Physics at Future e^+e^- Colliders

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LHCP, virtual Taipeh
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2022
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TAIPEI

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The Big Picture

Where we are

- Over the last ~ three decades, a consistent view of the fundamental principles of the largest structures and smaller constituents of our Universe have been established

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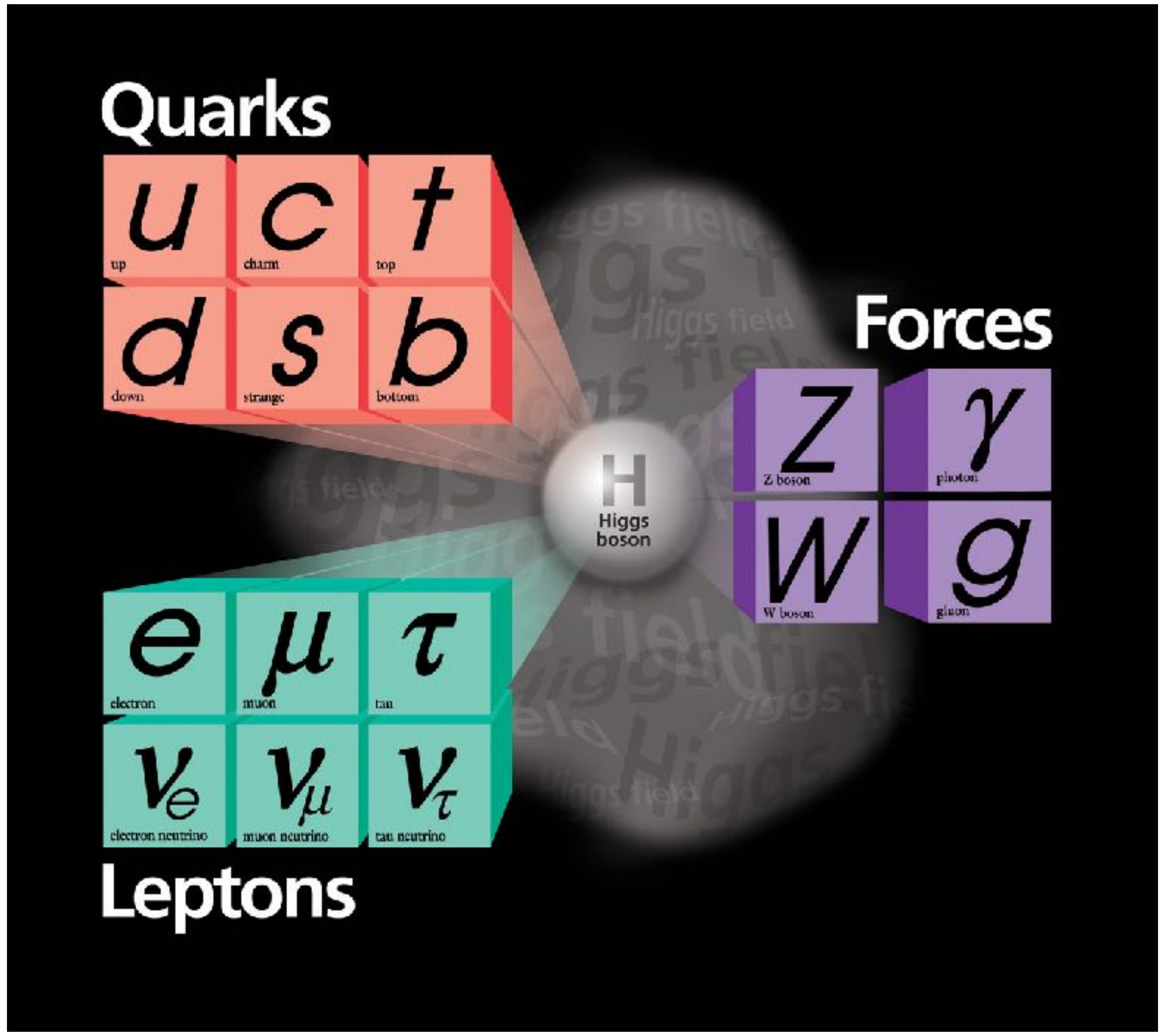

The Standard Model of Particle Physics describing the “Micro-World”

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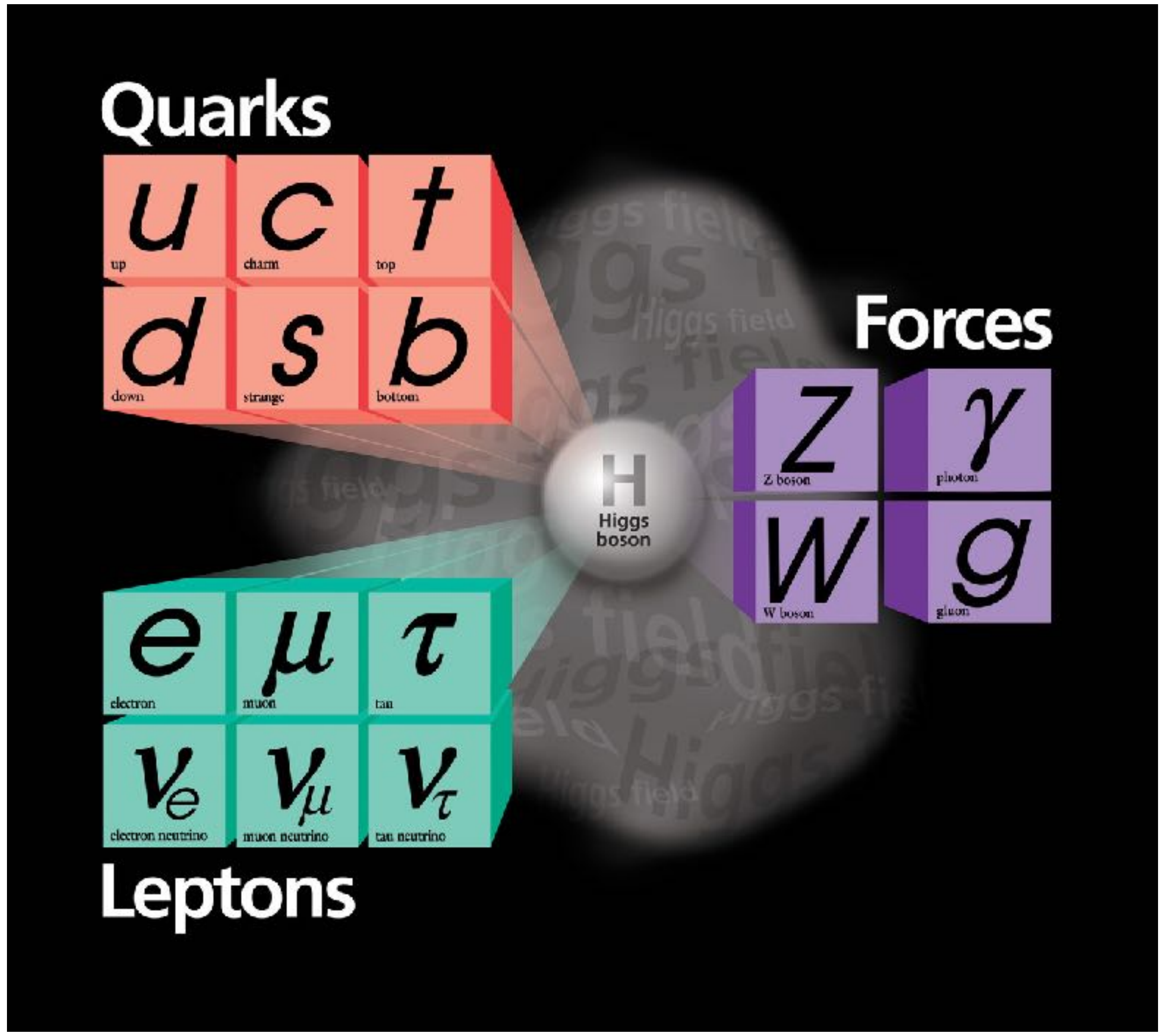

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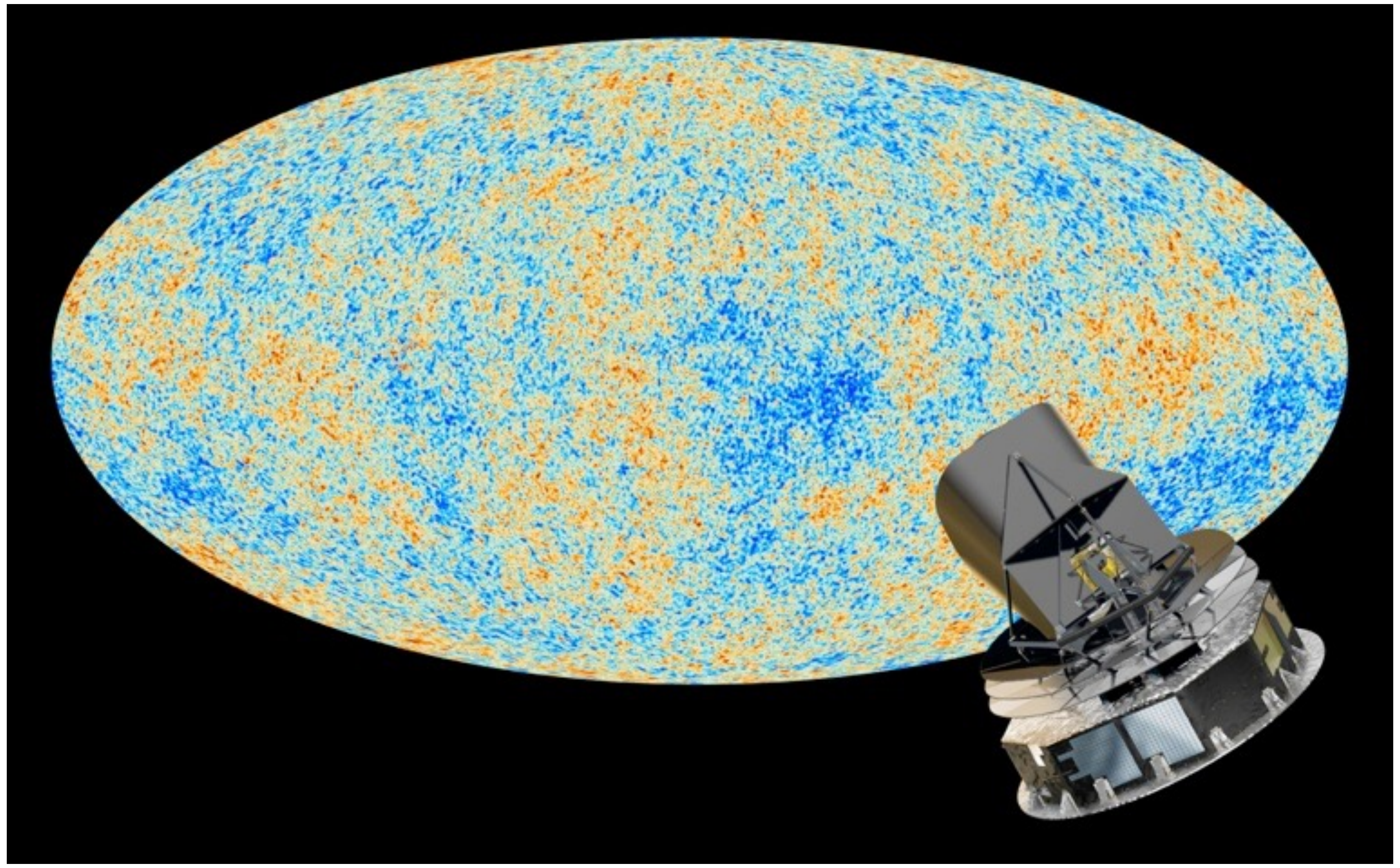

ΛCDM + Inflation

The Standard Model of Cosmology describing the evolution of the Universe

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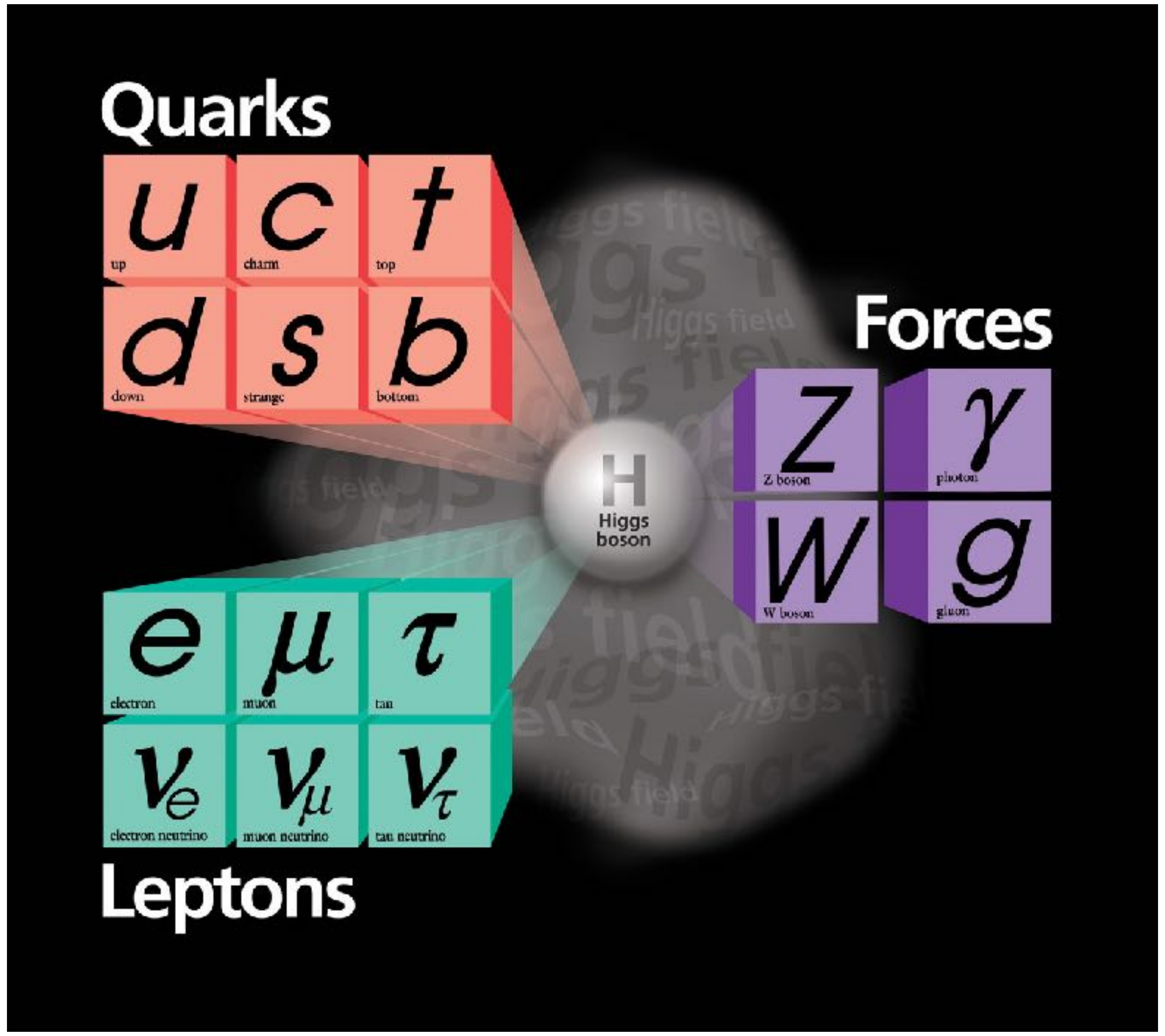

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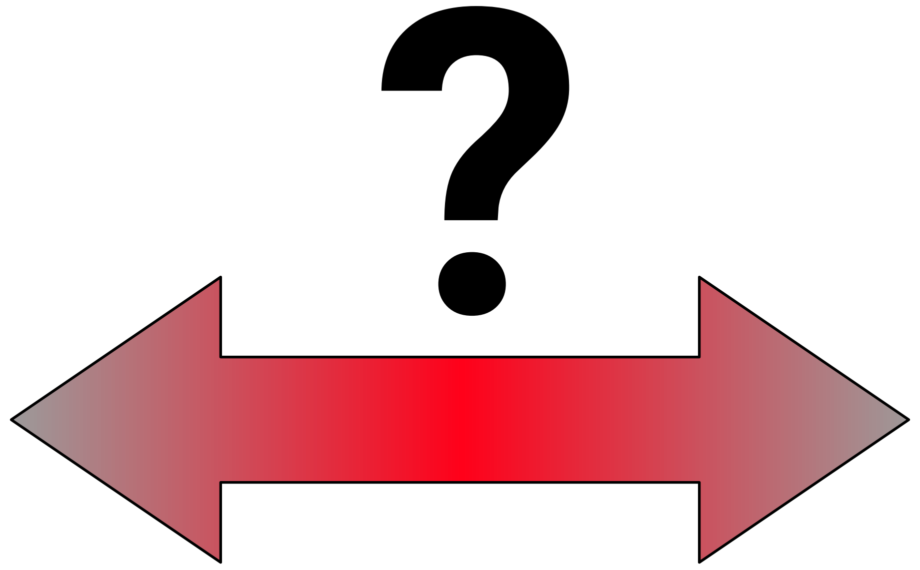

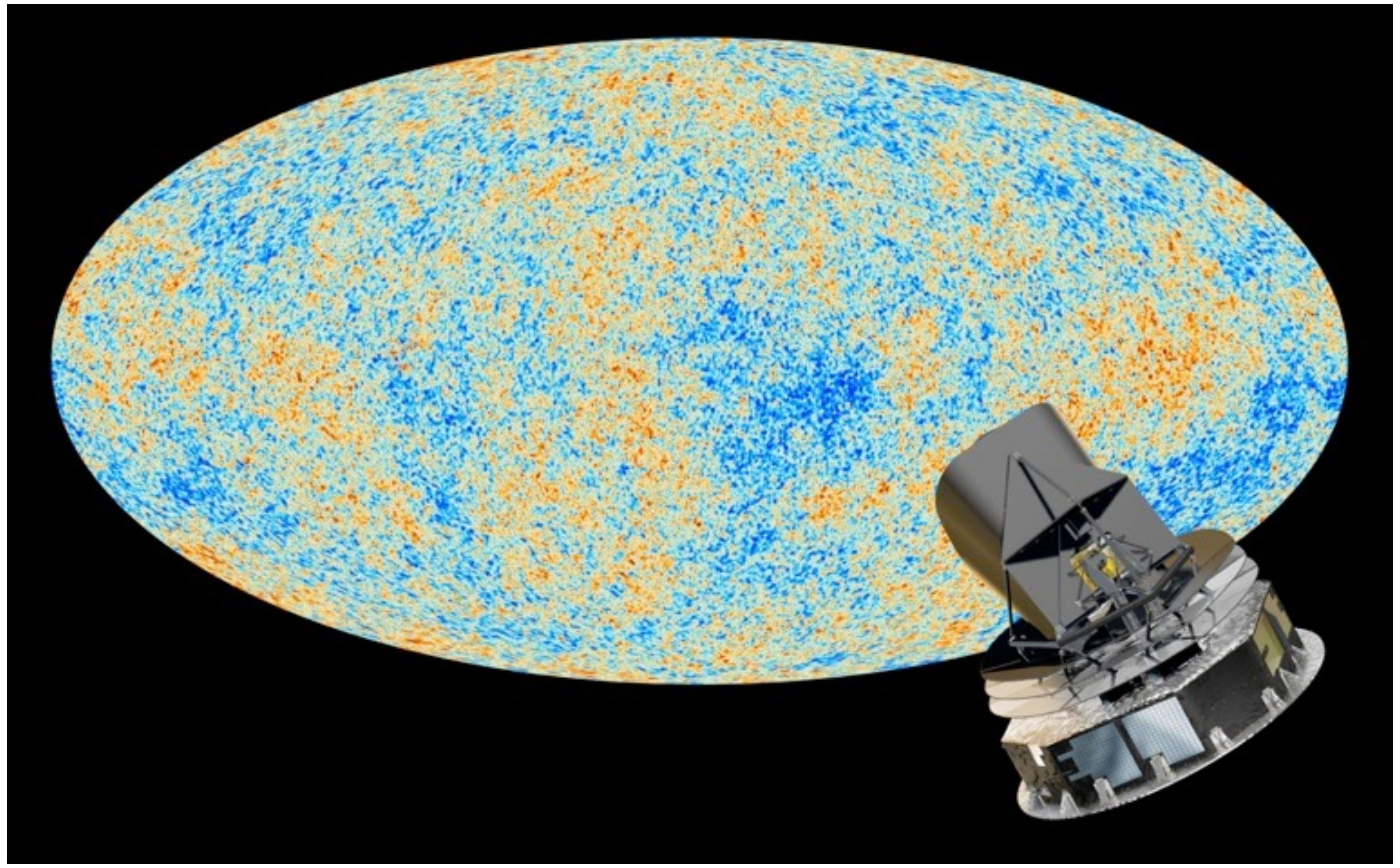

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The Big Questions

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

The Big Successes

How we got to where we are

SPEAR / AGS 1974

Fermilab 1977

Tevatron 1995

AGS 1962

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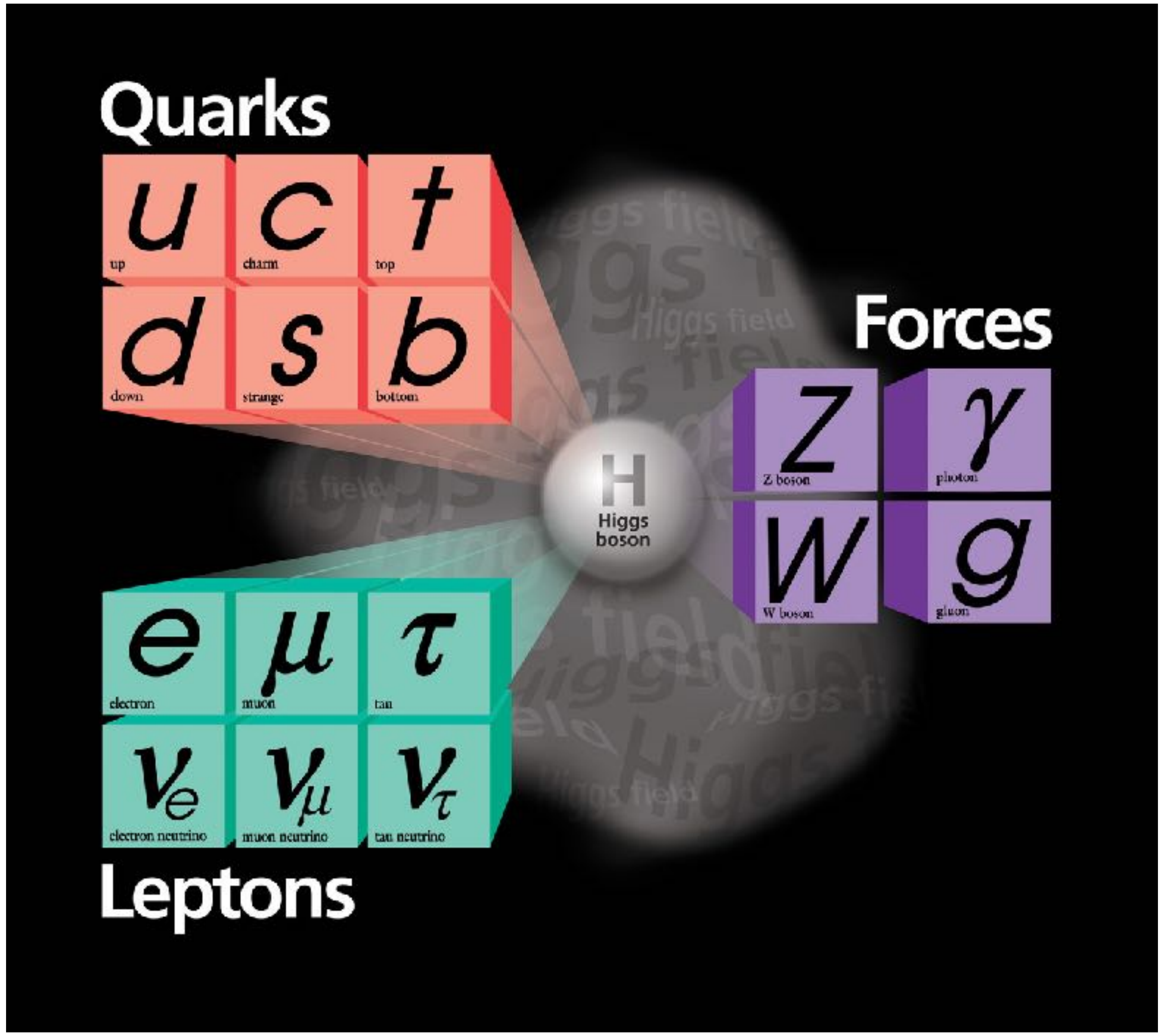
Fermilab 2000



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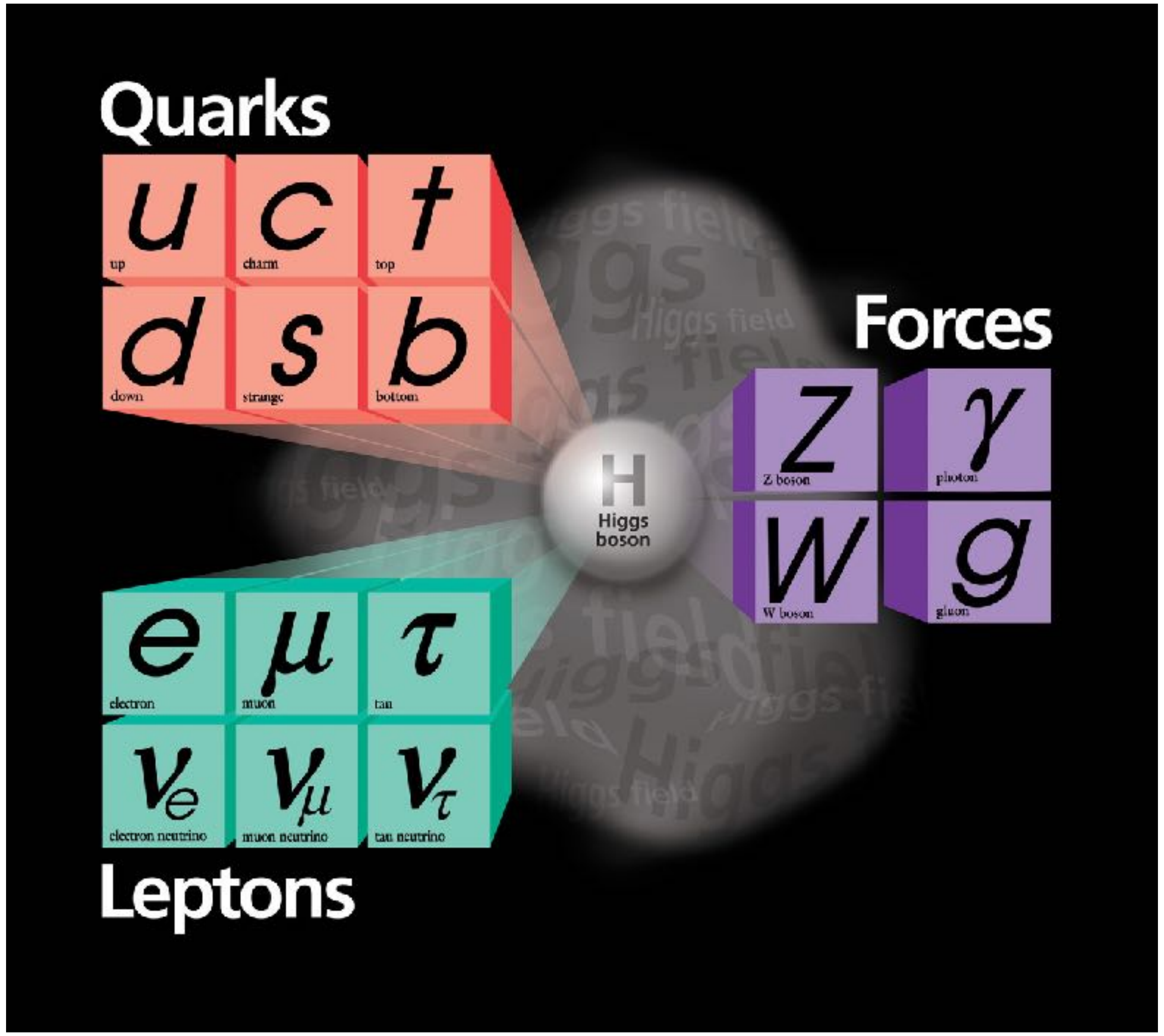

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A success story of HEP.
The result of:

- generations of accelerators: colliders and fixed target; leptons and hadrons
- generations of detectors with a wide range of different technologies
- the interplay of experiment and theory

Providing testable predictions, which informed the next generation of experiments.

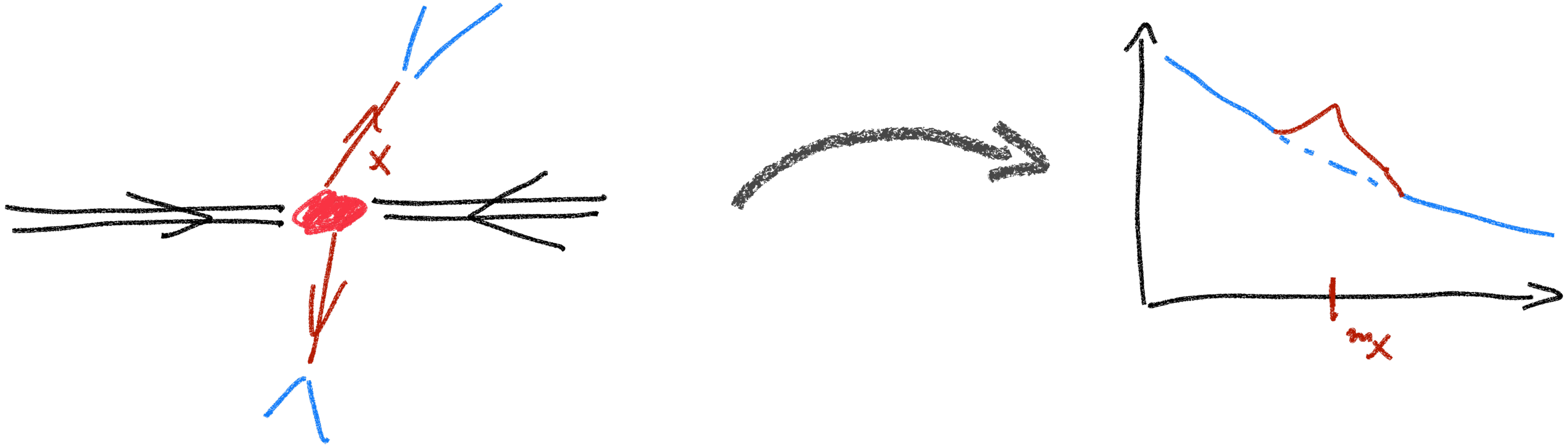
Where to go from here

- 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

The Business Model

Strategies for Discoveries



Direct observation of new particles: Requires sufficient energy for production

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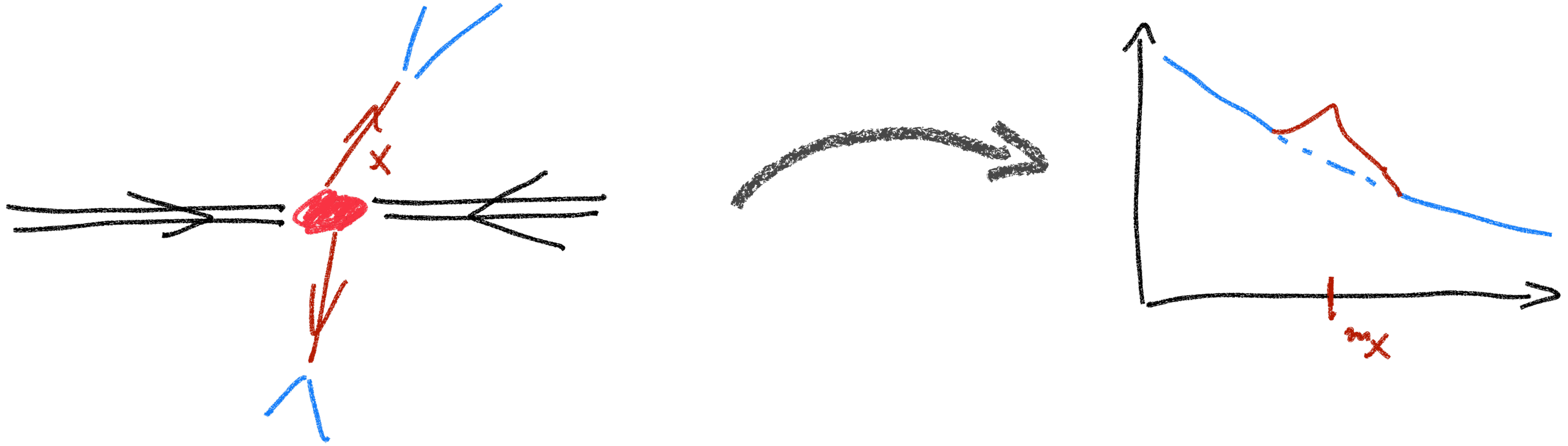

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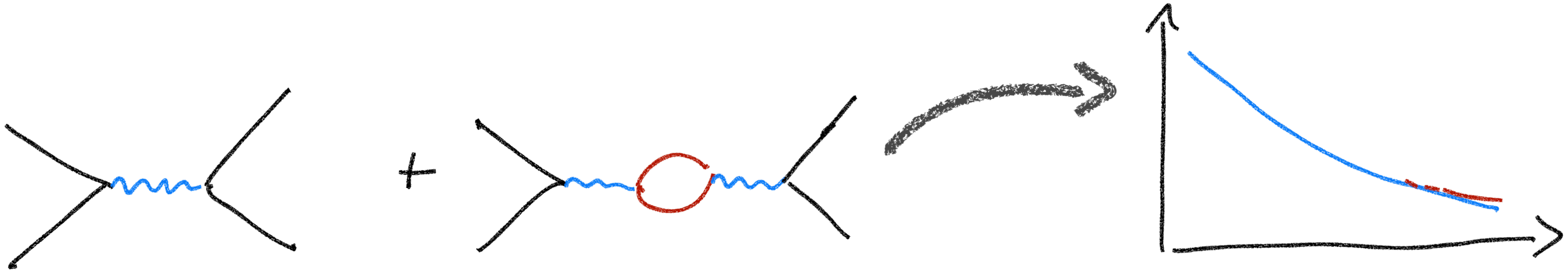


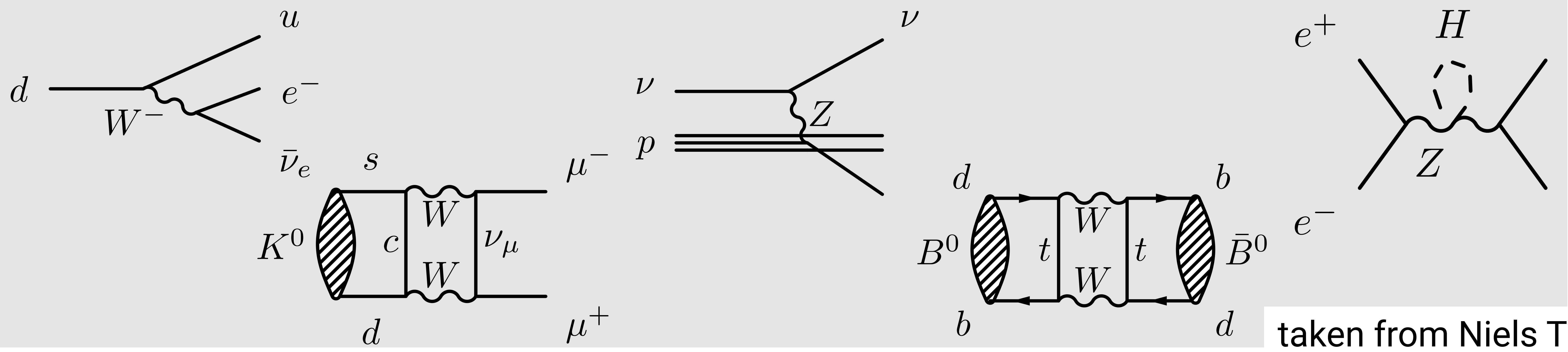
Indirect discovery: Deviations from expectation hinting at new phenomena at (much) higher energy scale

The Case for Precision Measurements

An established discovery strategy - getting guidance early

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	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

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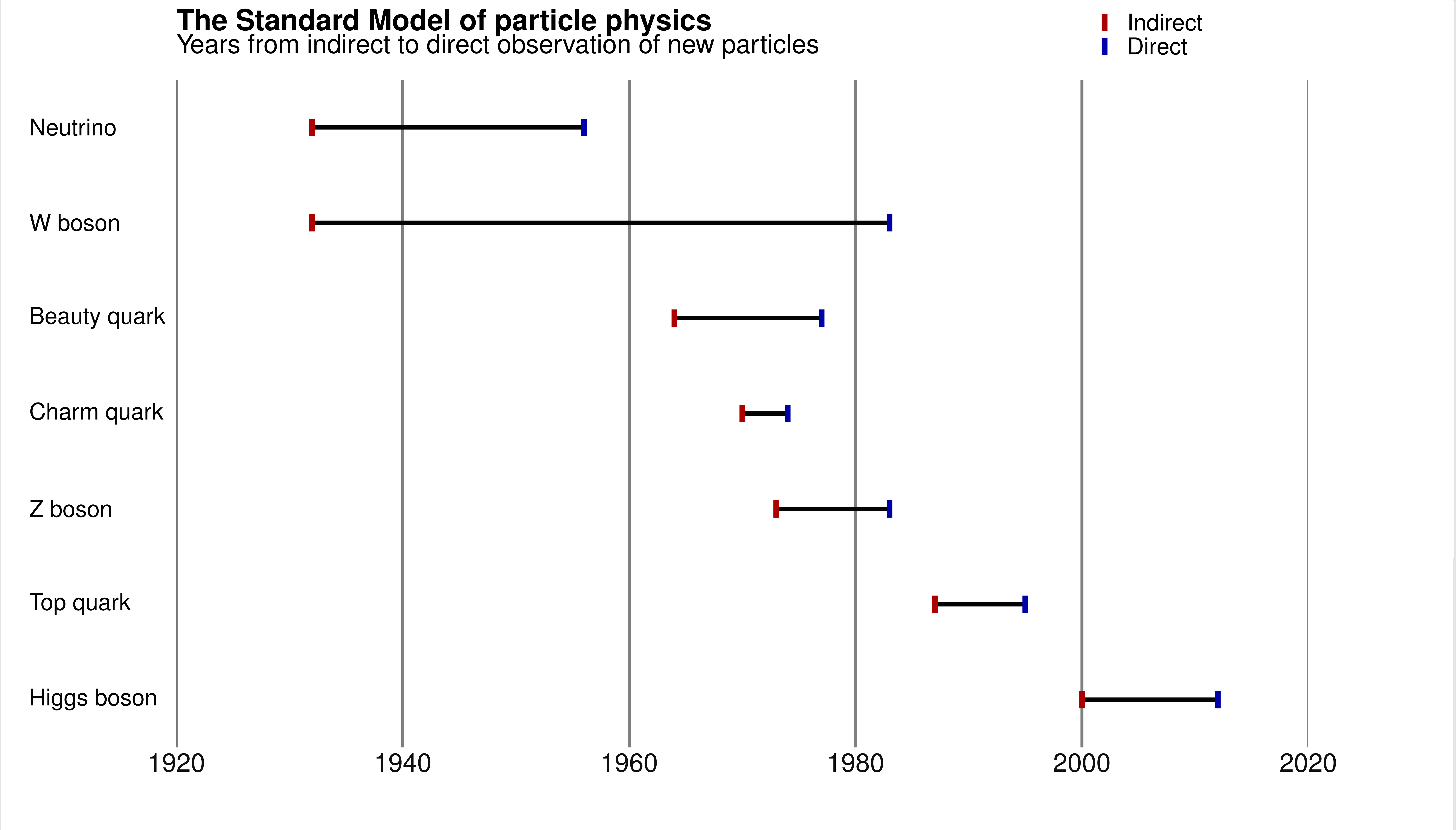

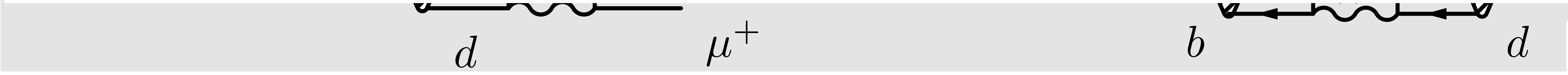

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reaching higher scales: direct discoveries only follow with new generations of experiments

taken from Niels Turing, ICHEP 2018

A Higgs Factory

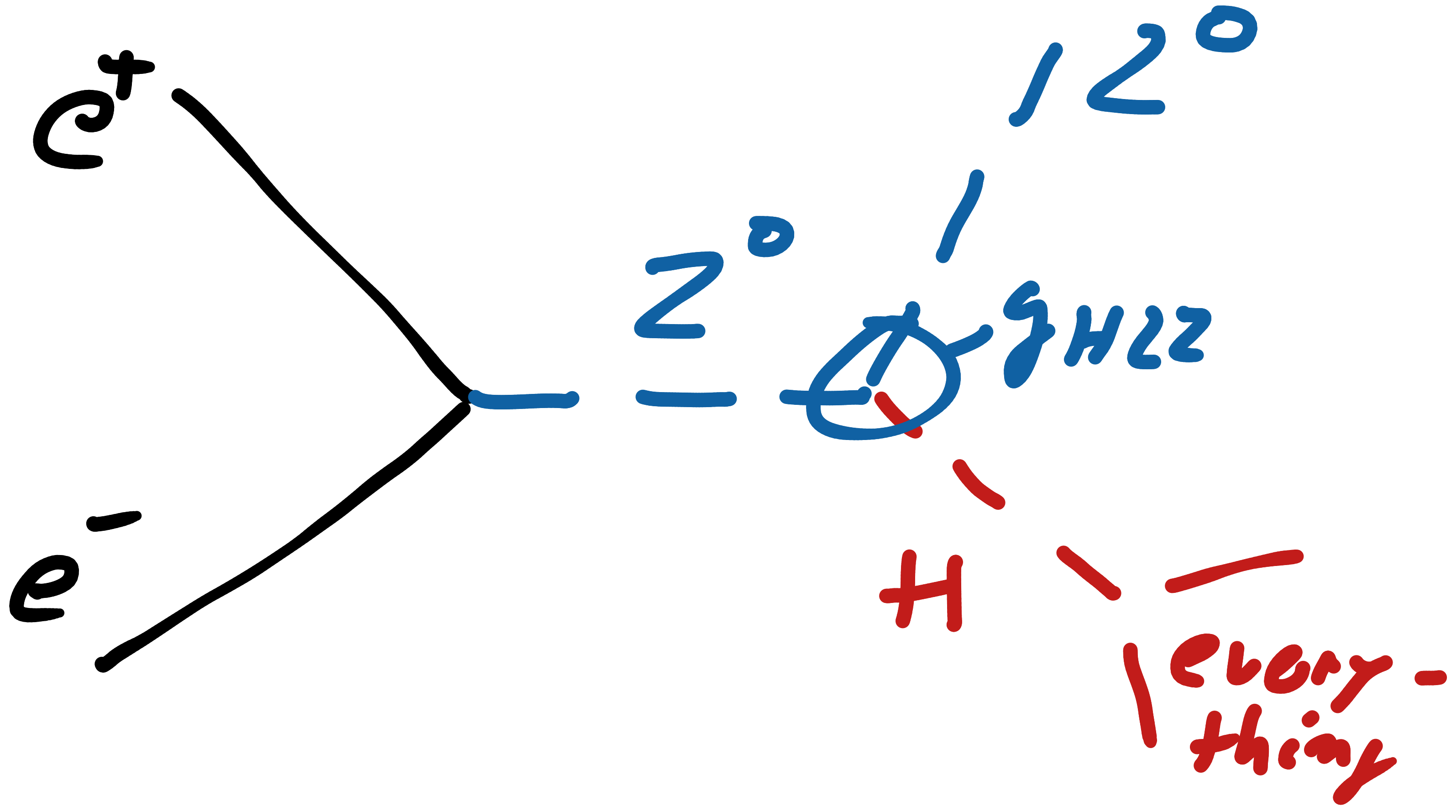
An Energy Frontier e^+e^- Collider

Higgs-Strahlung

The key process

- The unique feature of e^+e^- colliders: *model independence*

knowing the
initial state…



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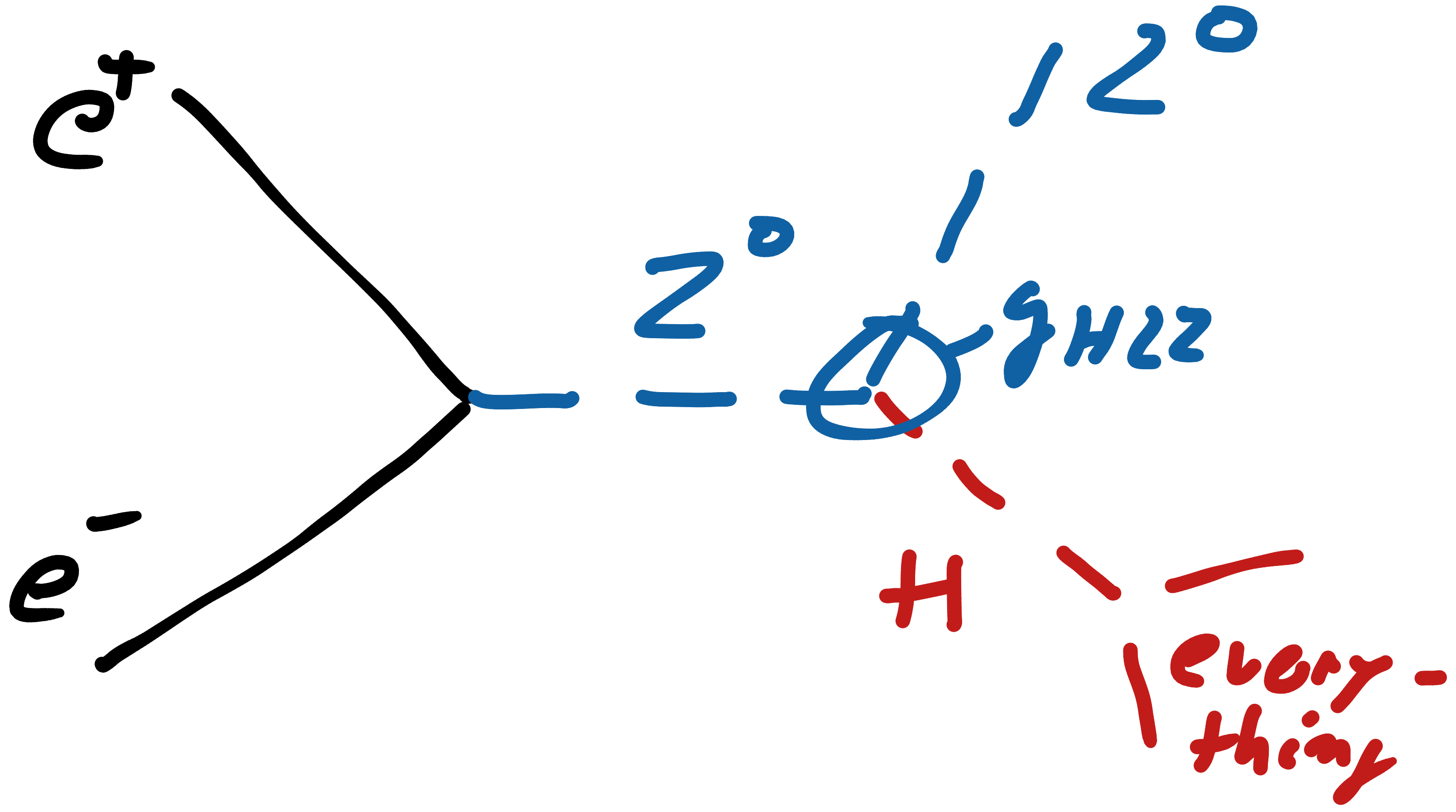

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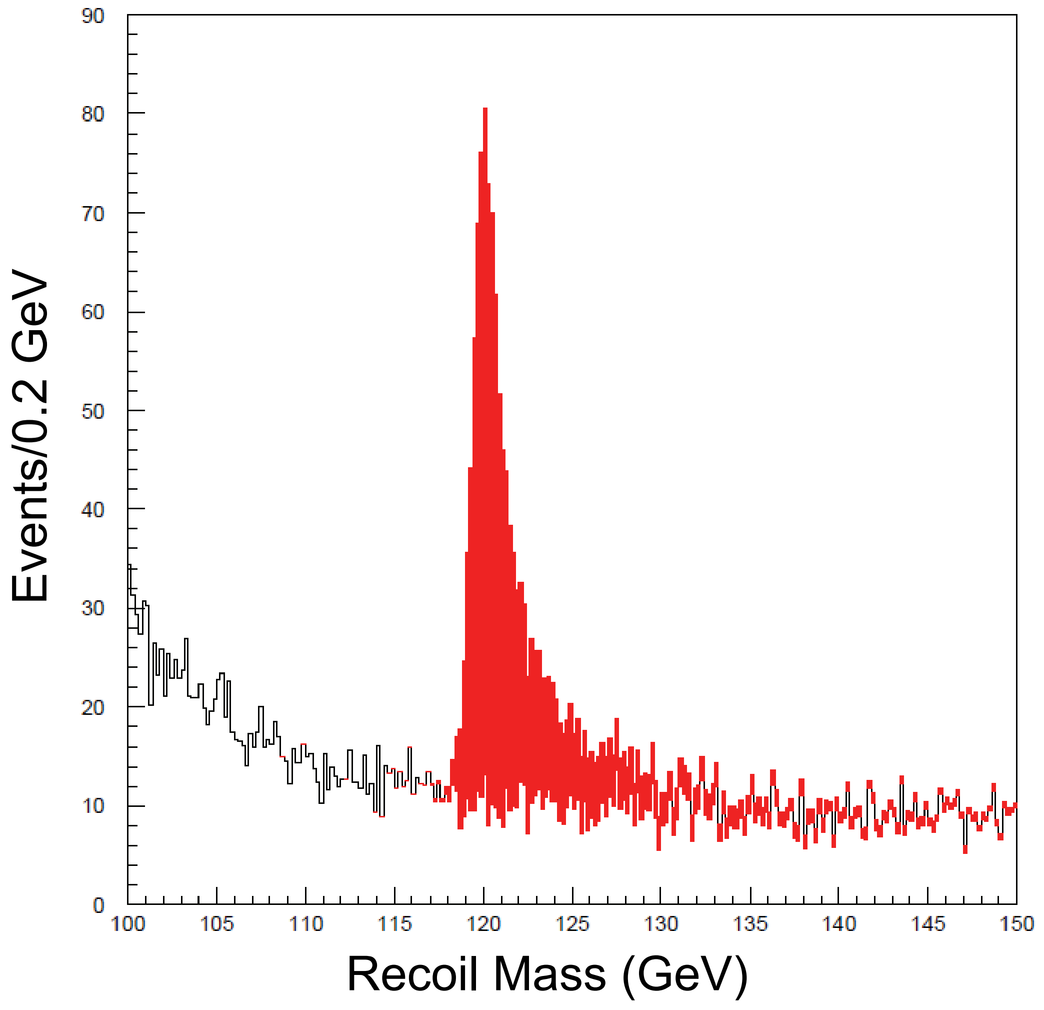

Z recoil mass provides a measurement of the total cross section

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

Cross section maximum ~ **250 GeV**

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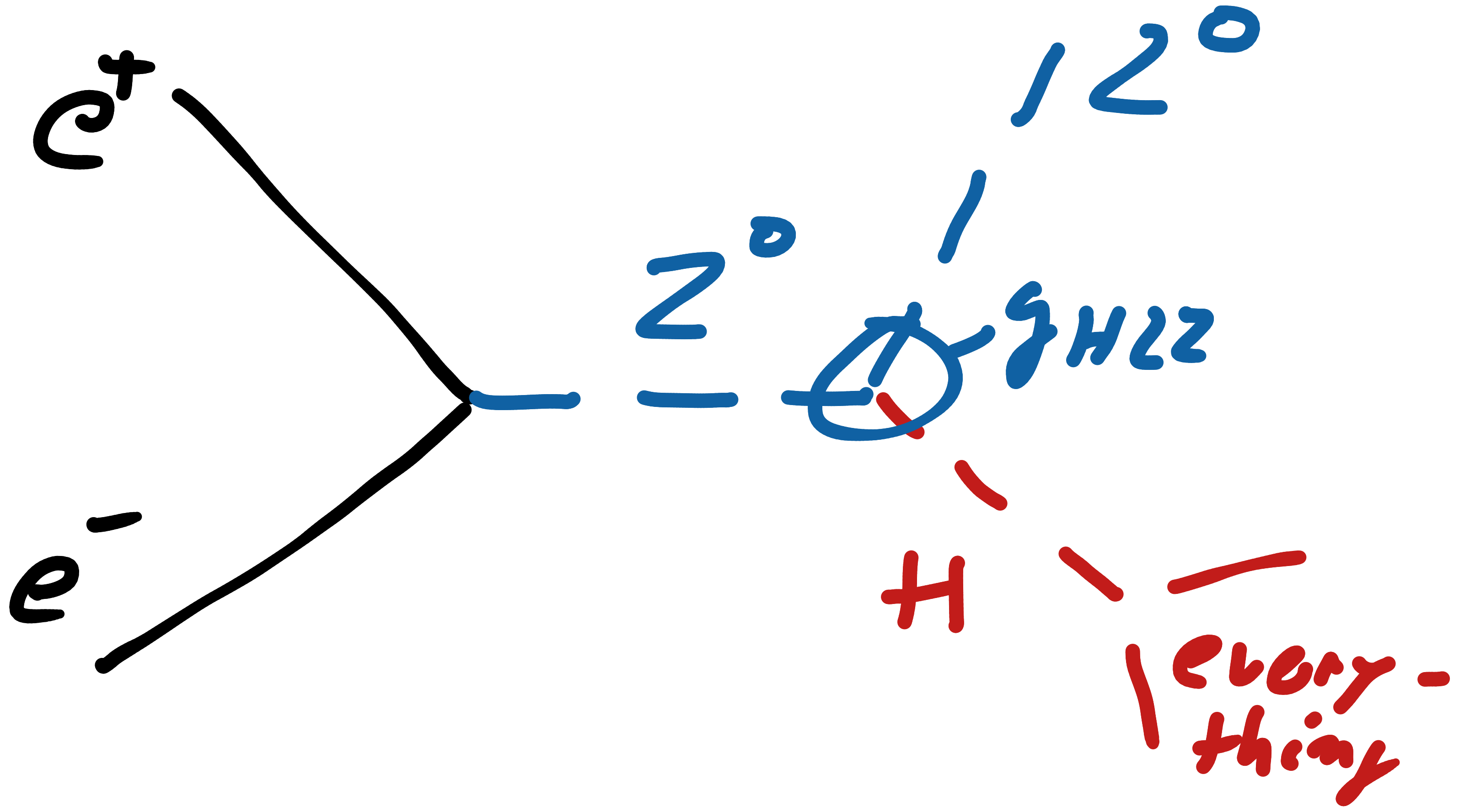

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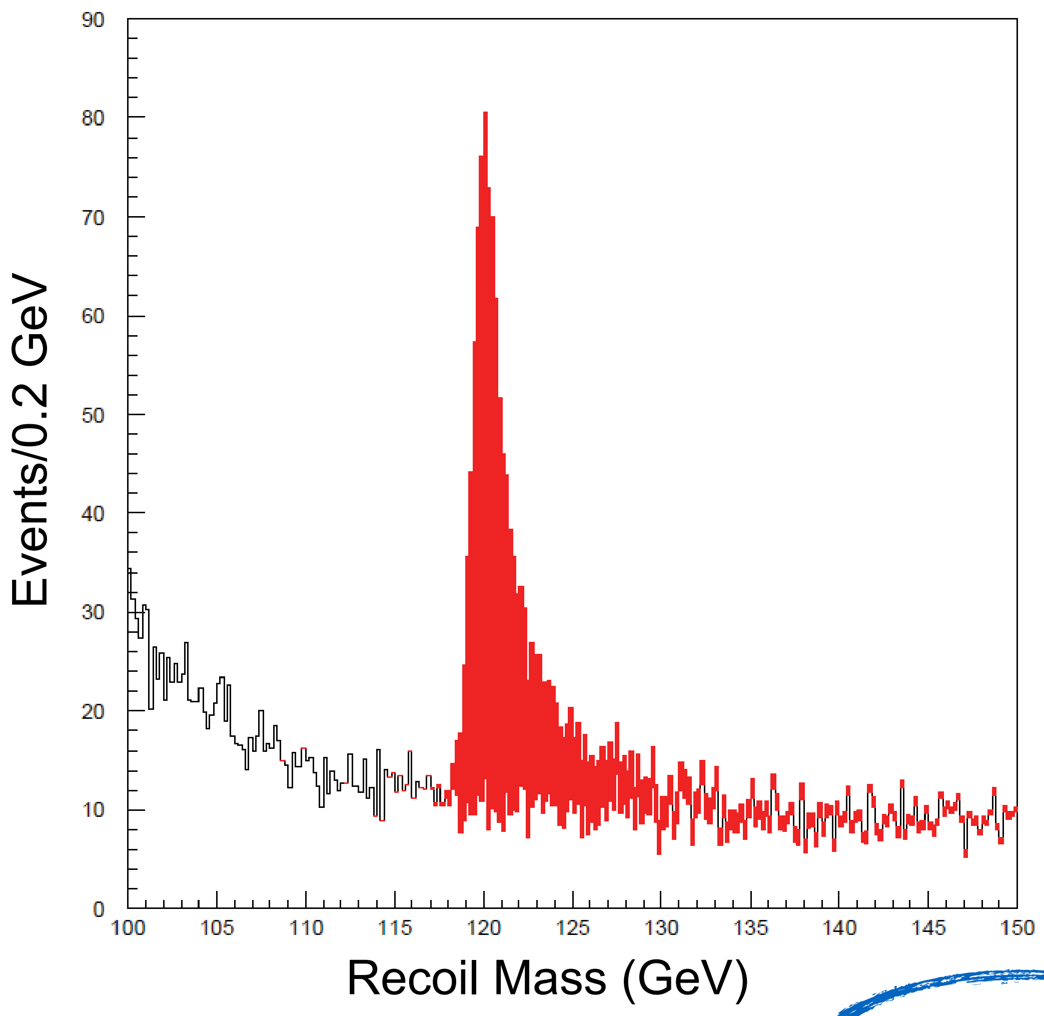

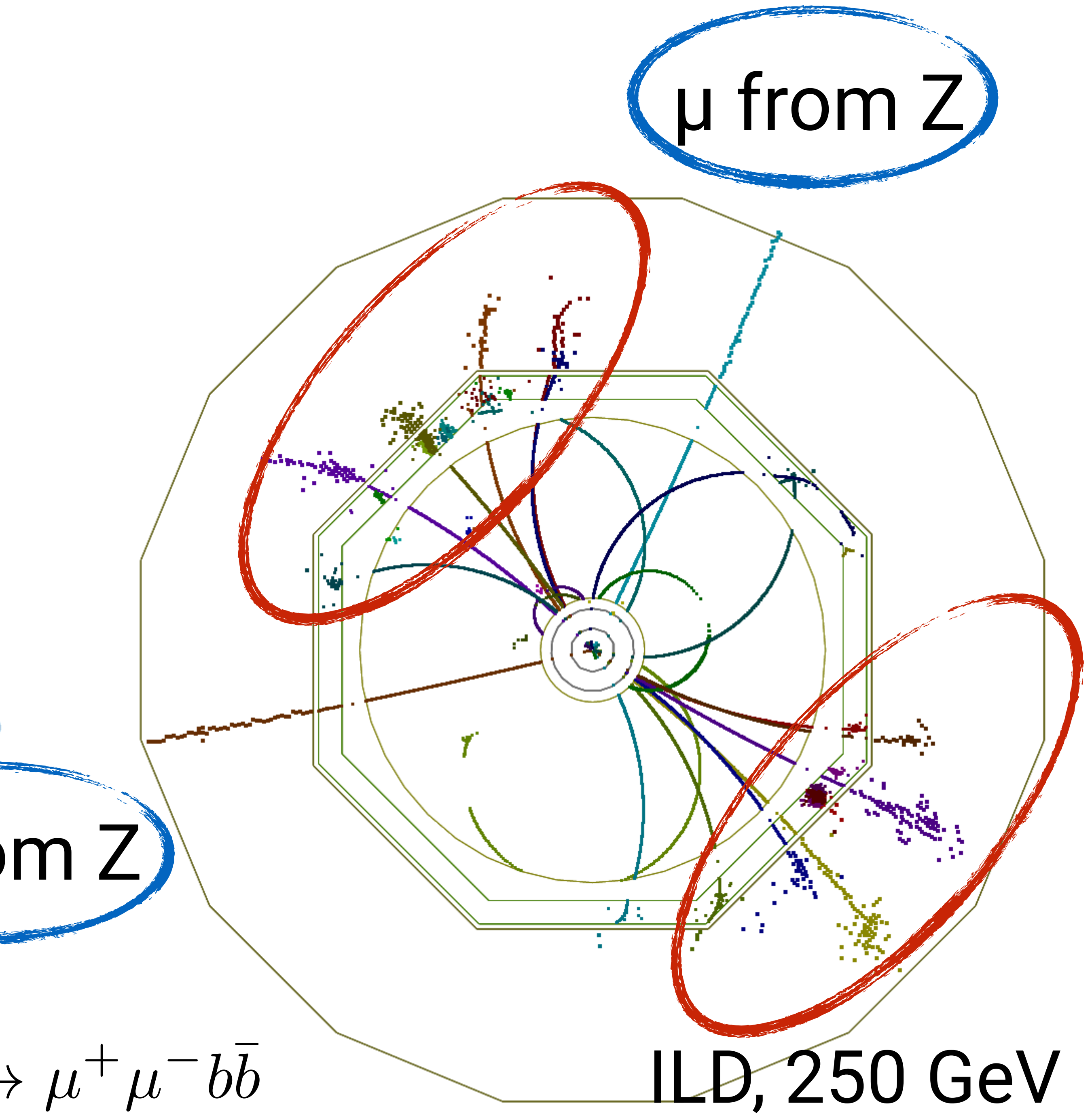

$e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$

ILD, 250 GeV

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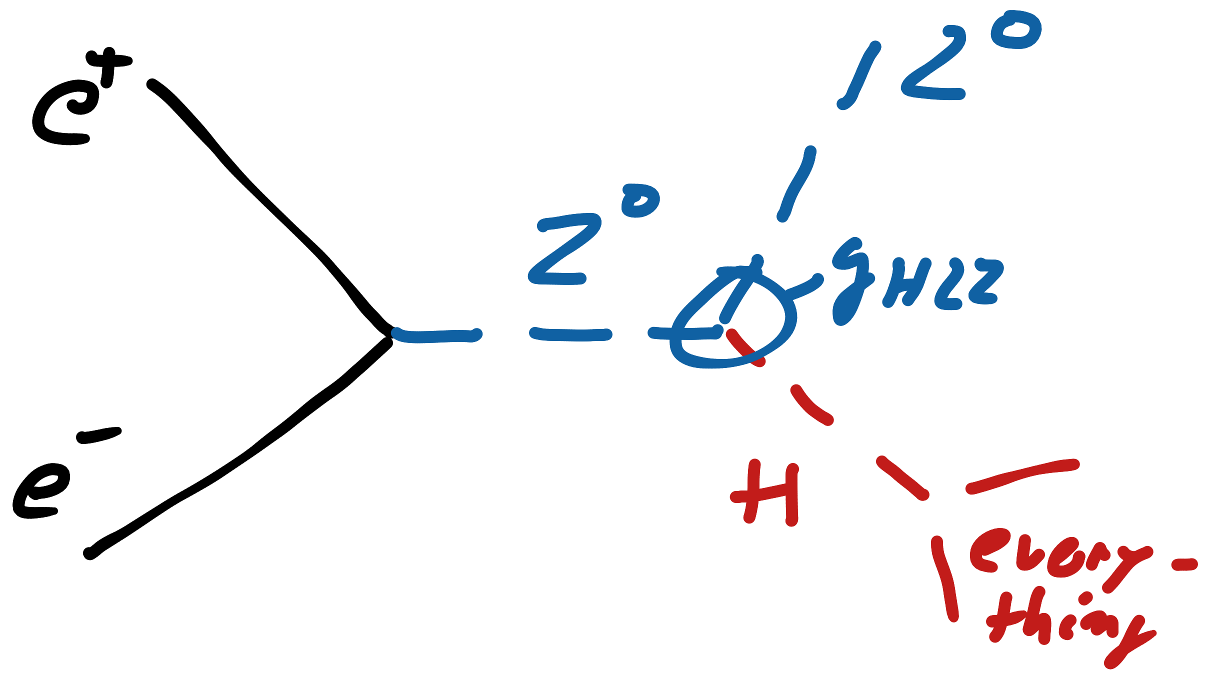
Exploring the Higgs Sector

Precision measurements of couplings

- The main measurements to make:

σ for Z recoil measurements

$$\sigma_{\text{recoil}} \propto g^2_{\text{HZZ}}$$



directly constrain the coupling of Higgs to Z in a model-independent way

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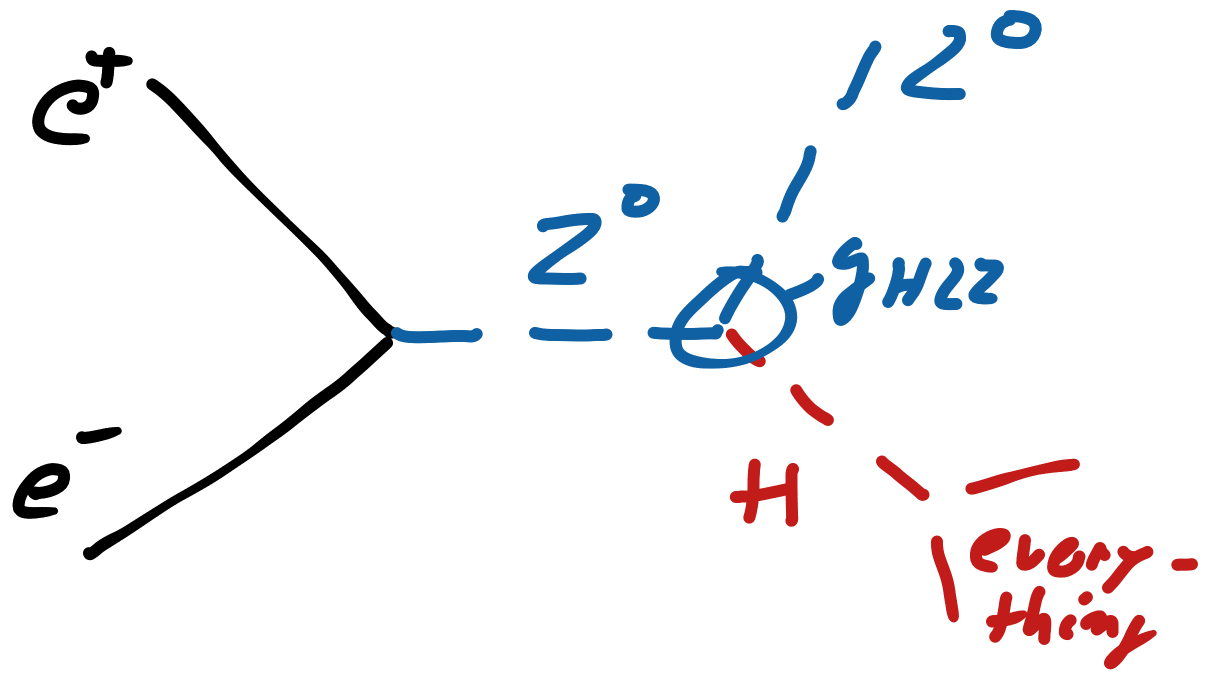

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σ x BR for specific Higgs decays

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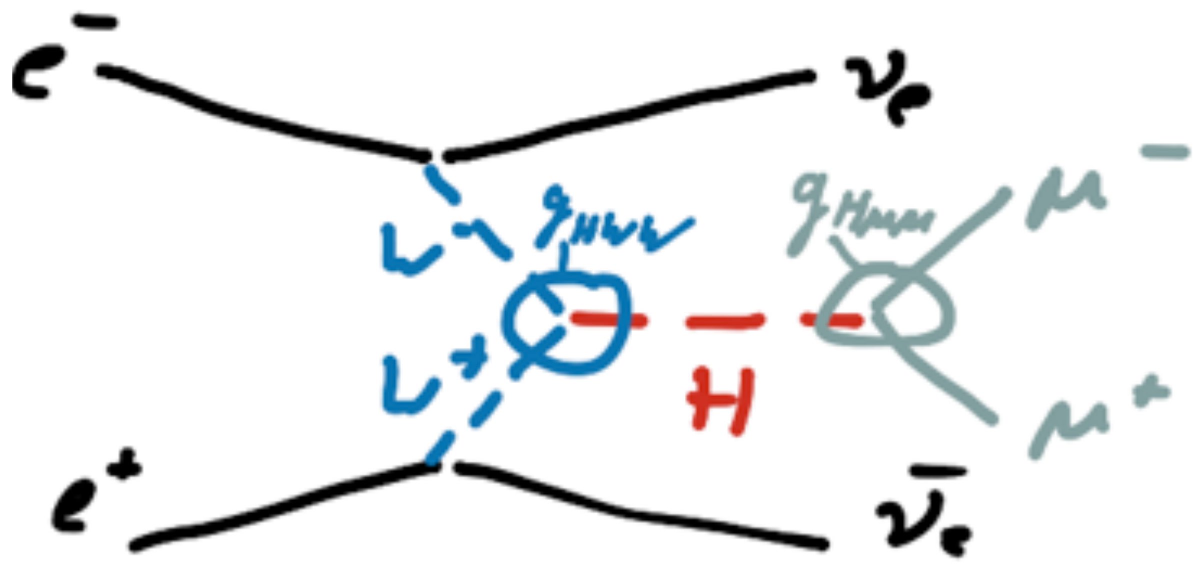

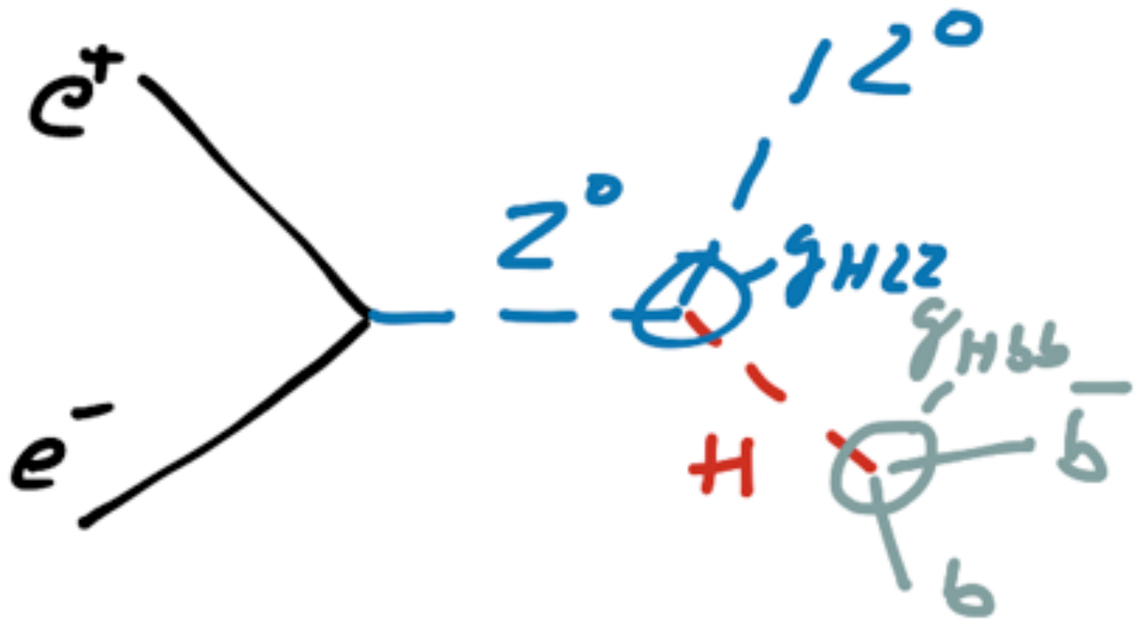

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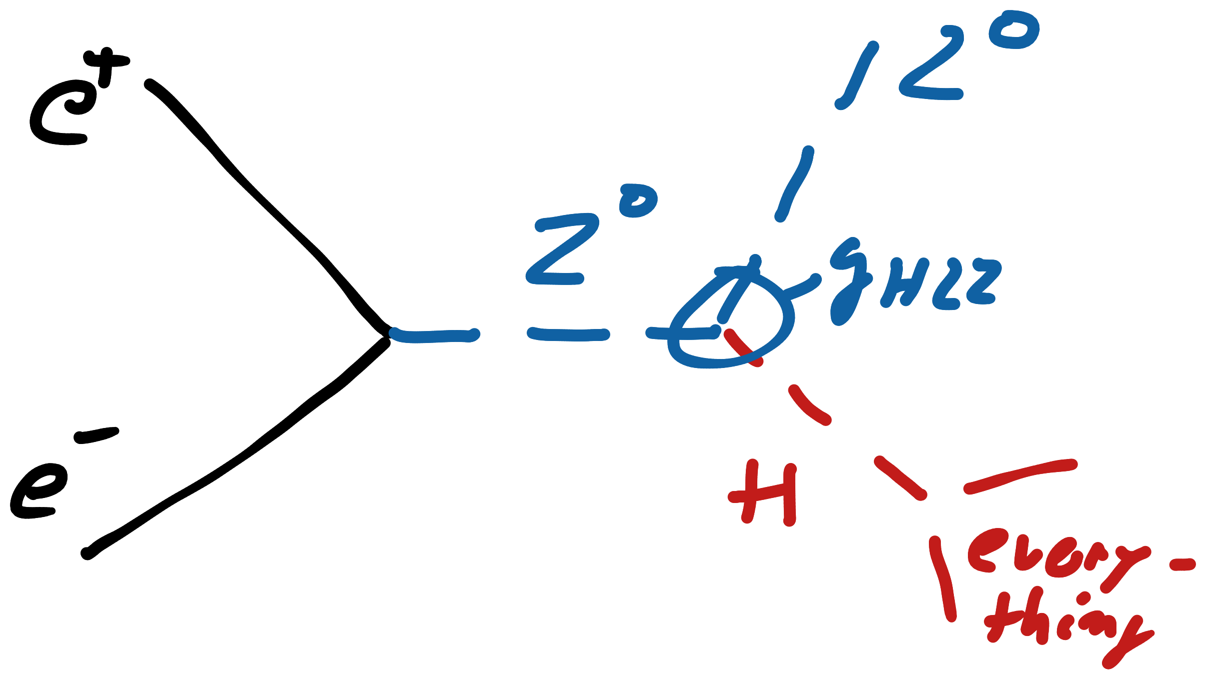

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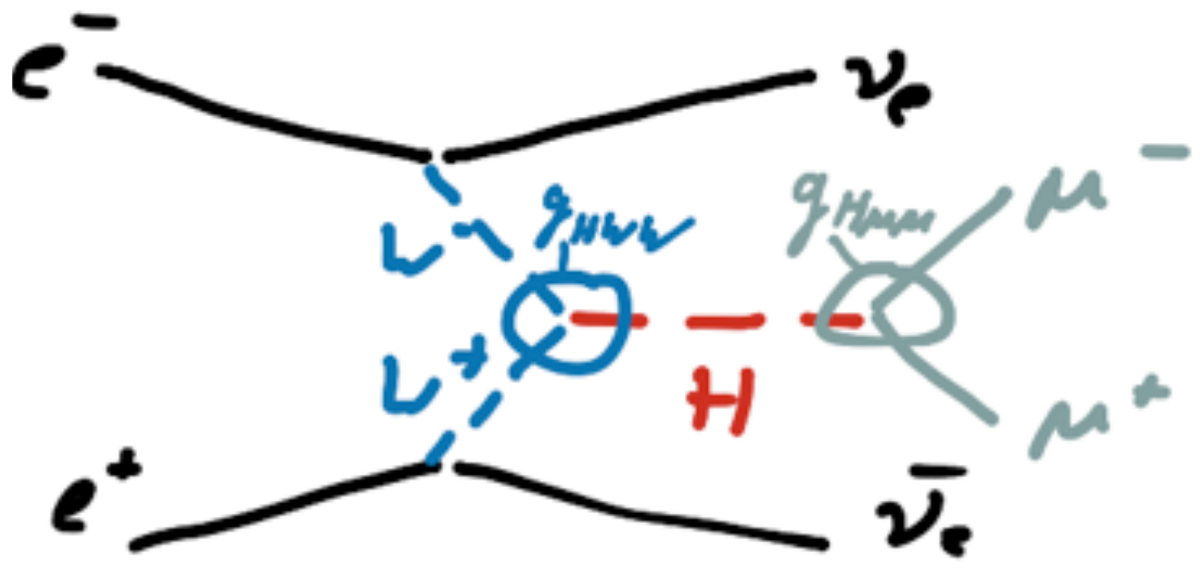
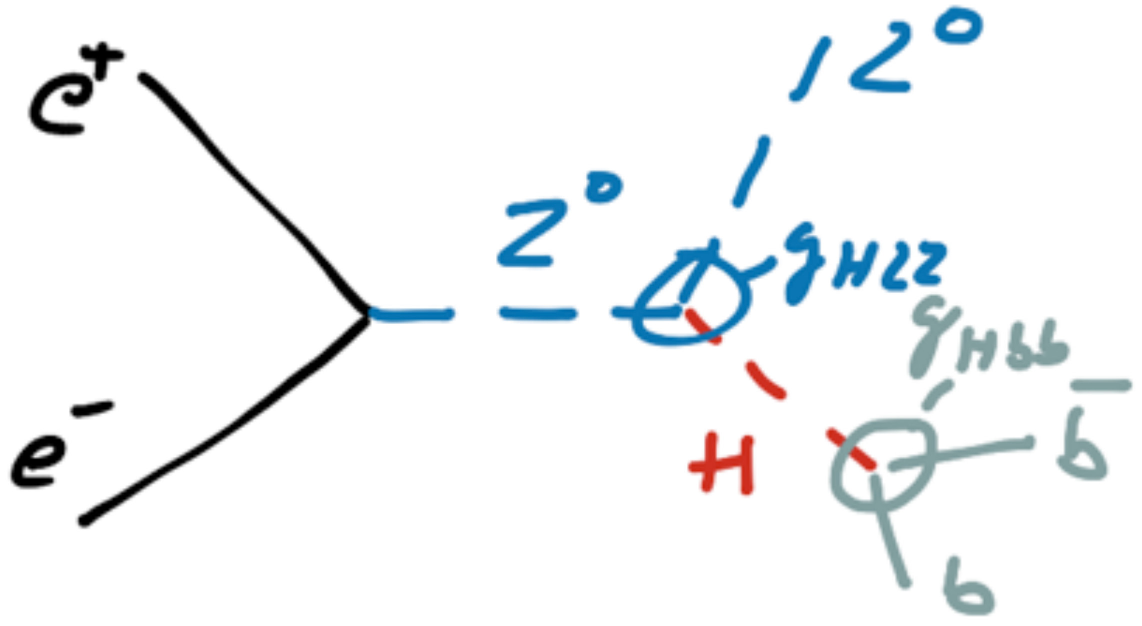




measure couplings to fermions and bosons using production and decay

➯ can be made model-independent in combination with the measurement of the HZ coupling in recoil

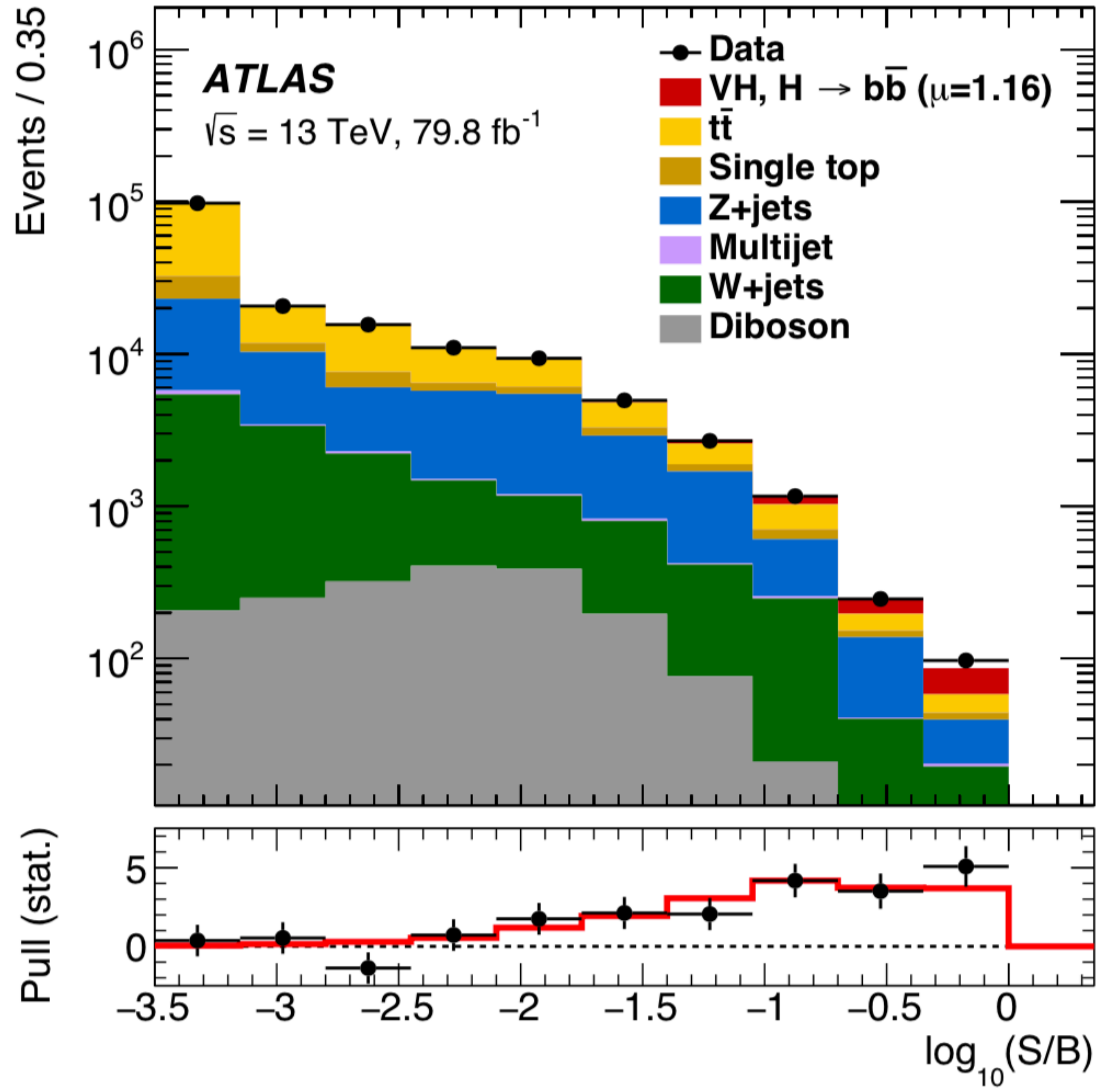
➯ total width with identical particles in production and decay: WW, ZZ

Unique Measurements at Lepton Colliders

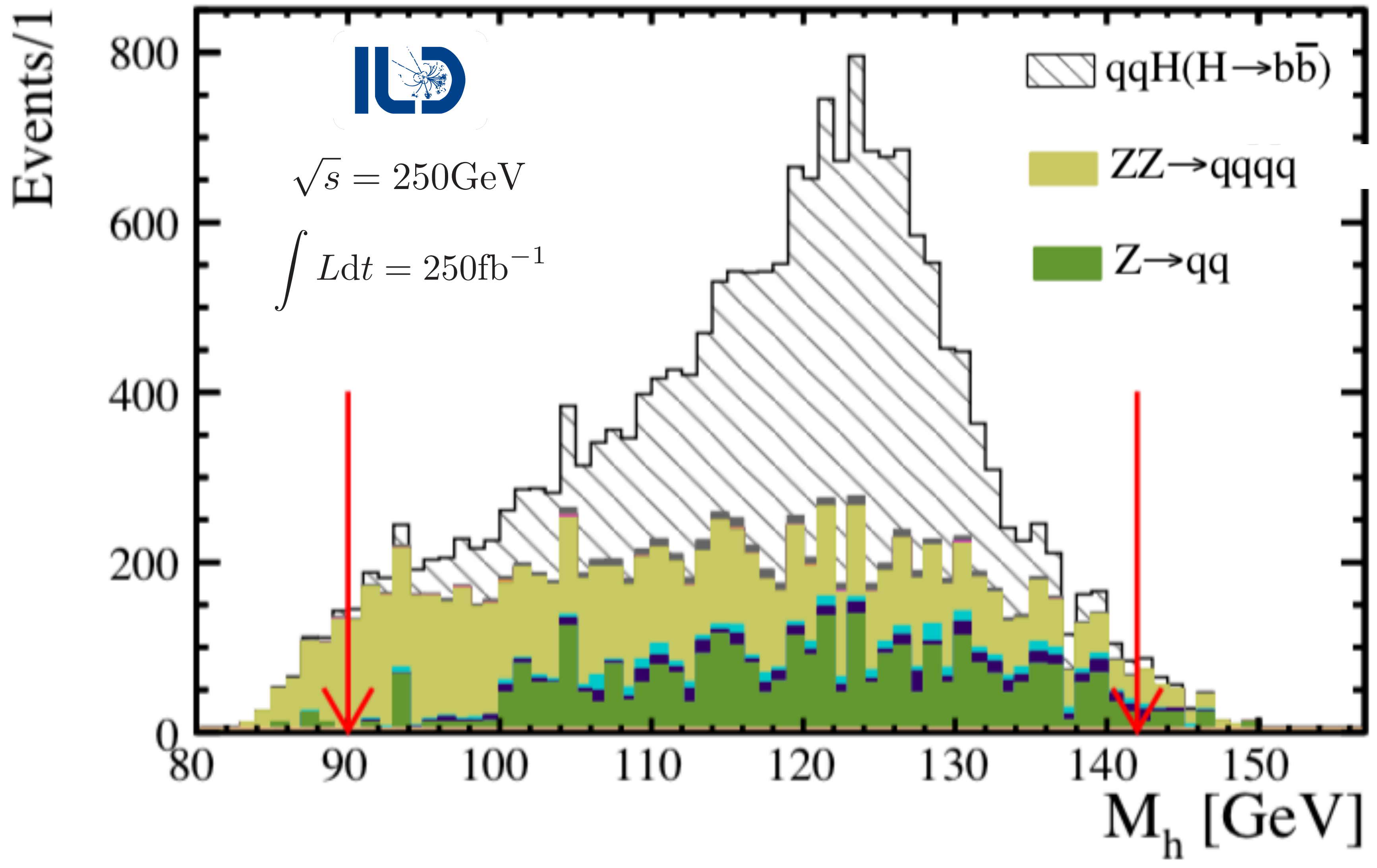
Enabled by the clean environment

- H->bb: A difficult channel at LHC, a “simple” measurement in e⁺e⁻

at LHC

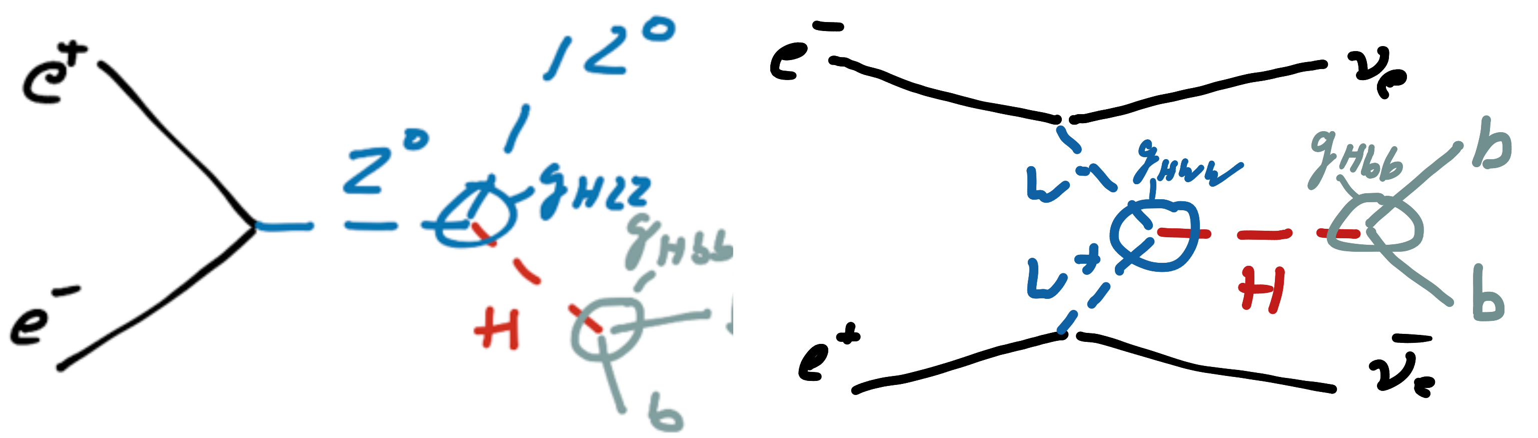


at e+e-



with 1.3 fb⁻¹ data ~ 2 days running

# of Higgs produced:	~4,000,000	~400
significance:	5.4σ	5.2σ



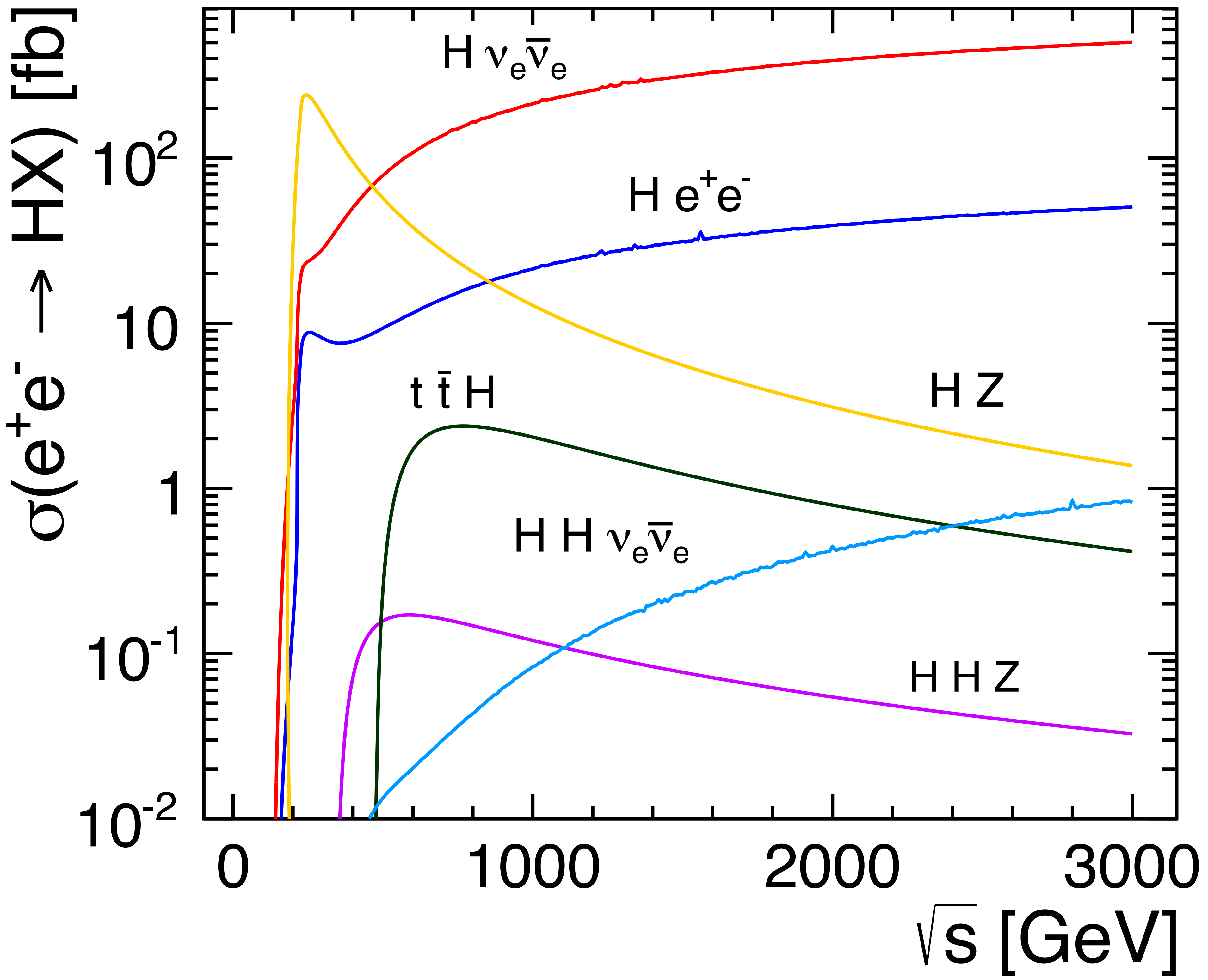
- Low backgrounds, and highly capable detectors enable observations of final states that are hard or impossible at LHC

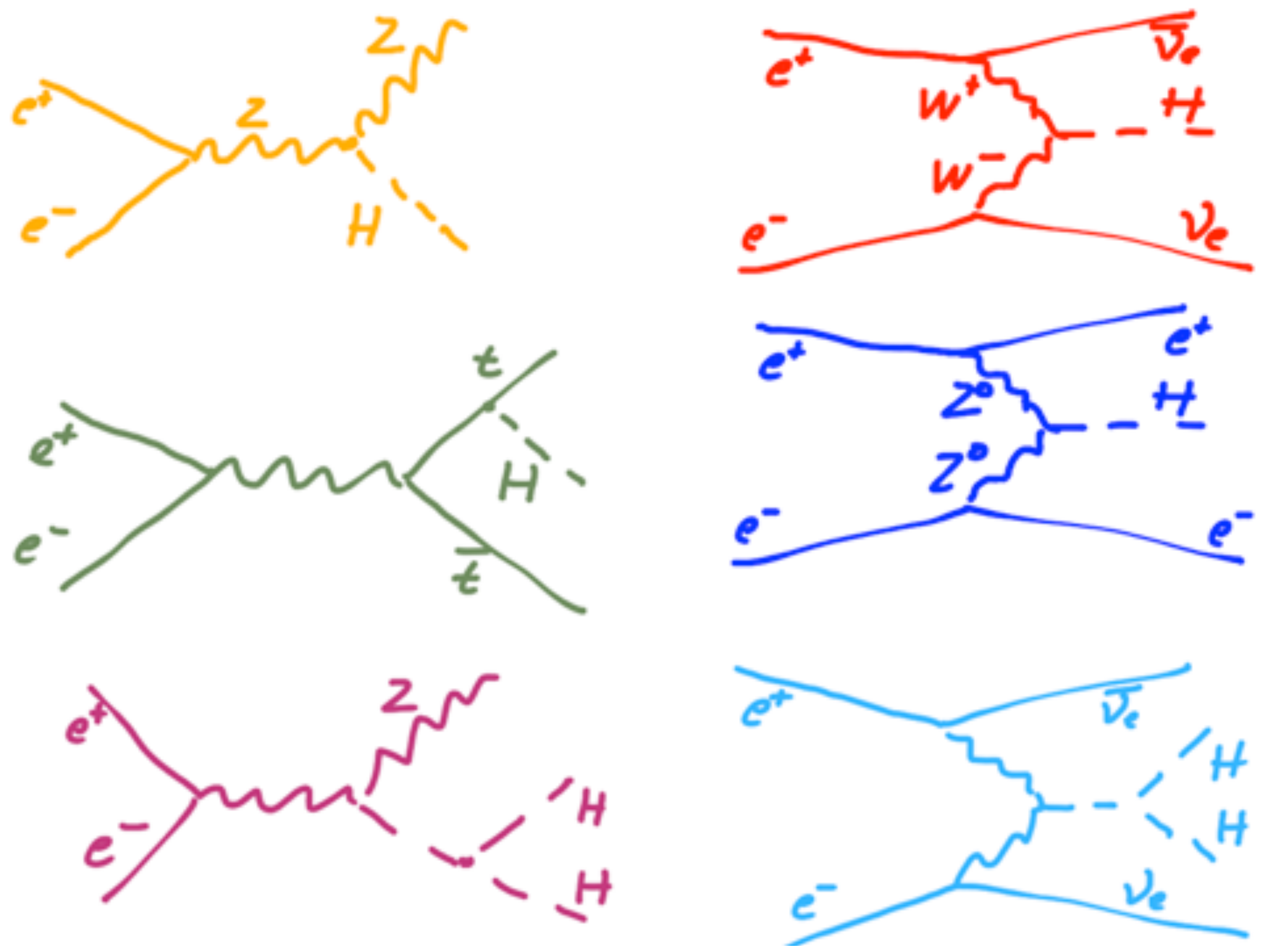
J. Tiang, LCWS 2018

- Also: Precise measurement of H -> cc, H -> gg

Beyond Higgsstrahlung

Richness of Higgs Processes in e^+e^-





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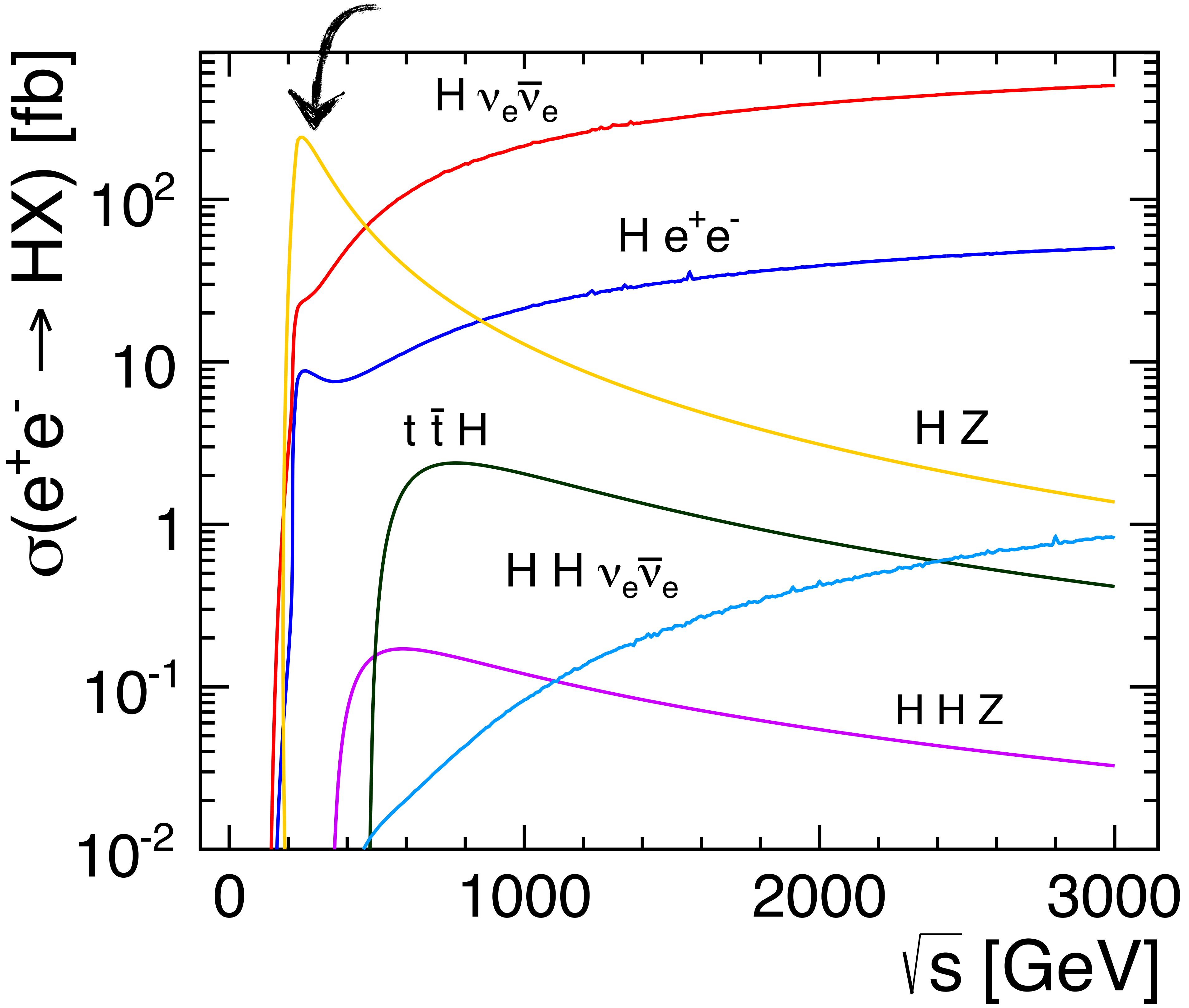

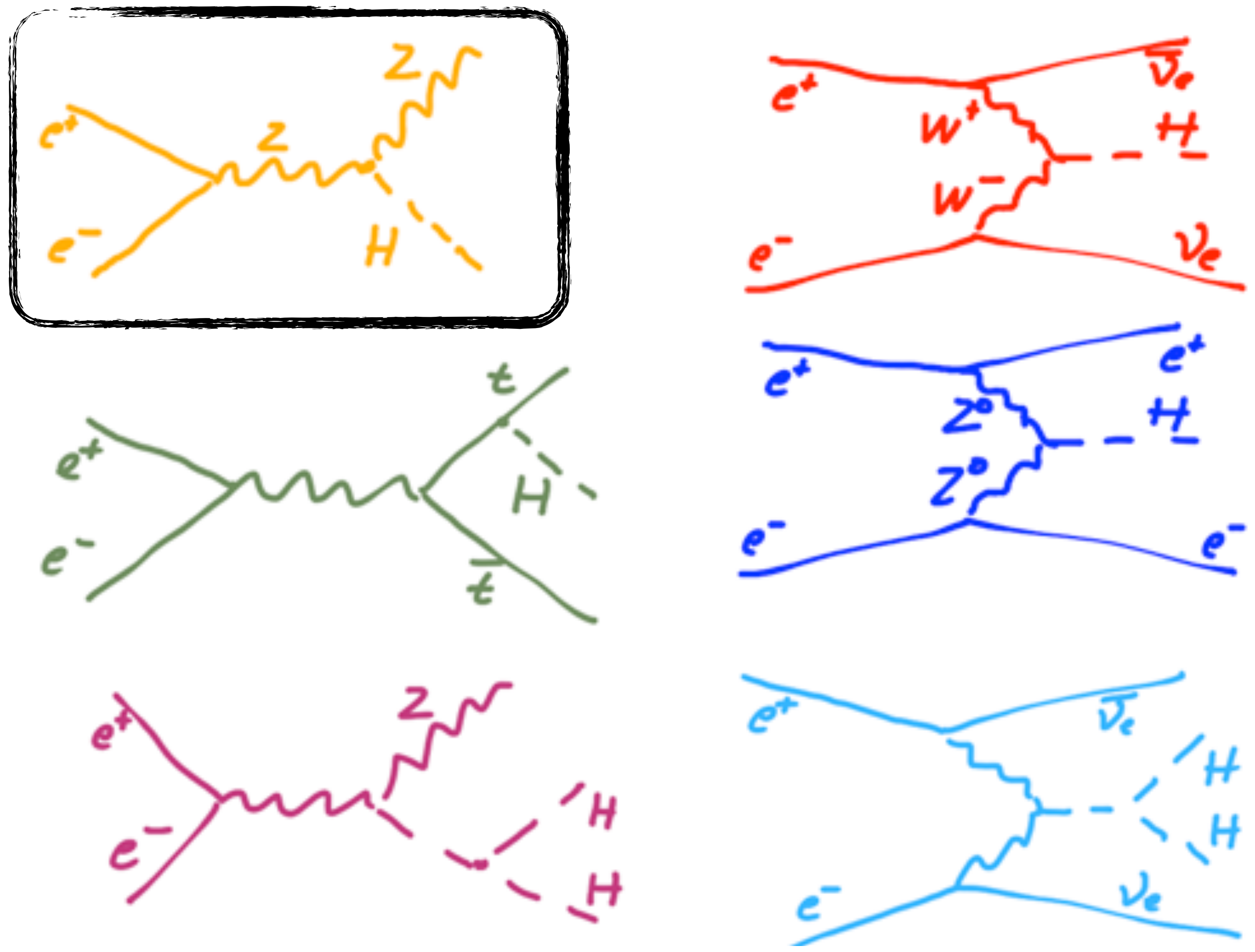

250 GeV:

Maximum of ZH production

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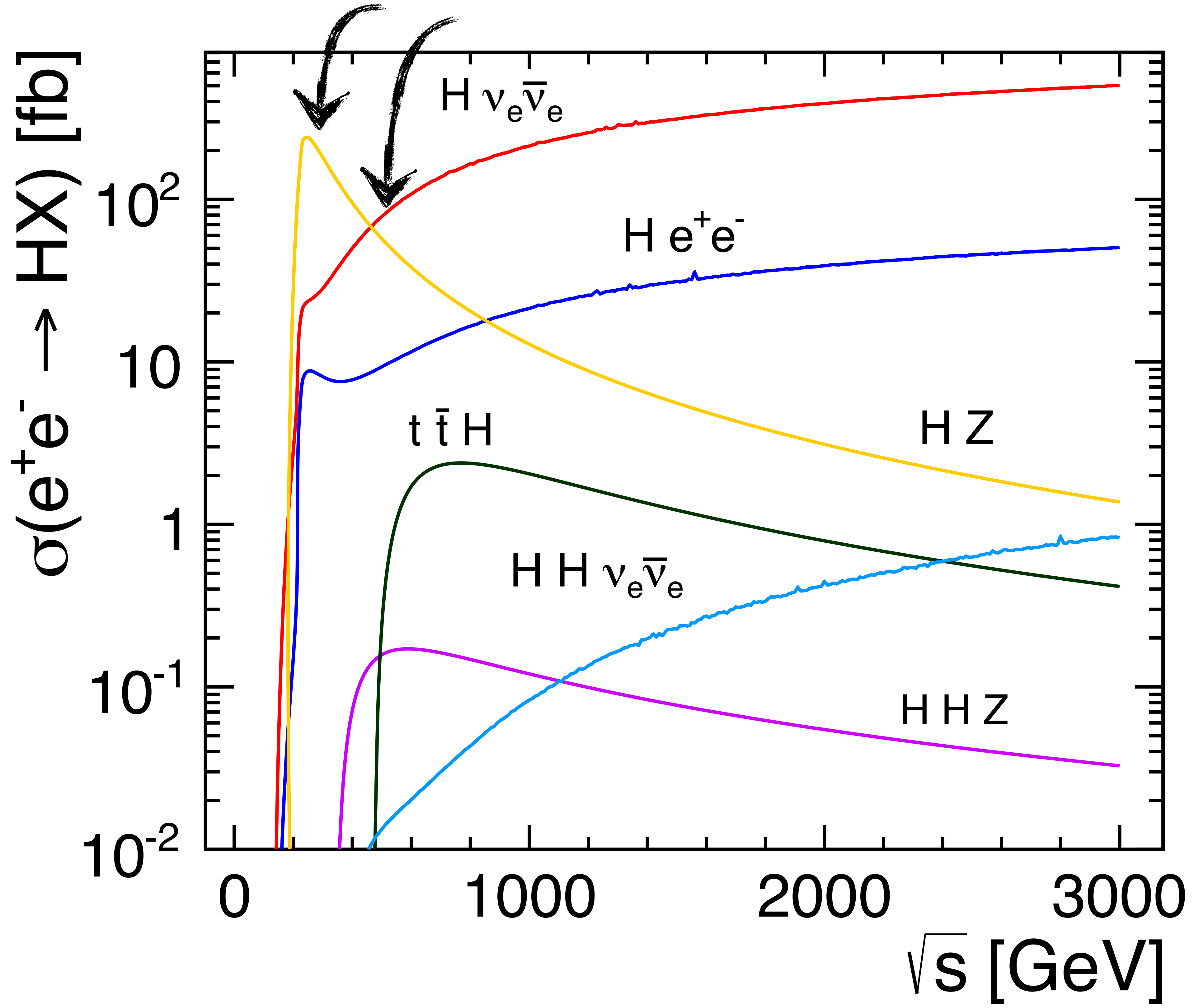

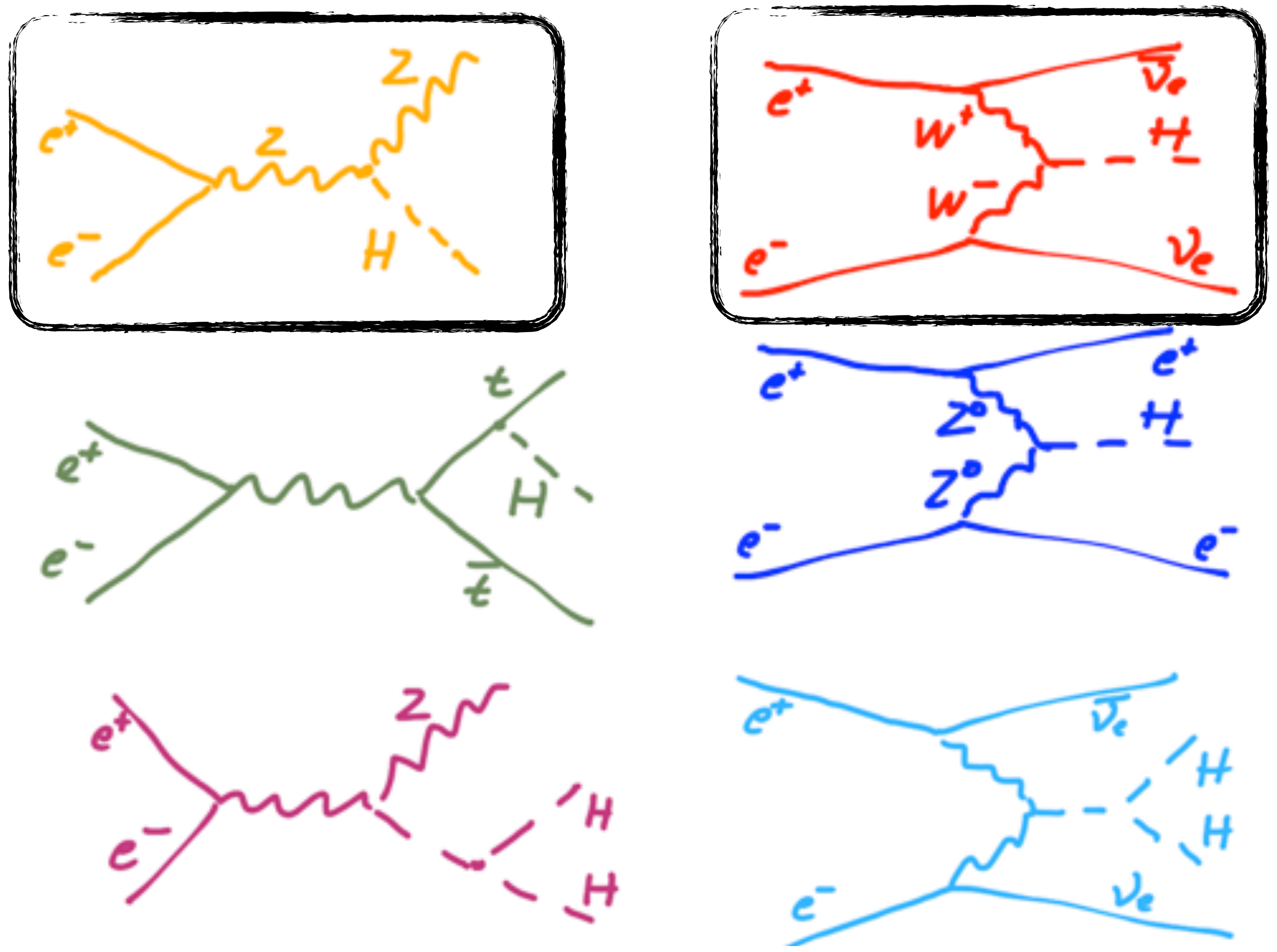

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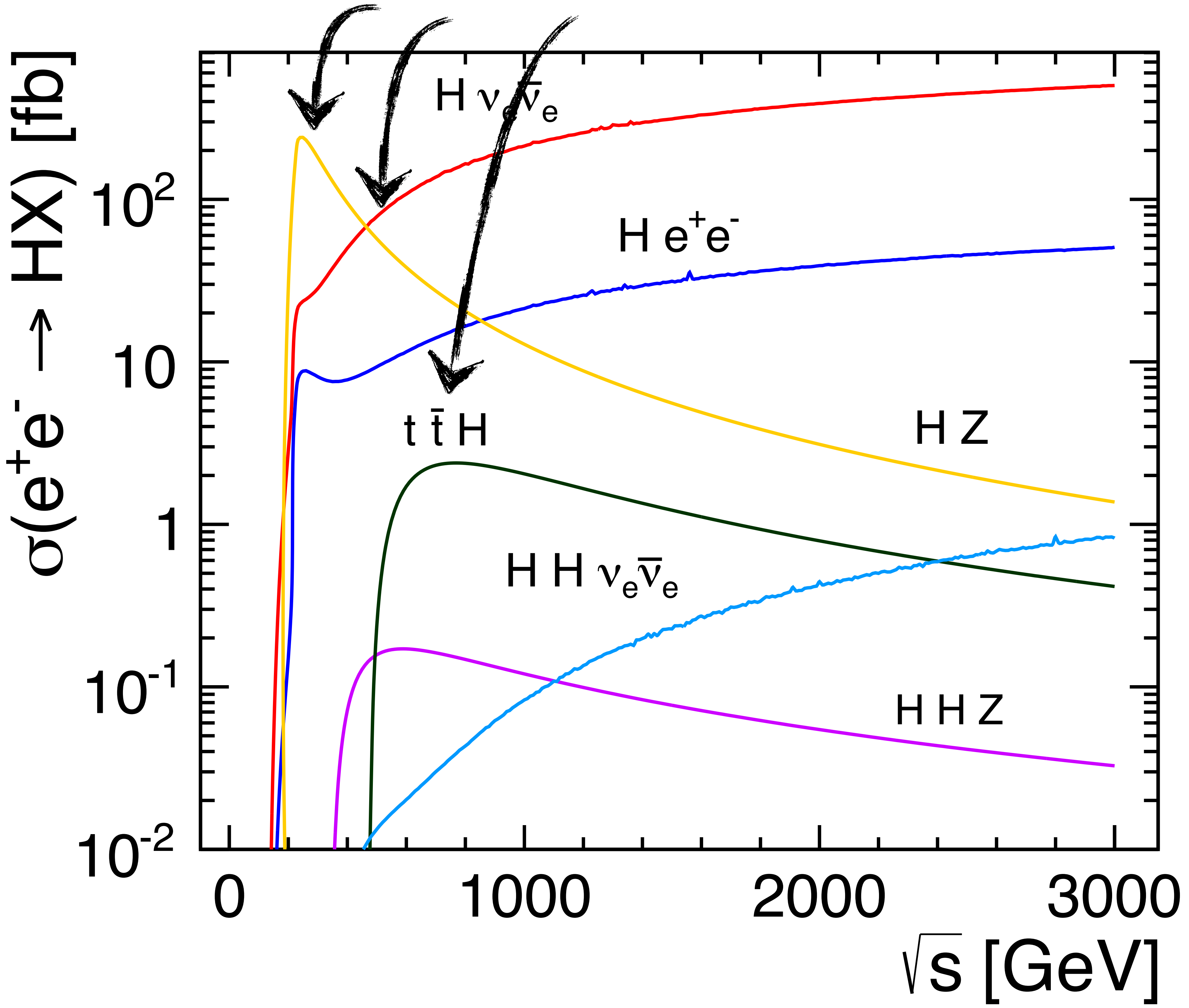

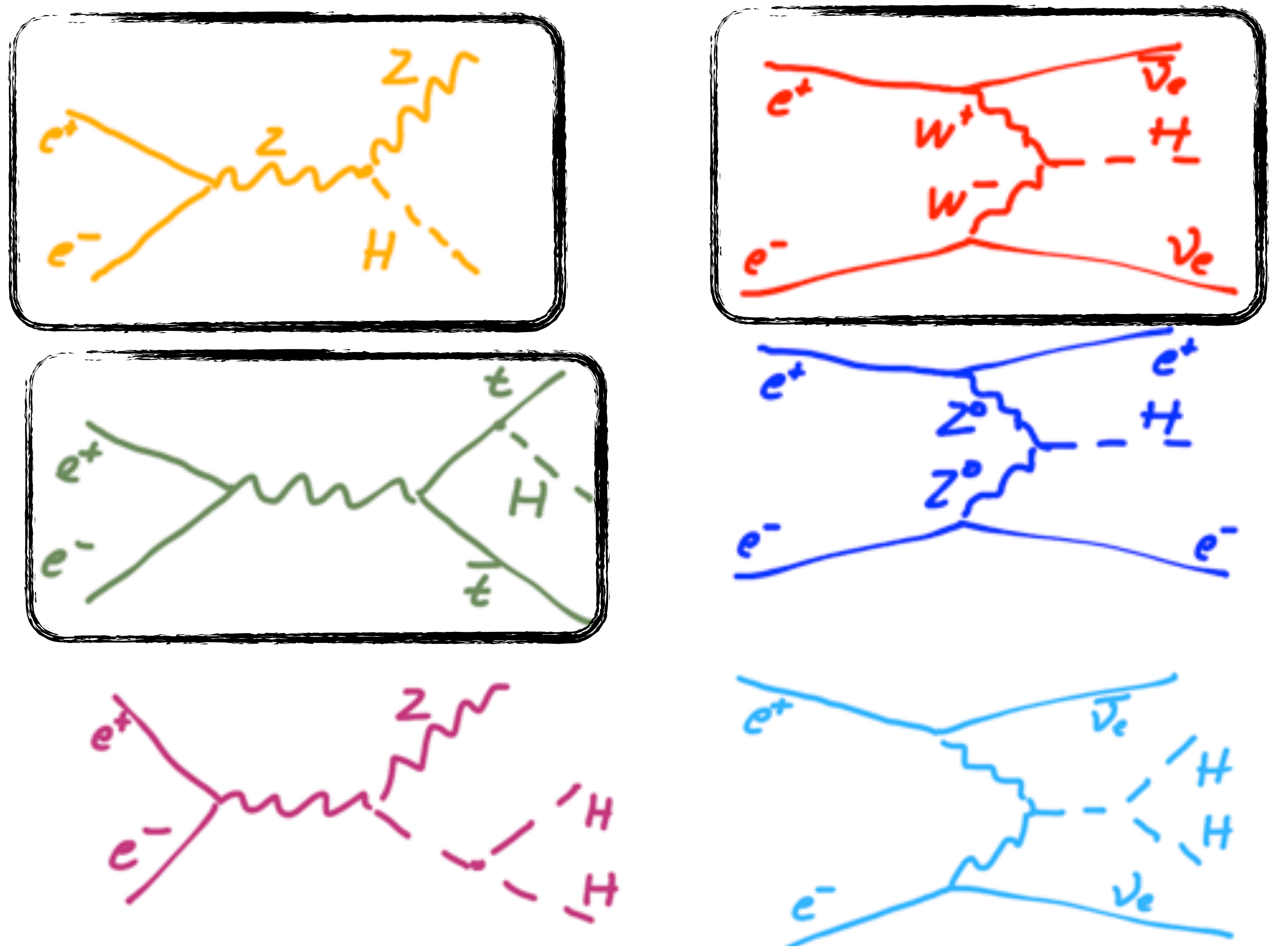

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ttH: direct access to top Yukawa coupling

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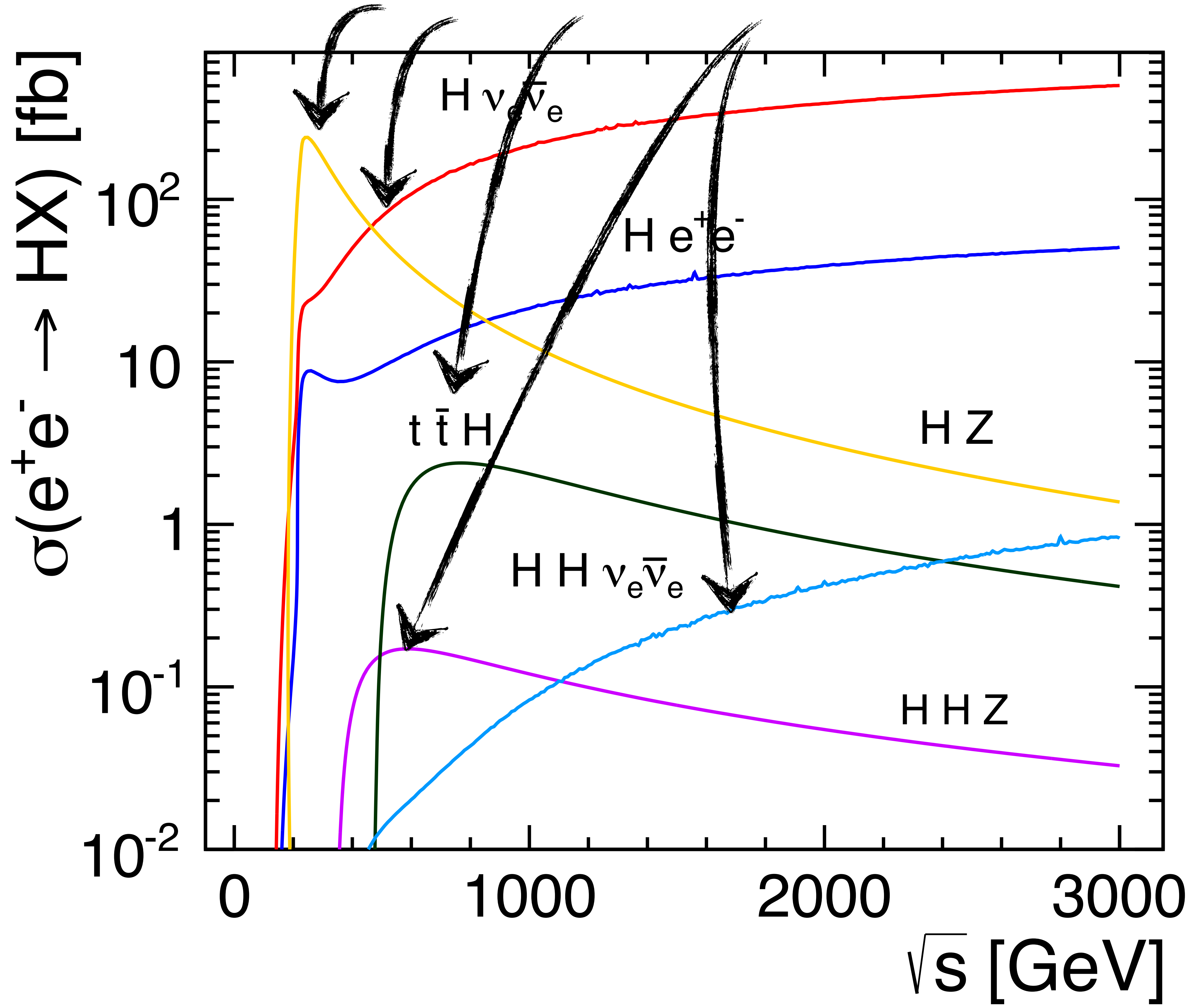

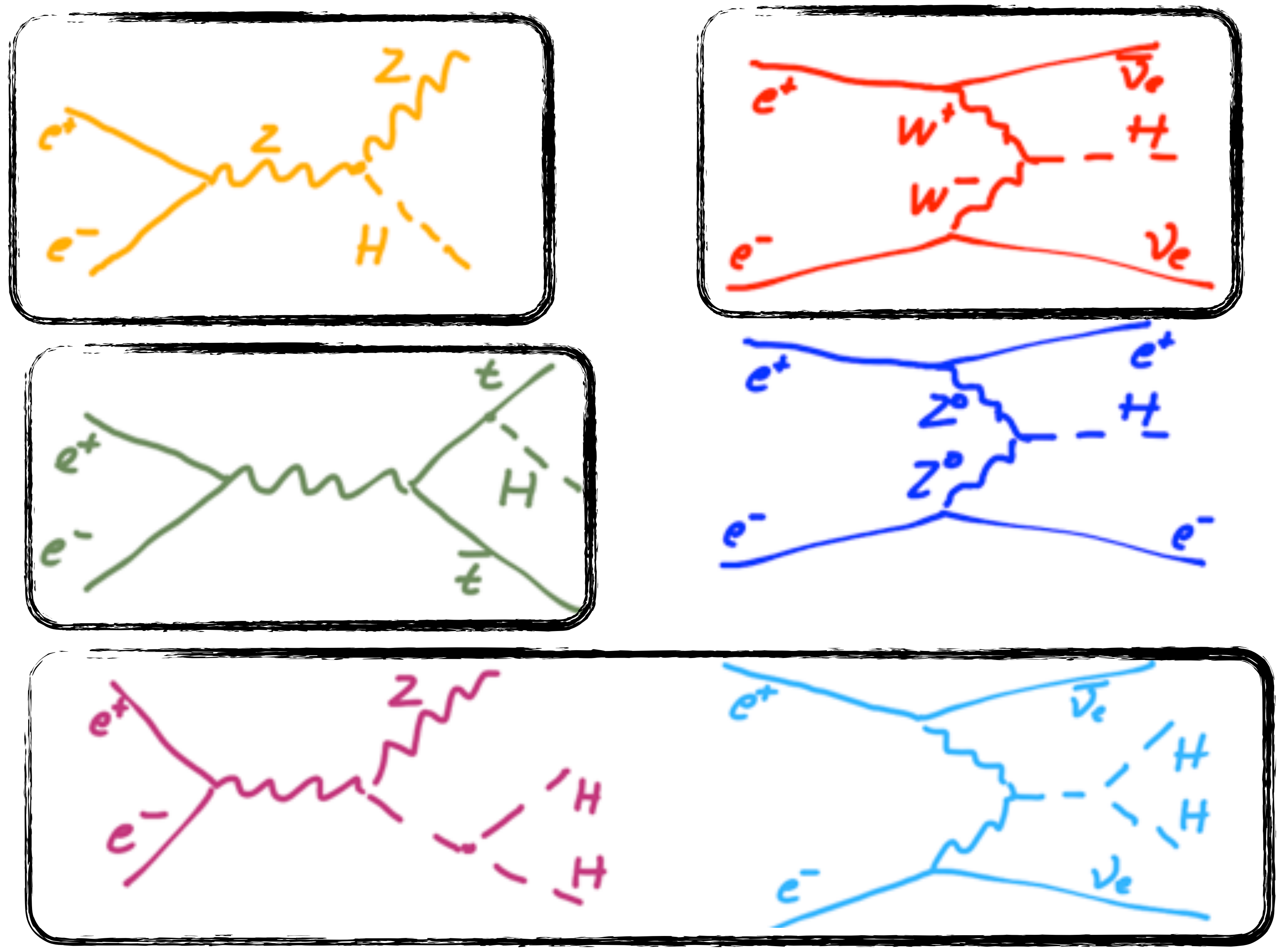

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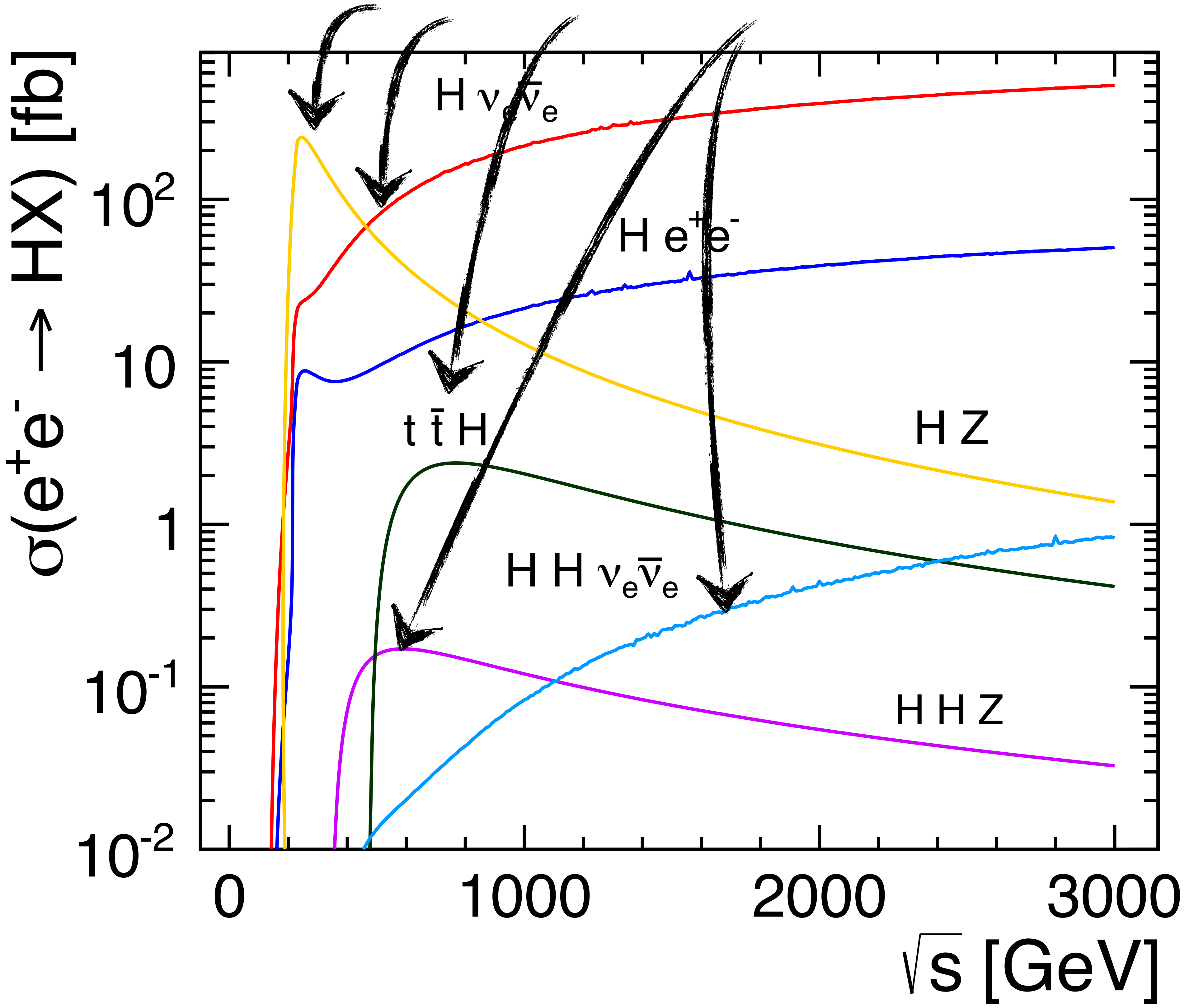

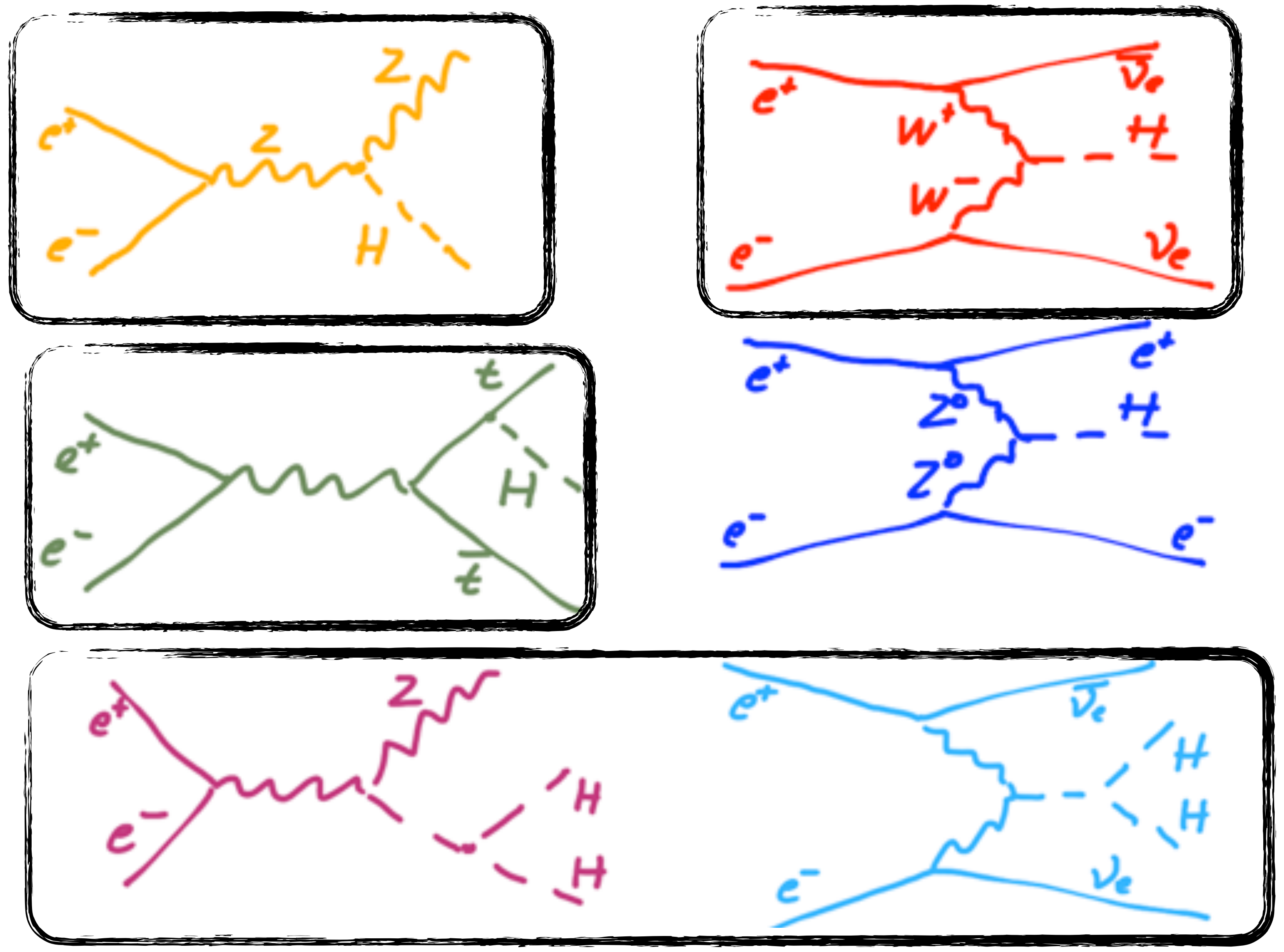

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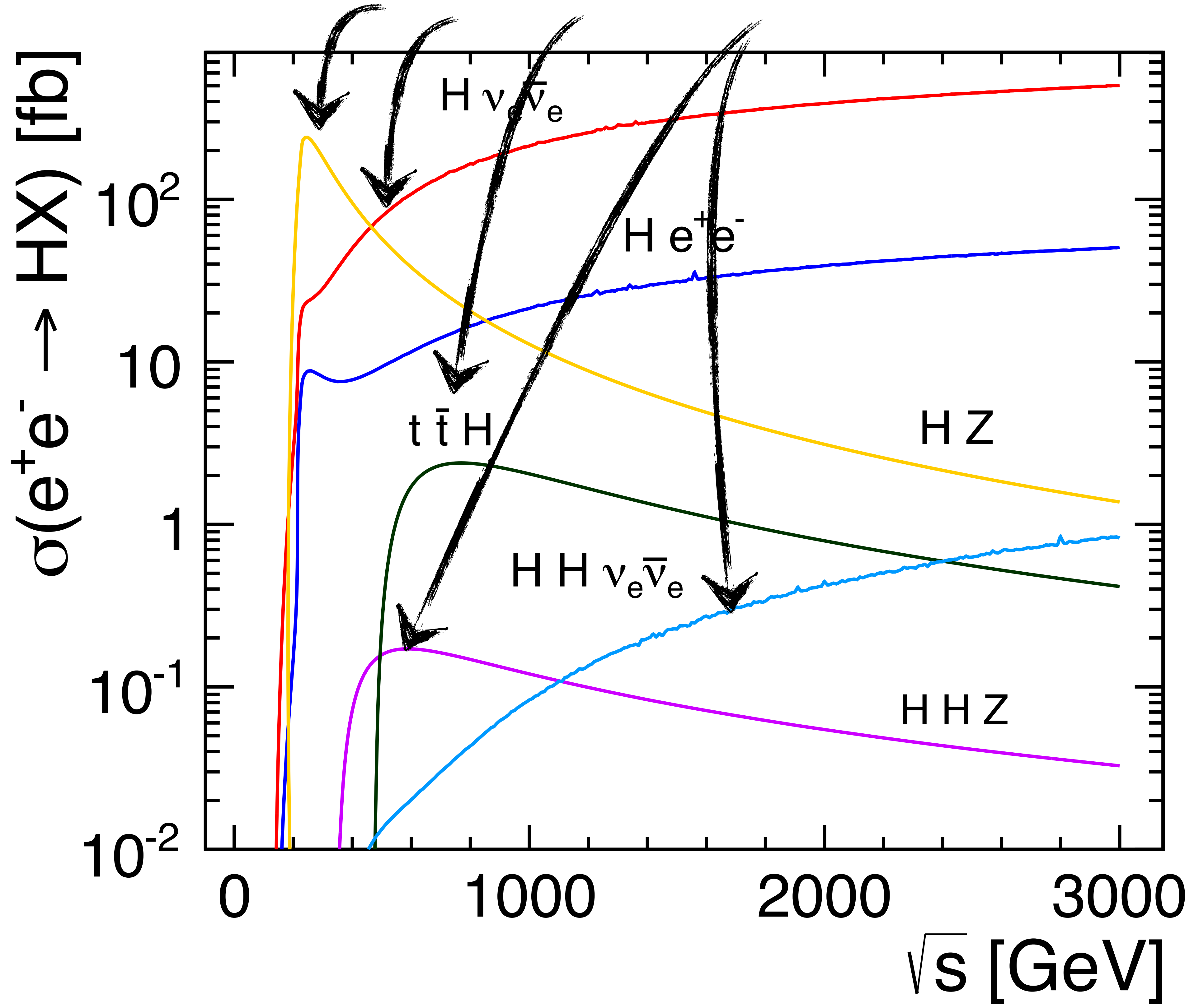

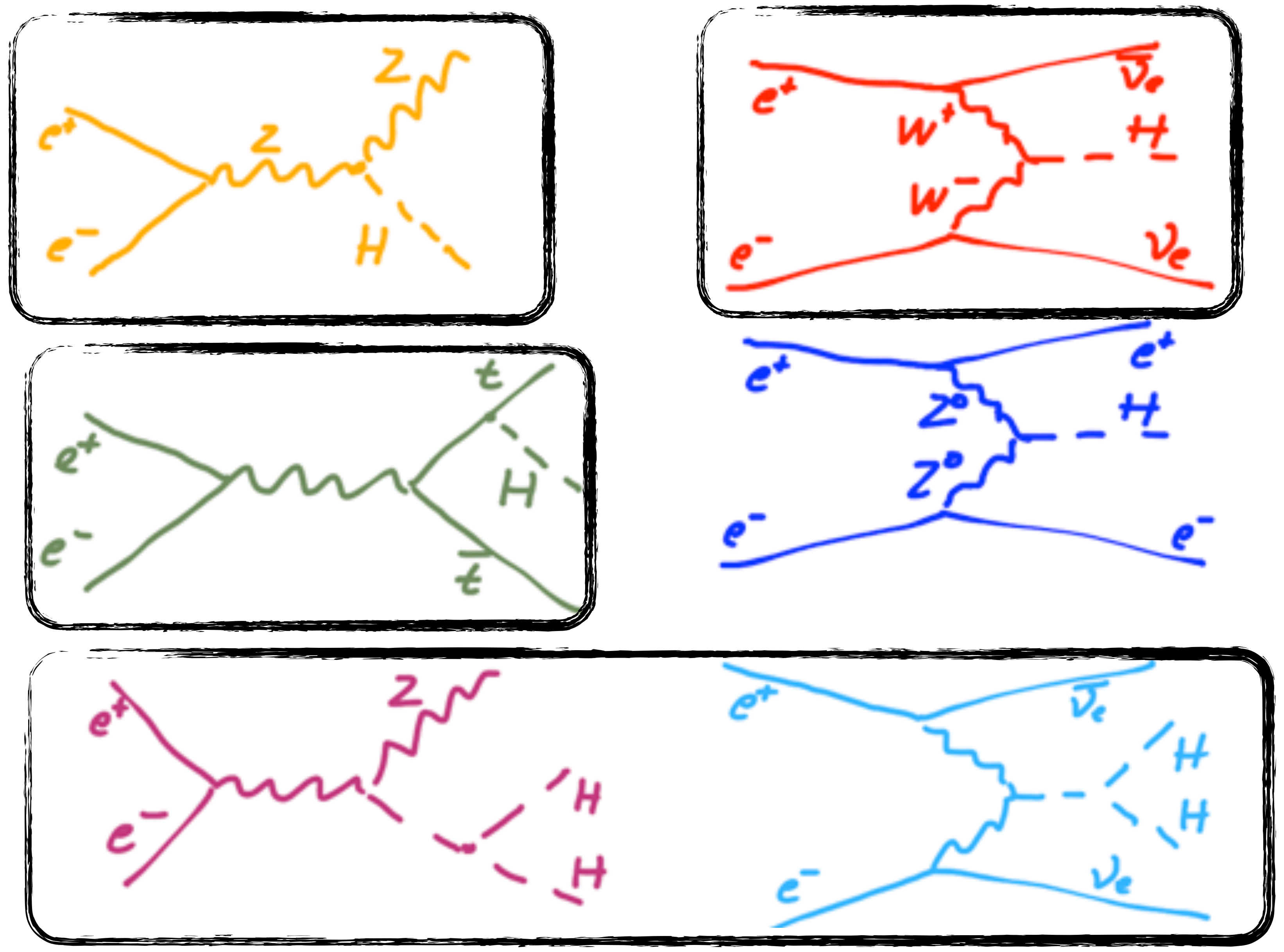

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125 GeV:
S-Channel Higgs production: Electron Yukawa

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A Comprehensive Picture of the Higgs Sector

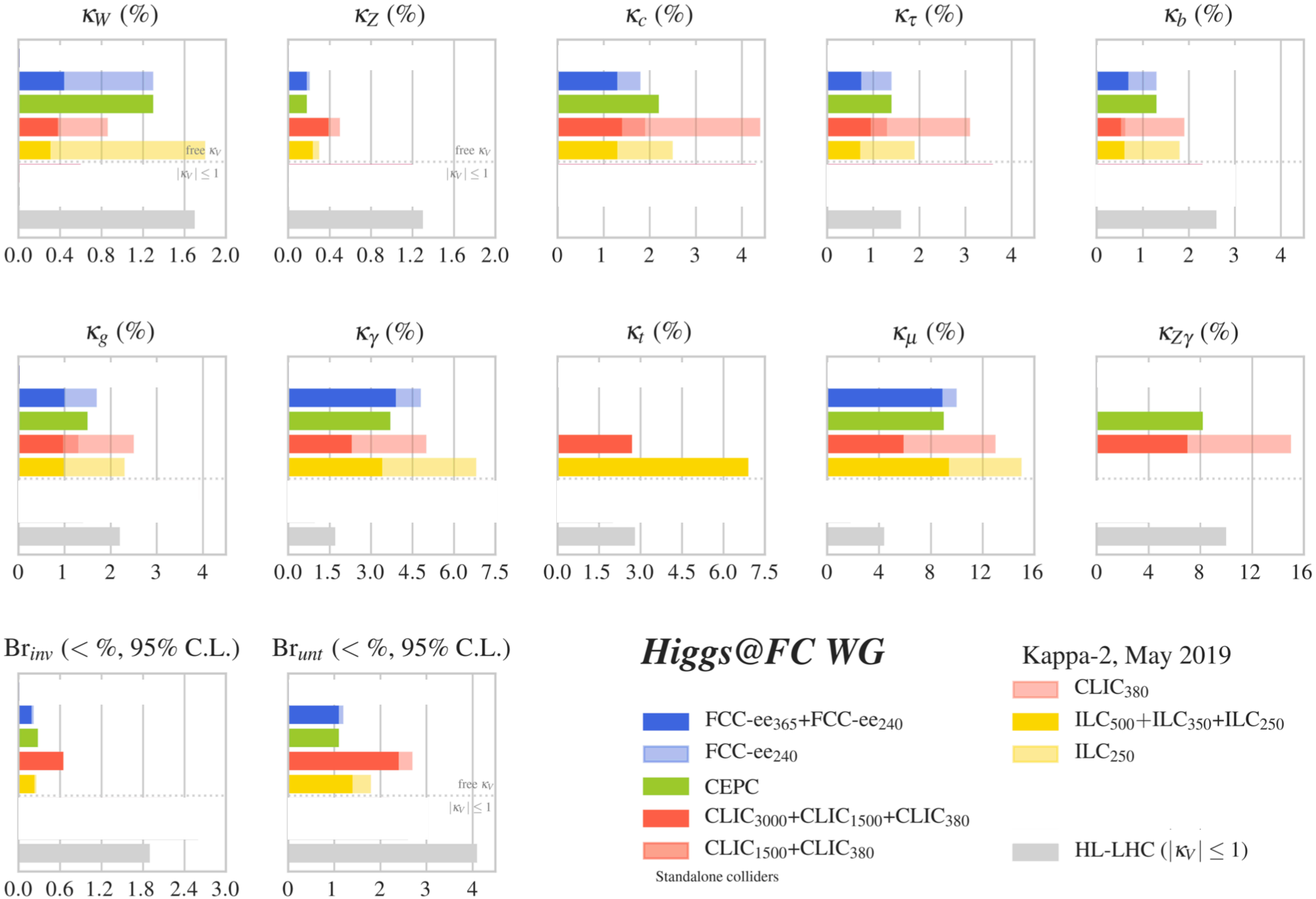
Projections of Global Fits

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-2	measured	measured	no

hadron collider cannot measure width
need an assumption to close the fit
e.g. $\kappa_V<1$

e⁺e⁻
standalone

not showing
HE-LHC,
LHeC, FCC-hh



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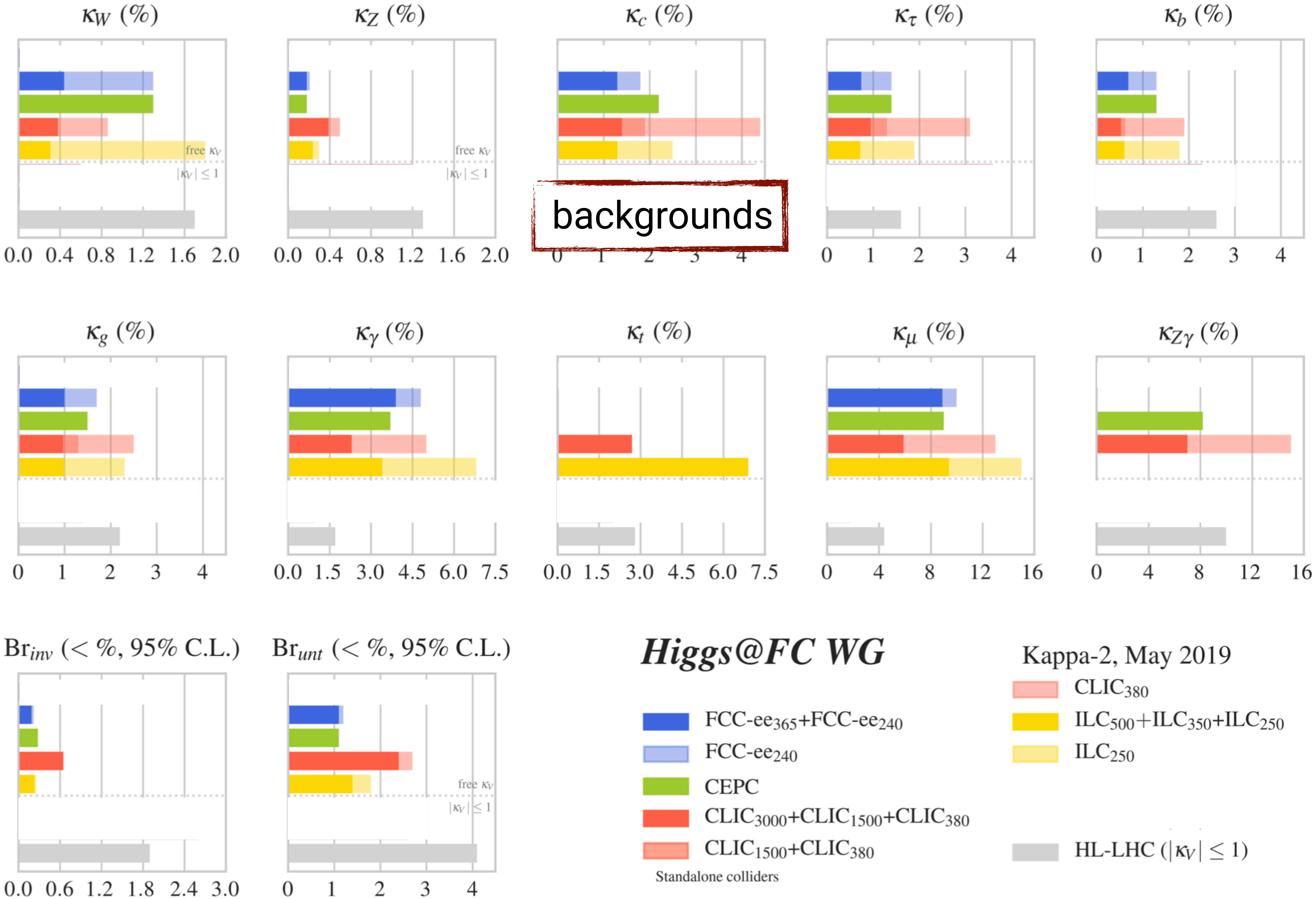

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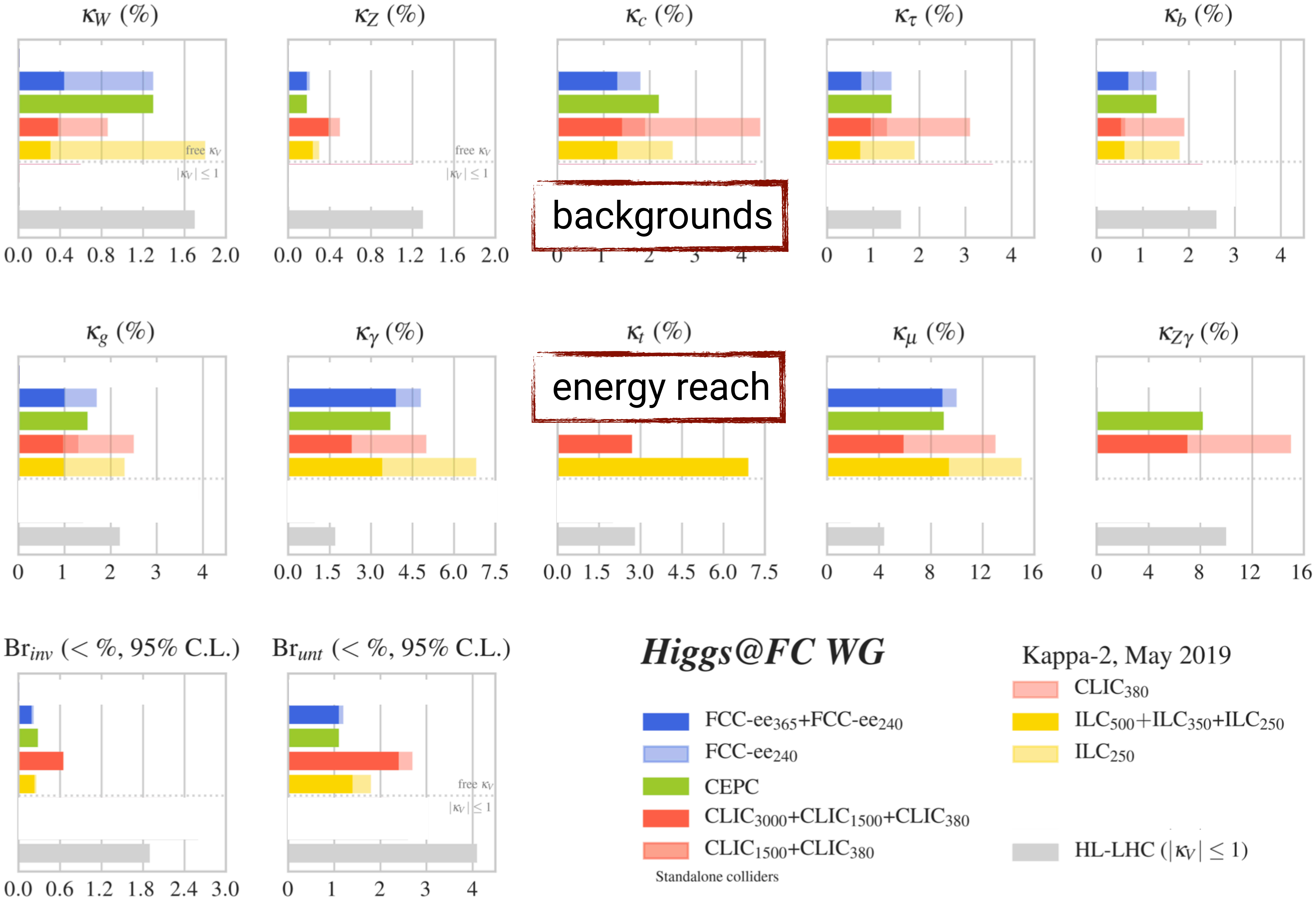

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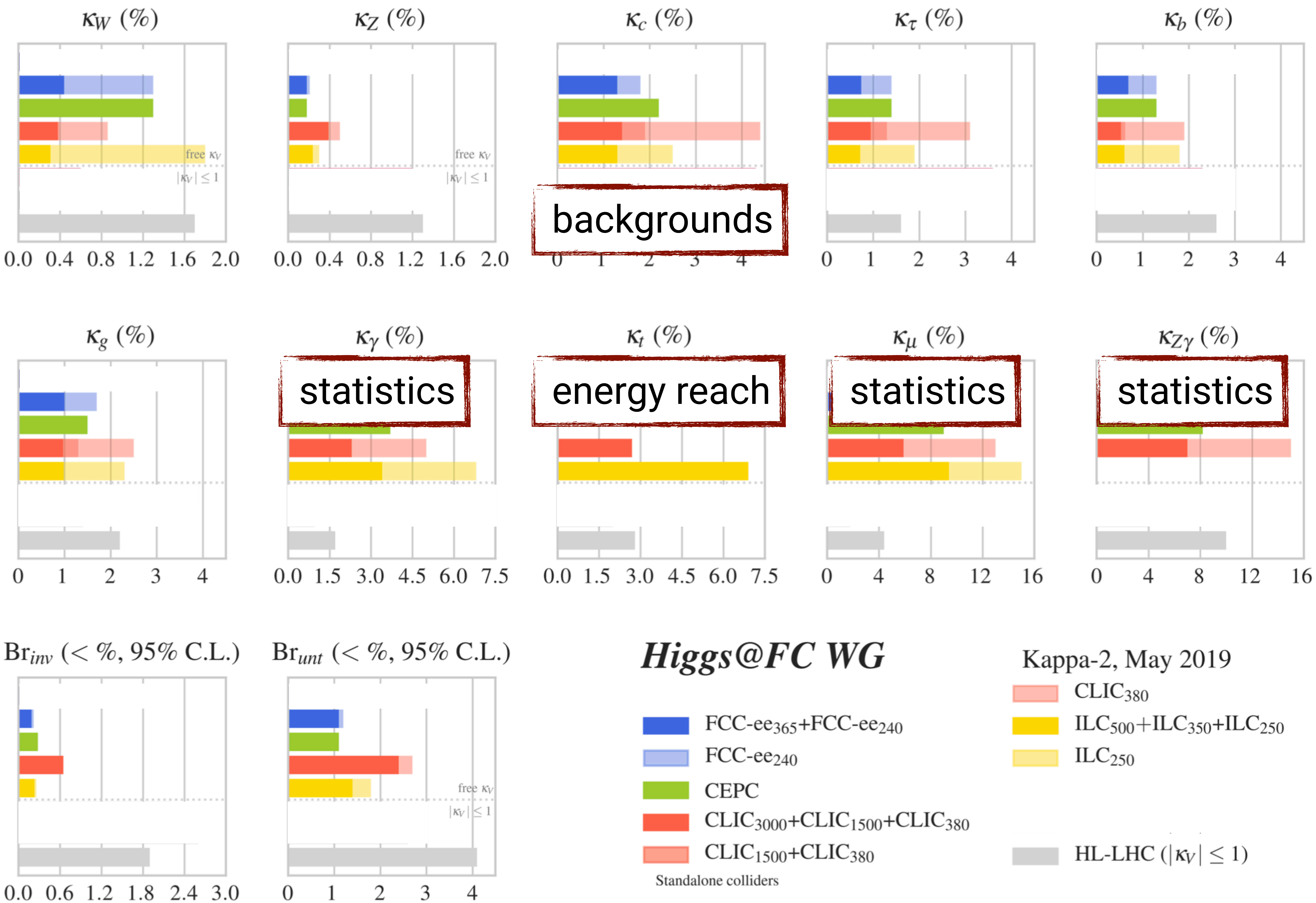


backgrounds

statistics

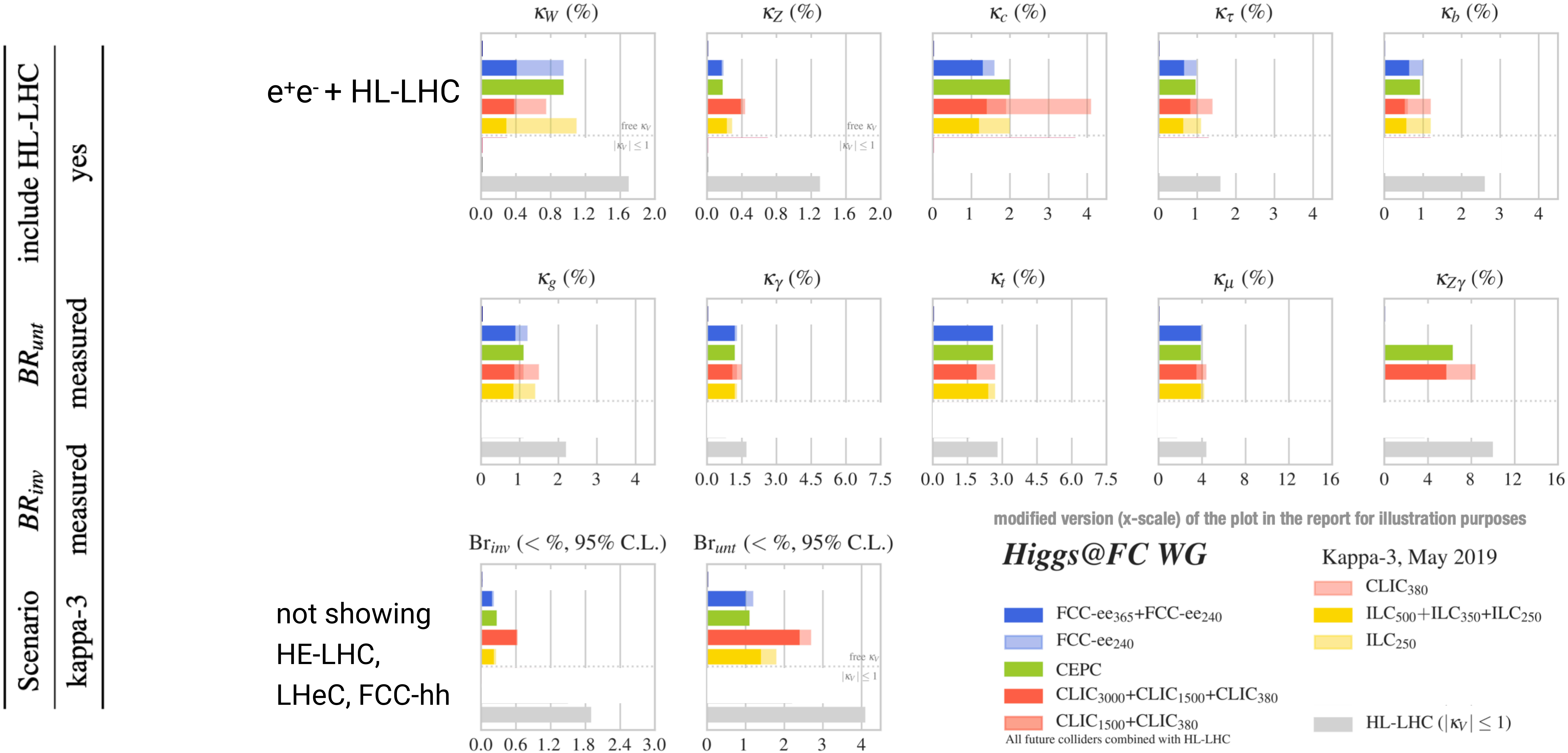
energy reach

statistics

statistics

A Comprehensive Picture of the Higgs Sector

Projections of Global Fits



e^+e^- + HL-LHC

not showing HE-LHC, LHeC, FCC-hh

modified version (x-scale) of the plot in the report for illustration purposes

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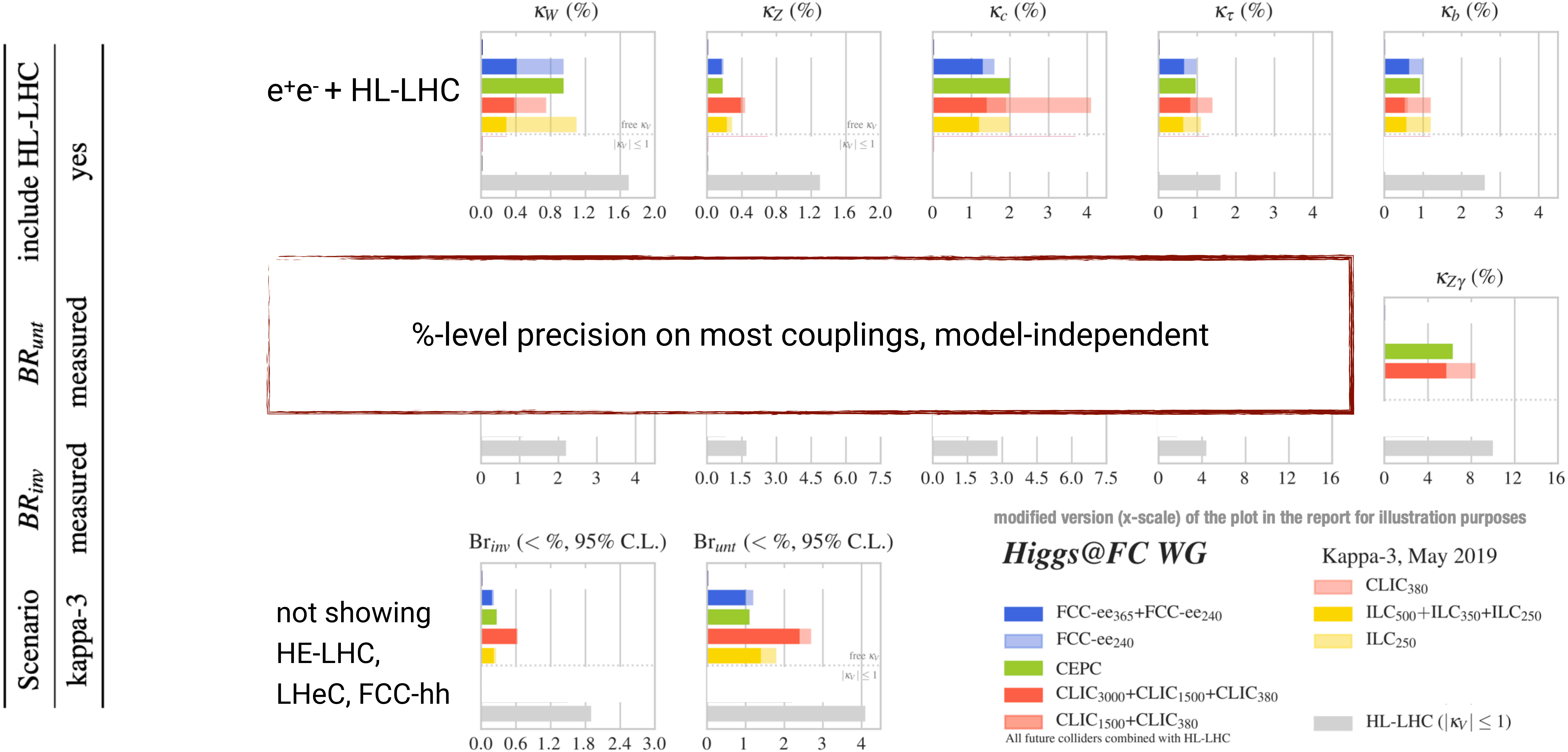

e^+e^- + HL-LHC

%-level precision on most couplings, model-independent

not showing HE-LHC, LHeC, FCC-hh

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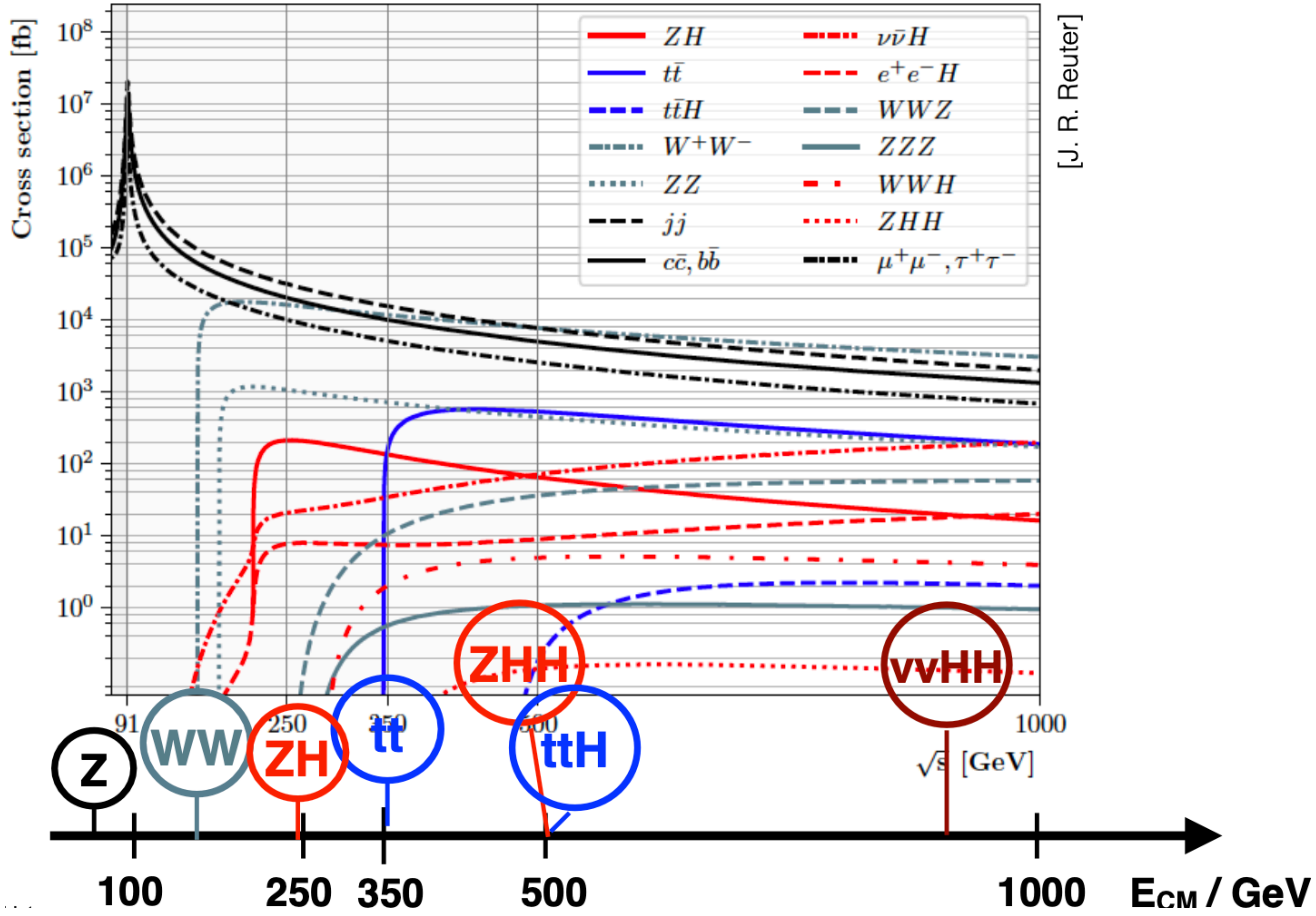
Take a Step back: Beyond the Higgs

The full panorama of e^+e^- collisions

- A high-energy e^+e^- collider is more than just a Higgs Factory:
  A ***Higgs-Electroweak-Top Factory***



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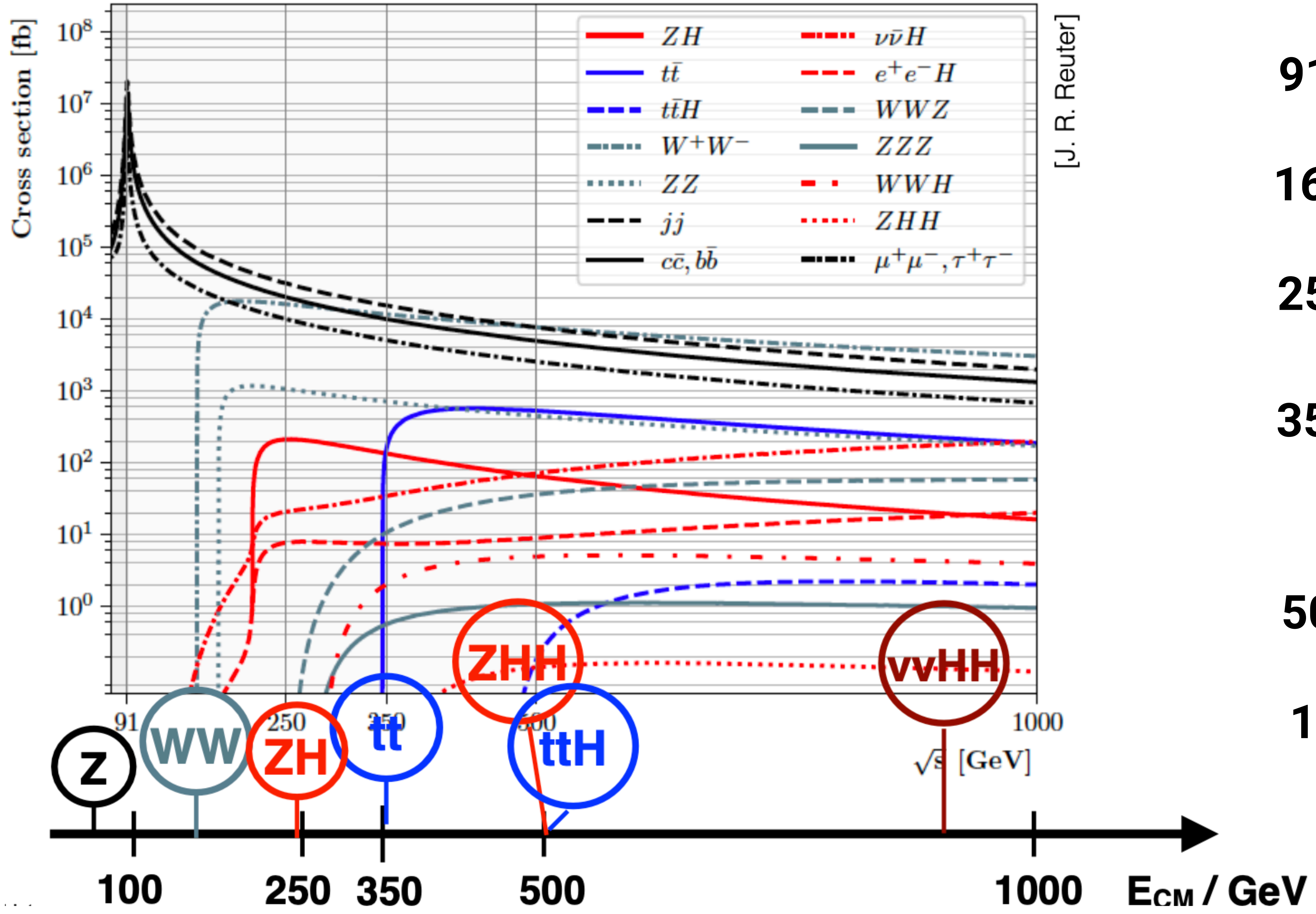
Thresholds and cross sections set collider energy targets:



[J. R. Reuter]

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

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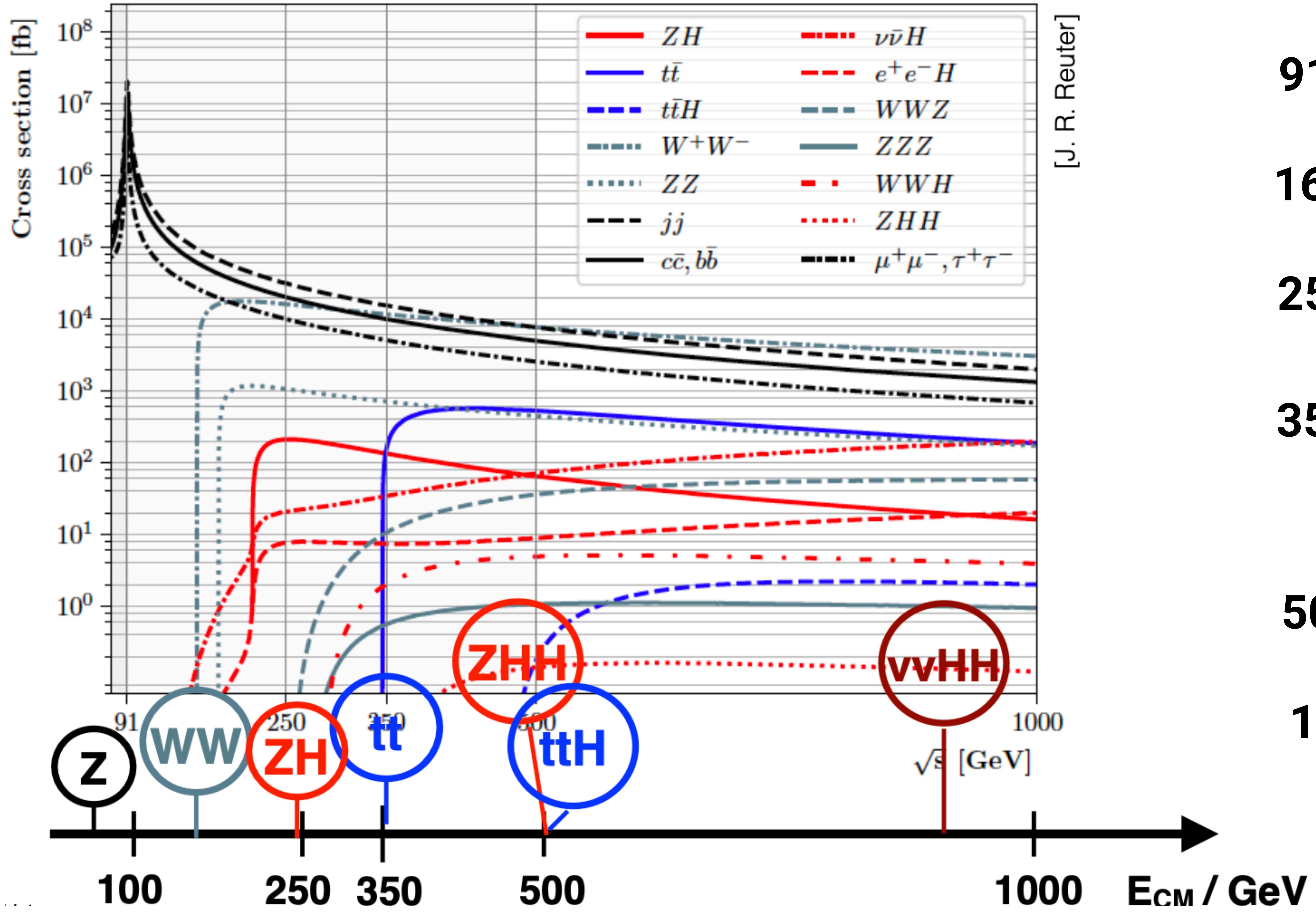

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Precision electroweak,
Flavour, QCD, …

Higgs properties &
couplings

Top properties,
Top as probe

Direct top Yukawa
Higgs selfcoupling

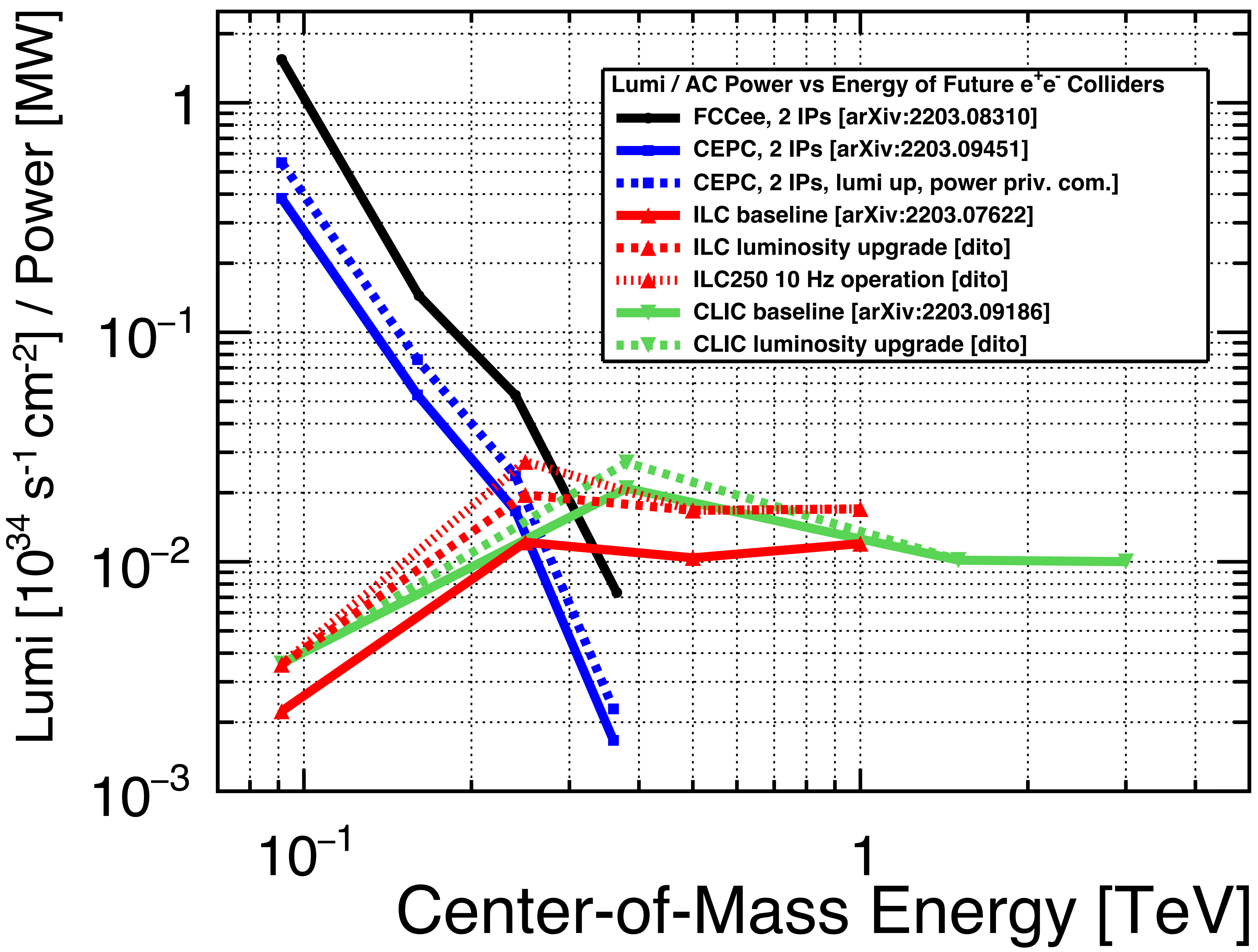
Search at the
energy frontier

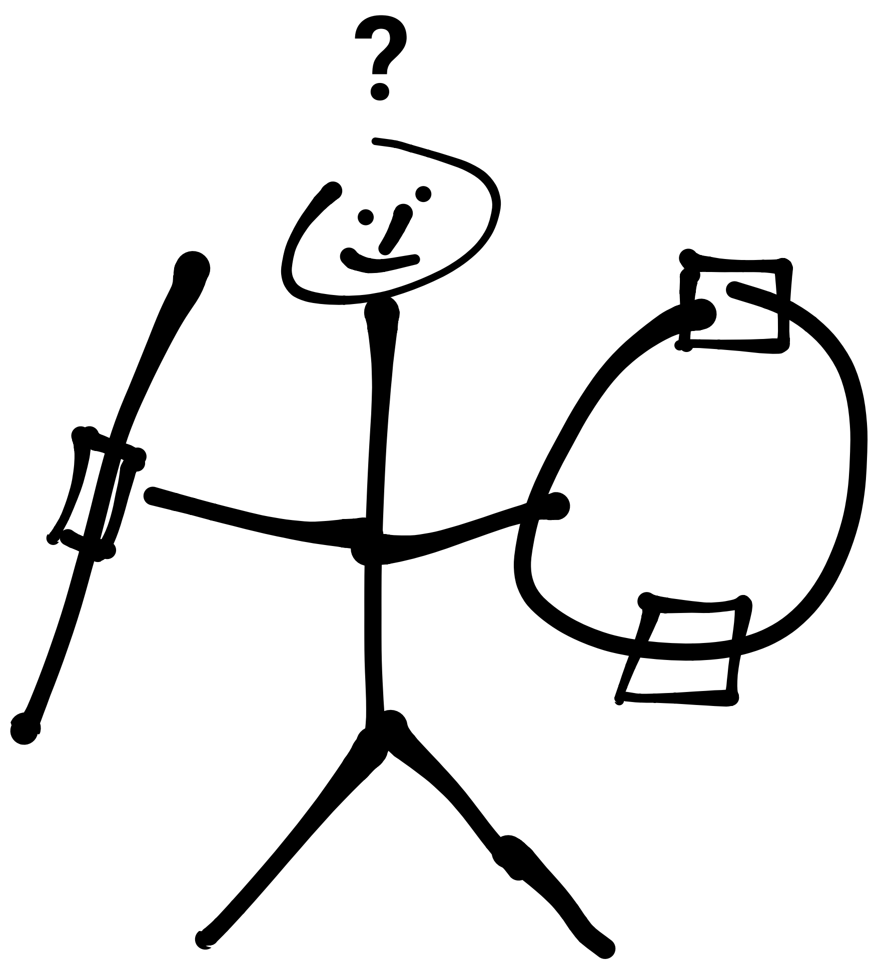
Interlude: Physics Emphasis & Collider Geometry

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



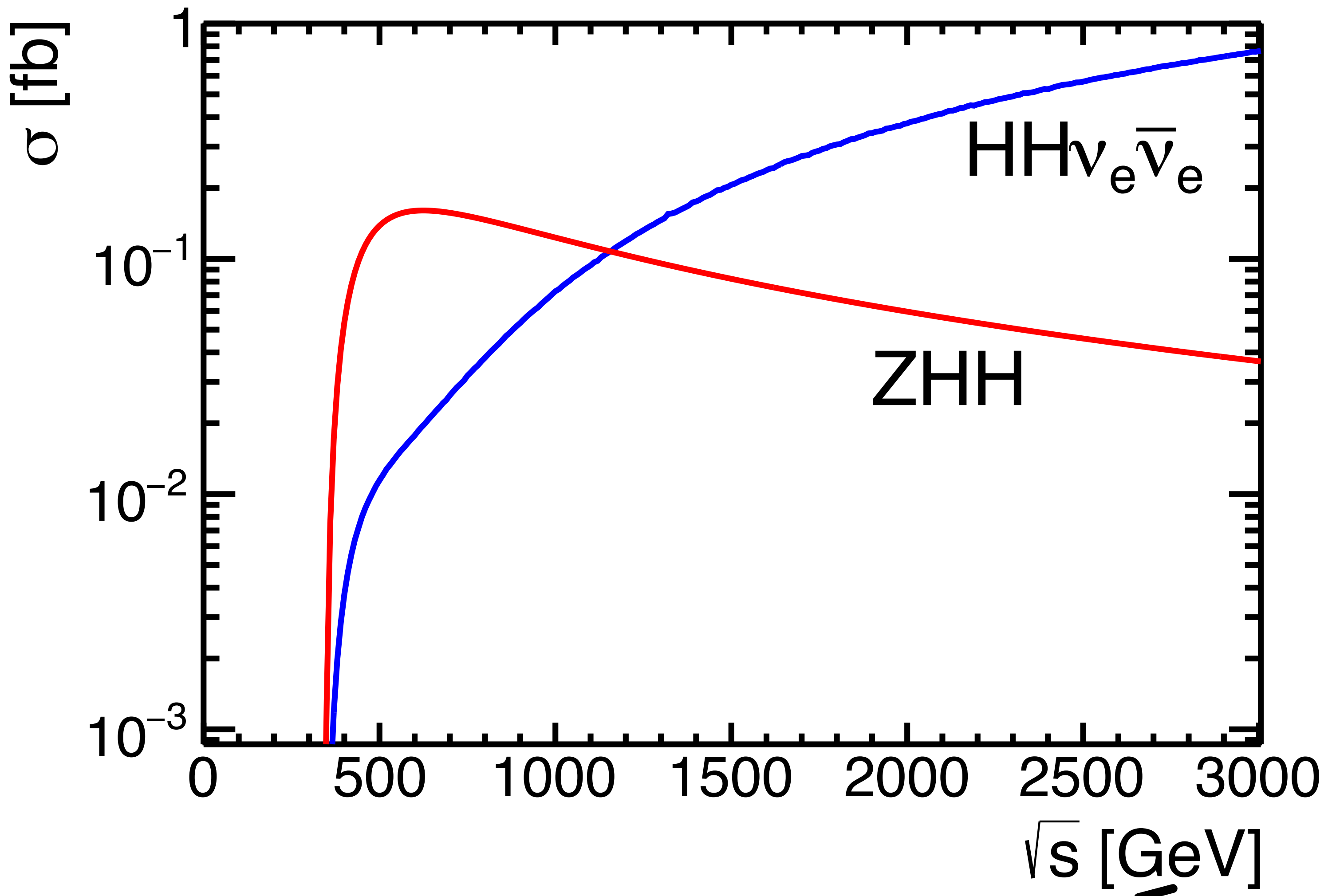


Linear:
reach to (multi-)TeV energy - double higgs production, high energy exploration

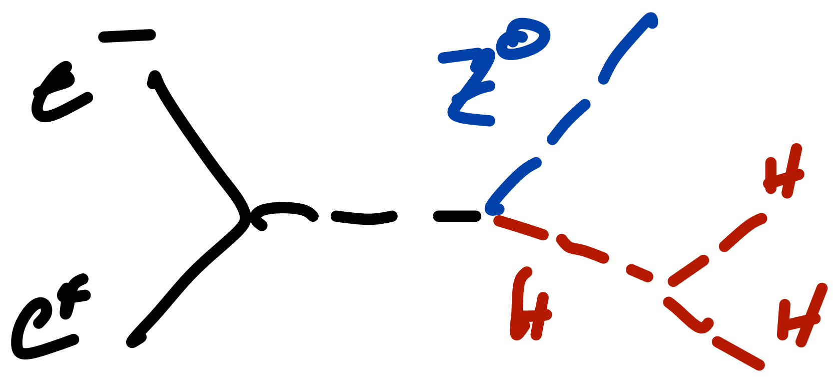
The Self-Coupling

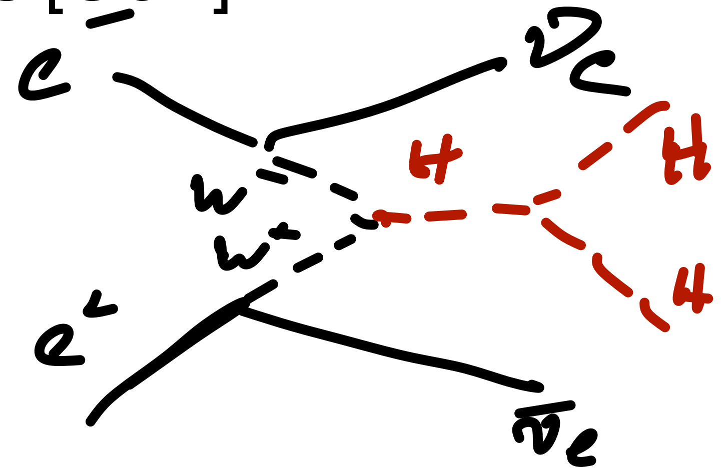
Direct and Indirect Measurements

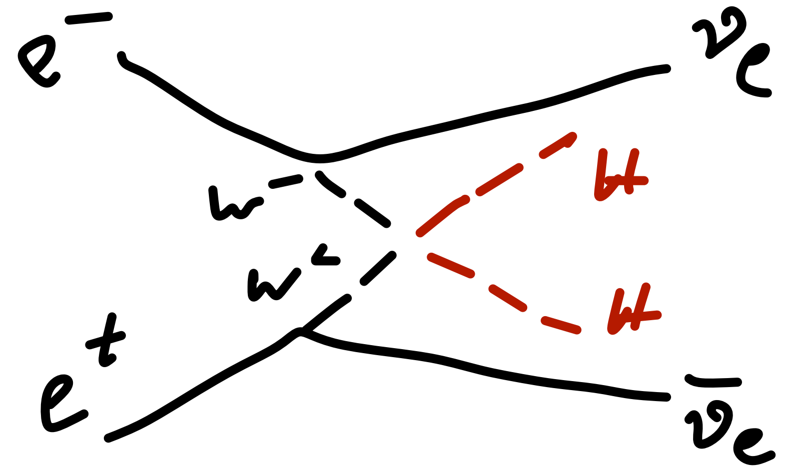
- Direct measurement requires high energy:



cross section depends non-linearly on λ, measurements at different energies / of different processes lift degeneracies

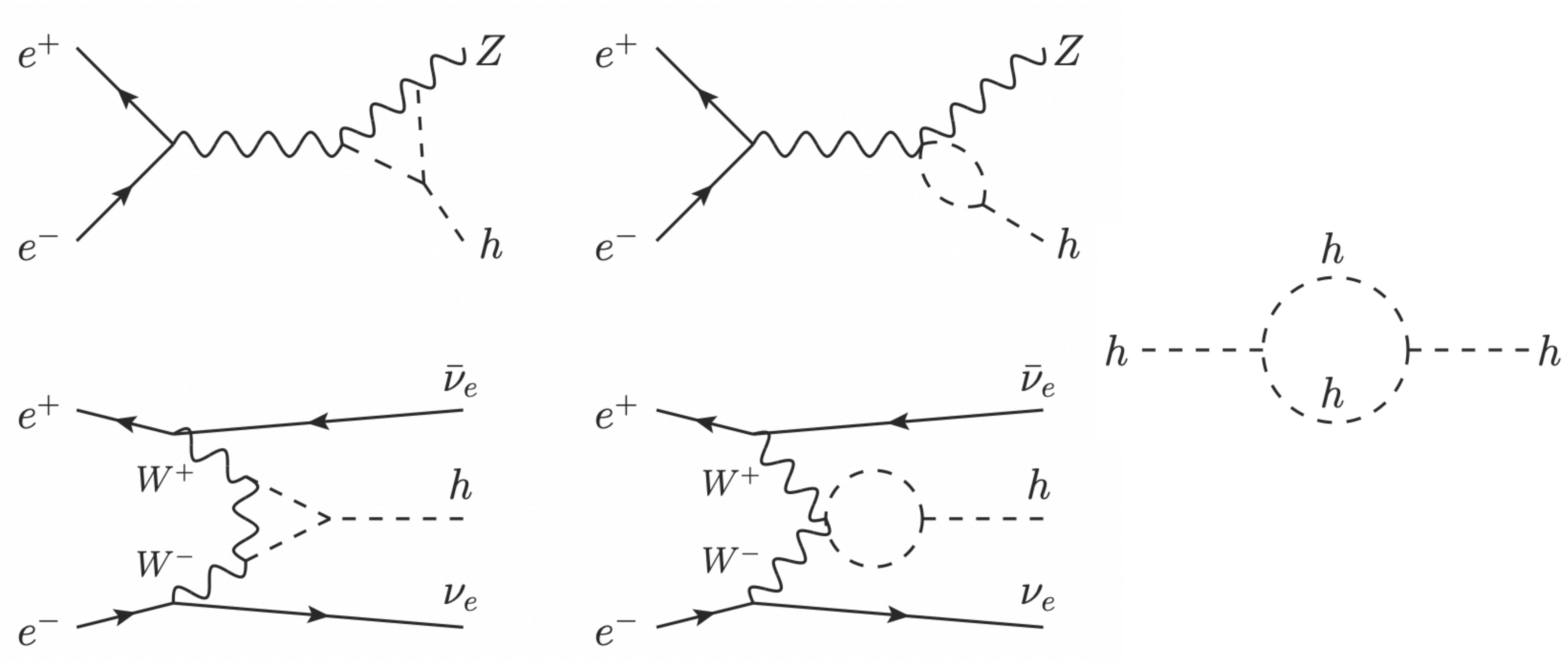






the final state also receives contributions from the quartic coupling

- Indirect, model-dependent sensitivity in single Higgs production and decay



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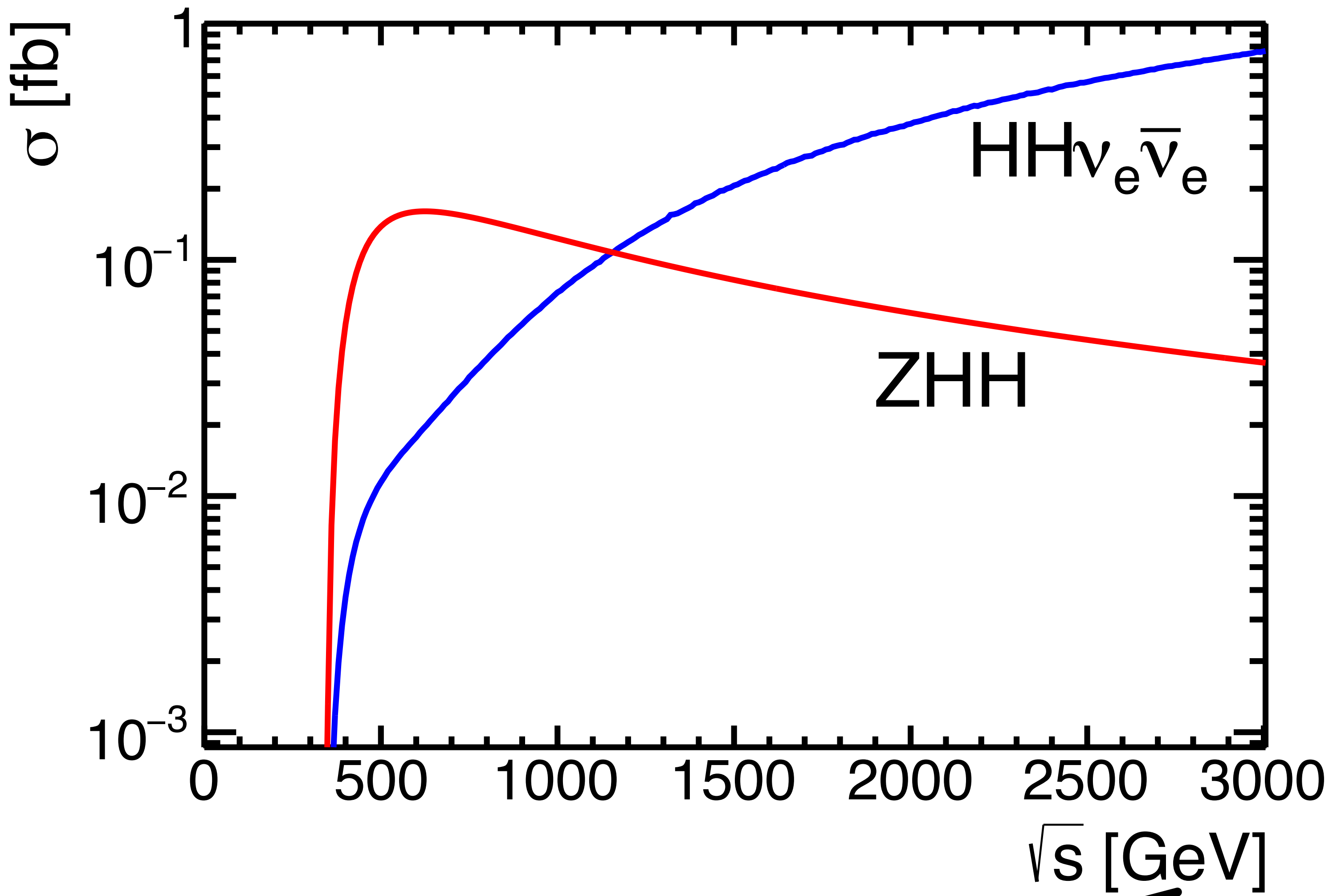

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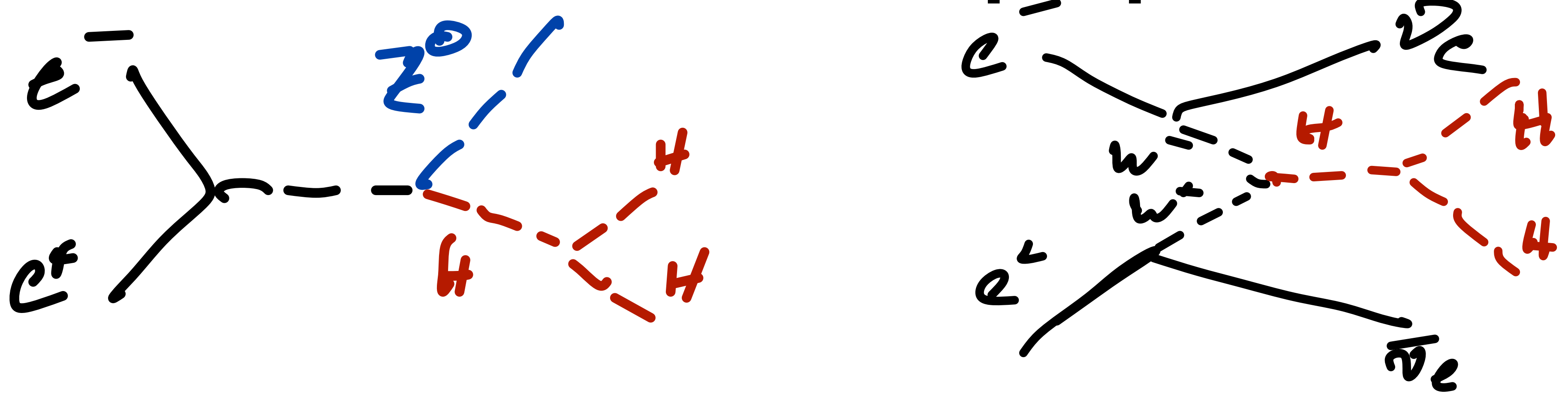

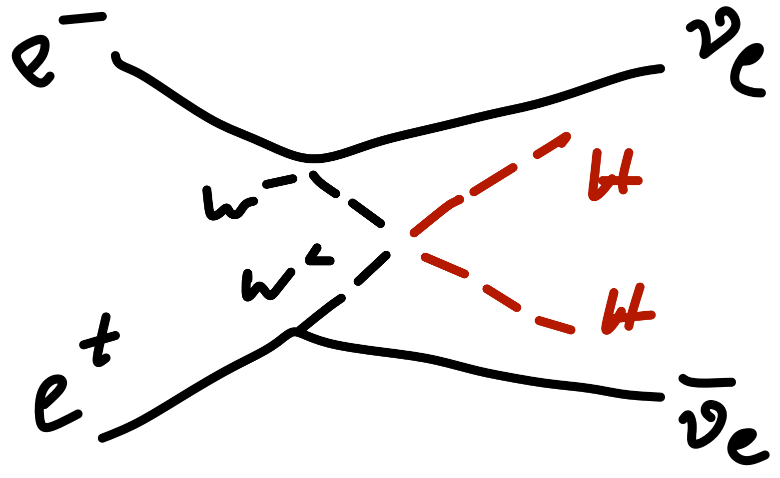

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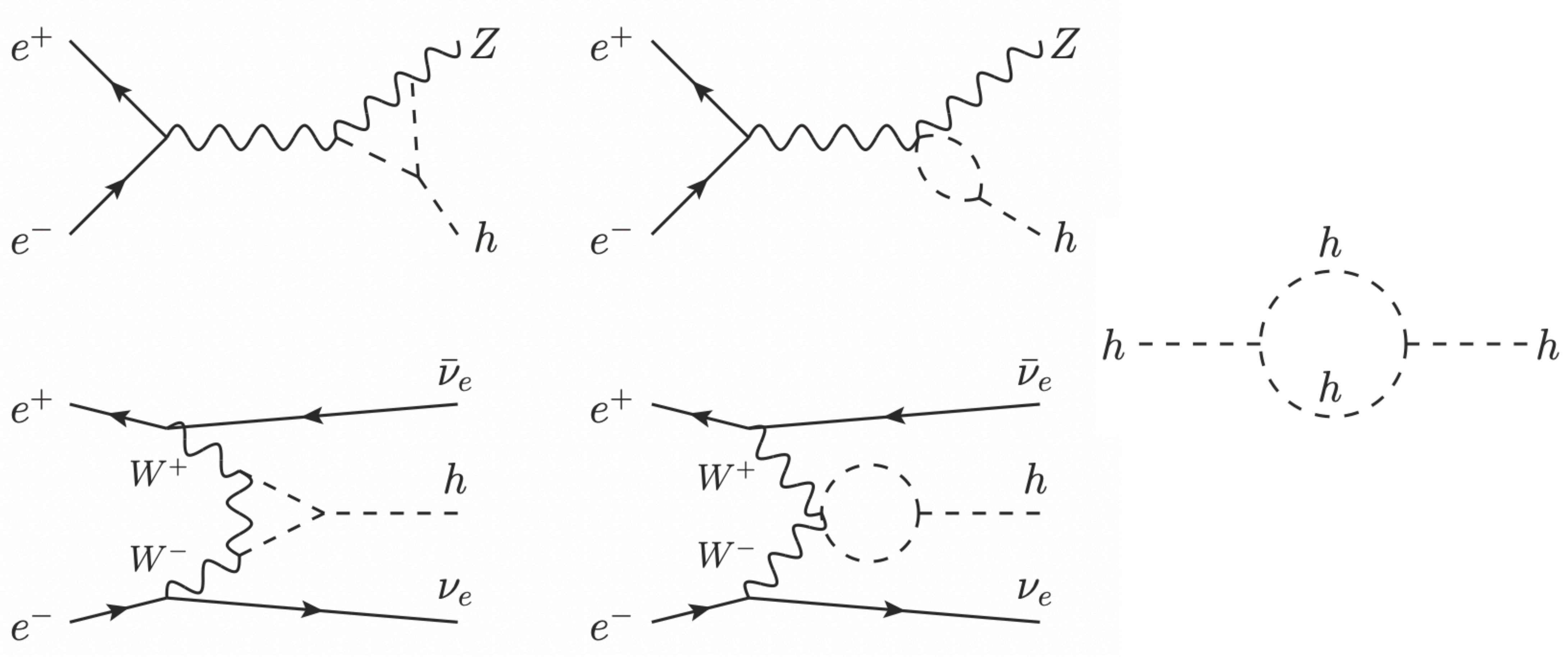


Full potential unfolds in the (multi-)TeV region, combining ZHH and VBF double Higgs production

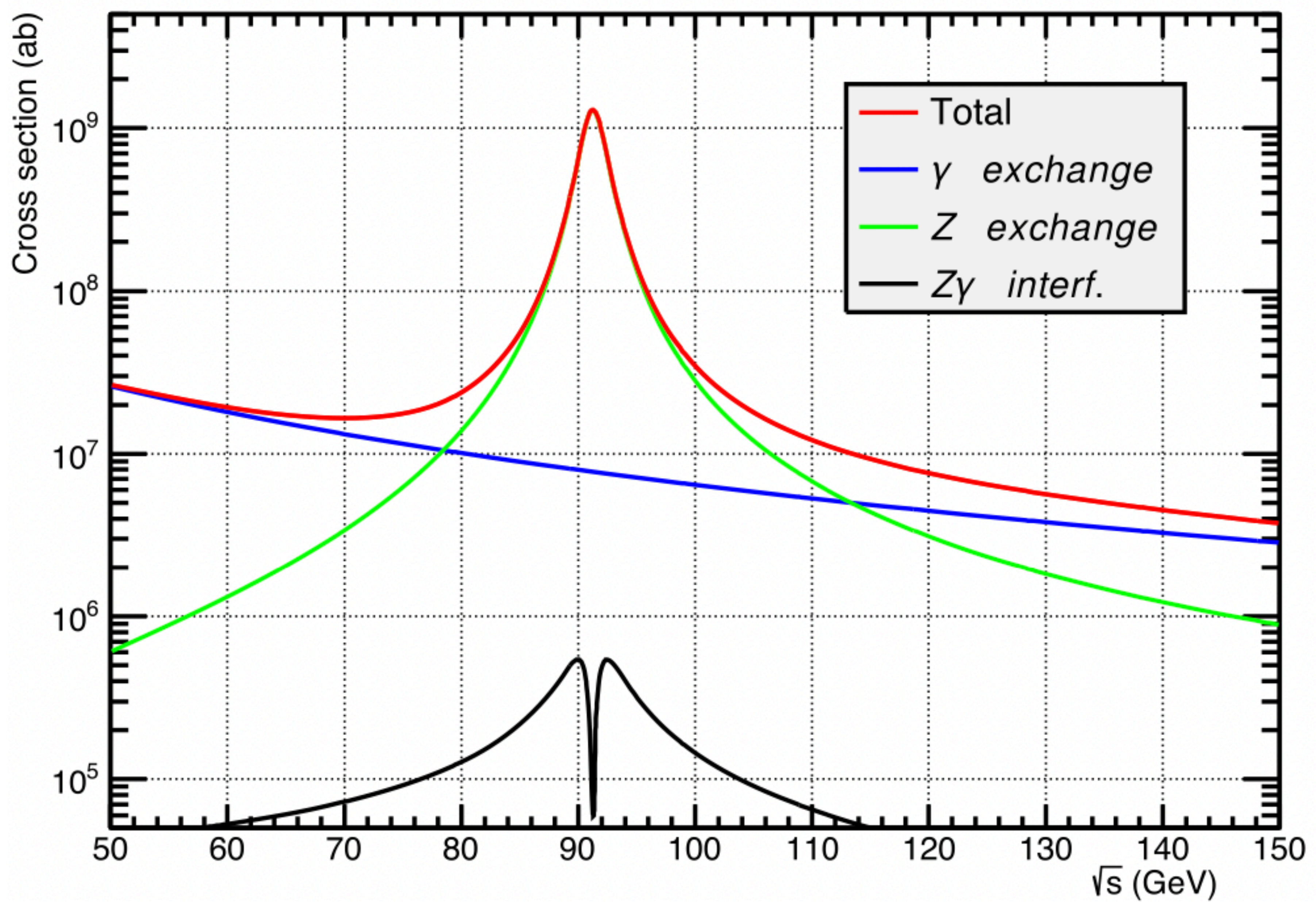
⇨ ~10% measurement feasible

Single-Higgs observables can provide ~35% sensitivity in combination with HL-LHC.

A New Era of Electroweak Precision

Tera-Z and Oku-W

- The high luminosities of circular colliders at low energy enable a program with
  ~ 10^{12} events at the Z pole
  ~ 10^8 events at the WW threshold



A full suite of measurements from the Z pole and line shape around 91.2 GeV

- m_Z to ~ 100 keV
- $\sin^2\Theta_W^{eff}$, N_ν, A_{FB}^b, …
- α_s to 1.2 x 10^4 (0.1%)
- …

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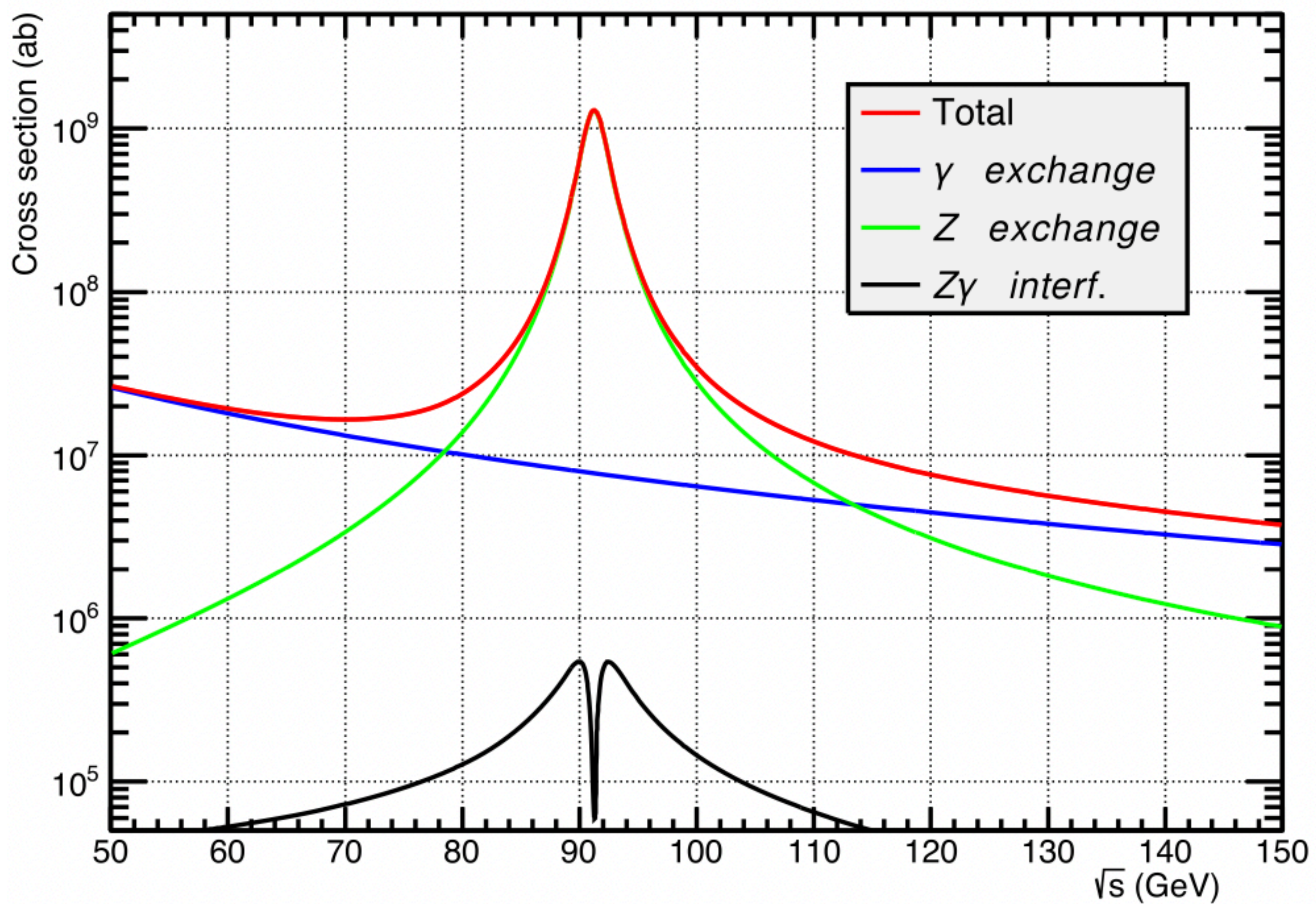

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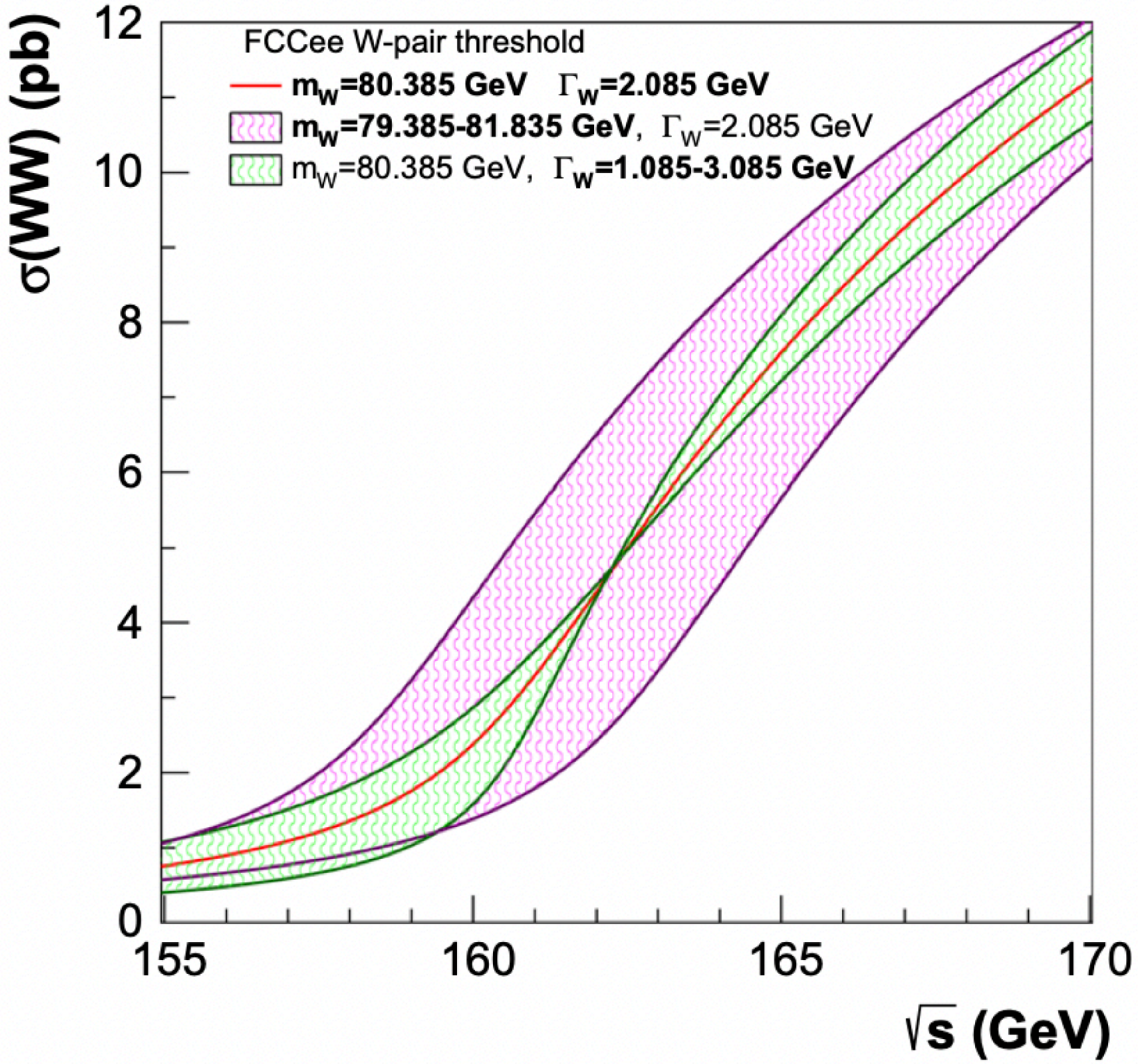
W measurements around the pair production threshold of 160.7 GeV

- m_W to ~ 1 MeV (CDF: 9 MeV)

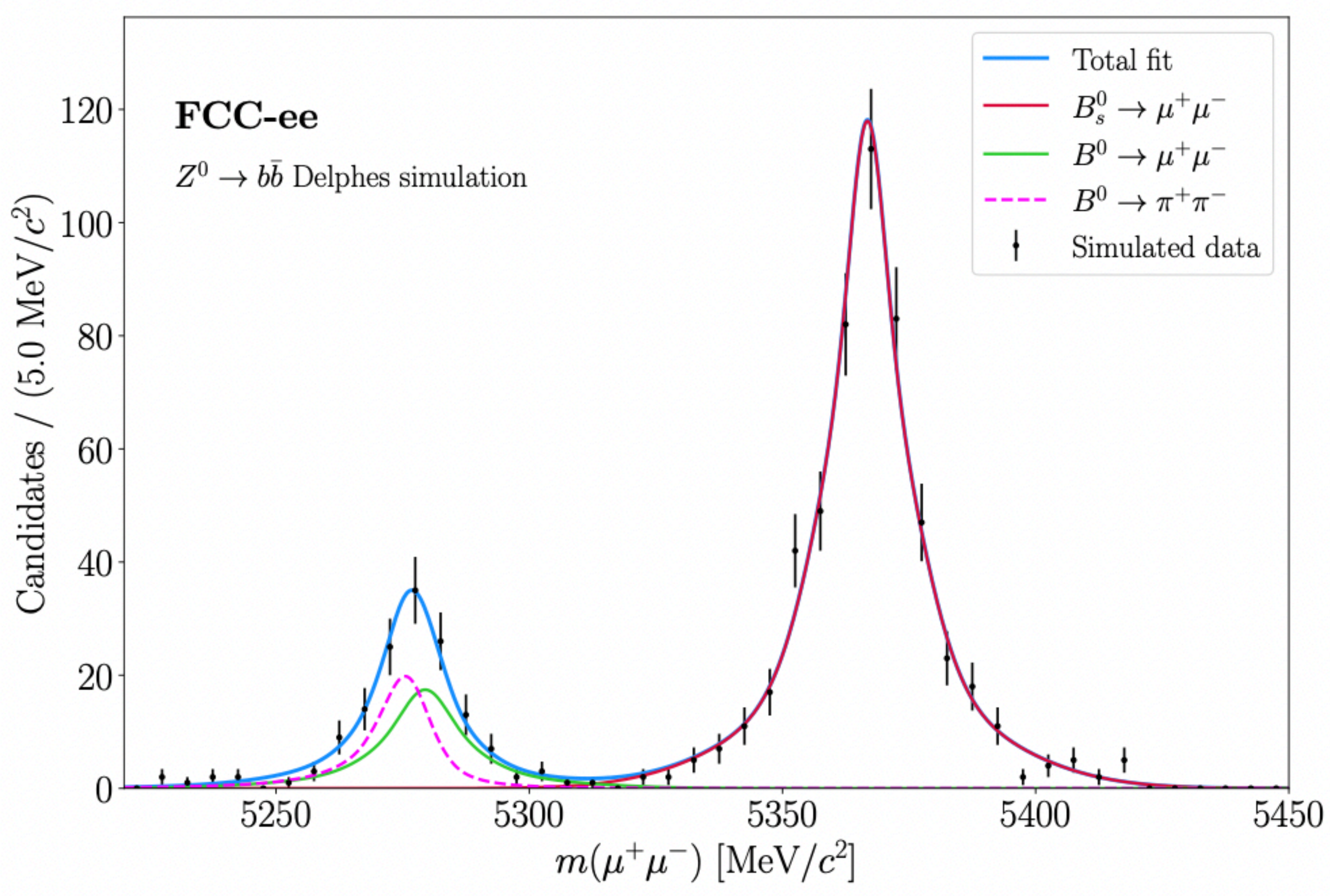


Beyond Z and W

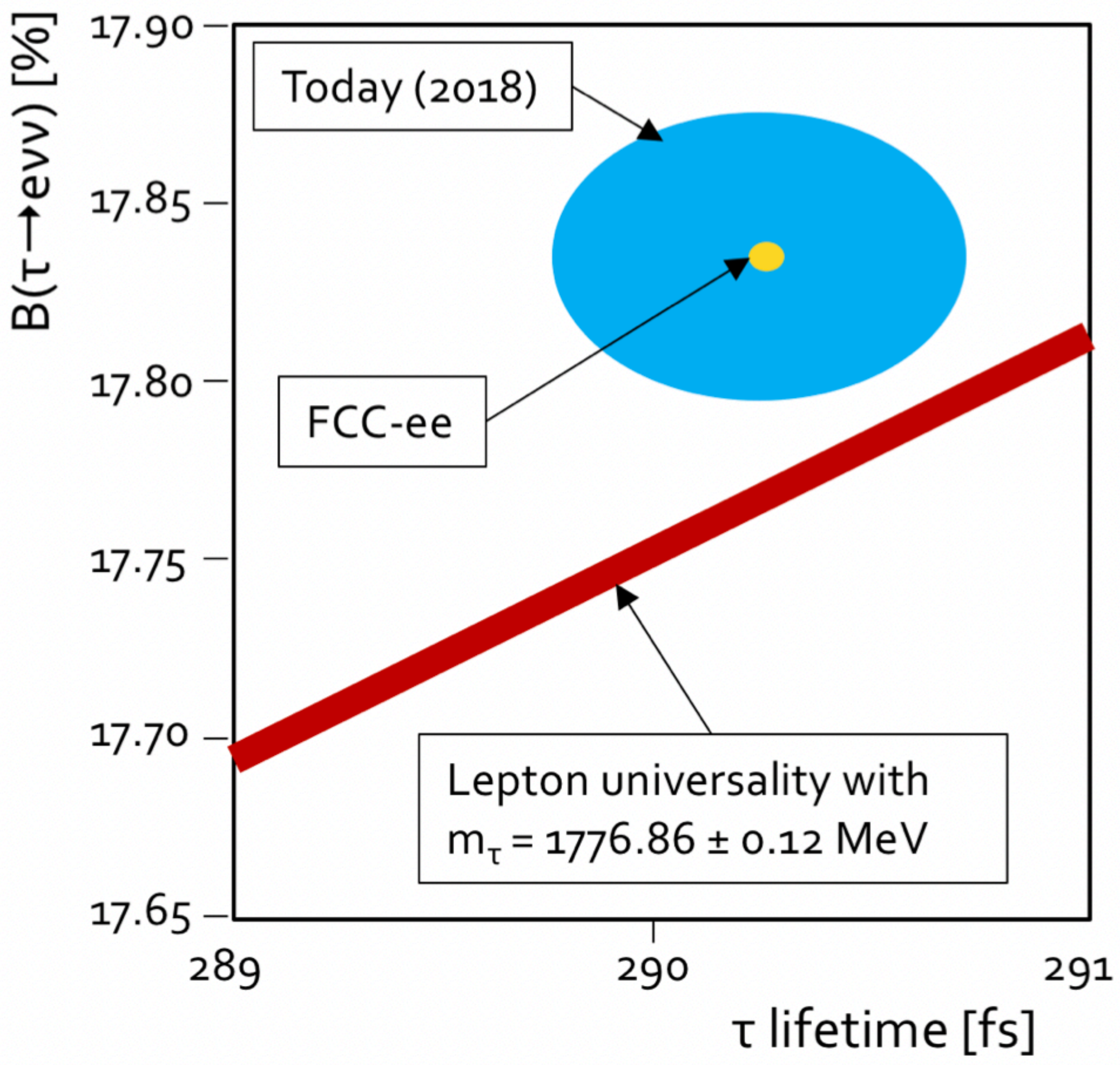
A rich program at the Z pole

- High statistics at the Z also imply very large samples of
  - bb pairs: 5 x 10^{12} Z -> 10^{12} b pairs
  - $\tau^+\tau^-$ pairs: ~ 1.7 x 10^{11} pairs

A next-generation e^+e^- flavour physics program beyond Belle II / SuperKEKB



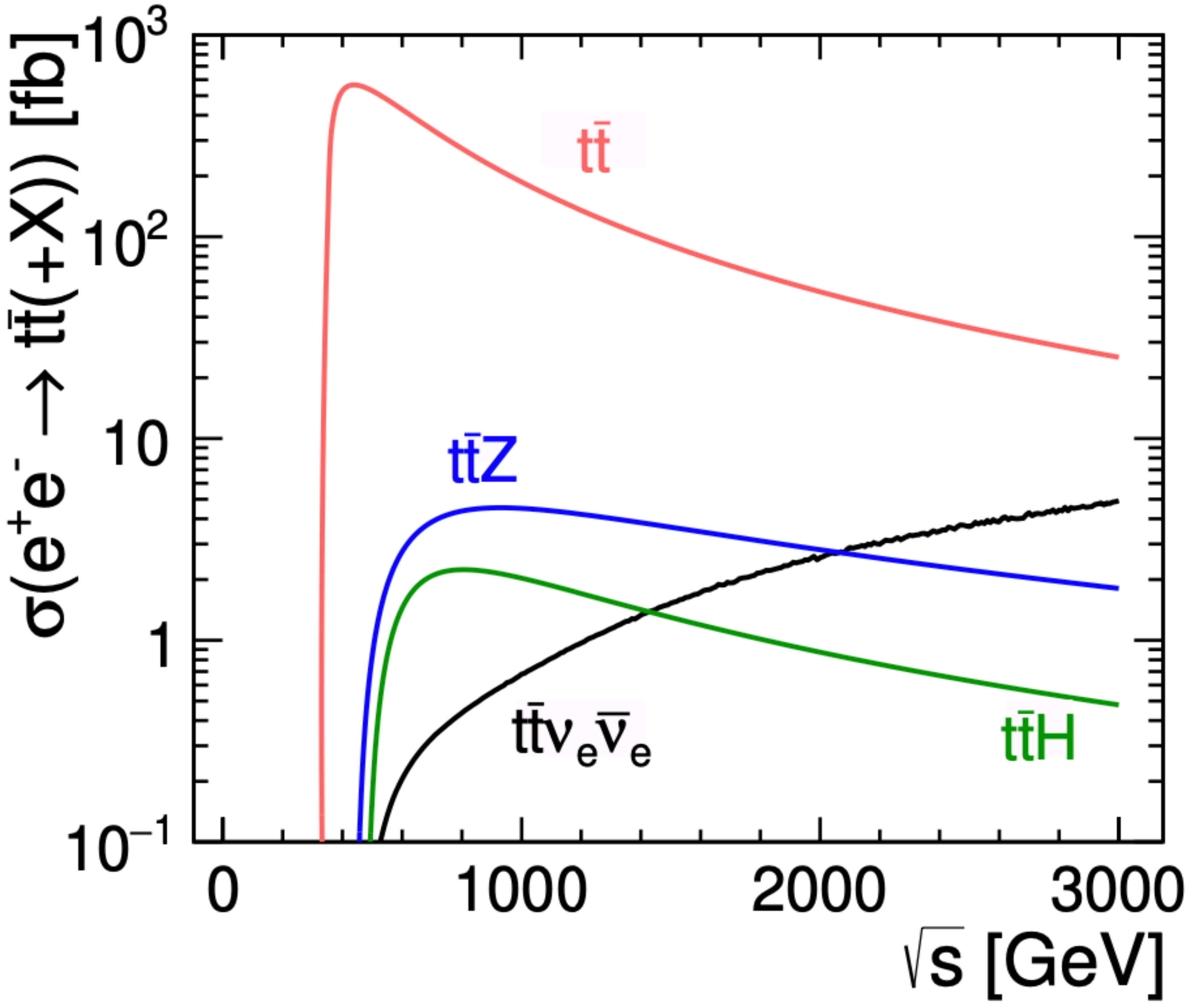
CKM, CPV, rare decays & anomalies, …



lepton universality test, electroweak precision, …

The Top Quark

Understanding the Top, using the Top



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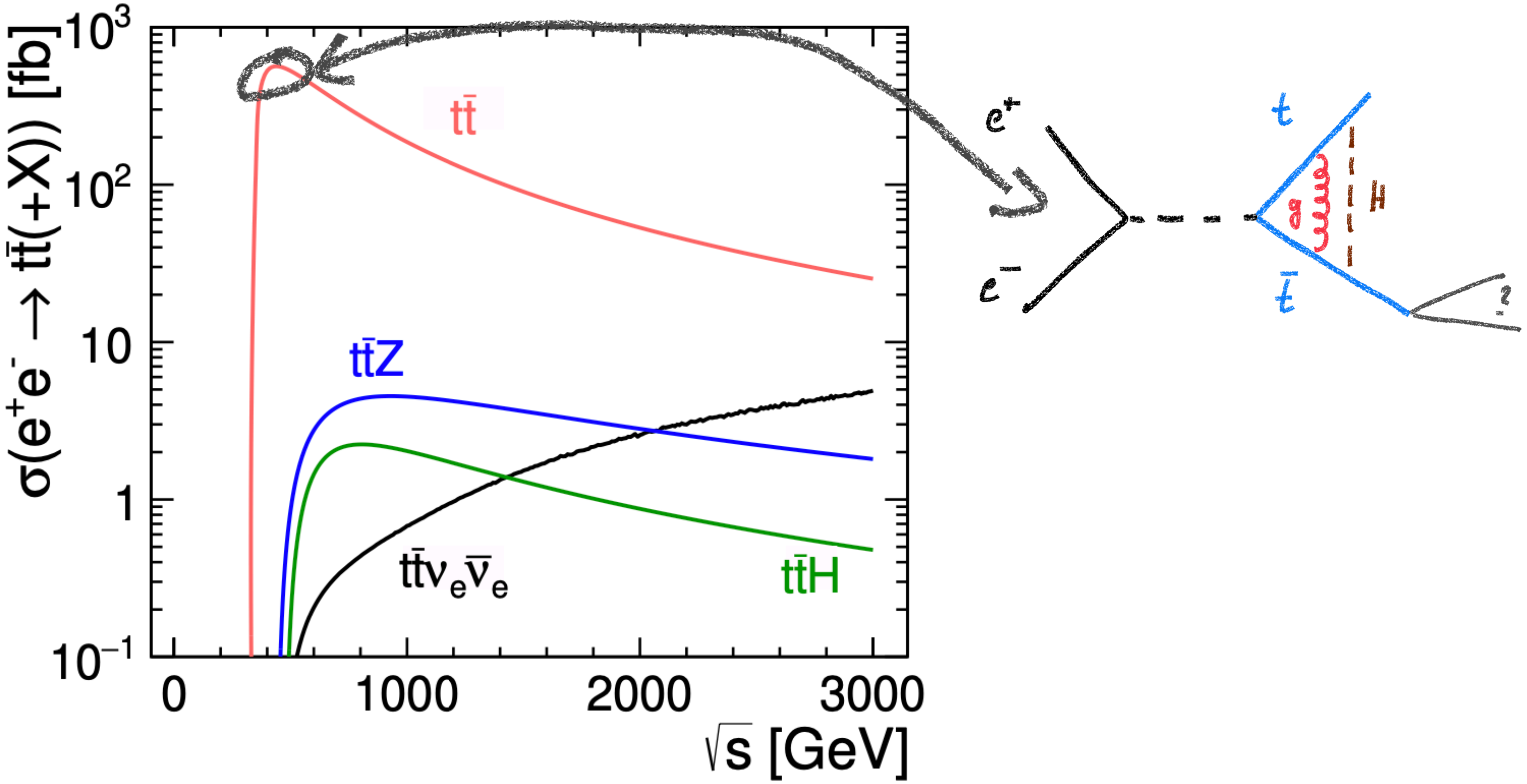

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- Search for BSM decays in clean environment

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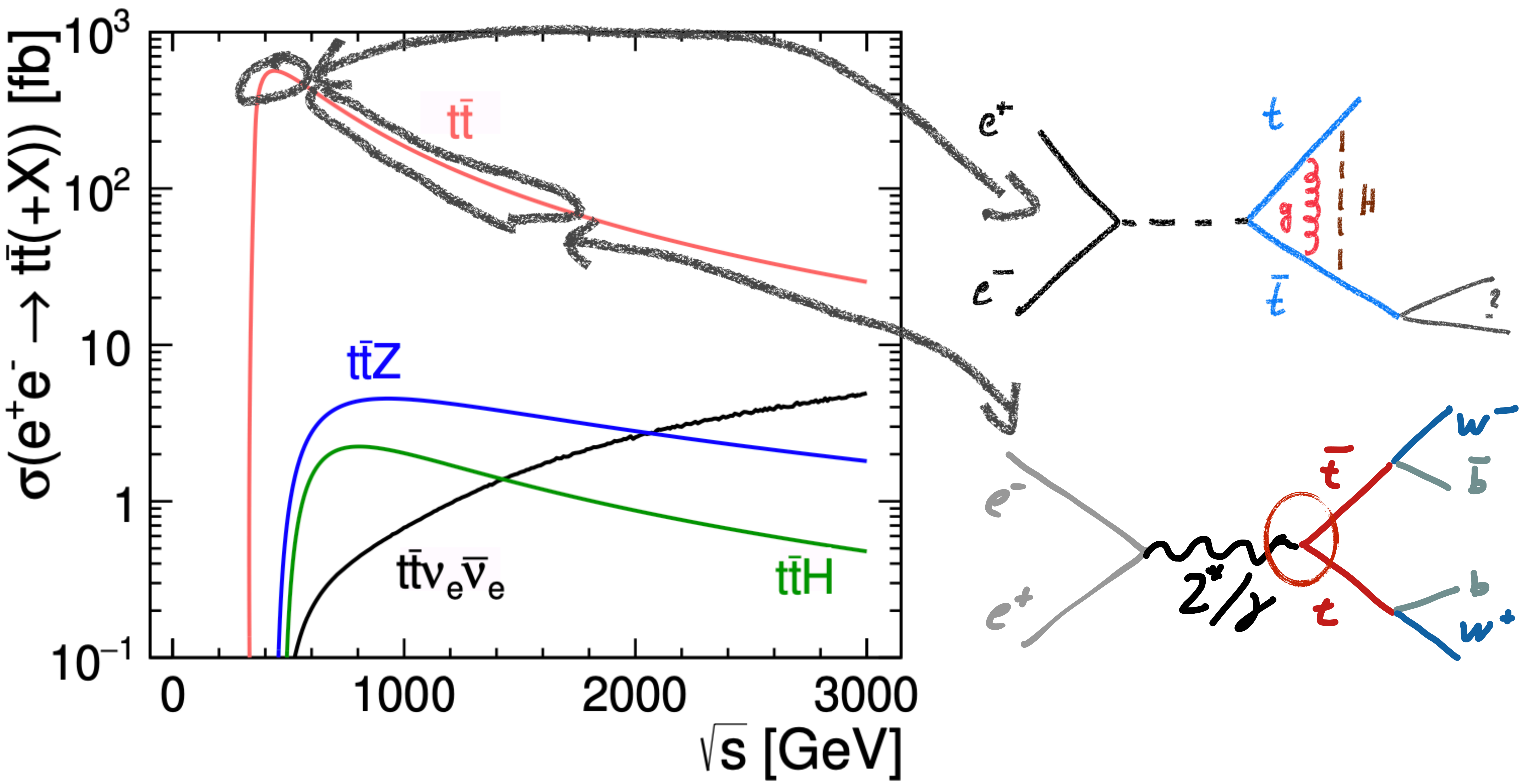

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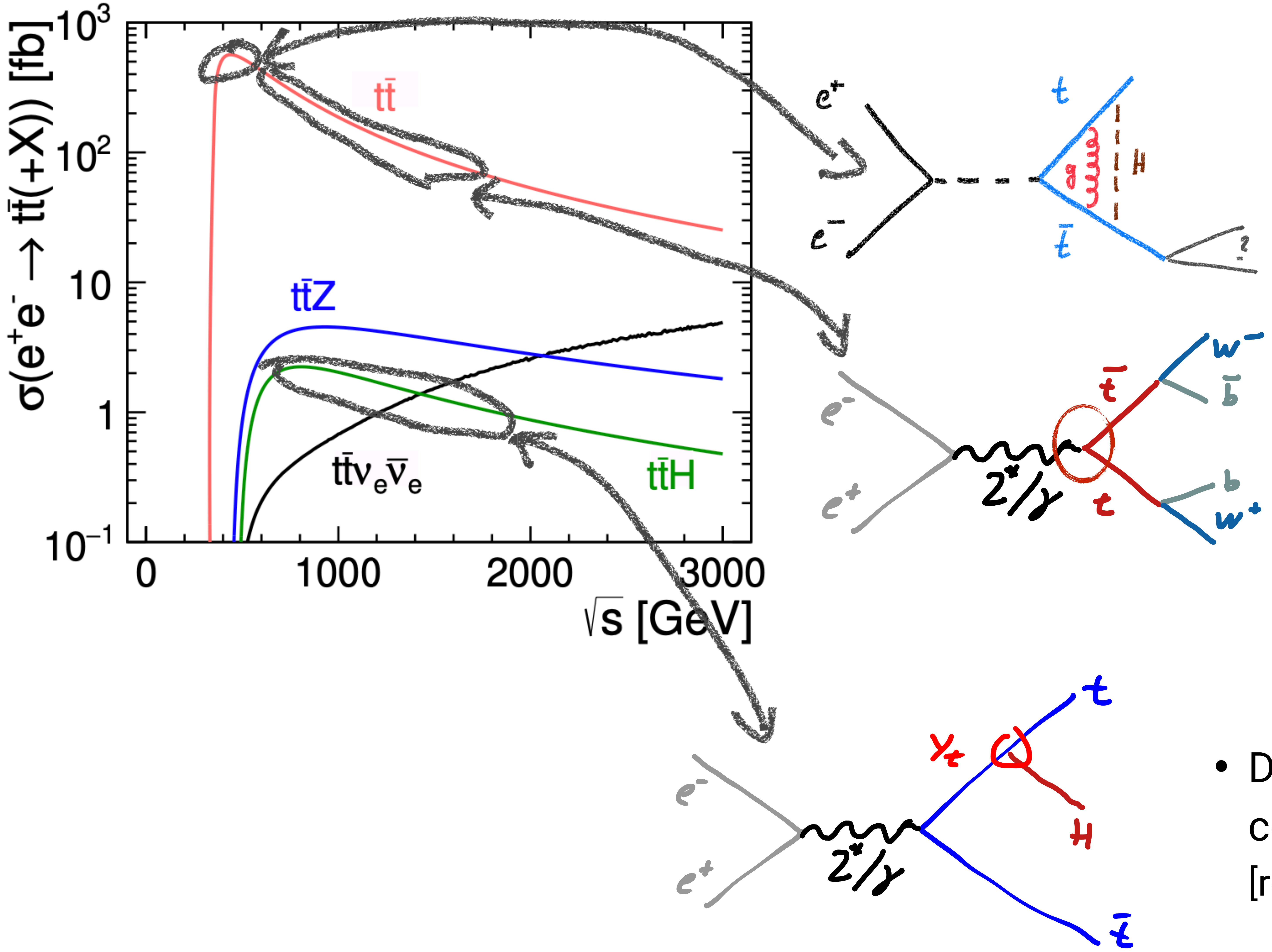
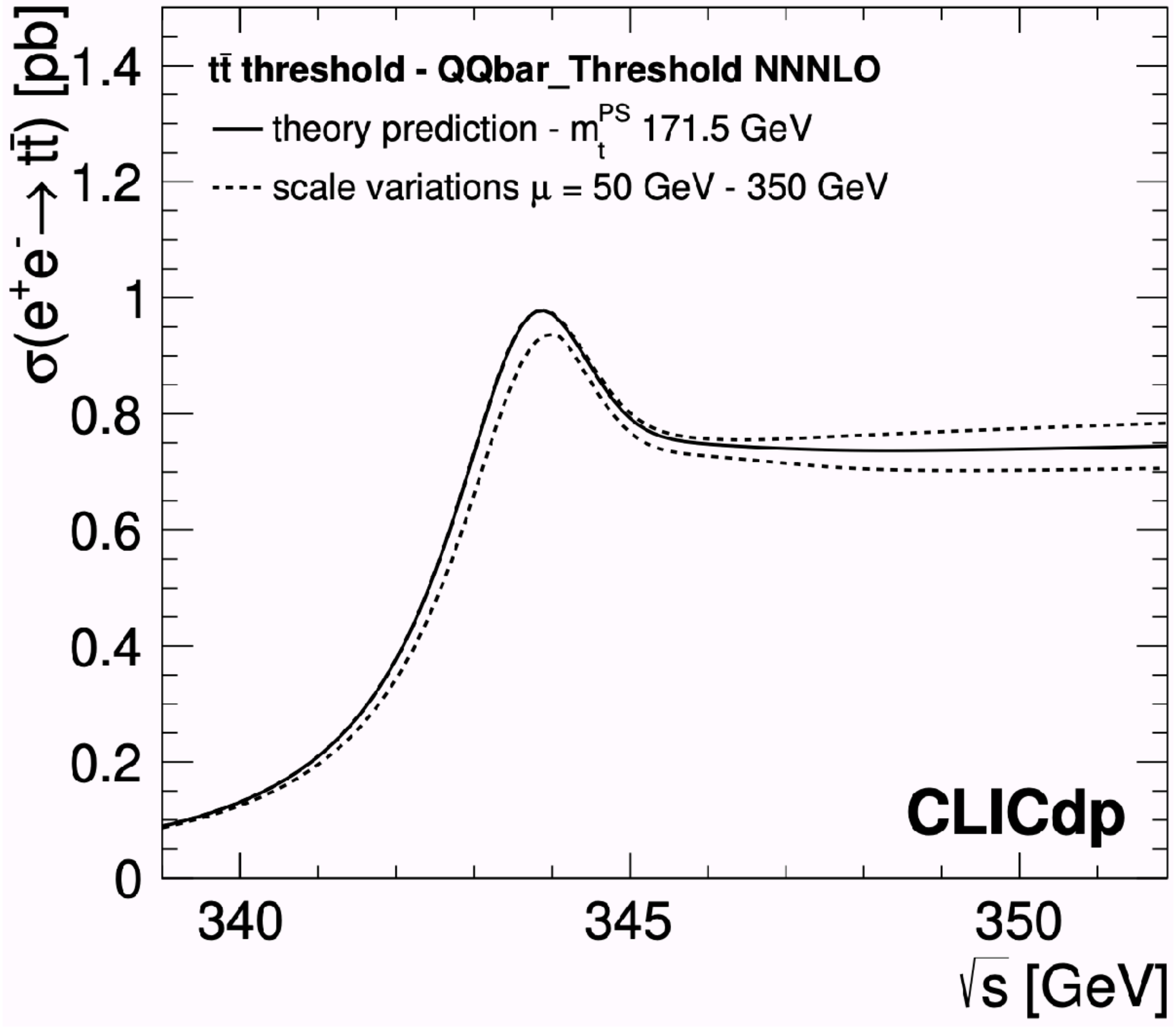


- Measuring the top quark mass (and other parameters) in theoretically well-defined frameworks
- Search for BSM decays in clean environment
- Electroweak couplings of the top quark as a probe for New Physics
- Direct measurement of the top Yukawa coupling, ultimate potential of 2%
  [requires > 500 GeV, full scope assumes ~ 1 TeV]

The Top Quark

Examples - Mass at Threshold; Asymmetries to probe New Physics



- Exploit precise theoretical calculations of cross section in the threshold region, in well-defined mass schemes (m_t^{PS}, m_t^{1S}…) -> Can be converted directly into MSbar mass.

The Top Quark

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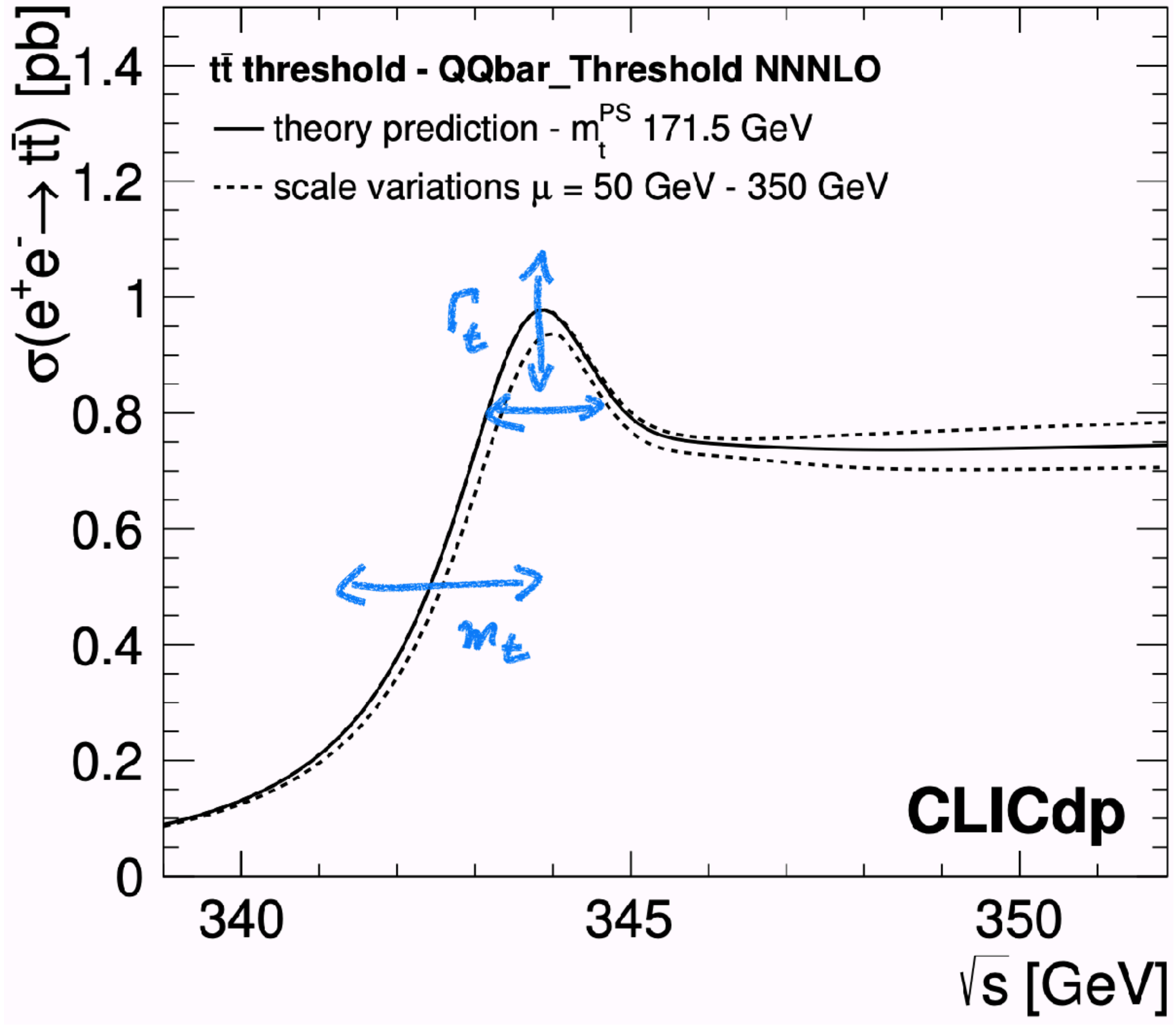

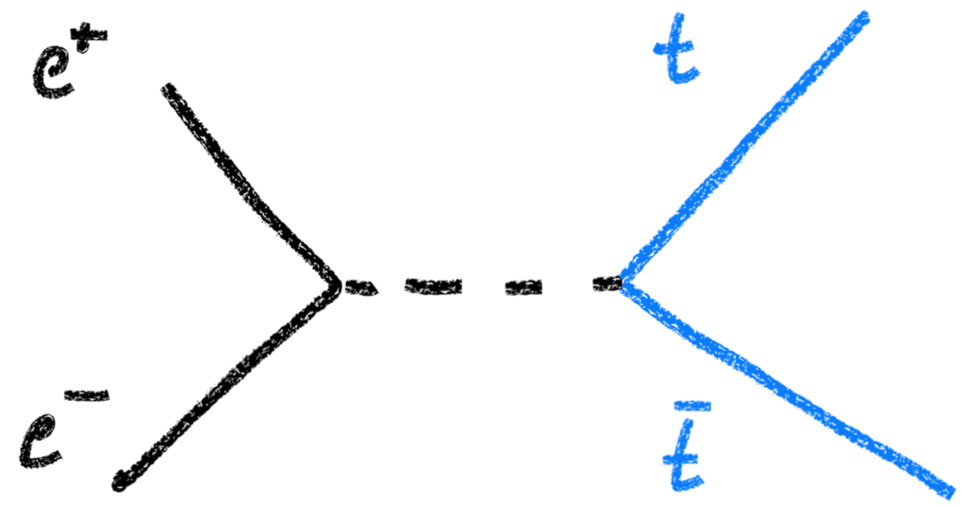

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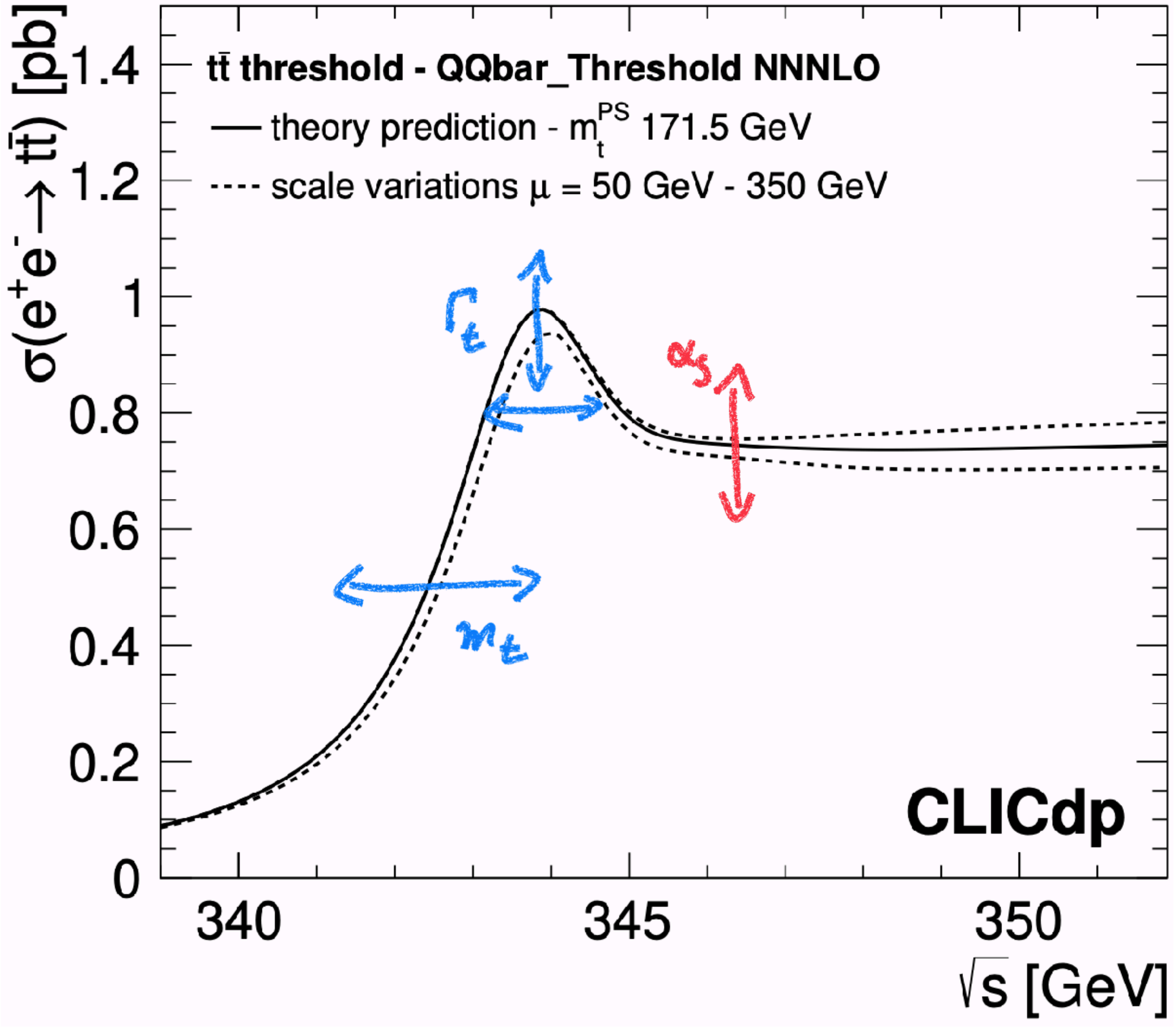

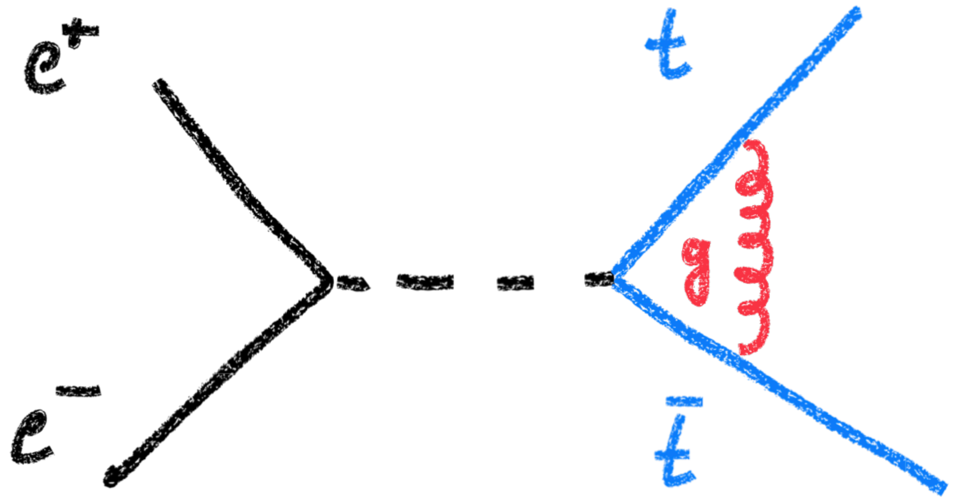

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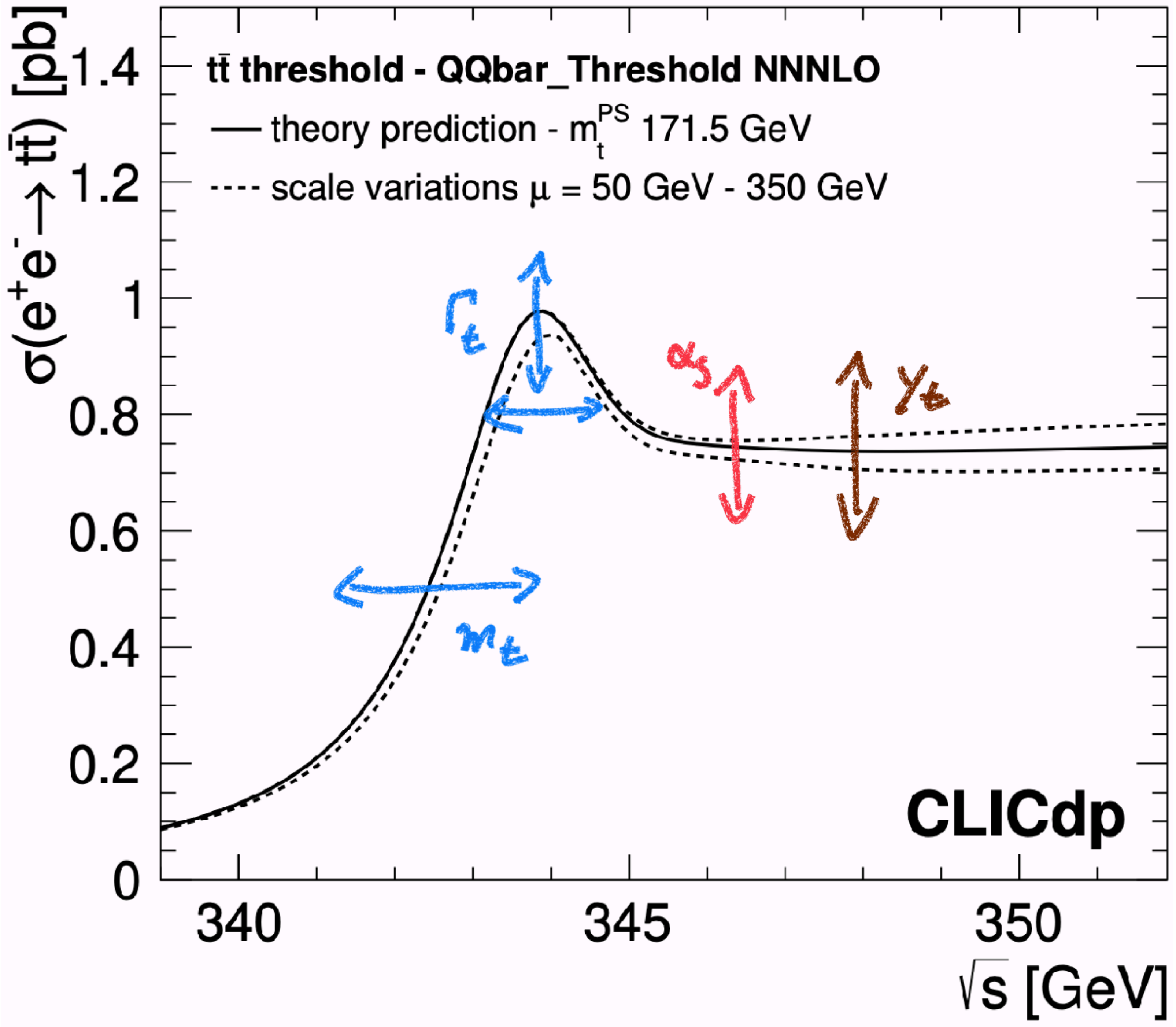

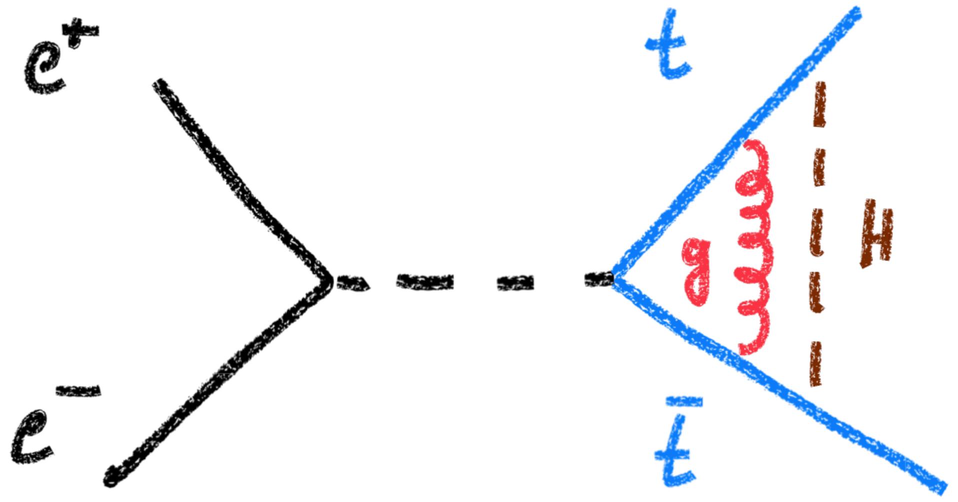

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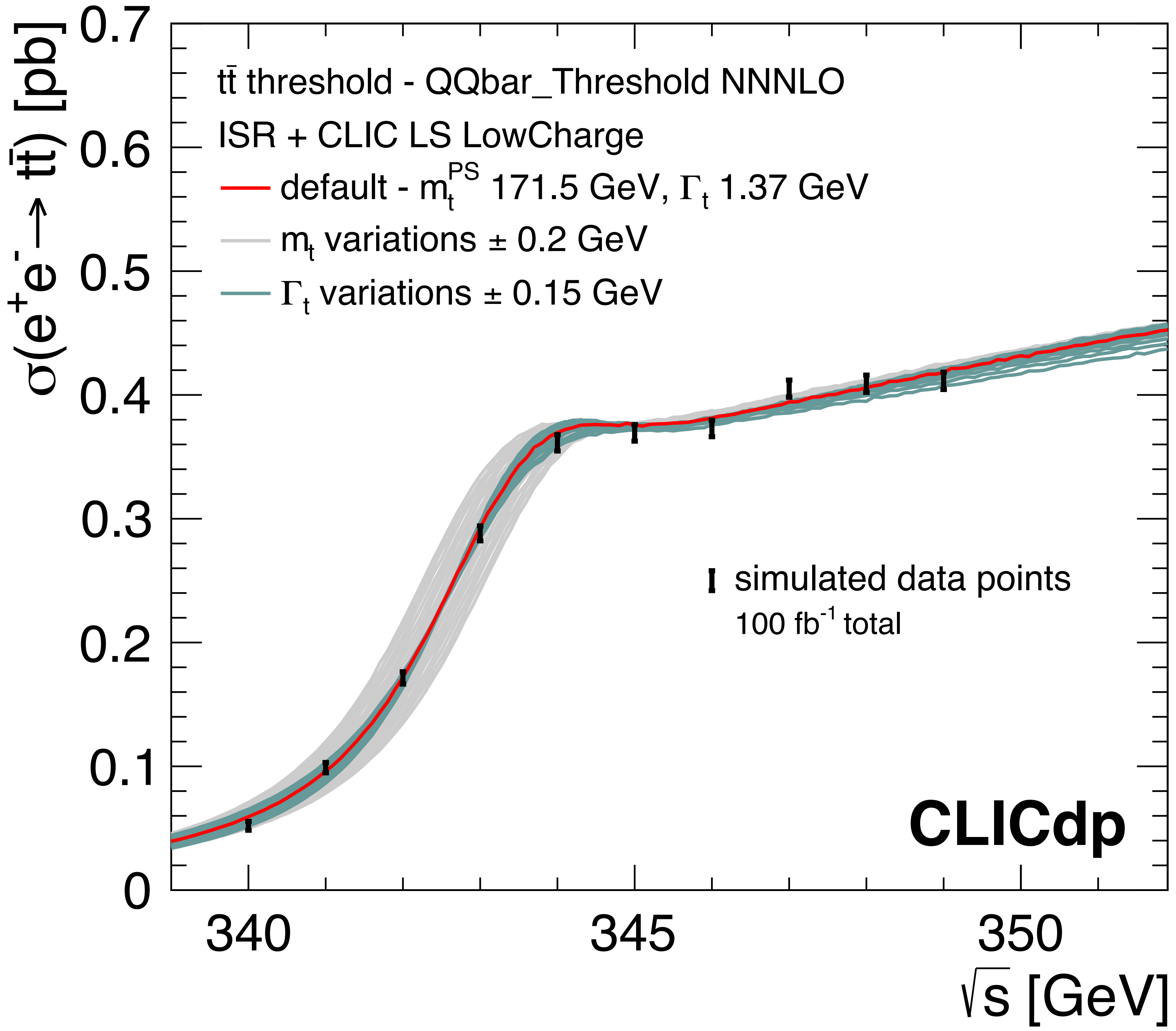

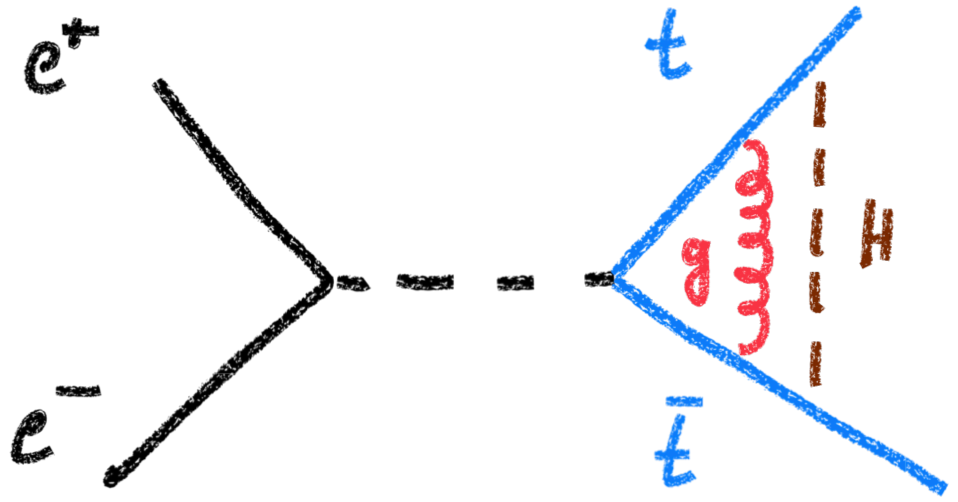

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ISR, luminosity spectrum, reconstruction

The potential for a measurement of the mass with **< 50 MeV** total uncertainty (dominated by theory)

The Top Quark

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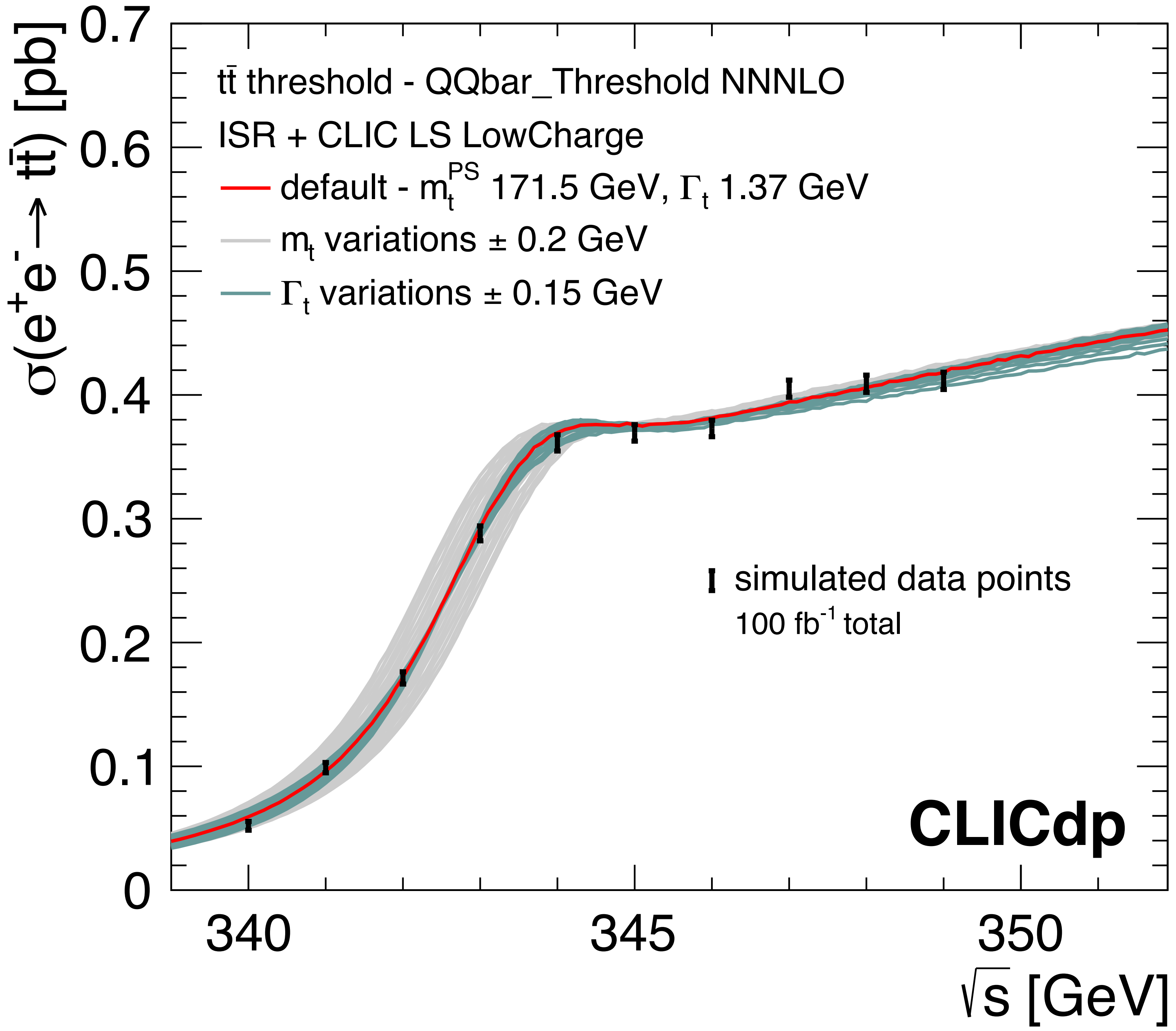

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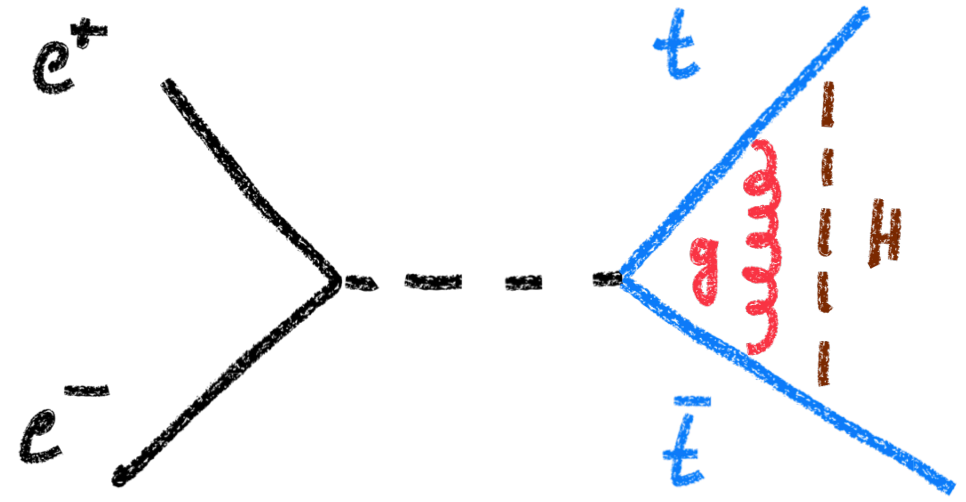
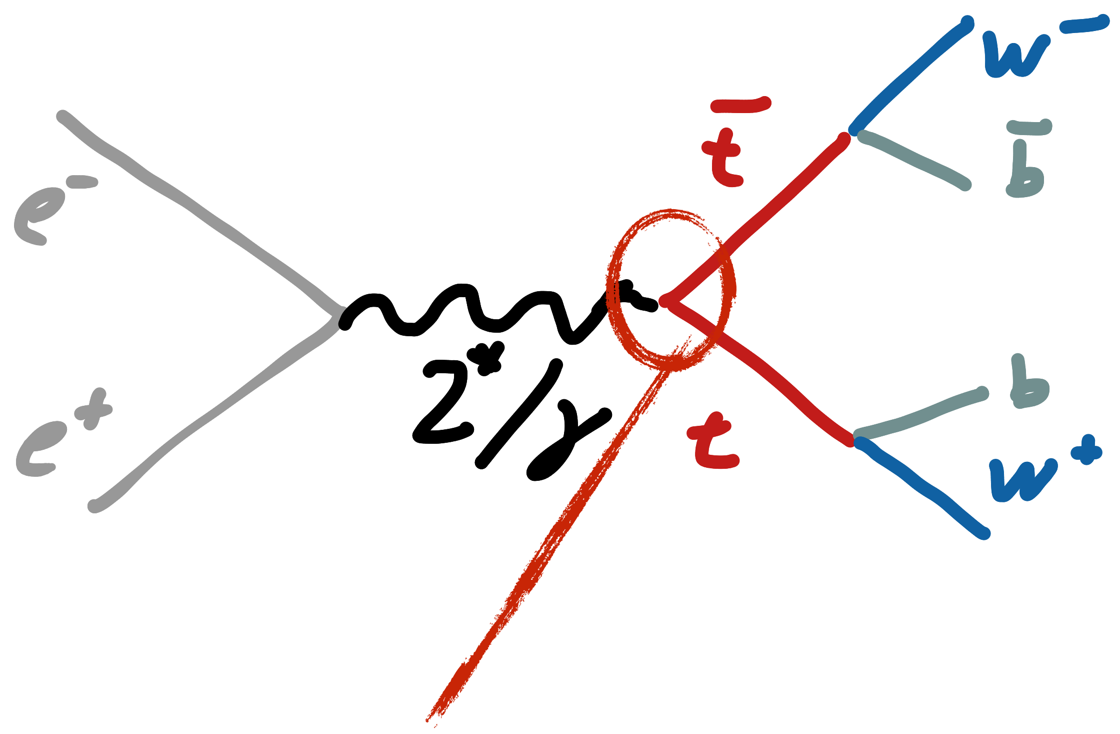
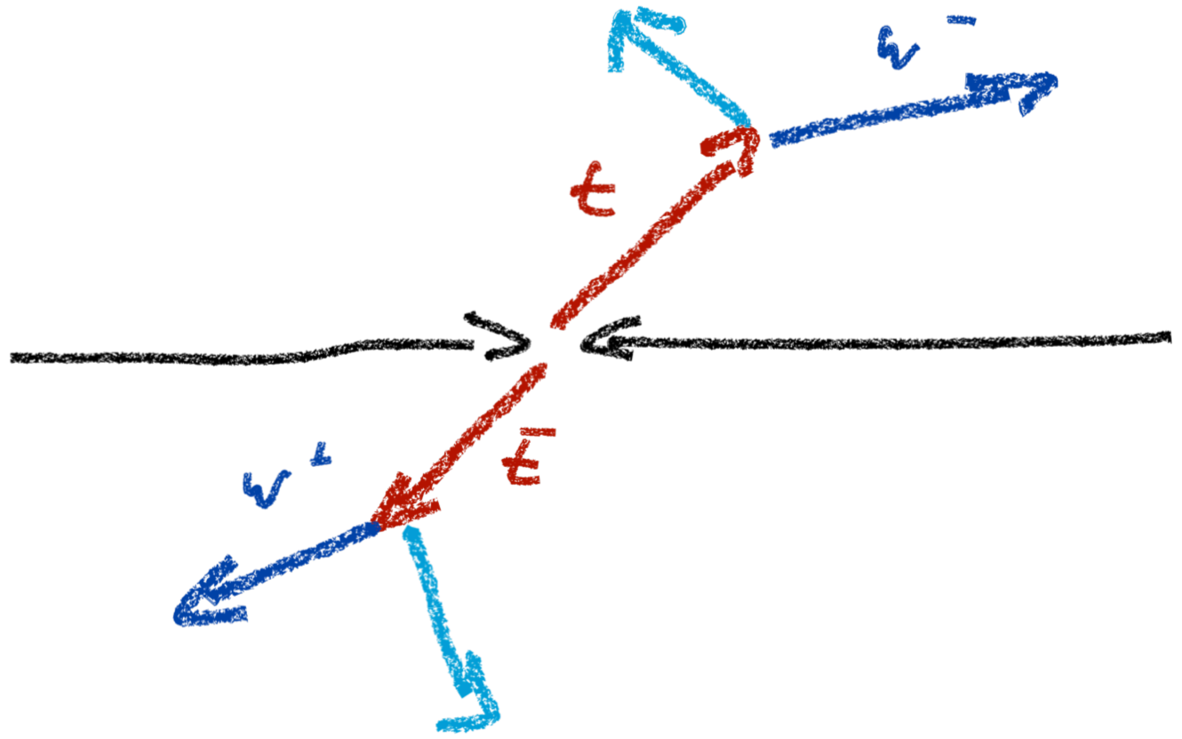


- Probing electroweak top production





contributions from axial and vector form factors:

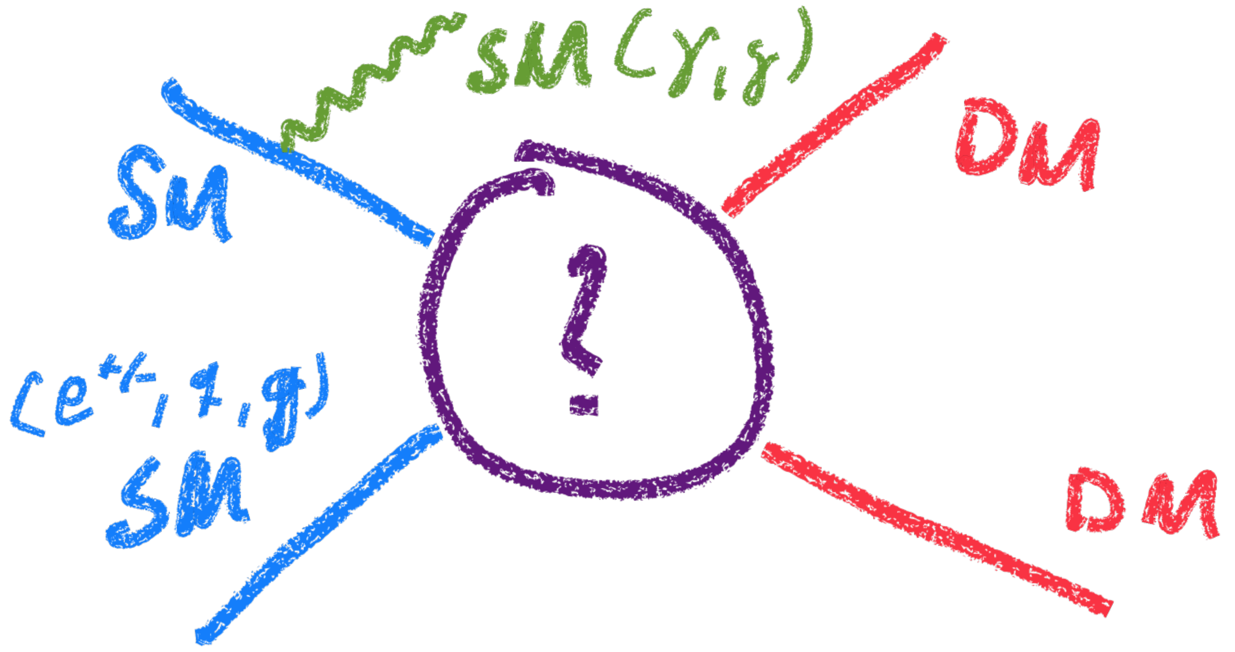
Measured via asymmetries - above threshold, polarisation can help

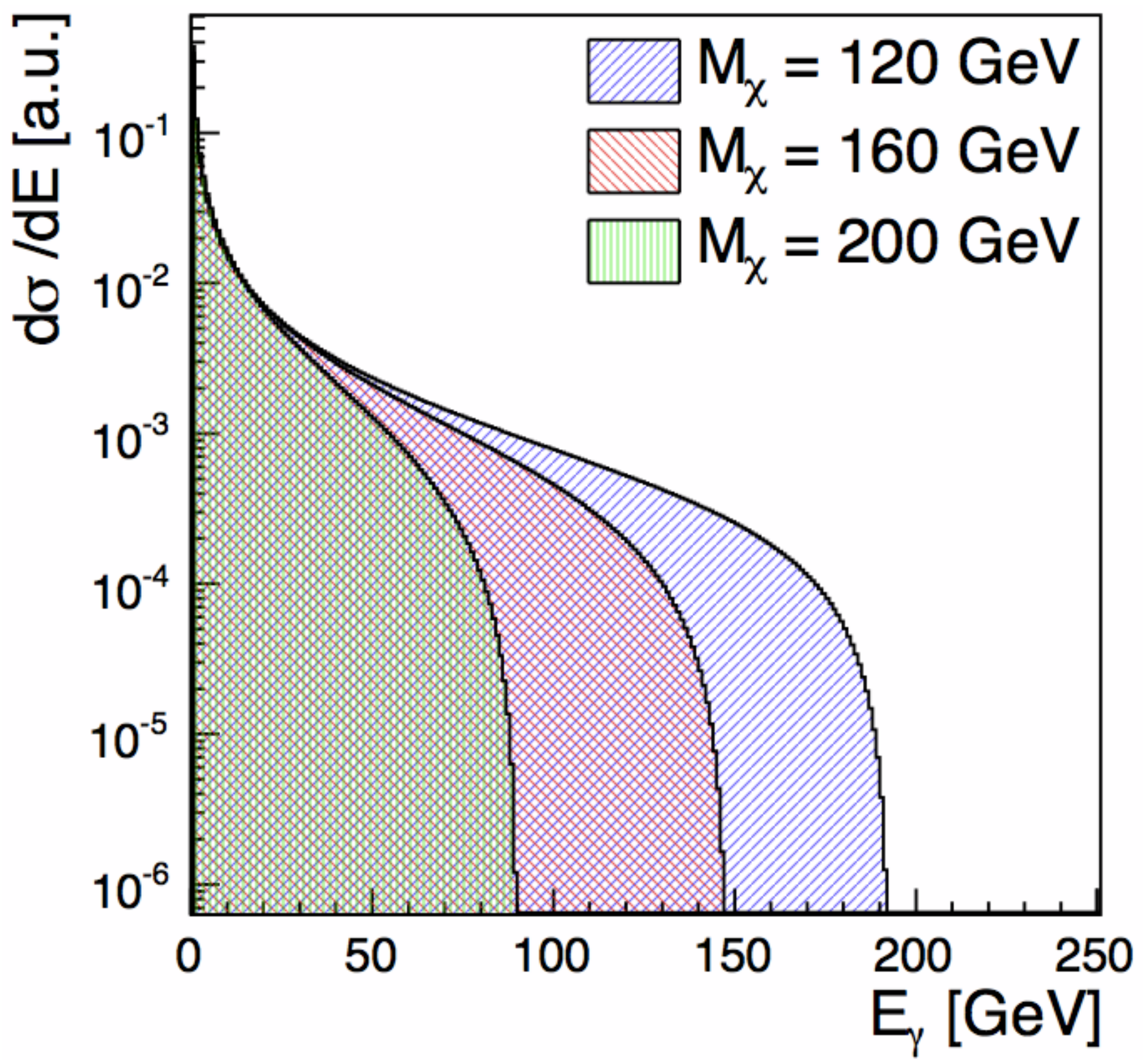
Open Exploration

Into the Unknown

- Endless possibilities…

Dark matter, dark sectors…





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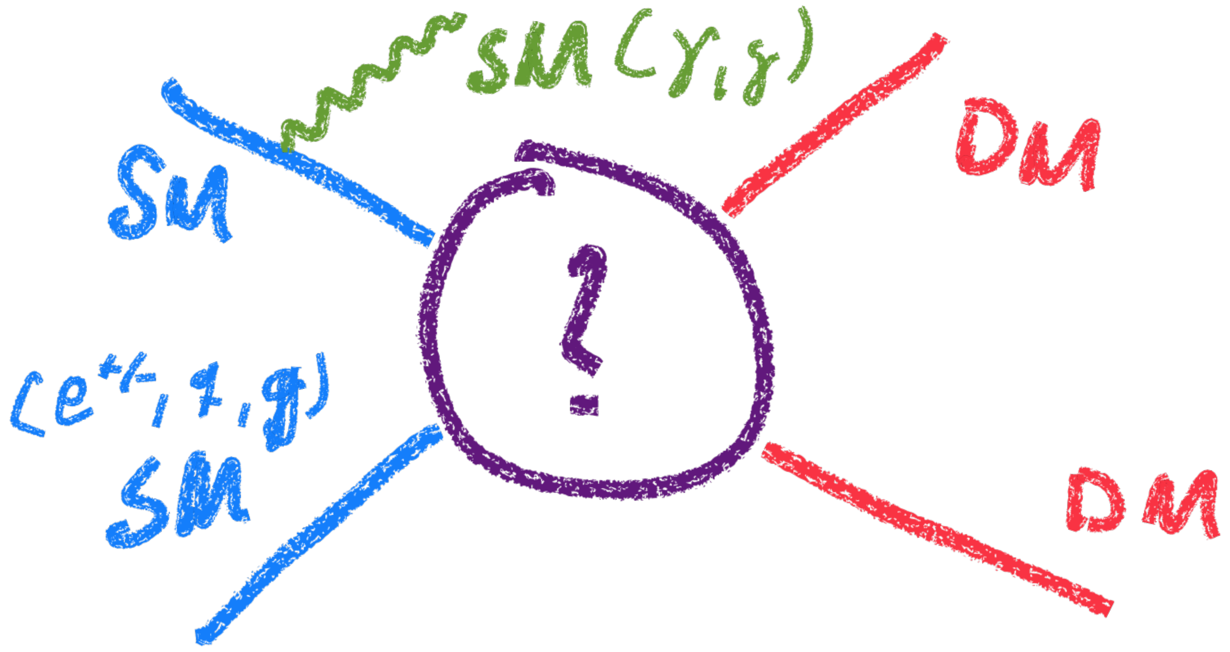

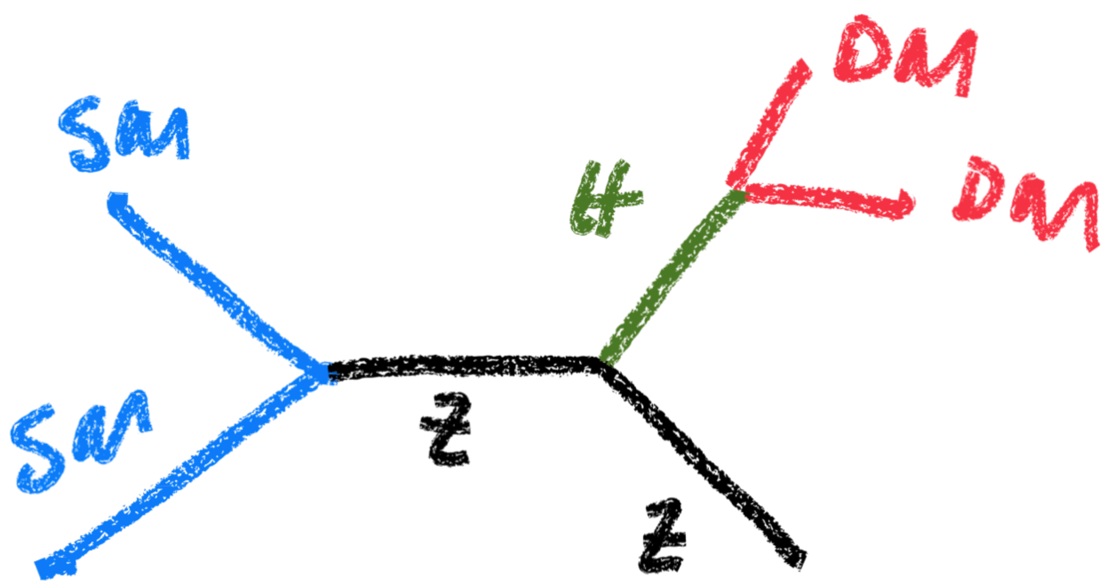

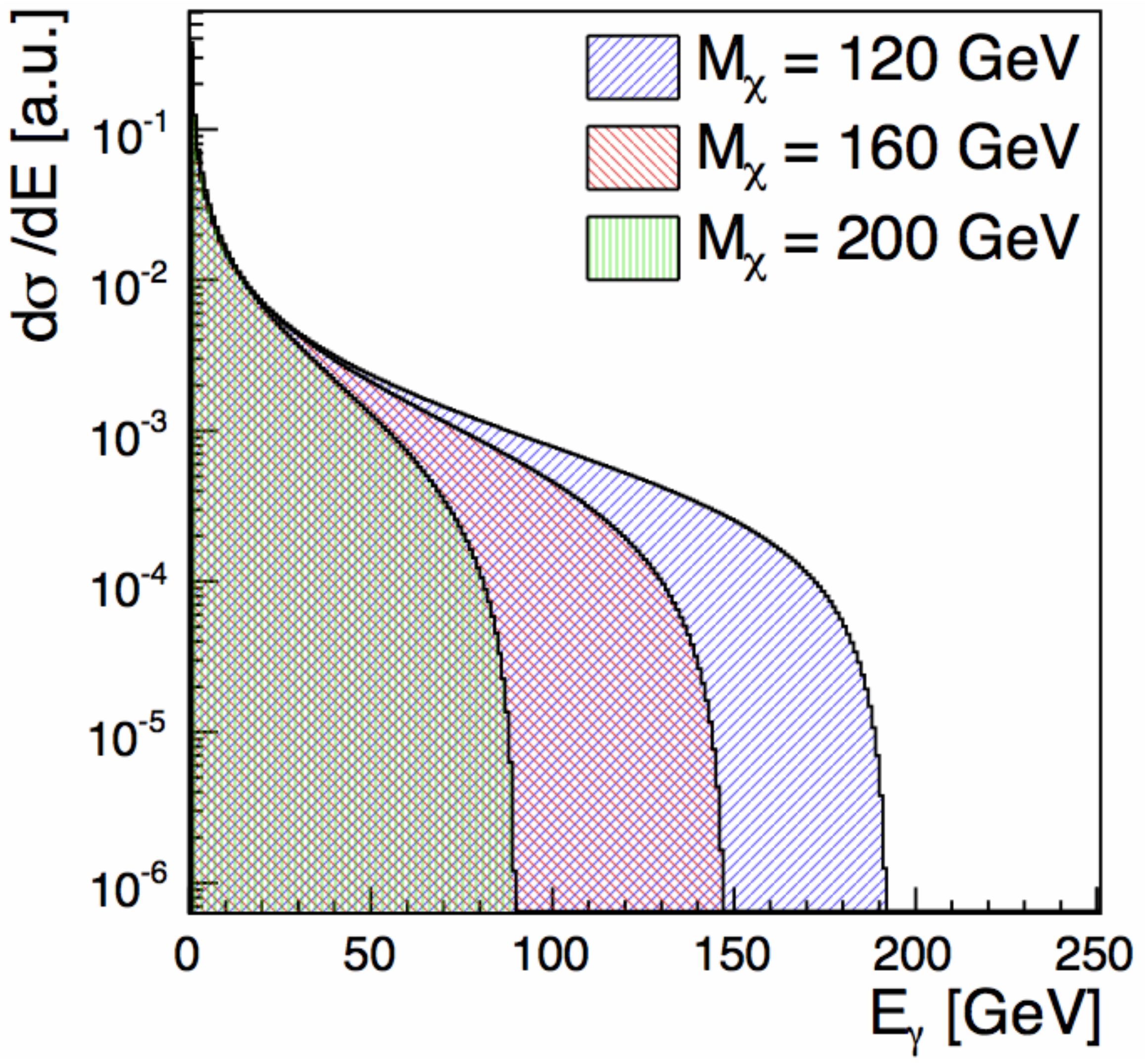

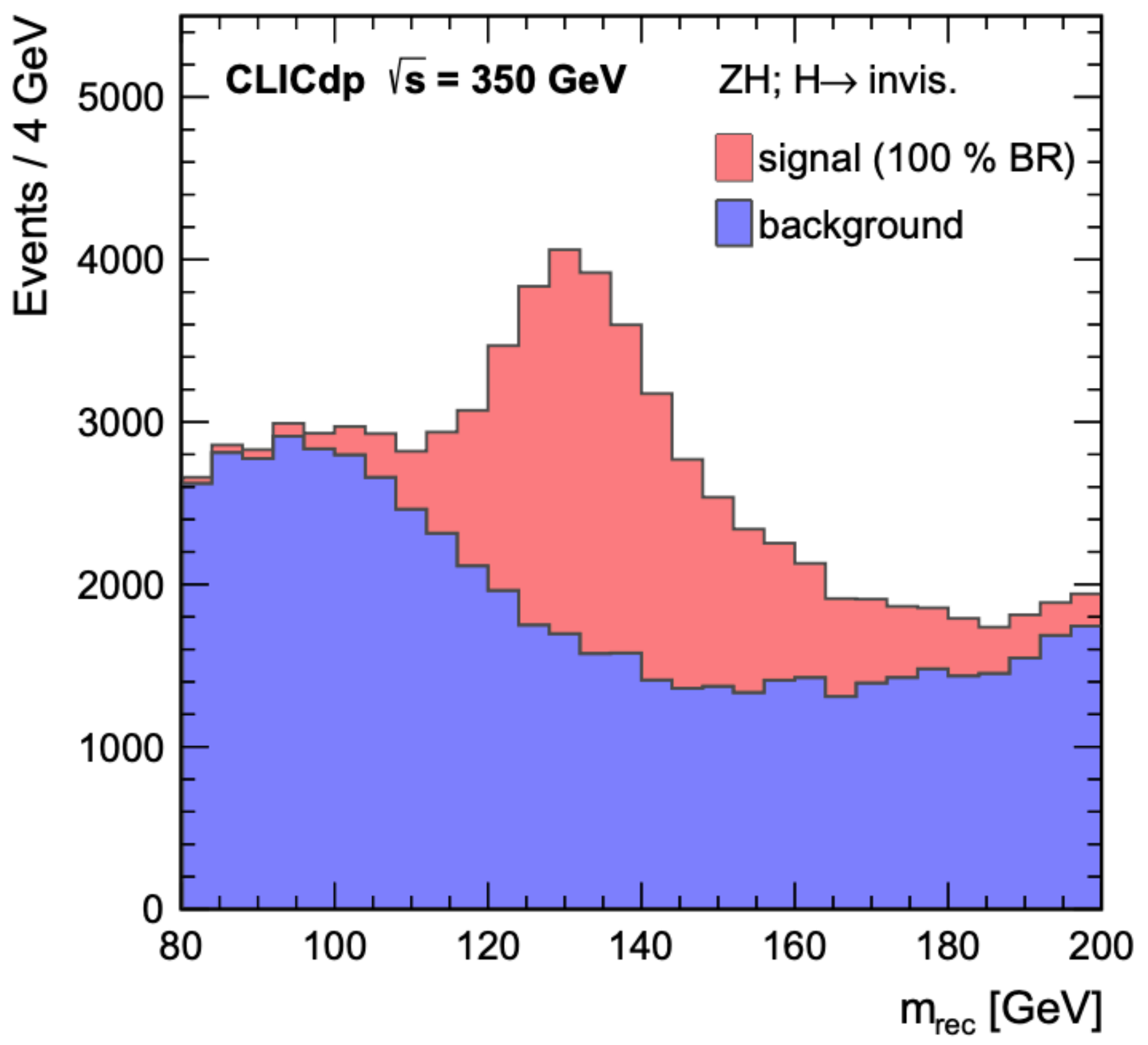

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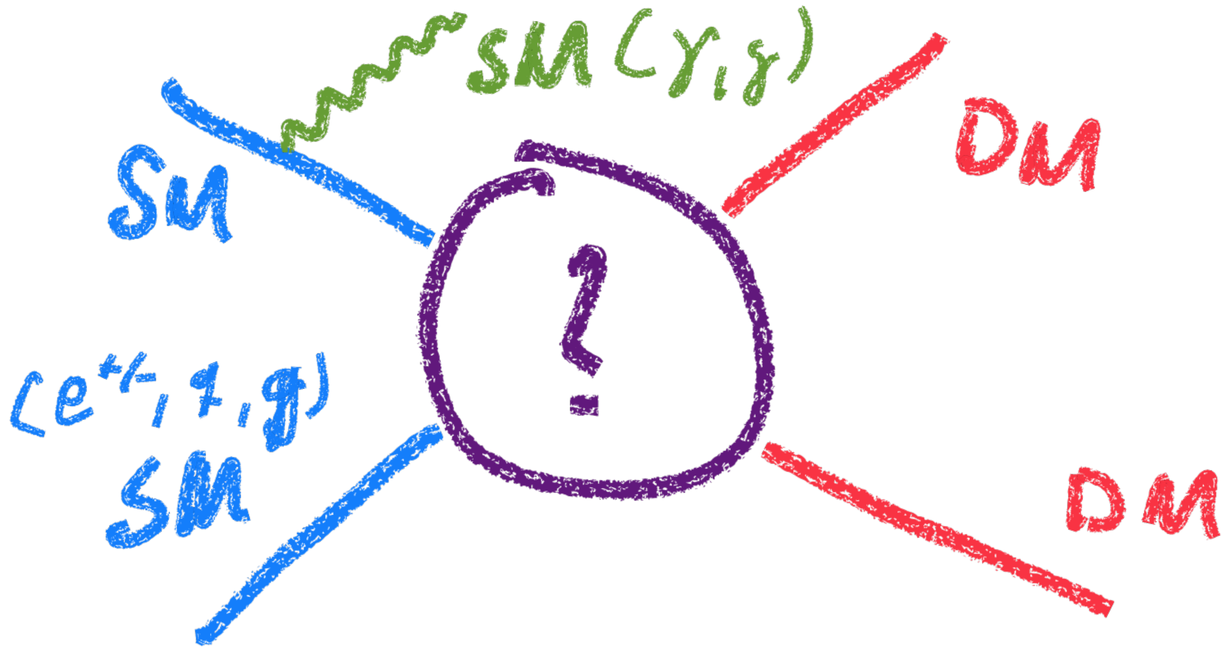
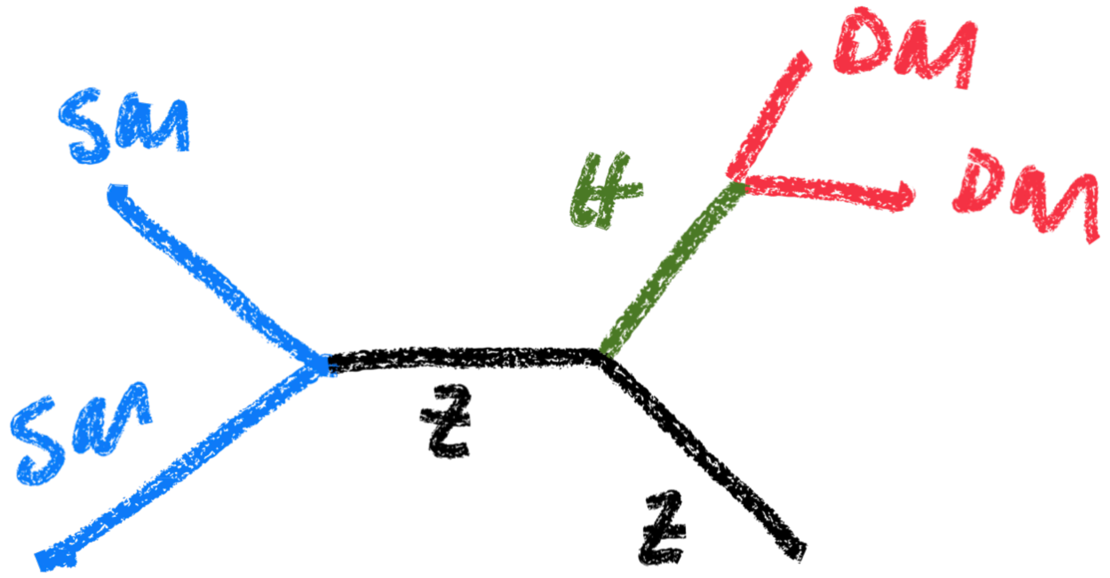
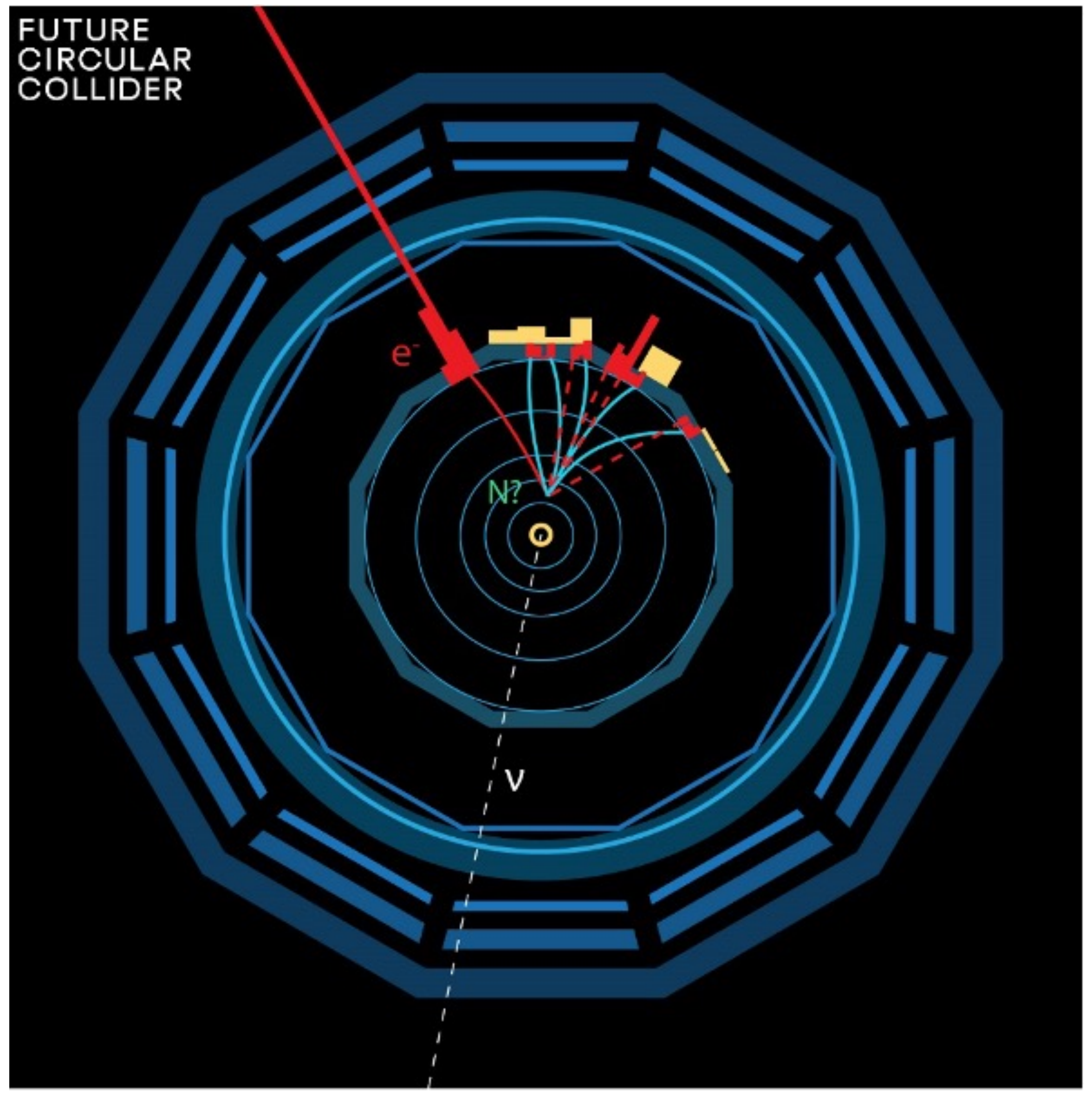
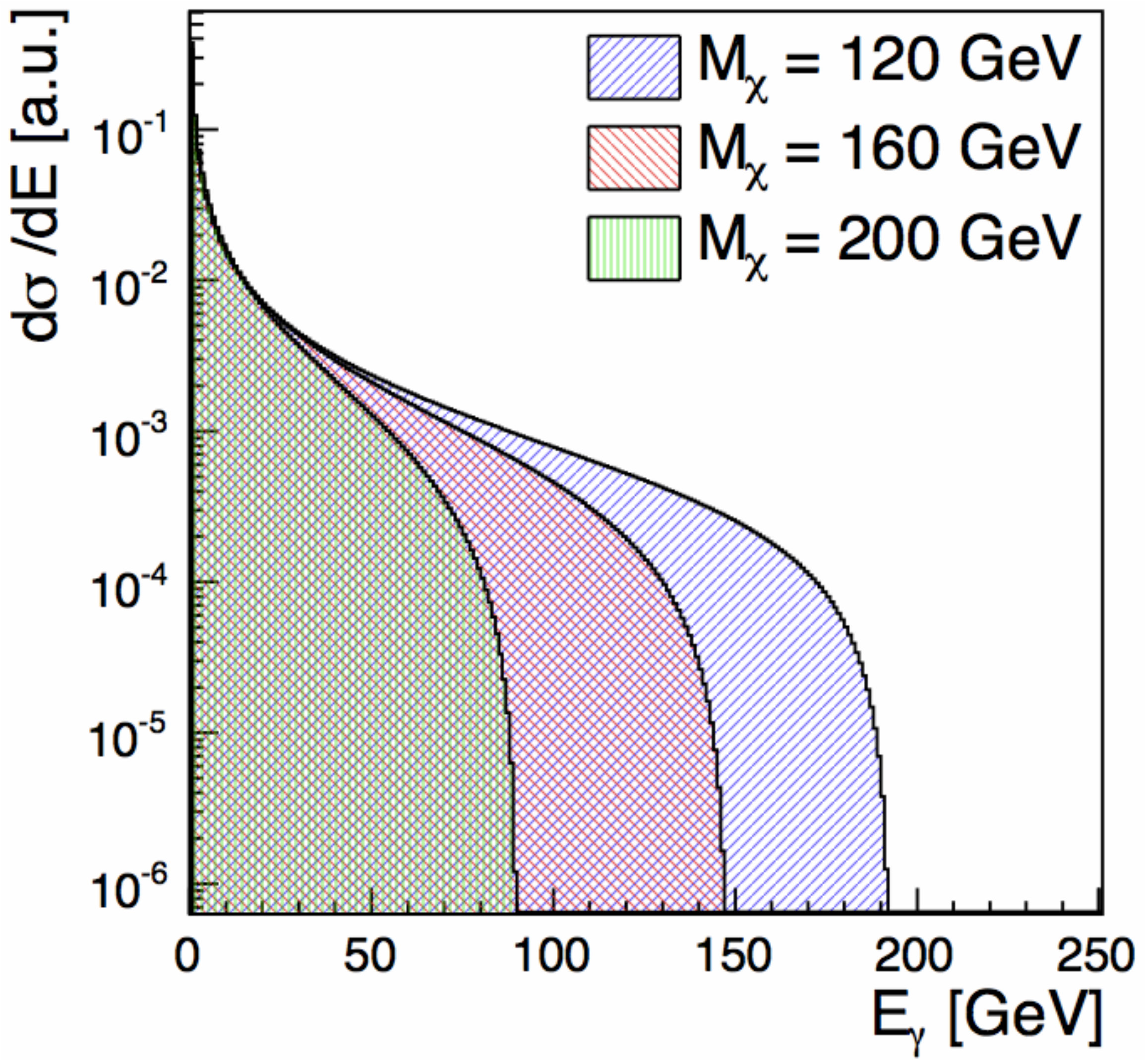


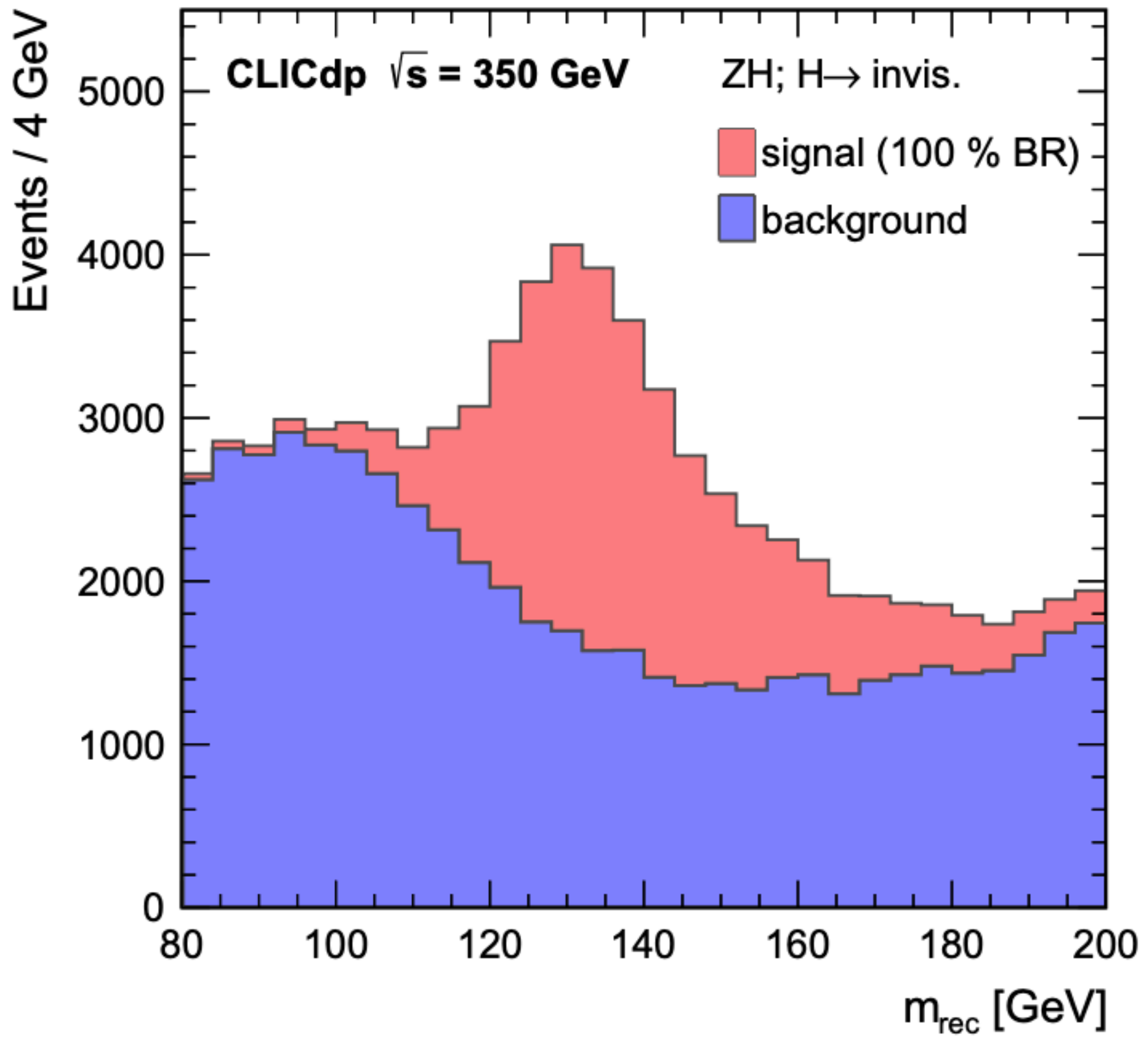




Heavy neutral leptons (HNL)

…





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Into the Unknown

MAX-PLANCK-INSTITUT
FÜR PHYSIK

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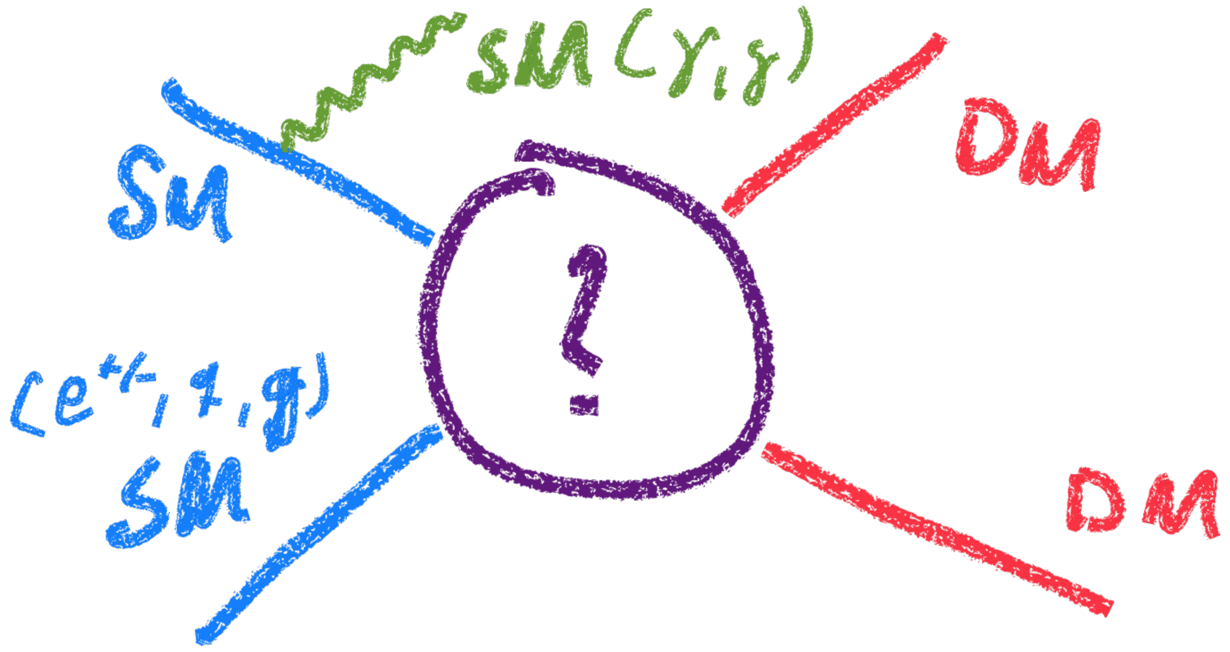
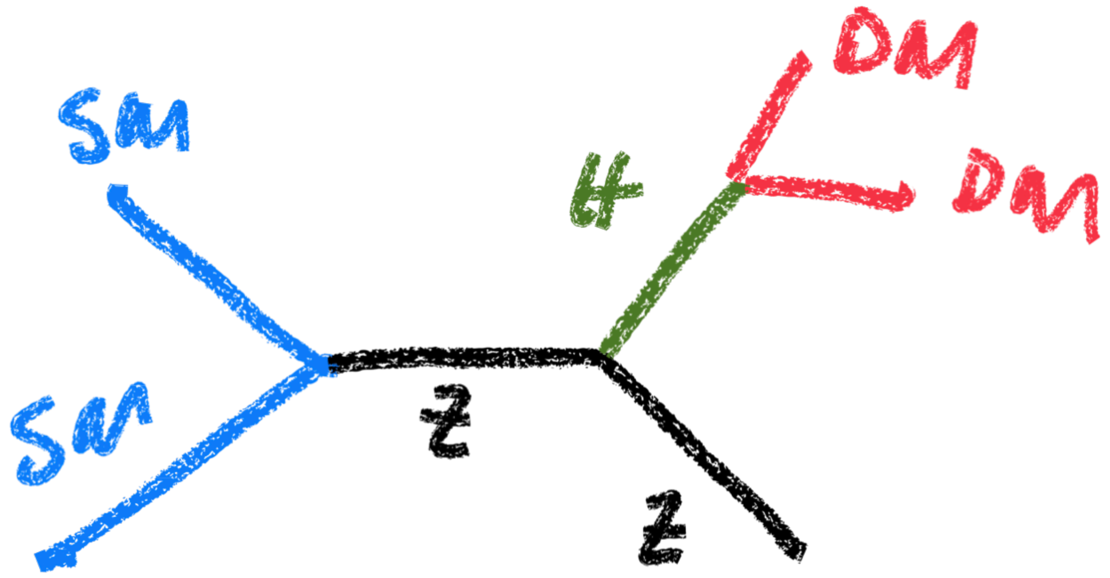
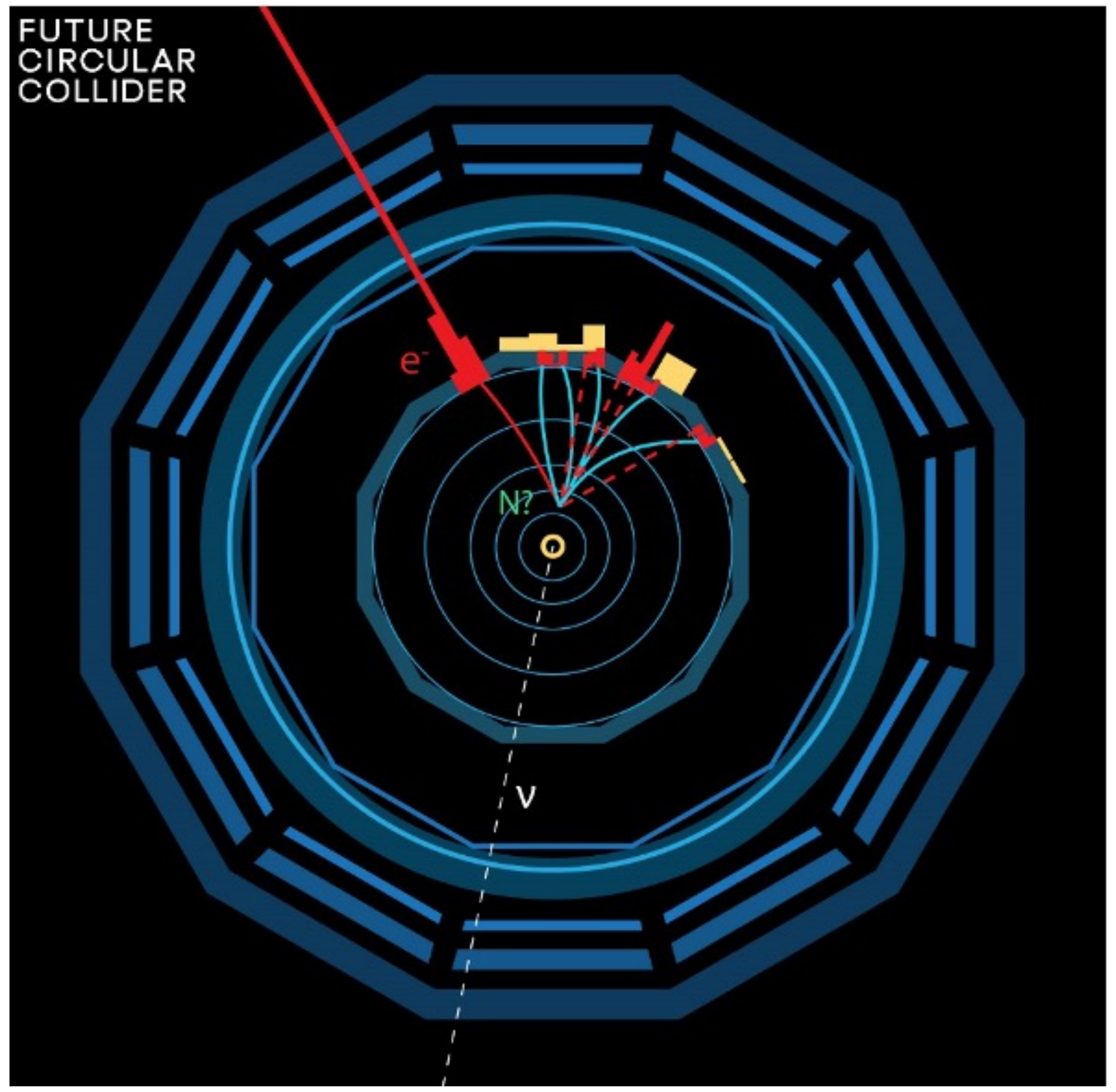


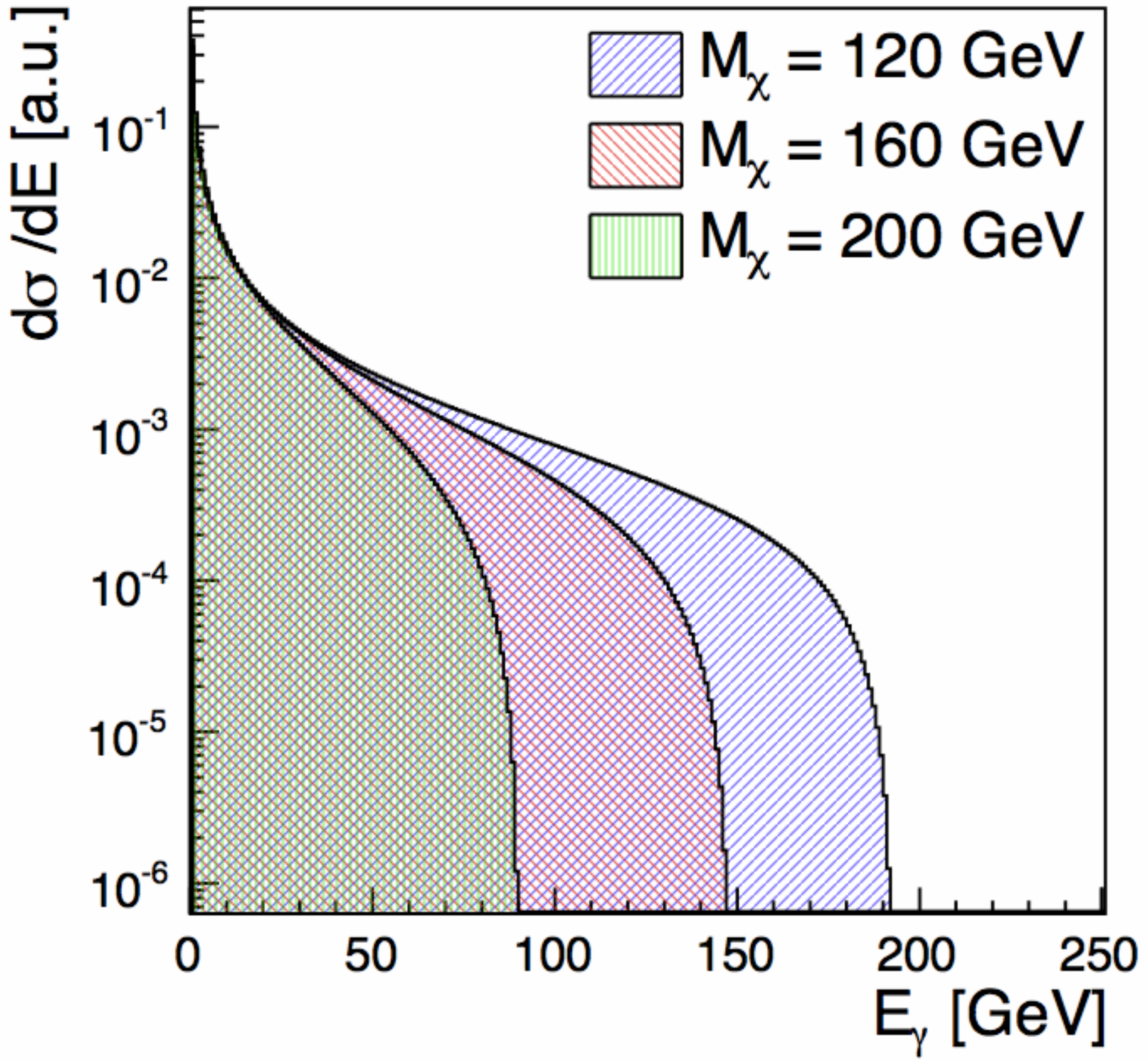


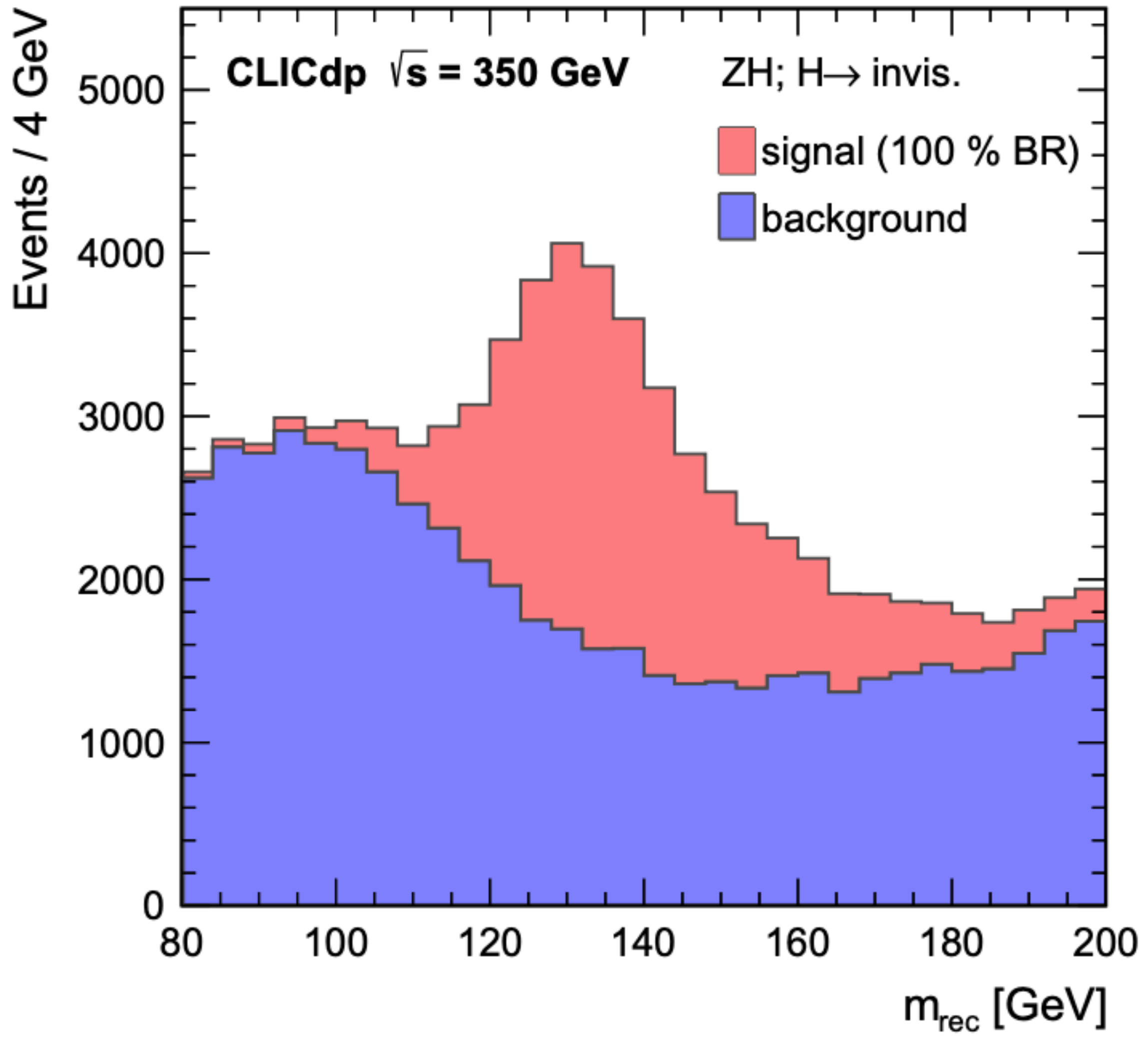


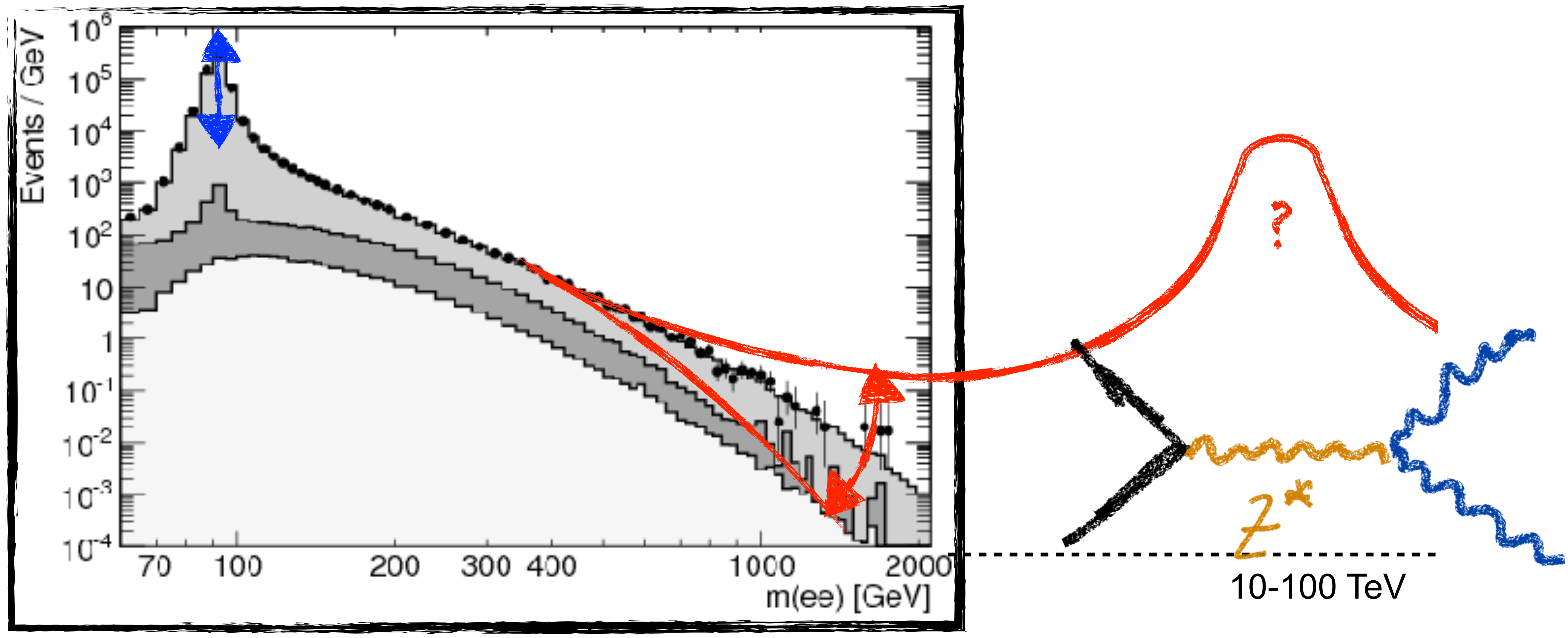
Heavy neutral leptons (HNL)

…

New particles - Z' *et al.*







A Higgs-Electroweak-Top Factory

The next facility in HEP

- Update of the European Strategy for Particle Physics 2020:
  An electron-positron Higgs factory is the highest-priority next collider.

Summary: The expected Harvest

Towards a New Era of Precision and Discovery

- A next-generation energy frontier e^+e^- collider promises a rich and diverse scientific harvest
  - A comprehensive exploration of the Higgs sector, with model-independent measurements of couplings to fermions and bosons at the (sub-) percent level
  - Precision top quark physics: Mass and other properties, top quarks as a tool for BSM searches
  - A broad electroweak program - far beyond the precision achieved with LEP
  - Flavour physics
  - QCD
  - and the search for new phenomena in many regions of unexplored phase space

Summary: The expected Harvest

Towards a New Era of Precision and Discovery

- A next-generation energy frontier e^+e^- collider promises a rich and diverse scientific harvest
  - A comprehensive exploration of the Higgs sector, with model-independent measurements of couplings to fermions and bosons at the (sub-) percent level
  - Precision top quark physics: Mass and other properties, top quarks as a tool for BSM searches
  - A broad electroweak program - far beyond the precision achieved with LEP
  - Flavour physics
  - QCD
  - and the search for new phenomena in many regions of unexplored phase space

- The relative weight and reach of the different scientific avenues depends on the details of the collider: Circular or Linear? Which maximum luminosity, which maximum energy, which energy stages?

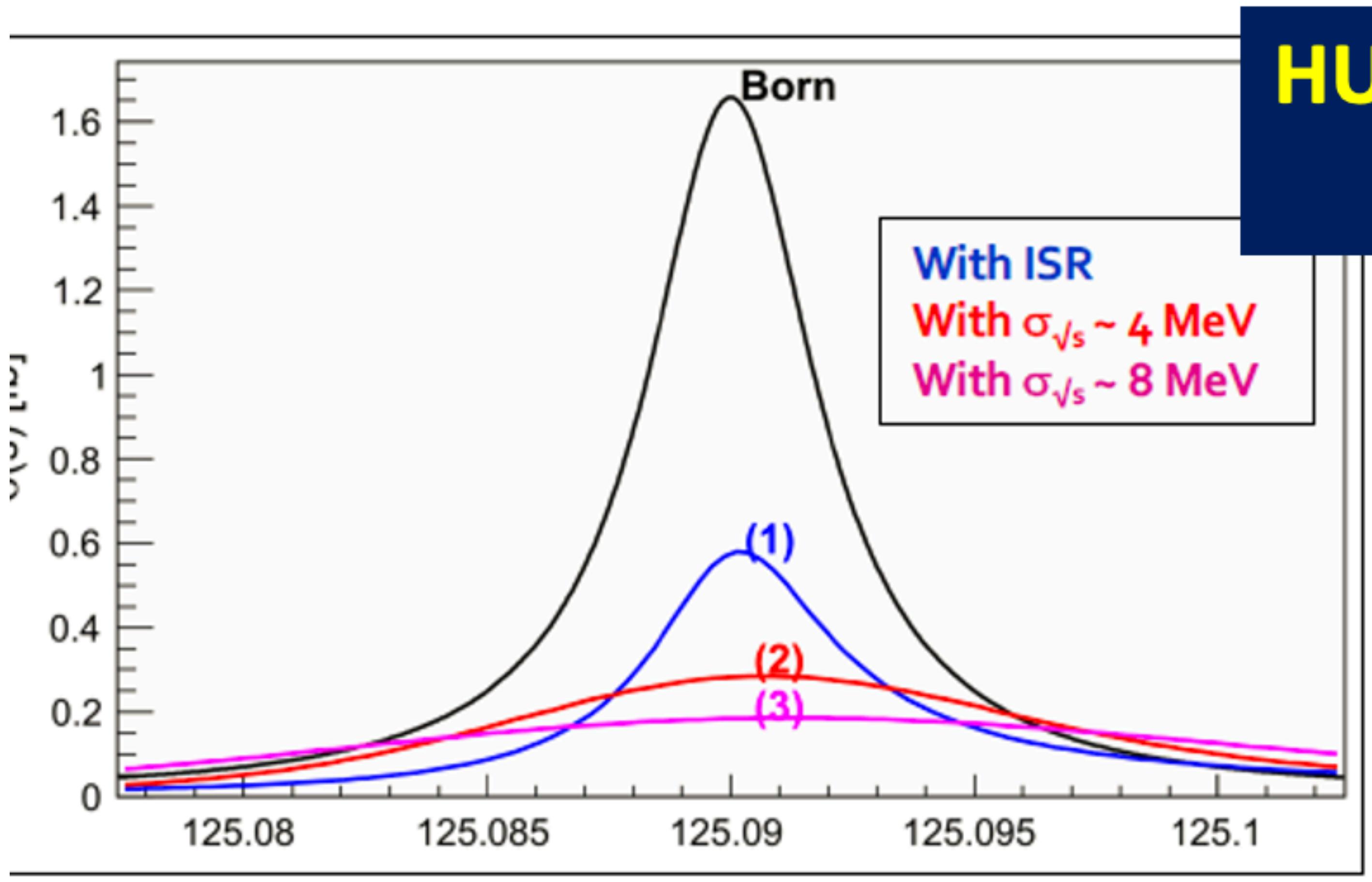
  Join us to contribute to this decision - and to making such a facility a reality!

Extras

S Channel Higgs Production

A challenge of luminosity and energy spread

Unique: electron Yukawa coupling

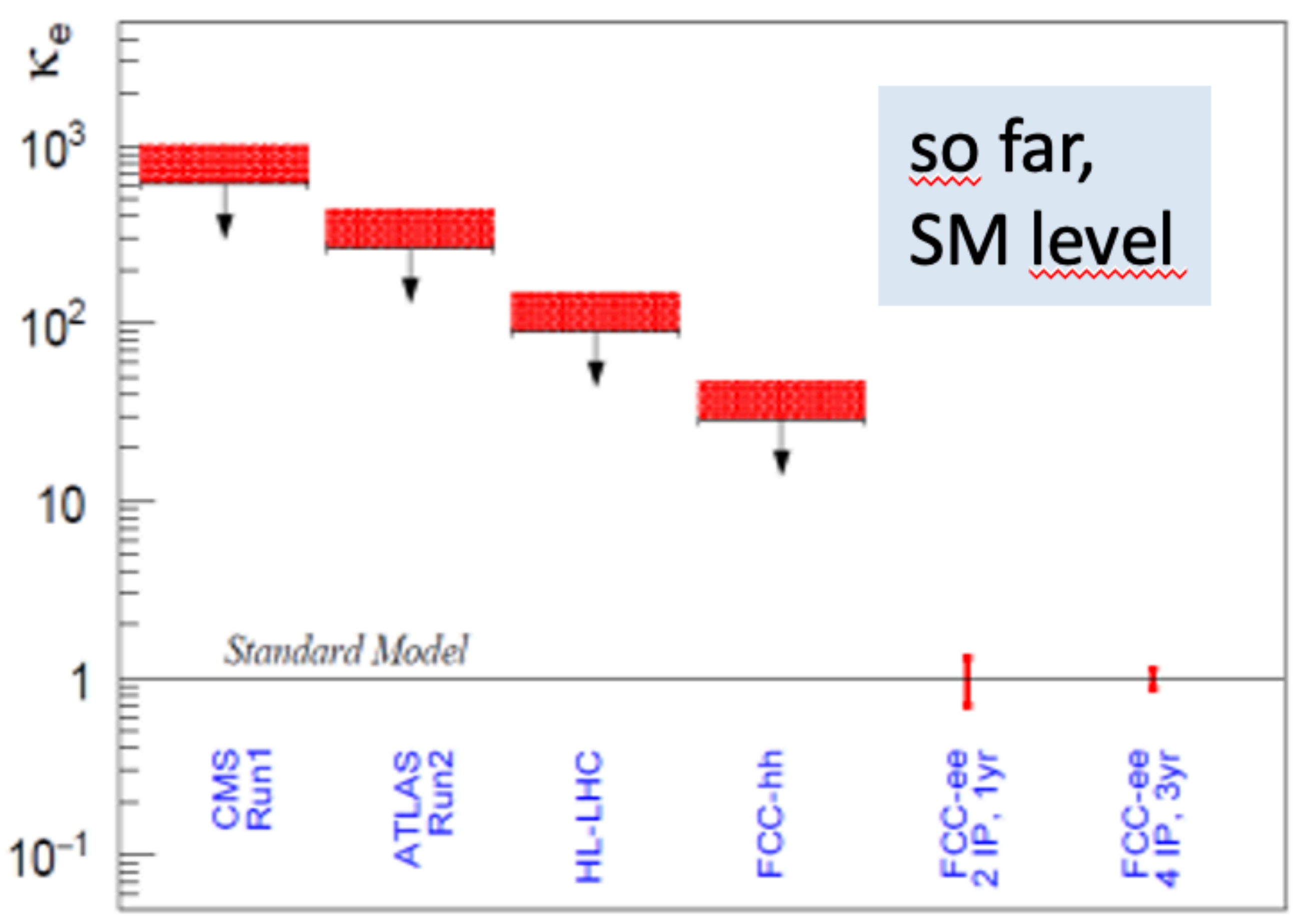


HUGE CHALLENGE under study

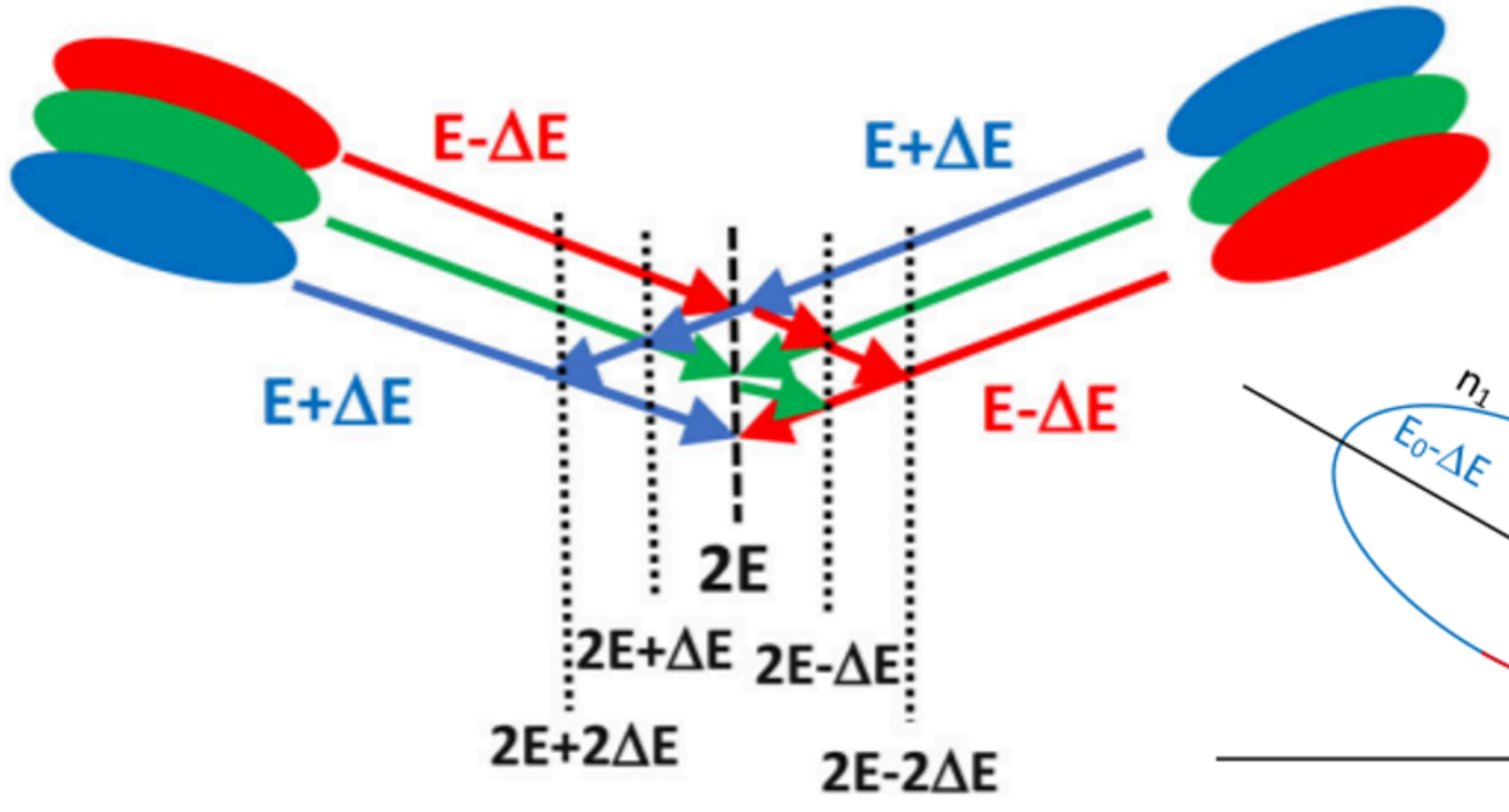
Measure e+e- → H @ 125.xxx GeV
requires
-- Higgs mass to be known to <<5 MeV (OK, 3 MeV)
-- **Huge luminosity** (several years)
-- **monochromatization** to reduce σ_{ECM}
-- **continuous adjustment of E_{CM}** (transv. Polar.)
-- an extremely sensitive event selection

Monochromatization: **UNDER STUDY**
taking advantage of the separate e+ and e- rings, one can distribute in opposite way high and low energies in the beam (in x, z time)

Upper Limits / Precision on κ_e



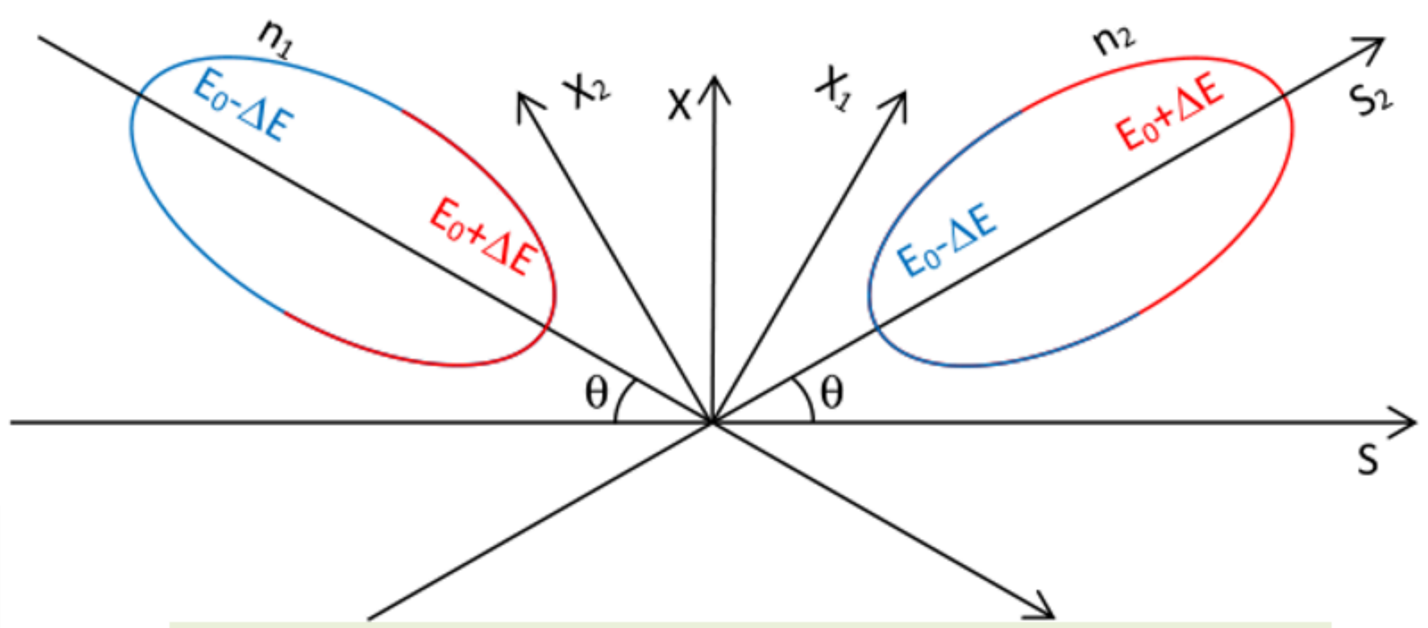
so far, SM level



opposite sign horizontal dispersion

Alain Blondel FCC-ee Physics

combine?



opposite difference in arrival time

From A. Blondel