not ensured
- Requires international cooperation



AWAKE: proton-driven plasma

Full reuse of the CERN accelerator complex

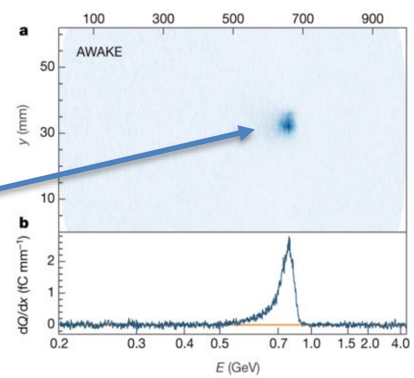


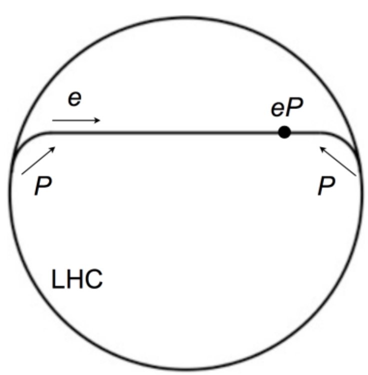


E. Adli et al. (The AWAKE collaboration), Nature 561, 363–367 (2018)

AWAKE is installed at the CNGS beam line. An SPS bunch drives the plasma.

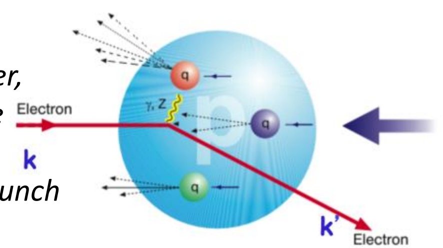
Electrons plasma-accelerated by SPS protons





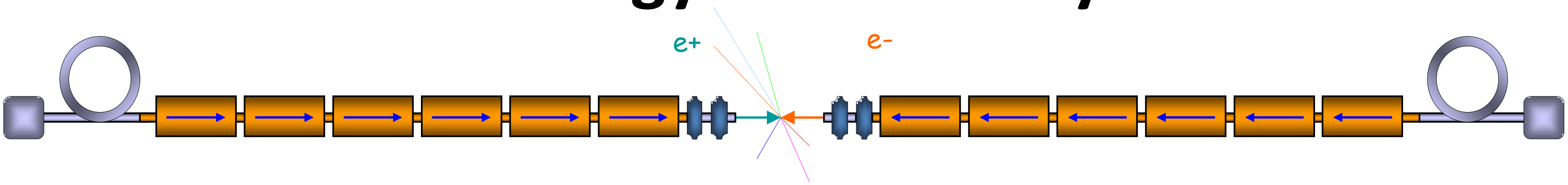
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022ff
Proton and laser beam-line	Study, Design, Procurement, Component preparation		Installation	Commissioning	Data taking RUN 1		Long Shutdown 2 24 months		Data taking RUN 2	
Experimental area	Modification, Civil Engineering and installation; Study, Design, Procurement, Component preparation				Phase 1					
e⁻ source and beam-line	Studies, design		Fabrication	Installation	Commissioning	Phase 2				

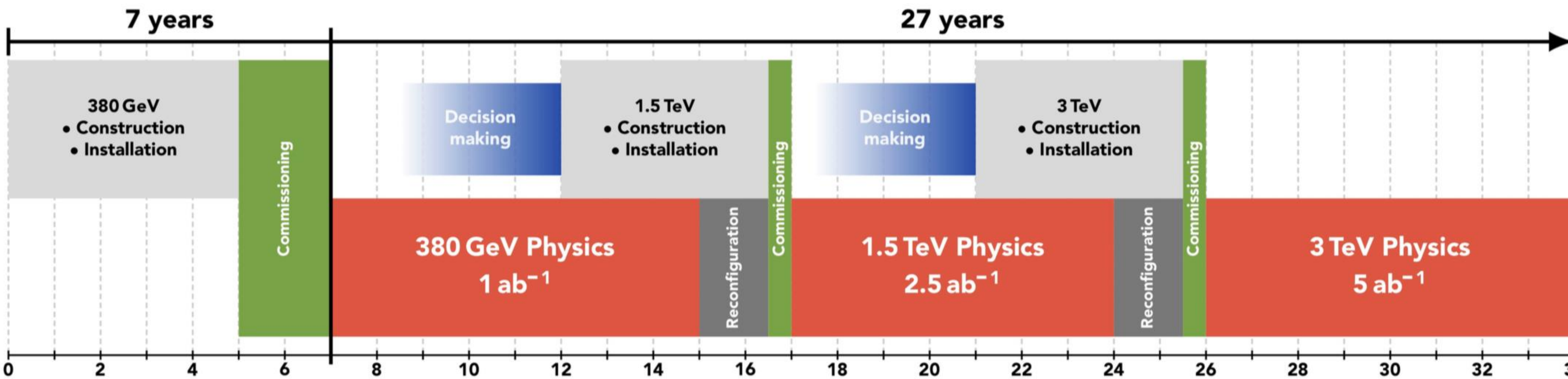
Using an LHC bunch as driver, Multi TeV- electron could be produced in a few km, and collided with another LHC bunch



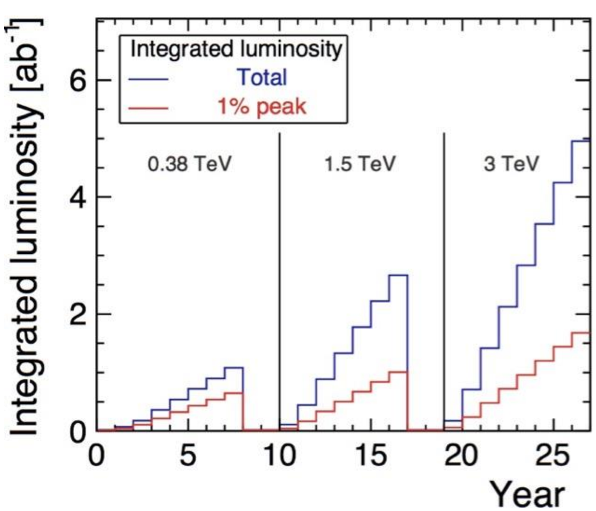
M. Wing, Phil. Trans. R. Soc. A 377: 20180185 (2019)

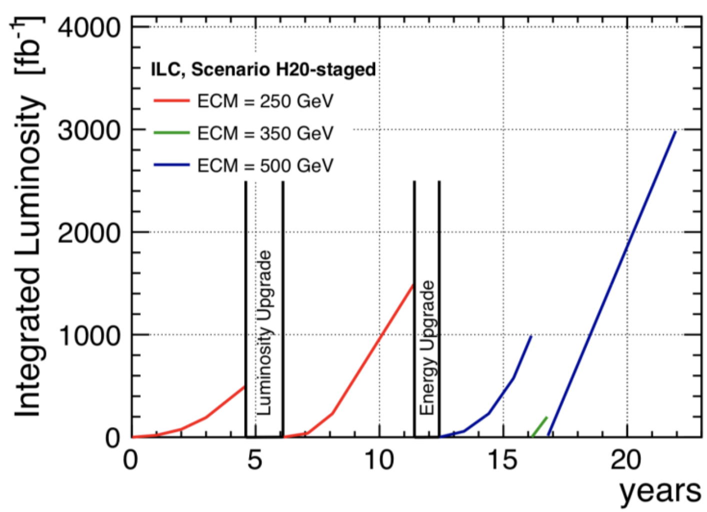
Linear Colliders: energy extendibility



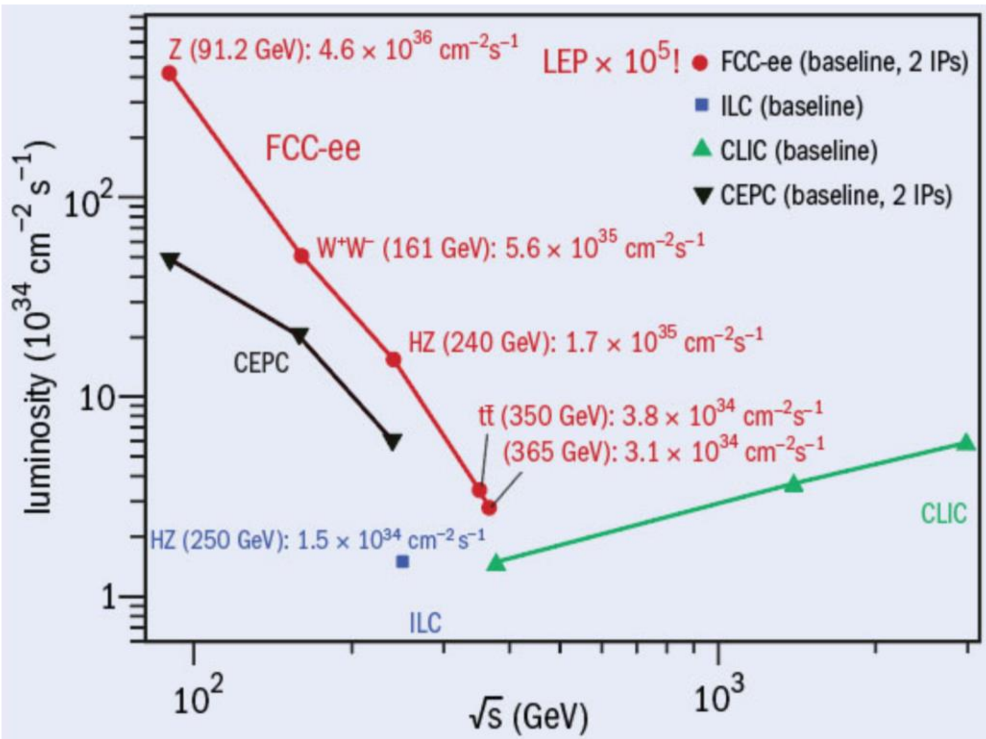


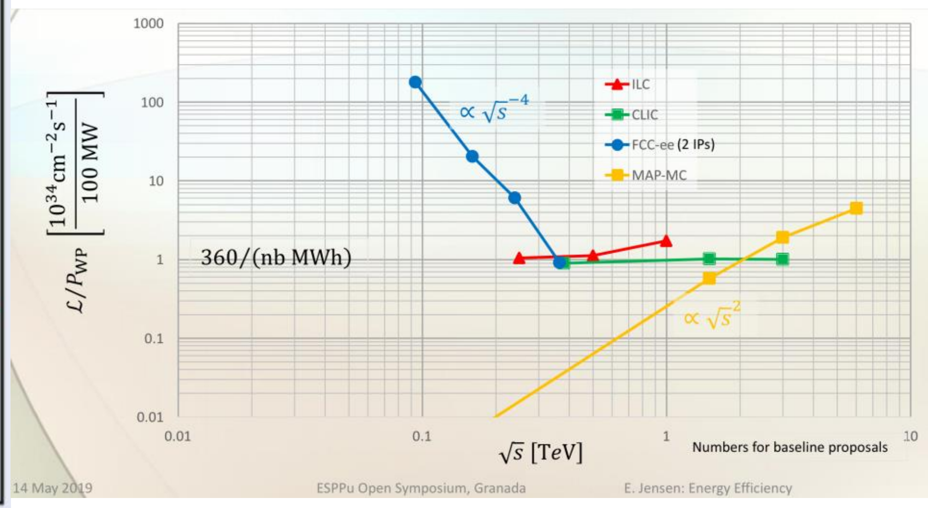
CLIC cost: **5.9 GCHF** (380 GeV) + 5.1 GCHF (1.5 TeV) + 7.3 GCHF (3 TeV) = **18.3 GCHF total**





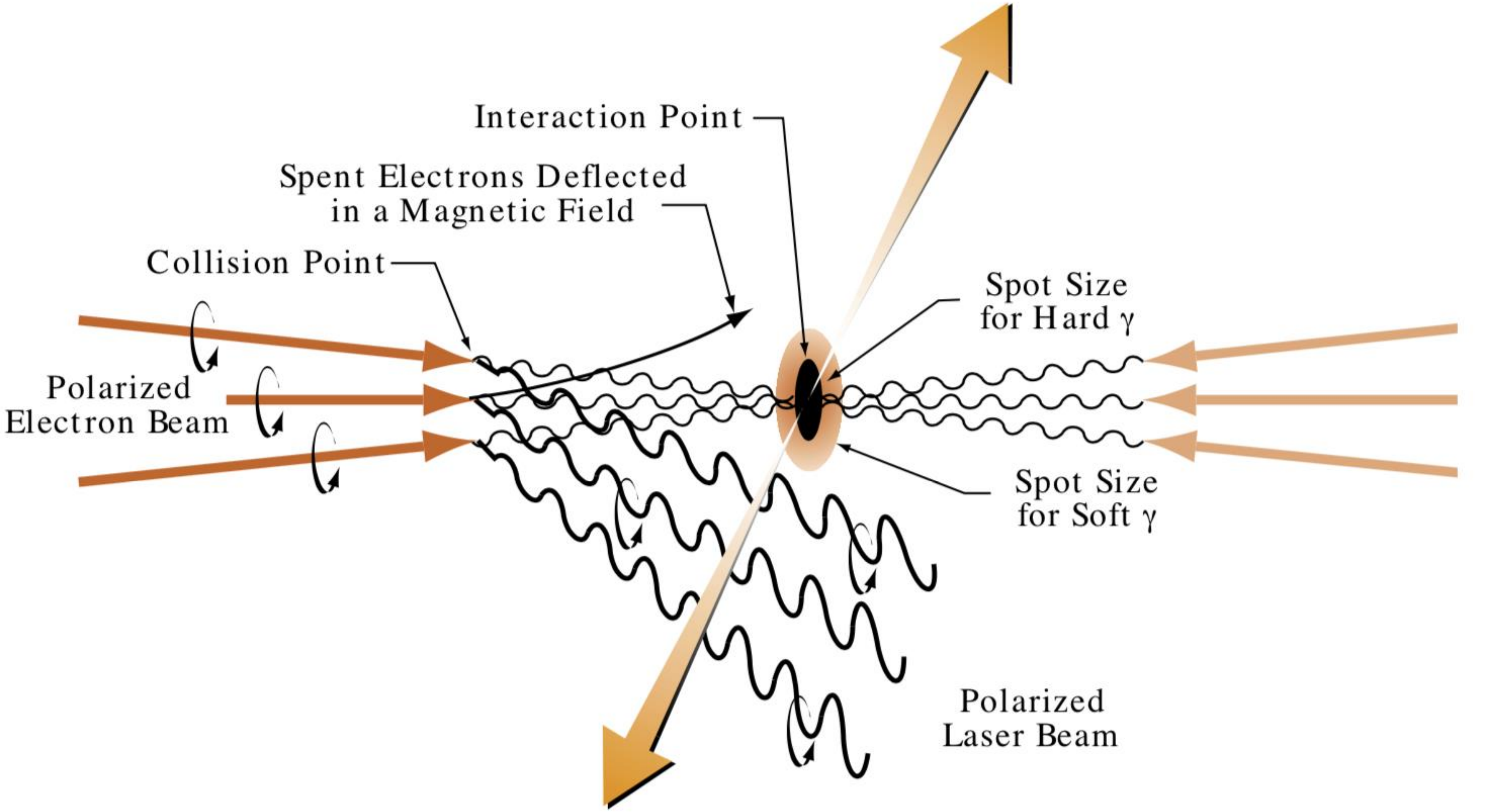
Luminosity, Luminosity per power

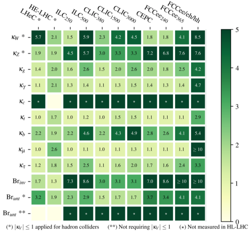




All projects strive towards energy efficiency.

Gamma-gamma collider





arXiv:1905.03764 [hep-ph]

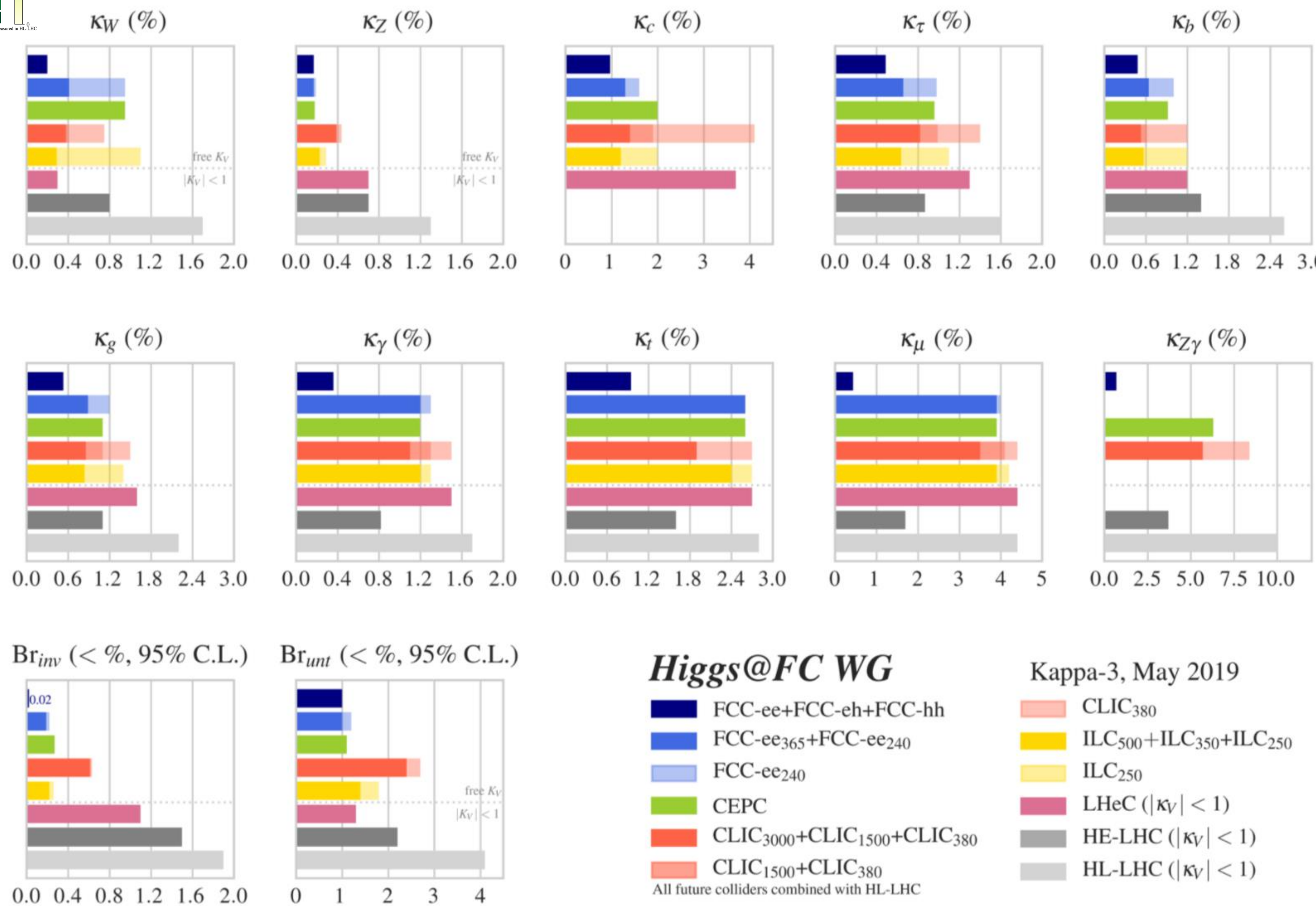
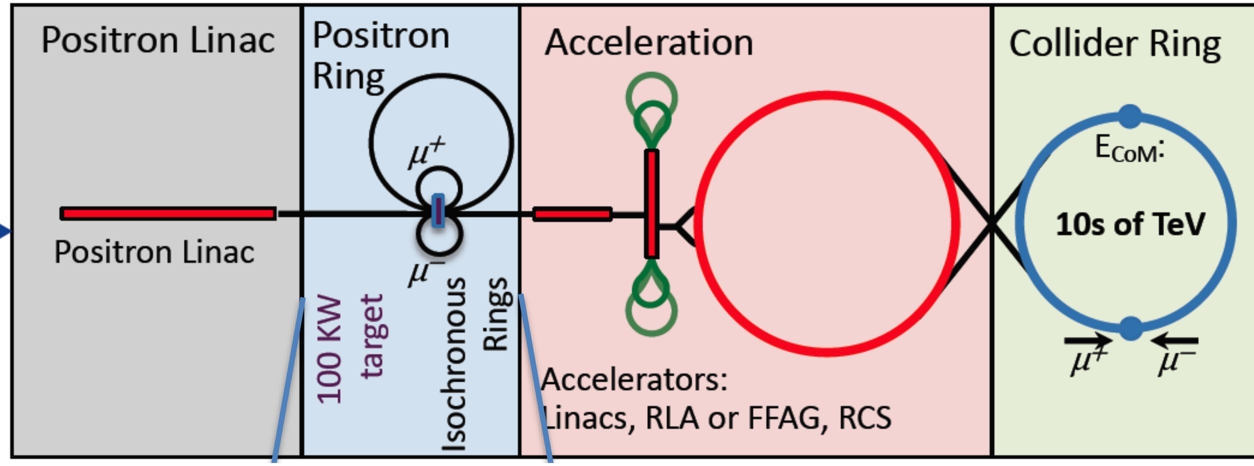


Figure 2. Expected relative precision (%) of the κ parameters in the kappa-3 scenario described in Section 2. For details, see Tables 4 and 5.

The Muon Collider LEMMA Scheme

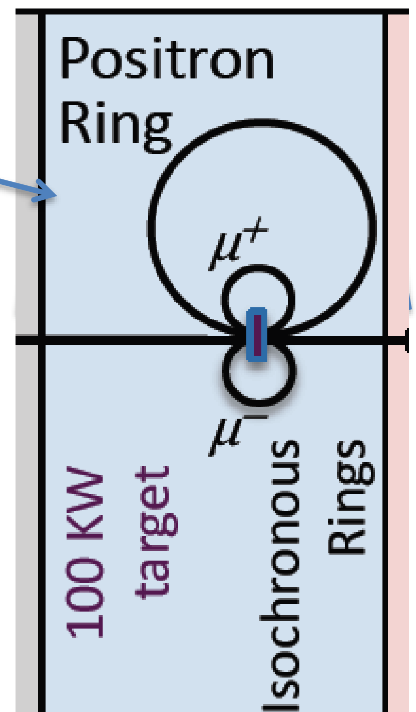
Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Key concept:

Produce muon beam with low emittance using a positron beam

No cooling required



Muon current 10^{11} s^{-1} is 300 times lower compared to 3 x 10^{13} s^{-1} for proton driver

Emittance $O(10^{-3})$ smaller than in proton scheme, 40 ns vs. 25 μm

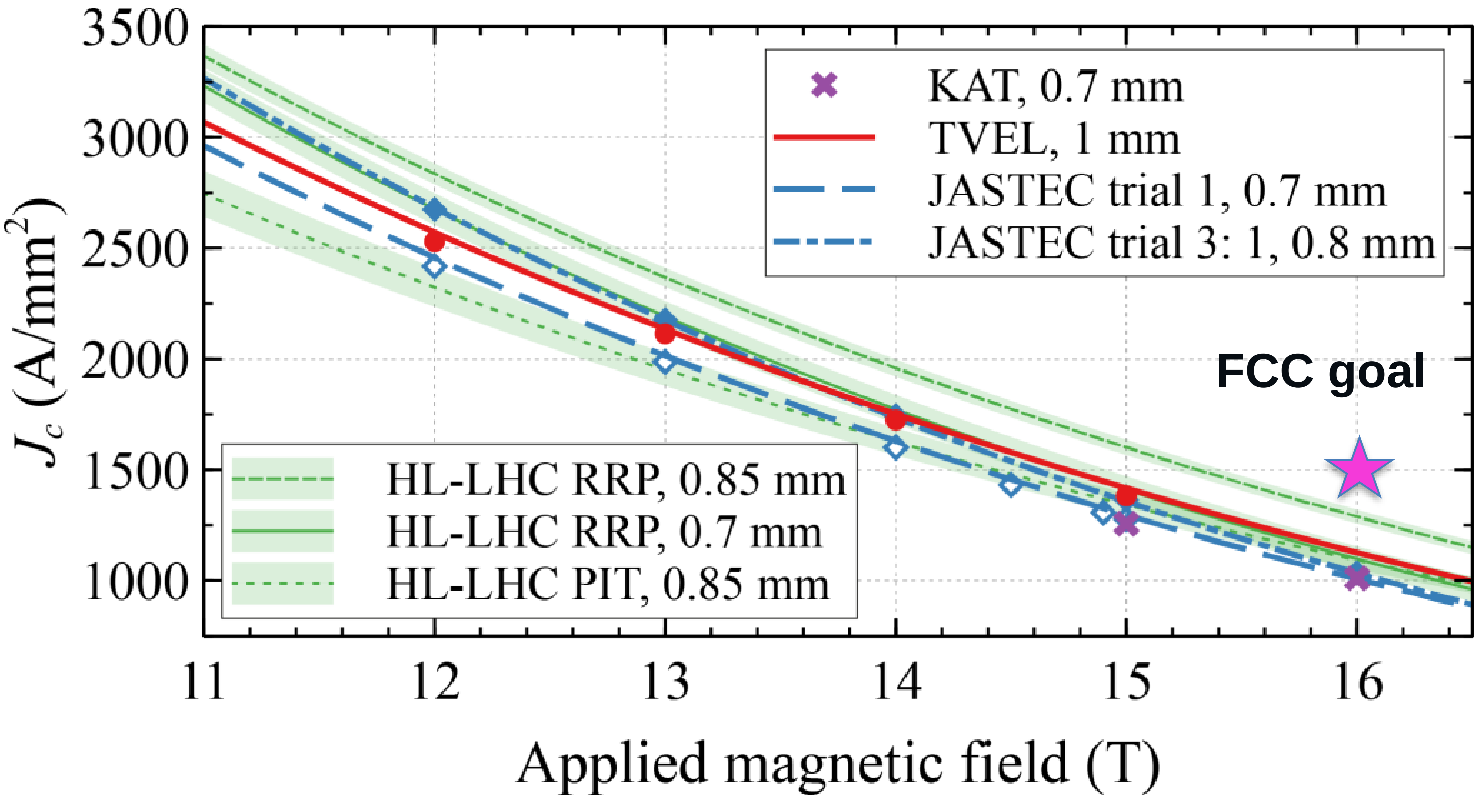
In design of 2018 two important issues were found

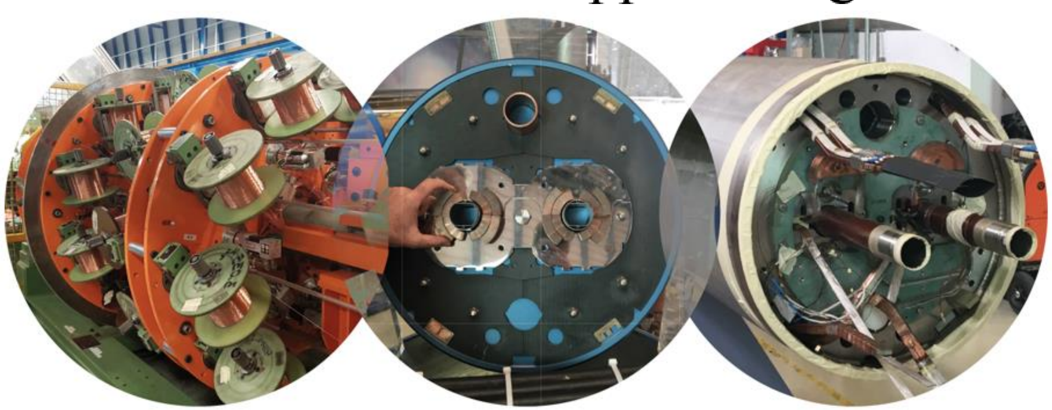
- Muon multiple scattering
- Issue with phase space

Attempt to consolidate is ongoing

⇒ Nadia's talk

FCC magnet developments





- The move from the 8T NbTi LHC magnet, to the 16T Nb^3Sn FCC magnets are considered the **major challenge for FCC-hh**
- Requires many years of intensive R&D