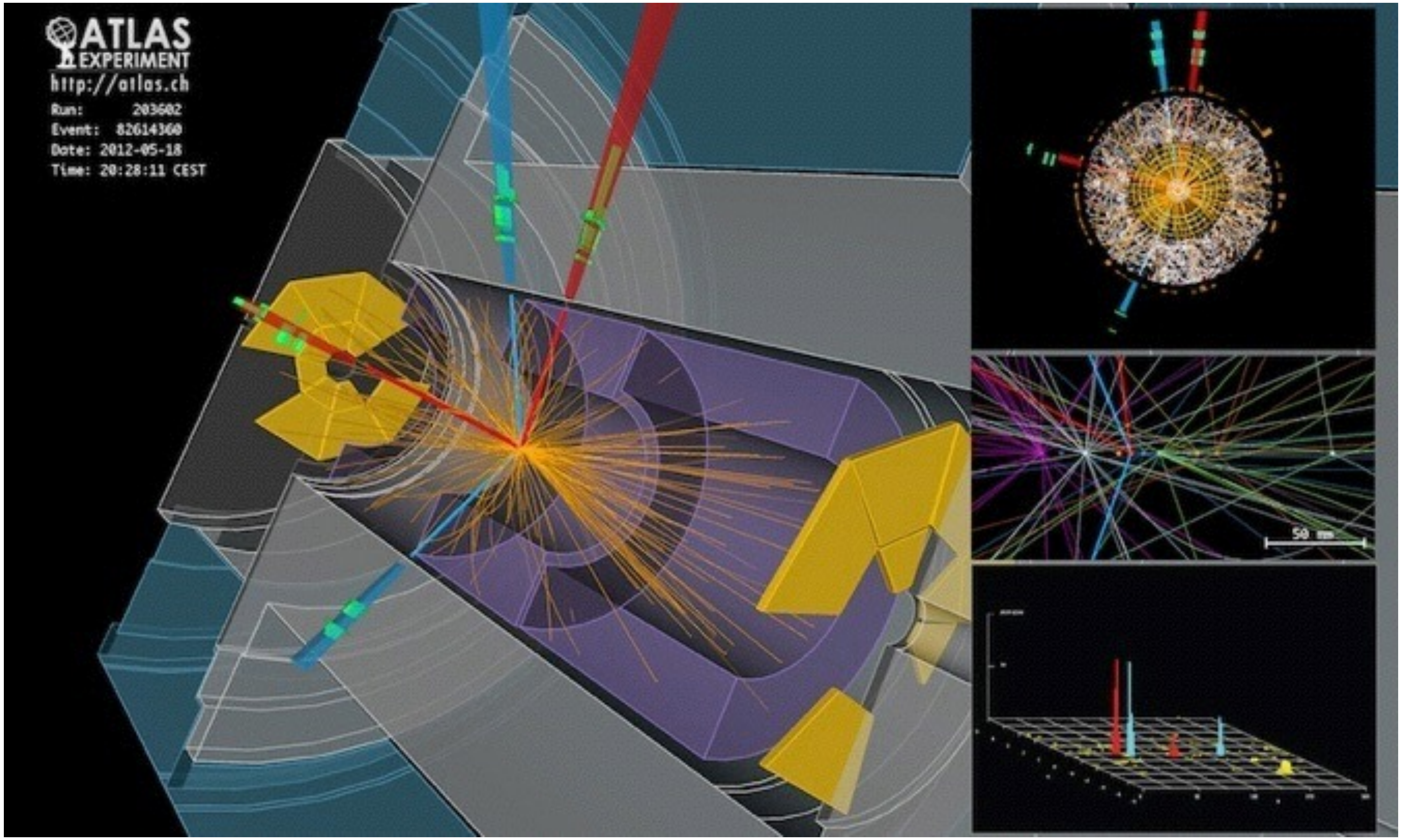
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



13. Future Colliders

25.01.2015

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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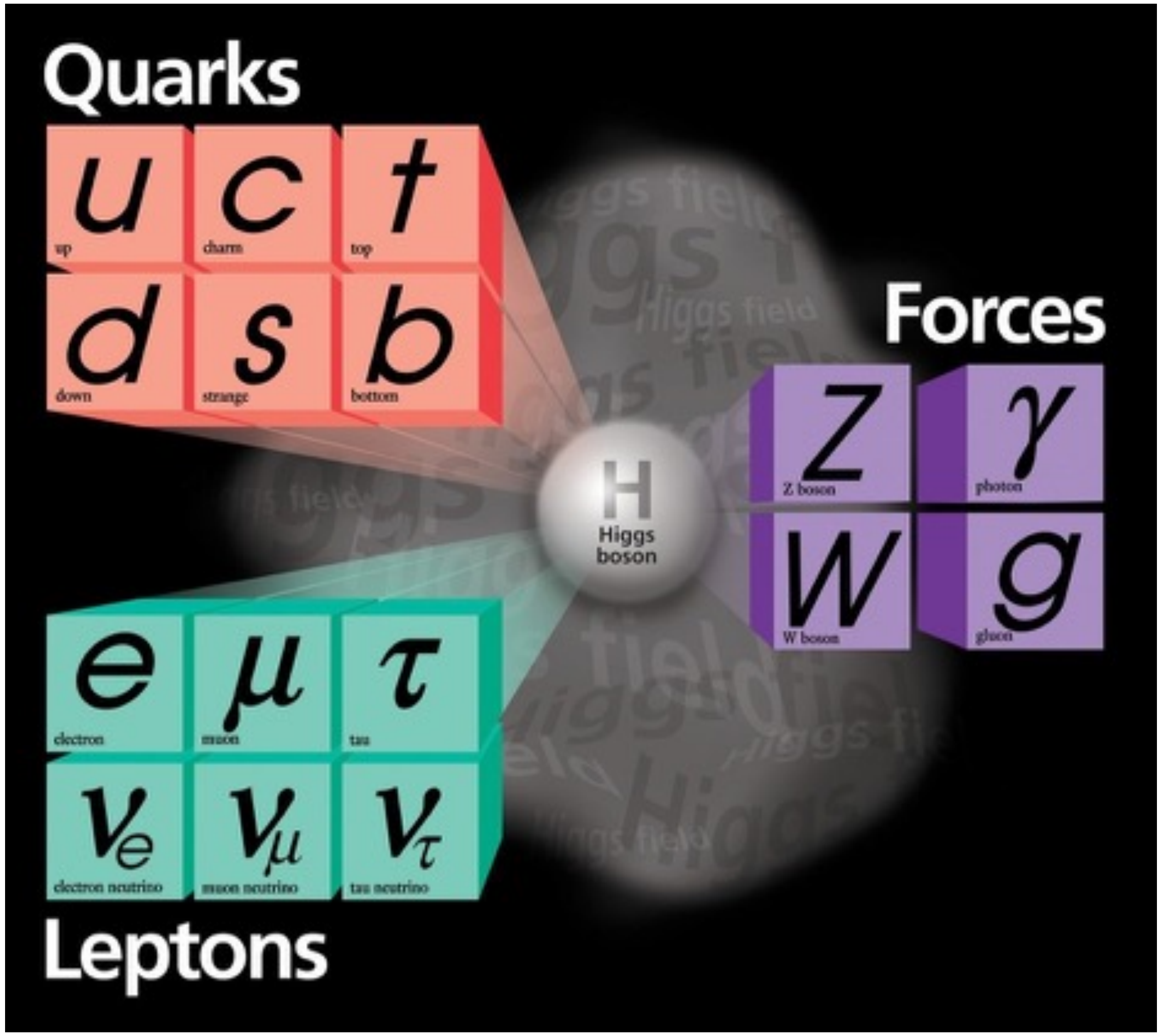
(ν_τ: Fermilab 2000 ✔)



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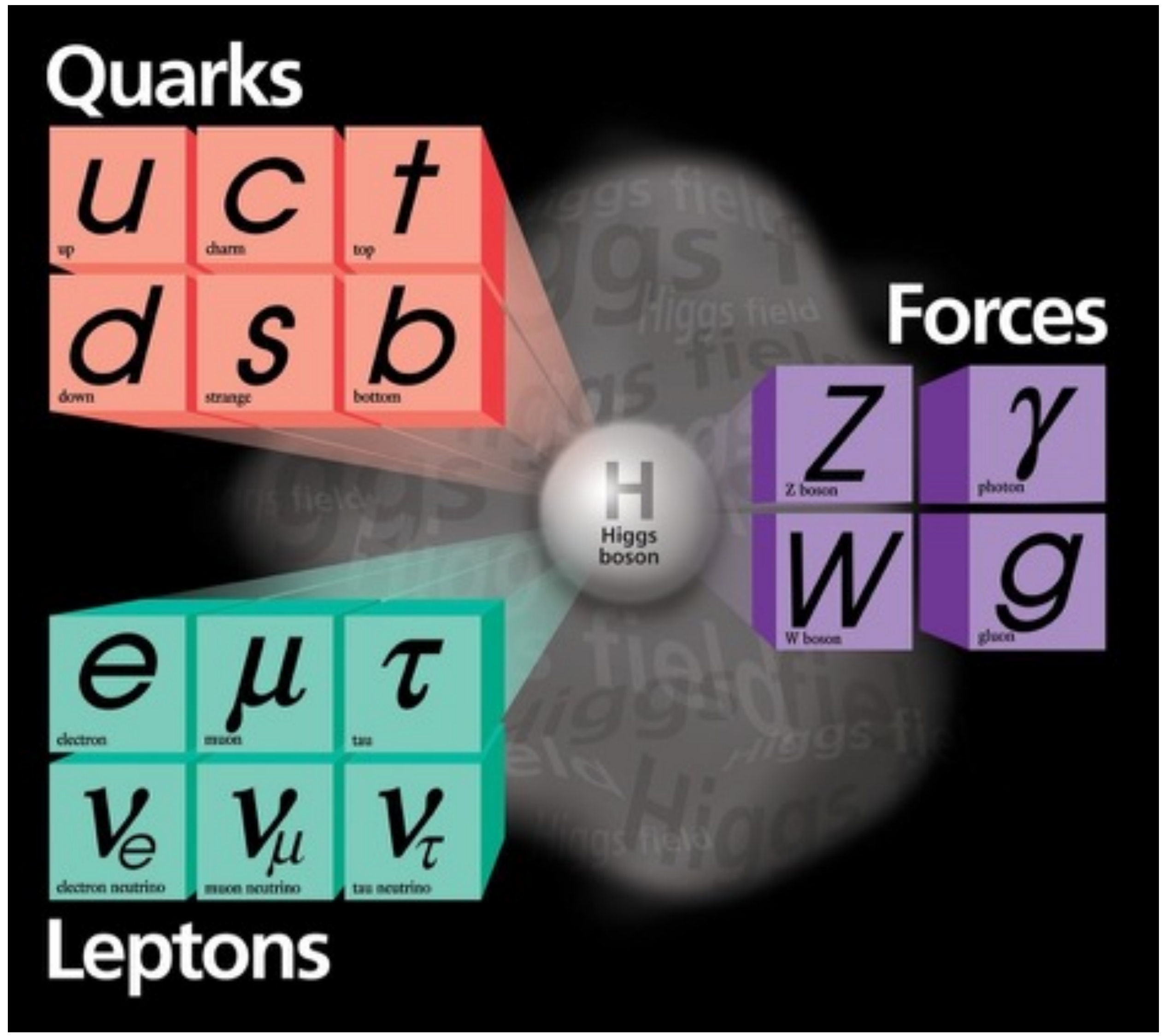

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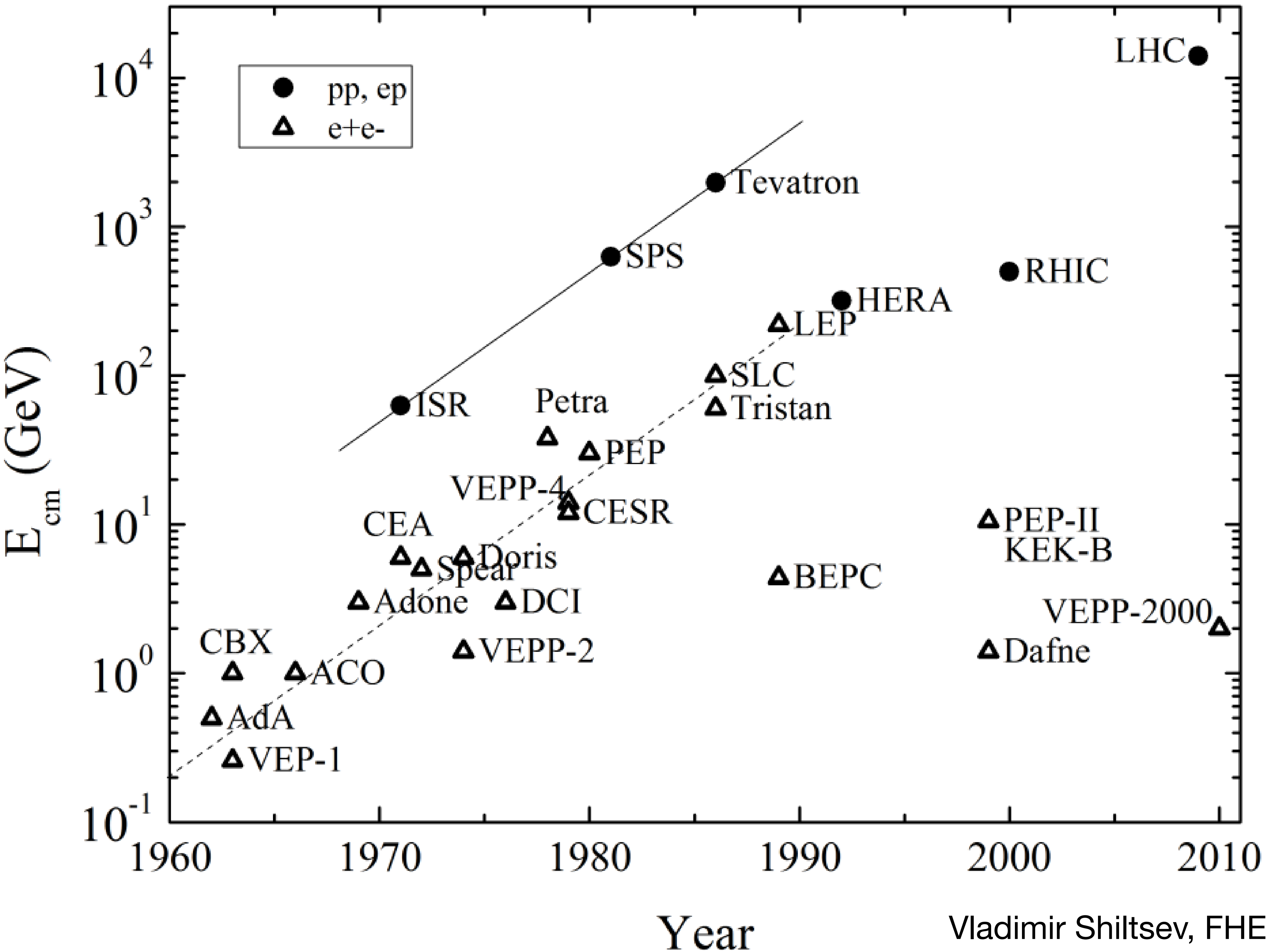
… the Standard Model was established with results from lepton and hadron colliders.

The World of Colliders



Vladimir Shiltsev, FHEP Hong Kong, Jan. 2015

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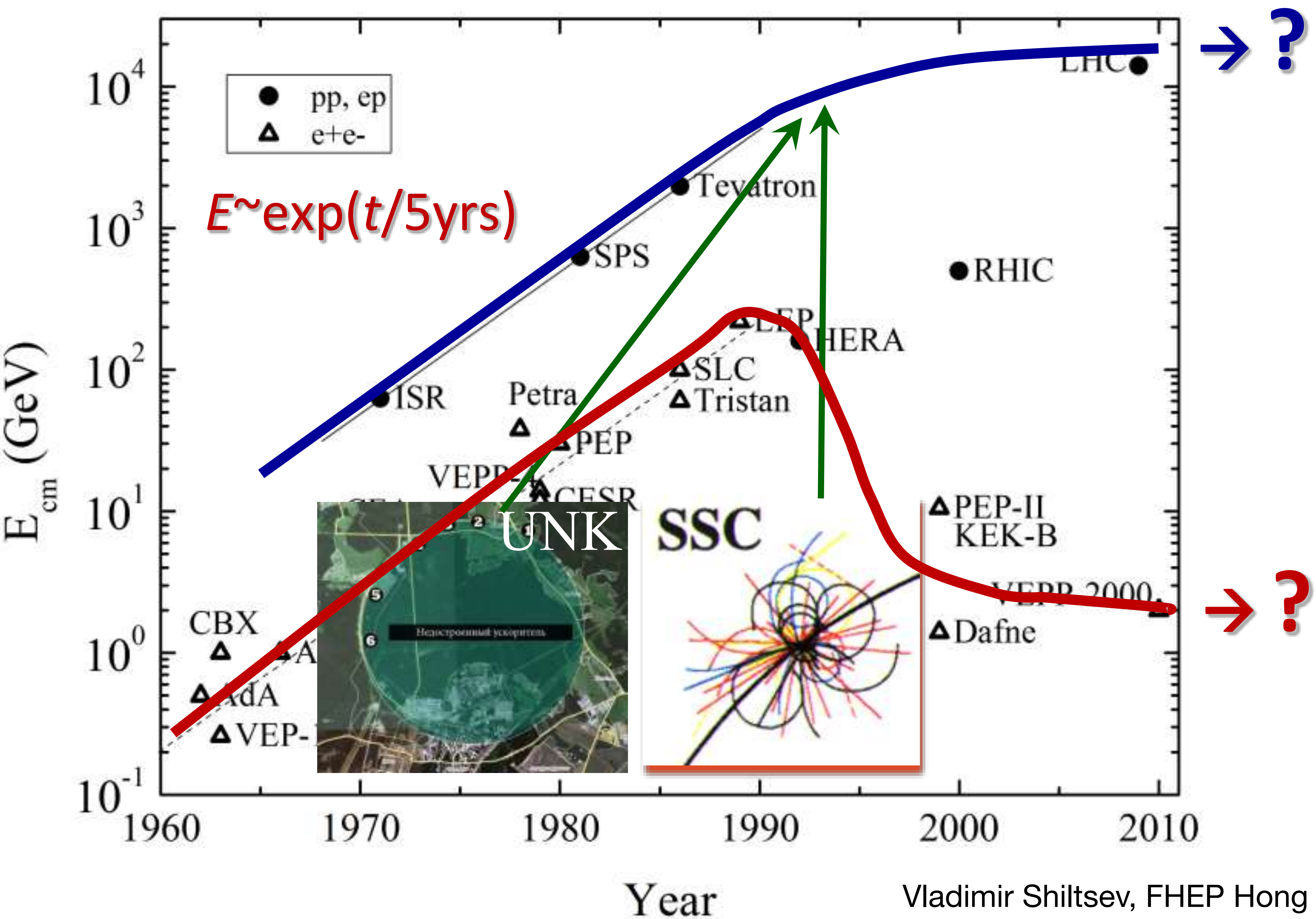

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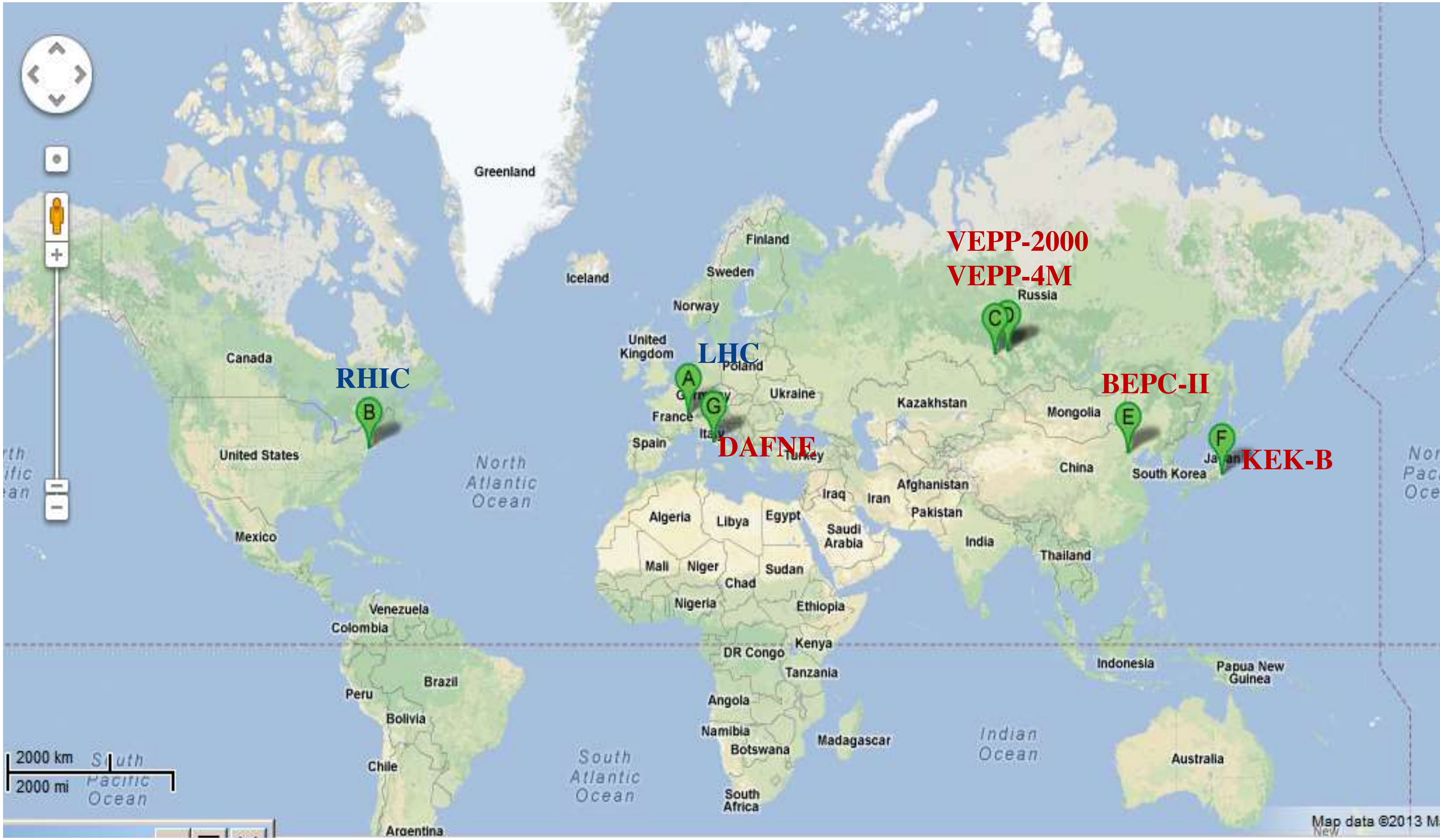
Currently Operating or Approved Colliders

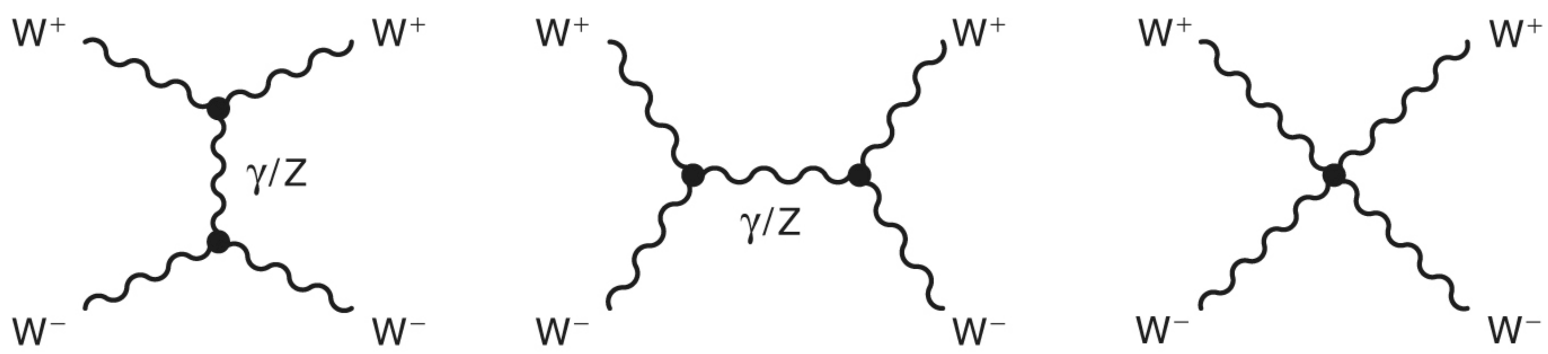


- In total 29 colliders, 7 run “now”

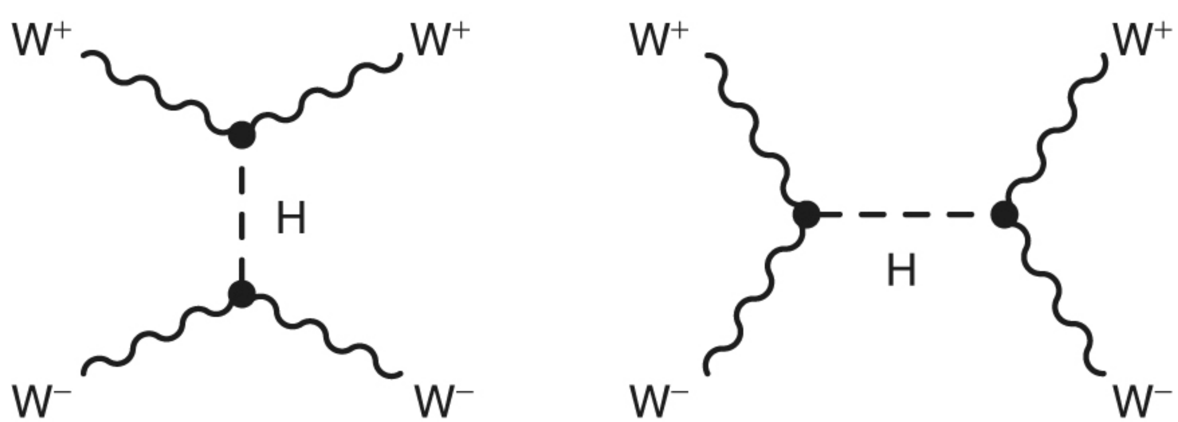
Vladimir Shiltsev, FHEP Hong Kong, Jan. 2015

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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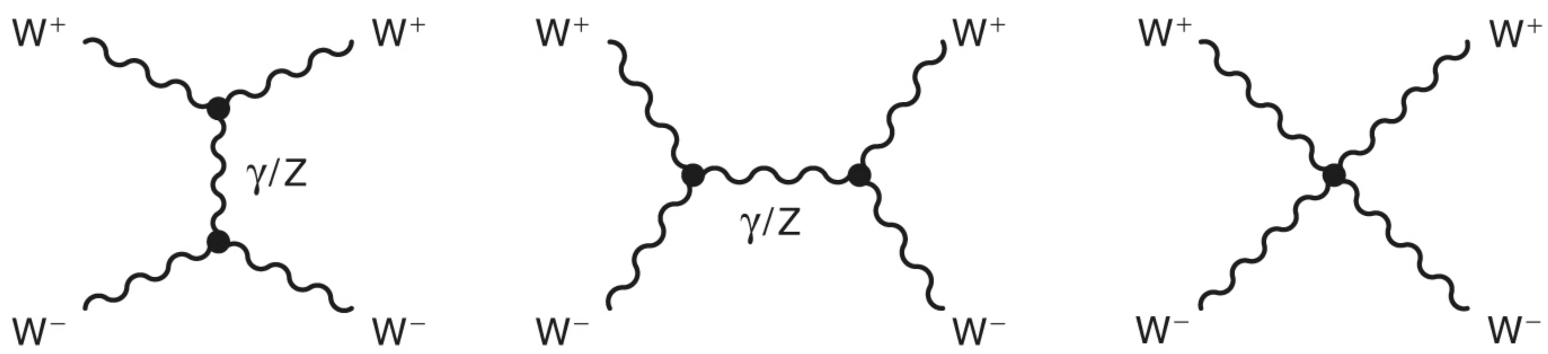

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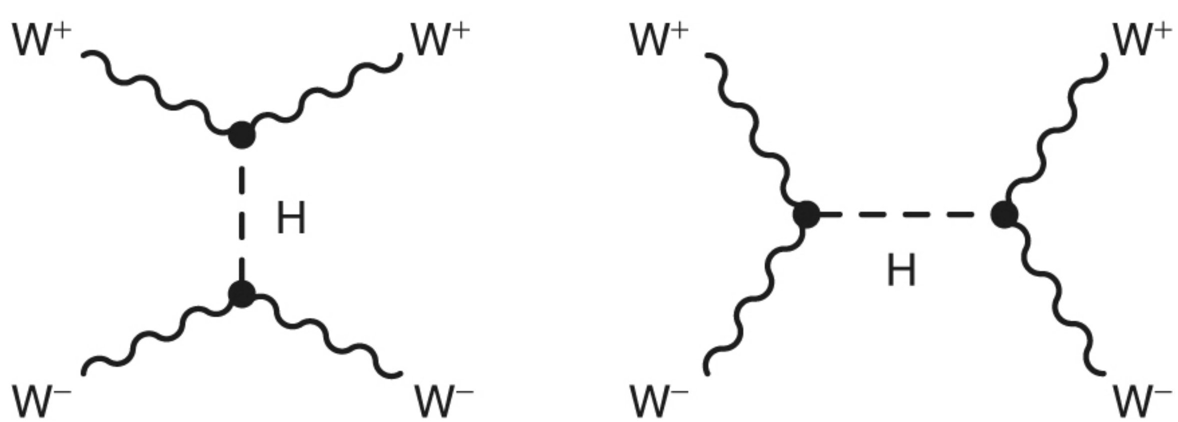

A guarantee that something has to turn up in the TeV region - either the Higgs, or some new dynamics in WW scattering

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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Two options to move forward:

➯ Maximise our knowledge based on things we already know
  - The Higgs: Fully understand electroweak symmetry breaking and the nature of the Higgs potential
  - The Top: Measure its properties as precisely as possible - use it as a potential window for New Physics
  - Other electroweak precision measurements to look for cracks in the SM

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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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- *"Is the End in Sight for Theoretical Physics?"* – Stephen Hawking, **1980**

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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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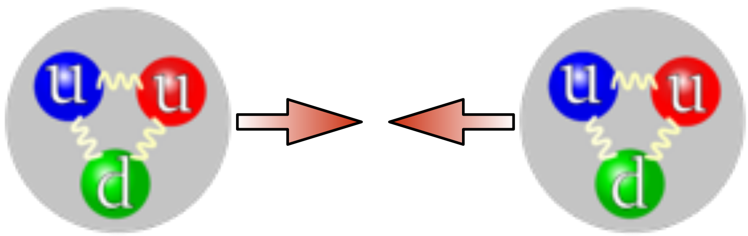
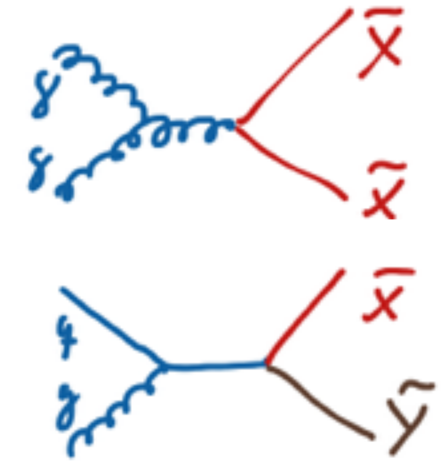
Possible Future Facilities at the Energy Frontier

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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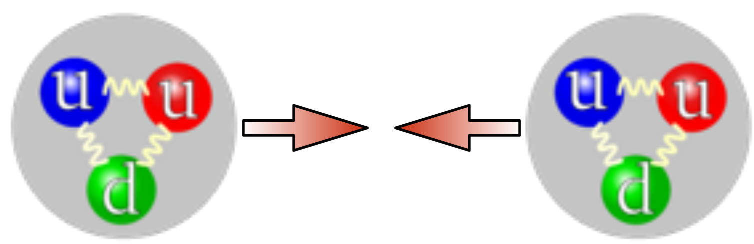

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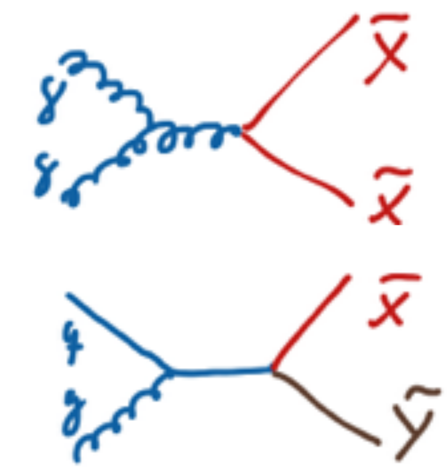

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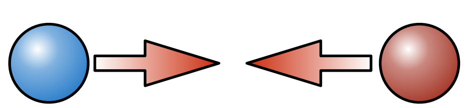
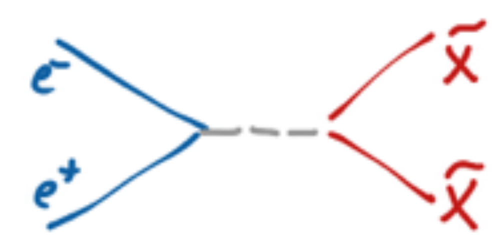
- electron-positron colliders:



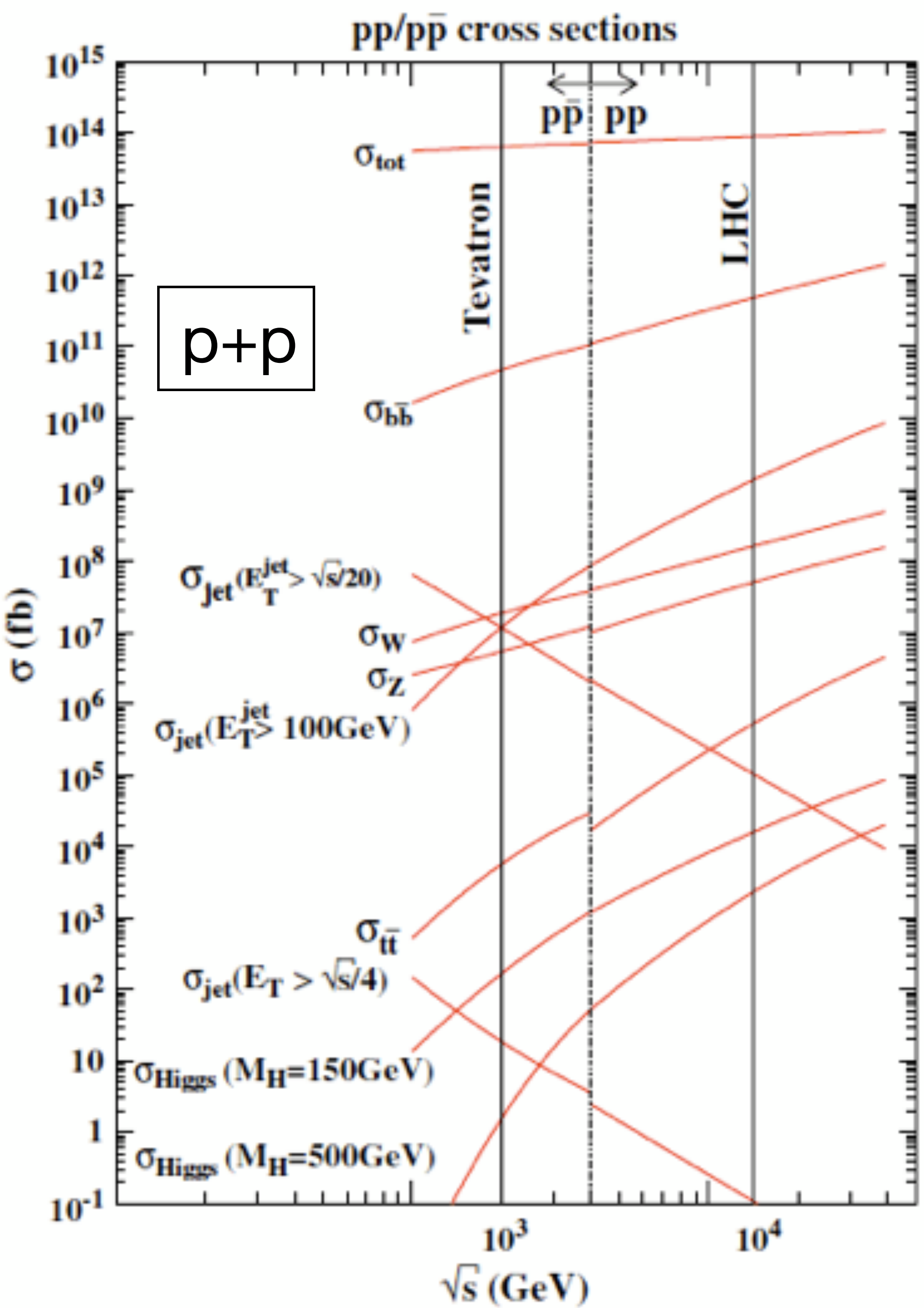
~ full energy available in reaction - can explore thresholds

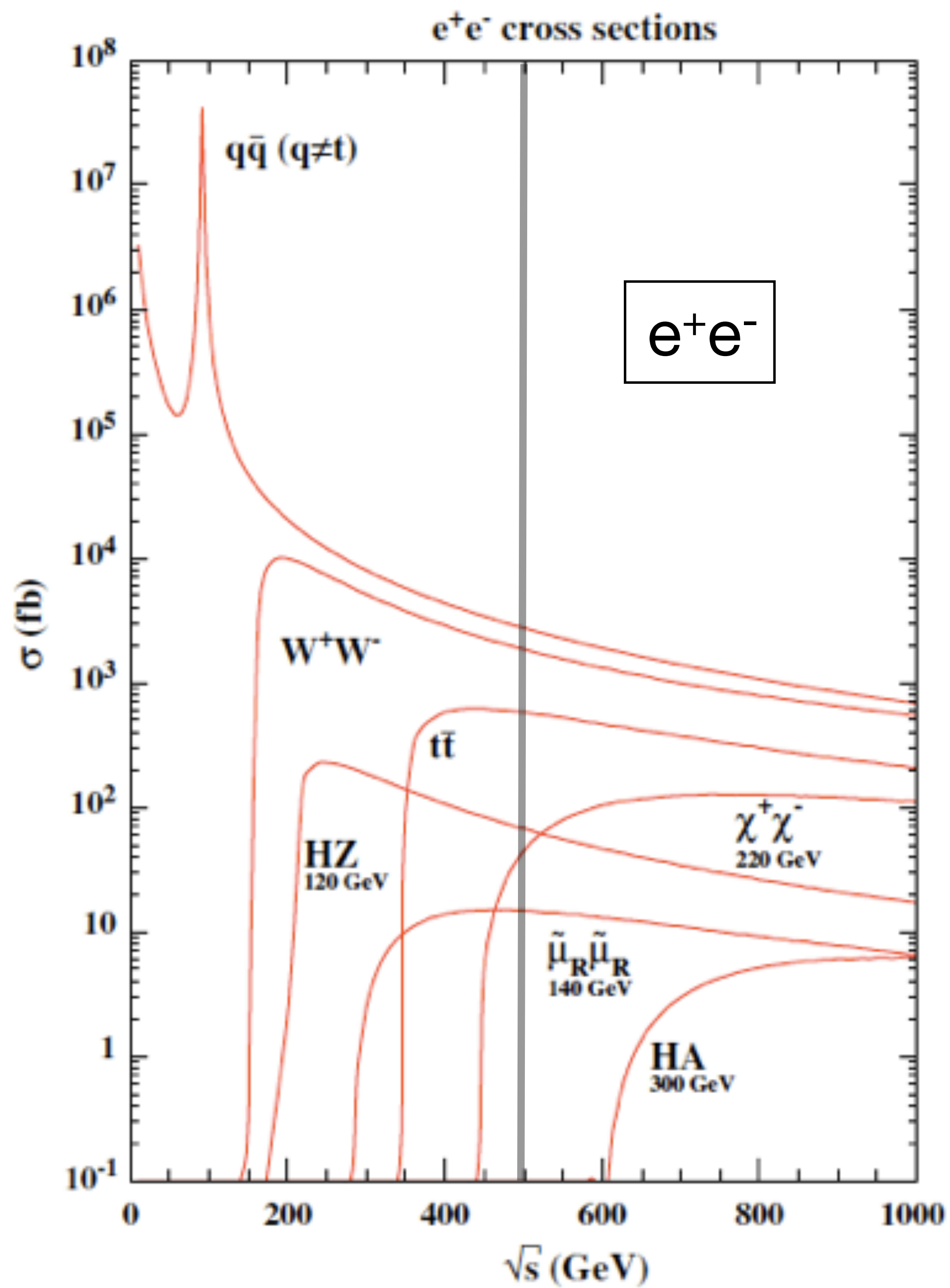


electroweak production:
all particles produced with ~ equal probability - particularly sensitive to electroweak particles, which are suppressed at hadron colliders

Hadrons vs Leptons

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





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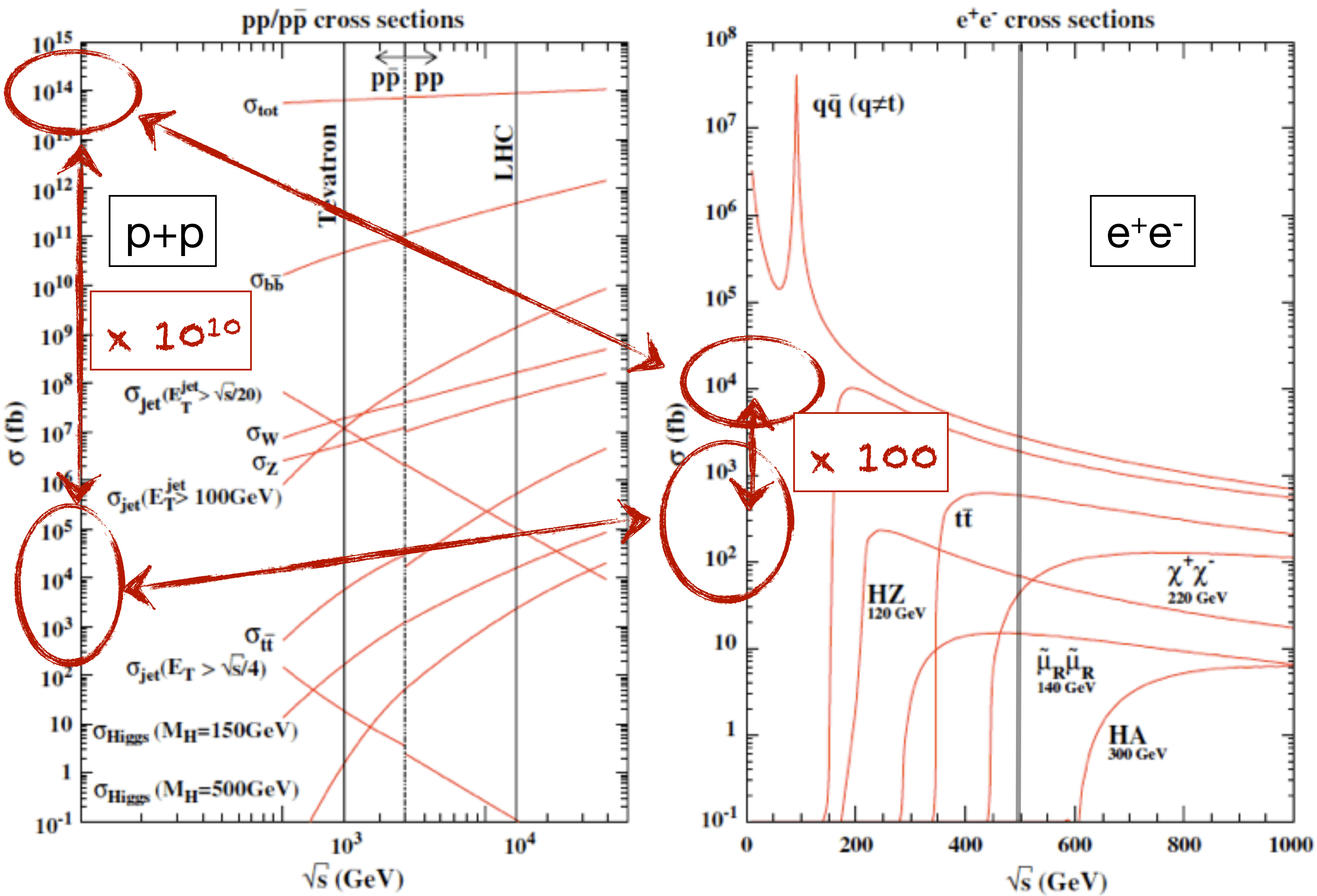

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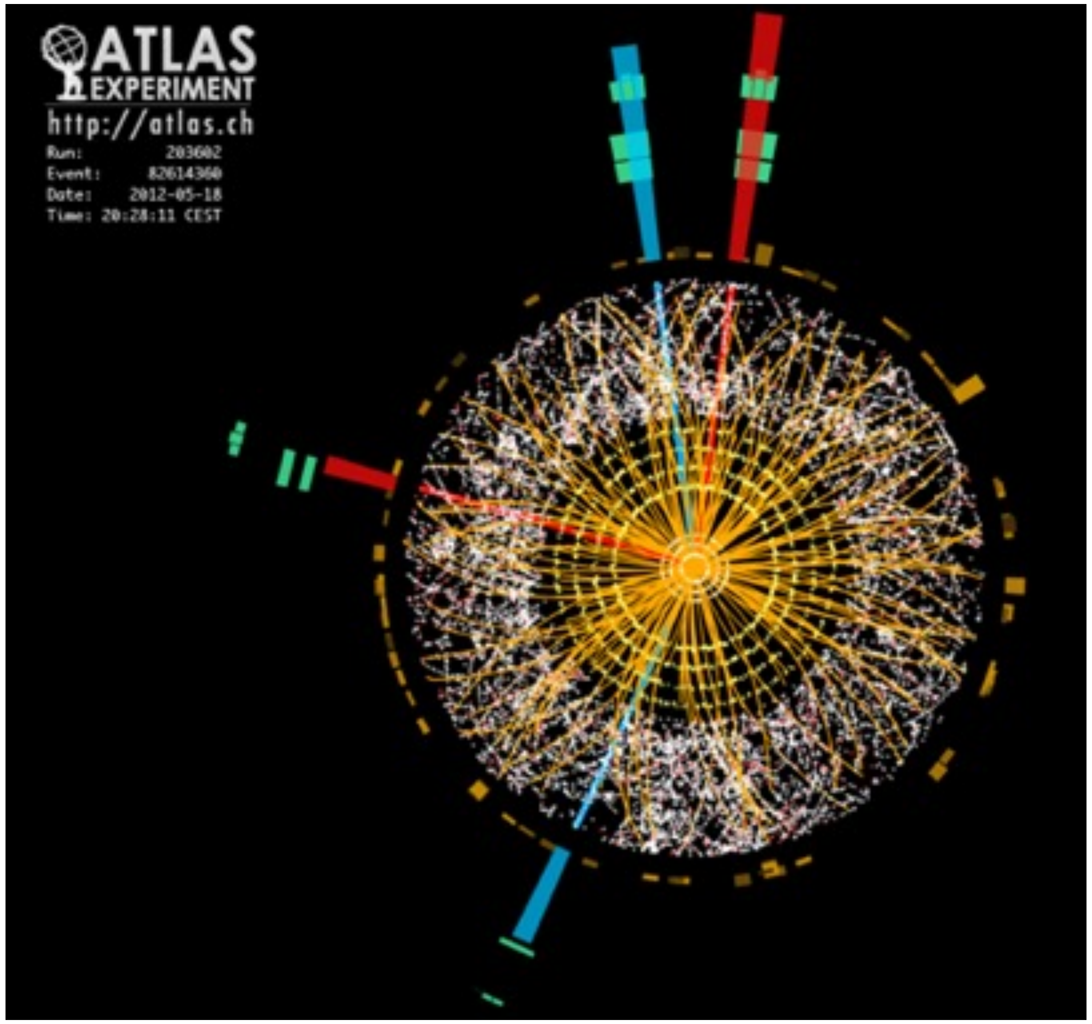
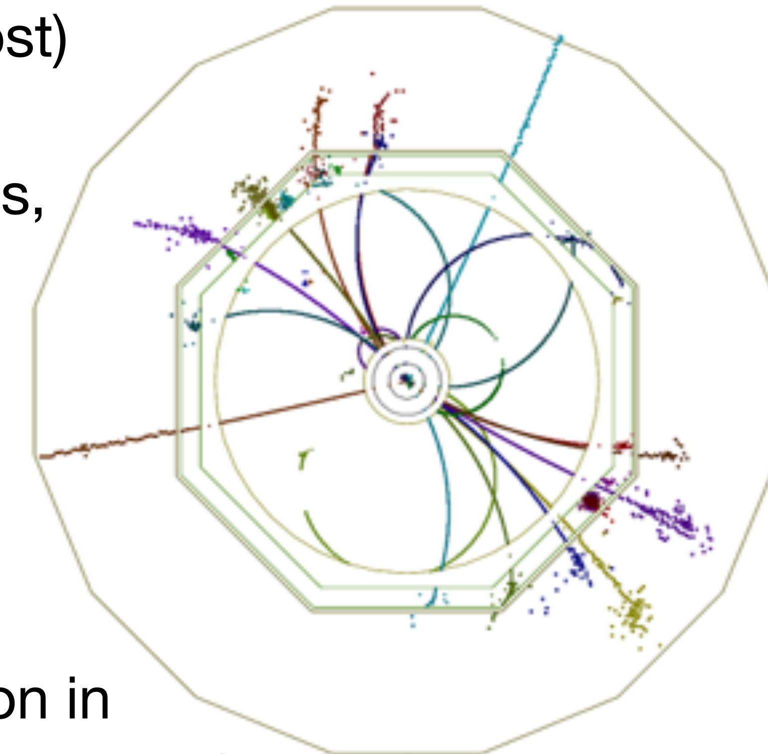


Higgs production in pp: (almost) every particle in the event originates from other reactions, only four leptons are from the Higgs decay



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

Frank Simon (fsimon@mpp.mpg.de)

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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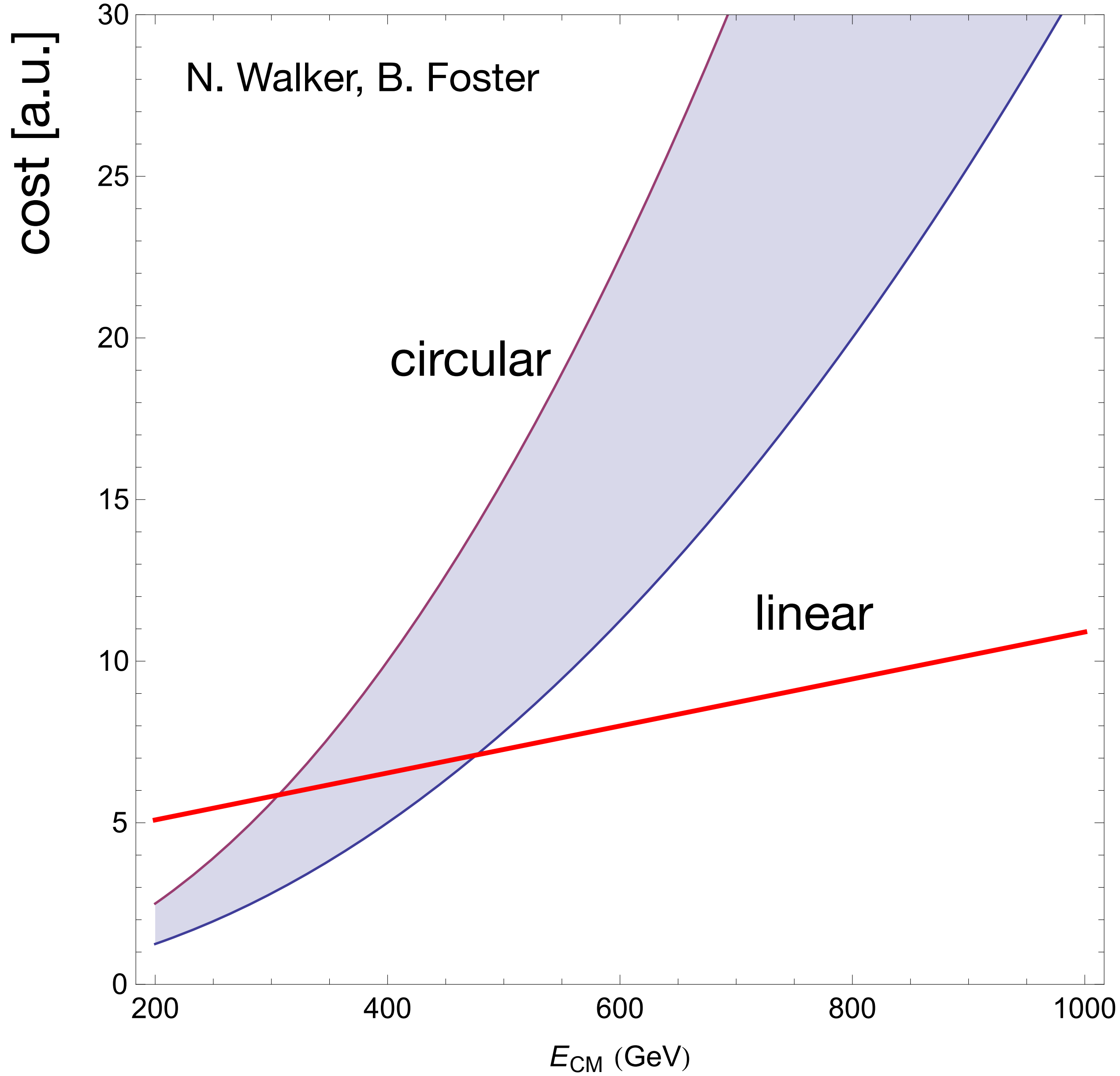

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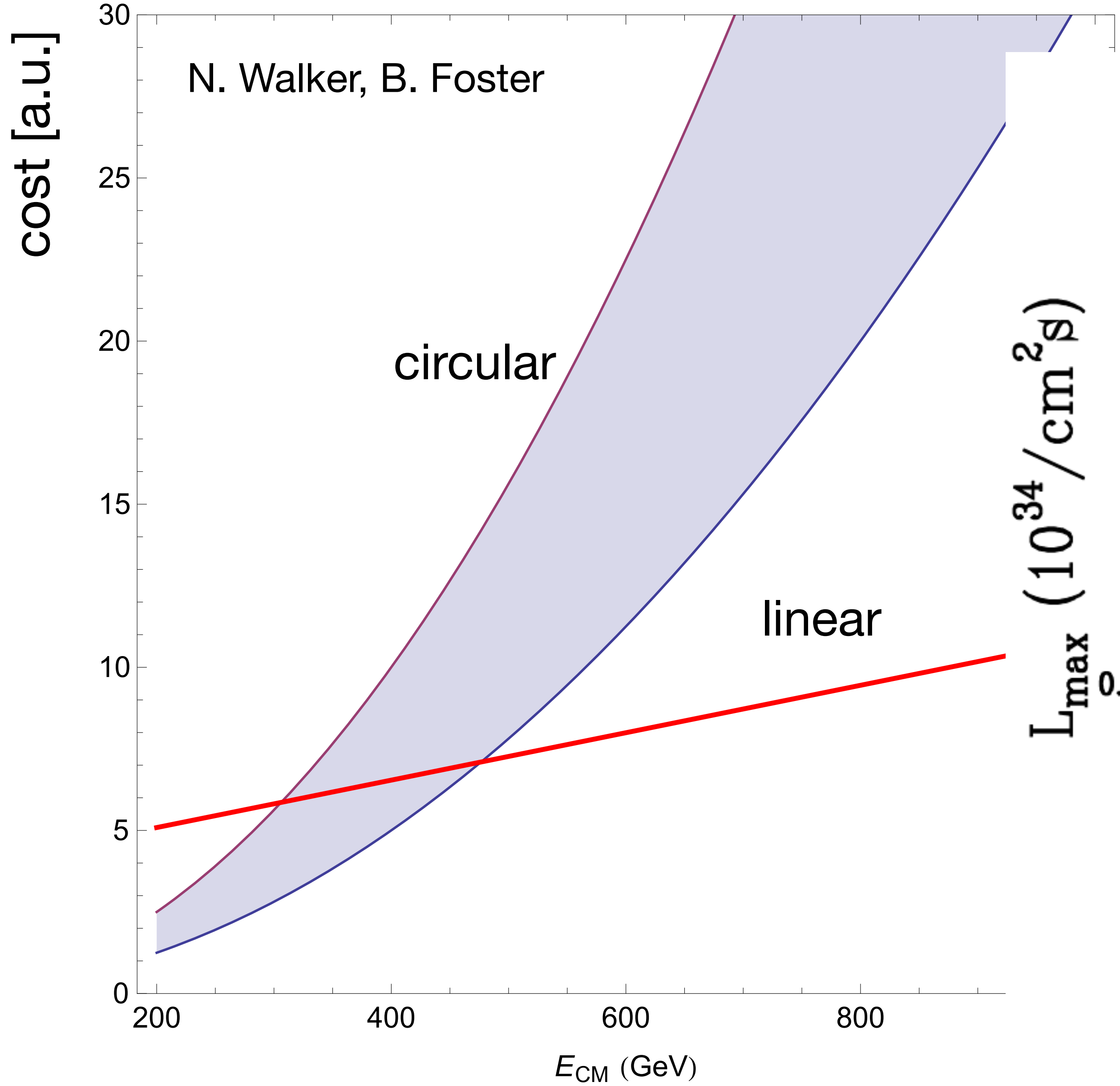
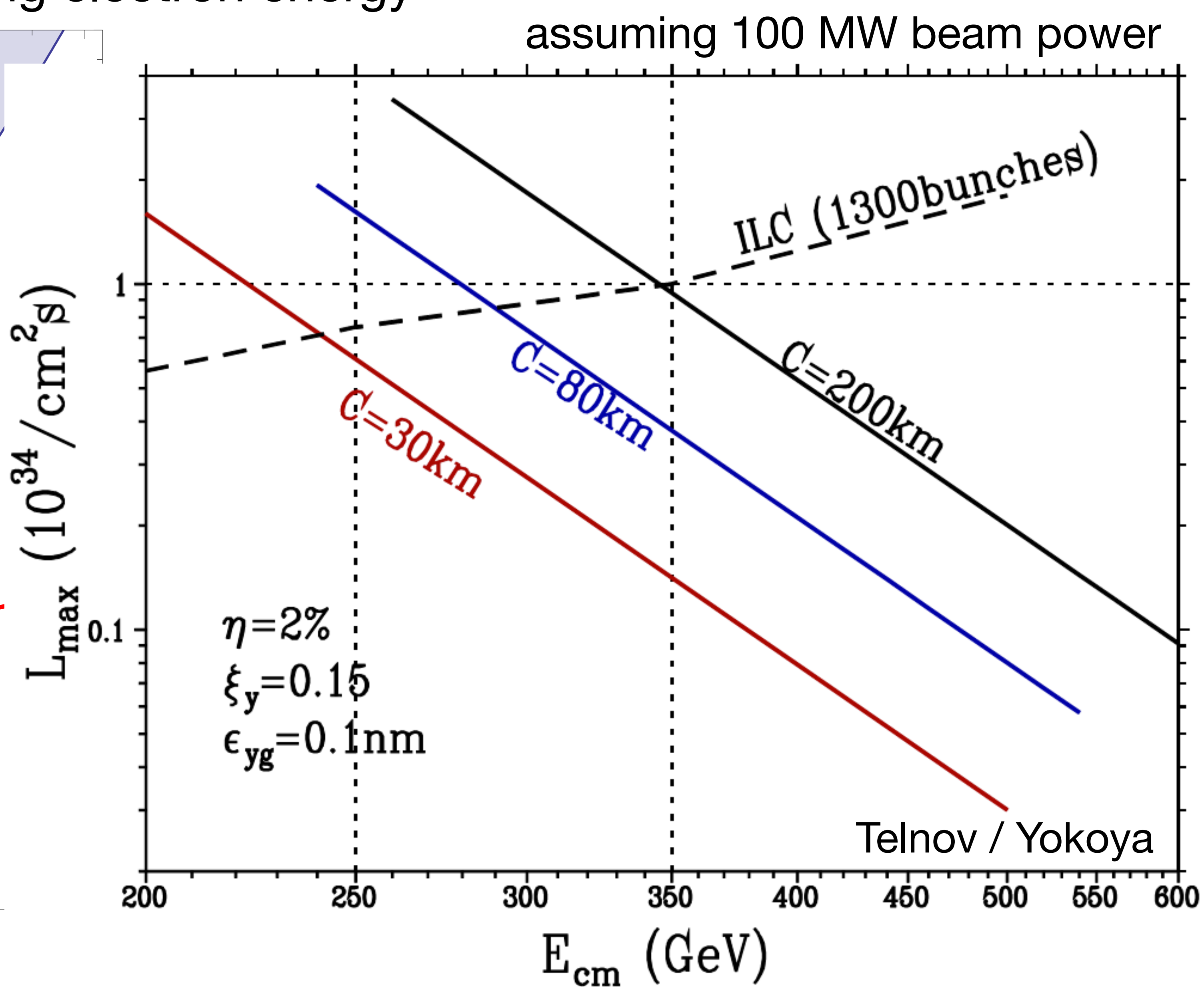
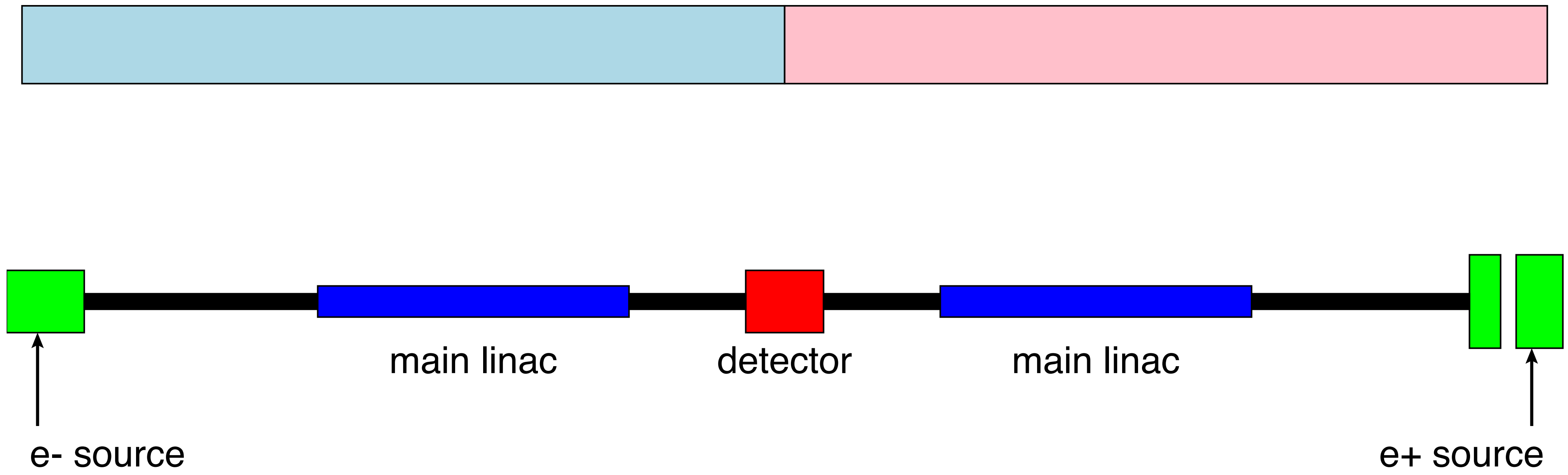




Challenges: Linear Colliders

- 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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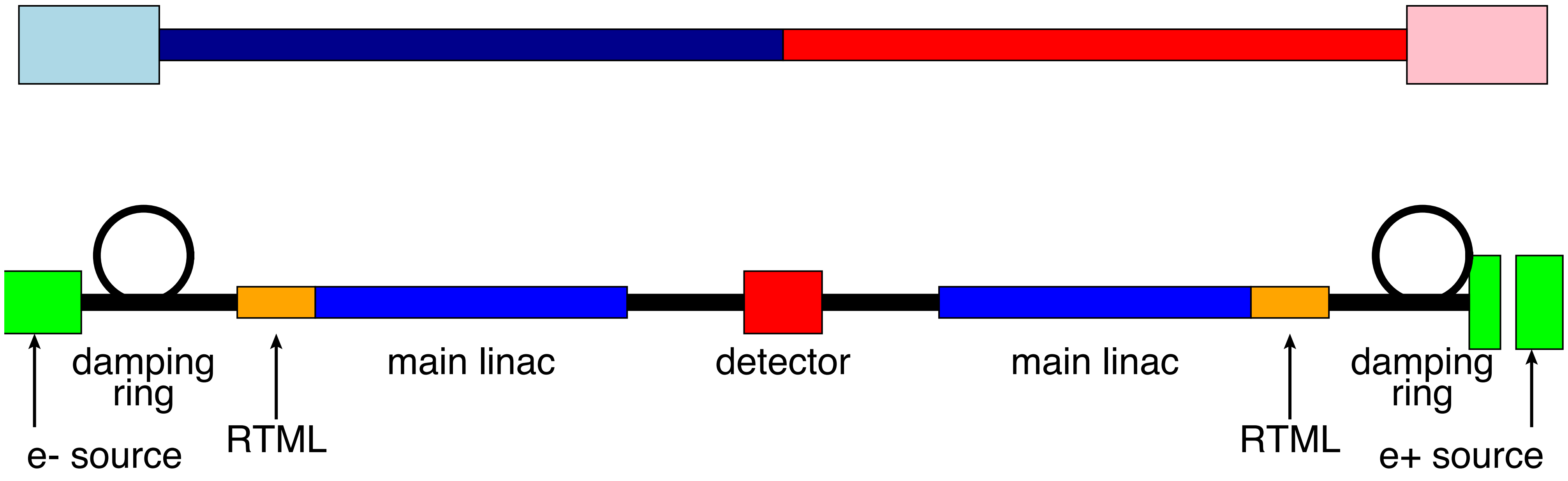

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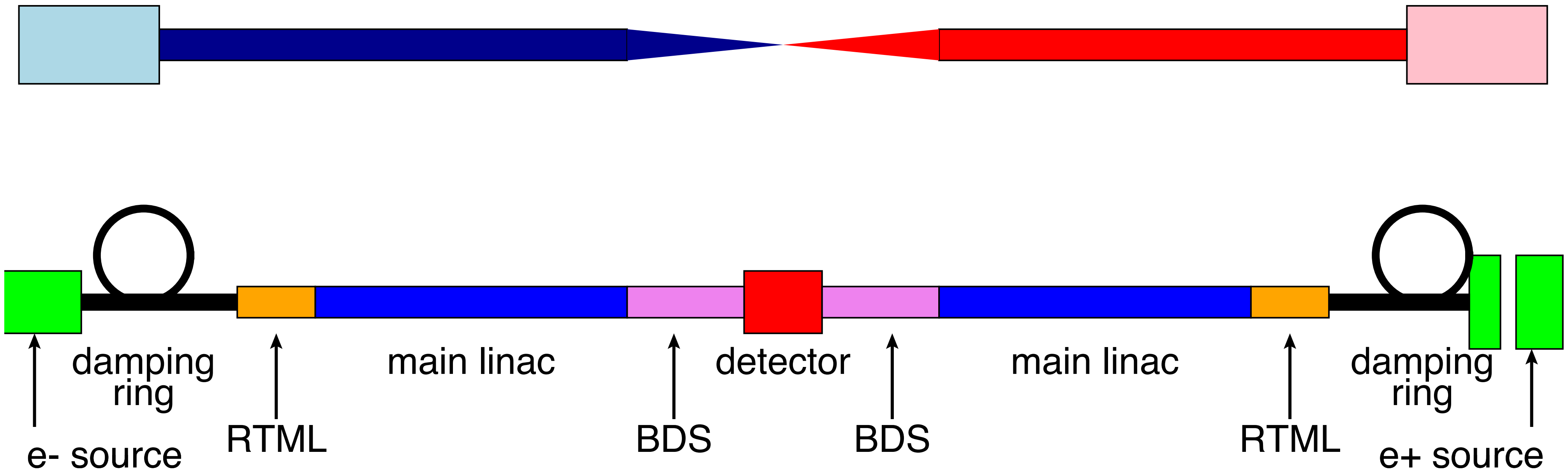
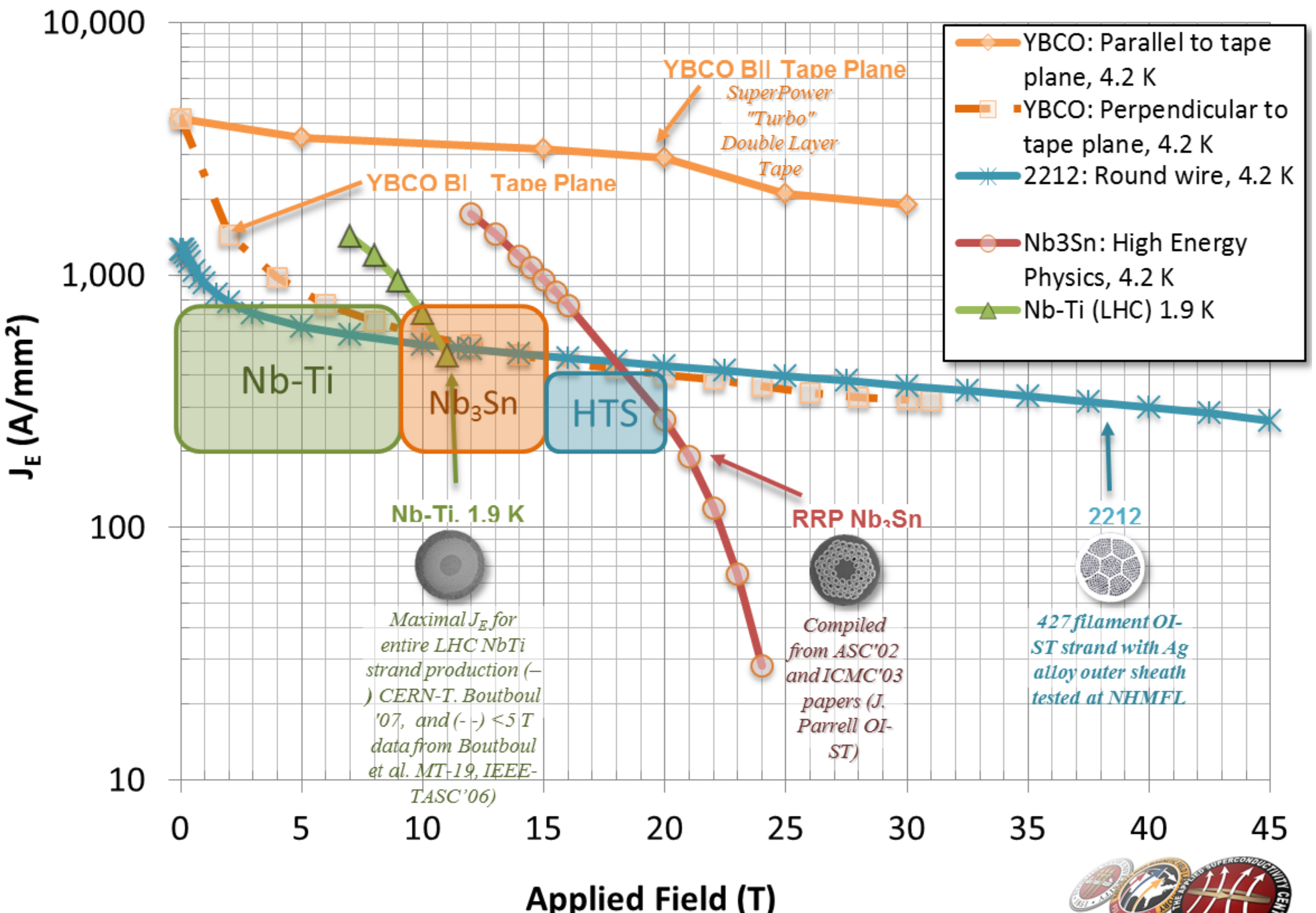


Challenges: Hadron Colliders

- Main Dipole field (and radius) determines maximum energy: E ~ B x R
  - ▸ 100 TeV requires 16 T main dipoles for a circumference of 100 km (20 T for 80 km)
    - 16 T seem achievable with Nb_3Sn
    - 20 T require HTS magnets - substantial additional challenge



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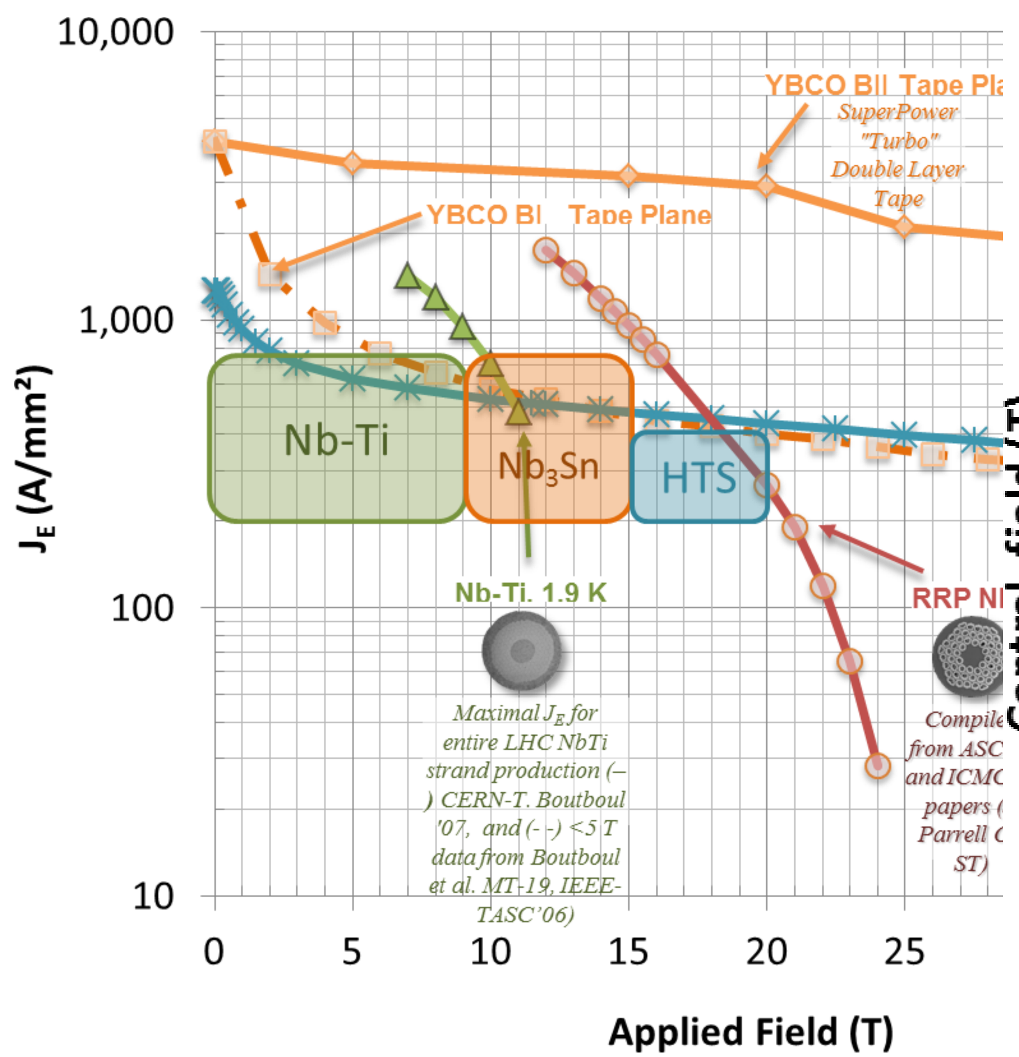
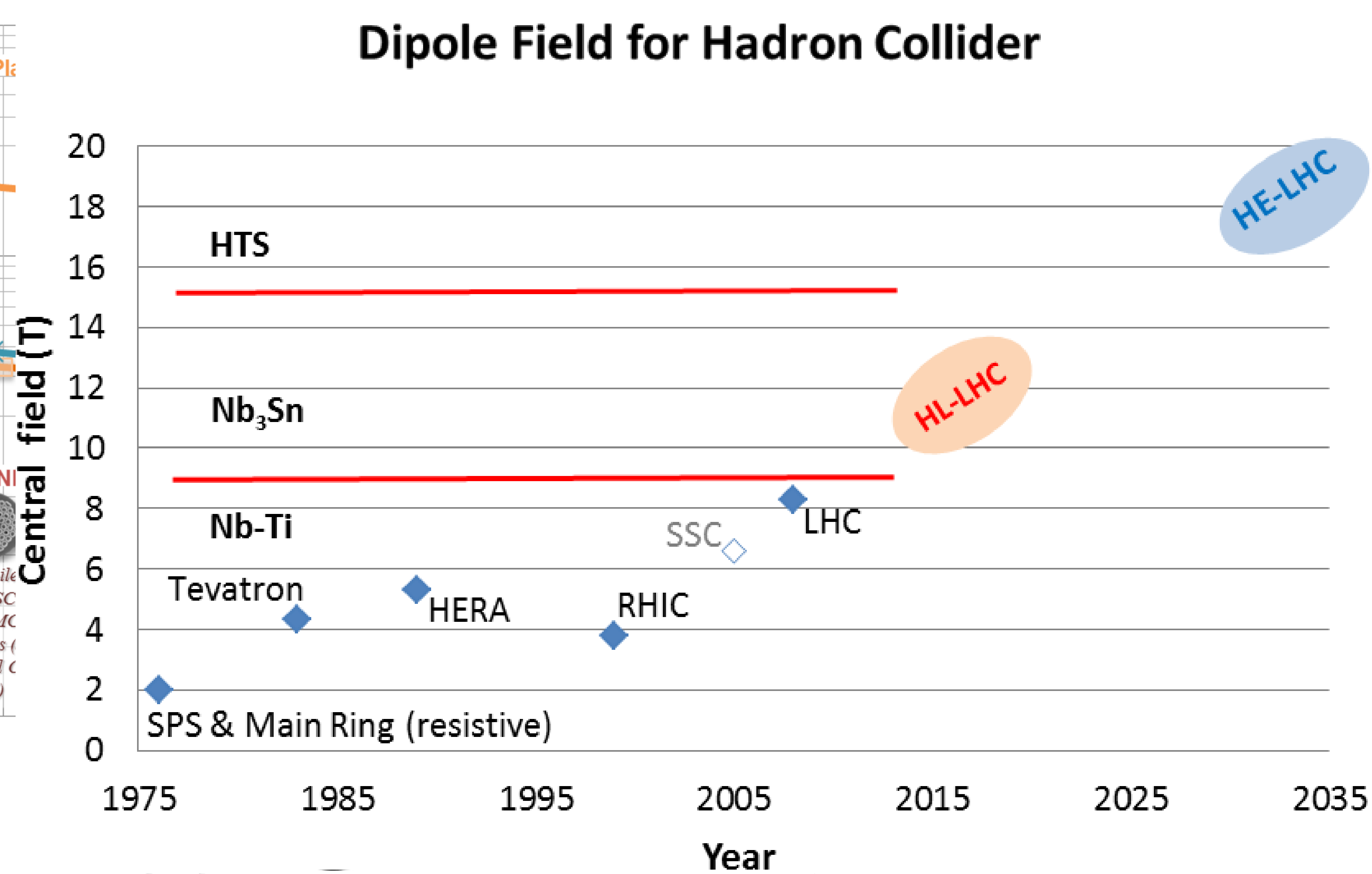
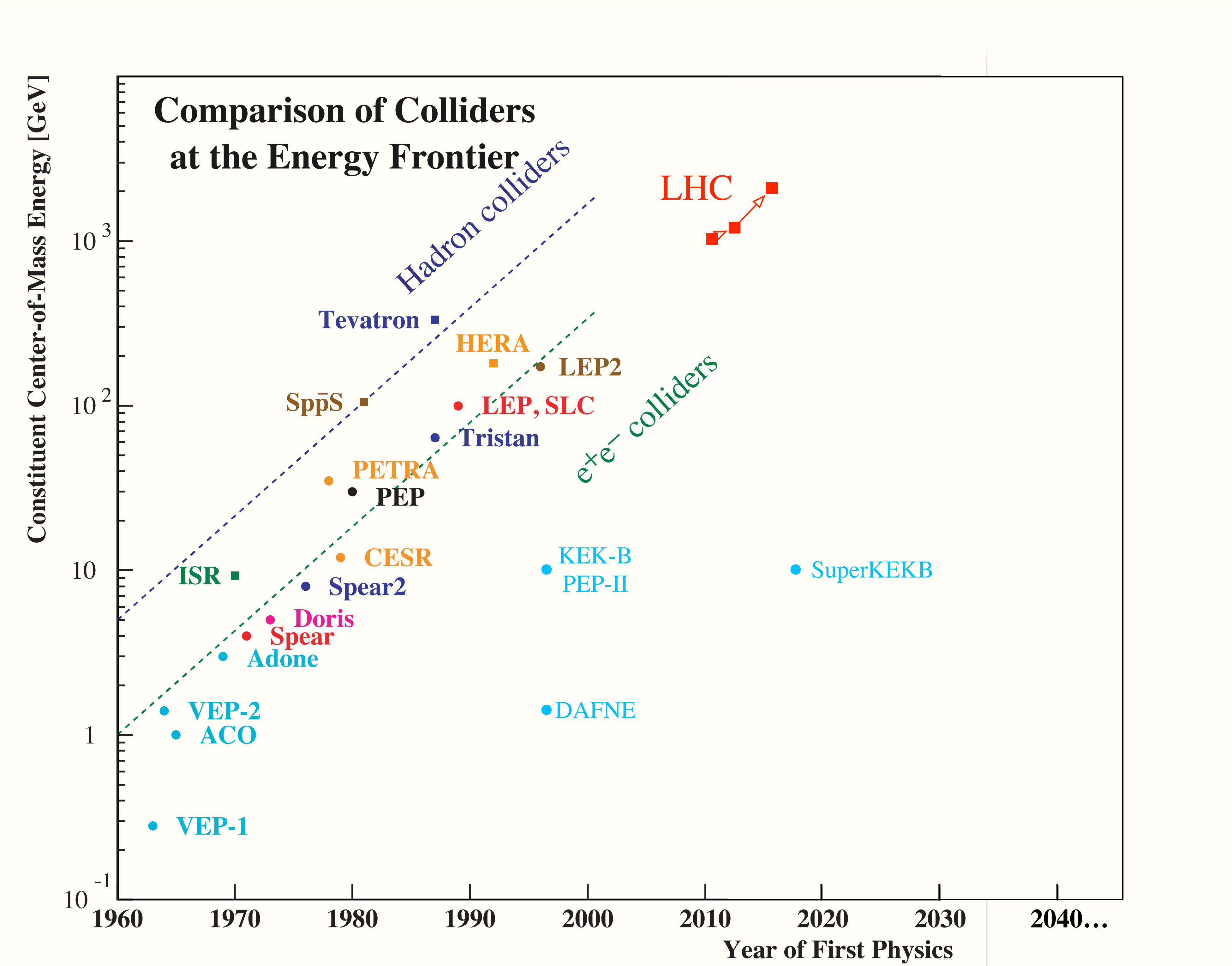




The Landscape - Past, Present and Future Colliders



taken from Nick Walker

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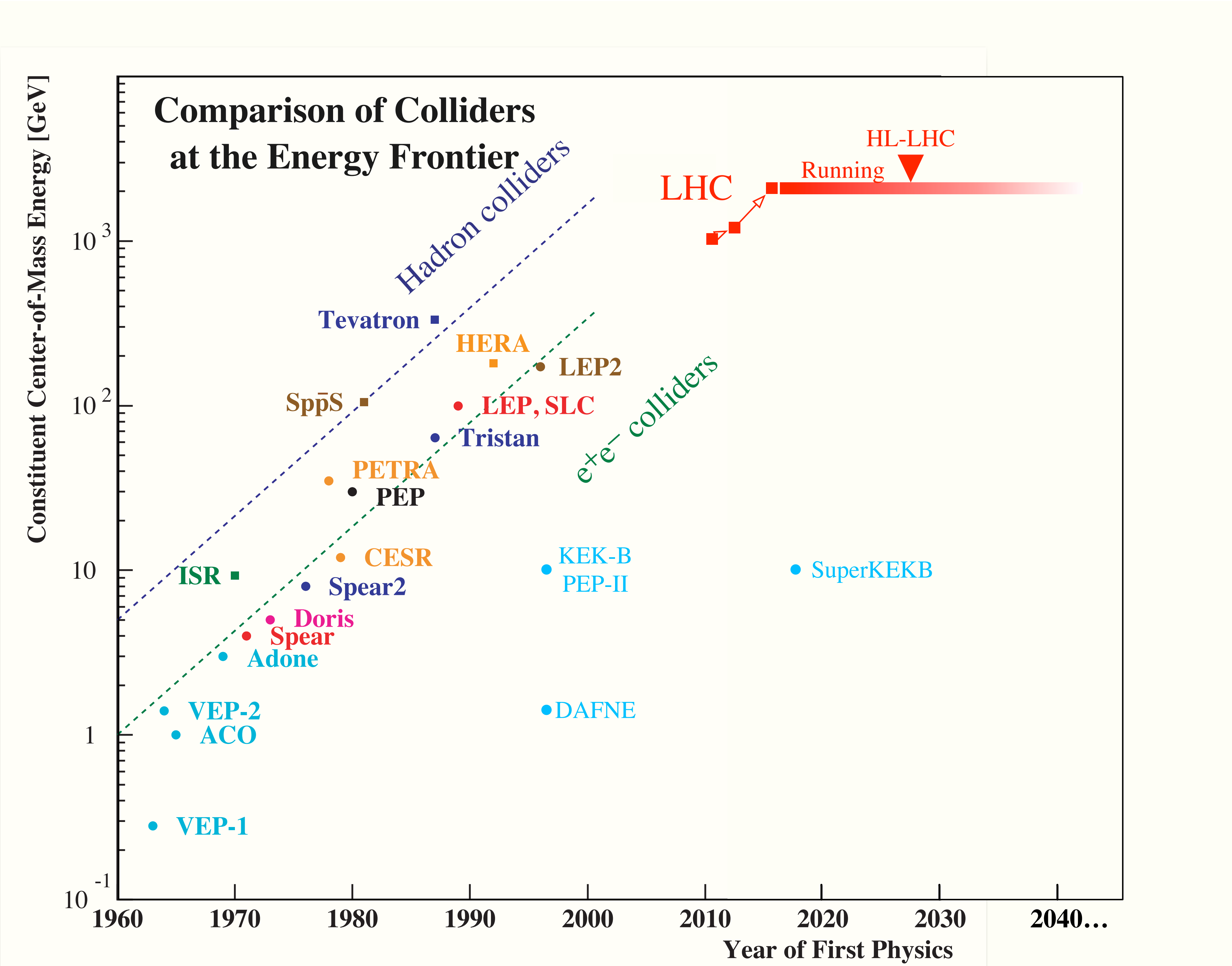

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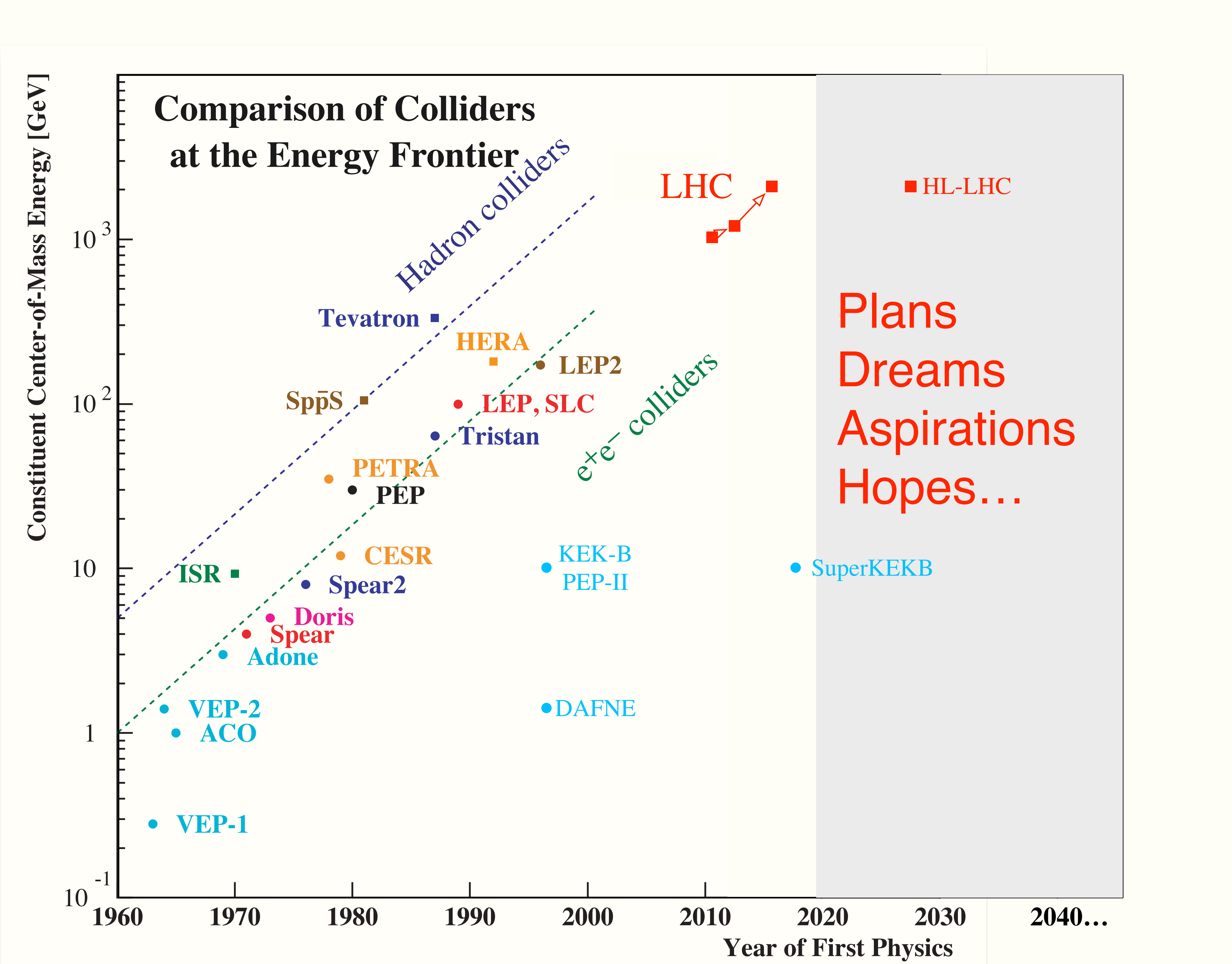

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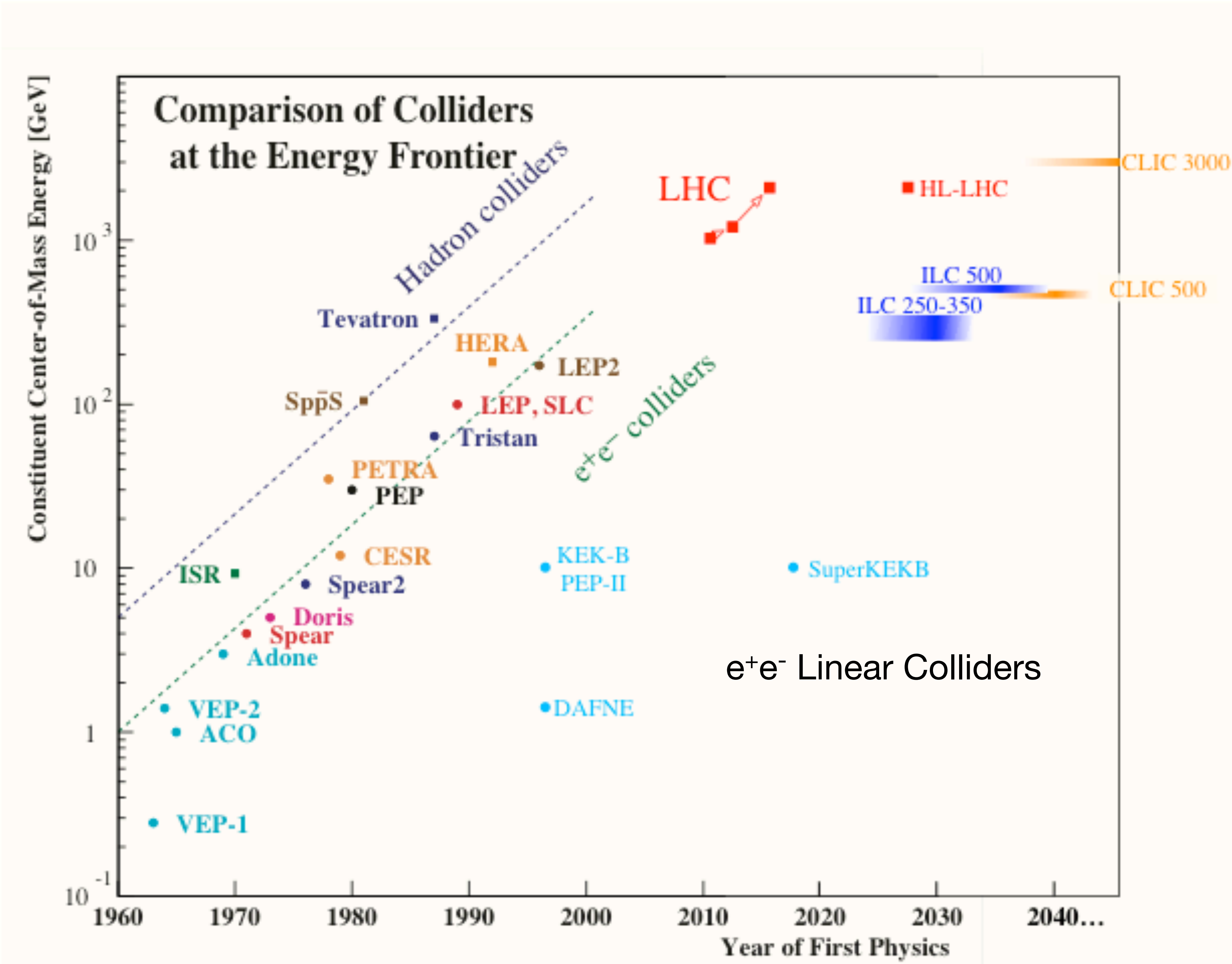

Linear Colliders:
30 - 50 km in length

taken from Nick Walker

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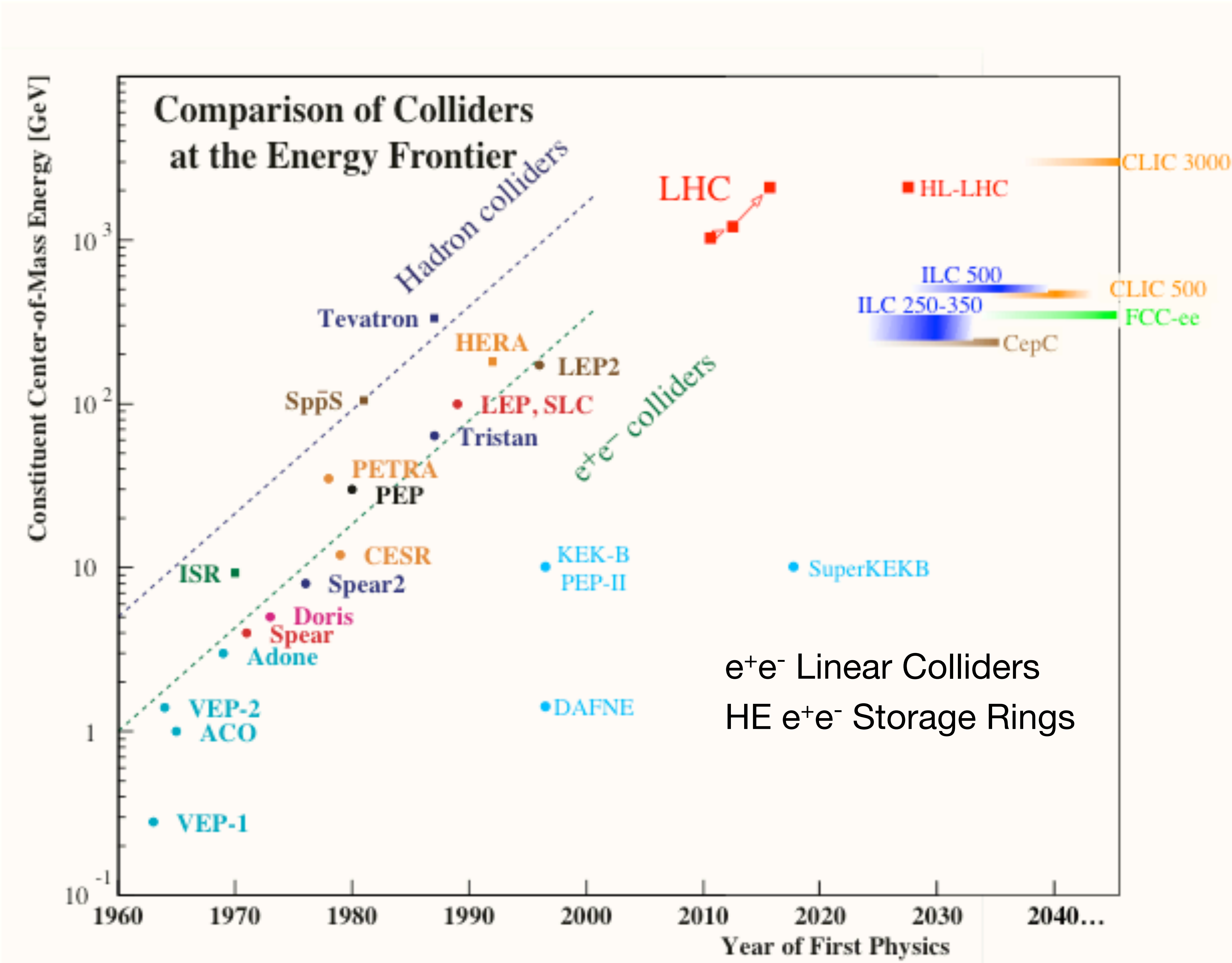

Linear Colliders:
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Synchrotrons:
50 km - 100 km tunnels, main drivers typically pp, also come with e^+e^- option

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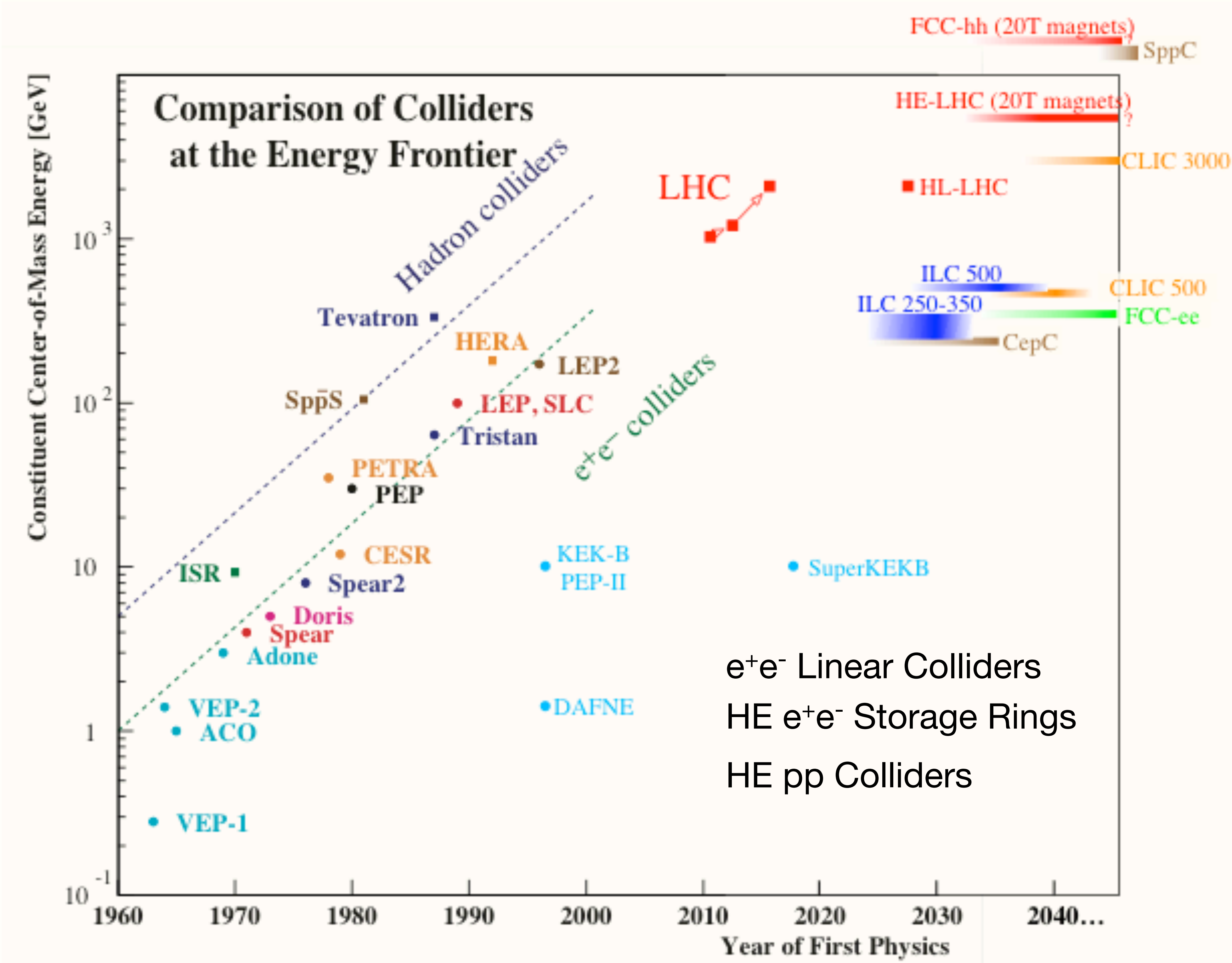

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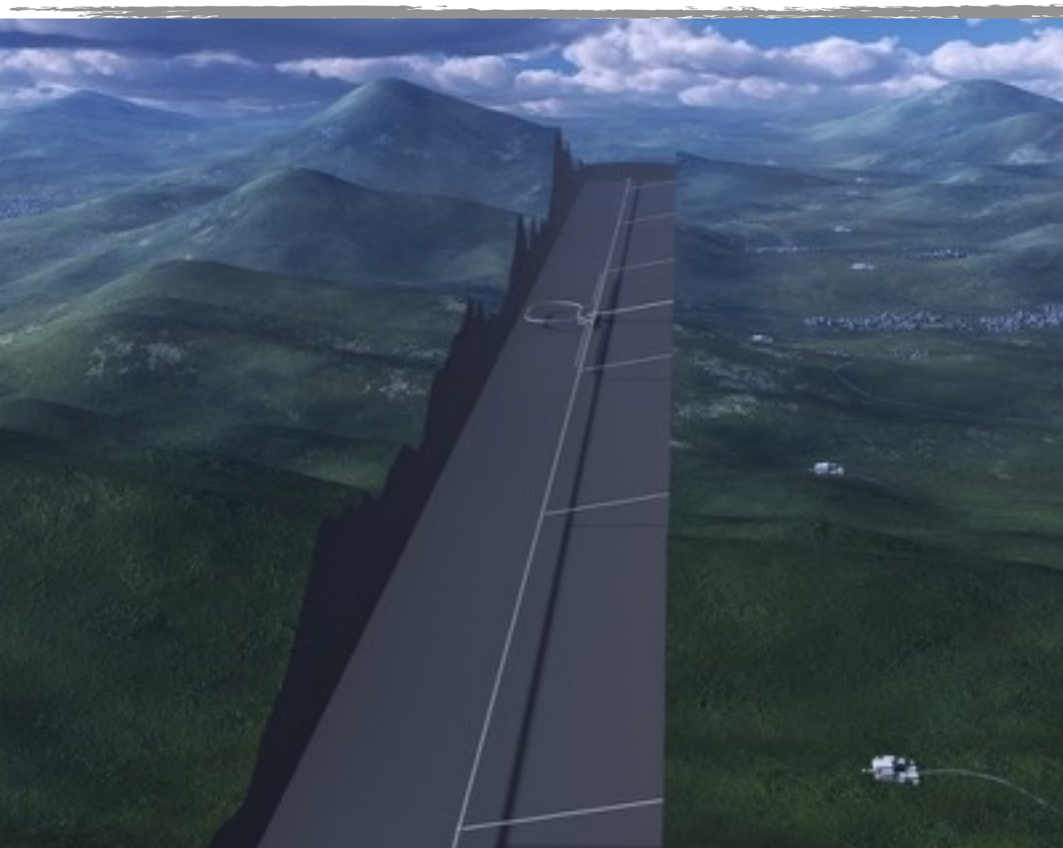
New Colliders - The Line-Up: Linear Colliders

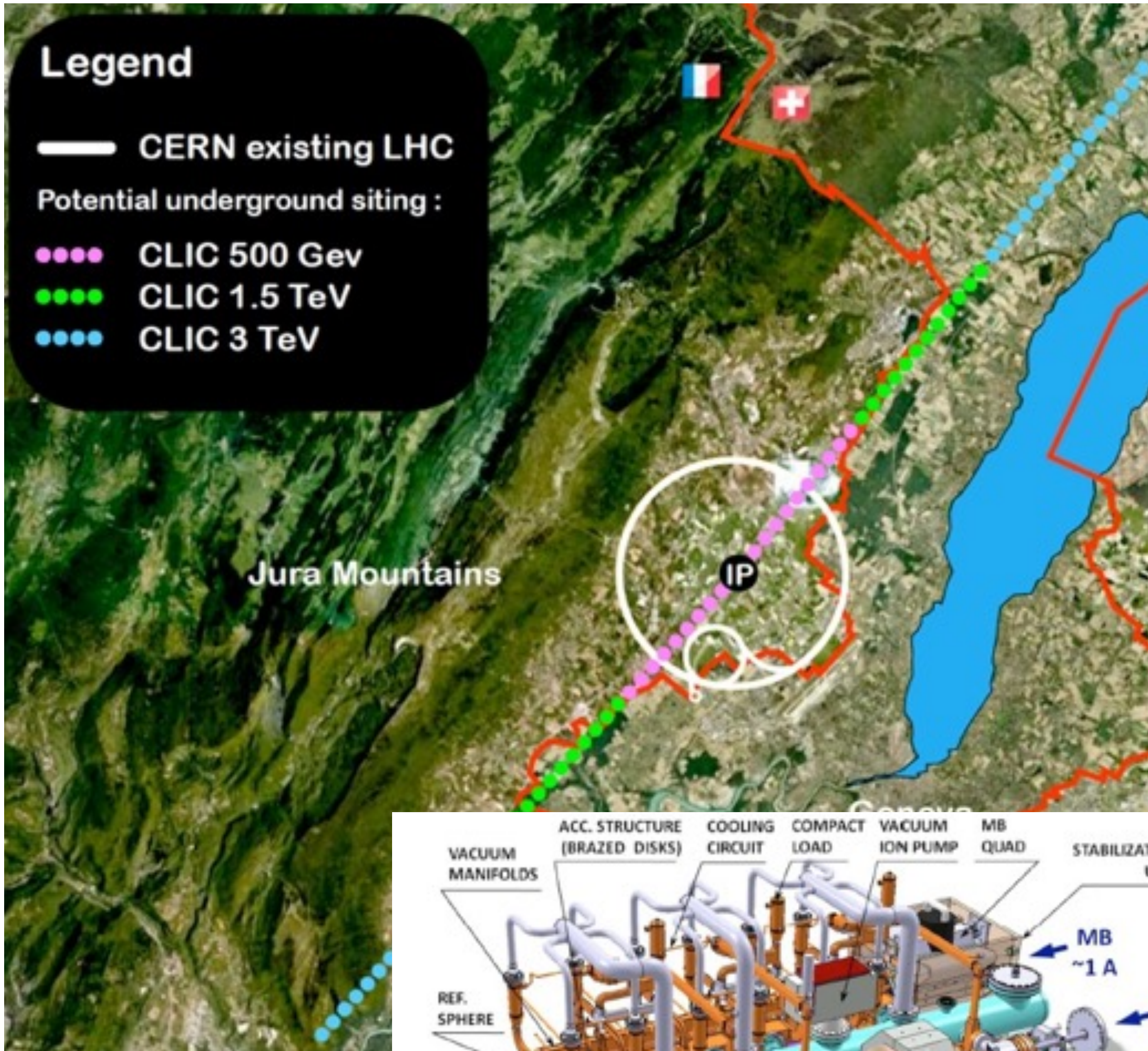


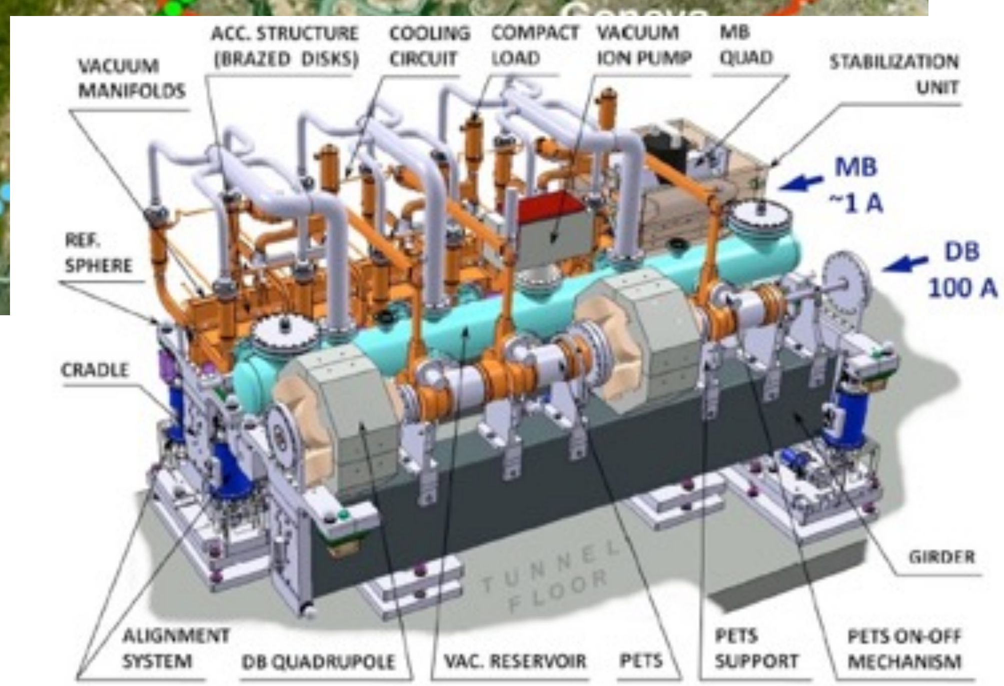
- The **I**nternational **L**inear **C**ollider: a 30 - 50 km long linear tunnel
  - e^+e^- collisions up to 500 GeV / 1 TeV for Higgs, Top, BSM
  - Superconducting acceleration structures, ~ 30 MV/m
  - Technologically far advanced: Technical design report completed in 2012, ILC technology is being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

Current time line

- Construction starting in 2018, physics 2027

New Colliders - The Line-Up: Linear Colliders





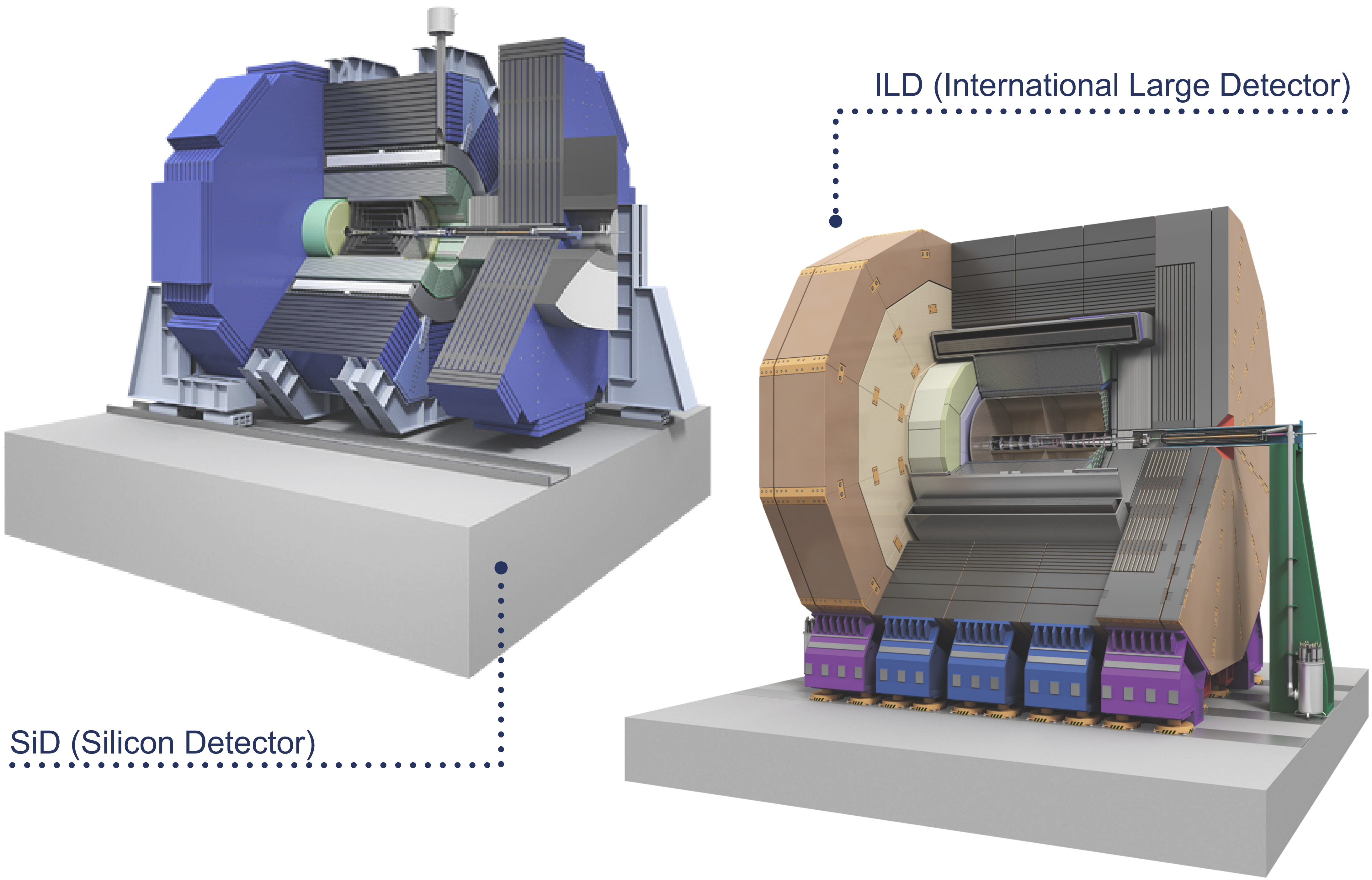
- The **C**ompact **Li**near **C**ollider:
  A 50 km long linear tunnel as one of CERNs future options
  - e^+e^- collisions up to 3 TeV for Higgs, Top, BSM
  - Two-Beam acceleration, 100 MV/m
  - Main technological issues demonstrated, Conceptual Design report published in 2012

Current time line

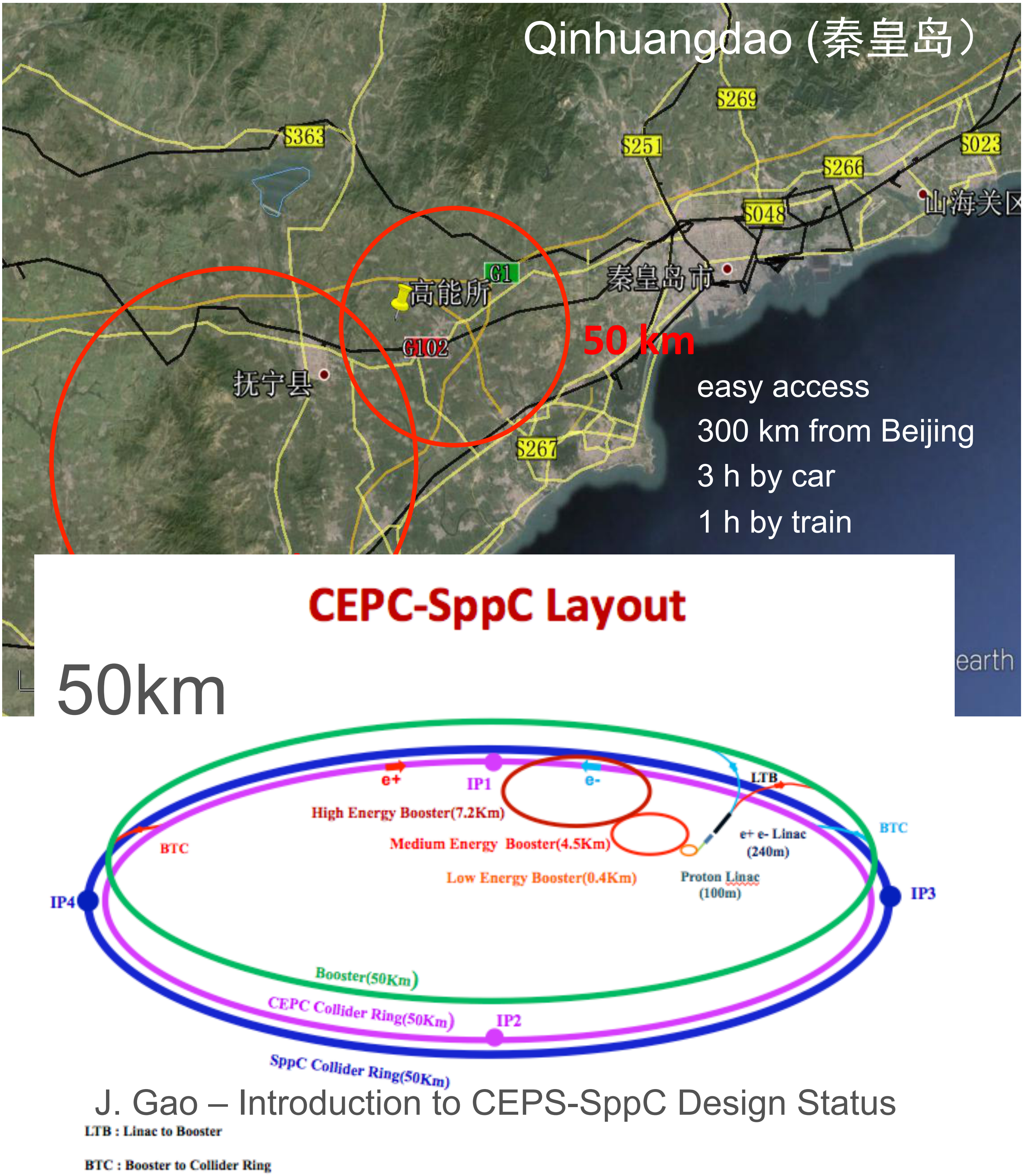
- Technical Design by 2018
- Construction could start in 2025, physics by 2035

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

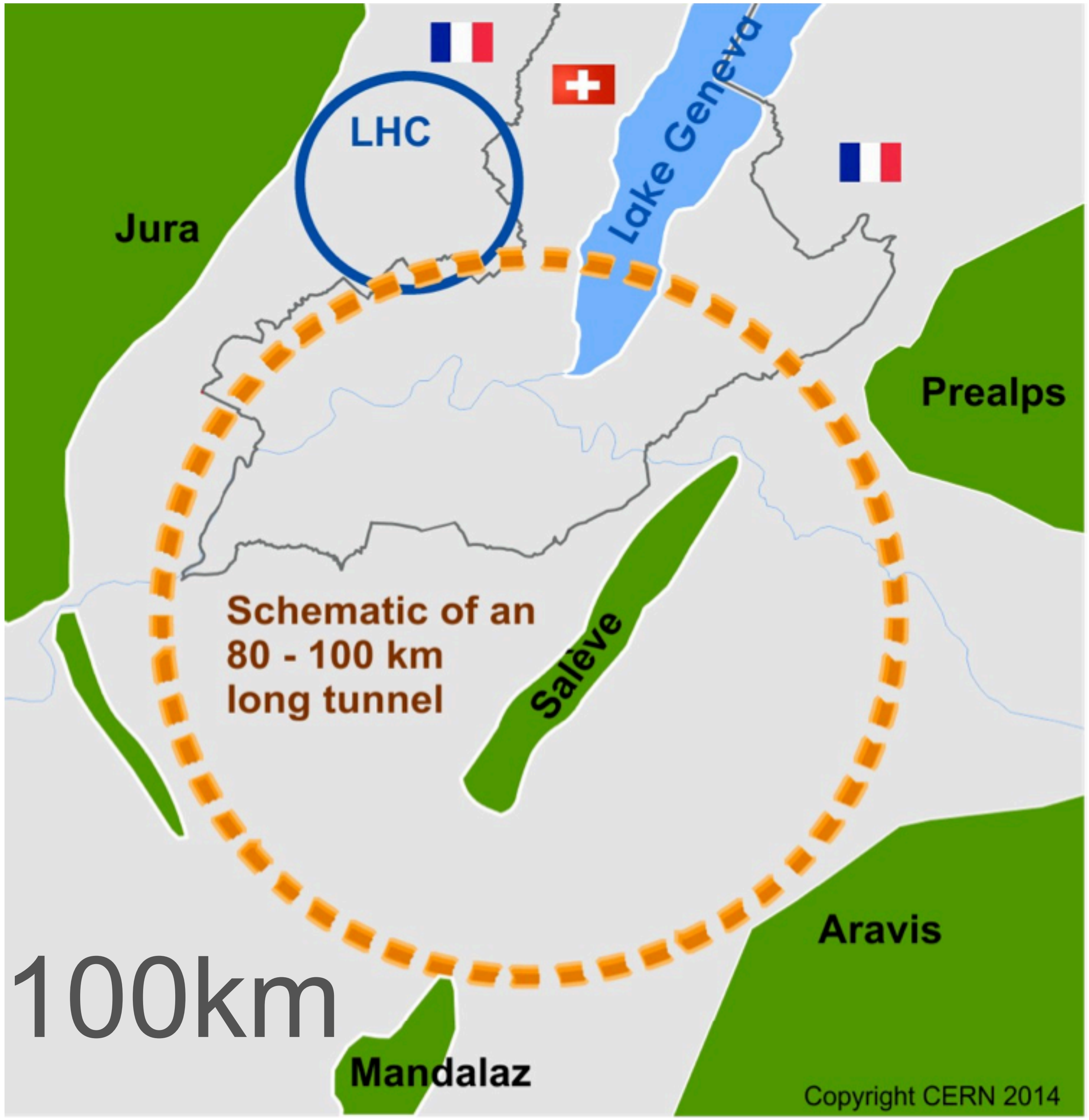


- A ~ 50 km (maybe 70 - 100 km) circumference ring in China (compare: LHC 27 km)
- "Dual-use":
  - CEPC - e^+e^- collider with 240 GeV - just enough for Higgs production
  - SppC - pp collider with ~ 60 TeV - relies in 20 T dipole magnets

Current time line

- First stage: e^+e^- - R&D until 2020, could run by 2030
- Second stage: pp - R&D until 2030, technical design until 2035, could run by 2042

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

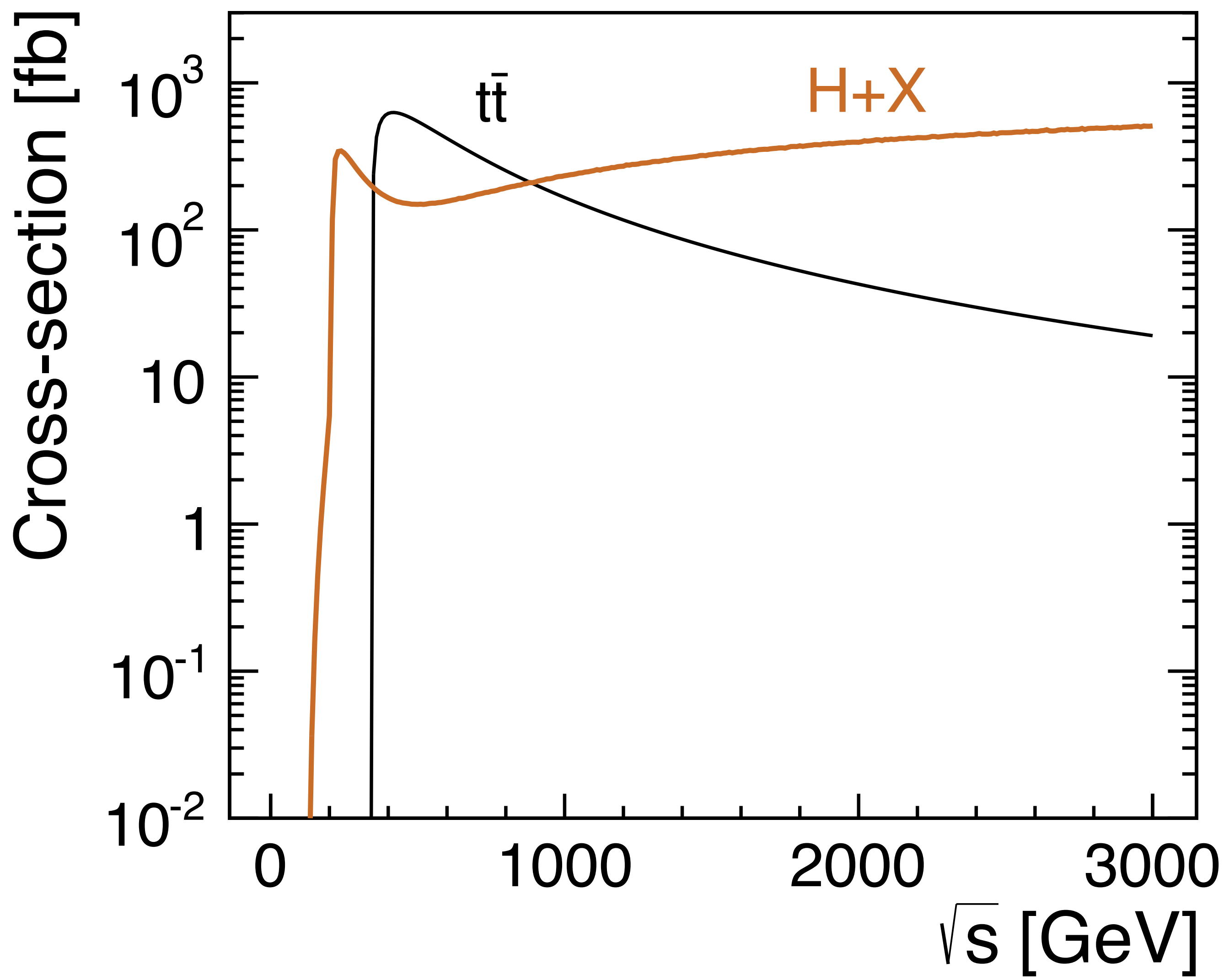
- Conceptual Design by 2018
- R&D, Prototyping until ~2027
- Could run by ~ 2038

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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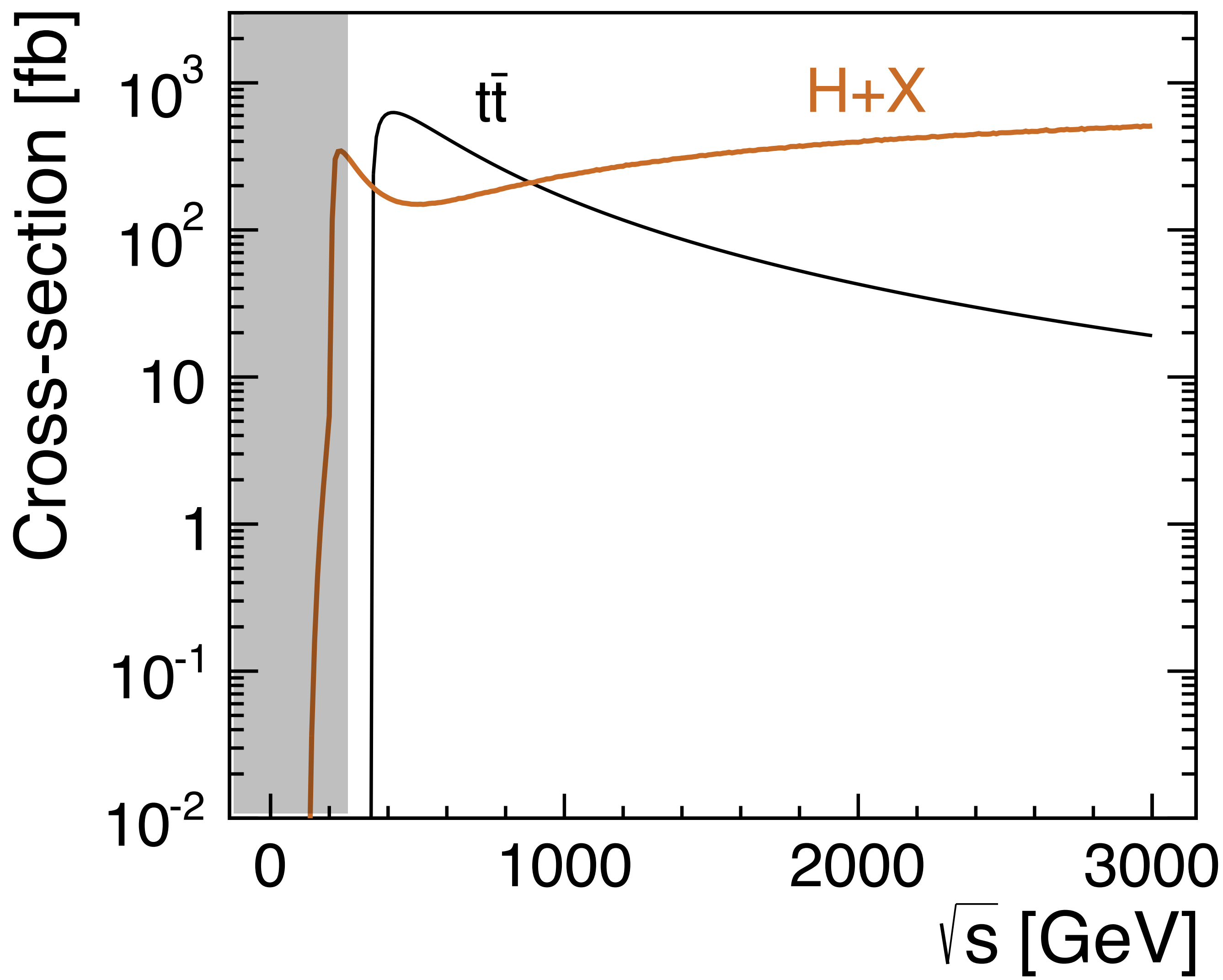

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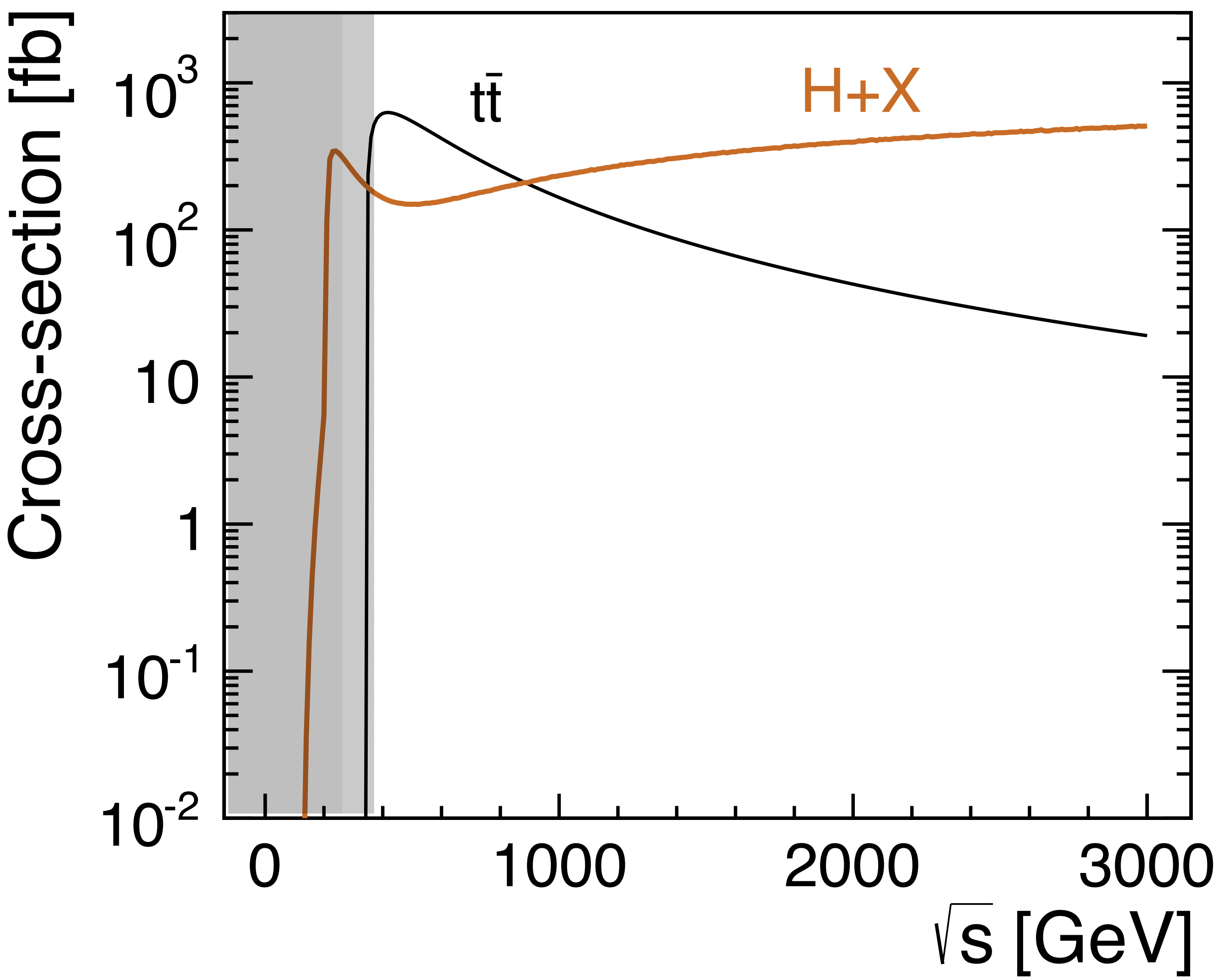

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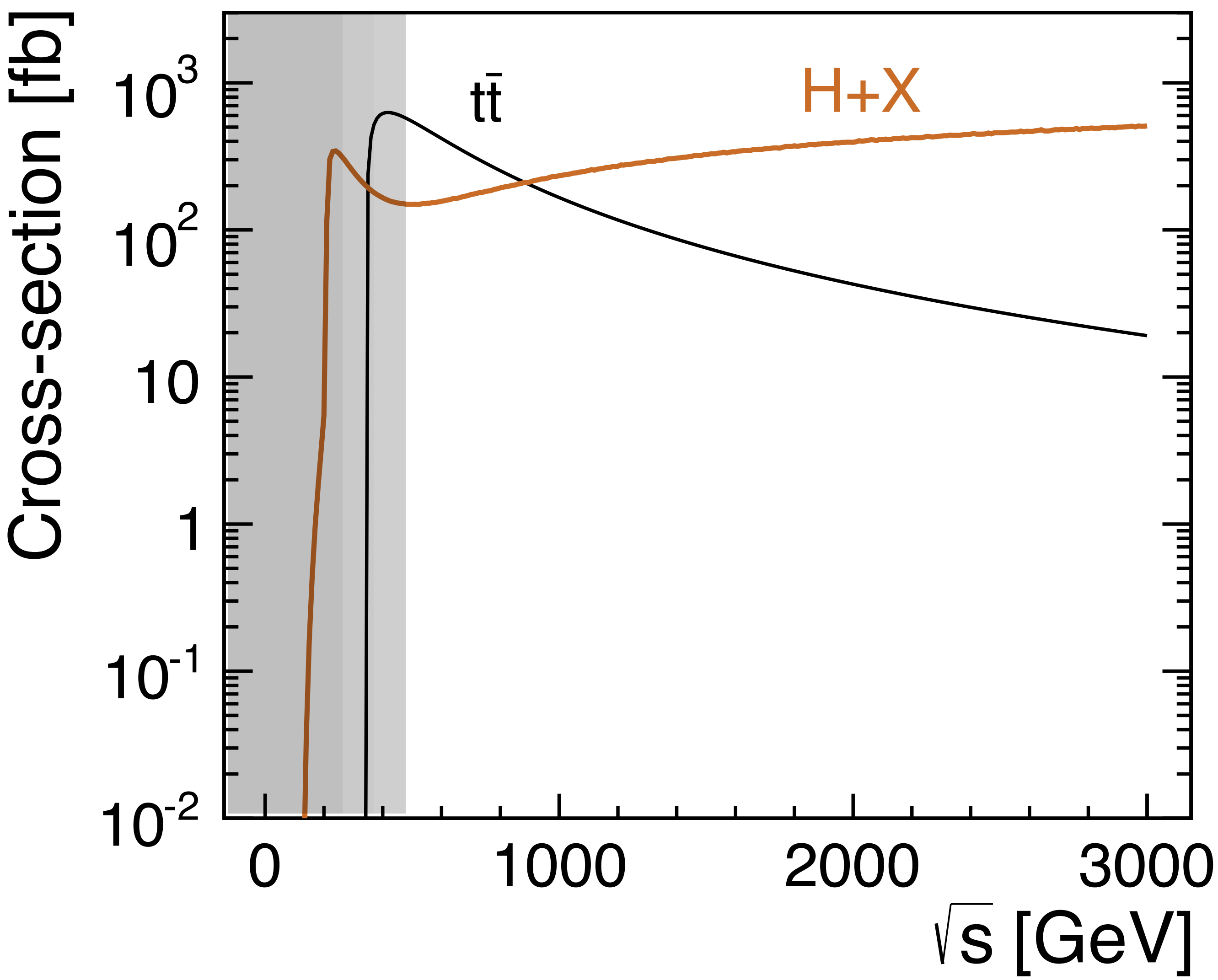

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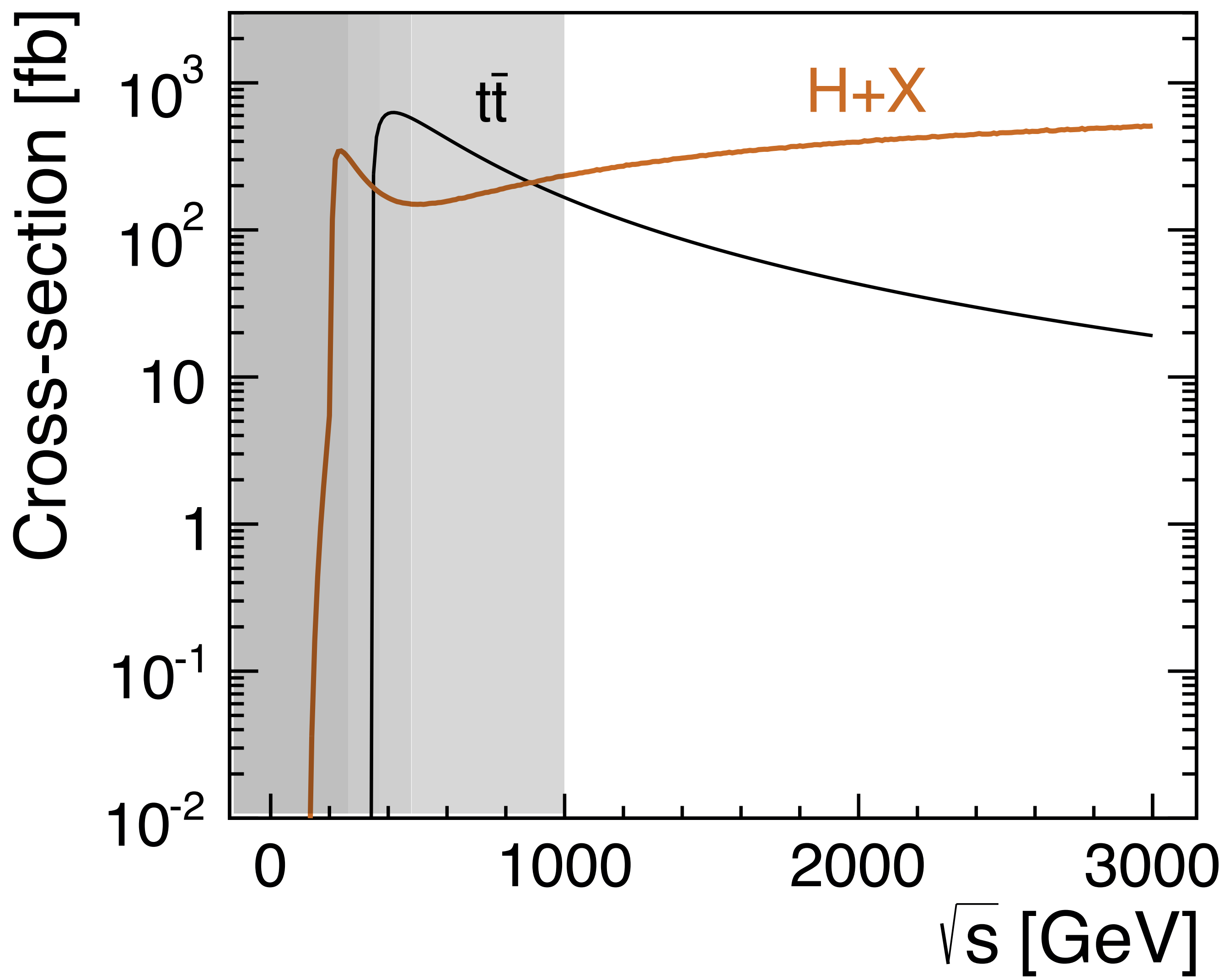

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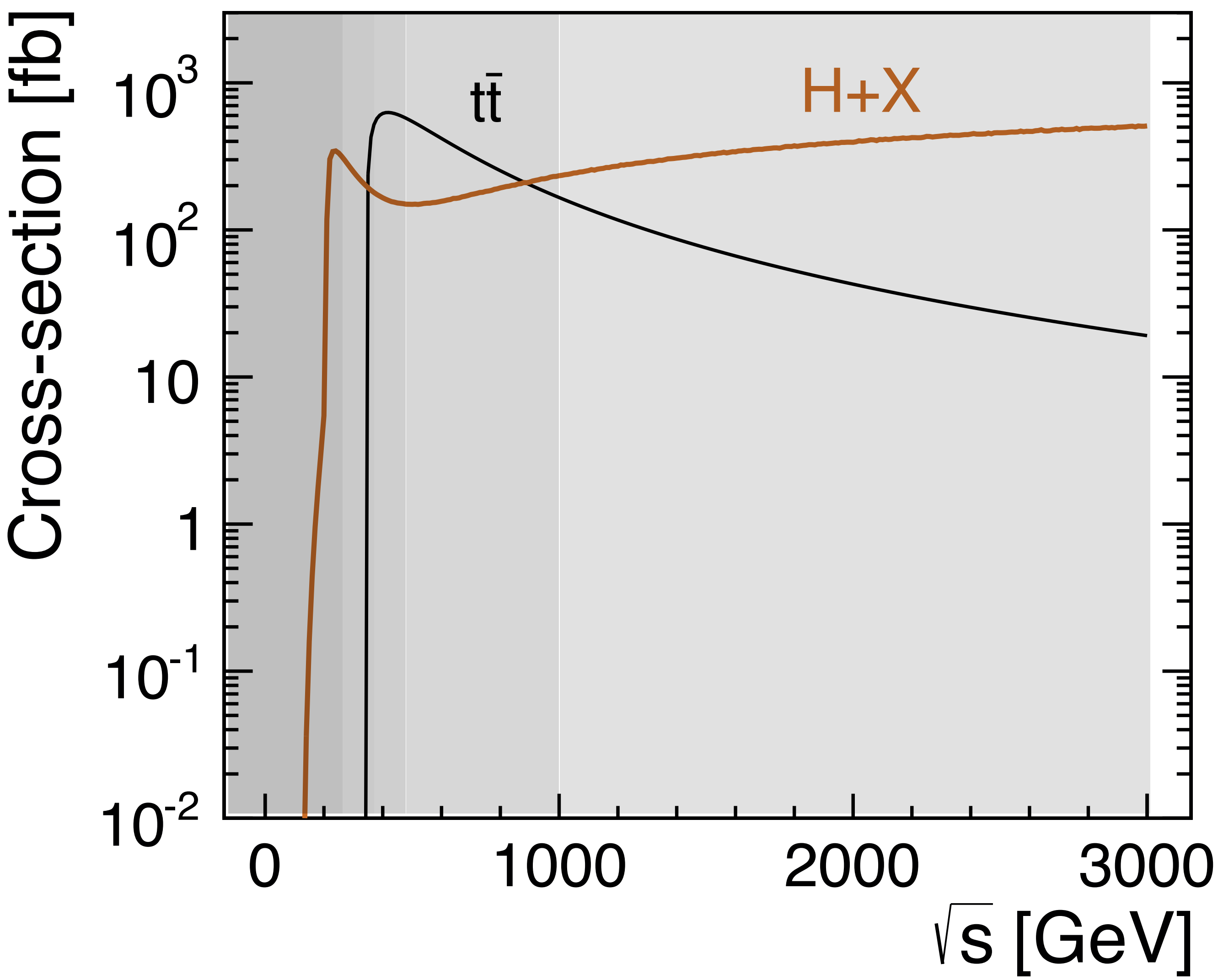

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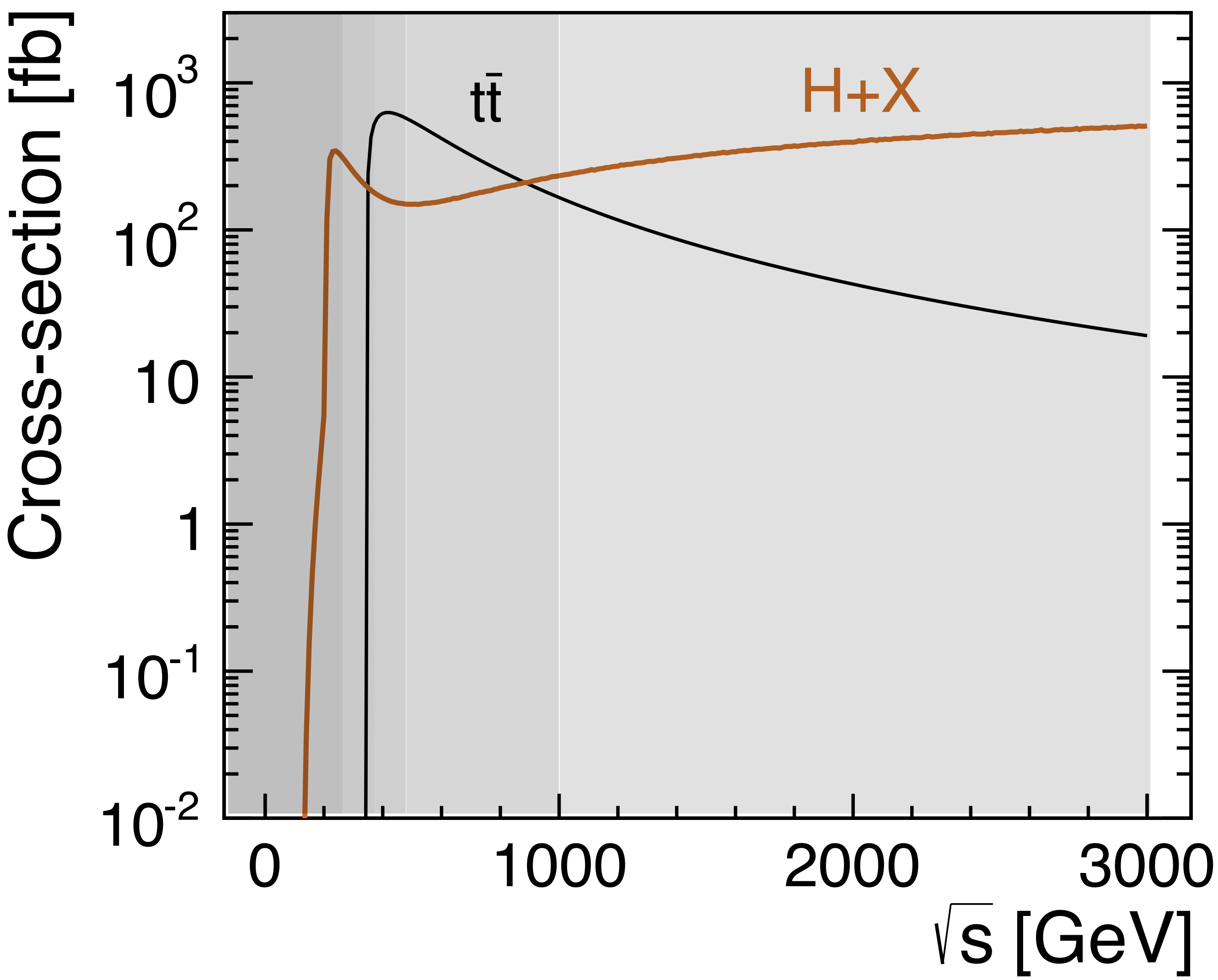

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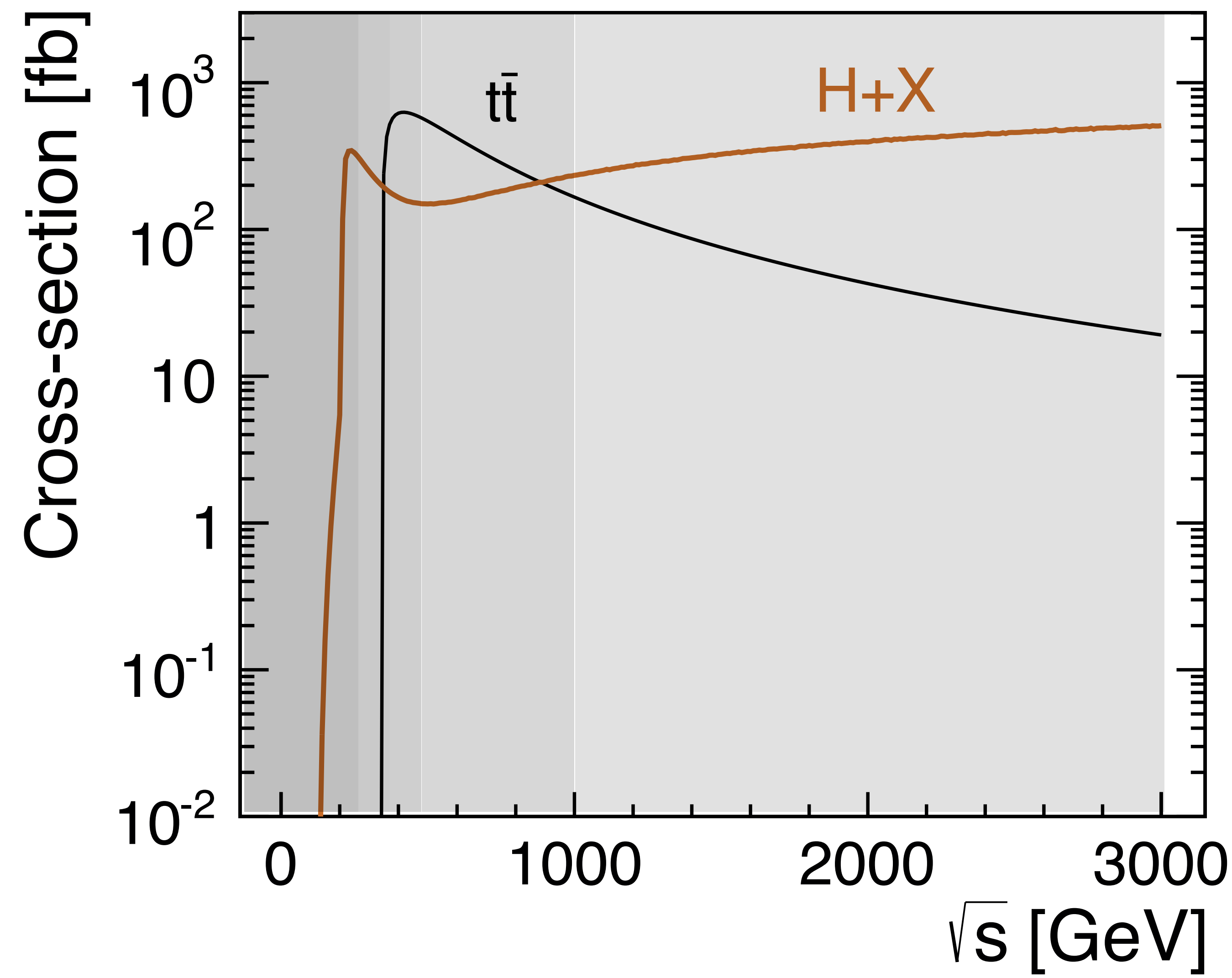
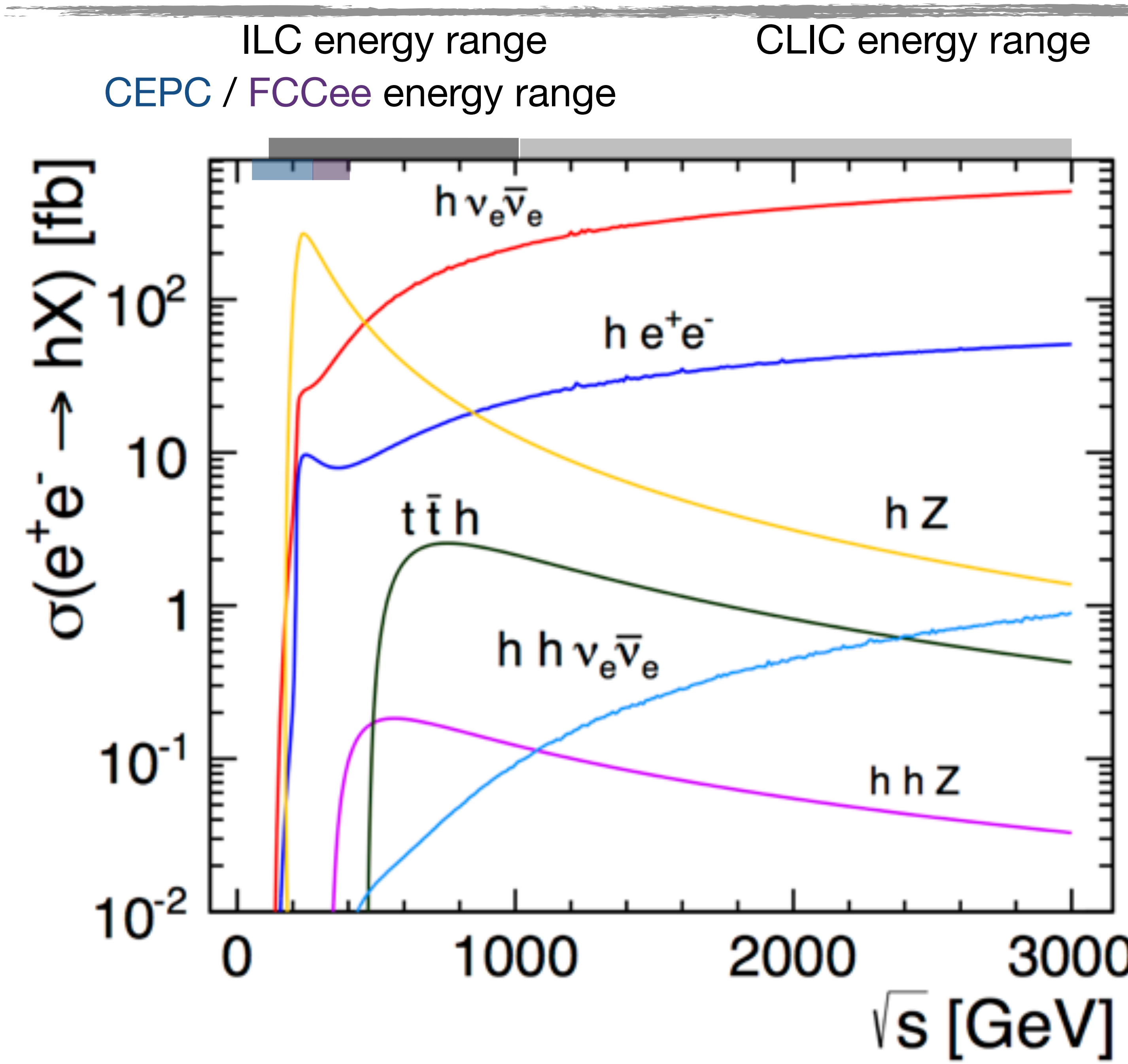
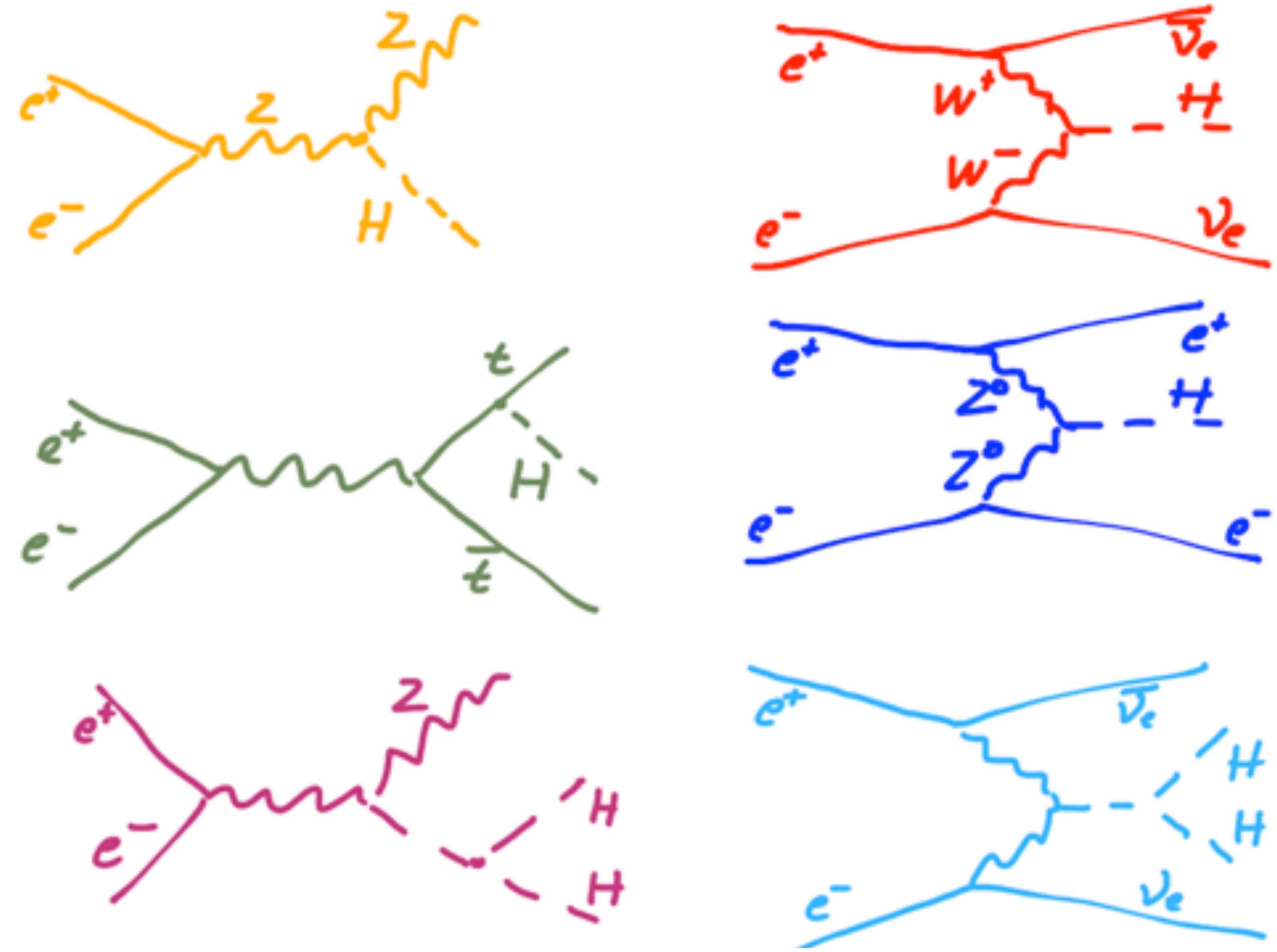


The strength of circular machines: High luminosity at low energy - Z and W physics, some aspects of Higgs physics with high statistics, potentially top threshold physics

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
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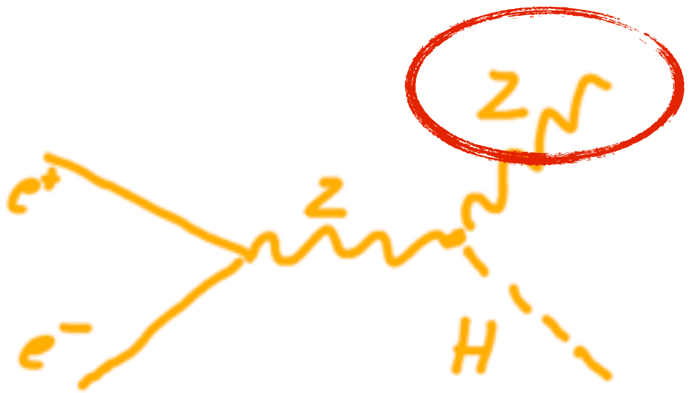
The strategy in e^+e^- collisions:

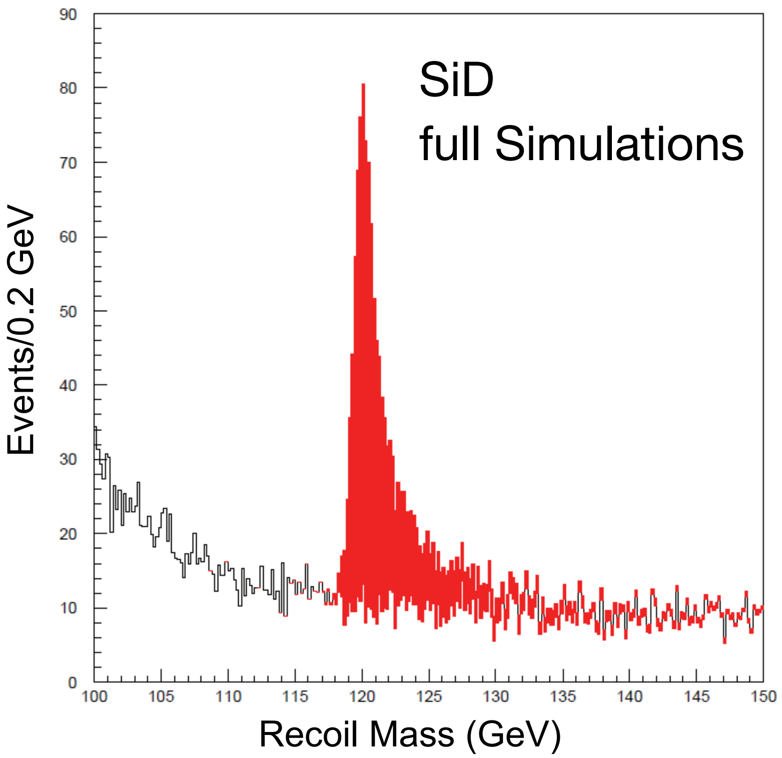


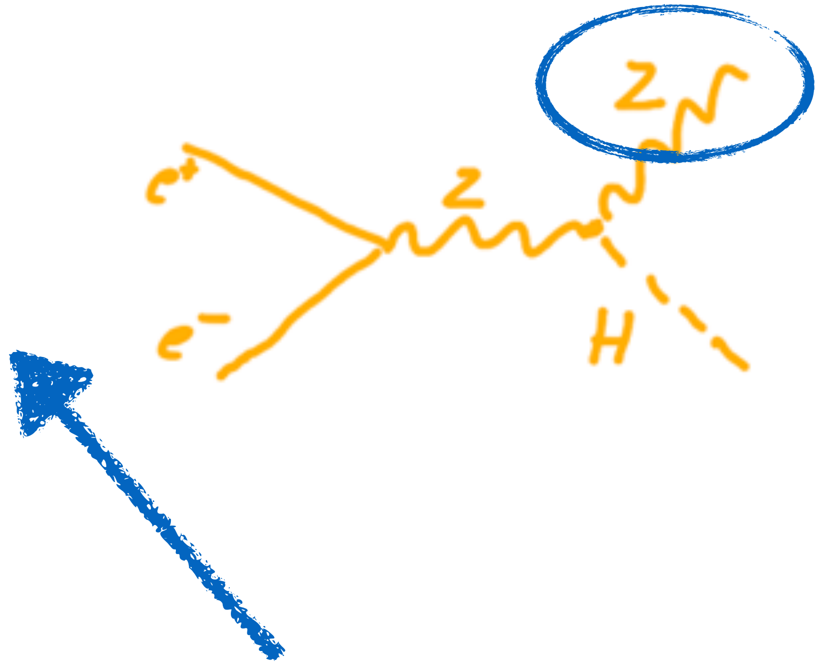
measure ***only*** the Z boson
from the known e^+e^- center-of-mass energy, calculate the “recoil mass”:

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

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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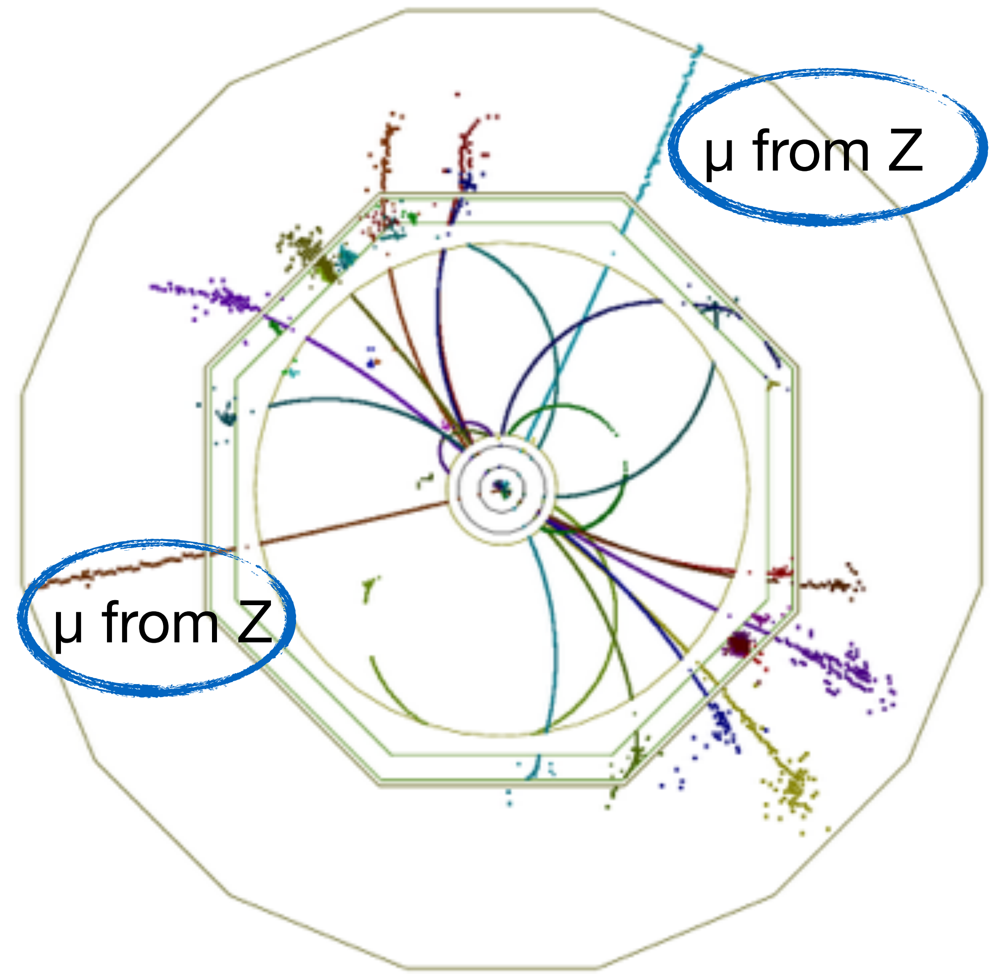

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What this provides: Total ZH cross section, and with coupling of H to Z

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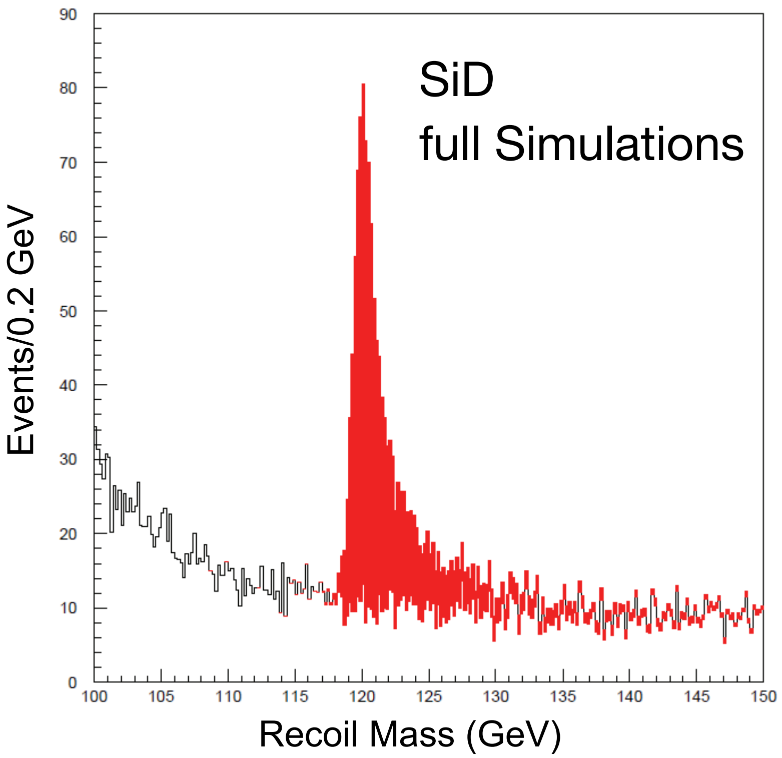

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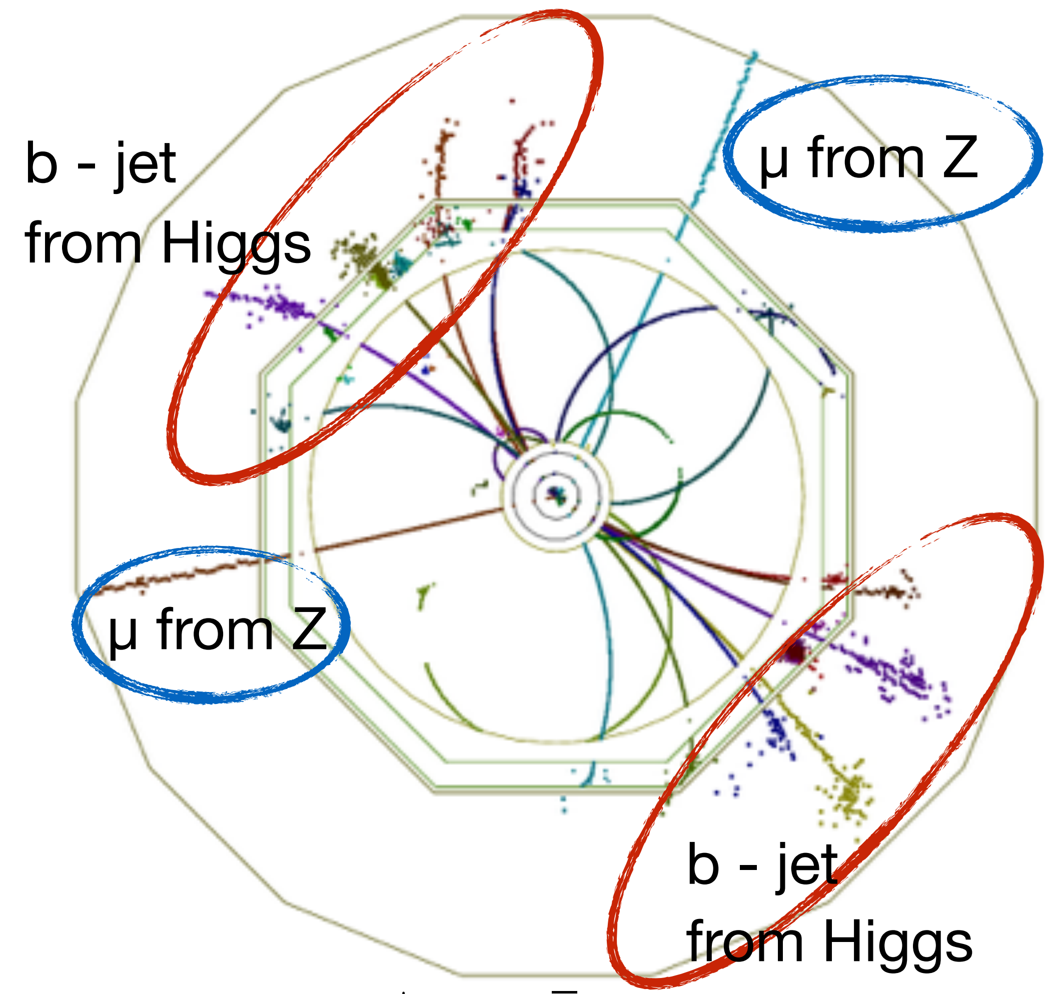

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- In addition: Reconstruction of specific final states provides access to couplings to fermions and bosons via Higgs decay
  - Makes use of “clean” e^+e^- environment - also allows the reconstruction of final states which are not accessible at hadron 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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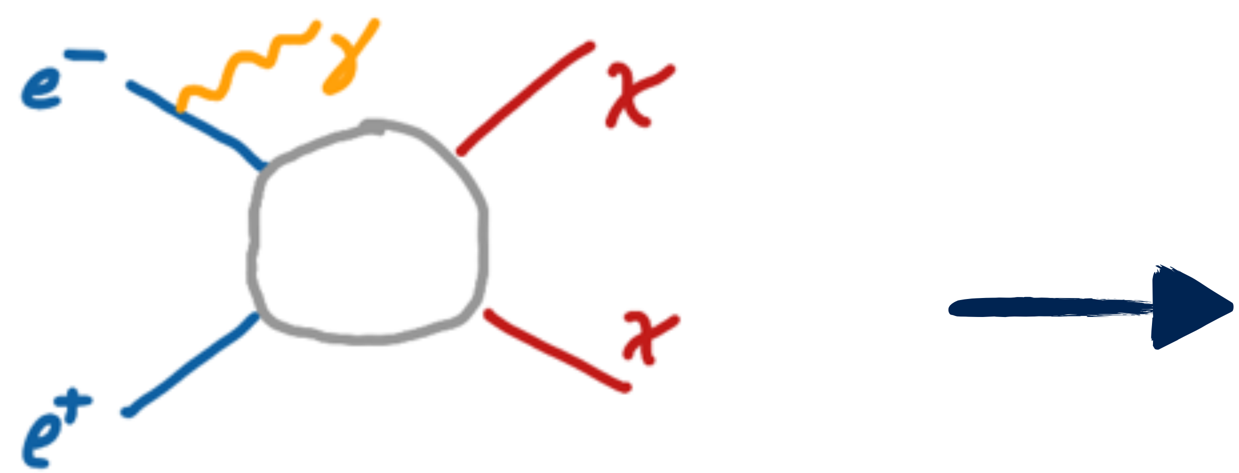
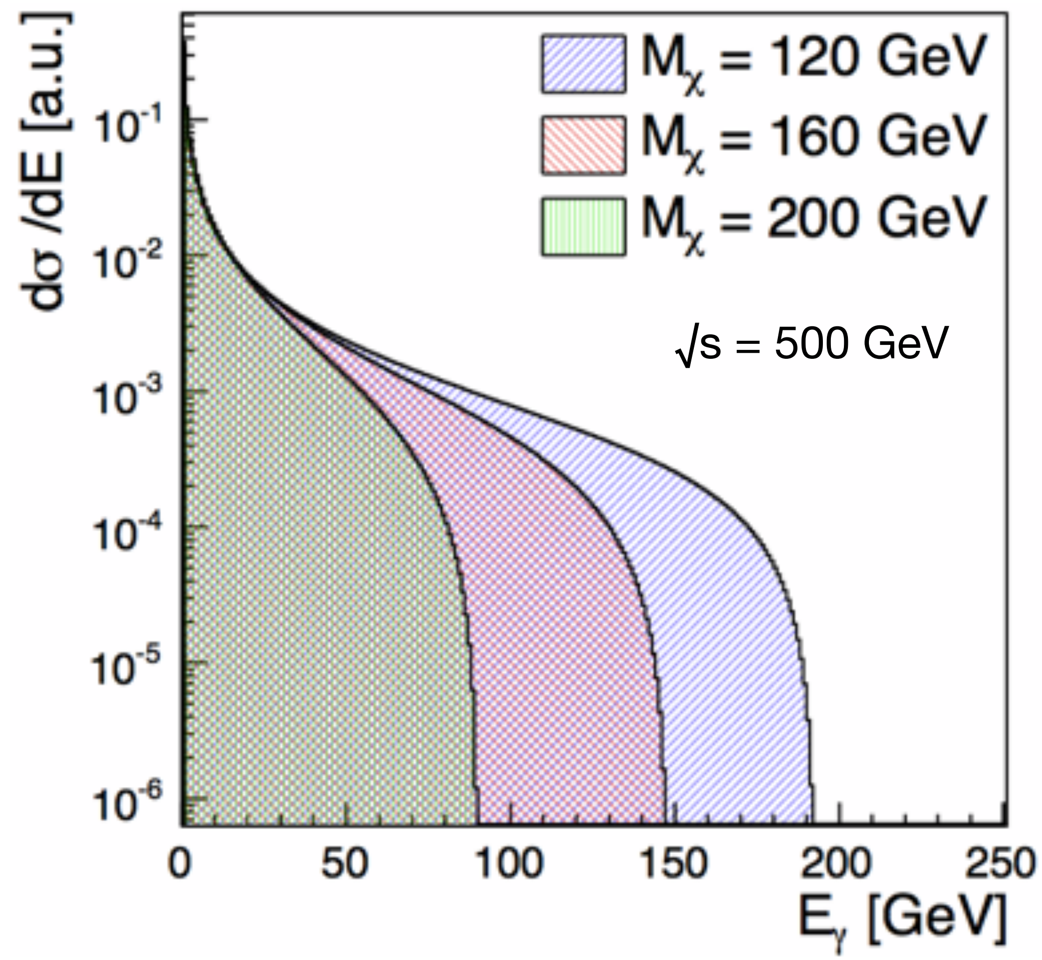
- The ultimate challenge: The Higgs self-coupling
  - Directly study the Higgs potential - prove (or disprove) the Higgs mechanism

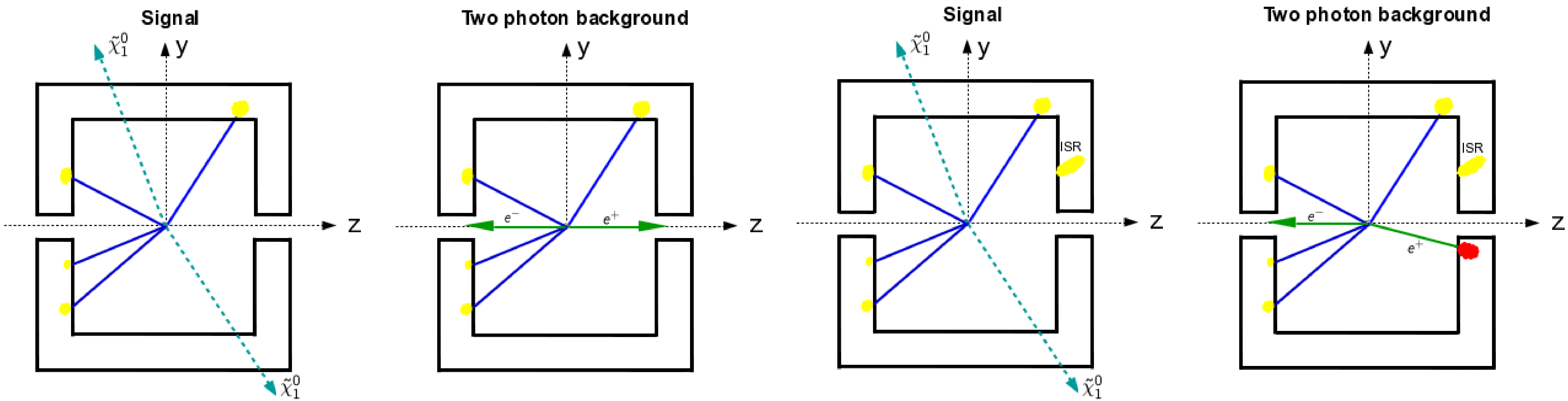
- First measurements possible at 500 GeV - significant results require 1+ TeV and high luminosity

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

- A key goal: Studying dark matter at colliders





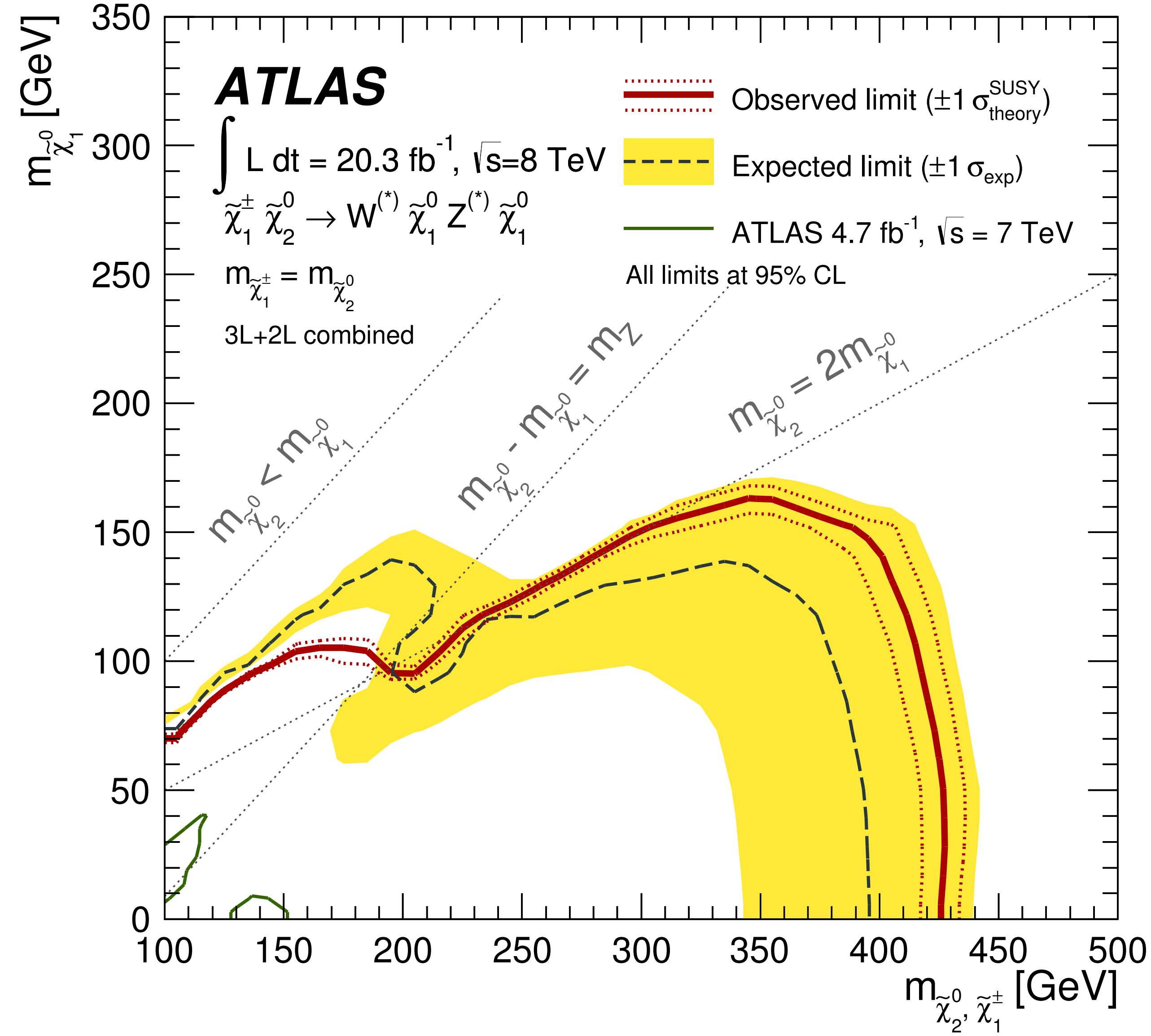


New Physics in e^+e^- - Direct Searches

- 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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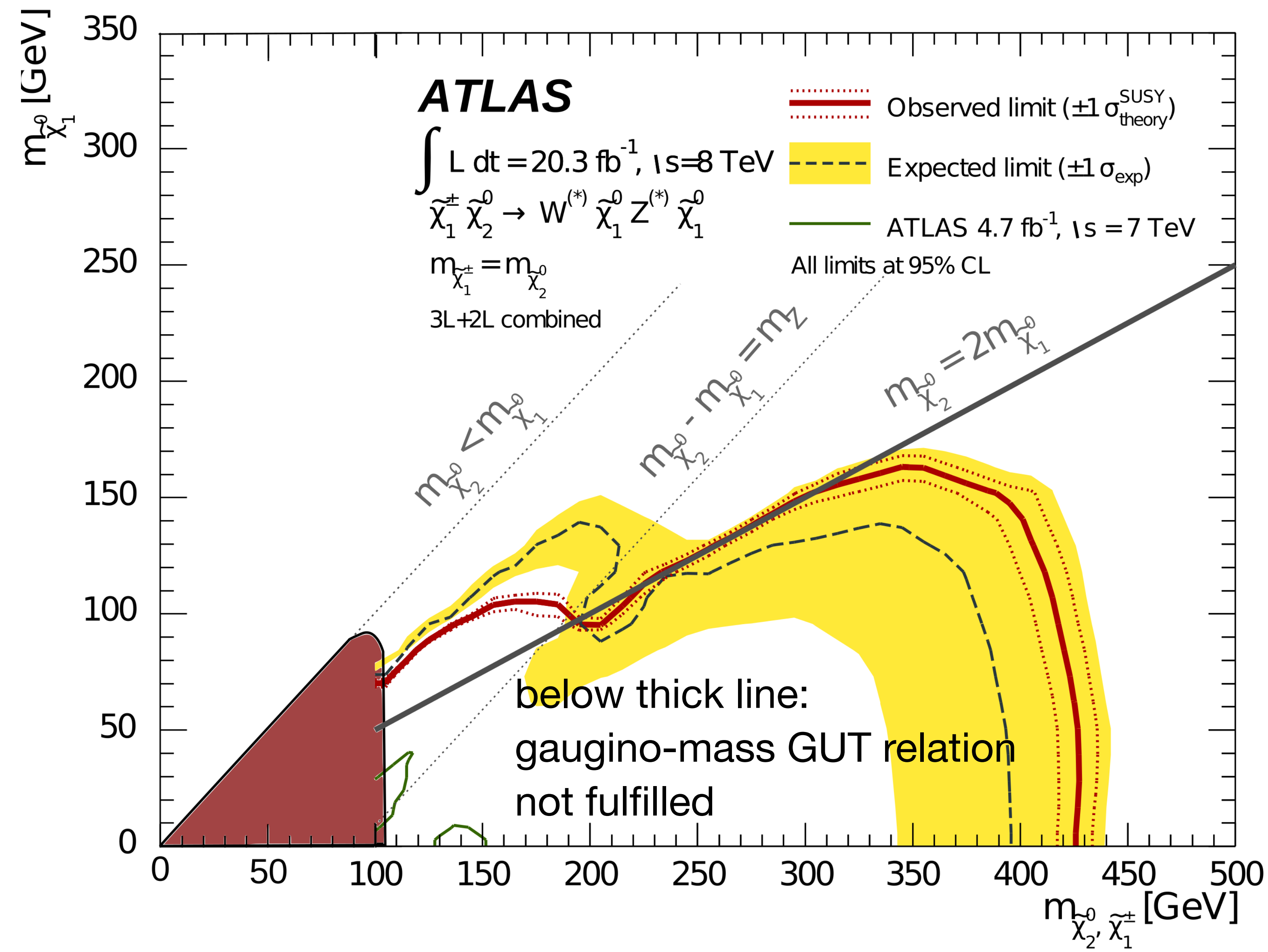

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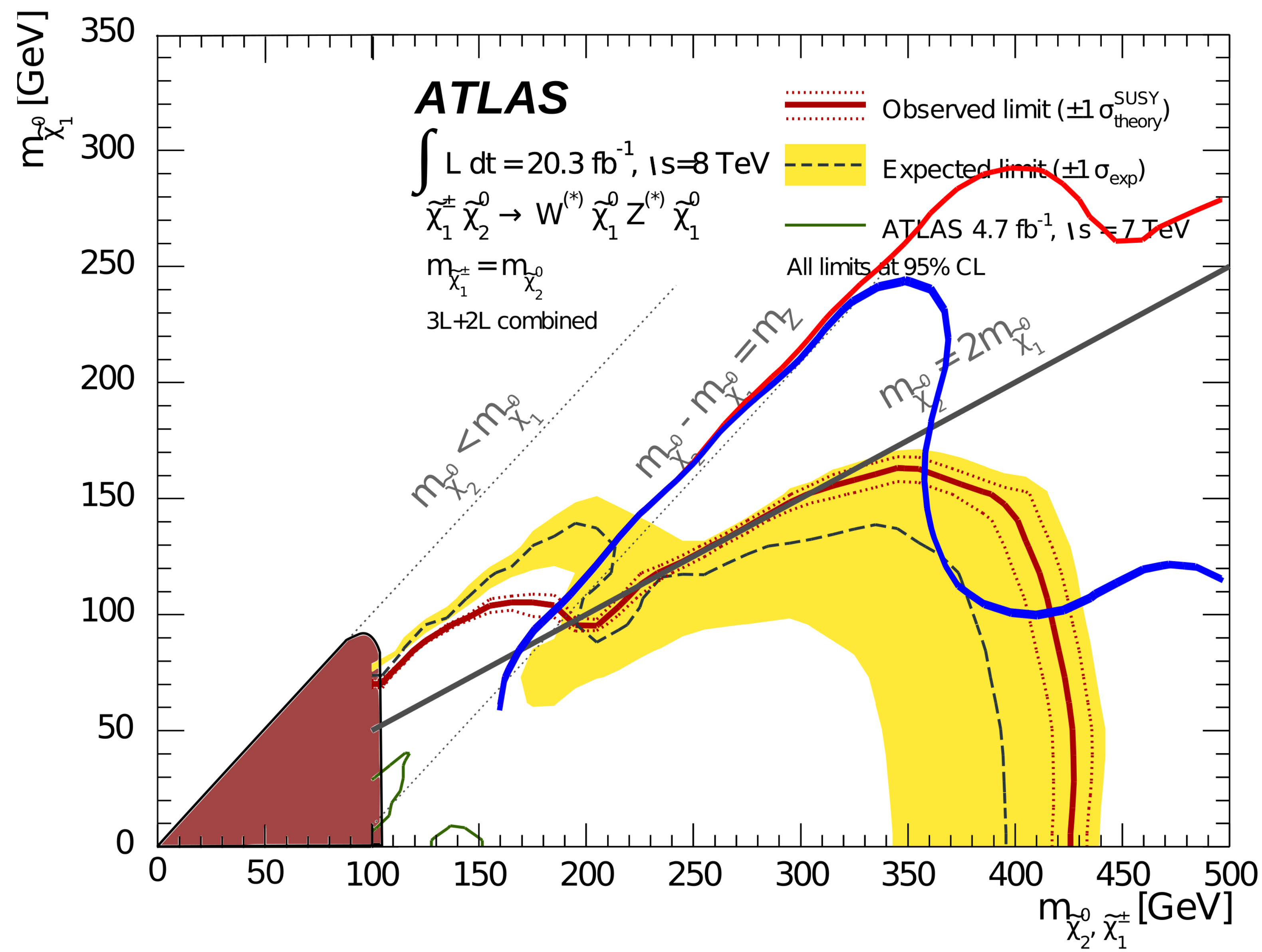

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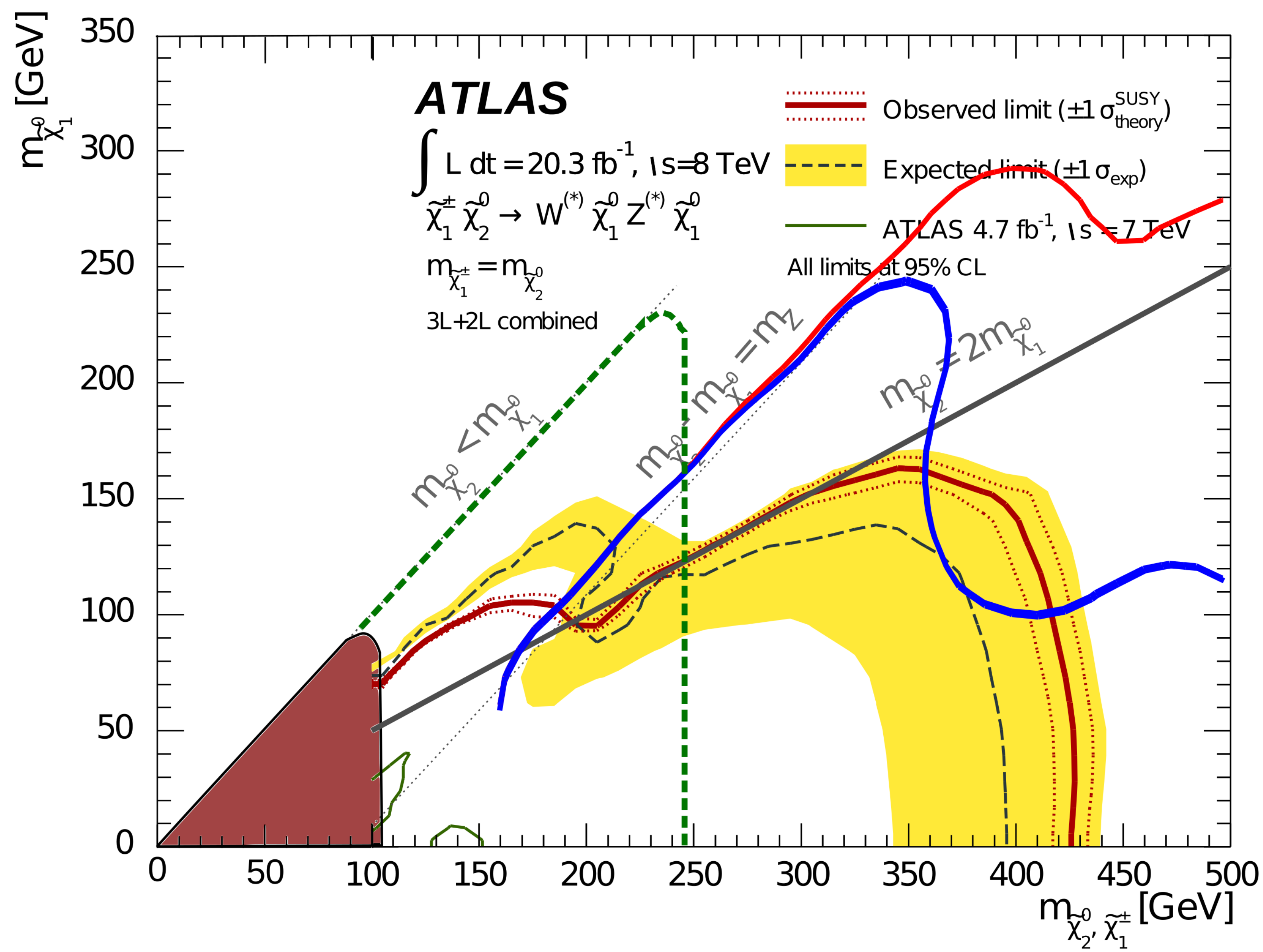

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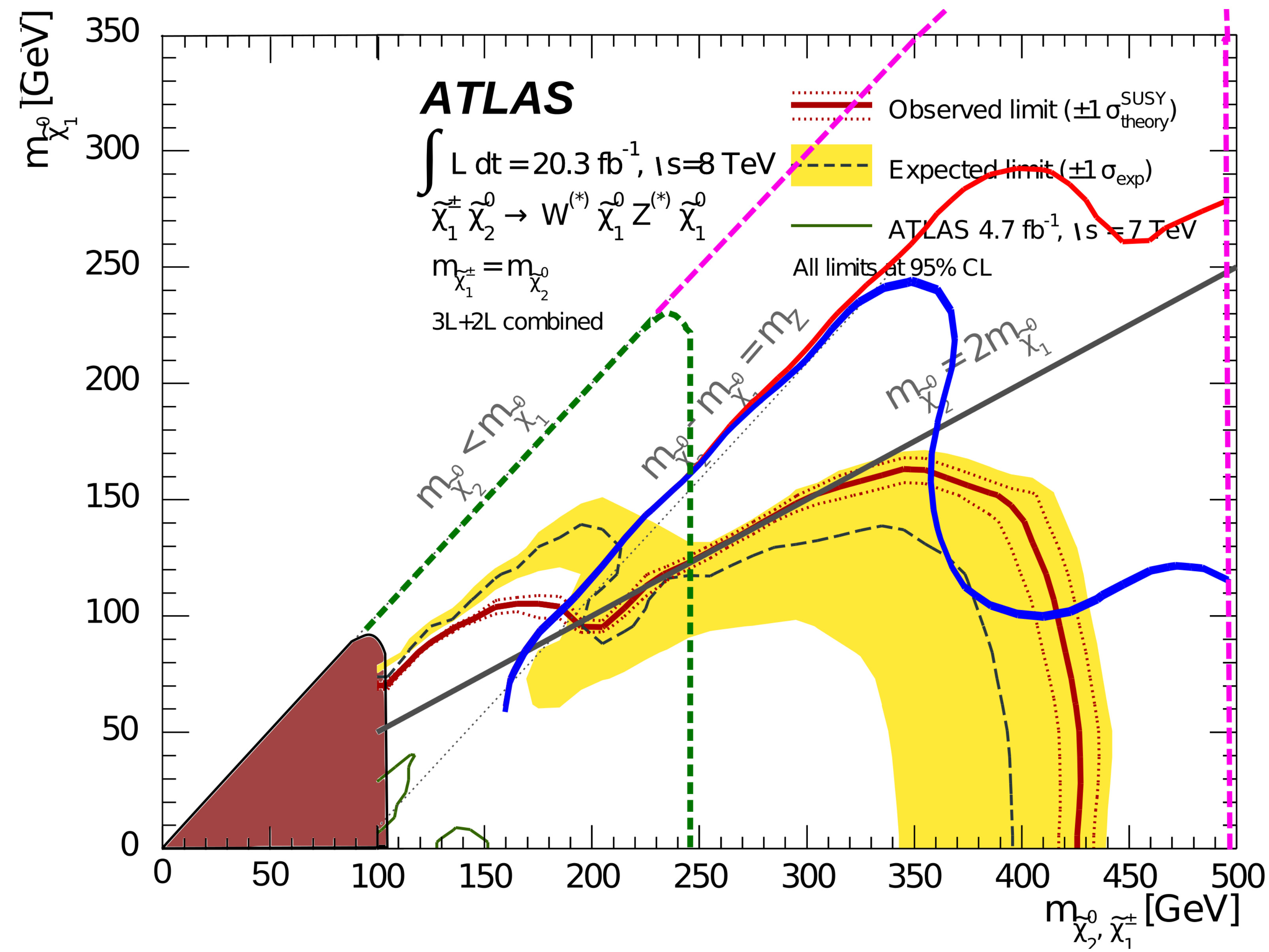

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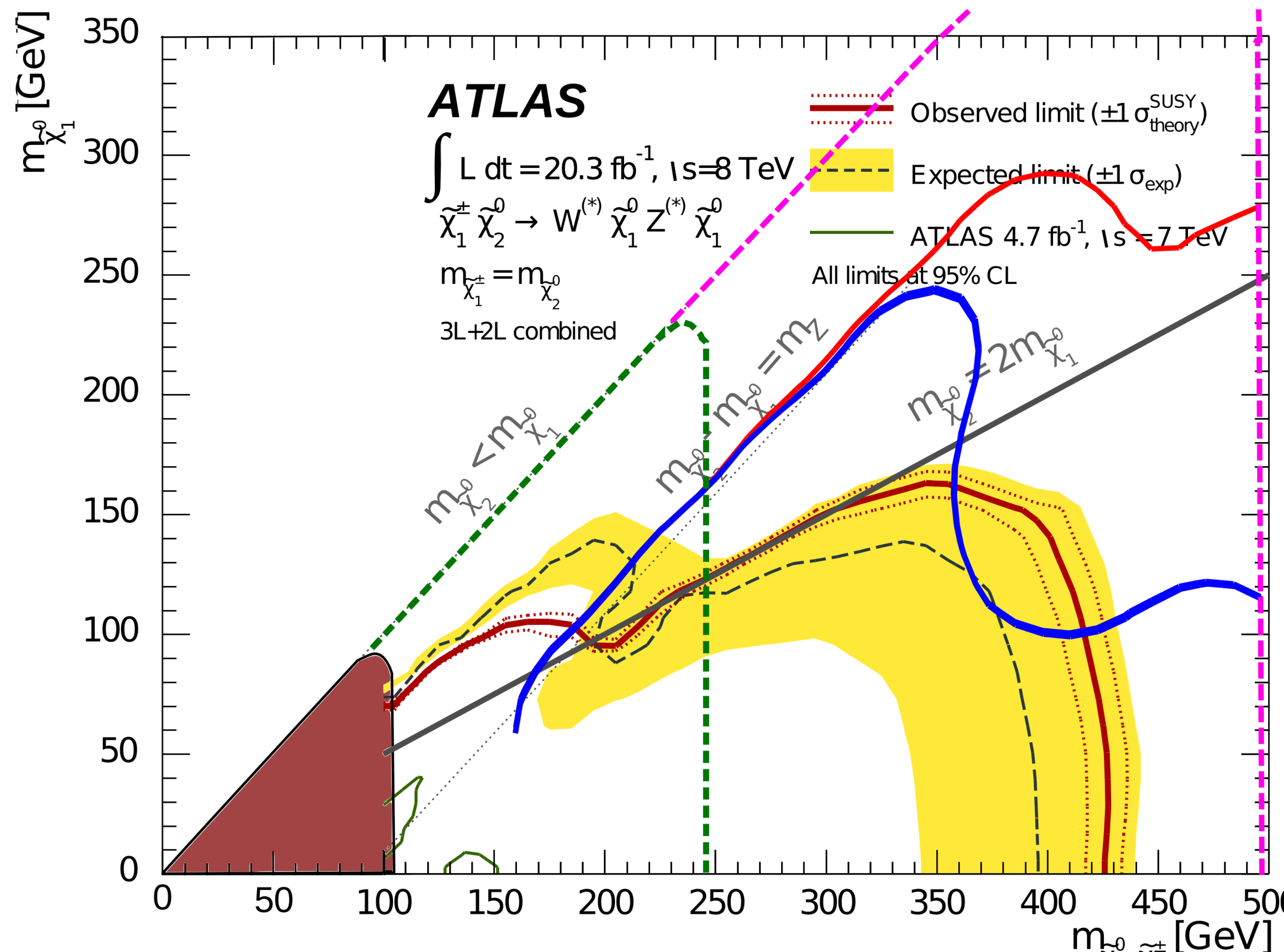

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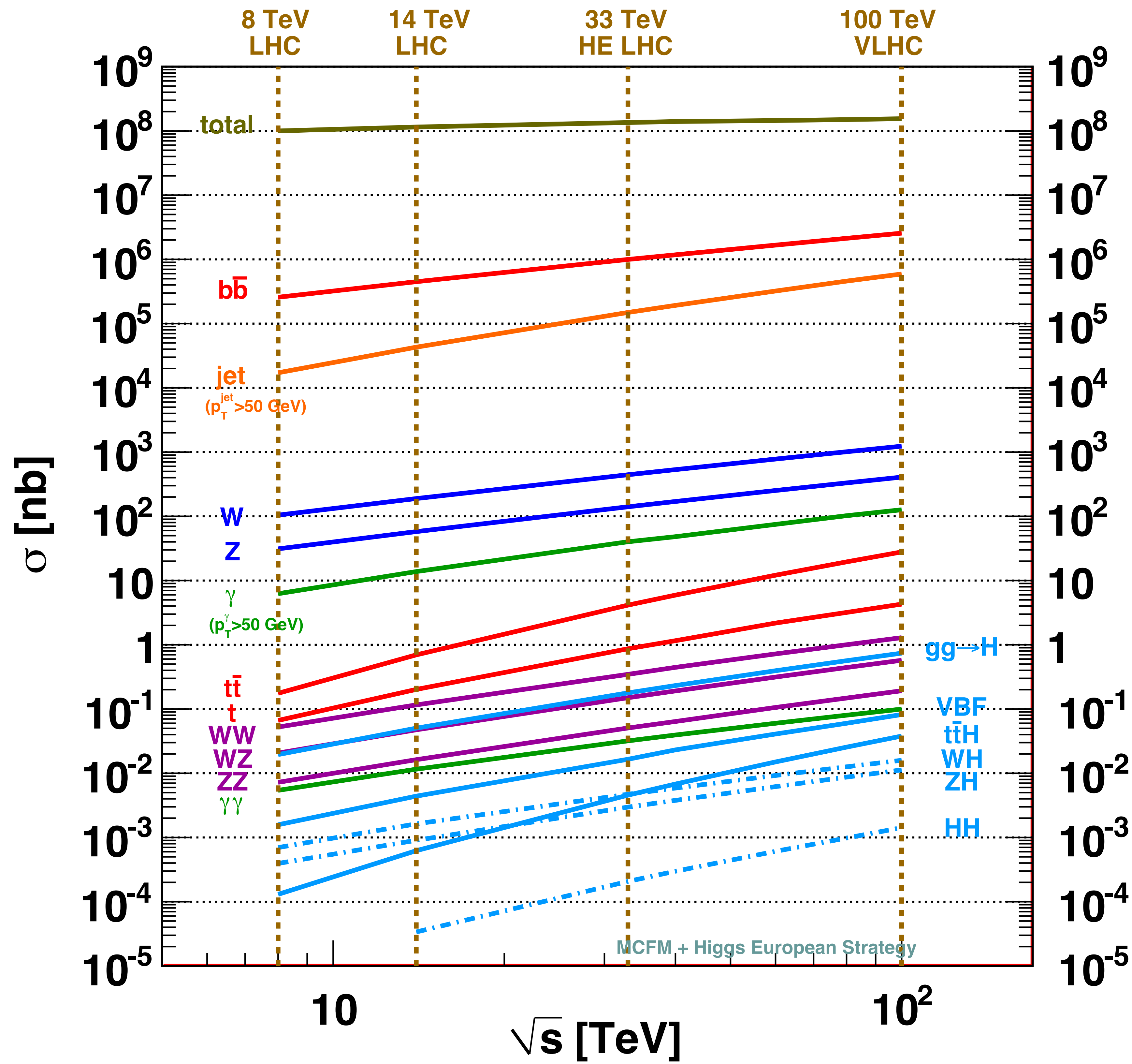
In general: (almost) any type of new particle up to $\sqrt{s}/2$

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

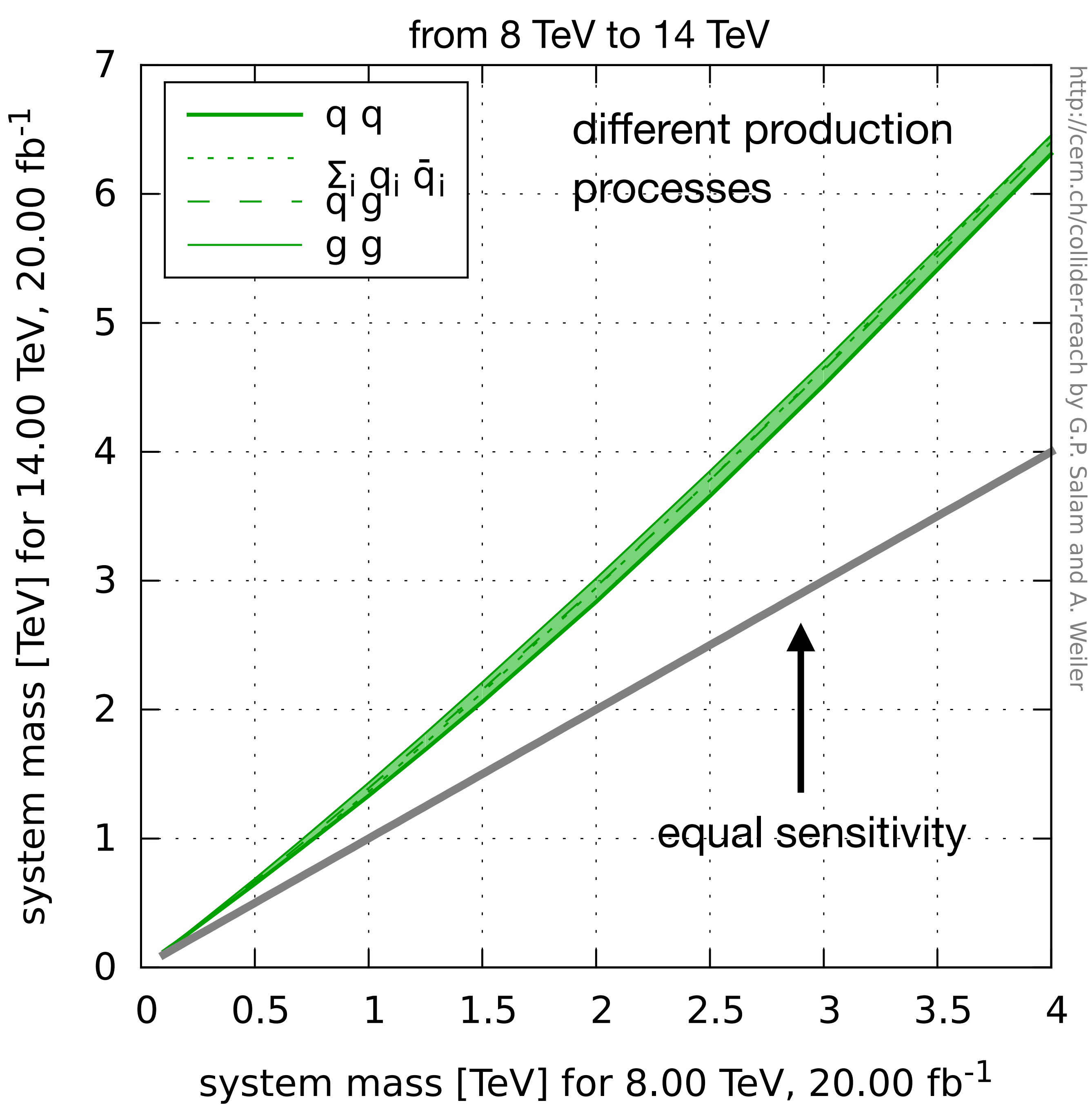


New Physics in Proton-Proton Collisions

- 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 / m^2
    - 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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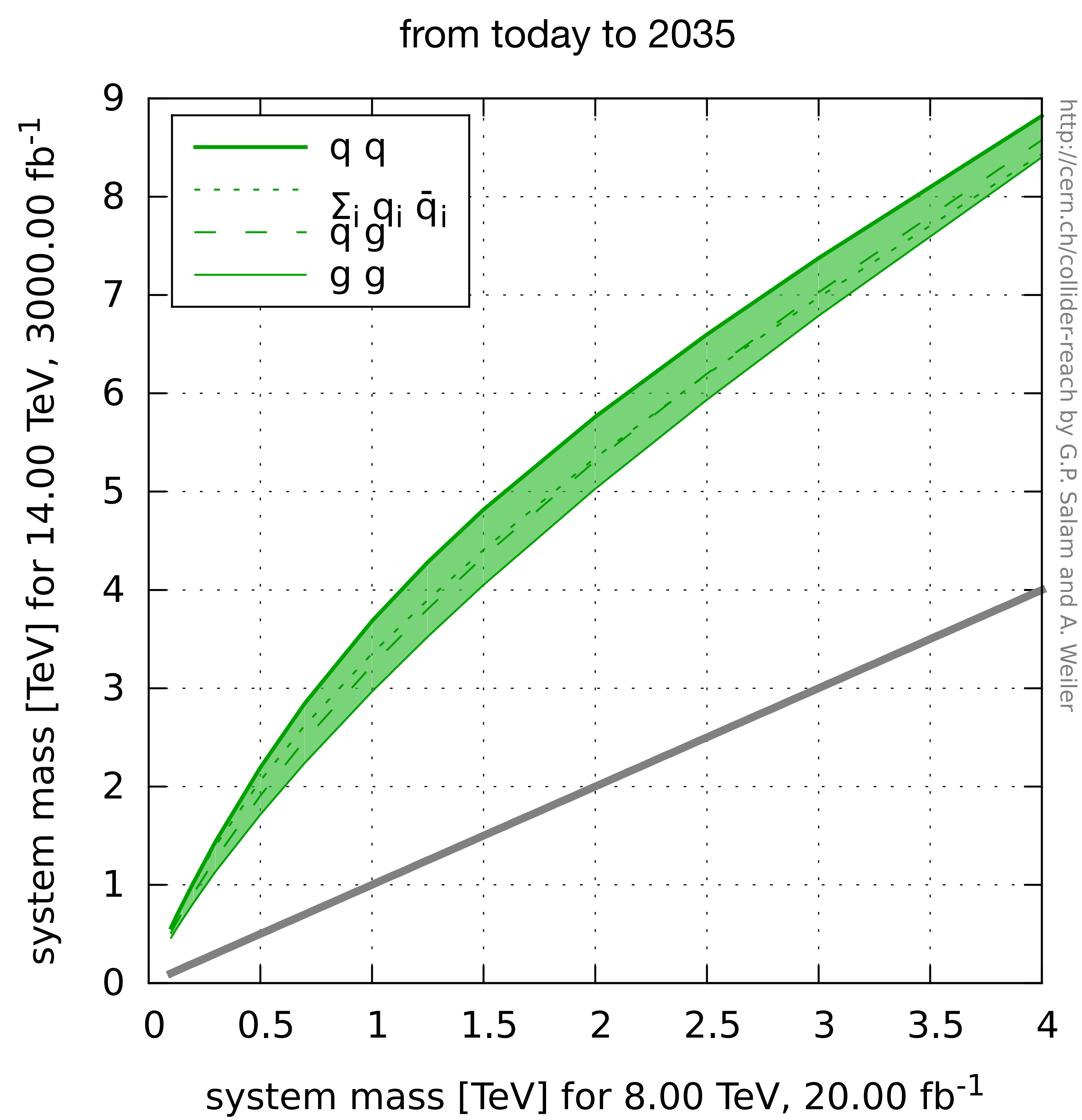

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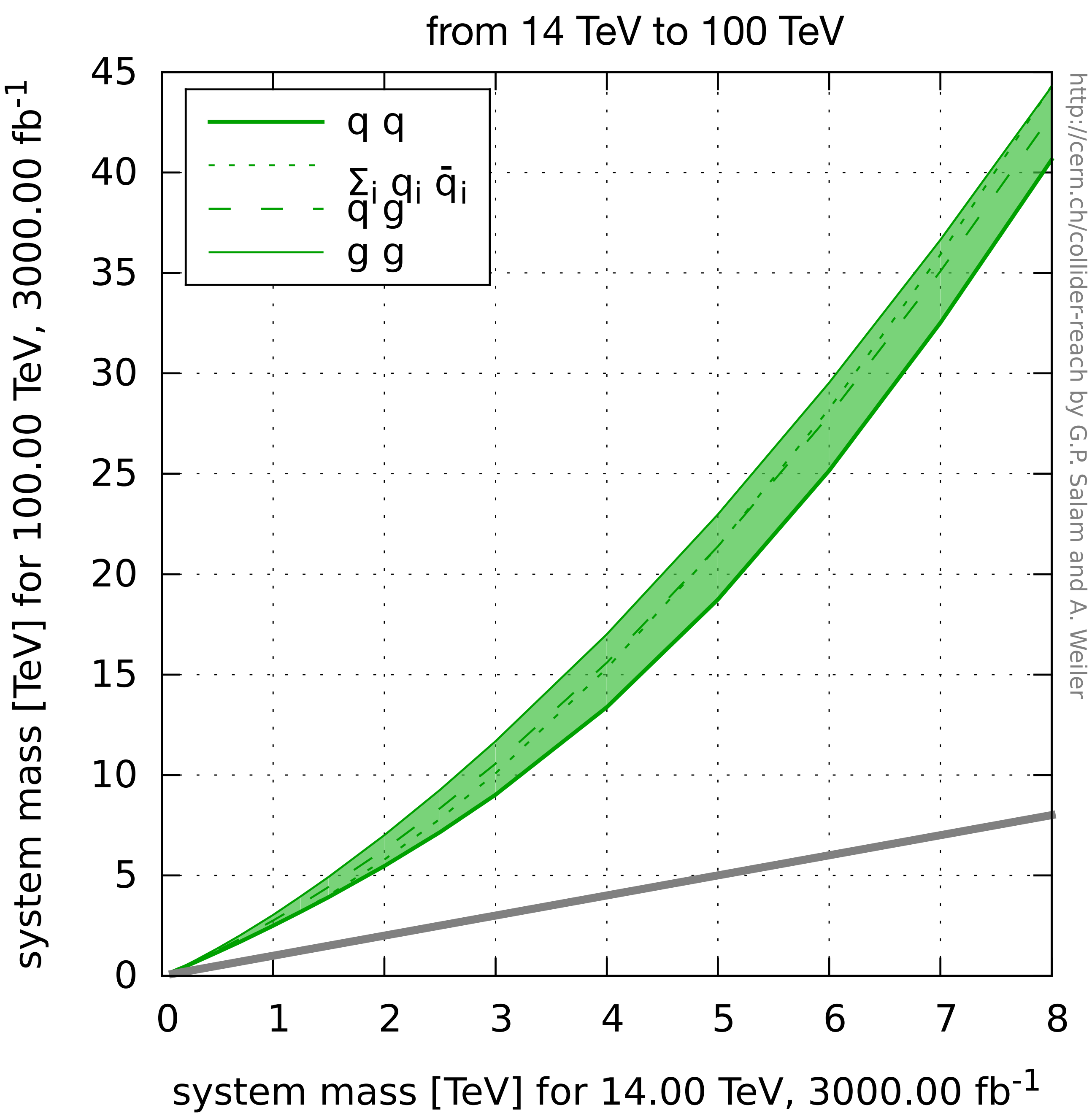
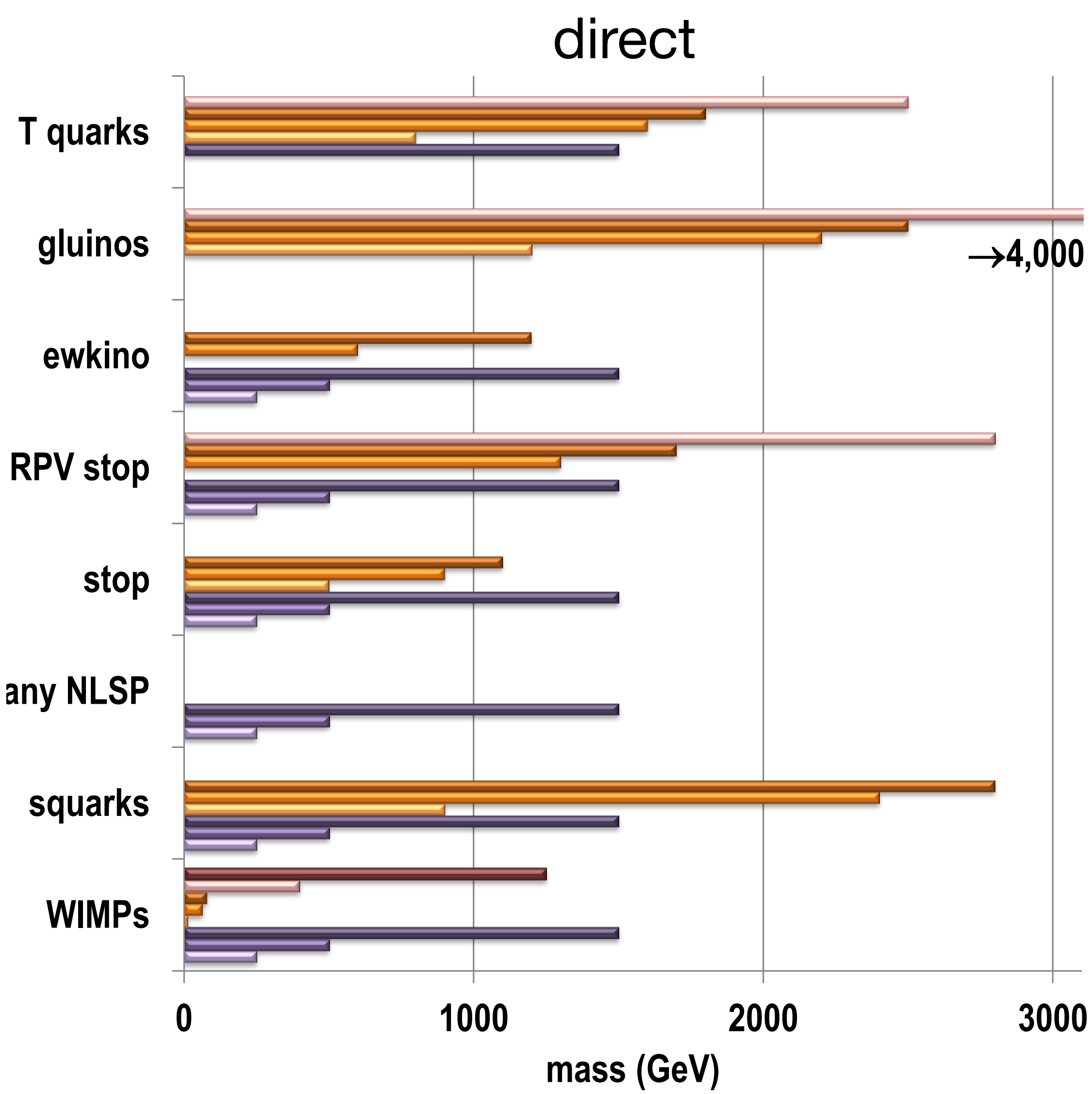
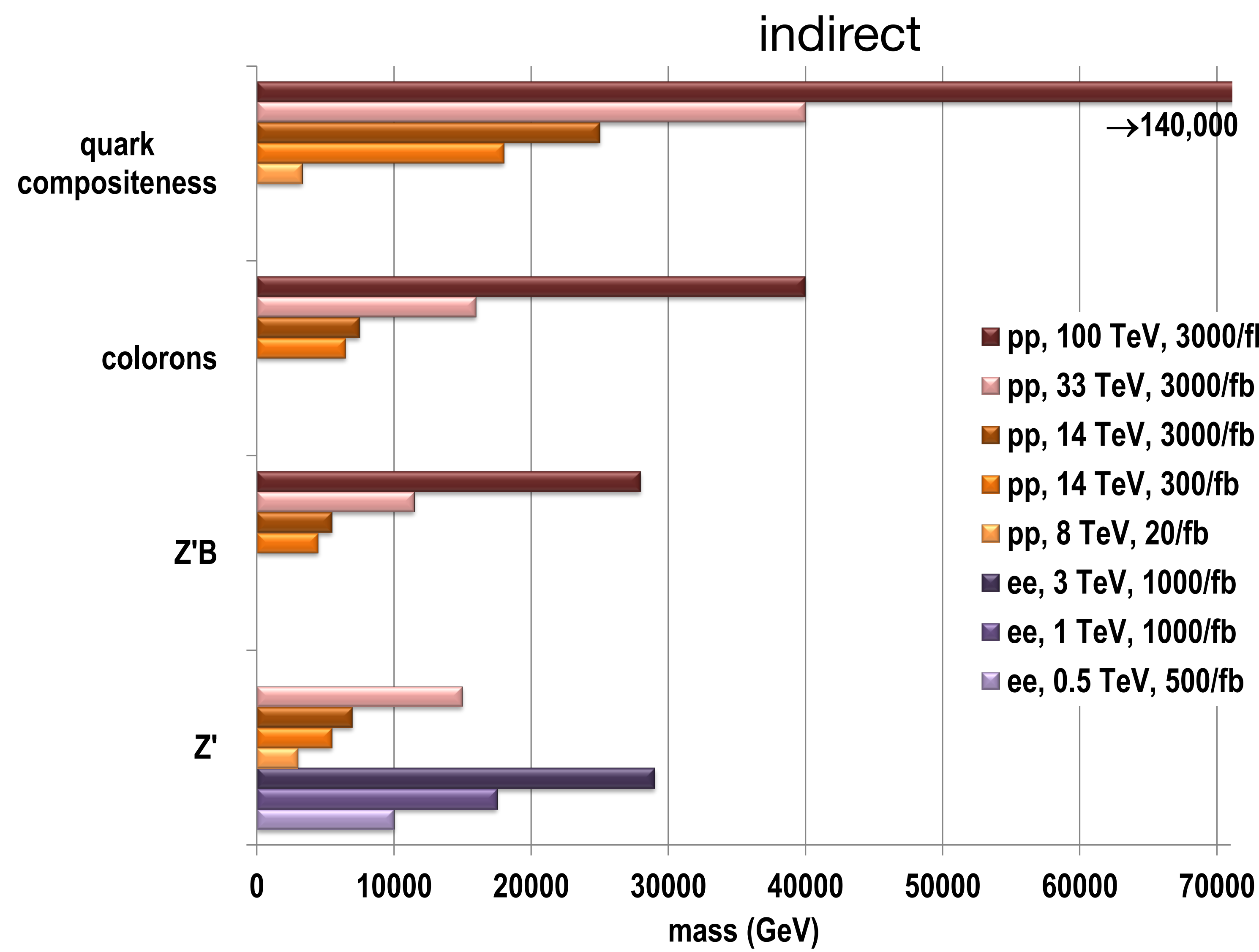


New Physics at Future Colliders - Summary Attempt





Snowmass 2013 - arXiv:1311.0299

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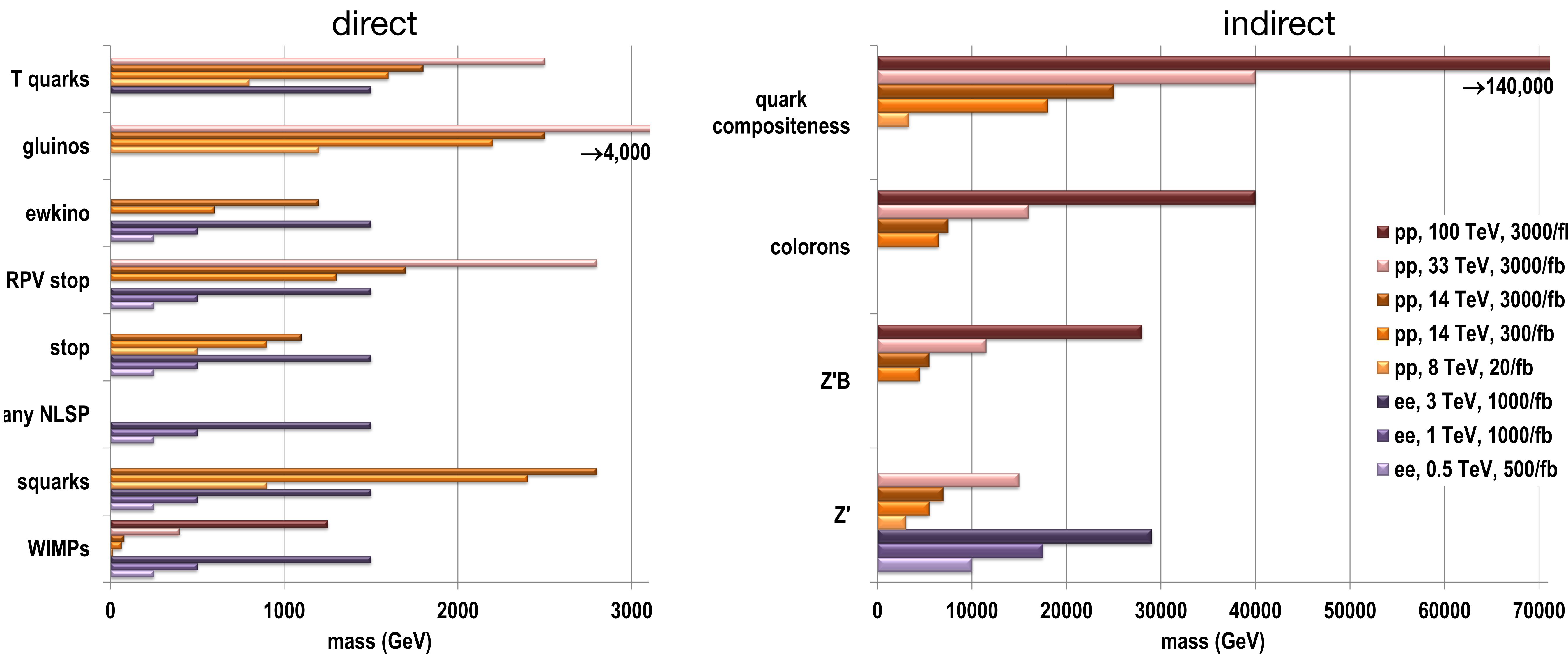


Snowmass 2013 - arXiv:1311.0299

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

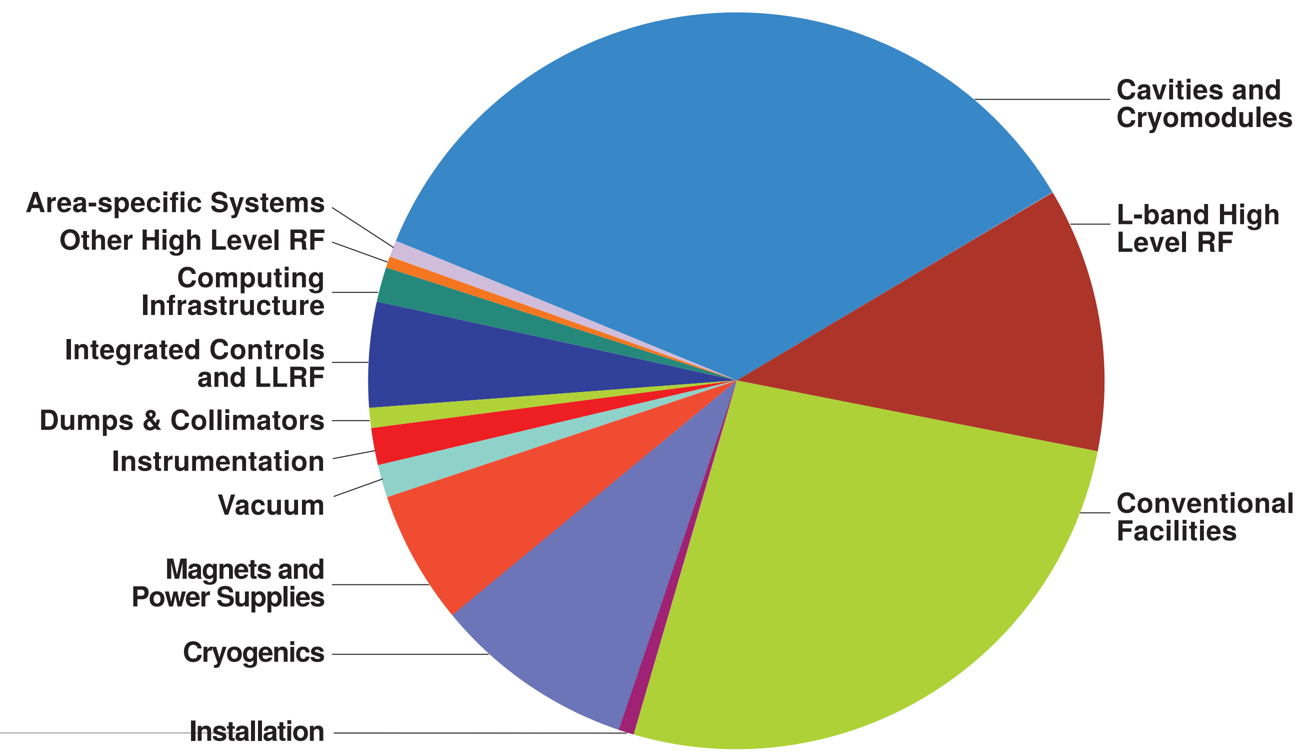
- New energy-frontier collider projects take a very long time - ILC (under various labels) has been developed for over 20 years
  - Technologically challenging
  - Expensive
  - Requires world-wide collaboration, not just for financial reasons, but also manpower: Experimental collaborations with (several)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

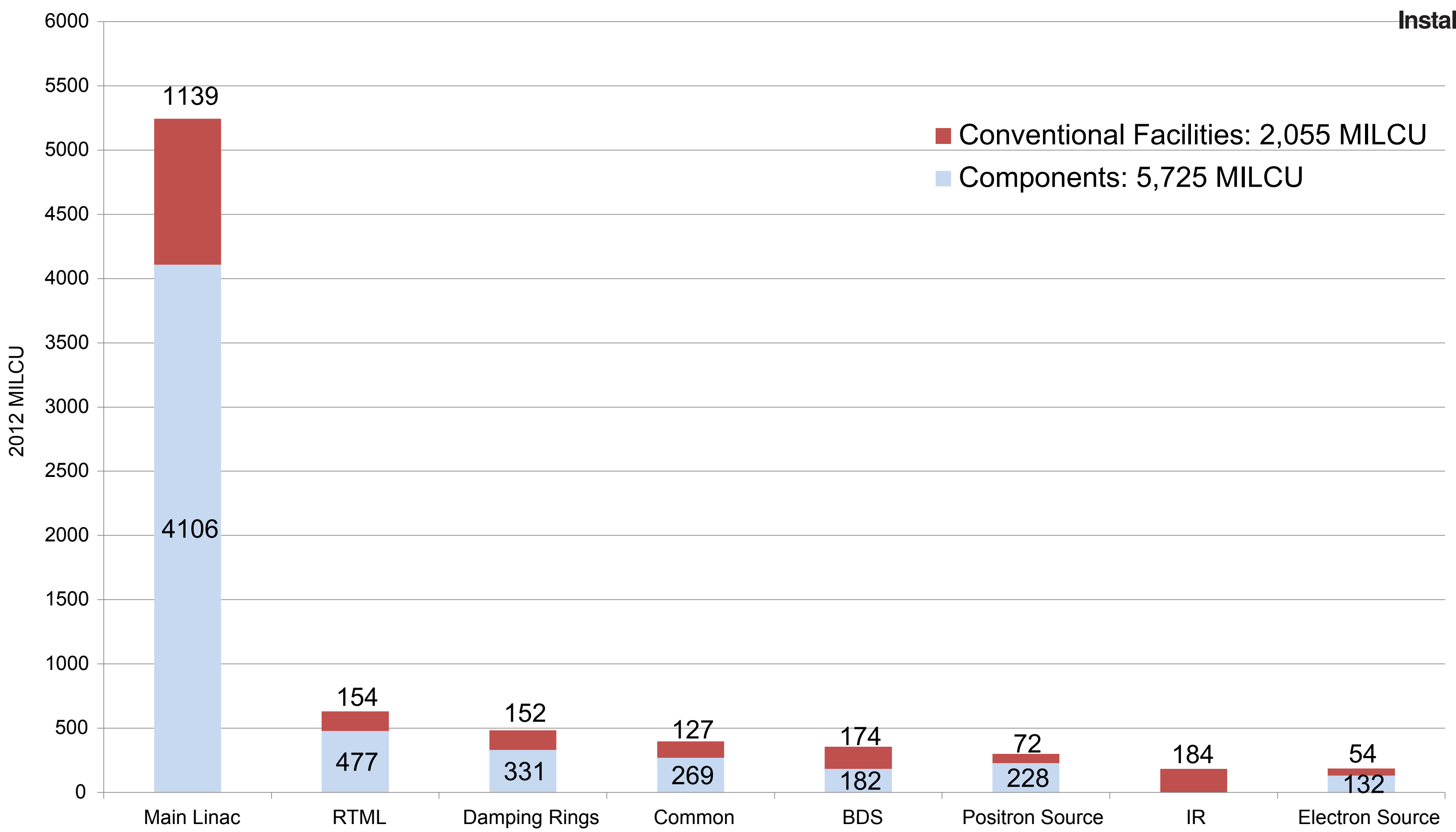
So far: Projects typically have been “local” with international participation

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

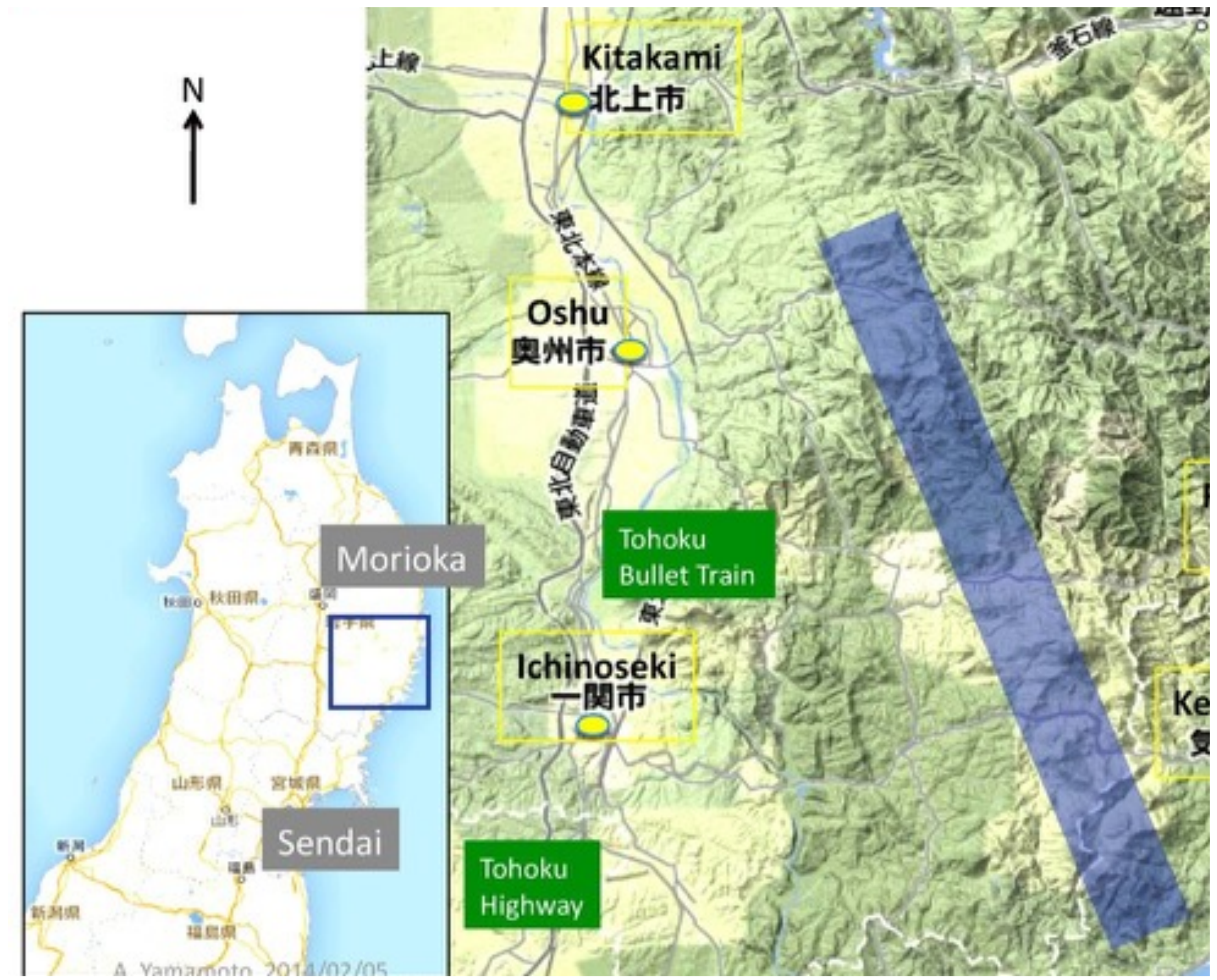




- The construction cost will be spread over ~ 10 years, and shared across the globe - details to be worked out!
- Many contributions expected “in kind”: production of components “at home”, installation in ILC

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
- Over the next ~ year, a review process with committees by the Japanese science ministry MEXT will take place - physics case and technical issues
- First contacts on government level about international participation have started

International Strategies & Priorities

- Community-driven strategy processes in Europe and the US have been completed recently
  - Update of the European Strategy for Particle Physics 2012/2013
    1. Full exploitation of LHC, including high luminosity upgrade - a program until 2035
    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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2. Support ILC development, increased involvement if ILC proceeds
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  - After positive decision: (At least) 2 years of preparation, ~ 10 years construction earliest start 2028

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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

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- **FCC** - a new addition to CERN's future possibilities - in response to the European Strategy for Particle Physics - conceptual design until 2018, then, after a first decision to go ahead, technical design until ~ 2024
  - Would likely start first with e^+e^-, then, as a second stage, p+p

Timescales and Evolution

- The landscape of future projects is evolving at the moment: The discussions of a project in China have started in earnest only after the completion of strategies
- **CLIC** - for a long time CERNs only long-term future R&D project - conceptual design completed, technical design phase until ~ 2018, then in principle ready for a first decision - construction could start ~ 6 years after that
- **FCC** - a new addition to CERN's future possibilities - in response to the European Strategy for Particle Physics - conceptual design until 2018, then, after a first decision to go ahead, technical design until ~ 2024
  - Would likely start first with e^+e^-, then, as a second stage, p+p

Updates of the European Strategy for Particle Physics planned for ~ 2019 and ~ 2024
In 2024 there will be 300 fb^{-1} of LHC 14 TeV data
➯ The basis for an informed decision
(N.B.: Discoveries at the LHC could also show the way earlier…)

To Put Things into Perspective

The possible
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To Put Things into Perspective

Next Week

- Other models beyond the SM, LHC Outlook - S. Bethke
  - Stay tuned for intriguing results from the LHC!

Zeitplan

1.	Introduction	12.10.
2.	Particle Detectors I	19.10.
3.	Particle Detectors II	26.10.
4.	Accelerators	02.11.
5.	Trigger, Data Acquisition, Computing	09.11.
6.	Monte Carlo Generators and Detector Simulation	16.11.
7.	Tests of the Standard Model	23.11.
8.	QCD, Jets, Proton Structure	30.12.
9.	Higgs Physics I	07.12.
10.	Higgs Physics II	14.12.
	----------- no lecture -------------	21.12.
	----------- Christmas ---------------------	
11.	Supersymmetry	11.01.
12.	Top Physics	18.01.
13.	Future Collider Projects	25.01
14.	Other models beyond the SM, LHC Outlook	01.02