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Future Circular Collider Options

as part of “Past, present, future: LHC and future possibilities”

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ETH Zürich

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After having heard about CLIC: what about circular colliders?

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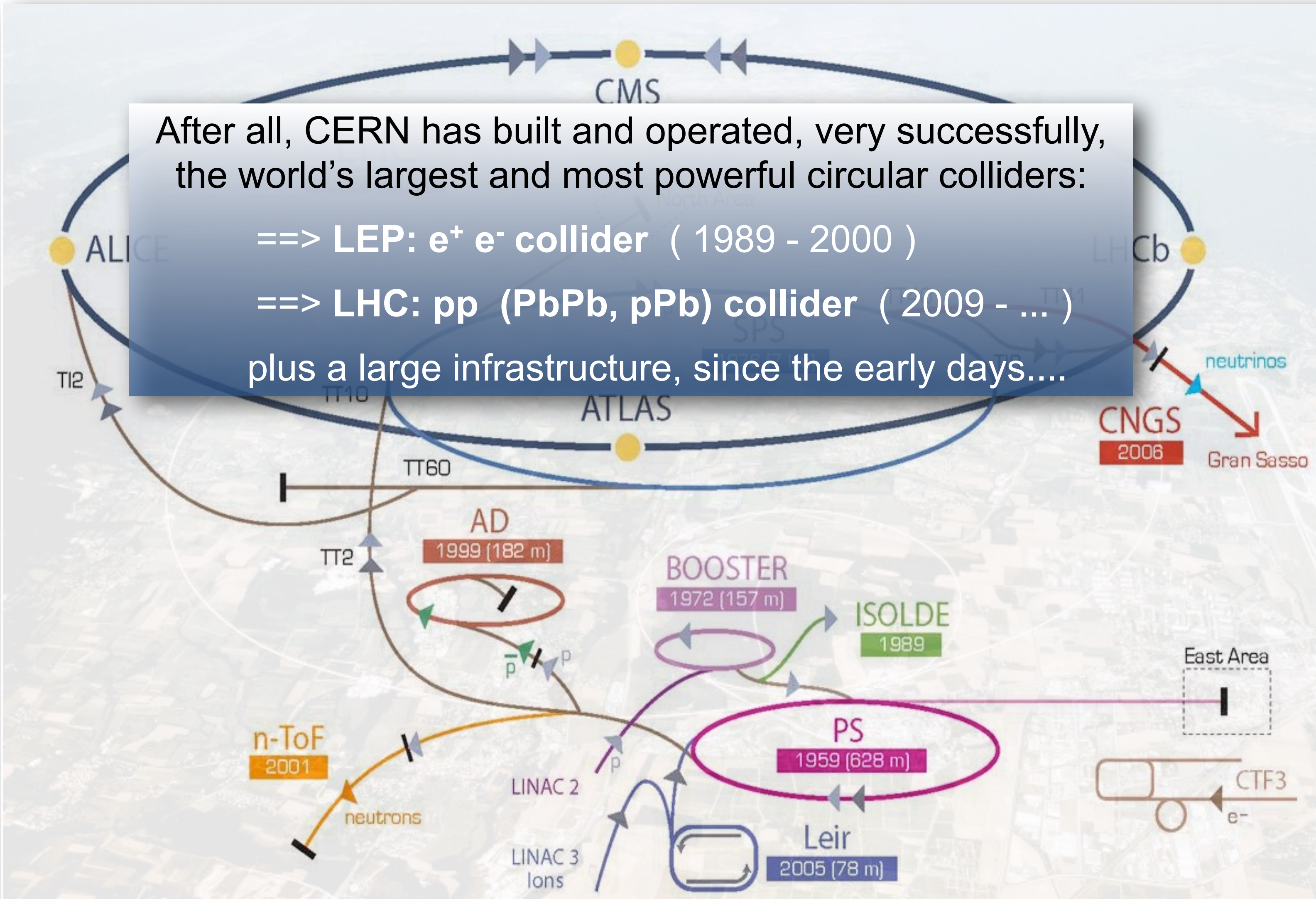
After all, CERN has built and operated, very successfully, the world's largest and most powerful circular colliders:

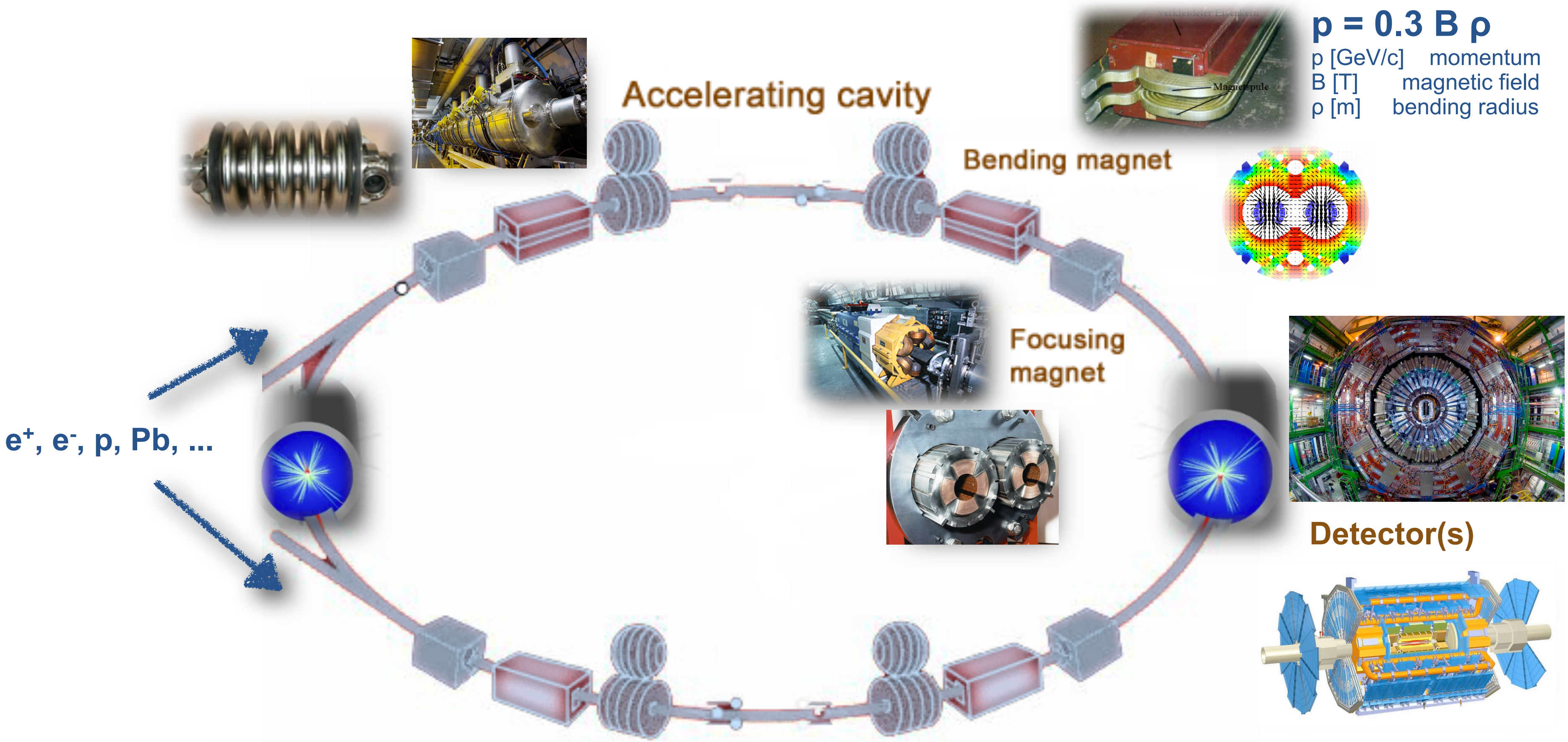
==> **LEP: $e^+ e^-$ collider** (1989 - 2000)

==> **LHC: pp (PbPb, pPb) collider** (2009 - ...)

plus a large infrastructure, since the early days....



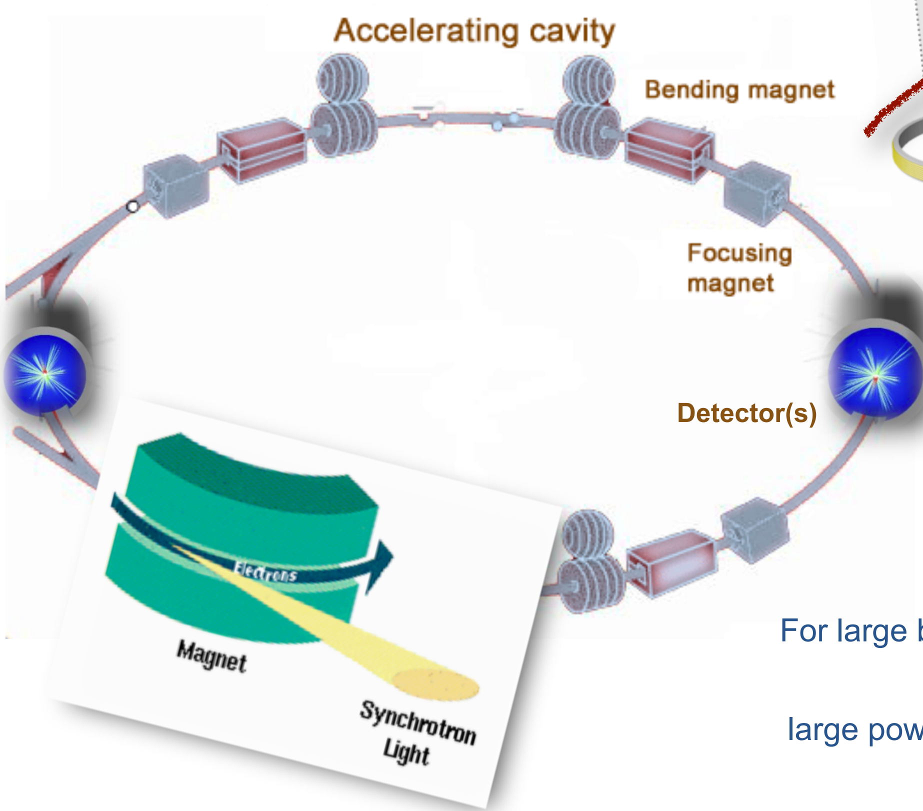
The main elements of a circular collider

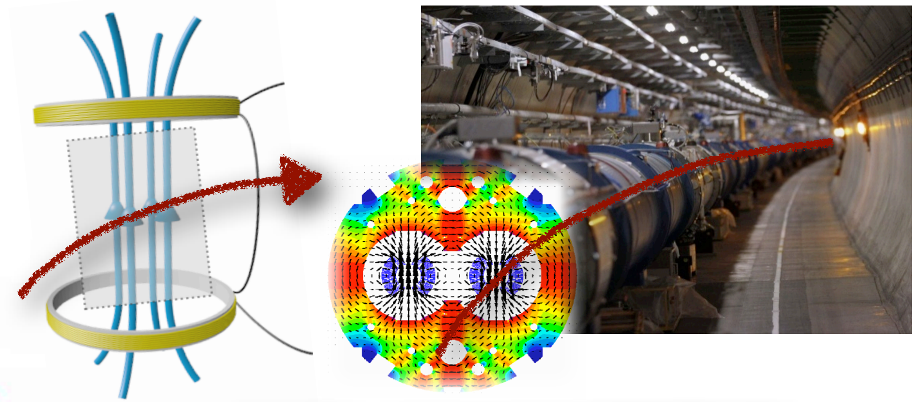


Advantages:

relatively short sections of accelerating RF cavities needed;
several experiments in simultaneous data taking;
beams circulate and collide over many hours; large luminosities.

The challenges





$$\rho \sim \frac{E}{B}$$

$$B \sim I$$

$$P = R I^2$$

For large beam energies : **large bending radius** and/or **magnetic field**!

Magnetic field strength prop. to electrical current;
large power dissipated for large currents; eliminate ohmic resistance ☞

go for superconductors !

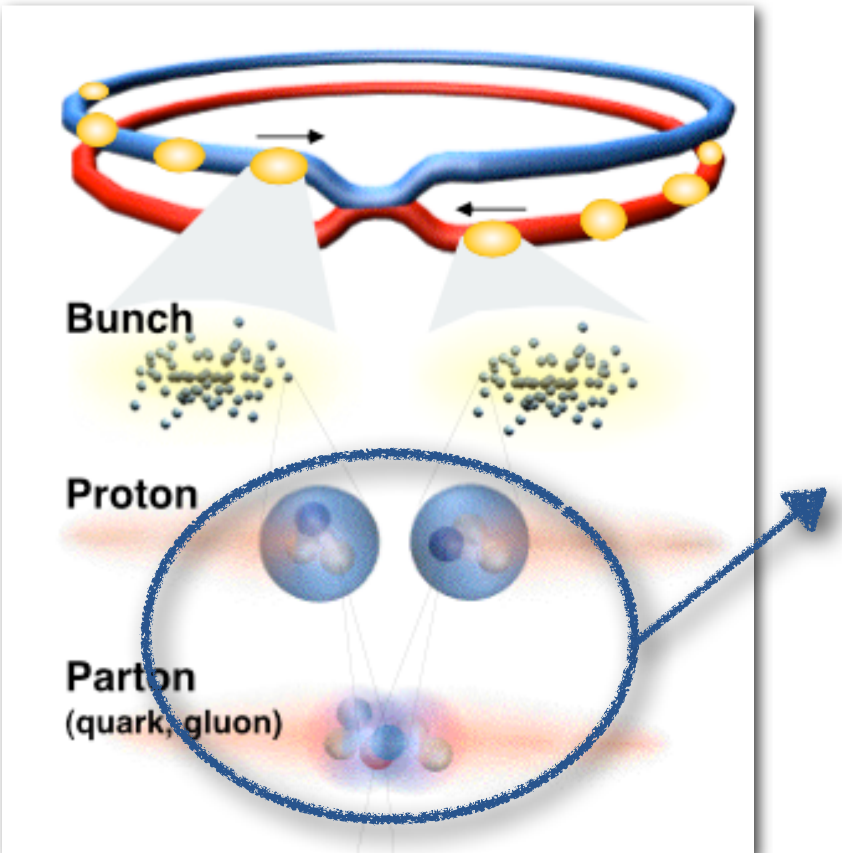
$$\Delta E \sim \frac{1}{\rho}\left(\frac{E}{m}\right)^4$$

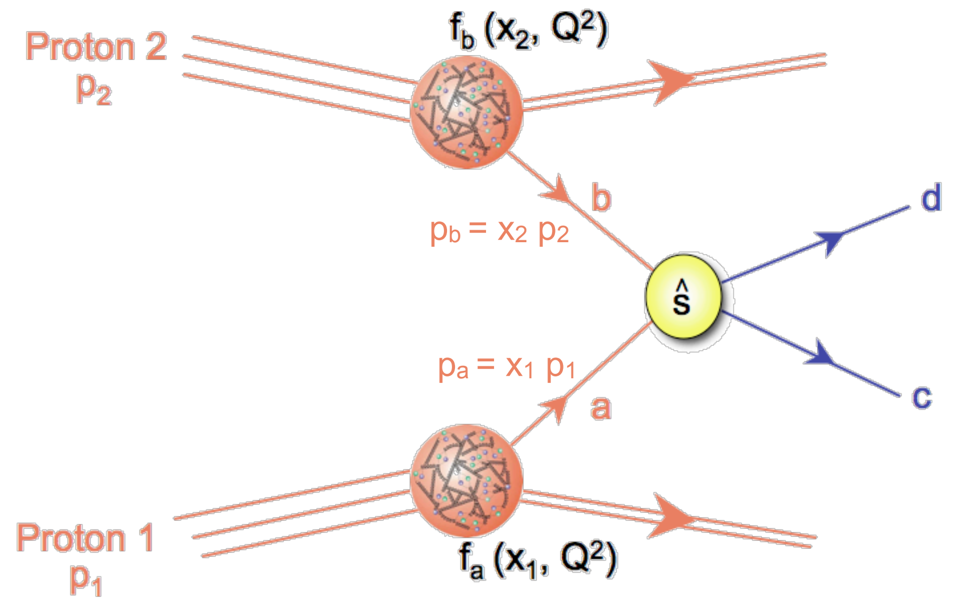
e.g. 3.5 GeV/turn at LEP2

To reduce the lost energy and the "heat load" on the accelerator structures:

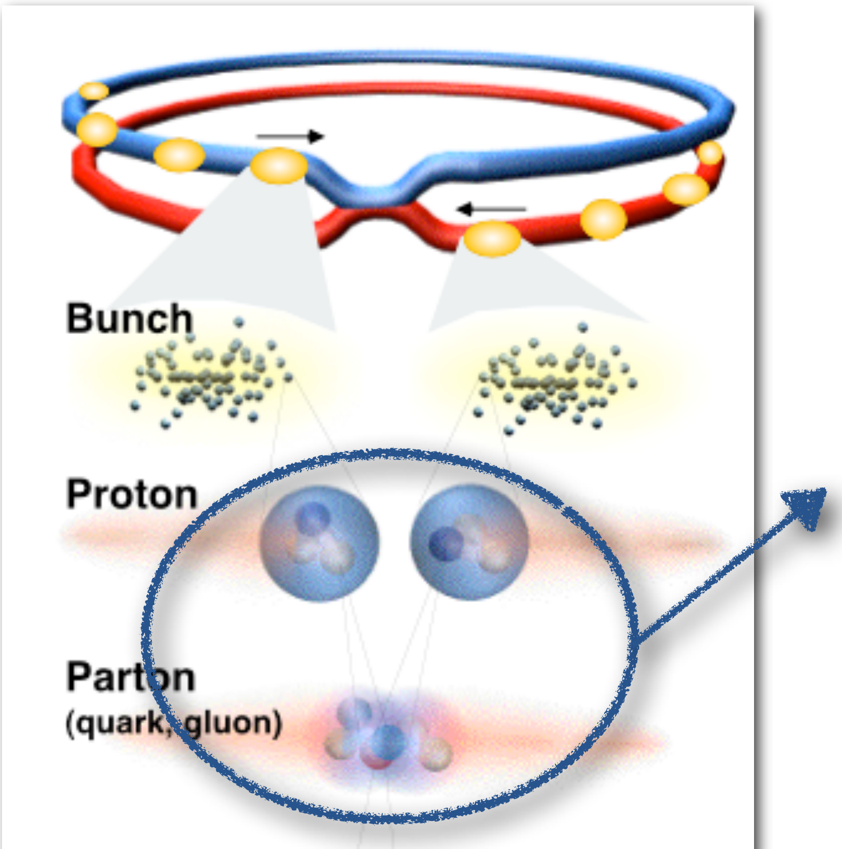
large bending radius and/or **heavy particles** ($m_{proton} \sim 2000\ m_{electron}$)

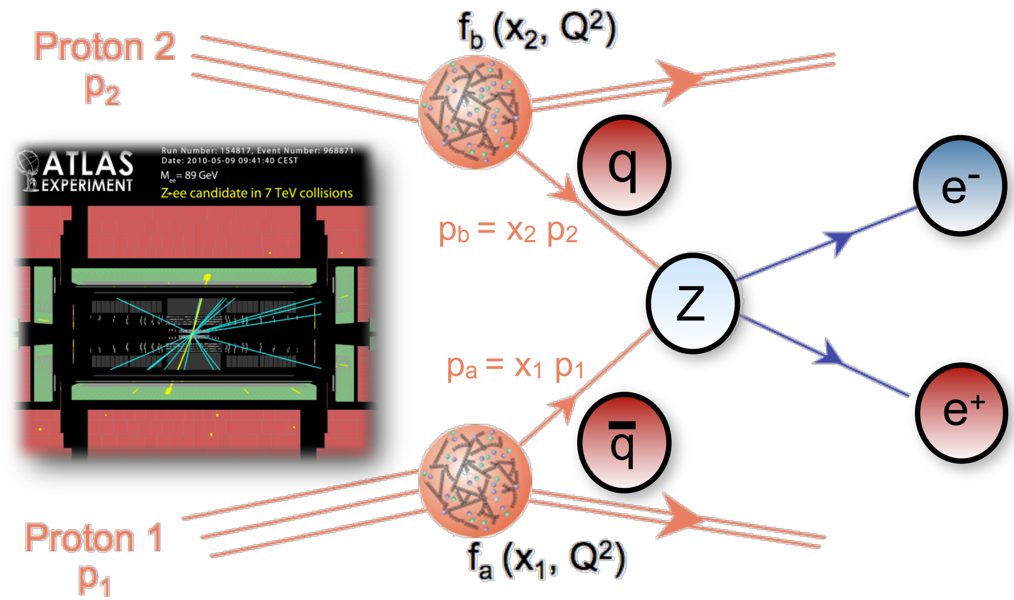
Hadron vs lepton collider: the proton case





Hadron vs lepton collider: the proton case





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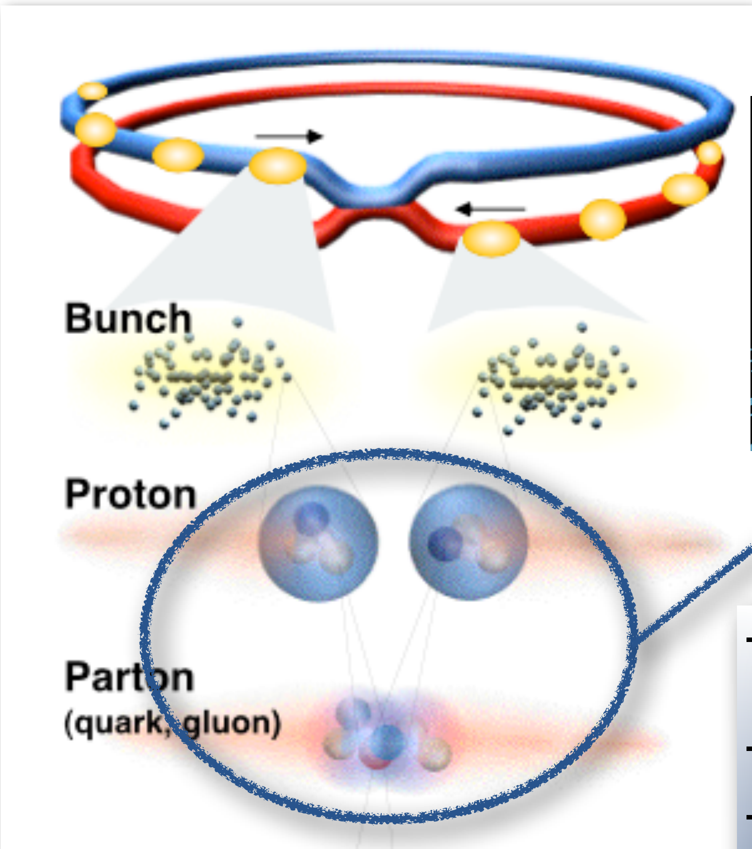
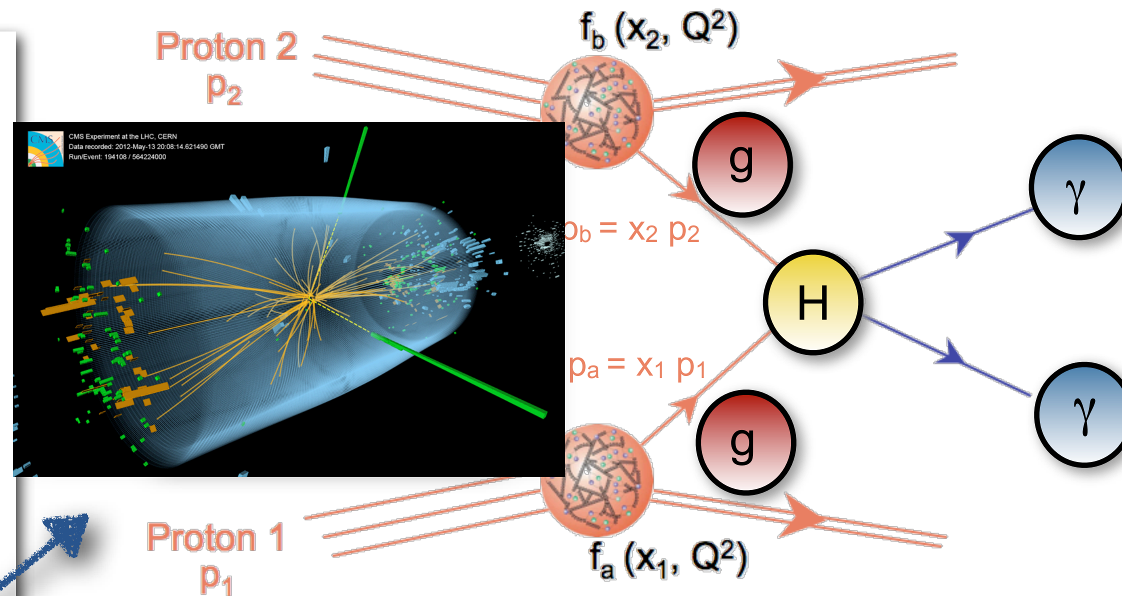




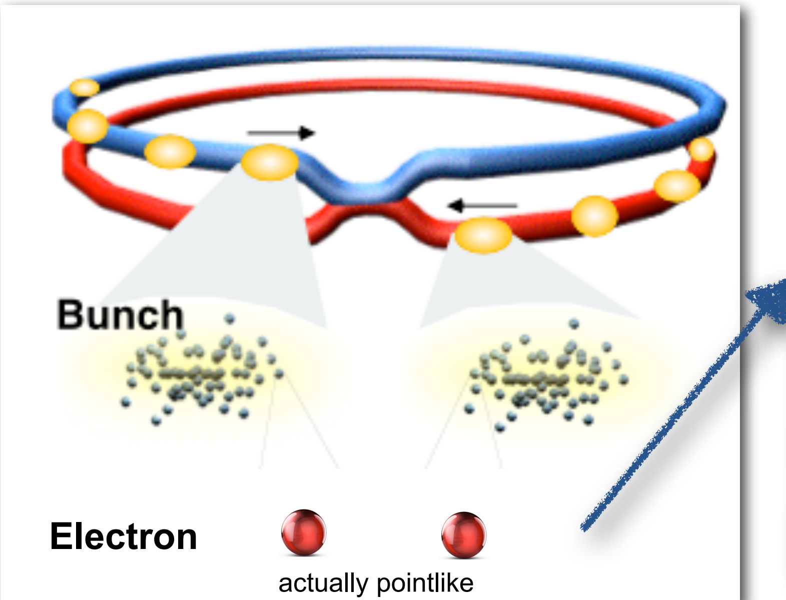
- every collision between partons at a different energy, full kinematics difficult or impossible to reconstruct
- a lot of activity, many particles, lots of radiation at high luminosity
- ratio of “interesting” to “uninteresting” events **very** small → trigger
- proton structure : limits precision of theoretical predictions

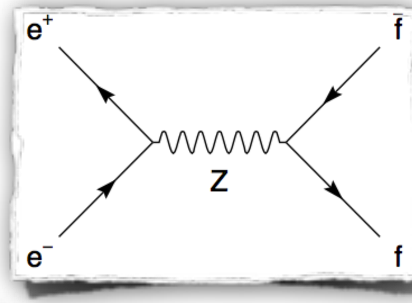
✓ much lower synch. rad. : THE way to reach highest energies

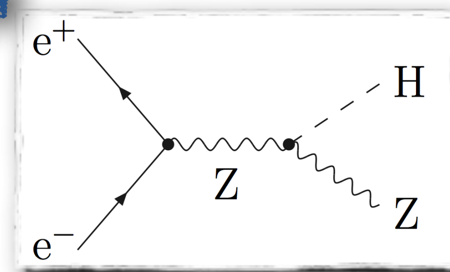
✓ “automatic energy scan” : **good for discoveries**

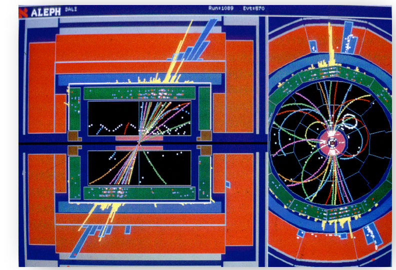
✓ a very large spectrum of different processes accessible

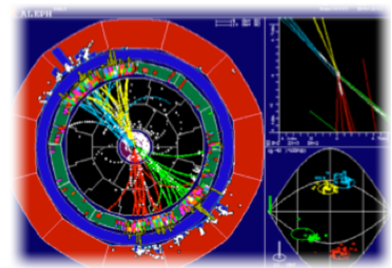
Hadron vs lepton collider: the electron case











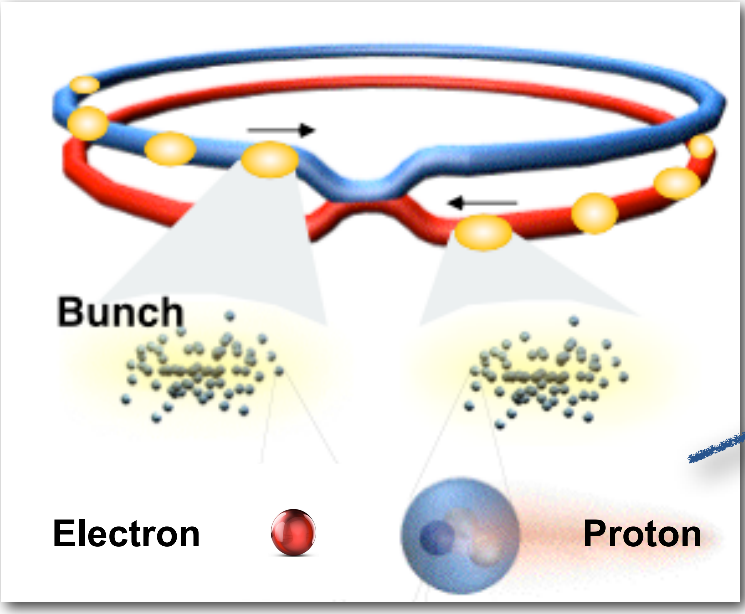
- strong synchrotron radiation limits highest energies achievable
- energy scan only “by hand”, not optimal when searching “into the dark”
- less rich spectrum of accessible processes

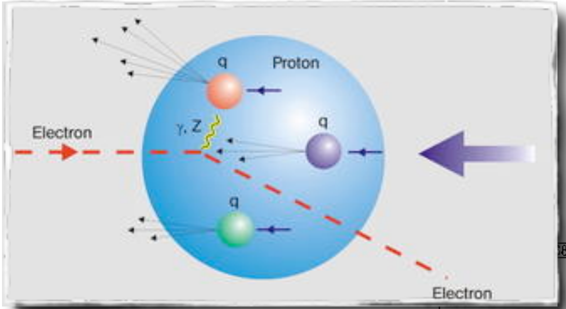
✓ no issue with the particle’s structure : THE way to reach highest precision

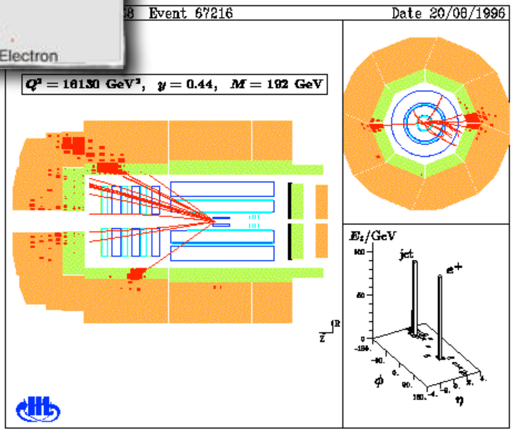
✓ full kinematics well reconstructable; again, excellent for precision studies

✓ “cleaner” events, less activity, less radiation problems for detectors

Hadron vs lepton collider: the mixed case







- requires combination of two different accelerator structures
- requires special, asymmetric, detectors

✓ THE way to study in detail the proton structure

✓ delivers necessary input for describing proton-proton collisions

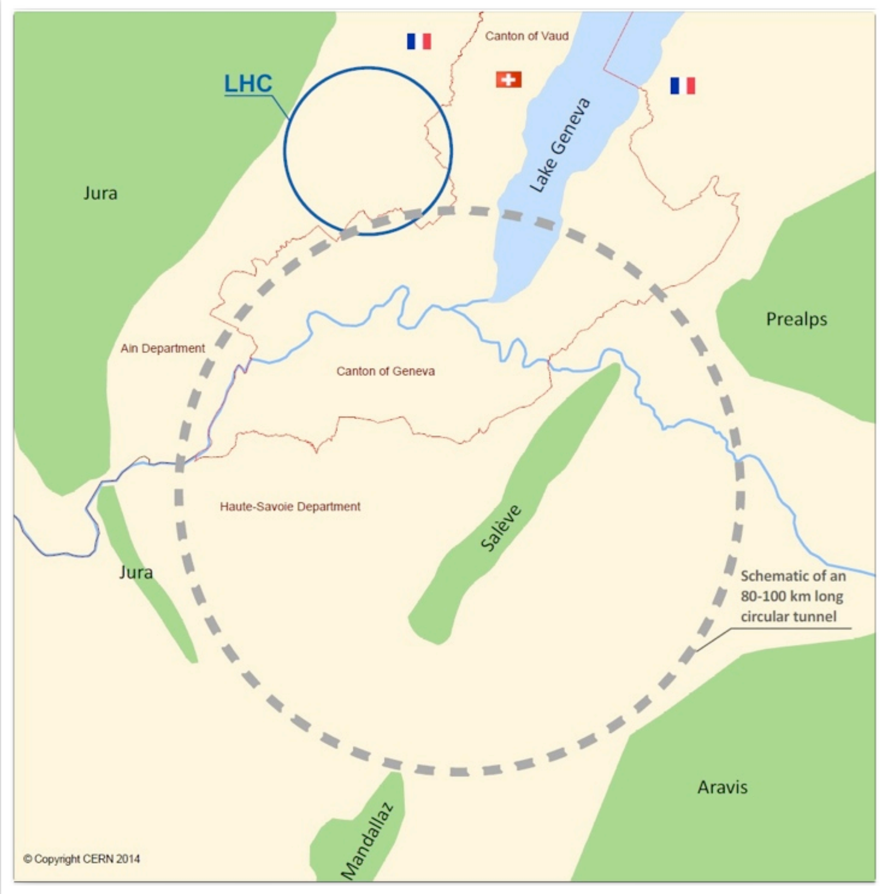
✓ also possible to study certain Higgs processes and to search for new phenomena

Future **C**ircular **C**ollider(s)

FCC motivation: pushing the energy frontier

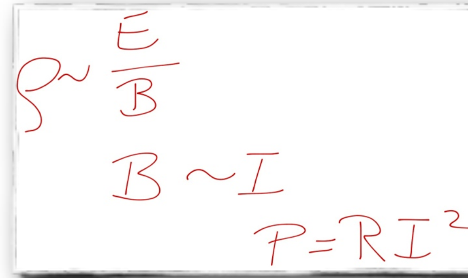
The energy frontier is a high priority within the European Strategy for Particle Physics

- **High-energy pp collider (FCC-hh) as long-term goal**
  - currently only viable approach to reach the 100 TeV range in the coming decades
  - a discovery machine, and a machine to study further the Higgs sector and possible new particles to be discovered at the LHC
- **Lepton collider, e^+e^- (FCC-ee), as potential intermediate step**
  - share part of the infrastructure (cf. LEP → LHC)
  - high luminosity machine
  - perform very-high precision studies of Z and W bosons, top quarks and the Higgs boson; search for new physics in rare decays and rare processes
- **Lepton-hadron collider ep (FCC-he) as option**
  - high precision study of proton structure, Higgs physics, search for new phenomena
- prepare **Conceptual Design Report (CDR)** and cost review for the next European Strategy Update in 2018

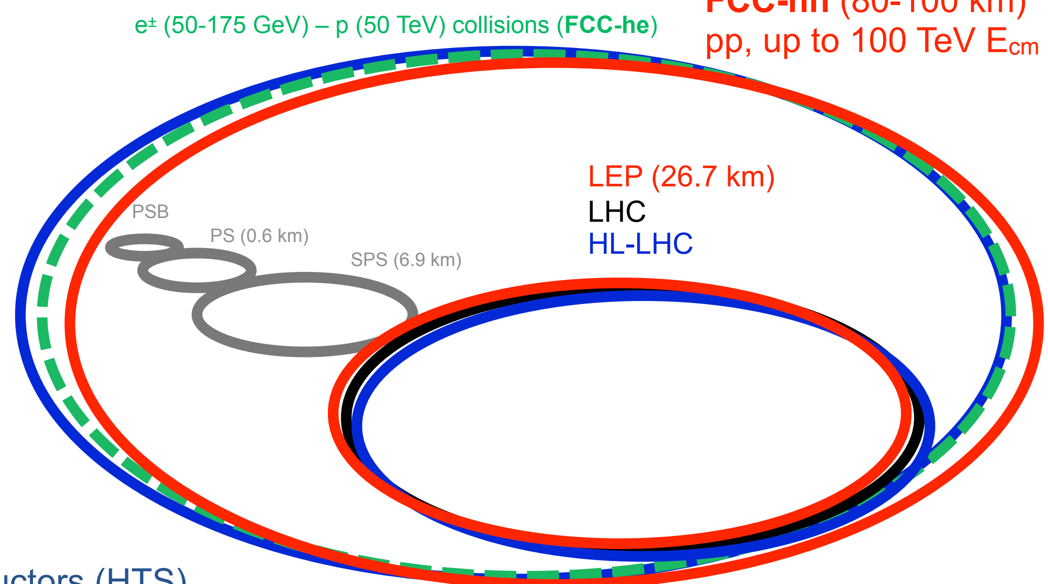


Lead time design & construction > 20 years (cf. LHC)
➡ must start the studies now, to be ready in ~2040

The Rationale



- **How to go to the highest energies?**
  - build a proton-proton collider
  - with available or “achievable” superconducting magnets:
  - **B = 16 (20) Tesla → 100 TeV in a 100 (80) km ring**
  - in the LHC ring, now: B = 8 T for up to 14 TeV and with B = 20 T could reach max. of 33 TeV



- **Put together something that is reasonable**
  - to criticize, improve, guide the design work and identify the challenges
  - **set a baseline**

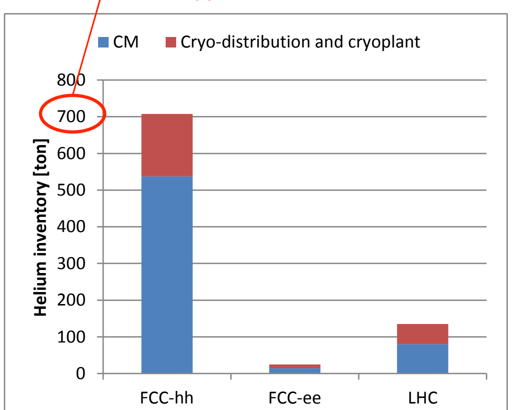
- **Some of the challenges** (see also later)
  - superconducting magnets (also cost driver)
  - 20 T will require High-Temperature Superconductors (HTS)
  - synchrotron radiation
    - large heat load
    - large overall power consumption

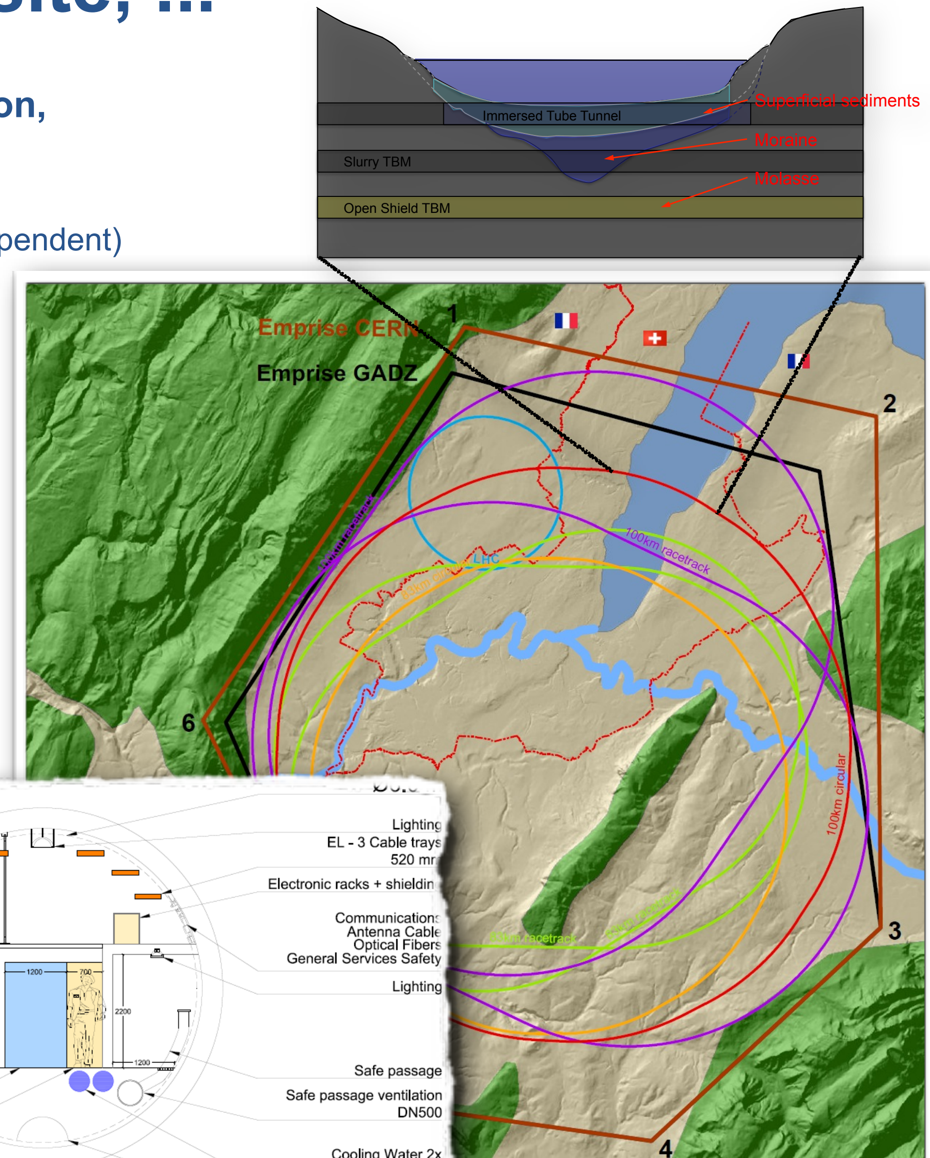
energy per proton beam
LHC: 0.4 GJ → *FCC-hh*: 8 GJ (20x more !)
– kinetic energy of Airbus A380 at 720 km/h
– can melt 12 tons of copper, or drill a 300-m long hole

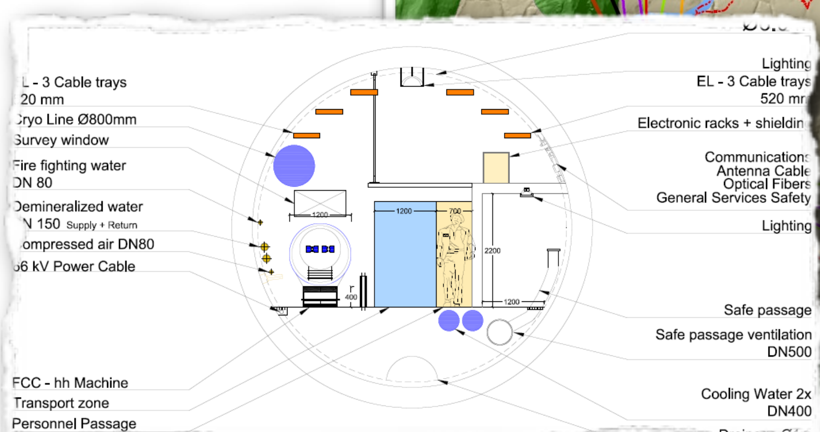
Geology, infrastructure, site, ...

- **Work has started on FCC Infrastructure & Operation, in liaison with accelerator design and technology**
  - siting studies, based on geology, hydrology, topography
  - accelerator geometry, arc design (magnet performance dependent)
  - tunnel layout, tunneling options
  - insertion layouts
    (where to put experiments, RF cavities, beam dumps, ...)
  - novel safety aspects (large size of the machine)
  - power, energy, electrical distribution
  - cryogenics systems

~ 12 % of EU annual market
~ 2.5 % of annual world market





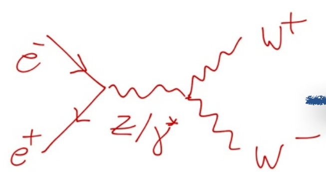


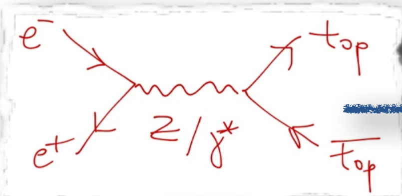
FCC-ee : an intermediate step

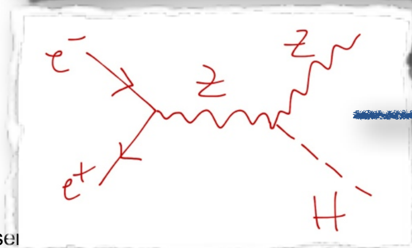
- use the infrastructure, in particular the large tunnel, prior to the installation of the FCC-hh, to construct an e^+e^- collider for **high-precision studies** (remember: LEP → LHC)

- **Physics potential:**

produced at LEP1 and LEP2







Beam energy [GeV]	Nr. of evts/year
45	10^{12} at LEP: $2\text{x}10^7$
80	10^8 at LEP2: $4\text{x}10^4$
175	$5 \text{ x } 10^5$
120	$5 \text{ x } 10^5$

repeat the LEP1 programme every 15 mins

Z physics with **250x** smaller stat. errors

indirectly probe new physics effects up to the **100 TeV** scale,ie. **$2\text{x}10^{-21}$ m** ! (10^{-19}m now at LHC); or look directly for new effects in rare decays.

$2\text{x}10^6$ top pairs after 4-5 years!

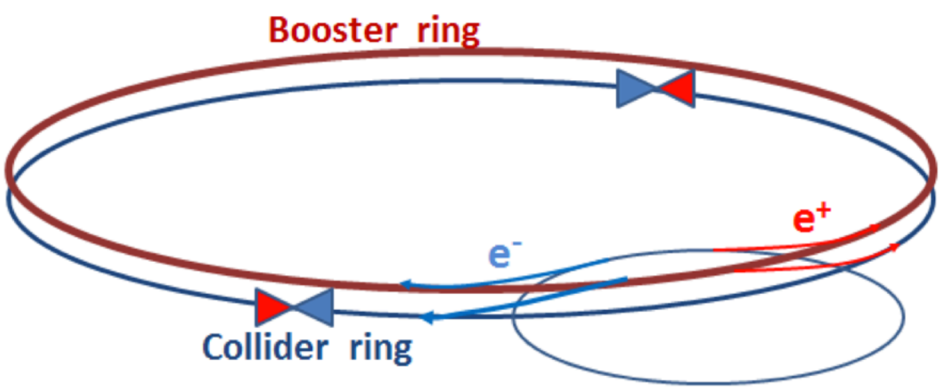
measure **Higgs couplings** with **sub-% prec** ! indirect sensitivity to new physics

$2\text{x}10^6$ Higgs events after 4-5 years!

FCC-ee : some of the challenges

- remember: a circular lepton collider is limited by the power lost due to synchrotron radiation
- design choice: max. synchrotron radiation power set to **50 MW/beam** !

- at these very high luminosities:
  very short beam lifetime
  - **top-up injection**
    - single injector booster in the collider tunnel, in addition to two-ring layout

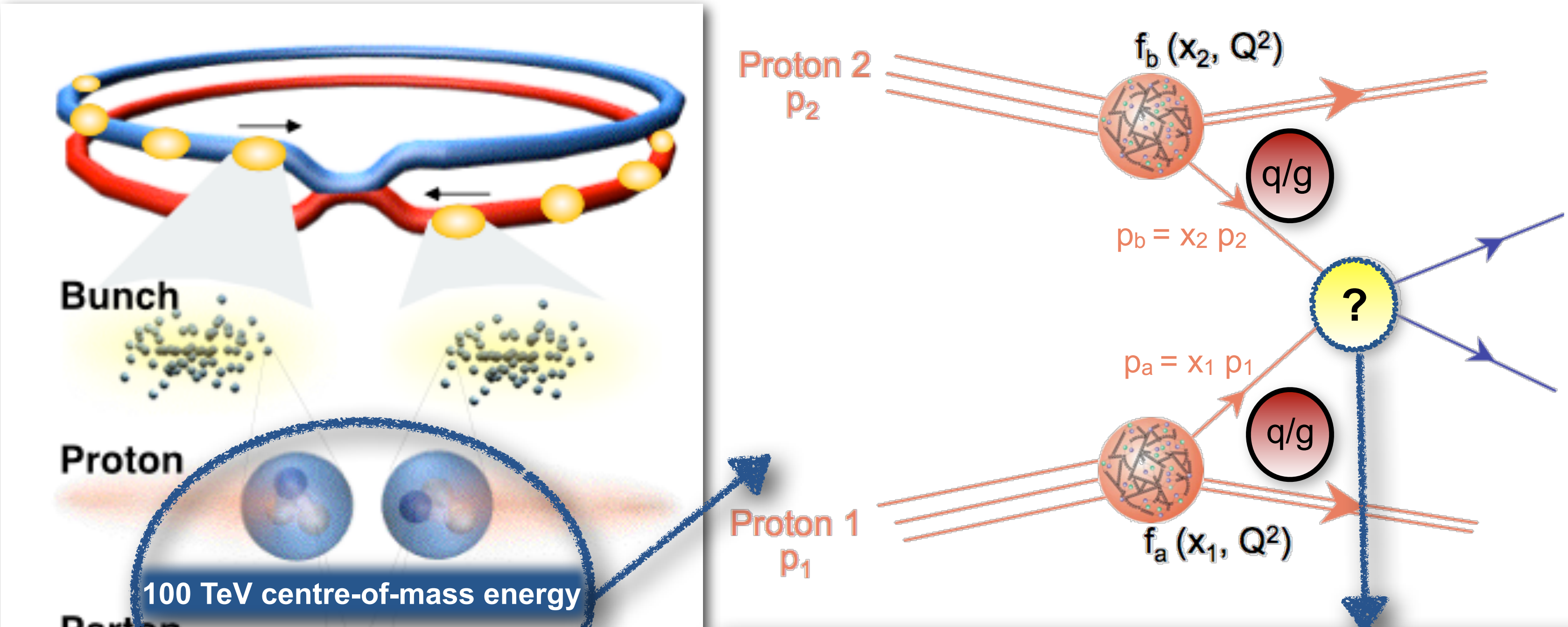


- **beam polarization** for high-precision energy calibration, with long polarization times (Z pole: ~200 hours; WW threshold ~10 hours)

- **important expertise available** worldwide from lower-energies e^+e^- colliders, **synergies** possible

- inject (top-up) every 10 seconds
- by-passing of experiments?

FCC-hh: physics potential



- ✓ directly discover new particles/physics up to mass scales of **30** (Z') - **50 TeV** (excited quarks) (**~ 5-10 x LHC reach**)
- ✓ eg. a new heavy Z' or W' boson, up to 30-40 TeV mass !
  → possibly probing interactions 10^{-10} times weaker than the known weak interactions!
- ✓ probe **substructure of particles to ~10^{-20} m - 10^{-21} m** (**~ 10 x smaller** than testable at the LHC)
- ✓ study self-interaction of the Higgs field (difficult at the HL-LHC)

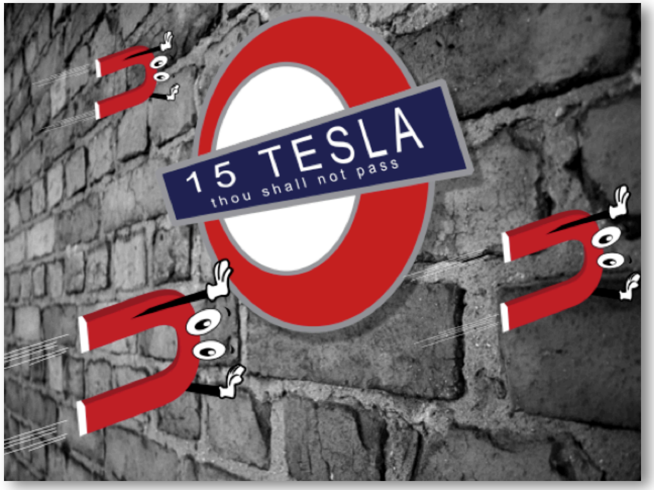
FCC-hh : the ultimate goal

- some current design parameters and related challenges....

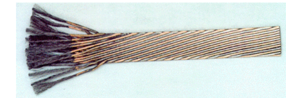
	LHC	HL-LHC	FCC-hh
Center-of-Mass Energy [TeV]	14	14	**100**
Luminosity [10^{34} cm^{-2} s^{-1}]	1	5	≥5
Dipole Field [Tesla]	8.33	8.33	**16 (20)** R&D on SC magnets
Total length [km]	26.7	26.7	**100 (83)** infrastructure, tunnel (3.7 x bending radius)
Energy loss per turn [MeV] $\Delta E \sim \frac{1}{\rho}\left(\frac{E}{m}\right)^4$	0.007	0.007	**4.6 (5.9)** the proton is a "light" particle at such energies...
Total synch. rad. power [MW]	0.0072	0.0146	**4.8 (5.8)** heat load on magnets, total wall plug power (~several 100 MW?)

values in brackets for 20 T magnetic field

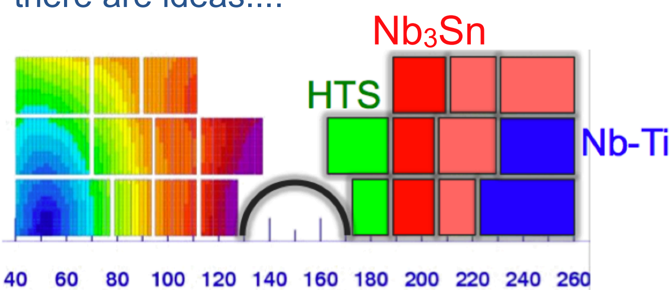
Superconducting Magnets R&D



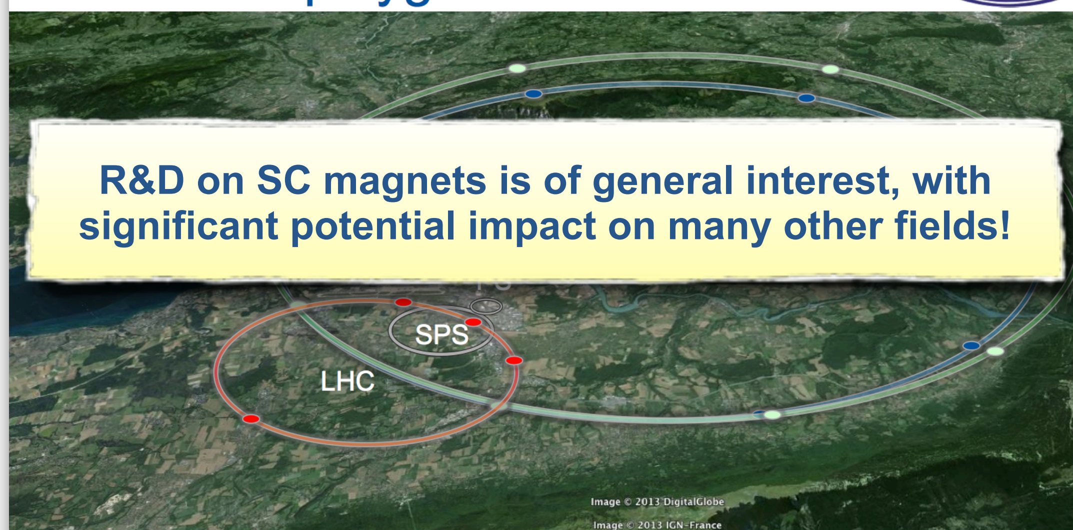
- now in LHC: NbTi - limit at 9-10 T
- **with Nb_3Sn: 16 T appears reachable**
- **but**: with realistic bores (eg. 40mm aperture), at an acceptable cost, large quantity and quality?
  - Needs **int. R&D** in the coming years/decades
- Note: first Nb_3Sn magnets planned already for HL-LHC



- **20 T** : requires **High-Temperature Superconductors (HTS)**
- "even more" R&D
- there are ideas....



The FCC playground

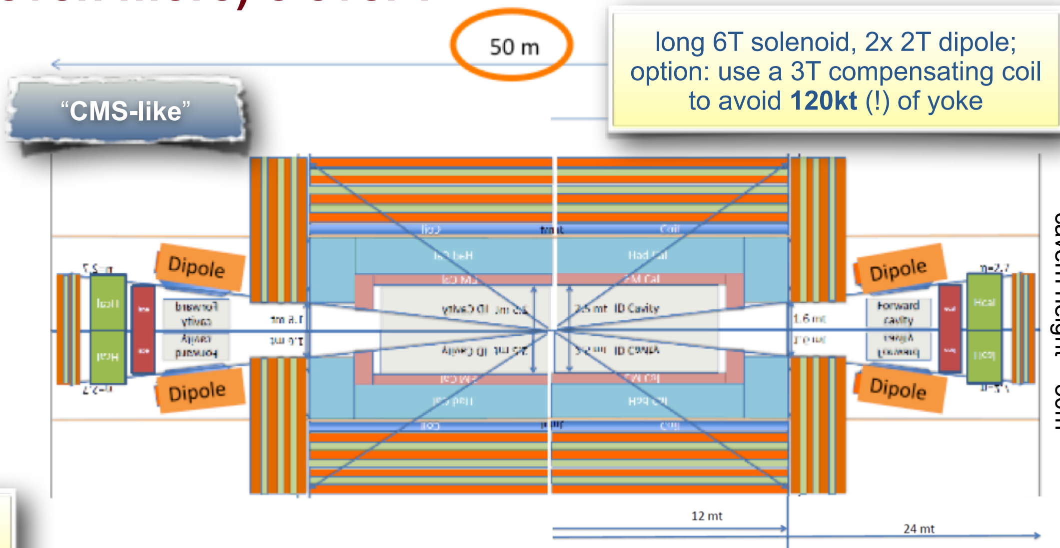


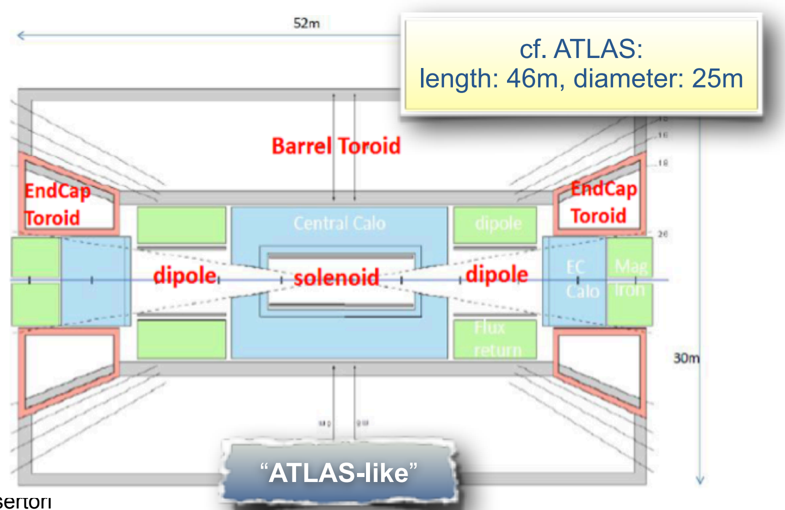
LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	3000 tons LTS 700 tons HTS	9000 tons LTS 2000 tons HTS	6000 tons Nb_3Sn 3000 tons Nb-Ti

FCC-hh : Detectors and related challenges

- compared to the LHC detectors (already “non-trivial”), the FCC-hh detectors represent formidable challenges
- In short: **bigger, thicker, faster, (even more) clever !**

- **thicker calorimeters**
  to contain high energetic jets
- **larger angular coverage**,
  especially for Higgs studies
- **high granularity**
- might have to be **very fast**,
  in case a 5ns bunch separation chosen
- need to measure **muons up to 10-20 TeV**





- experimental cavern and maintenance....
- **radiation**: About 100kW of hadron power around each experiment
  - about 45 times LHC, 8 times that of HL-LHC

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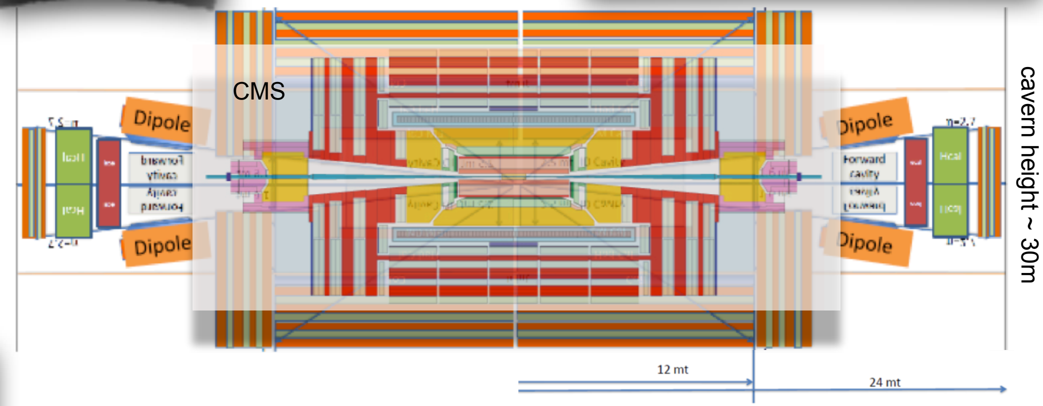
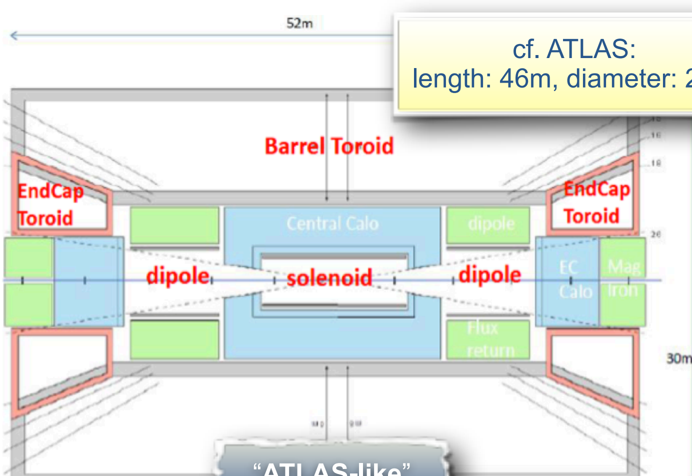
50 m

“CMS-like”

long 6T solenoid, 2x 2T dipole;
option: use a 3T compensating coil
to avoid **120kt** (!) of yoke



cf. ATLAS:
length: 46m, diameter: 25m

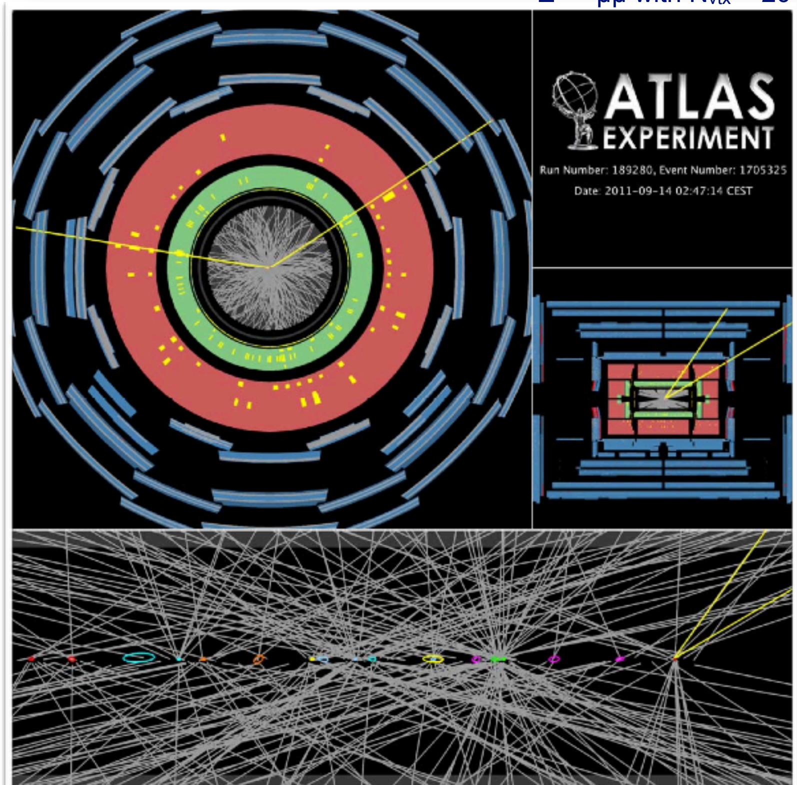


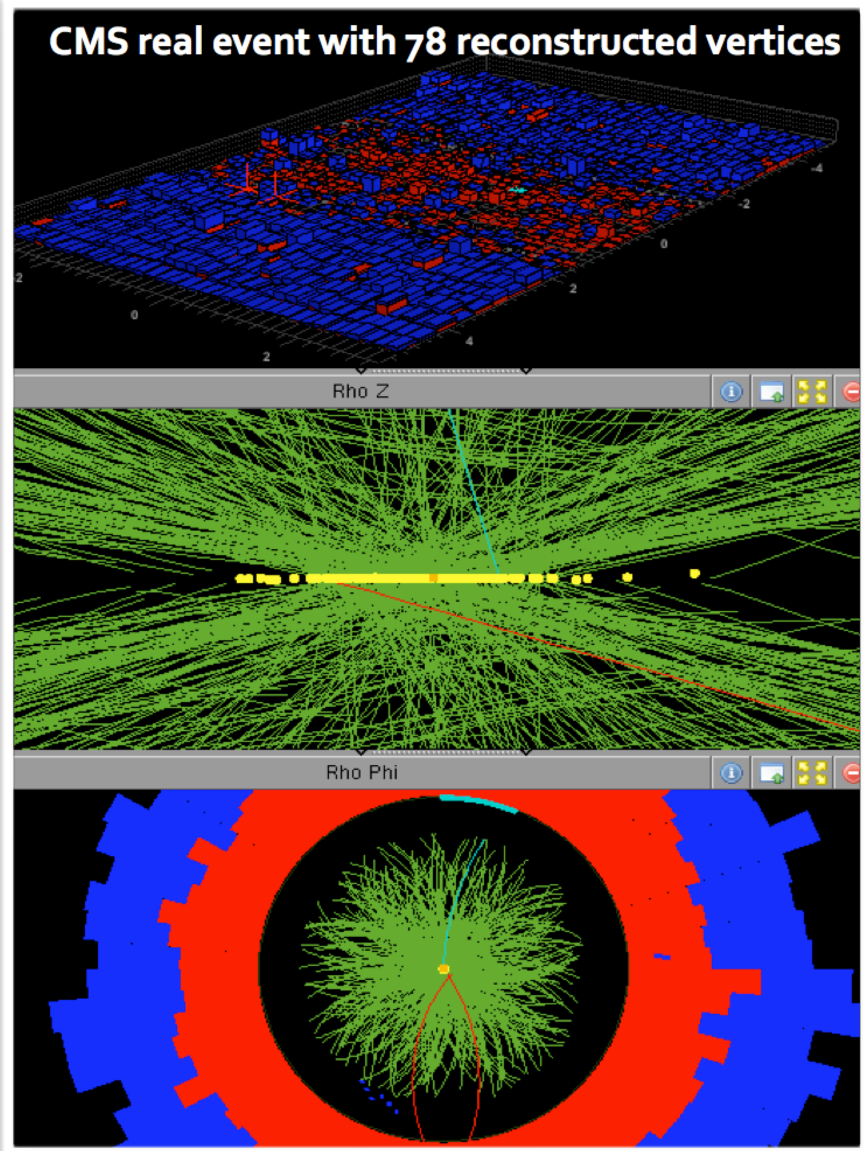
“ATLAS-like”

- experimental cavern and maintenance....
- **radiation**: About 100kW of hadron power around each experiment
  - about 45 times LHC, 8 times that of HL-LHC

Pile-Up !

$Z \to \mu\mu$ with $N_{vtx} = 20$

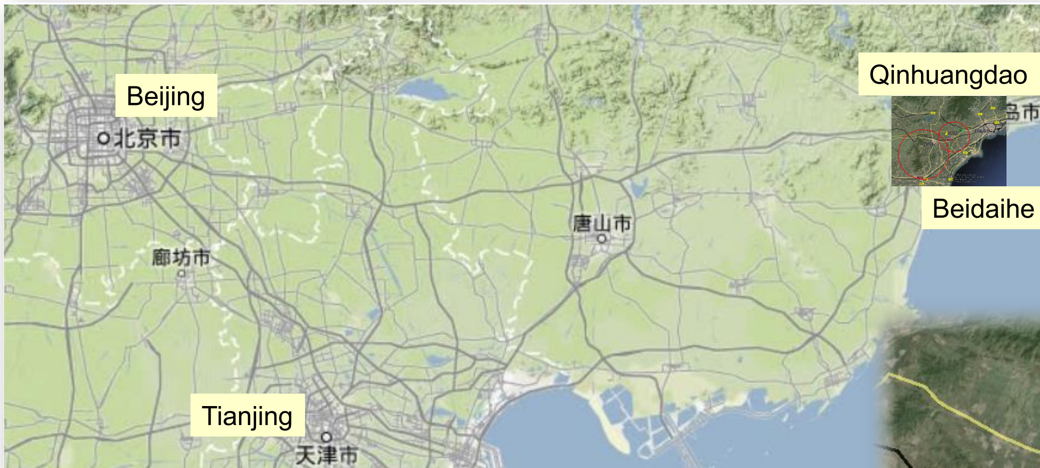




- **FCC-hh: ~170 simultaneous** pp-interactions (pile-up) expected for 25 ns bunch spacing
- could be reduced to ~34 with 5 ns bunch spacing

Meanwhile, elsewhere...

In China, proposal for



- **CepC: e^+e^- collisions at 240 GeV**
  - Higgs factory
- **SppC: pp collisions at 50-70 TeV**
  - Highest energies

Some concluding remarks

- Our **mission** as high-energy particle physicists is to **explore nature** at the smallest distance (alas highest energy) scales
  - such future collider(s) are the necessary tools for directly probing this regime, and thus to advance our knowledge of fundamental physics
- Besides the scientific interest, consider the following aspects:
  - CERN has developed, over these last 60 years, a **world-wide unique infrastructure** and **know-how**. Let's make sure this is exploited in the best way, over many years to come
  - with the LHC, Europe (CERN) has gained the **international leadership** in the exploration of the energy frontier
  - we should have an interest to keep the leadership in this so important and fascinating area of fundamental research
  - it is not only about **scientific leadership**, but also about **technological leadership**
    - we want to keep the most brilliant, young, ambitious minds in Europe
    - they will go where the most challenging and interesting projects are
    - Europe (**science and industry**) has shown to be capable of bringing big and challenging projects to success (eg. CERN/LHC, ESA/Rosetta/Philae, ...)
    - **The option(s) presented could be the next big, challenging project...**

Opening the door to future explorations

References, acknowledgments

- A lot of material taken from talks by

  M. Benedikt, A. Blondel, L. Bottura, D. Fournier, F. Gianotti, P. Janot, P. Lebrun, D. Schulte, B. Strauss, F. Zimmermann

- Many thanks for comments and inputs to

  A. Blondel, F. Gianotti, P. Janot, L. Rivkin

Links to images and other material

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