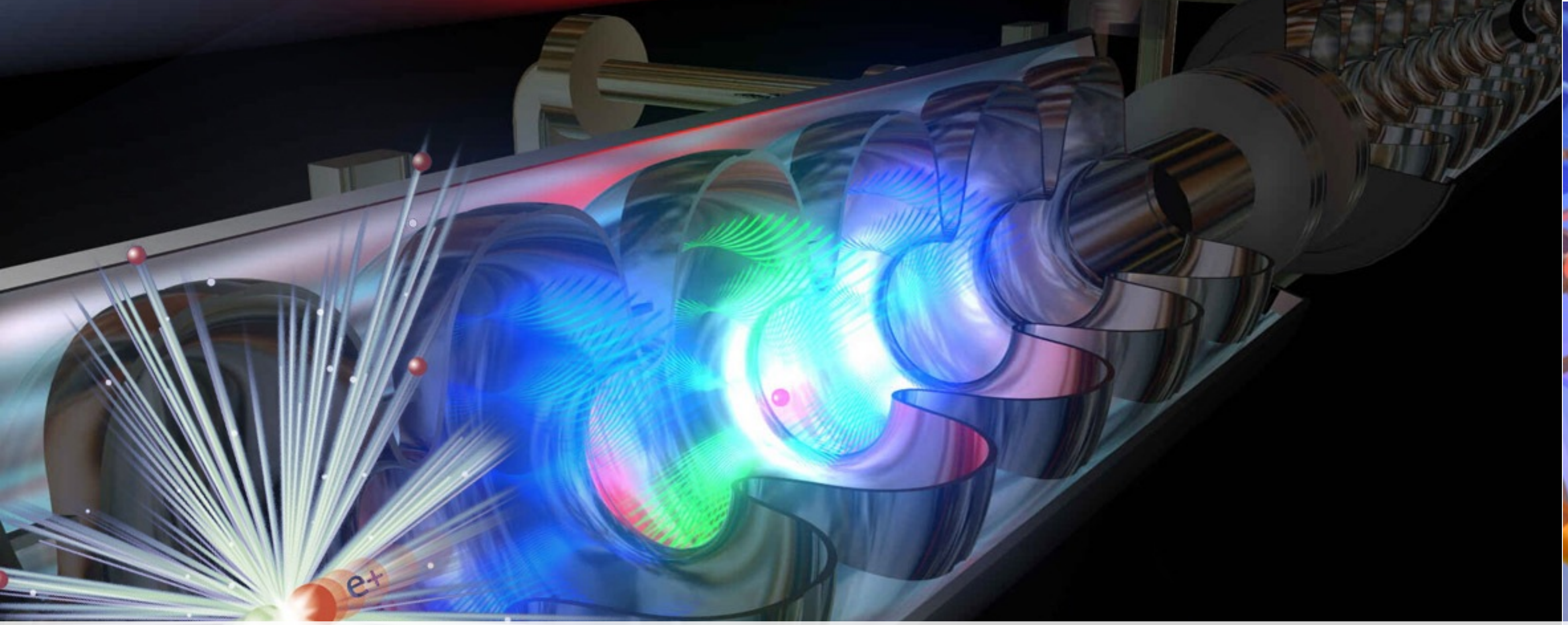



Experimental Physics at Lepton Colliders

Karlsruhe Institute of Technology

Frank Simon

@ Summer Student Lectures

CERN - July 2024

Institute for Data Processing and Electronics

Overview

A two-part story

- **Part I:**
  - Scientific motivation
  - Future e^+e^- colliders in broad strokes
- Part II:
  - Detectors at future e^+e^- and $\mu^+\mu^-$ colliders
  - Some physics examples

Disclaimer

I have taken material from many different presenters - impossible to list them all. I want to single out Mogens Dam, who gave excellent lectures on the same topic a few years ago, which I took as inspiration. An excellent resource reflecting a recent survey of this field is the Snowmass ’21 CSS Meeting in Seattle in July 2022: https://indico.fnal.gov/event/22303

The selection of material reflects my personal bias. I am not trying to “sell” a particular future facility - but use your own judgment to form you opinion!

Part I

Introduction

Where we are, how we got there

The Standard Model of Particle Physics

A Collider Success Story

SPEAR / AGS 1974

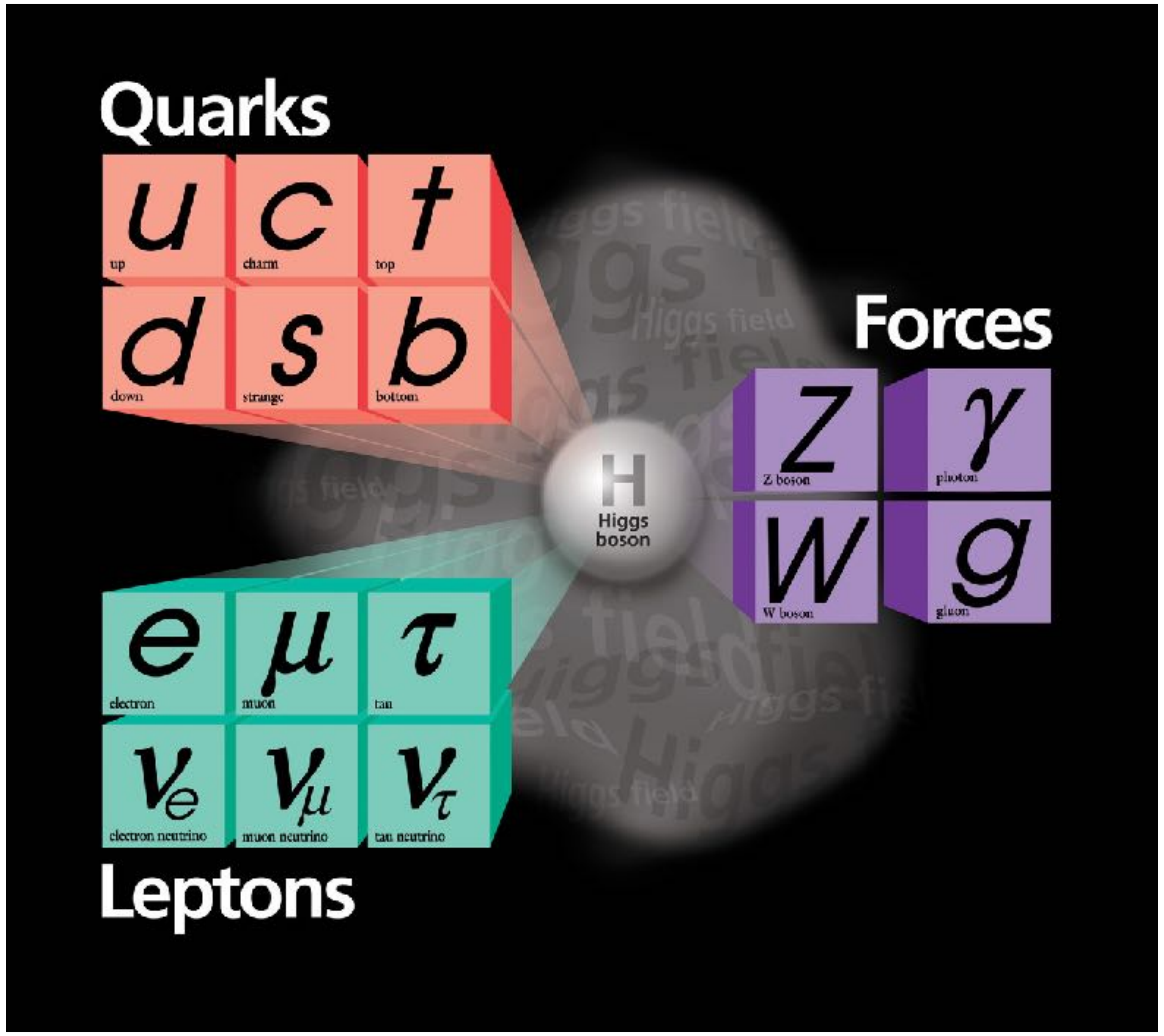
Fermilab 1977

Tevatron 1995

AGS 1962

SPEAR 1975

Fermilab 2000



PETRA 1979

SppS 1983

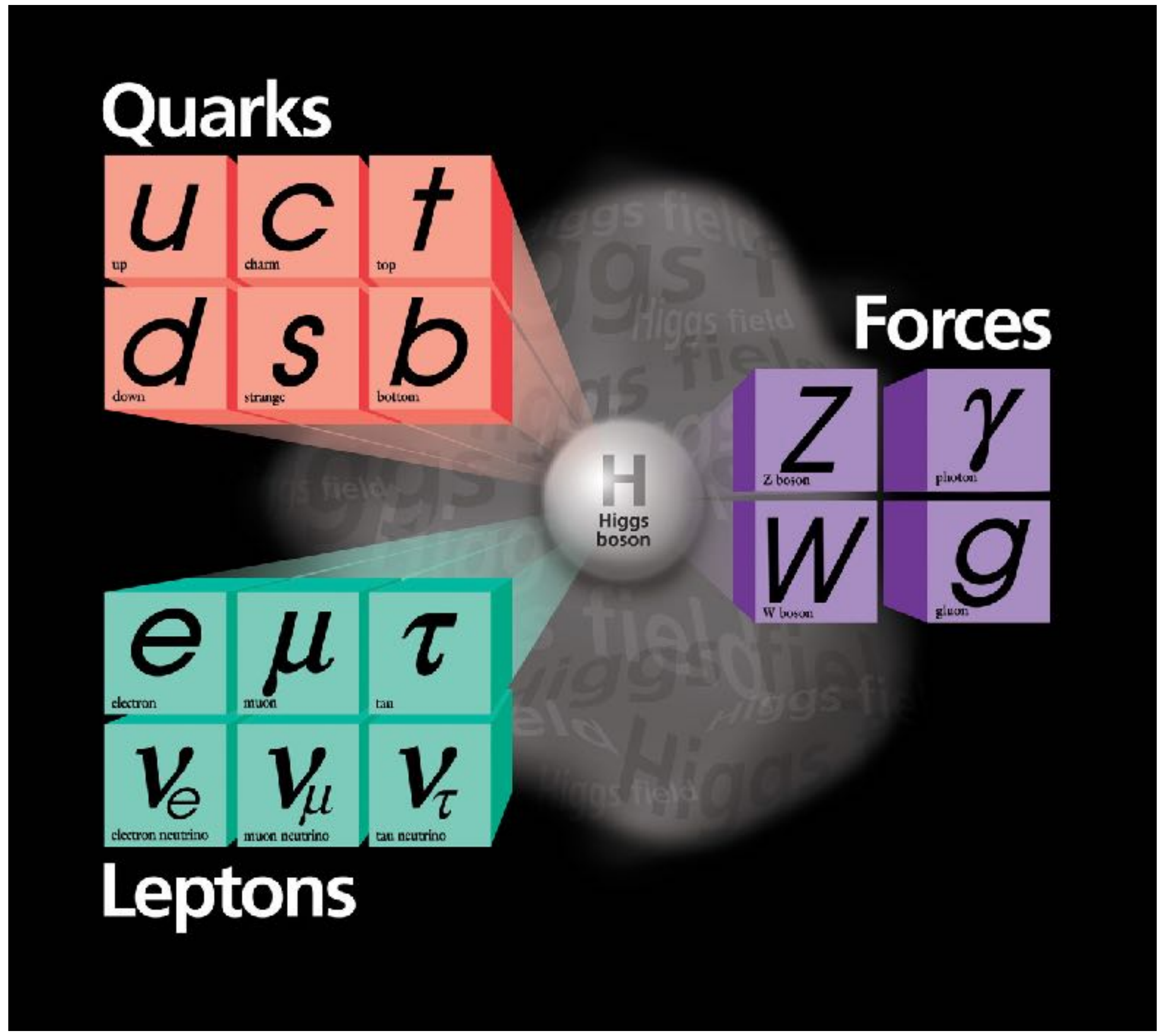
LHC 2012

- The result of generations of accelerators, and the interplay of experiment and theory
  Providing testable predictions

Contributions from

- e^+e^- colliders
- hadron colliders
- fixed target

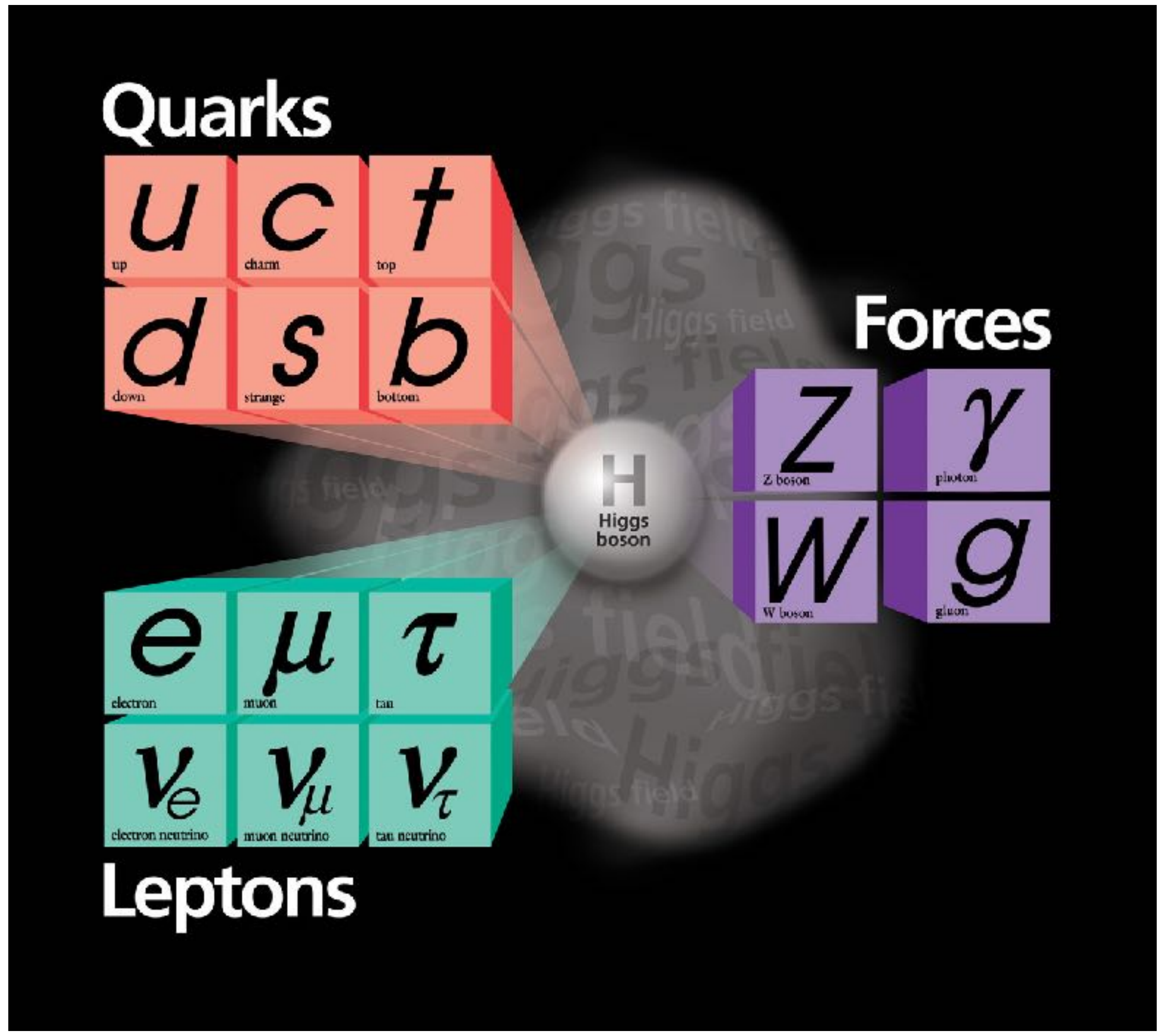
- The Standard Model: Explaining the micro-world



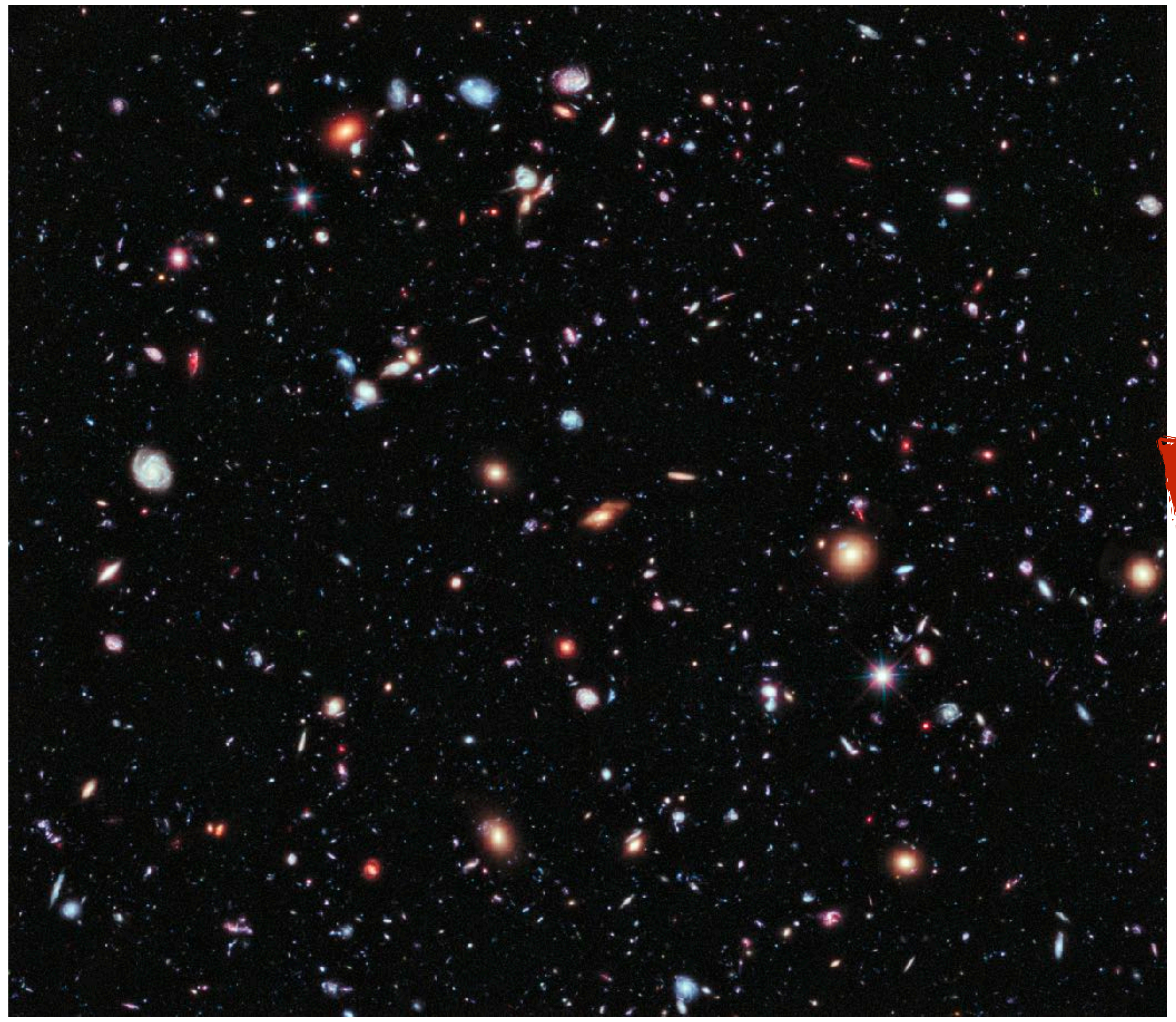
The Universe at Large and Small Scales

Open Questions

- The Standard Model: Explaining the micro-world



But: does not explain key astrophysical observations…



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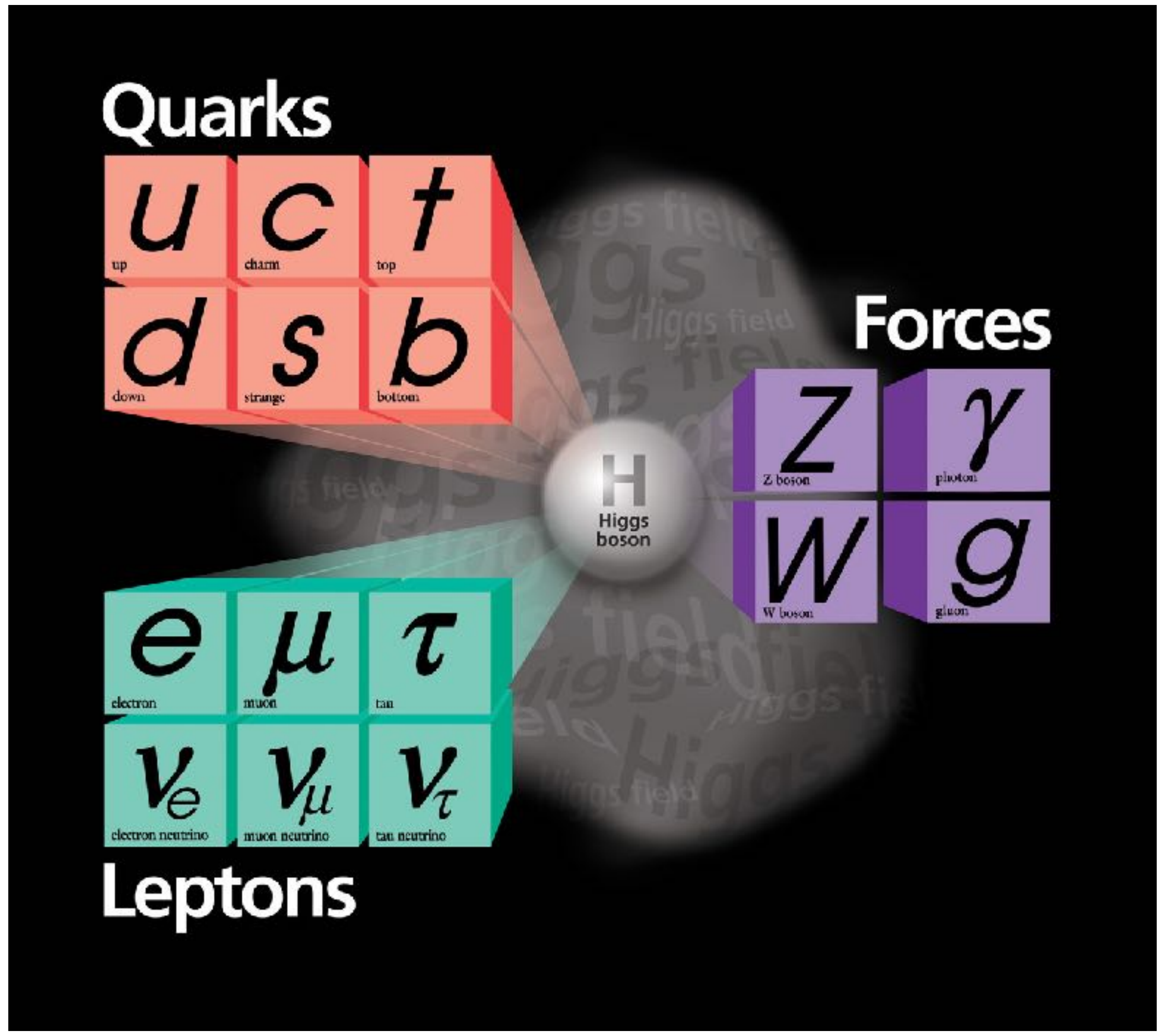

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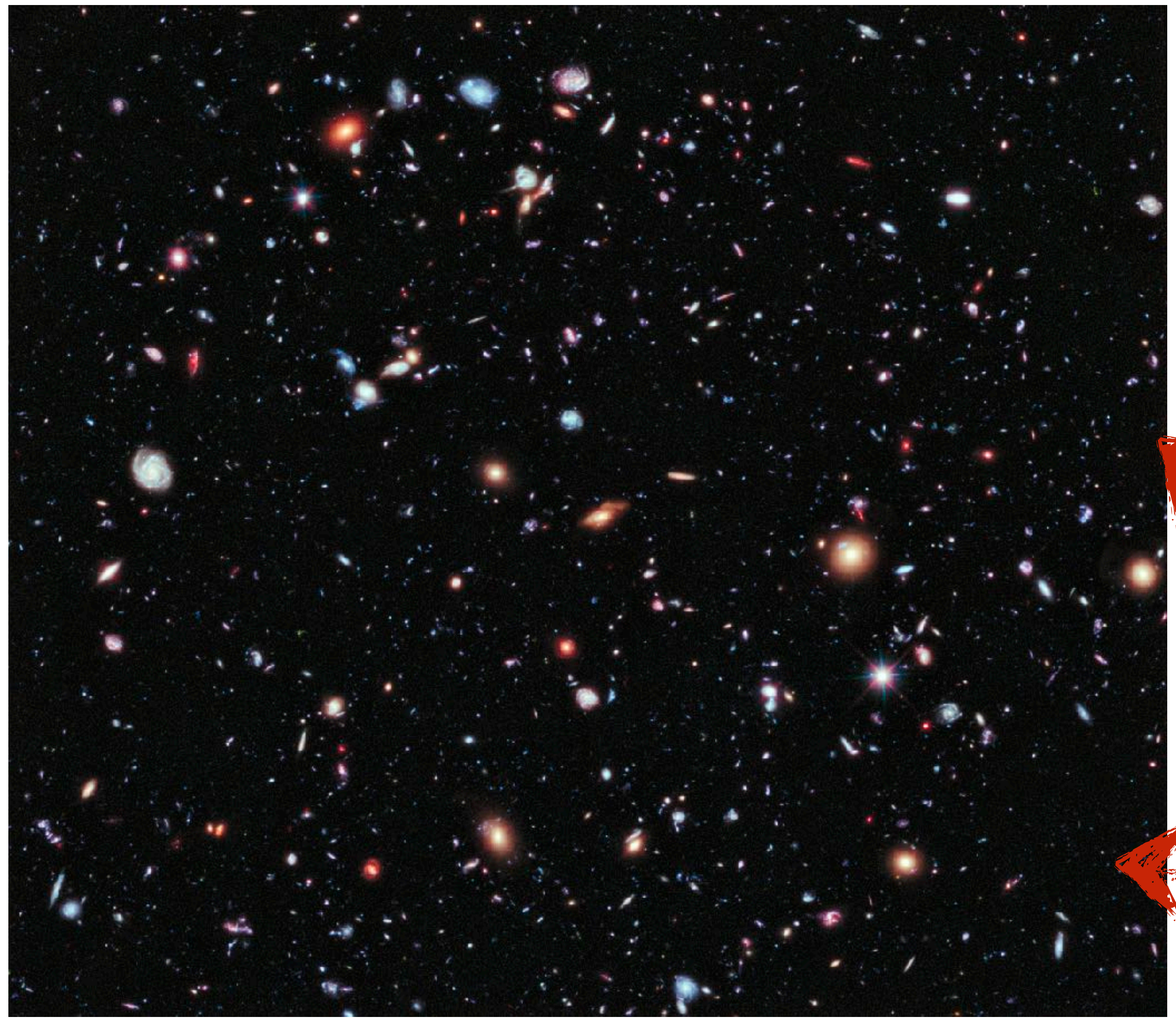

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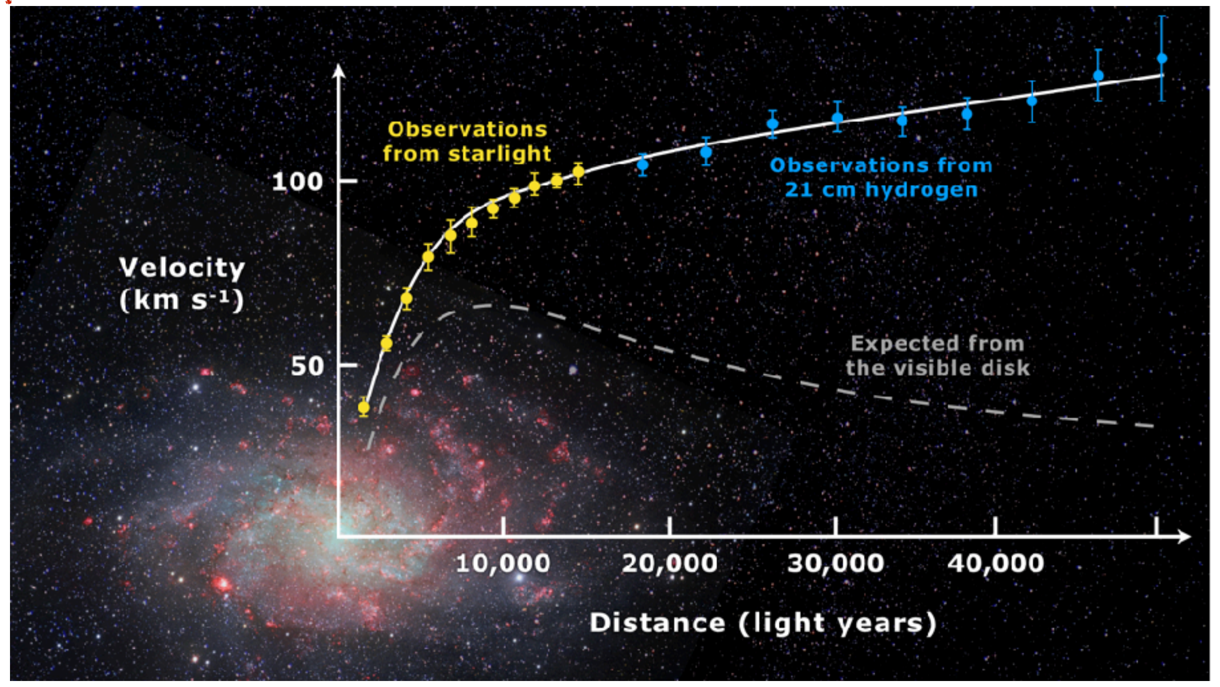

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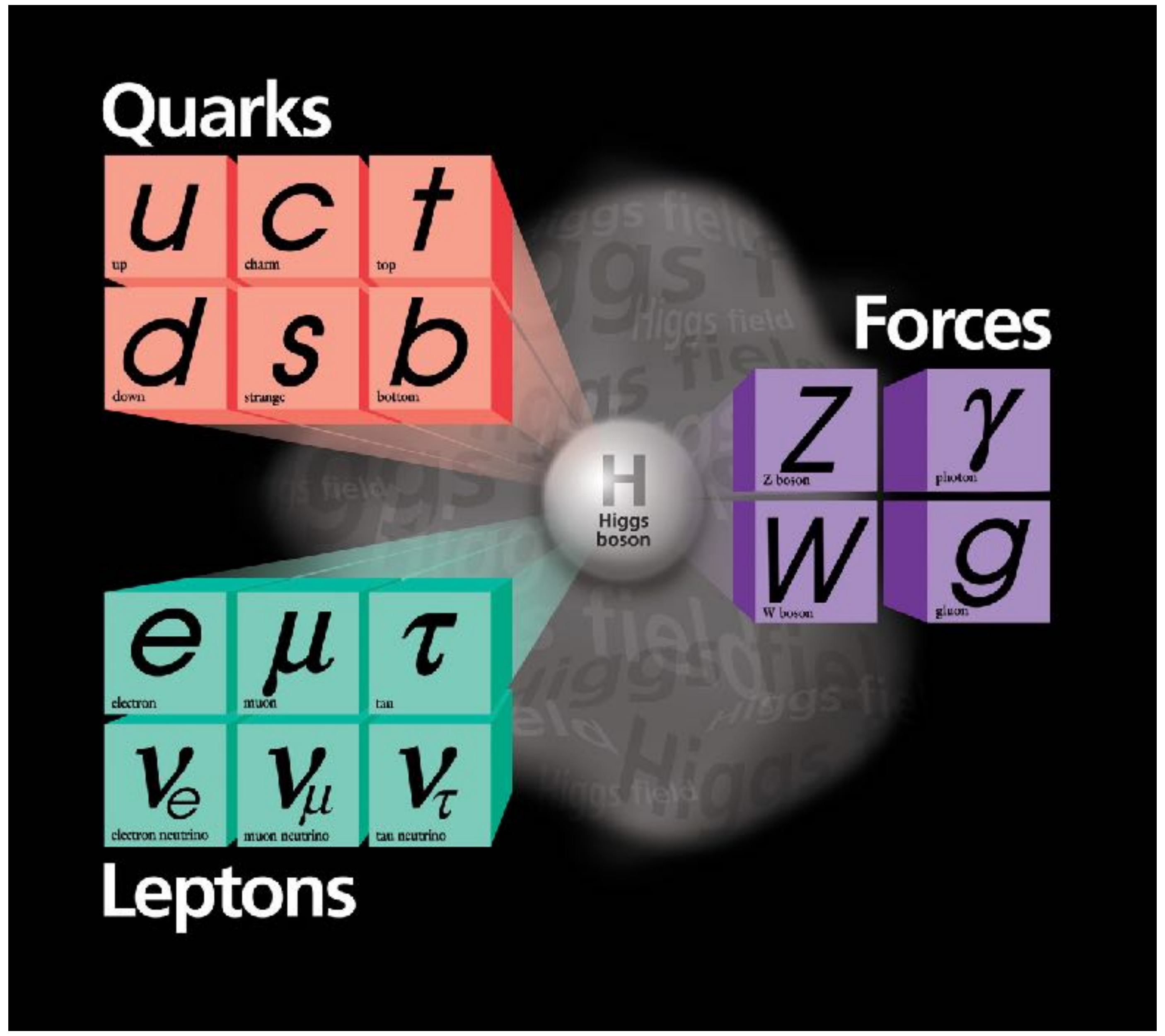

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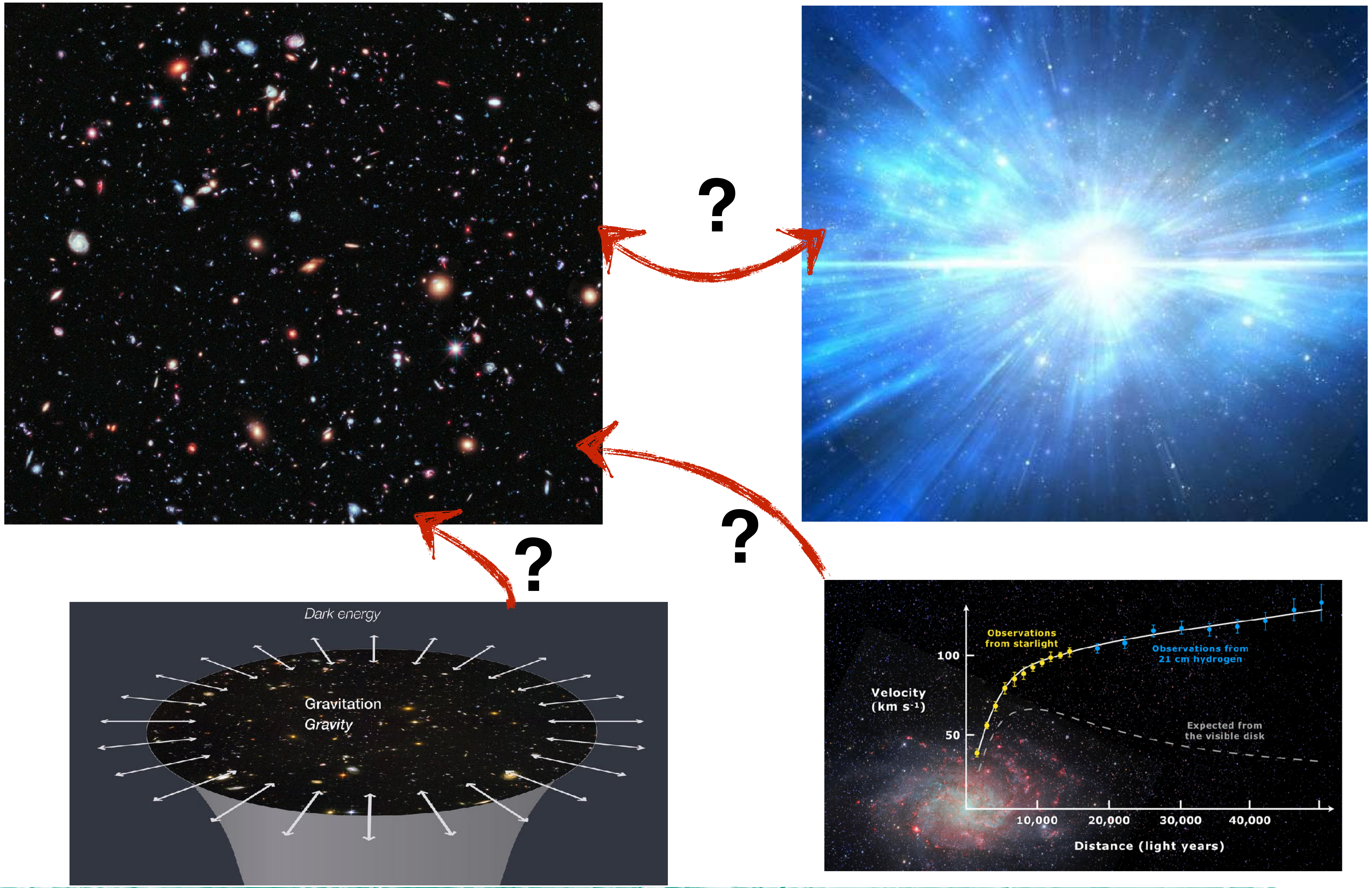

The Universe at Large and Small Scales

Open Questions

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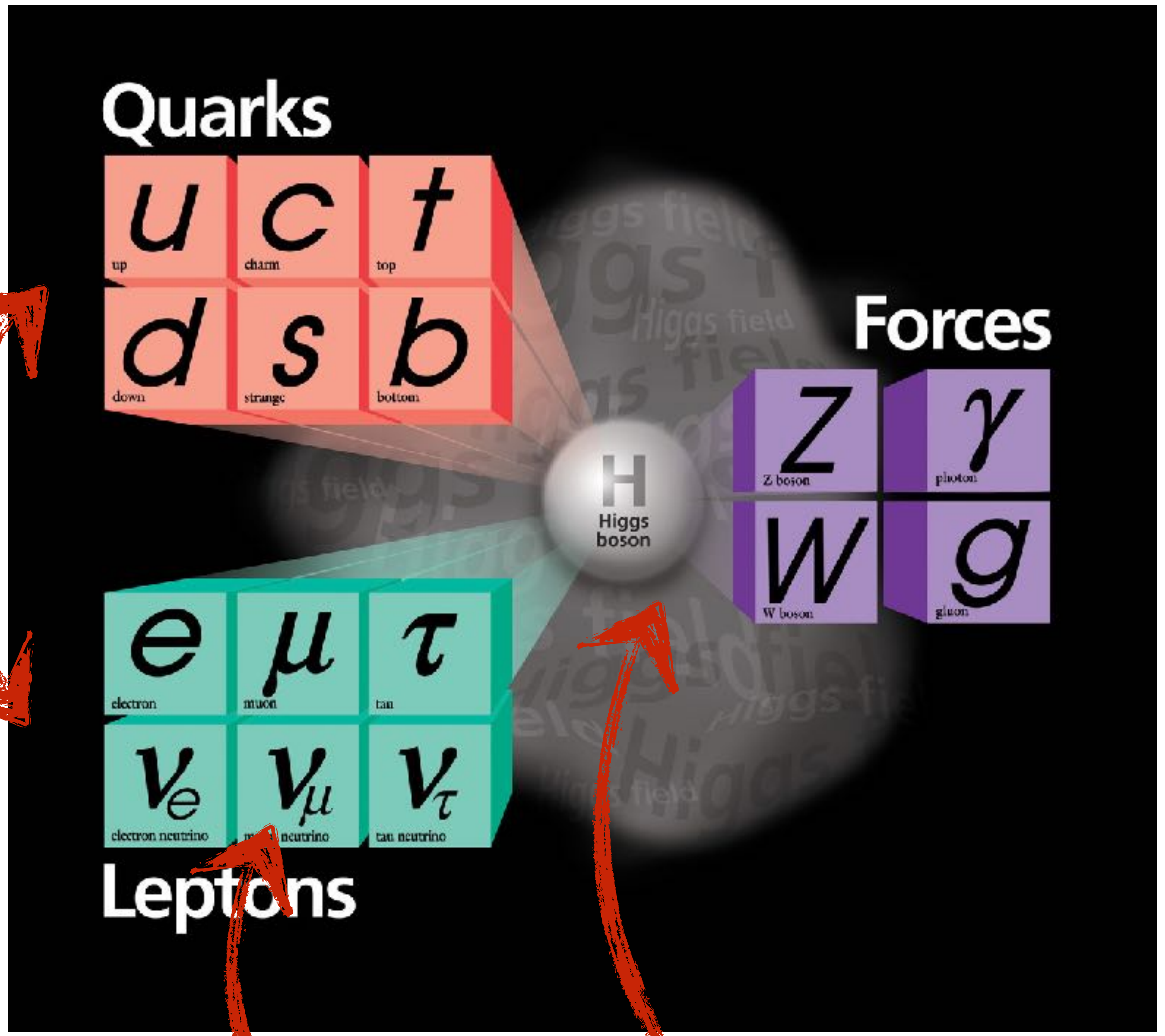

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… and raises new questions by itself!

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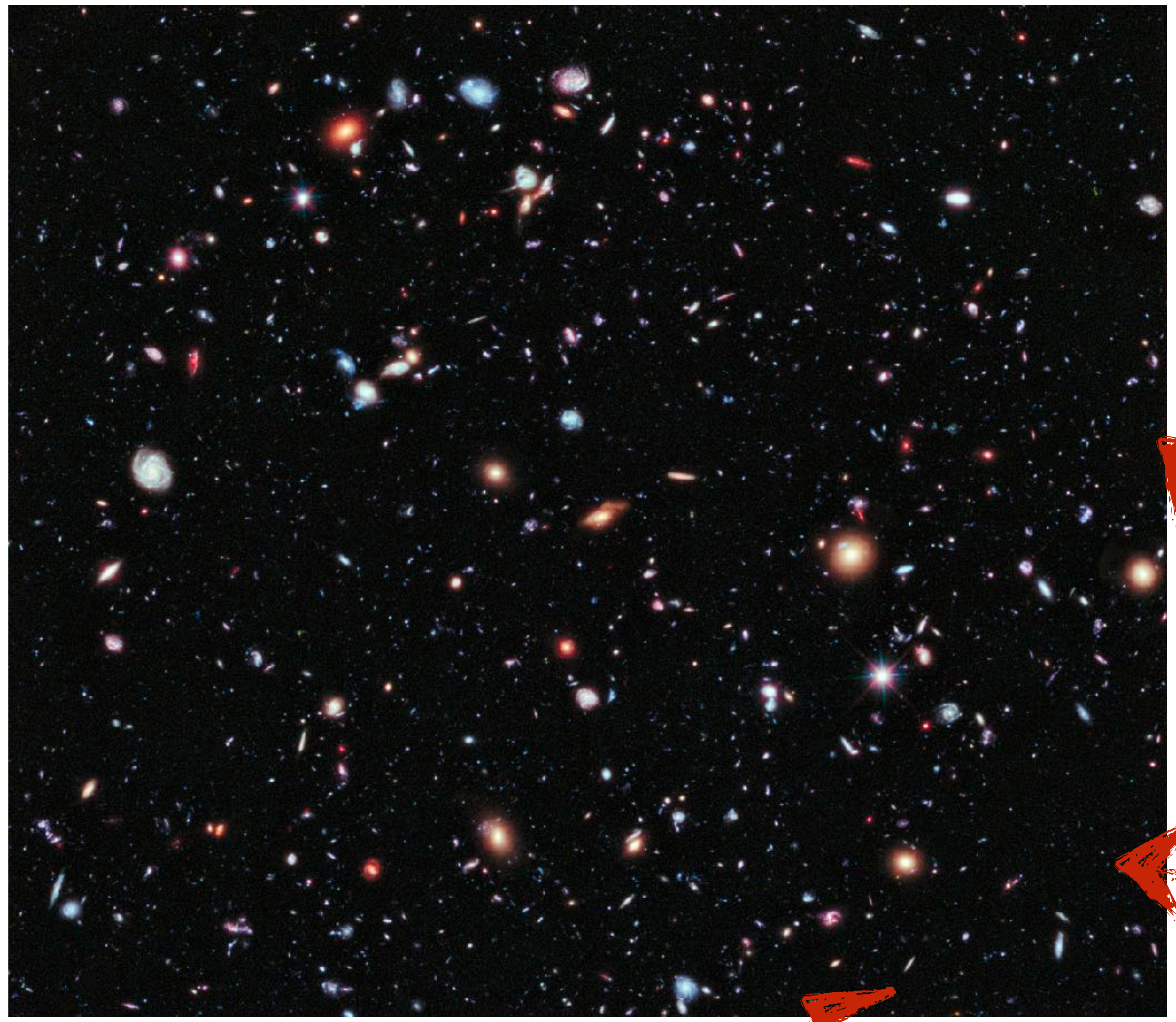

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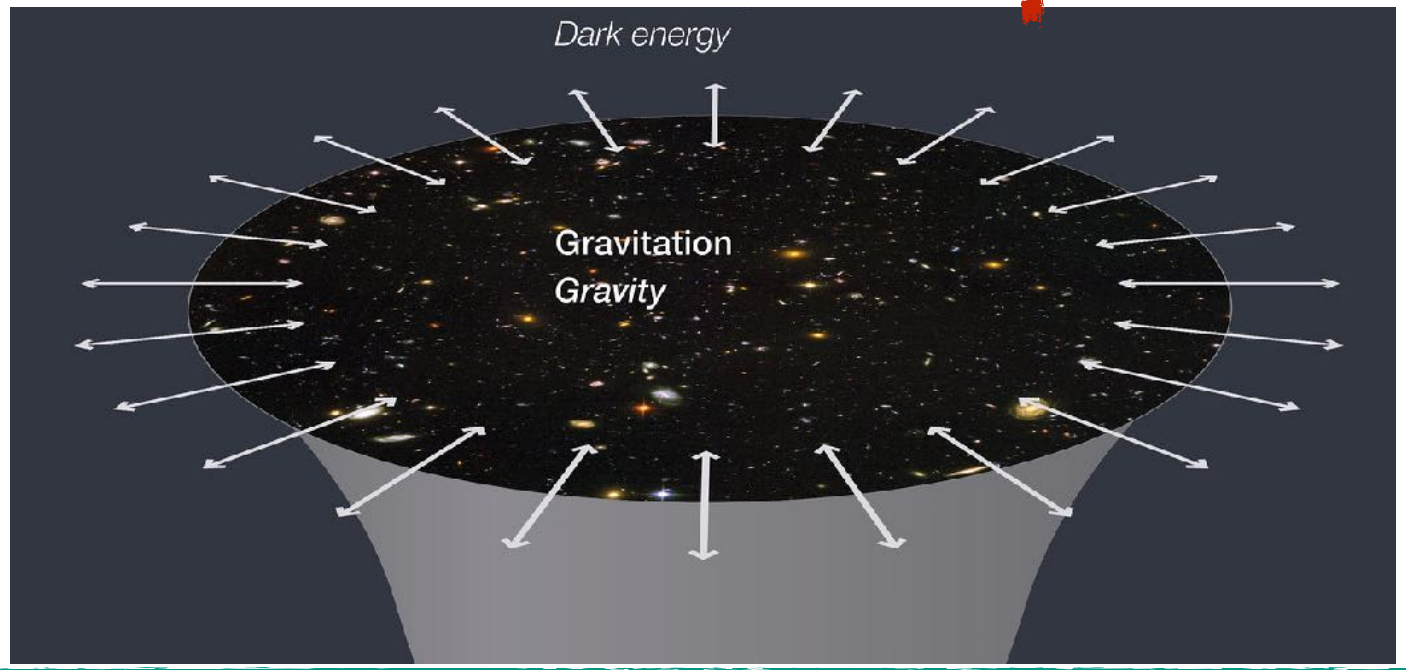
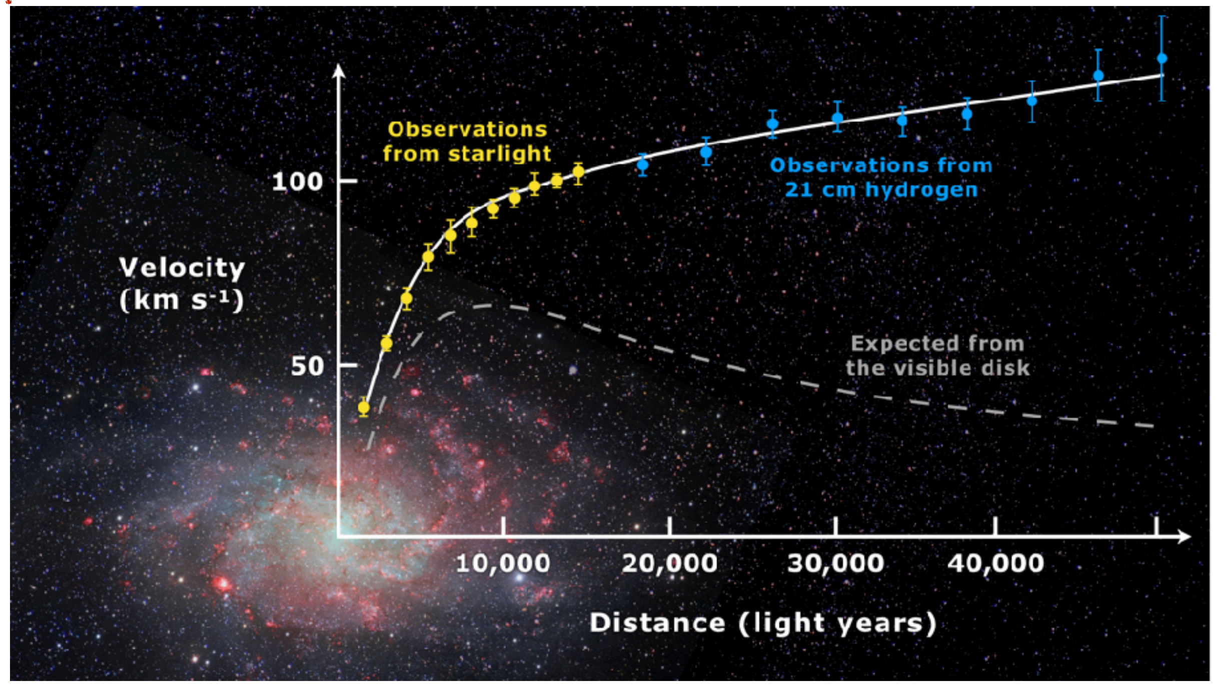
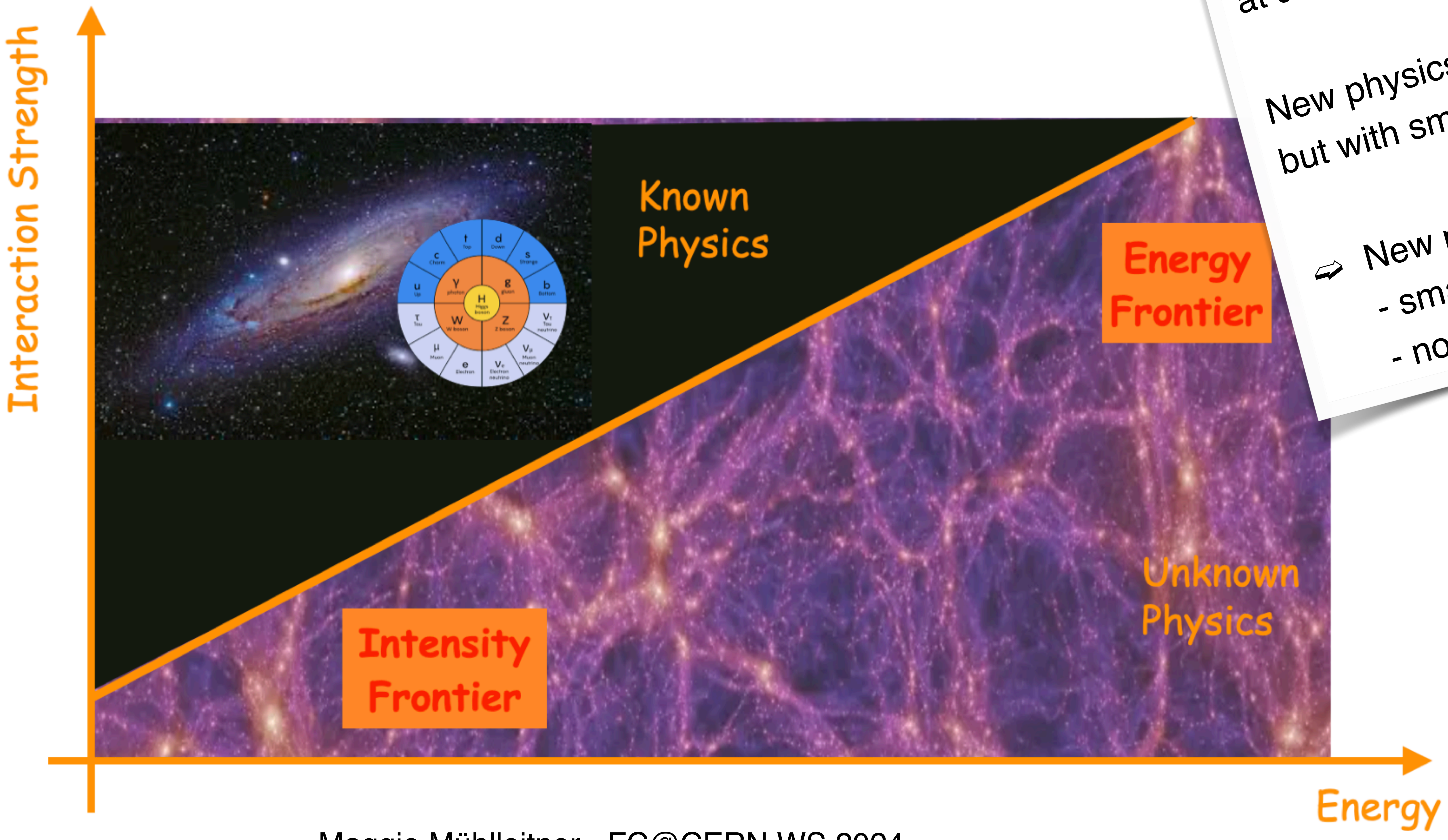




The Path Forward

Responding to missing Guidance



Maggie Mühlleitner - FC@CERN WS 2024

New physics may be heavy, with new particles at a large mass scale.

New physics may be light, but with small couplings.

➩ New physics is subtle:
- small cross sections
- novel signatures

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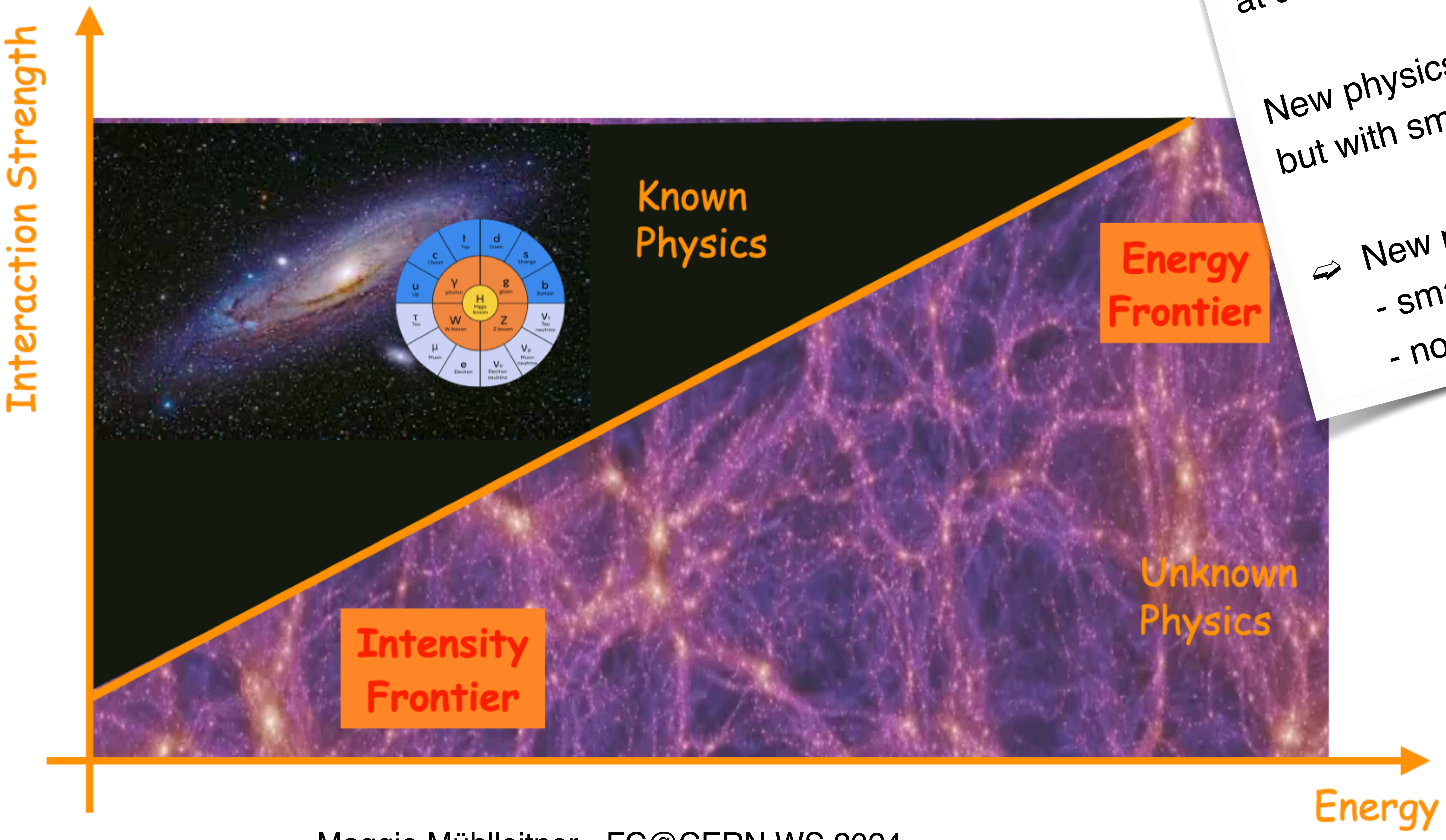

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No single right experimental path forward.

The Path Forward

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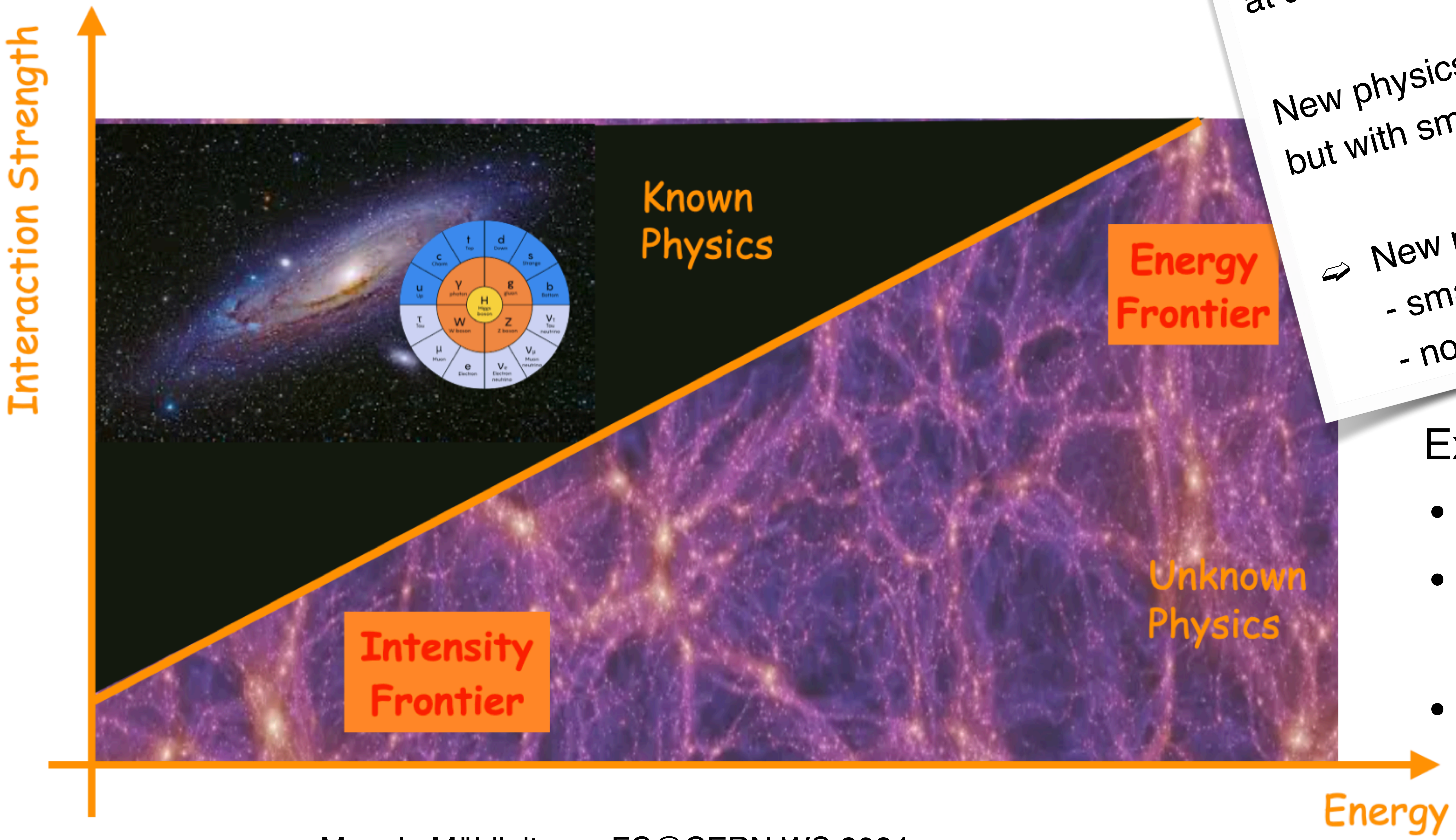

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Exploiting different strategies:

- Direct production at high energies
- Precision measurements + precise theory: Indirect probe of high scales
- Direct detection of “dark sector” particles

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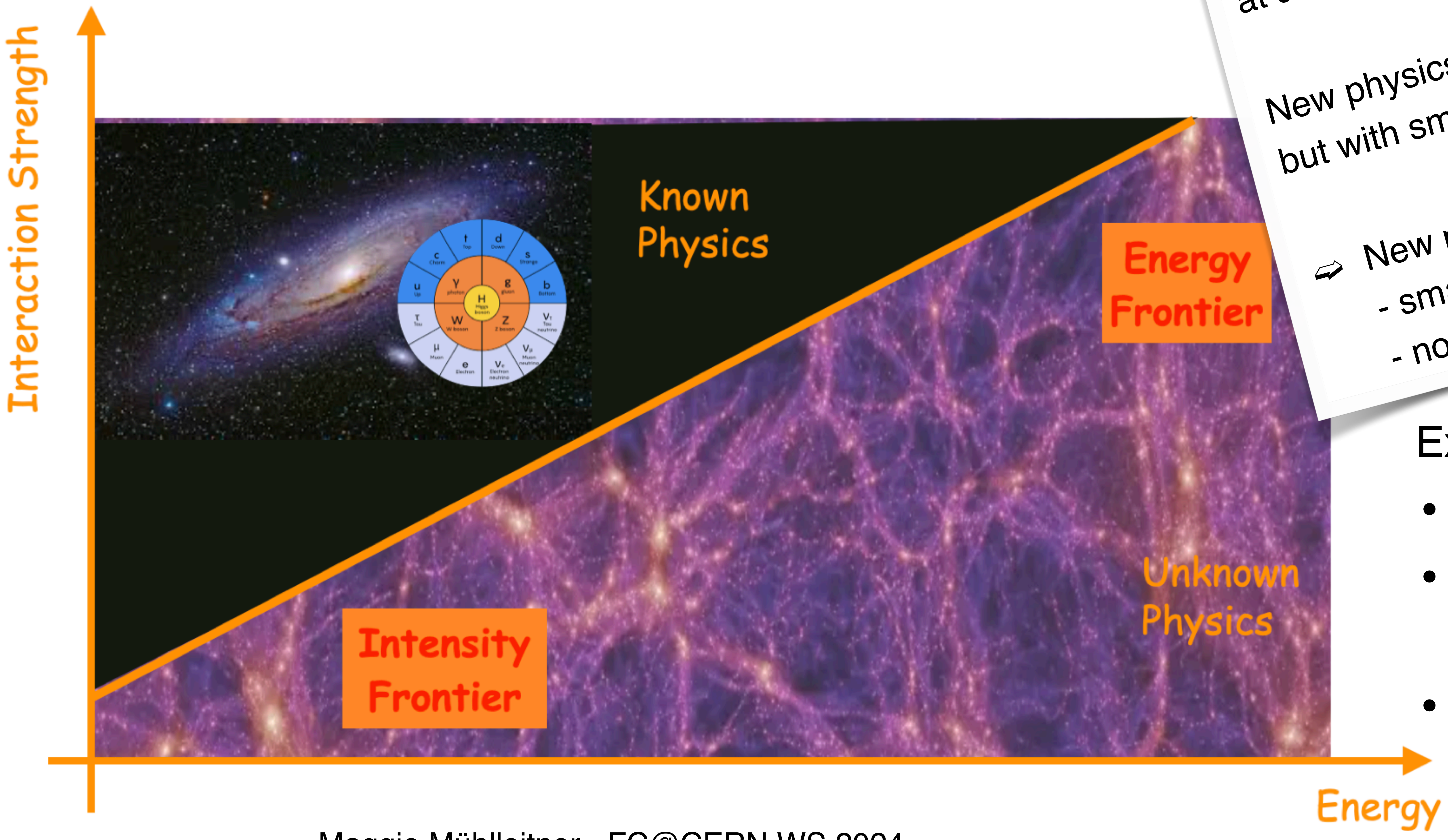

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Exploiting different strategies:

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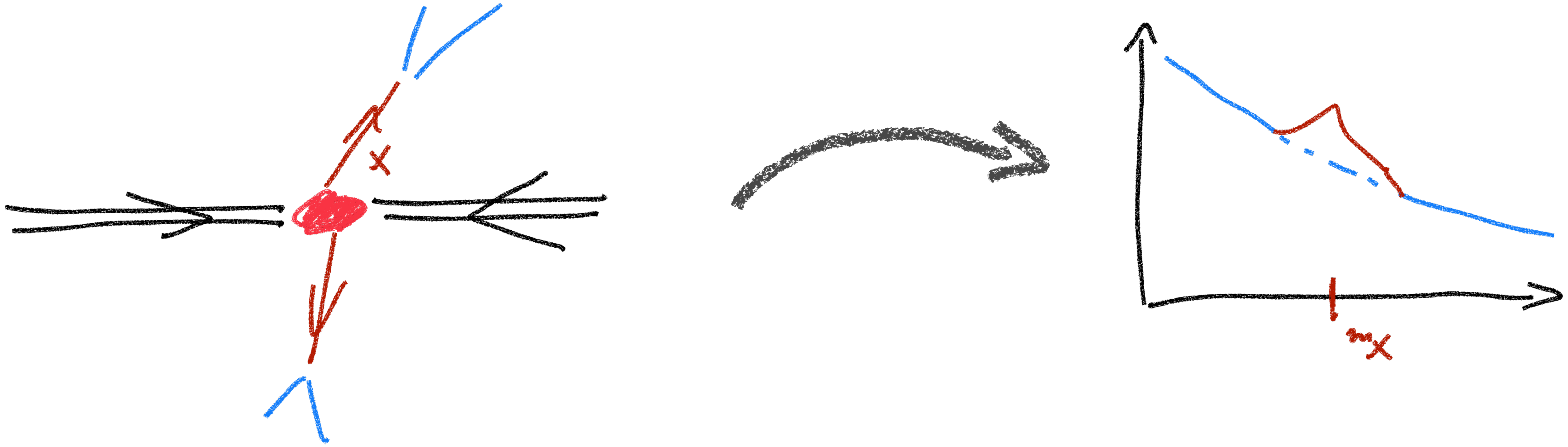
- Direct detection of “dark sector” particles

Particle colliders contribute in all categories!

Strategies for Discovery in Particle Physics

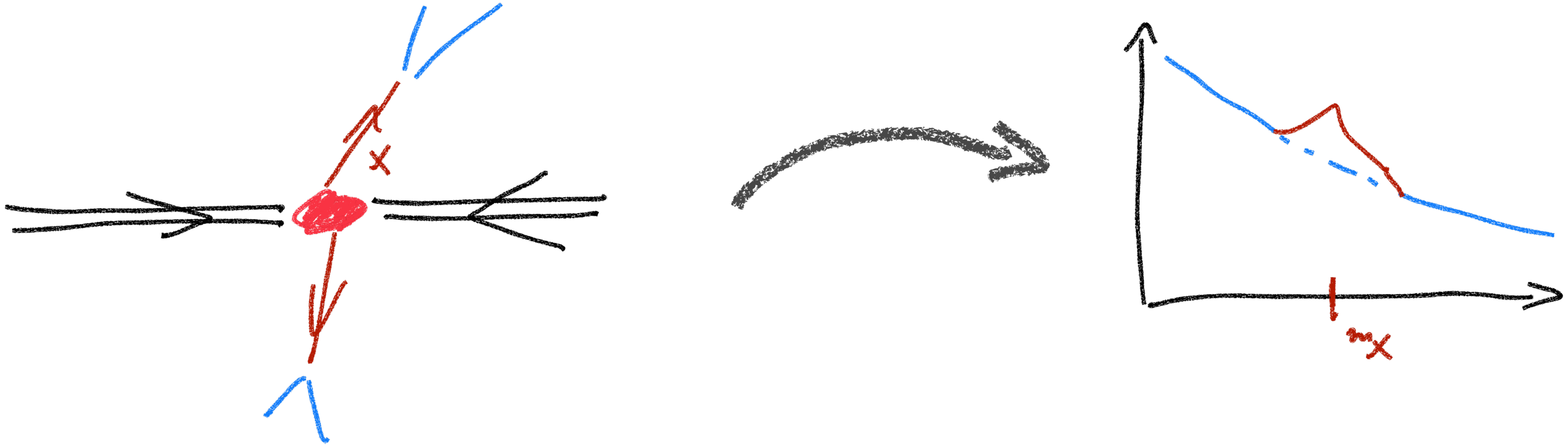
Direct and indirect



Direct observation of new particles: Requires sufficient energy for production

Strategies for Discovery in Particle Physics

Direct and indirect



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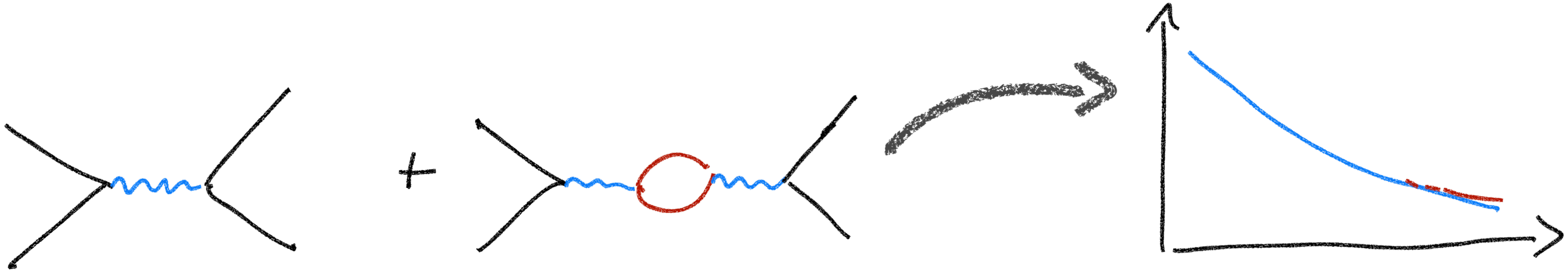


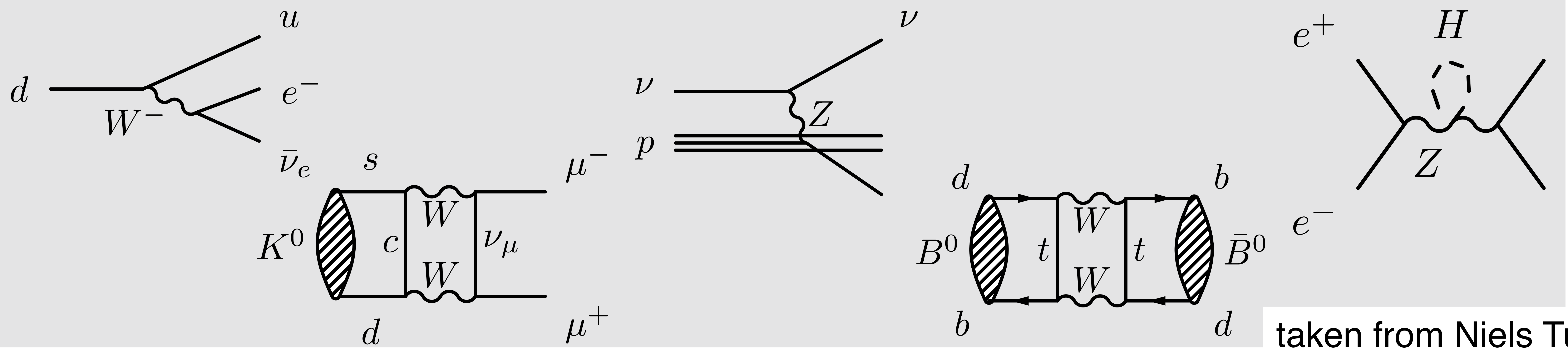
Indirect discovery: Deviations from expectation hinting at new phenomena at (much) higher energy scale

Precision Measurements

An established discovery strategy

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	*W→eν*	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	*J/ψ*	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	*Υ*	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?

with a well-founded theoretical model, precision measurements can be turned into discoveries - and precision measurements can guide the development of new models.



taken from Niels Turing, ICHEP 2018

Precision Measurements

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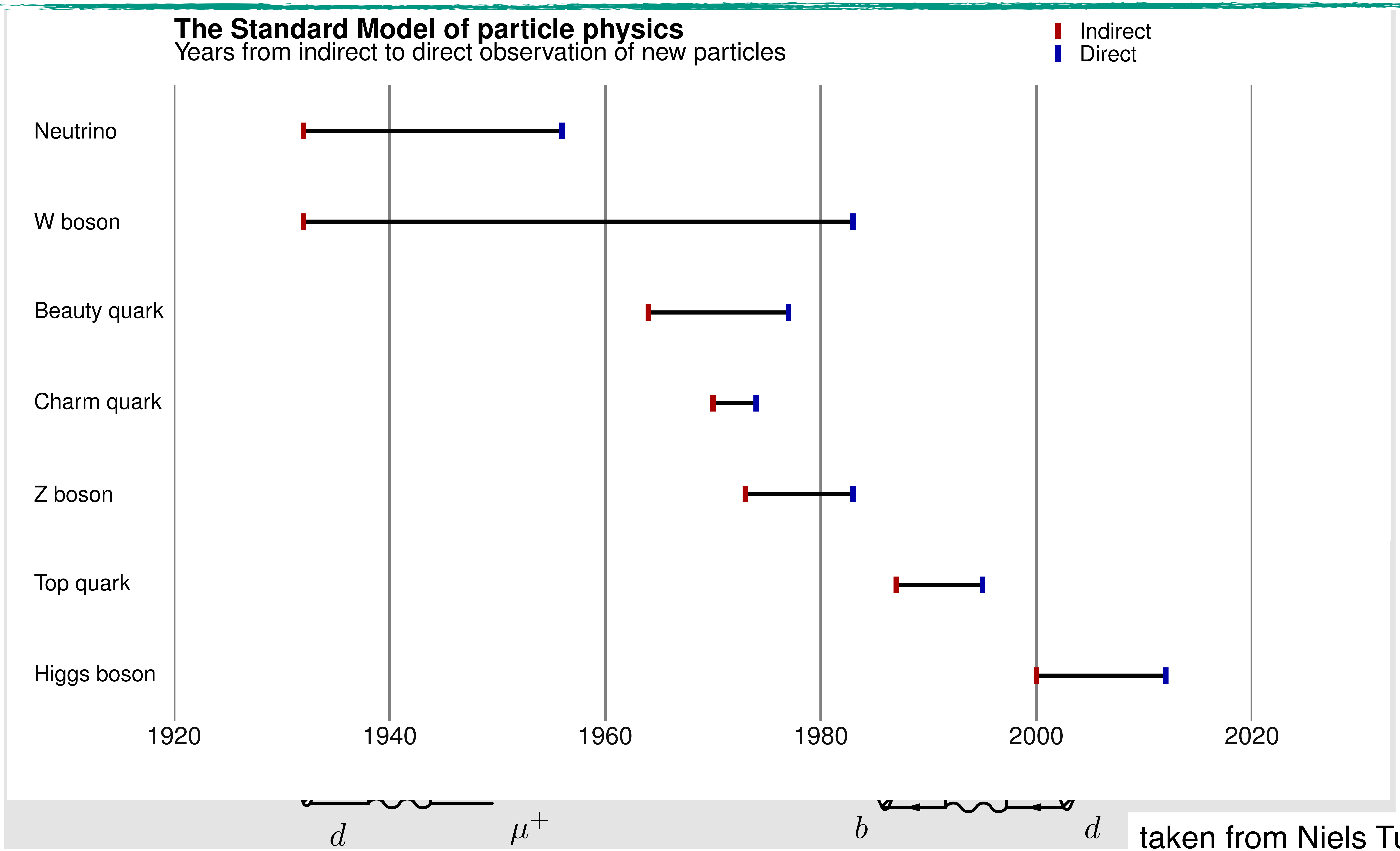

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reaching higher scales: direct discoveries only follow with new generations of experiments

taken from Niels Turing, ICHEP 2018

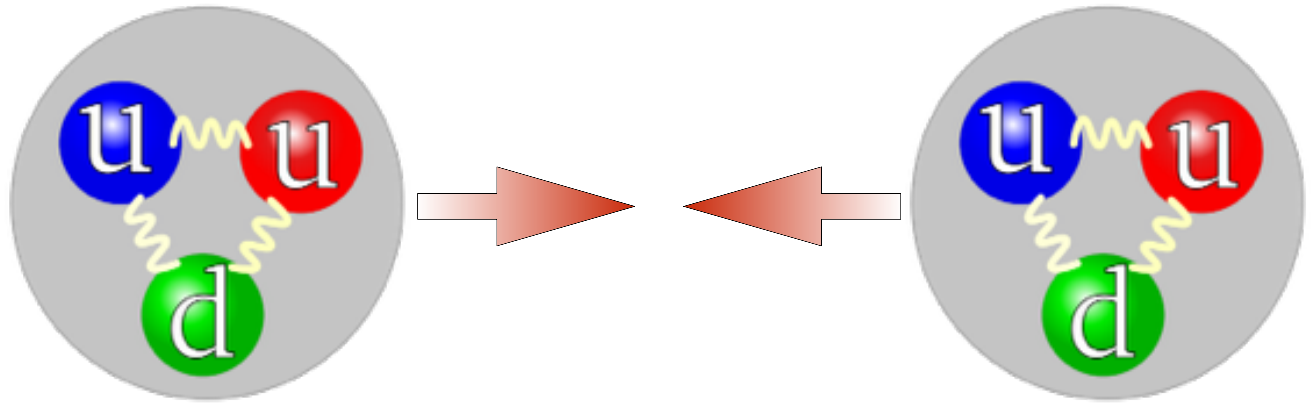
Why e^+e^- Colliders?

Electron and Proton Colliders

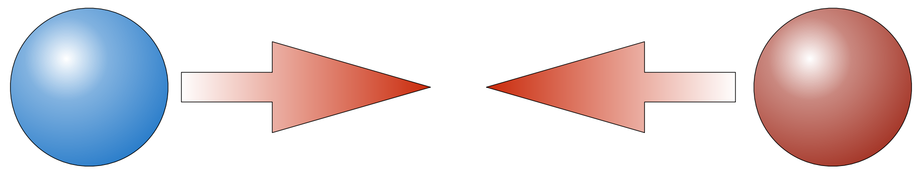
The main workhorses of HEP

- Colliders accelerate charged particles to high energy and bring them to collision - two main types so far:

proton-proton collider



electron-positron collider



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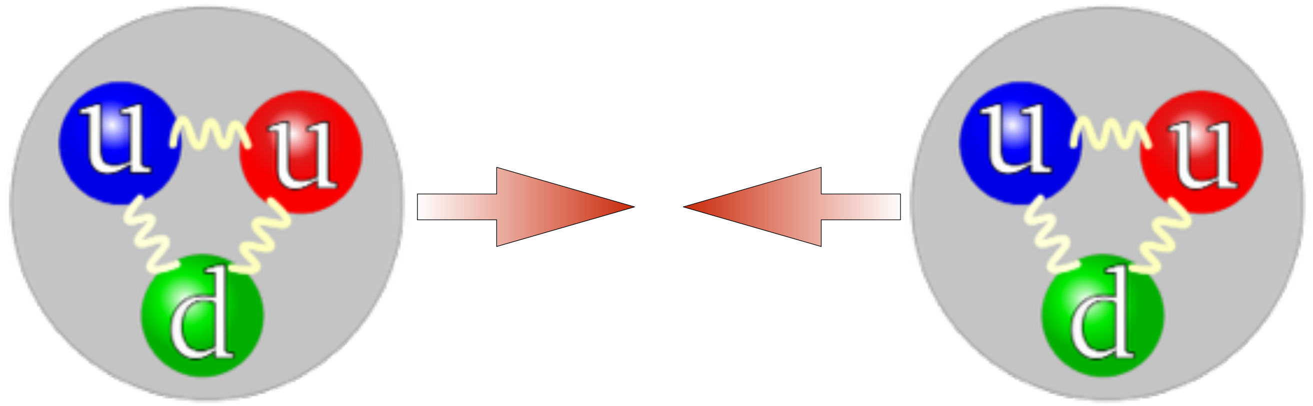
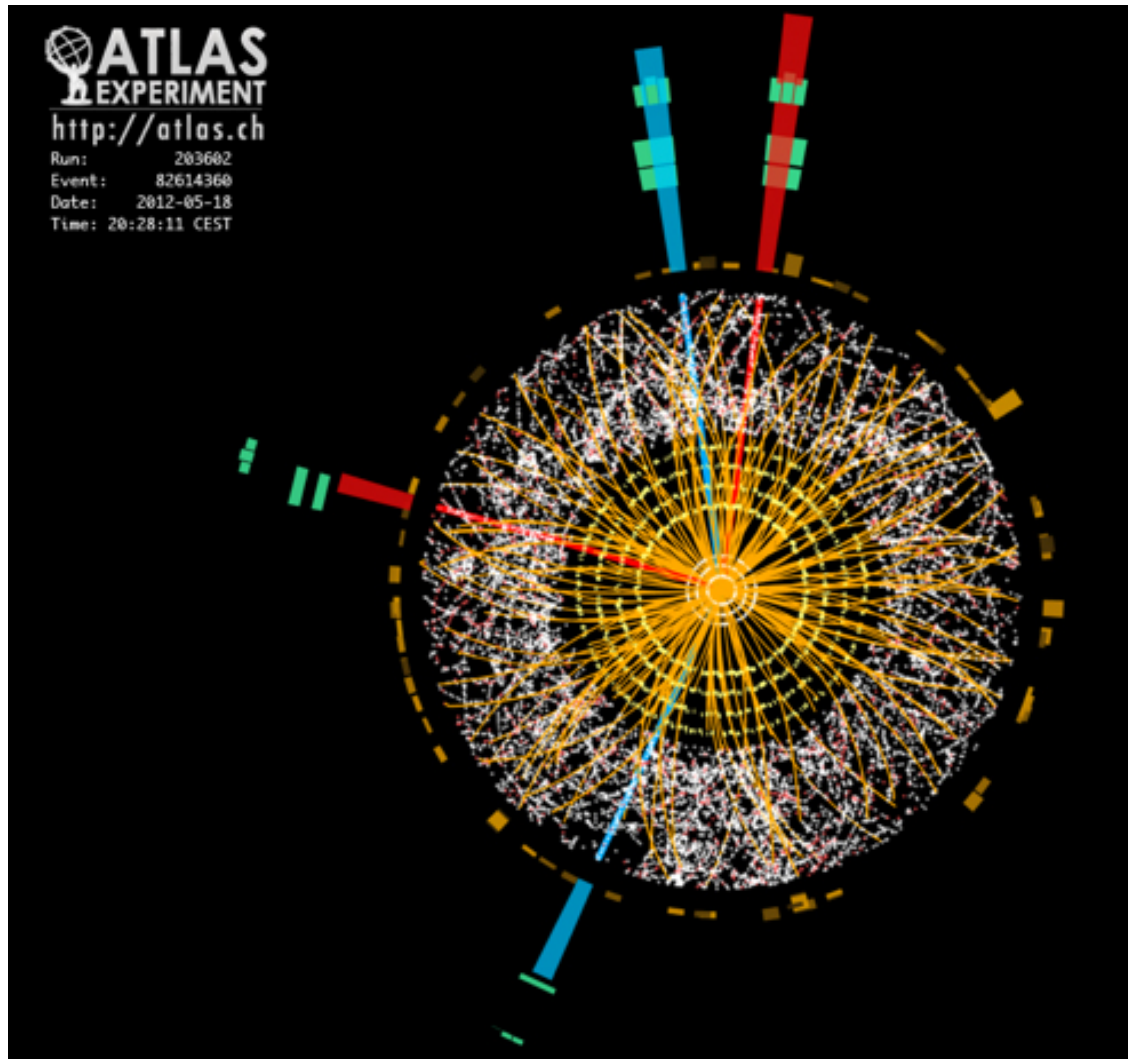
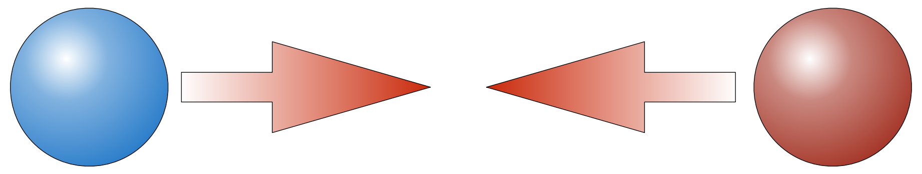




composite particles

dominated by strong interaction

electron-positron collider



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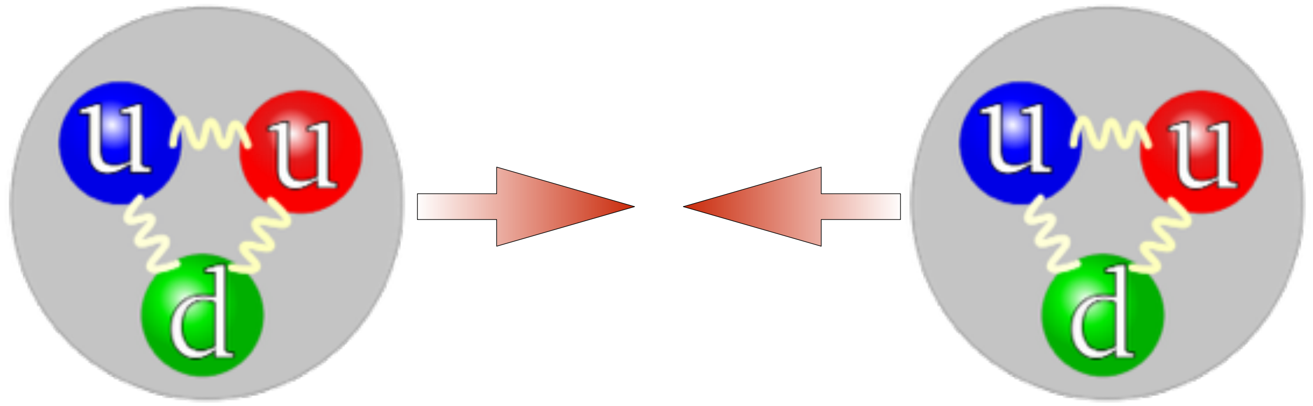

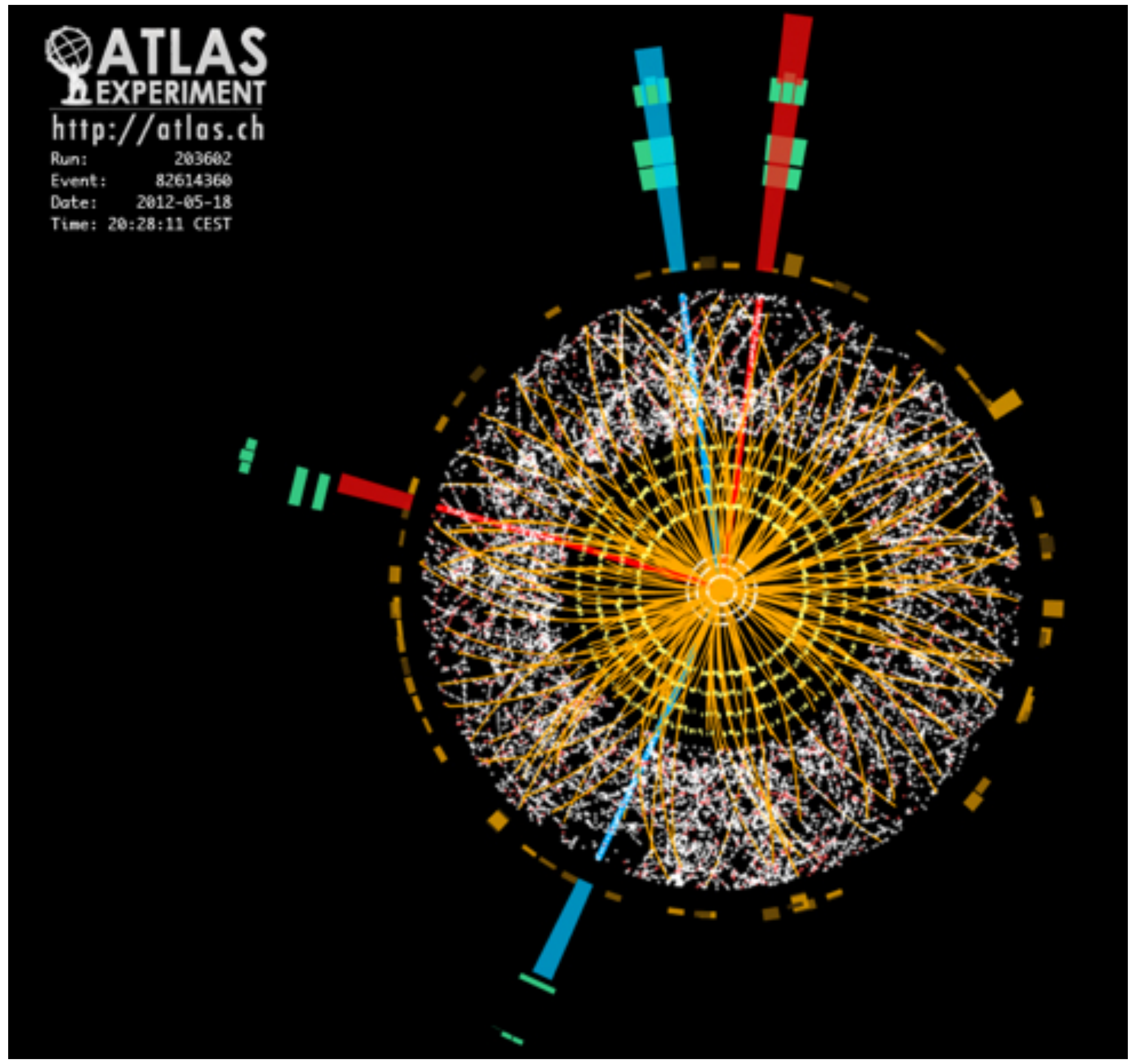

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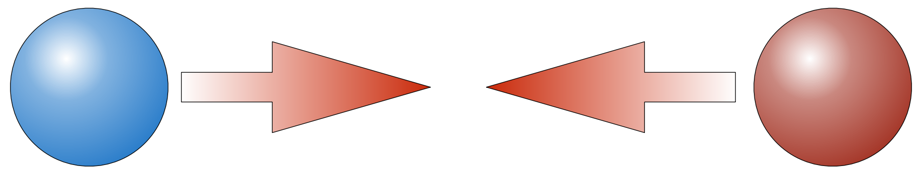
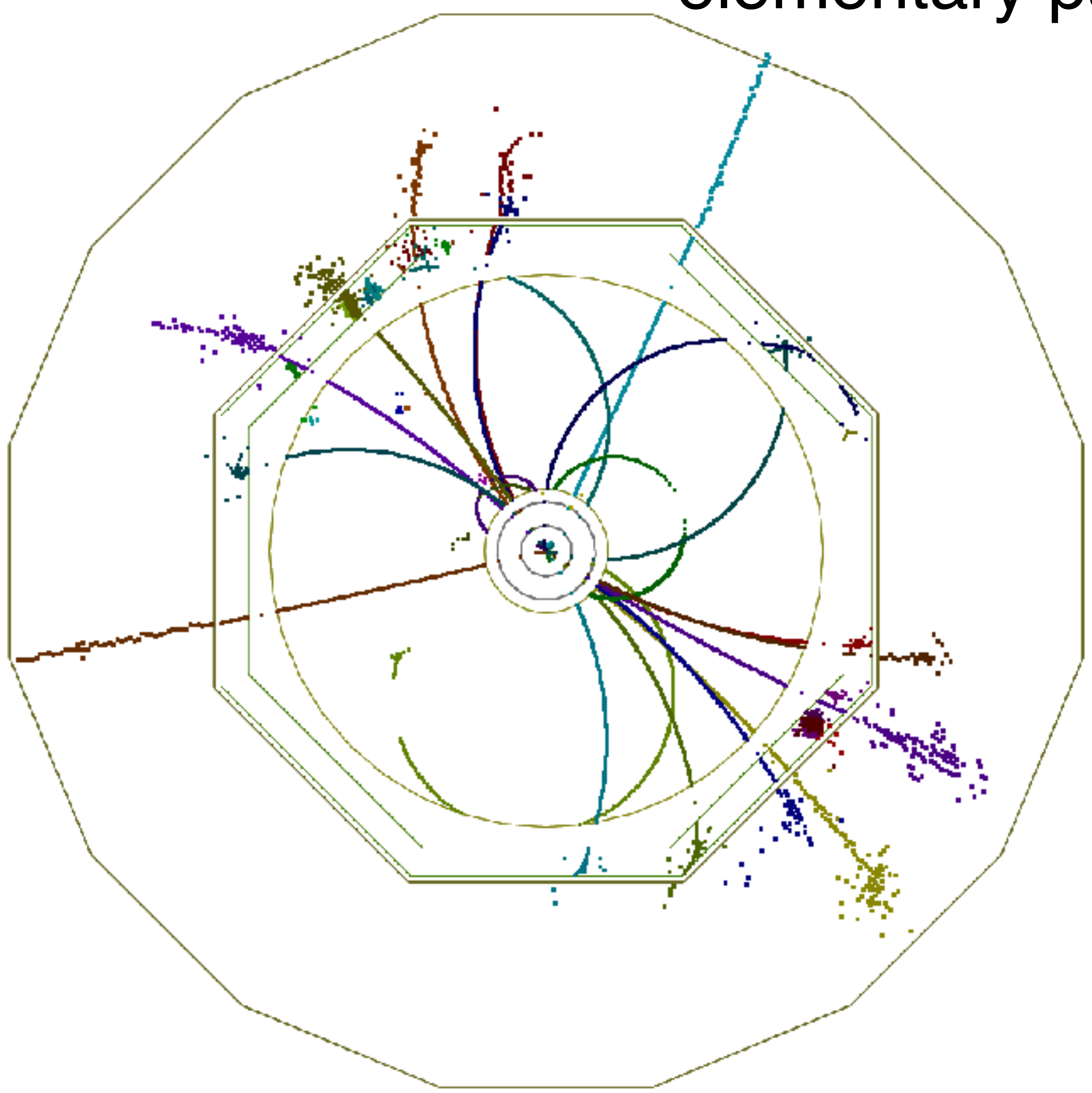


elementary particles



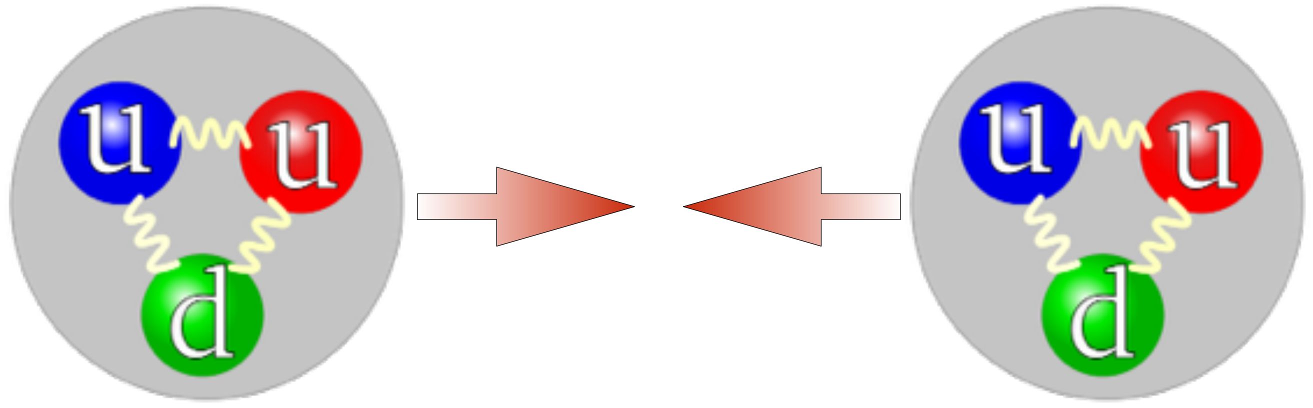
dominated by electroweak interaction

Electron and Proton Colliders

The main workhorses of HEP

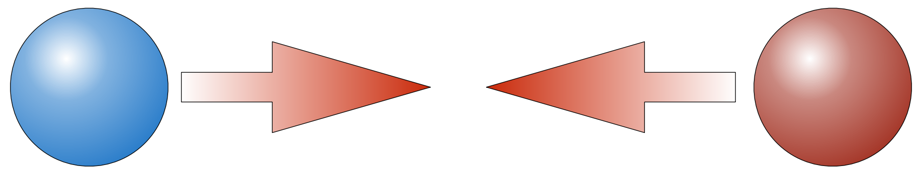
- Colliders accelerate charged particles to high energy and bring them to collision - two main types so far:

proton-proton collider



High complementarity of p+p and e^+e^- colliders

electron-positron collider



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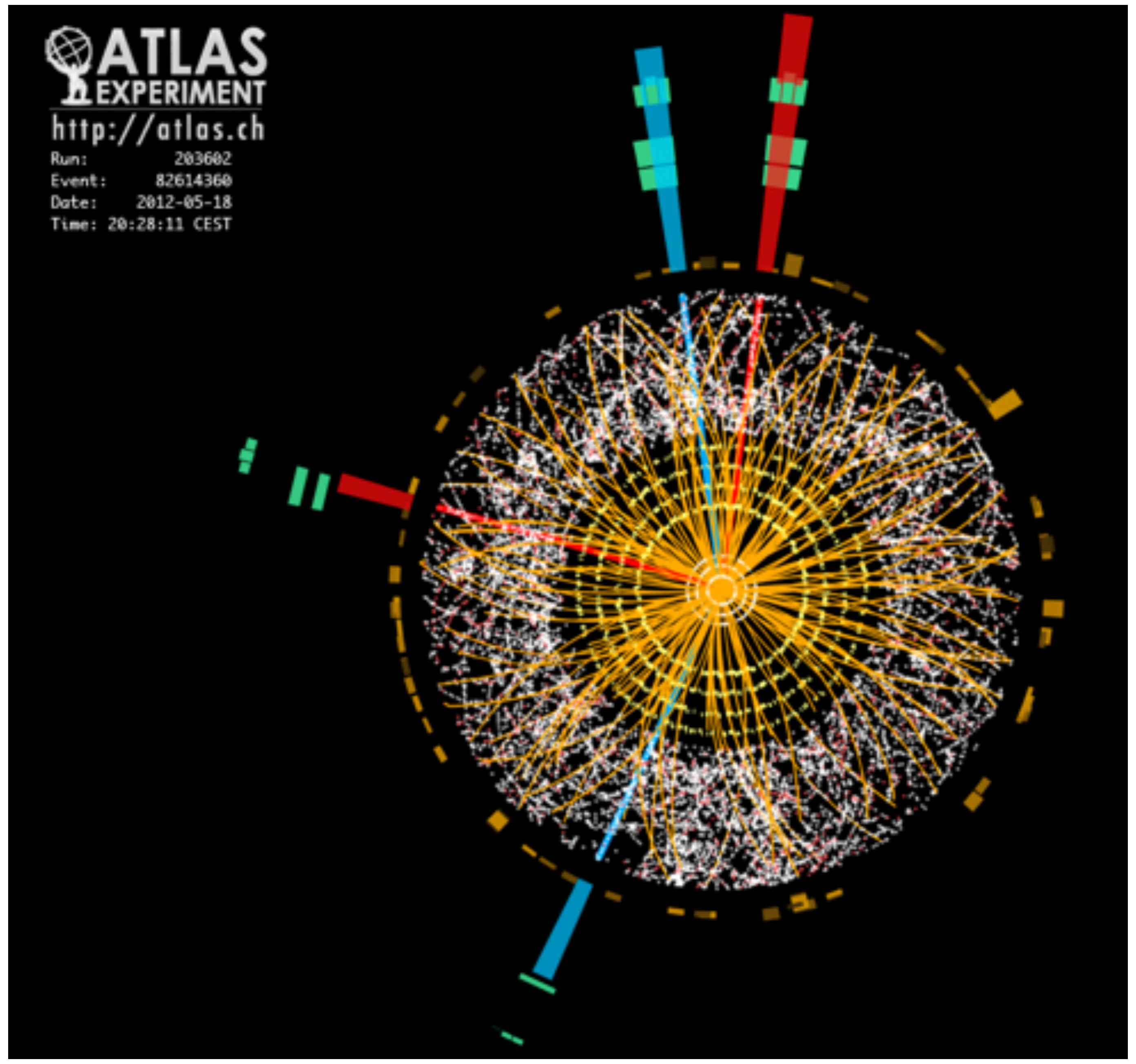

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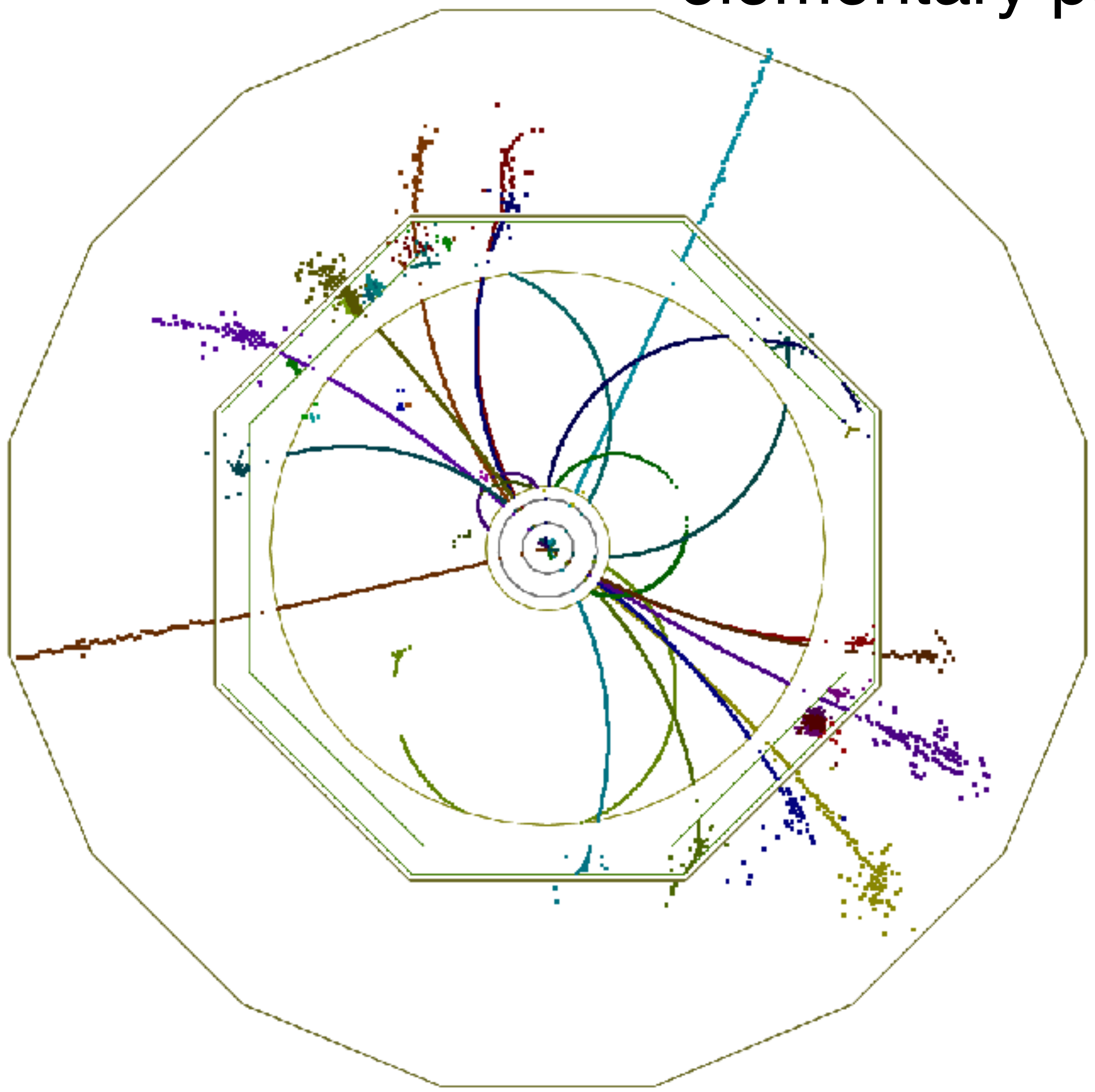
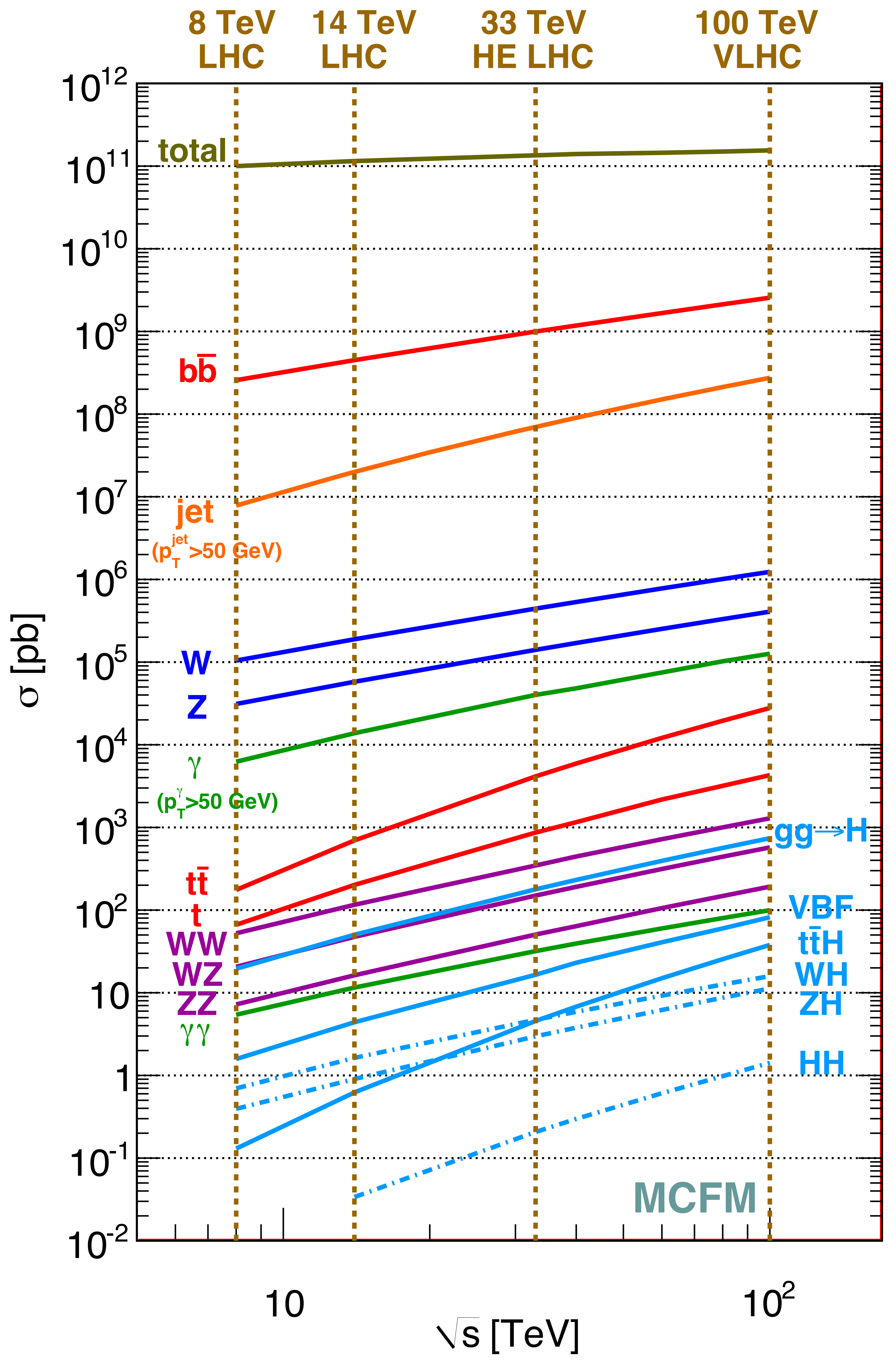
dominated by electroweak interaction



Electron & Proton Colliders

Higgs production as an example to illustrate differences



~ 9 orders of magnitude

Electron & Proton Colliders

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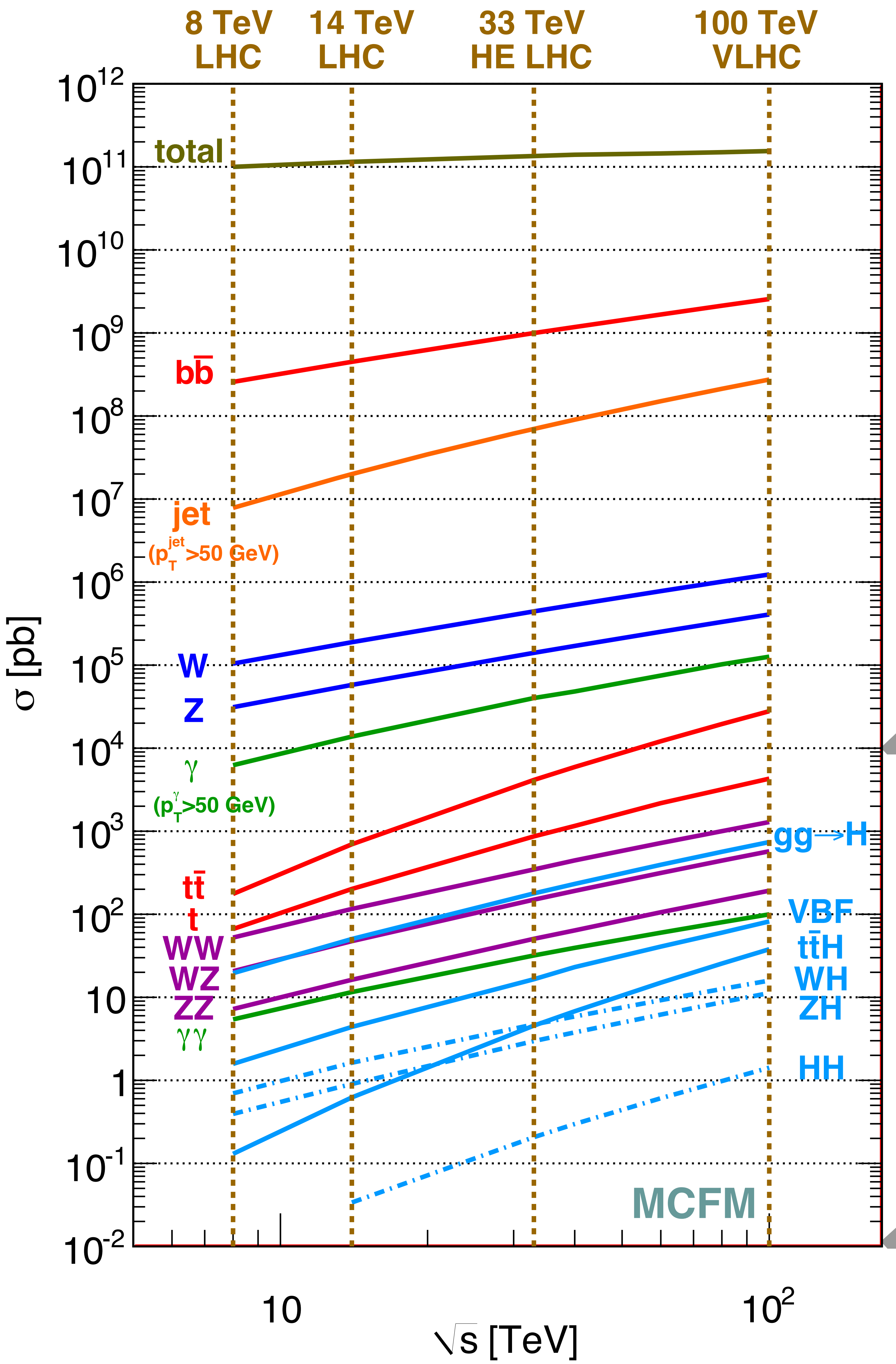

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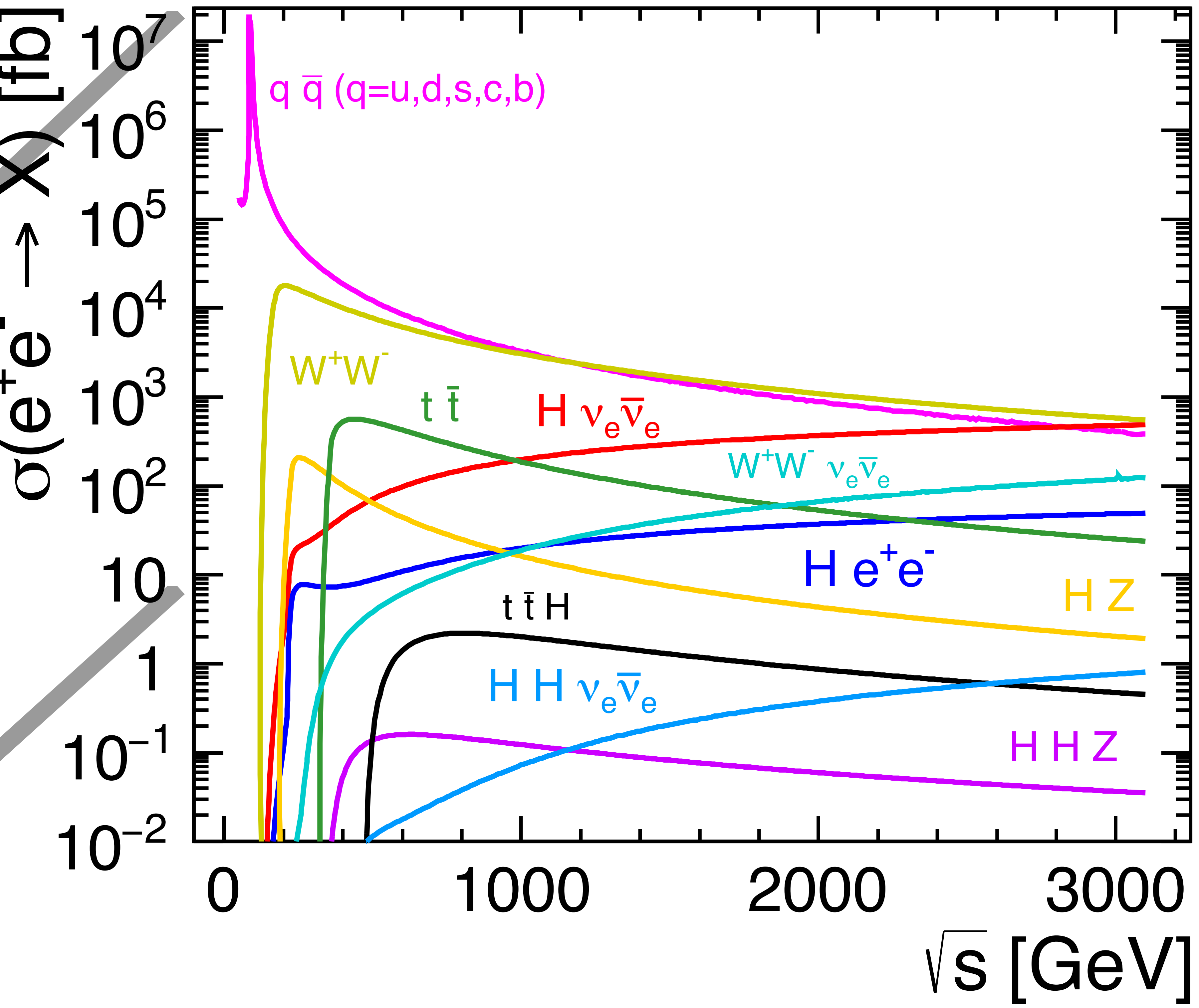

~ 2 orders of magnitude

Electron & Proton Colliders

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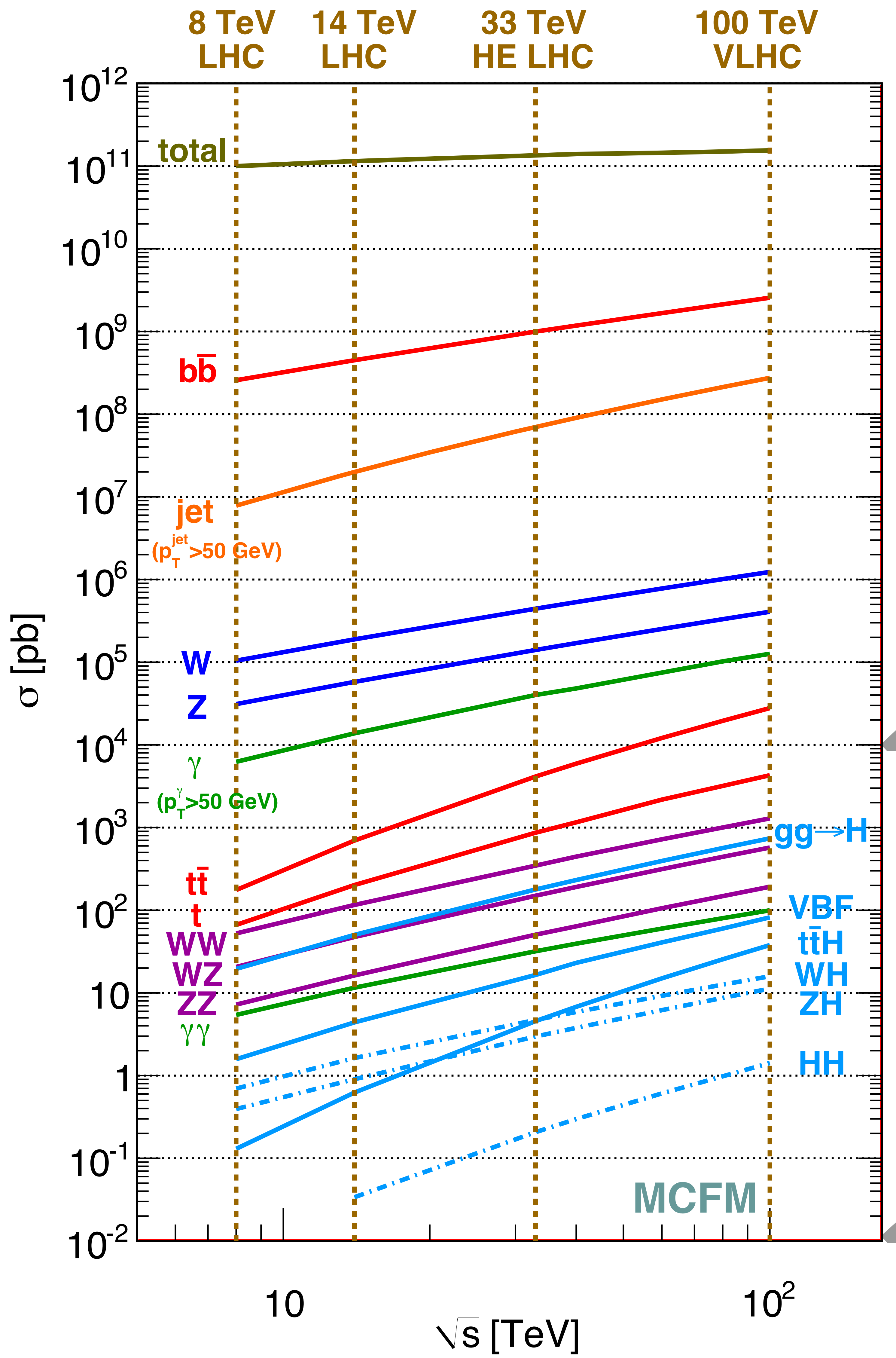

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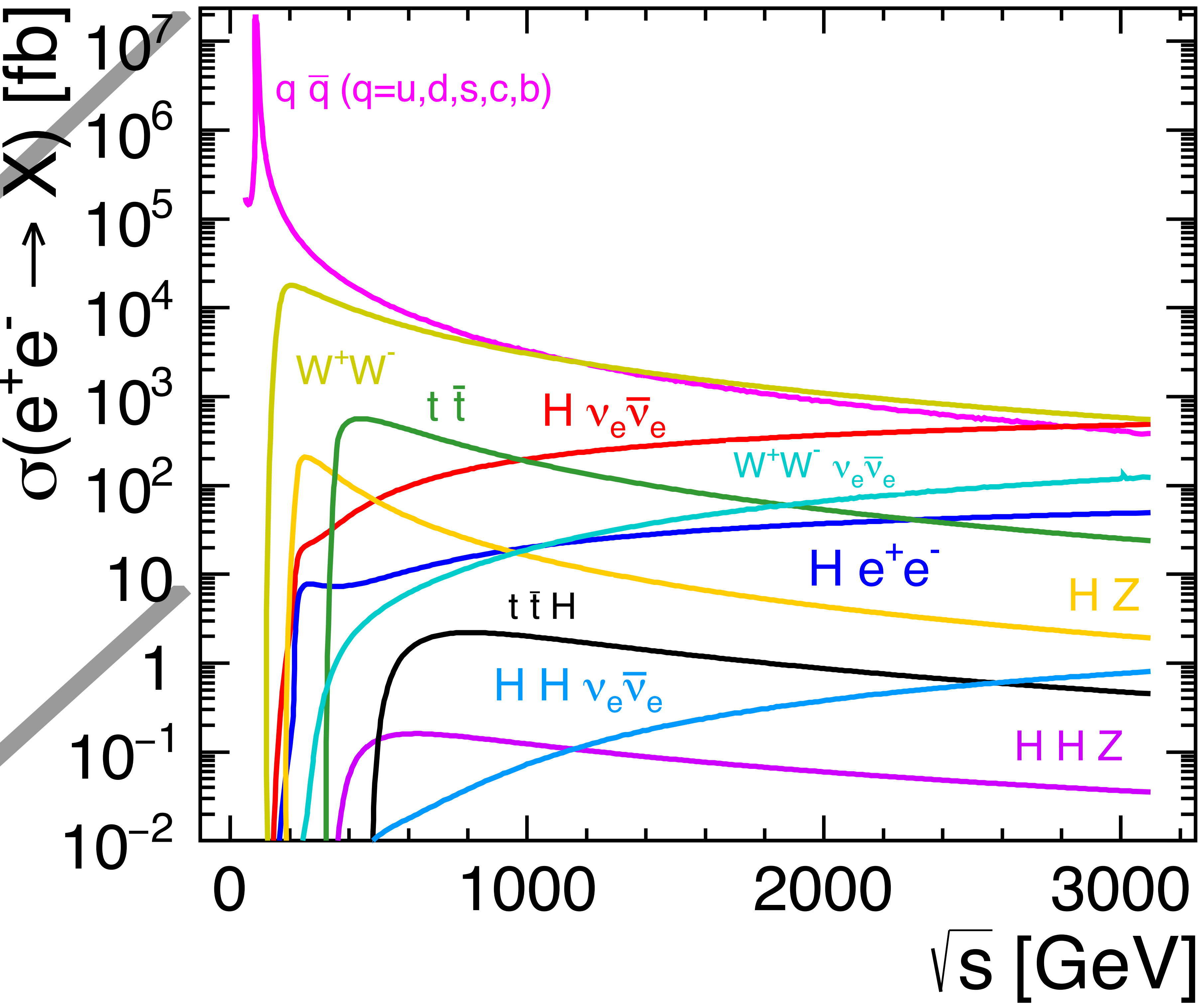


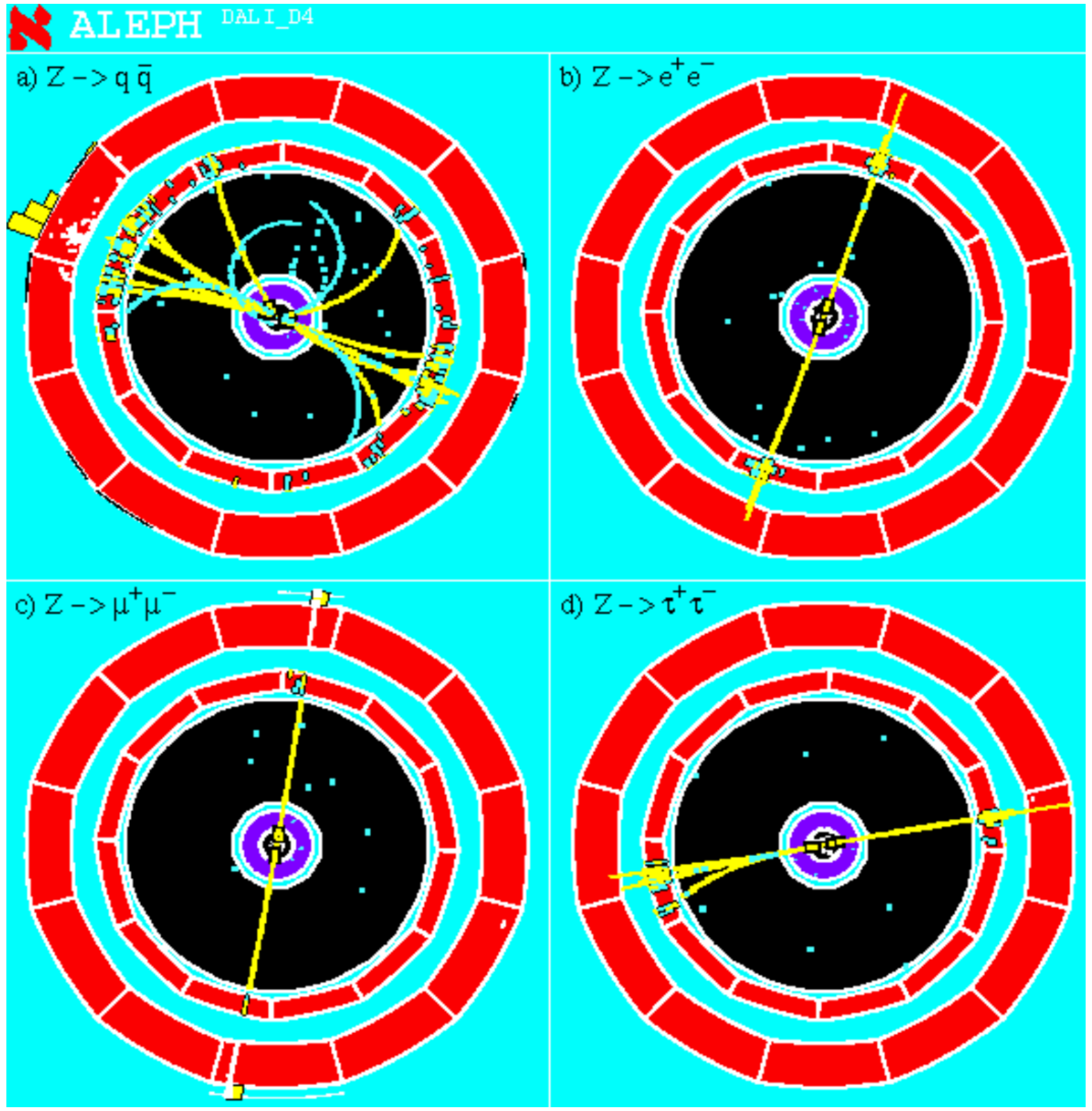
~ 2 orders of magnitude

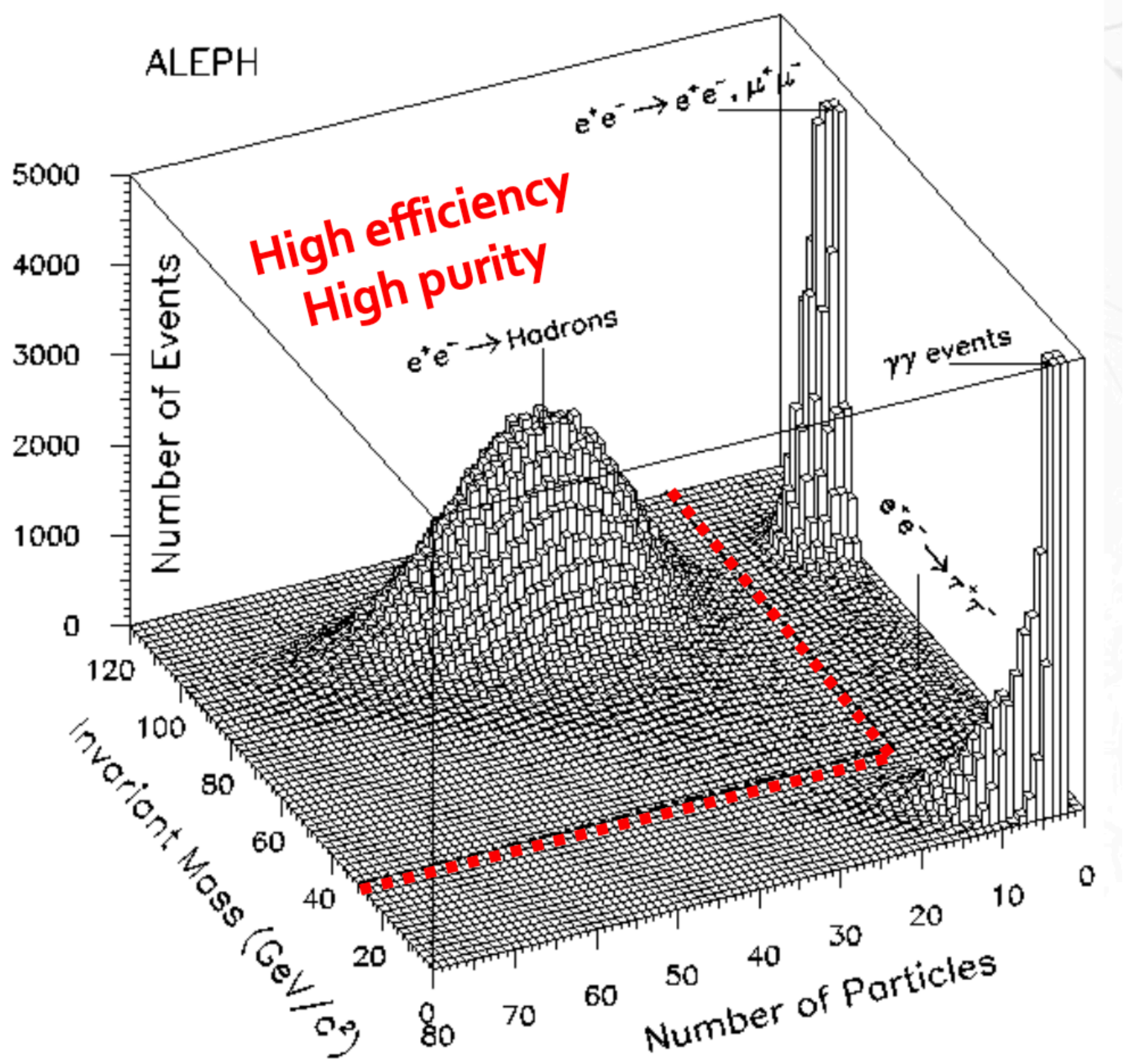
- Significantly higher signal yields in pp (2 - 3 orders of magnitude), but also ~ 9 orders of magnitude higher physics backgrounds

Experimental Conditions at e^+e^- Colliders

Looking back at LEP

- LEP - the first occupant of the tunnel we now know as the “LHC tunnel”: 1989 - 2000, 91 - 209 GeV
  - Fantastically clean events: No pile-up, no underlying events -> All you see is the physics!
  - Signal and physics background cross sections comparable: no trigger challenge!

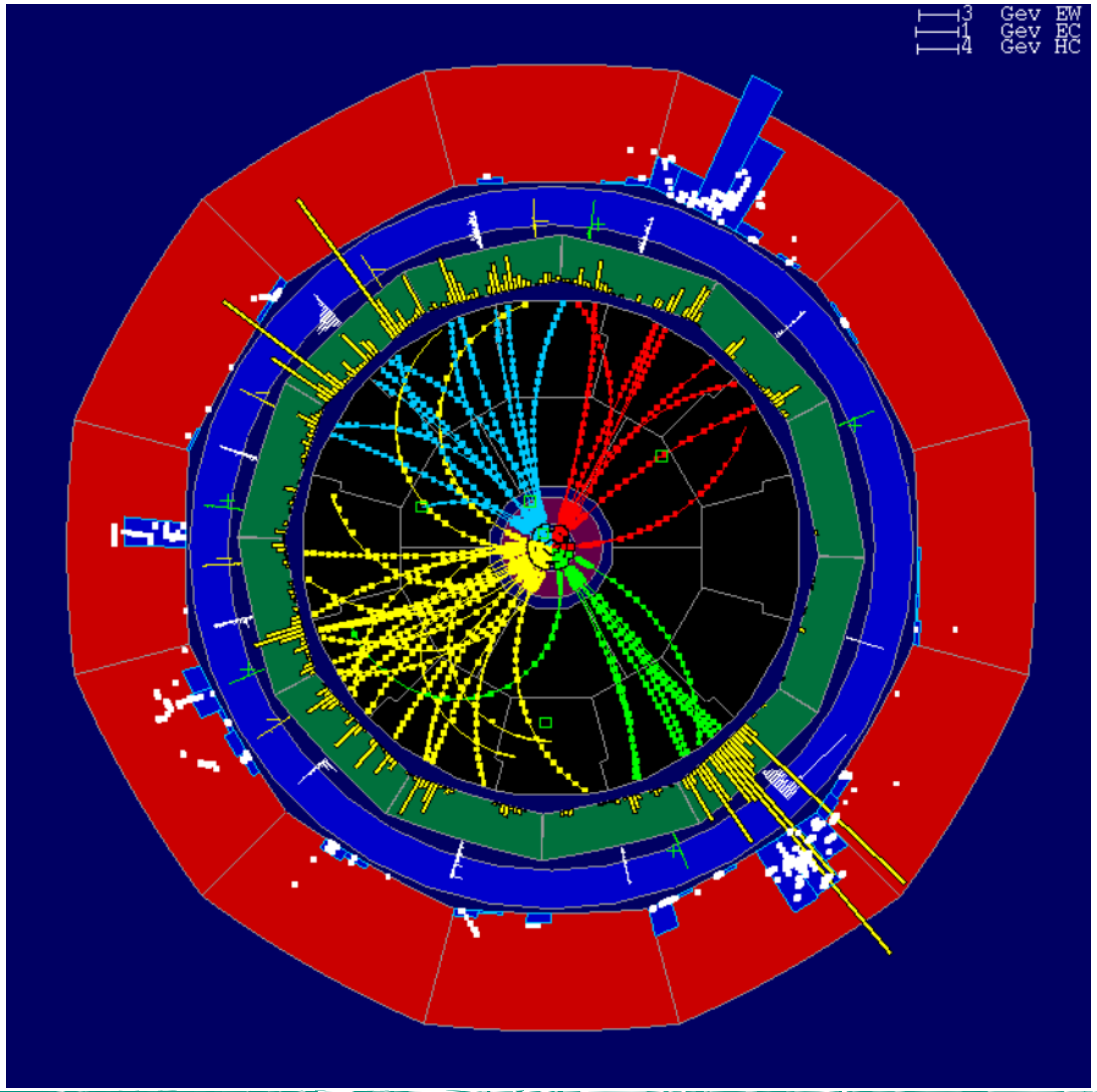




Experimental Conditions at e+e- Colliders

Looking back at LEP

- A key feature: Excellent knowledge of initial state, given by √s -> Energy conservation means the four-vector of the final state is known.
  - Can be exploited in event reconstruction - kinematic fitting, et. al., used to eliminate jet energy scale uncertainties in WW events, for example



Here:

$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$

accurate measurements of the jet directions, together with event constraints provide precise jet energies and di-jet masses (W mass)

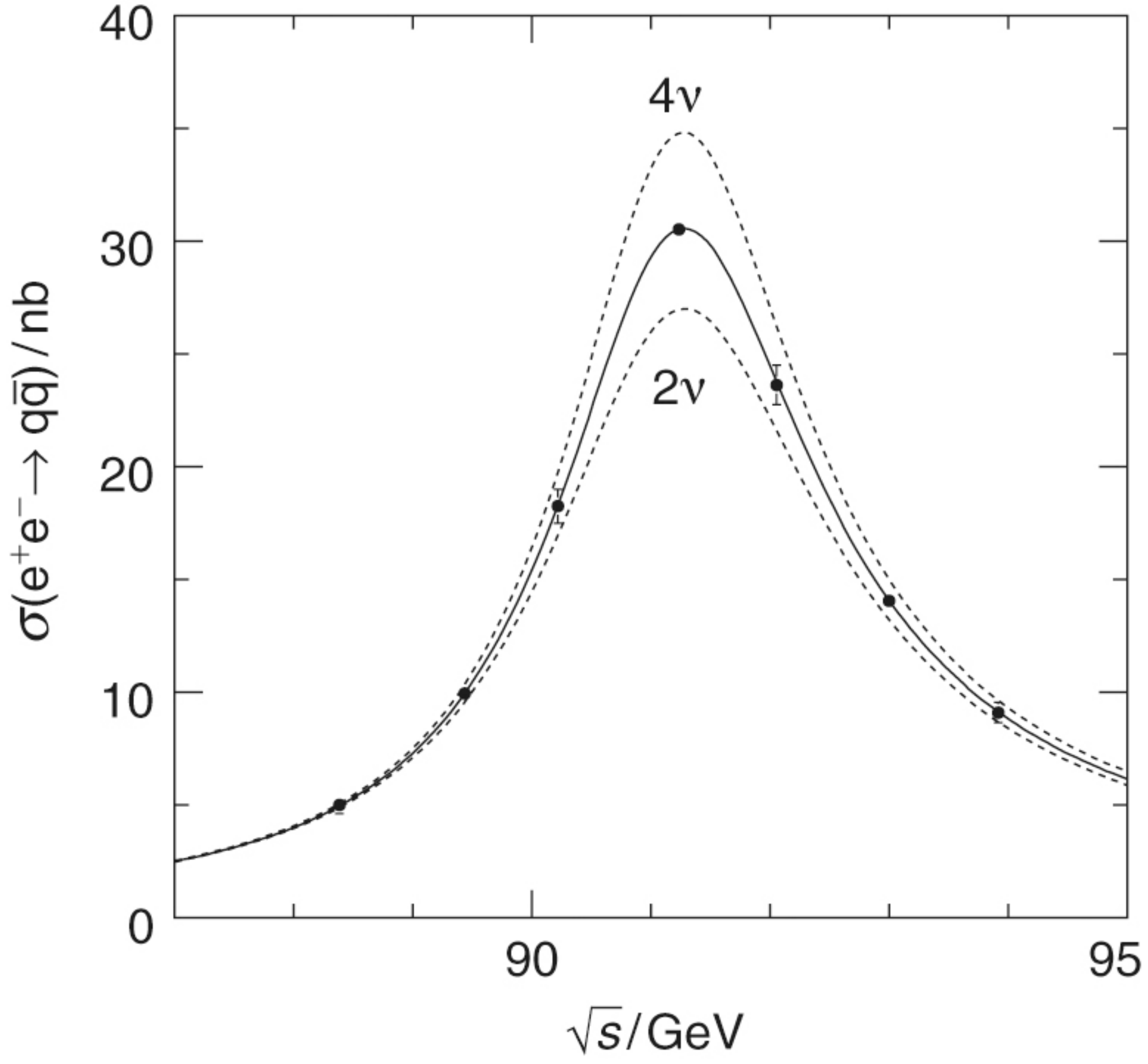
LEP Legacy

A few examples

Karlsruhe Institute of Technology

- An era of precision measurements - still dominating many parameters 25 years later…

A result directly after first LEP data: The number of light neutrinos



After 5 years at LEP1: per-mille level precision

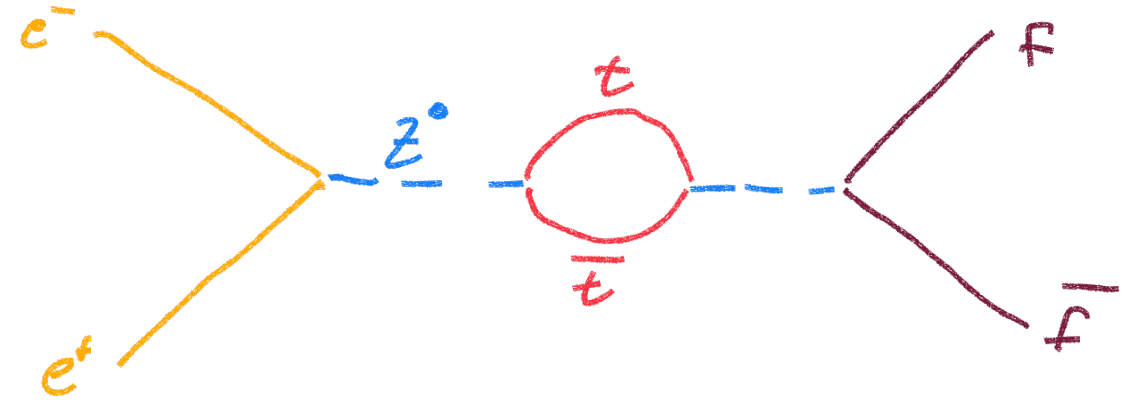
$N_\nu = 2.984 \pm 0.008$

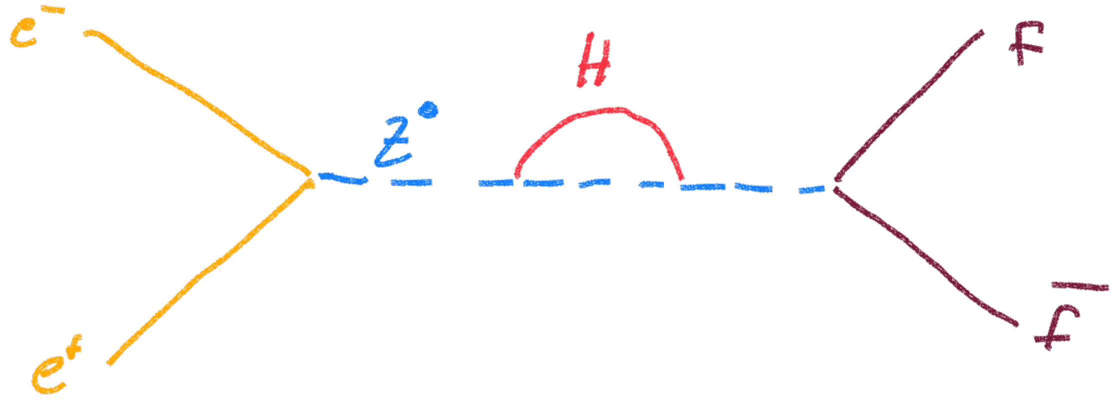
$\Gamma_Z = 2495.2 \pm 2.3$ MeV

$m_Z = 91187.5 \pm 2.1$ MeV

$\alpha_s = 0.1190 \pm 0.0025$

Precision measurements could predict the top and Higgs masses prior to discovery





The Big Questions

What we know we don't know

- How can the Higgs boson be so light?
- What is the mechanism behind electroweak symmetry breaking?
- What is Dark Matter made out of?
- What drives inflation?
- Why is the universe made out of matter?
- What generates Neutrino masses?

...

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Karlsruhe Institute of Technology

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- Why is the universe made out of matter?
- What generates Neutrino masses?

...

The answers to these questions have to be *outside* of the Standard Model!

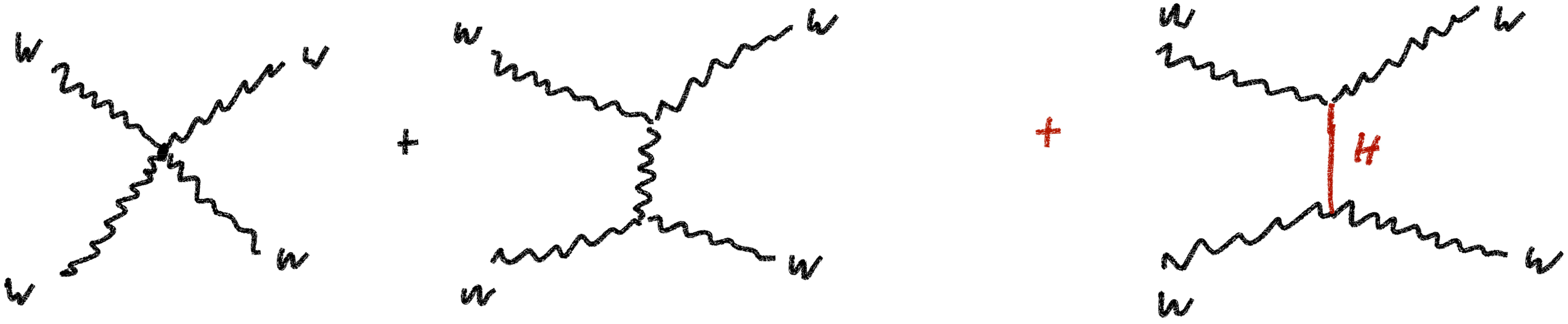
The Way Forward

- What we do know:
  - The Higgs is connected to all particles we know - and is at the center of some of our questions
  - Most hints for new phenomena come from the electroweak + Higgs sector:
    Expect some new particles to be charged under electroweak interactions
- What we don't know:
  - The energy scale of new particles / phenomena

No Guarantees

The challenge of making the case for future colliders

- Before the start of LHC: The “no-lose theorem”



No Guarantees

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Karlsruhe Institute of Technology

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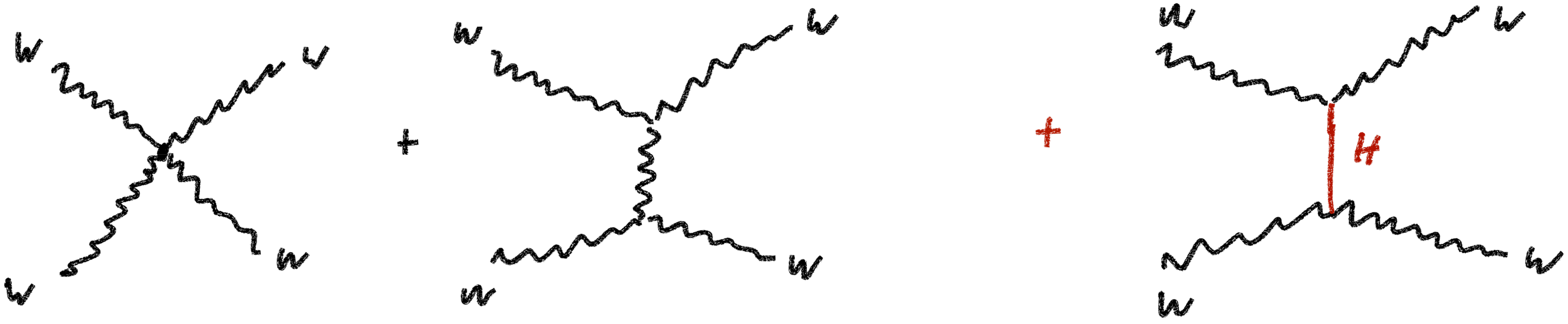

With the “completion” of the standard model:

No certainty - and no clear indication of the energy scale of new phenomena

Frank Simon (frank.simon@kit.edu)
Institute for Data Processing and Electronics

Asking for Directions

Promising Areas for a New Precision Program

- Study with highest precision what has not yet been scrutinized in depth:
  The Higgs Boson, the top quark

- Revisit areas of previous precision exploits with a whole new level of scrutiny:
  The Z pole: Electroweak, QCD, flavour; the W boson

- Explore the unknown:
  Search for new phenomena at high energies,
  and with extreme luminosity / sensitivity at lower energies

Higgs-Electroweak-Top Factory Physics Menu

A new precision program

The Higgs Boson

model-independent study
of all accessible couplings

Higgs-Electroweak-Top Factory Physics Menu

A new precision program

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

The Higgs Boson

model-independent study of all accessible couplings

Higgs-Electroweak-Top Factory Physics Menu

A new precision program

Karlsruhe Institute of Technology

Electroweak Precision

push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

The Higgs Boson

model-independent study of all accessible couplings

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

Higgs-Electroweak-Top Factory Physics Menu

A new precision program

Karlsruhe Institute of Technology

Electroweak Precision

push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

The Higgs Boson

model-independent study of all accessible couplings

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

Flavour Physics

use extremely large data sets to explore, resolve and understand the puzzles in the flavour sector

Higgs-Electroweak-Top Factory Physics Menu

A new precision program

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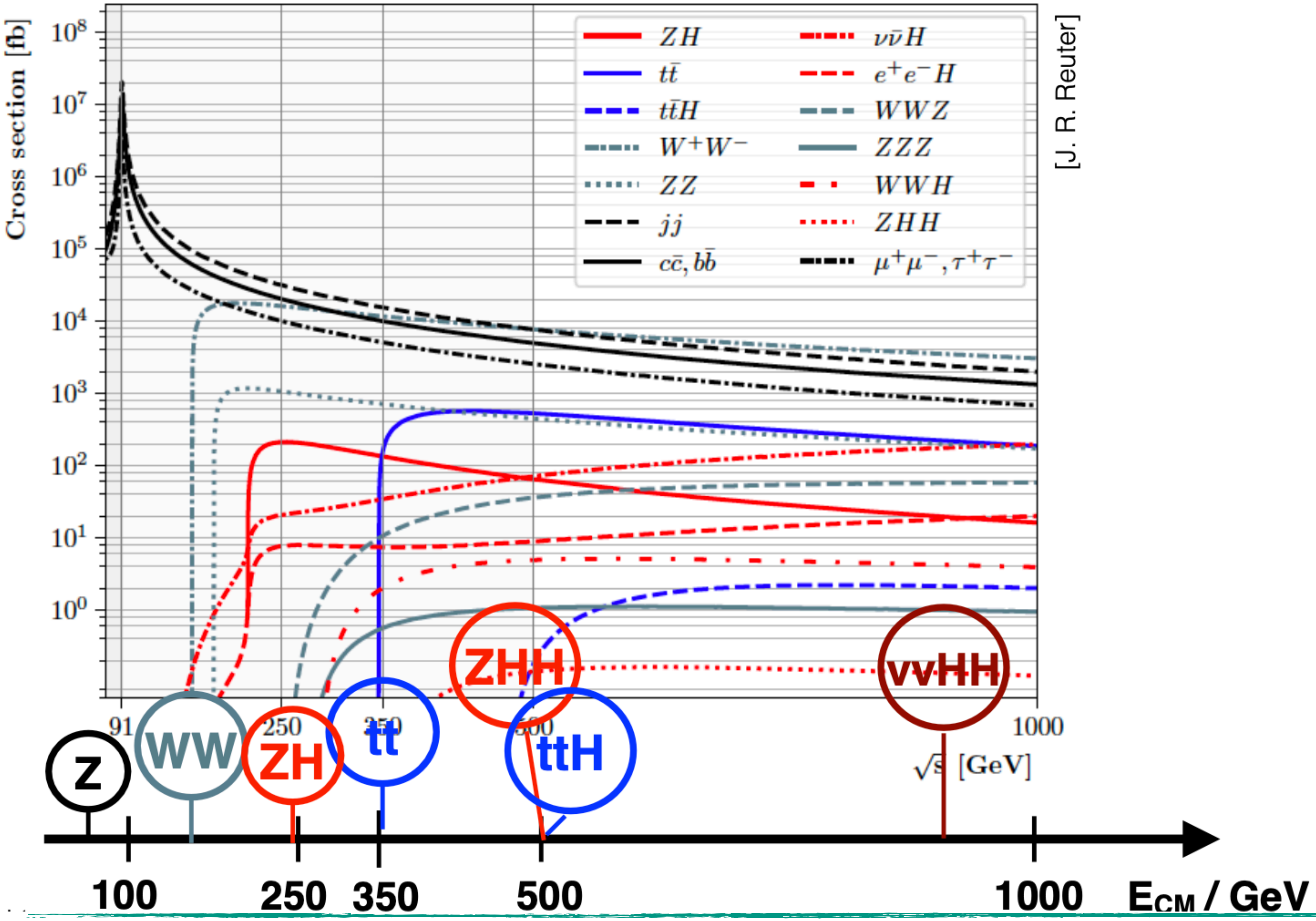
New Particles

searches for weakly coupled new particles with high luminosity / high energy in a clean environment

Perspectives of Energy

Bringing together physics goals and collider energy



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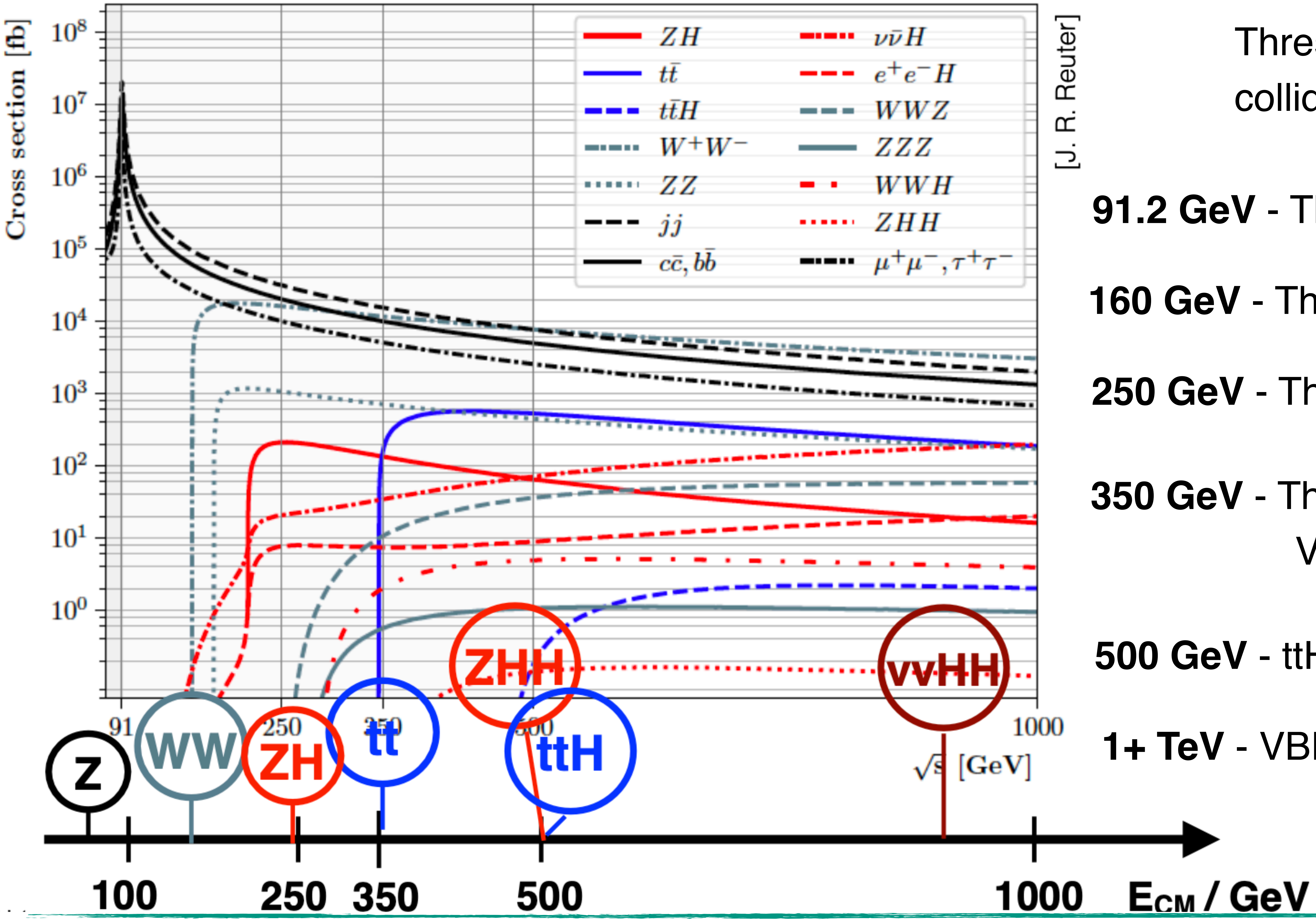

Thresholds and cross sections set collider energy targets:

91.2 GeV - The Z pole

160 GeV - The WW threshold

250 GeV - The ZH maximum

350 GeV - The top threshold, VBF Higgs production

500 GeV - ttH, ZHH

1+ TeV - VBF double Higgs

Perspectives of Energy

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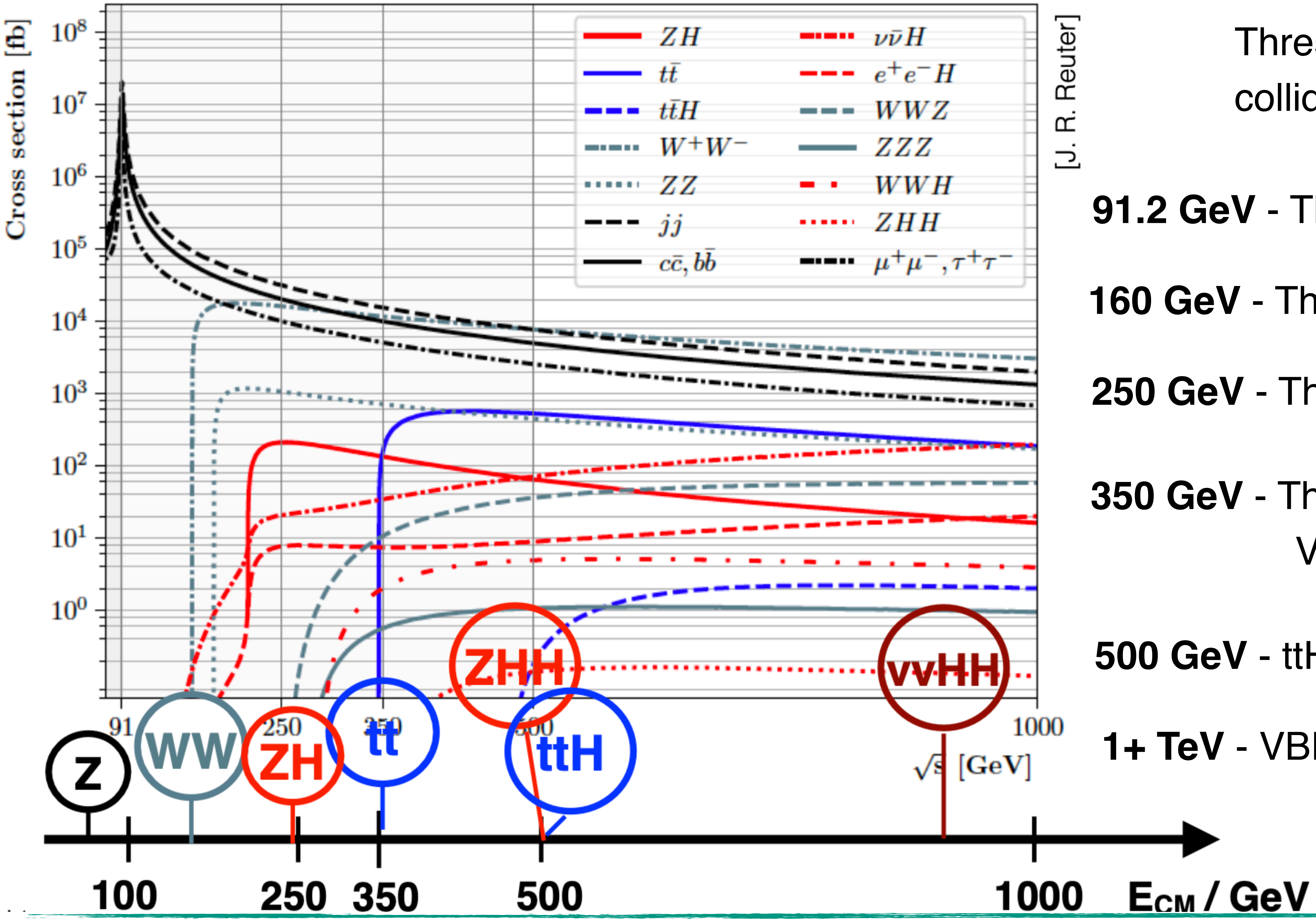


Thresholds and cross sections set collider energy targets:

91.2 GeV - The Z pole — Precision electroweak, Flavour, QCD, …

160 GeV - The WW threshold

250 GeV - The ZH maximum — Higgs properties & couplings

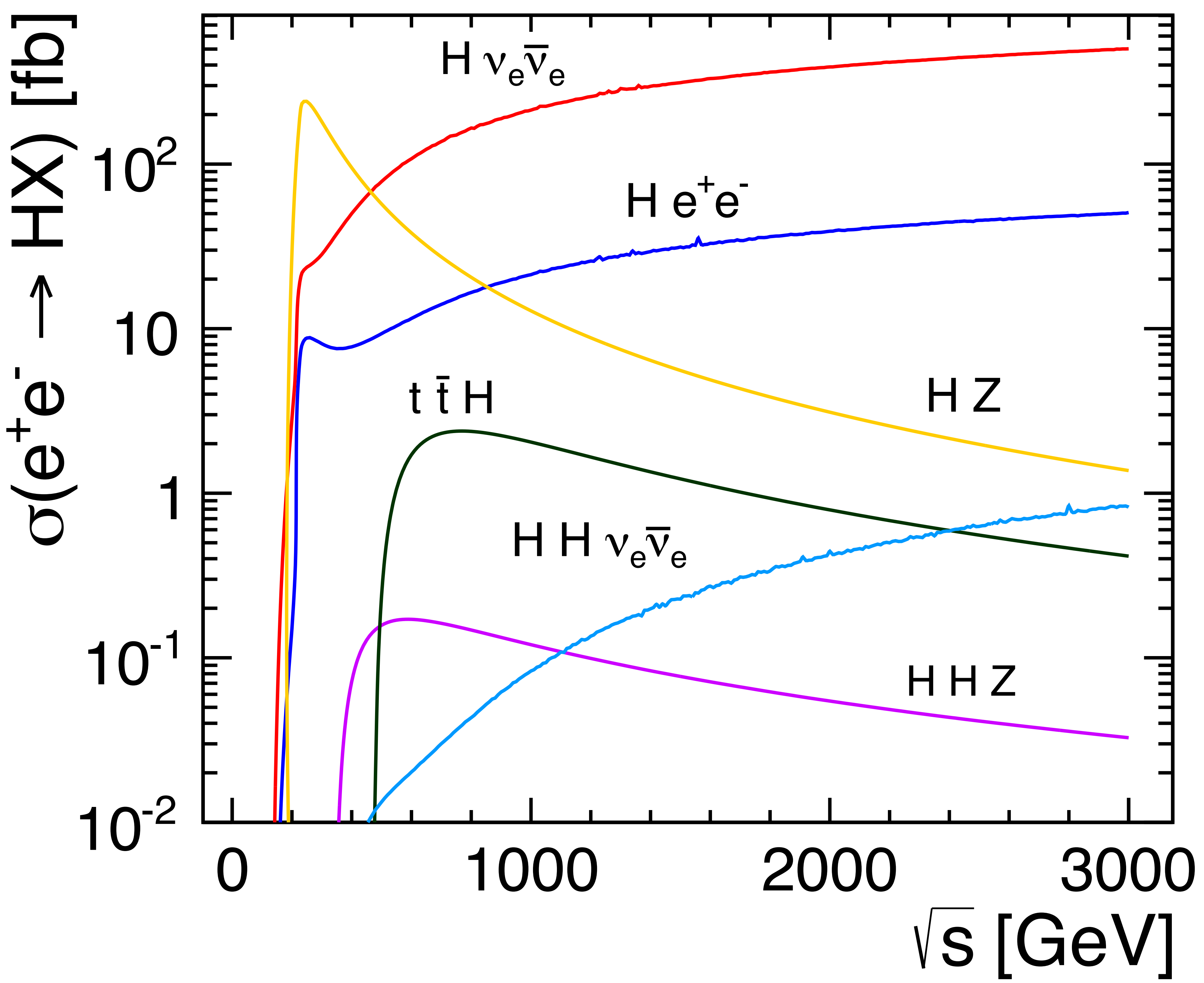
350 GeV - The top threshold, VBF Higgs production — Top properties, Top as probe

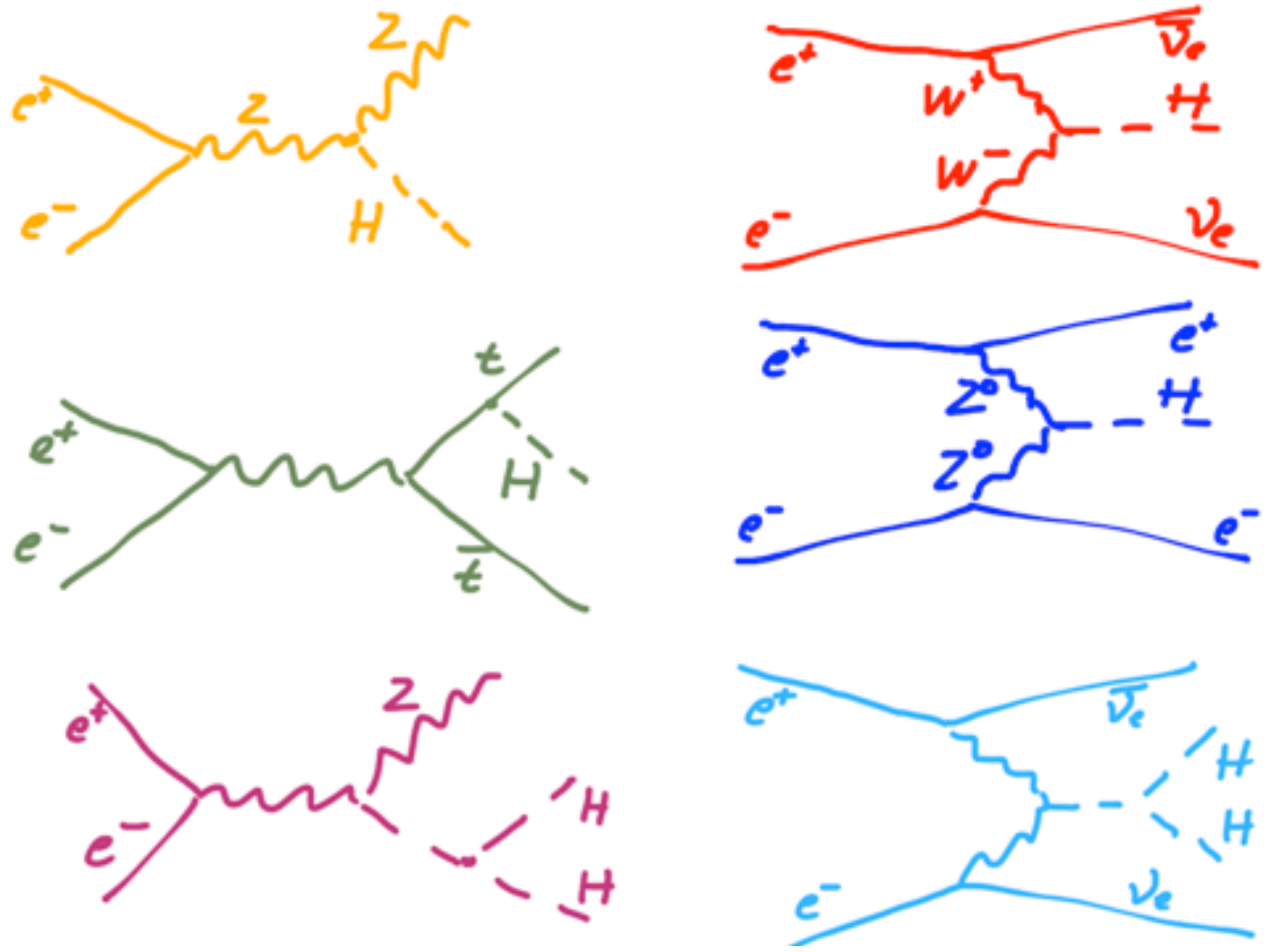
500 GeV - ttH, ZHH — Direct top Yukawa, Higgs selfcoupling

1+ TeV - VBF double Higgs — Search at the energy frontier

Higgs Boson Production in e+e-

A rich field to explore





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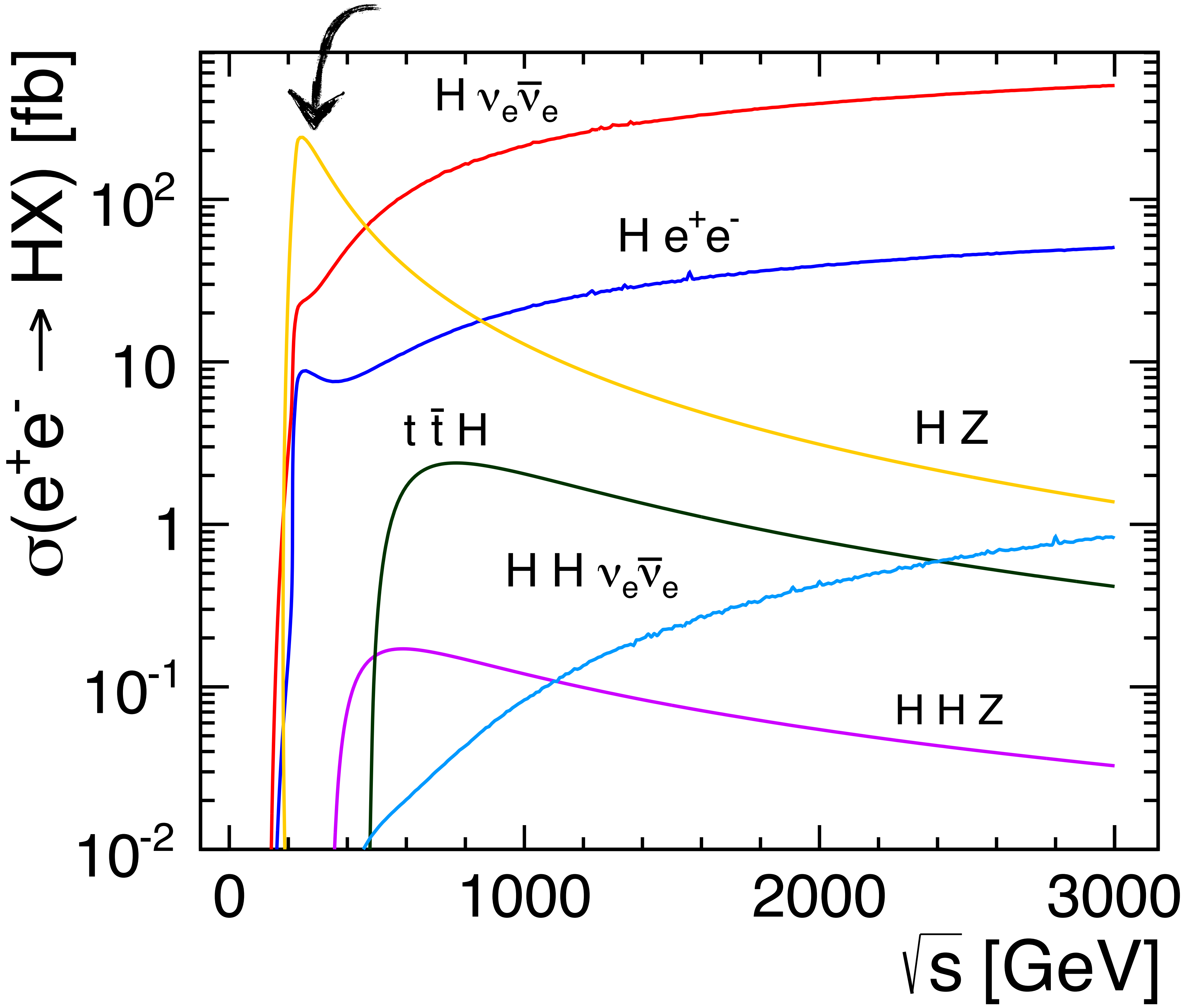

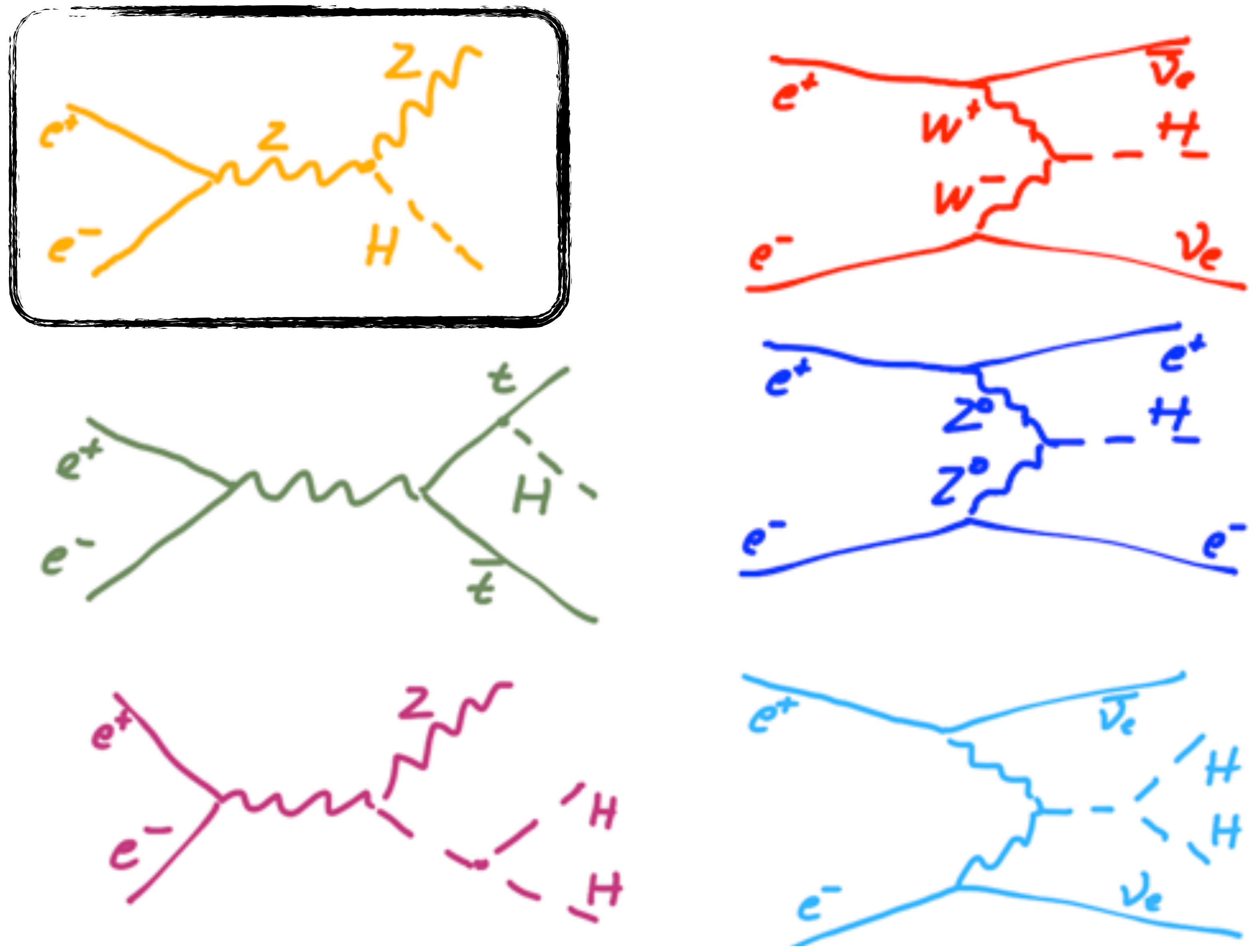

250 GeV:

Maximum of ZH production

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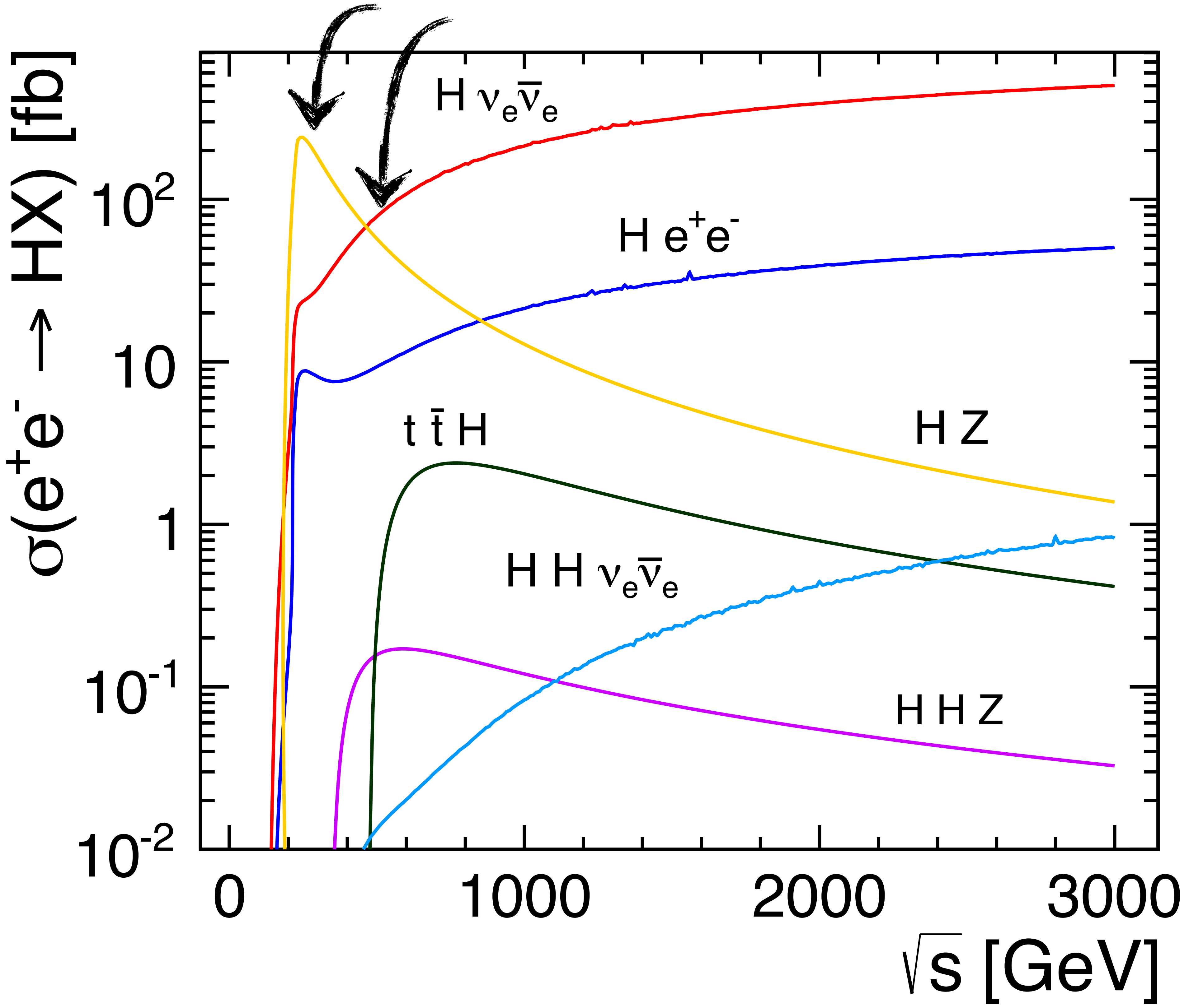

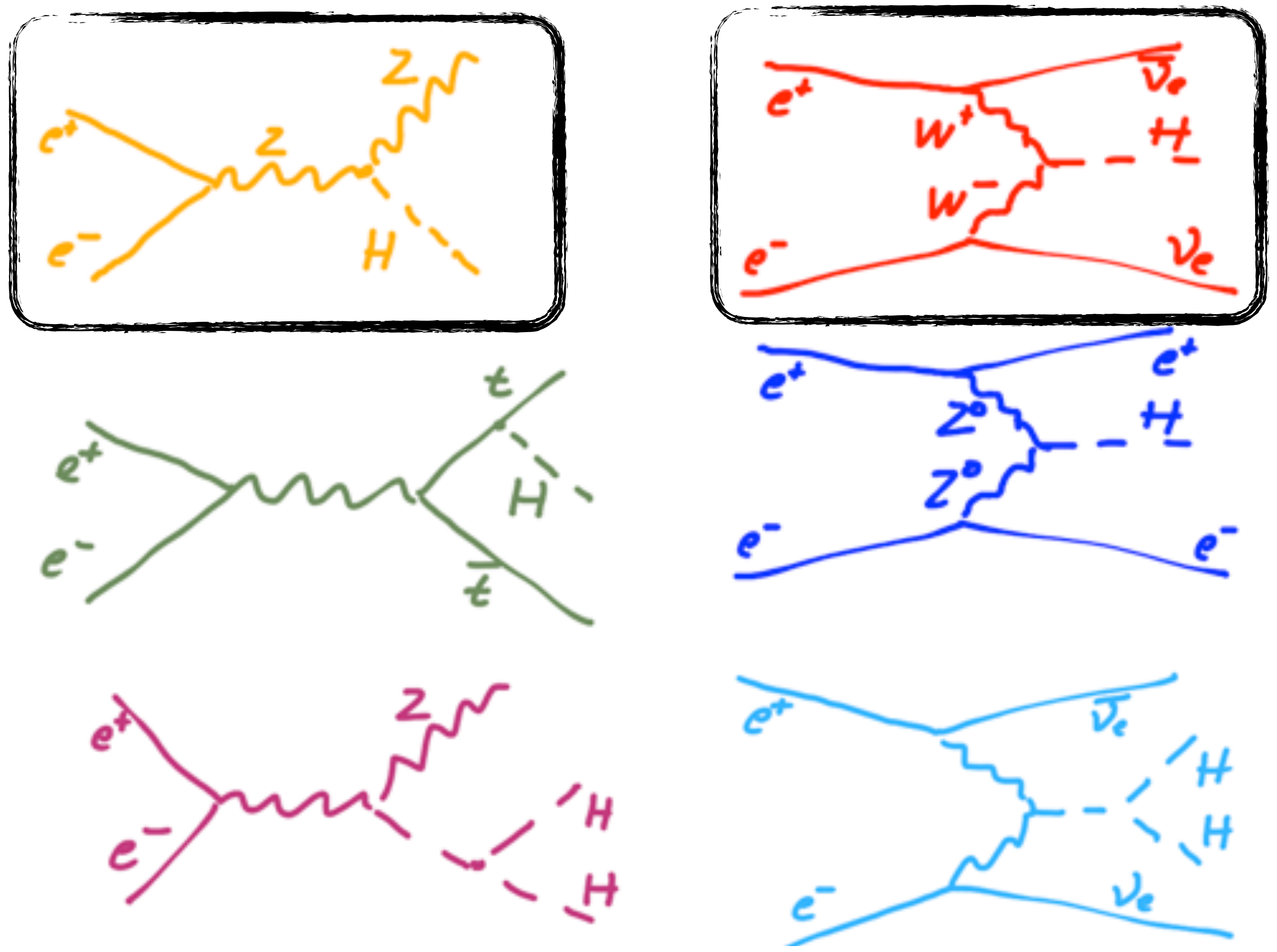

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Maximum of ZH production

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WW fusion kicks in

(and top pair production)

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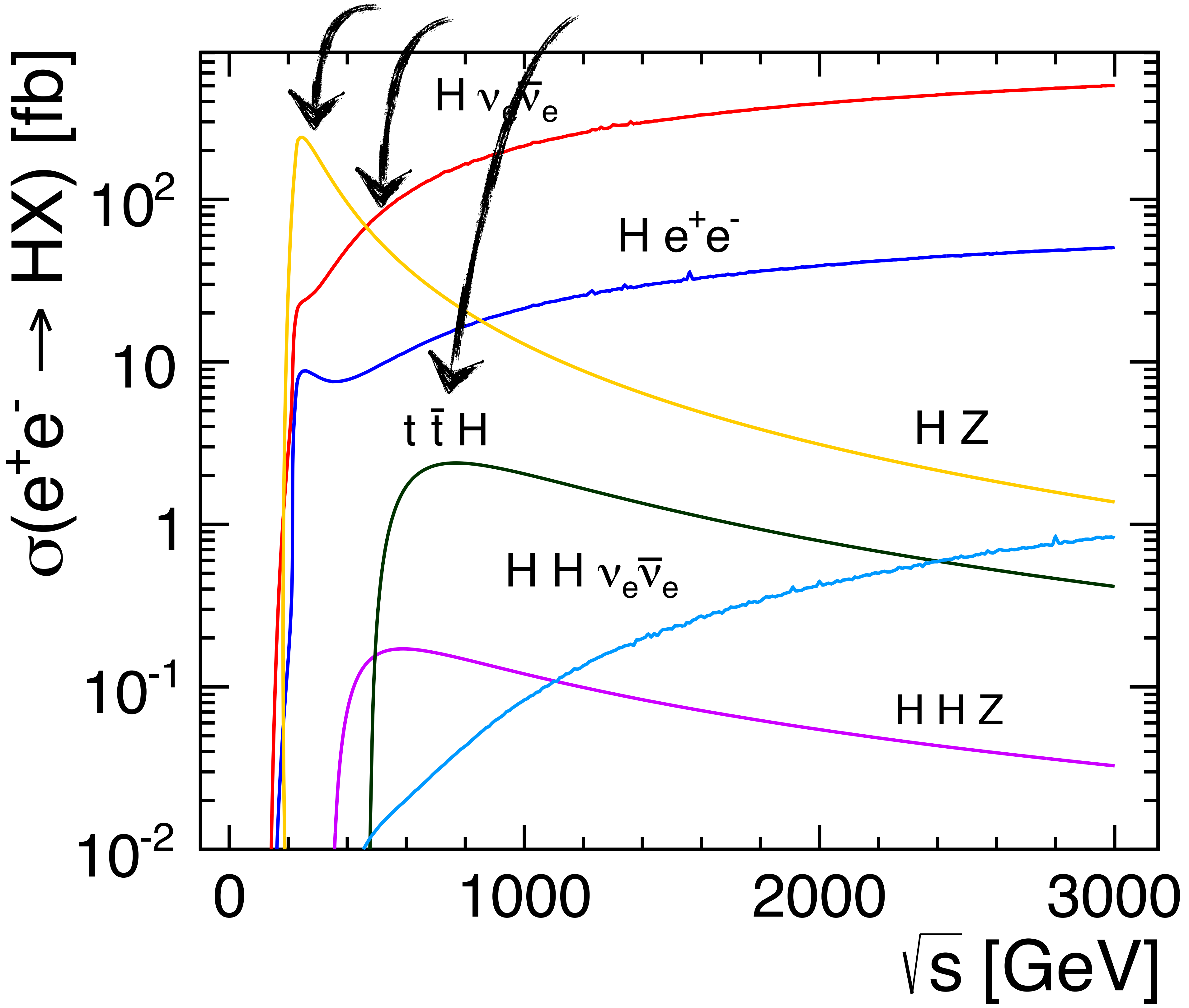

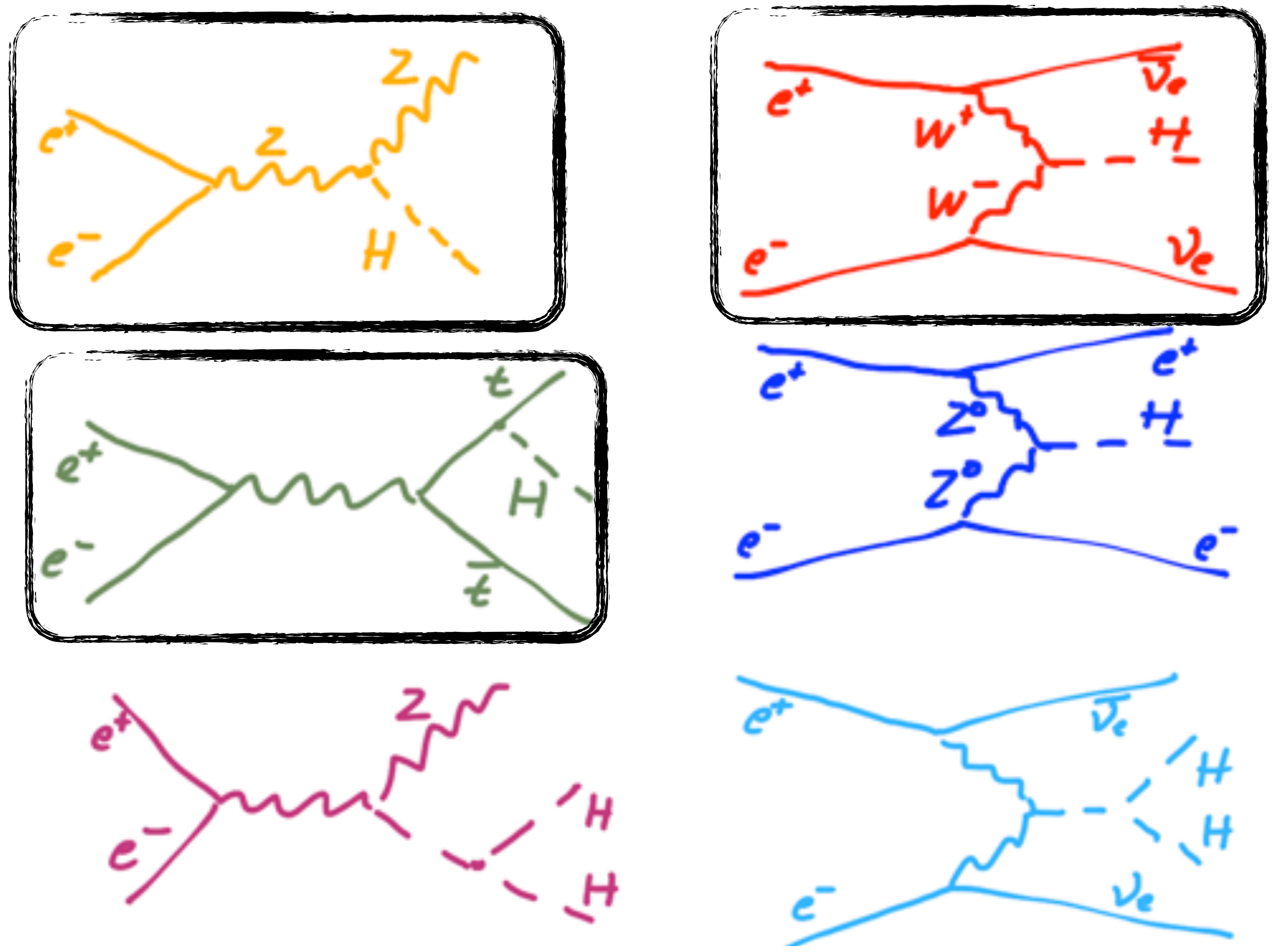

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ttH: direct access to top Yukawa coupling

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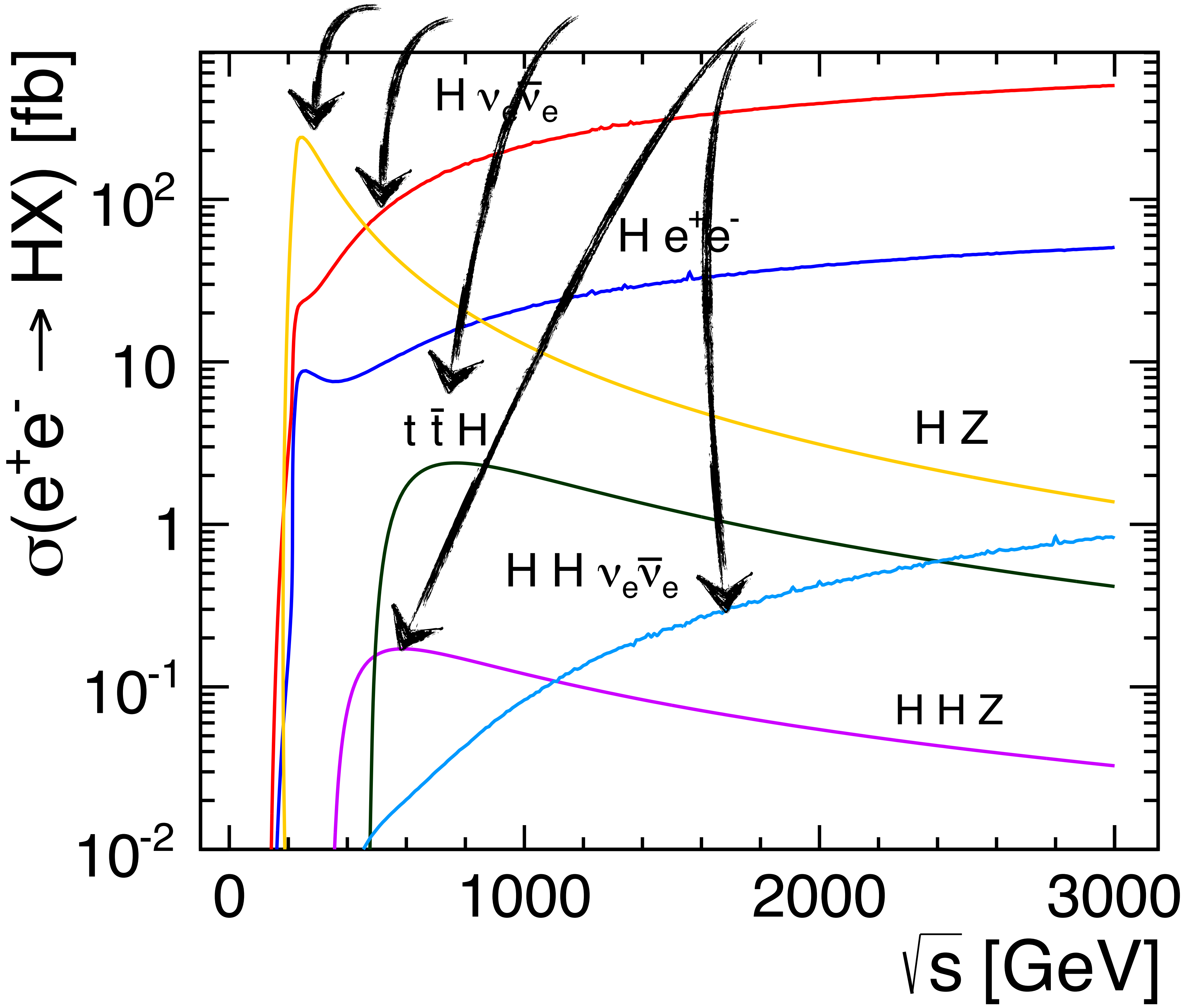

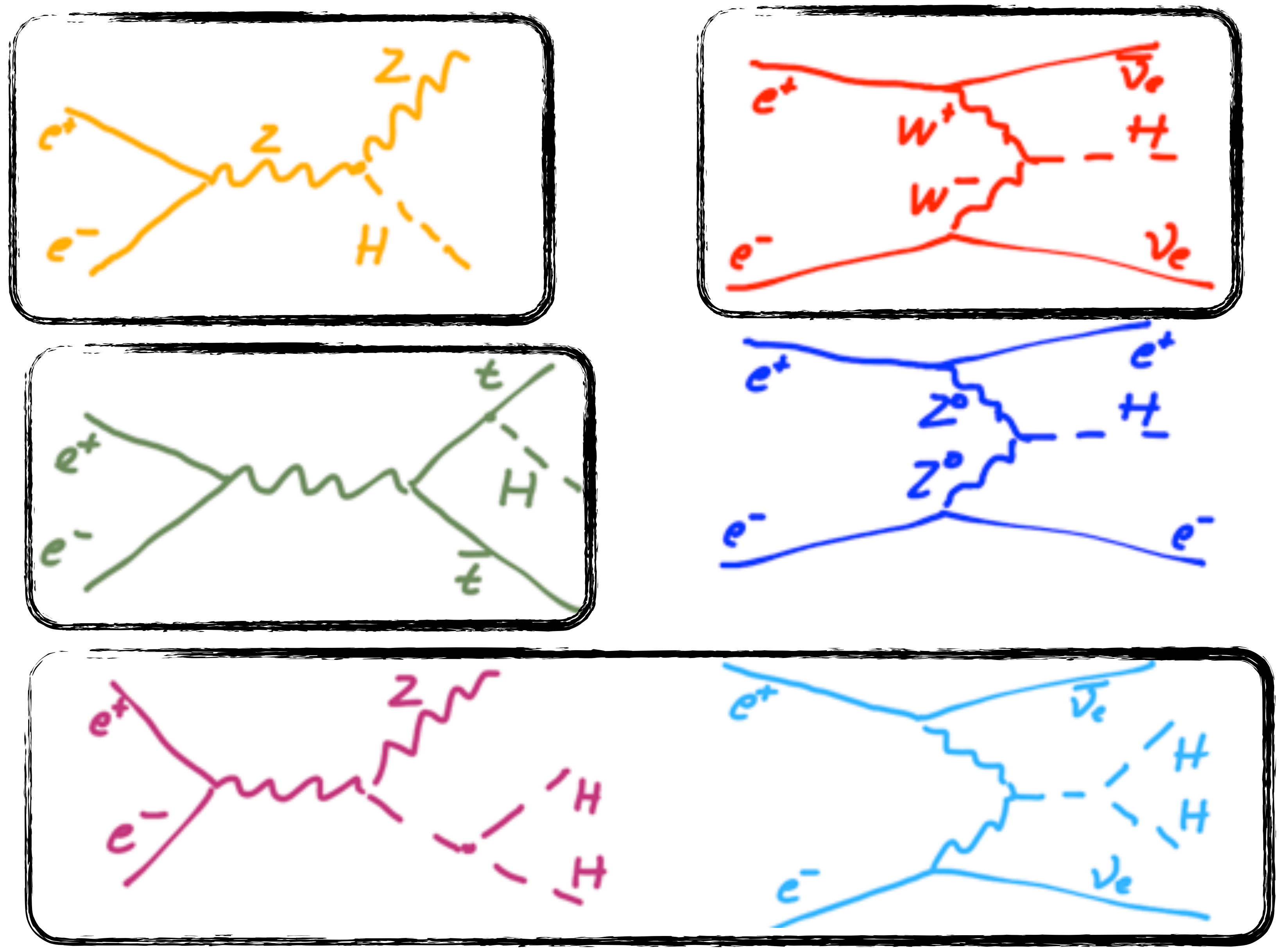

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Higgs self-coupling

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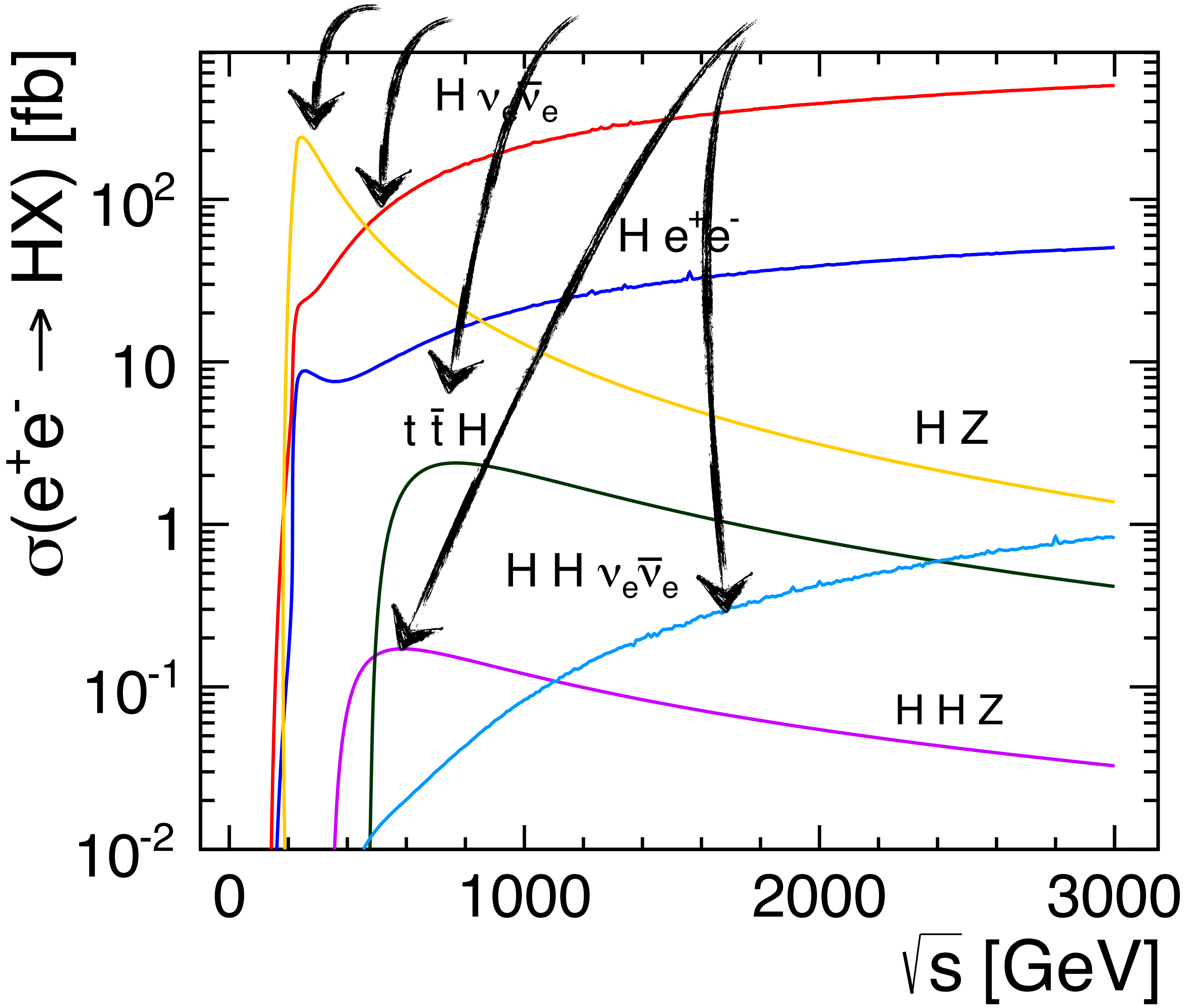

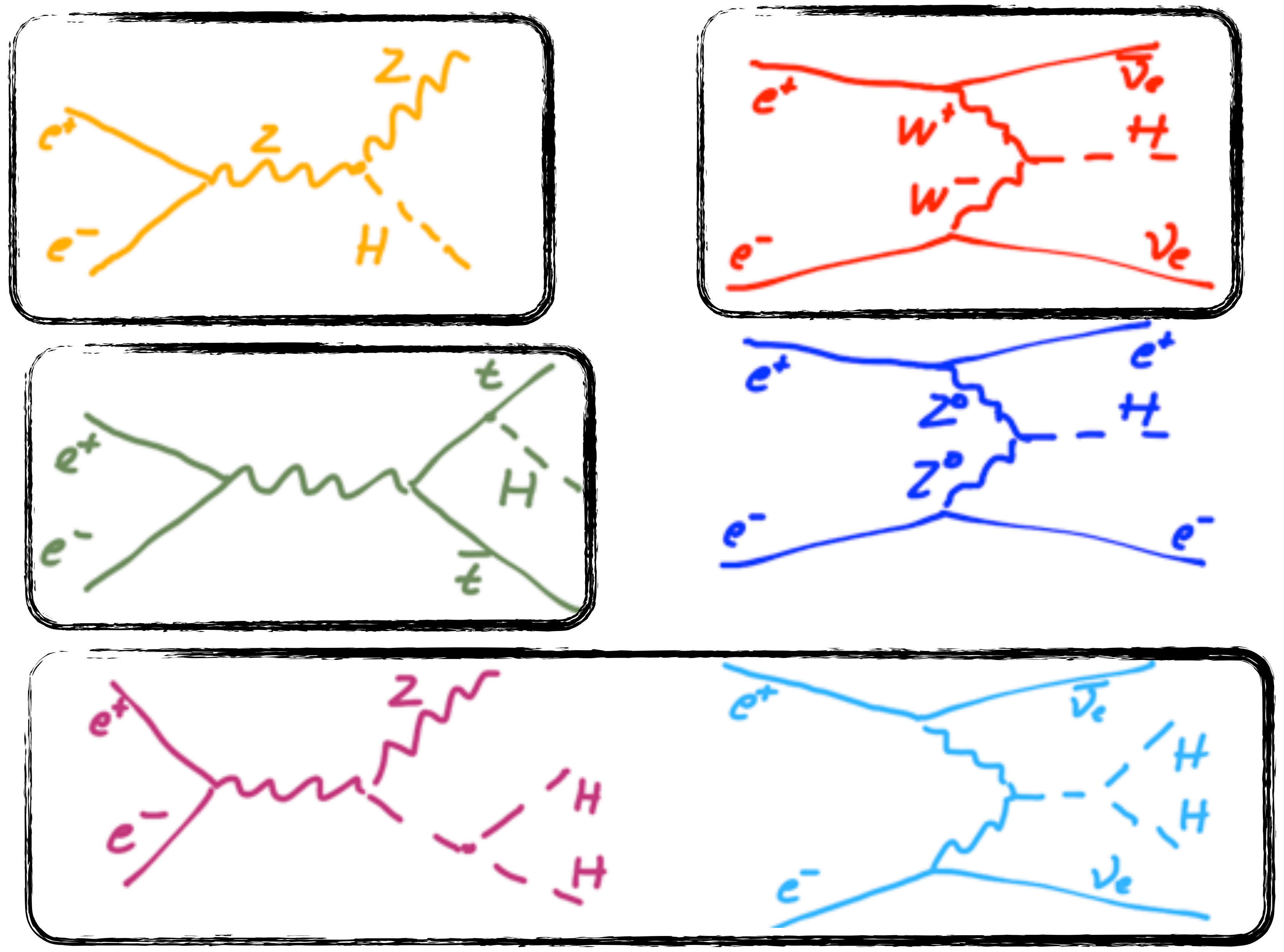

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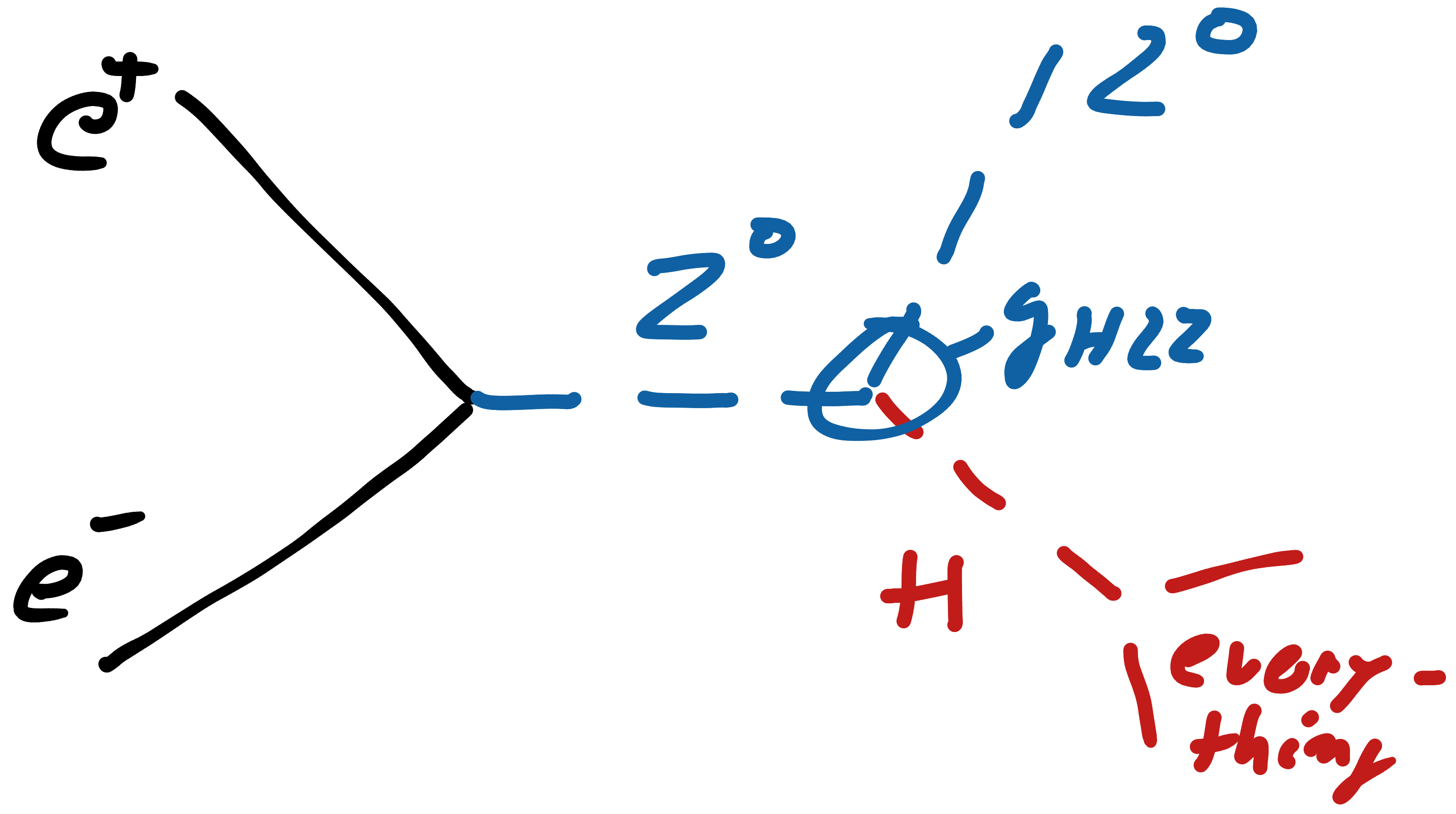
500 GeV; 1+ TeV:
Higgs self-coupling

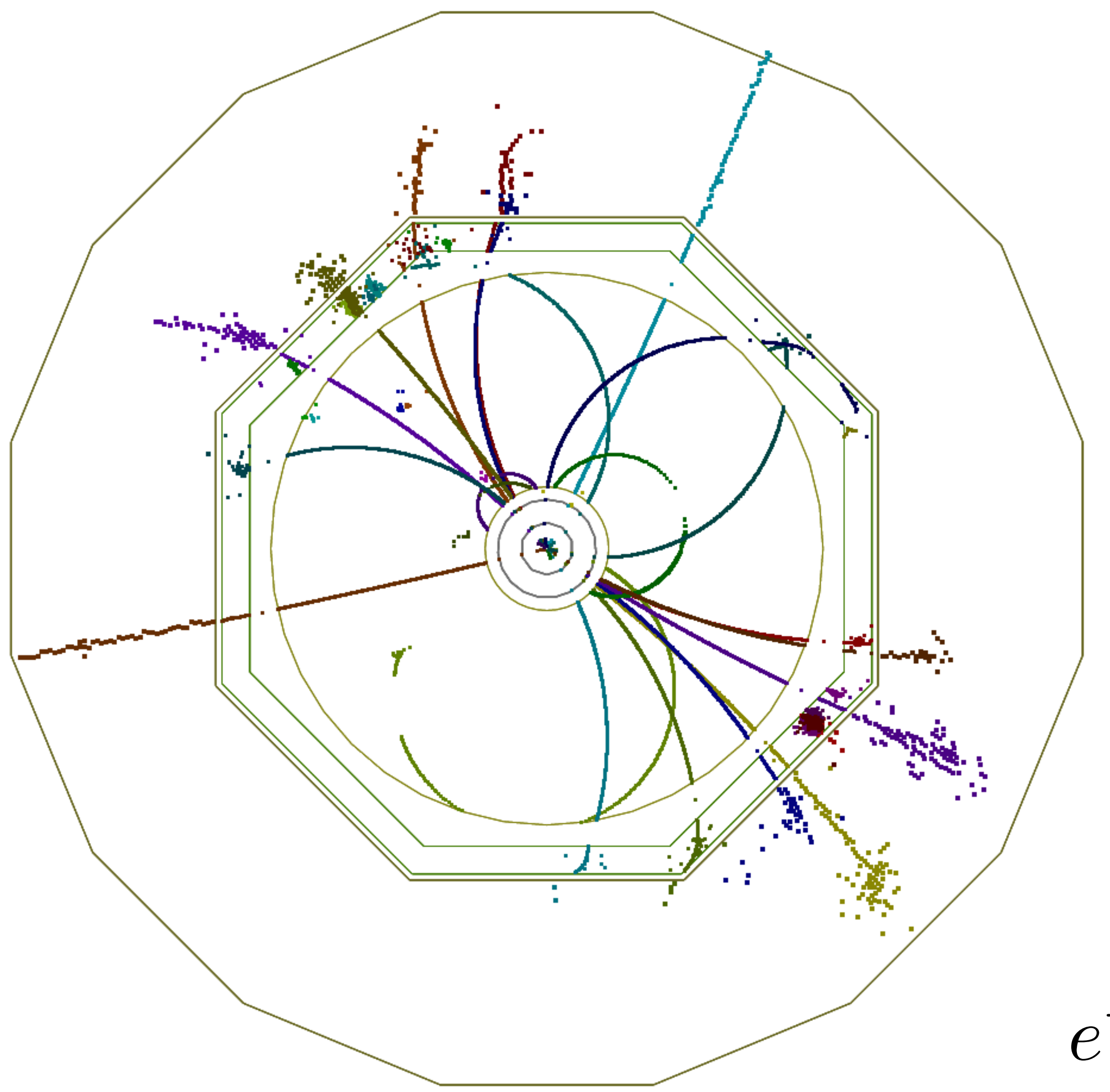
- 240 - 250 GeV: the minimum energy for a Higgs factory
- ~ 350 GeV: Additional production mode, also still access to ZH
- Higher energies: More processes
- 125 GeV, and extreme luminosity: A possibility to measure electron Yukawa coupling

Model Independence: The Pillar of Higgs Physics in e+e-

The ZH Higgsstrahlung process

- What model independence means: Measure the coupling of the Higgs Bosons to elementary particles 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





ILD, 250 GeV

$e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$

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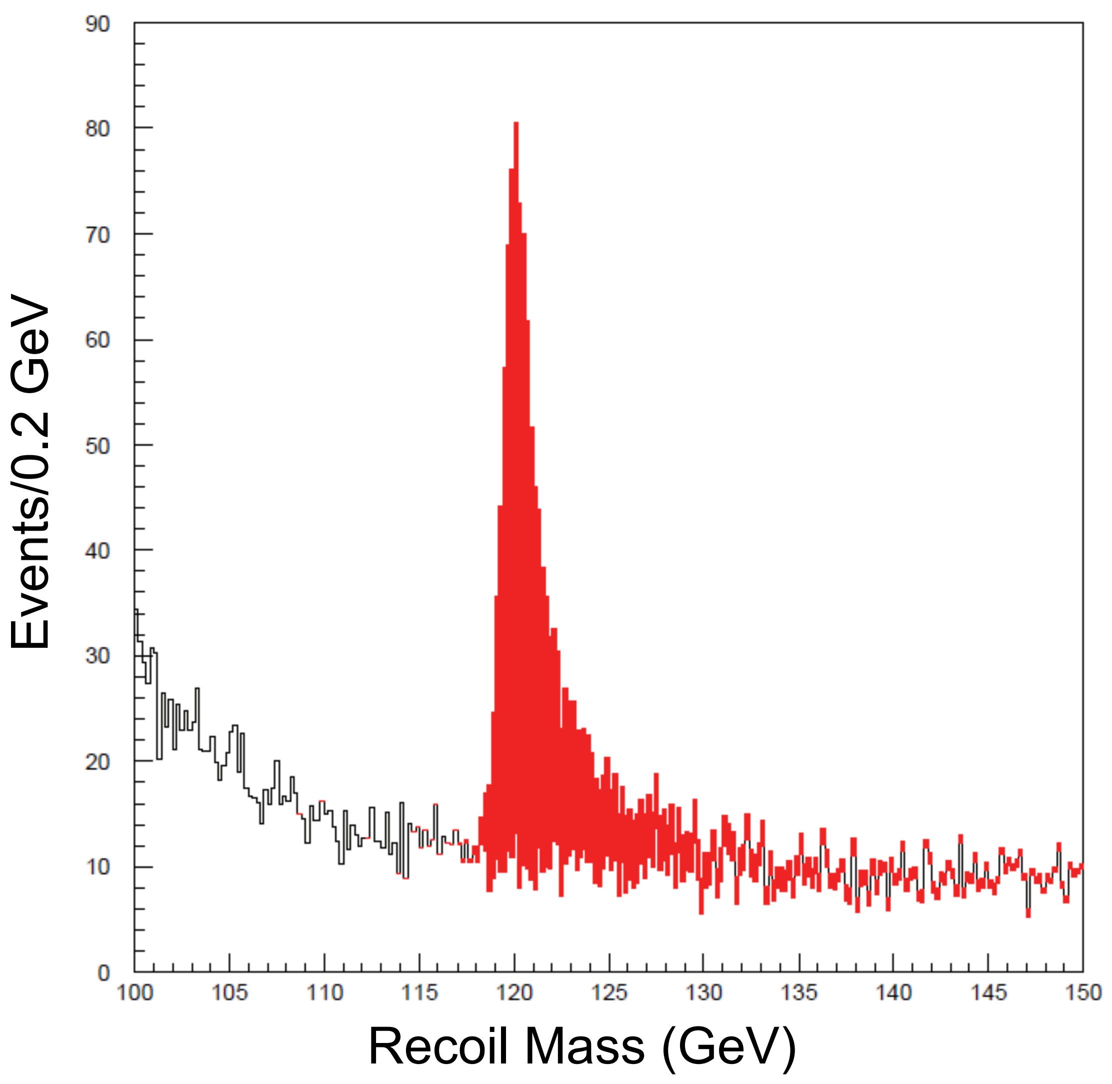
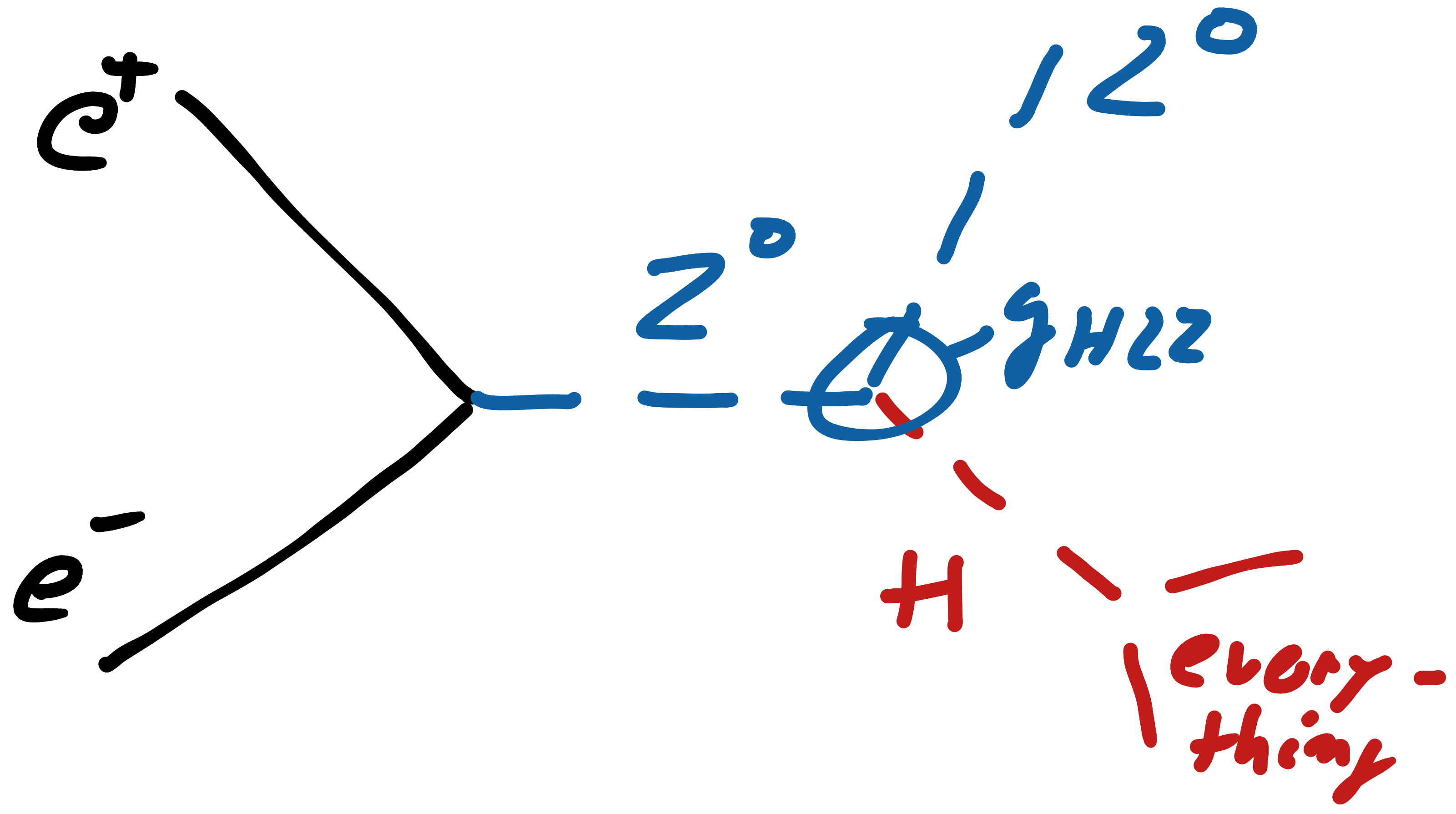
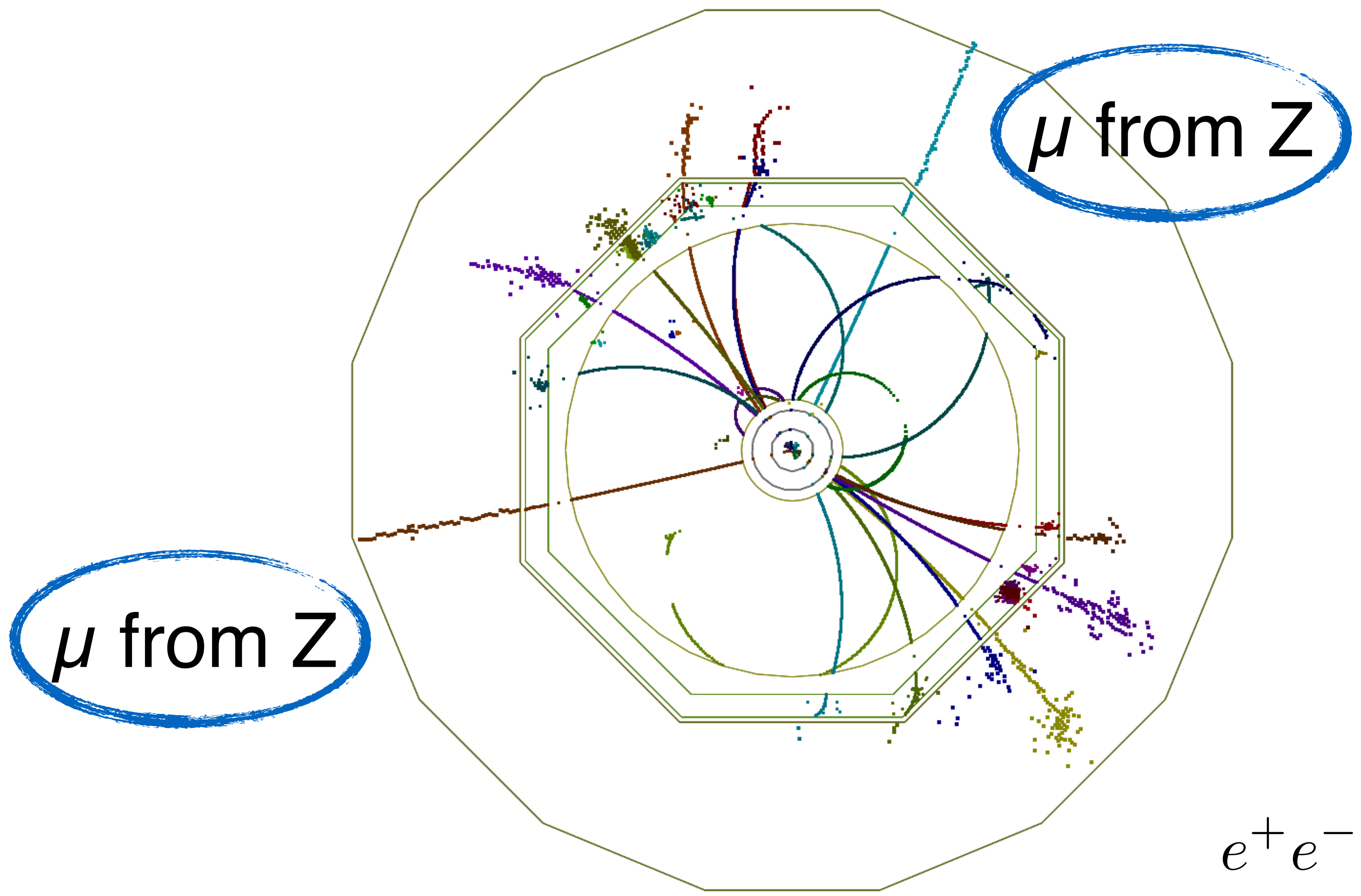
recoil mass:
measure only the Z!

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







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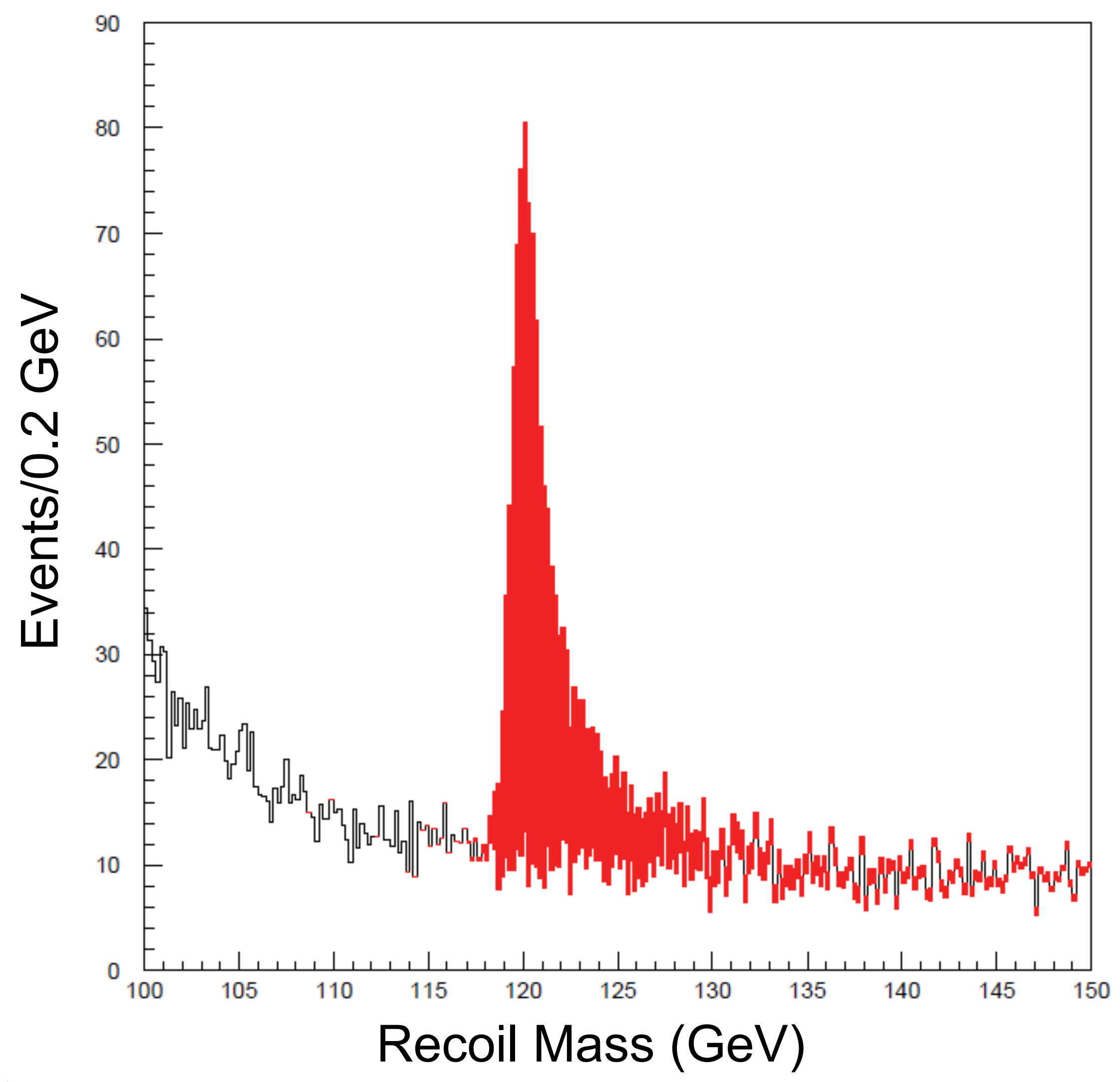

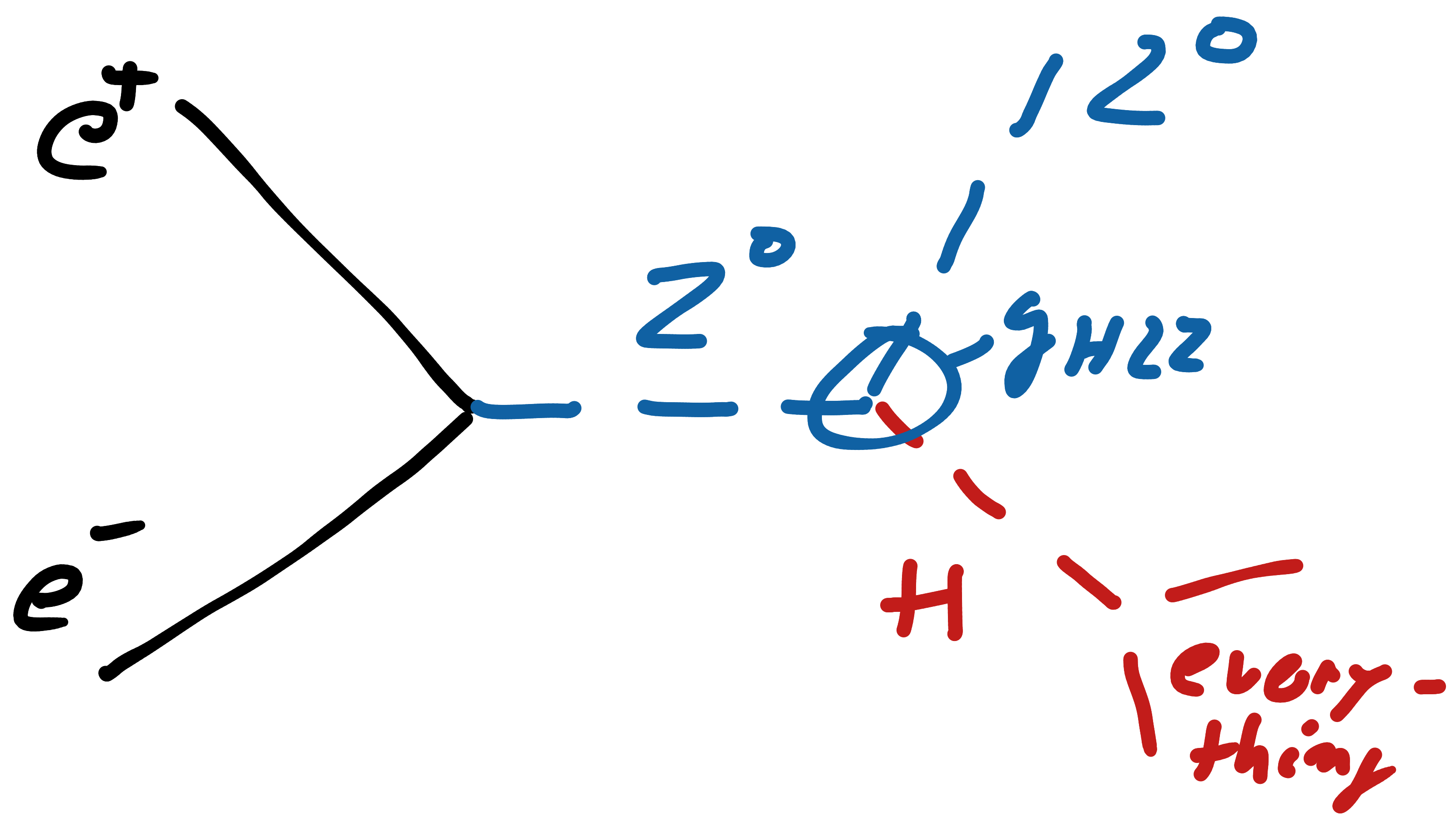

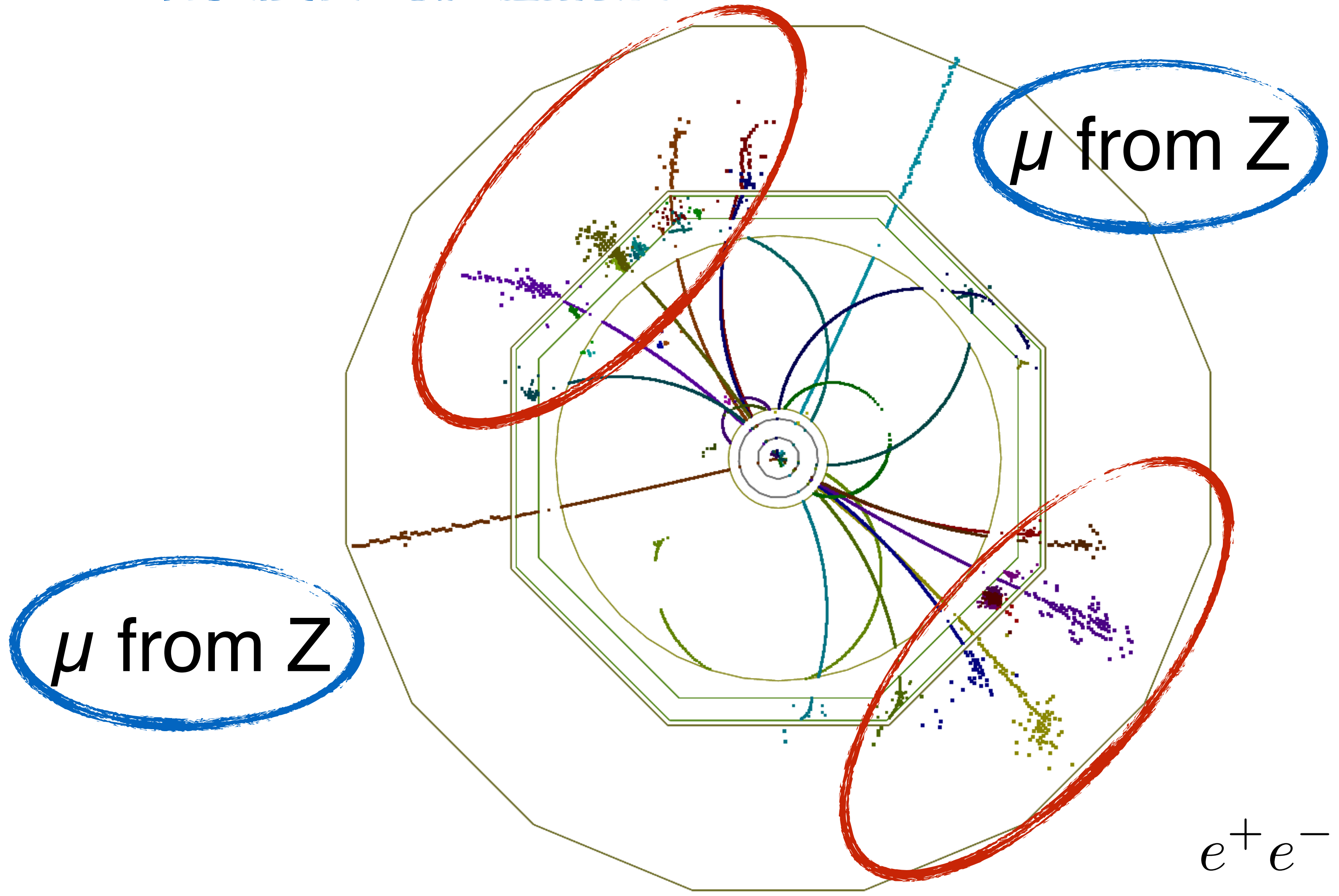

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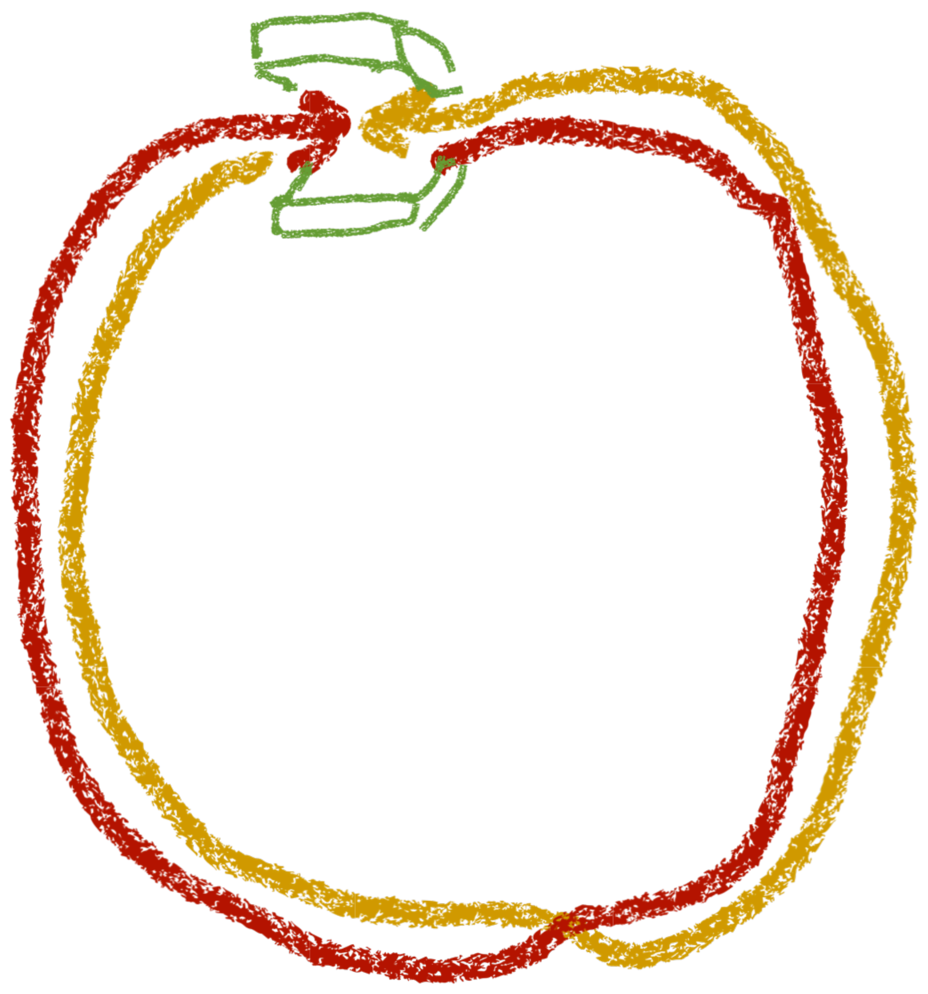
Circular Colliders:

Collision of two particle beams on circular orbits in opposite direction



Re-use of non-collided particles in future turns, acceleration can proceed over many revolutions. Need for bending magnets to keep particles on track.

Collider Types

Circular and Linear

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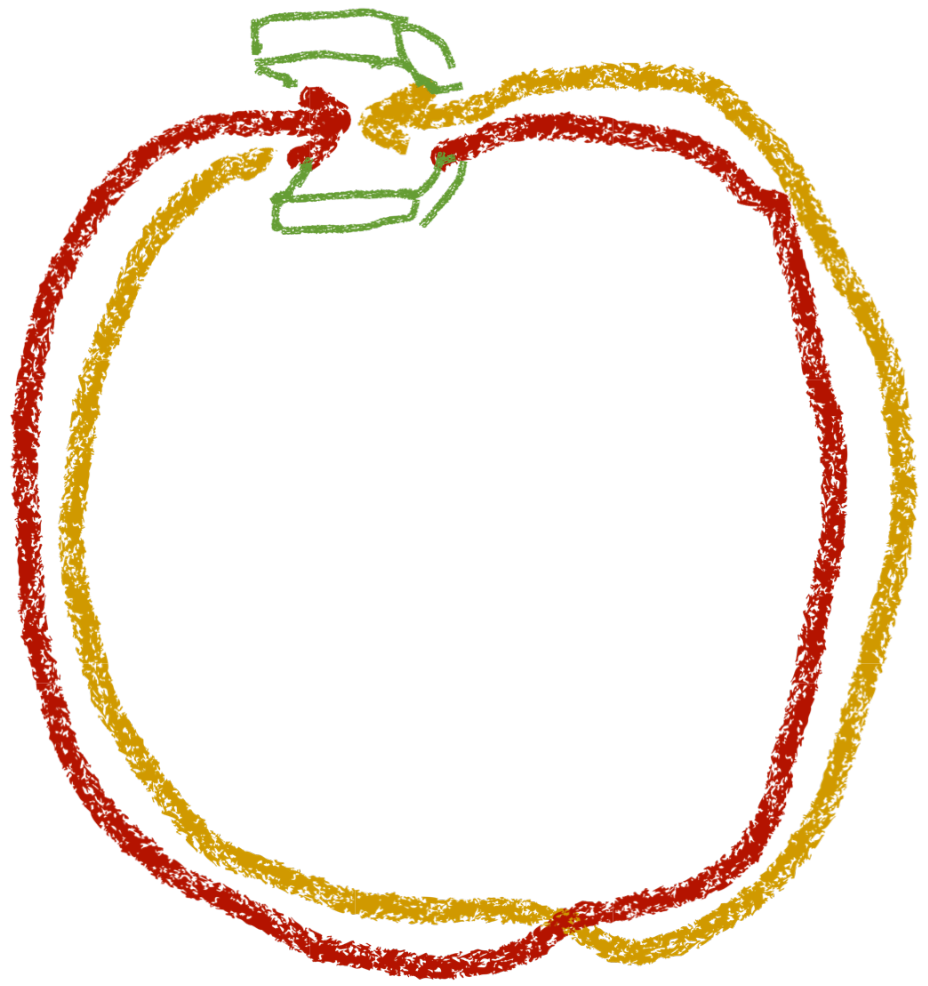

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Linear Colliders:

Collision of two particle beams from linear accelerators pointed at each other

Full acceleration in a “single shot”, unused particles are lost. No need for magnets

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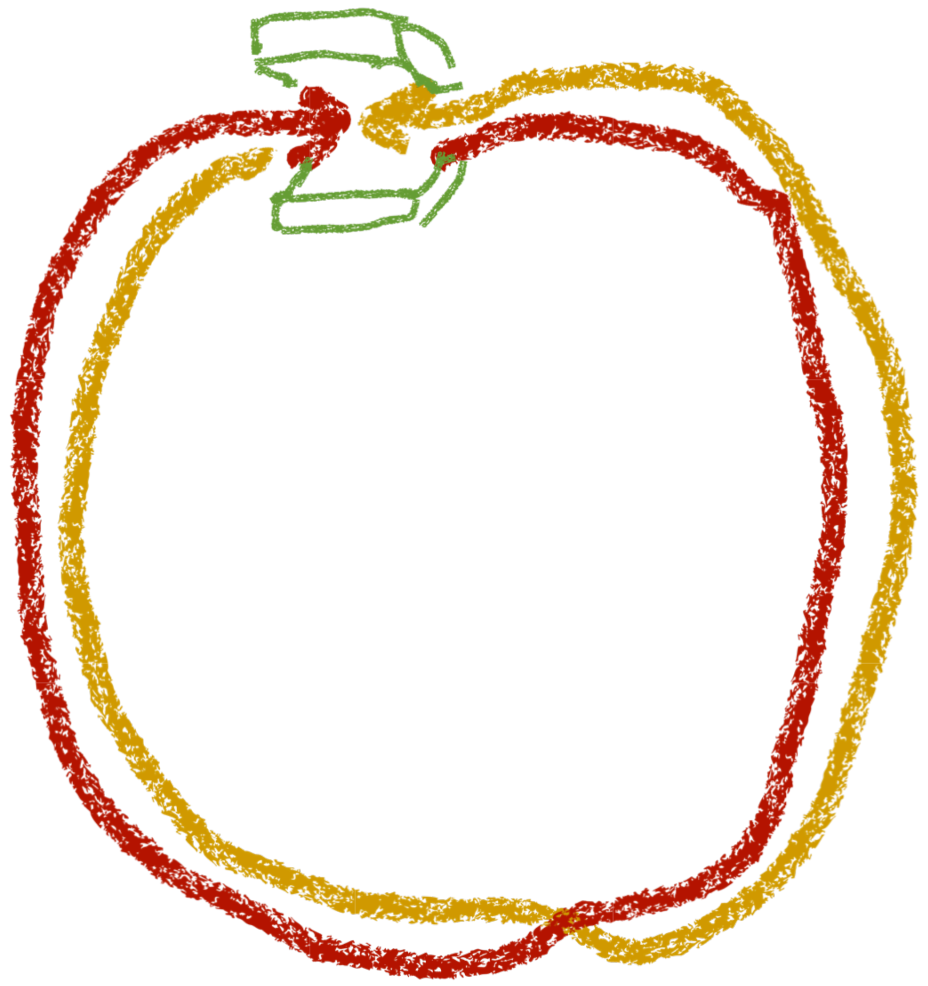

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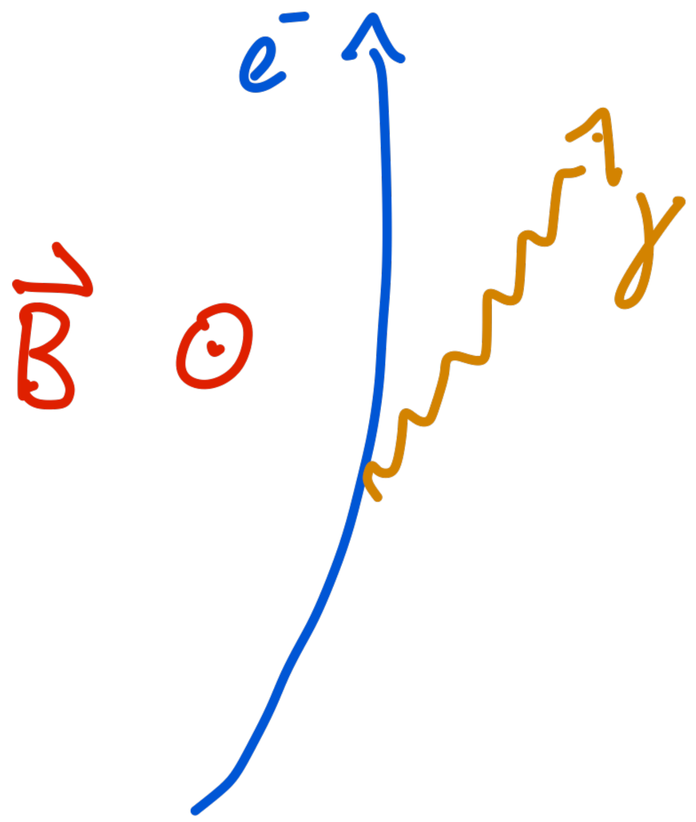

Linear Colliders:

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Full acceleration in a “single shot”, unused particles are lost. No need for magnets

Makes sense for light particles at high energy: Synchrotron radiation losses scale with E^4 and m^{-4} and r^{-2}

Frank Simon (frank.simon@kit.edu)

Circular vs Linear e^+e^-

Differences in luminosity and energy reach

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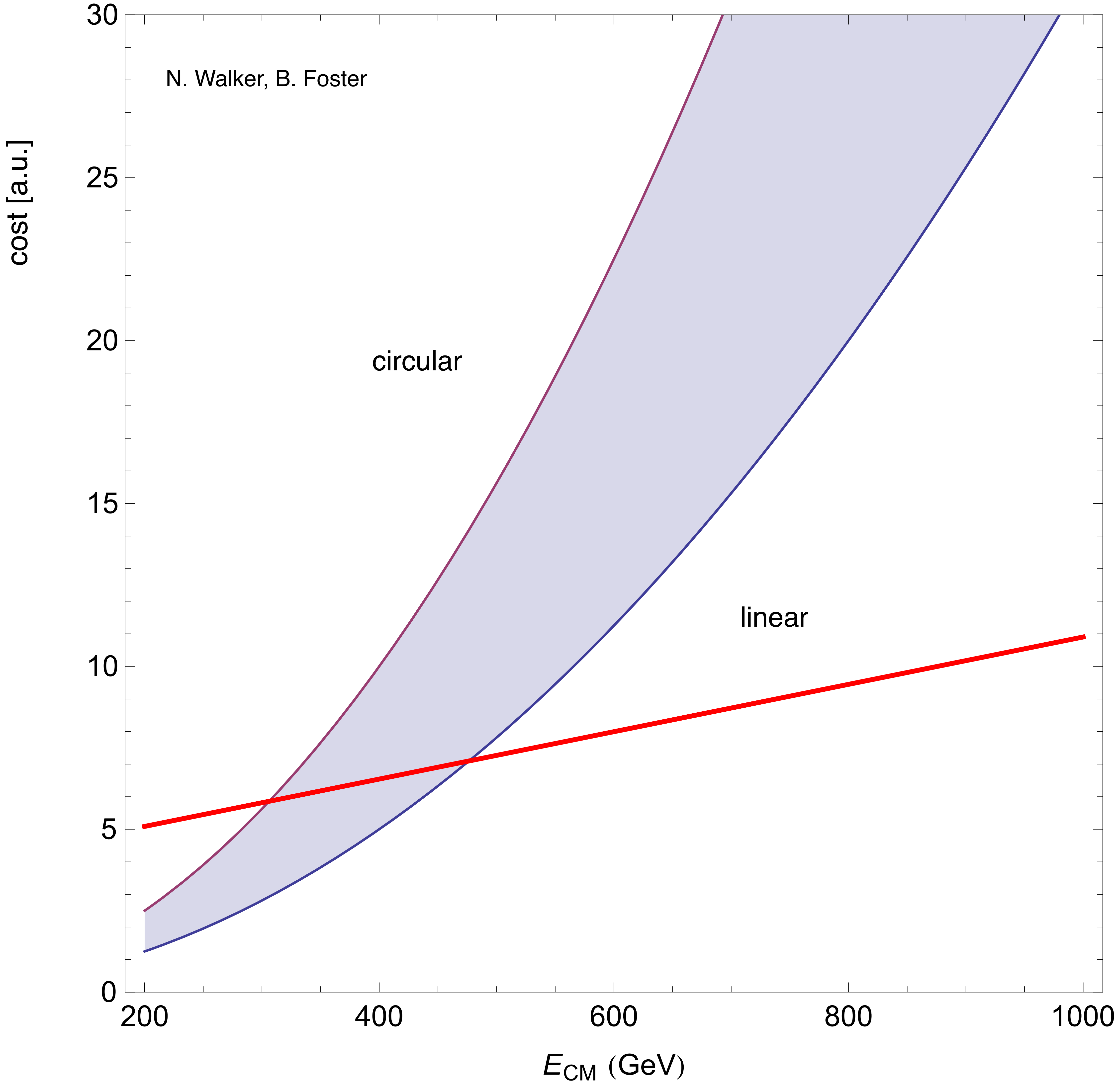


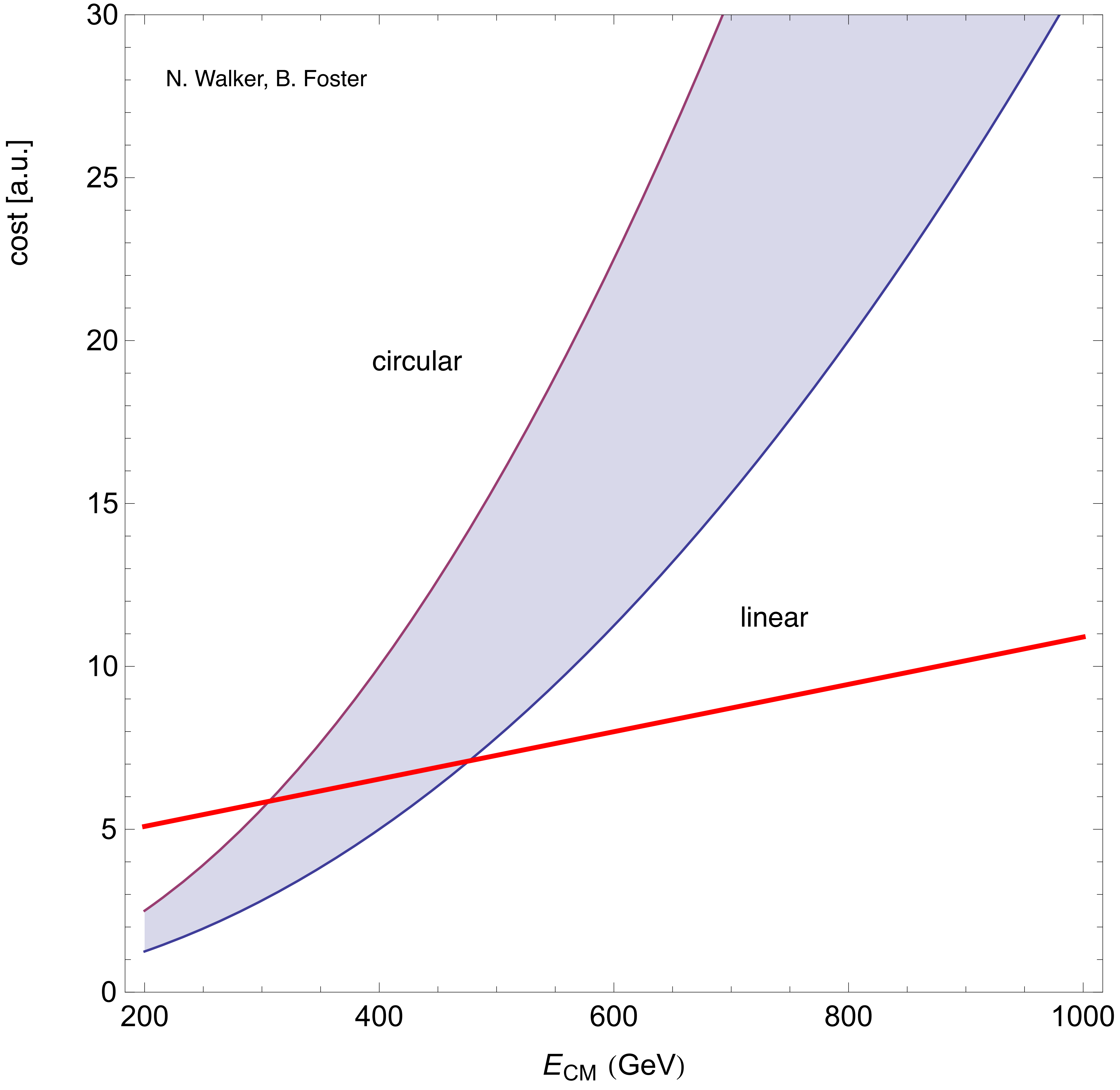
- Circular colliders very efficient at low energies, at higher energies synchroton radiation becomes a key limiting factor:
  Power proportional to E^4/R^2 - Loss per turn ~ E^4/R

➡ The scaling of the size of the facility with energy is very different:

- Circular colliders have to grow at least with E^2
- Linear colliders grow with E - but inherently more complicated, with a large cost offset

Circular vs Linear e+e-

Differences in luminosity and energy reach



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More details, and a discussion of different facilities: Lectures of Roderic Bruce.

Collider Options

Conceptual differences in physics reach

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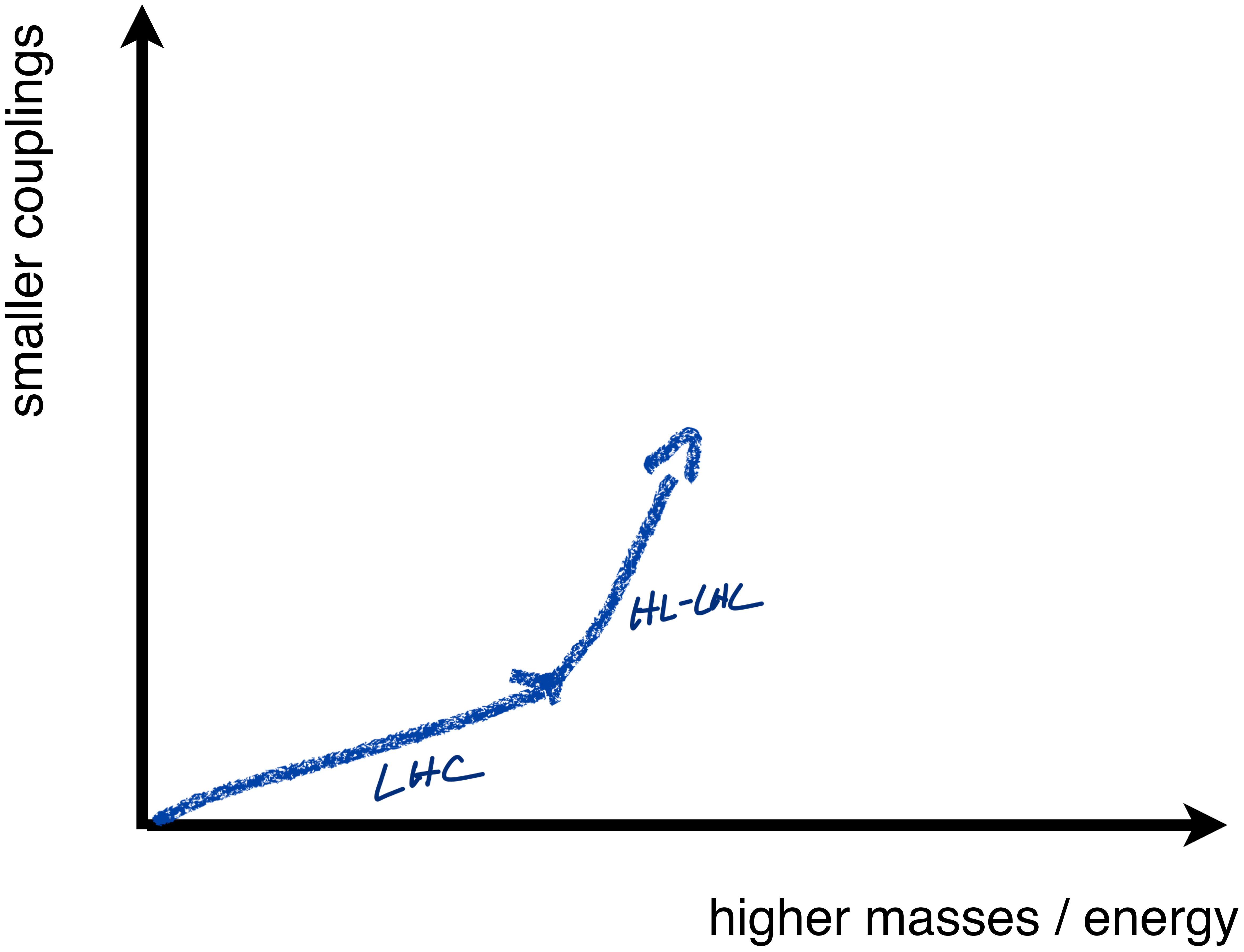
higher luminosity / statistics =



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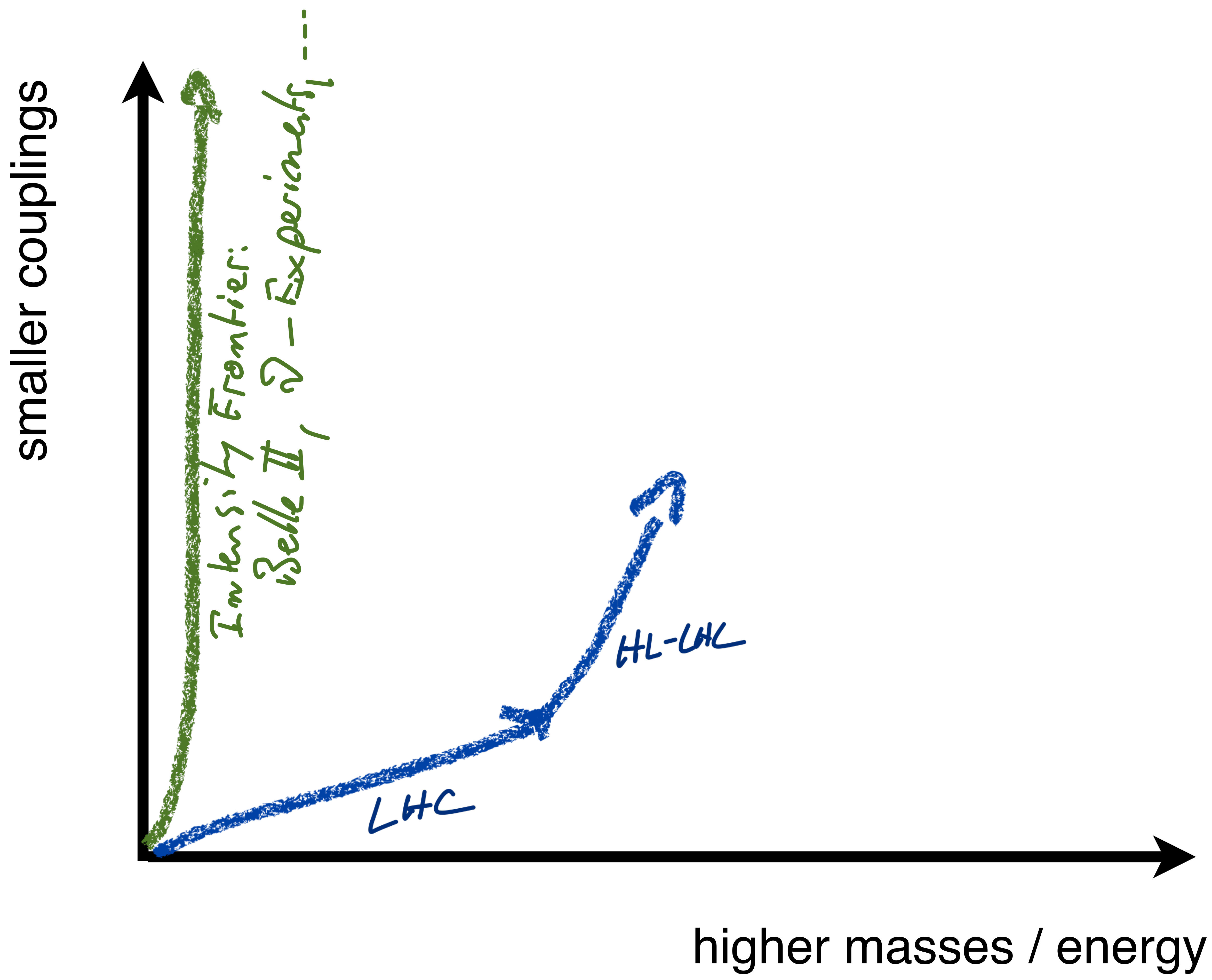

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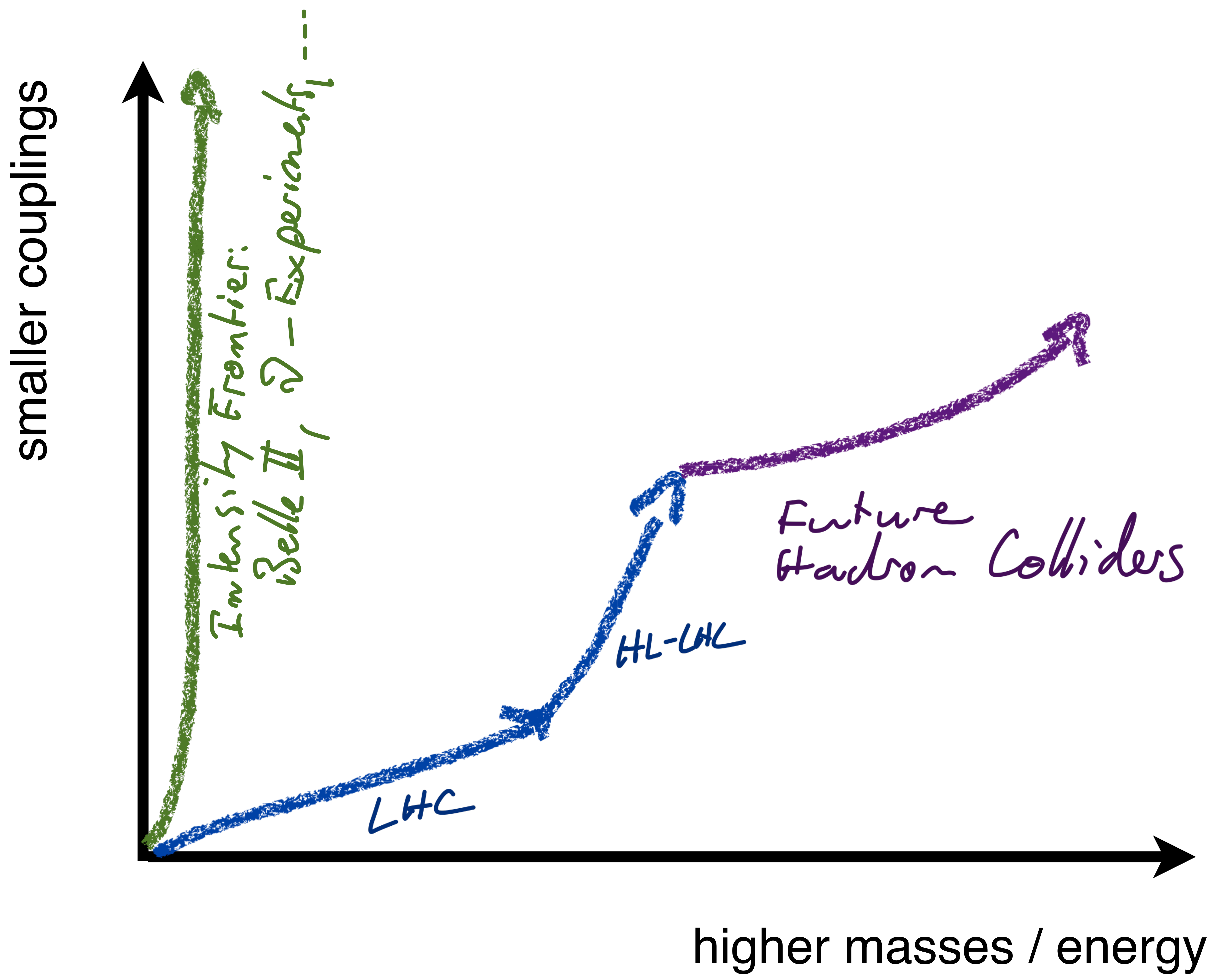

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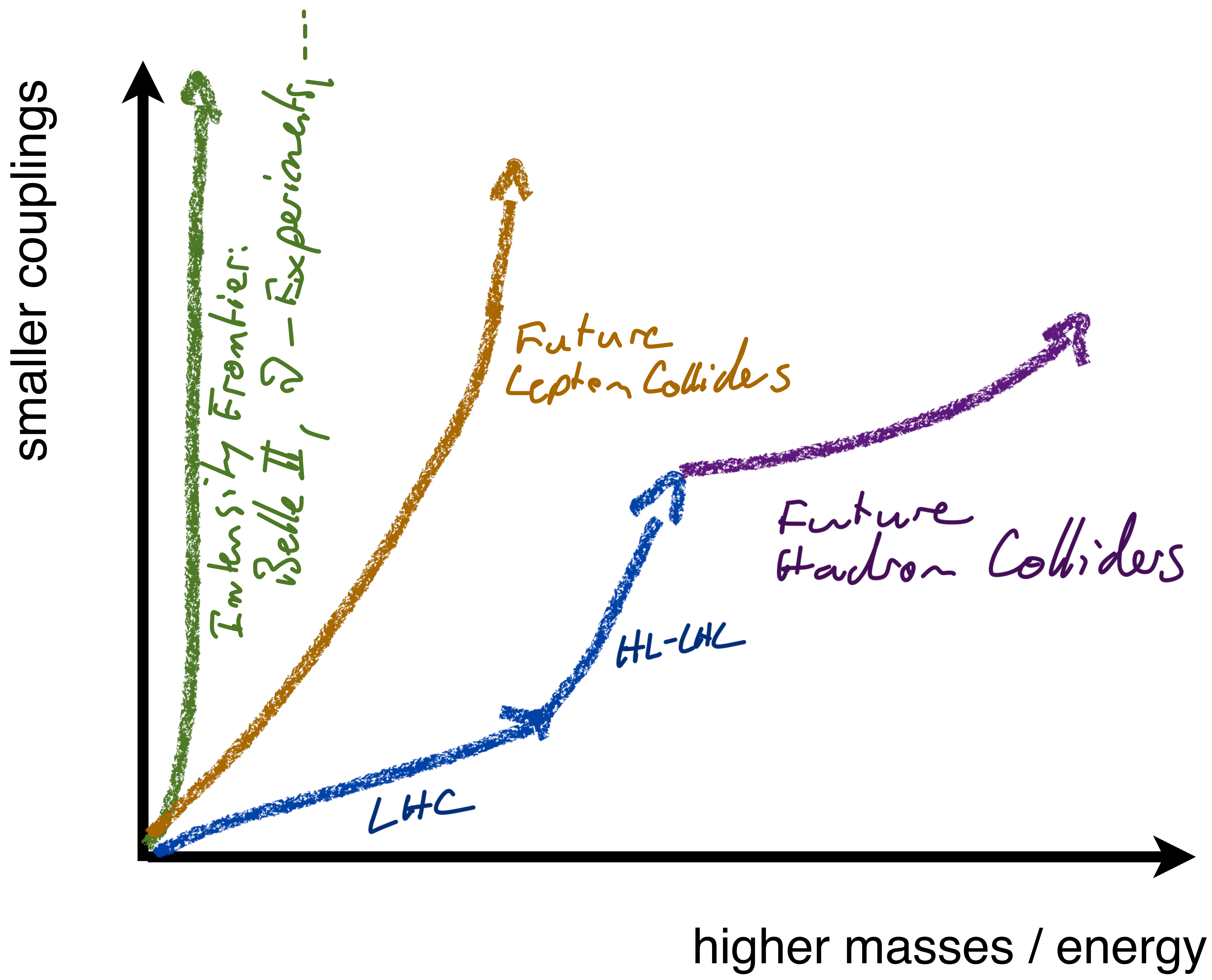

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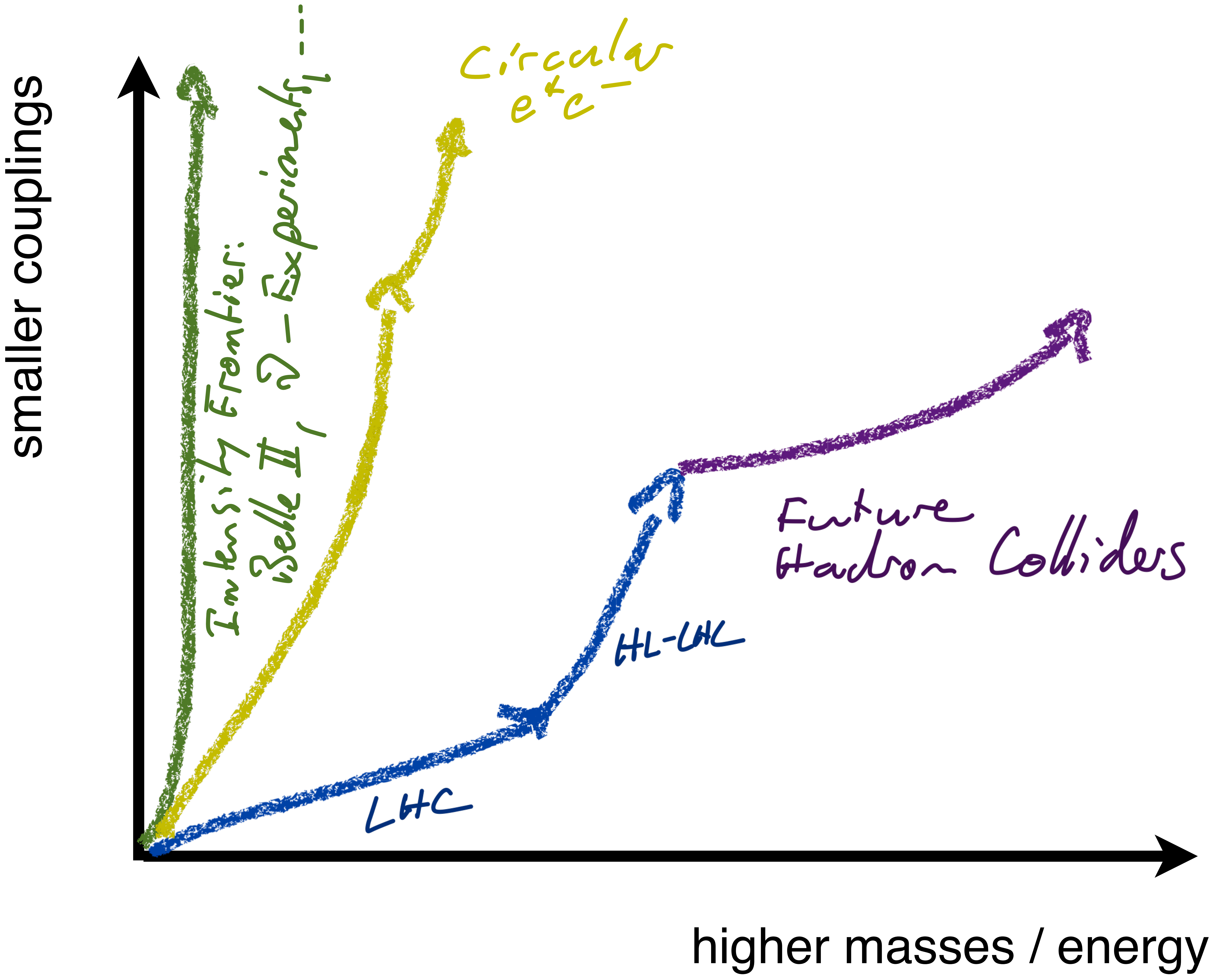

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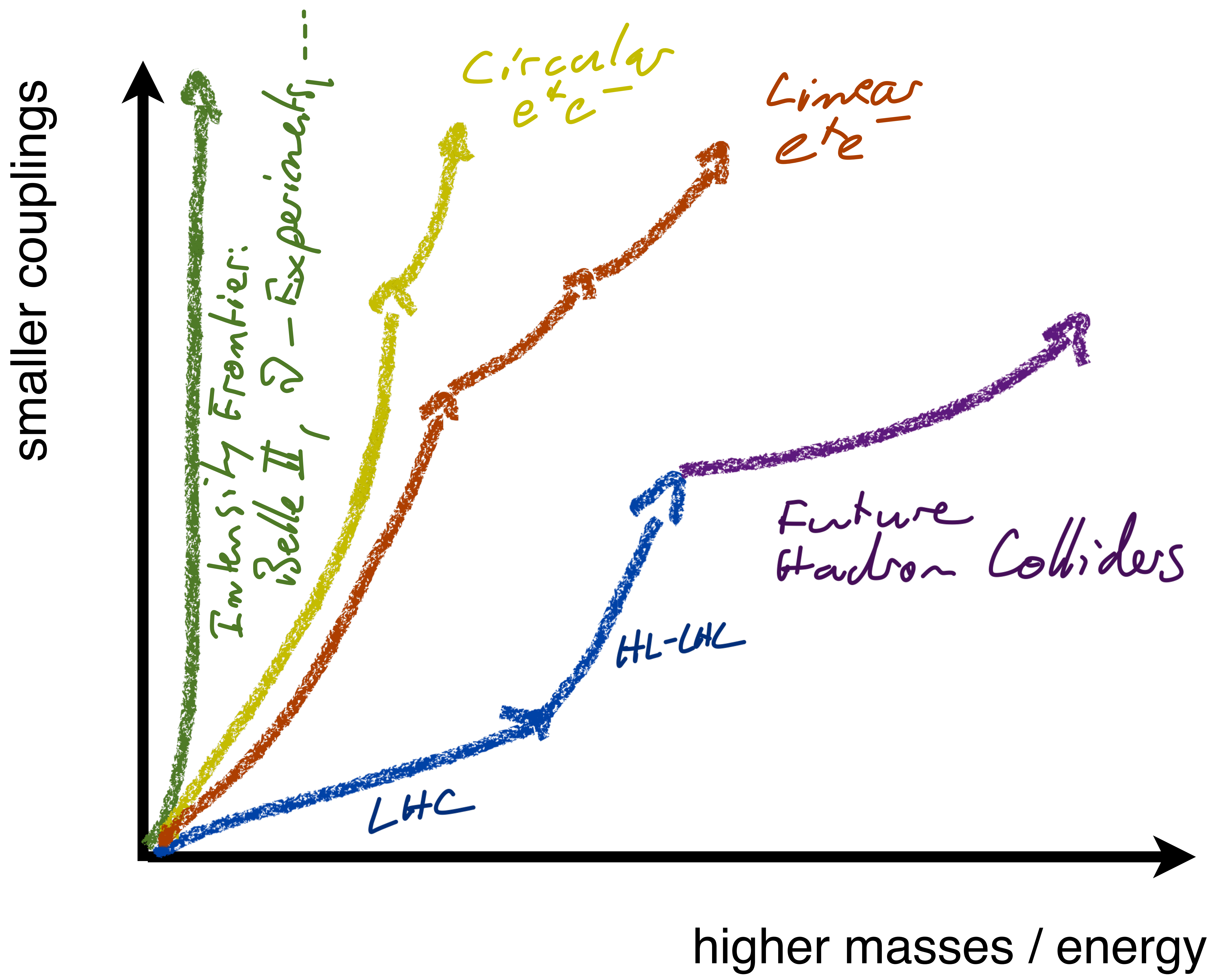
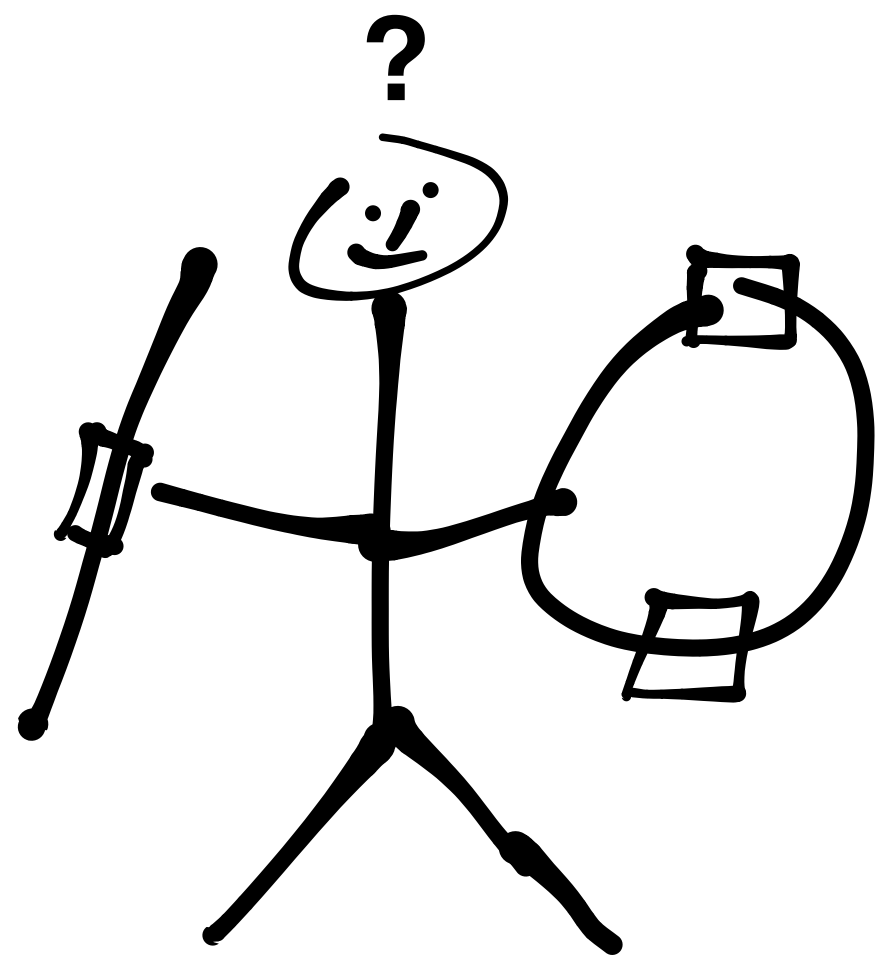


Evolving Collider Infrastructure

Maximising physics output, react to discoveries

- A general challenge: Colliders and the associated infrastructure are expensive - making long-term scientific exploitation mandatory
- It is basic research:
  Discoveries or new insights may call for changes in direction



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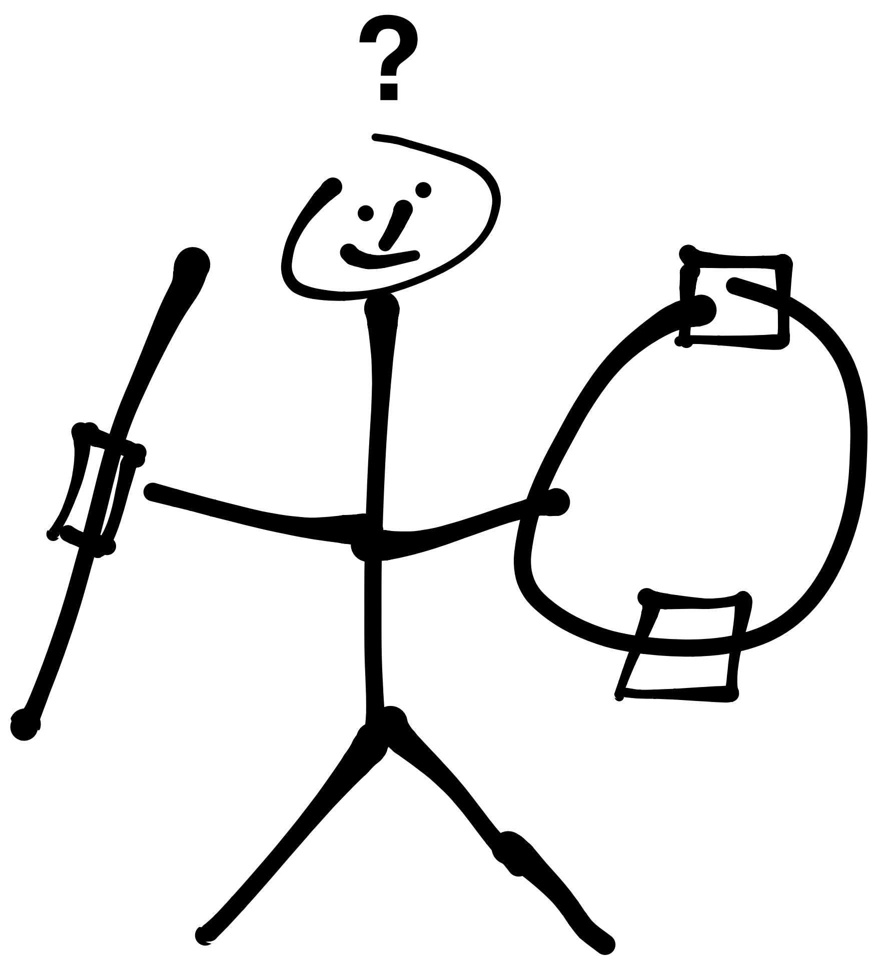

Evolution scenarios:

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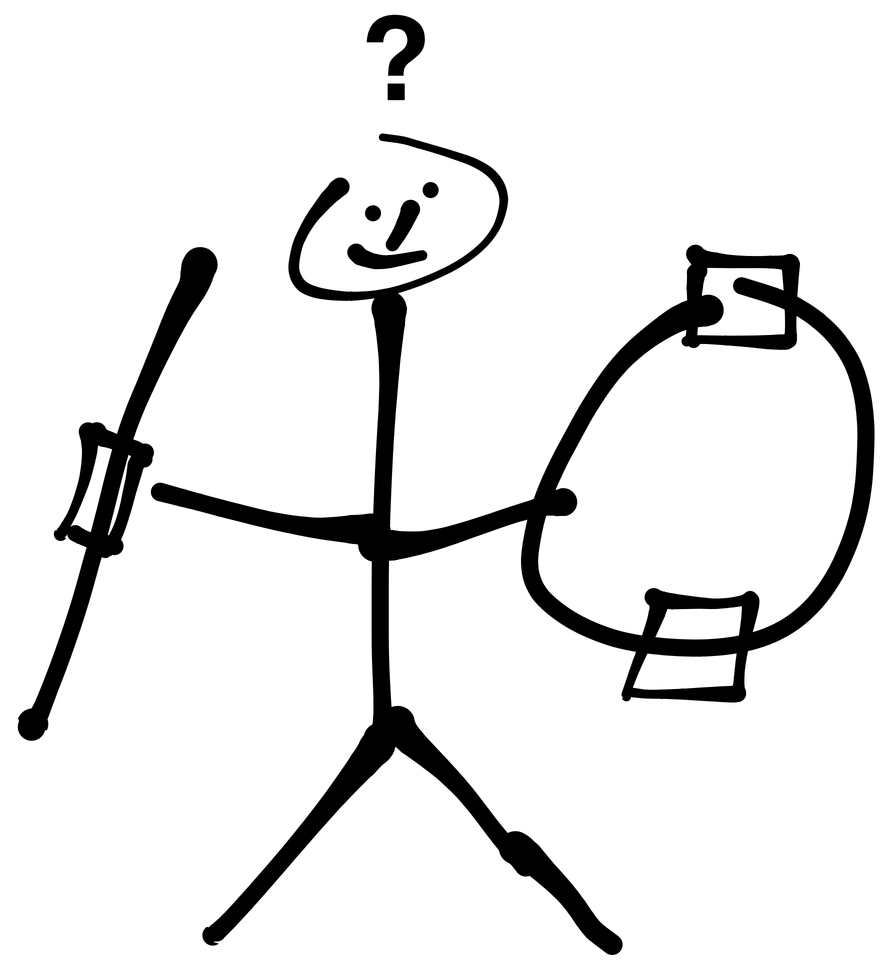

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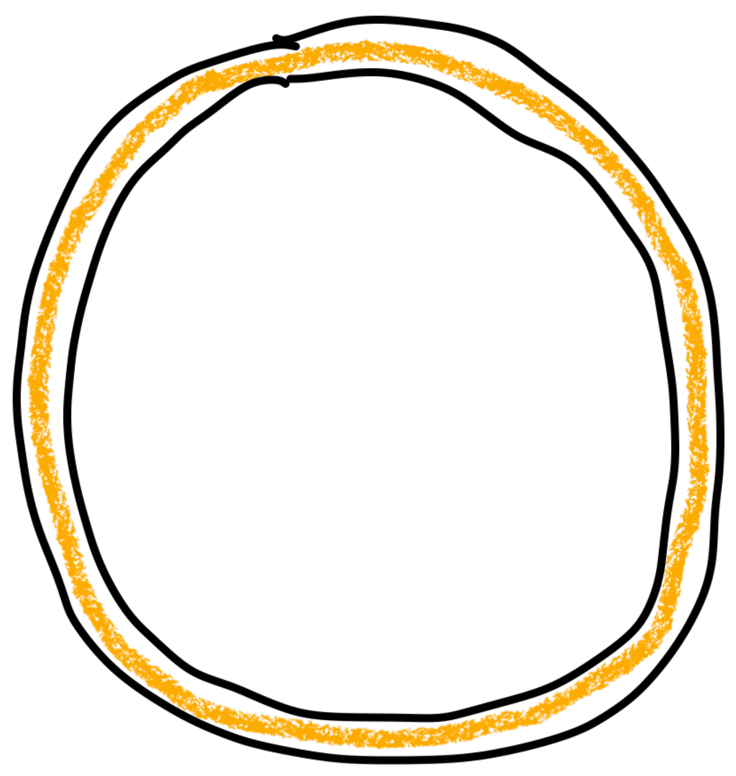

e^+e^- Collider

A big ring: Full length required on day one, then can be used for a lepton and a hadron collider sequentially

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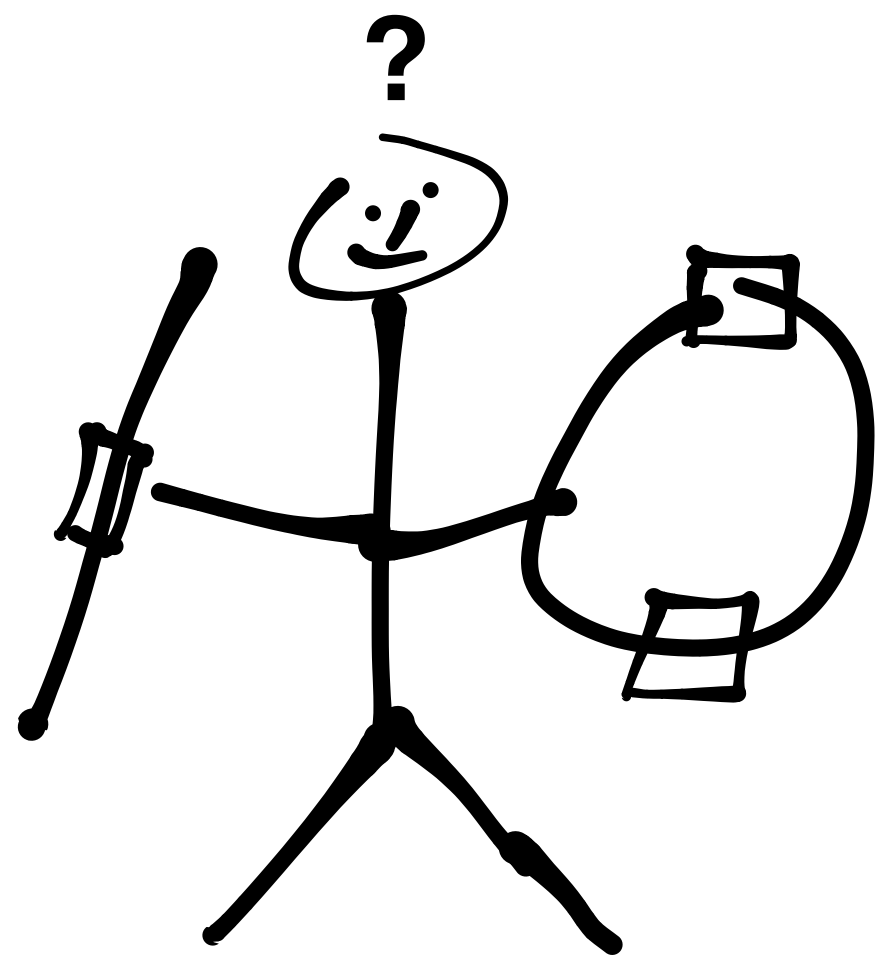

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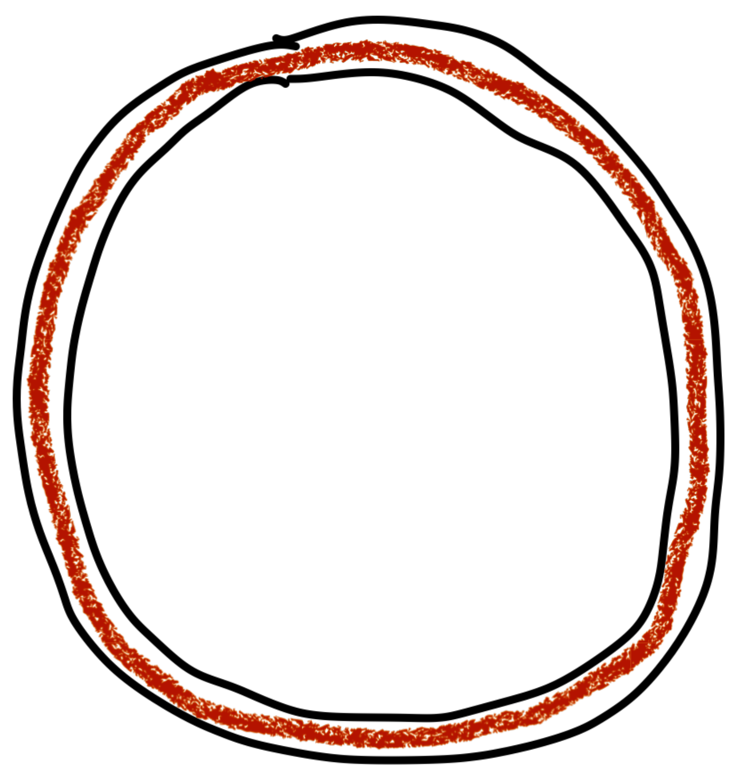

e^+e^- Collider

Hadron Collider

highest possible
energy:
100(+) TeV

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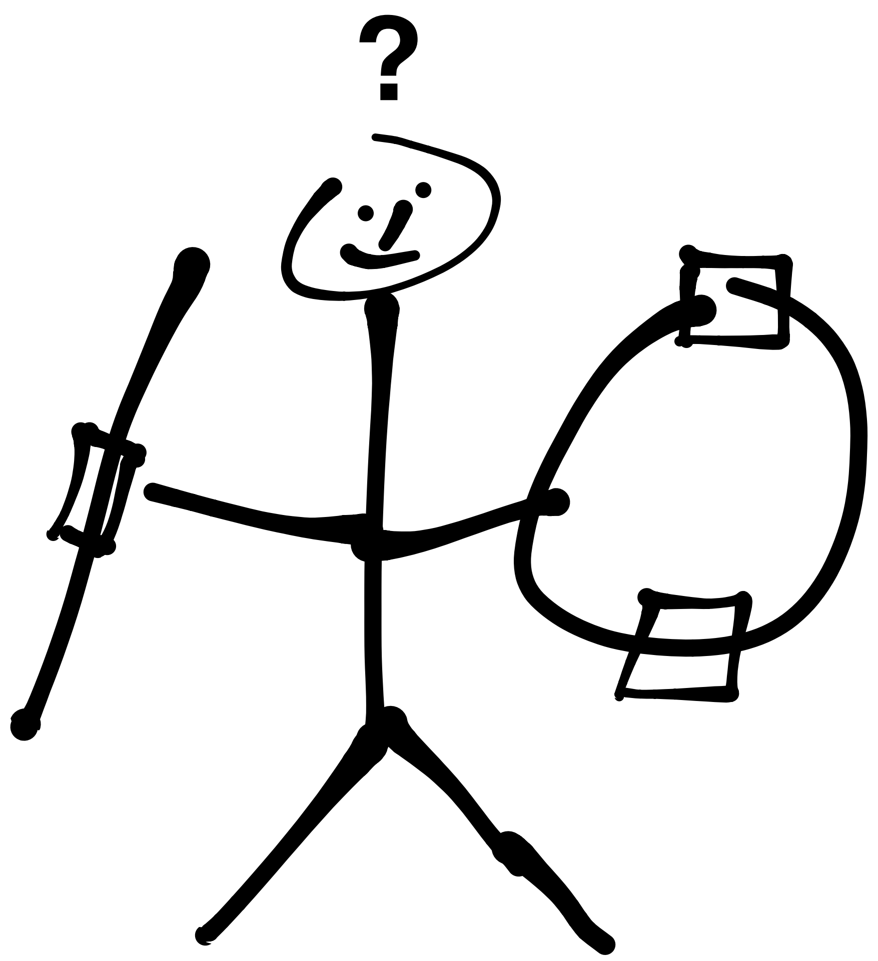

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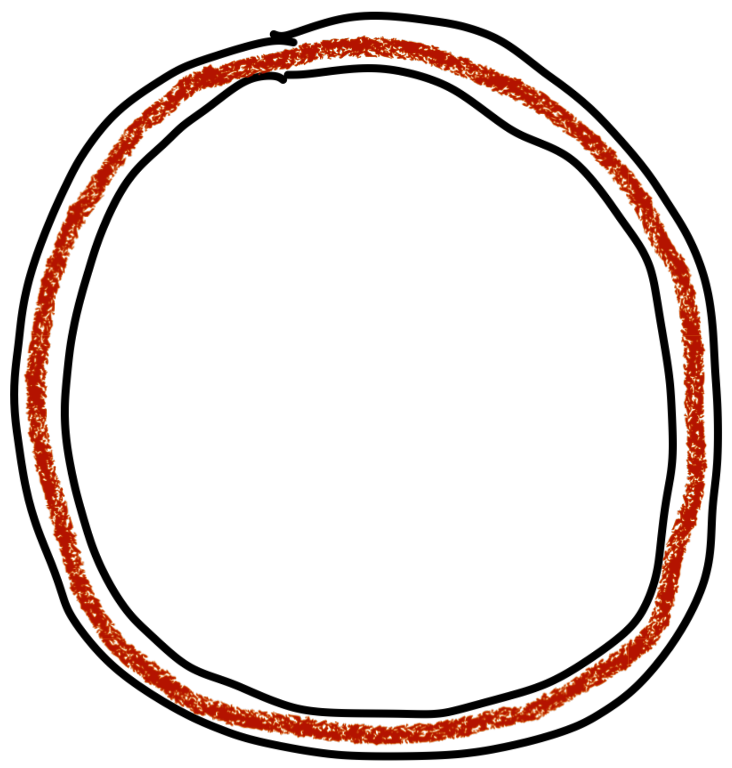

e^+e^- Collider

Hadron Collider

highest possible energy: 100(+) TeV

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e^+e^- Collider

A linear collider: Step-wise extension, lepton collisions at different energies in sequence

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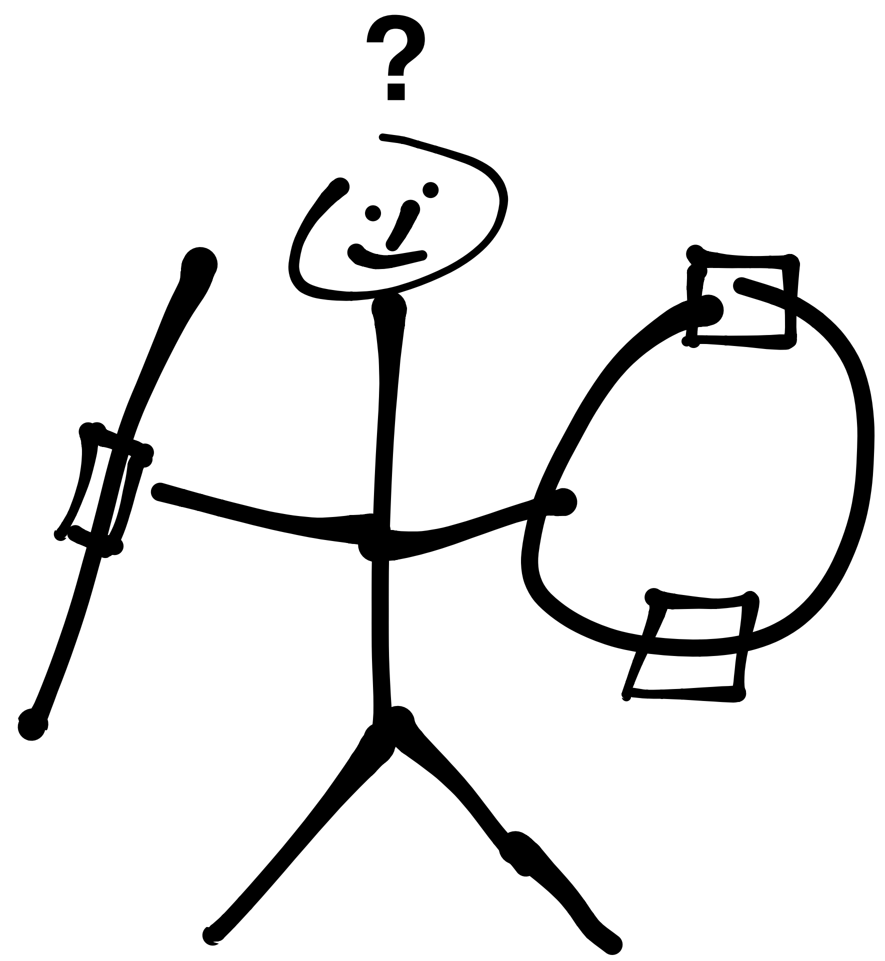

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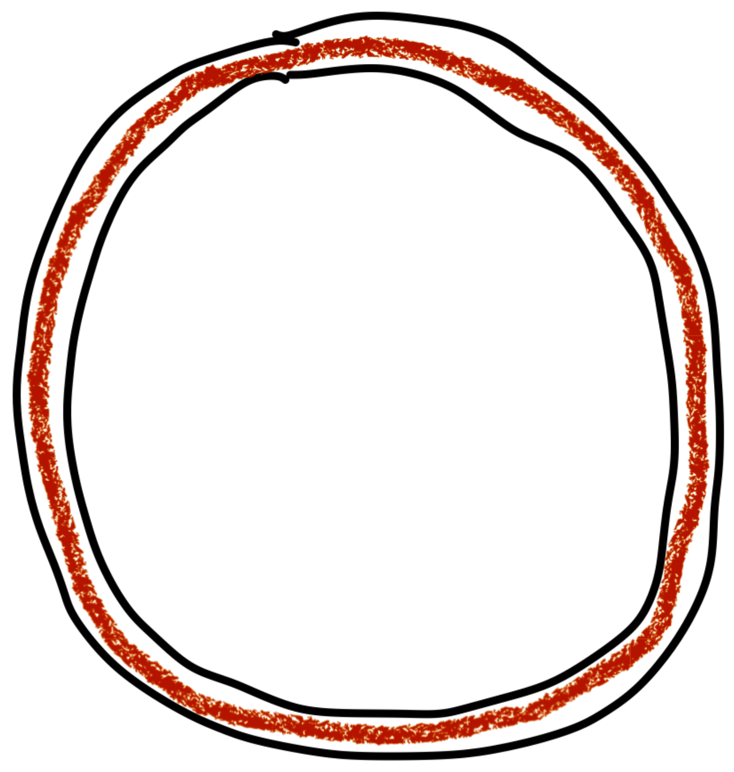

e^+e^- Collider

Hadron Collider

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e^+e^- Collider

longer tunnel: higher energy

A linear collider: Step-wise extension, lepton collisions at different energies in sequence

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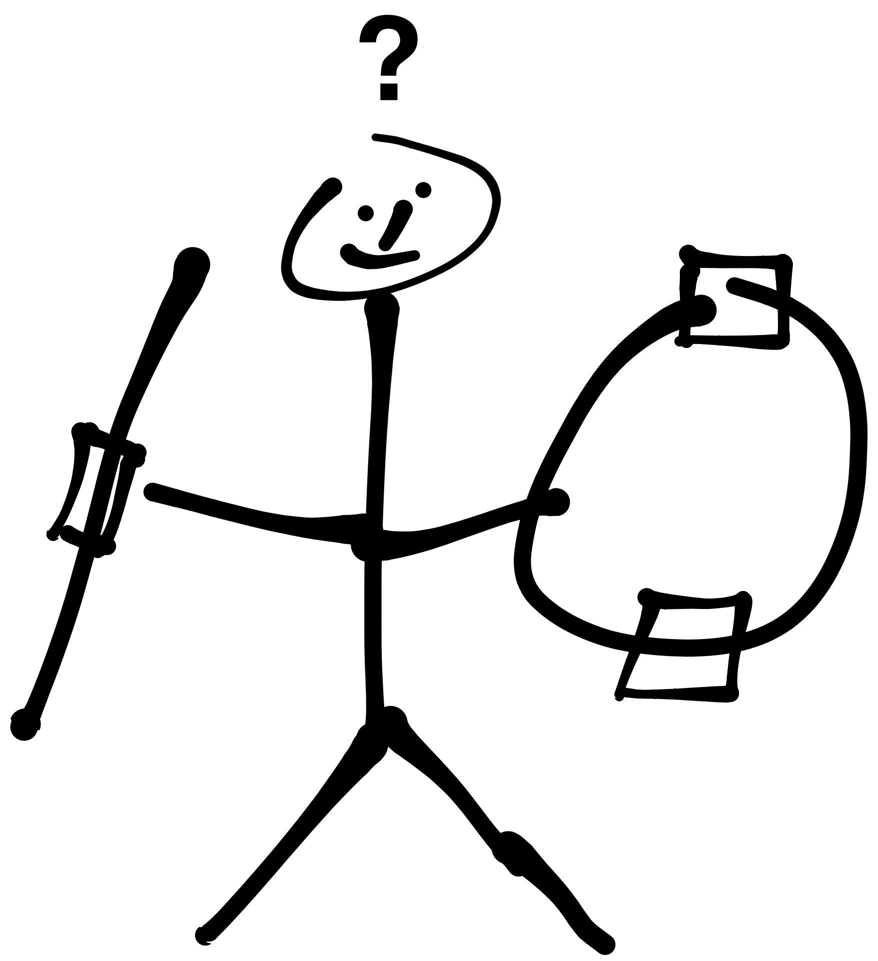

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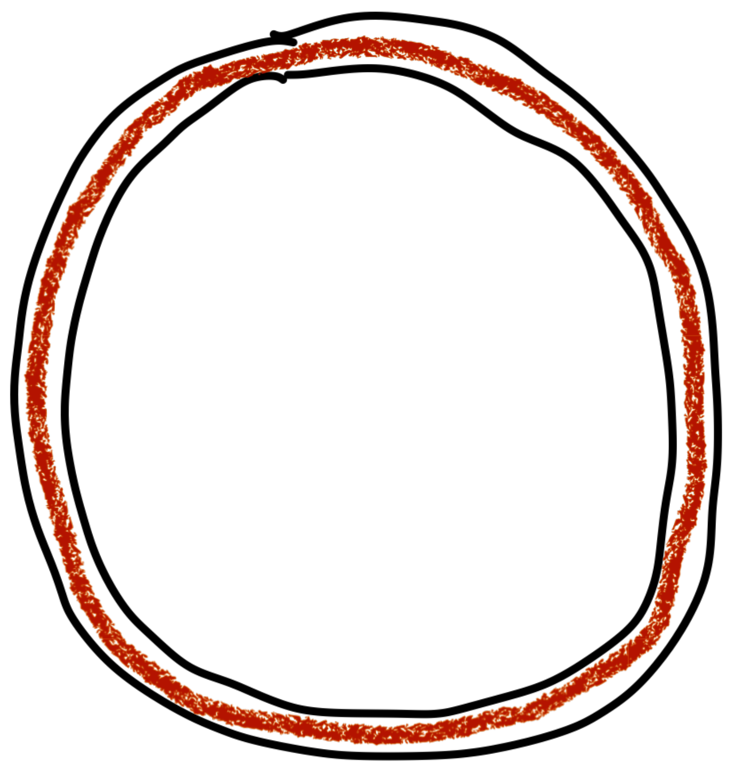

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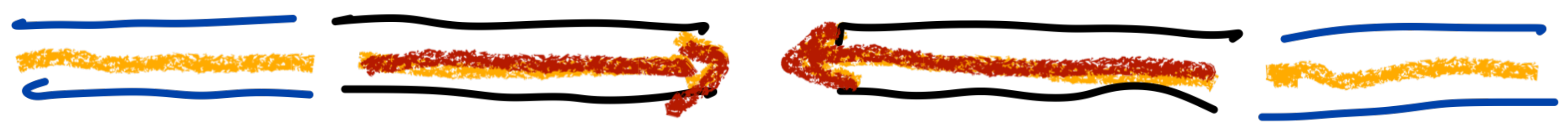

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new acceleration technology

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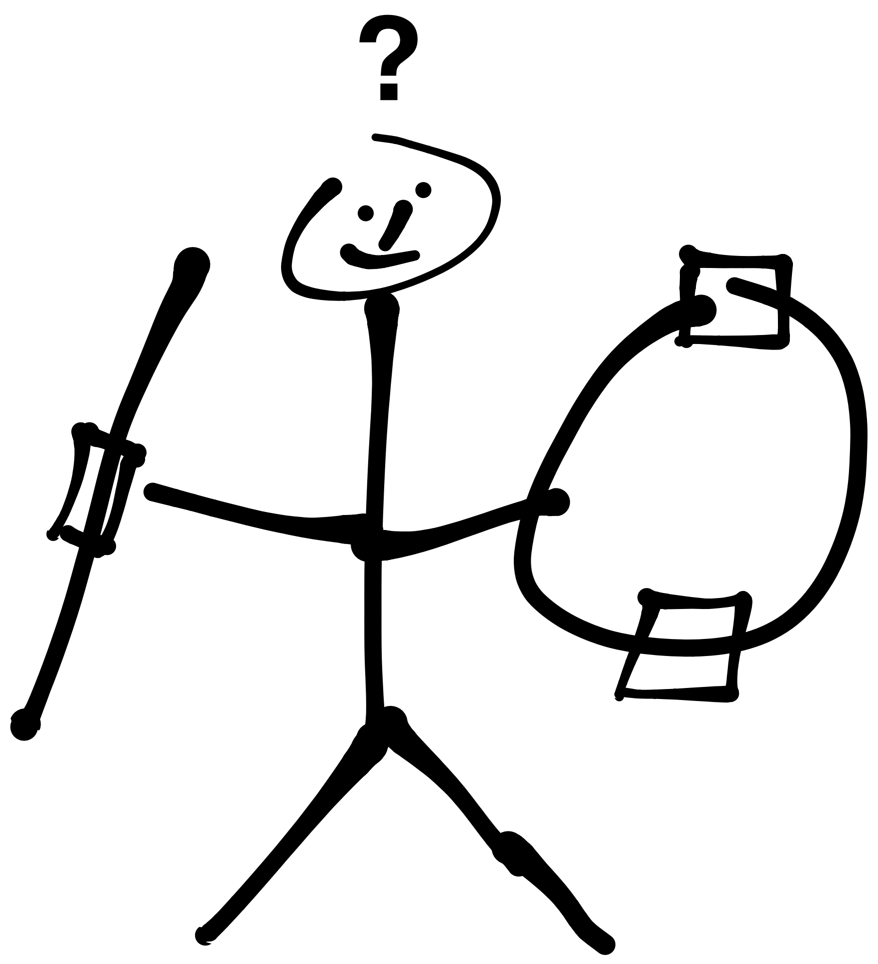
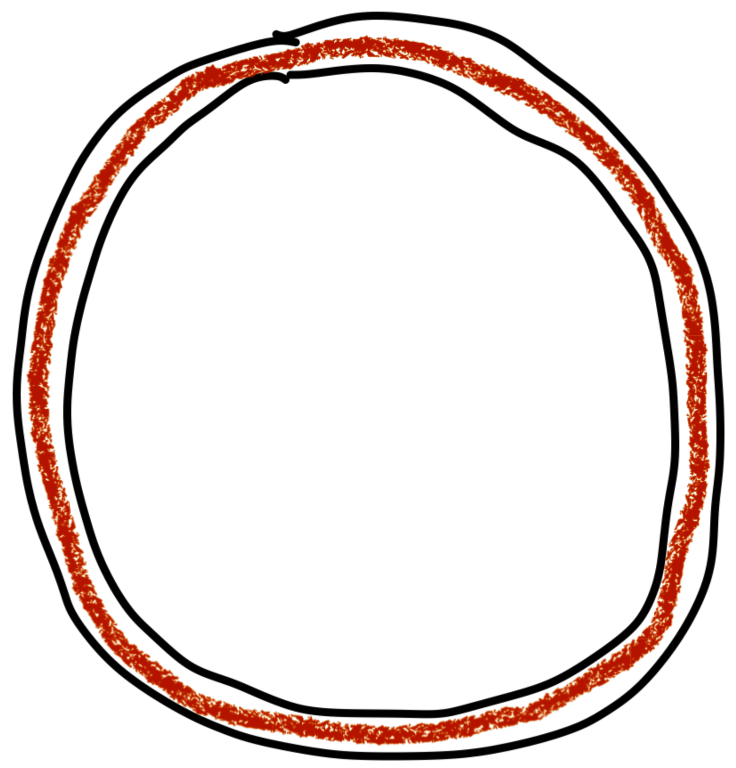


Evolution scenarios:

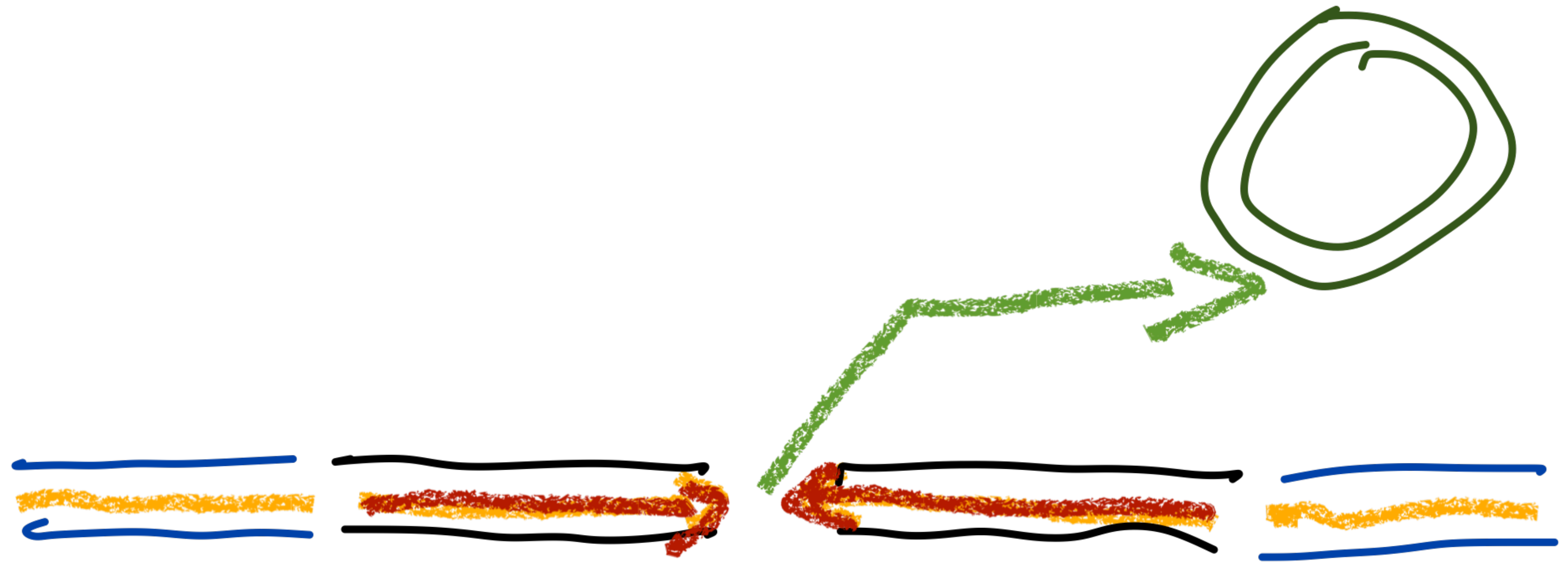


e^+e^- Collider

Hadron Collider

highest possible energy: 100(+) TeV

A big ring: Full length required on day one, then can be used for a lepton and a hadron collider sequentially



e^+e^- Collider

longer tunnel: higher energy

new acceleration technology

as source for other accelerators

A linear collider: Step-wise extension, lepton collisions at different energies in sequence

Energy Flexibility

A Linear Collider Story

- Linear colliders provide a *staged* physics program - matched to the variety of center-of-mass energies relevant for a broad e^+e^- program

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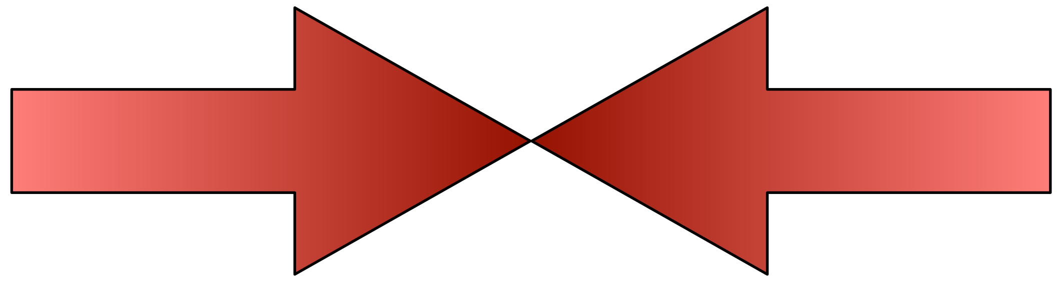

~ 250 GeV

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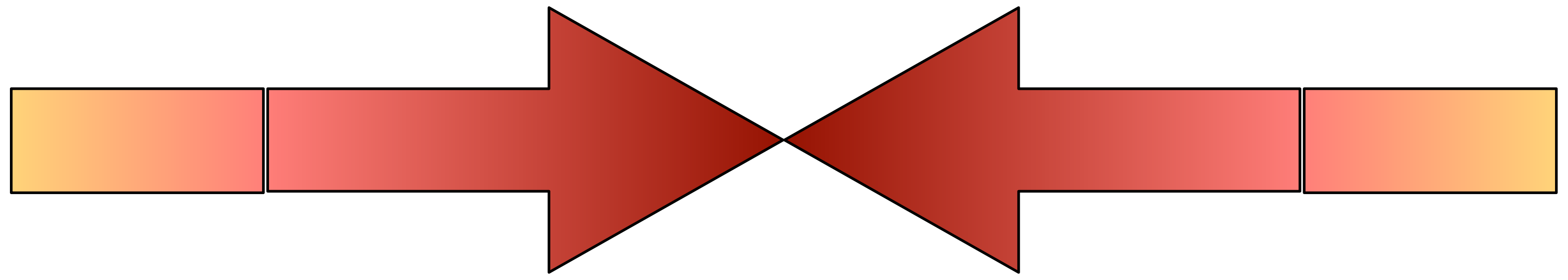
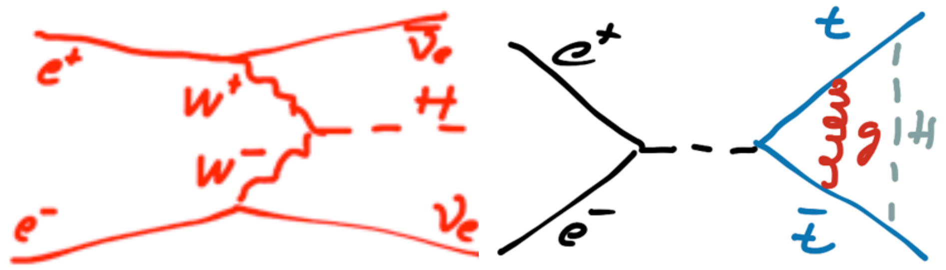


~ 250 GeV

~ 350 - 380 GeV



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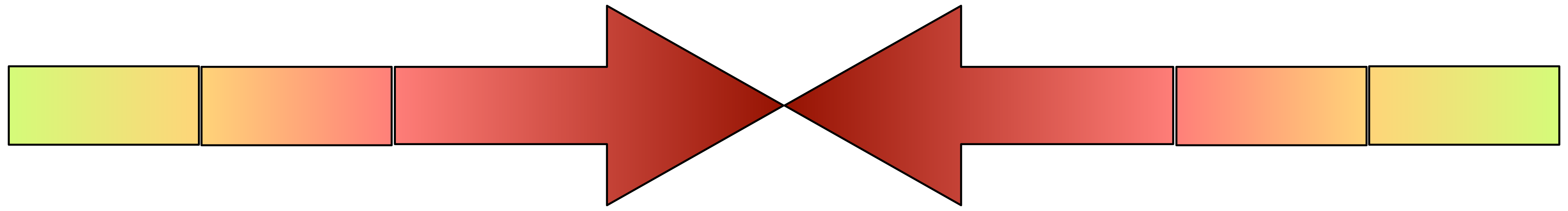

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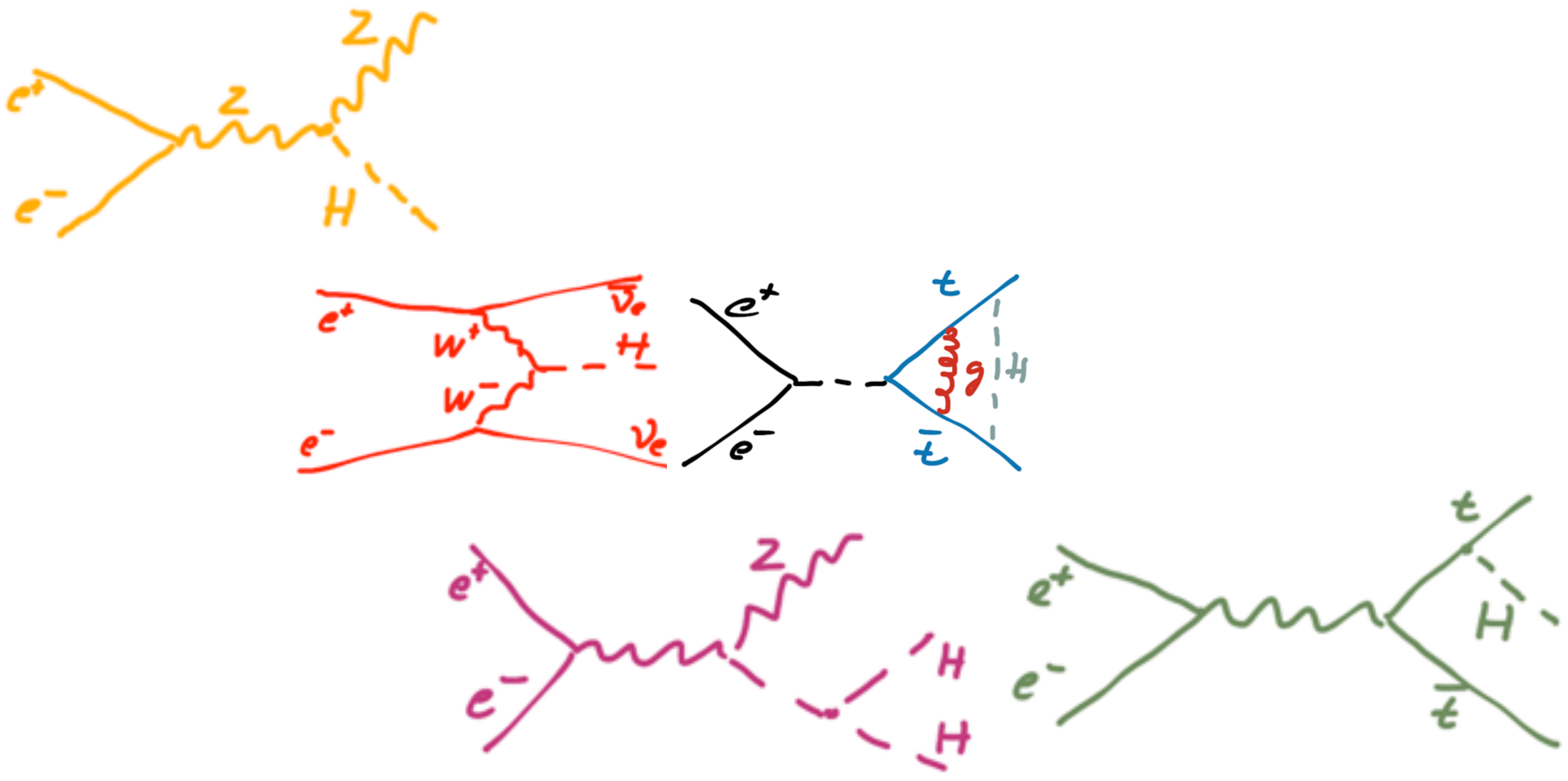

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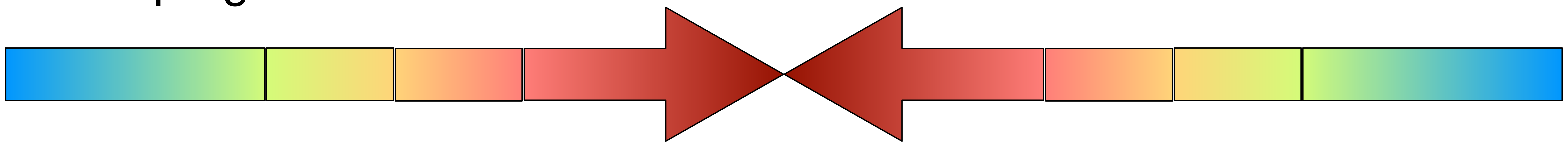

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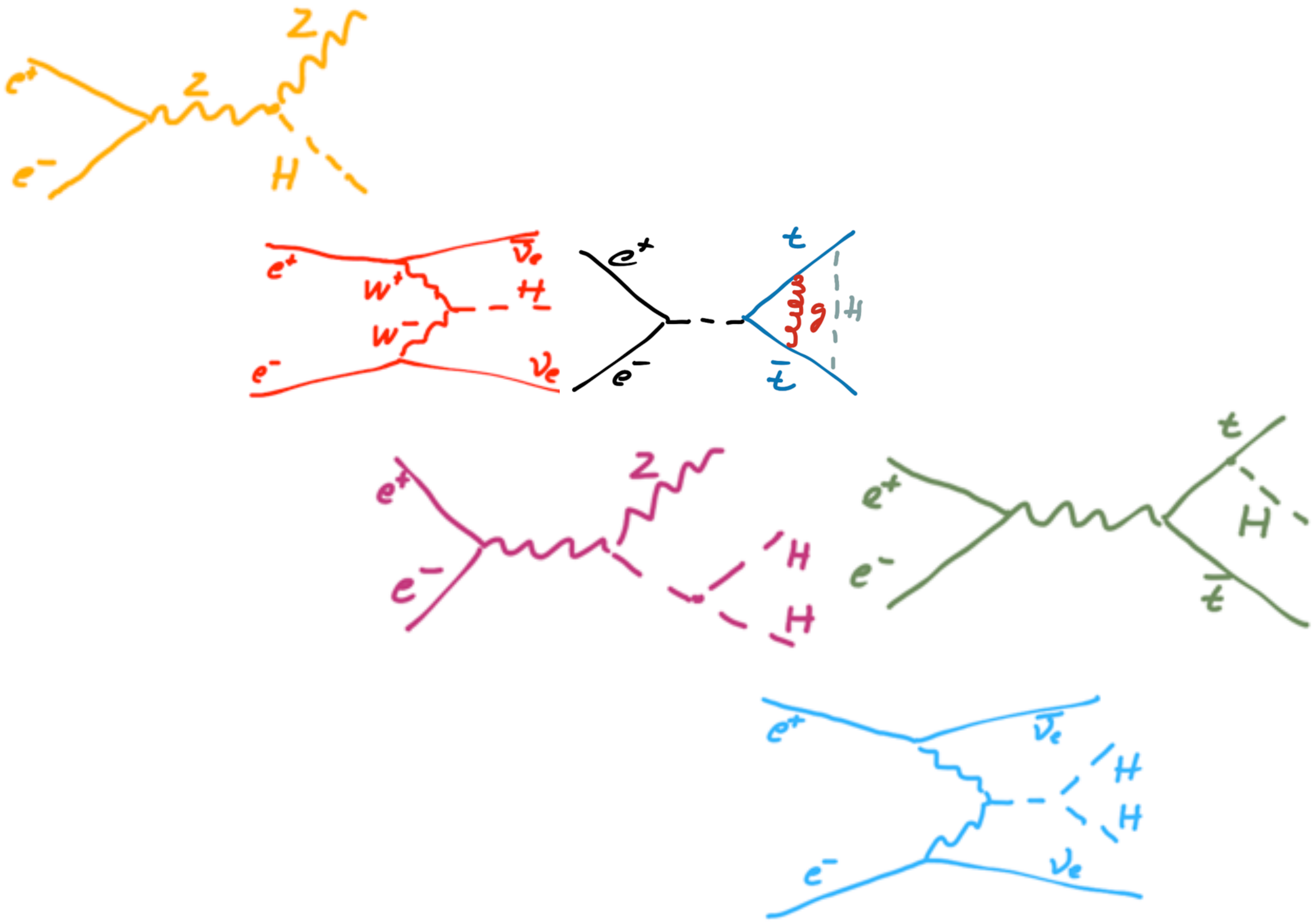

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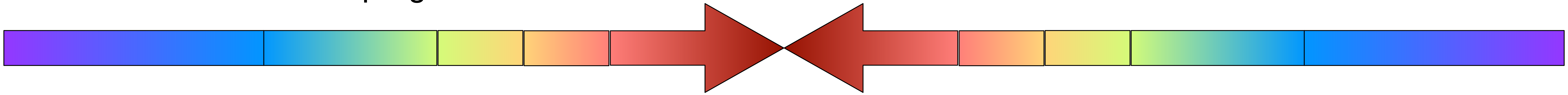

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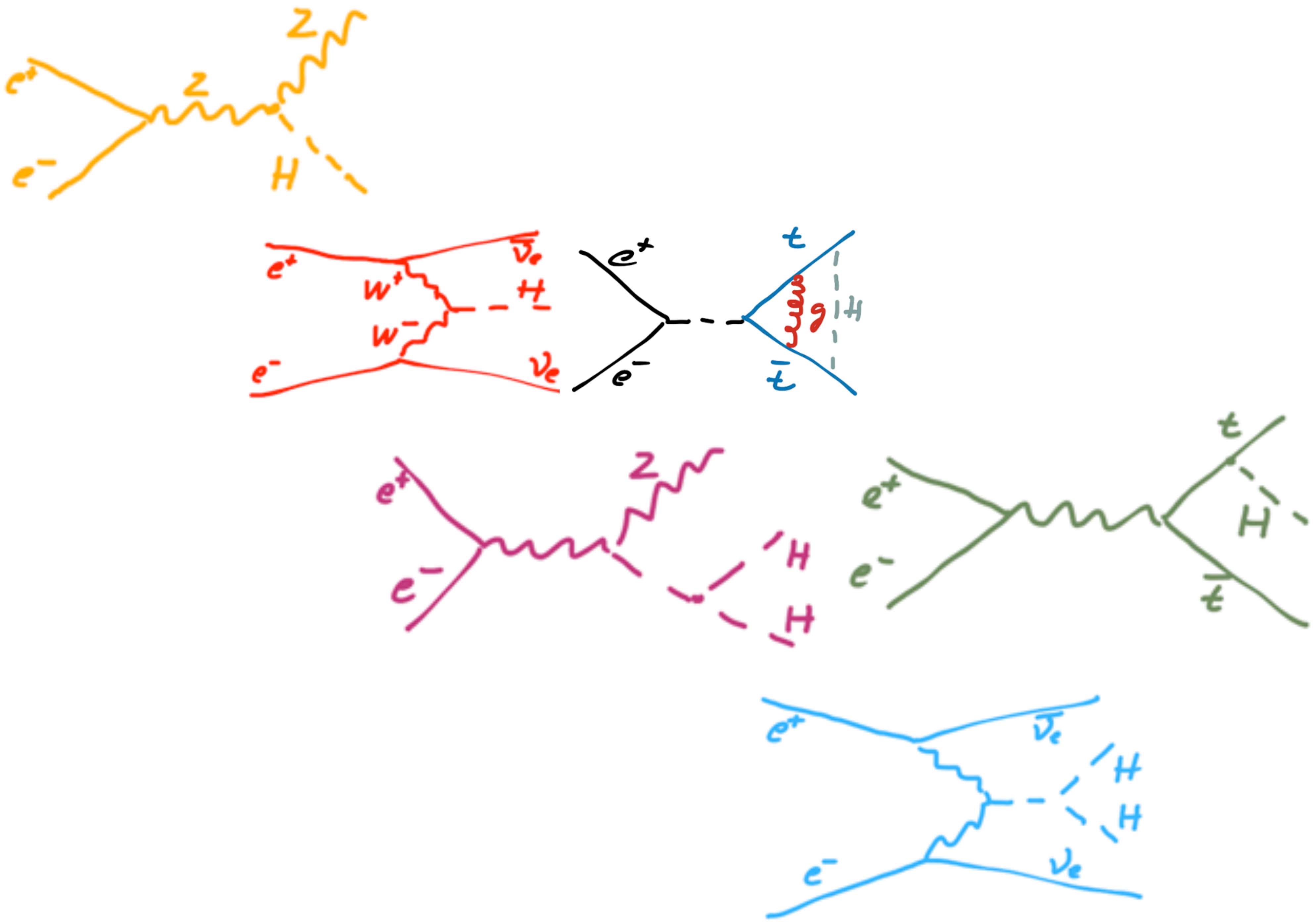

+ direct & indirect discovery potential increasing with energy

Energy Flexibility

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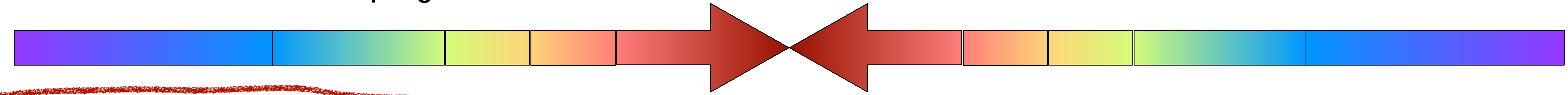

the "minimum" program to cover most aspects of Higgs and Top physics with high precision

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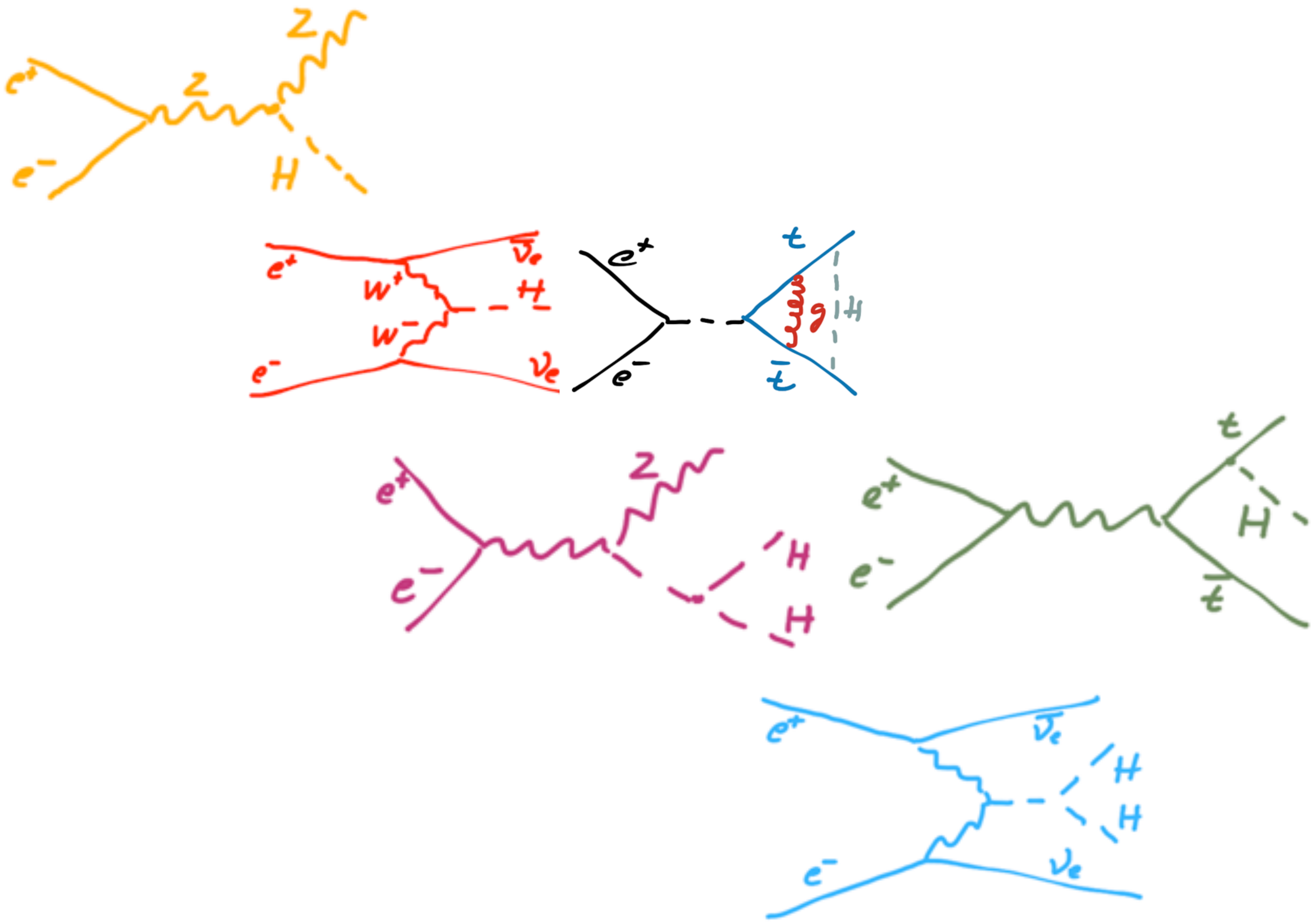

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Energy Flexibility

A Linear Collider Story

Karlsruhe Institute of Technology

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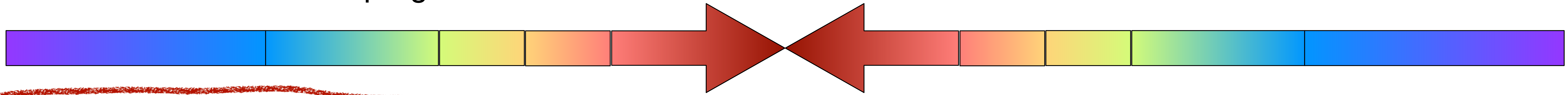

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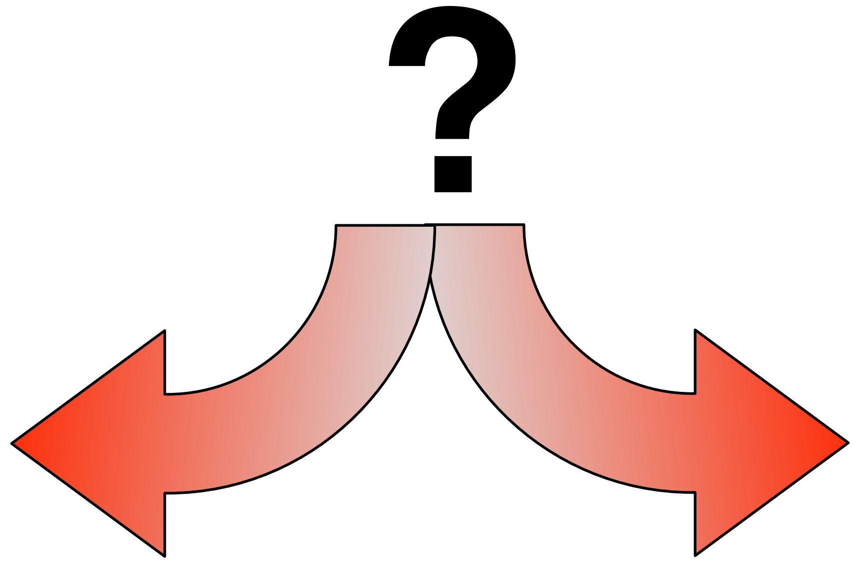
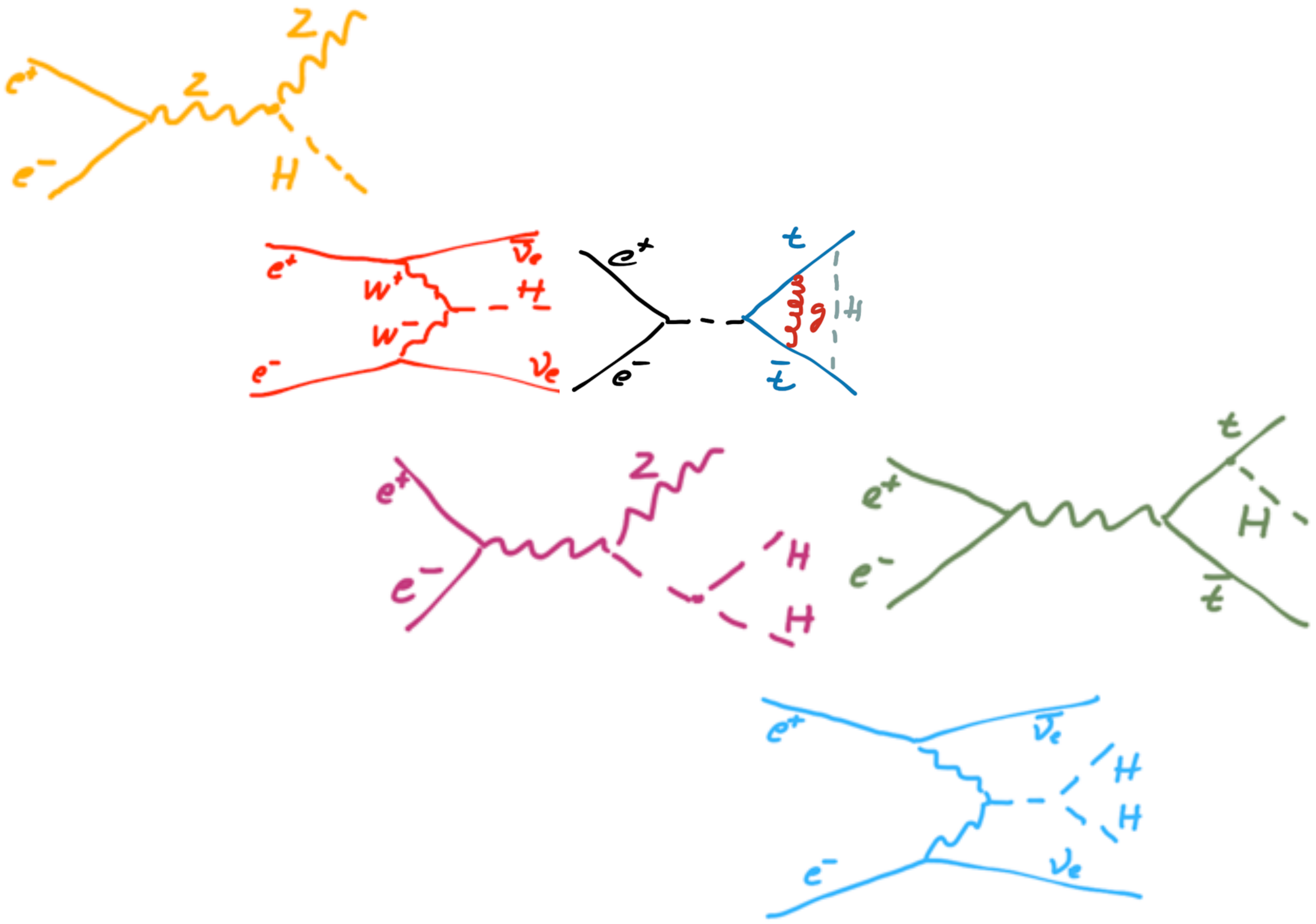


at each stage: Possibility to change focus / direction depending on results

total program ~ 25 years from first collisions



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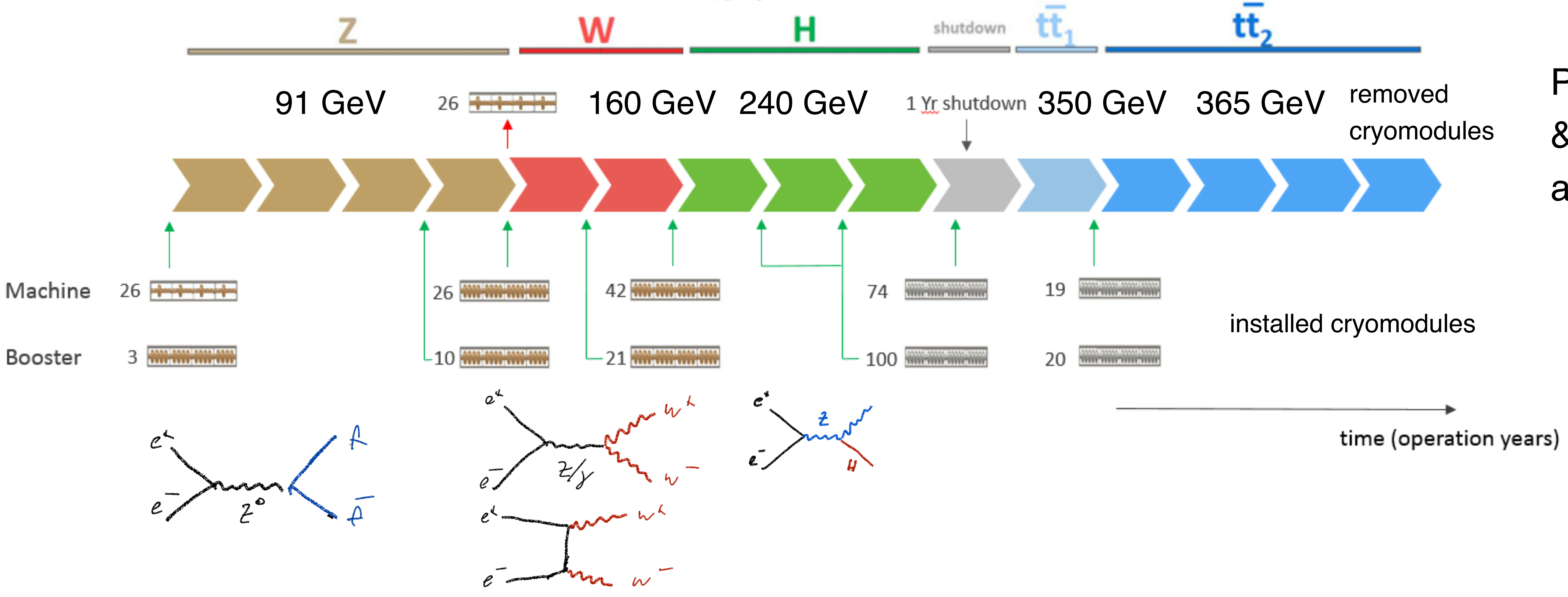
Electroweak Precision and Ultimate Energy Reach

A Circular Collider Story

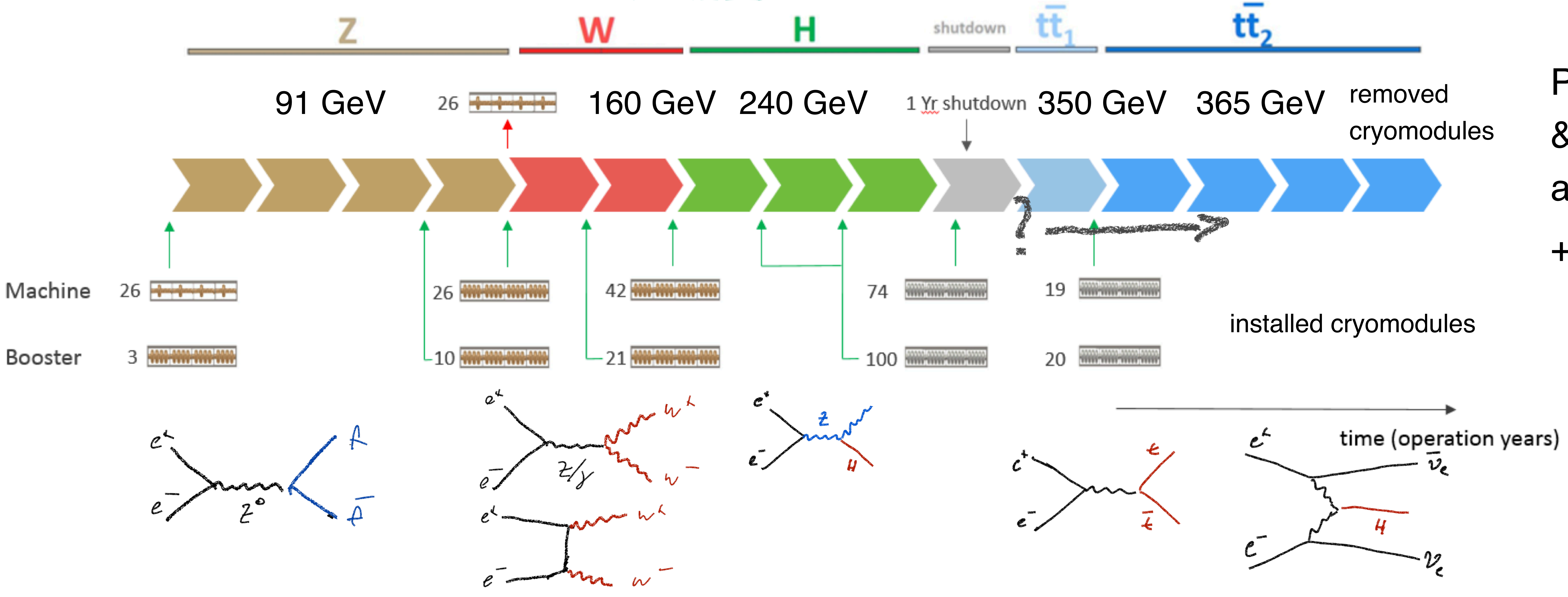
Karlsruhe Institute of Technology



Precision electroweak & Higgs program with an e^+e^- collider

Electroweak Precision and Ultimate Energy Reach

A Circular Collider Story



Precision electroweak & Higgs program with an e^+e^- collider

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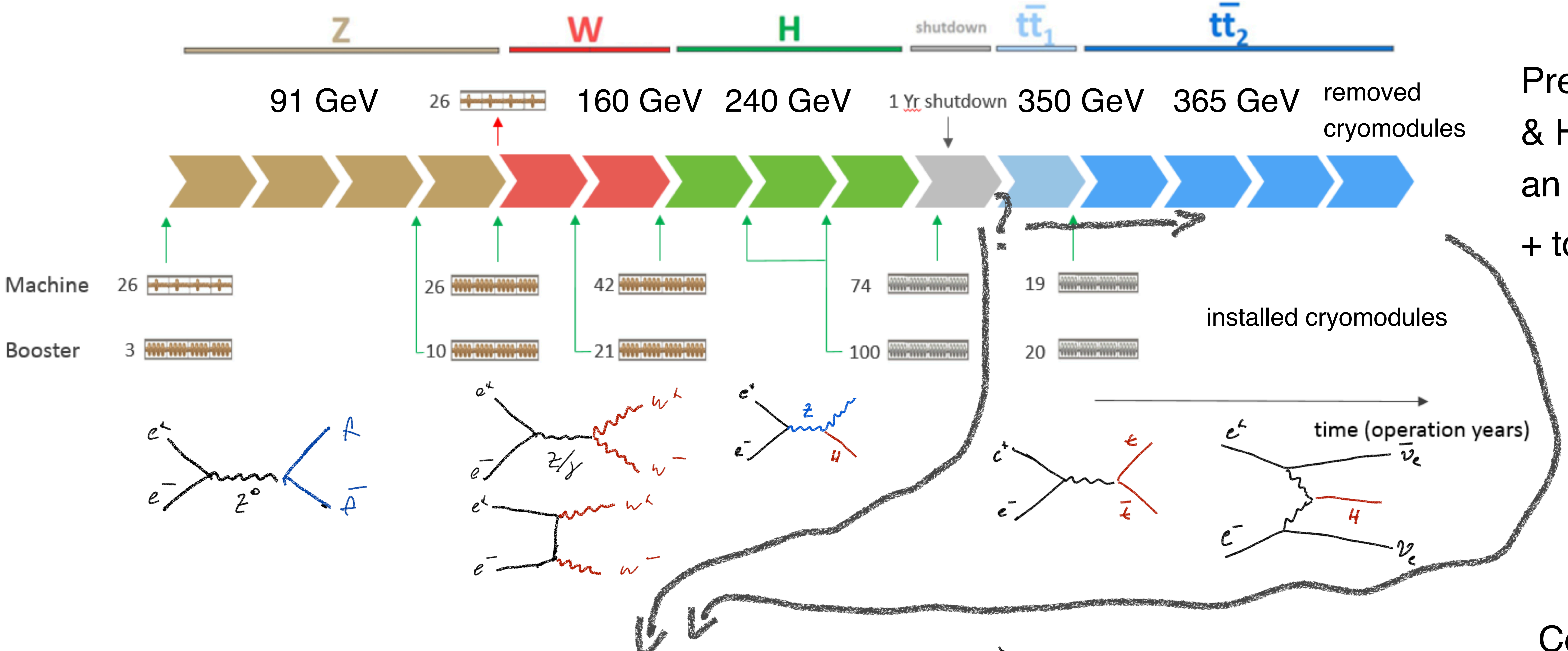

Precision electroweak & Higgs program with an e^+e^- collider

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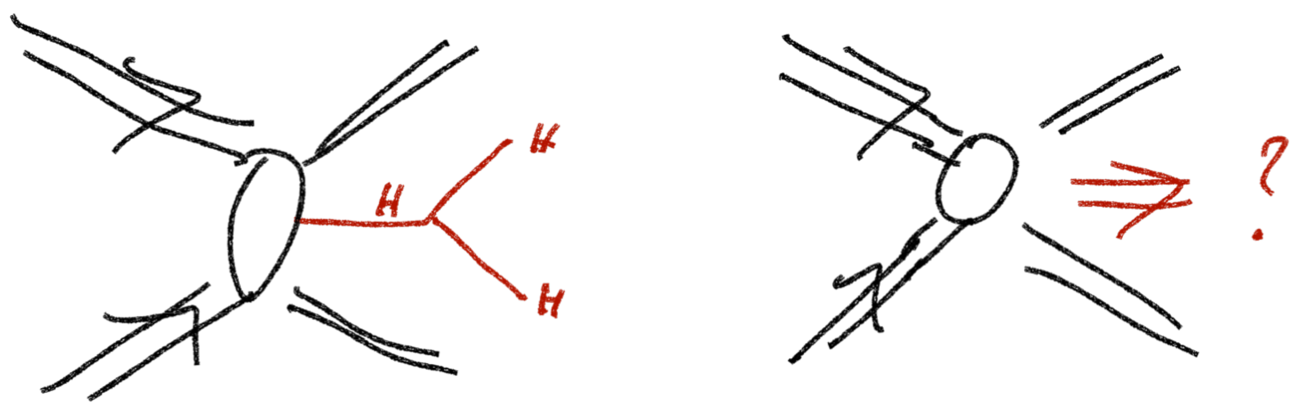
Installation of a hadron collider in the same tunnel (removal of lepton machine):

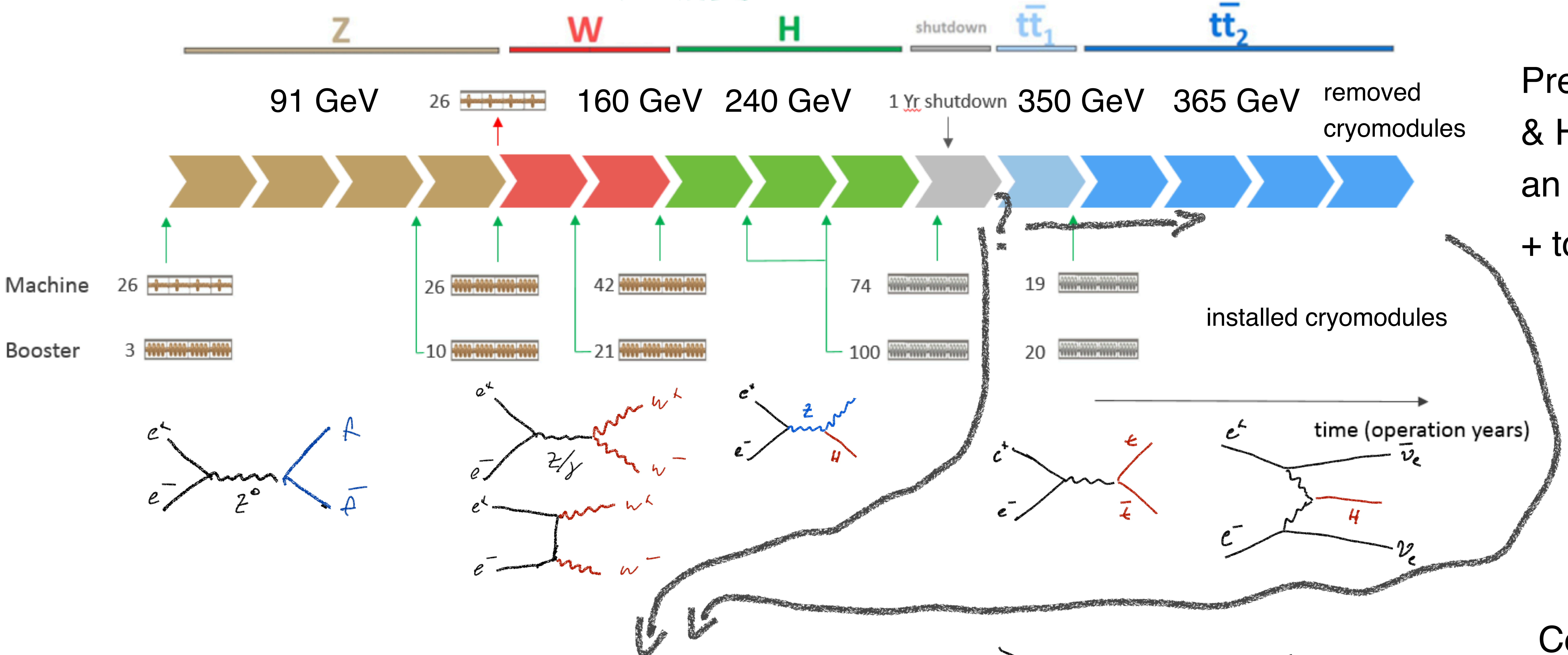
~10 year shutdown, then: **100(+) TeV** pp collisions



Completing the Higgs sector study, exploration of highest energy scales

Electroweak Precision and Ultimate Energy Reach

A Circular Collider Story



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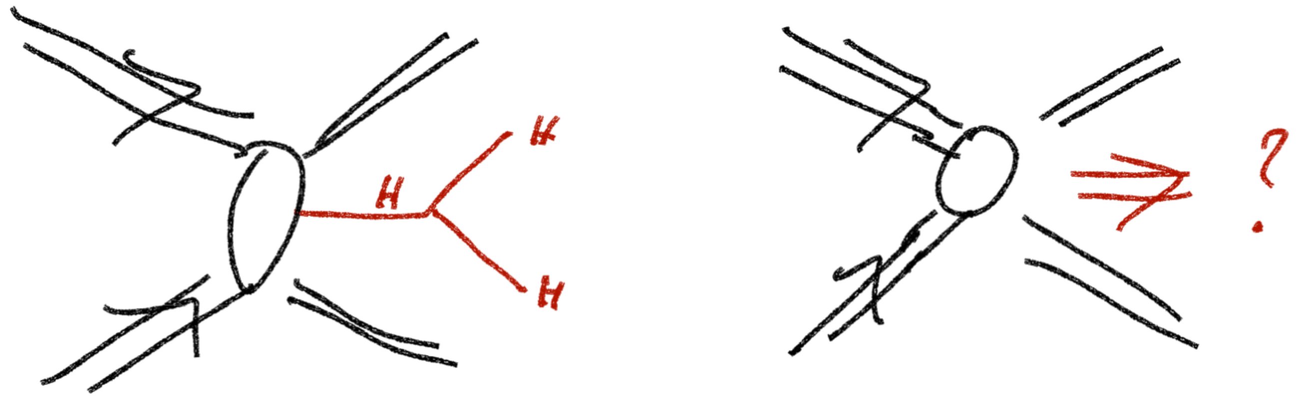


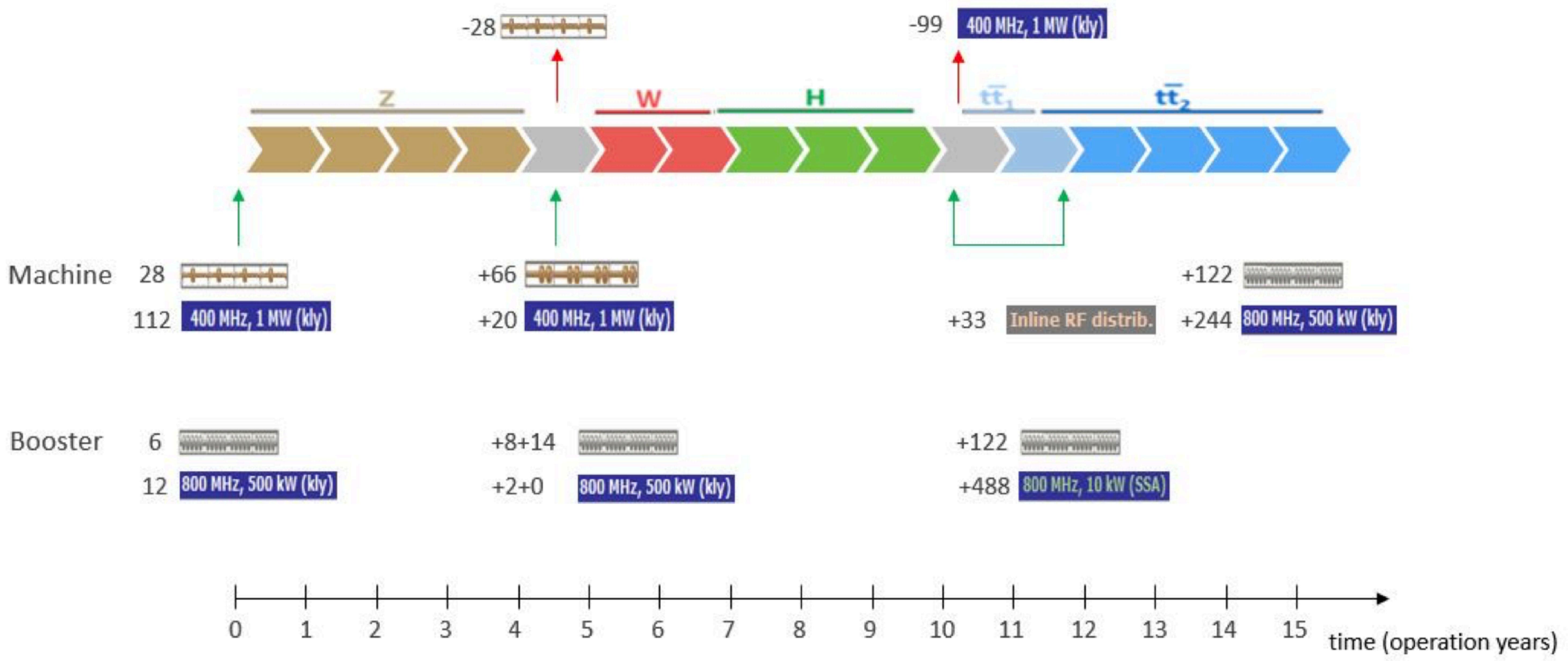
Completing the Higgs sector study, exploration of highest energy scales

together: 50+ years from first e^+e^- collisions to completion of pp program

Flexibility in Energy Sequence

A Balance between Physics Interest and Accelerator Technology Constraints

- Options are being studied:



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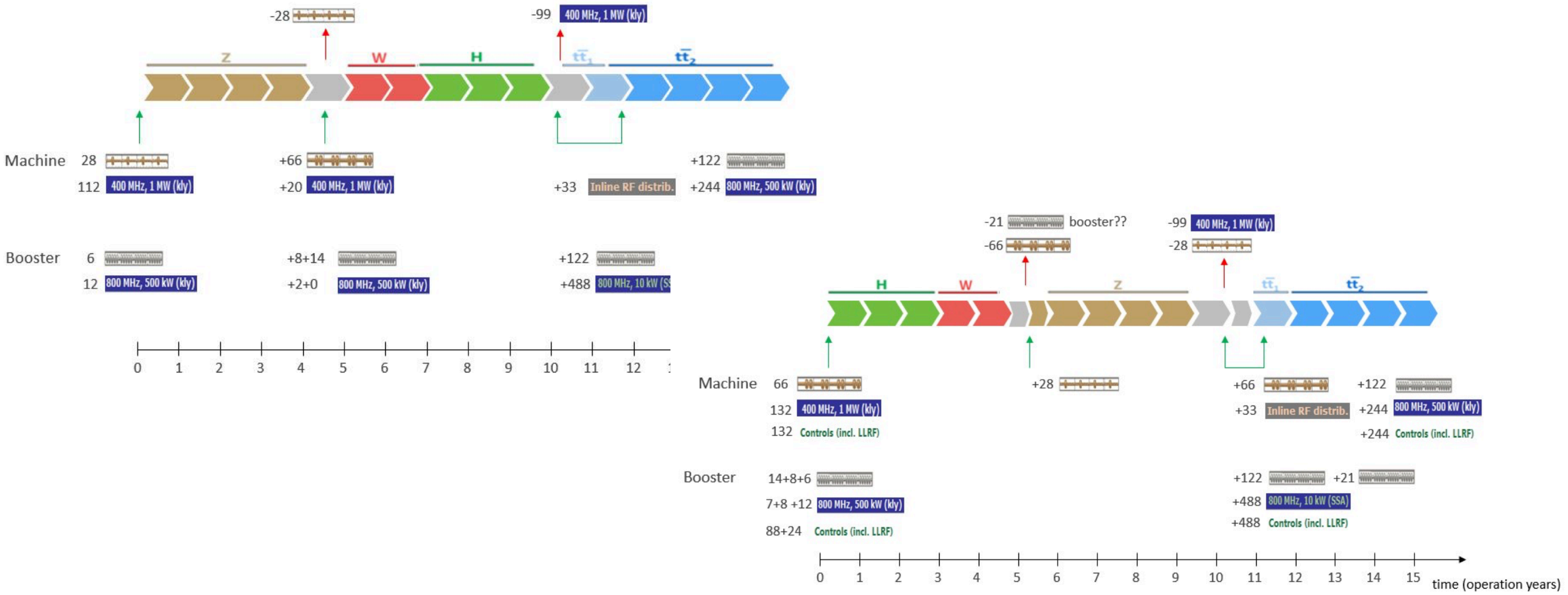

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Karlsruhe Institute of Technology

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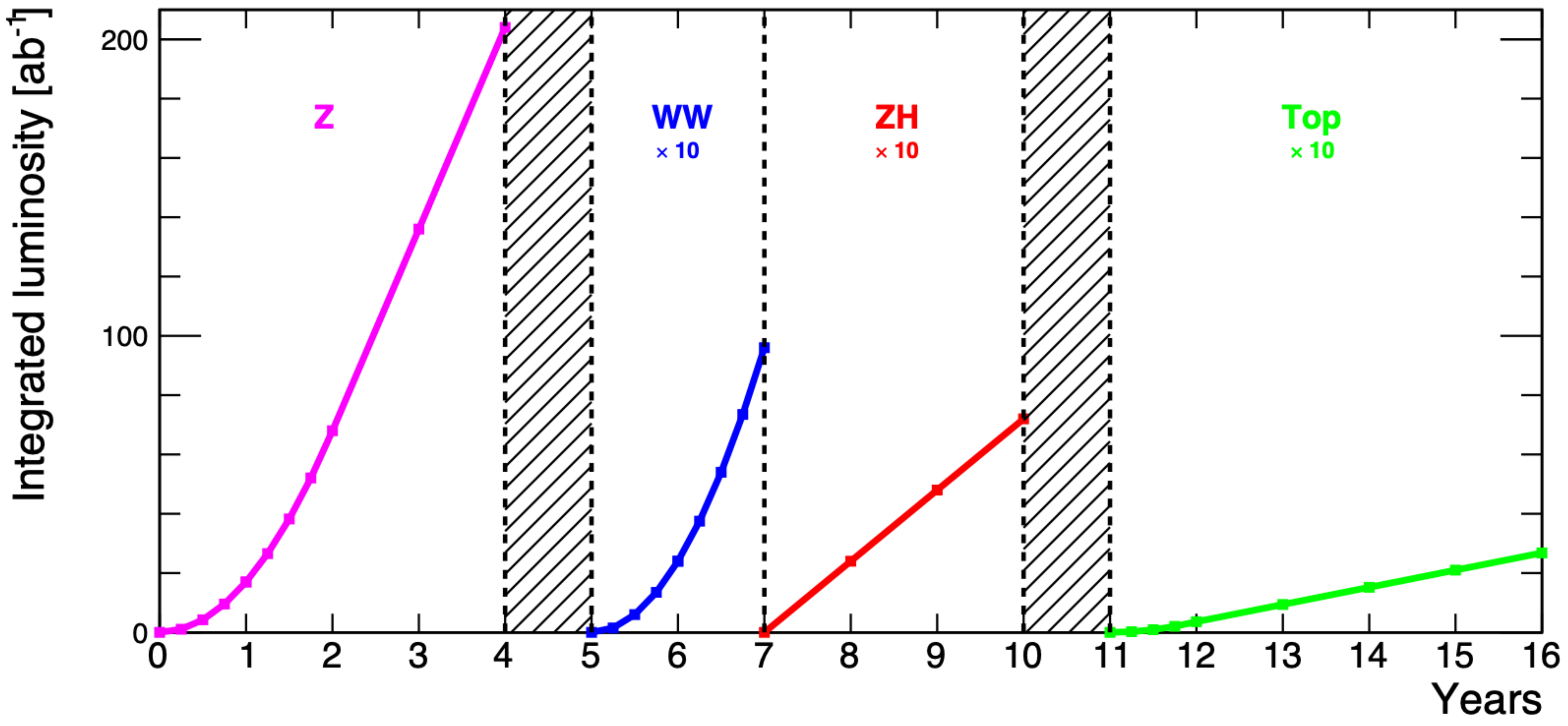

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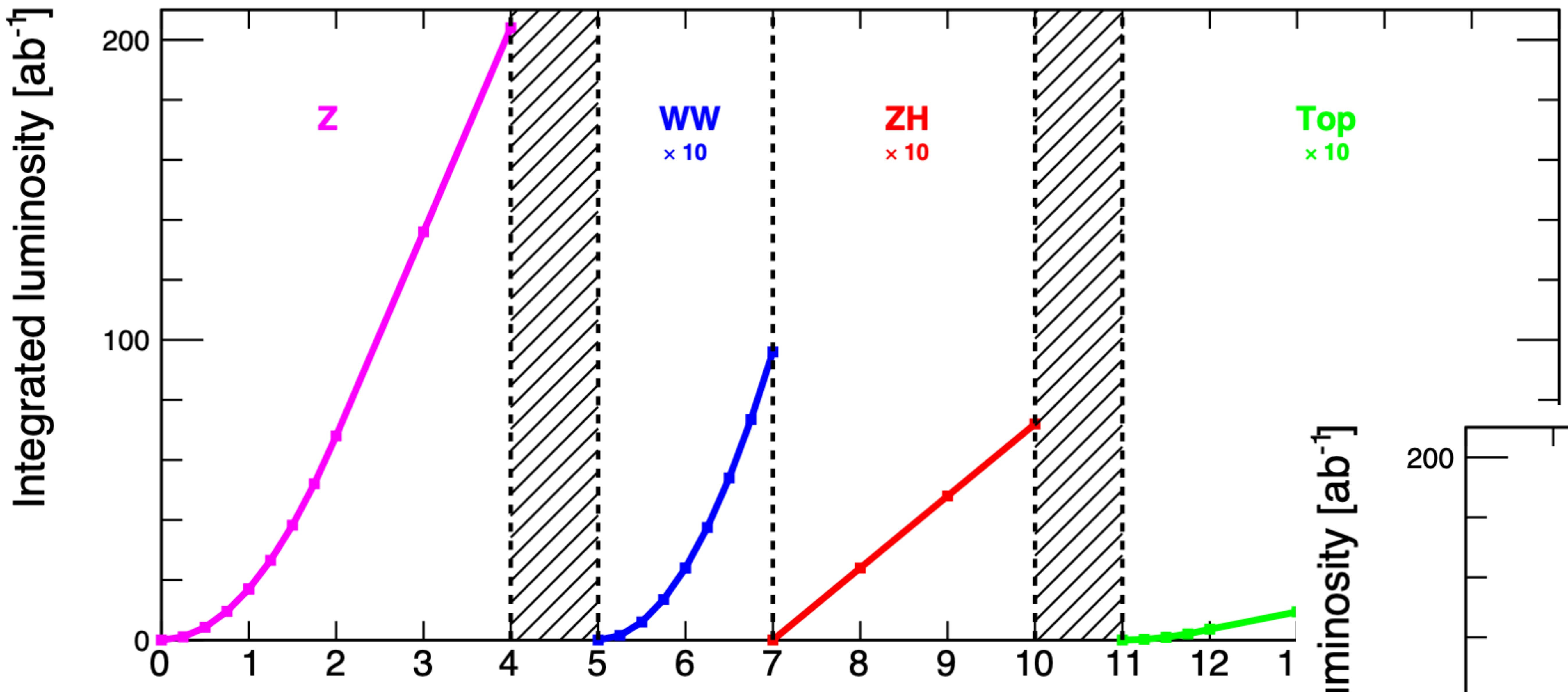
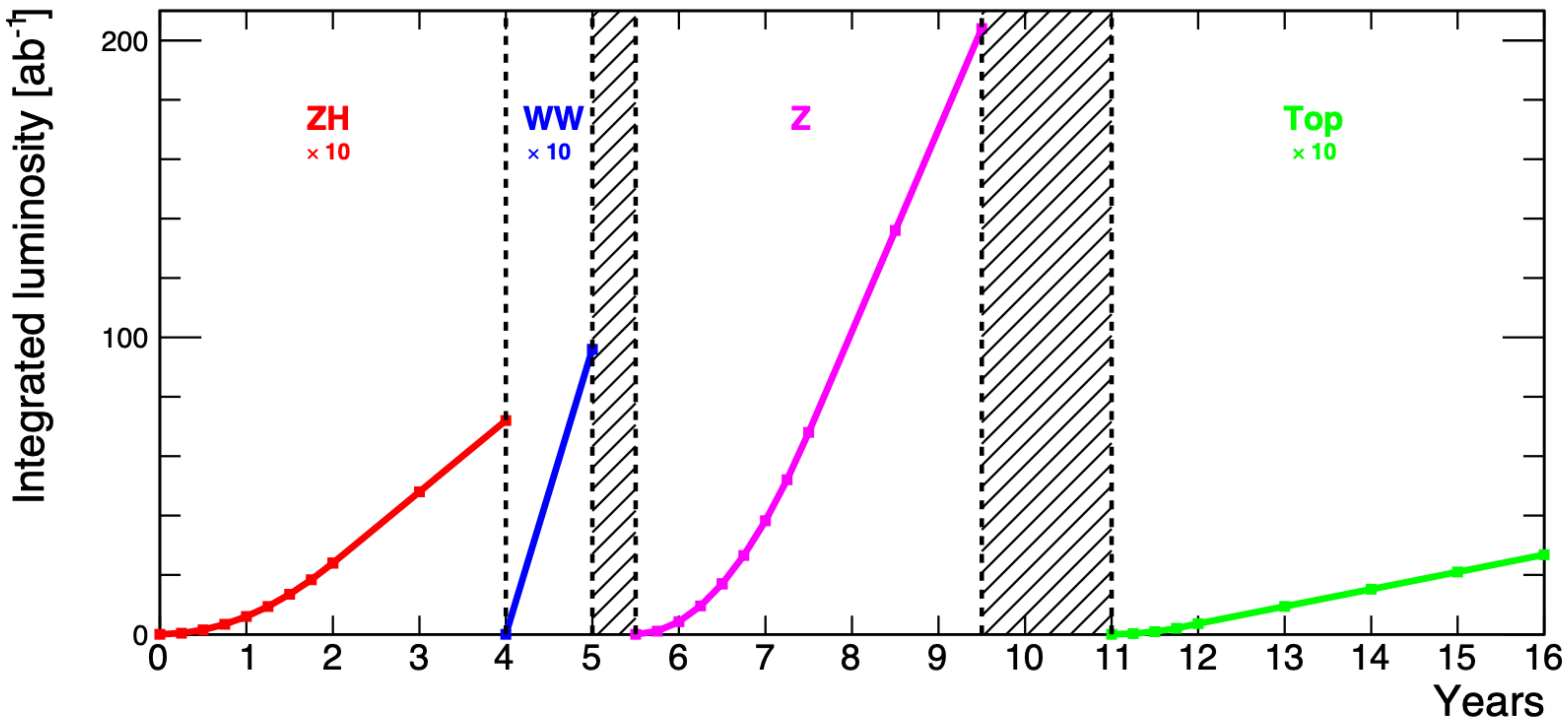




Lecture 1 Wrap-up

Conclusions

Key Points Part 1

- Lepton and hadron colliders have been instrumental in firmly establishing the Standard Model. The next generation of experiments needs to show where it breaks.

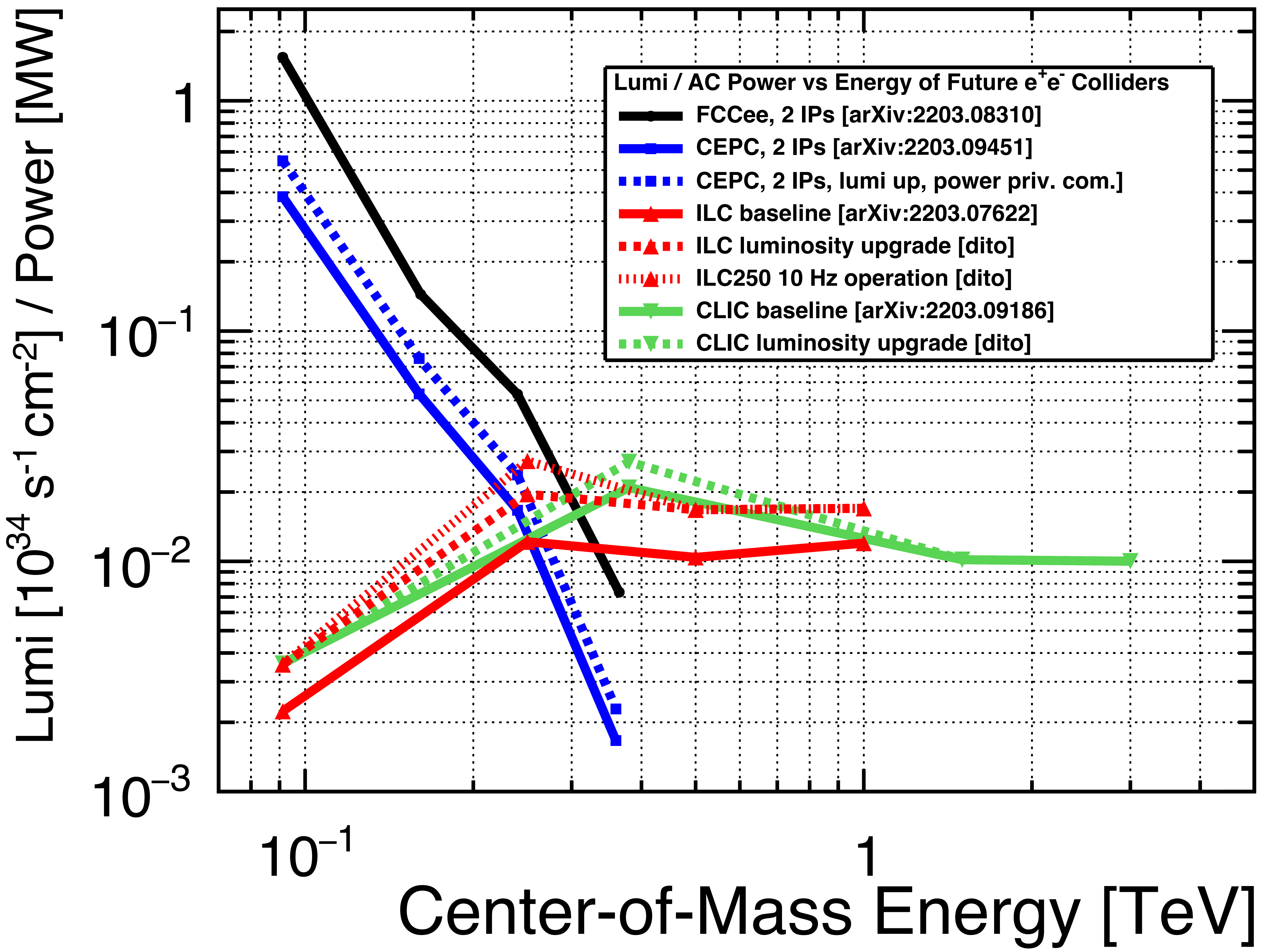
- Global agreement: a e^+e^- Higgs-Elektroweak-Top Factory as the next step:
  - A new era of precision measurements, profiting from benign background conditions, well-defined initial state, and low physics backgrounds.
    Qualitative differences wrt to (HL-)LHC - features such as model-independent Higgs boson measurements
  - Different possible realisations - linear or circular, each with specific strengths and weaknesses

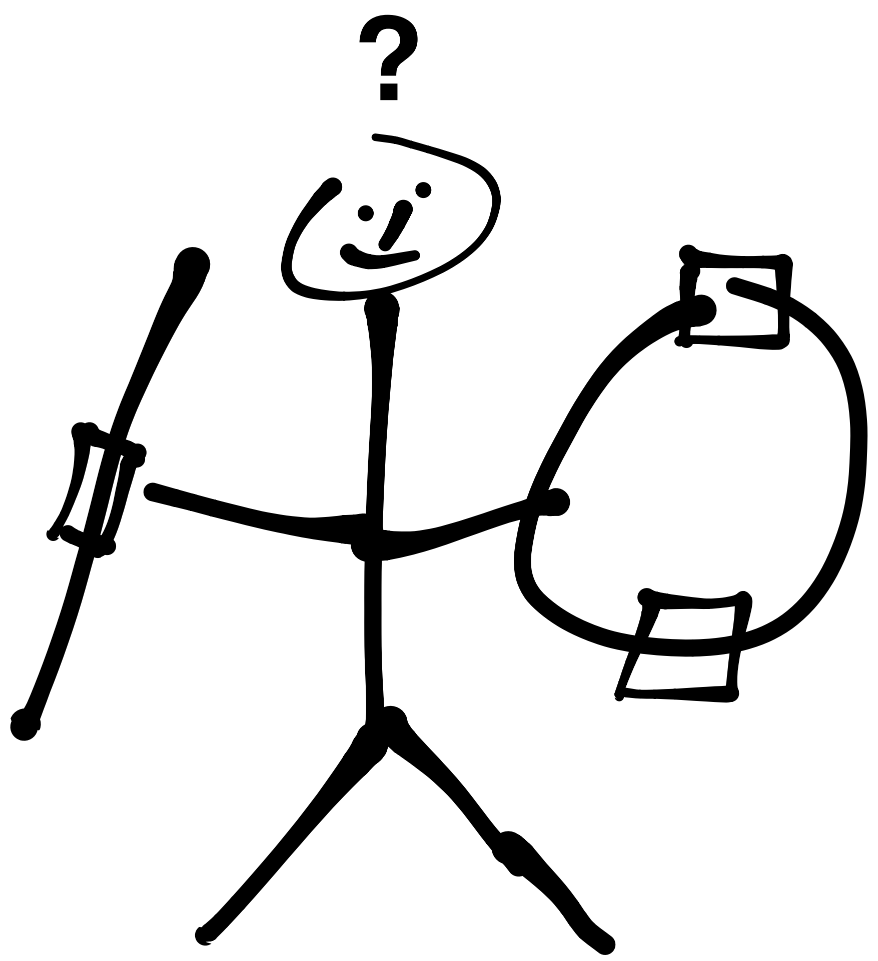
Perspectives: Physics Emphasis & Collider Geometry

In broad strokes

- e^+e^- collider geometry determines experimental focus beyond the core Higgsstrahlung program:

Circular:
extreme statistics at the Z pole and W threshold: precision electroweak

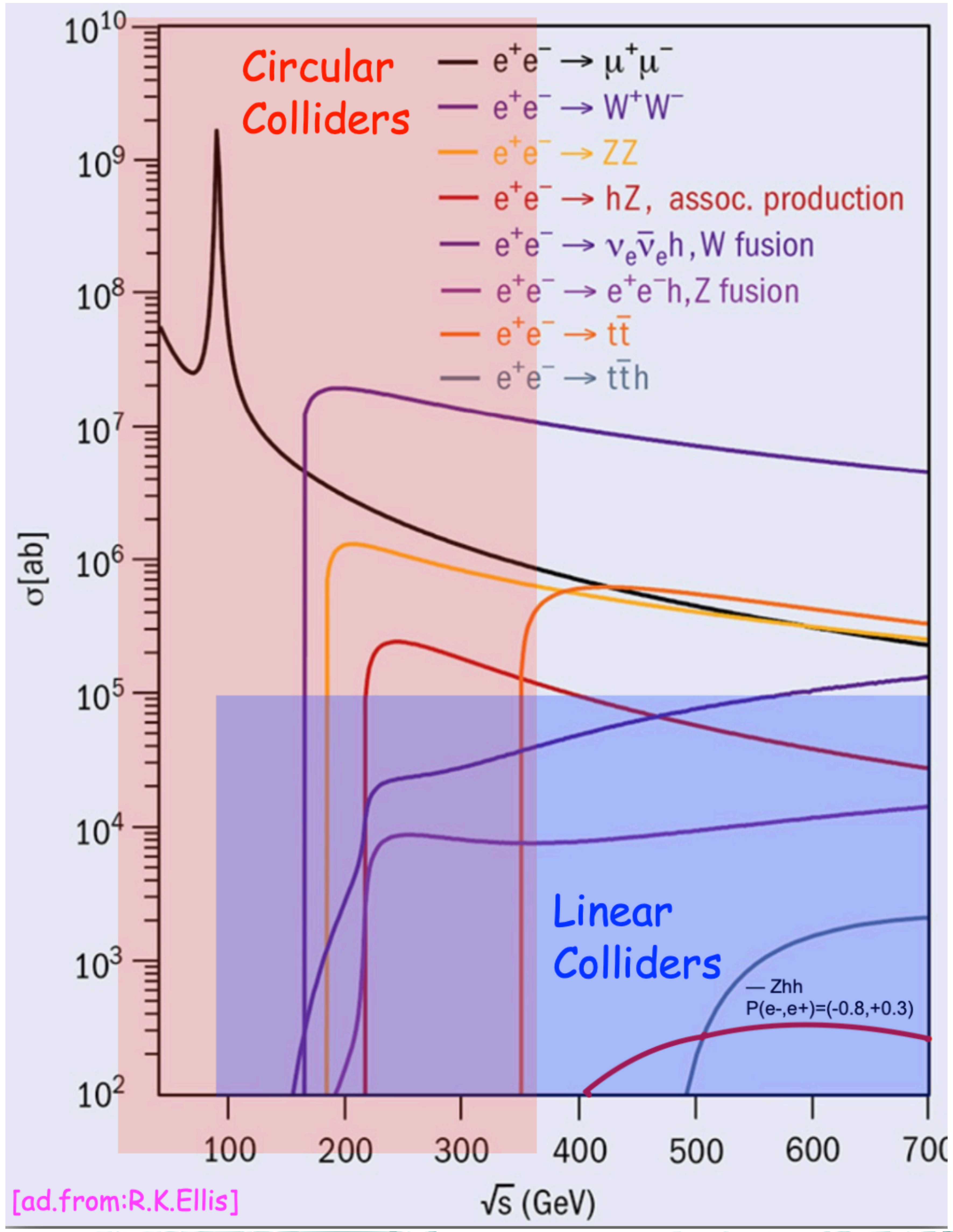


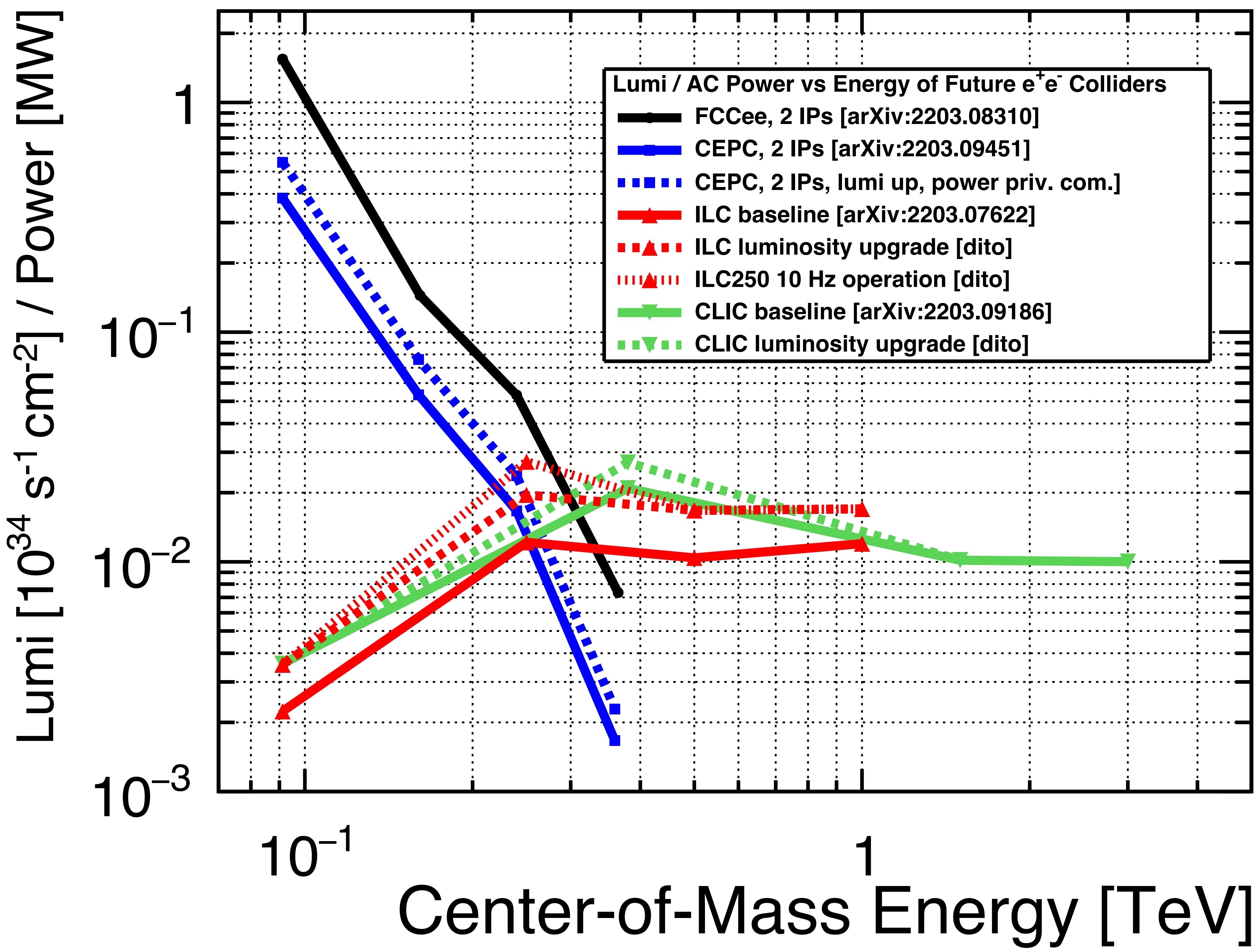


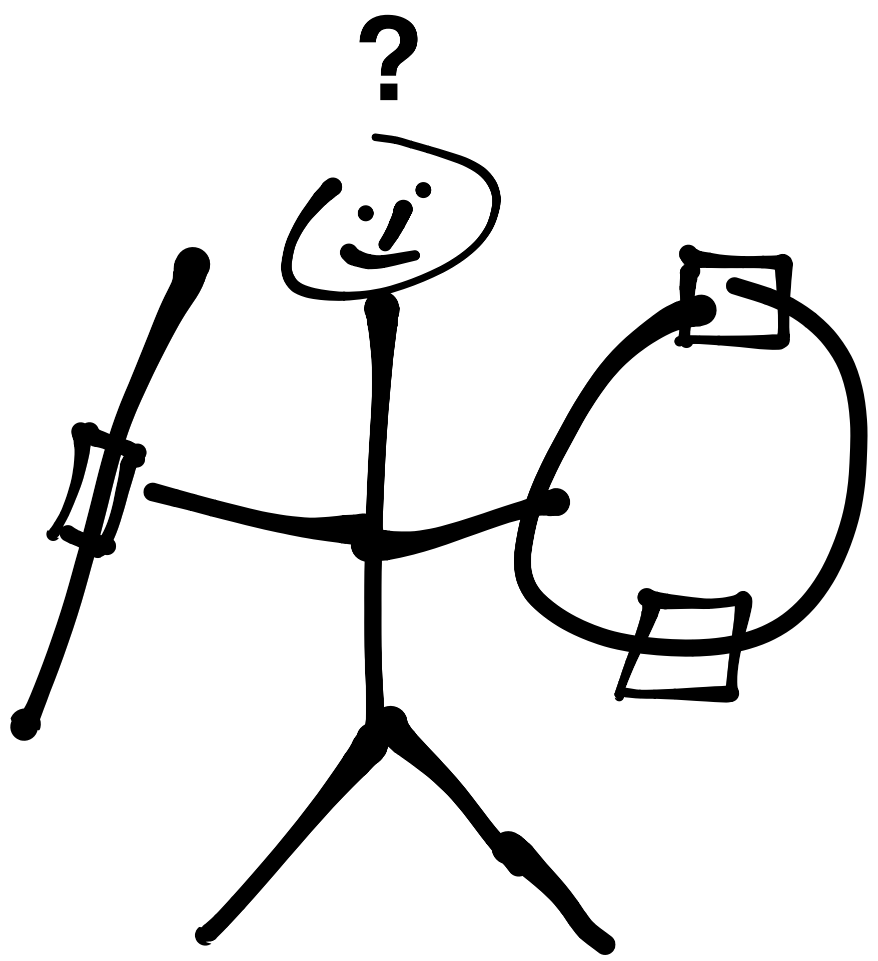
Linear:
reach to (multi-)TeV energy - double higgs production, high energy exploration

Perspectives: Physics Emphasis & Collider Geometry

In broad strokes







- Circular colliders: 3 orders of magnitude more Z's: Tera-Z vs Giga-Z
- Both: Similar at Higgs, top threshold (also consider polarisation!)
- Linear colliders: The only path (significantly) beyond tt with e^+e^- ttH, direct measurement of Higgs self coupling, extended BSM reach