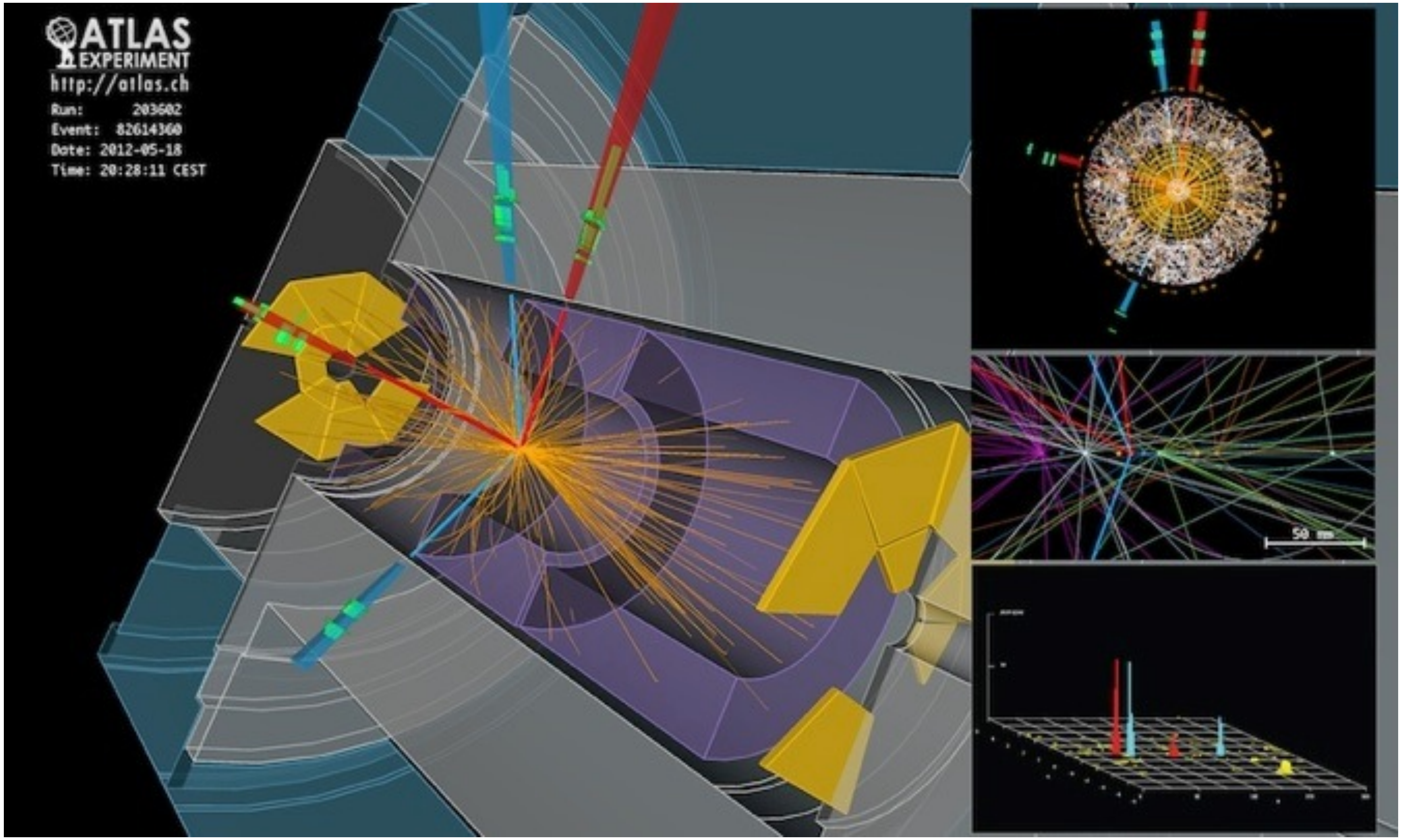
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



14. Future Colliders

05.02.2018

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

Important: Exams

If you want to take an exam in this course remember to register!

The time & date for the exam is flexible
(the one given in TUMOnline is a dummy date) - Send me an email to fix one!

Prelude: Particle Physics Today

The Role of Colliders

- To explore the smallest constituents of matter, and the particles and interactions that governed the earliest phases of the Universe, one needs high energies

- In a controlled laboratory setting, such energies can only be reached with accelerators - and the highest energies are reached in colliding beam configurations

- Progress in particle physics has been closely linked with progress in accelerator (and detector) technologies - Advances in energy have brought the discovery of new particles

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The current state of the art marks the **“Energy Frontier”**

The Standard Model - A Collider Success Story

- The “Standard Model” is a result of generations of accelerators, and the interplay of experiment and theory - it provides testable predictions

c: SPEAR/AGS 1974 ✔

b: Fermilab 1977 ✔

t: Tevatron 1995 ✔

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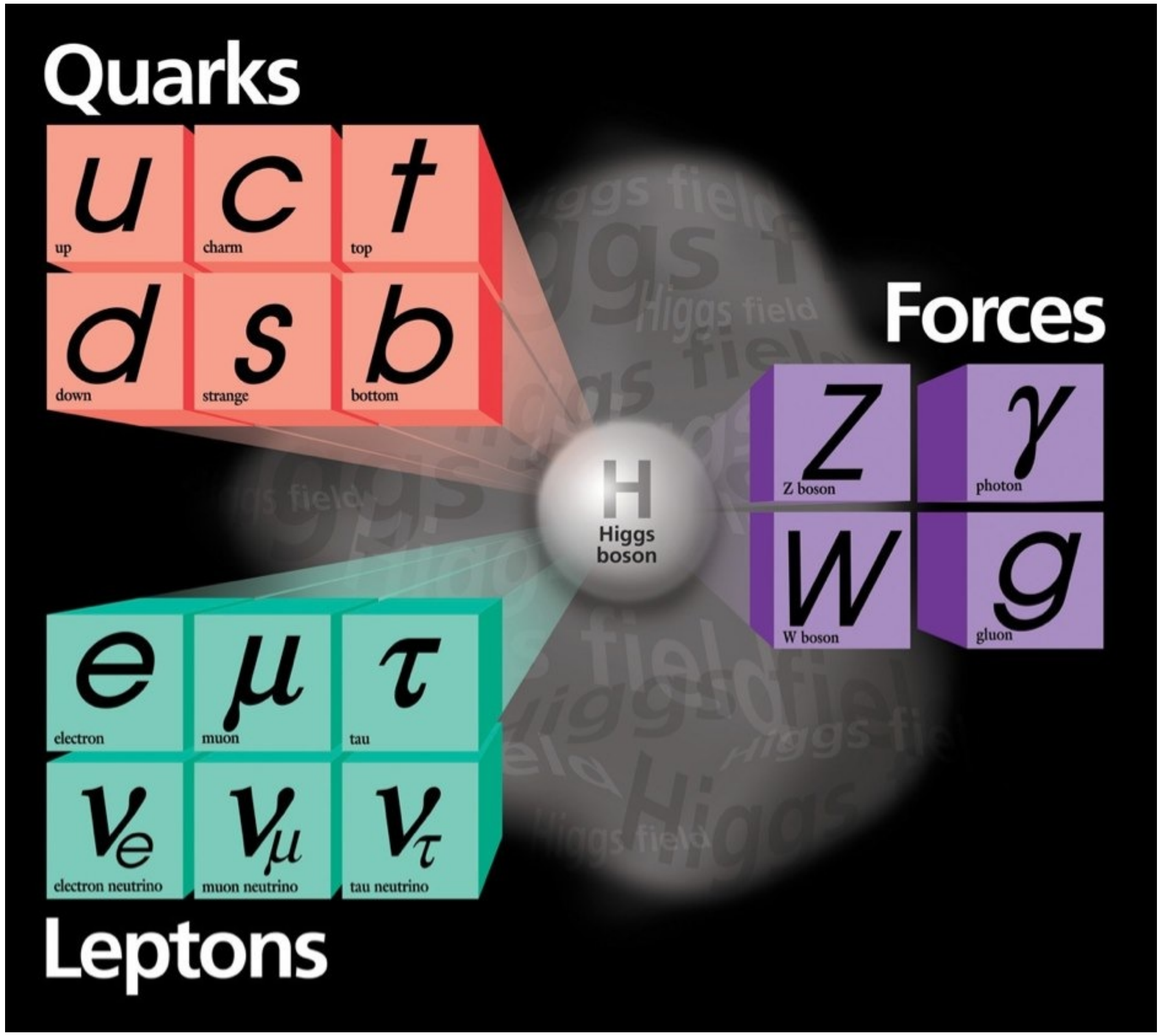

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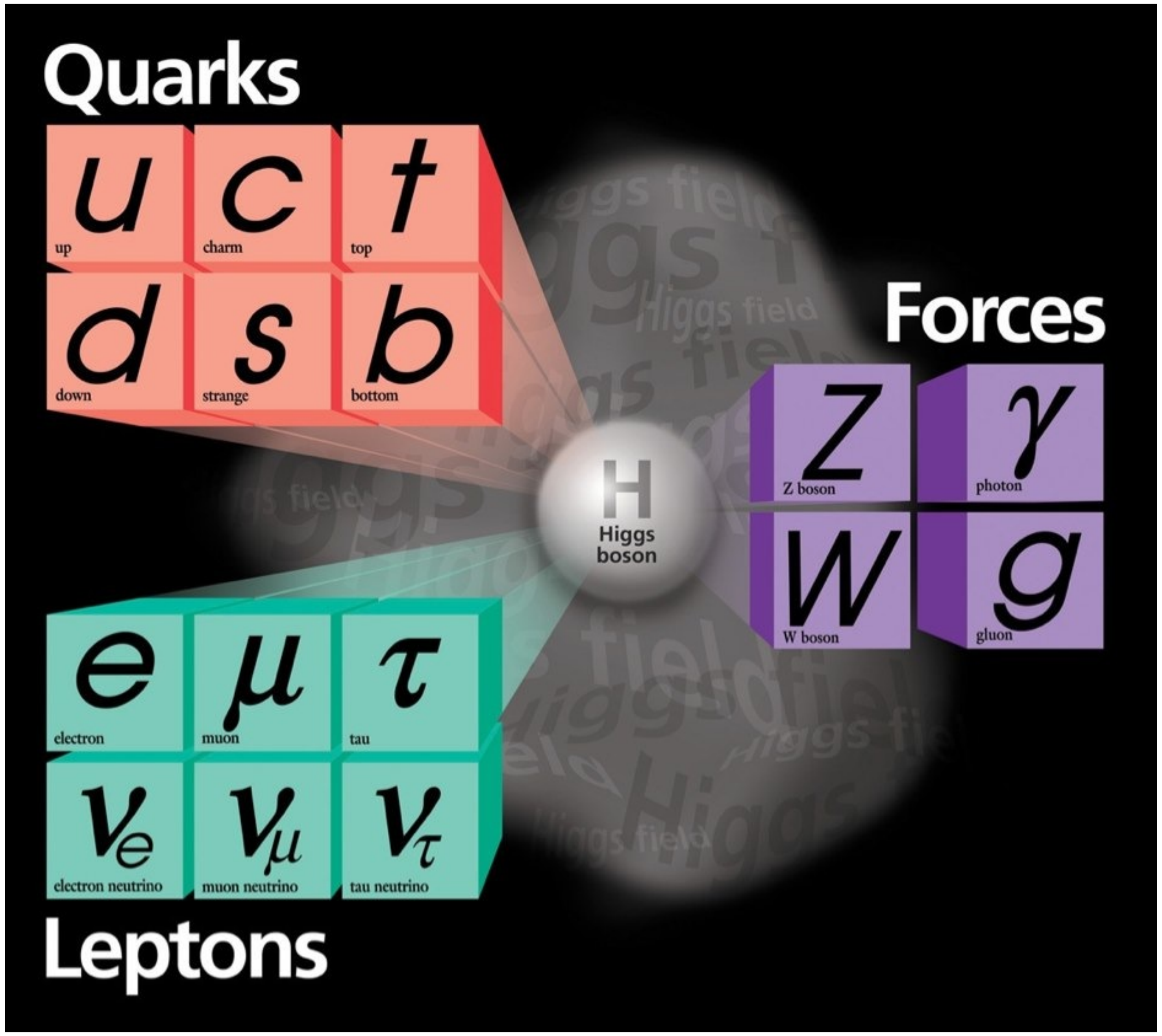

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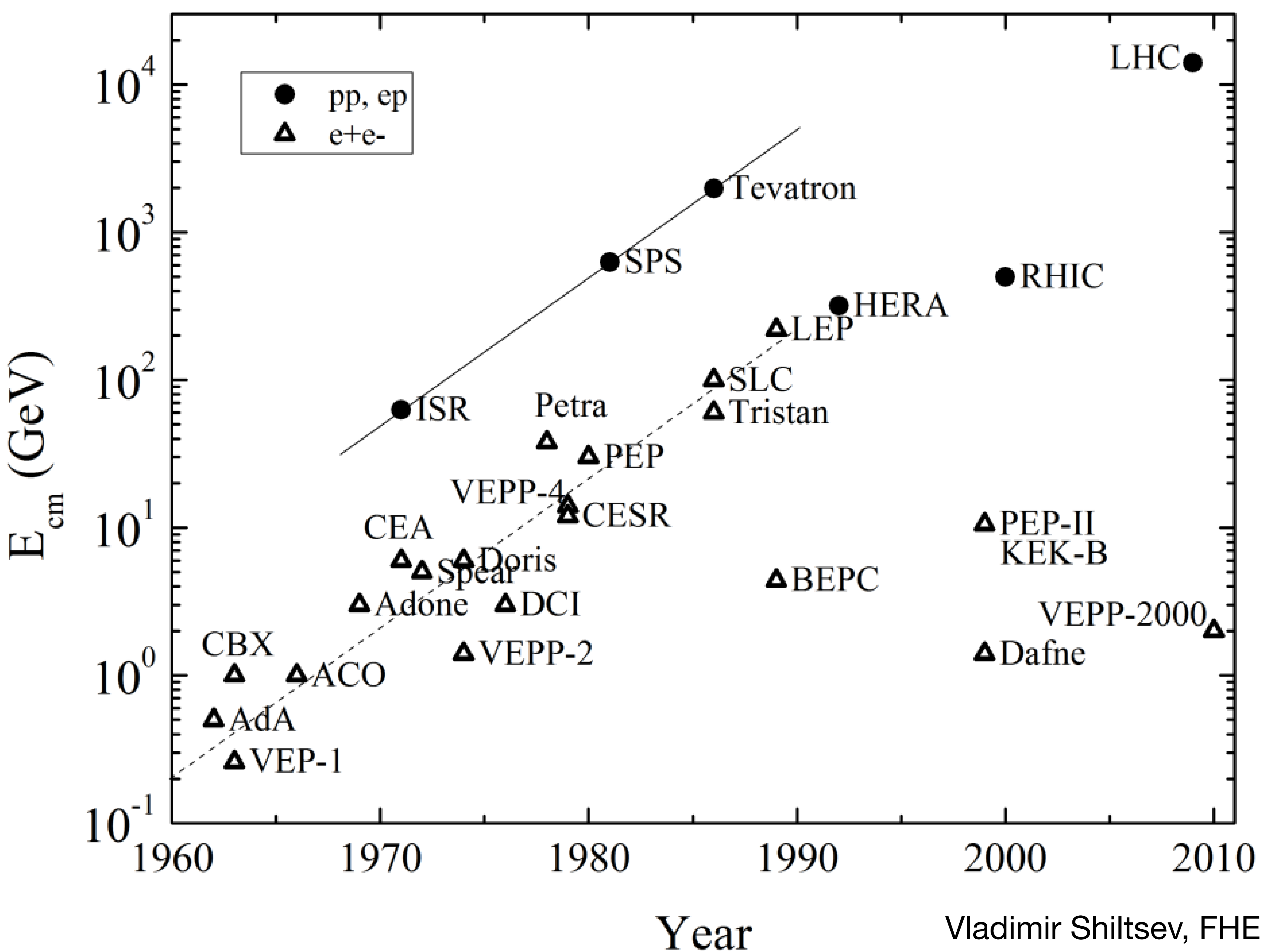
… the Standard Model was established with results from lepton and hadron colliders.

The World of Colliders



Vladimir Shiltsev, FHEP Hong Kong, Jan. 2015

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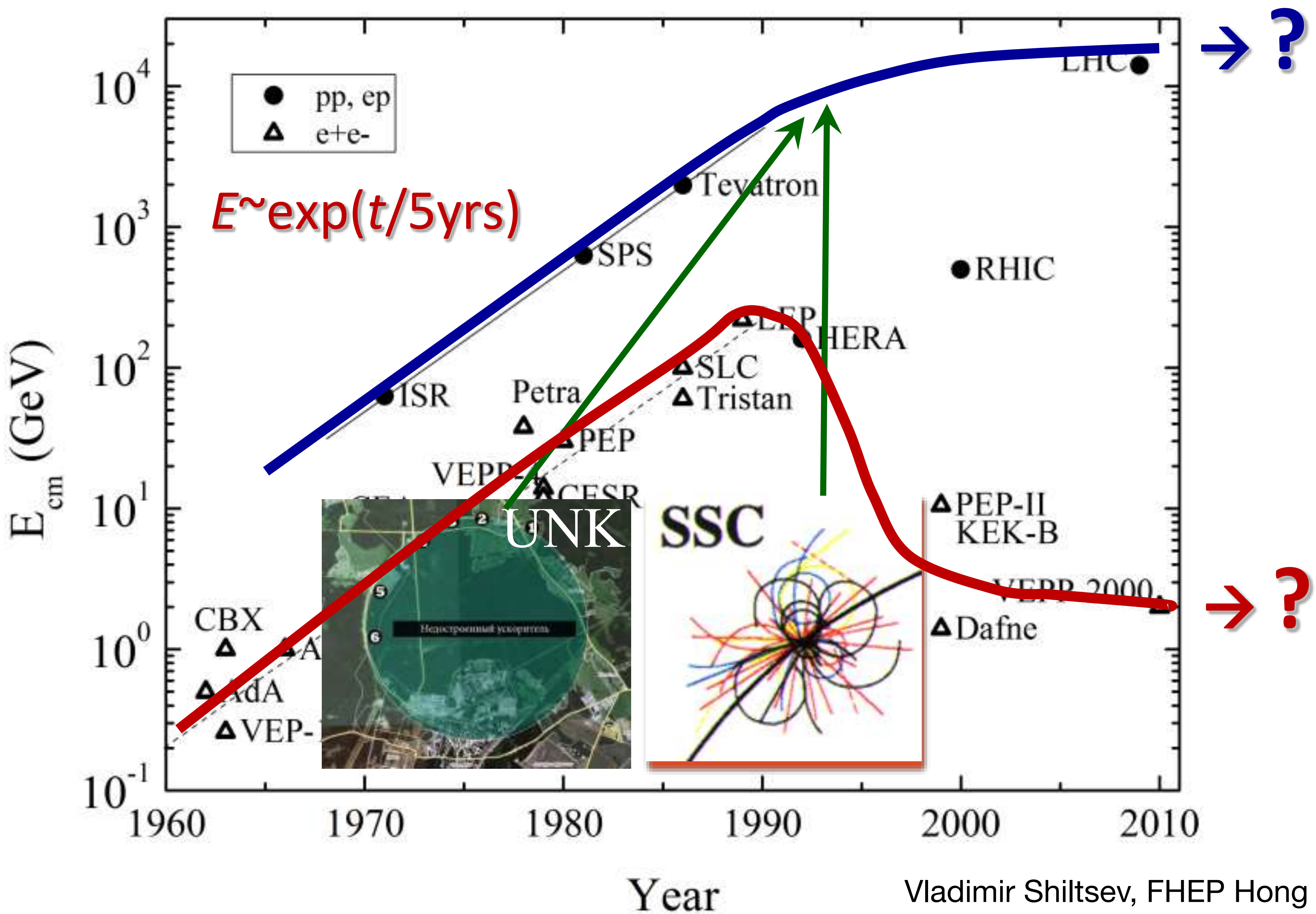

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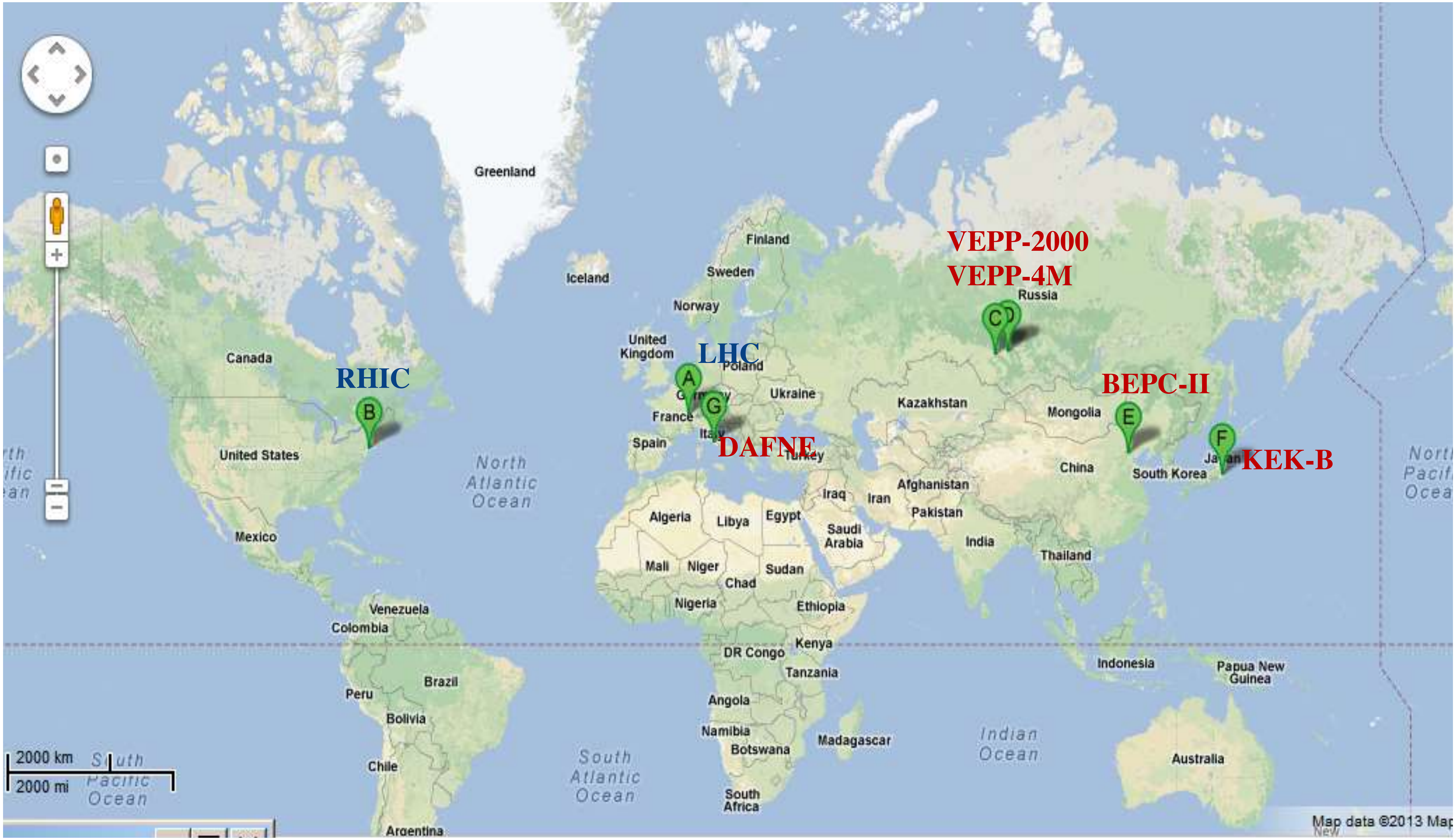
Currently Operating or Approved Colliders

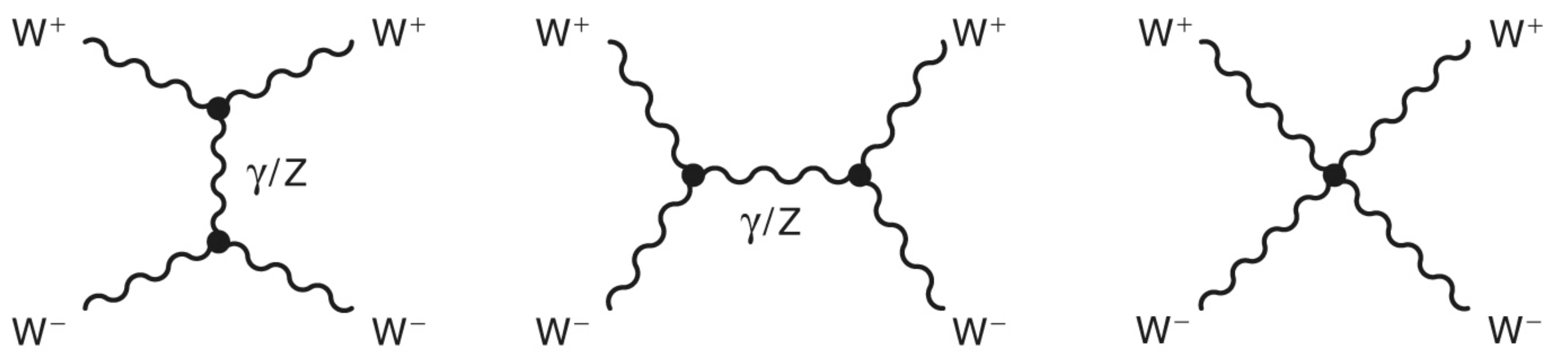


- In total 29 colliders, 7 run “now”

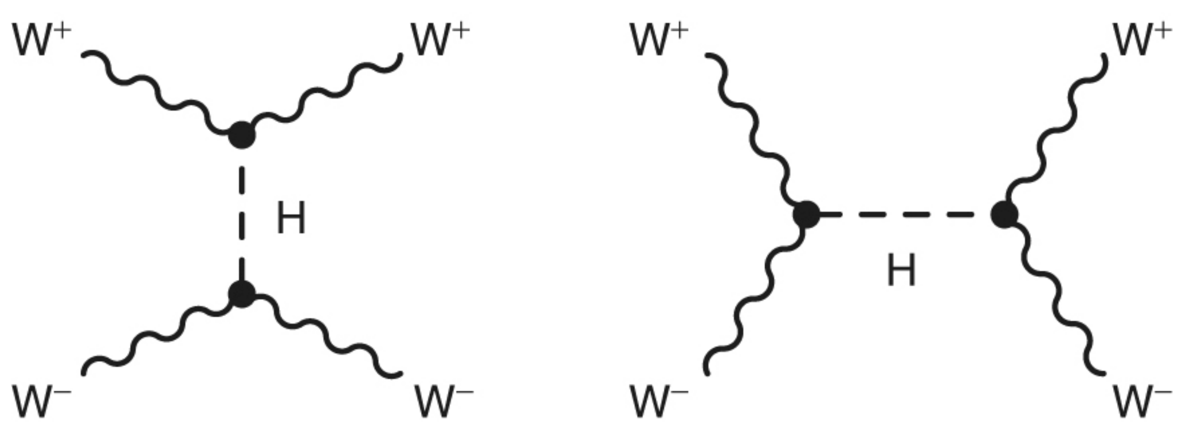
Vladimir Shiltsev, FHEP Hong Kong, Jan. 2015

The “Magic” of the Terascale

- Within the Standard Model, there were compelling arguments for discoveries at the “Terascale”:
  - Scattering of W bosons violate unitarity without the Higgs or new physics



needs in addition the exchange of a scalar particle:



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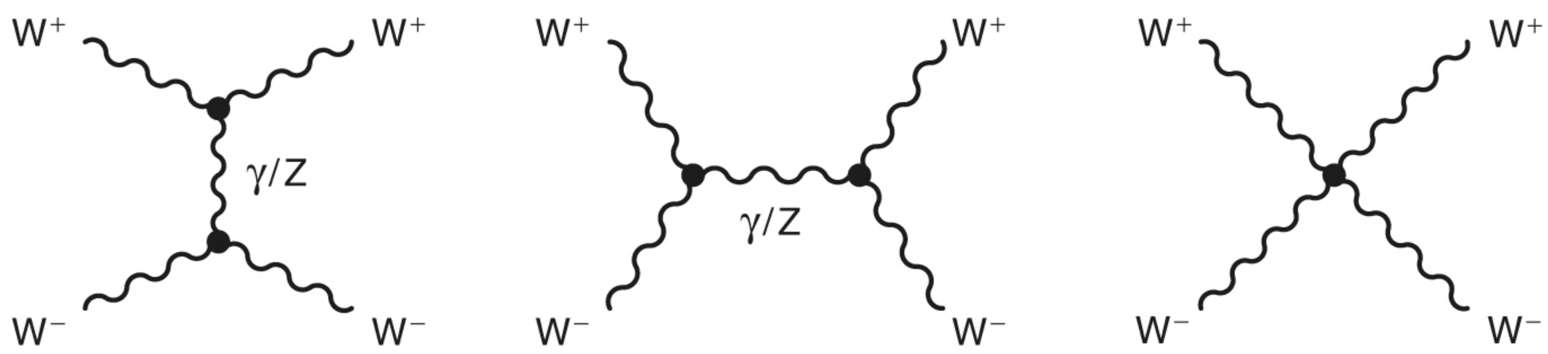

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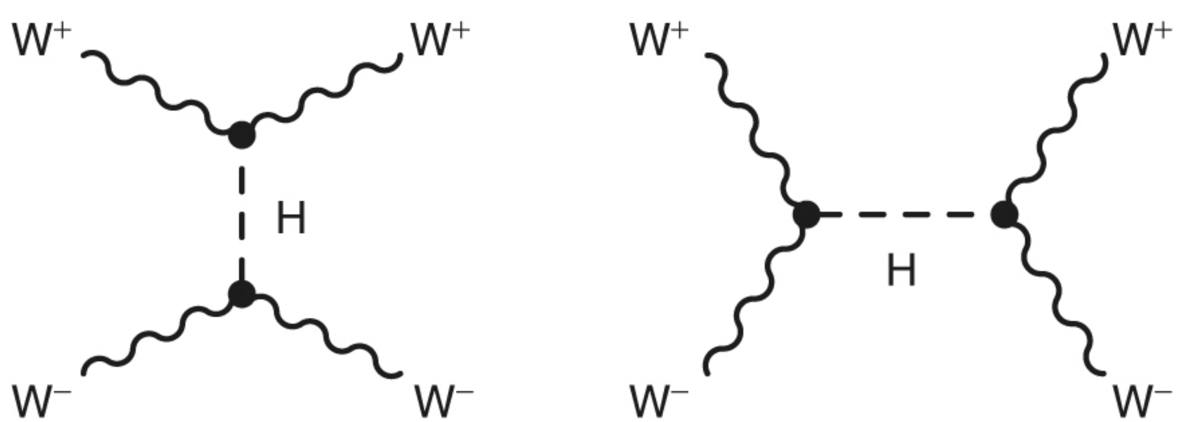

A guarantee that something has to turn up in the TeV region - either the Higgs, or some new dynamics in WW scattering

So: What Now?

- With the Higgs, the last particle of the SM has now been observed - and now?

  It is obvious that the SM cannot be the final answer, but there is no clear indication where things will break and what should be the next relevant energy scale - unlike the “no-loose” situation for the LHC and the Terascale

Two options to move forward:

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- The Higgs: Fully understand electroweak symmetry breaking and the nature of the Higgs potential
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➯ Direct searches for New Physics - Explore higher energy scales, and regions of phase space not yet accessible to find new particles and / or evidence for new fundamental interactions and phenomena

What will we find at the Energy Frontier?

- Many ideas - some have been discussed in this series:
  - Supersymmetry
  - New gauge bosons
  - “Exotic” phenomena - black holes, extra dimensions
  - Dark matter
  - ….

All of those ideas might be wrong - and nothing is guaranteed.

Remember: Fundamental research is about open exploration - with uncertain outcome.

The tools in particle physics: high-energy colliders - LHC, and future machines.

Interlude: No Sign for BSM - Give up?

stolen from John Ellis

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Interlude: No Sign for BSM - Give up?

- *“So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value”* – Spanish Royal Commission, rejecting Christopher Columbus proposal to sail west, **< 1492**

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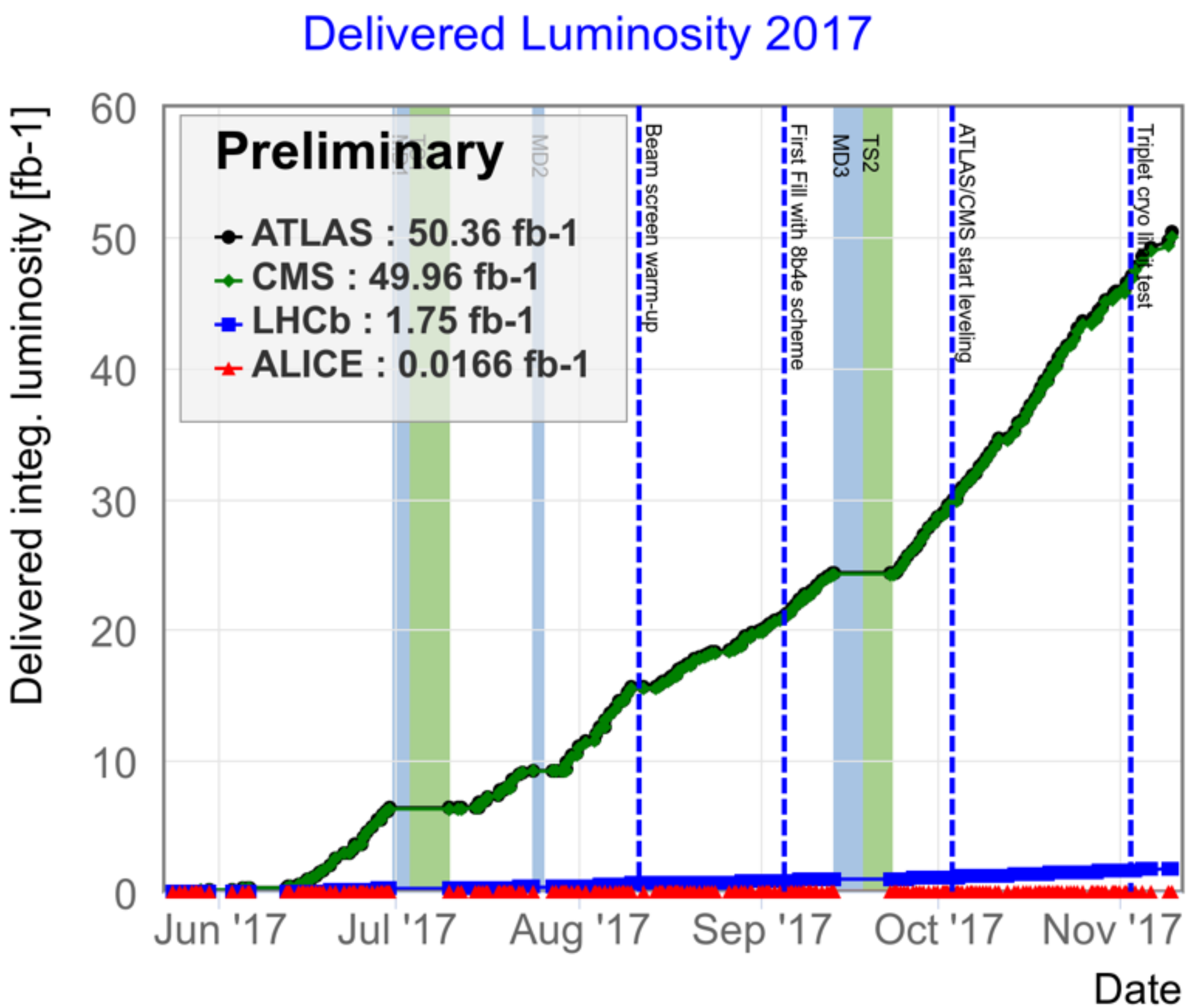
The immediate Future:
The LHC

LHC 2017 - A Record Year



- Very good performance of accelerator: Goal of 45 fb^{-1} exceeded
  - allowed stopping one week early for CMS maintenance

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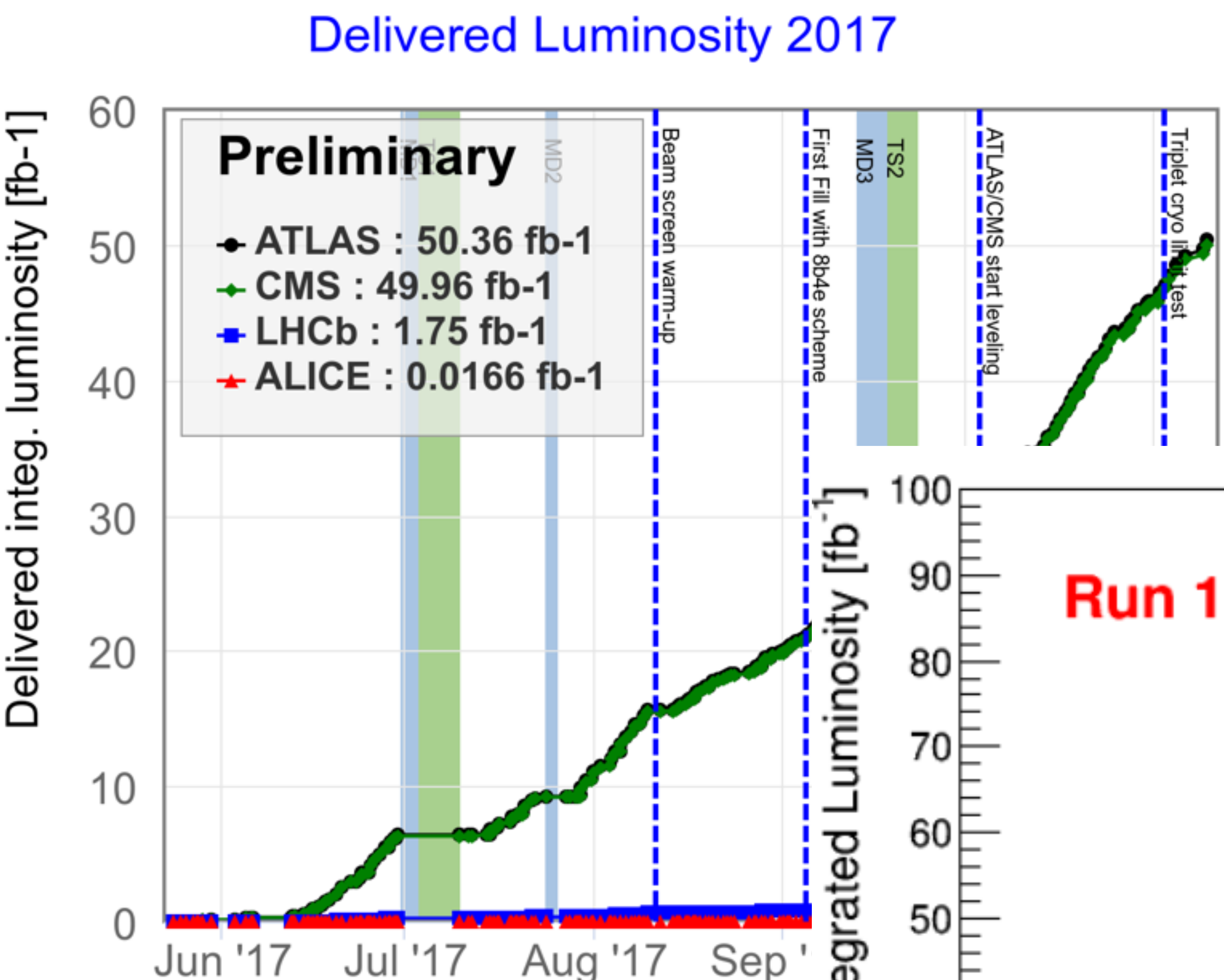

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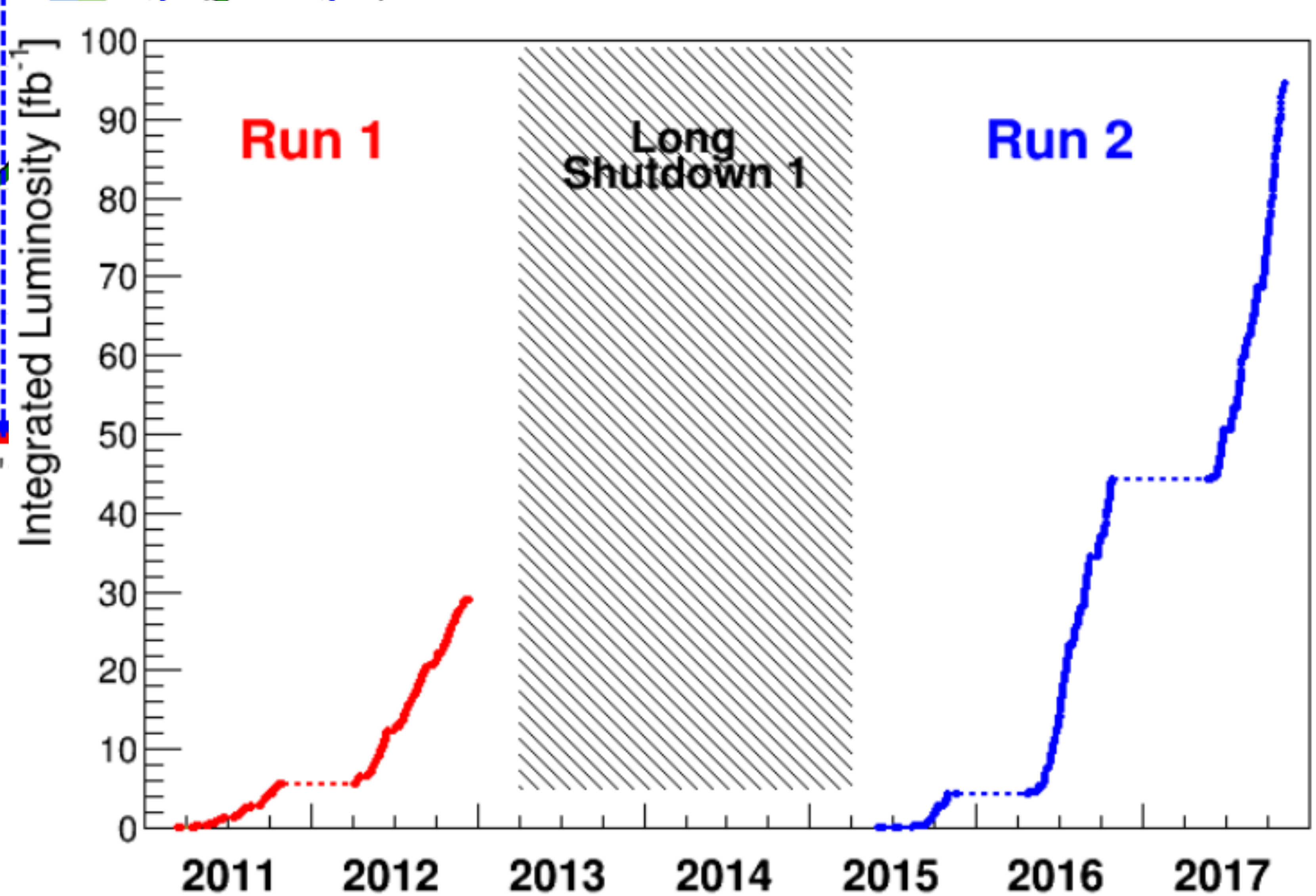
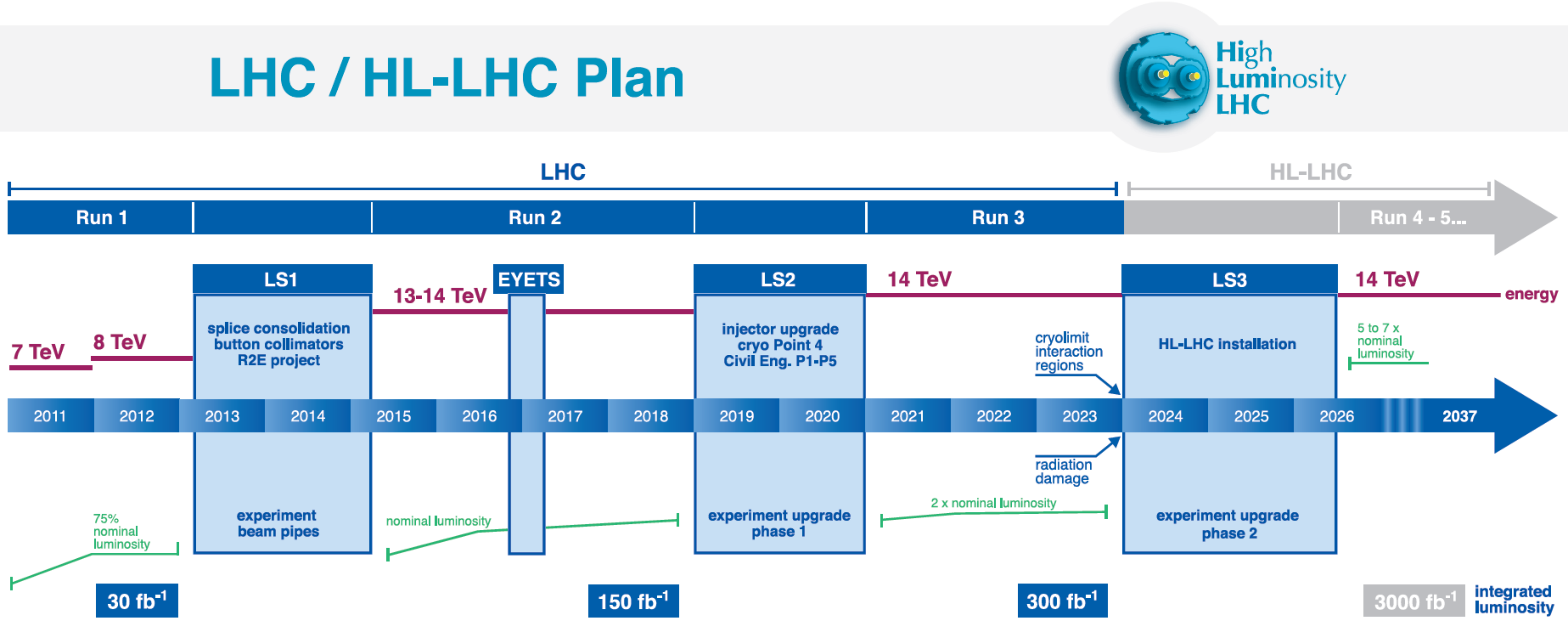


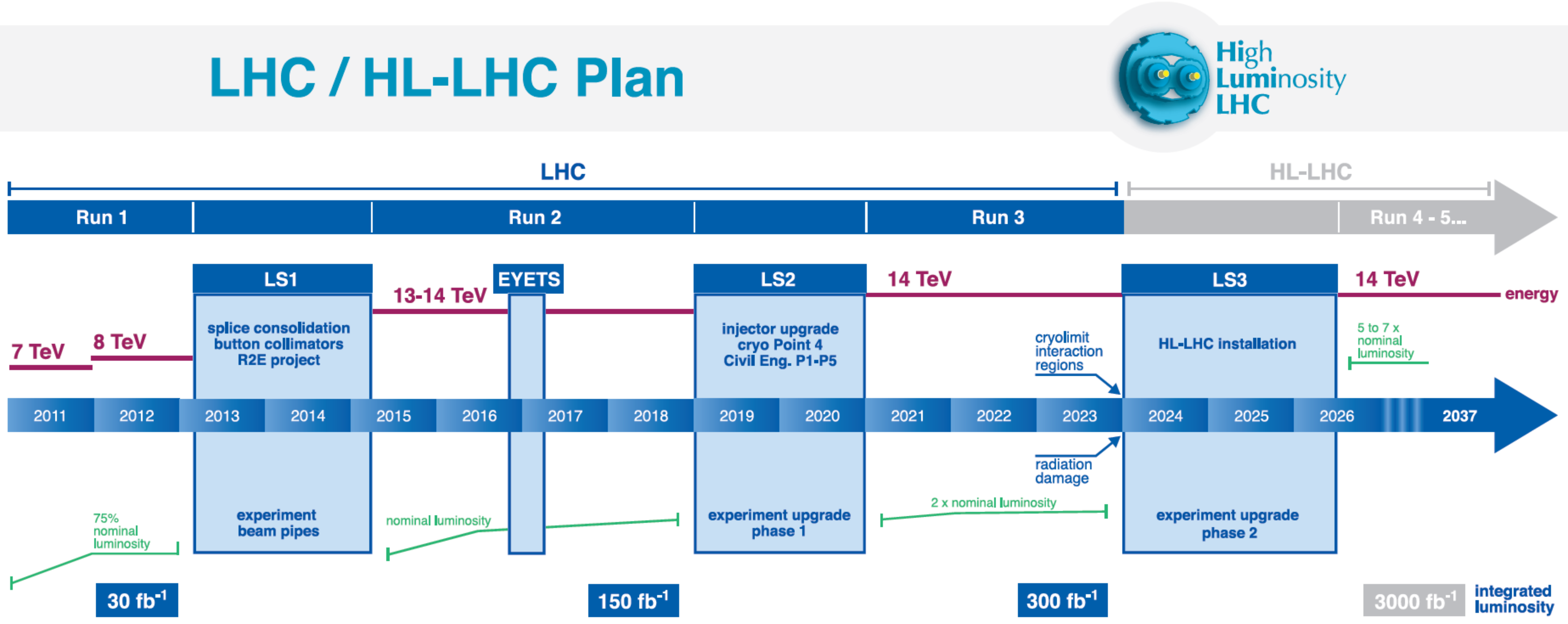
- Now more than 90 fb^{-1} at 13 TeV
- 123 fb^{-1} since start of LHC

The LHC Future



- Two mayor shutdowns with upgrades coming:
  - LS2: Upgrade of injectors, first detector upgrades
  - LS3: High Luminosity LHC installation, comprehensive upgrades of ATLAS & CMS

The LHC Future



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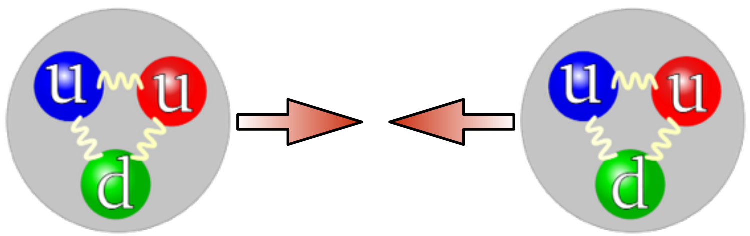
To come until 2037: 30 x more data, mild increase in energy

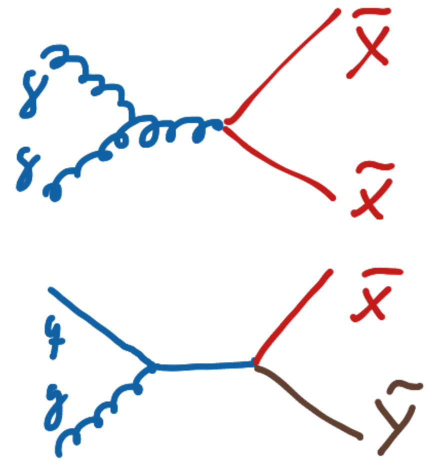
Possible Future Facilities at the Energy Frontier

Future Facilities at the Energy Frontier - Options

- Two different (complementary) approaches:
  - proton-proton colliders:



composite particles:
initial state unknown,
different processes contribute



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> dominant production via strong interaction (gluons, quarks):
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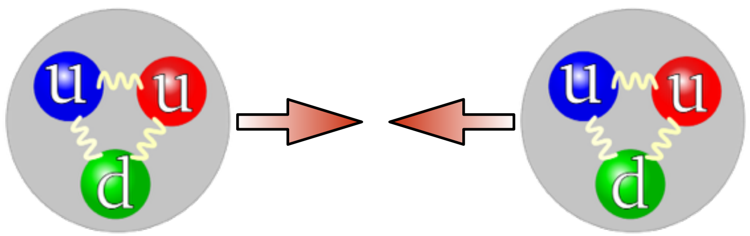

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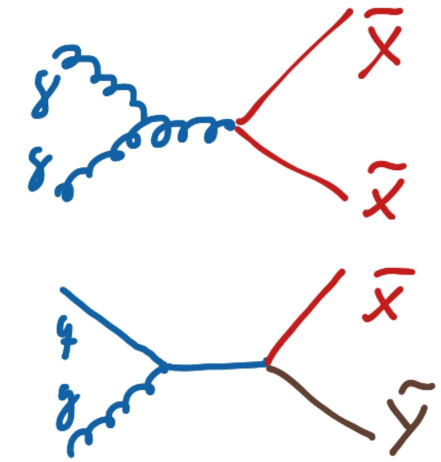

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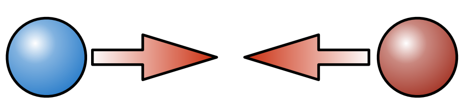
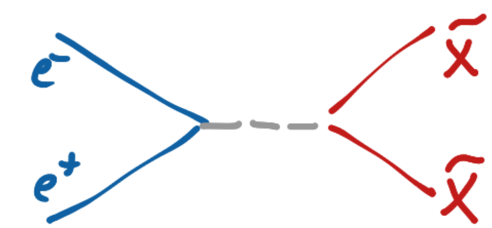
  - electron-positron colliders:



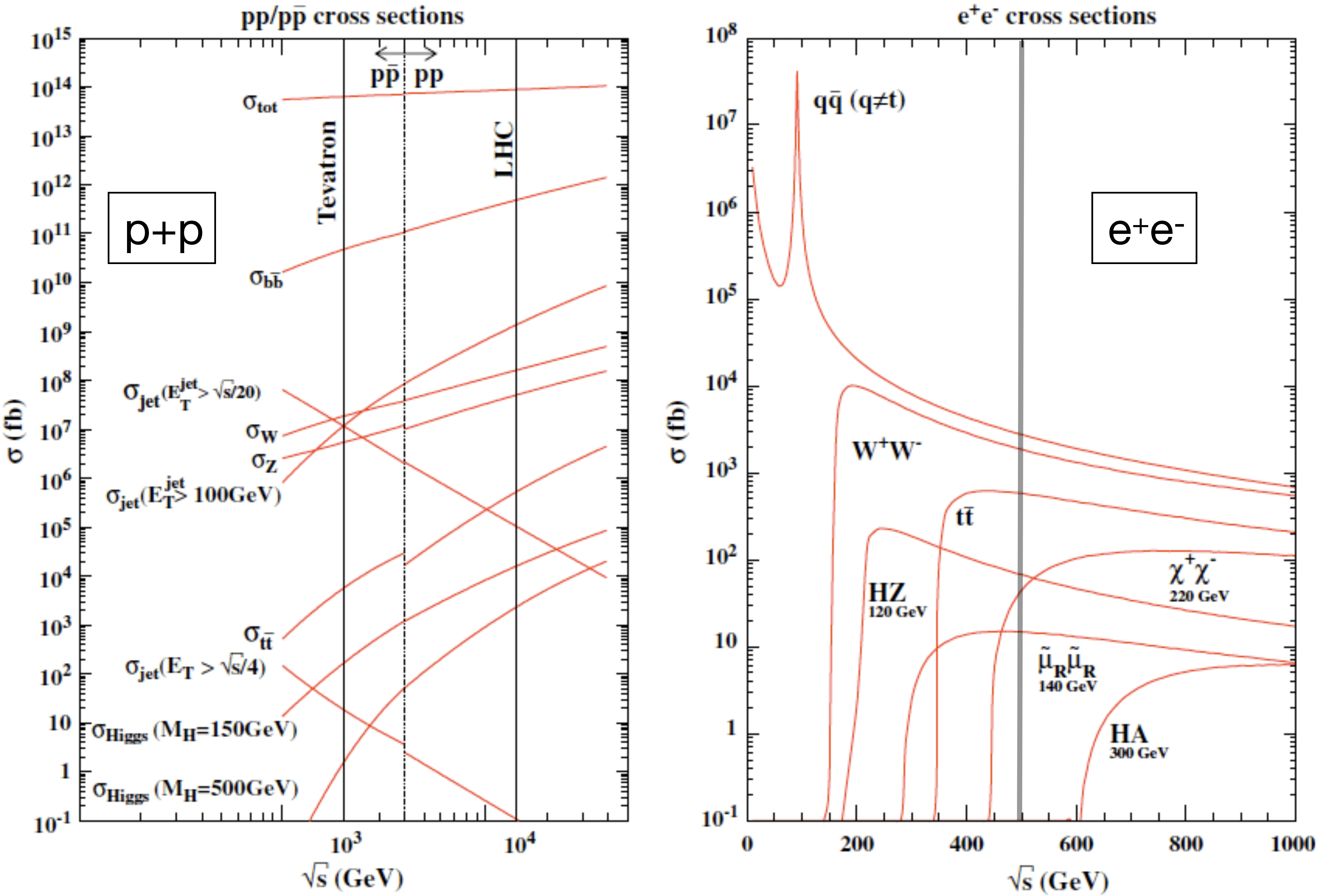
~ full energy available in reaction - can explore thresholds



electroweak production:
all particles produced with ~ equal probability - particularly sensitive to electroweak particles, which are suppressed at hadron colliders

Hadrons vs Leptons

- Colliding elementary particles, electroweak “universal” production
  - Much more favorable ratio of signal to background



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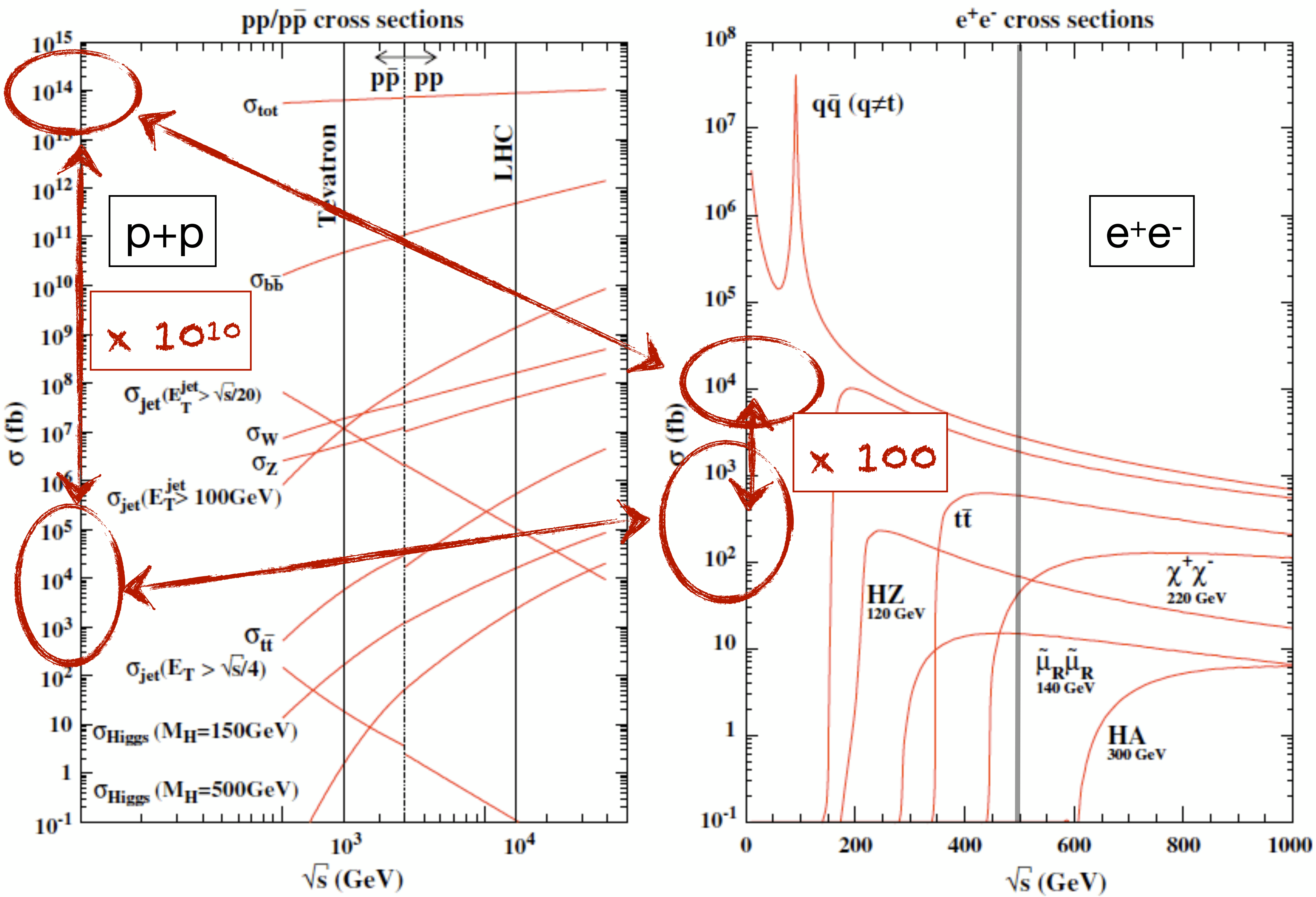

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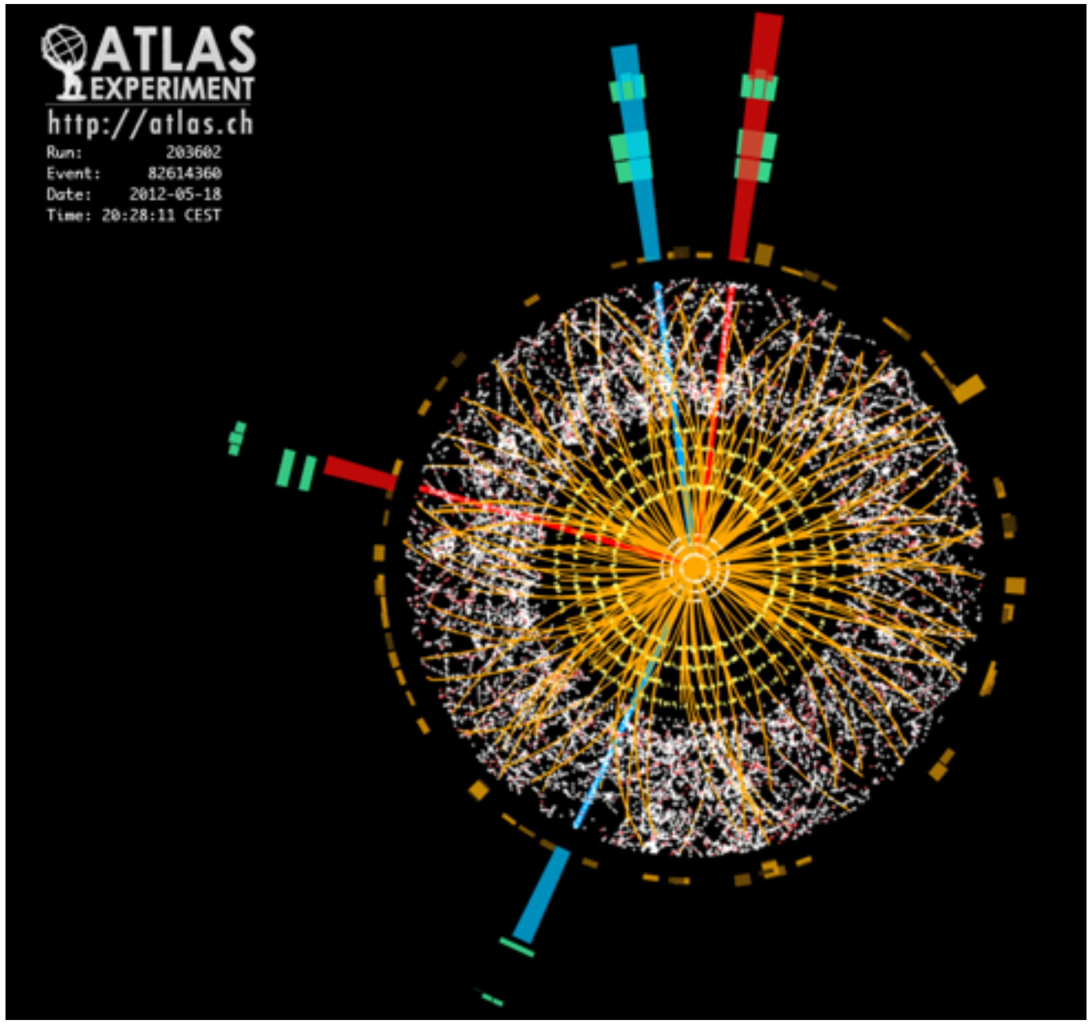
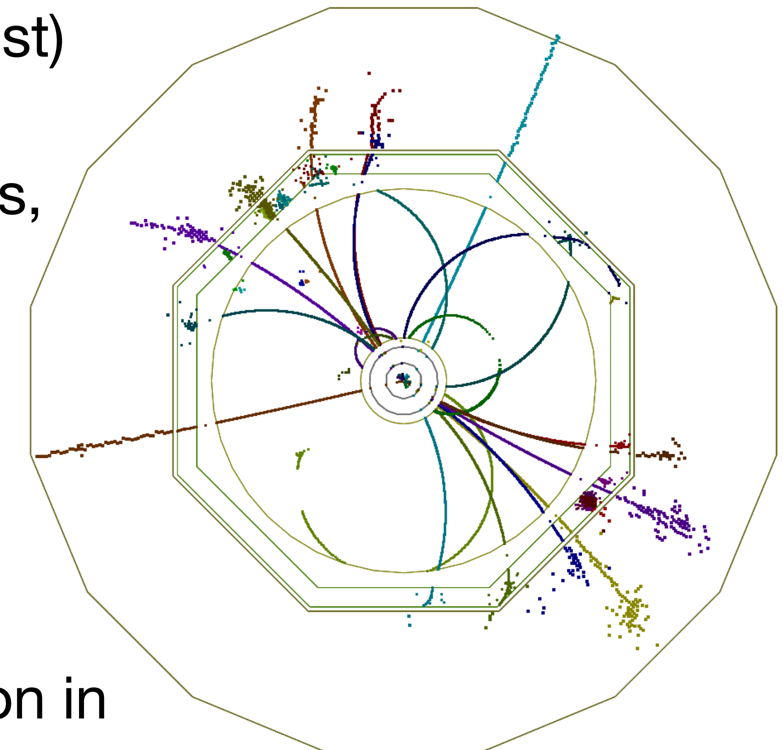


Higgs production in pp: (almost) every particle in the event originates from other reactions, only four leptons are from the Higgs decay



Higgs production in e^+e^-: (almost) every particle in the event originates from the Higgs or the Z produced with it

- At hadron colliders: Triggering is crucial - Need to pick out events based on “interesting” signatures out of 10^9 times higher background
- In e^+e^- collisions: All reactions are equally probable - overall low event rates, but most are interesting - no trigger needed, all collisions are analyzed offline

Challenges: Leptons

- Main challenge for circular colliders: Energy loss through synchrotron radiation
  - Power proportional to E^4/R^2 - Loss per turn ~ E^4/R
  - ‣ Very hard to compensate increasing energy by increasing radius: Linear colliders get more attractive with increasing electron energy

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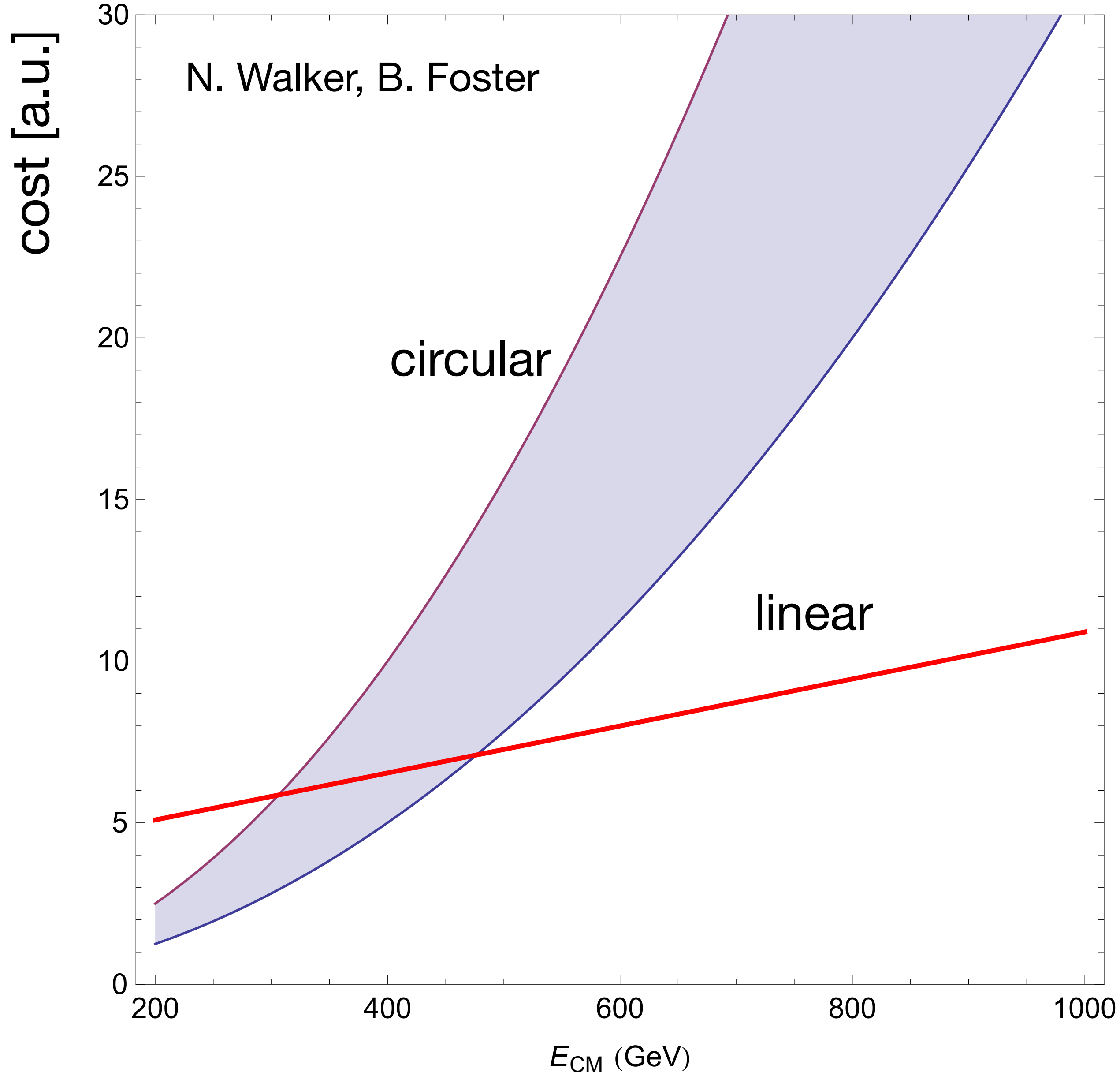

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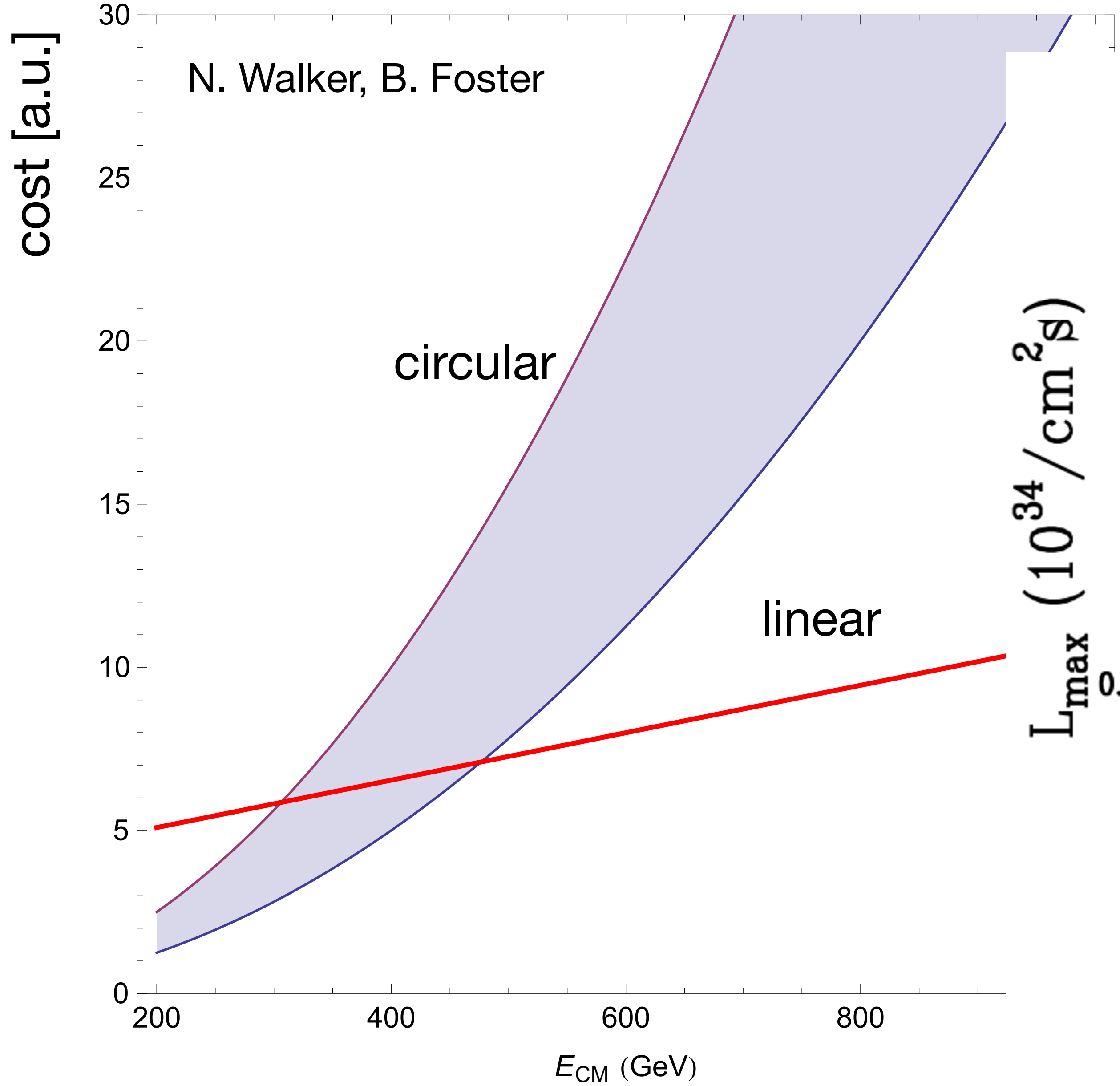
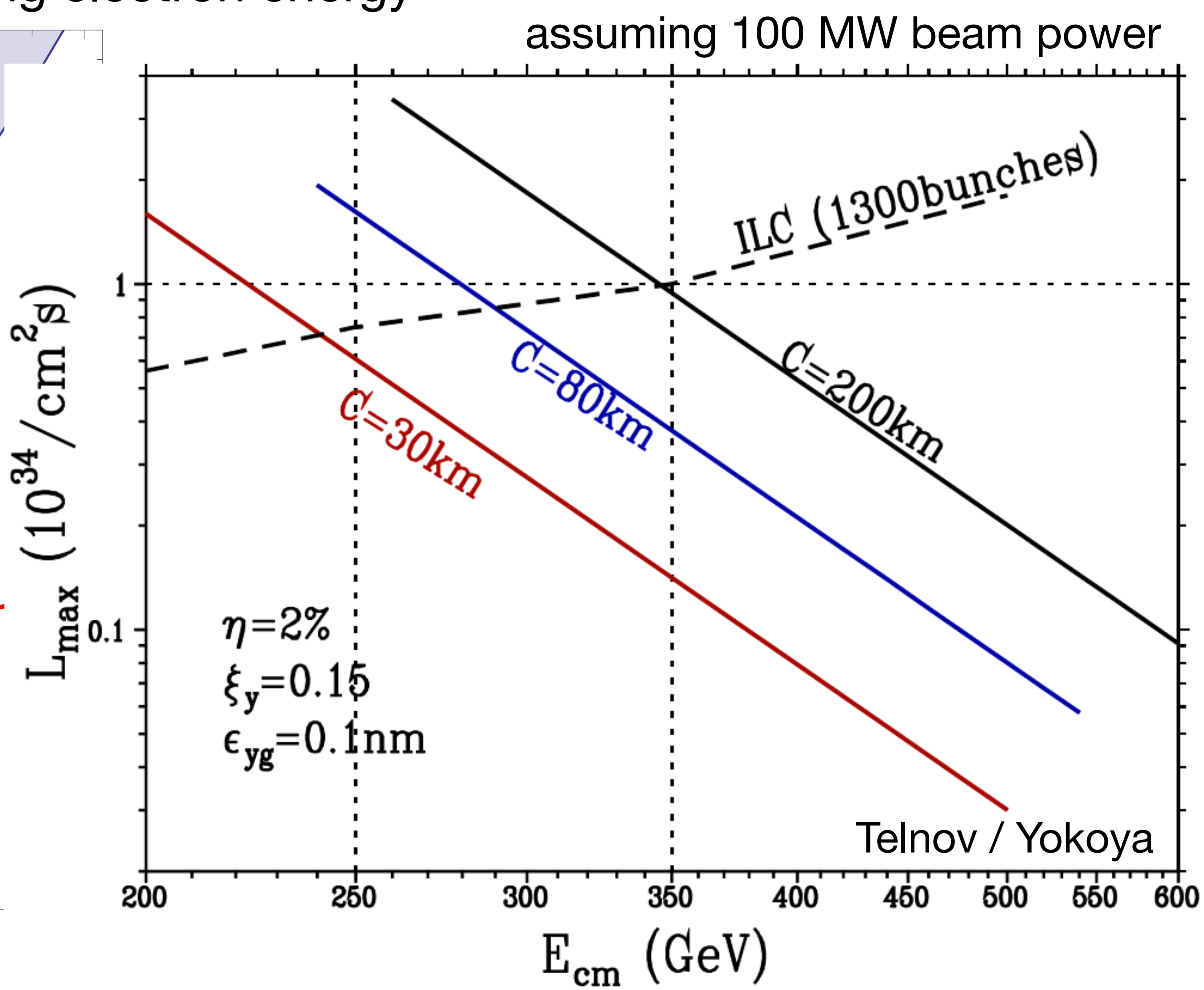
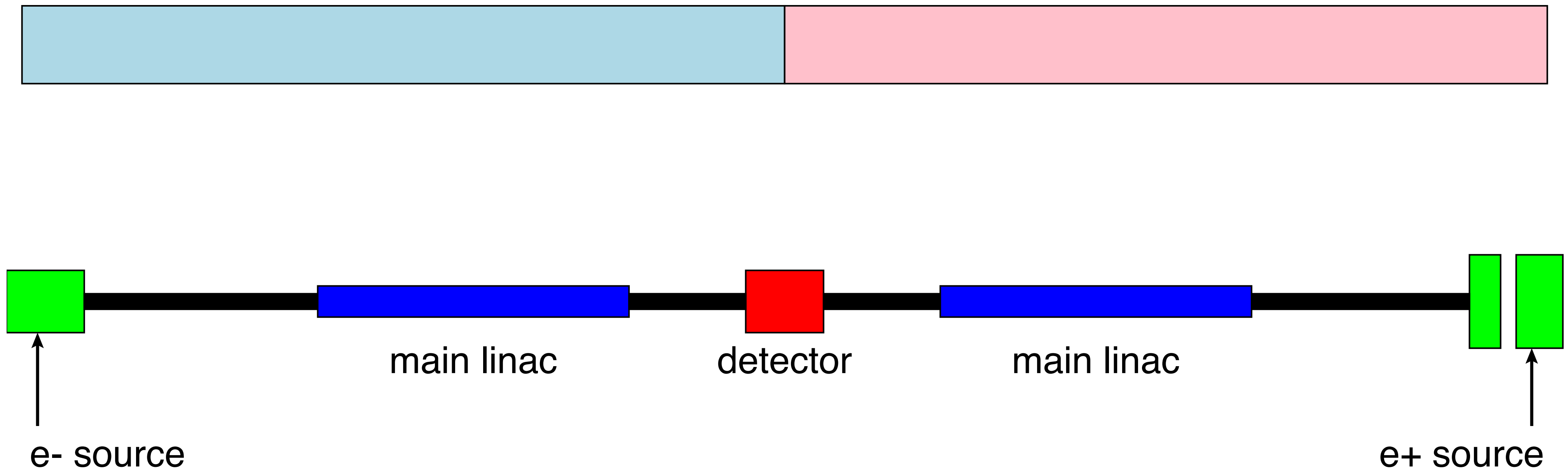




Challenges: Linear Colliders

- Need high energy ***and*** high luminosity

- High energy requires high acceleration gradients
- High luminosity requires low emittance and very small beam size at interaction point ("nano-beams")



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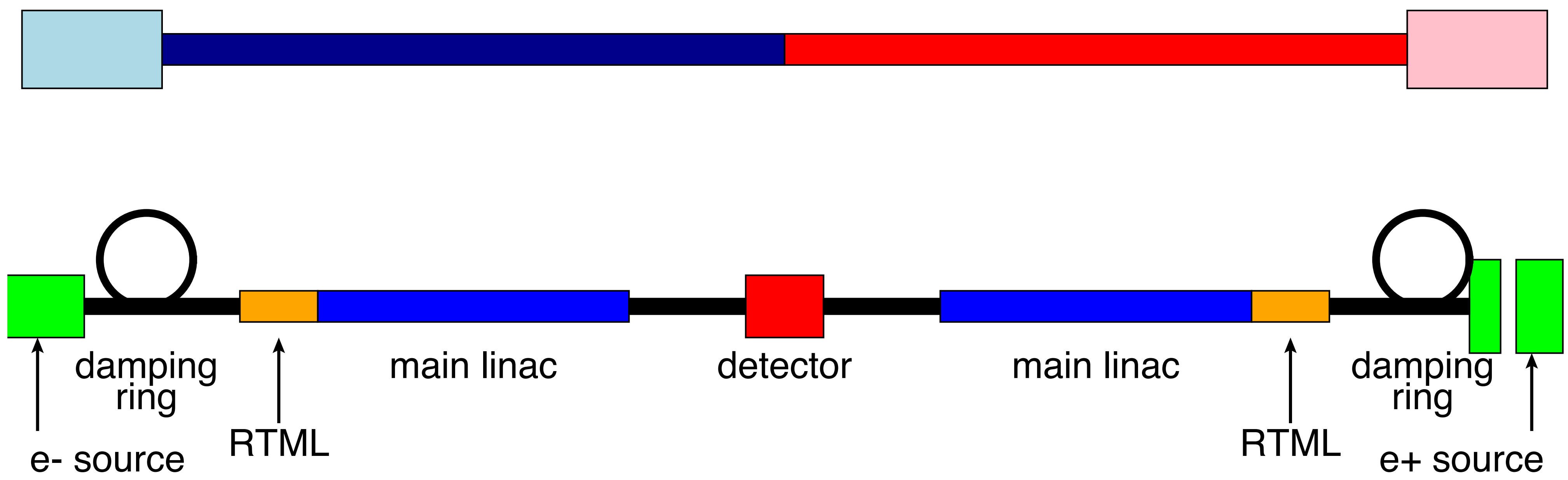

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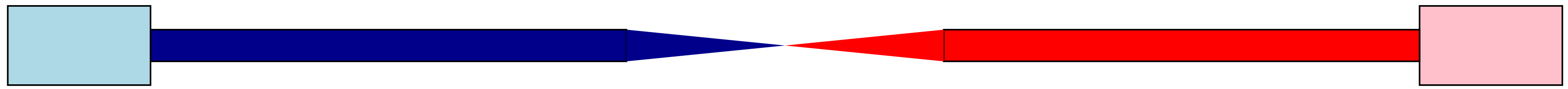

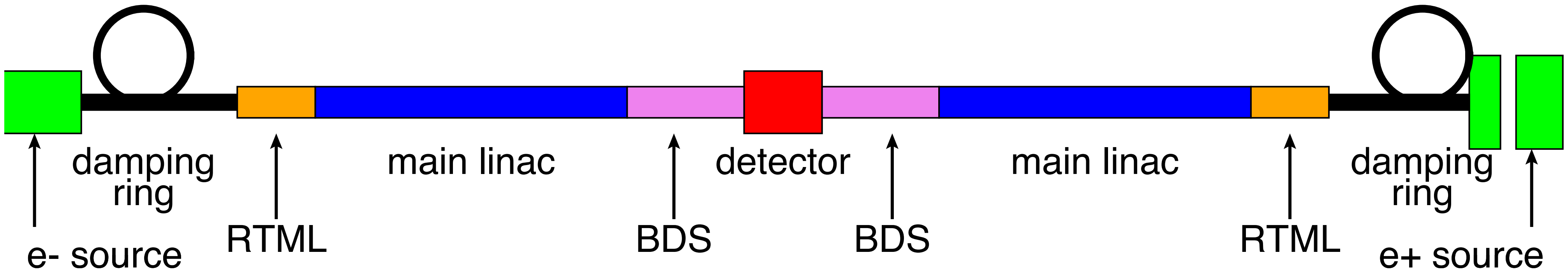

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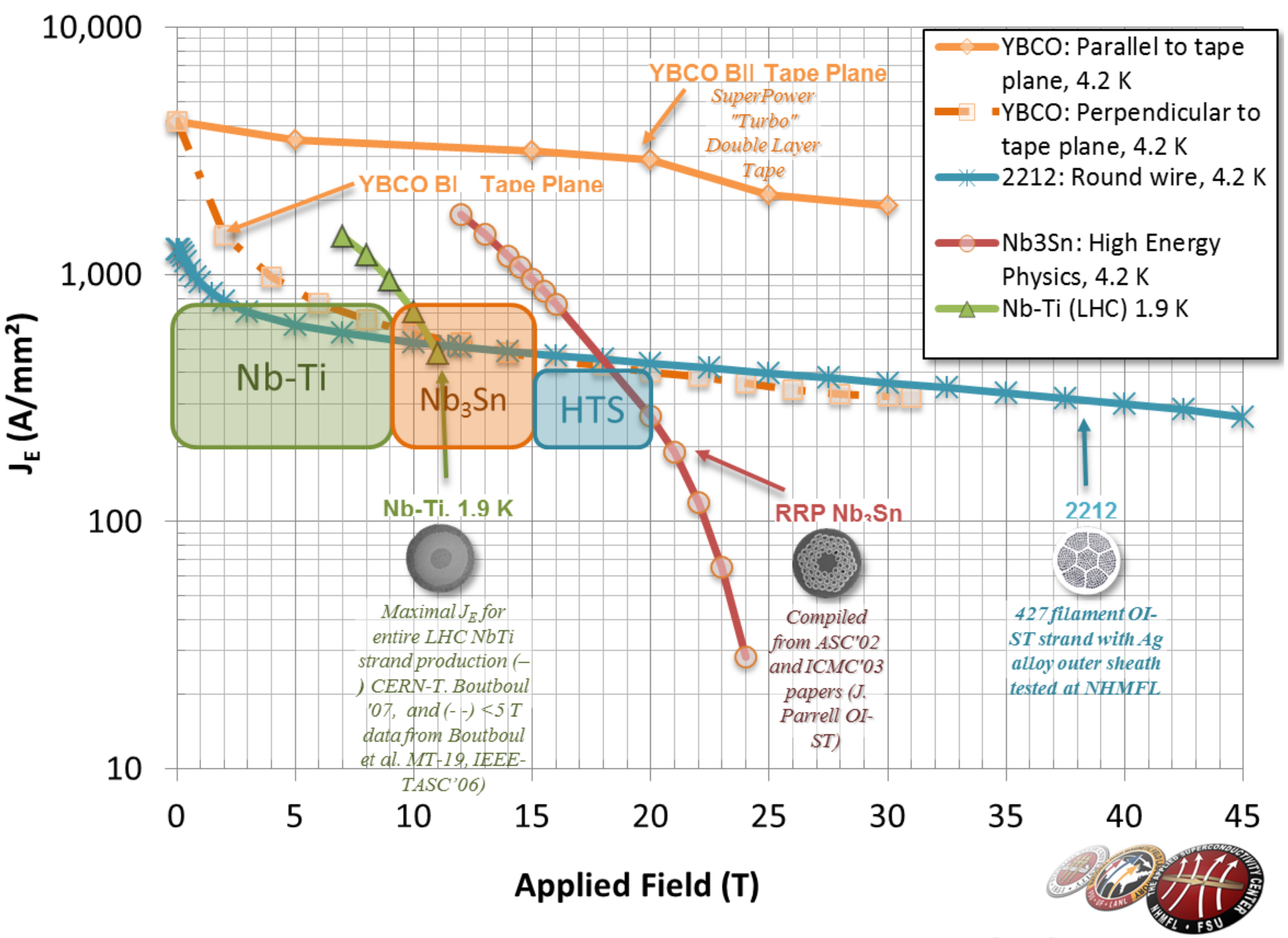
- 16 T seem achievable with Nb_3Sn
- 20 T require HTS magnets - substantial additional challenge



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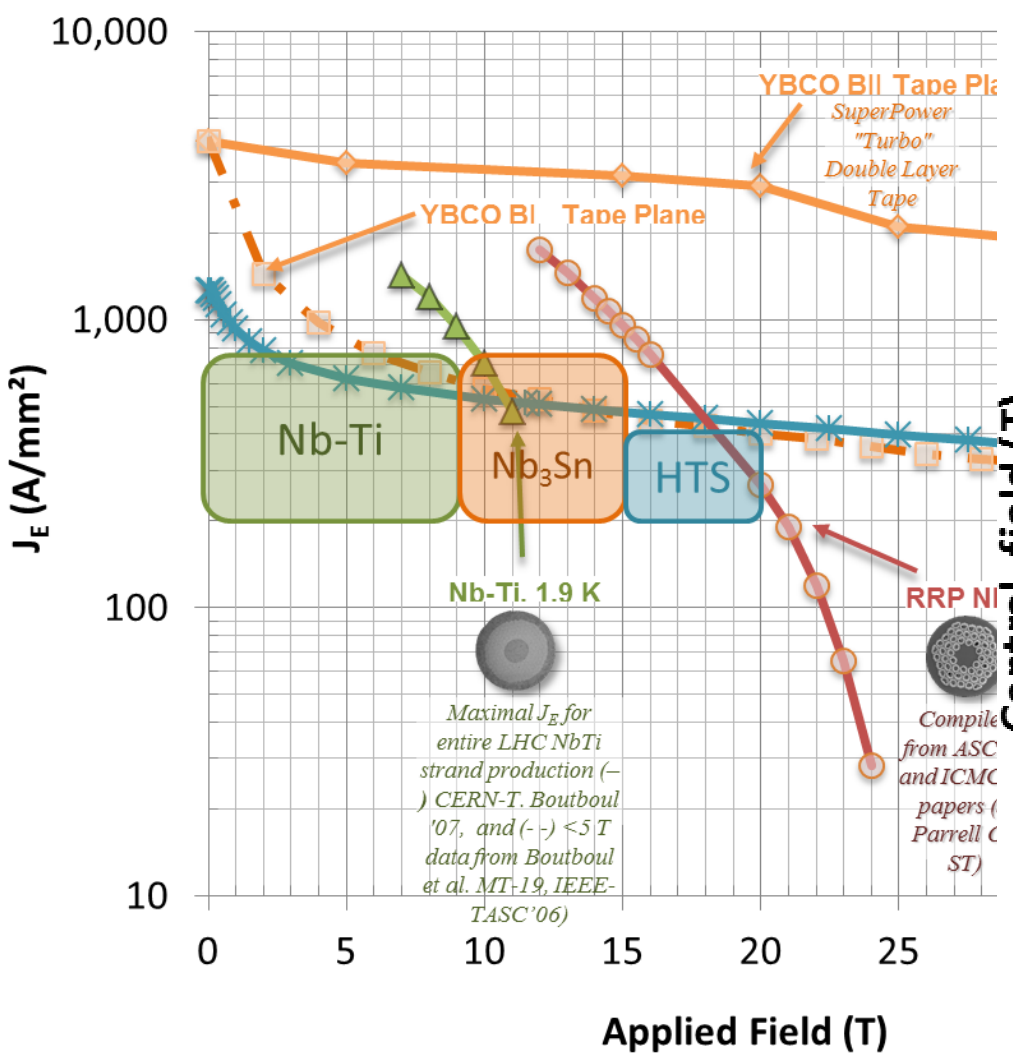
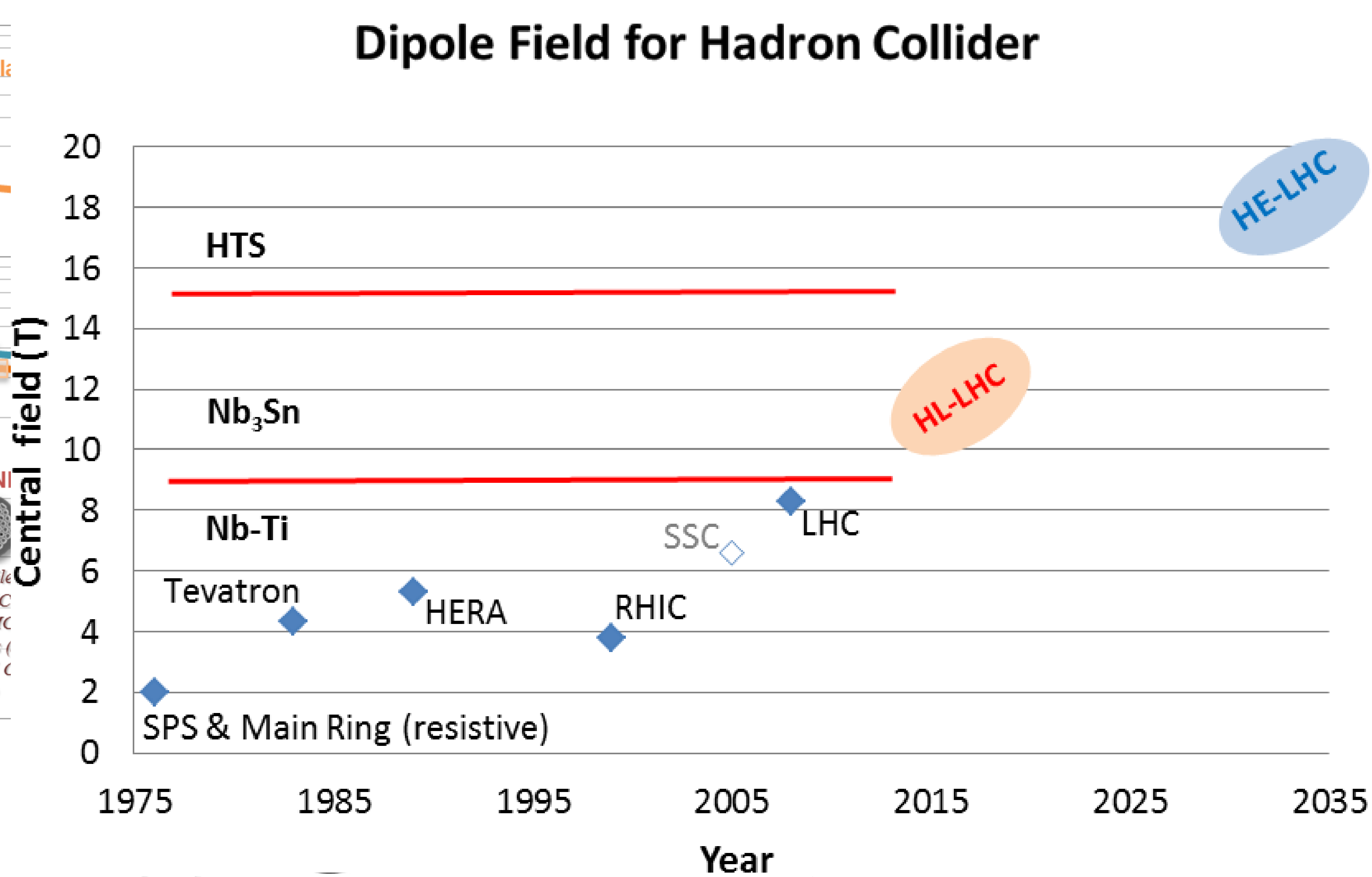
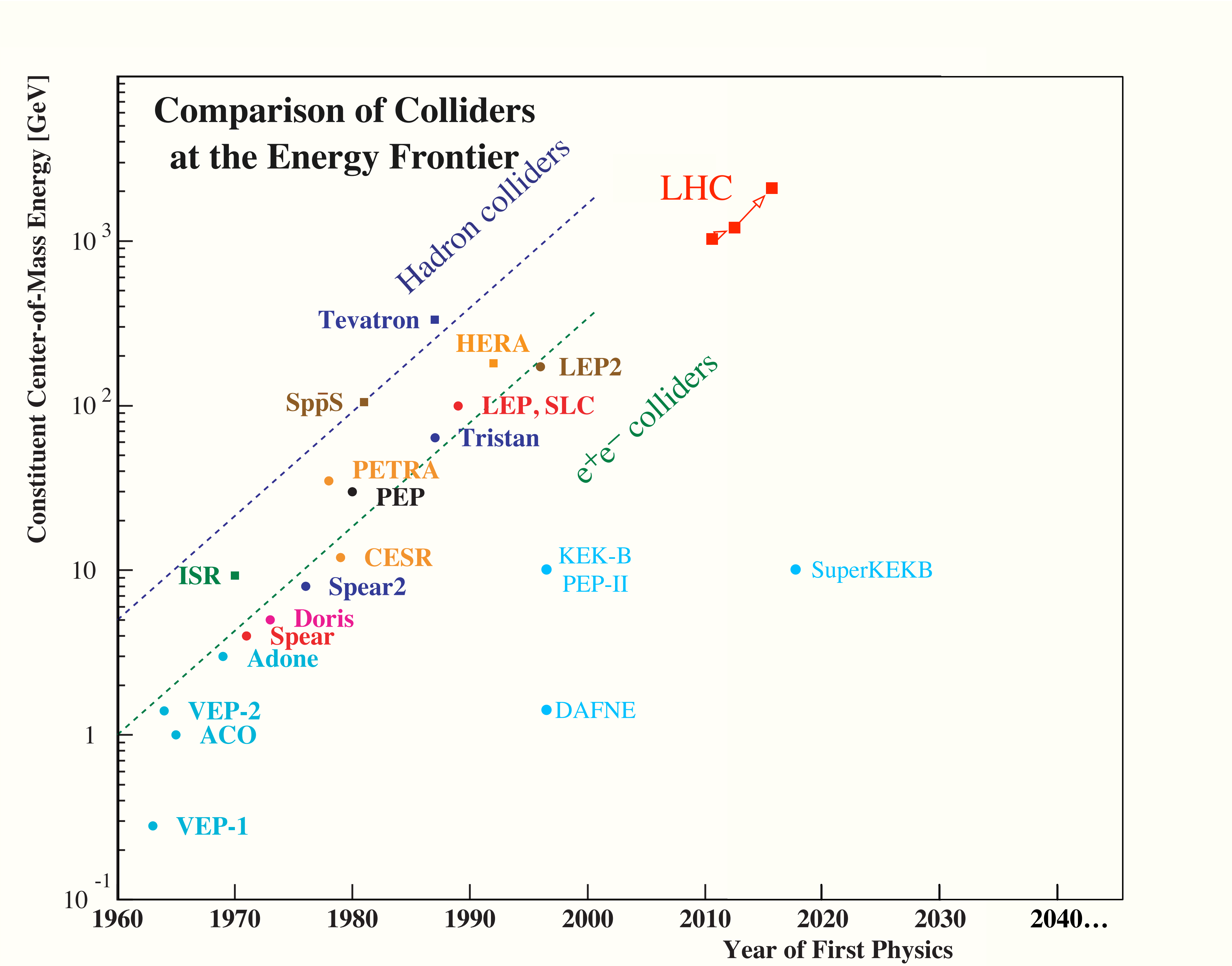




The Landscape - Past, Present and Future Colliders



taken from Nick Walker

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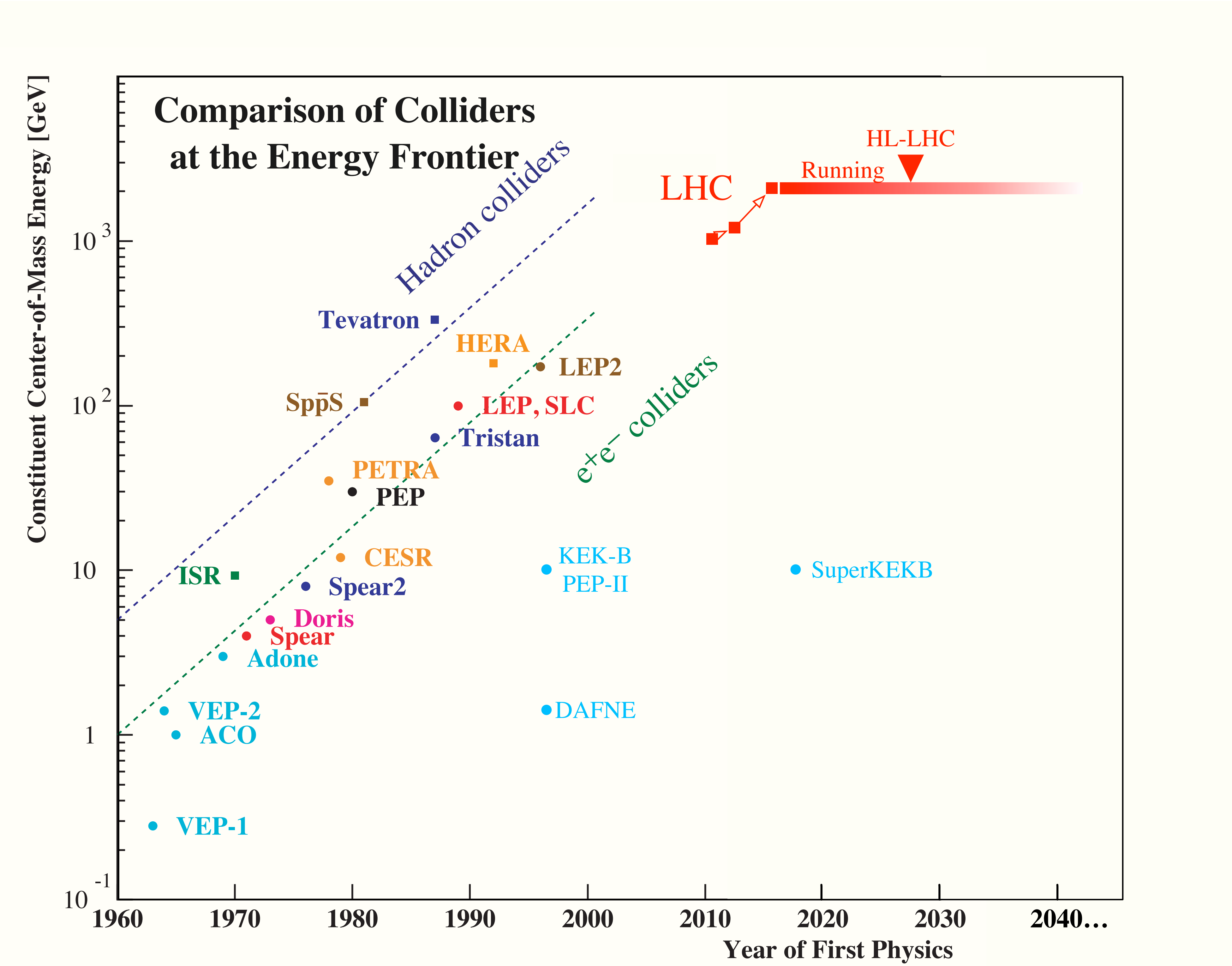

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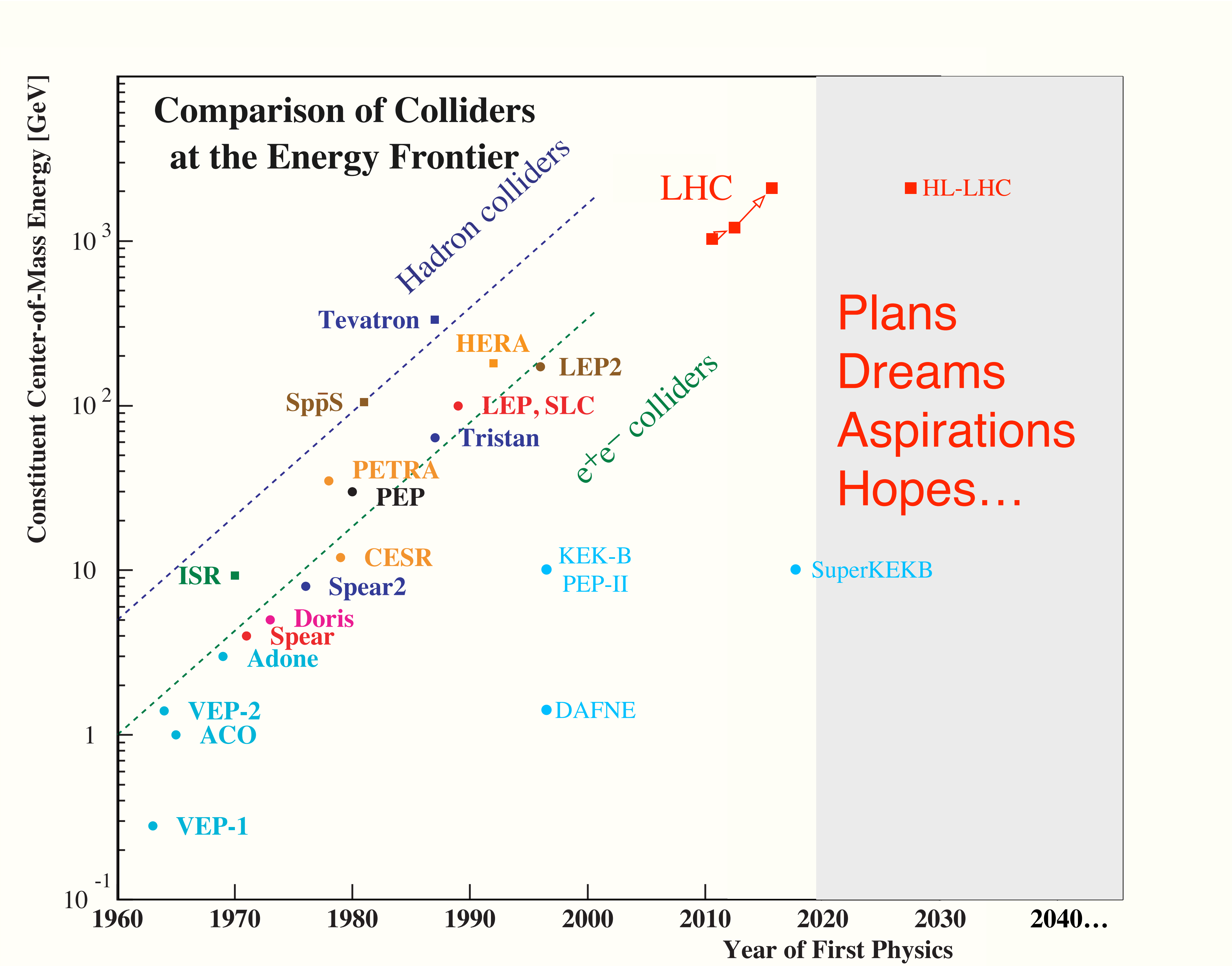

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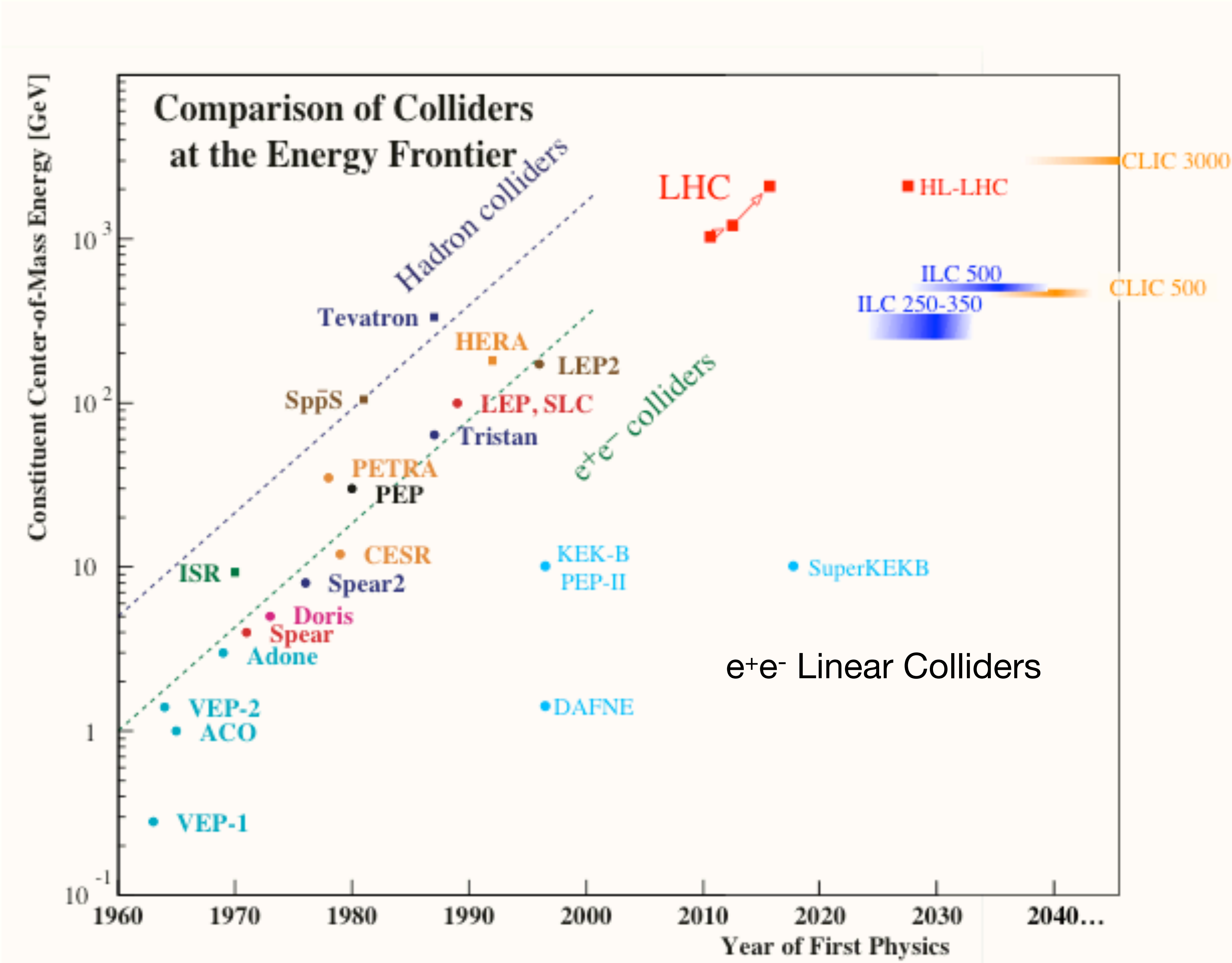

Linear Colliders:
30 - 50 km in length

taken from Nick Walker

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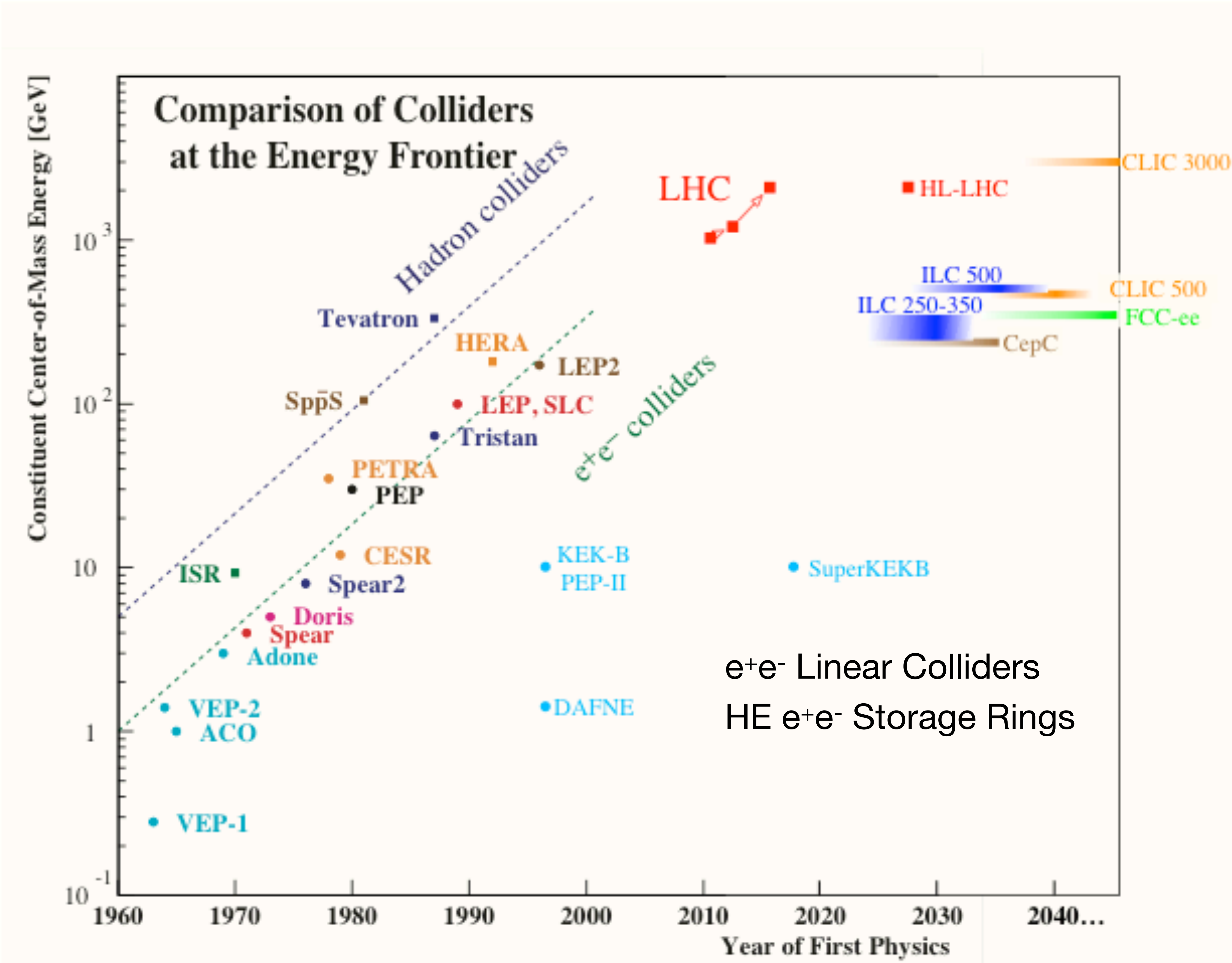

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Synchrotrons:
50 km - 100 km tunnels, main drivers typically pp, also come with e^+e^- option

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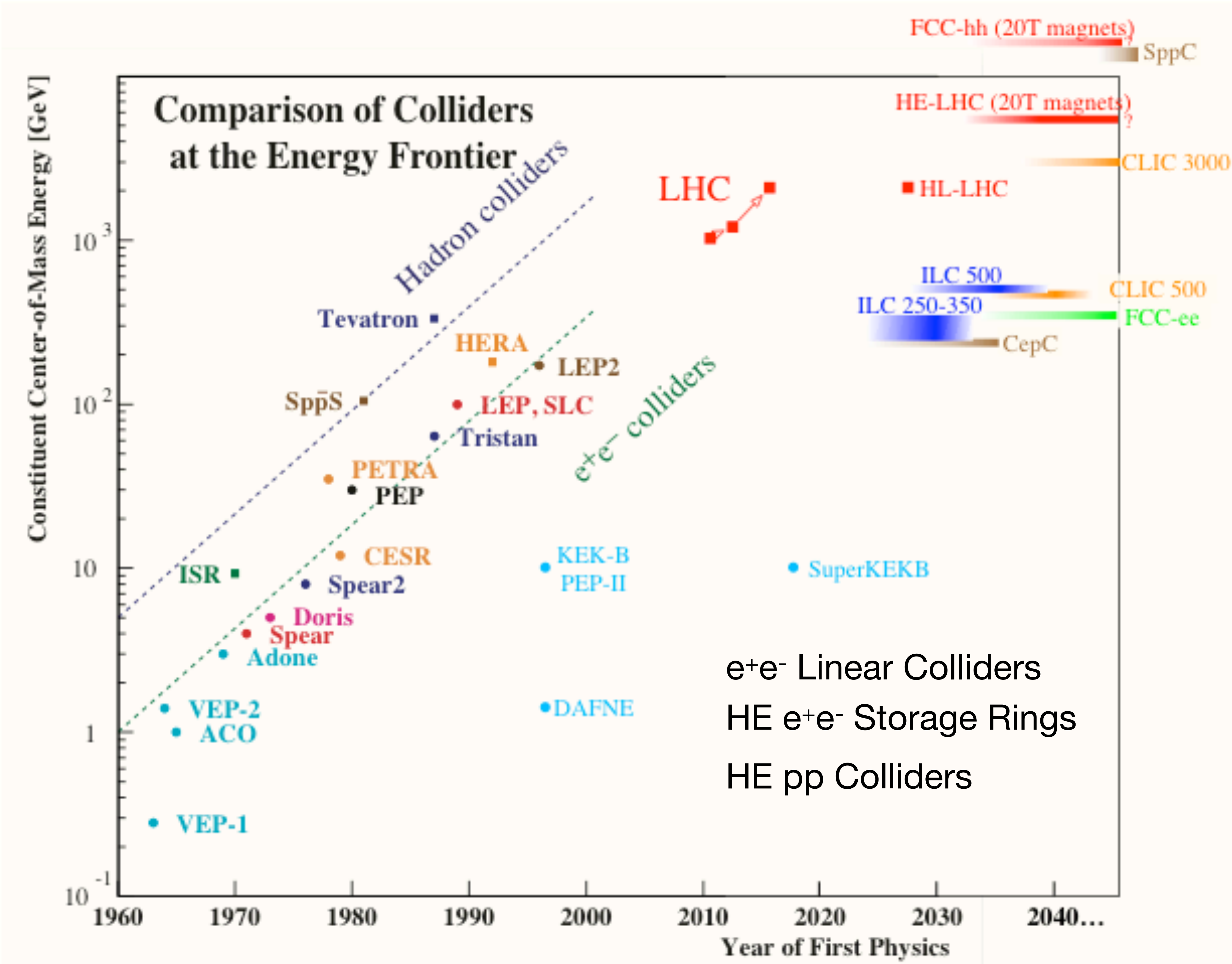

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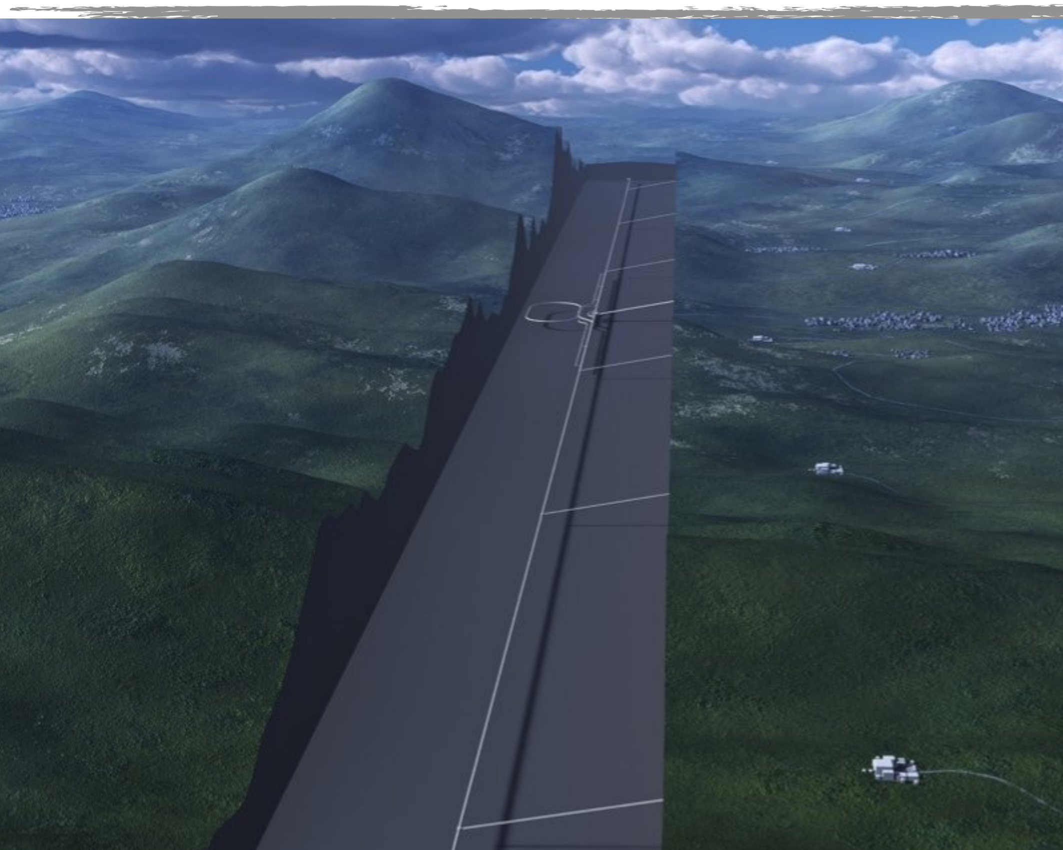
New Colliders - The Line-Up: Linear Colliders

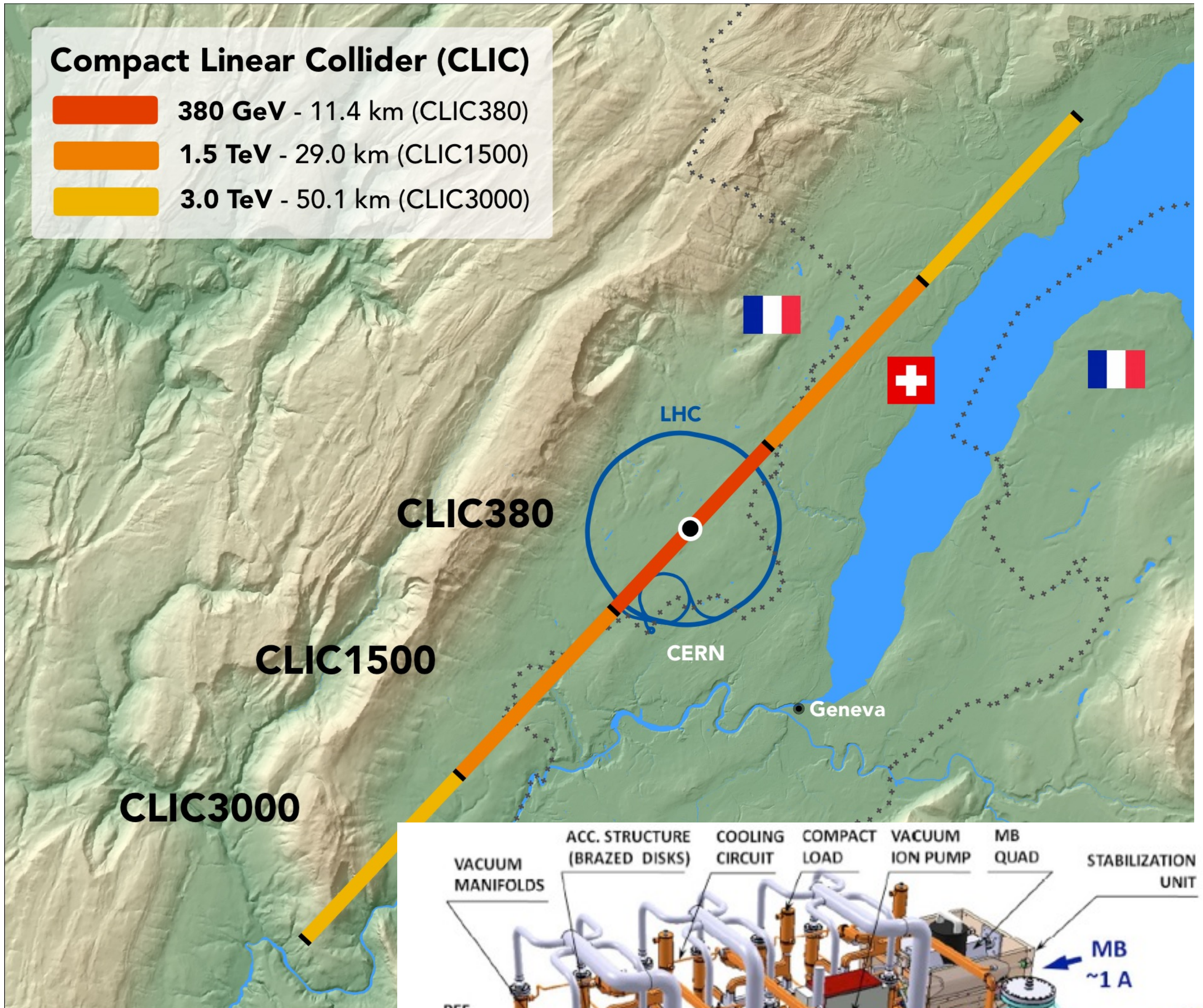


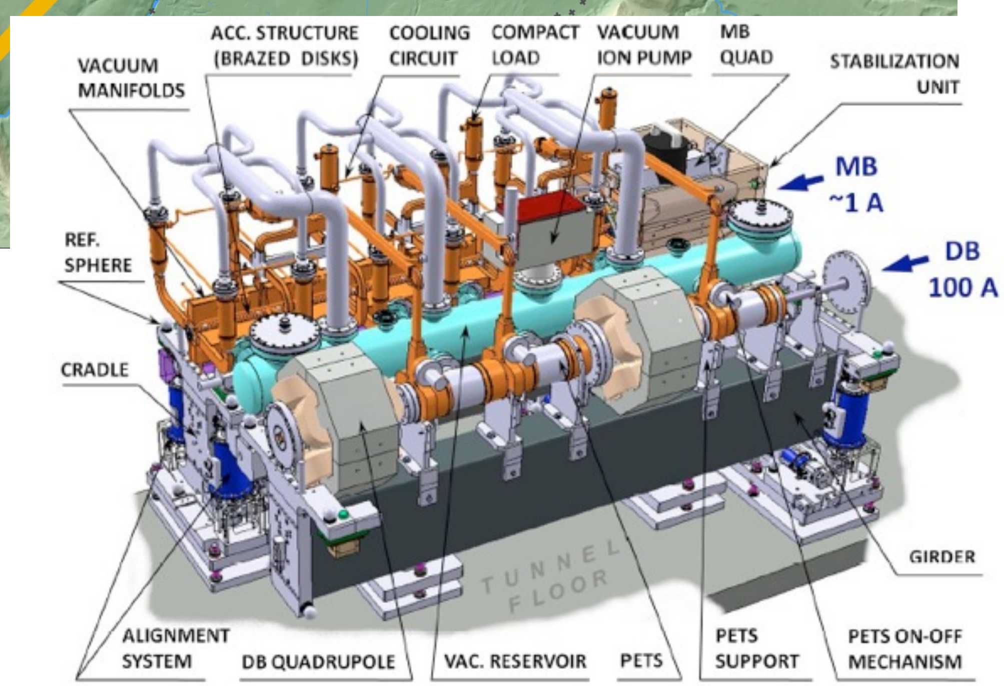
- The **I**nternational **L**inear **C**ollider: a 30 - 50 km long linear tunnel
  - e^+e^- collisions up to 500 GeV / 1 TeV for Higgs, Top, BSM
    - at present: 250 GeV starting scenario
  - Superconducting acceleration structures, ~ 30 MV/m
  - Technologically far advanced: Technical design report completed in 2012, ILC technology is being used for XFEL construction at DESY
  - Japan as potential host - Site north of Sendai (Kitakami)

Current time line

- Construction starting in 2023, physics 2032

New Colliders - The Line-Up: Linear Colliders





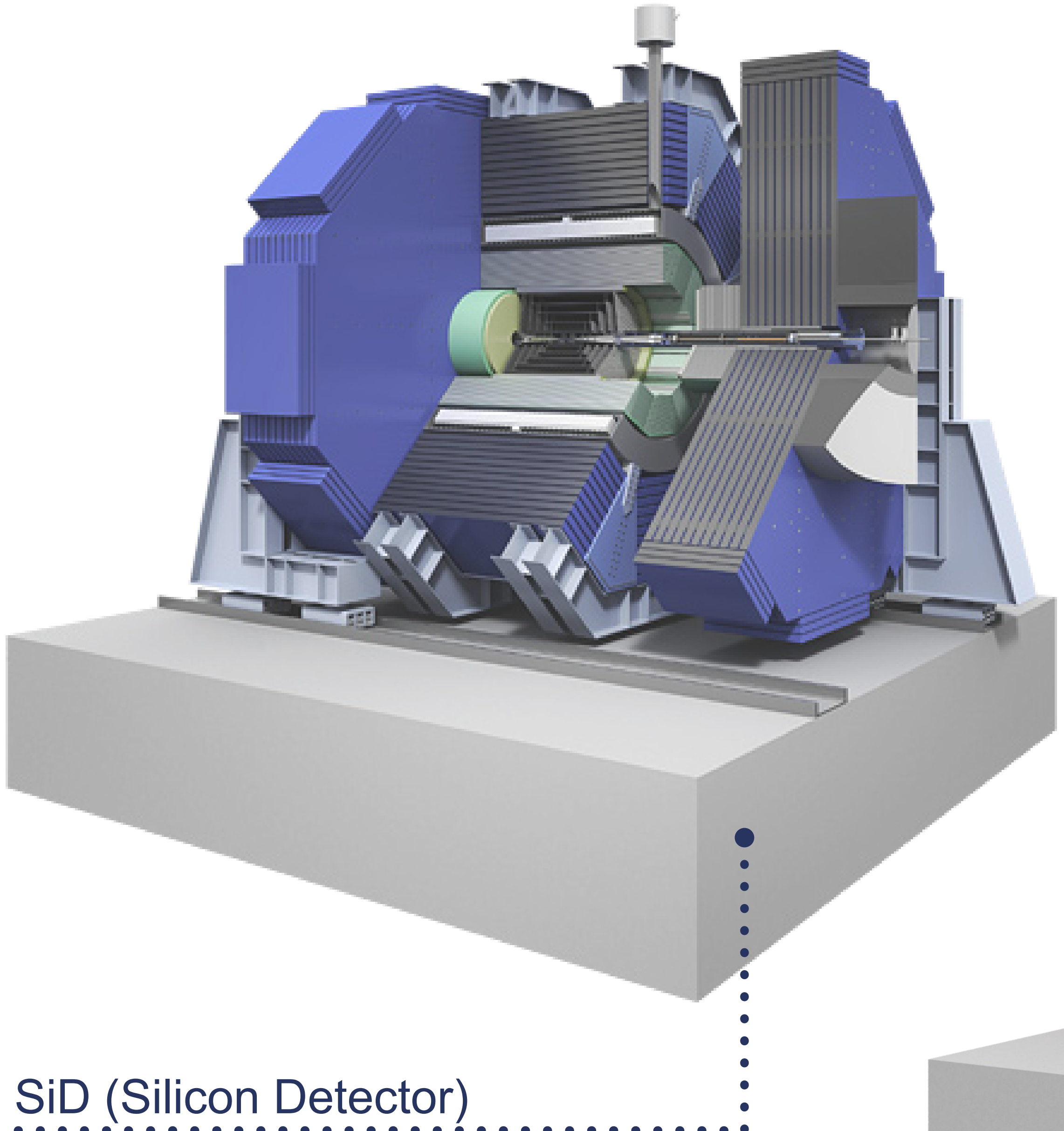
- The **C**ompact **Li**near **C**ollider:
  A 50 km long linear tunnel as one of CERNs future options
  - e^+e^- collisions up to 3 TeV for Higgs, Top, BSM
    - first stage at 380 GeV
  - Two-Beam acceleration, 100 MV/m
  - Main technological issues demonstrated, Conceptual Design report published in 2012

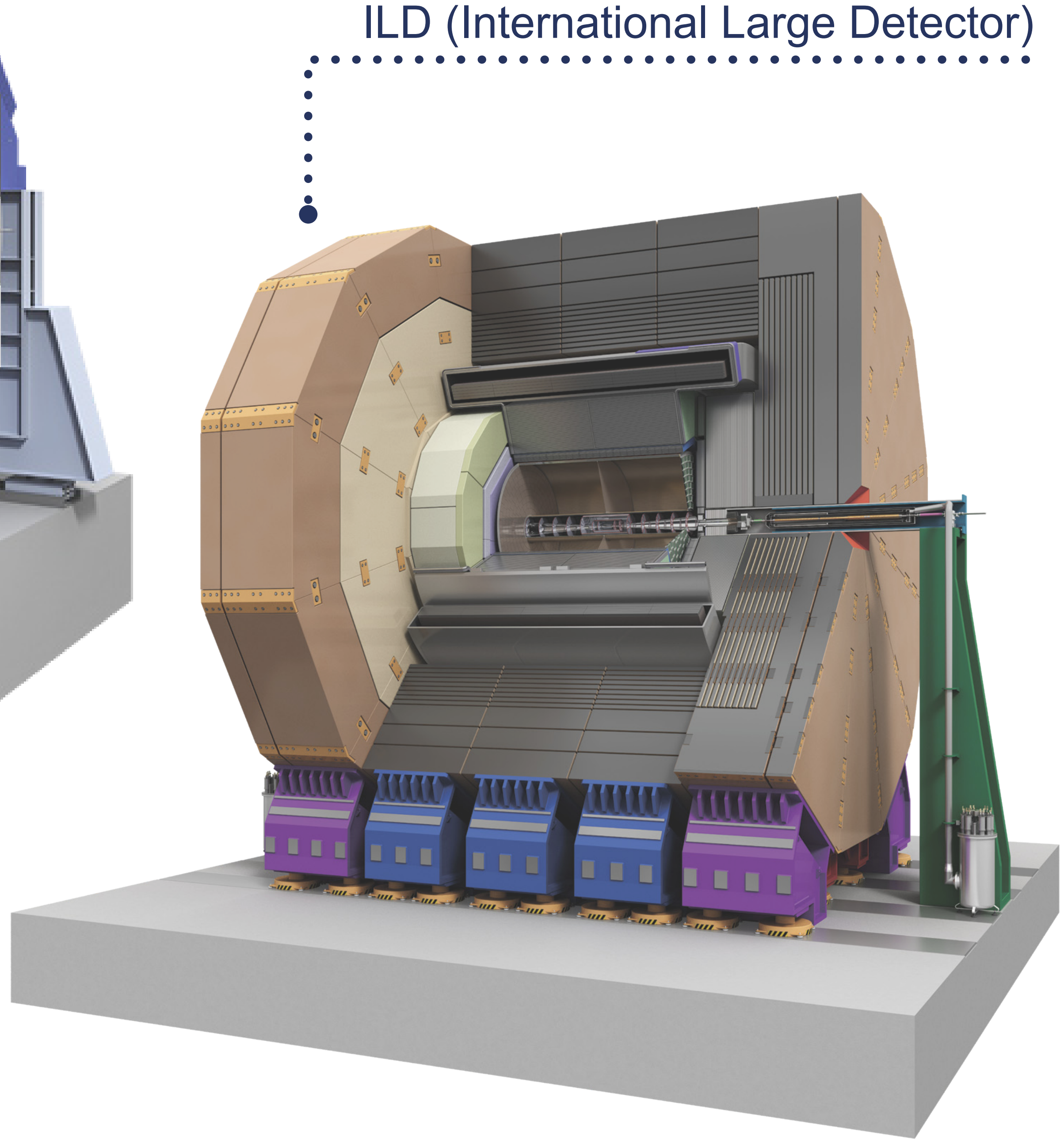
Current time line

- “Project Plan” this year
- Construction could start in 2025, physics by 2035

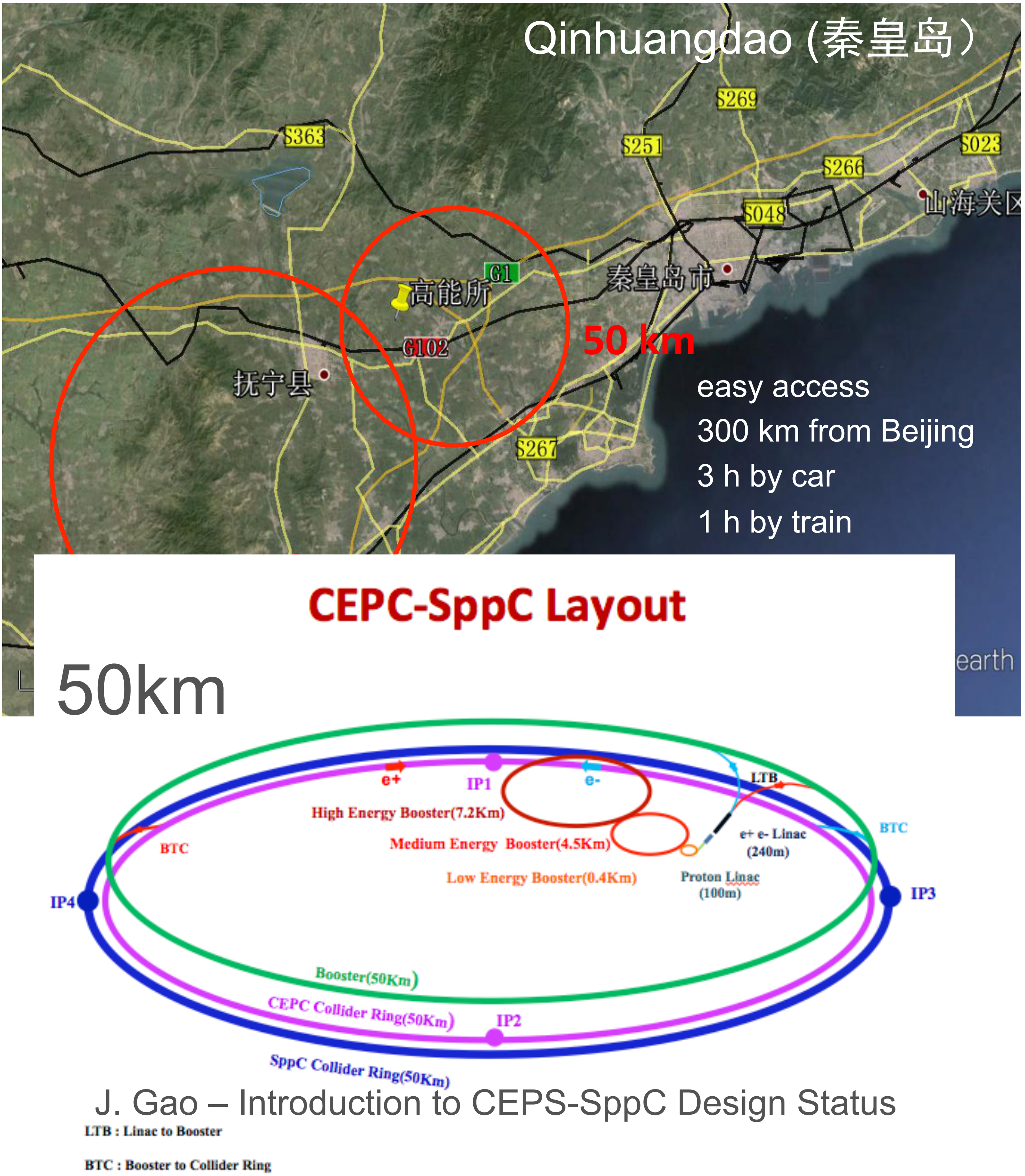
New Colliders - The Line-Up: Linear Colliders

- Concepts for the Experiments (“Detectors”) at ILC and CLIC exist, the physics capabilities have been studied in detailed simulations





New Colliders - The Line-Up: Rings

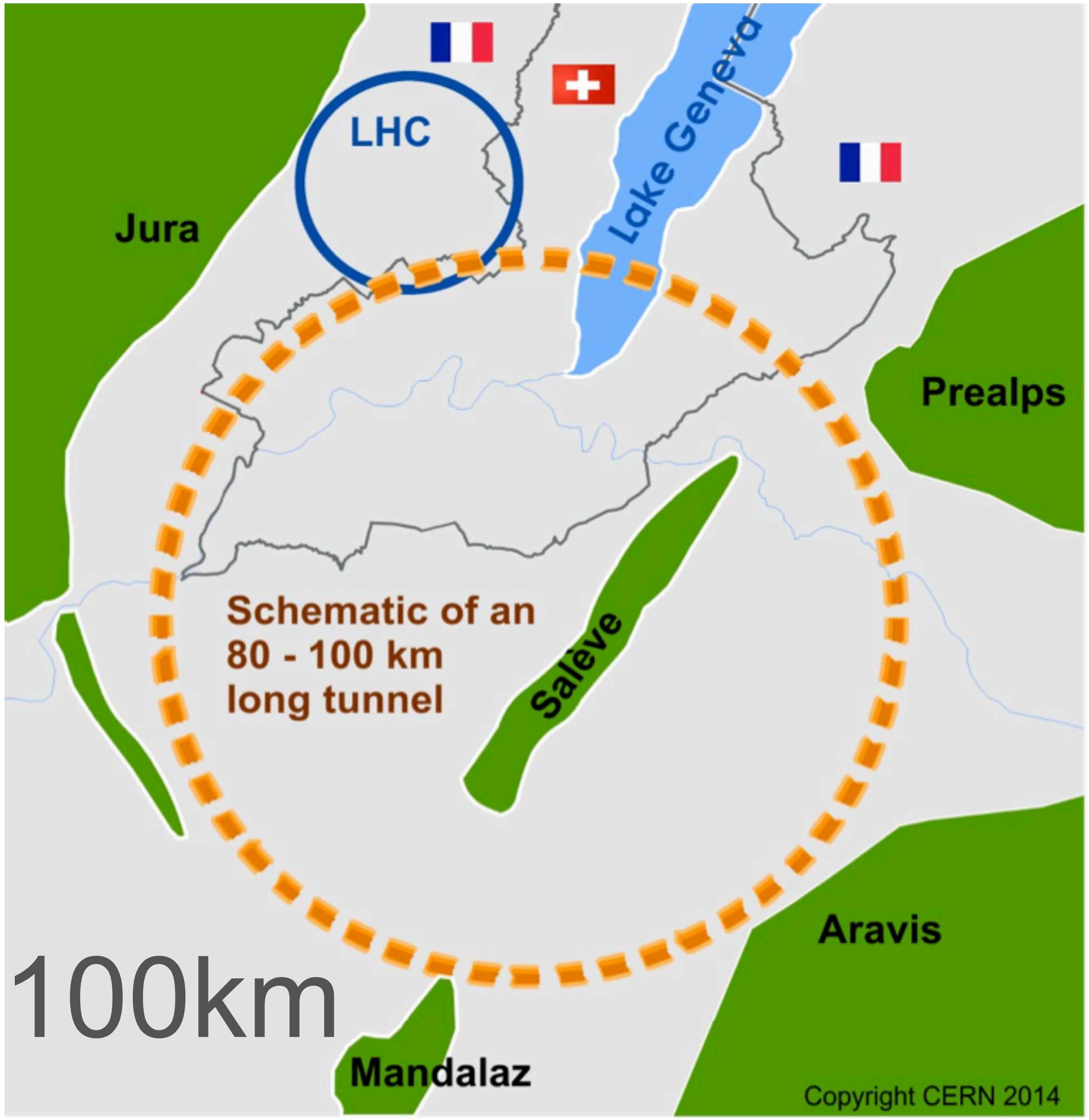


- A ~ 50 km (maybe 70 - 100 km) circumference ring in China (compare: LHC 27 km)
- “Dual-use”:
  - CEPC - e^+e^- collider with 240 GeV - just enough for Higgs production
  - SppC - pp collider with ~ 60 TeV - relies in 20 T dipole magnets

Current time line

- First stage: e^+e^- - R&D until 2022, could run by 2028
- Second stage: pp - R&D until 2030, technical design until 2035, could run by 2045

New Colliders - The Line-Up: Rings

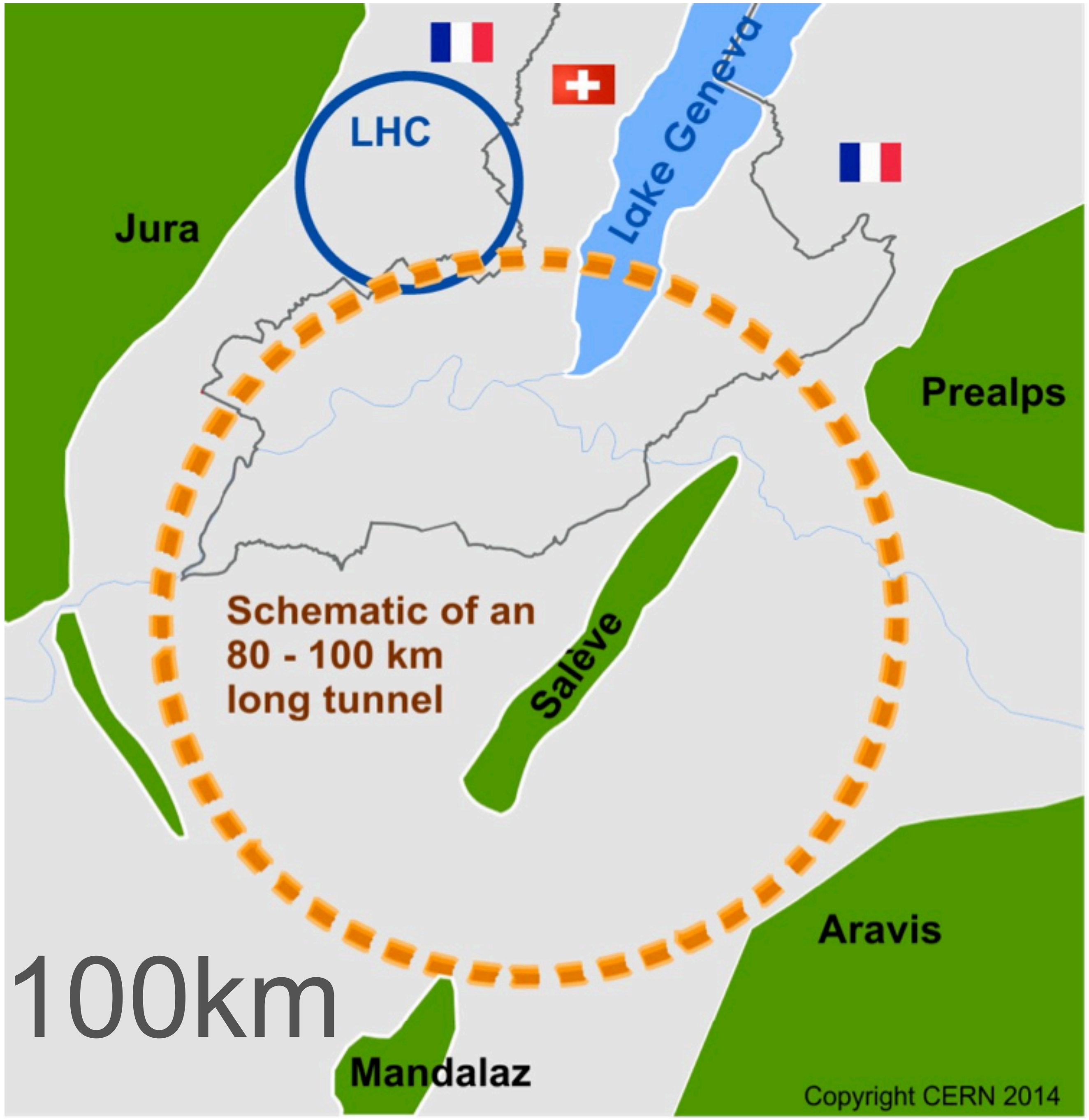


- A ~ 100 km circumference ring at CERN as one of CERNs future options (compare: LHC 27 km)
- "Dual-use":
  - FCCee - e^+e^- collider with ~ 400 GeV - Higgs and Top
  - FCChh - pp collider with ~ 100 TeV - ~16 T dipole magnets

Current time line

- Conceptual Design by 2018
- e^+e^-: R&D, Prototyping until ~2027, Could run by ~ 2038
- hh: R&D and prototypes until ~2036, Could run by 2045 (later if e^+e^- first)

New Colliders - The Line-Up: Rings



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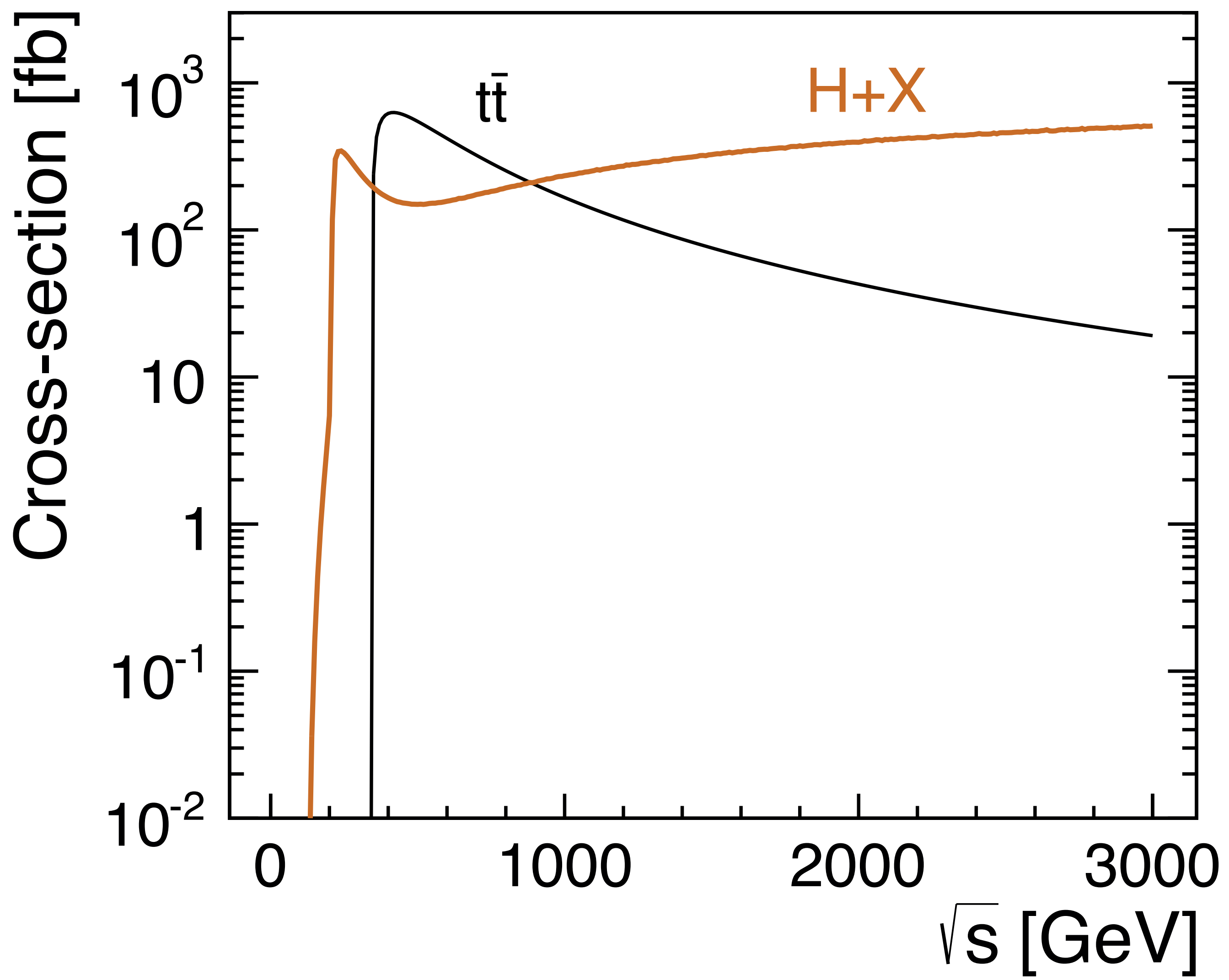
Also a likely (maybe more likely?) possibility within the same project:
HE-LHC: 16 T magnets in the LHC tunnel, to reach ~ 27 TeV

The Physics of Future Colliders

- with a slight emphasis on Linear Colliders -

Electron-Positron Colliders: Guaranteed Program

- The main focus of present studies: Higgs and Top physics
  - In addition: Interest in high precision measurements at the Z pole and at the WW threshold



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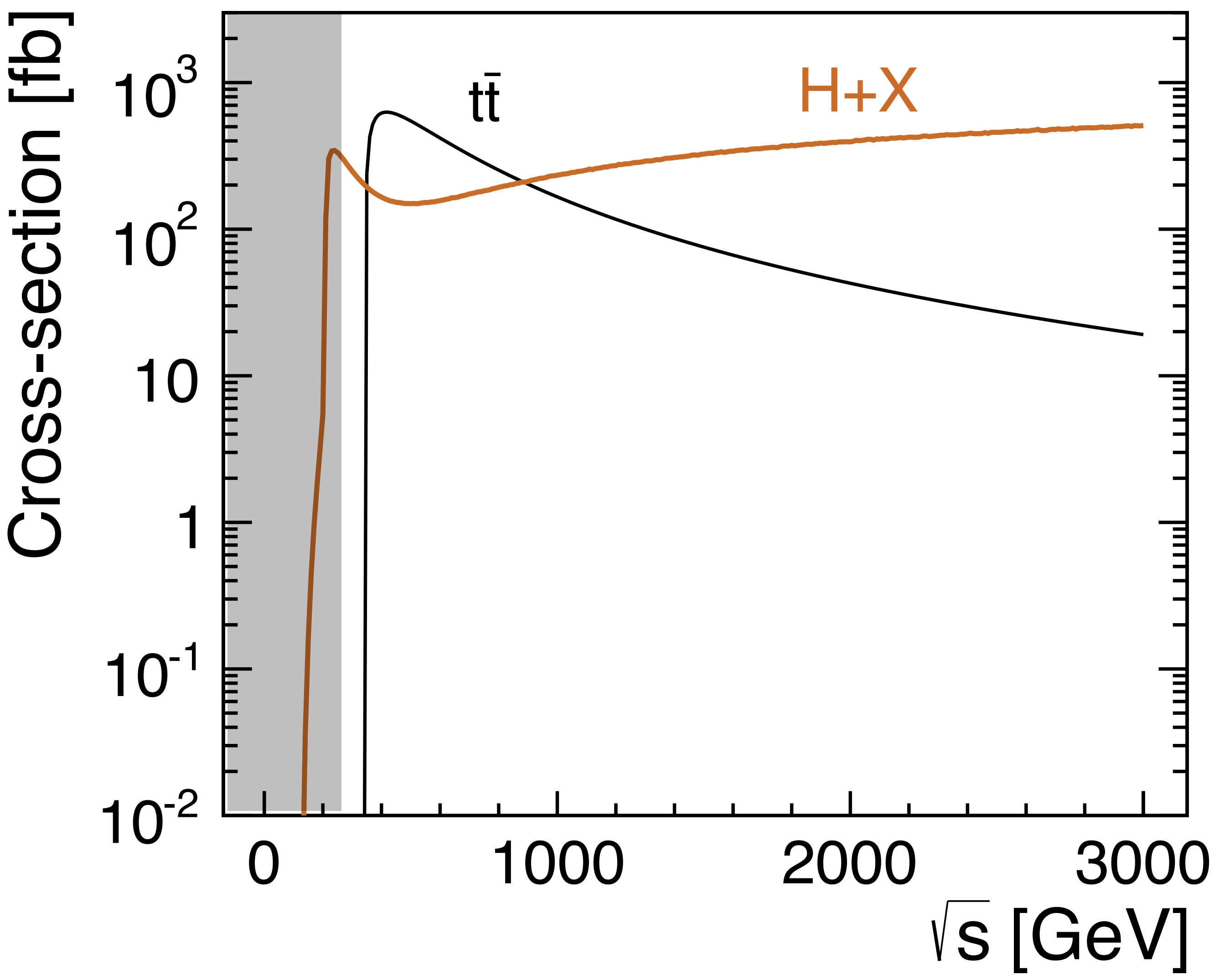
  CEPC / ILC250: 250 GeV



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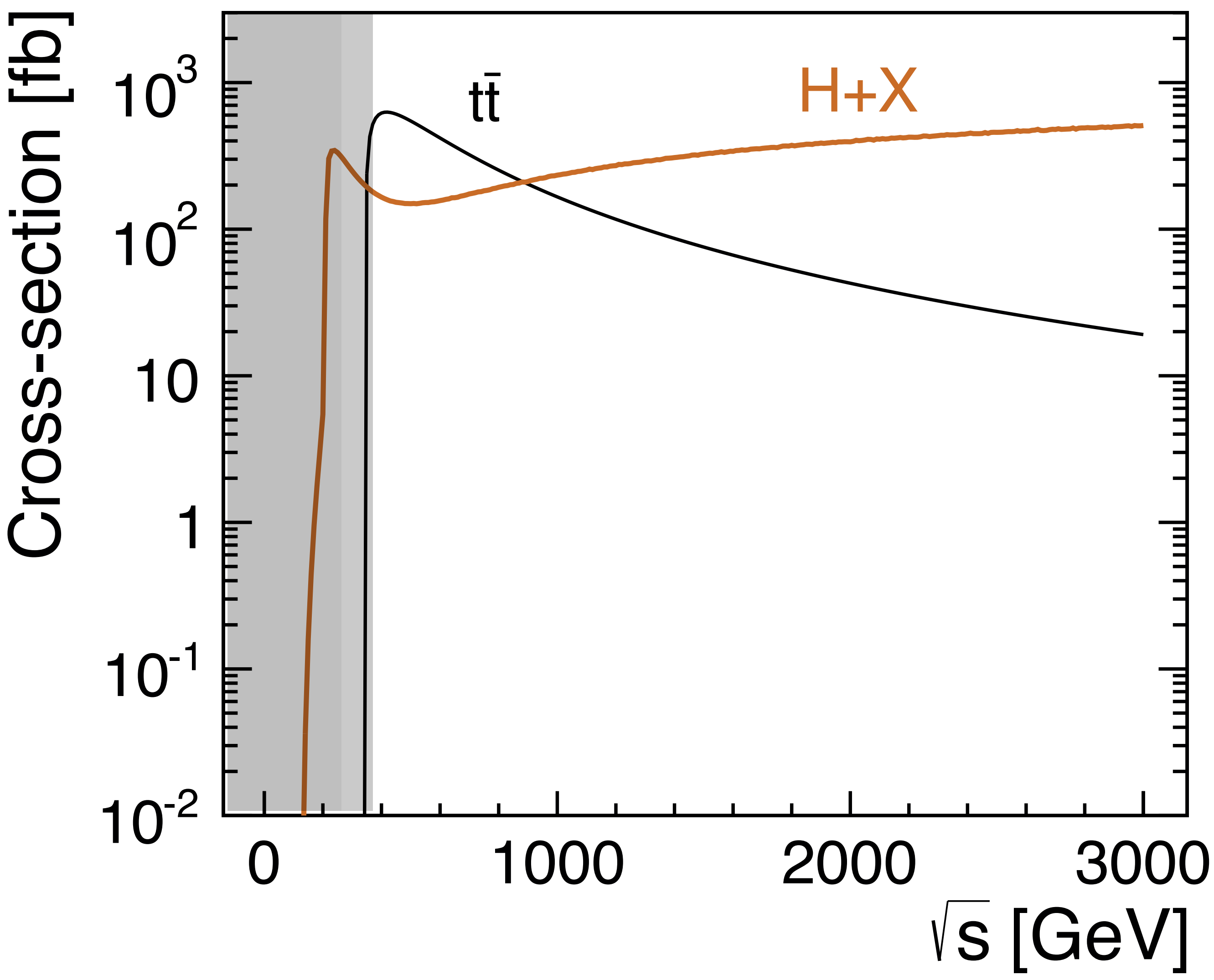

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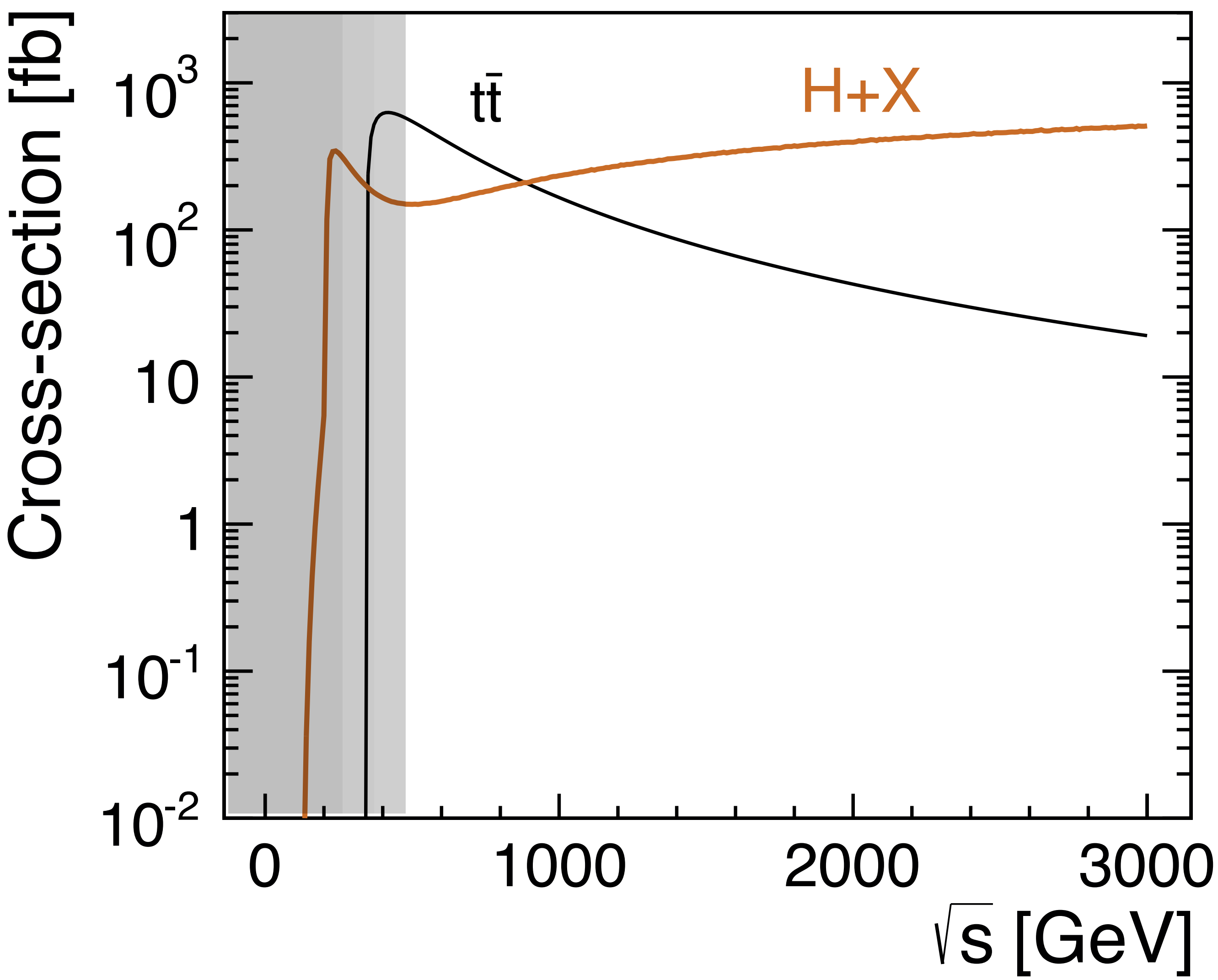

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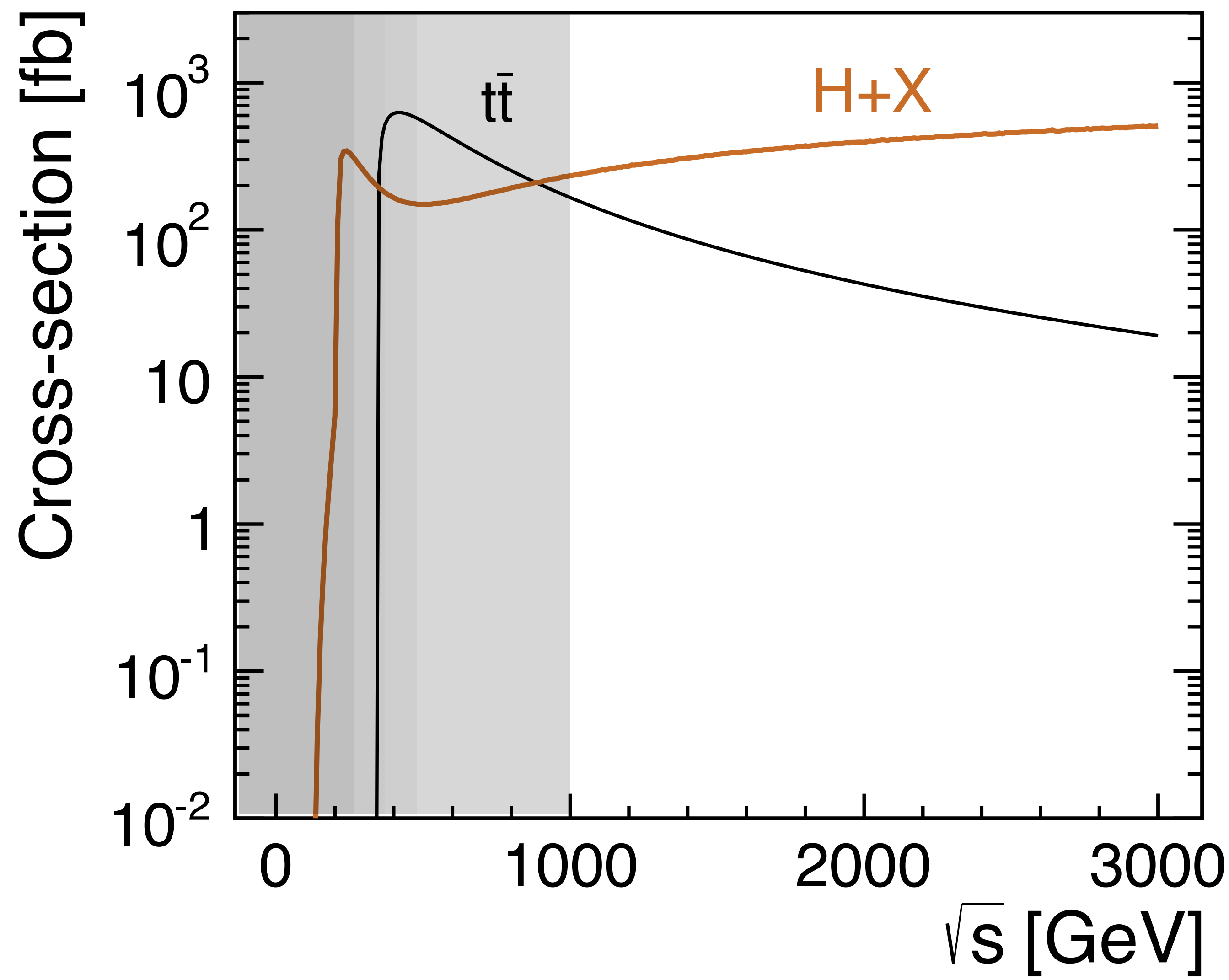
  ILC1TeV: 1 TeV



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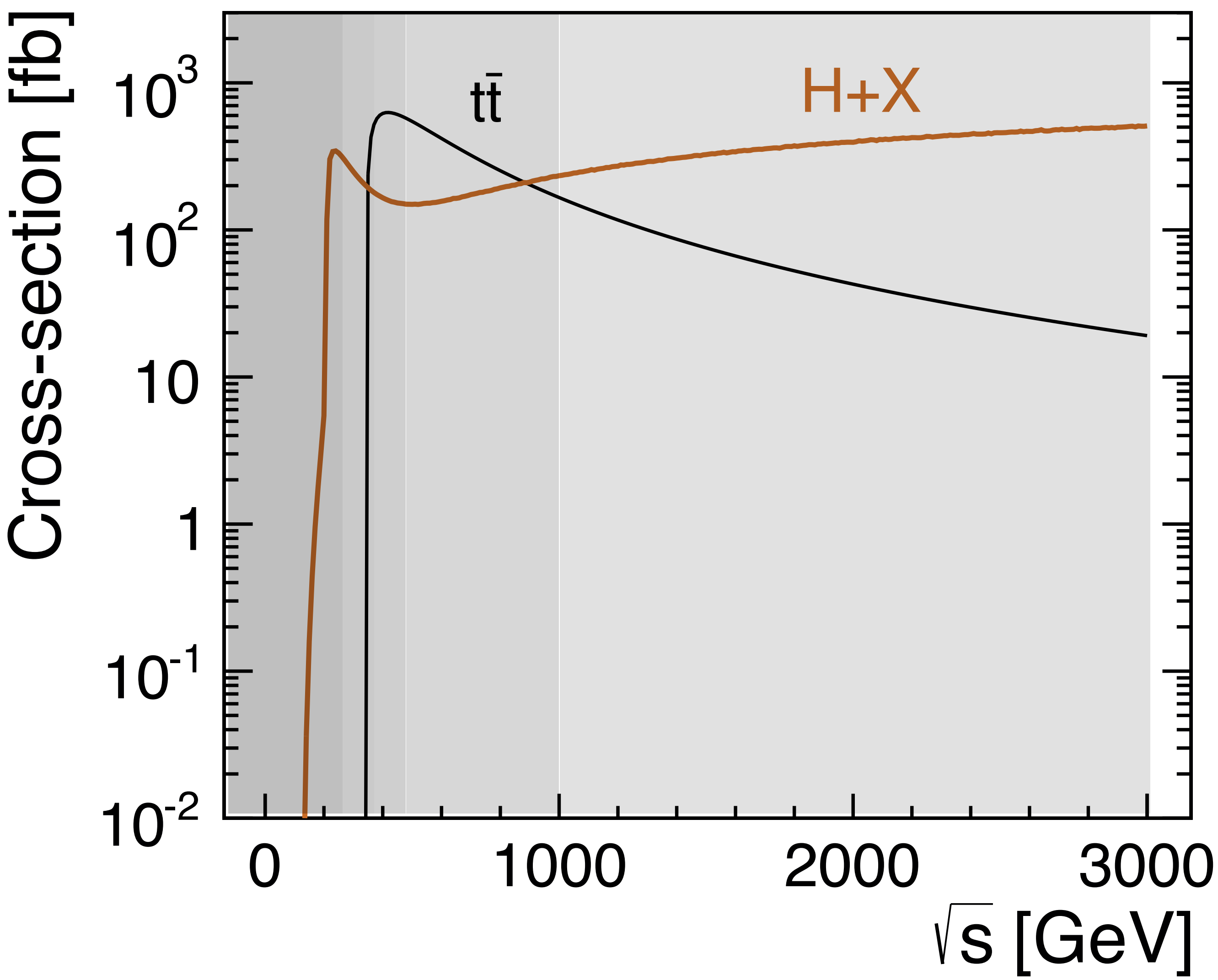
ILC1TeV: 1 TeV

CLIC: 3 TeV



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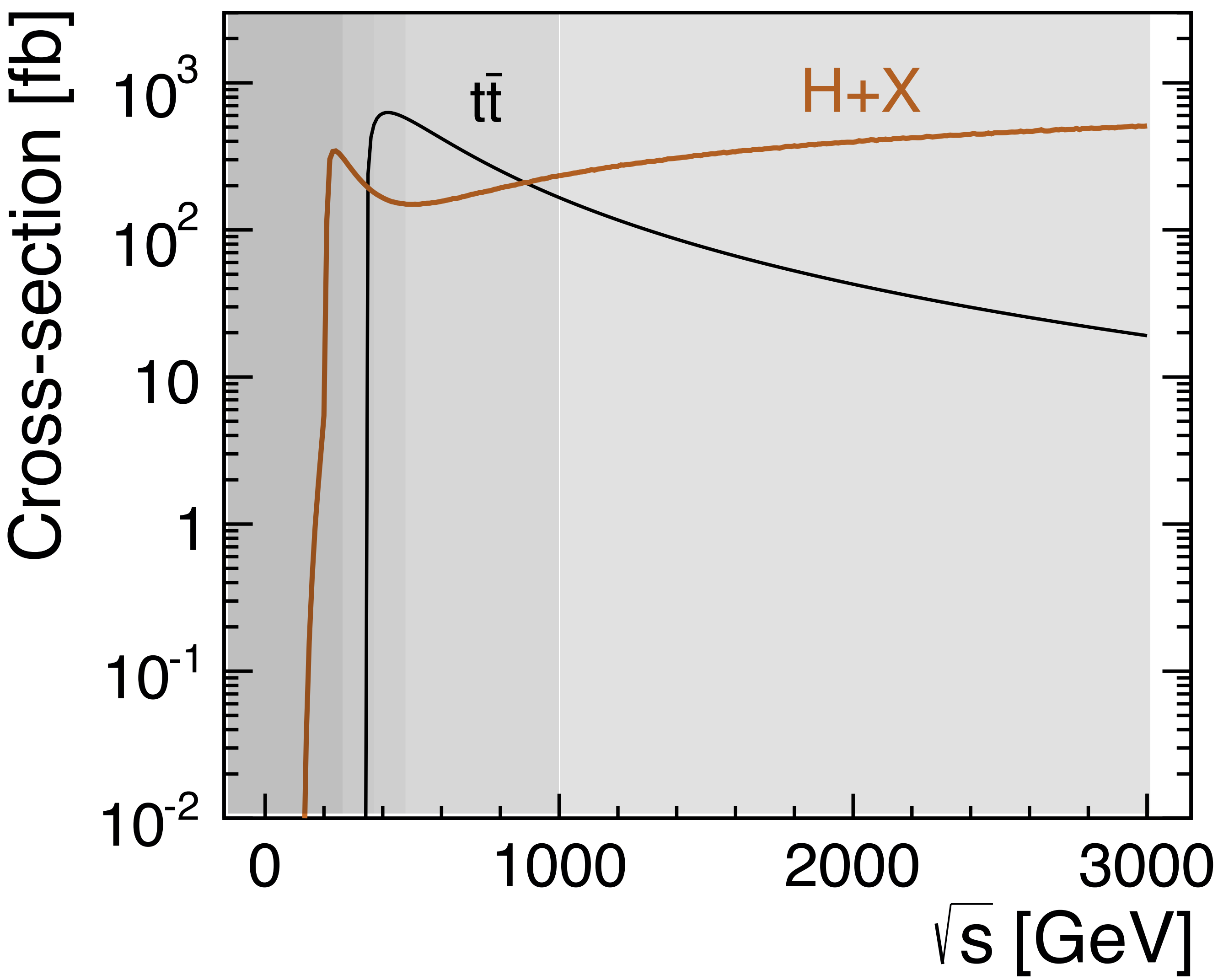

The strength of circular machines: High luminosity at low energy - Z and W physics, some aspects of Higgs physics with high statistics, potentially top threshold physics

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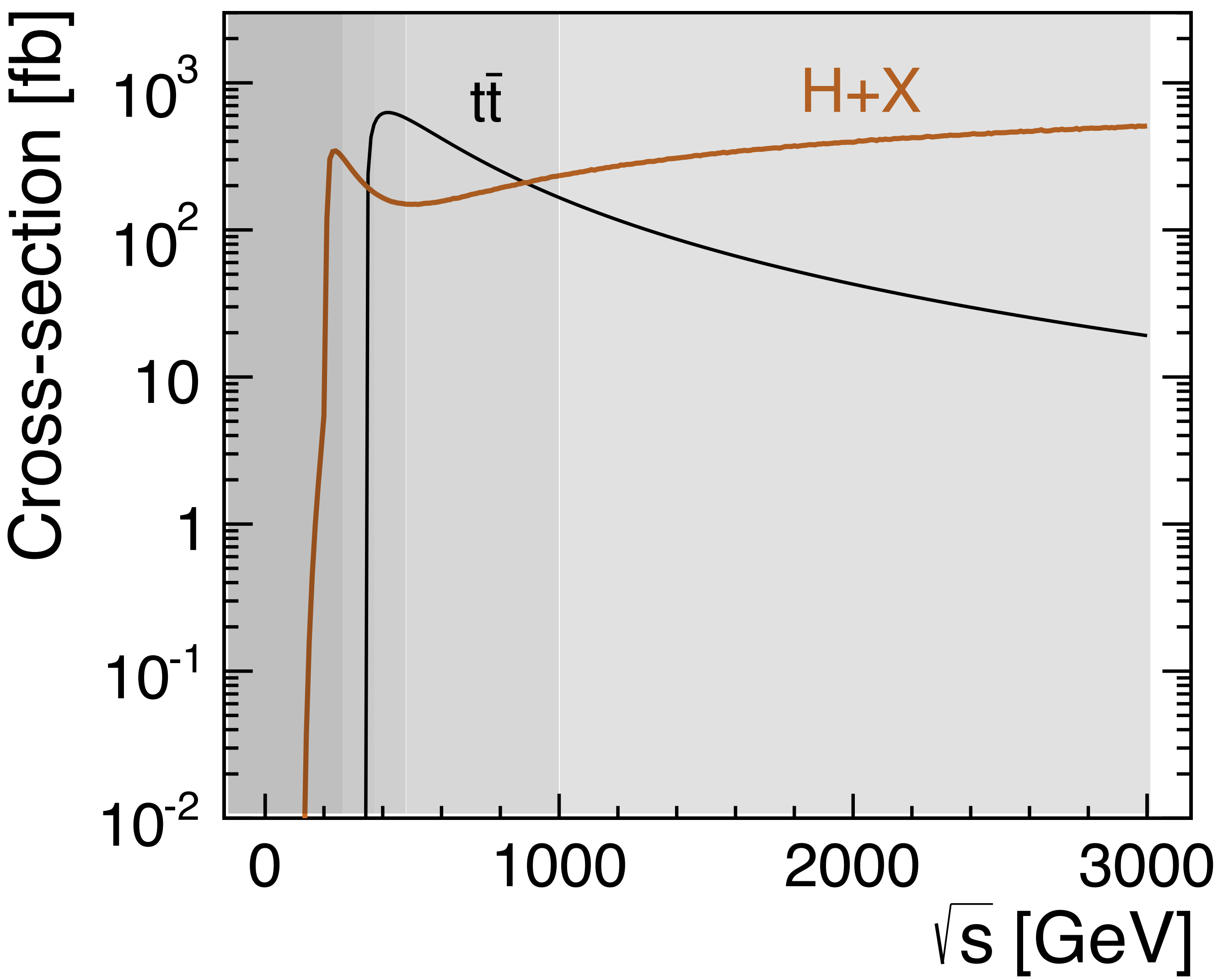
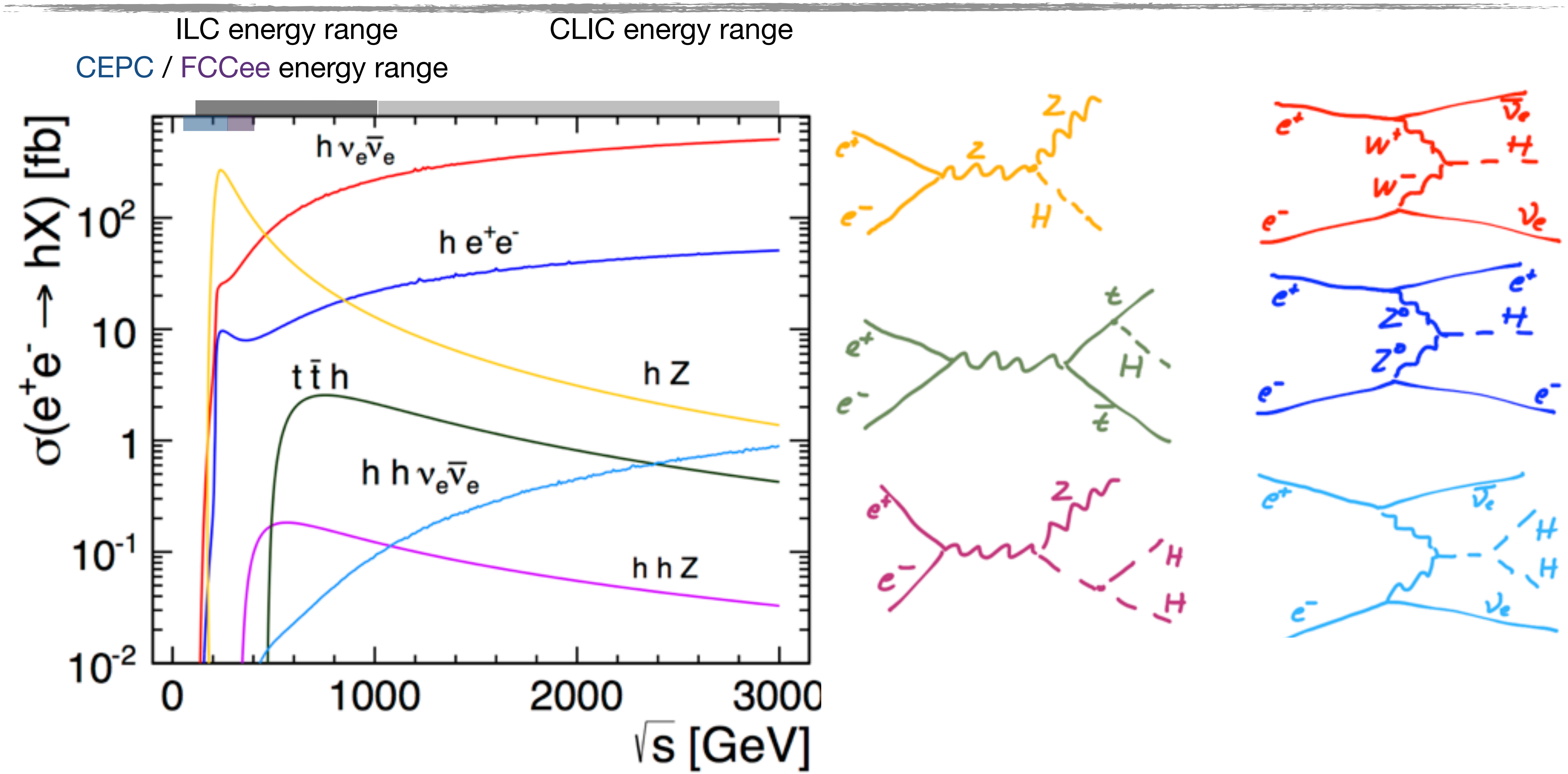


The strength of circular machines: High luminosity at low energy - Z and W physics, some aspects of Higgs physics with high statistics, potentially top threshold physics

The strength of linear machines: High luminosity at high energy - Full coverage of Higgs physics, top threshold and continuum physics

e^+e^-: A Closer Look at Higgs Production



- Several different Higgs production mechanisms
  - Access to various Higgs properties
  - Different energy to access different processes - from **250 GeV** to **1 TeV** and beyond

Precision Measurements of the Higgs

- A flagship measurement: Model-independent Higgs couplings
  What it means: Measure the coupling of the Higgs to bosons and fermions free from model assumptions (e.g. how it decays)
  - Requires: The “tagging” of Higgs production without observing the particle directly
    - Not possible at hadron colliders

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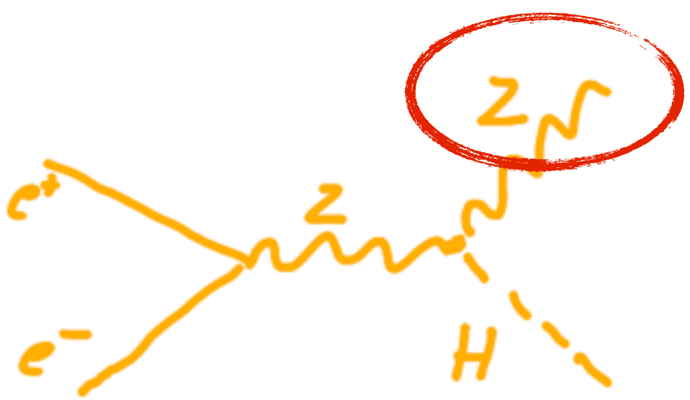
The strategy in e^+e^- collisions:

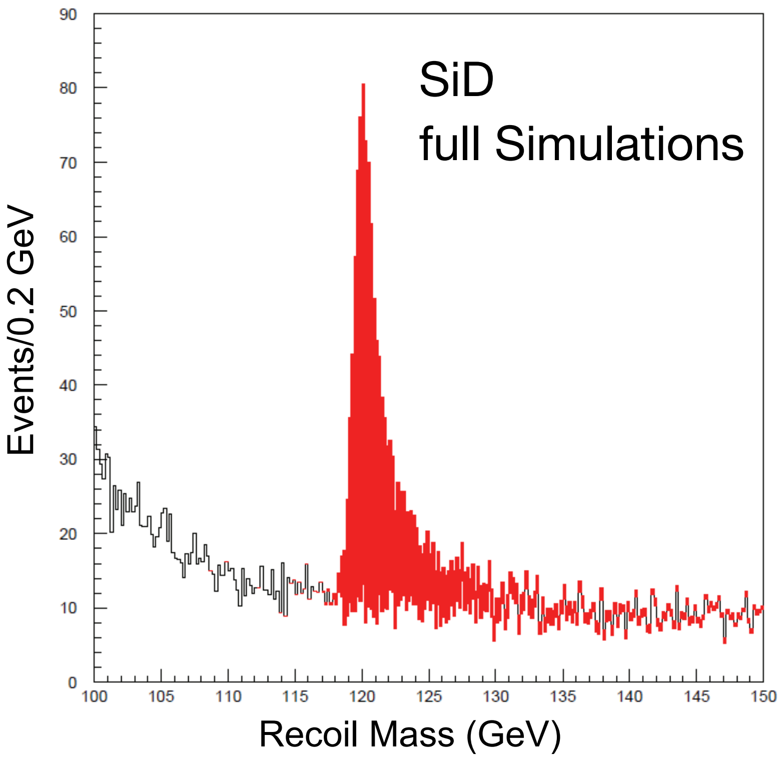


measure ***only*** the Z boson
from the known e^+e^- center-of-mass energy, calculate the “recoil mass”:

$$m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$

Exploits: known initial state in e^+e^-
Requires: Identification of Z independent of decay mode of H (or any other particle)
➯ Best results for Z -> μμ, but (almost) model-independent measurements also possible in Z -> qq

Model-Independent Measurement of H Production



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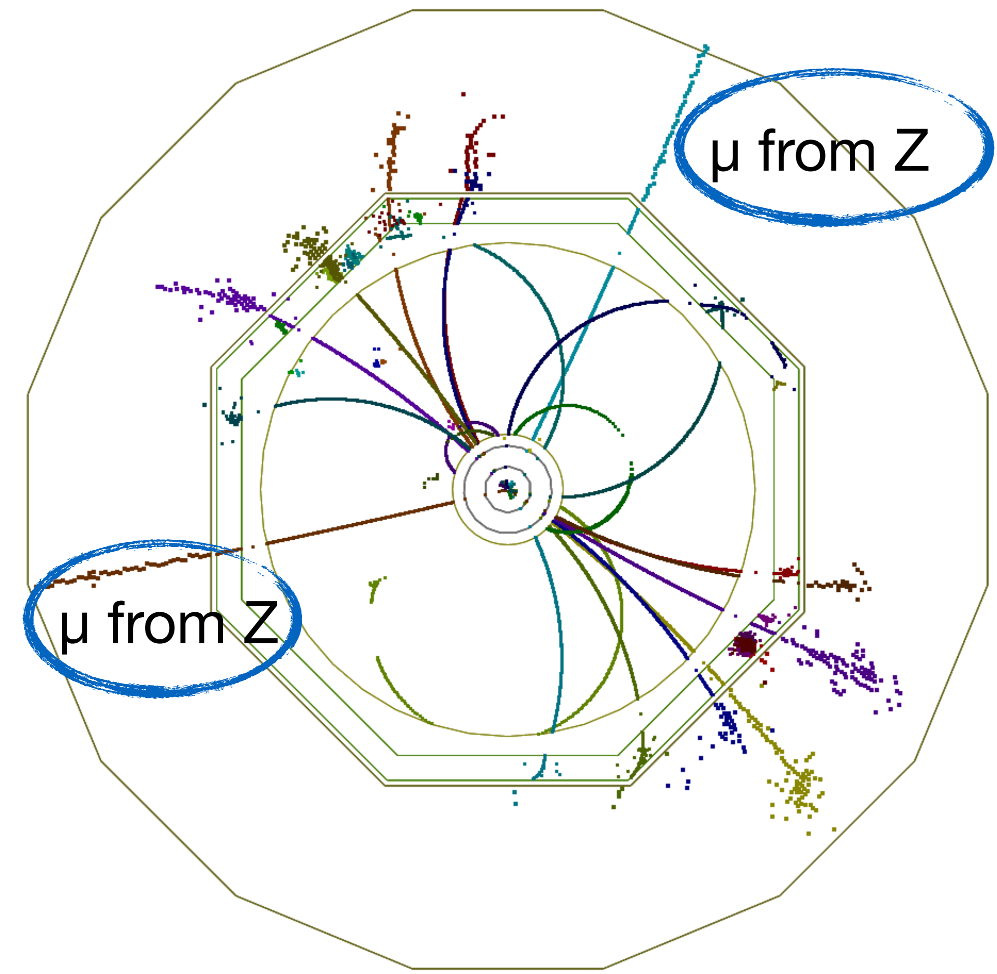

$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

What this provides: Total ZH cross section, and with coupling of H to Z

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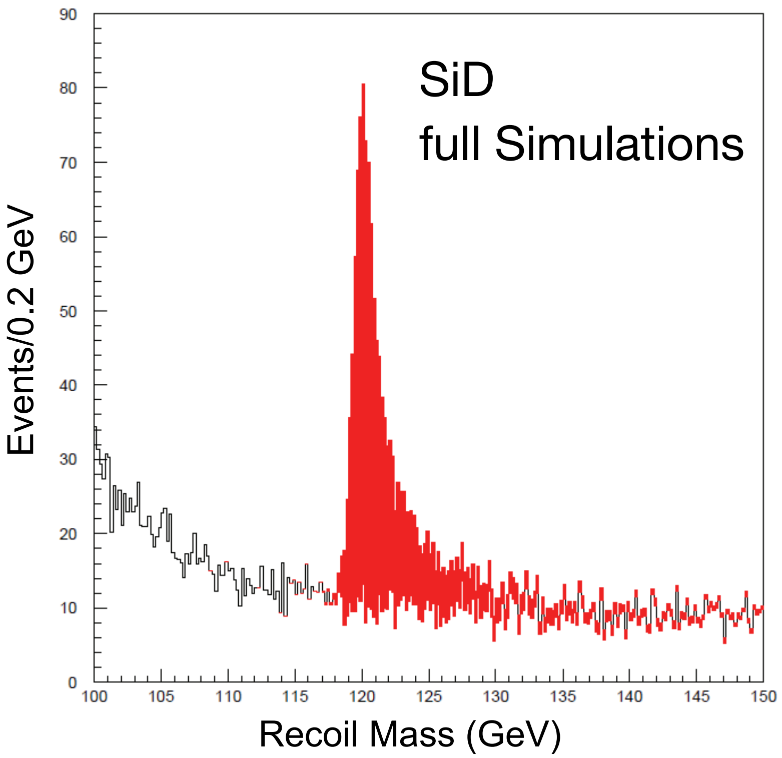

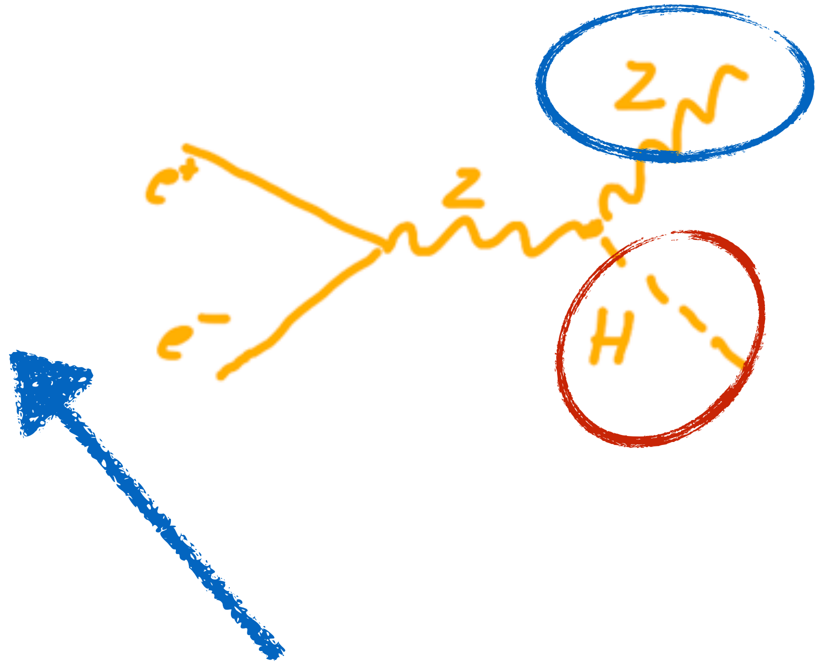

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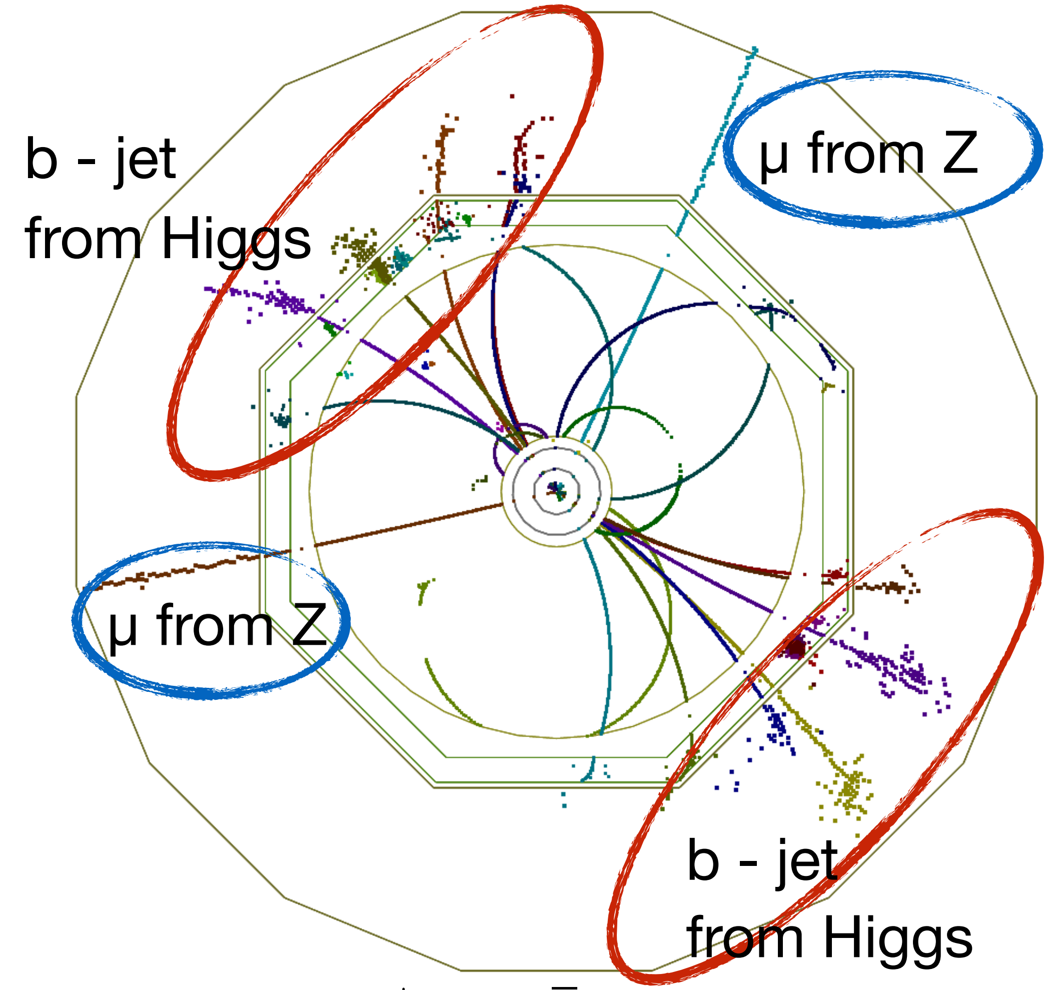

$e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

What this provides: Total ZH cross section, and with coupling of H to Z

- In addition: Reconstruction of specific final states provides access to couplings to fermions and bosons via Higgs decay
  - Makes use of “clean” e^+e^- environment - also allows the reconstruction of final states which are not accessible at hadron colliders: cc, gg

Higgs Processes at Higher Energy

- Direct measurement of the coupling to the top quark (requires at least 500 GeV)

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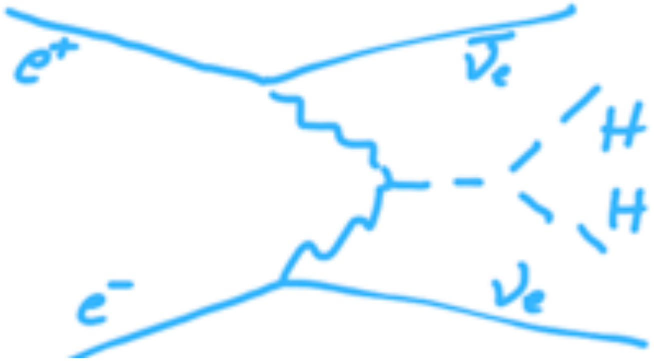
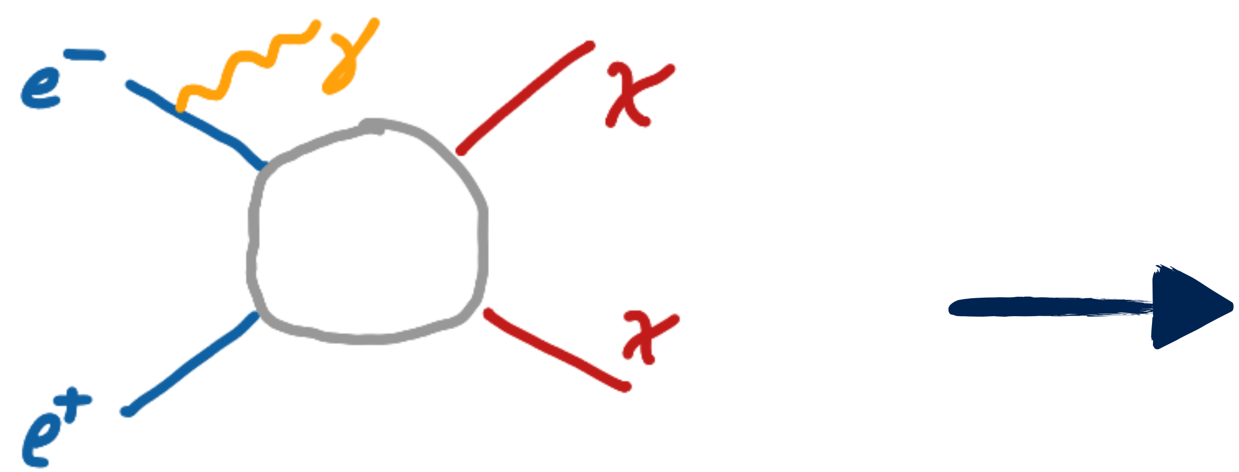
- The ultimate challenge: The Higgs self-coupling
  - Directly study the Higgs potential - prove (or disprove) the Higgs mechanism

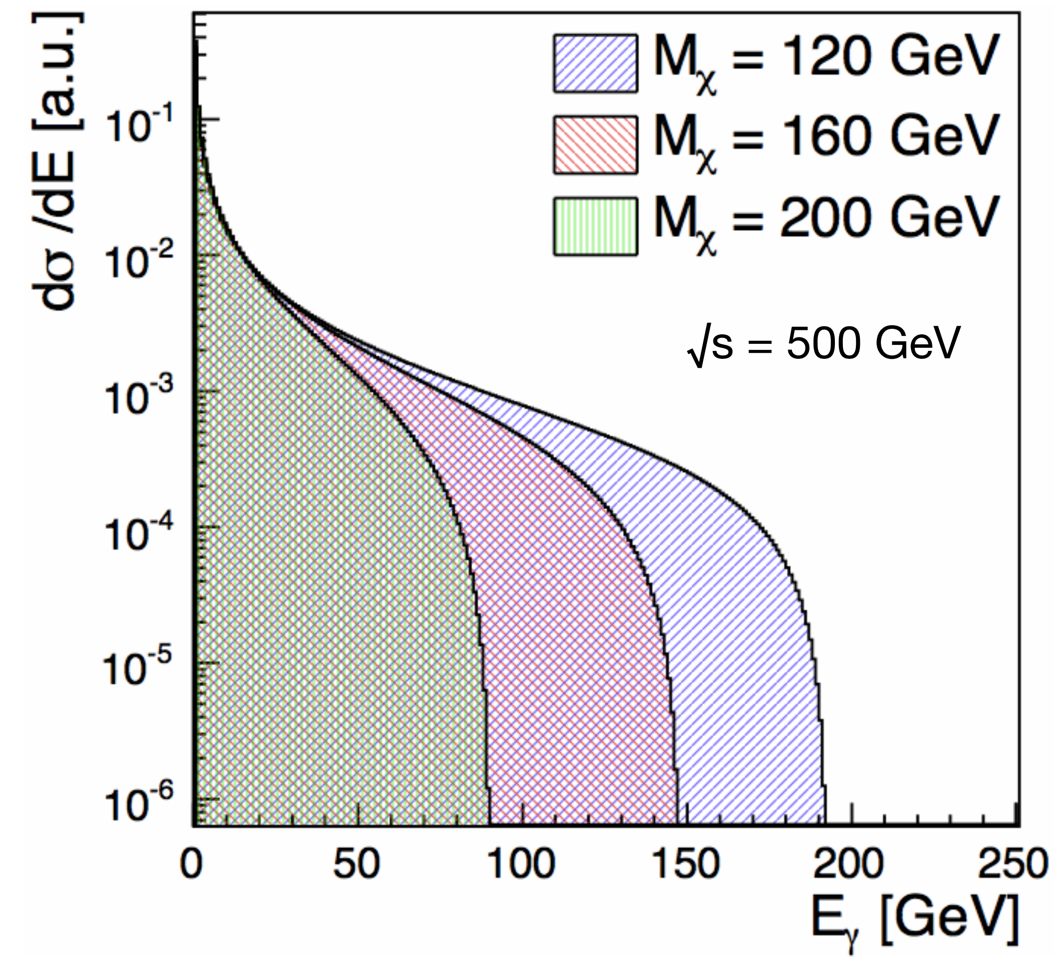


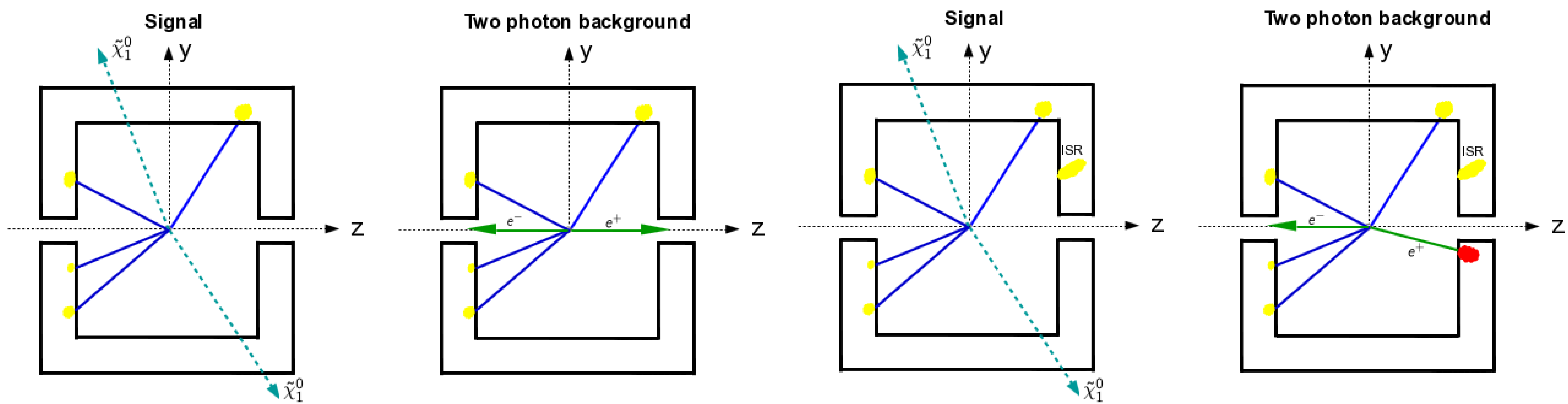
- First measurements possible at 500 GeV - significant results require 1+ TeV and high luminosity

New Physics in e+e- - Making the Invisible Visible

- A key goal: Studying dark matter at colliders





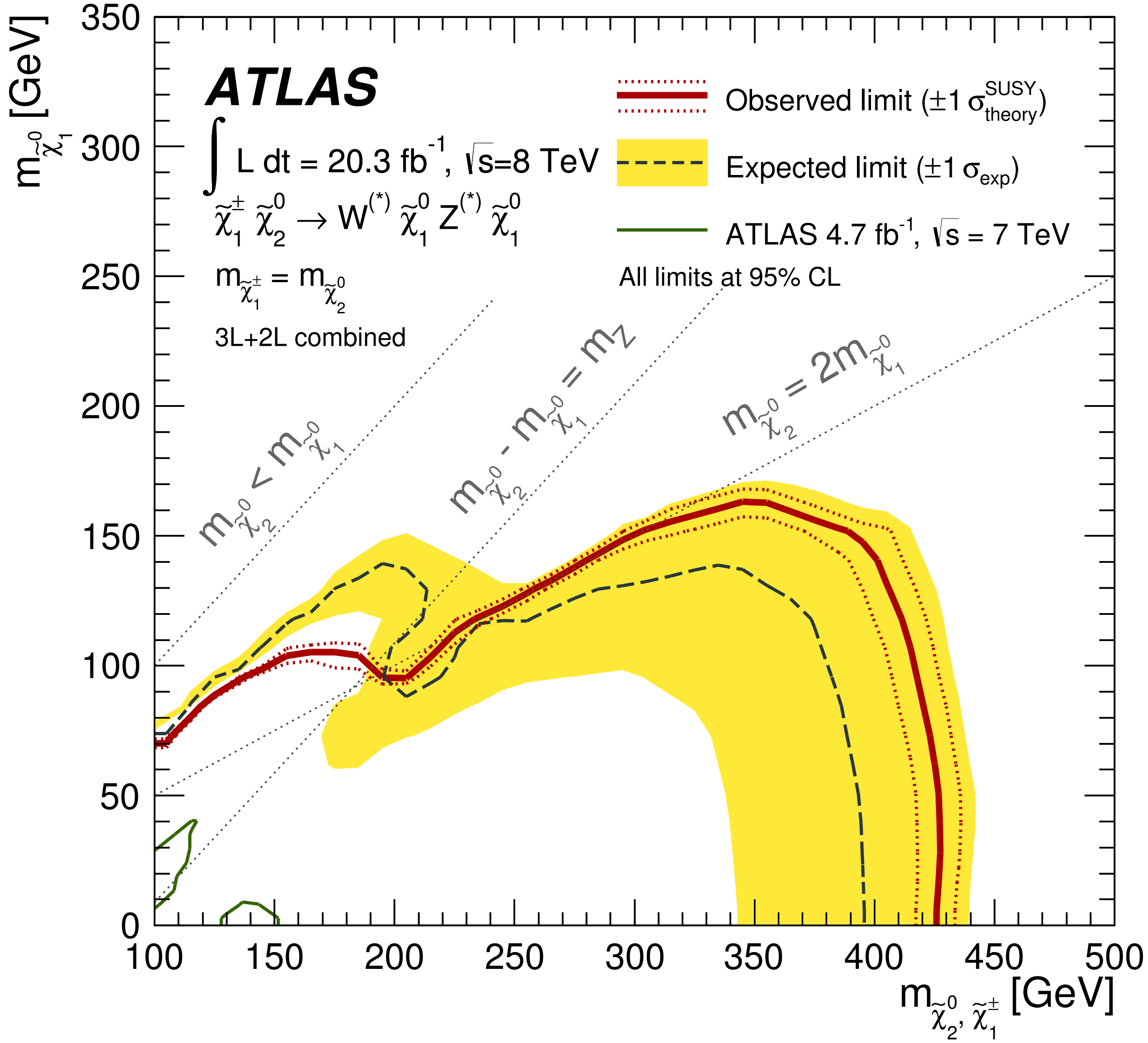


New Physics in e+e- - Direct Searches

- LHC has already covered quite a large phase space for new particles
    - Particularly powerful for strongly produced particles
- Universal electroweak coupling: EW particles not penalized in e+e-

The main strength of e+e-:
Small background -
no (or very modest) trigger requirements, also in analysis

As illustration:
ATLAS EW SUSY search
(di- / tri-lepton final states)
(JHEP 1405 (2014) 071),
e+e- study: M. Berggren



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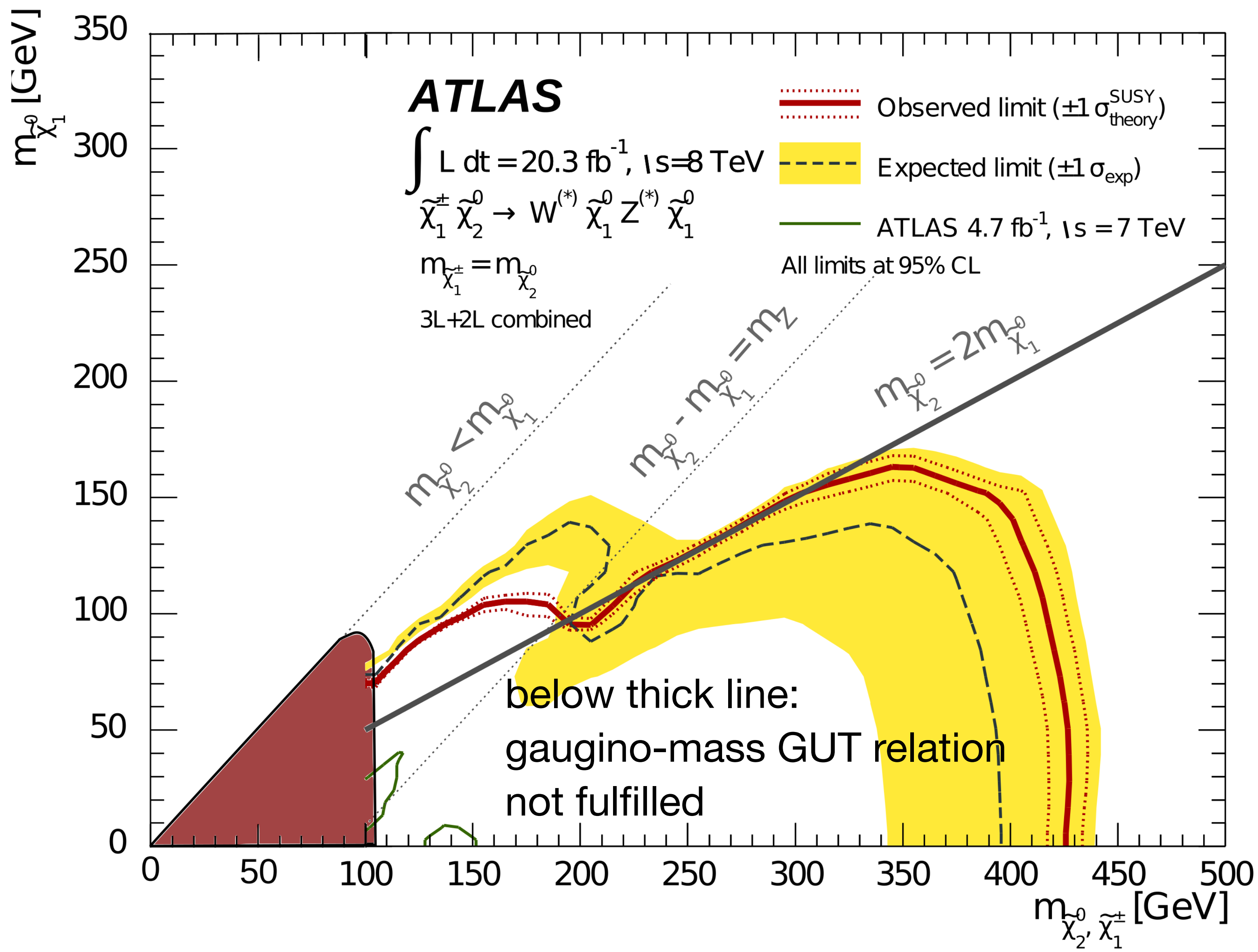
LEP (χ± only)



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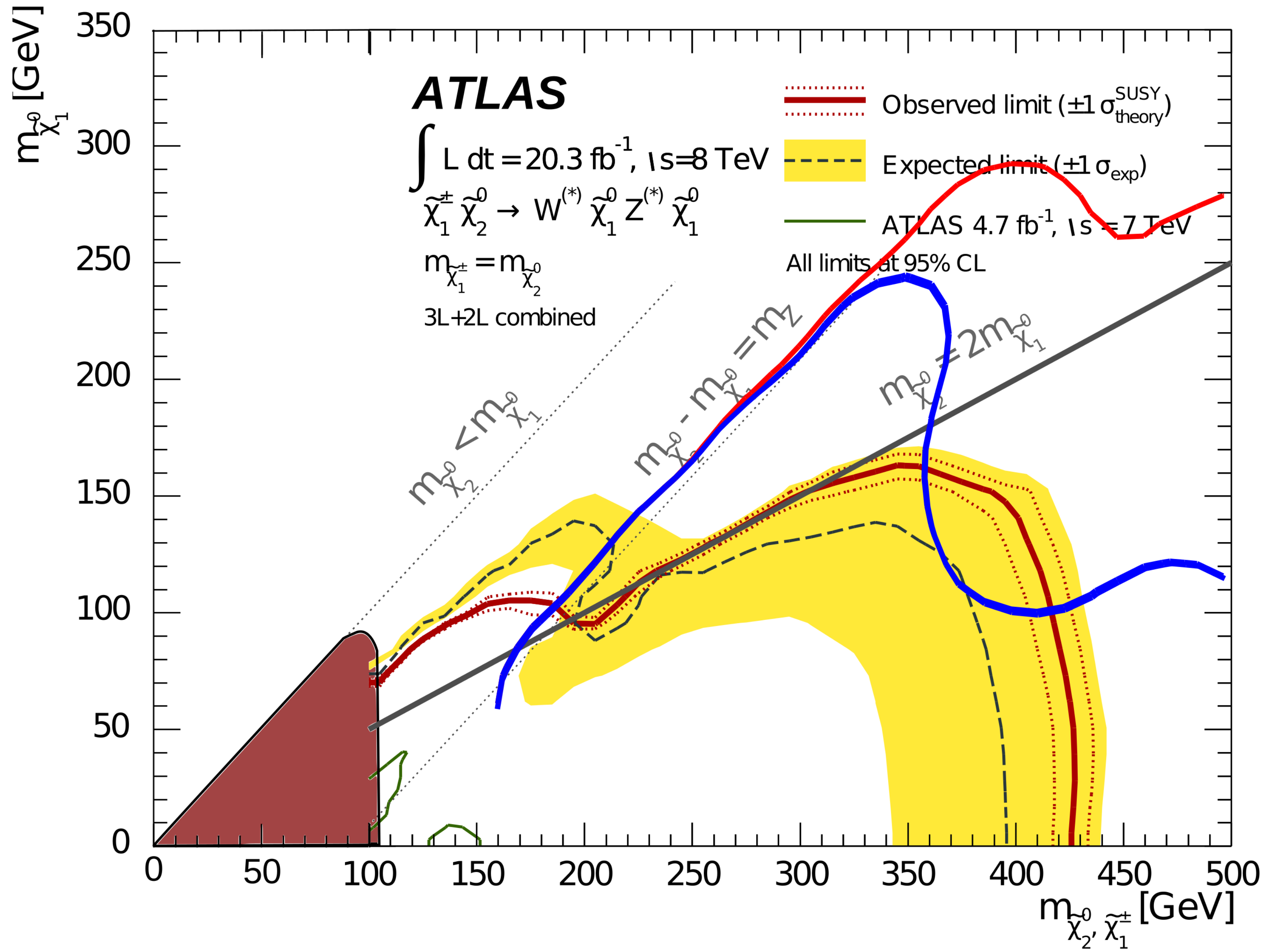

LEP (χ± only) LHC 300 / 3000 fb^{-1}

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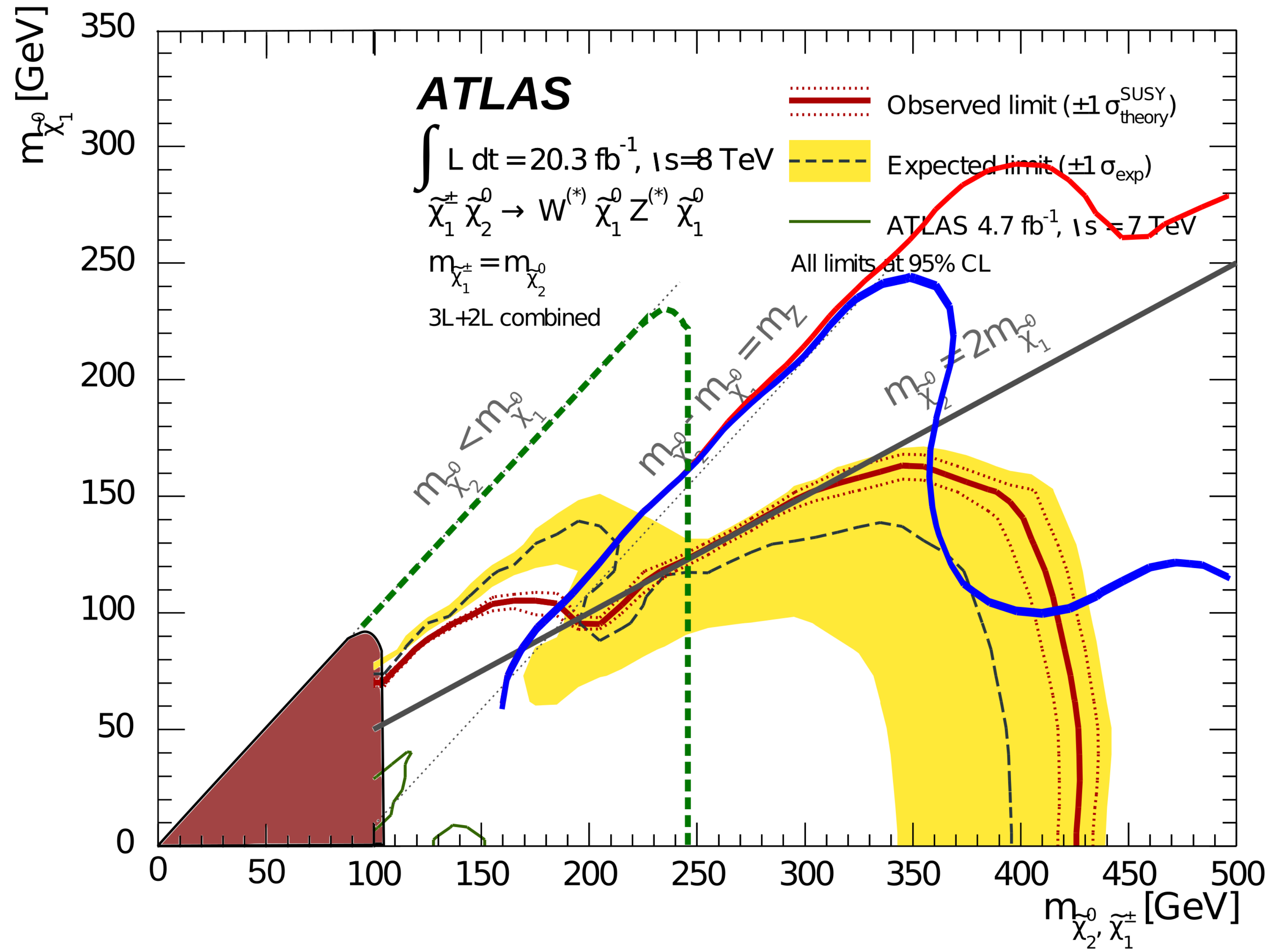

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e+e- 500 GeV

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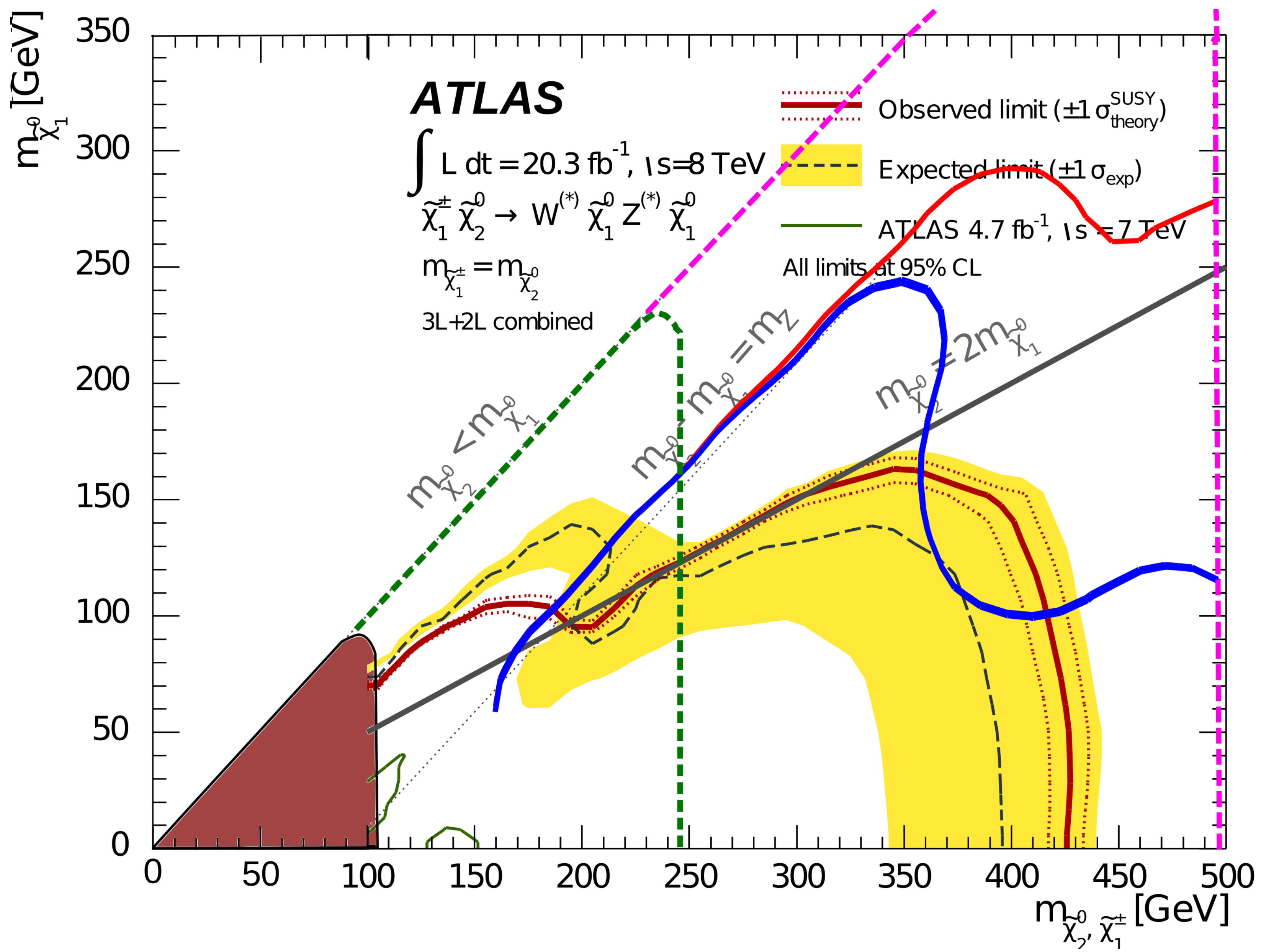

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e^+e^- 500 GeV e^+e^- 1 TeV

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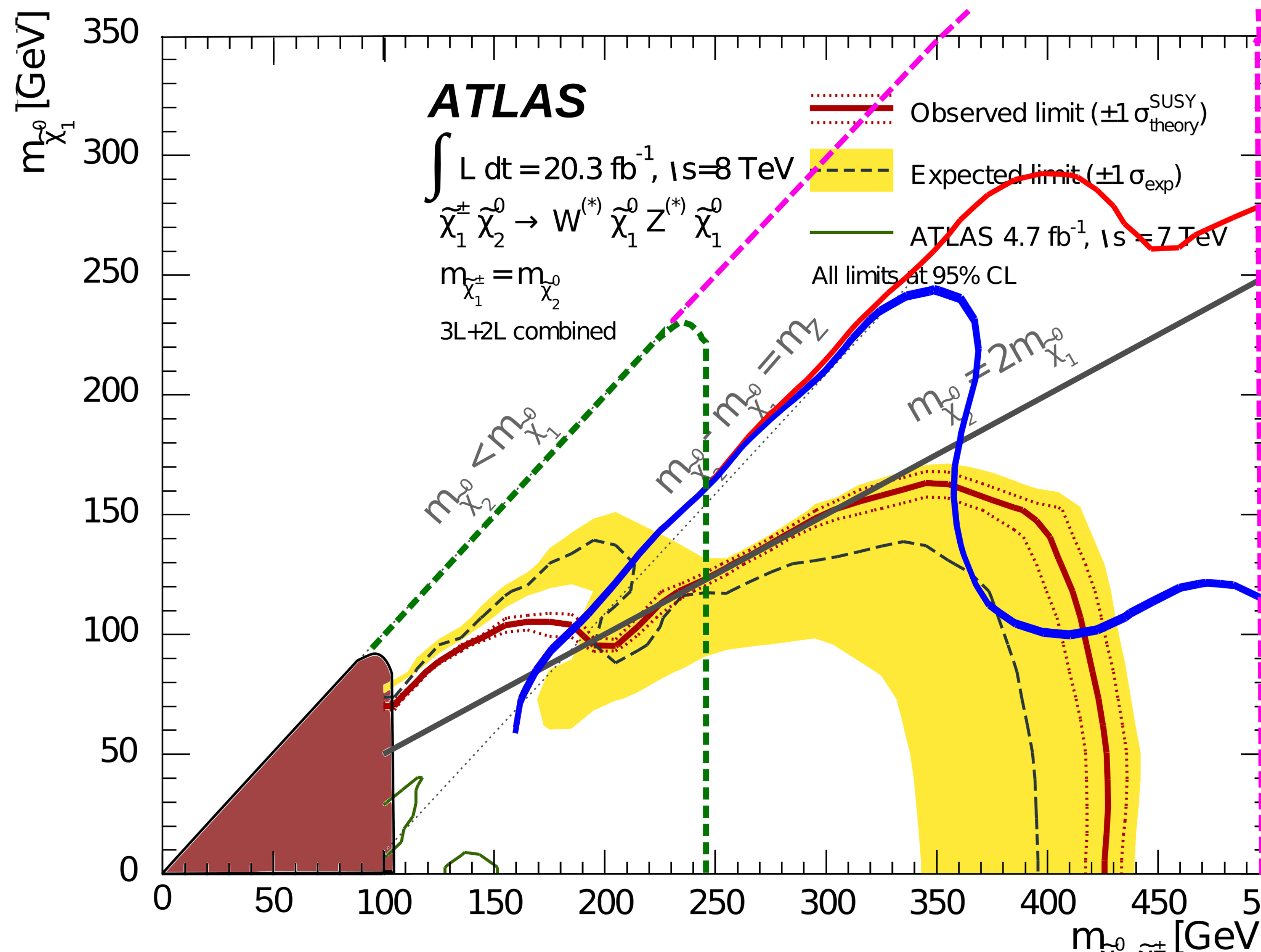


LEP (χ± only) LHC 300 / 3000 fb-1

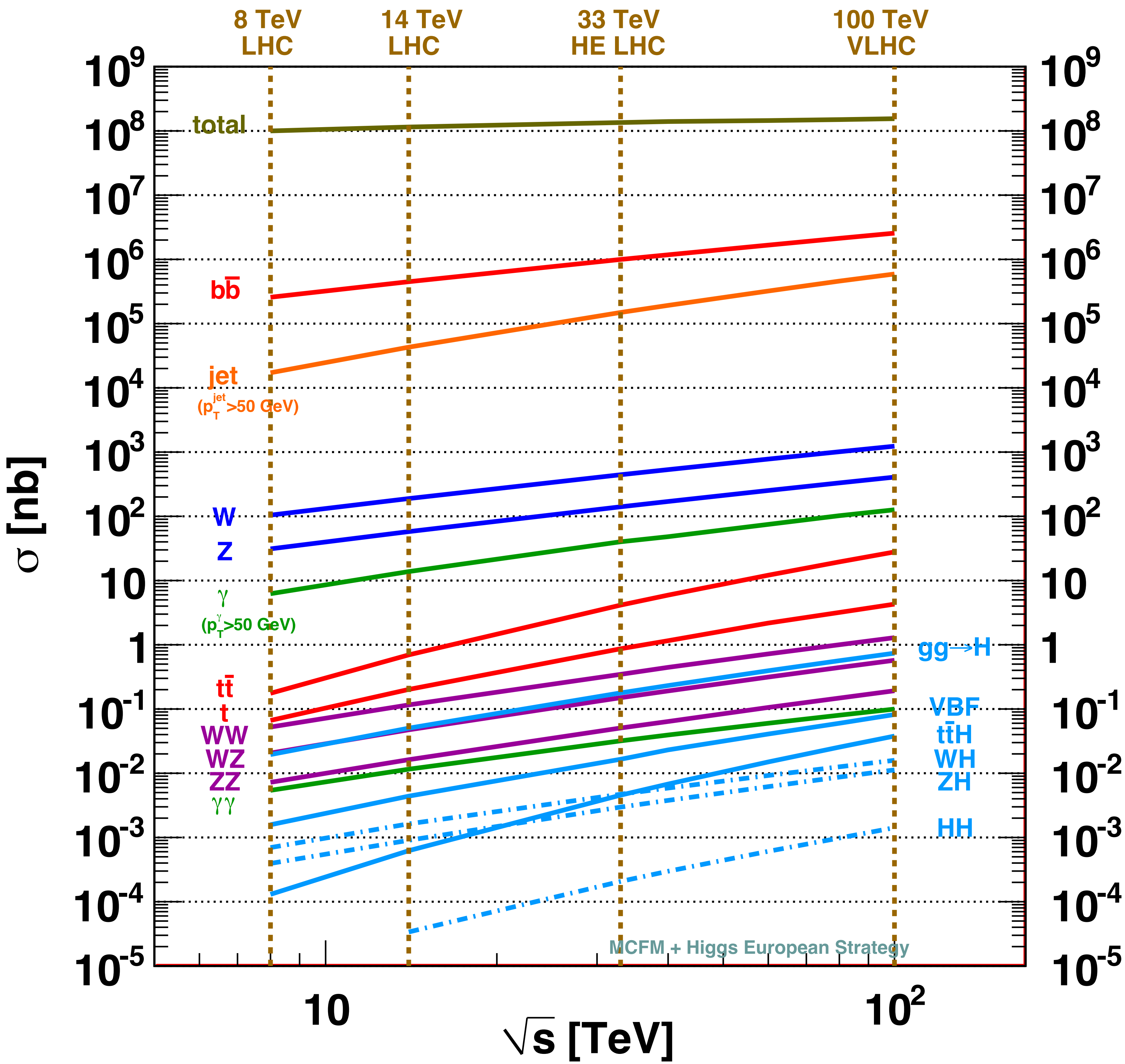
e+e- 500 GeV e+e- 1 TeV

In general: (almost) any type of new particle up to √s/2

Proton-Proton Colliders: Guaranteed Physics

- The full range of processes known from the LHC will be accessible at higher energies as well - details of analysis possibilities will strongly depend on experimental conditions

Double Higgs production up by x40 at 100 TeV: Crucial for a measurement of the self-coupling

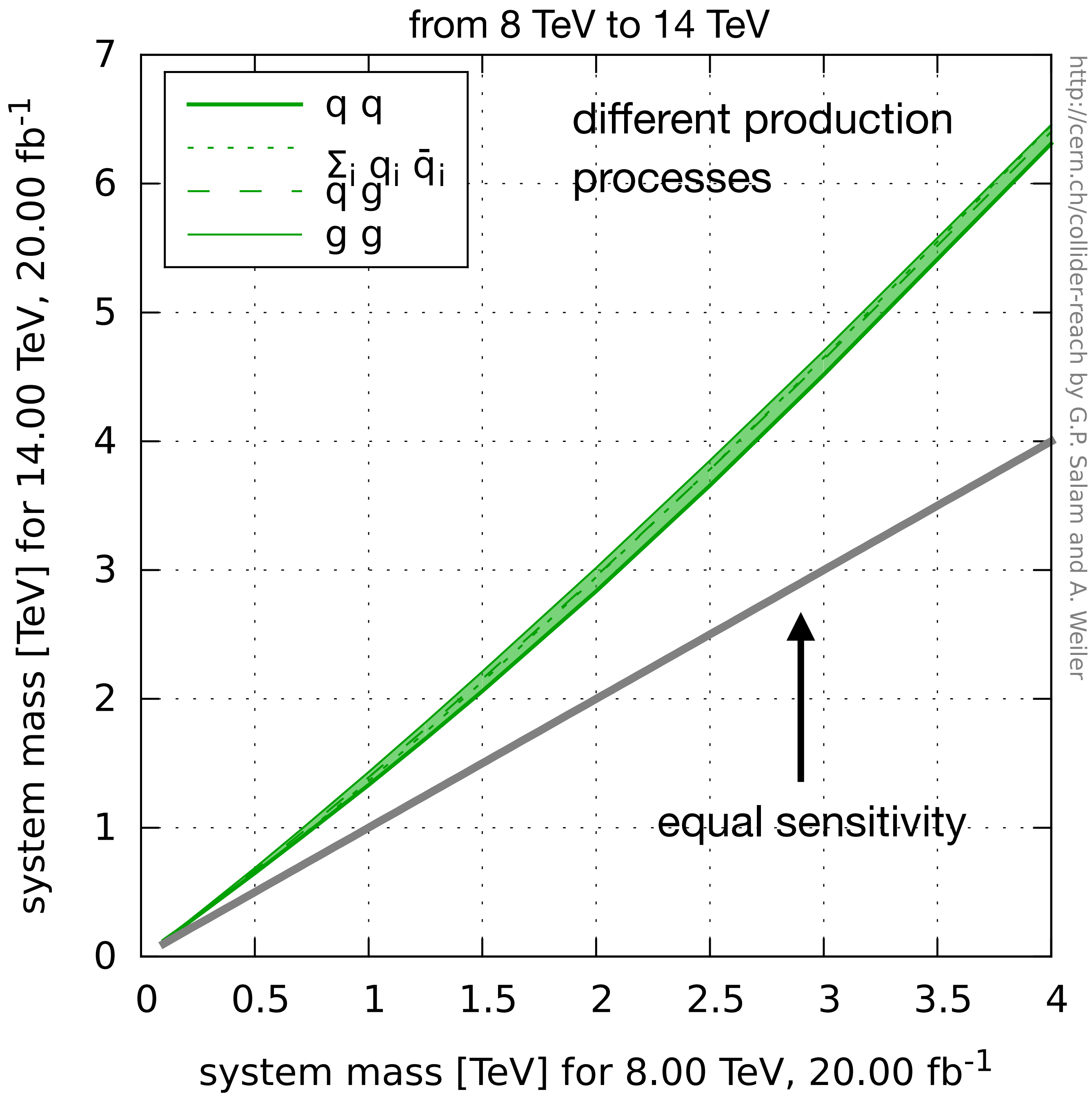


New Physics in Proton-Proton Collisions

- As for LHC: Highest sensitivity to strongly interacting particles

cern.ch/collider-reach

- Generic study to assess sensitivity as a function of energy:
  - Assumptions:
    - signal and background scale in the same way
    - Reconstruction efficiencies, background rejection etc. stay constant
    - Cross sections are proportional to partonic luminosity / m²
    - Given as system mass: mass of a single particle (Z' etc), or 2 x mass of pair-produced particles (SUSY-particles etc)



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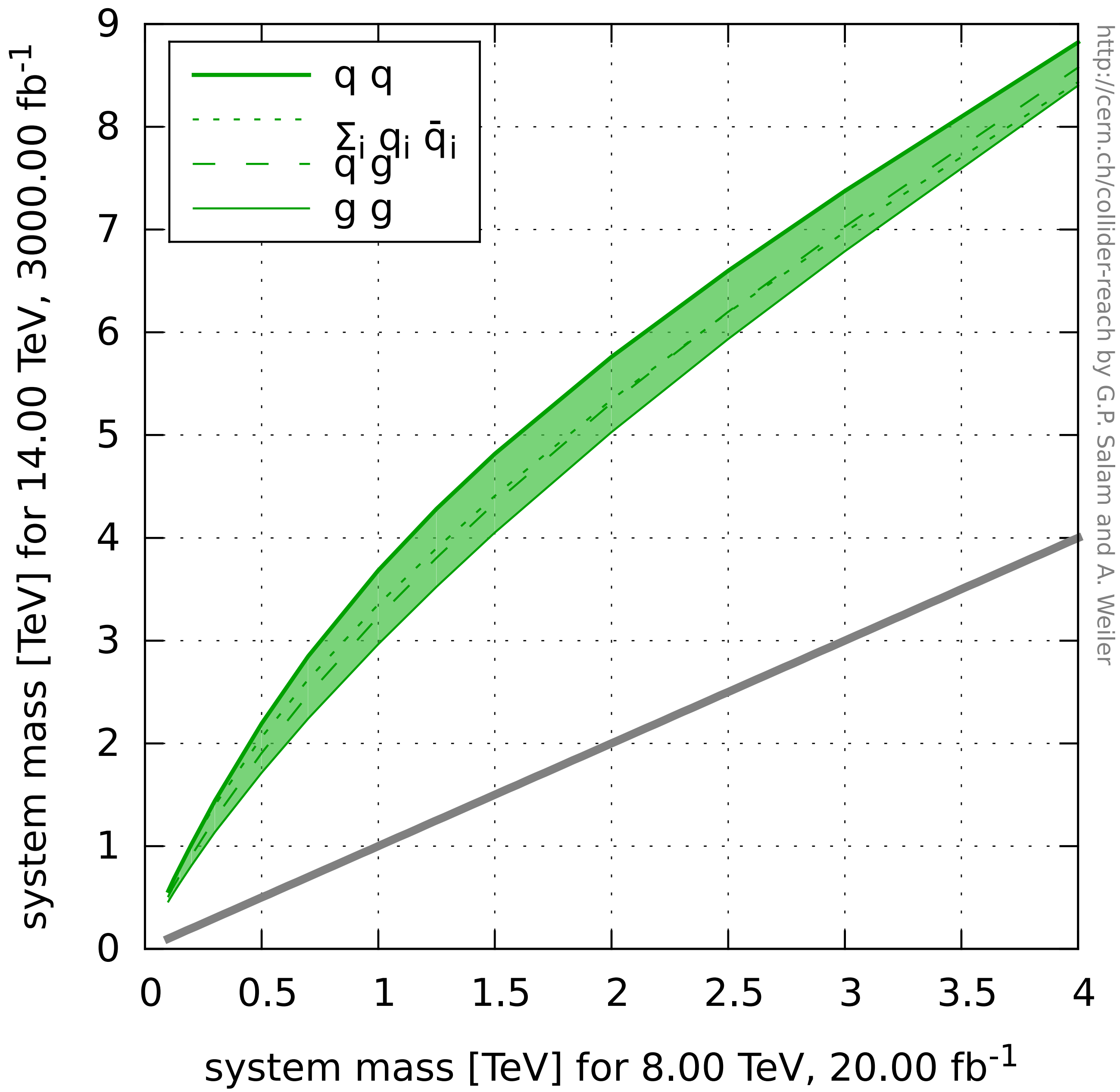
from today to 2035



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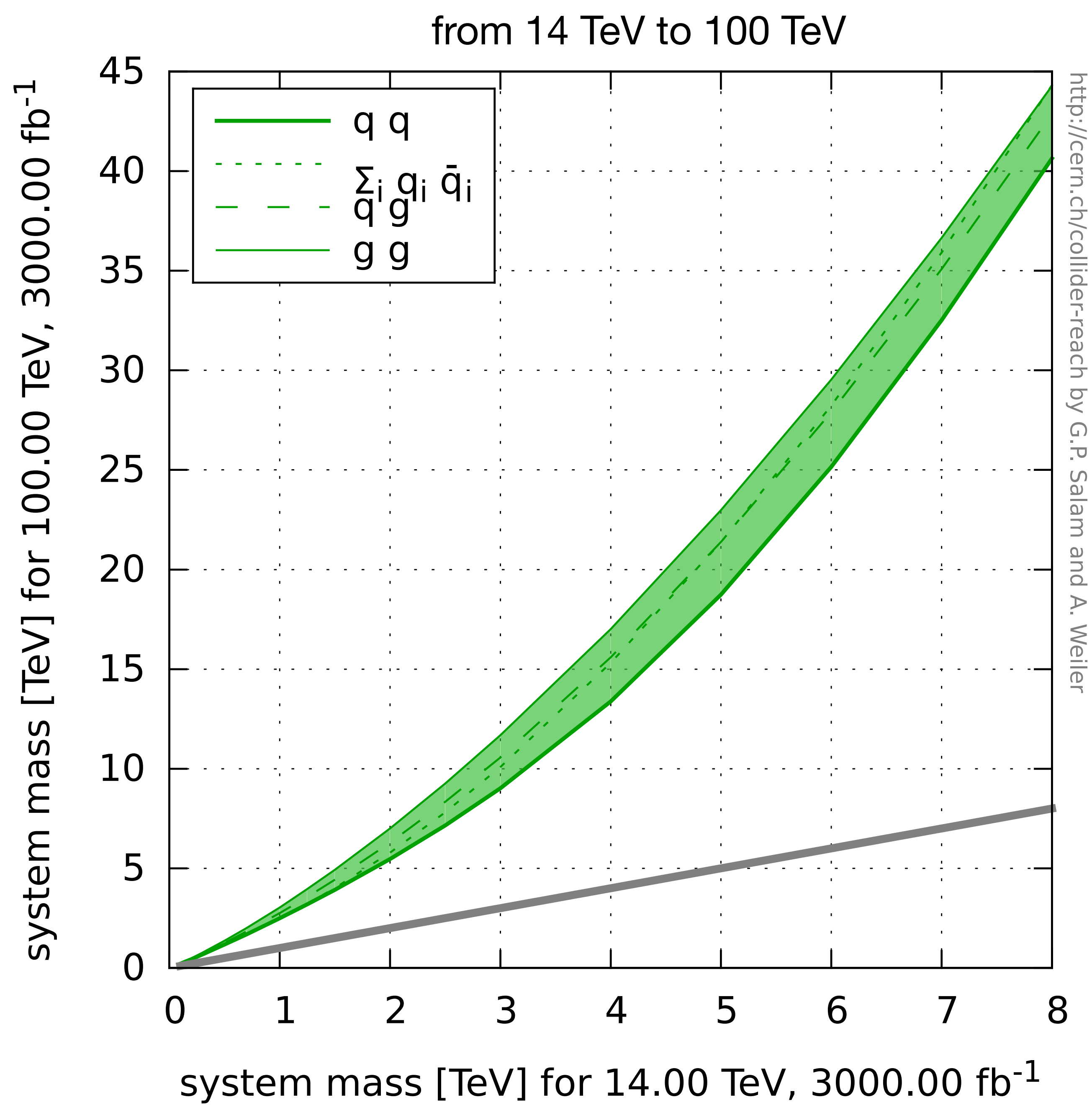
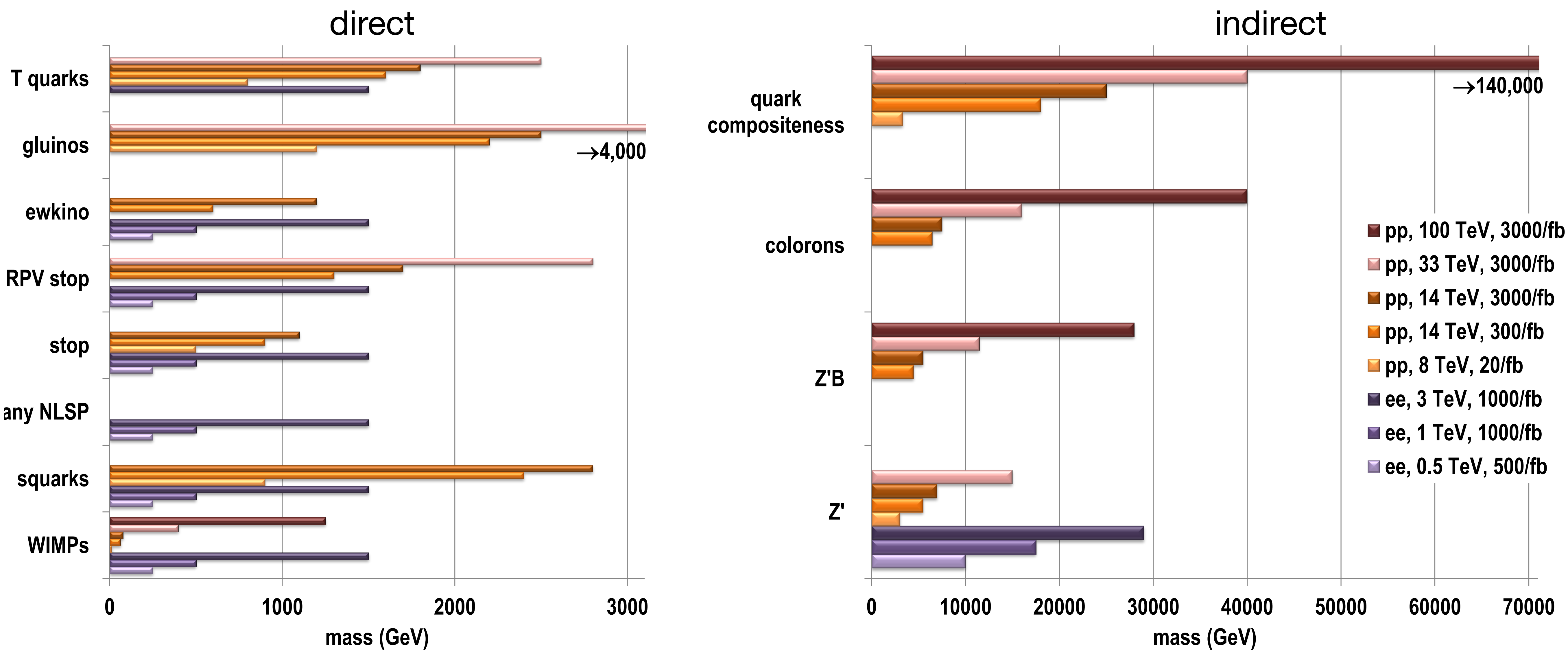


New Physics at Future Colliders - Summary Attempt



Snowmass 2013 - arXiv:1311.0299

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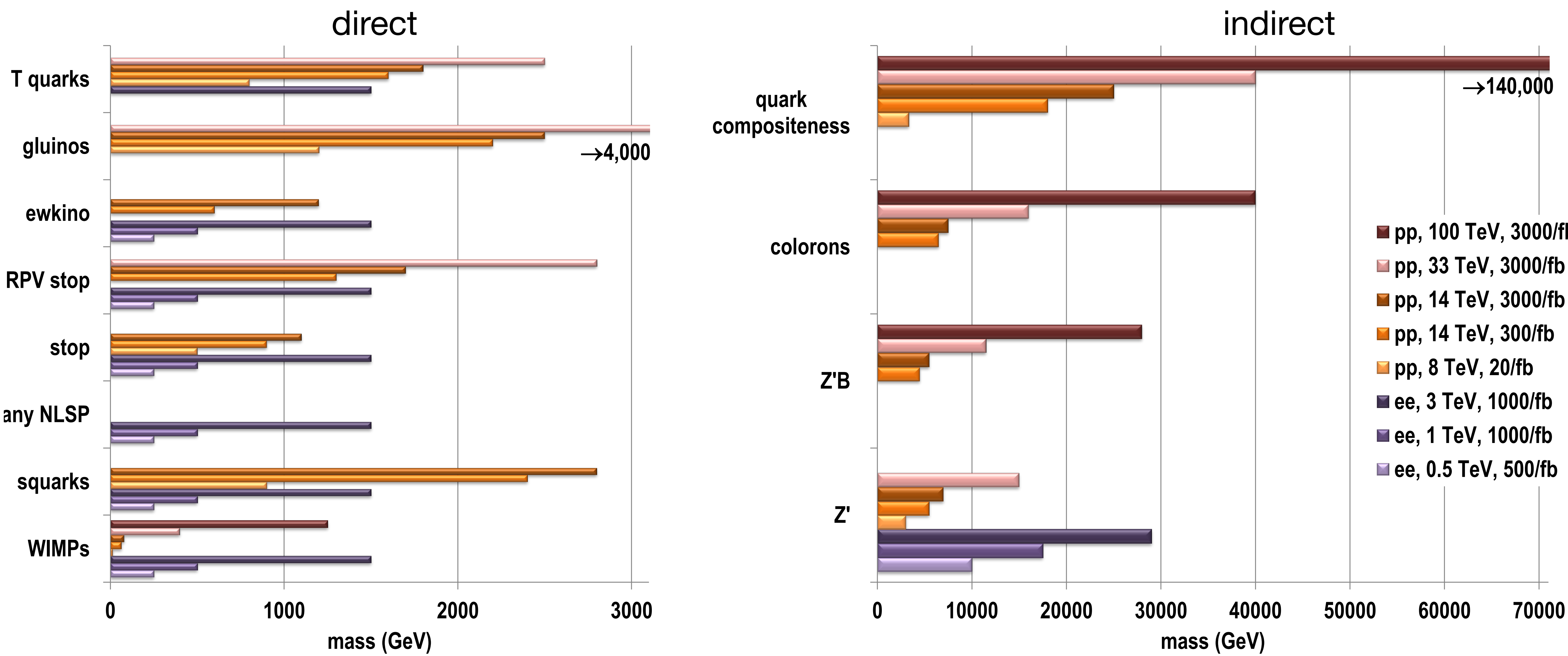


Snowmass 2013 - arXiv:1311.0299

NB: high energy p+p colliders in general have the most impressive limits - but often come with “loopholes” such as requirements on minimum mass differences between states enforced by triggering requirements or particular decay modes

Politics & Timescales

Getting a New Collider

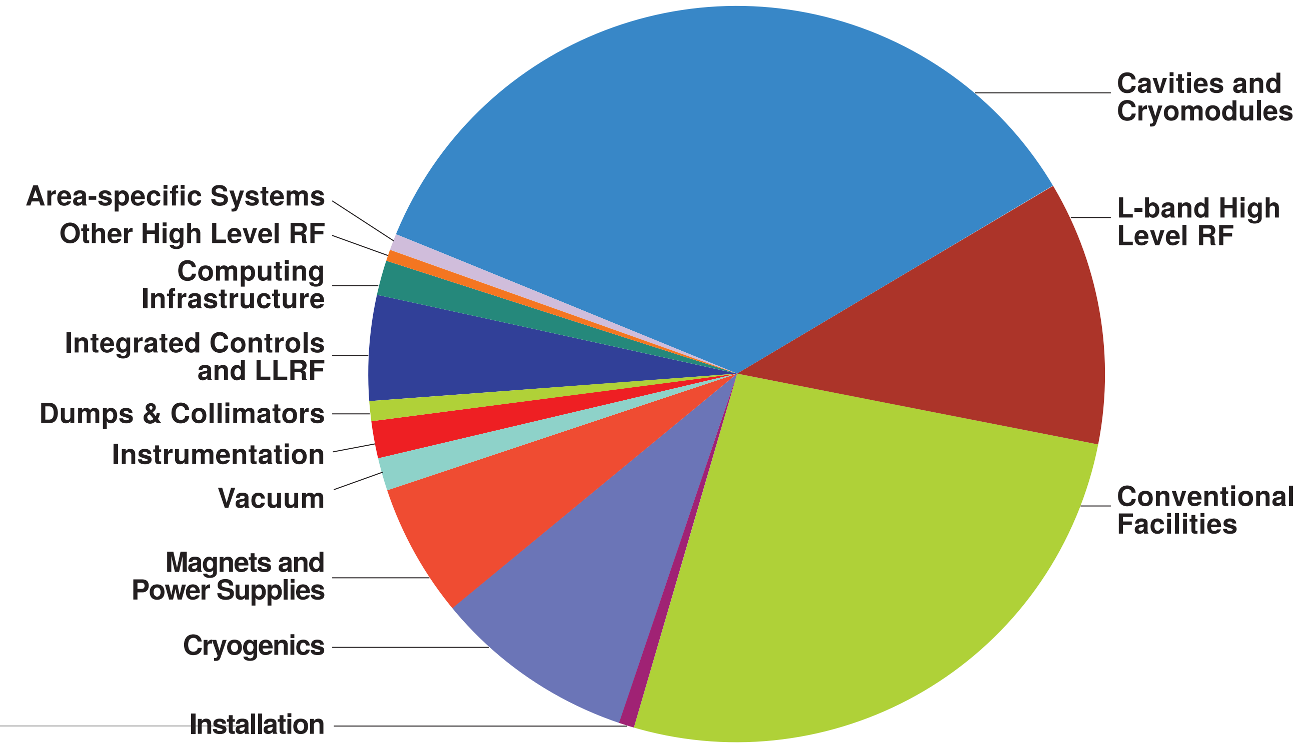
- New energy-frontier collider projects take a very long time - ILC (under various labels) has been developed for over 20 years
  - Technologically challenging
  - Expensive
  - Requires world-wide collaboration, not just for financial reasons, but also manpower: Experimental collaborations with (several) 1000 members, large numbers of accelerator and other specialists
    - Typically means complicated set-up procedures and international negotiations - far beyond the control of scientists

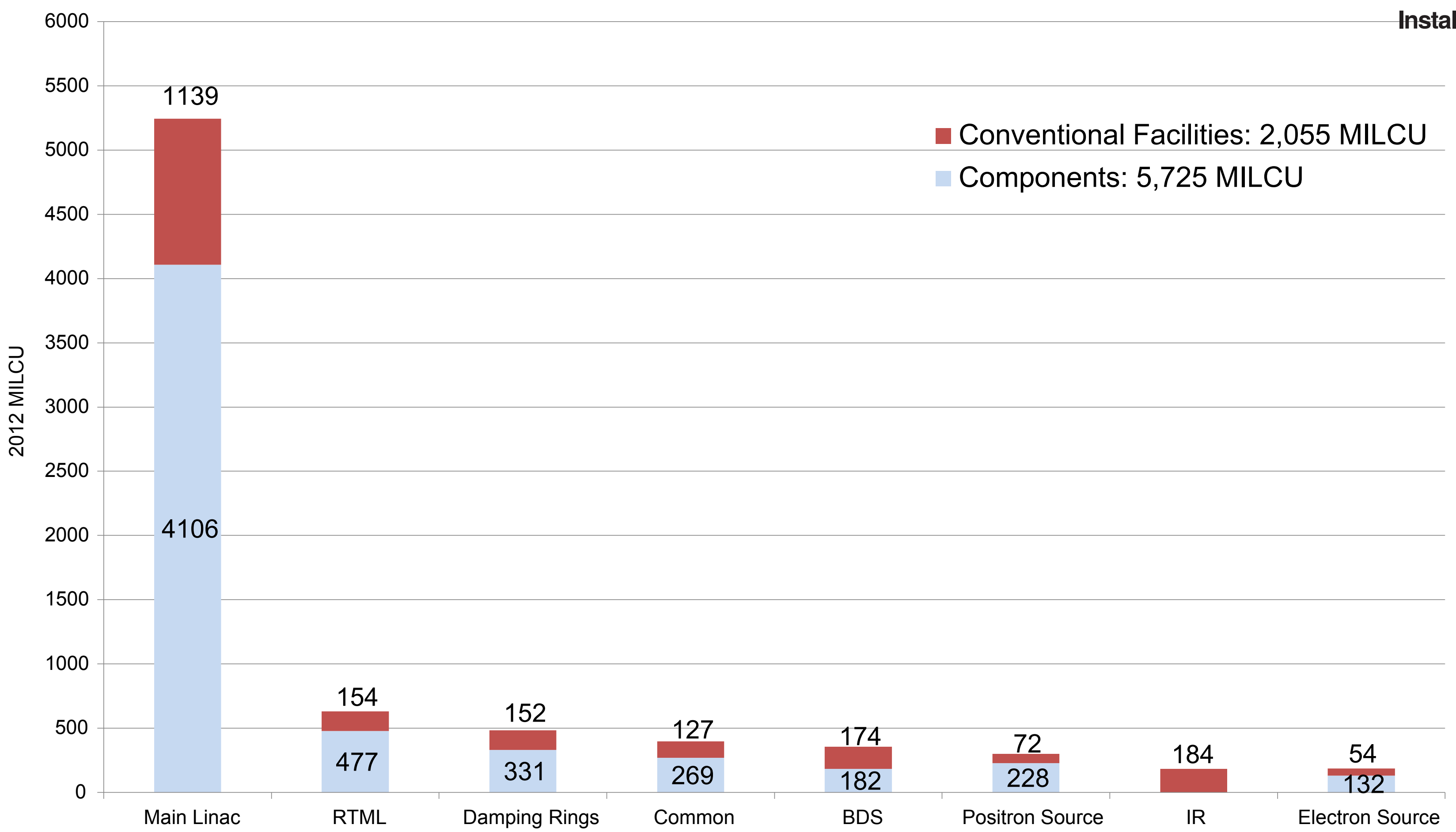
So far: Projects typically have been “local” with international participation

CERN is unique as an international organisation (still Europe-centric) - Similar things do not exist in other regions for particle physics

ILC Cost

- Not surprising: An energy frontier collider is expensive
    - Rather solid cost estimate for the 500 GeV machine: ~ 8 Billion USD (500 GeV version of CLIC similar)
    - Biggest component: Main linac, acceleration structures





- The construction cost will be spread over ~ 10 years, and shared across the globe - details to be worked out!
- Many contributions expected “in kind”: production of components “at home”, installation in ILC

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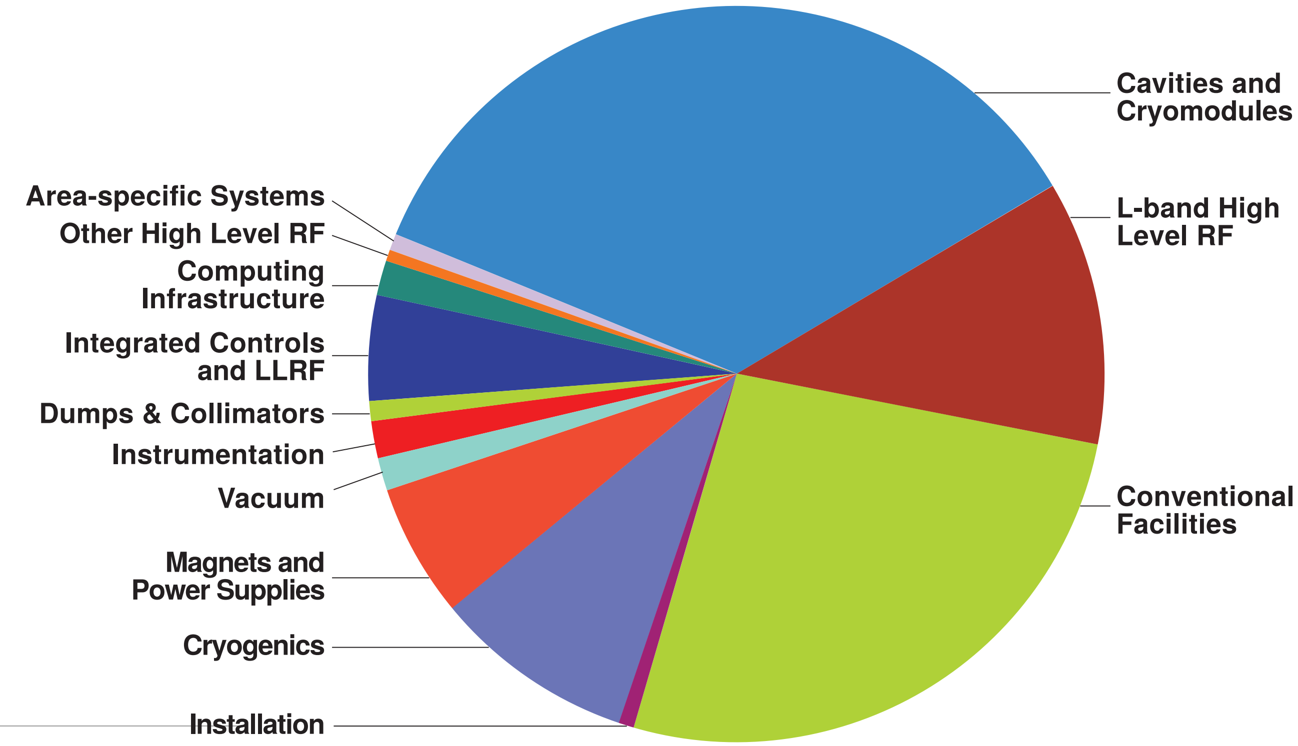

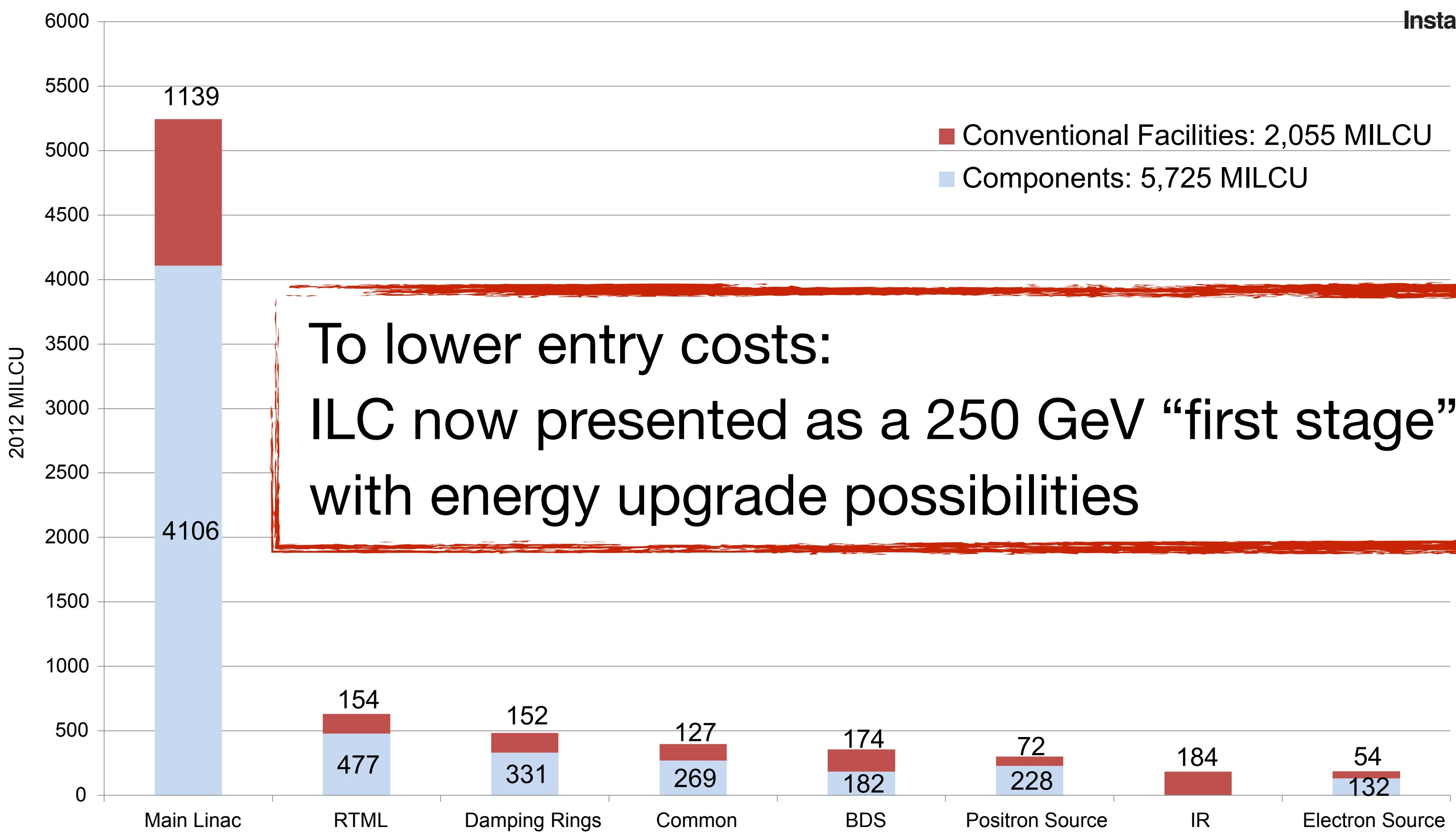

To lower entry costs:
ILC now presented as a 250 GeV "first stage", with energy upgrade possibilities

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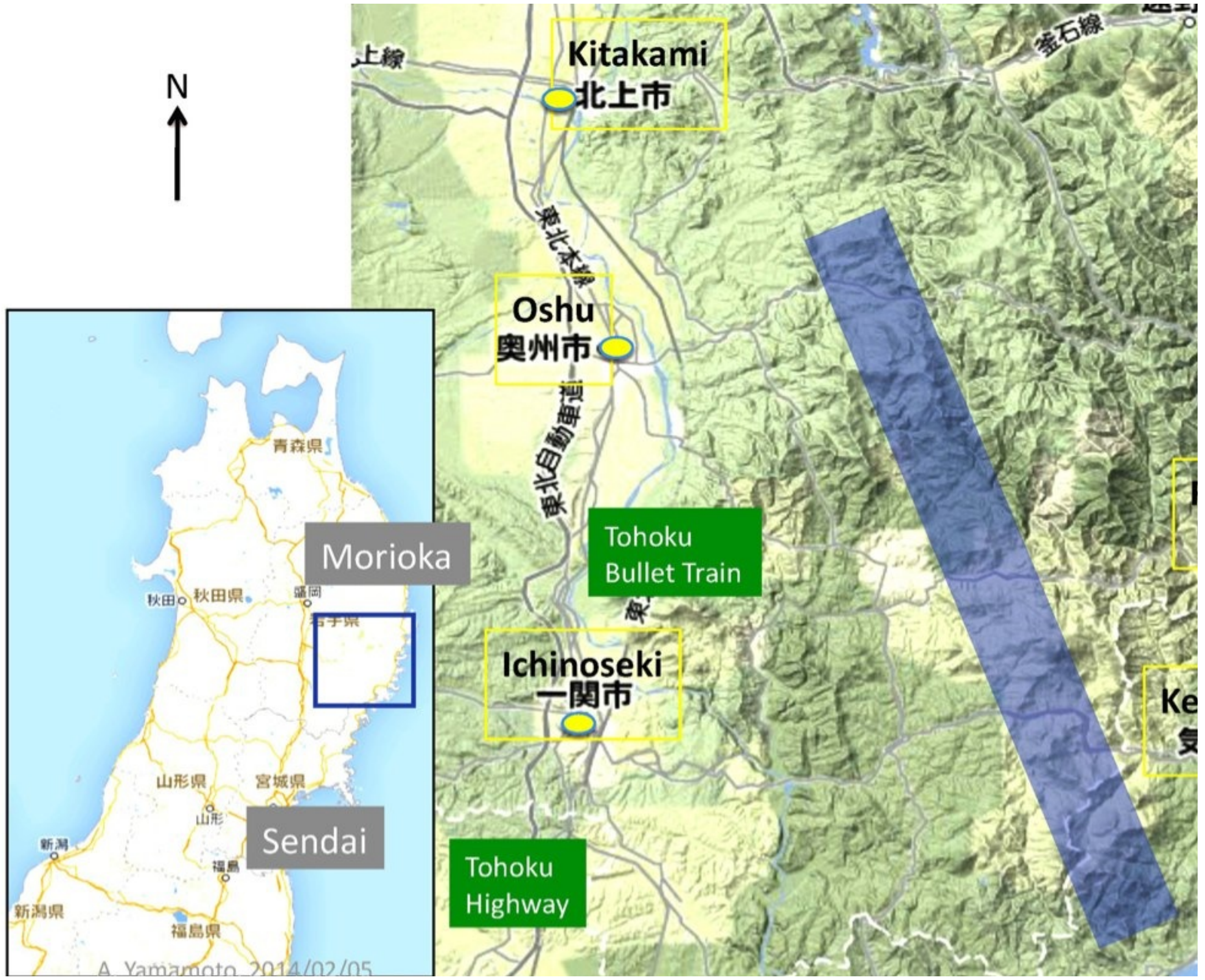
- Many contributions expected "in kind": production of components "at home", installation in ILC

ILC in Japan?

- Japan has expressed interest to host ILC - with the goal of a global project with substantial financial contributions from outside, and the establishment of an "international city"
  - A site recommendation has been made: Kitakami in Northern Japan



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  - A site recommendation has been made: Kitakami in Northern Japan
- Strong support by local government and population
- Currently a review process with committees by the Japanese science ministry MEXT is takin place - physics case and technical issues
- Contacts on government level about international participation have started

International Strategies & Priorities

- Community-driven strategy processes in Europe and the US have been completed in 2013
  - Update of the European Strategy for Particle Physics 2012/2013
    1. Full exploitation of LHC, including high luminosity upgrade - a program until 2037
    2. Design studies for future CERN projects after LHC, focus on p+p and e^+e^- energy frontier colliders (CLIC, HE-LHC, FCC-hh with FCC-ee as possible precursor) - Prepare for first decision in ~ 2018
    3. Support for ILC in Japan, discuss possible participation
    4. Neutrino programme at CERN to enable strong participation in US projects
  - US Snowmass and P5 (Particle Physics Projects Prioritization Panel) 2013/2014
    1. Continue LHC involvement, including HL-LHC detector upgrades
    2. Support ILC development, increased involvement if ILC proceeds
    3. Develop a coherent short- and long baseline neutrino program hosted at Fermilab
    4. Increase international collaborations for long-baseline neutrino program, highest priority near- and mid-term large project
    5. Long-term R&D on CLIC, Muon Collider and high-field magnets for p+p colliders

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Global consensus:
Fully exploit LHC, including detector and accelerator upgrades
Support ILC as a possible medium-term energy frontier collider
Continue long-term R&D for future projects at (much) higher energy

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International Strategies & Priorities

- The next strategy update is coming up: Will happen in 2020, process beginning now
  Will have:
  - A concrete statement from Japan (hopefully!)
  - Well-established design for CLIC
  - Conceptual design for FCC / HE-LHC

- => Expect concrete directions on future beyond LHC

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    - After positive decision: Assume 4 years of preparation, ~ 10 years construction earliest start 2032

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- **CEPC** - the “newcomer” - on a fast track. Currently in concept phase, just received funding to develop the technical design over the next 5 years, then decision
  - Could be completed on a similar timescale as ILC
- **SppC** - the extension of CEPC to proton-proton collisions - on a substantially longer time-scale, after > 10 years of operation of CEPC

Timescales and Evolution

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- **FCC** - a relatively new addition to CERN's future possibilities - in response to the European Strategy for Particle Physics - conceptual design until end of 2018, then, after a first decision to go ahead, technical design until ~ 2026
  - Would likely start first with e^+e^- (possibly shortly after HL-LHC), then, as a second stage p+p with up to 100 TeV
  - New magnet technology also opens up the possibility for higher energy in the LHC tunnel: HE-LHC @ 27 TeV
    - installation could begin after HL-LHC completion, start of operation maybe mid 2040ies

To Put Things into Perspective

The possible
ILC site
北上市

To Put Things into Perspective

A Final Word

- Collider physics will stay exciting over the next years - I hope you enjoyed this course!

- Next semester: A lecture series in the same style, focusing on astro-particle physics and particle physics precision measurements
    - Cosmic particles & accelerators
    - Precision experiments
    - Dark Matter & Dark Energy
    - Neutrinos

“Teilchenphysik mit kosmischen und erdgebundenen Beschleunigern”

Same time, same place.

Schedule

1.	Introduction	16.10.
2.	Accelerators	23.10.
3.	Particle Detectors I	30.10.
	----------- no lecture -------------	**06.11.**
4.	Particle Detectors II	13.11.
5.	Monte Carlo Generators and Detector Simulation	20.11.
6.	Trigger, Data Acquisition, Computing	27.11.
7.	QCD, Jets, Proton Structure	04.12.
8.	Top Physics	11.12
9.	Tests of the Standard Model	18.12.
	----------- Christmas ---------------------	
10.	Physics beyond the SM	08.01.
11.	Higgs Physics I	15.01.
12.	Higgs Physics II	22.01.
13.	Heavy Quarks	29.01.
14.	LHC Outlook & Future Collider Projects	05.02.