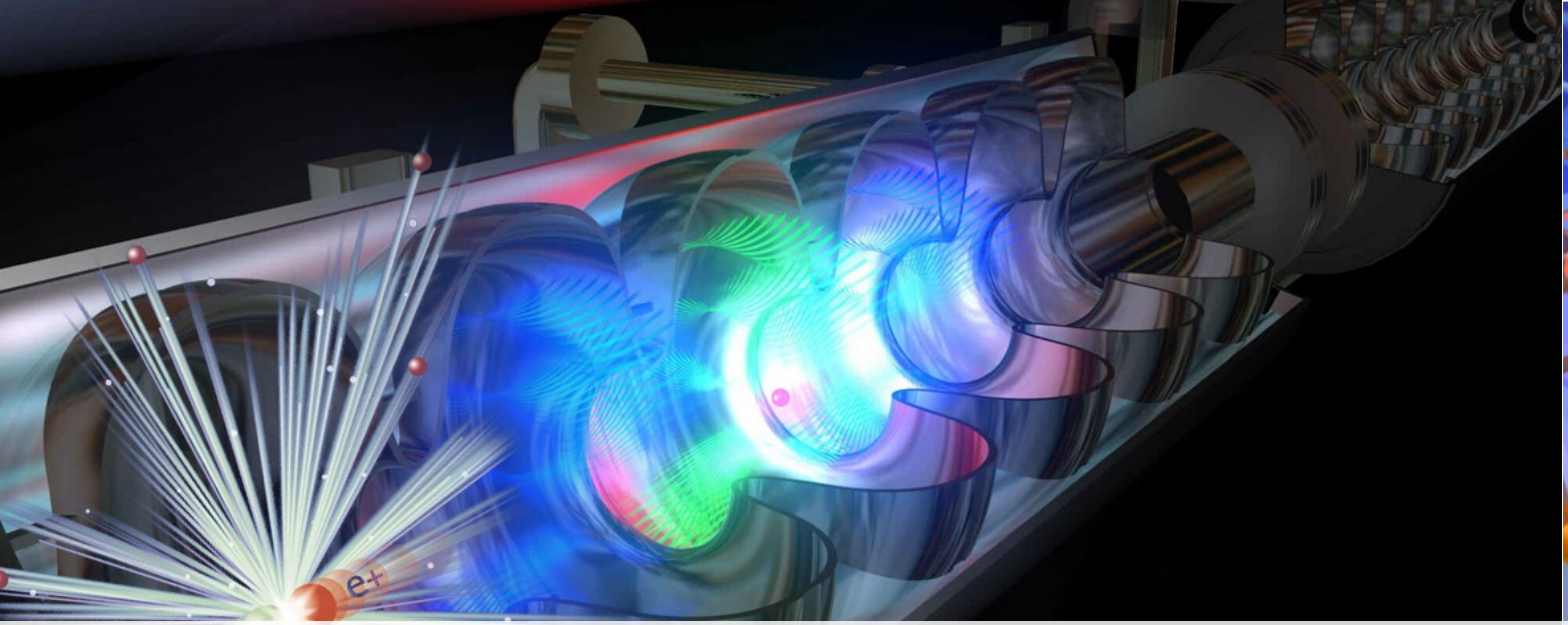


Experimental Physics at Lepton Colliders

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

Part II

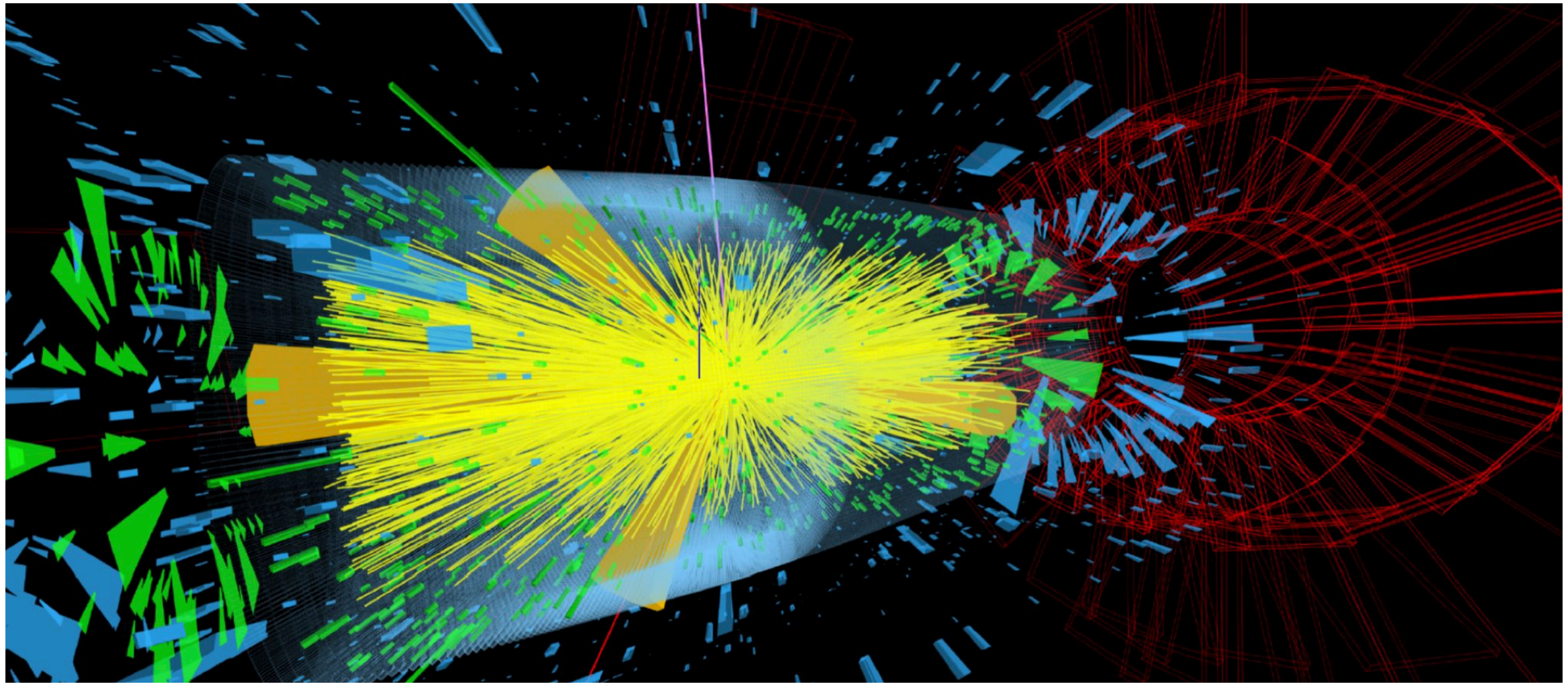
Detectors at Future Lepton Colliders

- Extensively developed for linear colliders (ILC, CLIC)
- Specific developments for FCC-ee firming up, requiring some modifications wrt LCs

- Muon colliders the latest addition, challenges being understood, concepts emerging

General Detector Features

Aiming for precision, profiting from benign backgrounds



HL-LHC

from this…

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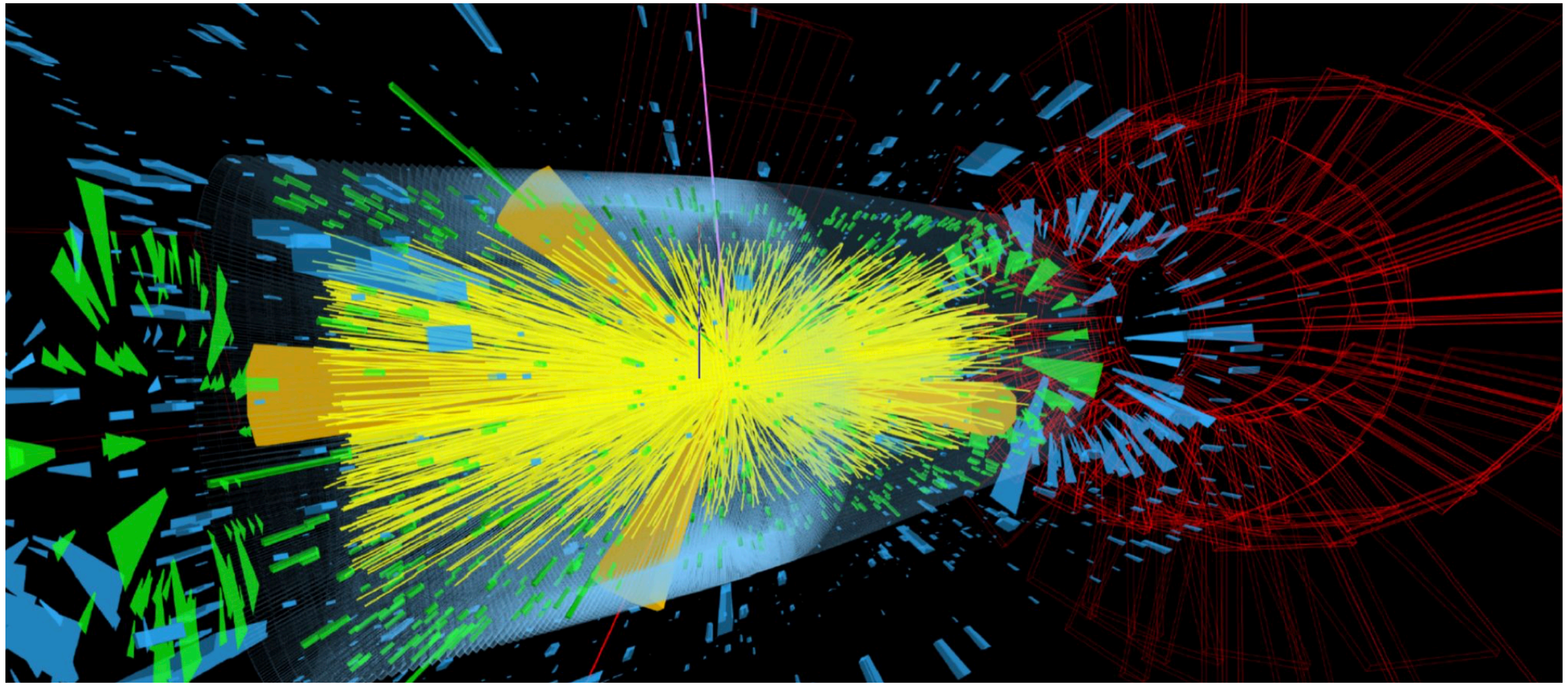

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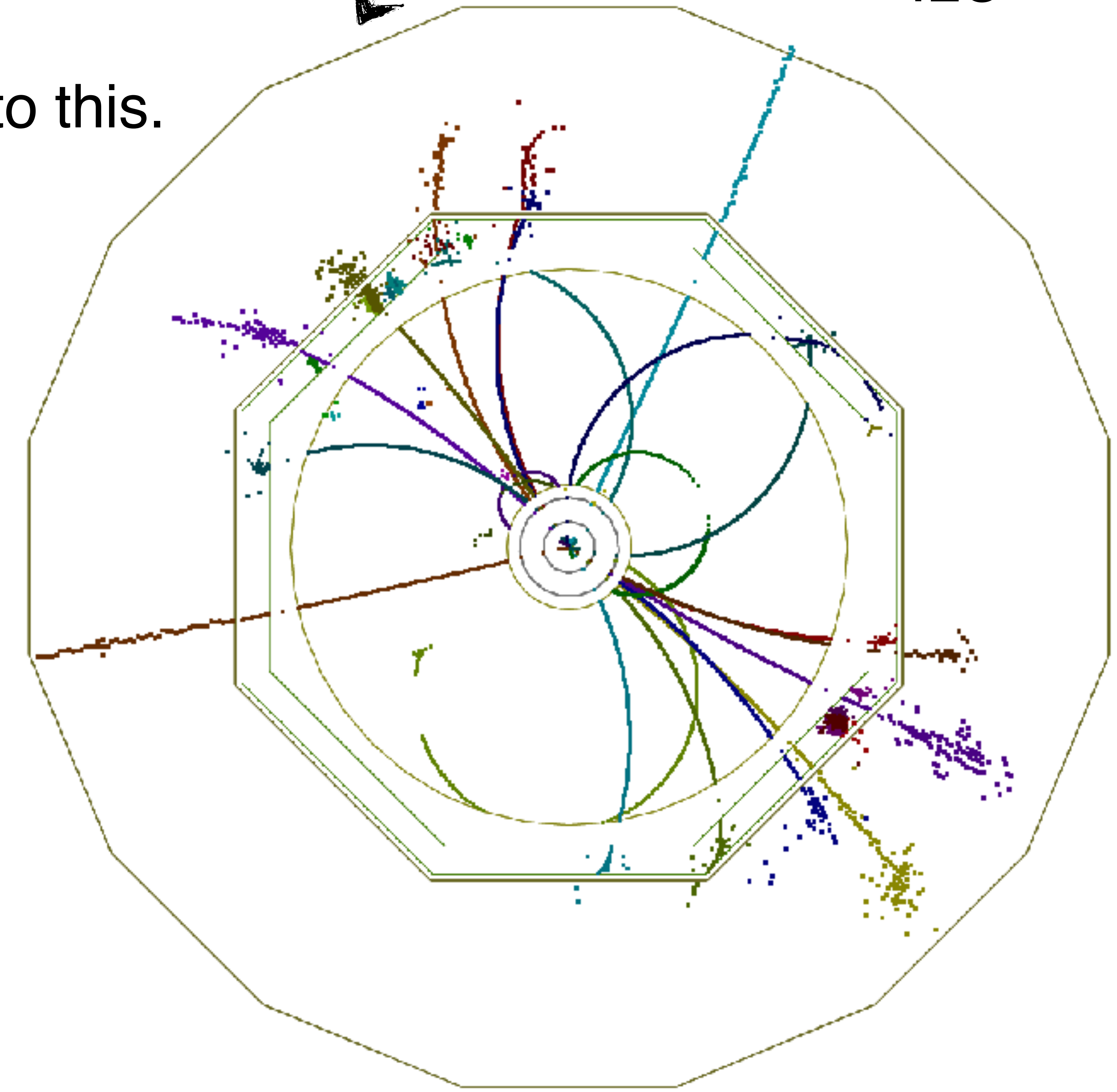

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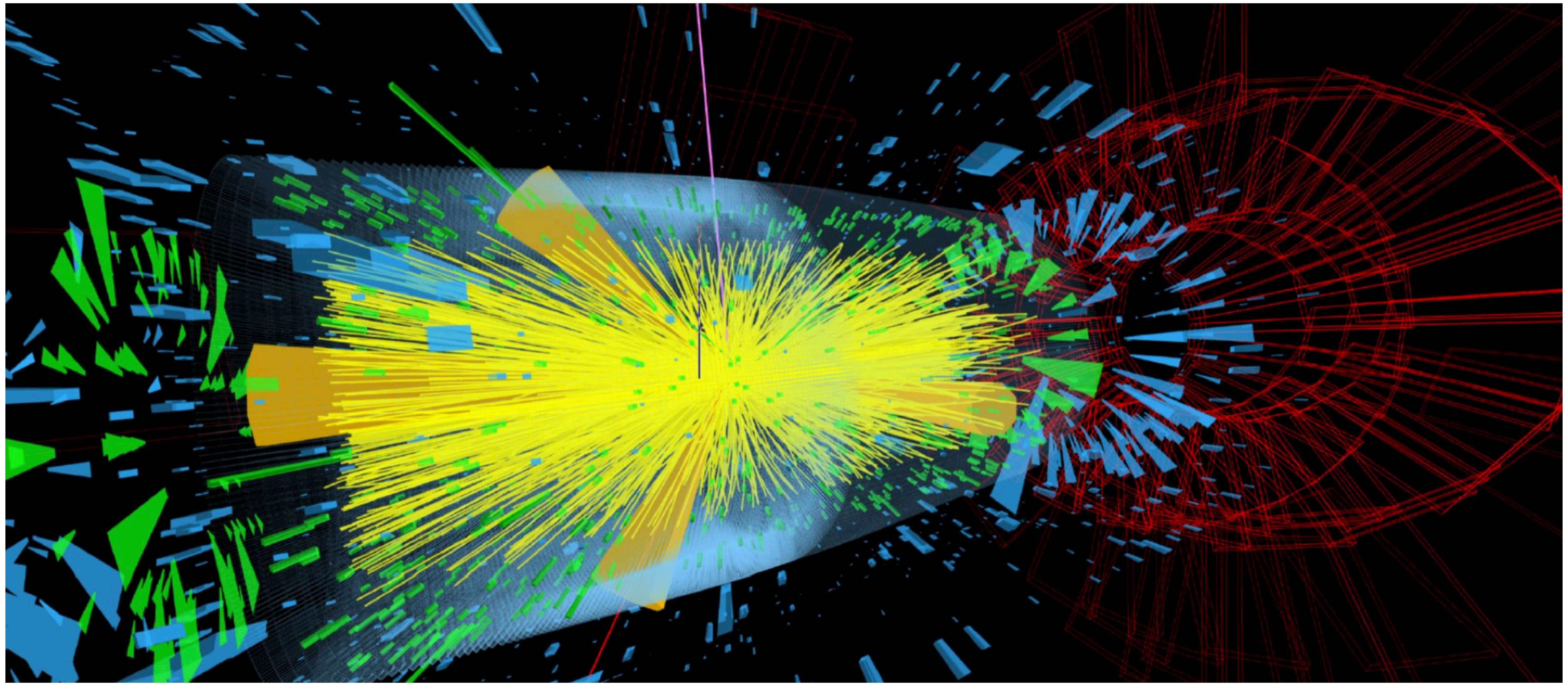

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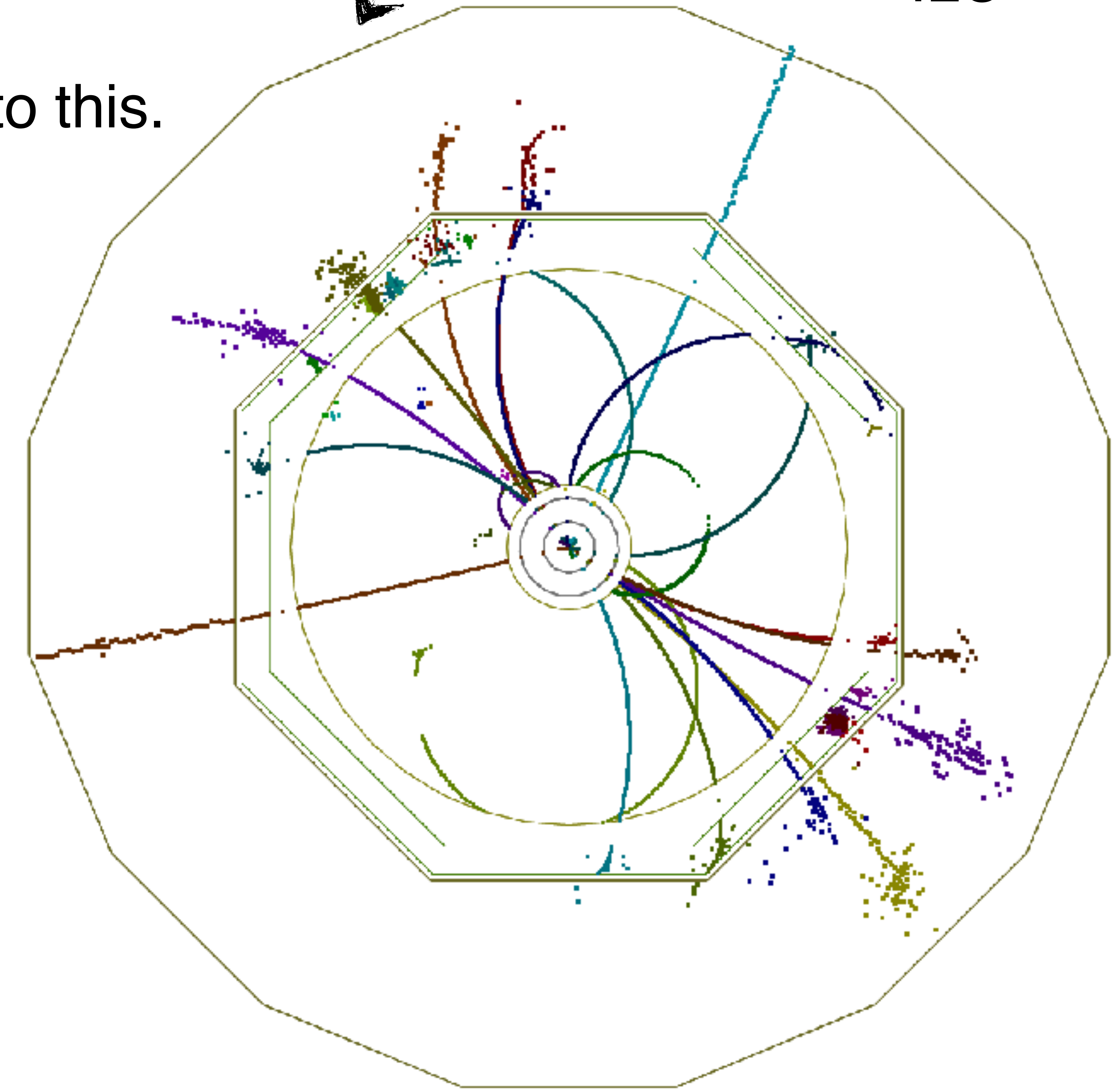


- Need detector systems that match the ambitious precision goals of lepton colliders: Resolution, calibration accuracy, stability…
- The main concern is not survival: (With very few exceptions) radiation tolerance requirements are very minor, occupancies and rates typically low

Detector Requirements: High Level

Depending on Physics / Energy Stage

Higgs Physics

- Charged particle momentum resolution
- Vertex resolution for flavour tagging
- Particle ID for flavour tagging
- Jet energy / angular resolution, particle flow

Electroweak Precision

- Acceptance
- Alignment and calibration
- Luminosity / precise normalisation

Flavour Physics

- Charged particle momentum resolution
- IP, vertex resolution
- General PID capabilities
- Photon resolution, neutral pion reconstruction

BSM / FIPs

- Instrumented volume
- High radial segmentation
- Displaced vertex reconstruction capability
- Specific trigger / filters
- Acceptance

Detector Performance Goals - Tracking

Motivated by key physics signatures

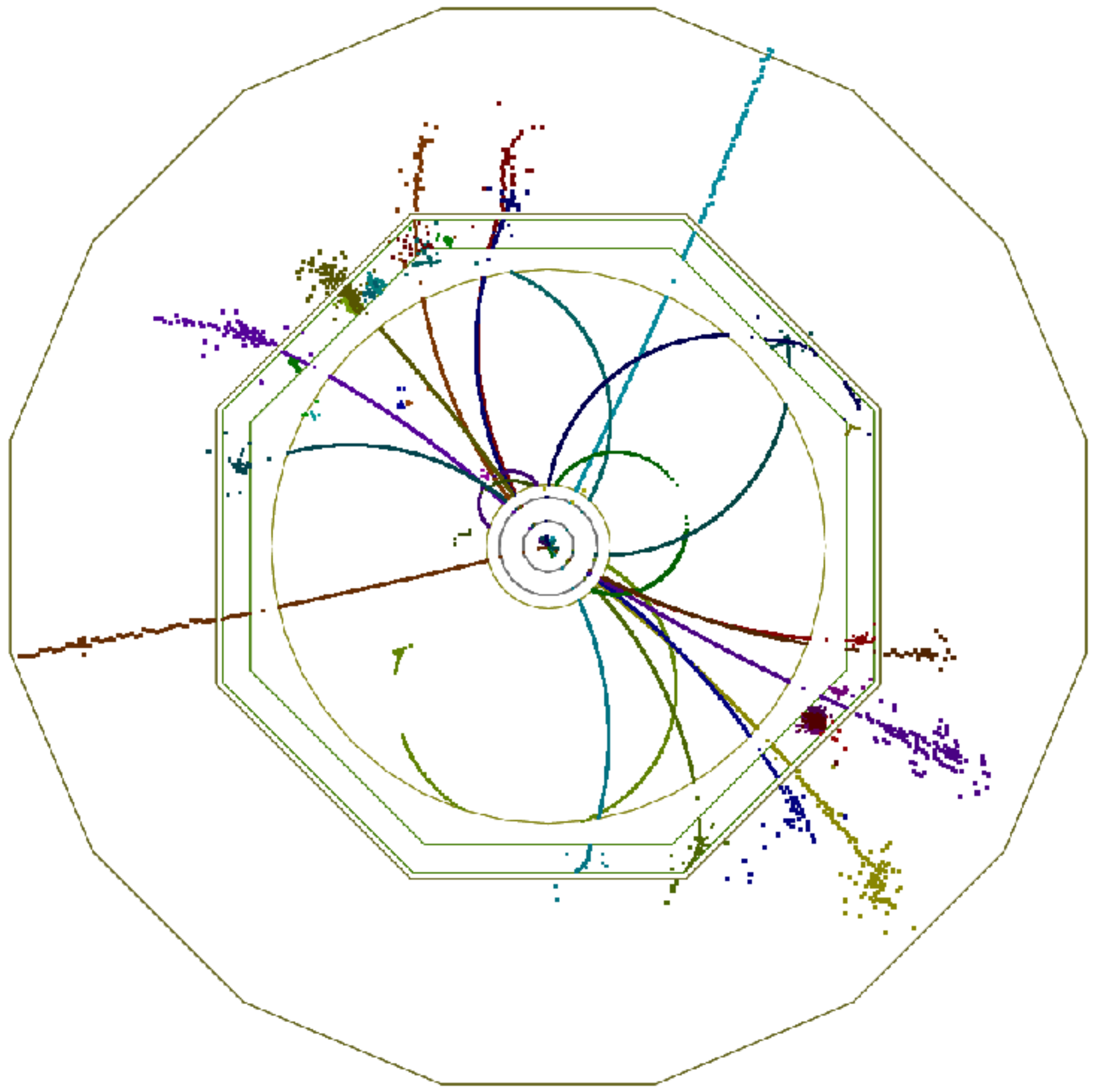
- ***Momentum resolution***

  Higgs recoil measurement, H -> $\mu\mu$,
  BSM decays with leptons

  $\sigma(p_T) / p_T^2 \sim 2 \times 10^{-5}$ / GeV

  precise and highly efficient tracking,
  extending to 100+ GeV

low mass, good resolution:
for Si tracker ~ 1-2% X_0 per layer, 7 μm point resolution



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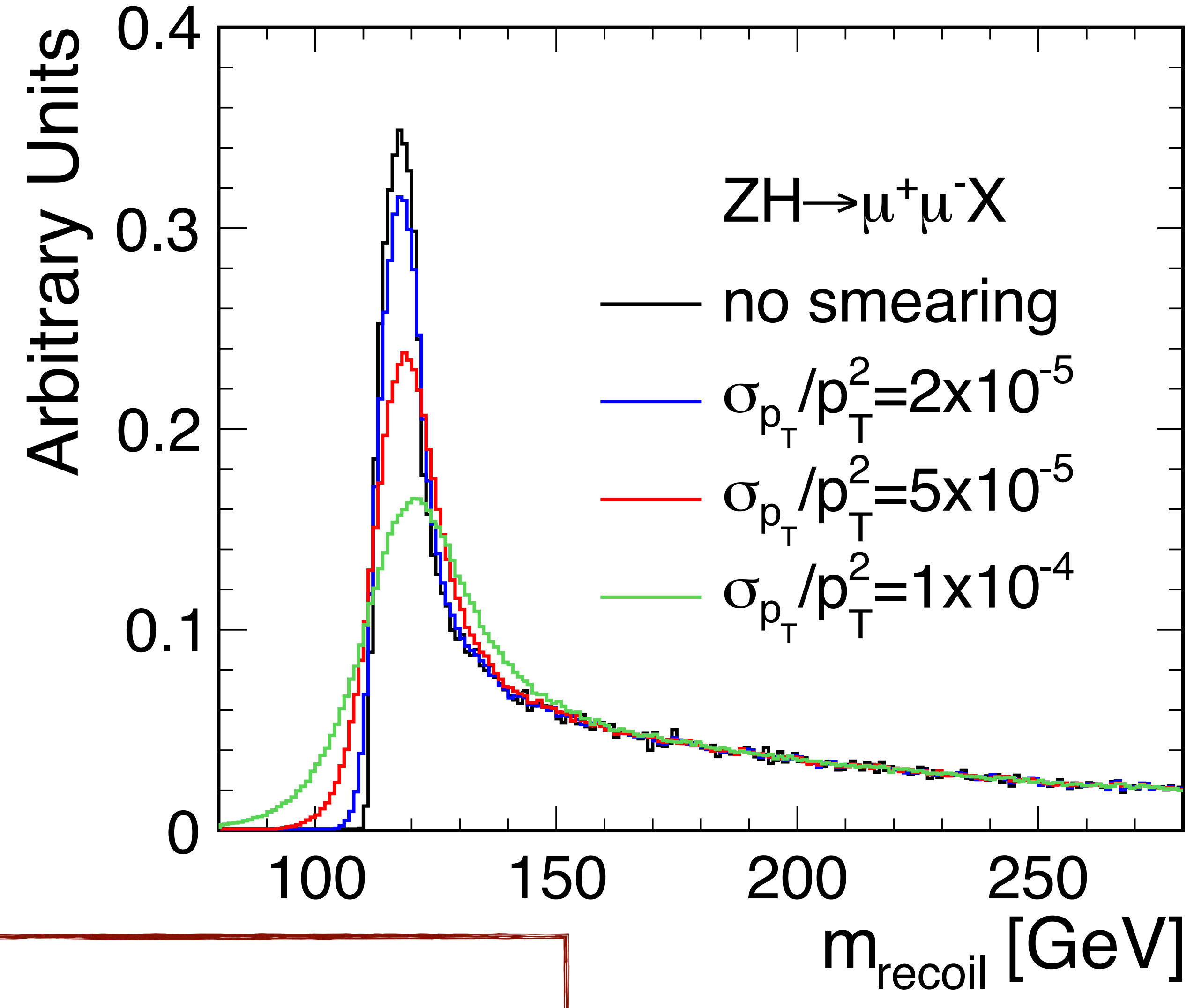

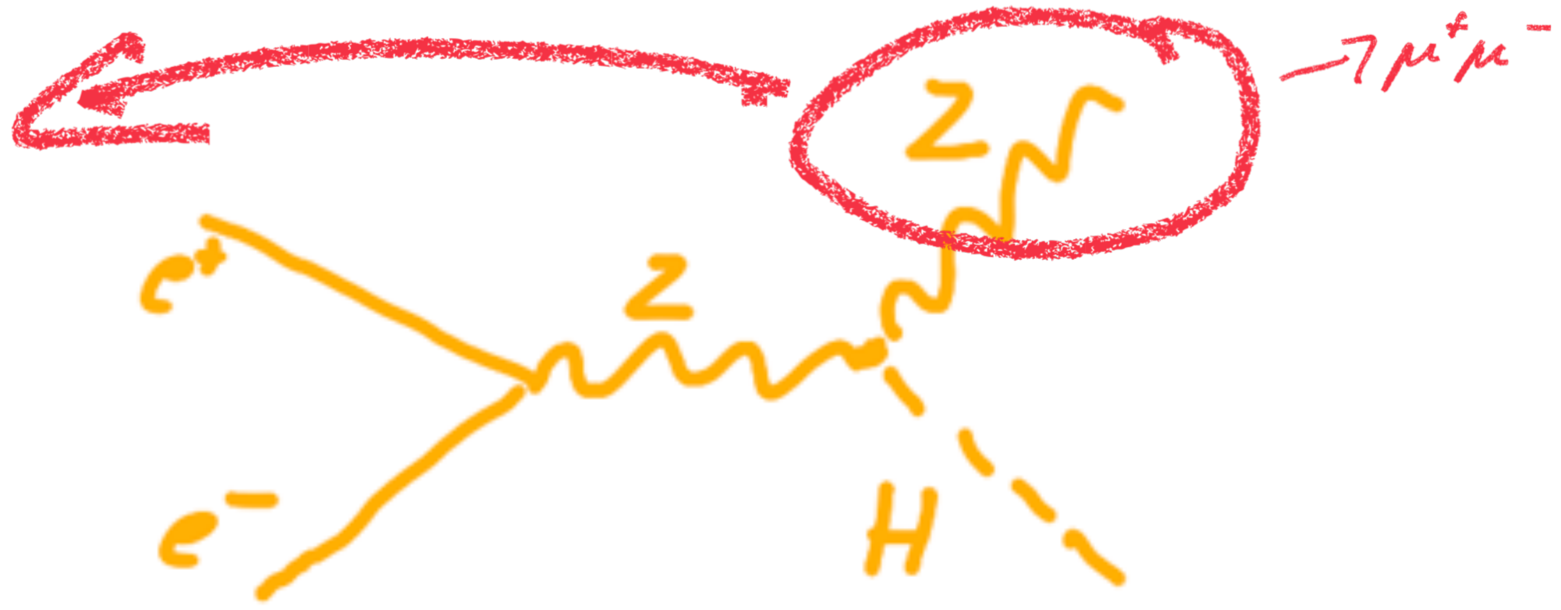

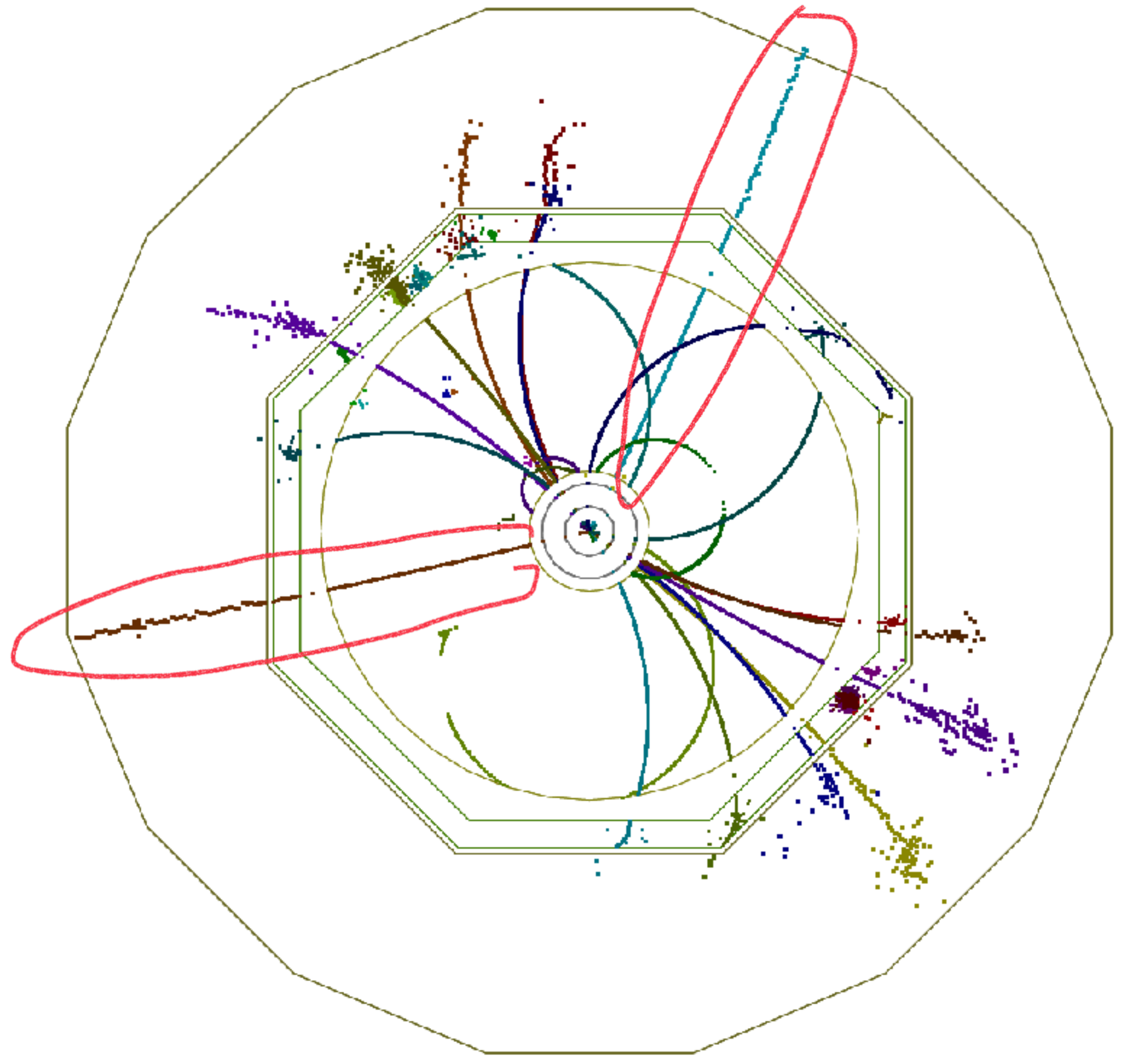

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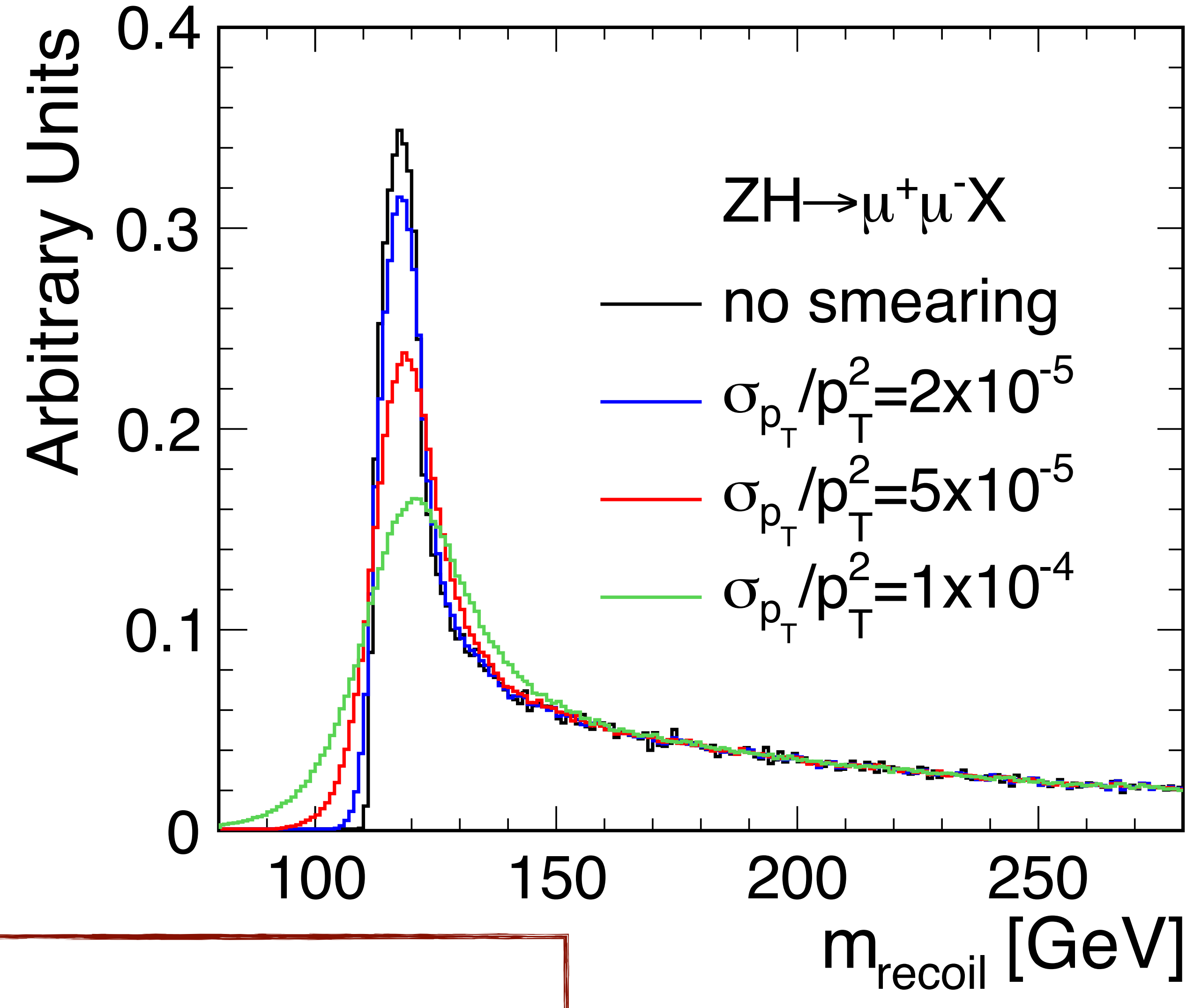

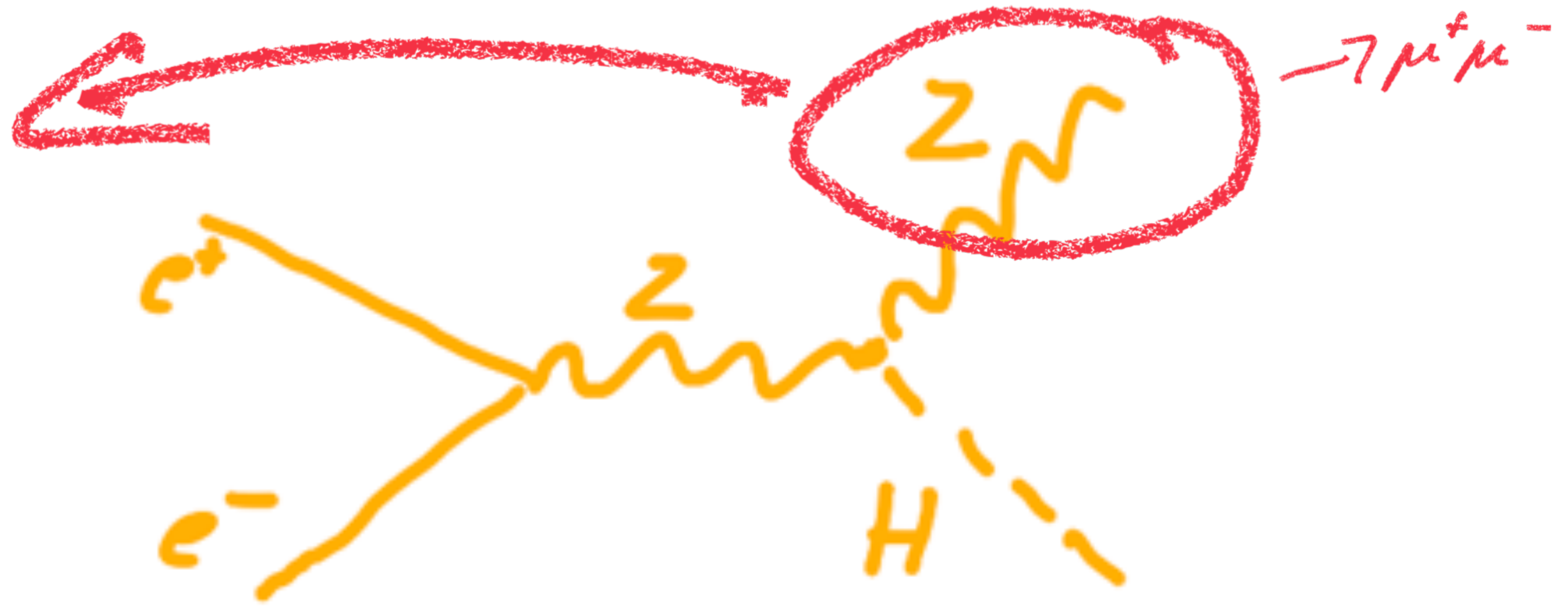

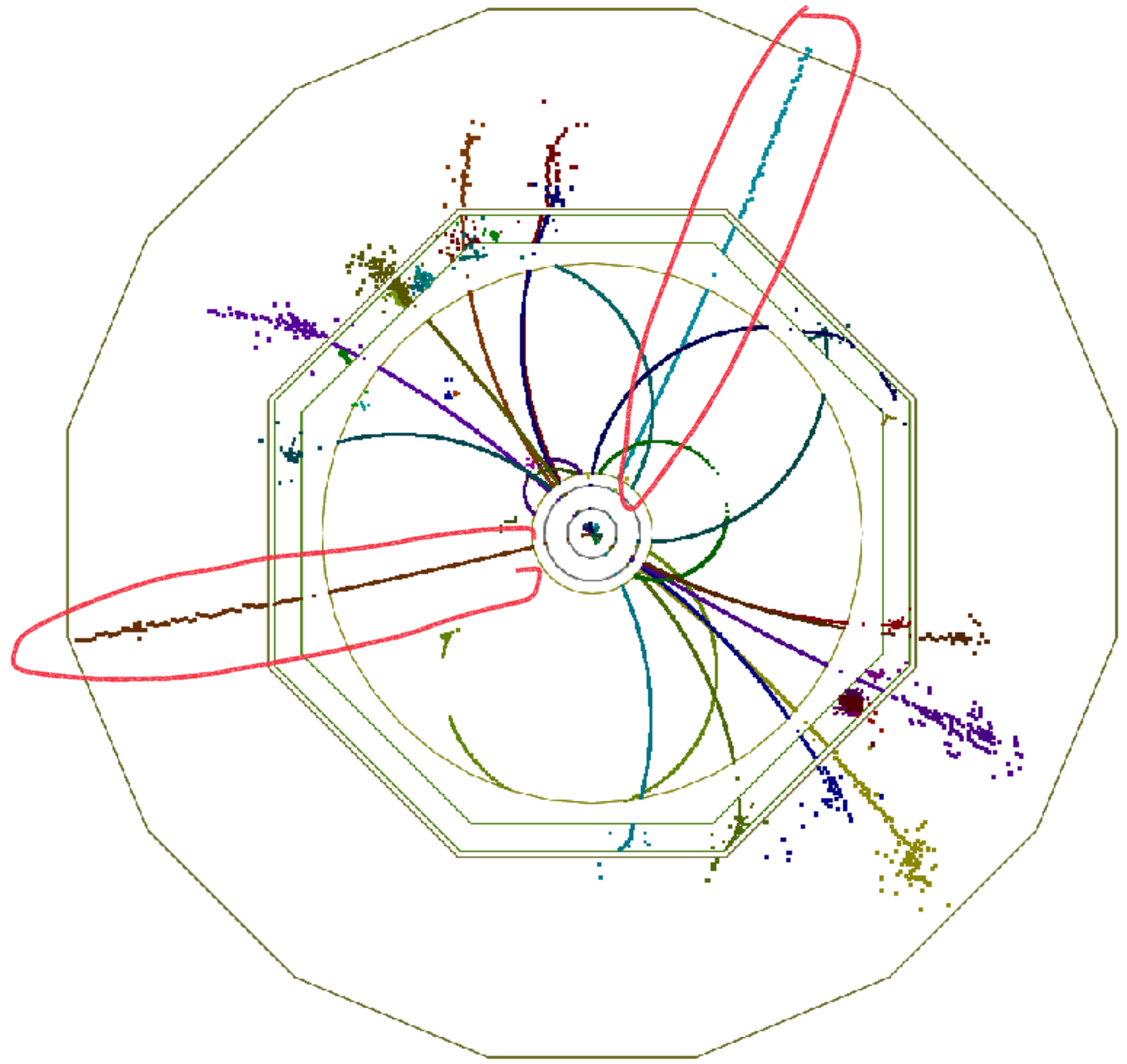

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$$\sigma(d_0) \sim [5 \oplus (10 - 15)/p\sin^{3/2}\theta]\ \mu m$$

single point resolution in vertex detector ~3 *μ*m
< 0.2 X_0 per layer

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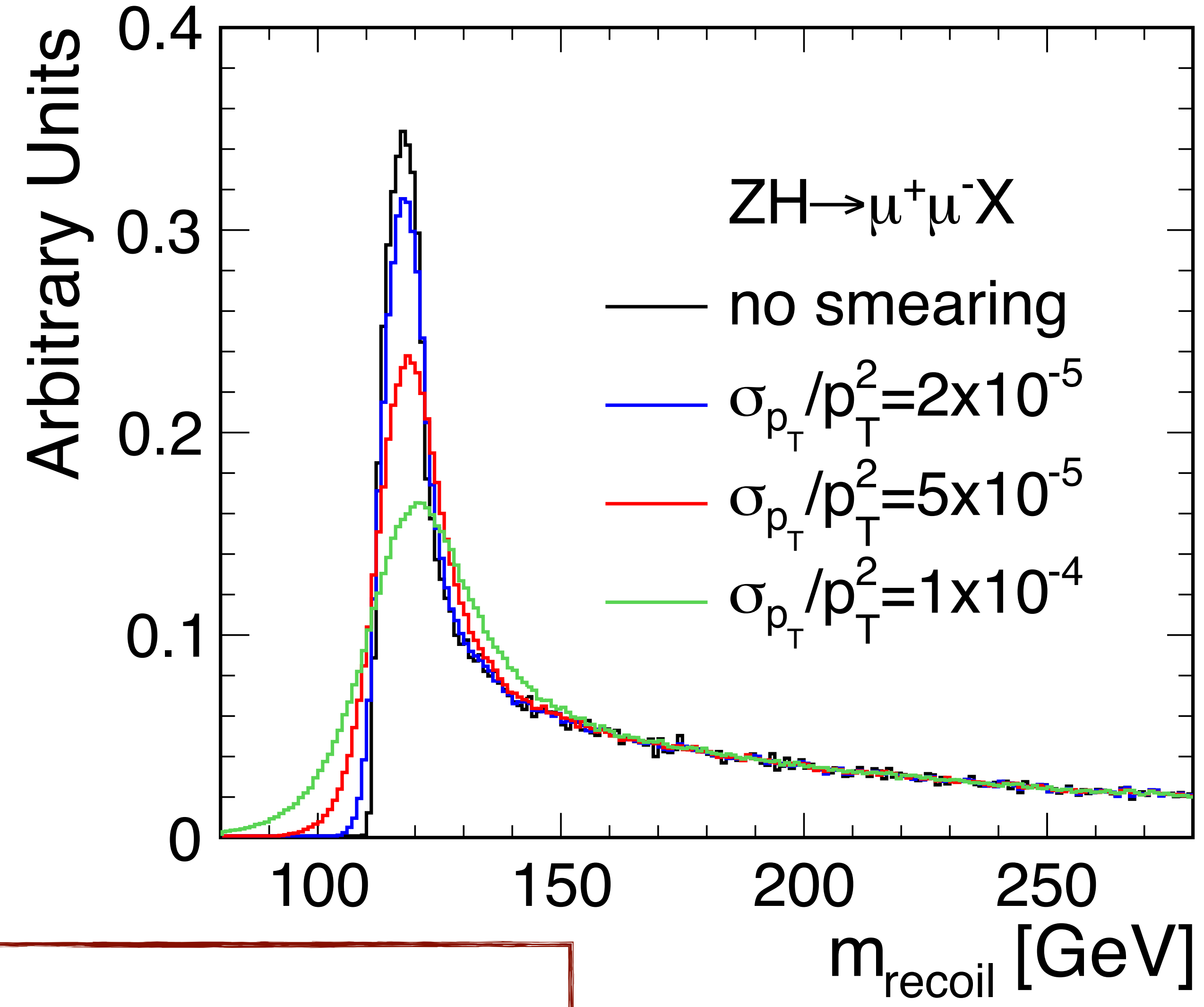

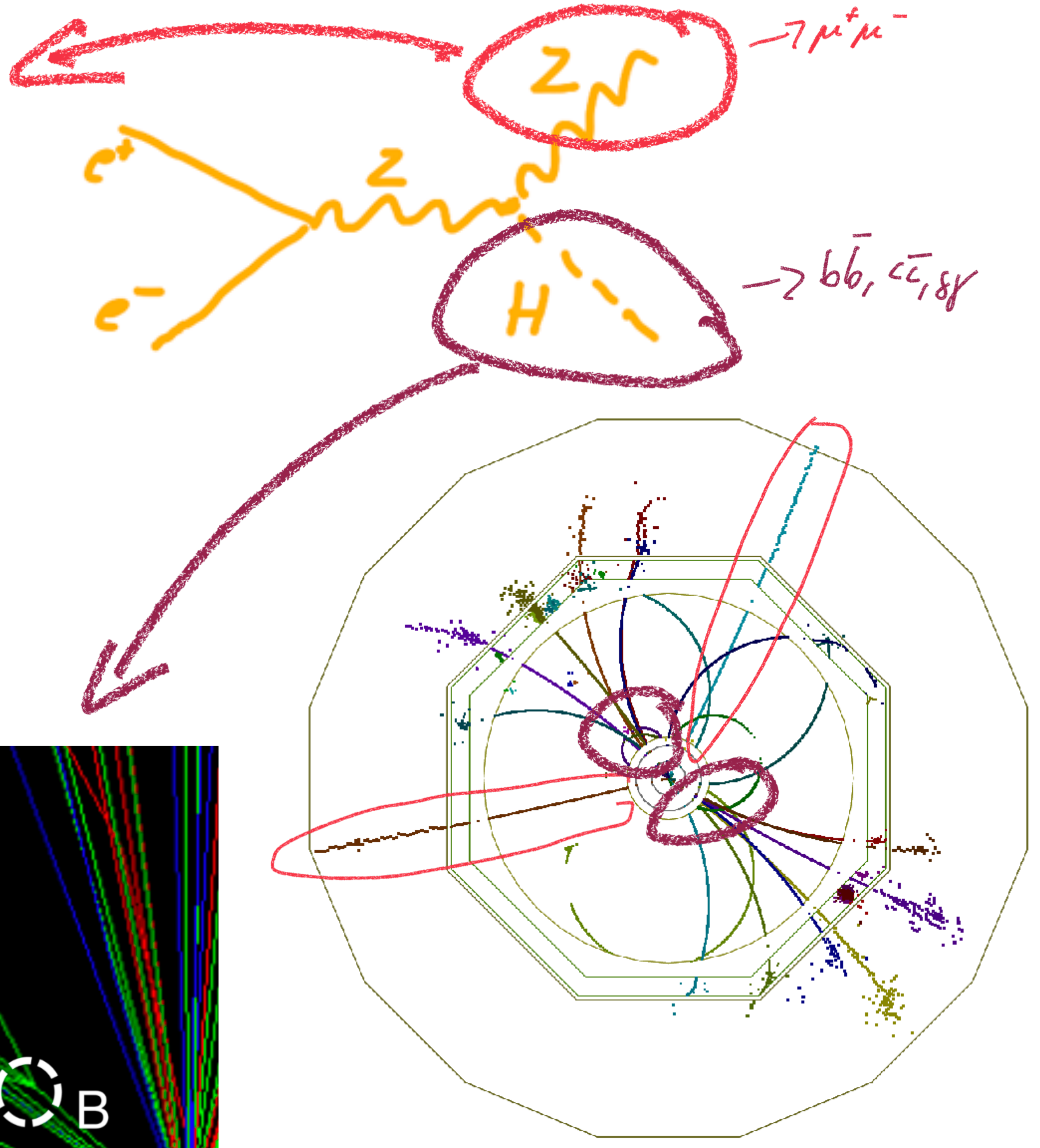

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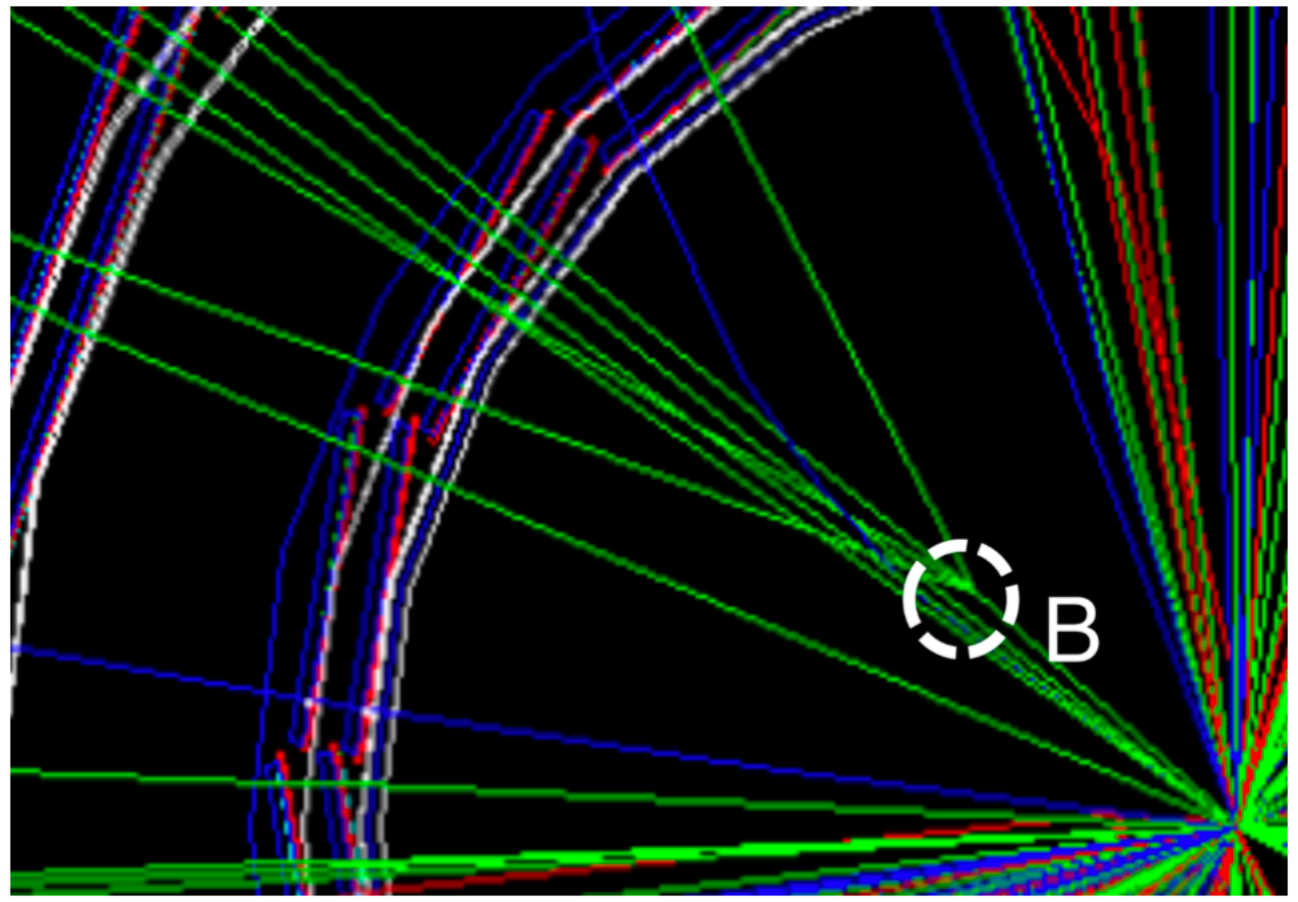

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  $\sigma(E_{jet}) / E_{jet}$ ~ 3% - 5% **for E_{jet} > 45 GeV**

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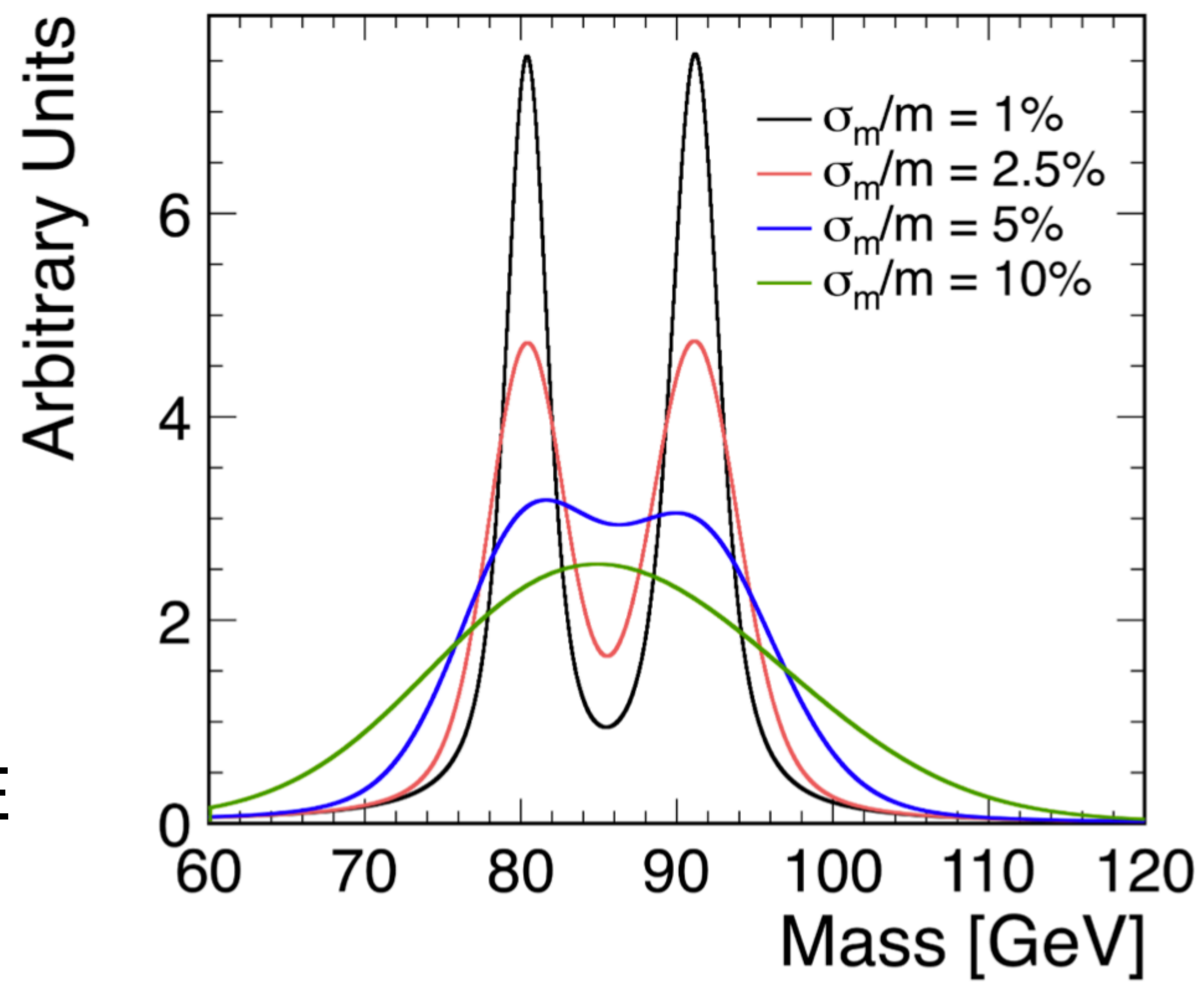

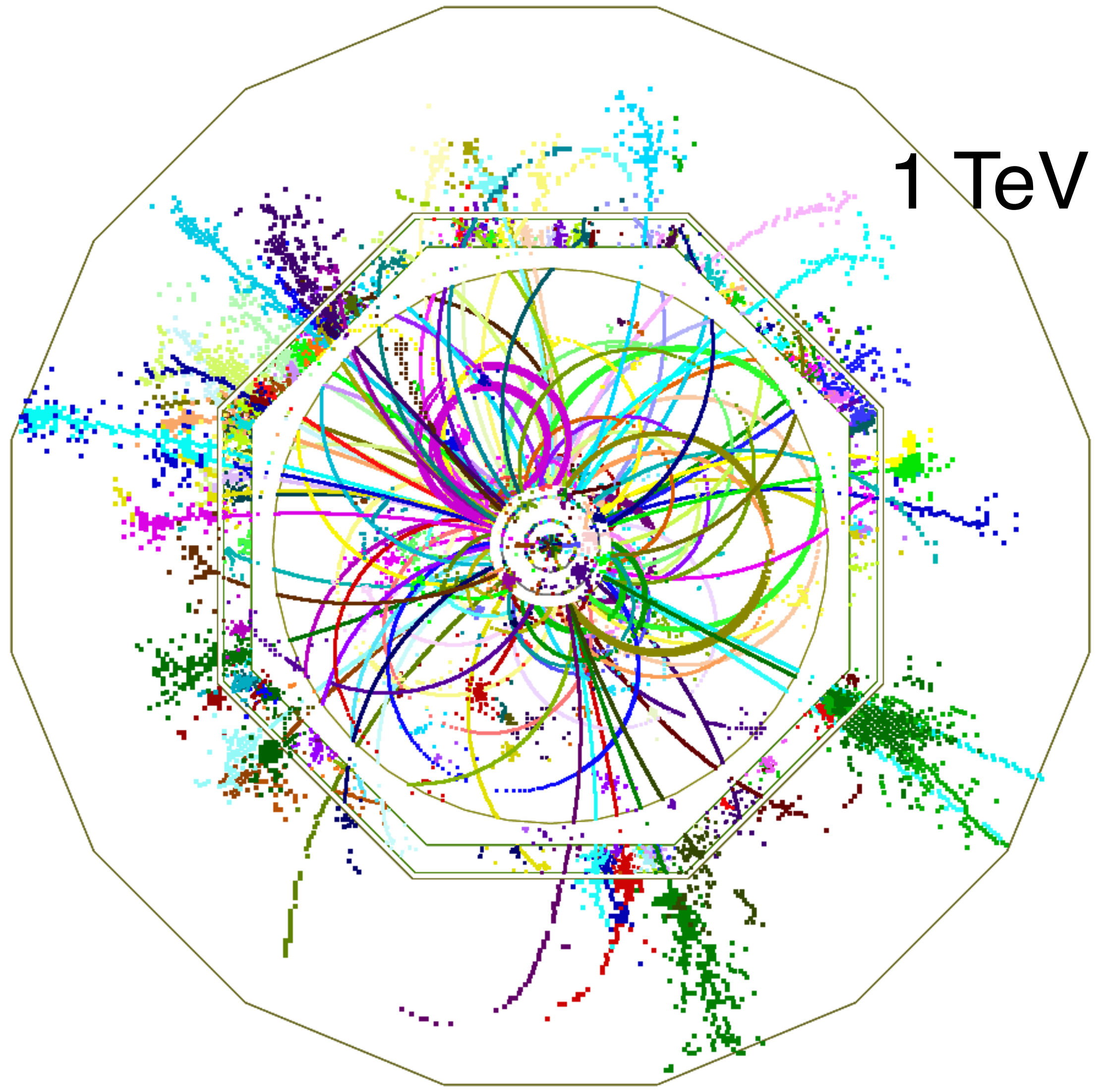

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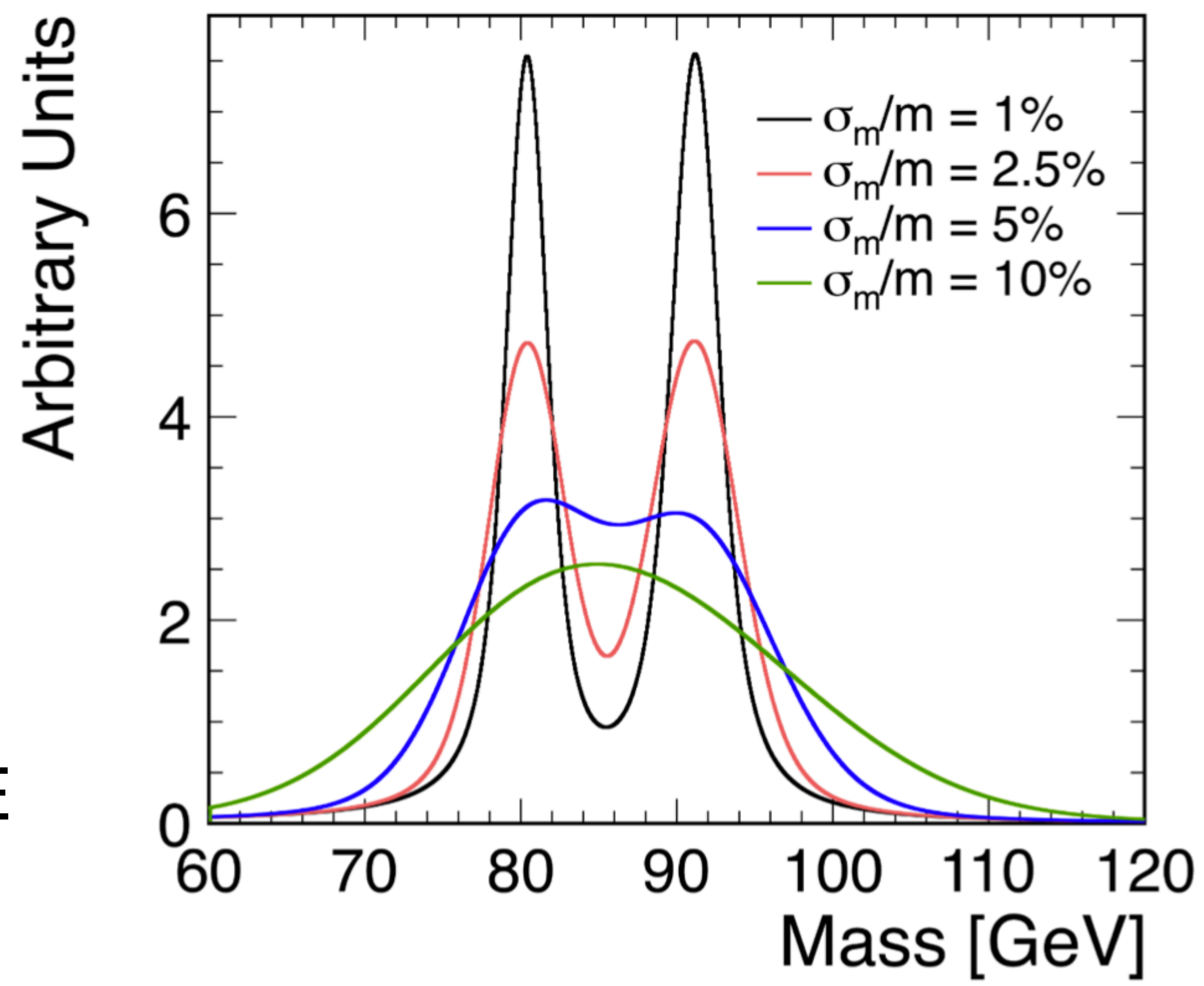
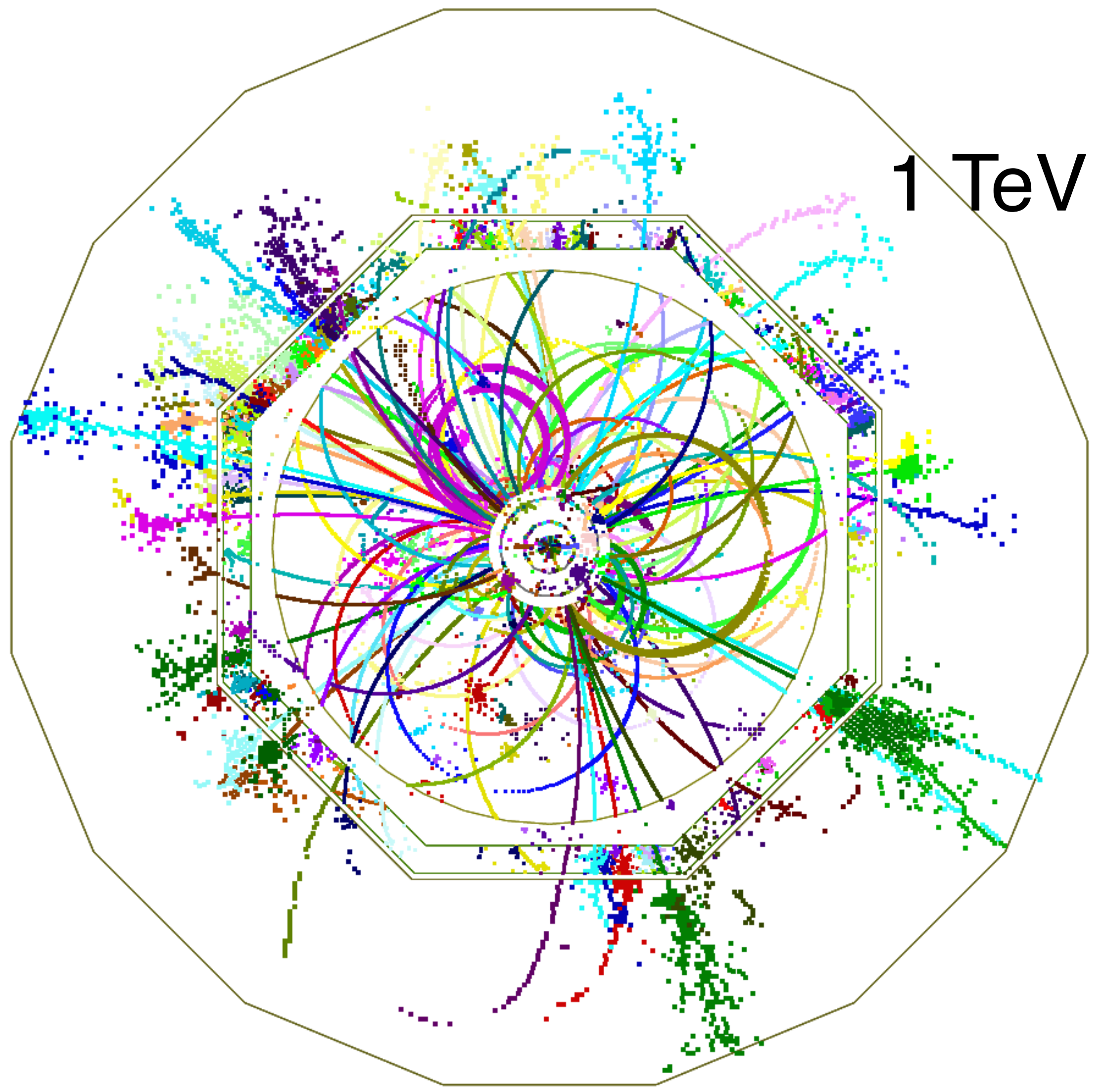
  Clean identification of e, μ up to highest energies
- PID of hadrons to improve tagging, jets,…





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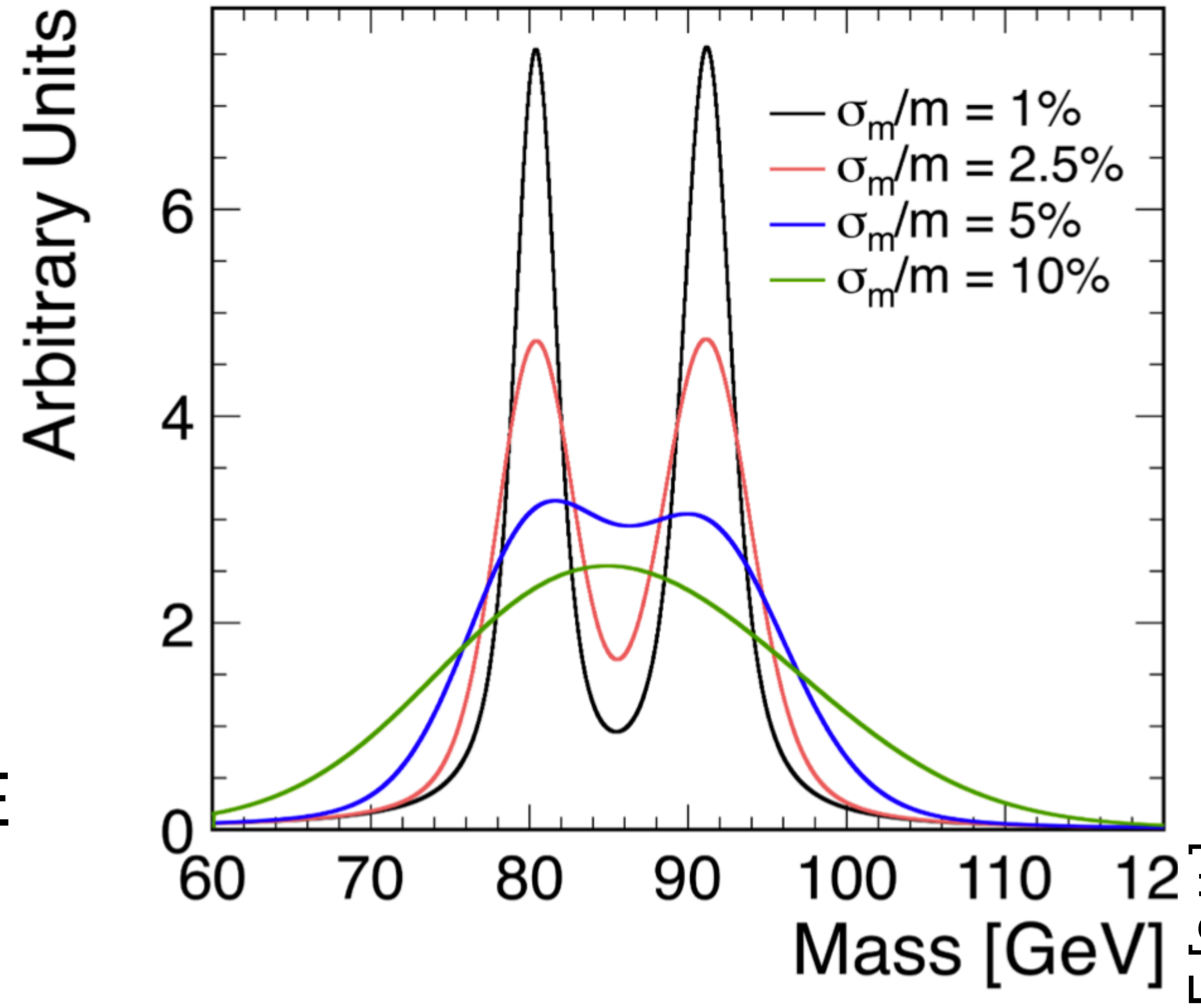

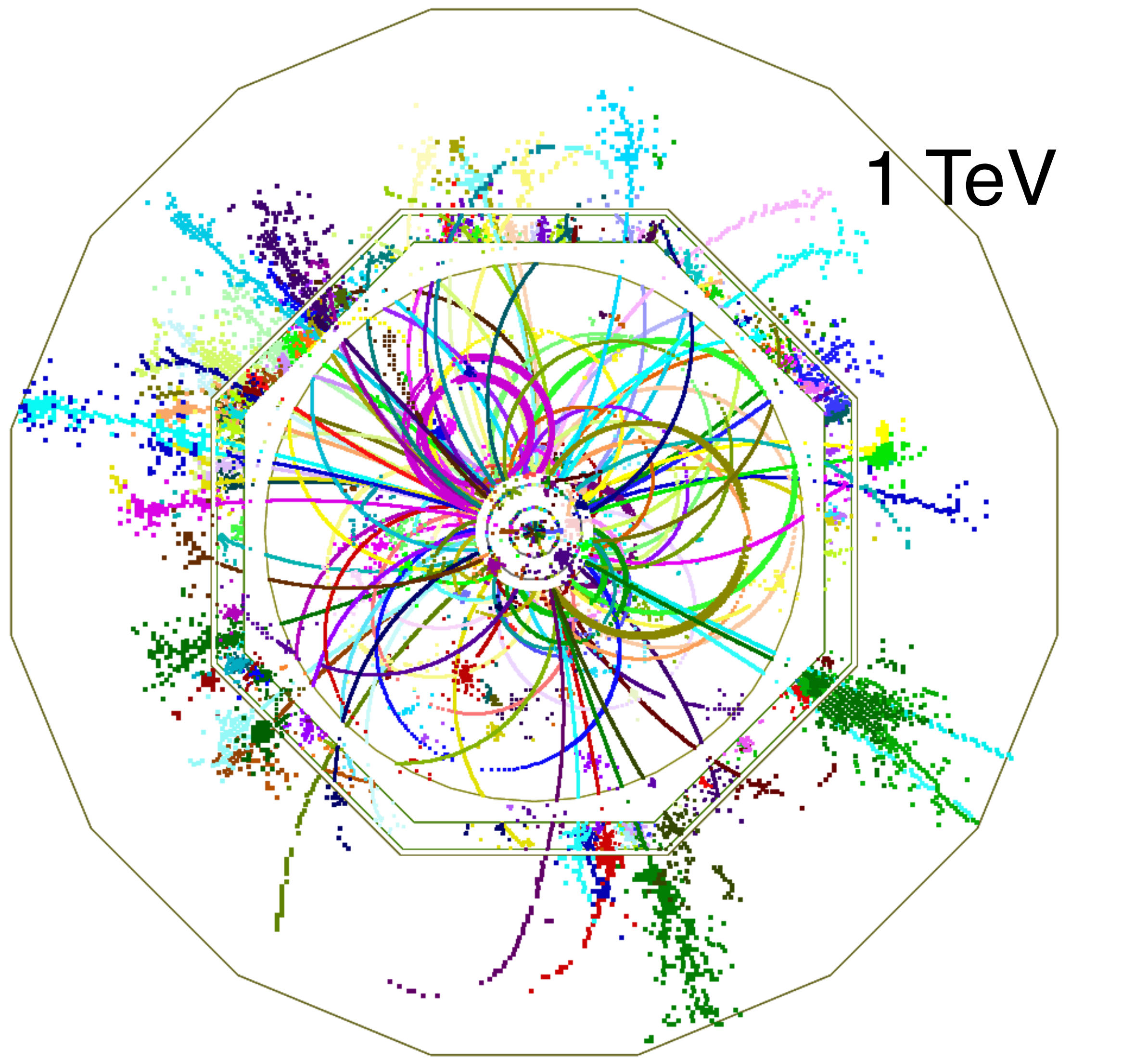

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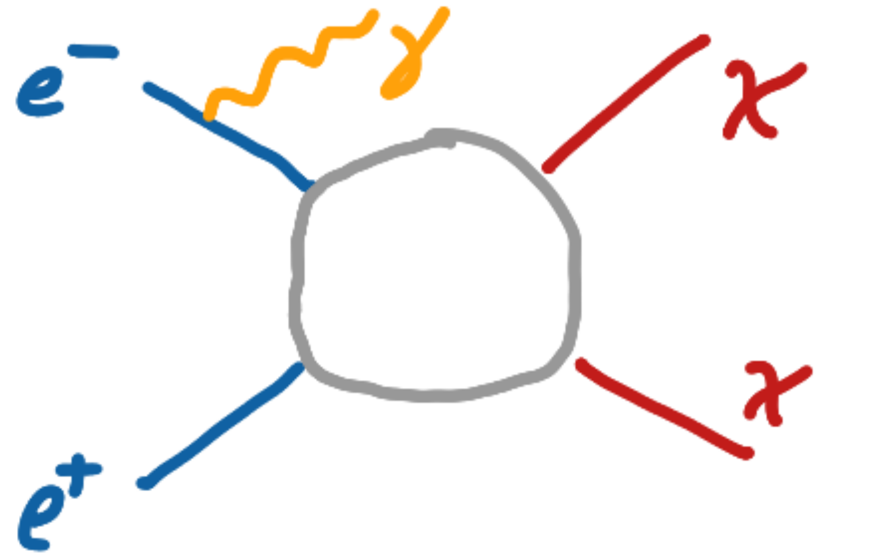
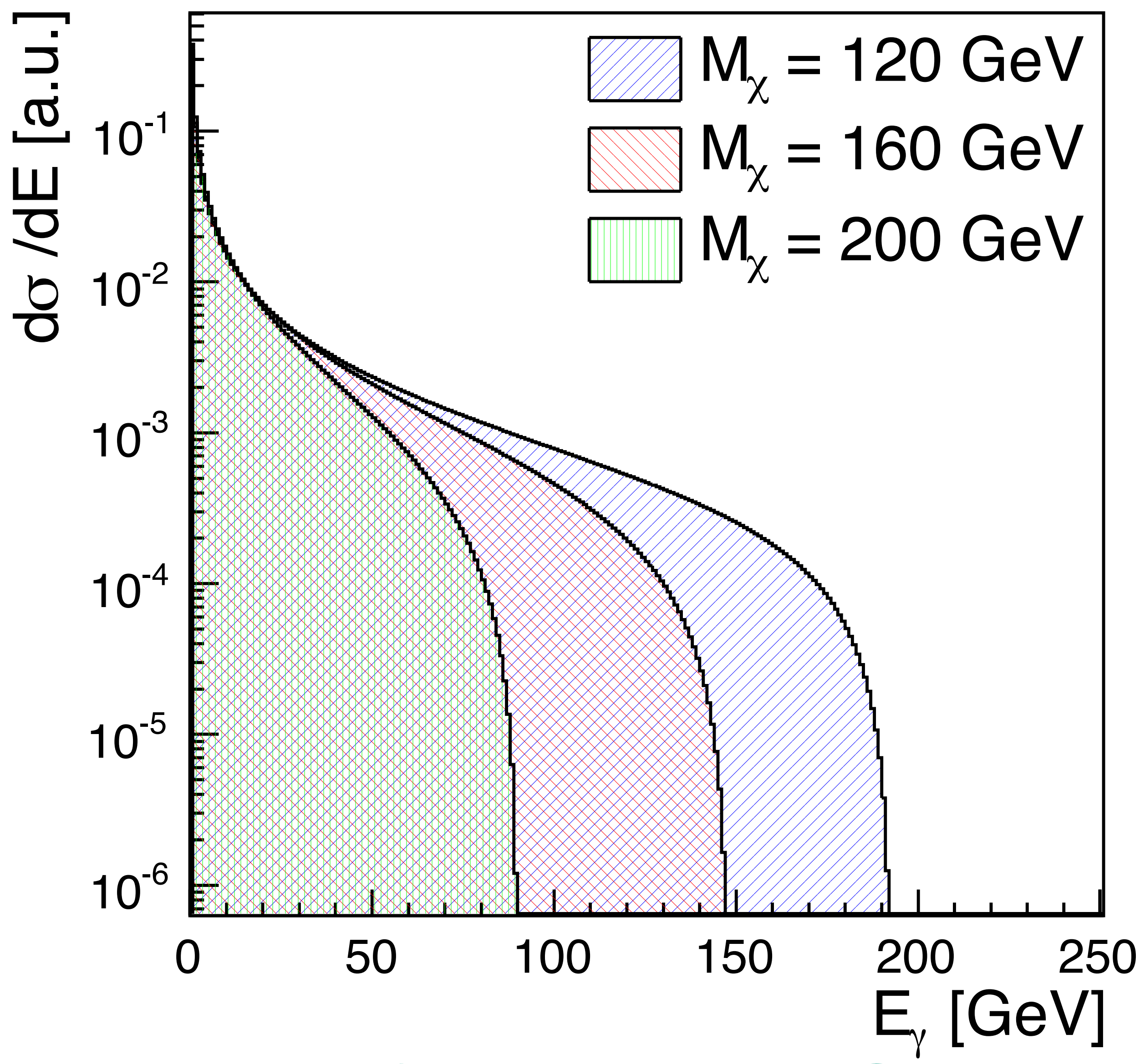
- ***Hermetic coverage***
  Dark matter searches in mono-photon events, …

  N.B.: Achievable limits do not depend strongly on $\sigma(E_\gamma)$

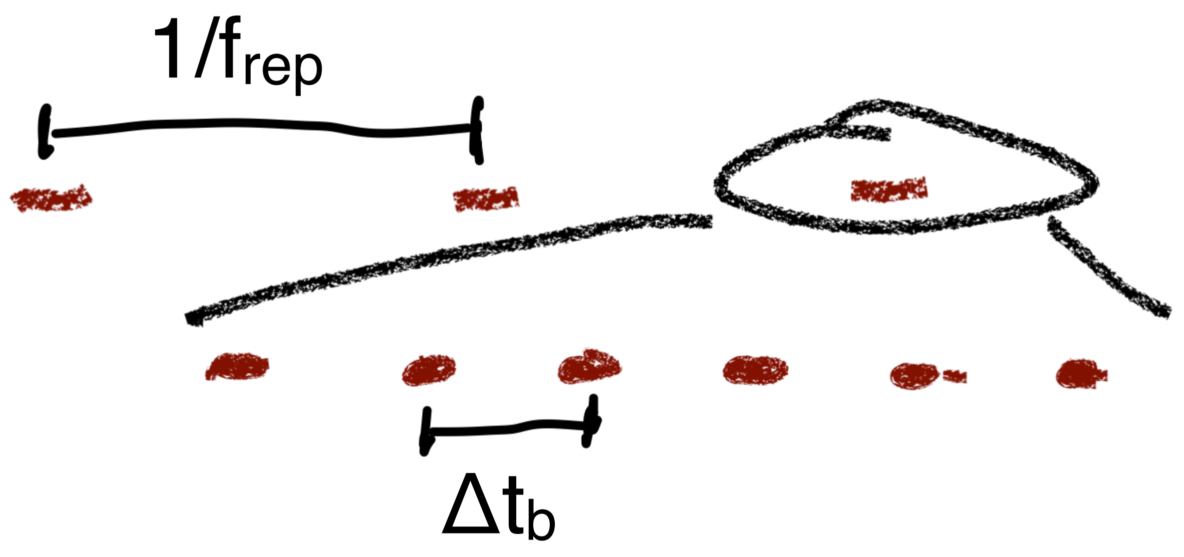




Linear Collider Conditions

… and the consequences for the detector design

- Linear Colliders operate in bunch trains:



  - at CLIC: $\mathbf{\Delta t_b = 0.5}$ **ns**; $f_{rep} = 50$ Hz
  - at ILC: $\Delta t_b = 554$ ns; $f_{rep} = 5$ Hz

➩ Enables power pulsing of front-end electronics, resulting in dramatically reduced power consumption

- ➩ Eliminates need for active cooling in many areas of the detectors: Reduced material, increased compactness

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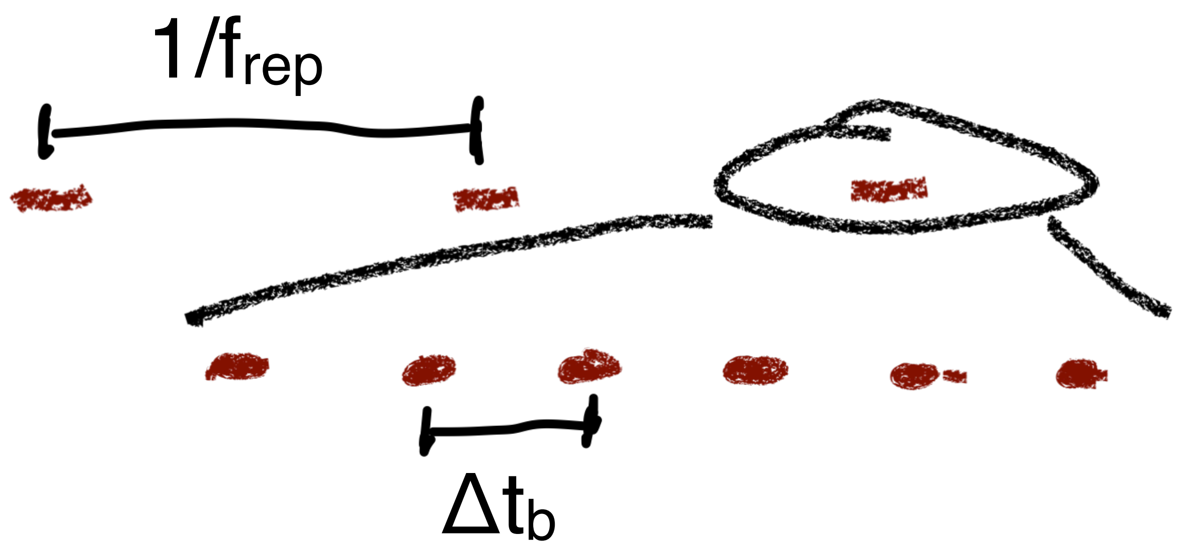

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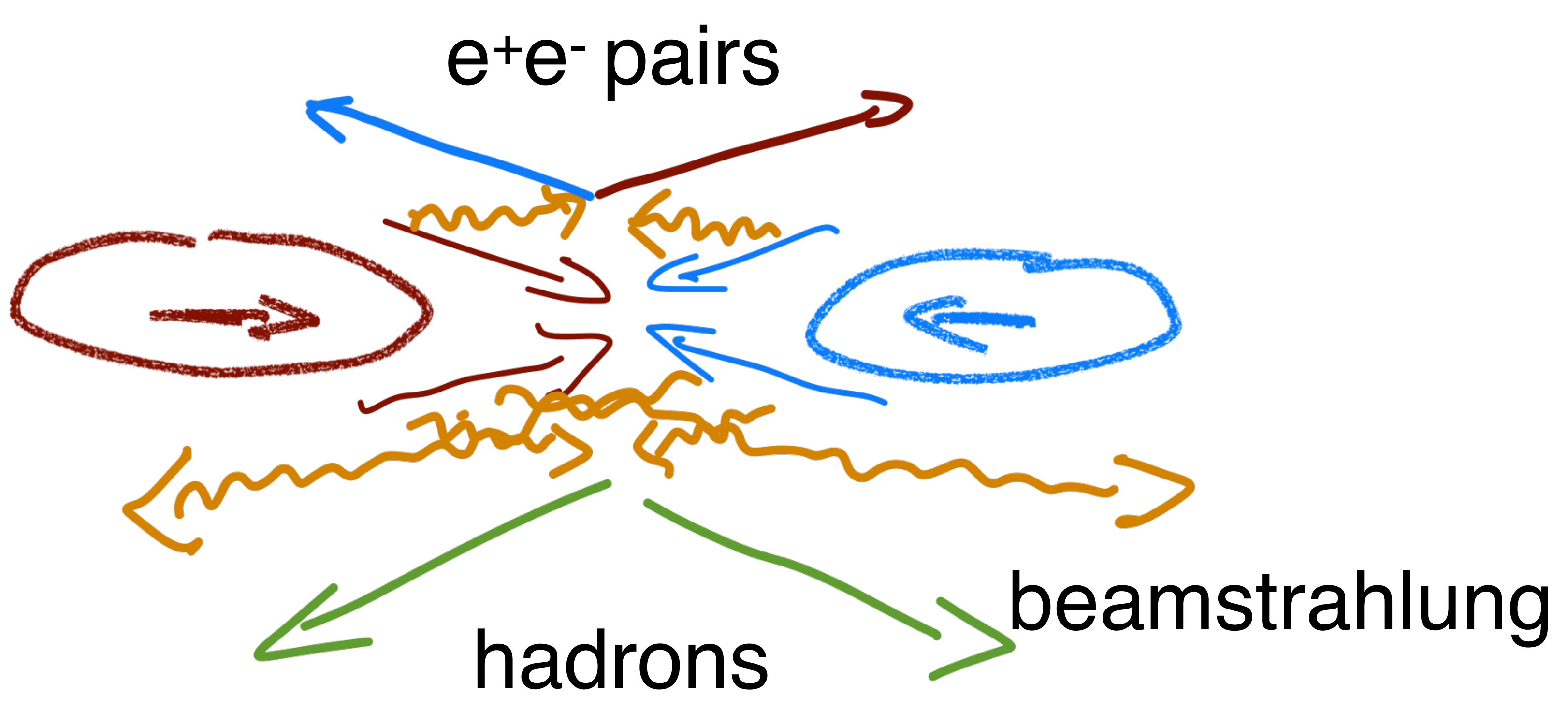
- … and require extreme focusing to achieve high luminosity



⇨ Enables power pulsing of front-end electronics, resulting in dramatically reduced power consumption

  ⇨ Eliminates need for active cooling in many areas of the detectors: Reduced material, increased compactness

⇨ Significant beam-induced backgrounds

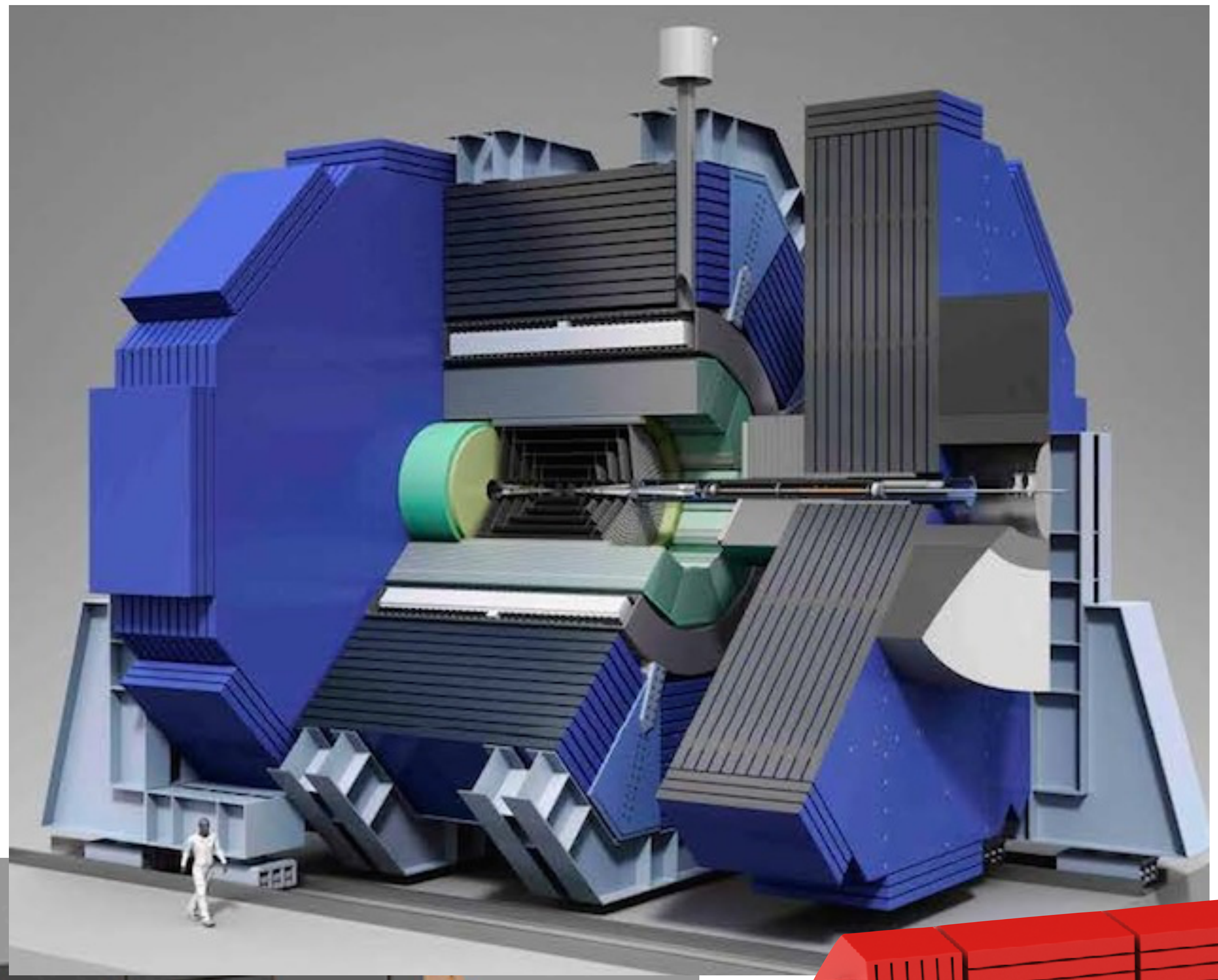
  ⇨ Constraints on beam pipe geometry, crossing angle and vertex detector radius

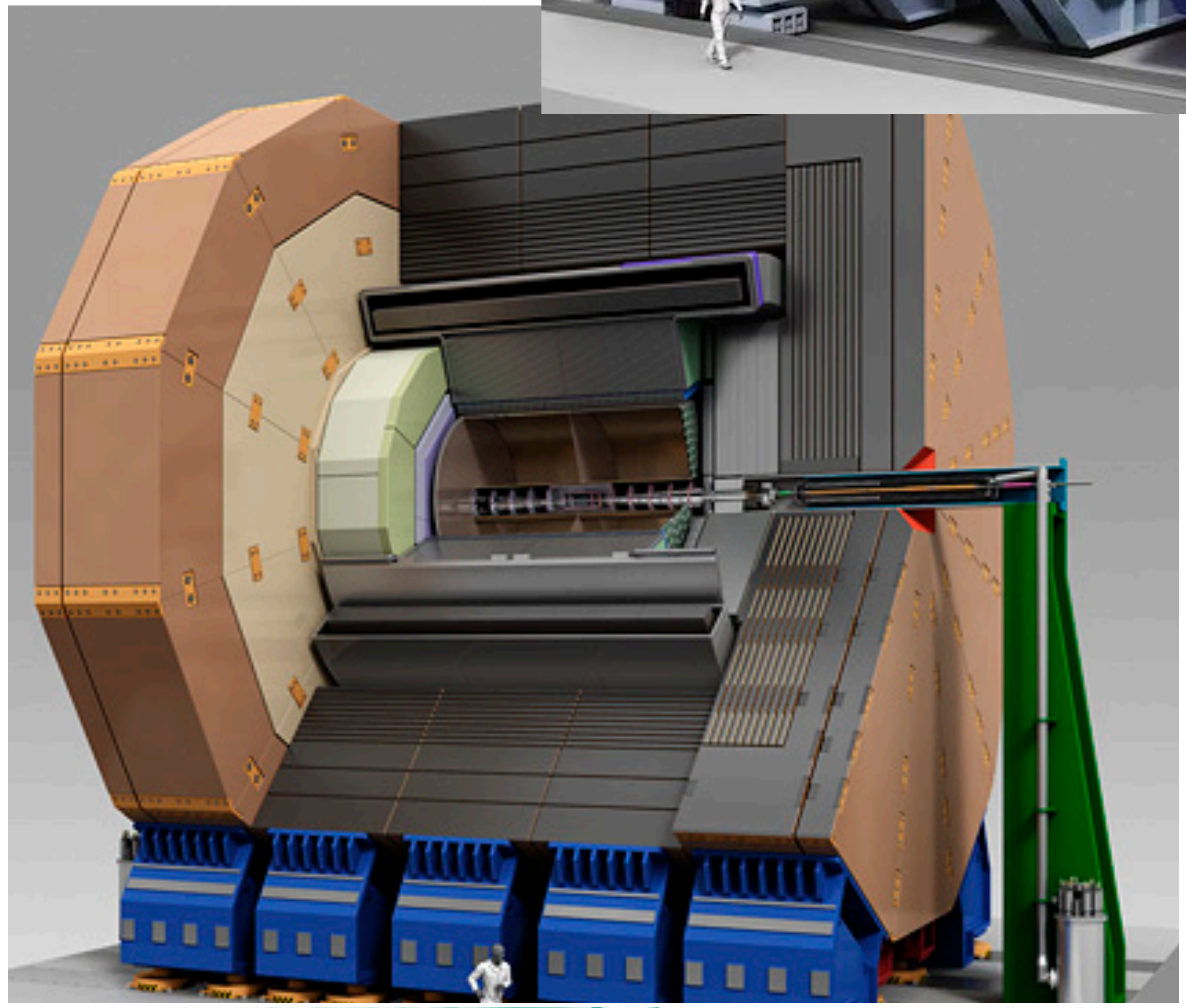
  ⇨ In-time pile-up of hadronic background: **sufficient granularity for topological rejection**

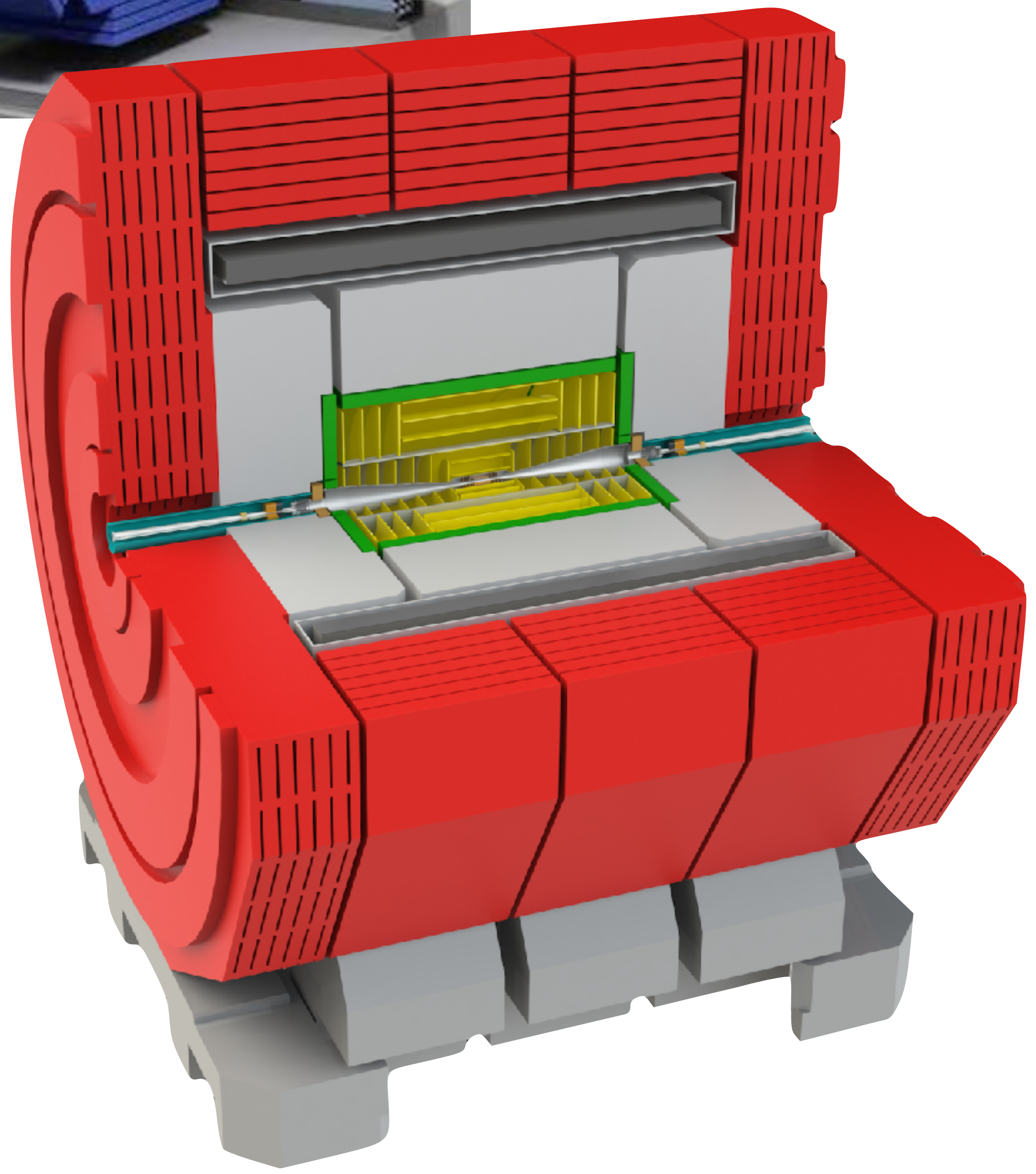
  ⇨ At CLIC: small Δt_b also results in out-of-time pile-up: **ns-level timing** in many detector systems

The Linear Collider Detector Design - Main Features

Focusing on general aspects







- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters,** for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*
- **Triggerless readout** of main detector systems

all: capable of dealing with beam background via timing, granularity, radiation hardness where needed

From linear to circular

Key differences with detector implications

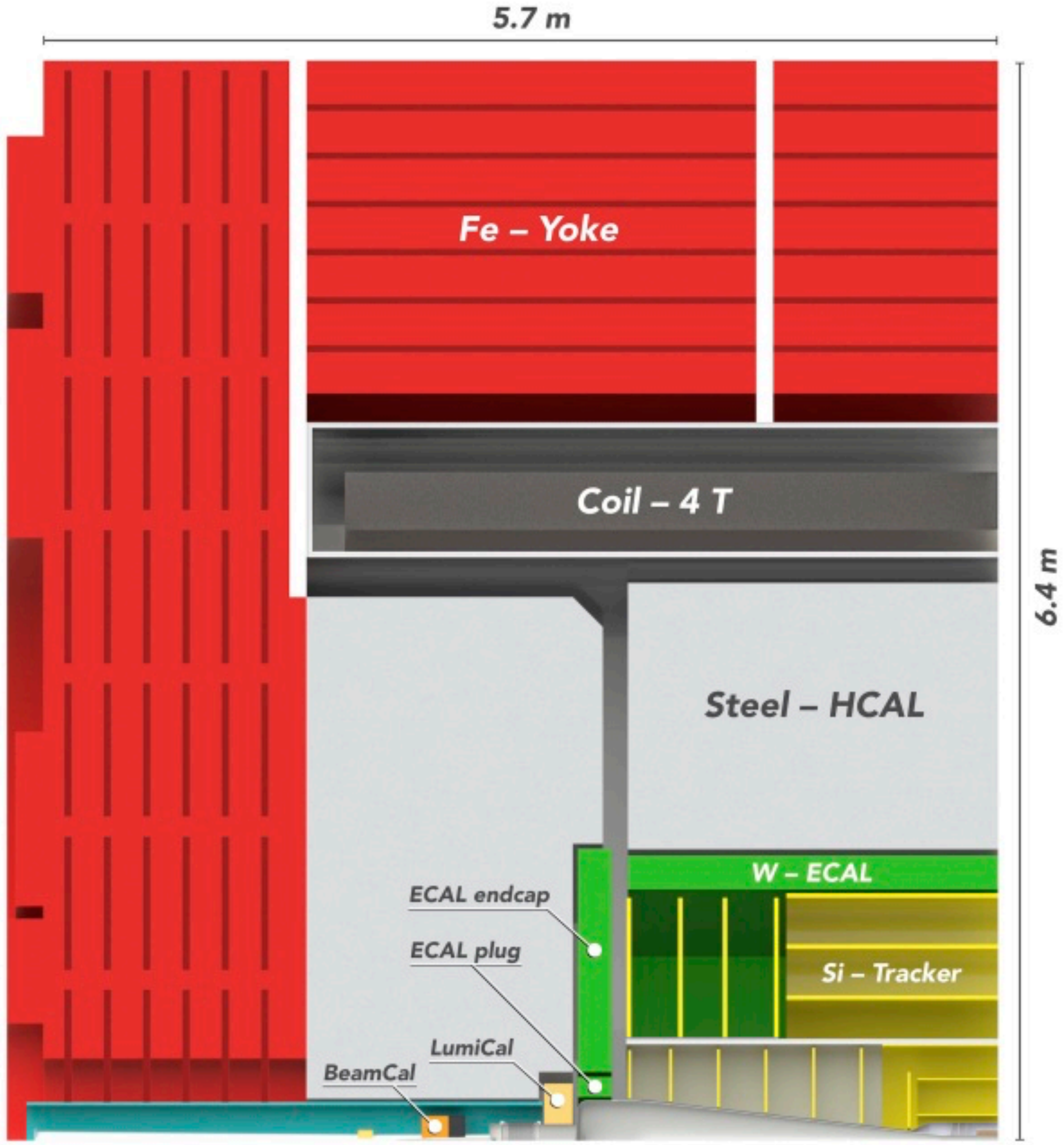
- Energy: Focus on lower energy for FCCee - a maximum of 365 GeV
  - Reduced calorimeter depth
  - Less collimated jets - can potentially compromise on calorimeter compactness, granularity
- Need the beams to survive, and reach high luminosity
  - Limits on solenoidal field
    - Reduced momentum resolution at constant tracker size
    - Larger magnetic volume “affordable”: A path to recover momentum resolution
- No bunch train structure: DC operation of the detector readout
  - Active cooling (or compromises on granularity, speed) required in many areas of the detector: Increased material, less compact construction of calorimeters
- Very high luminosity, sustained high rates
  - Revisit DAQ and trigger concepts - still in an early phase

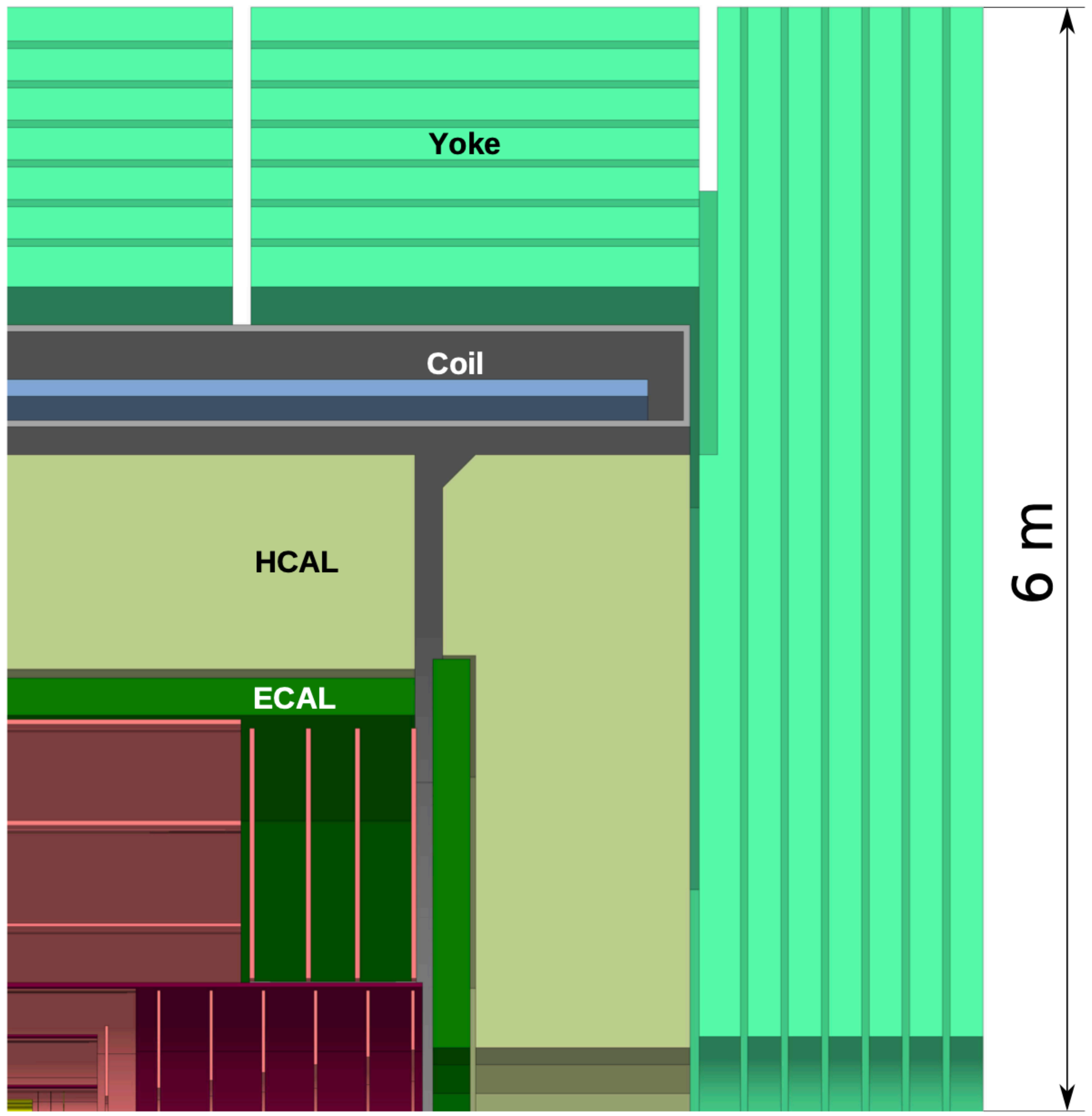
In addition: slightly different physics emphasis: Flavour at the Z pole in particular - which makes PID more important, adding additional detector requirements. Also: Absolute normalization to high precision!

Linear to Circular: Illustrating Detector Changes

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD





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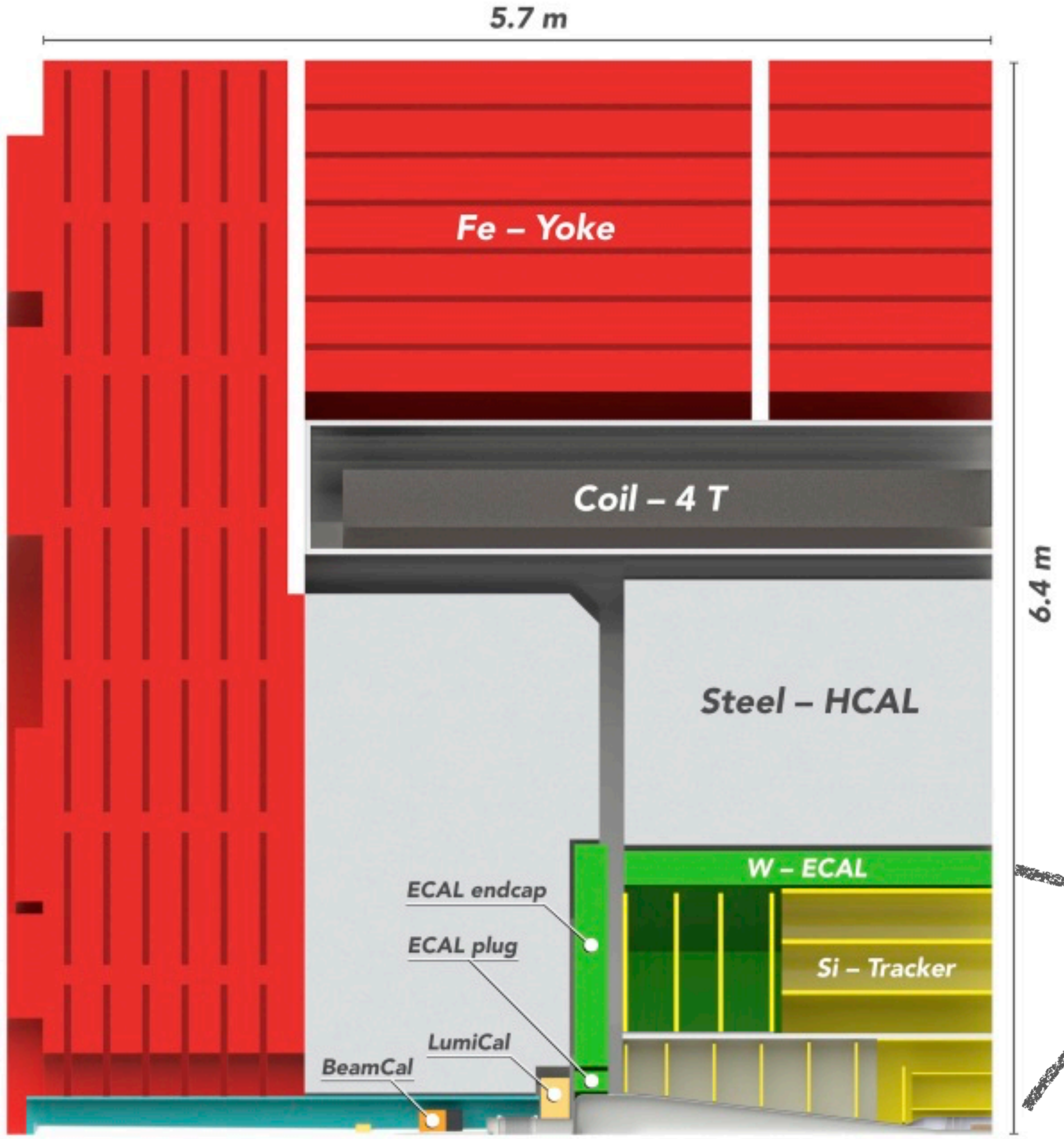
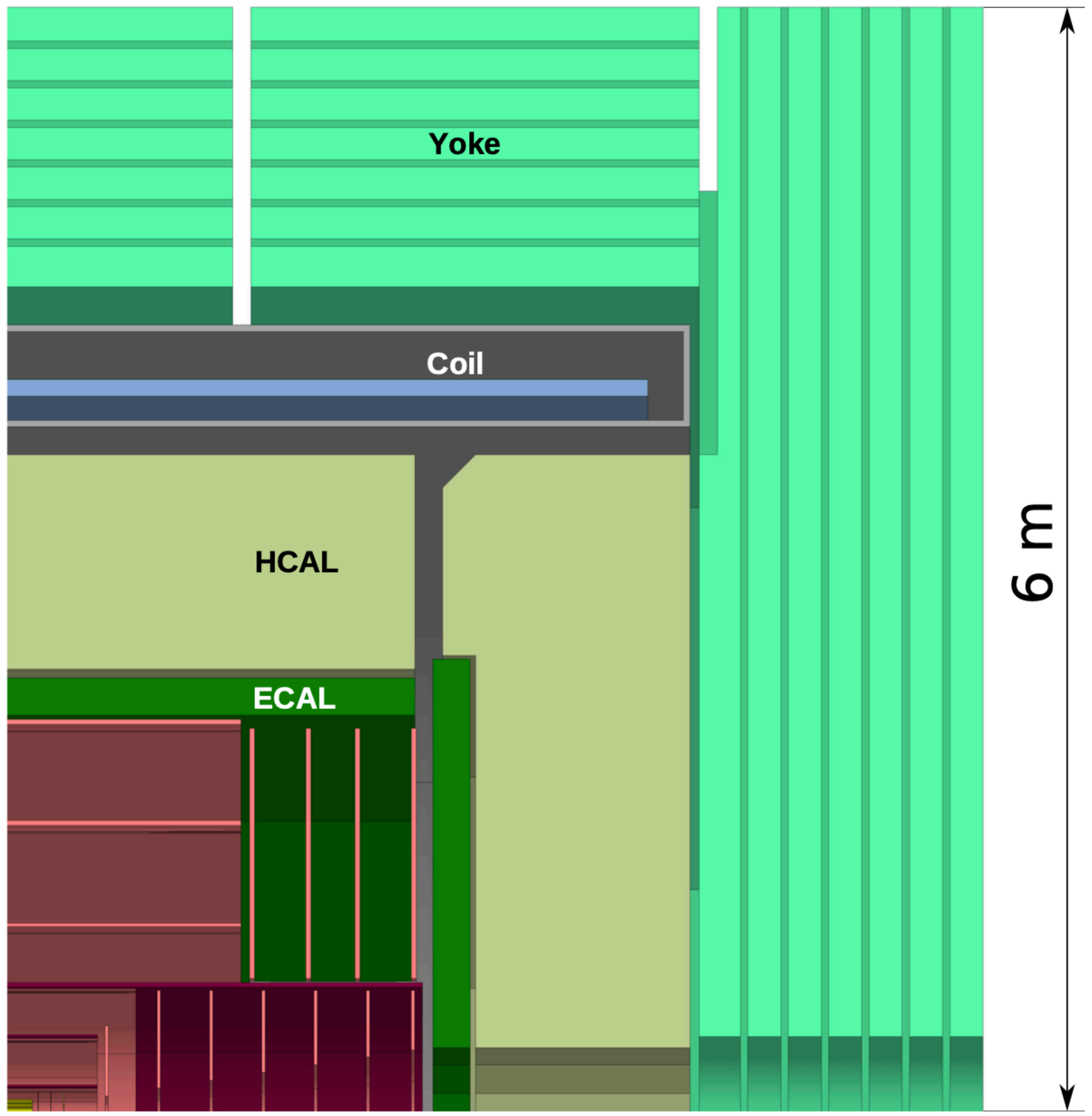


increase in tracker radius:
retain p resolution



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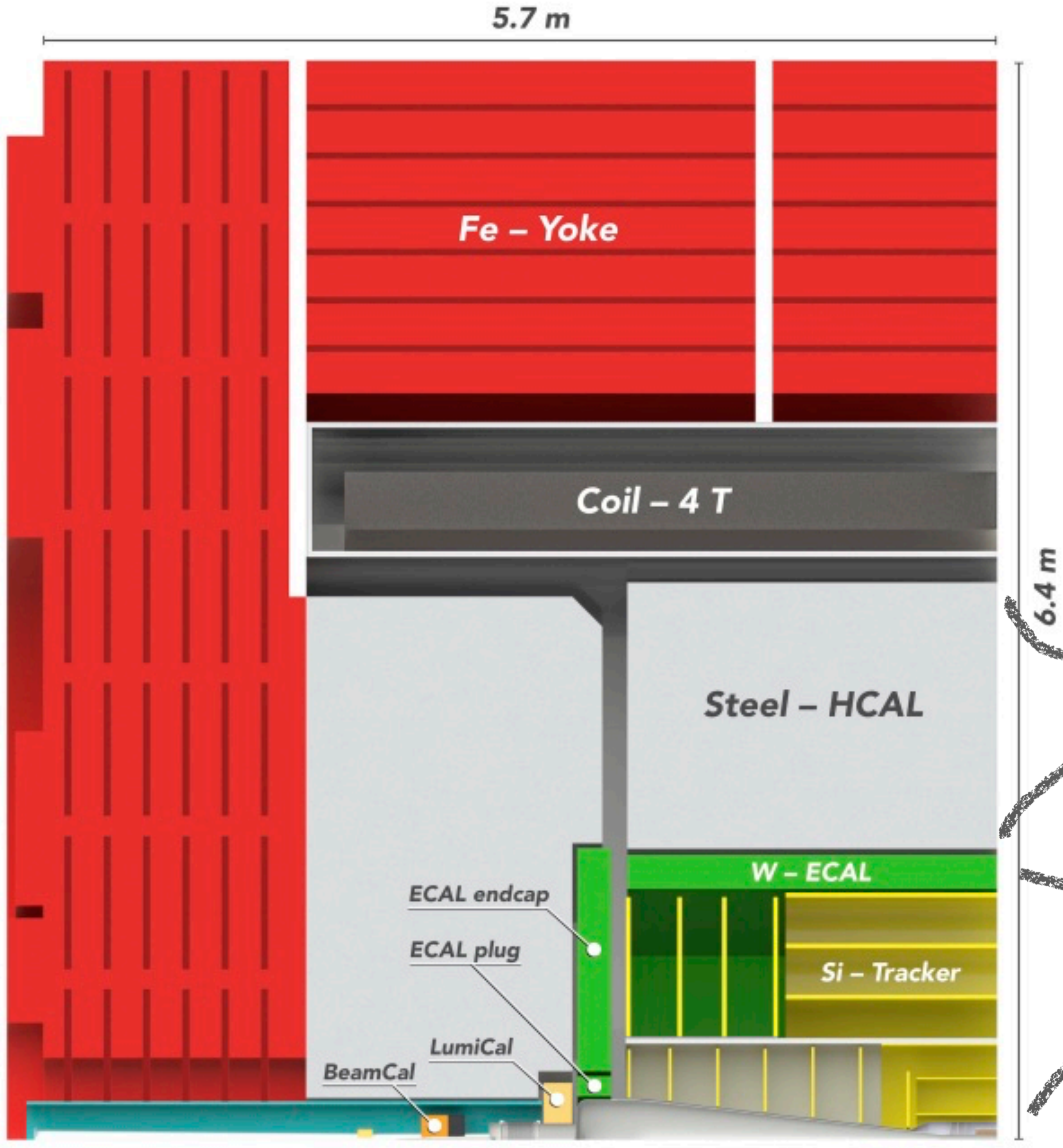
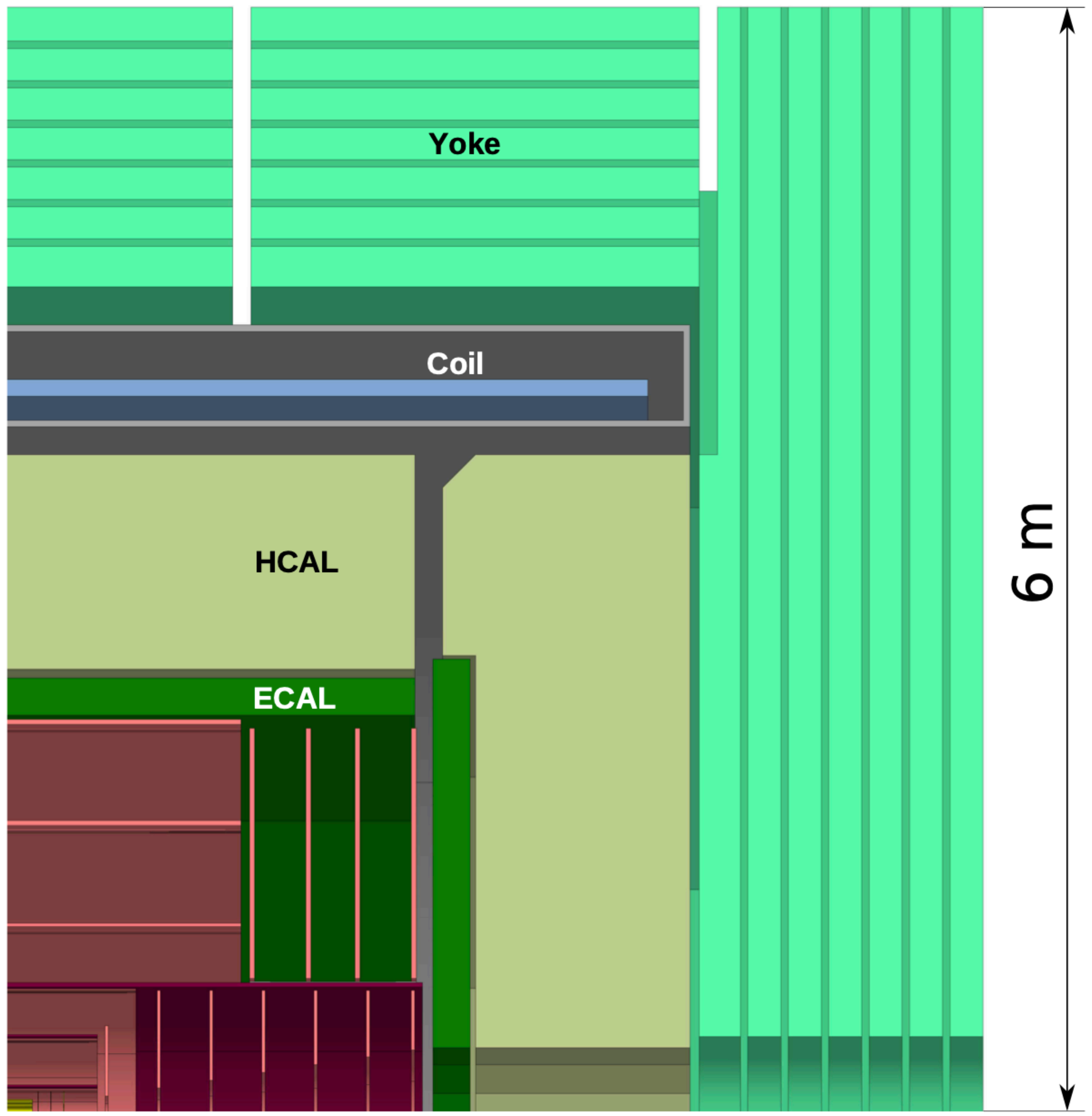


reduced HCAL thickness:
enabled by lower energy

increase in tracker radius:
retain p resolution



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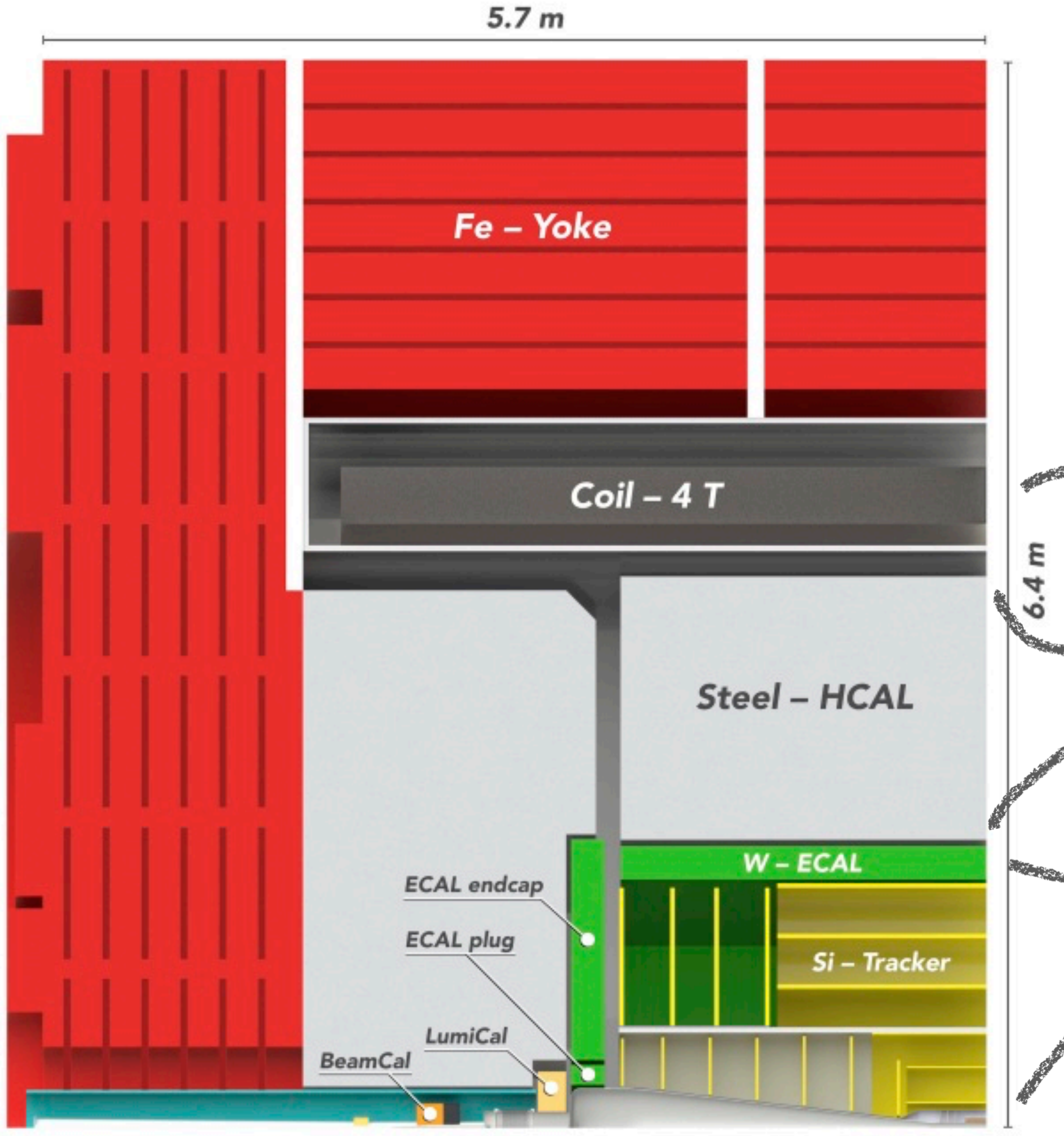
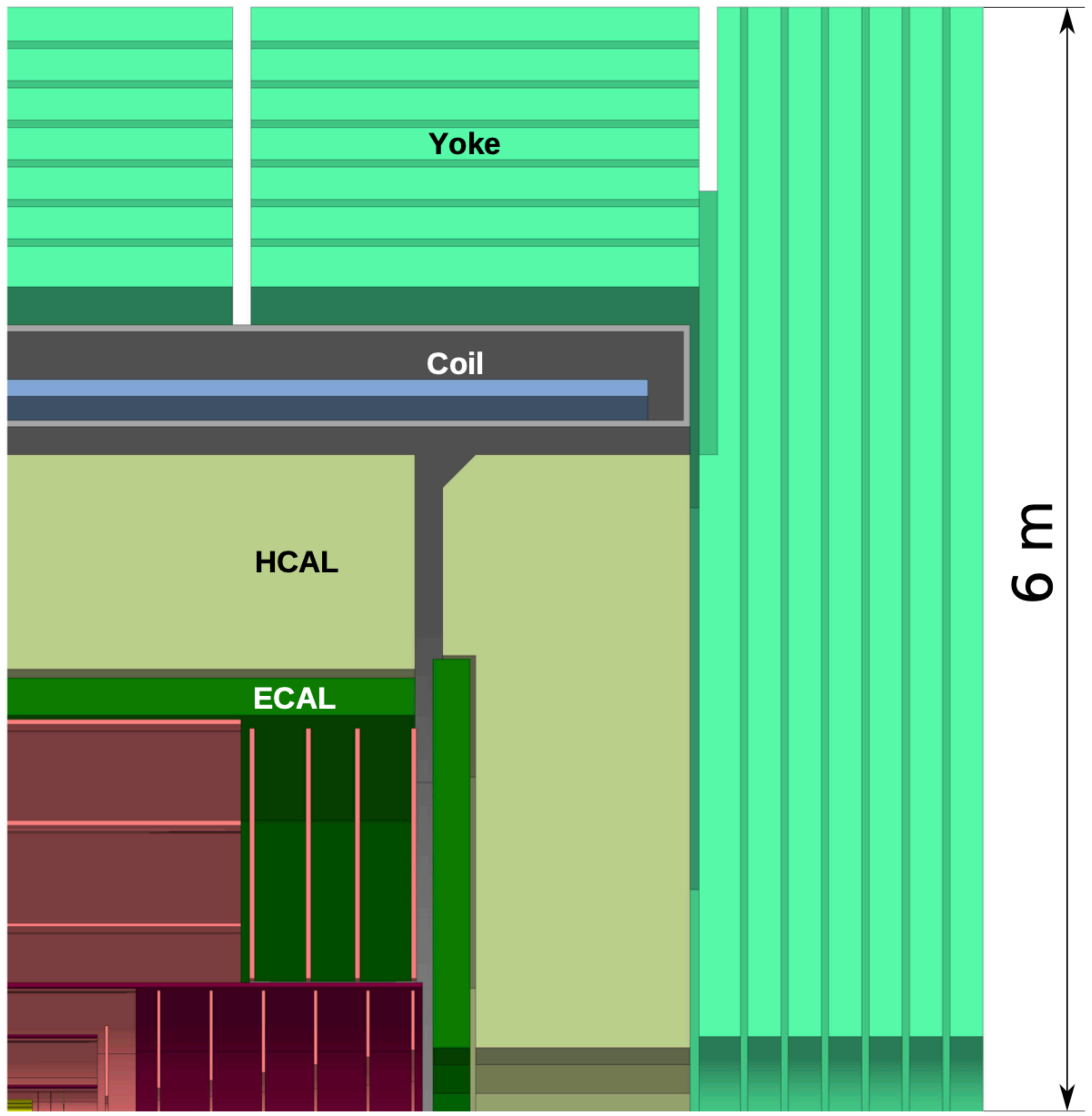


lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution



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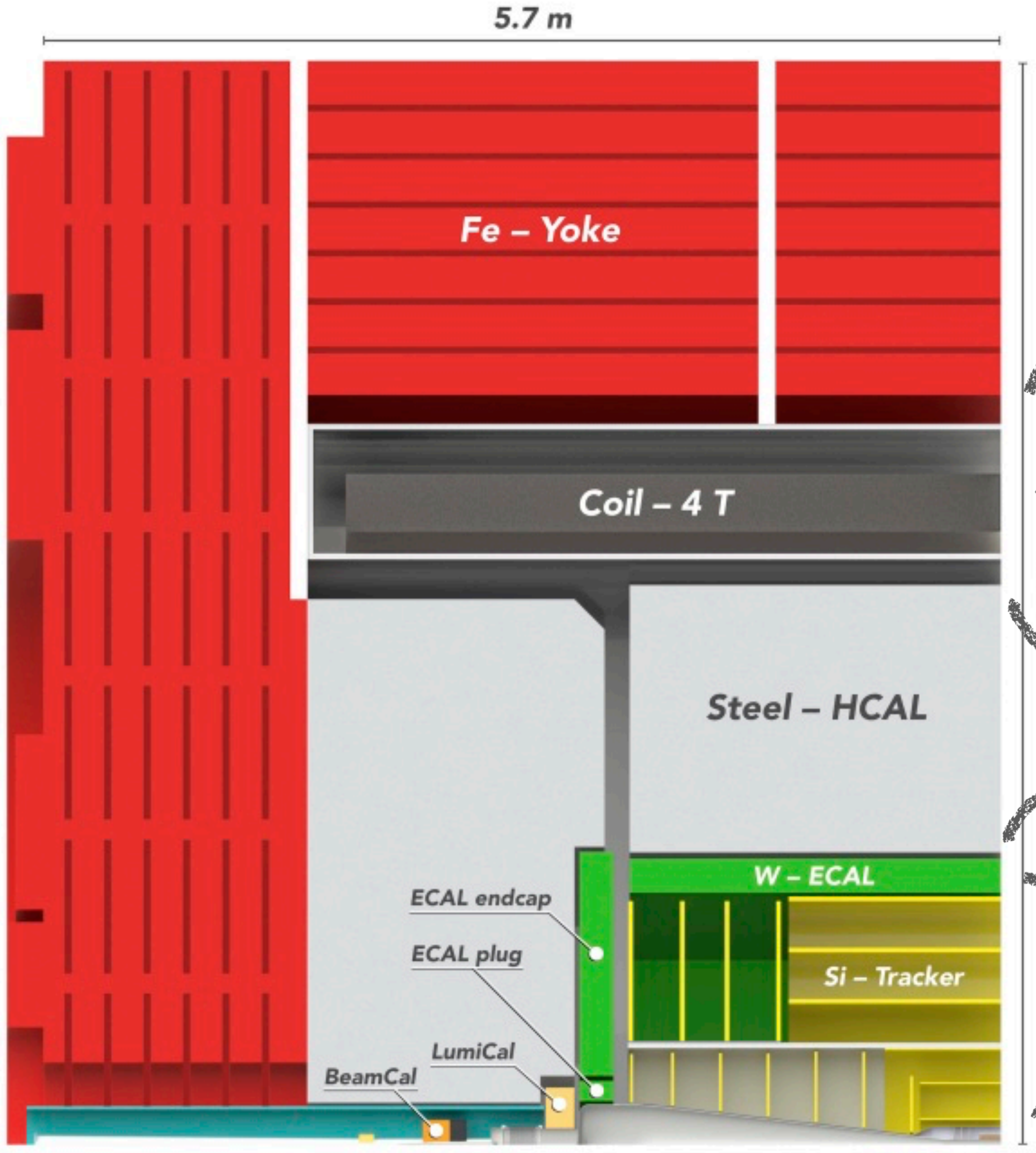

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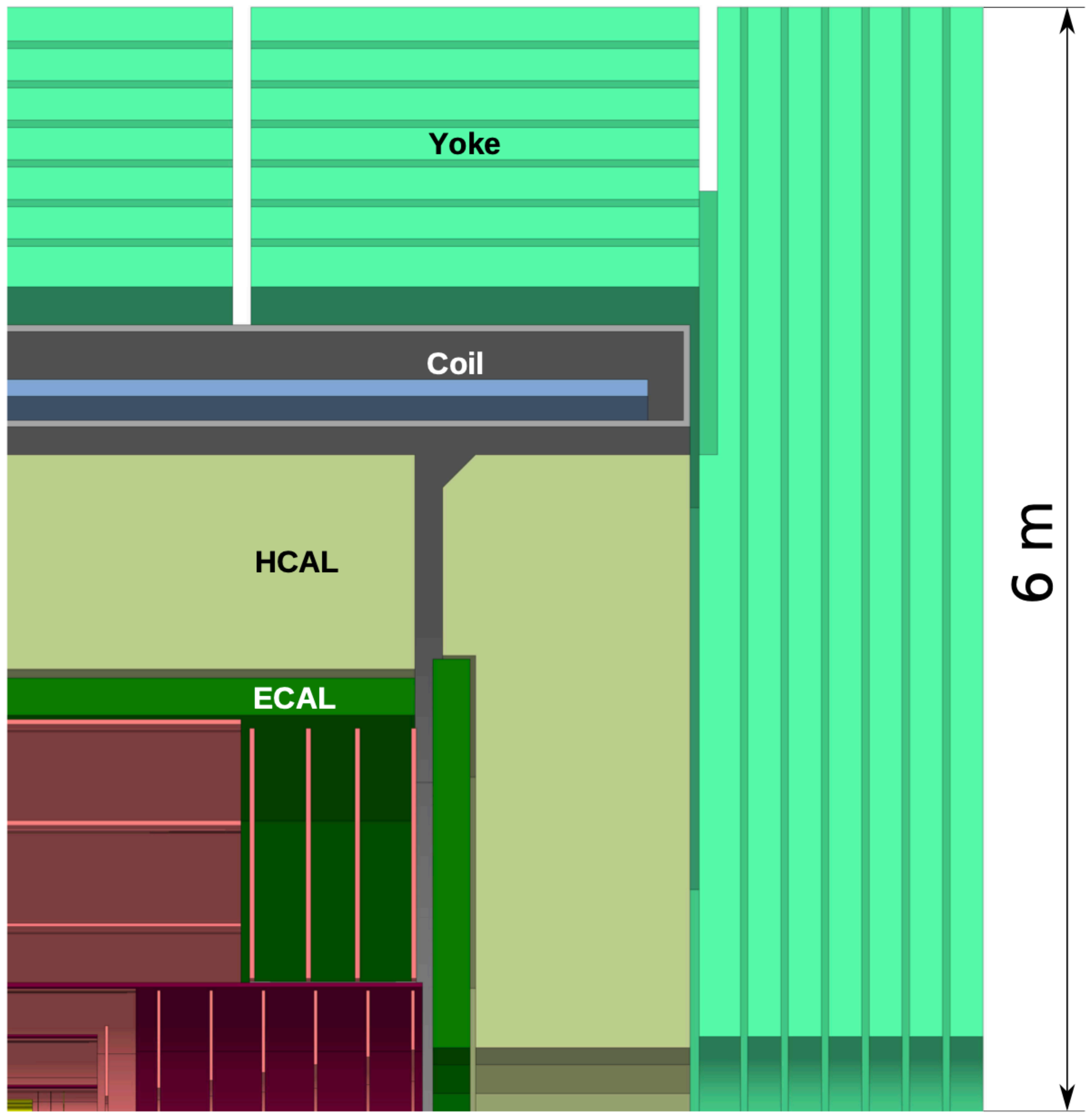
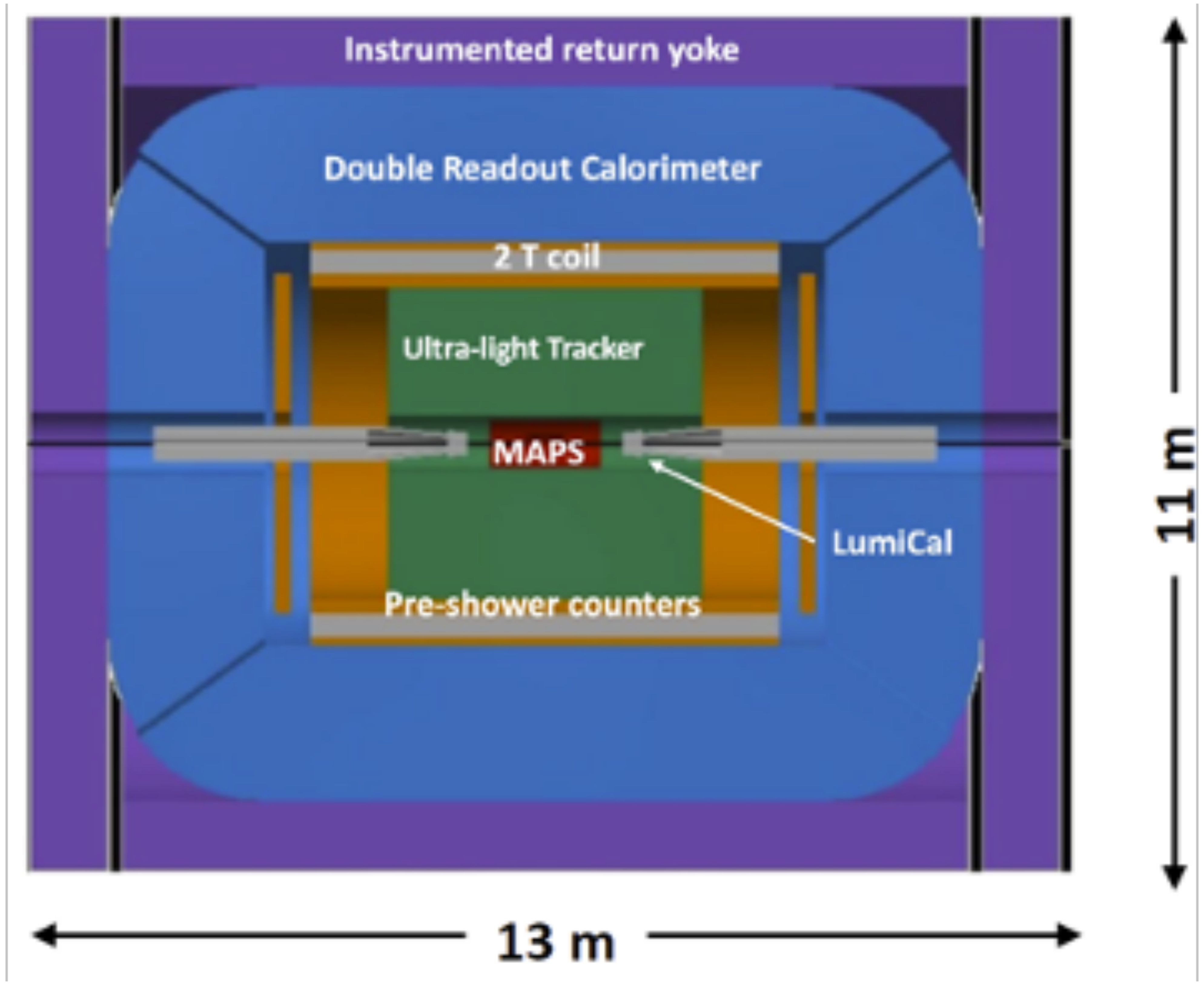


FCC-ee: Additional Concepts

Different calorimeter concepts, other track solutions

- Putting more emphasis on (low-energy) photons: Requires better resolution in the ECAL



IDEA: Based on dual readout calorimetry,
low-mass drift chamber as main tracker

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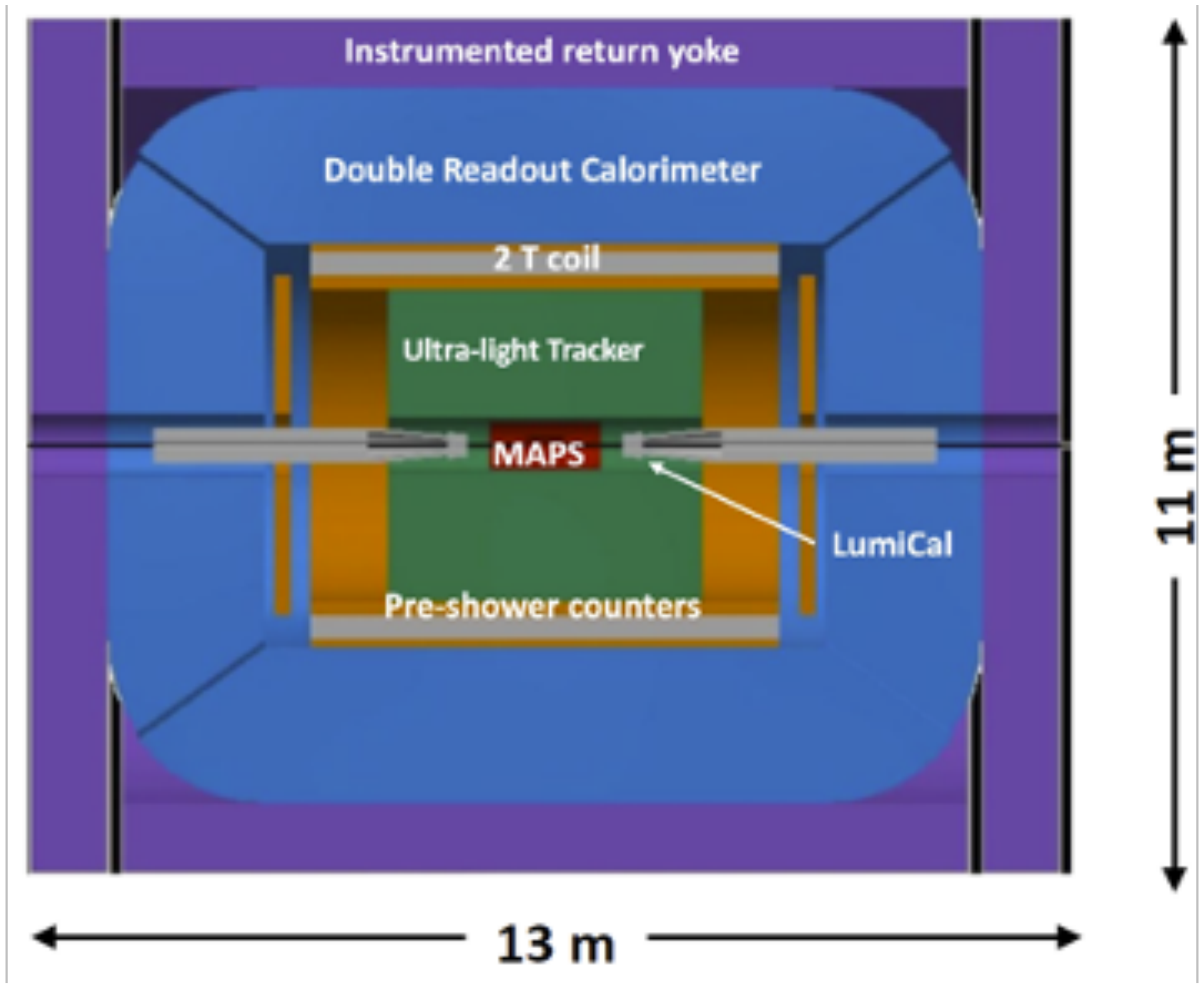

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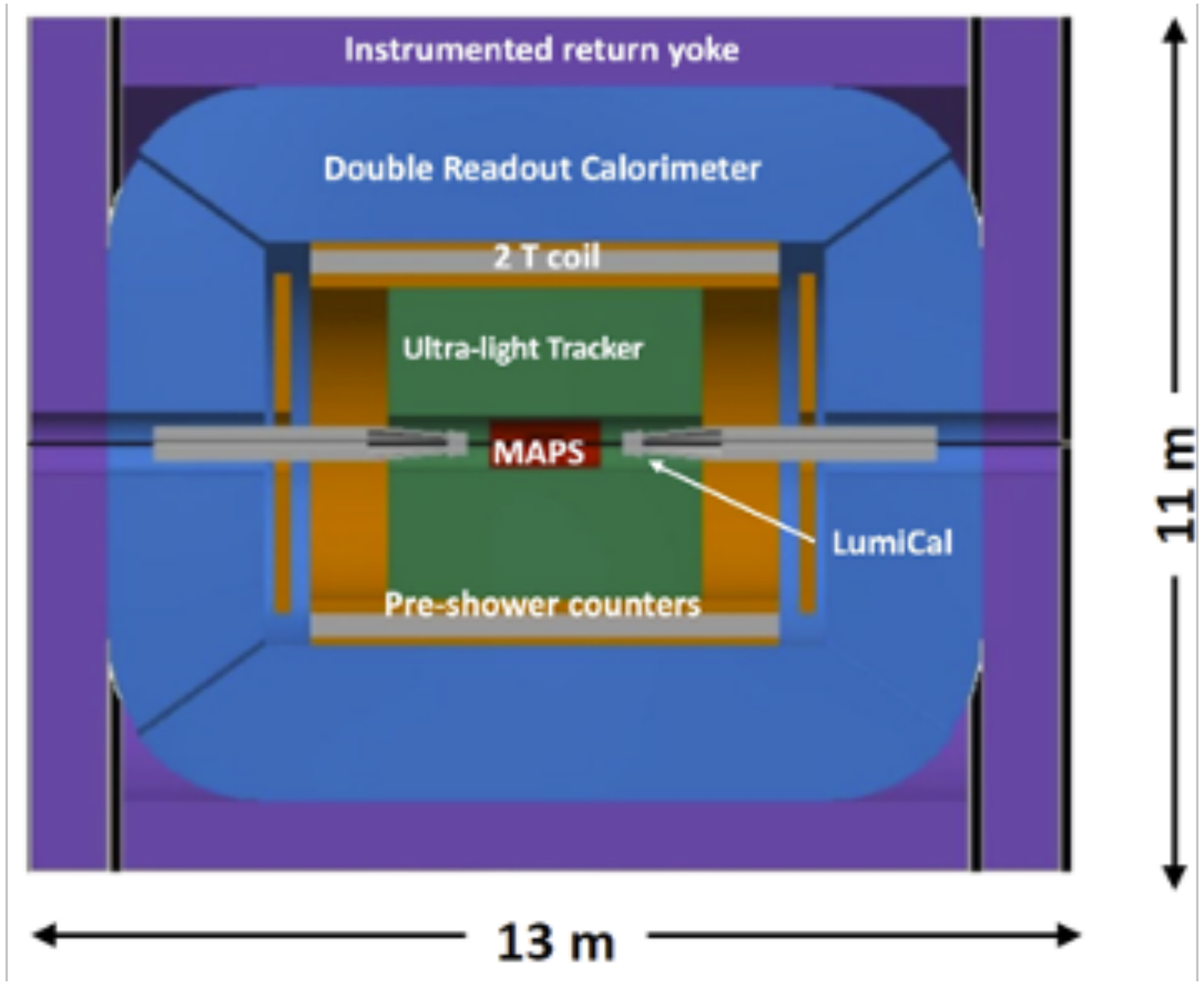

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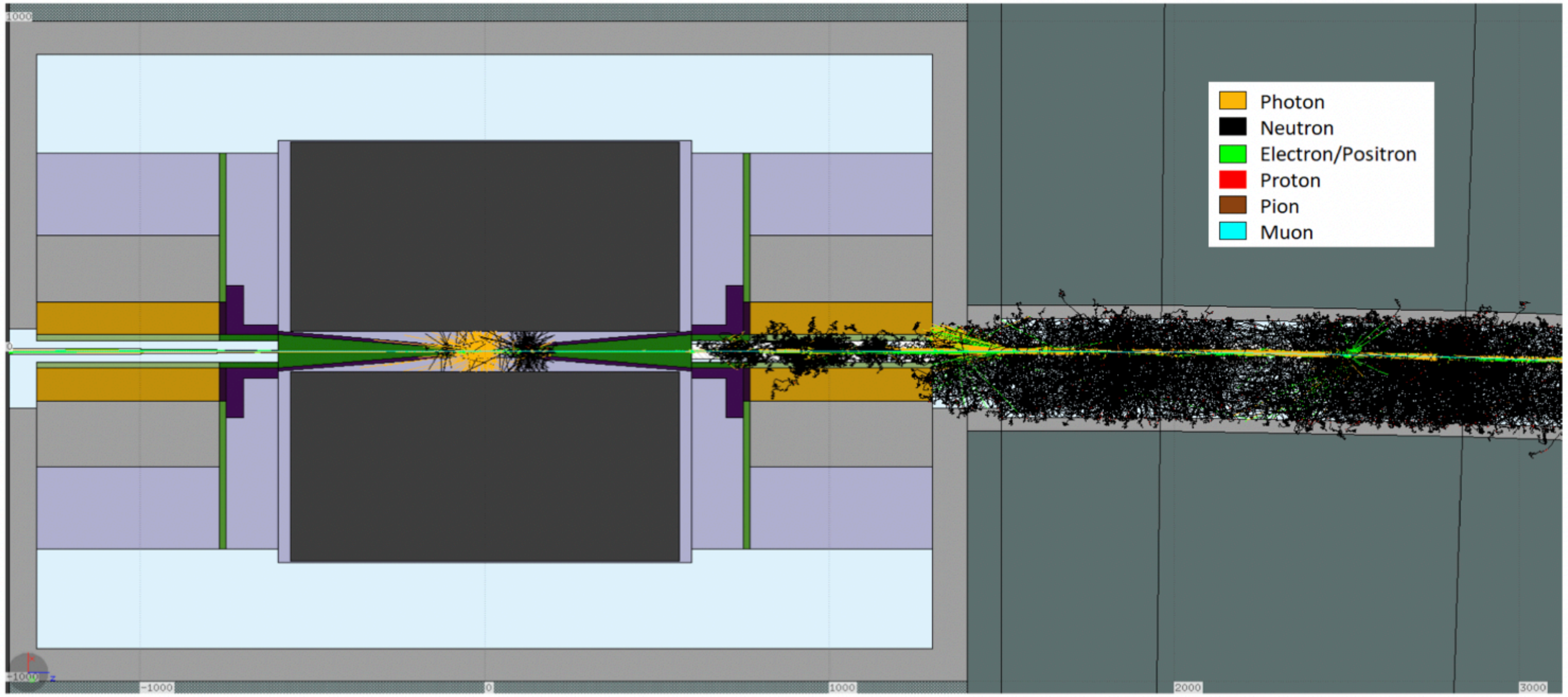
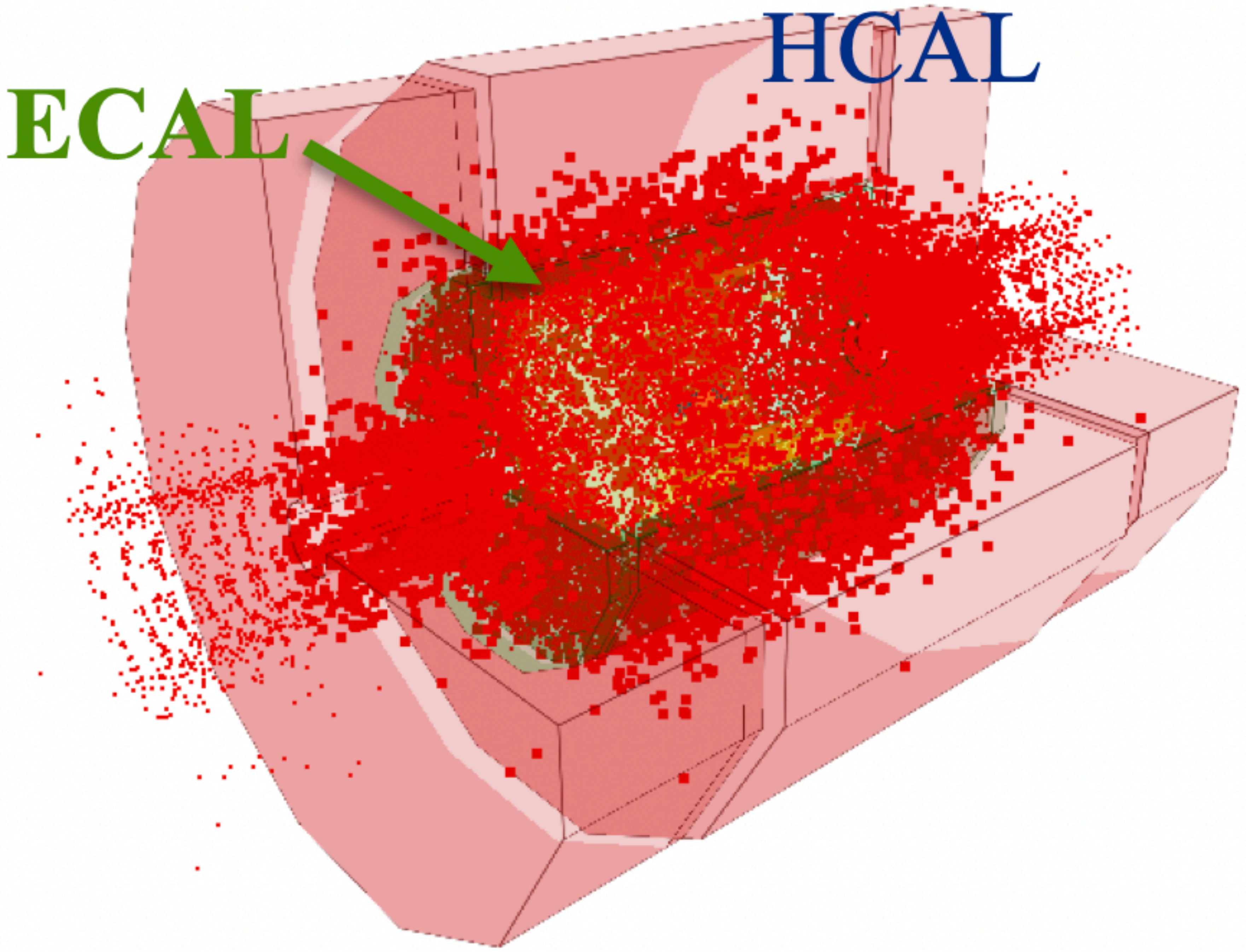
+ investigating detector concepts with added PID

- The constant decay μ -> e$\nu\nu$ creates a very large beam-induced background (BIB): High-energy showers induced by electrons, creating a wide range of different background particles.
  - Radiation levels comparable to HL-LHC.

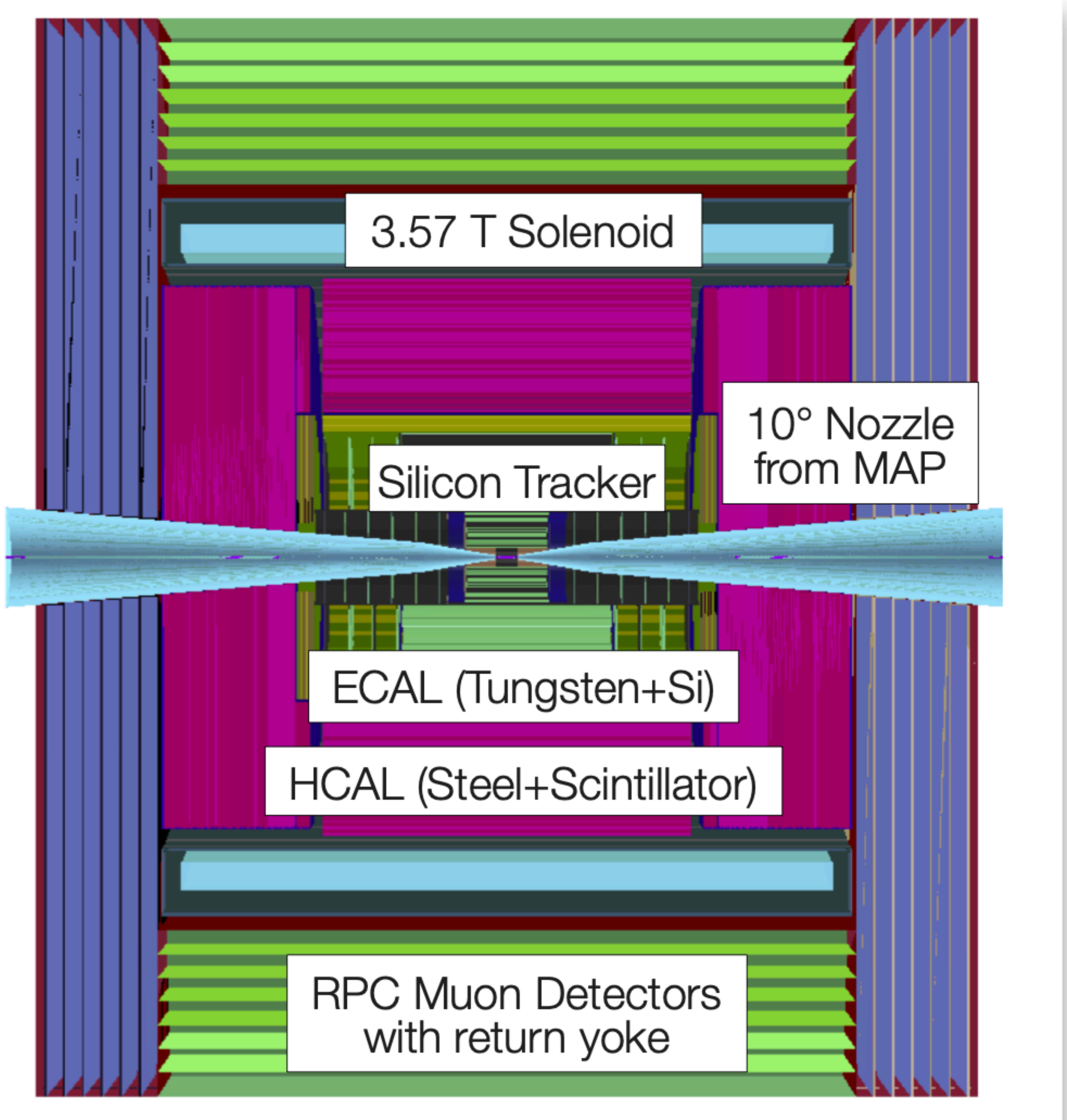
➩ The main challenge for experiments at muon colliders!





Detectors at Muon Colliders

First ideas



- 3 TeV μCol: A modified CLIC detector concept, adjusted for background conditions

  ~ 10 degree acceptance limitation in forward region due to tungsten nozzles

  precise timing throughout detector important to reject BIB

- For 10 TeV: Higher magnetic field to maintain momentum resolution, deeper calorimeters

Physics Examples

A Selection

- Higgs Boson
- Electroweak Precision & Flavour
- Top Quark
- Into the unknown

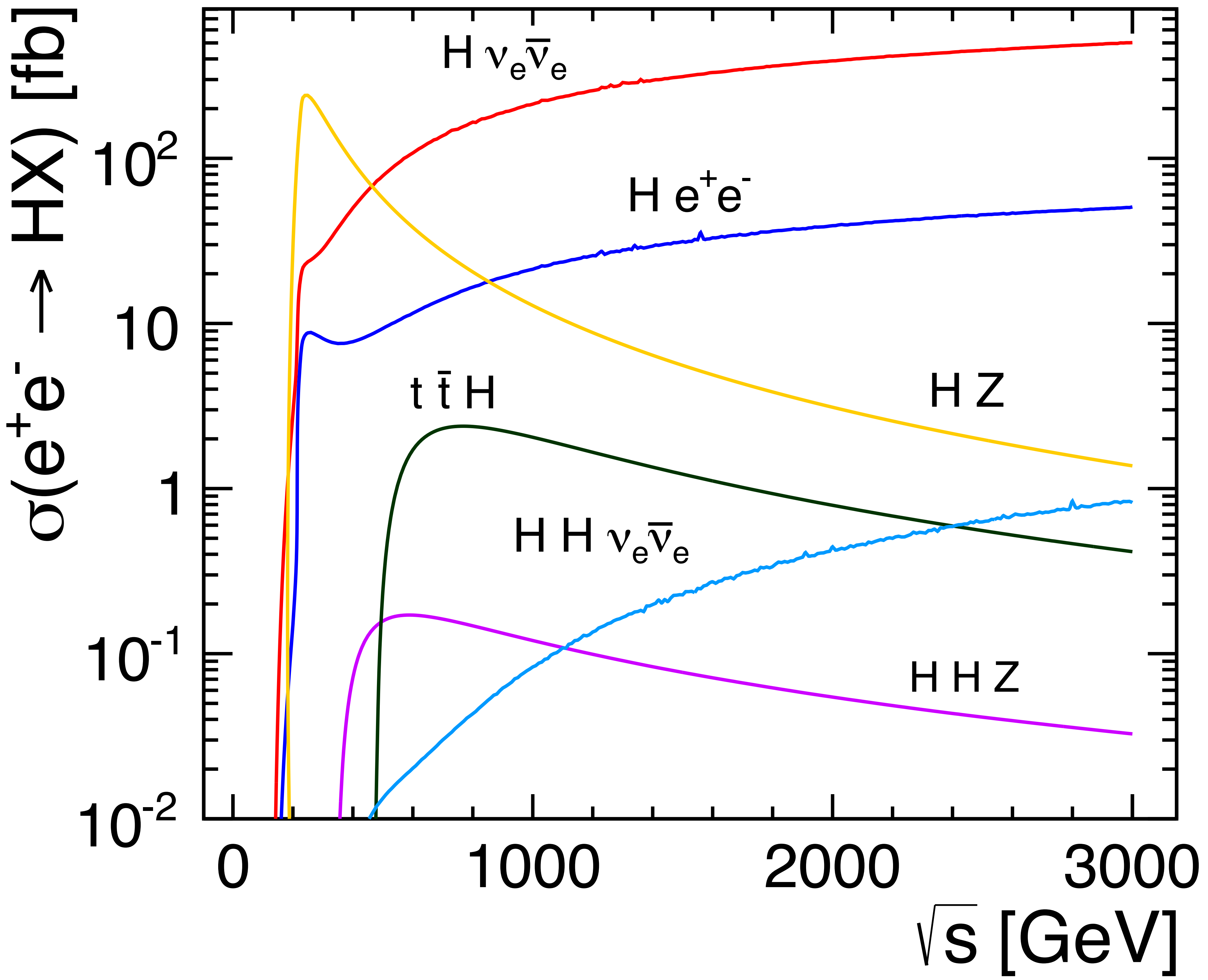
Disclaimer

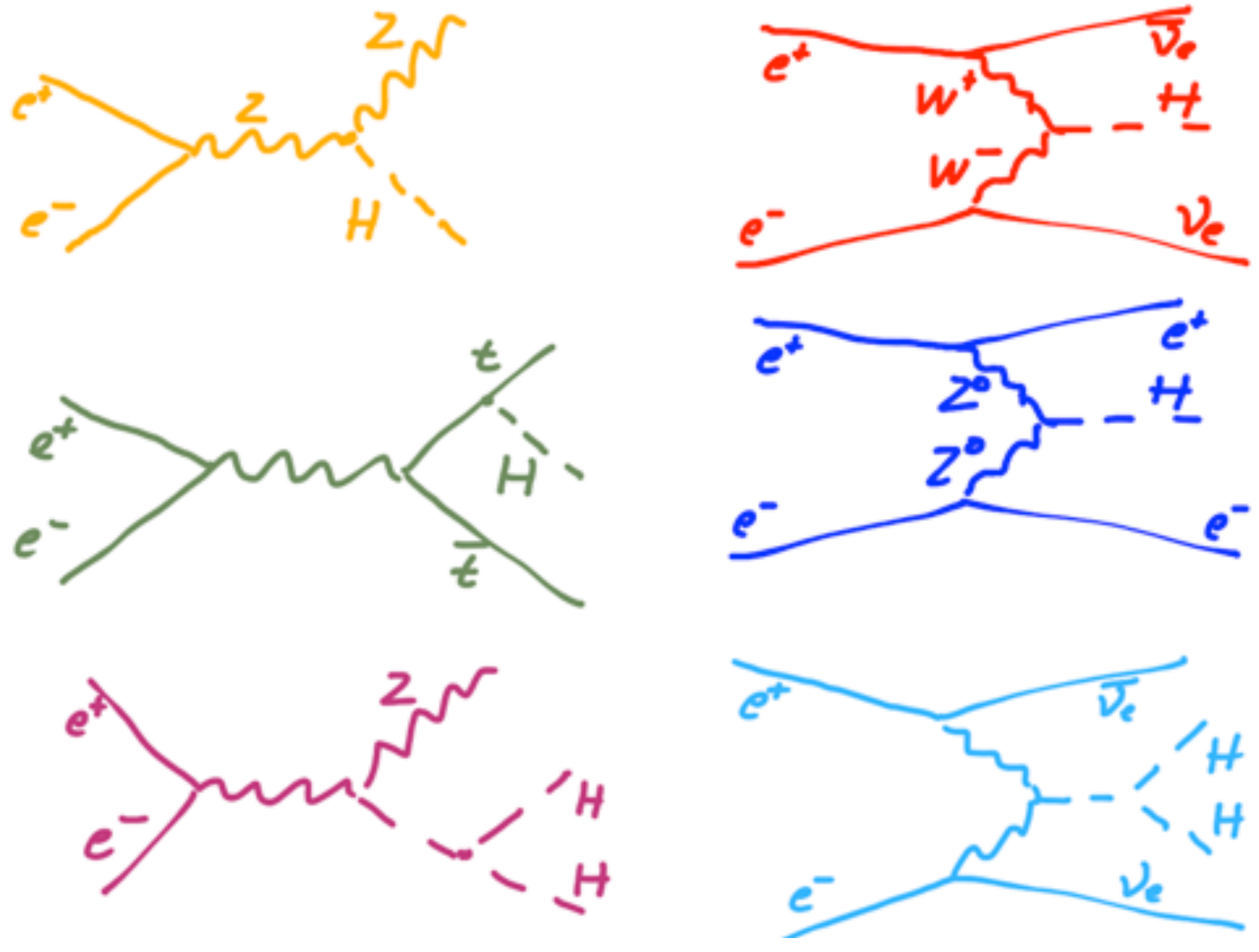
- The point of the following discussions is not to compare projects in the sense of drawing conclusions which one should be built - that is a multi-facetted question which extends beyond performance projections shown here.
- The numerical results may not always be perfectly up-to-date - again, the goal is not to compare, but to illustrate certain features of measurements and facilities

- I am focussing on e^+e^- colliders, only few remarks about $\mu^+\mu^-$

Reminder: Higgs Boson Production in e^+e^-

A rich field to explore





250 GeV:
Maximum of ZH production

350 GeV:
WW fusion kicks in
(and top pair production)

500 - 1000+ GeV:
ttH: direct access to top Yukawa coupling

500 GeV; 1+ TeV:
Higgs self-coupling

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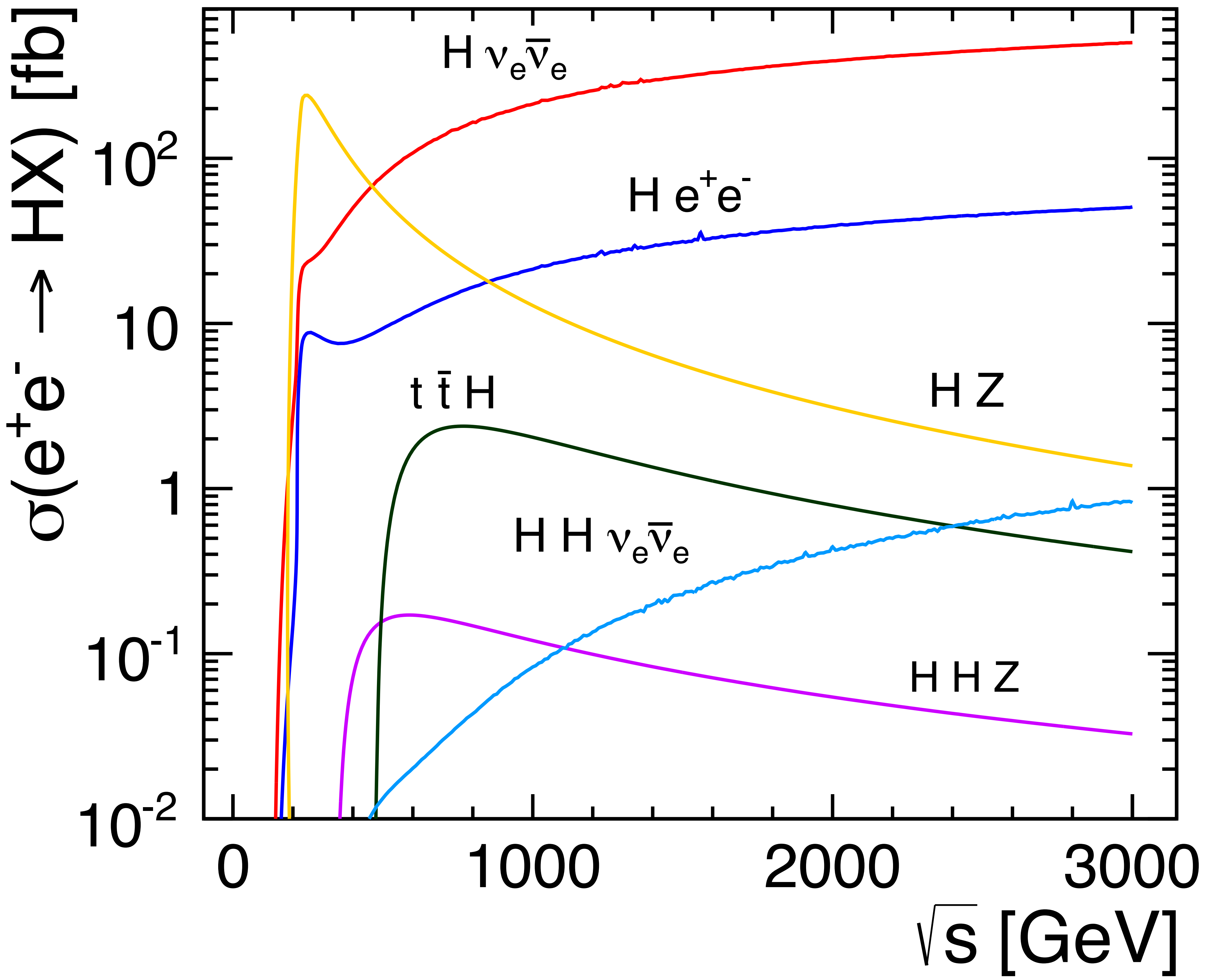

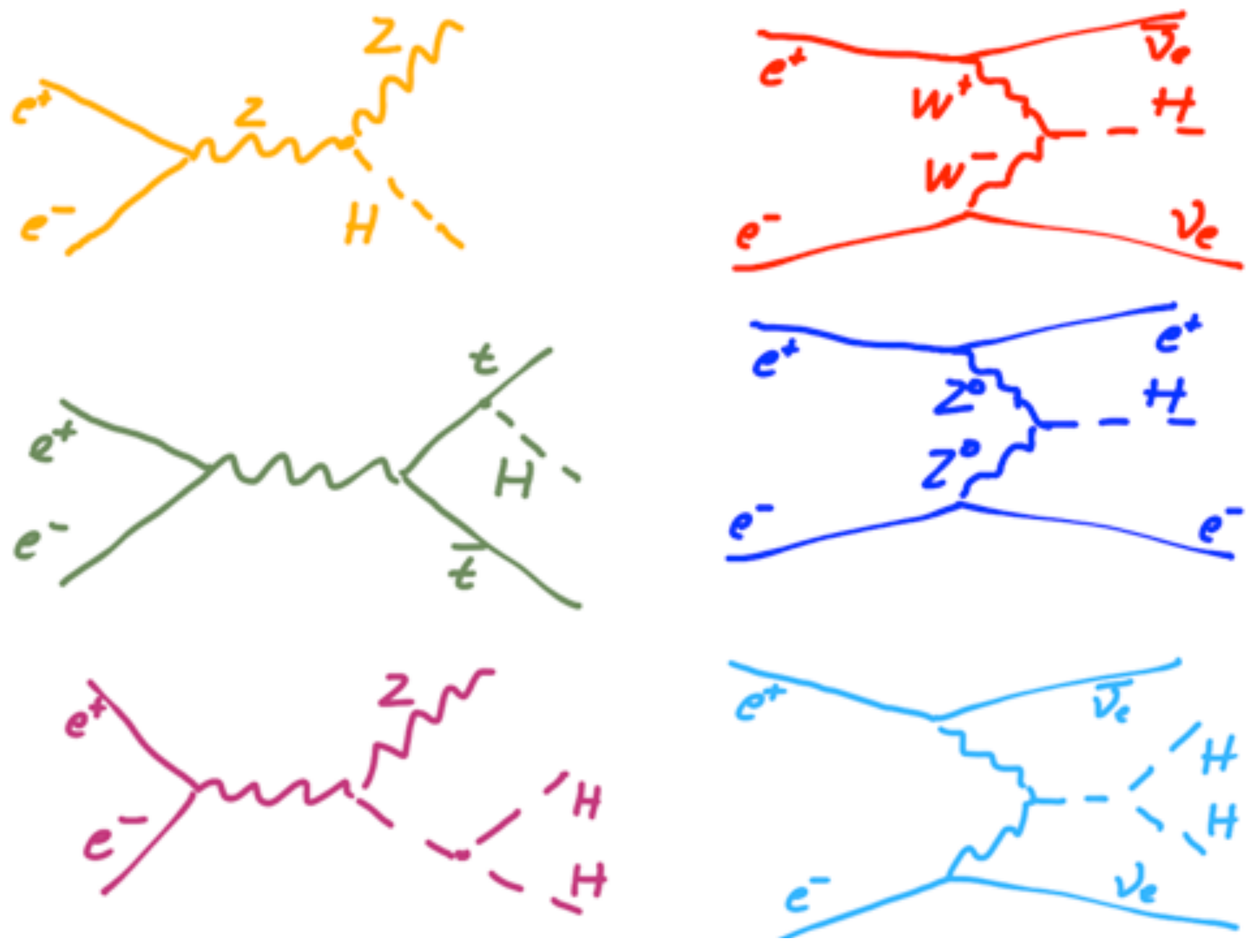

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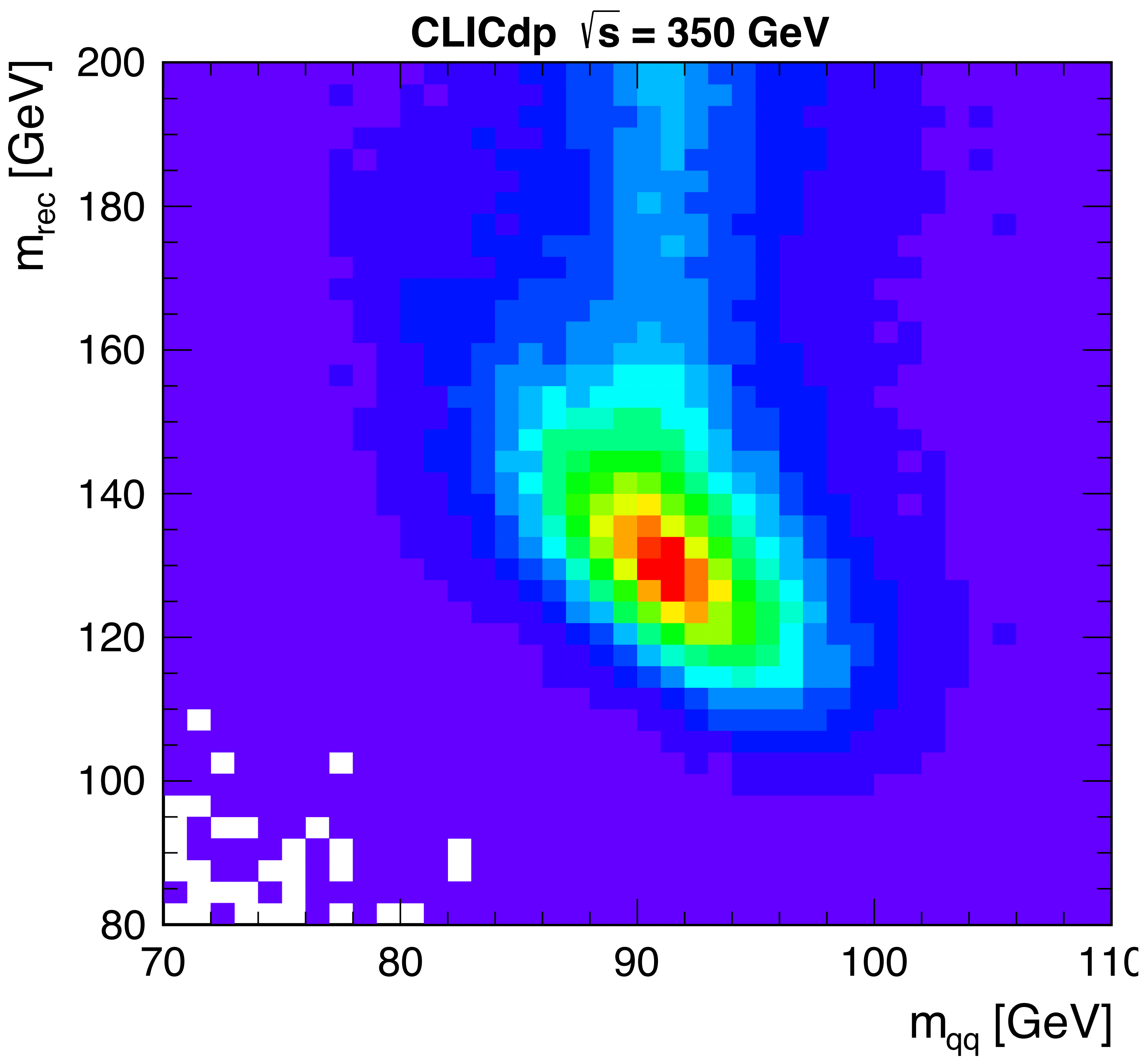
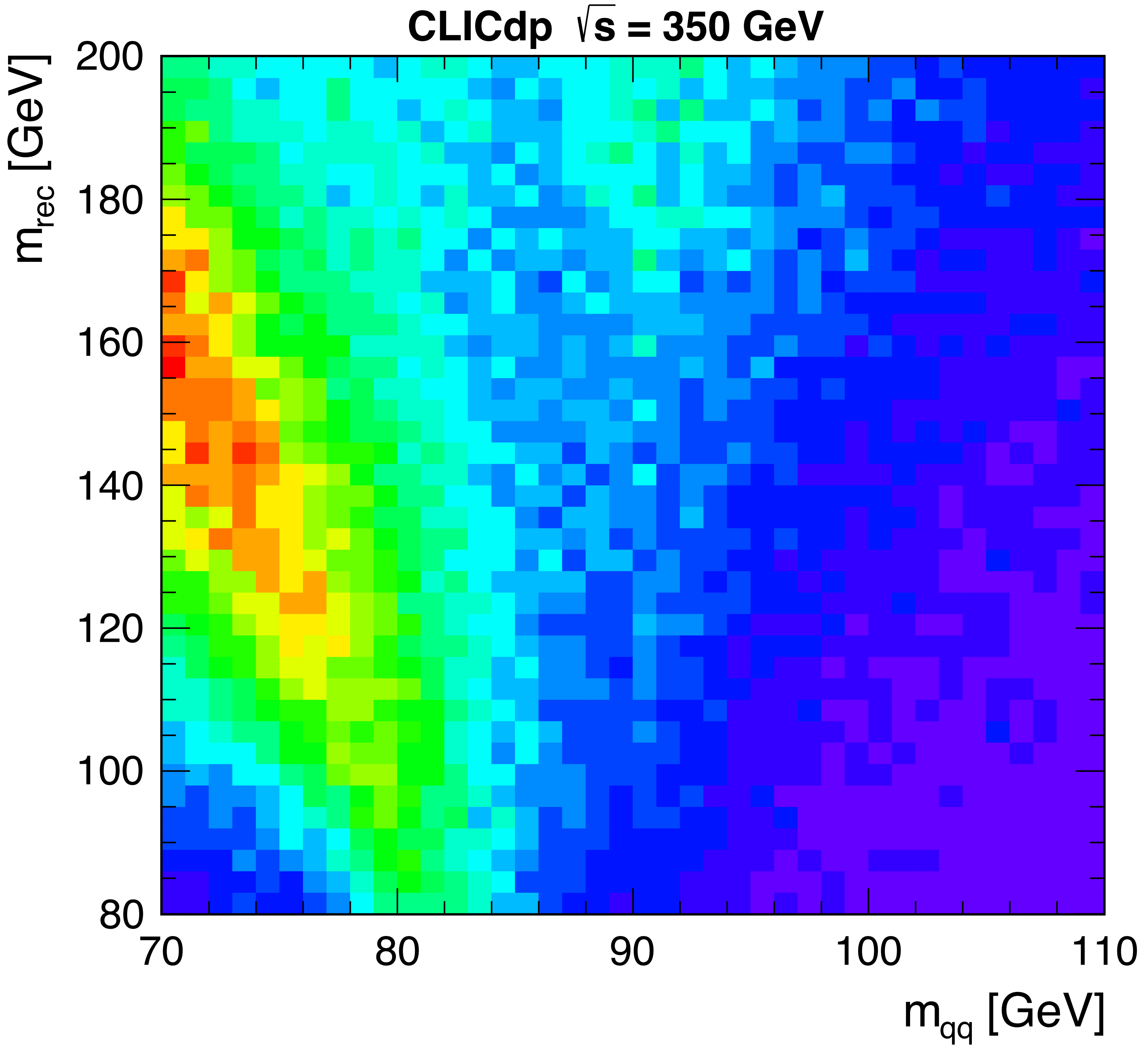
- 240 - 250 GeV: the minimum energy for a Higgs factory
- ~ 350 GeV: Additional production mode, also still access to ZH
- Higher energies: More processes
- 125 GeV, and extreme luminosity: A possibility to measure electron Yukawa coupling

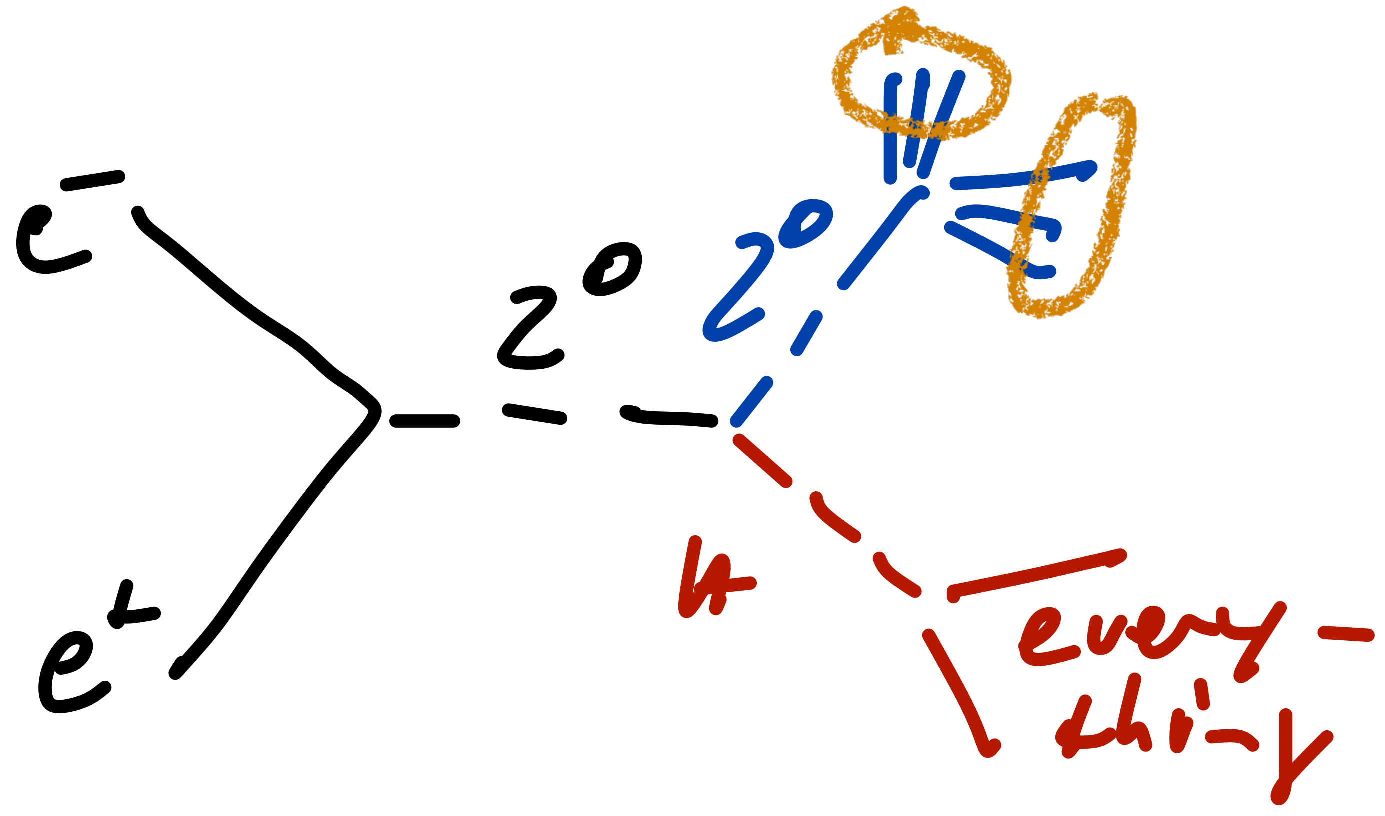
Hadronic Recoils & Invisible Decays

Fully exploiting Higgsstrahlung



- Significantly extending the HZ sample: Using hadronic Higgs decays - adds x4 in statistical sensitivity
  - requires careful analysis setup to ensure model independence





example from CLIC

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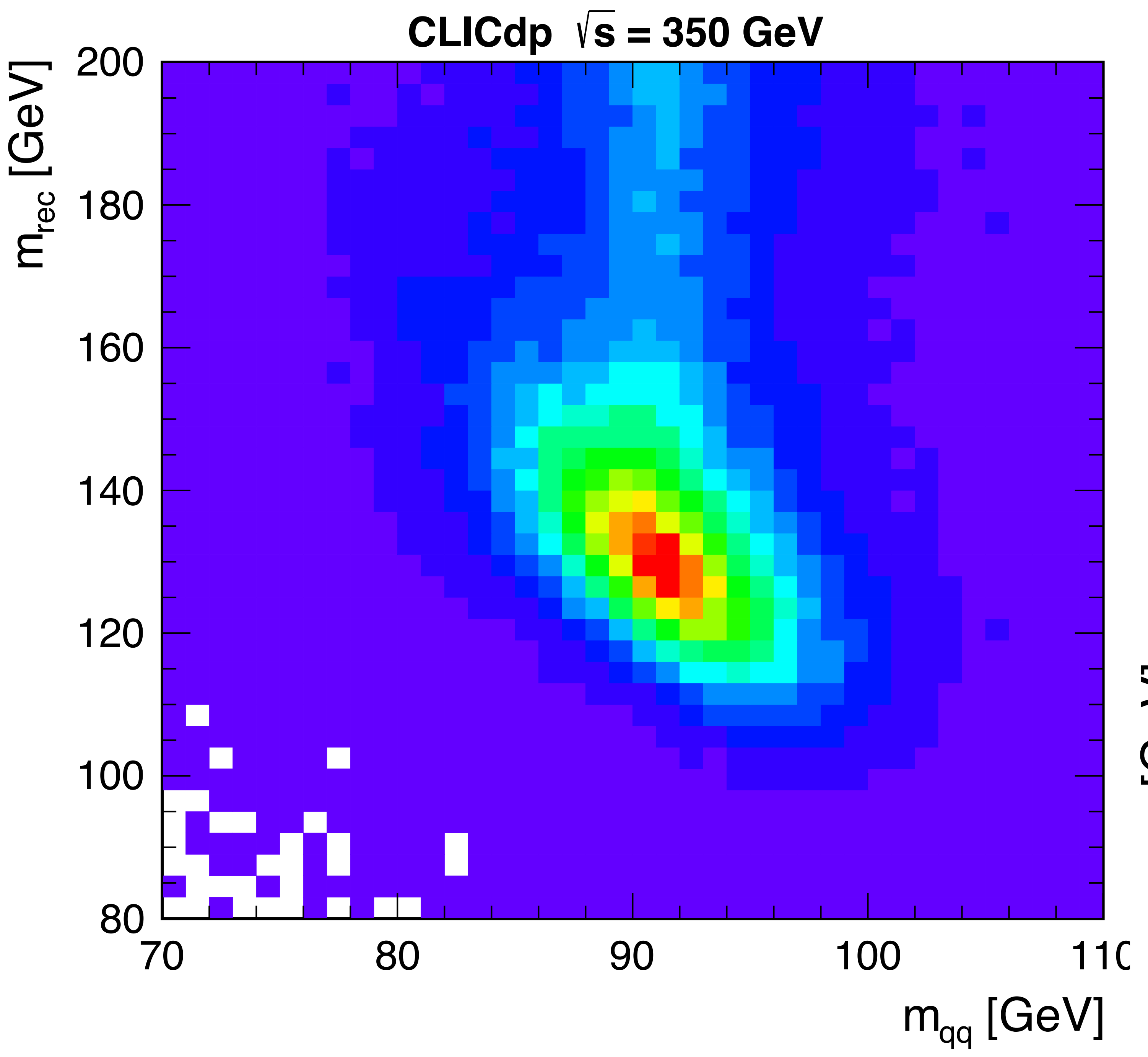

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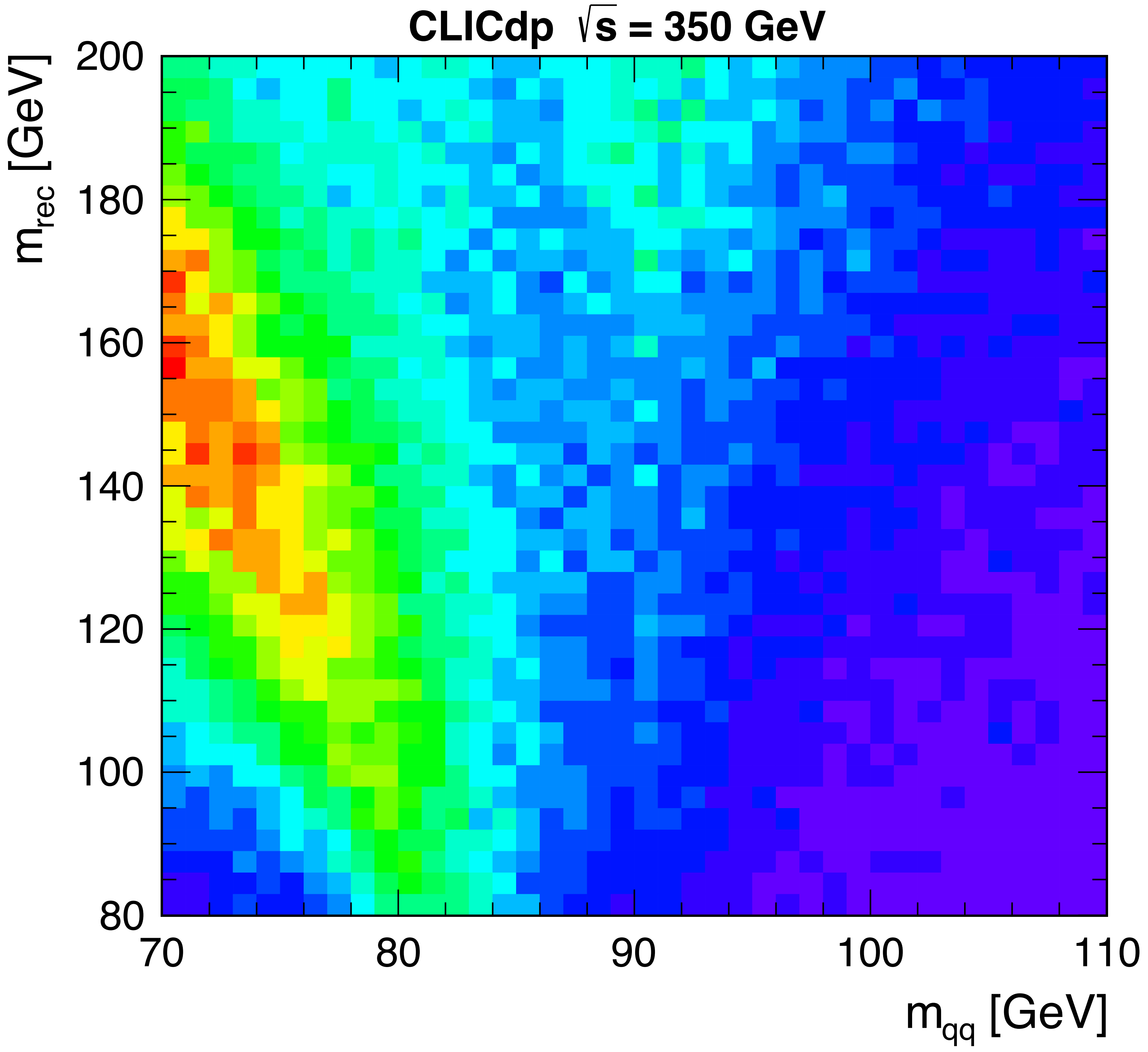
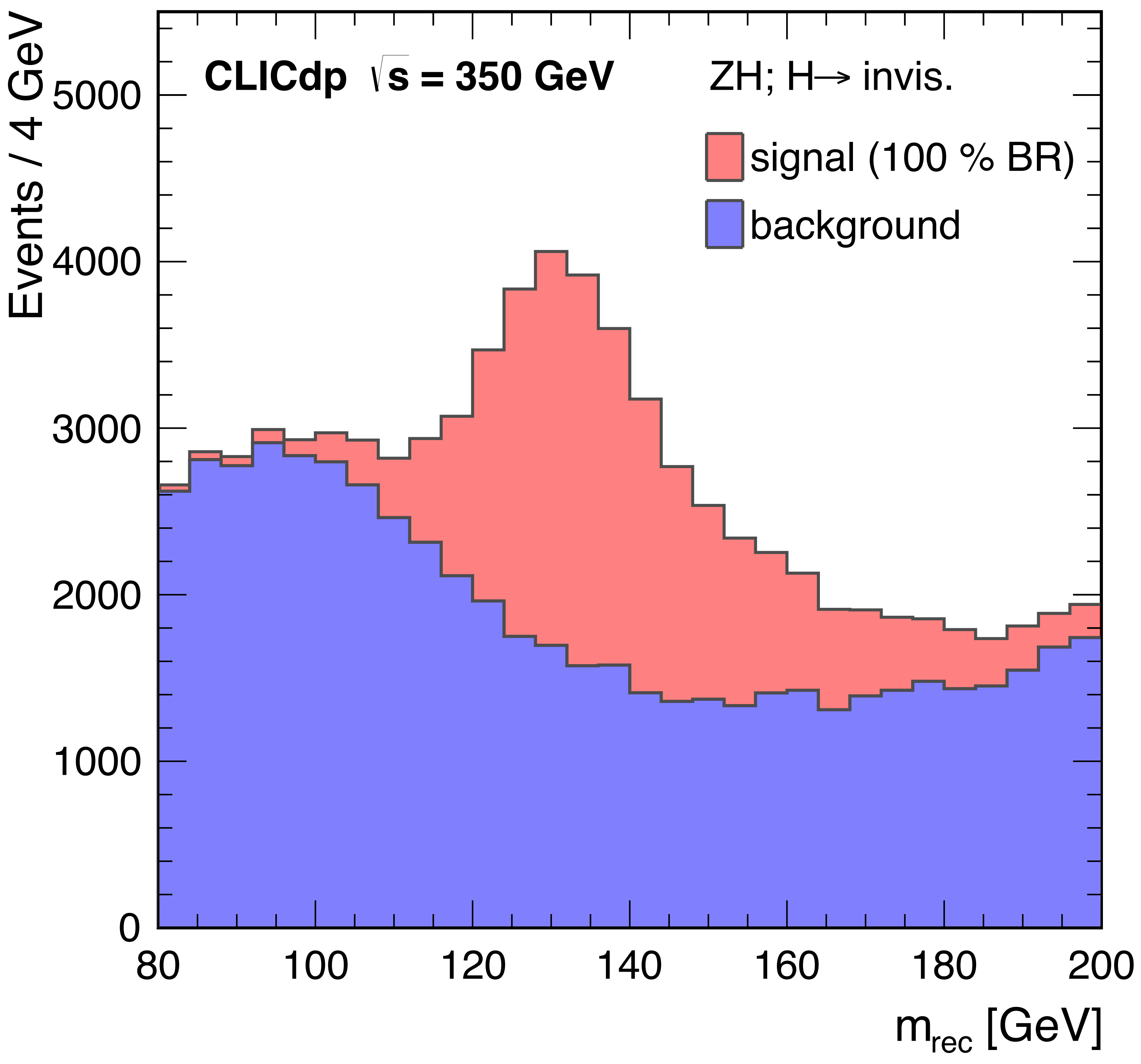
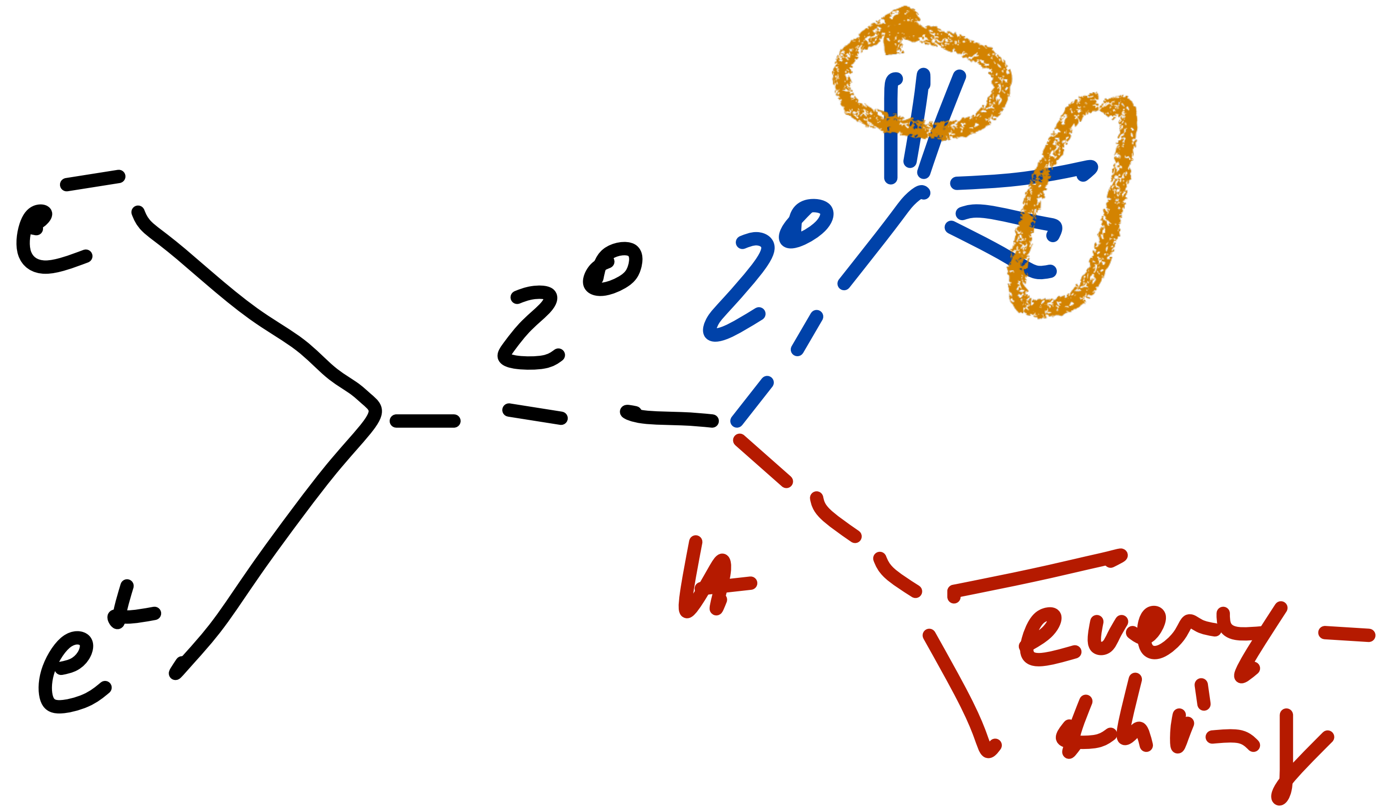






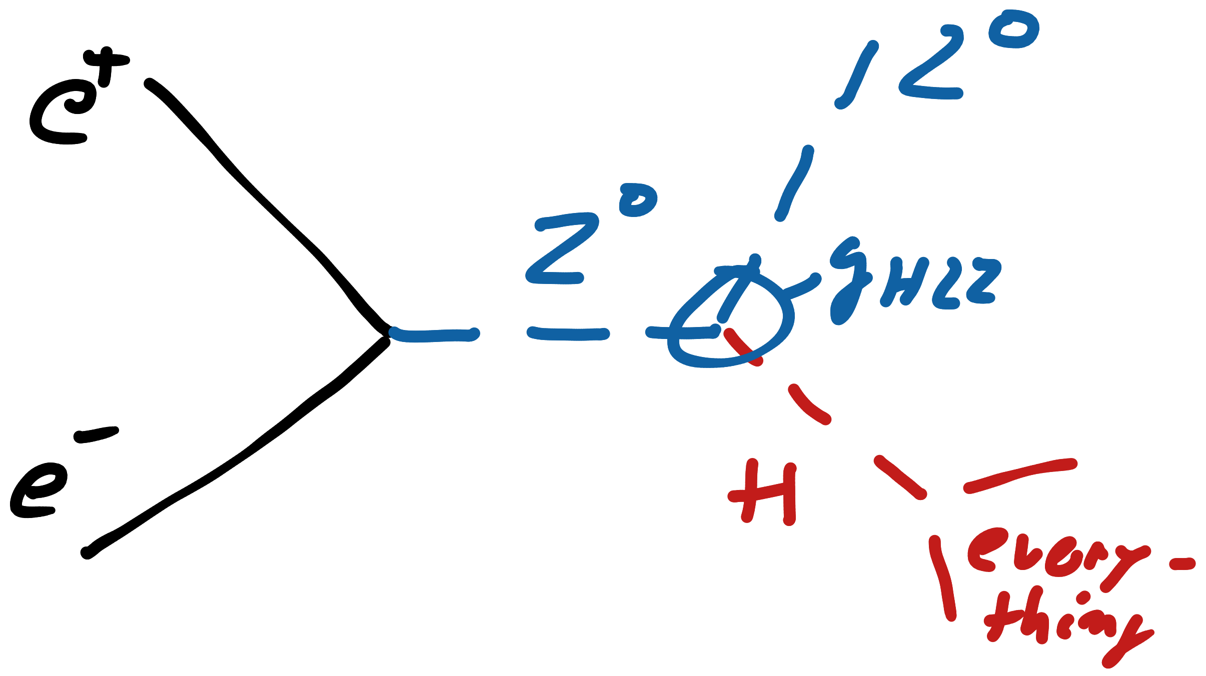
- HZ events can be used to constrain invisible Higgs decays: Limits on the few per mille level

example from CLIC

- The main measurements to make:

  σ for Z recoil measurements

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



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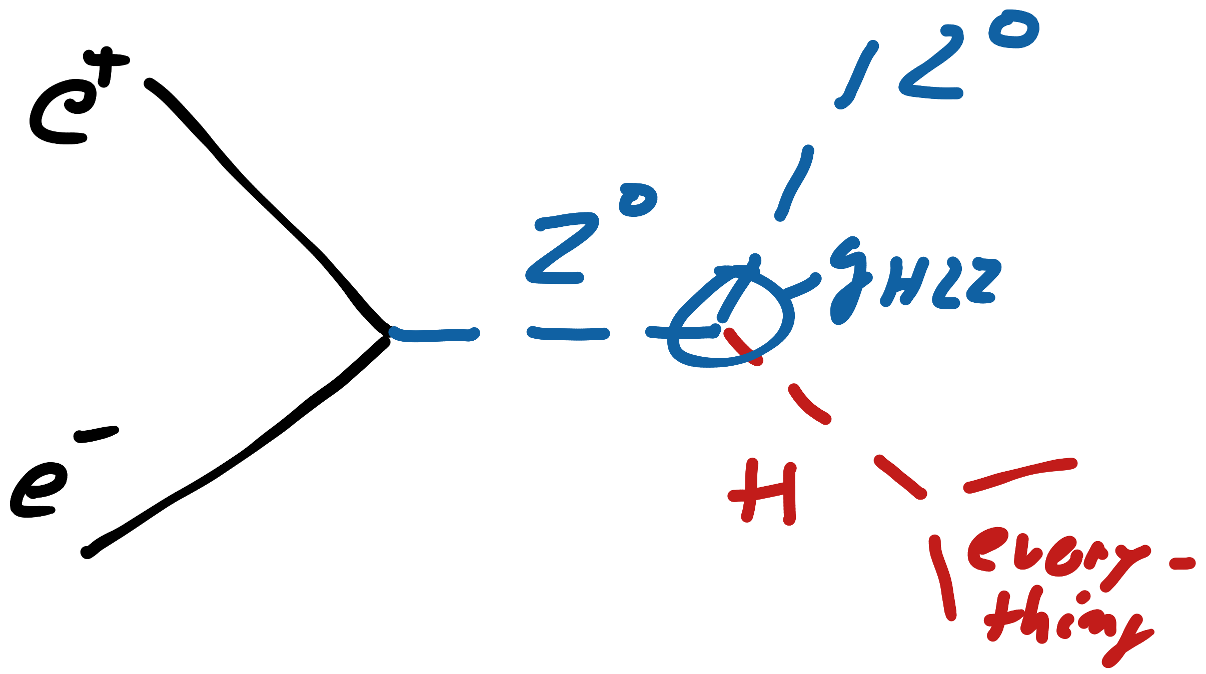

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σ x BR for specific Higgs decays - here the mass of 125 GeV is giving us many possibilites

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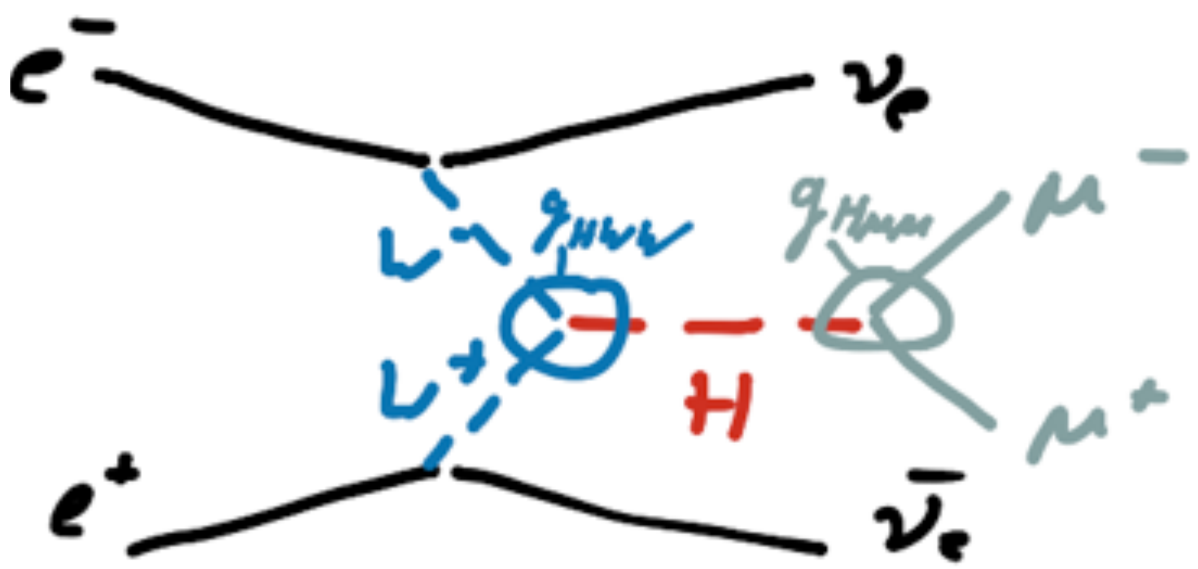

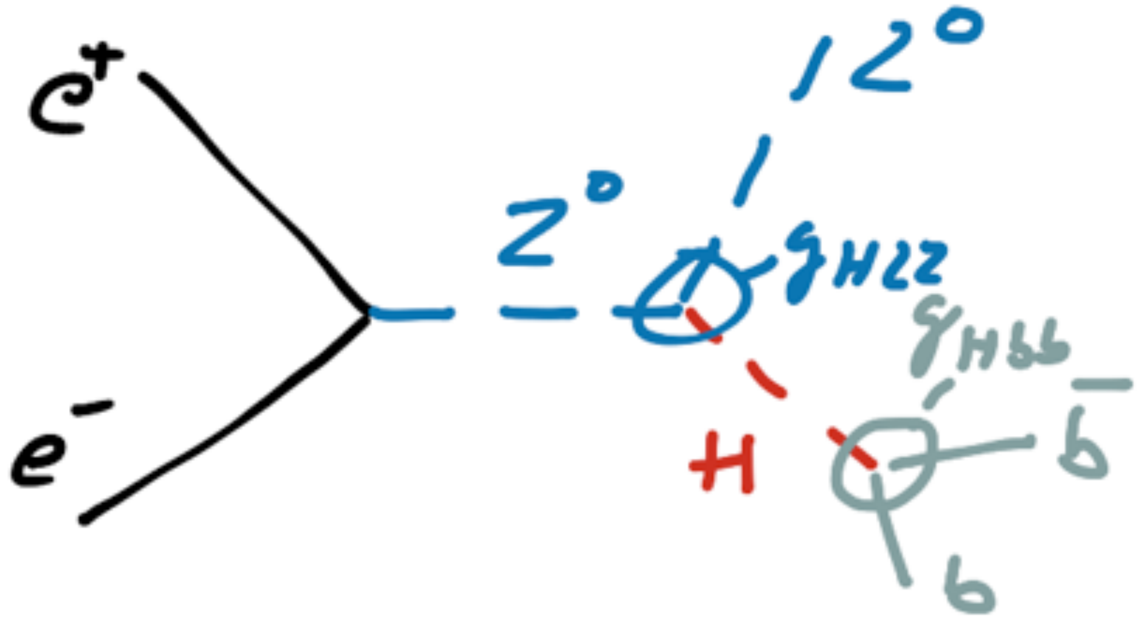

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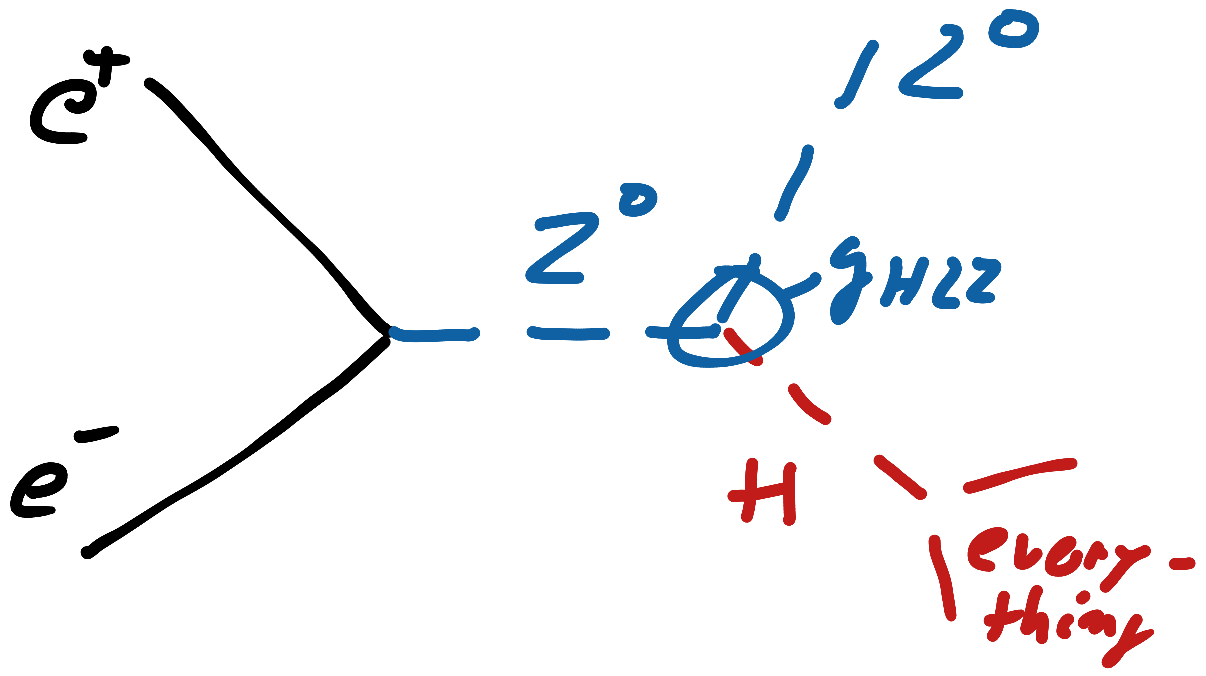

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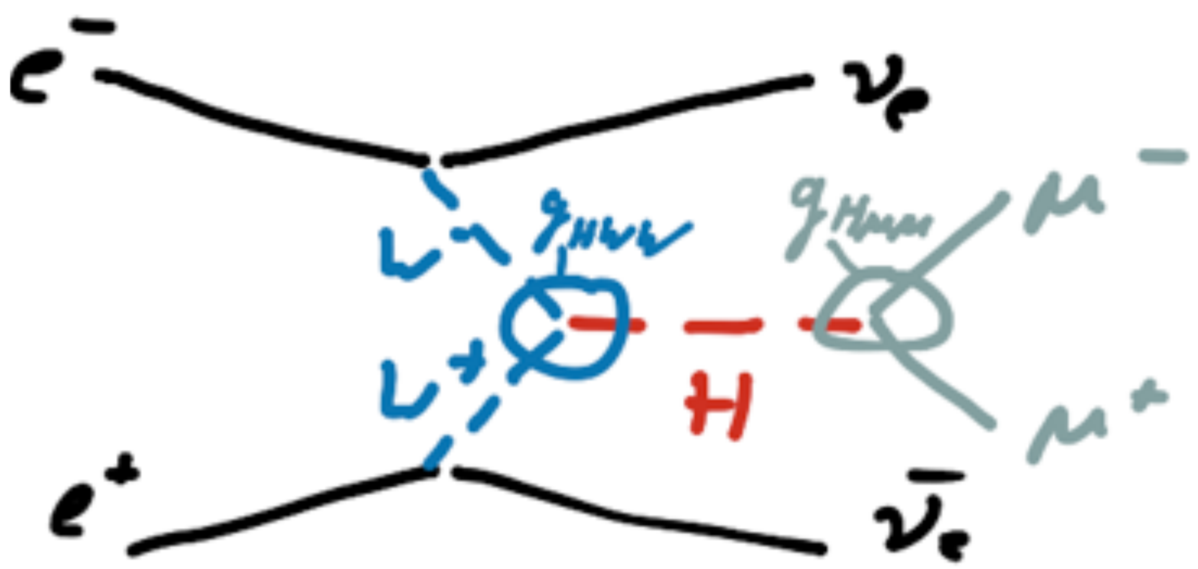

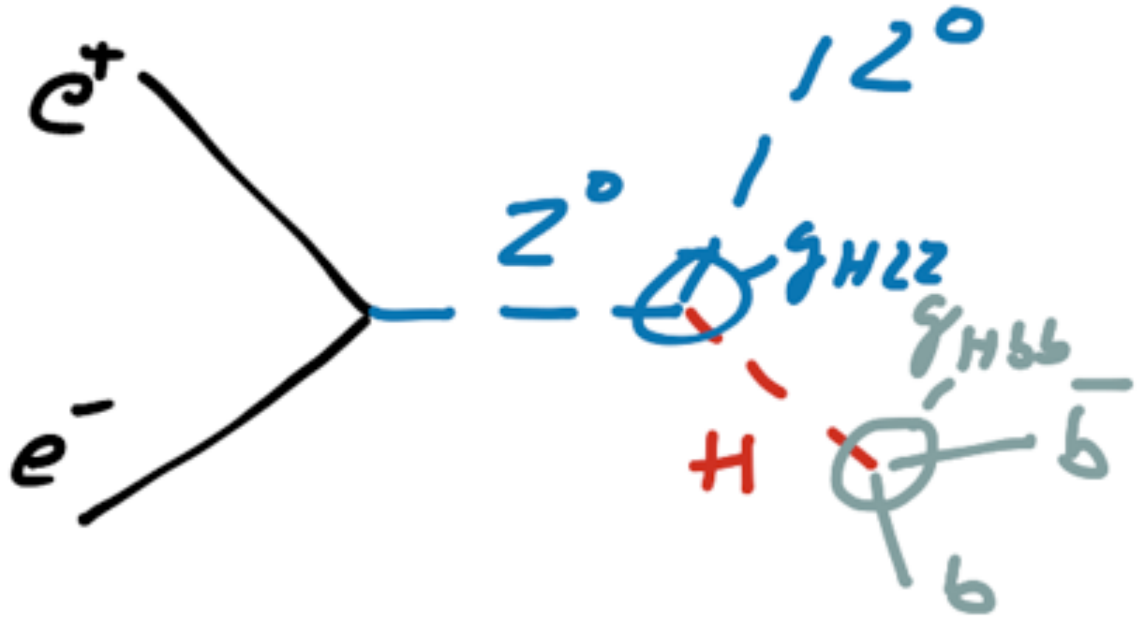

measure couplings to fermions and bosons using production and decay

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

Frank Simon (frank.simon@kit.edu)

Institute for Data Processing and Electronics

Extracting the Total Width

Model independent measurement at high precision

Asked yesterday

- e^+e^- colliders provide the possibility for a model-independent measurement of the total width at the level of a few %:

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➩ Profits substantially from higher energy, where WW fusion becomes relevant:

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Karlsruhe Institute of Technology

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need the “model-independent anchor” of the ZH measurement

➯ Higher energies important for width measurements

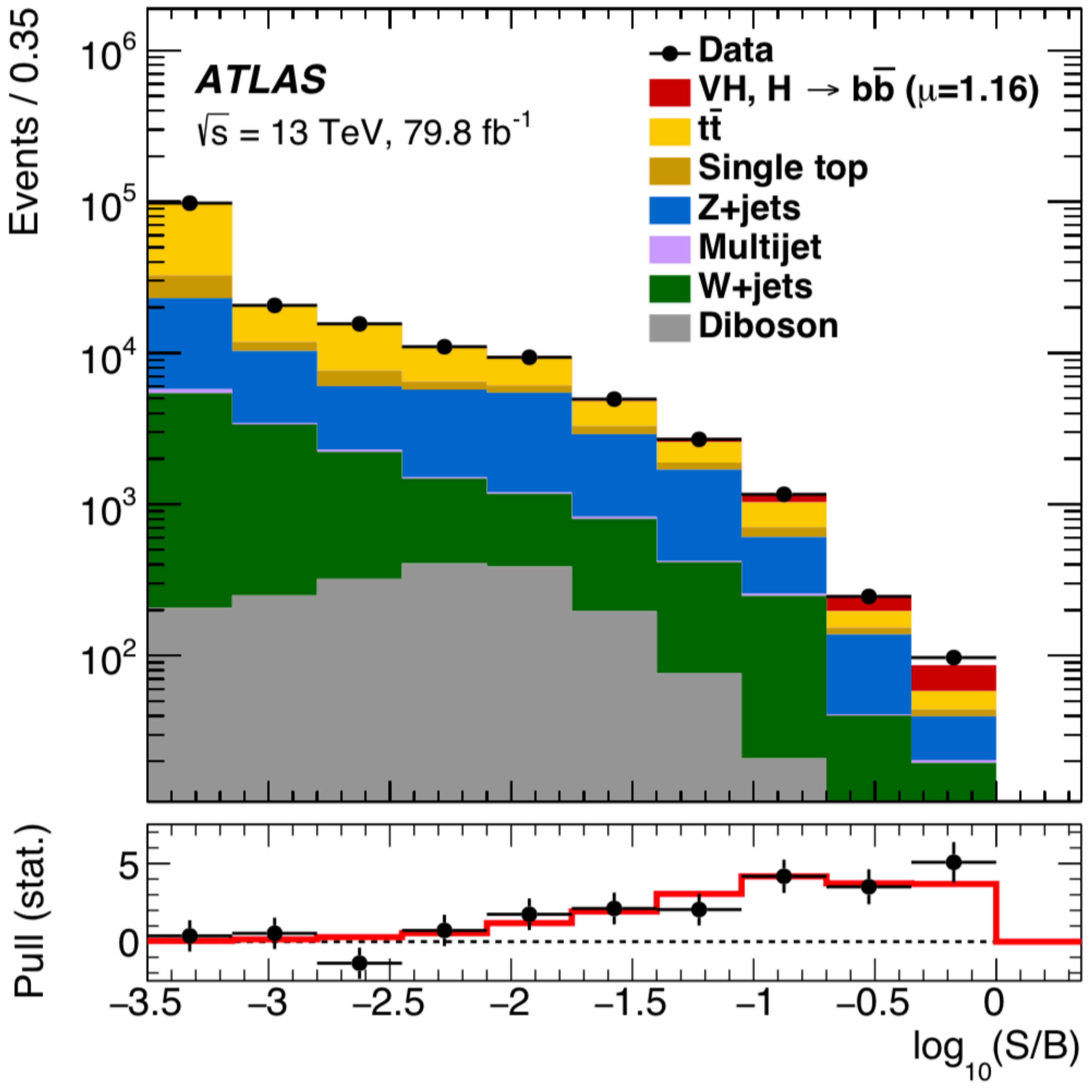
➯ In EFT fits W and Z are connected, there the width can be well constrained also without WW fusion

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



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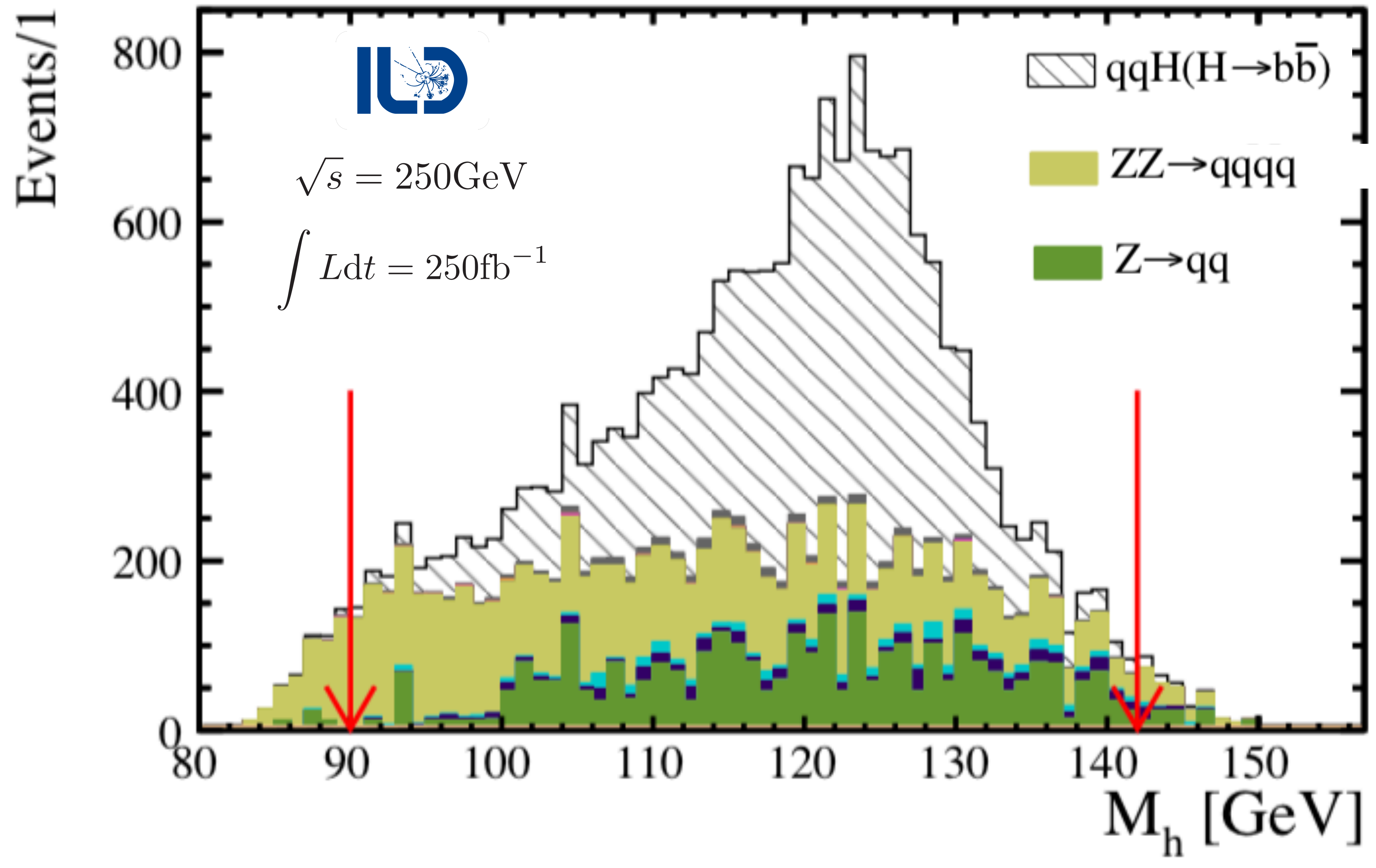

with 1.3 fb^{-1} data ~ 2 days running

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

\# of Higgs produced: ~4,000,000 ~400

significance: 5.4σ 5.2σ

J. Tiang, LCWS 2018

Unique Measurements at Lepton Colliders

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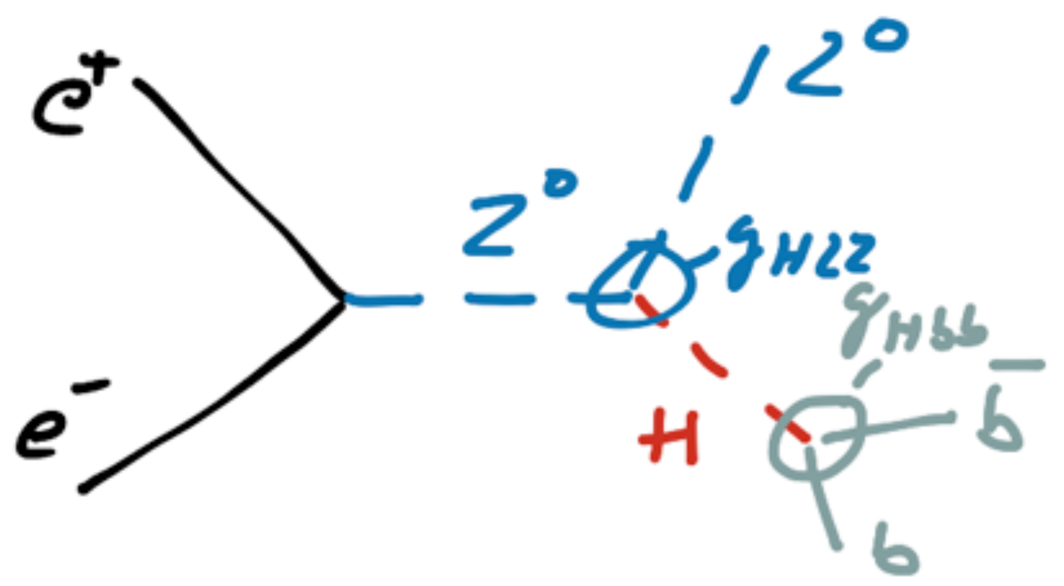
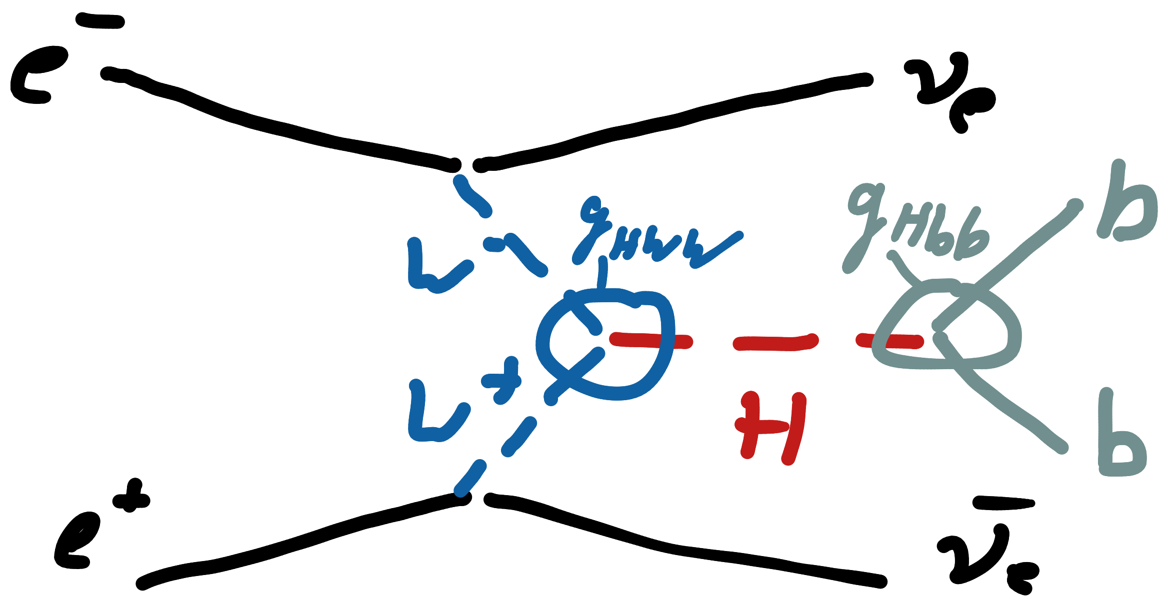
- Higgs decays to jets: difficult (or impossible) at hadron colliders

  Measurement of H->bb, cc, gg

  - Profits from excellent flavor tagging enabled by low-mass high-resolution vertex trackers in moderate background environment





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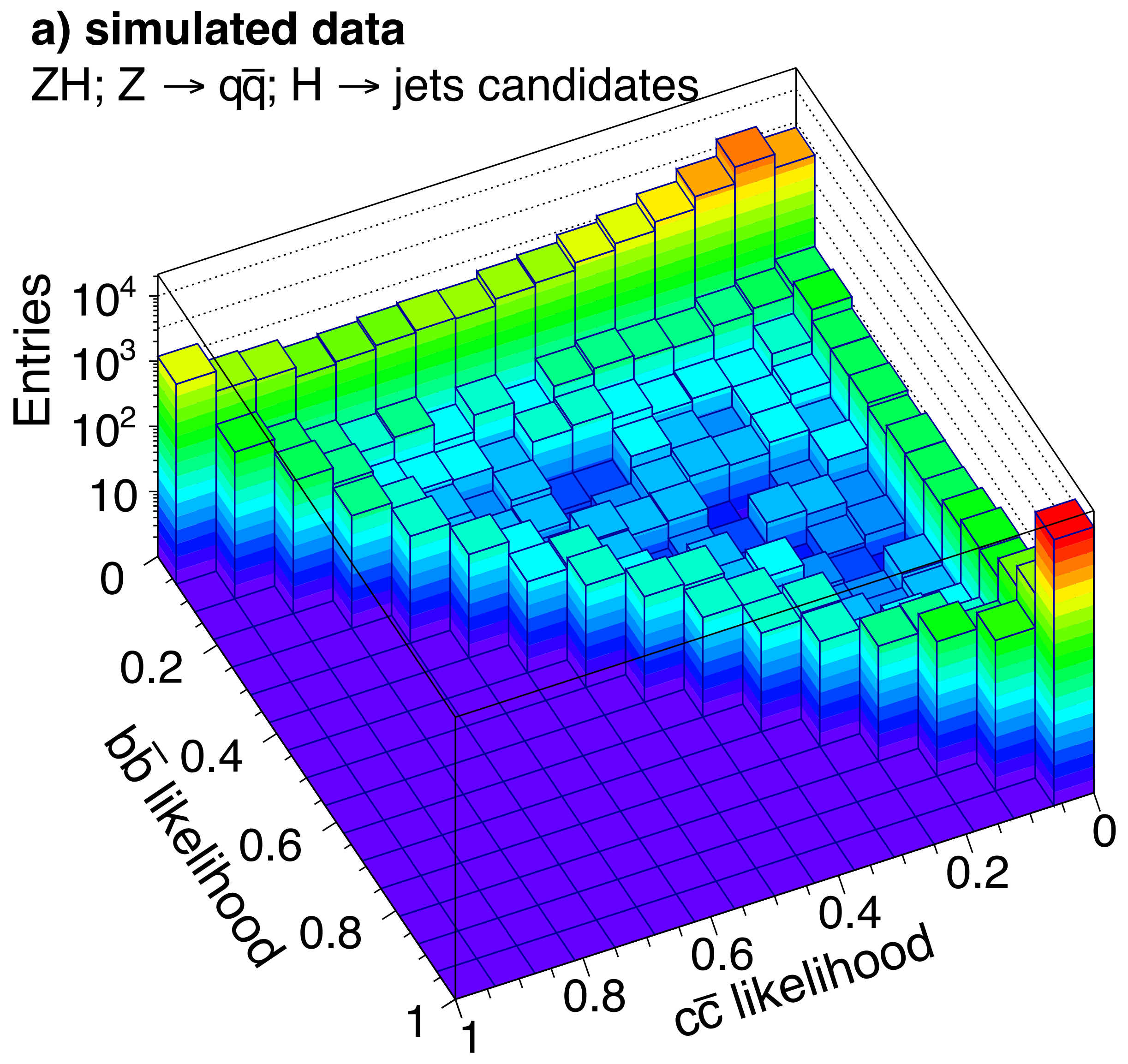
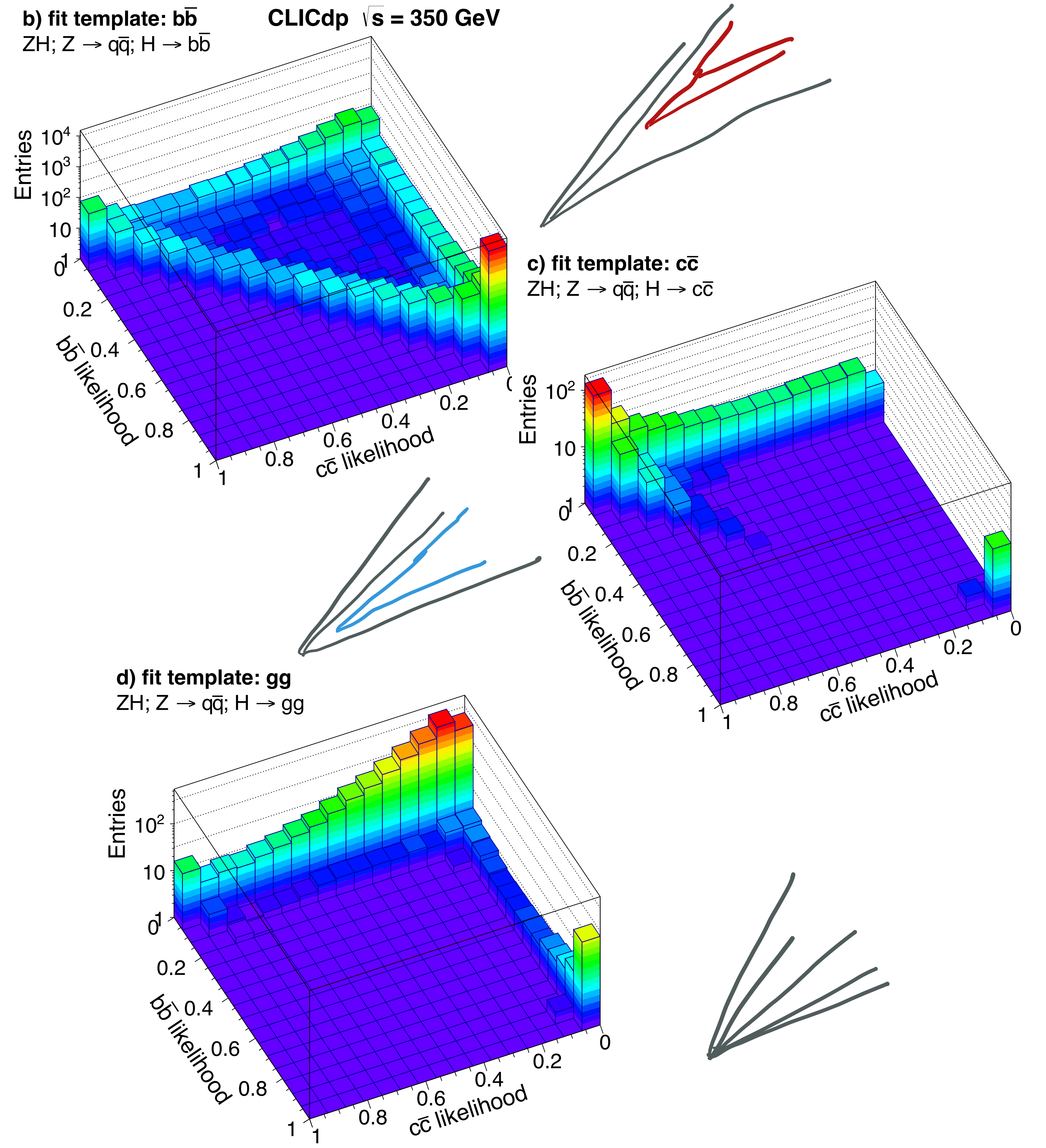
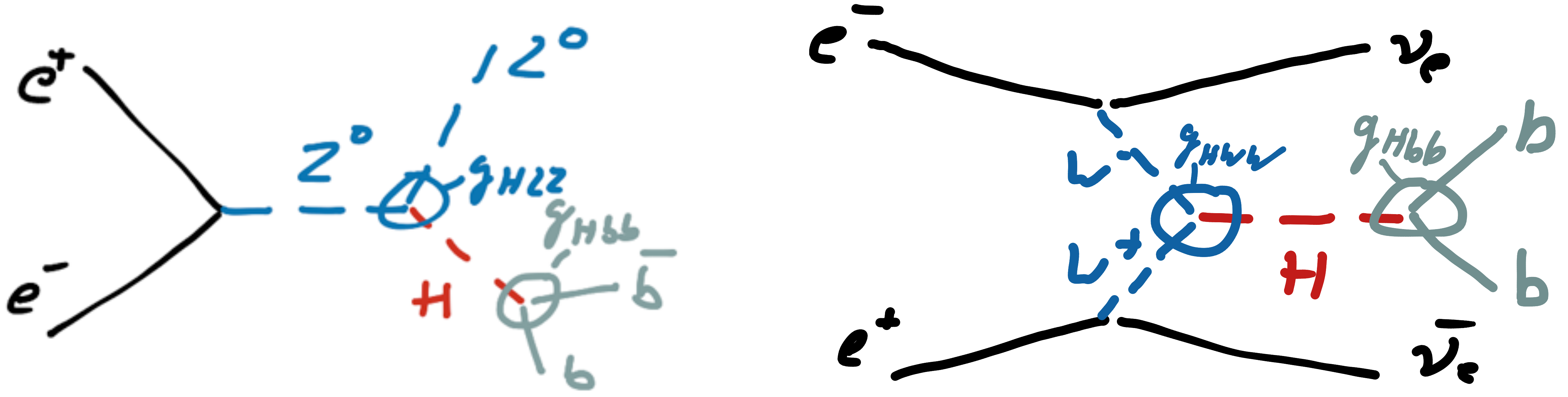




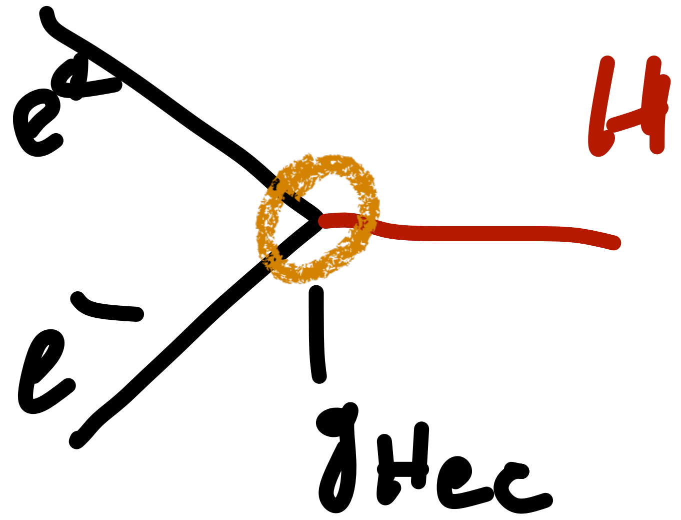


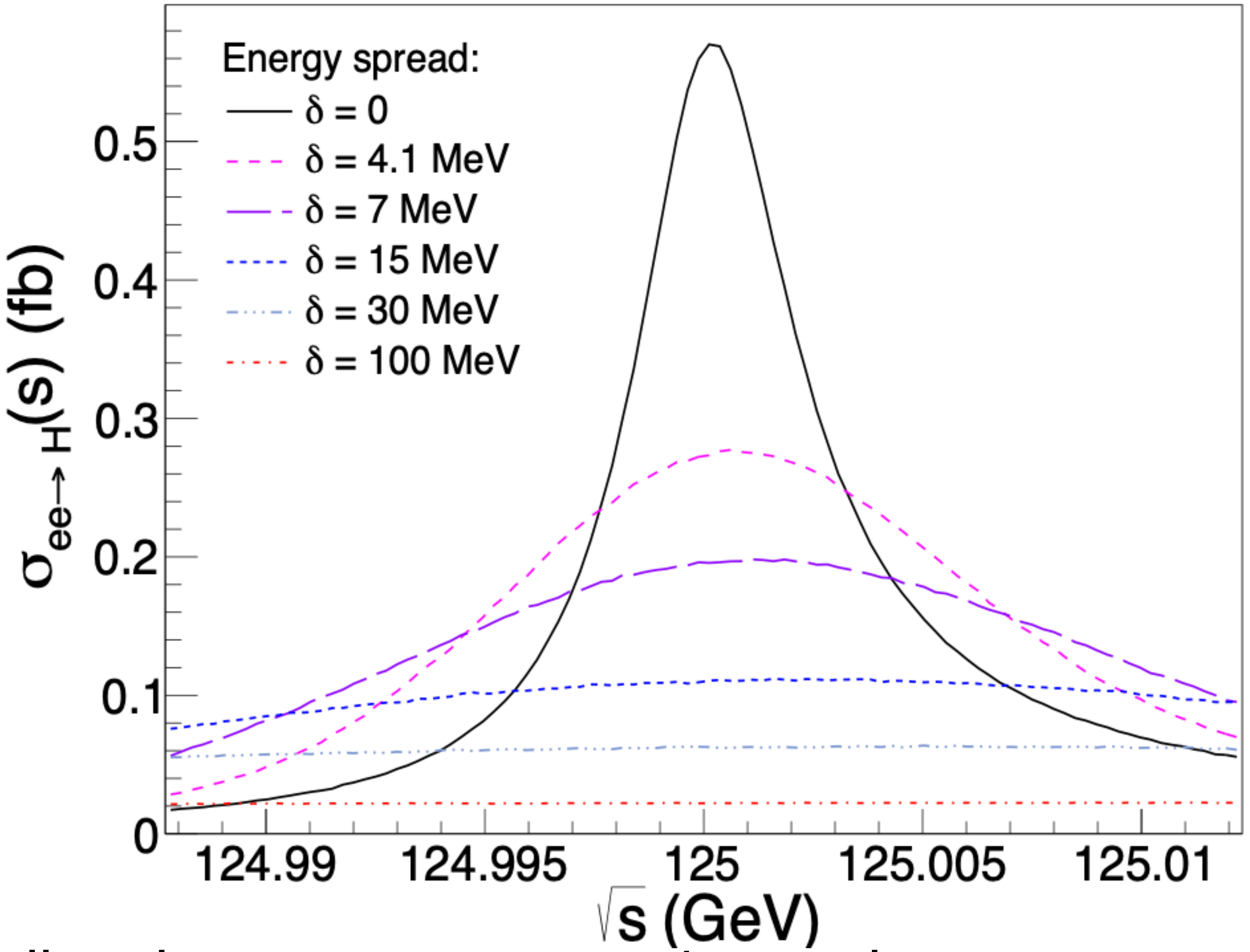
Accessing the Couplings to First Generation Leptons

Requiring extreme luminosities of circular colliders

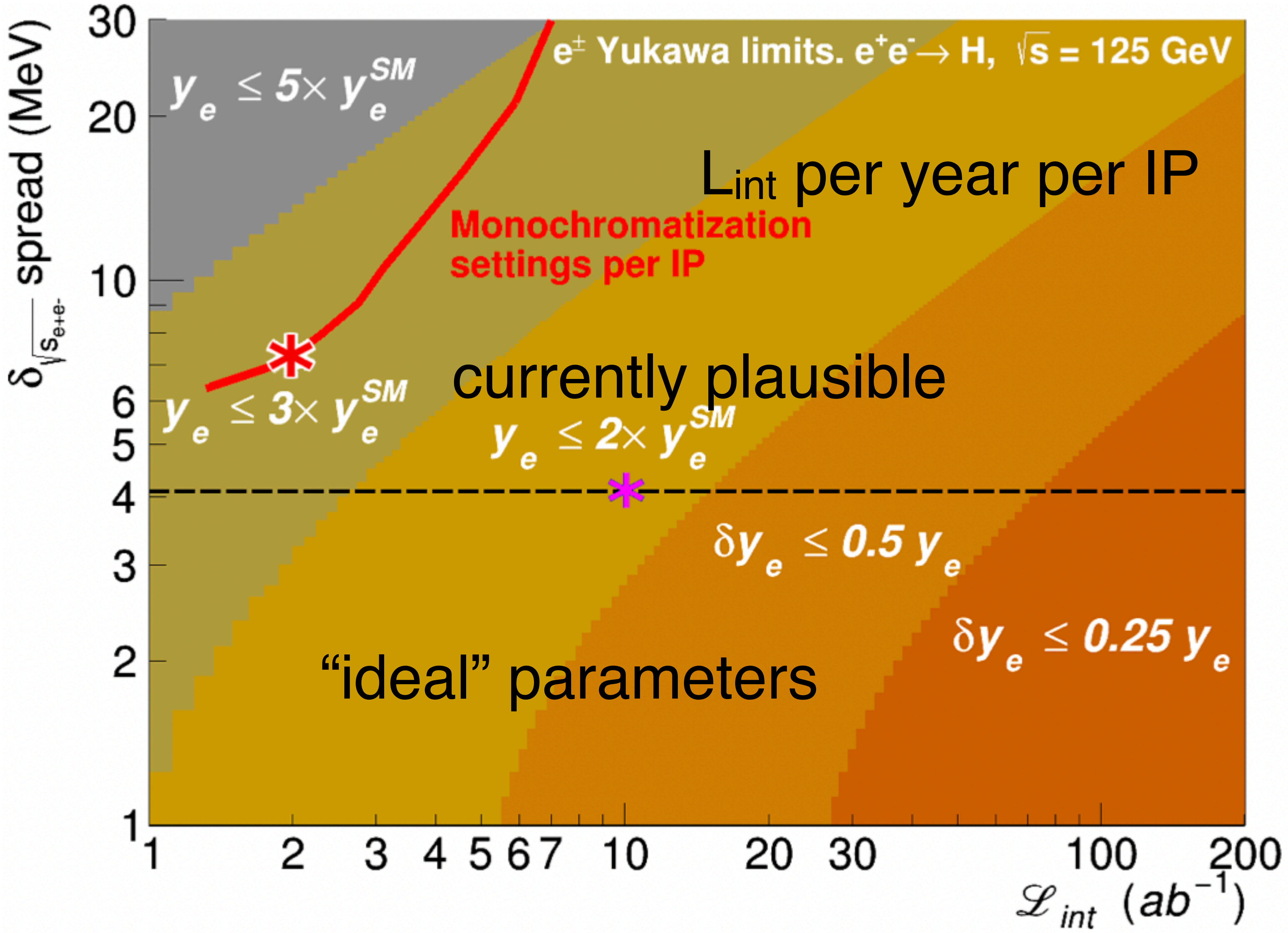
Karlsruhe Institute of Technology

- The only chance to access couplings to first generation: Study of s-channel Higgs production in e^+e^- collisions
  - Requires high luminosities and very small energy spread at 125.1 GeV





Requires special monochromatization to reduce energy spread

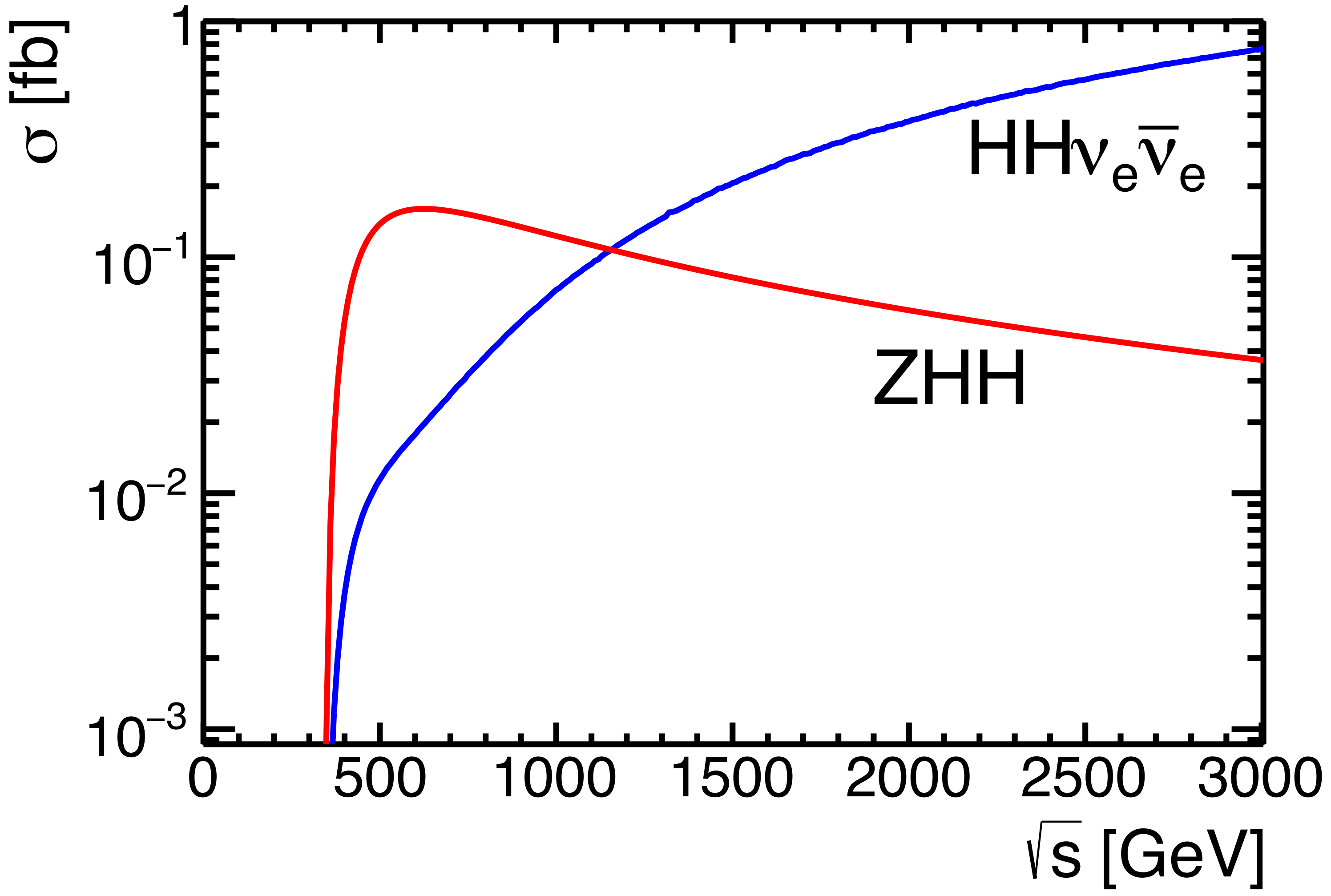


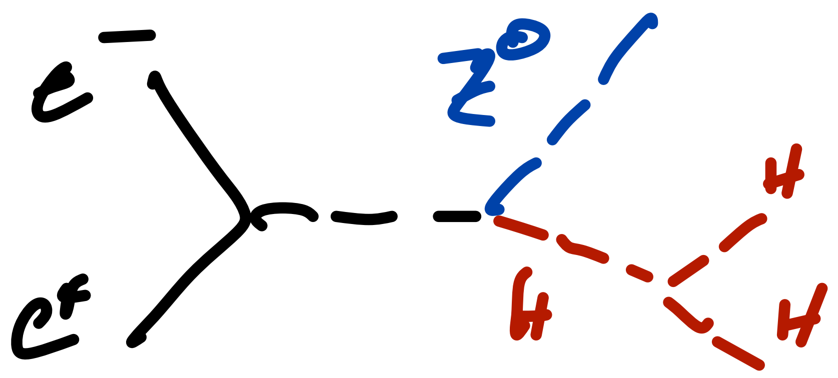
➯ A very challenging measurement, 4 experiments and 3 years may reach a result

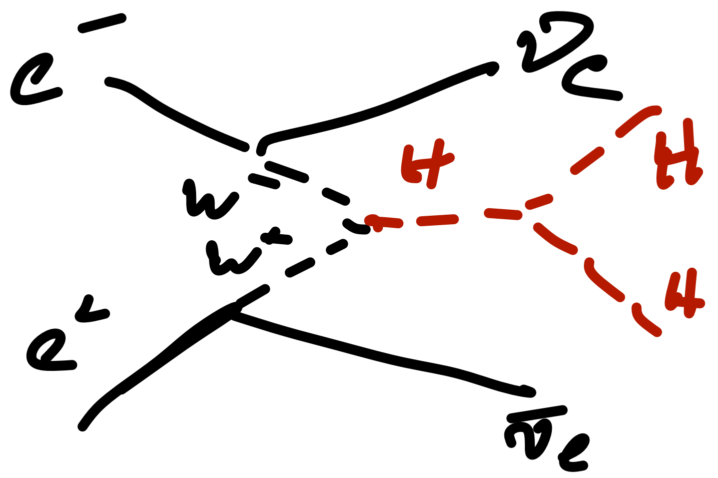
The Higgs Self-Coupling

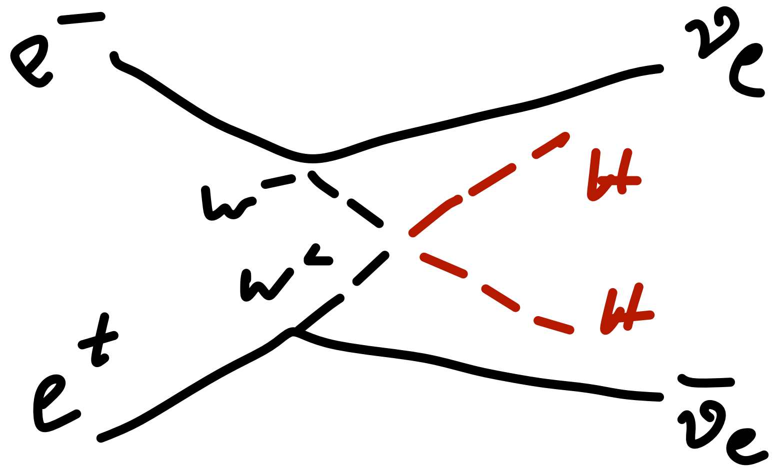
Requires higher energy - one of the key challenges of HEP

- Two processes with sensitivity at e^+e^- colliders:









the final state also receives contributions from the quartic coupling

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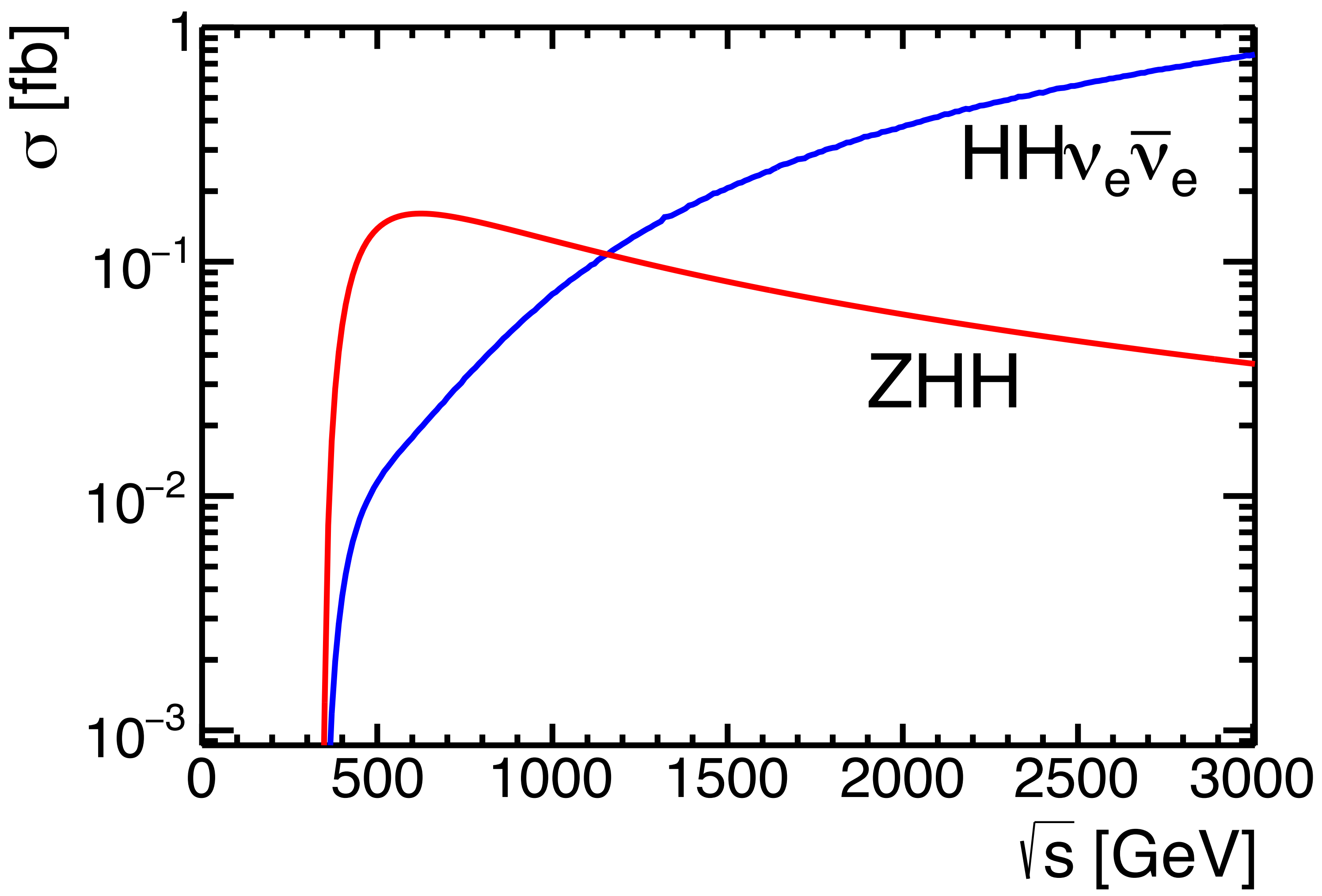

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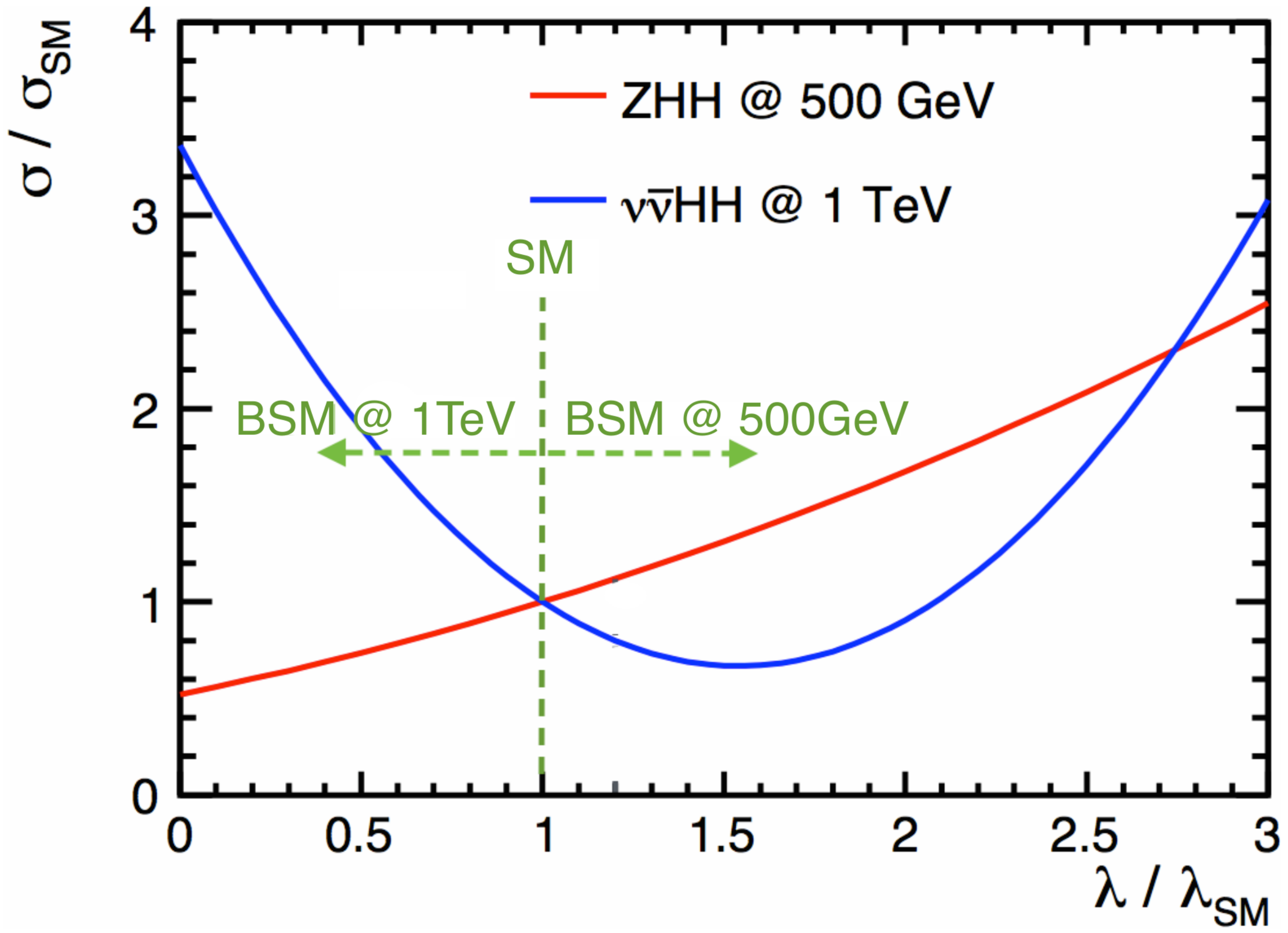

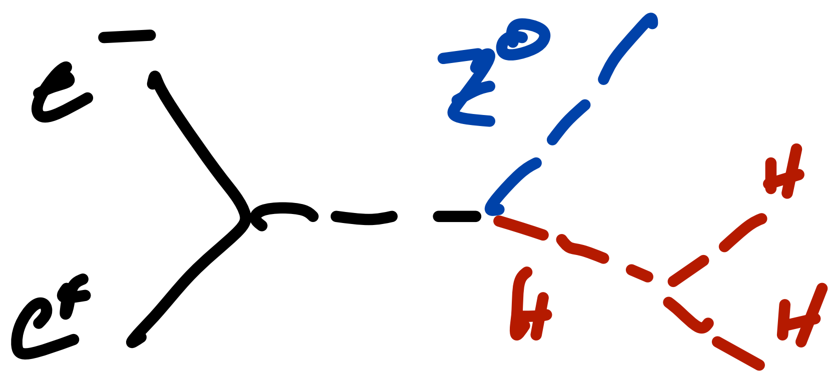

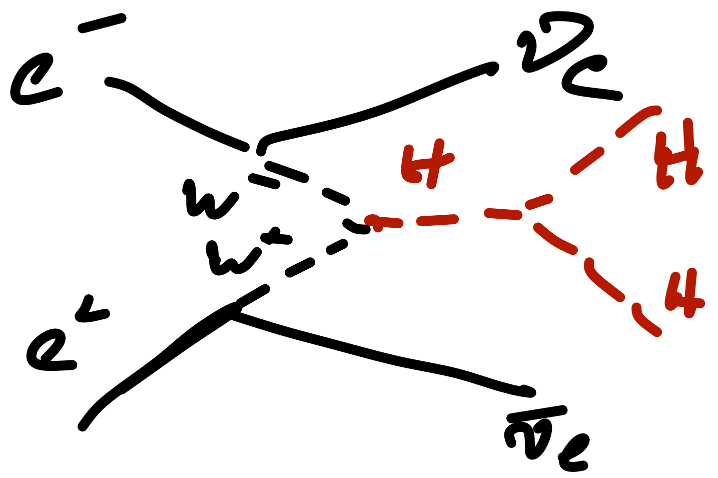

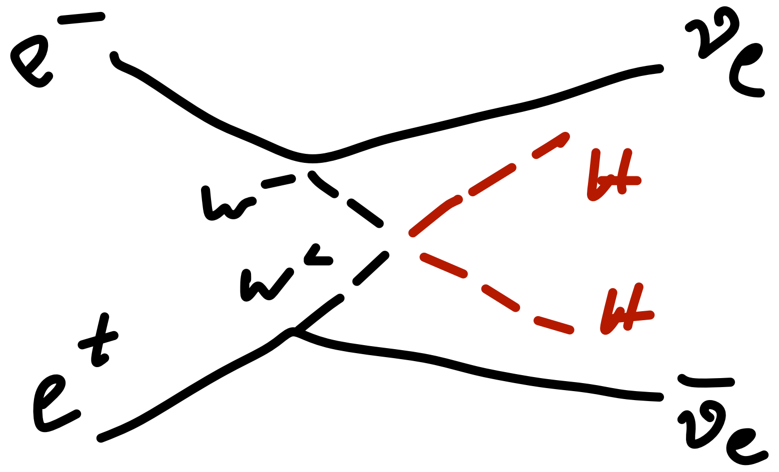

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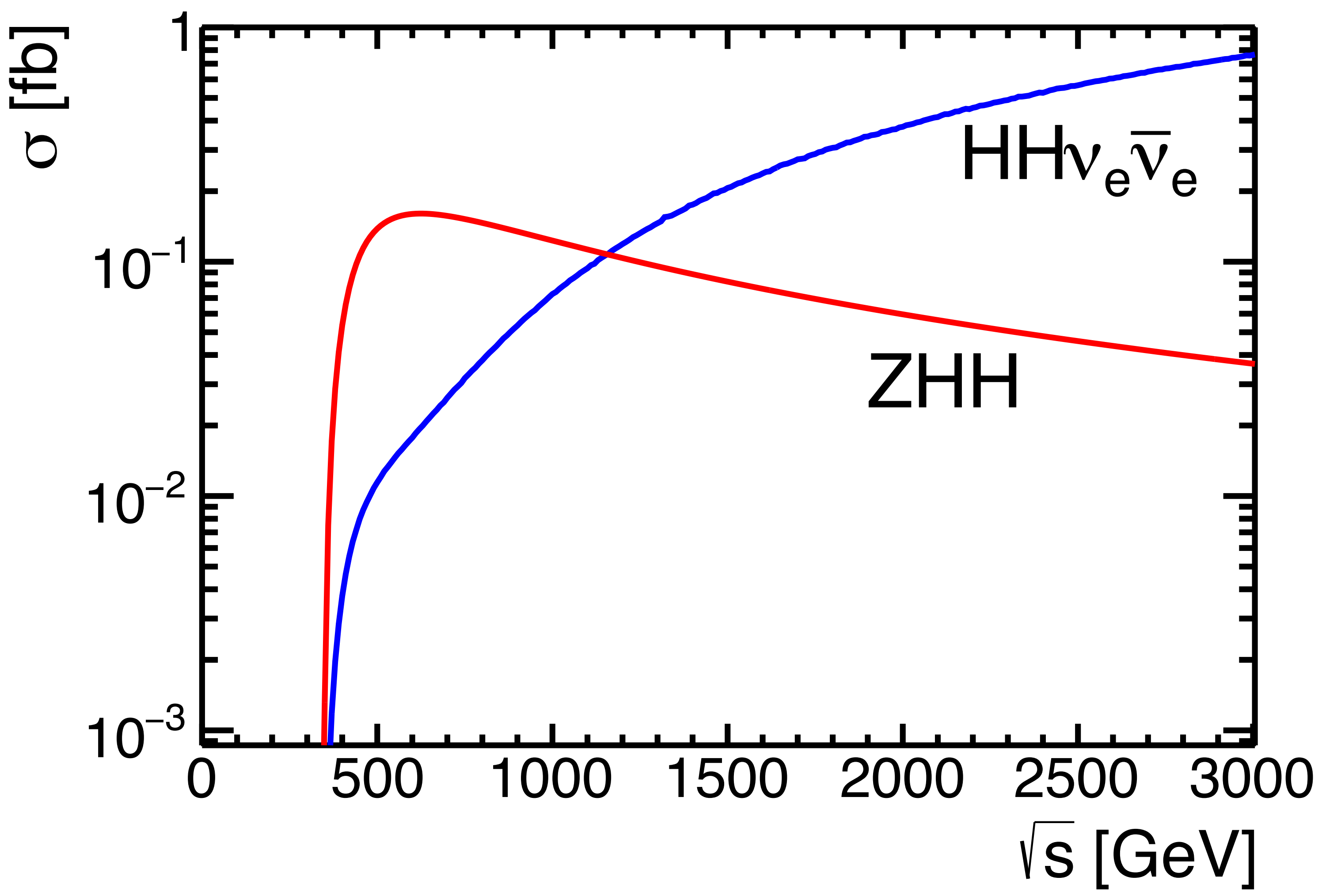

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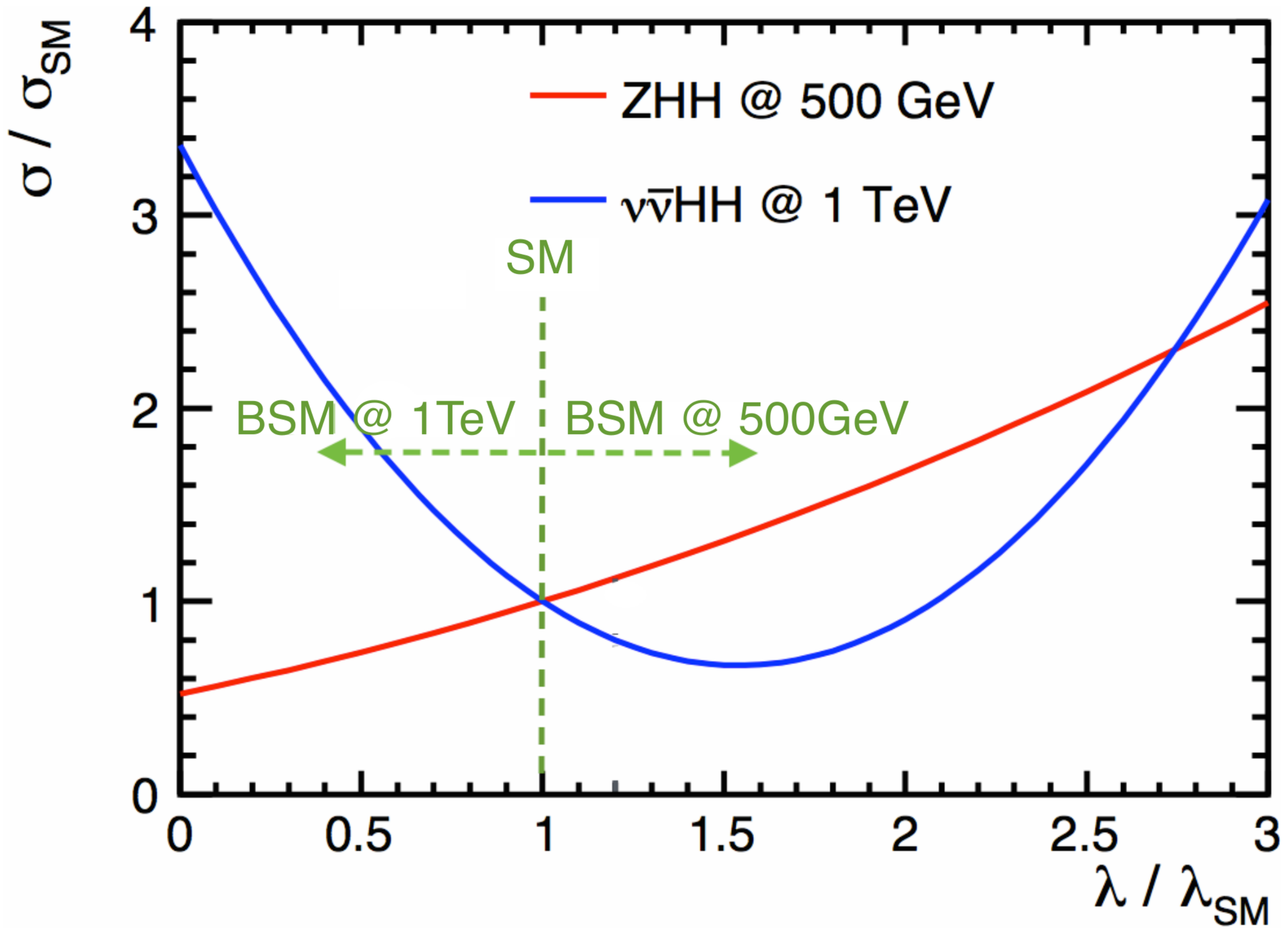
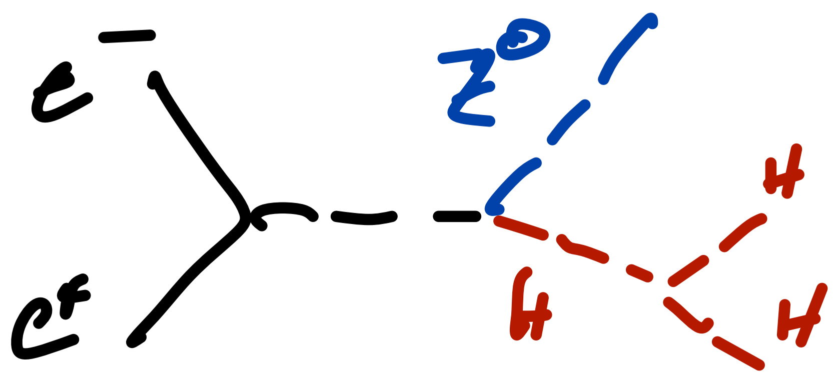
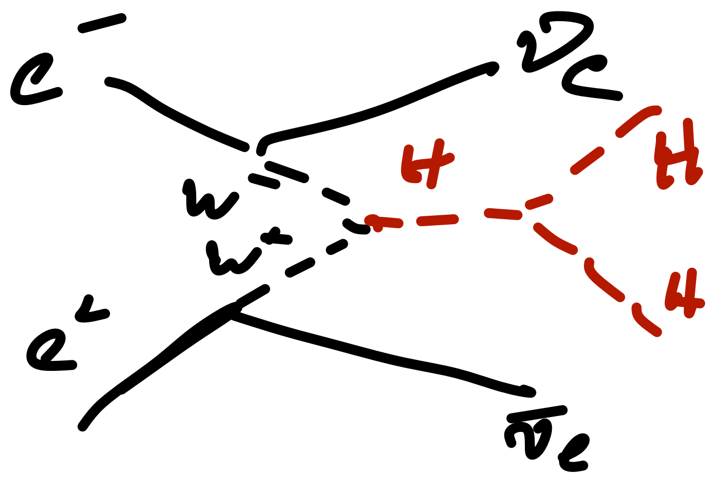
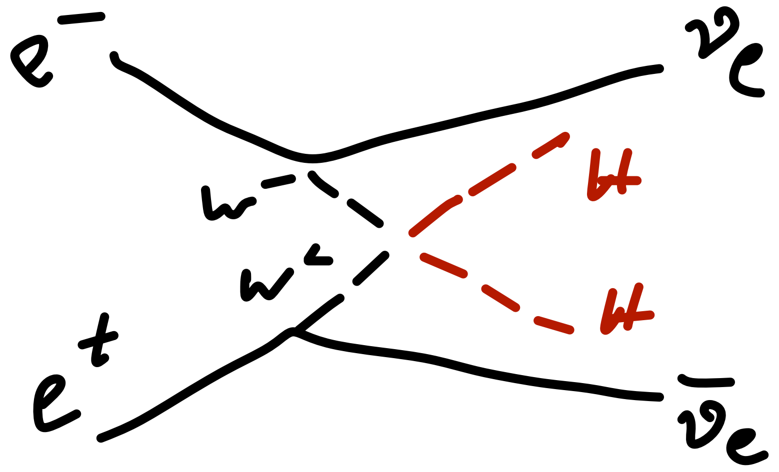








the final state also receives contributions from the quartic coupling

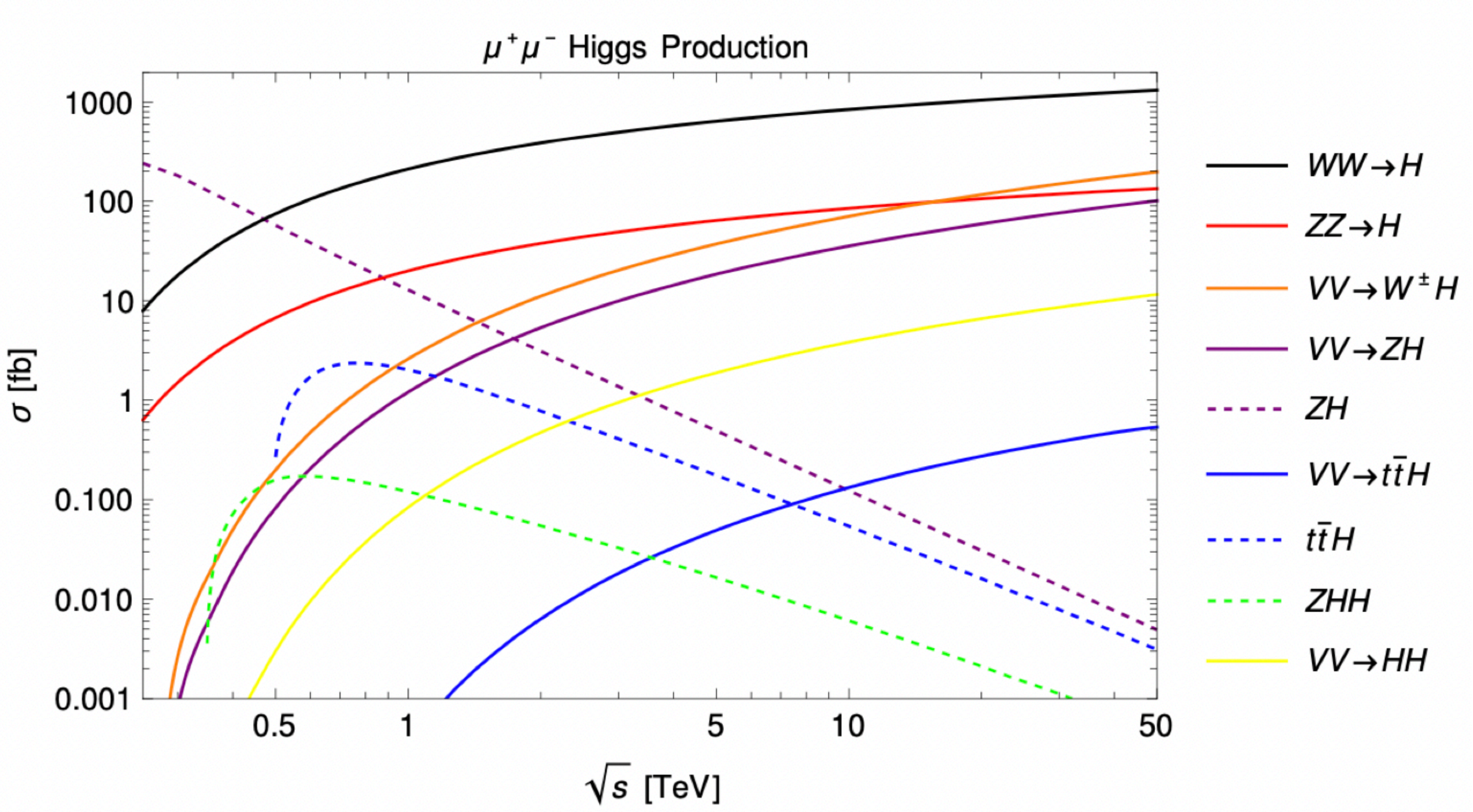
Full potential unfolds in the multi-TeV region through growing σ of VBF process:

- ➩ 10% measurement feasible
- ➩ Significant observation also of ZHH channel in lower-energy running (up to ~ 1.5 TeV)

Higgs Physics at Muon Colliders

Brief overview

- In general the same processes as for e^+e^-, but with the backdrop of a much larger background, and reduced acceptance at small angles (which has an impact on WW fusion processes in particular). Here (much) higher energy can compensate!



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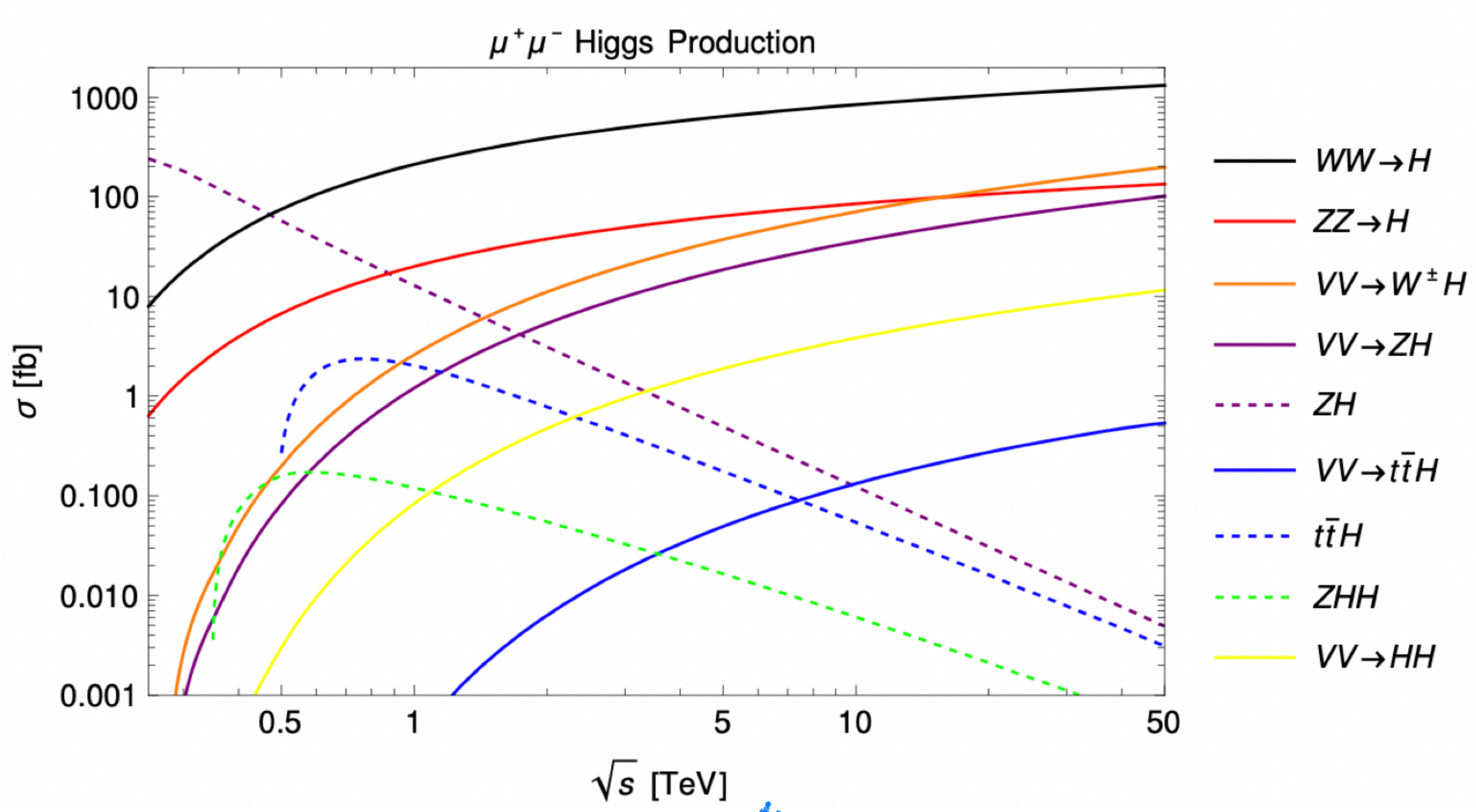
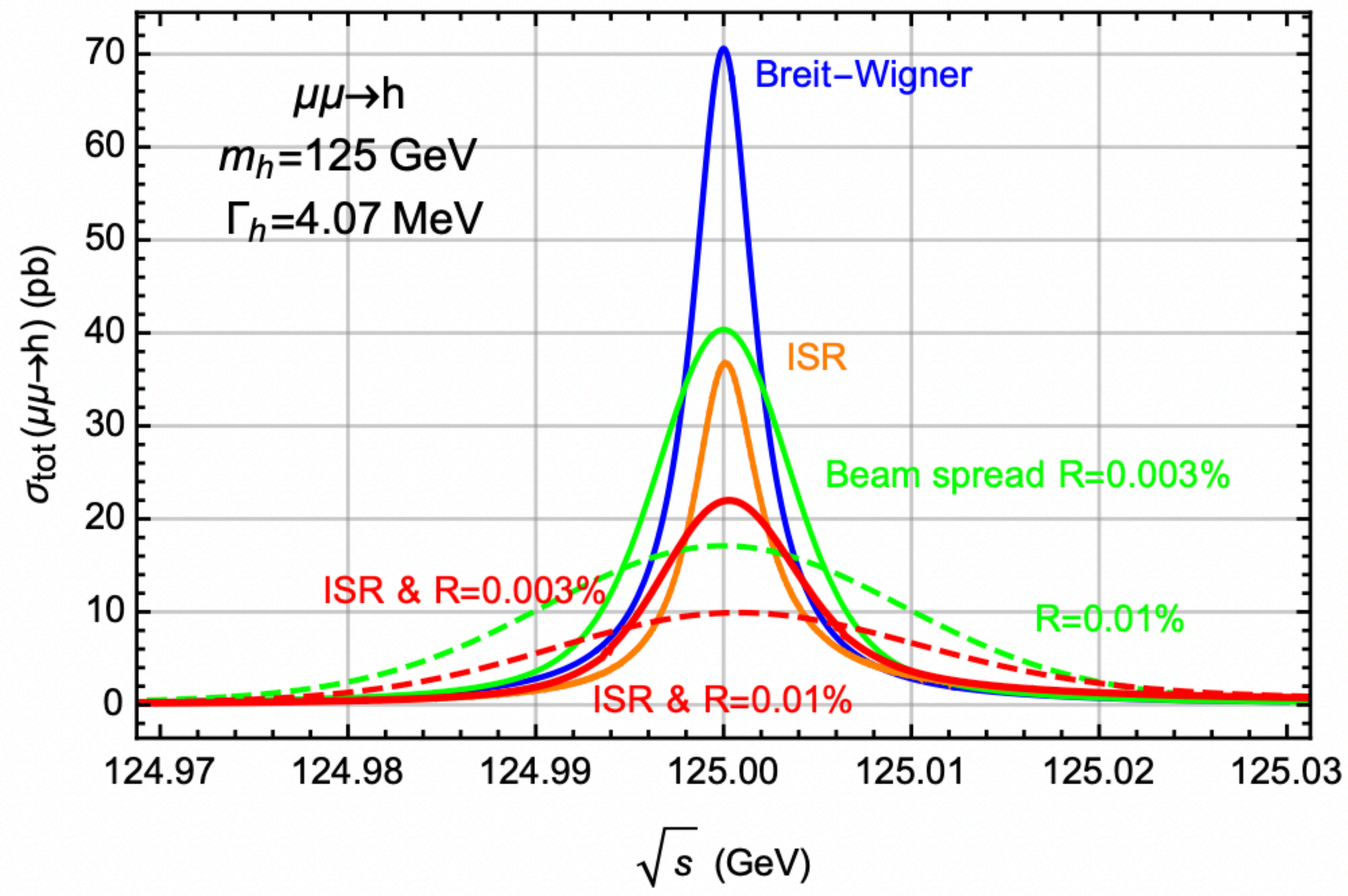
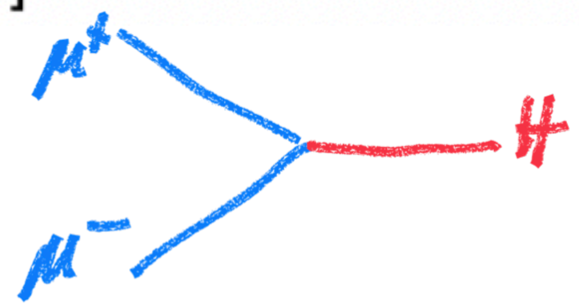






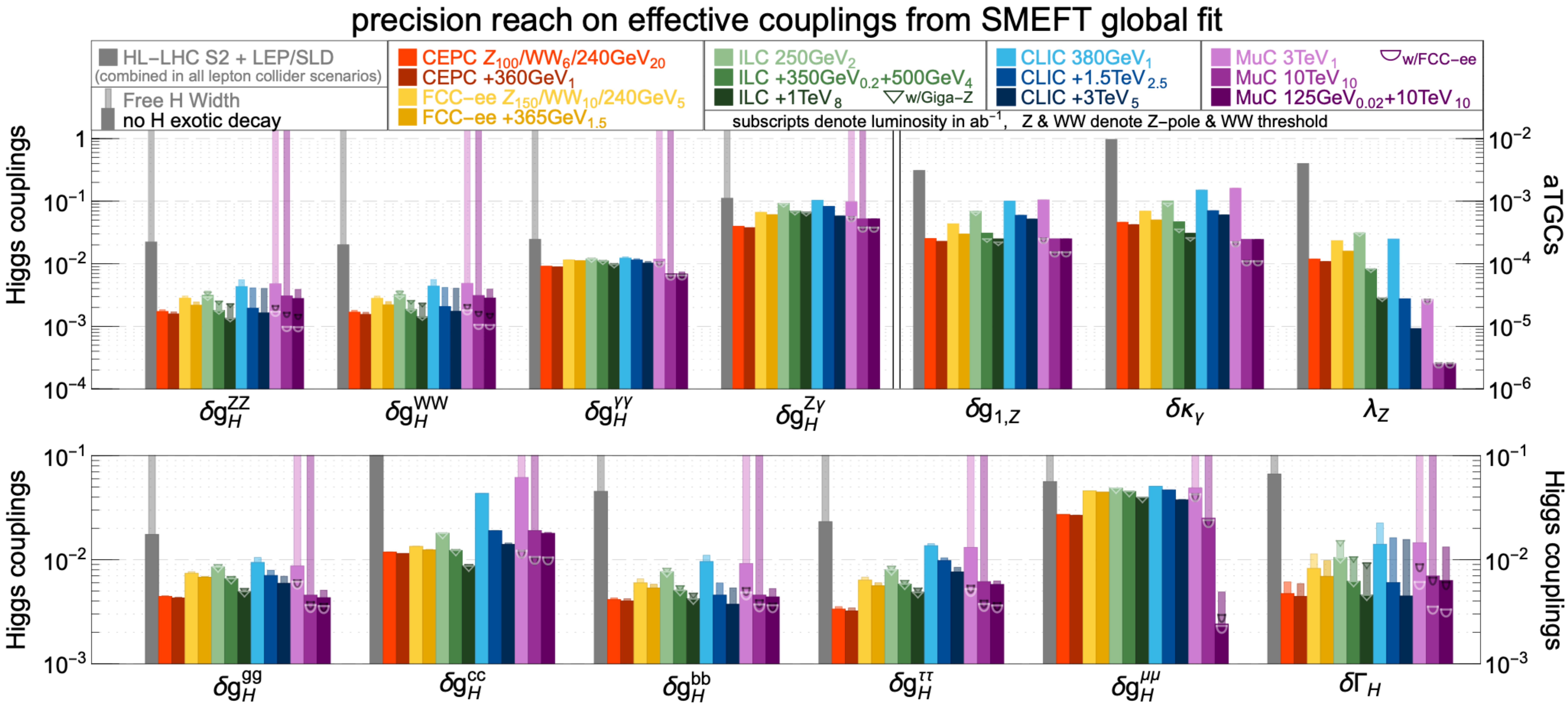
s-channel production at 125 GeV:

Cross section ~10^5 x e^+e^-: Coupling, + reduced ISR smearing for μ

Overall Precision Perspective

Including muon colliders

- An EFT fit, performed for Snowmass as a global summary [arXiv:2206.08326]



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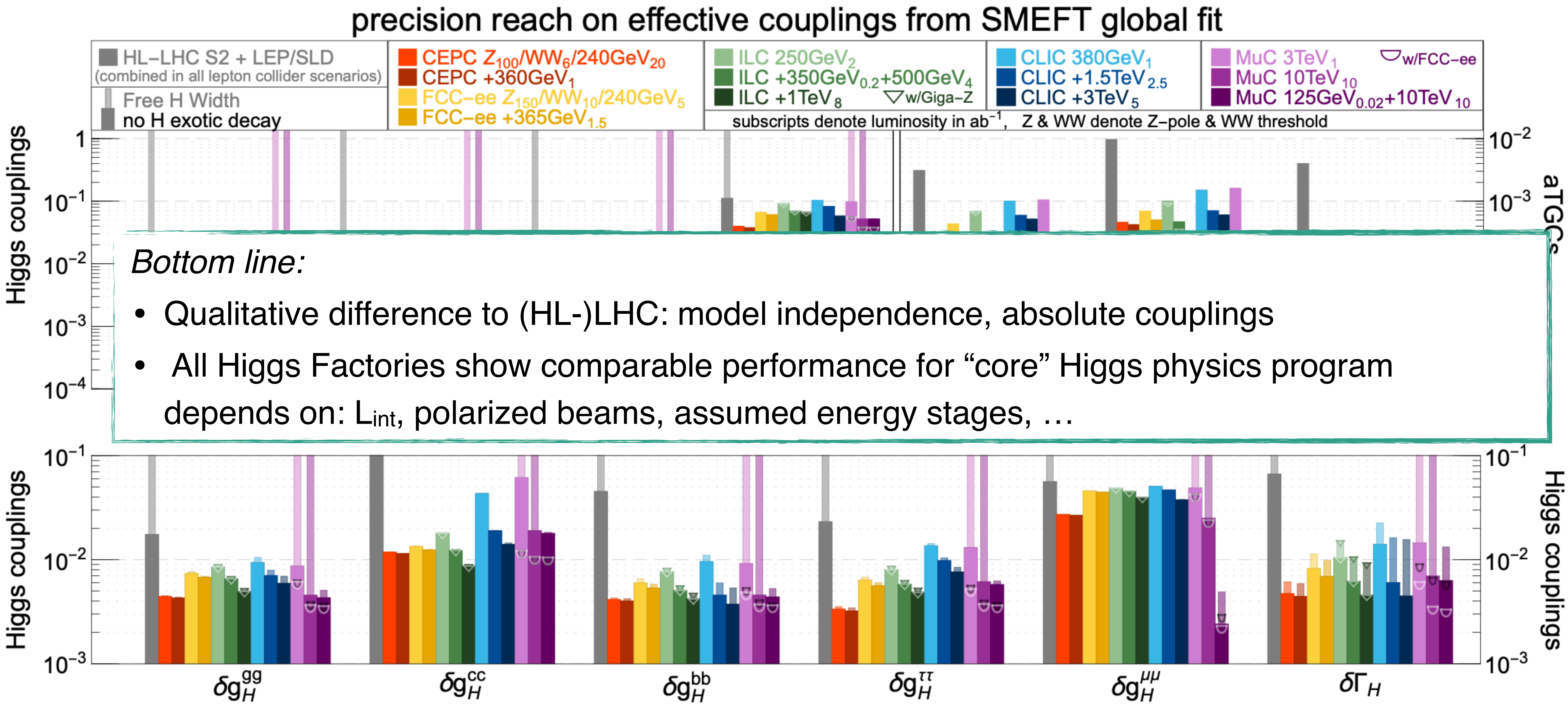


Bottom line:

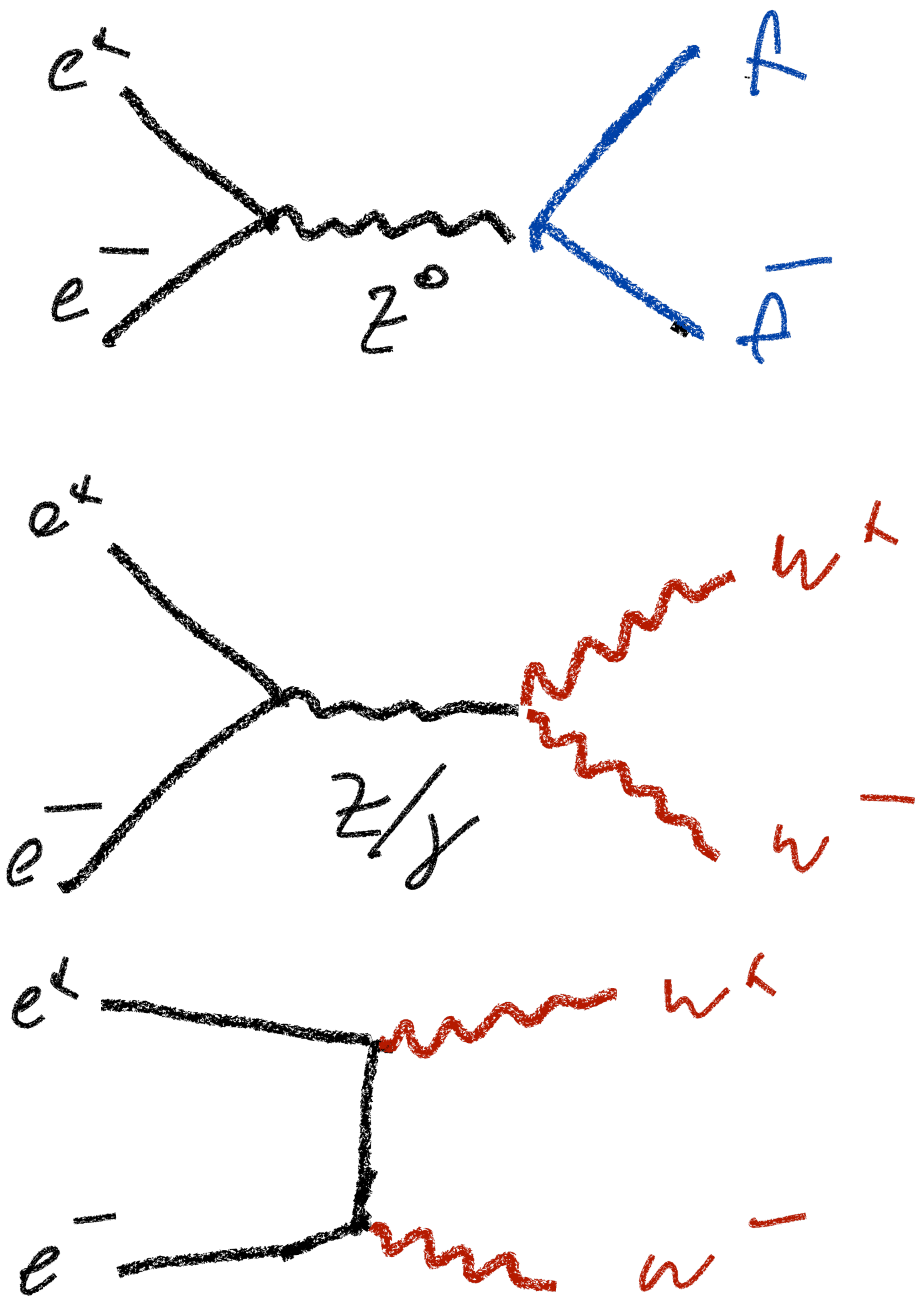
- Qualitative difference to (HL-)LHC: model independence, absolute couplings
- All Higgs Factories show comparable performance for “core” Higgs physics program depends on: L_{int}, polarized beams, assumed energy stages, …

Electroweak Precision

A Playground for Circular Colliders

The FCC-ee Program at Z and WW

The ultimate electroweak program



- Building on the success of LEP & LEP II
  - High-statistics program at the Z - pole
  - W pair production - mass measurement and beyond

with 2 IPs:

5×10^{12} Zs (10^5 x LEP)

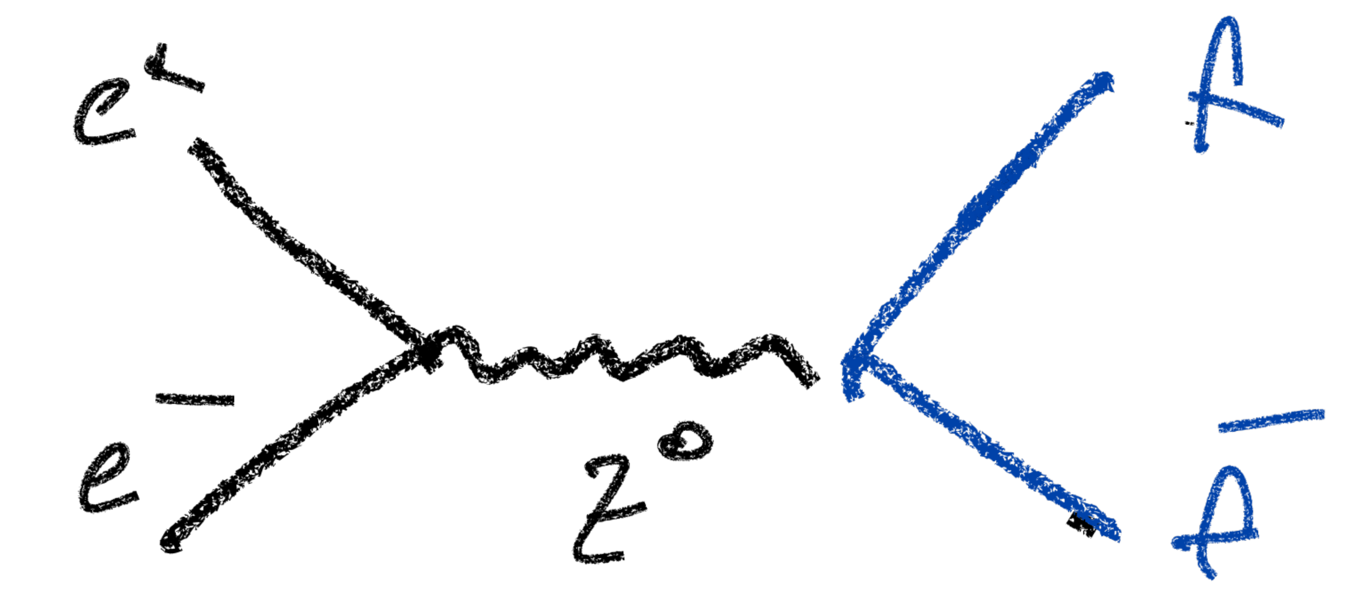
10^8 W pairs (2×10^3 x LEP)

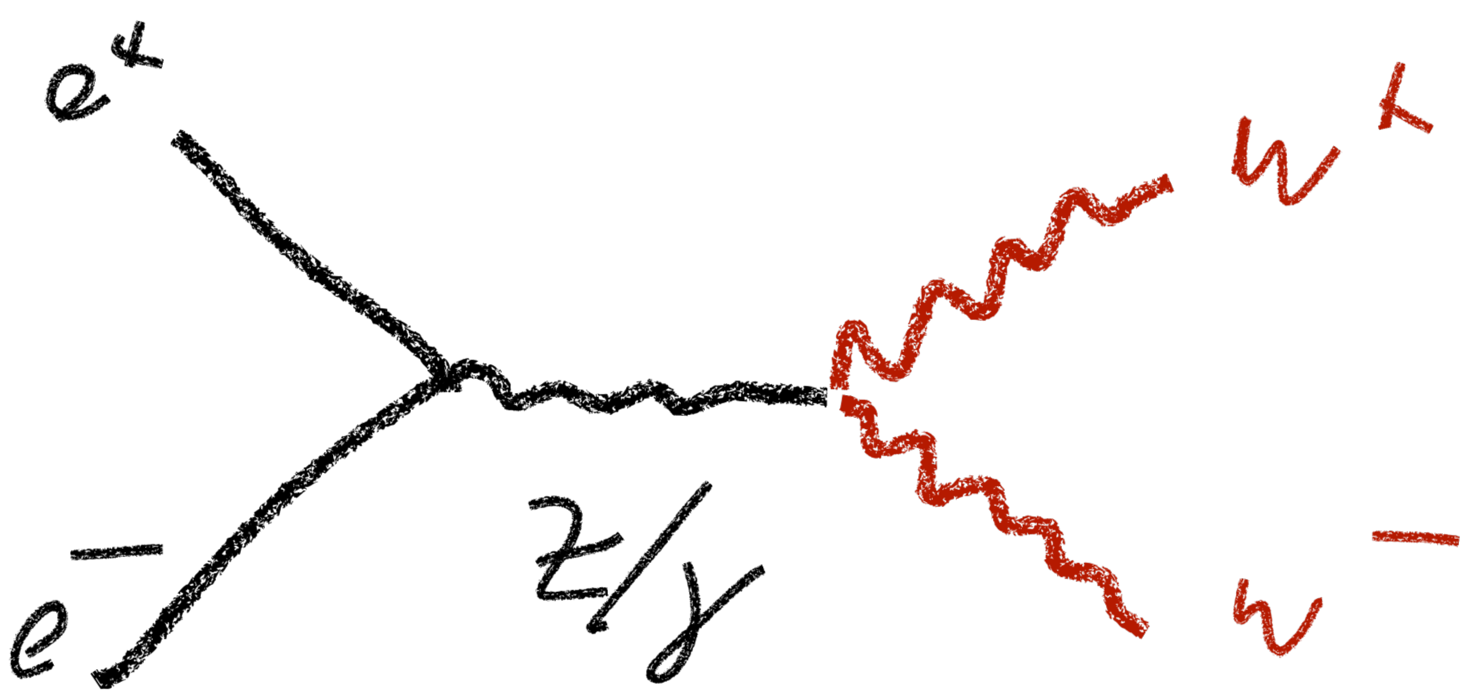
N.B.: Measurements also possible at linear colliders, but the statistics will be orders of magnitude smaller due to their lower luminosity at low energy.

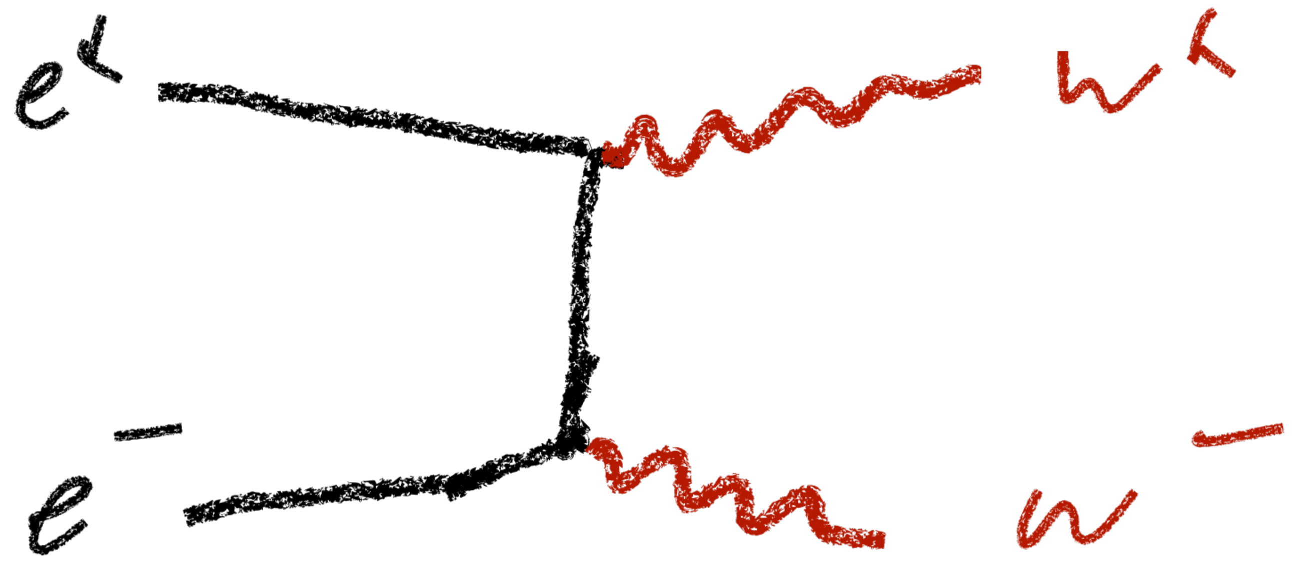
The FCC-ee Program at Z and WW

The ultimate electroweak program

Karlsruhe Institute of Technology







- Building on the success of LEP & LEP II
  - High-statistics program at the Z - pole
  - W pair production - mass measurement and beyond

with 2 IPs:

5×10^{12} Zs (10^5 x LEP)

10^8 W pairs (2×10^3 x LEP)

➯ Improving electroweak precision observables, enter into global fits

➯ Indirect searches for New Physics

N.B.: Measurements also possible at linear colliders, but the statistics will be orders of magnitude smaller due to their lower luminosity at low energy.

Flavour Physics

Beyond Super Flavour Factoriesß

- An e^+e^- collider running at the Z pole is also an excellent flavour factory!
  The 5 x 10^{12} Zs at FCC-ee will provide: 10^{12} bb events, 1.7 x 10^{11} $\tau^+\tau^-$ events
  An excellent testing ground of universality, rare decays; precision measurements of masses and lifetimes

  - Explore rare be decays with unprecedented precision.
  - Study of CP violation, the CKM matrix, possible lepton flavour non-universality

  - A comprehensive τ physics program

Observable	Current precision	FCC-ee **stat.**	**Possible syst.**
m_τ [MeV]	1776.86 **± 0.12**	**0.004**	**0.1**
τ_τ [fs]	290.3 **± 0.5 fs**	**0.001**	**0.04**
B(τ→eνν) [%]	17.82 **± 0.05**	**0.0001**	**0.003**
B(τ→μνν) [%]	17.39 **± 0.05**		

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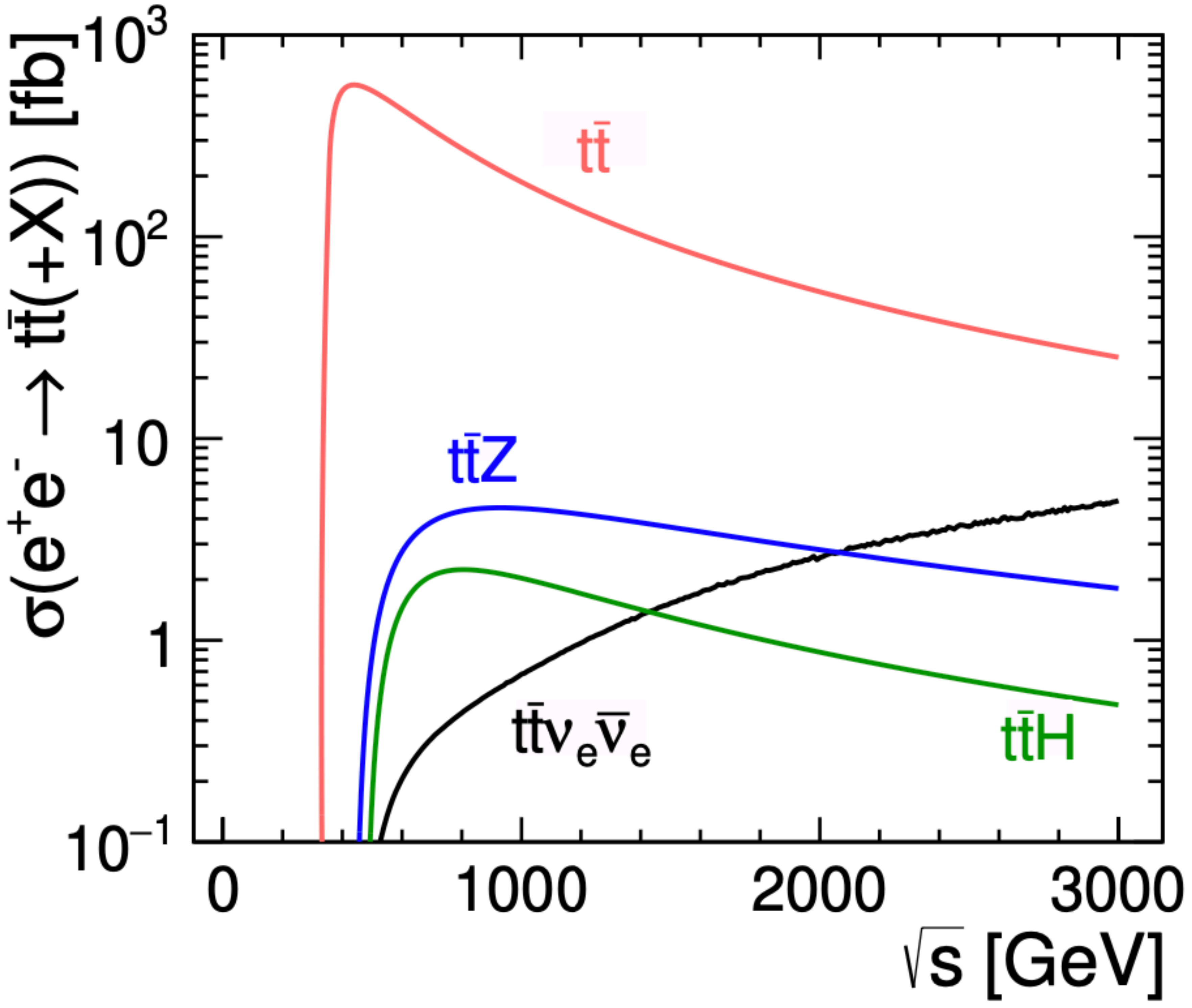
N.B.: Flavour physics introduces specific detector requirements such as PID, typically not front-and-center in Higgs Factory detector designs

The Top Quark

A new arena at 350 GeV and above

Overview: Top Physics at e+e- Colliders

Understanding the Top, using the Top



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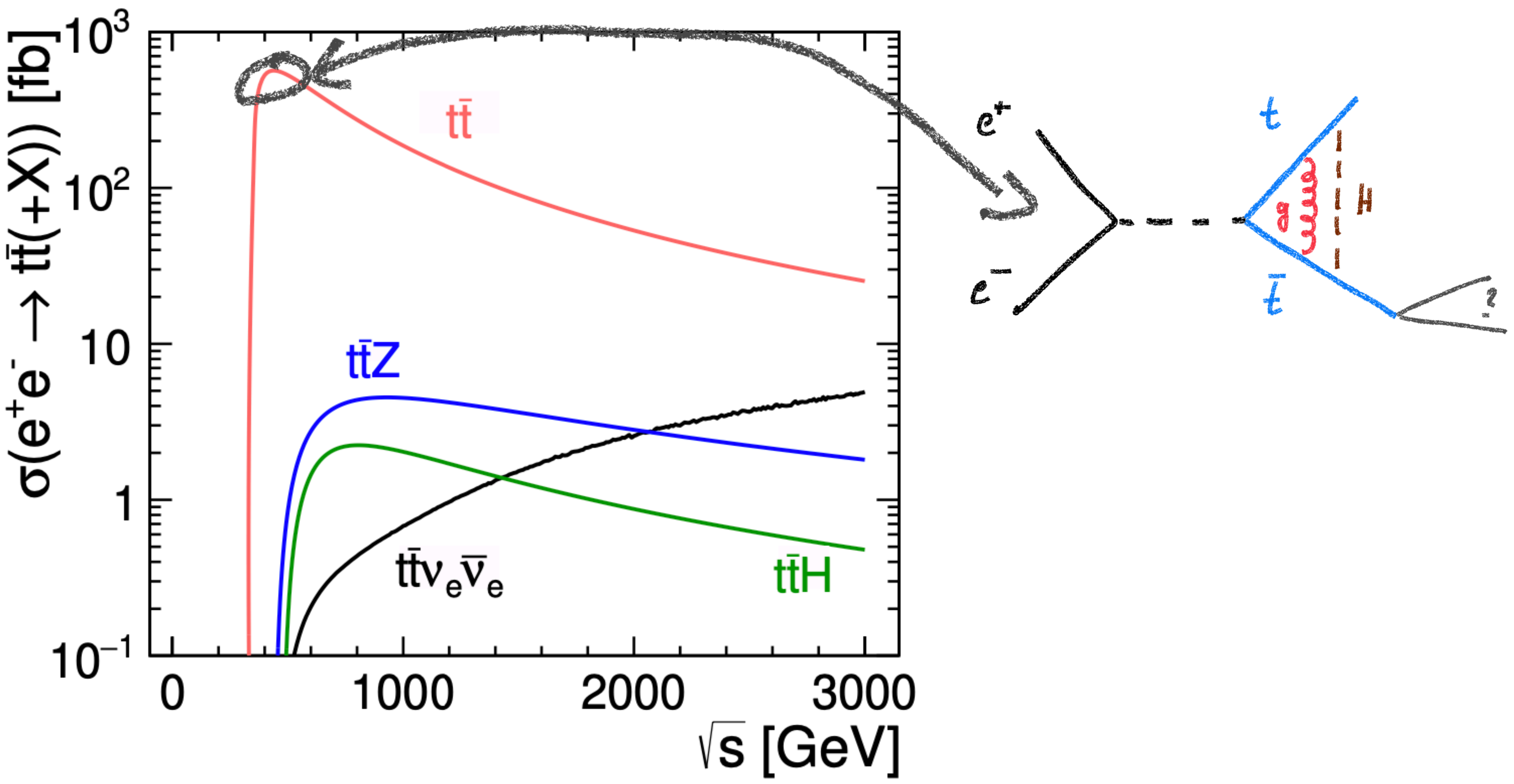

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- Search for BSM decays in clean

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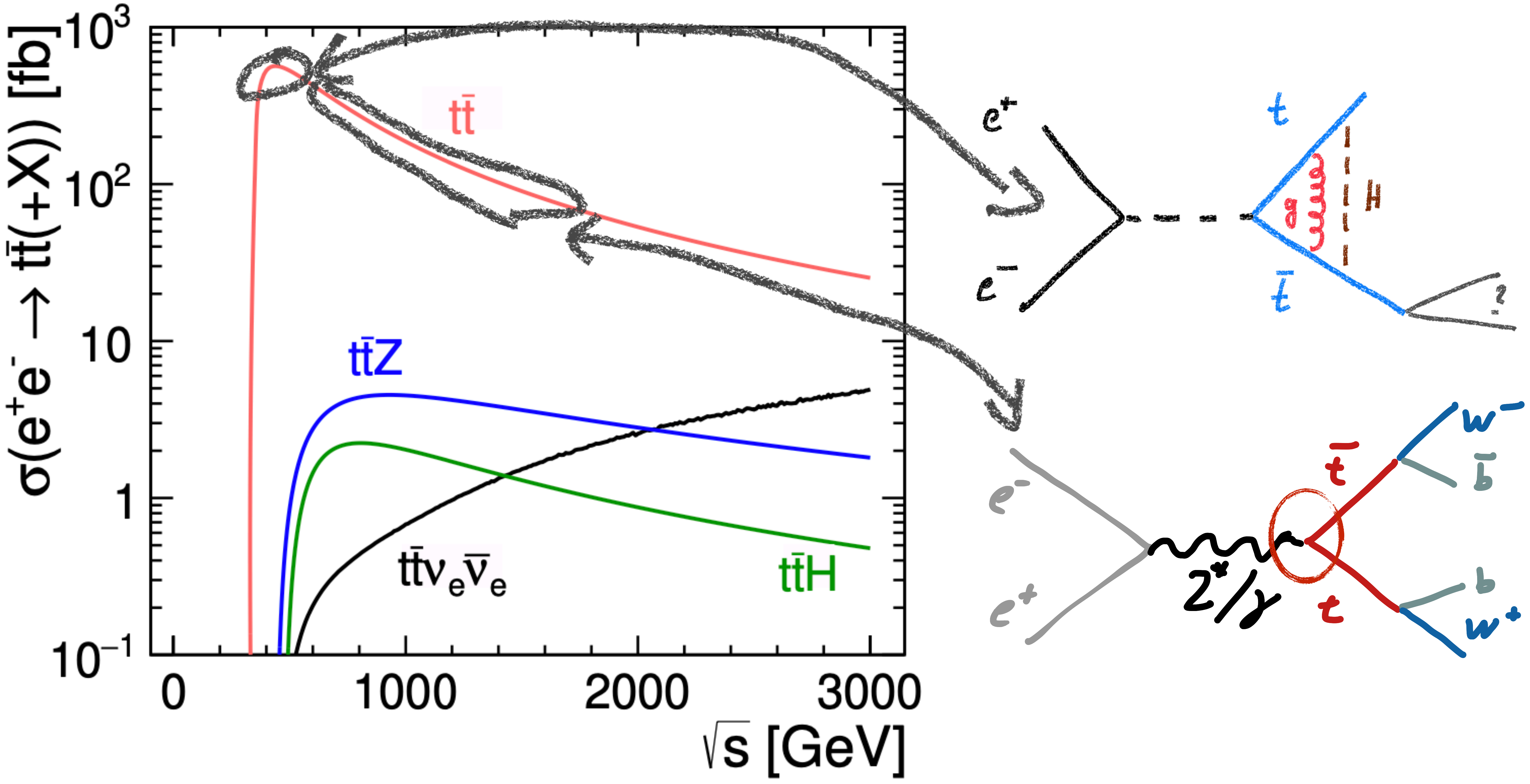

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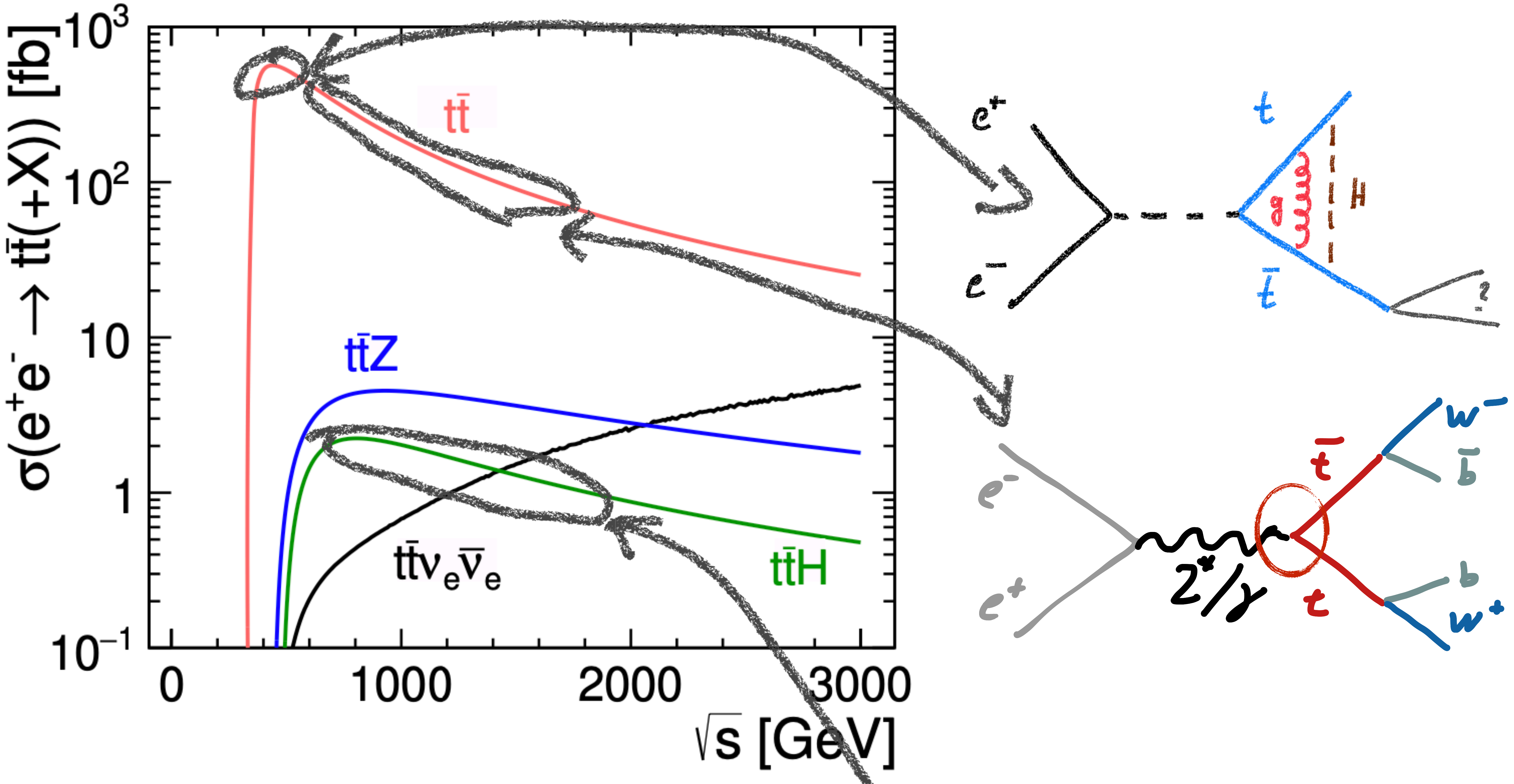

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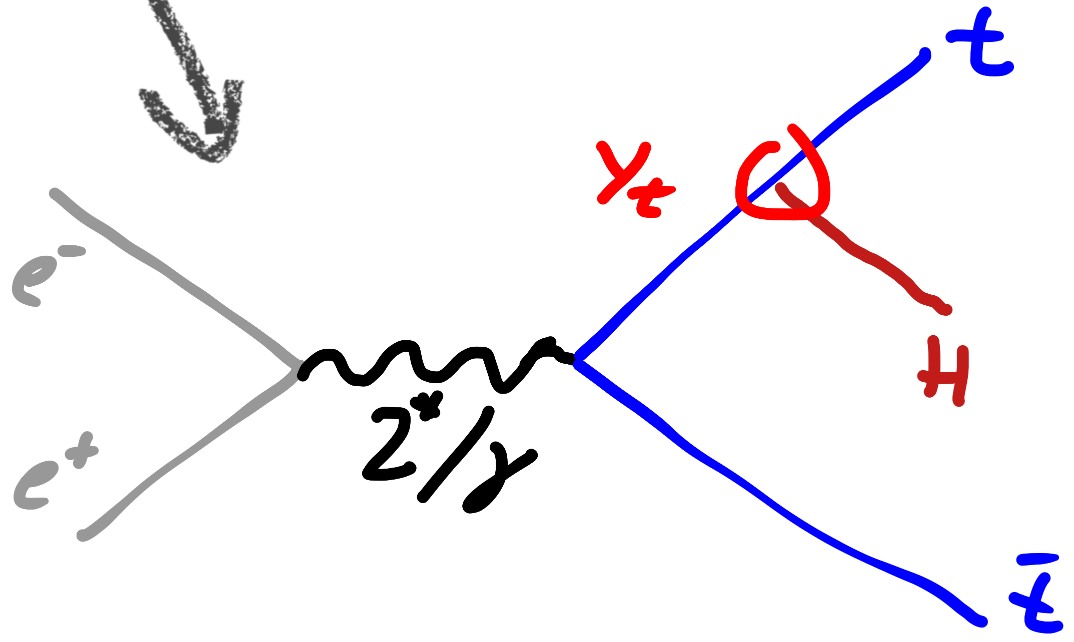
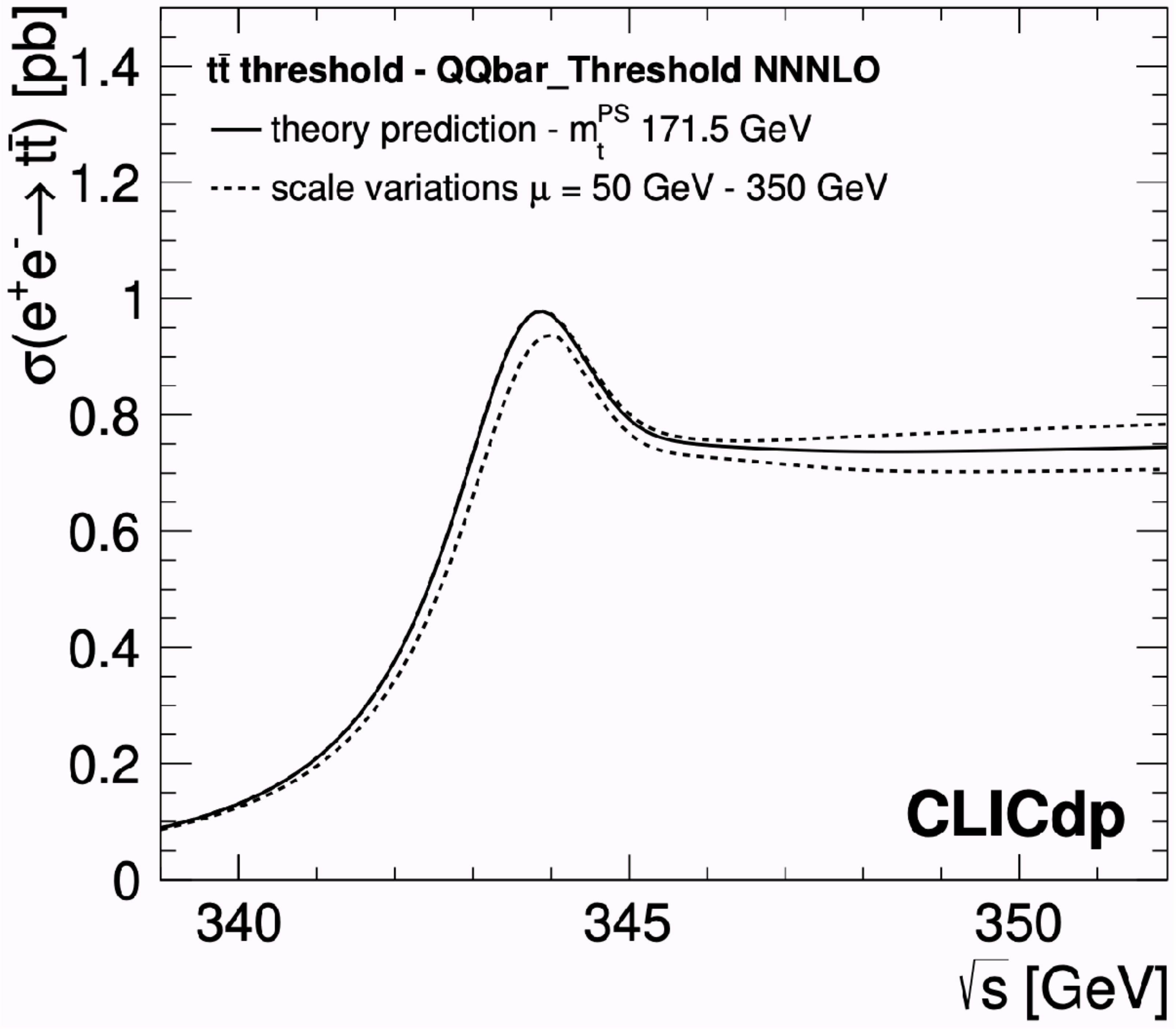


- Direct measurement of the top Yukawa coupling, ultimate potential of 2%
  [requires > 500 GeV, full scope assumes ~ 1 TeV]

The Top Quark Mass

Ultimate precision at the threshold



- 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.

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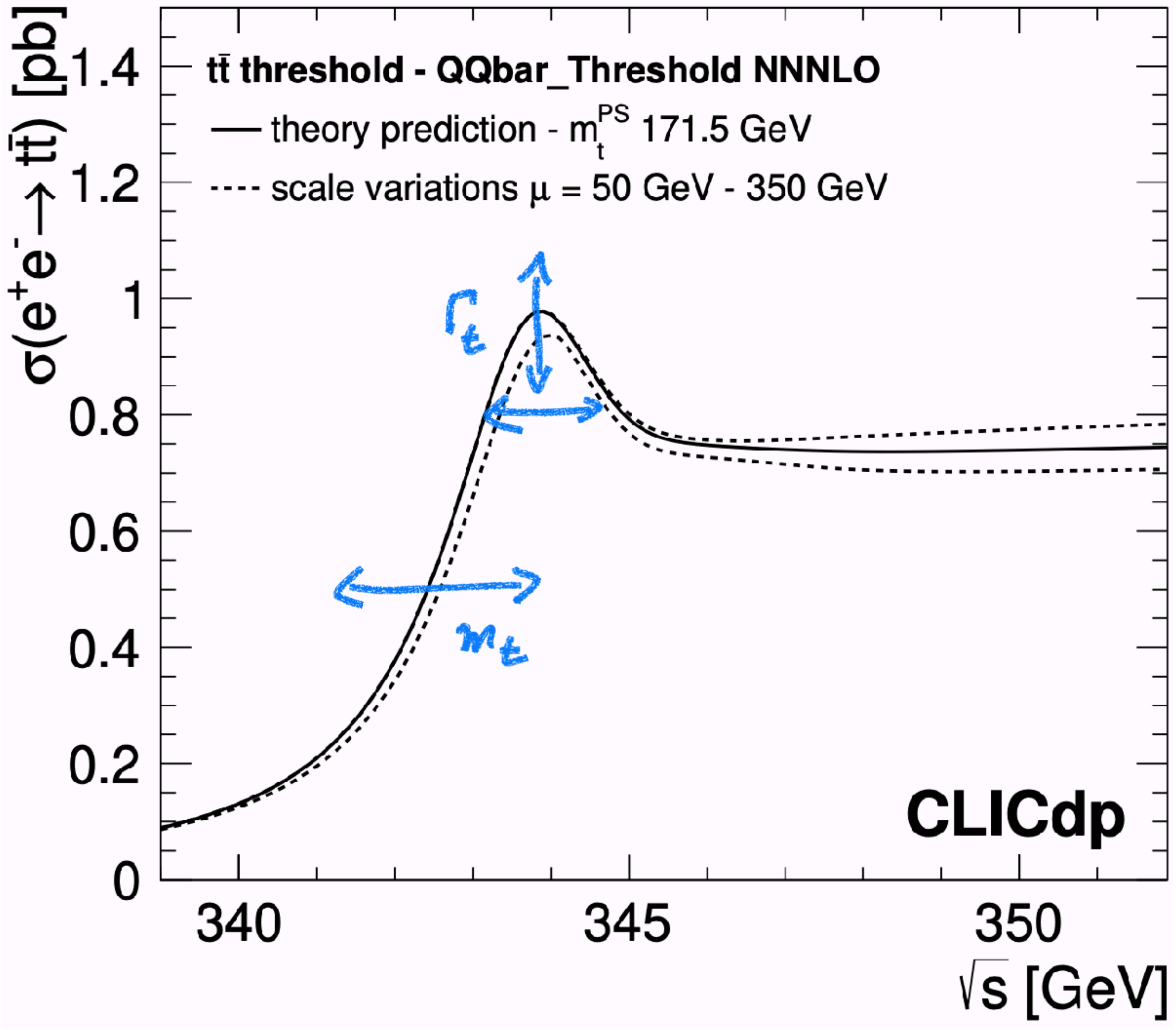

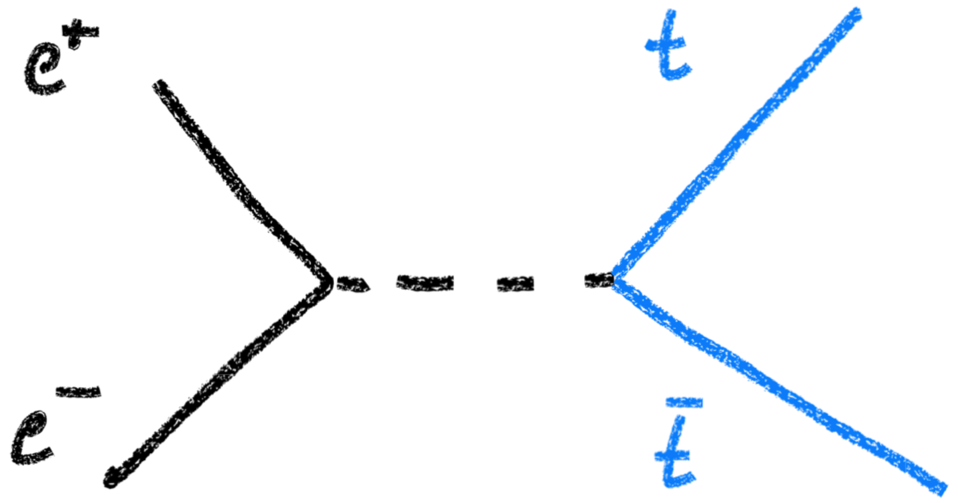

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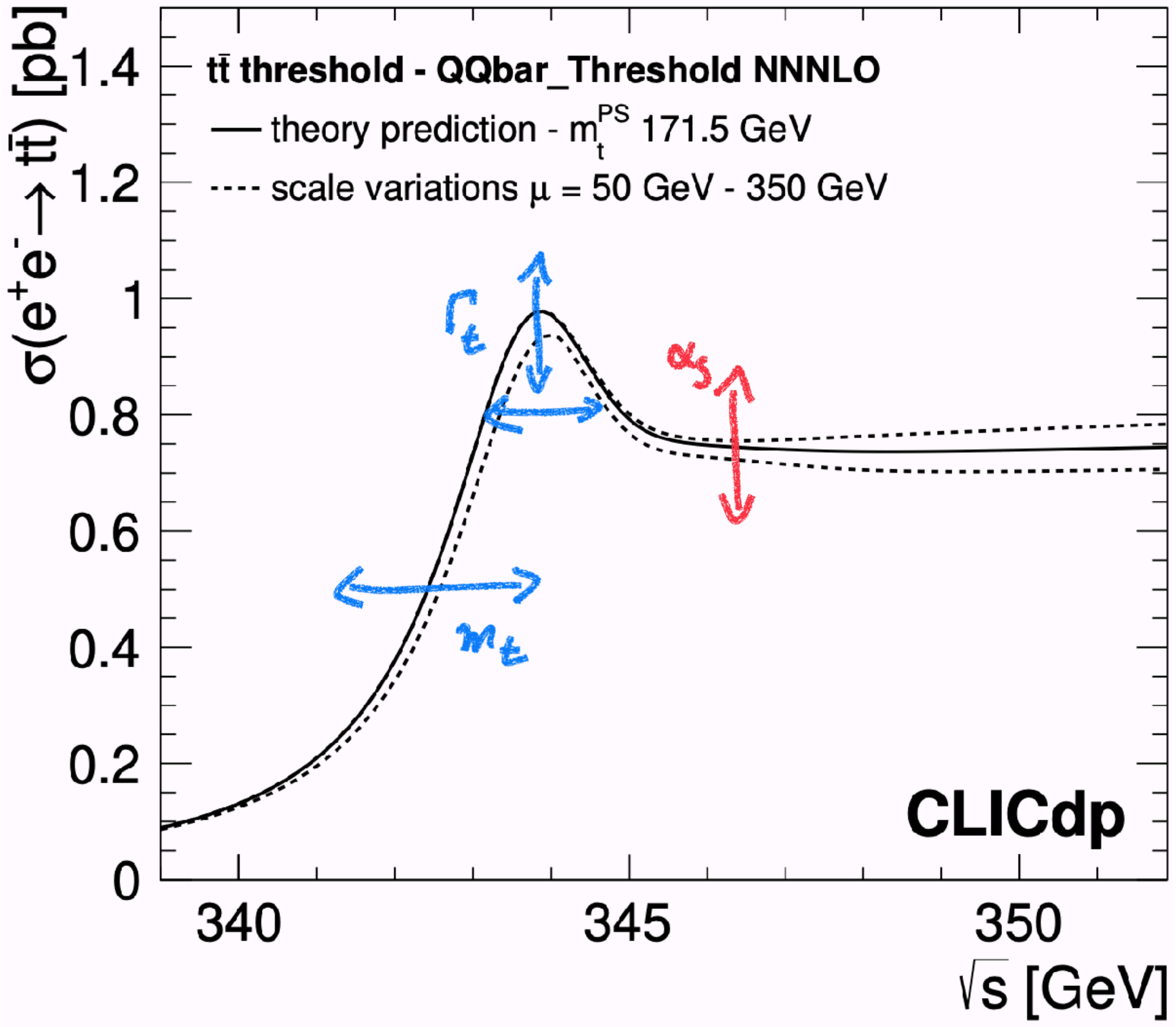

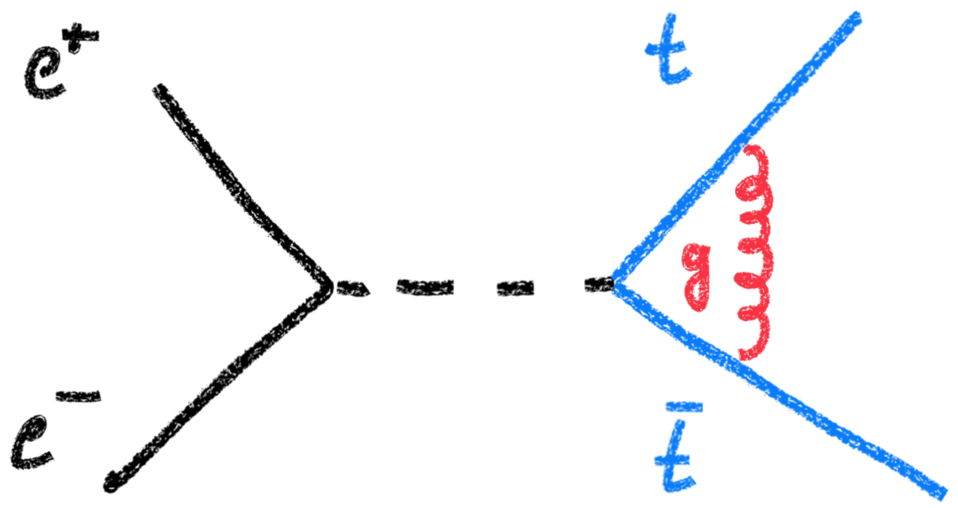

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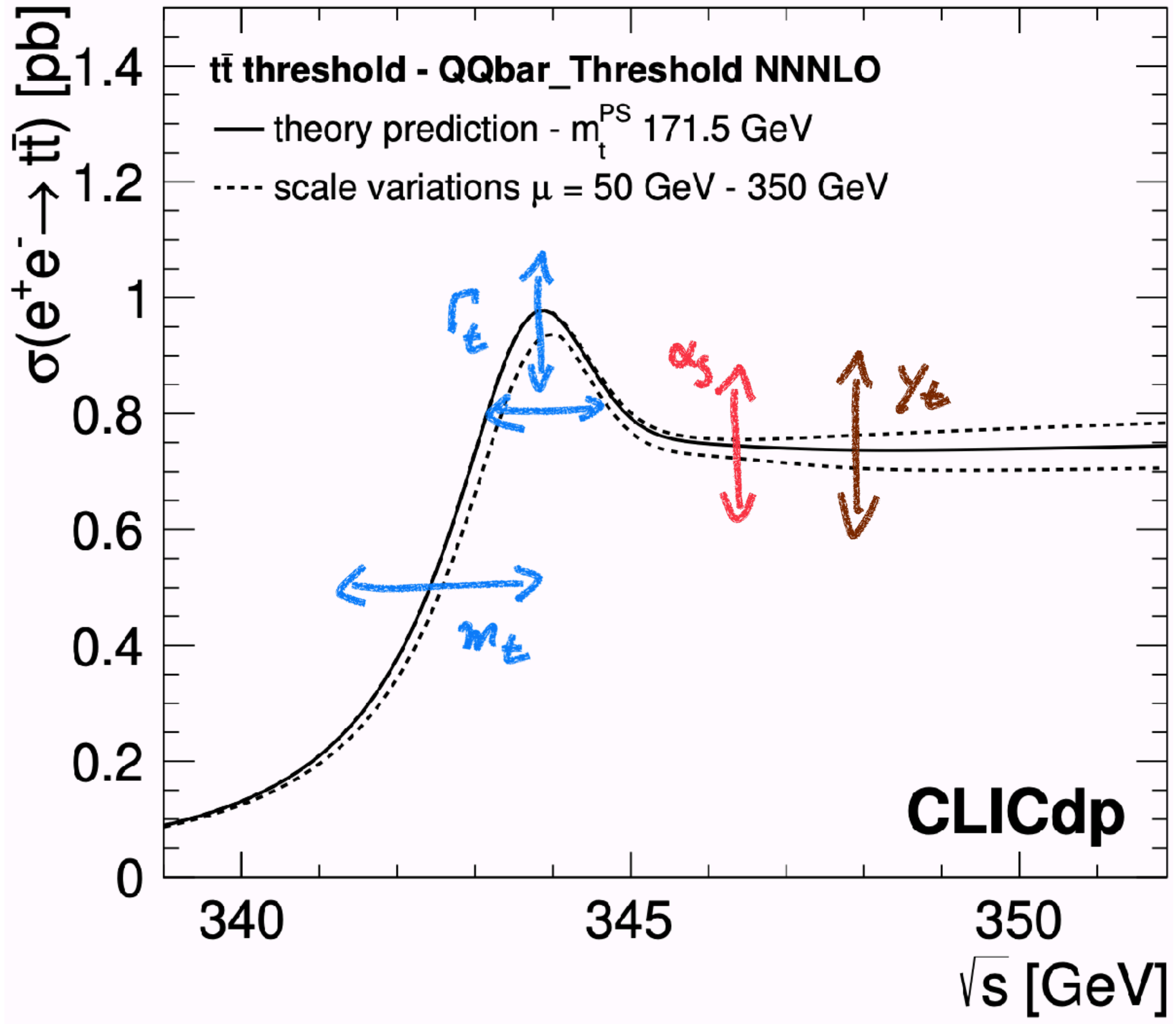

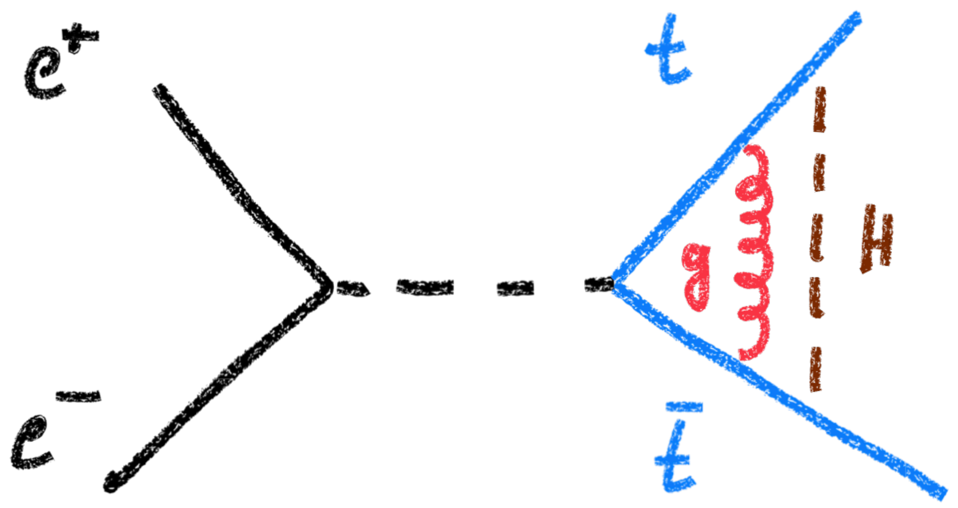

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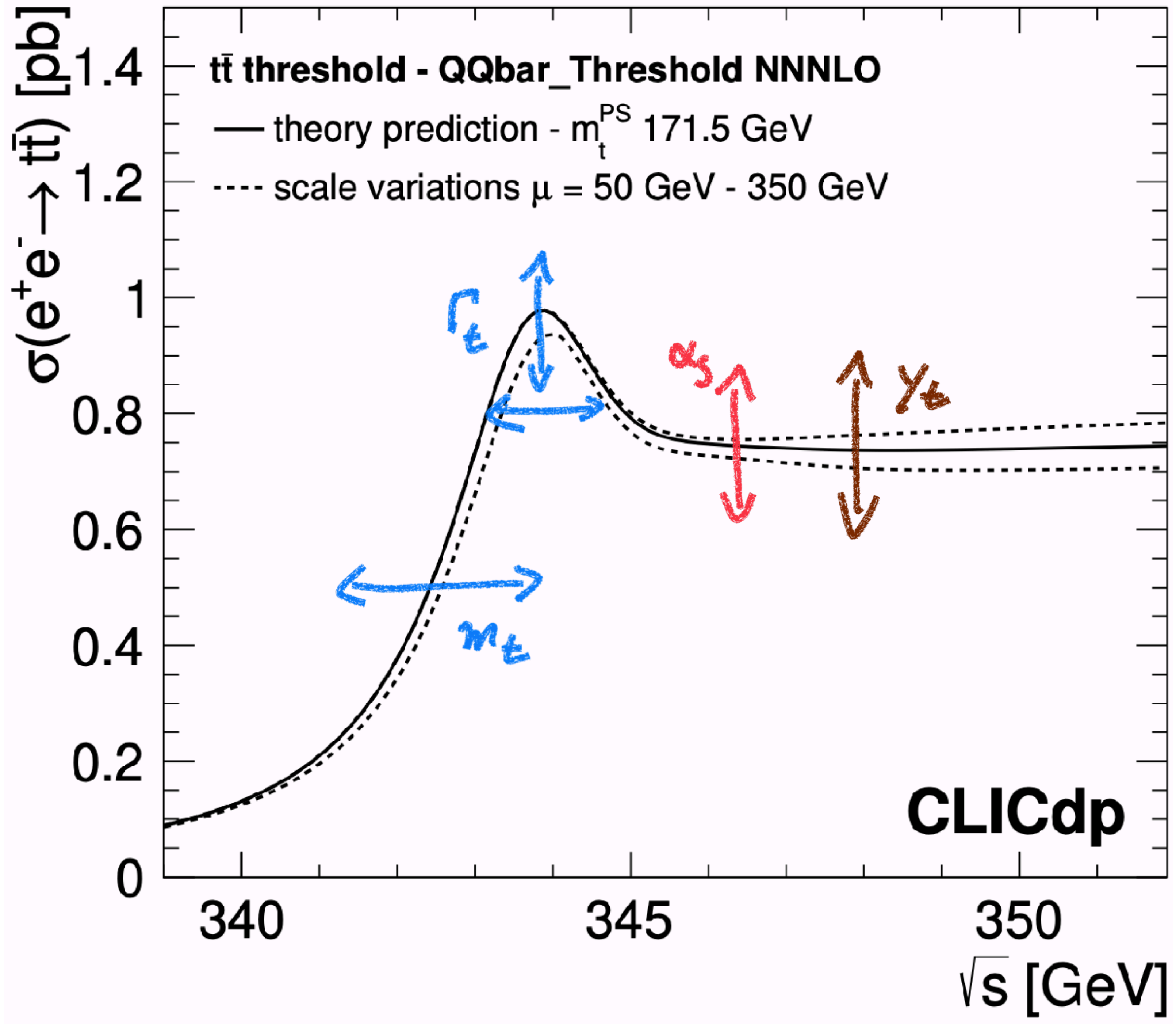

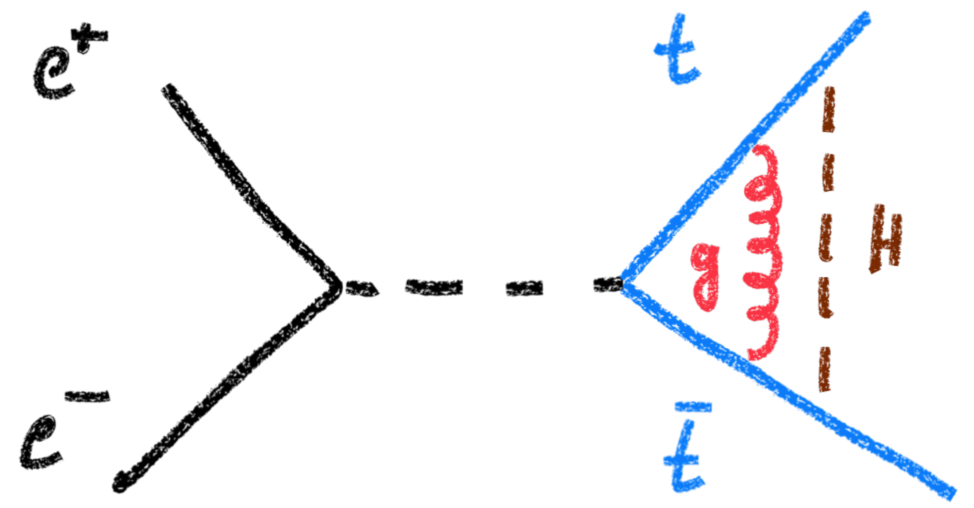

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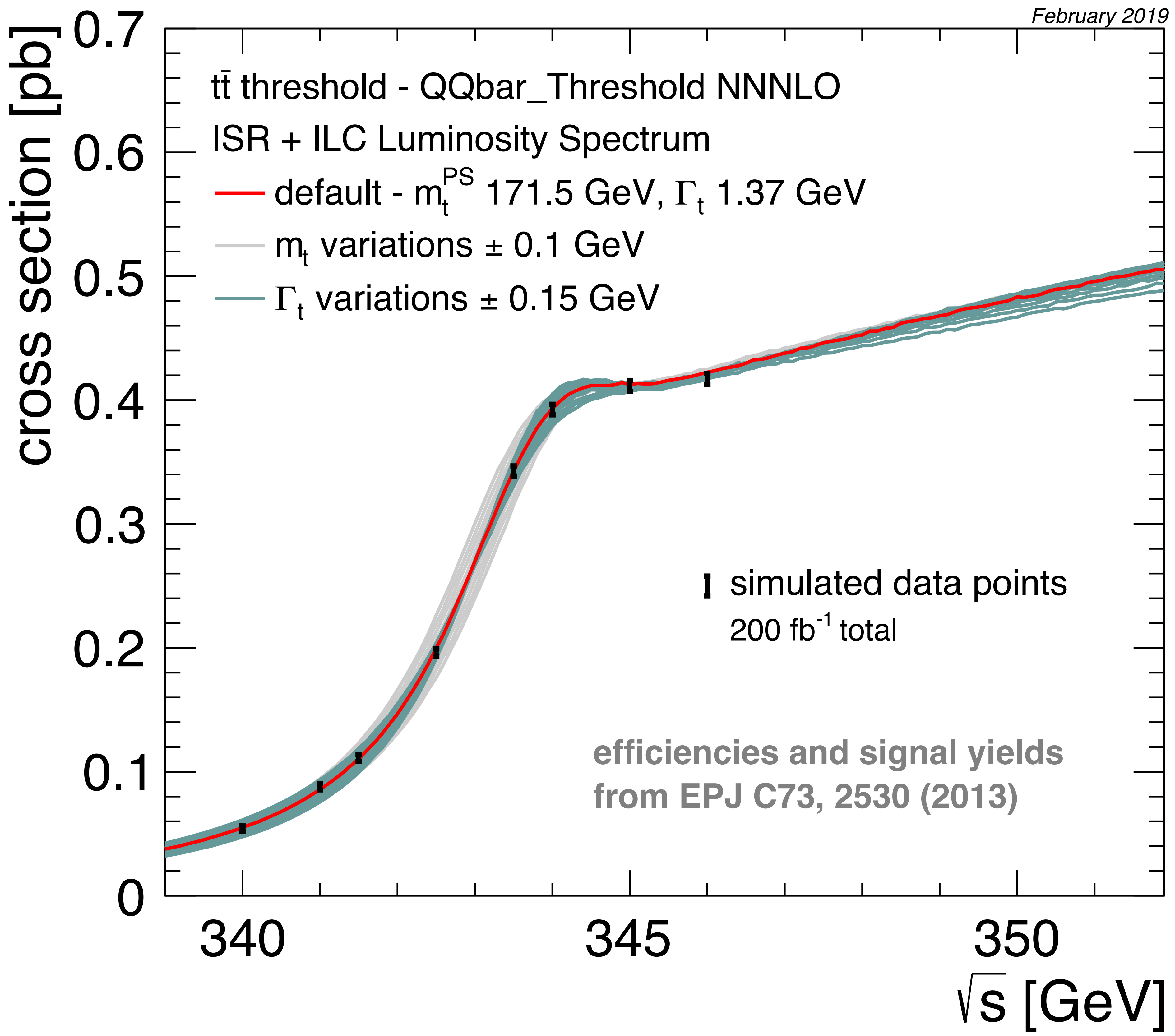
ISR, luminosity spectrum, reconstruction

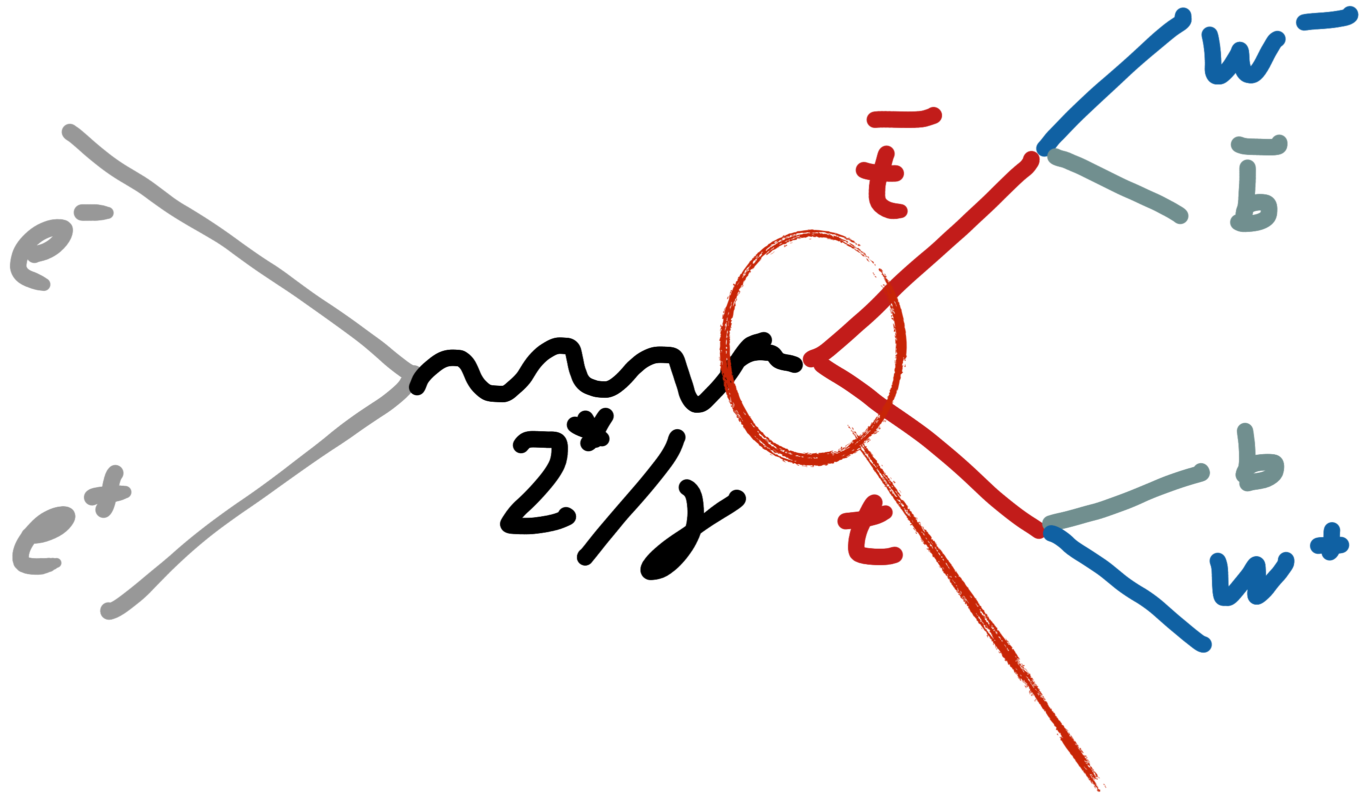
The potential for a measurement of the mass with < 50 MeV total uncertainty (dominated by theory) - stat. precision ~ 10 MeV



The threshold is sensitive to top quark properties

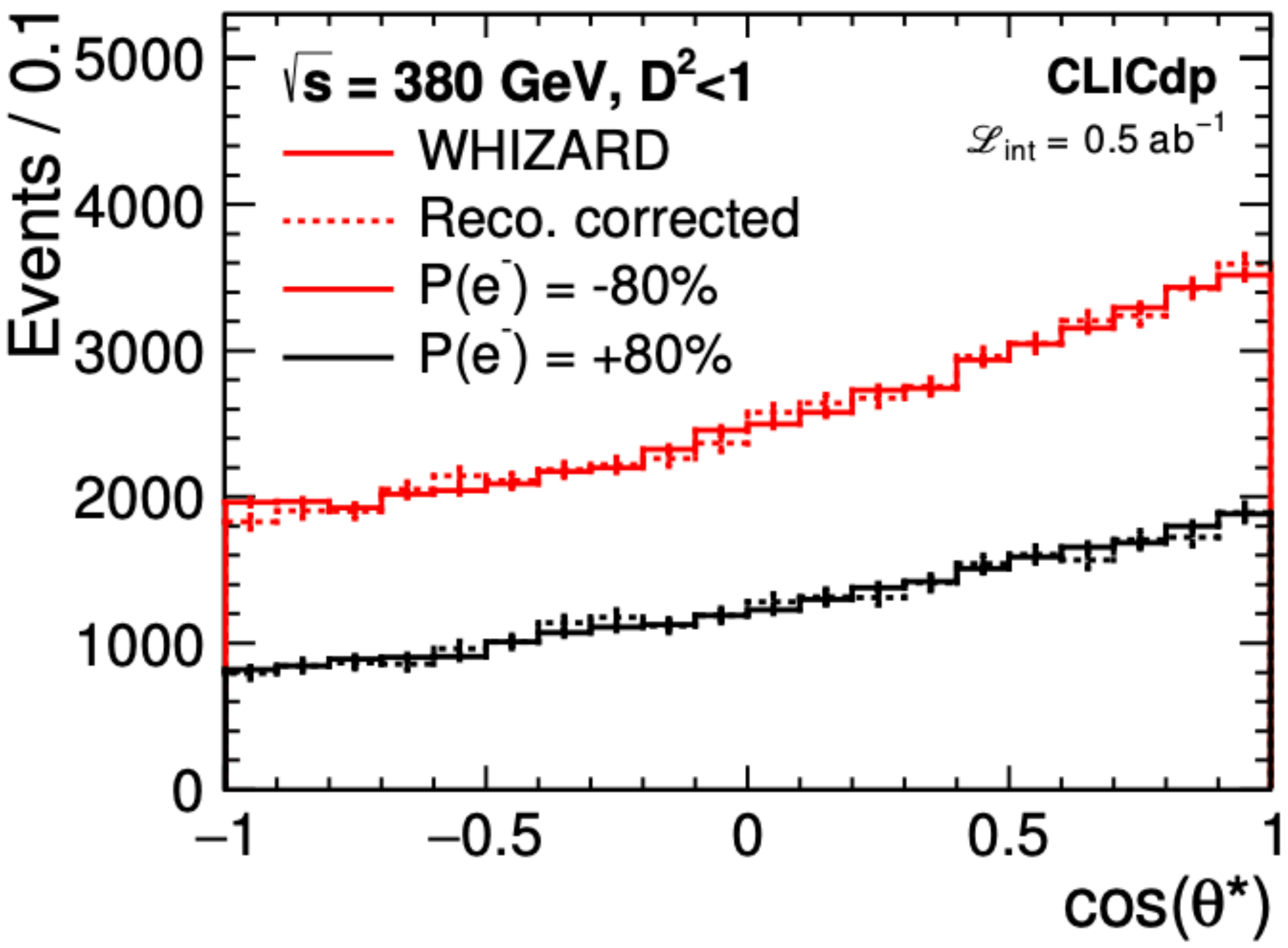
Electroweak Couplings of the Top Quark

Access via cross section and asymmetries



Accessing electroweak couplings in ttbar

- At Linear Colliders:
  - Using different beam polarisations
  - Measuring cross section, A_{FB}, and helicity angle (some studies)
  - Particularly powerful with two (or more) energy points



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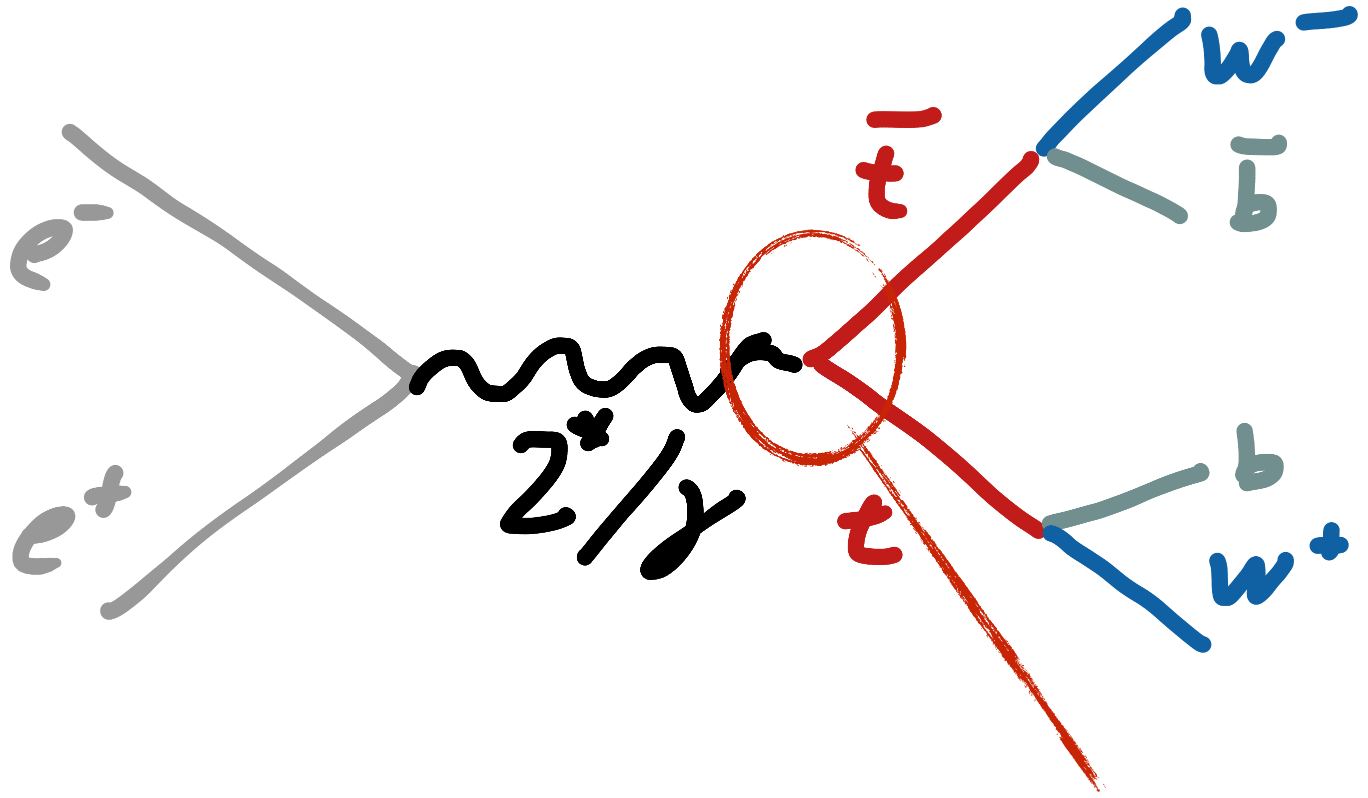

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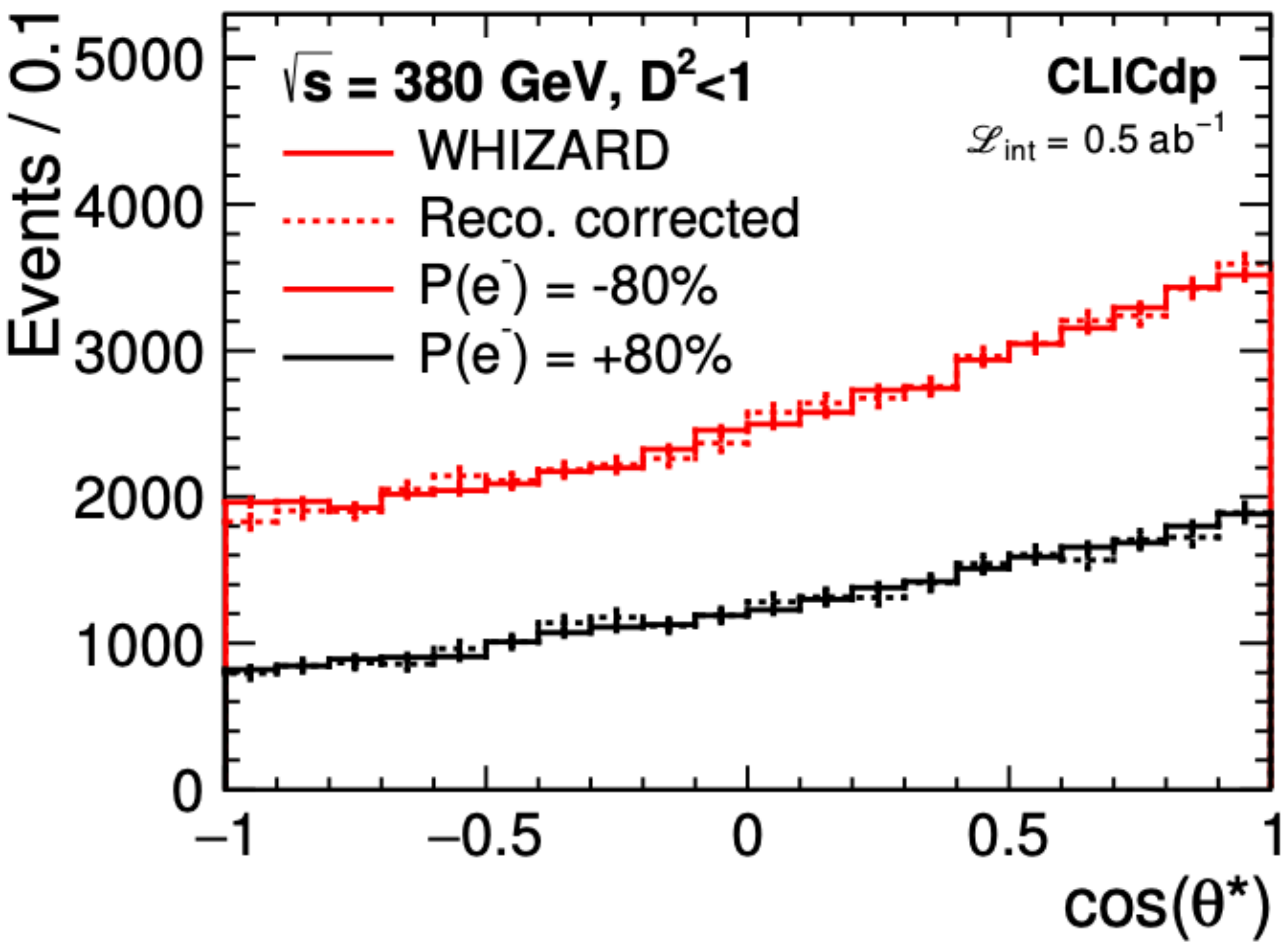
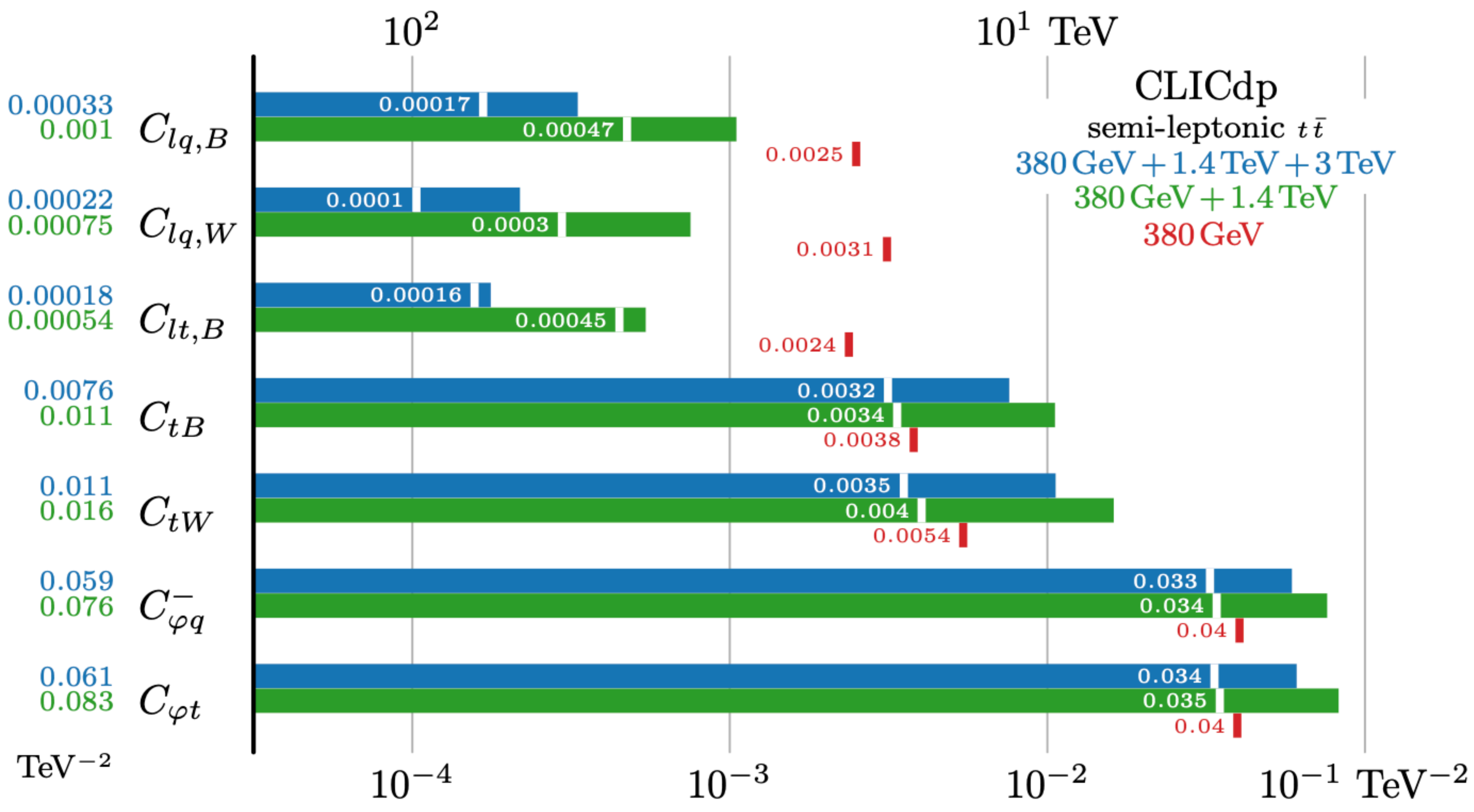


As an example: CLIC EFT-interpretation -> Reach up to 100 TeV

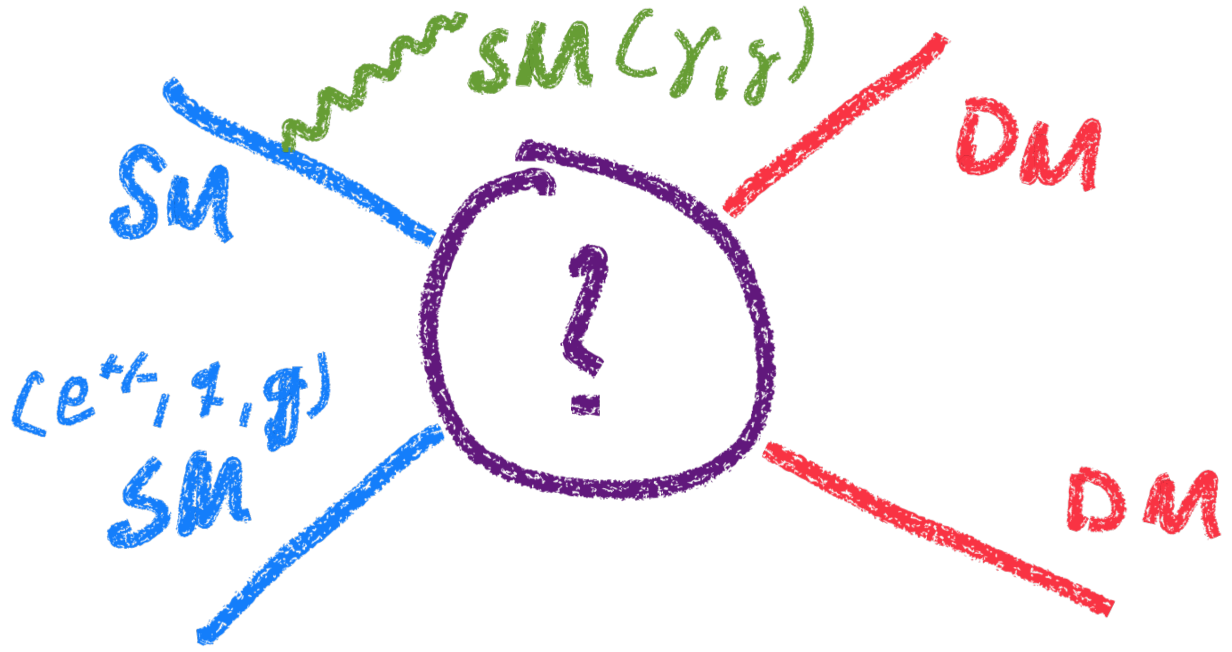


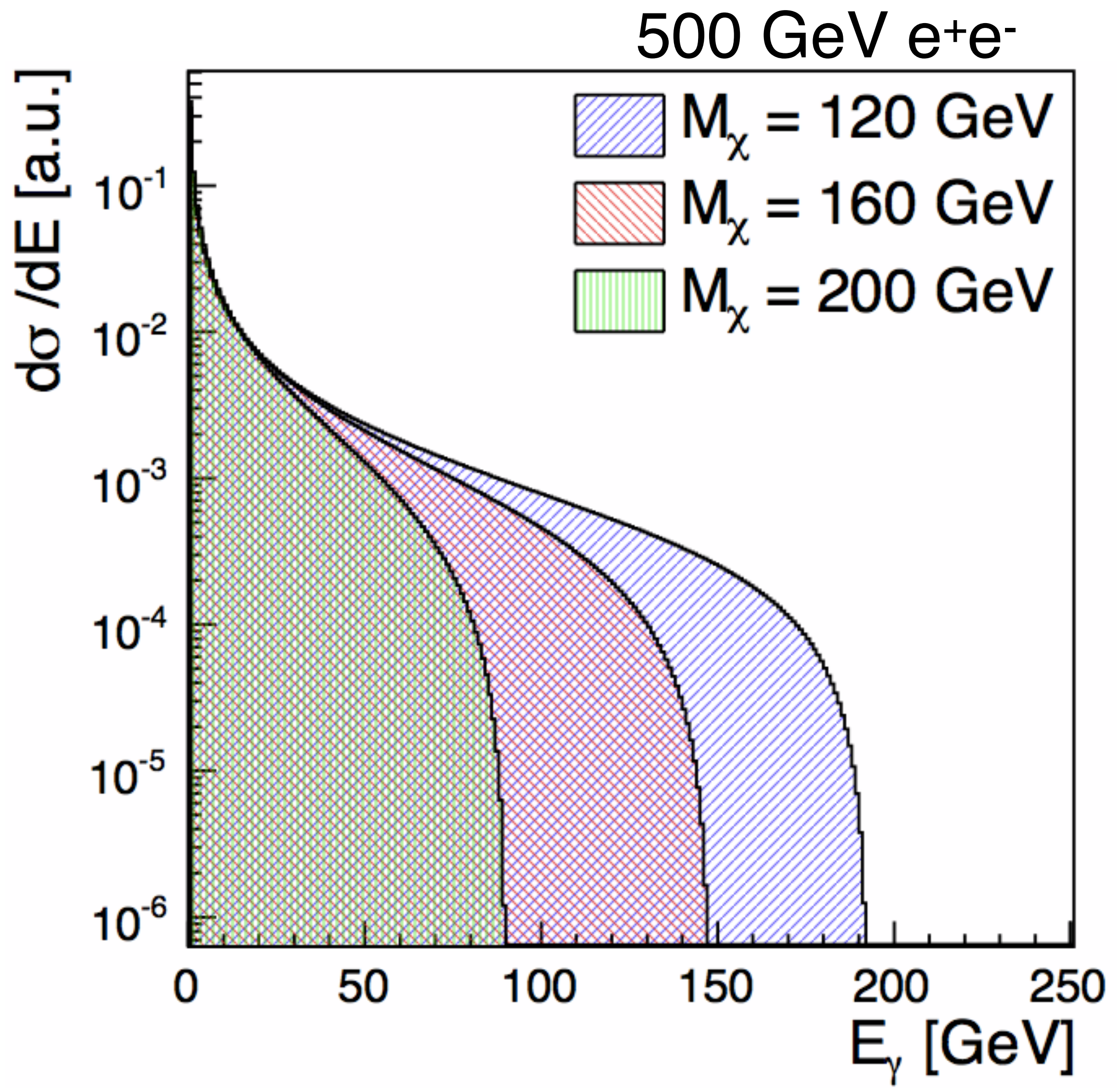
Into the Unknown

Searching for New Physics

- A (very) wide range of possibilities - a few obvious examples:

Search for Dark Matter





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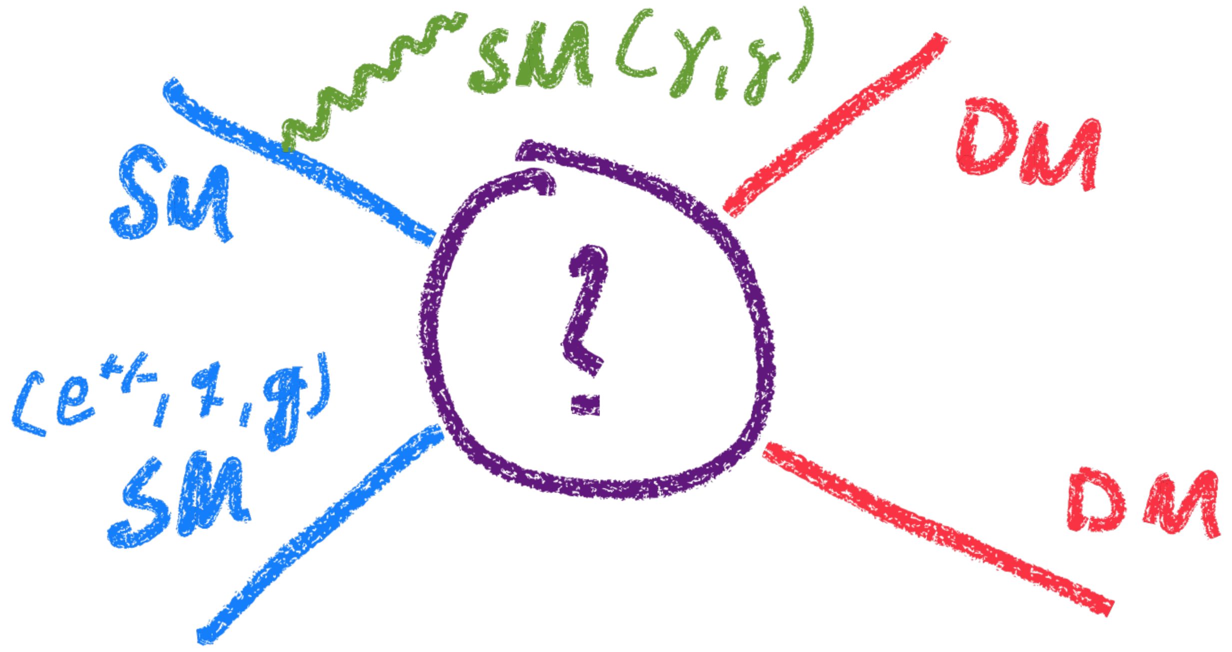

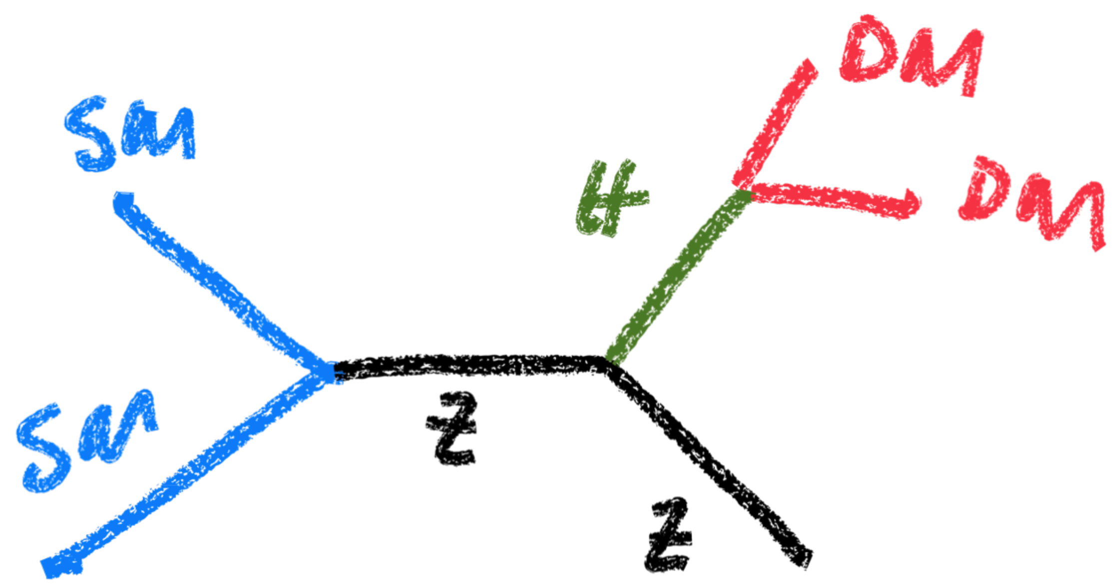

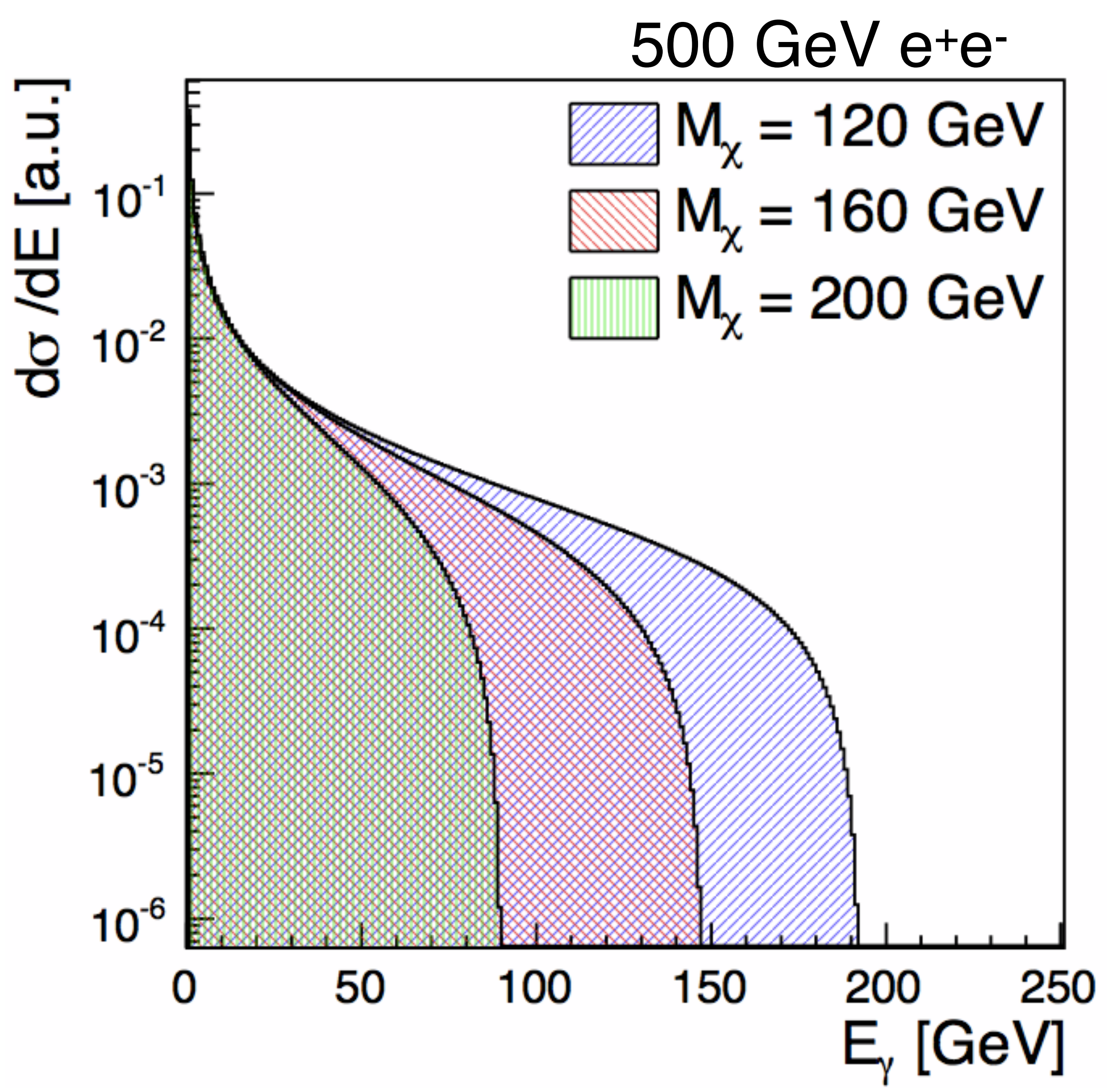

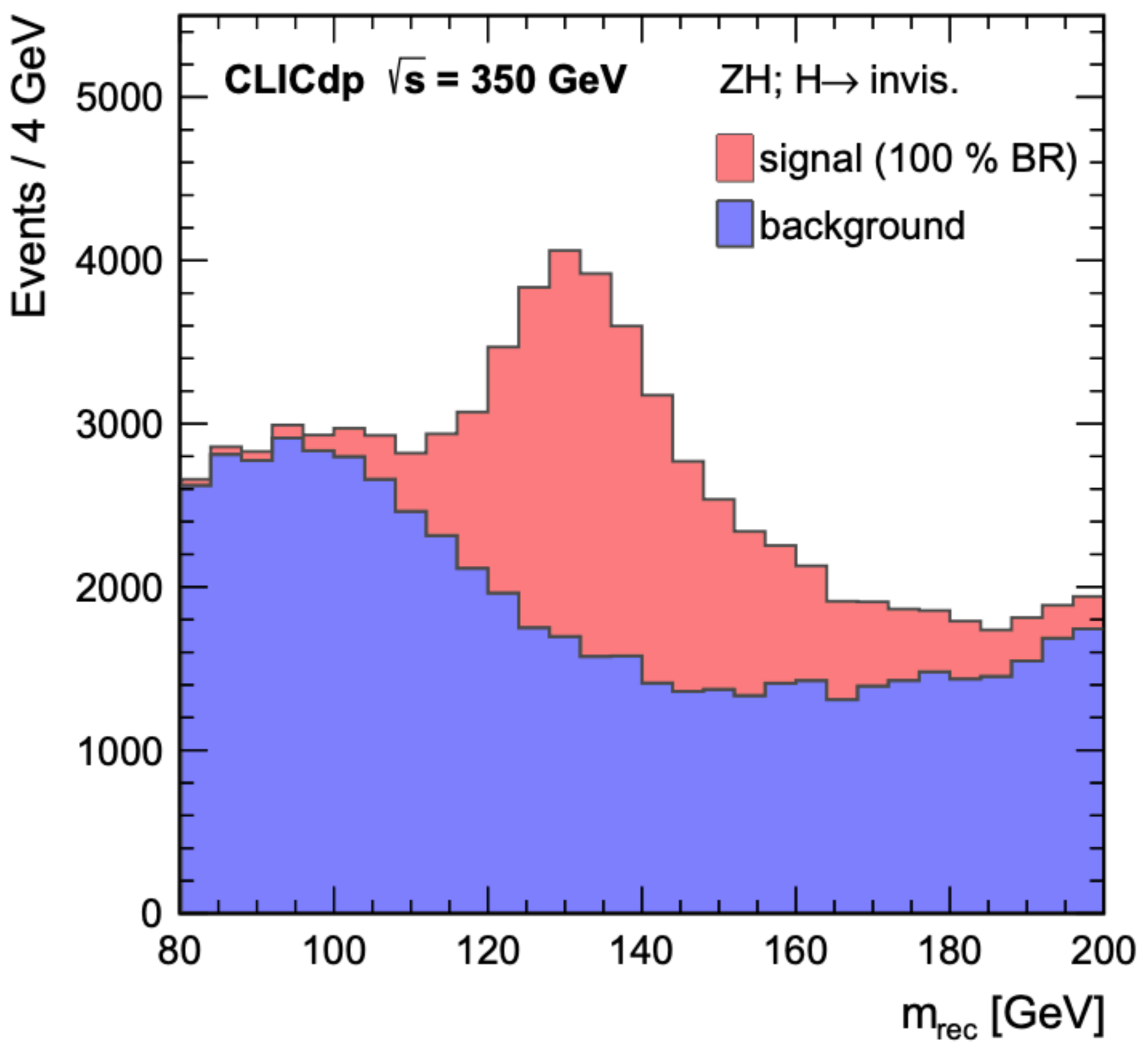

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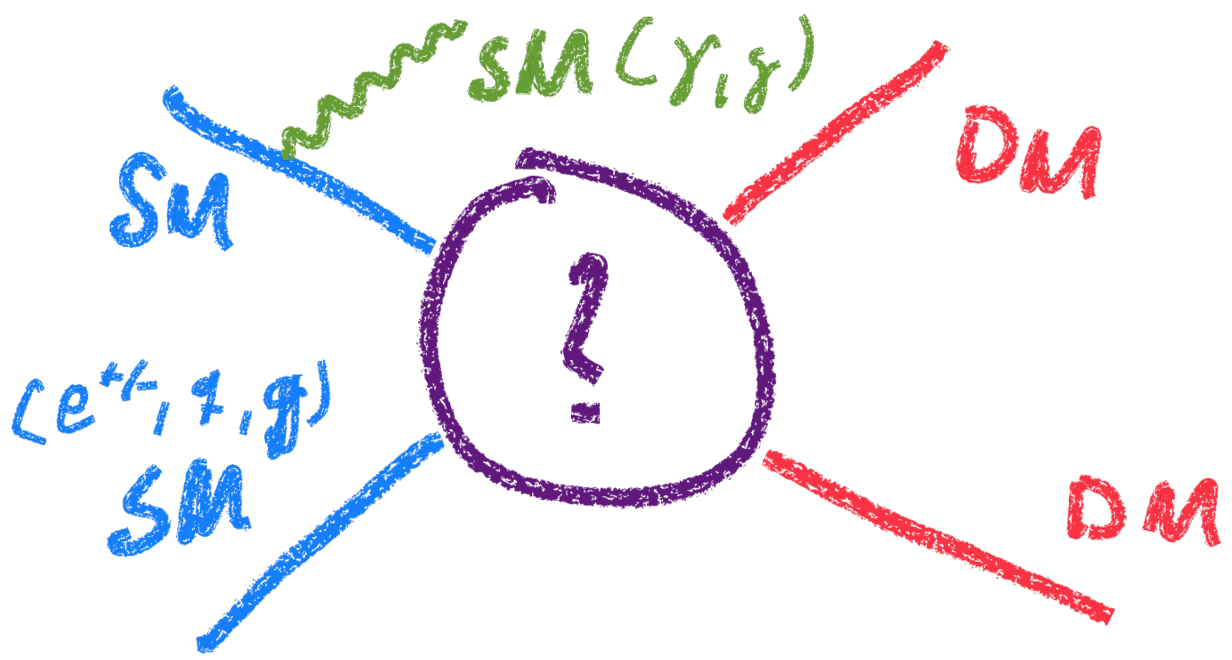
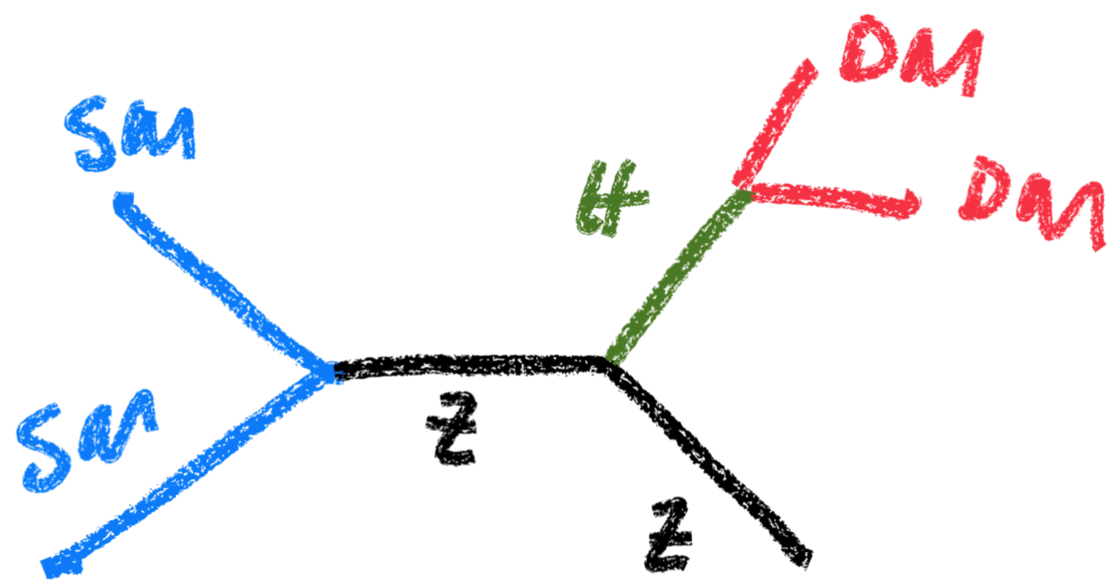
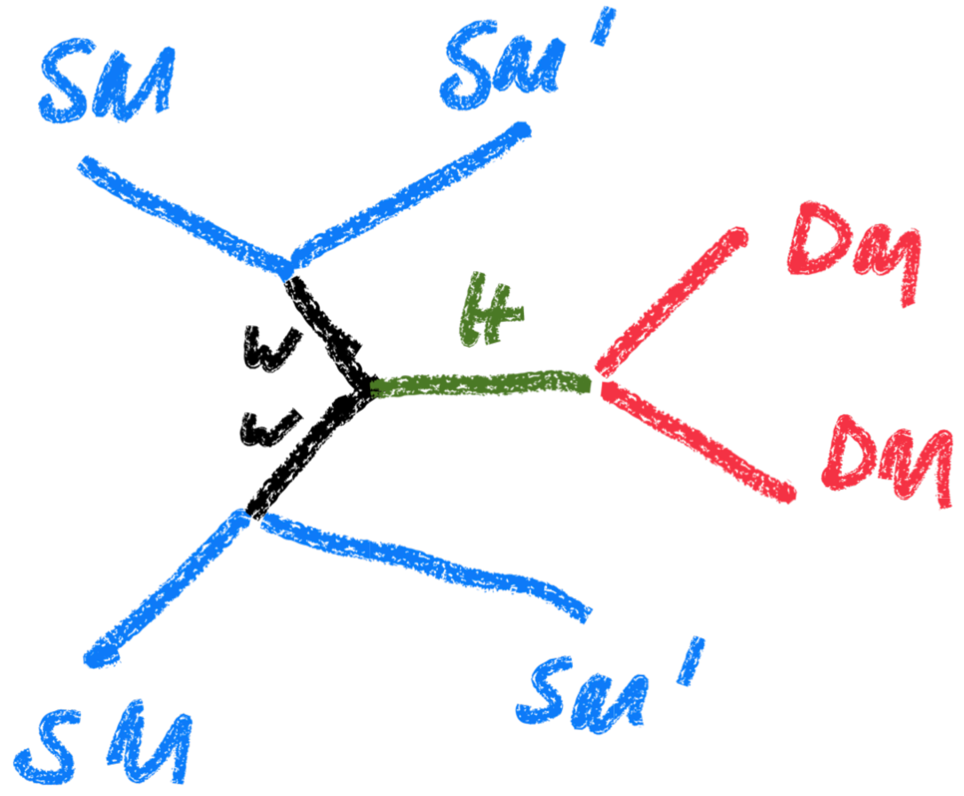
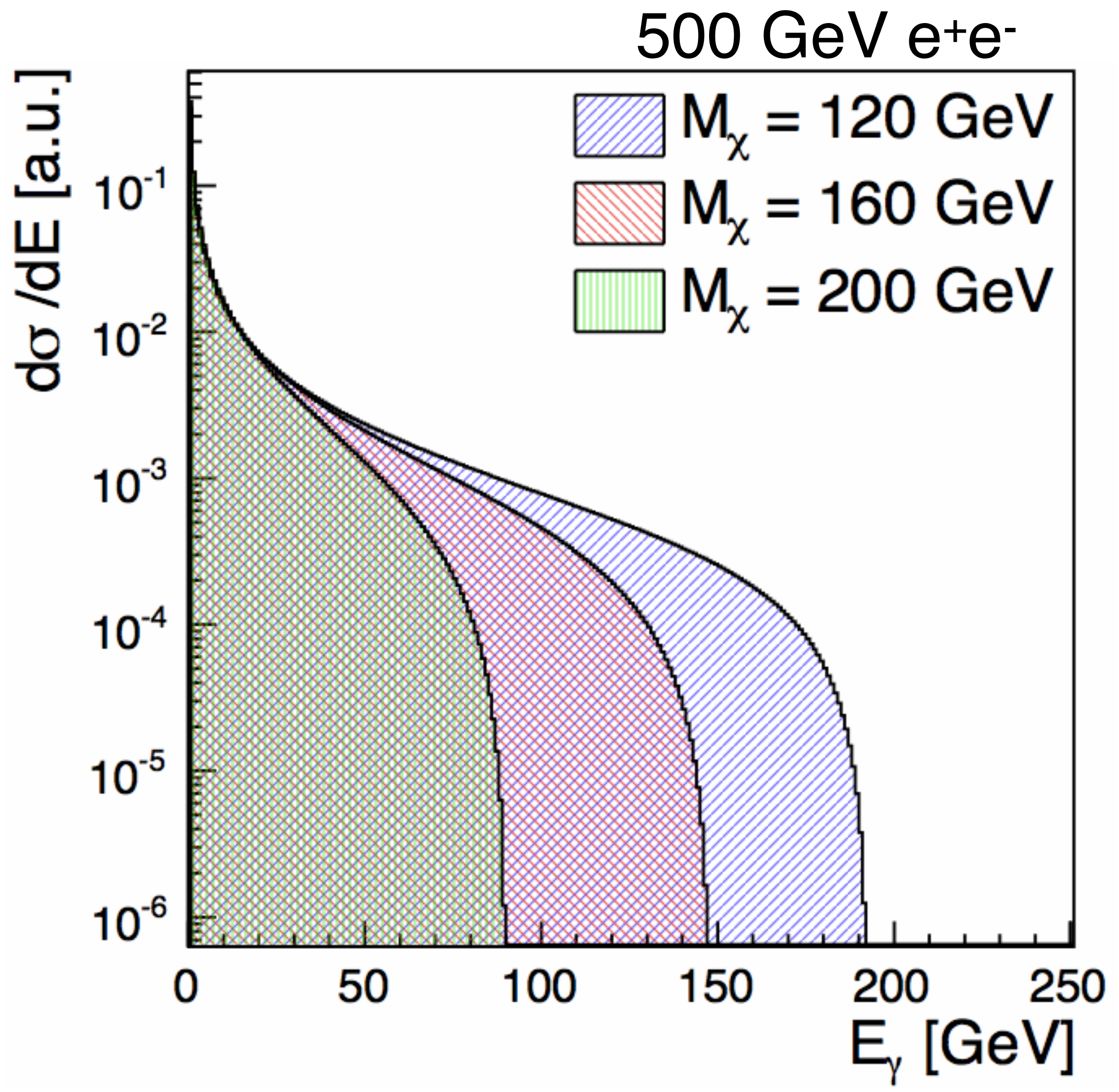
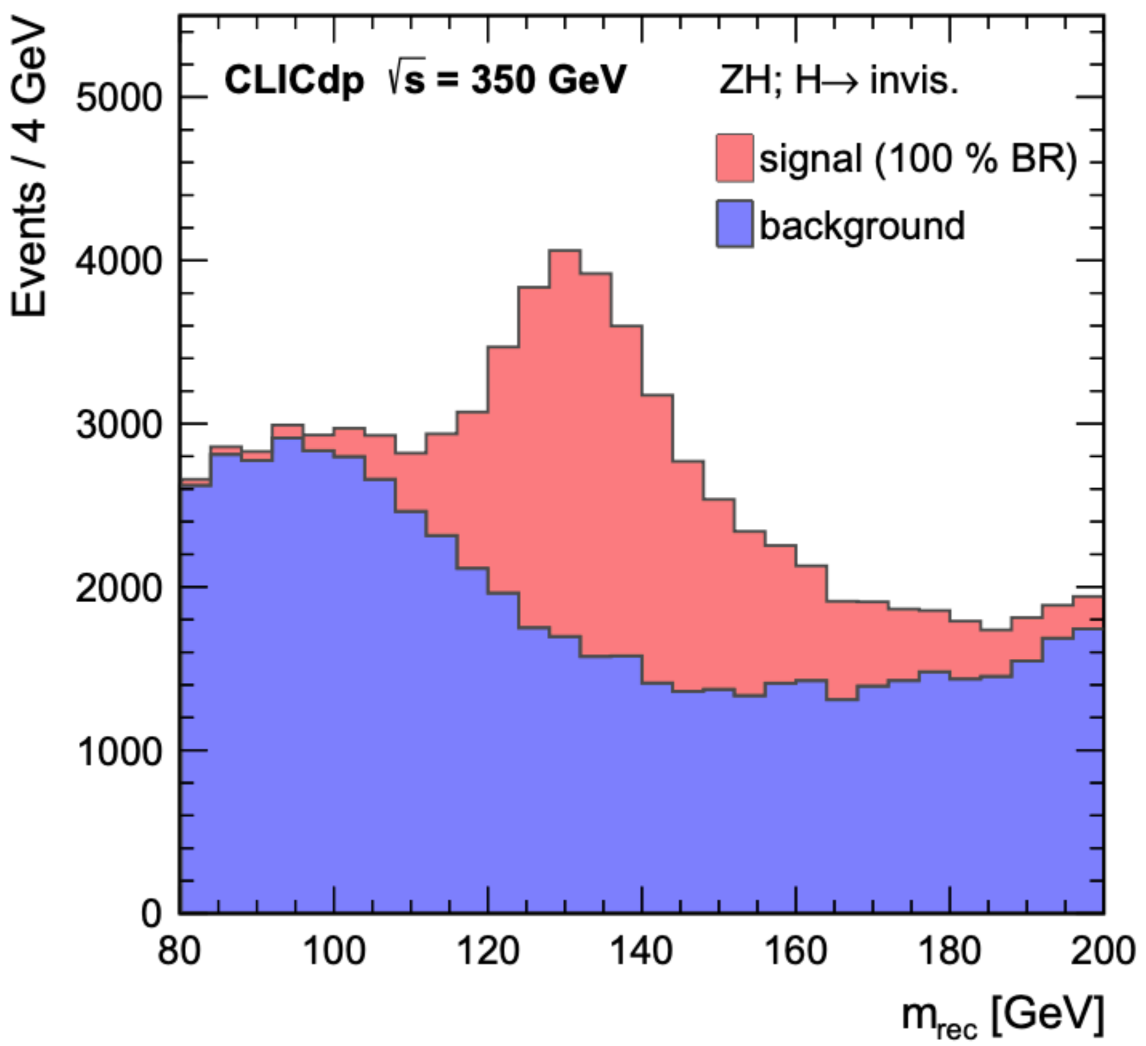








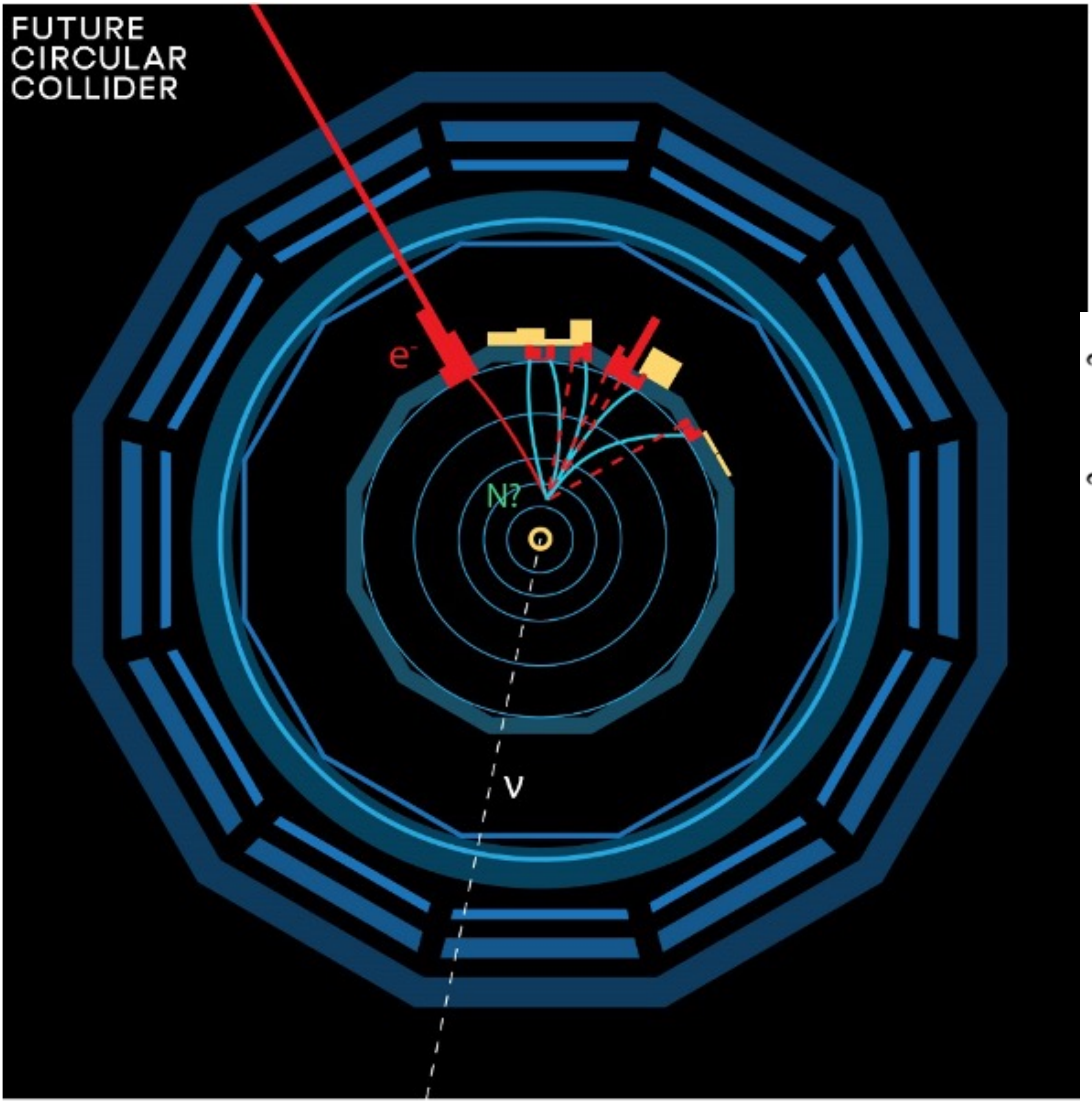


Sensitivity depends on

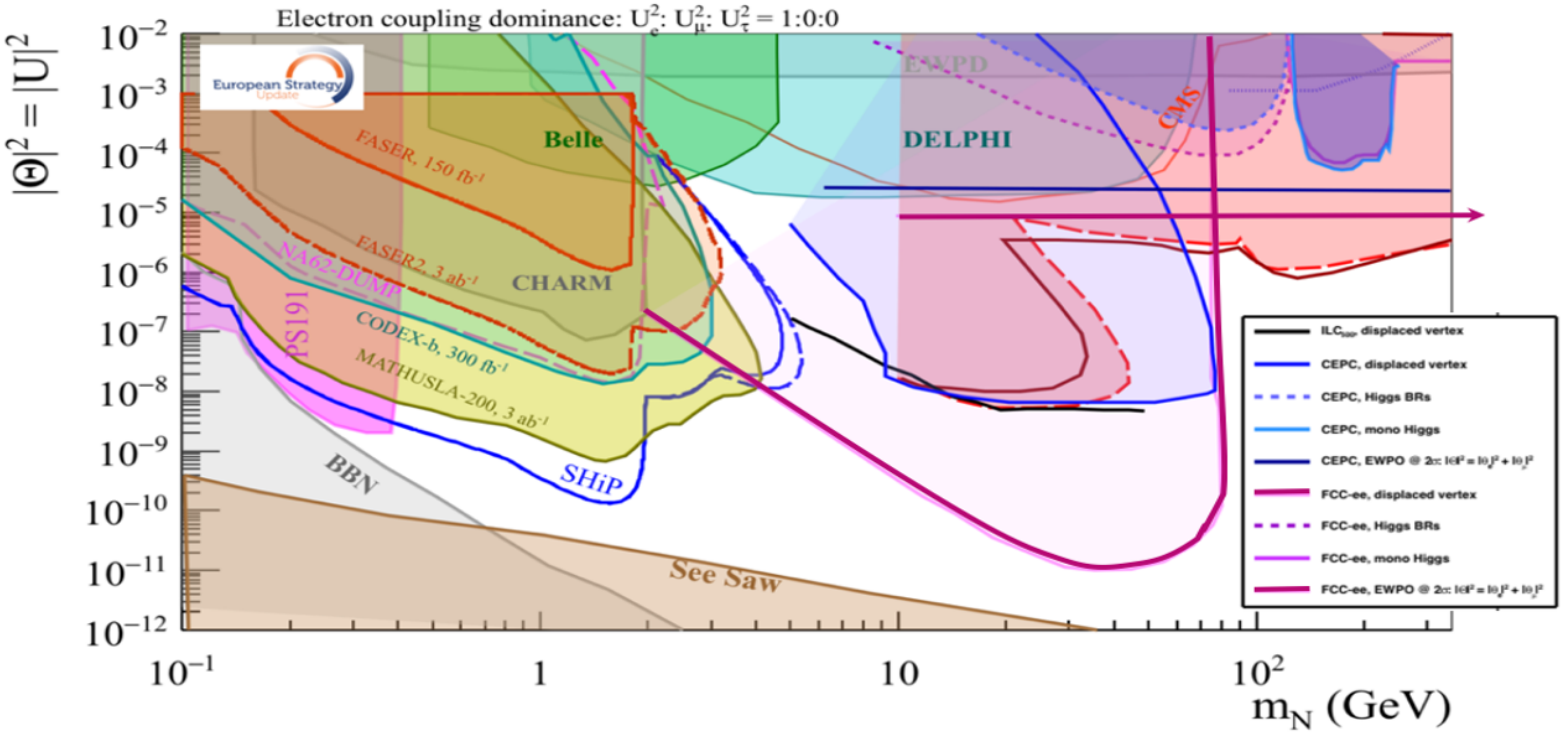
- Energy reach -> Mass coverage
- Background levels: Sensitivity to small couplings

Into the Unknown

Dark Sector Searches - an FCC-ee example

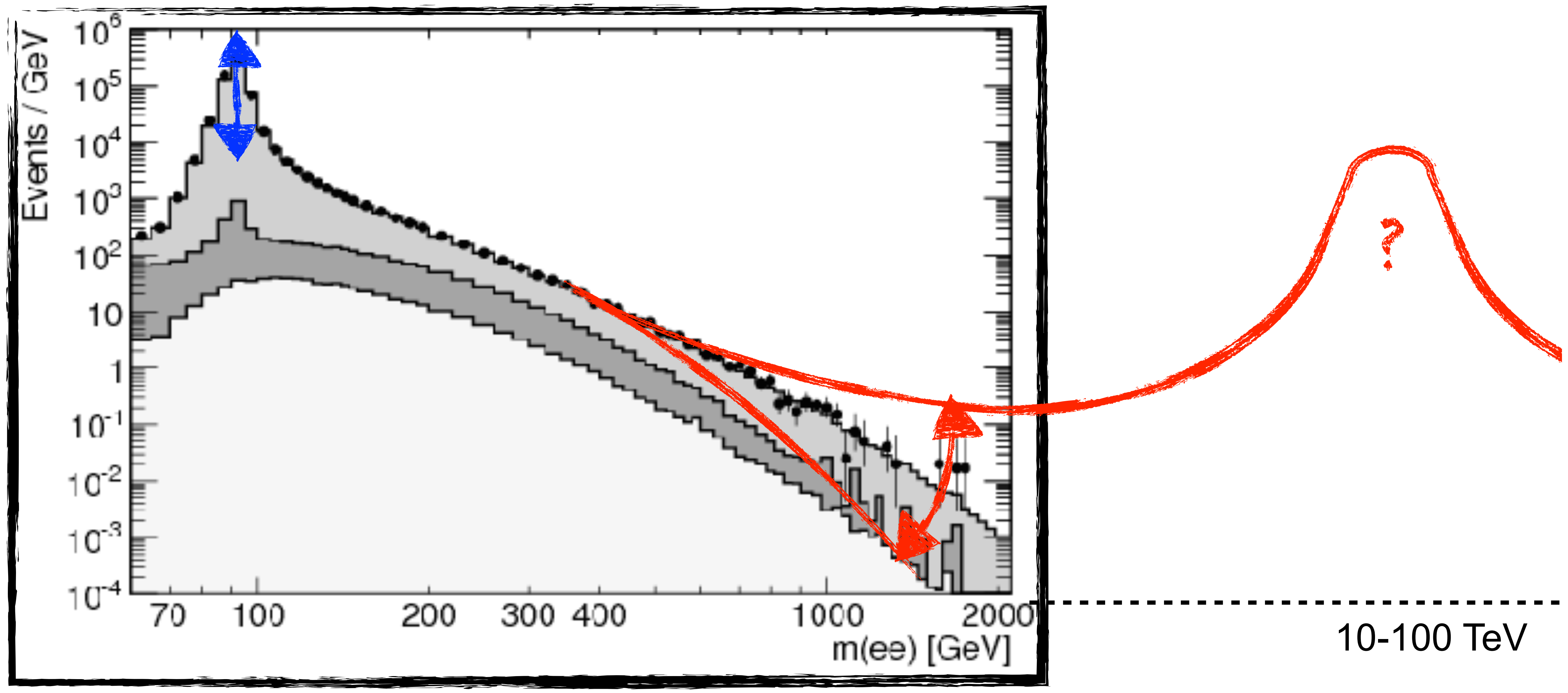


- Exploiting extreme statistics to search for heavy neutral leptons (right-handed sterile neutrinos, …): Z-> ν+HNL



mass vs mixing² - unique phase space covered by FCC-ee

- Indirect probes with lepton colliders



For many generic models & new interactions:

Corrections to SM suppressed by 1/(mass scale)^2

➯ Sensitivity grows with s

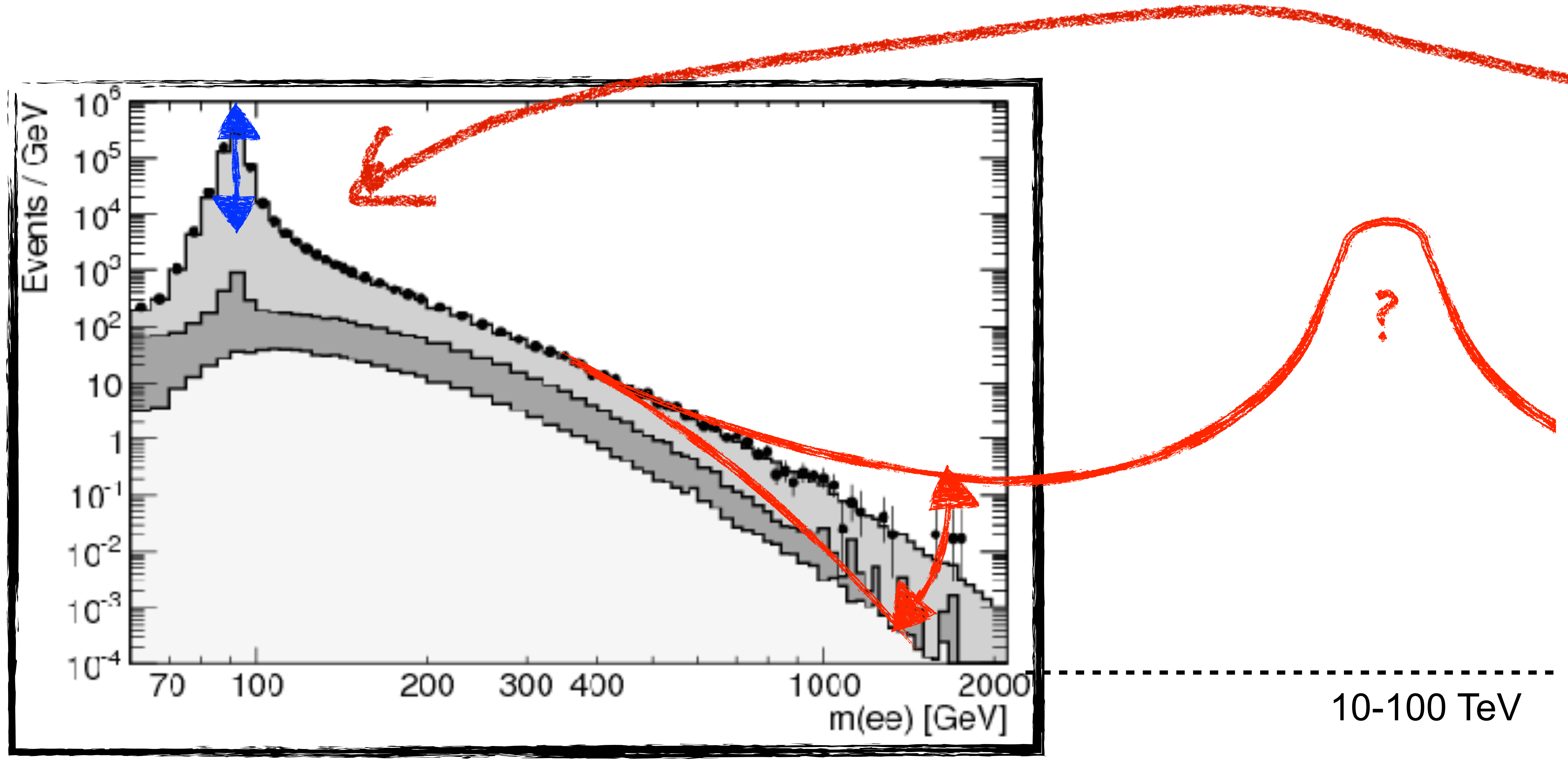
Into the Unknown

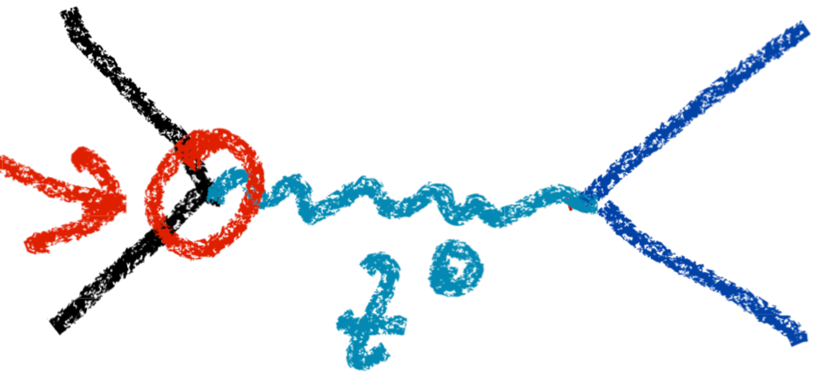
Indirect and direct exploration of the highest energy scales

- Indirect probes with lepton colliders

extreme precision with Z-pole programs

(and other measurements we talked about)





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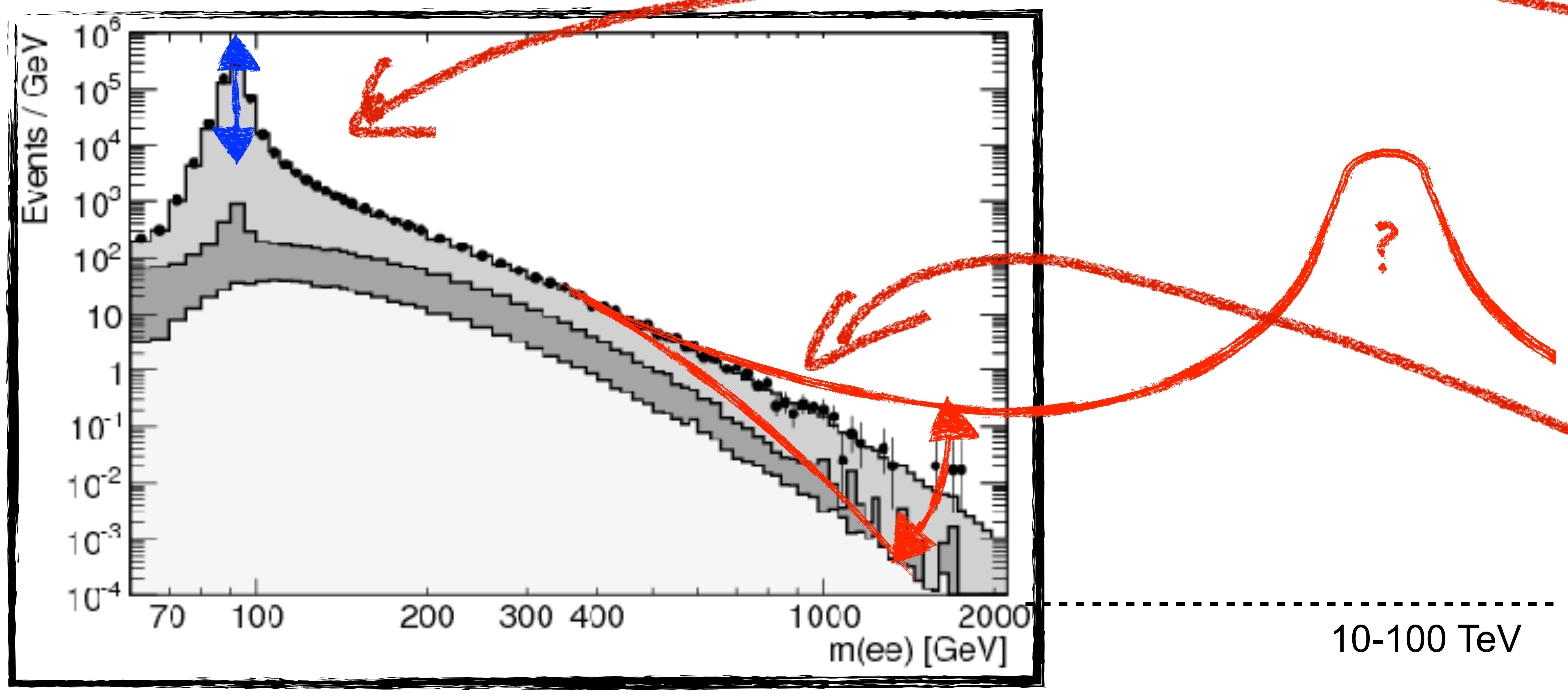

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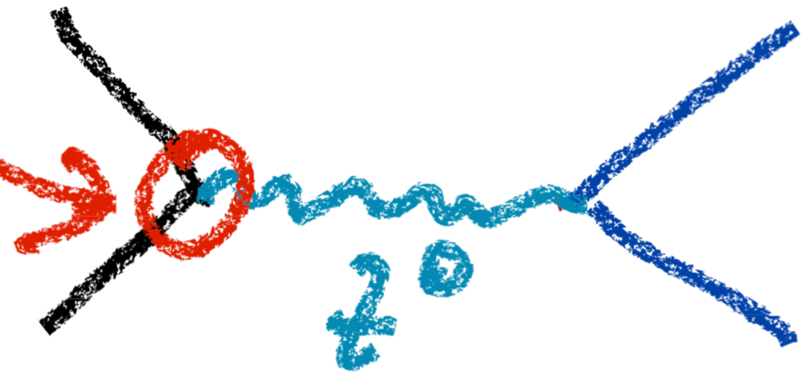
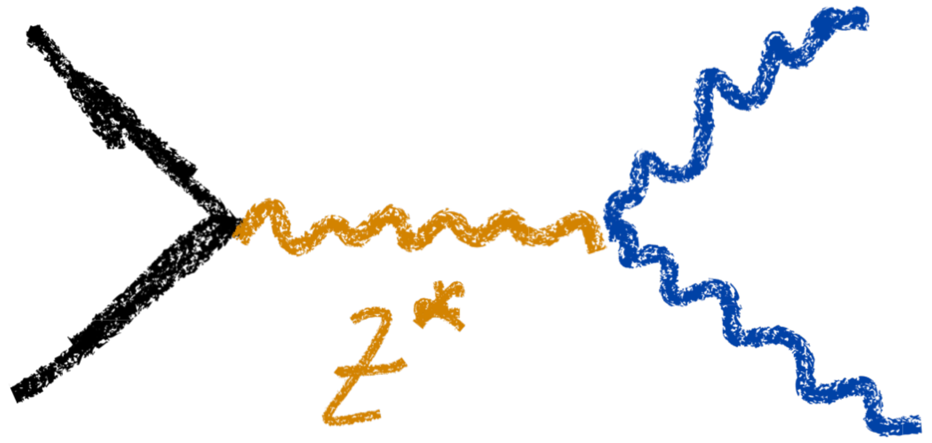


larger effects at higher energies



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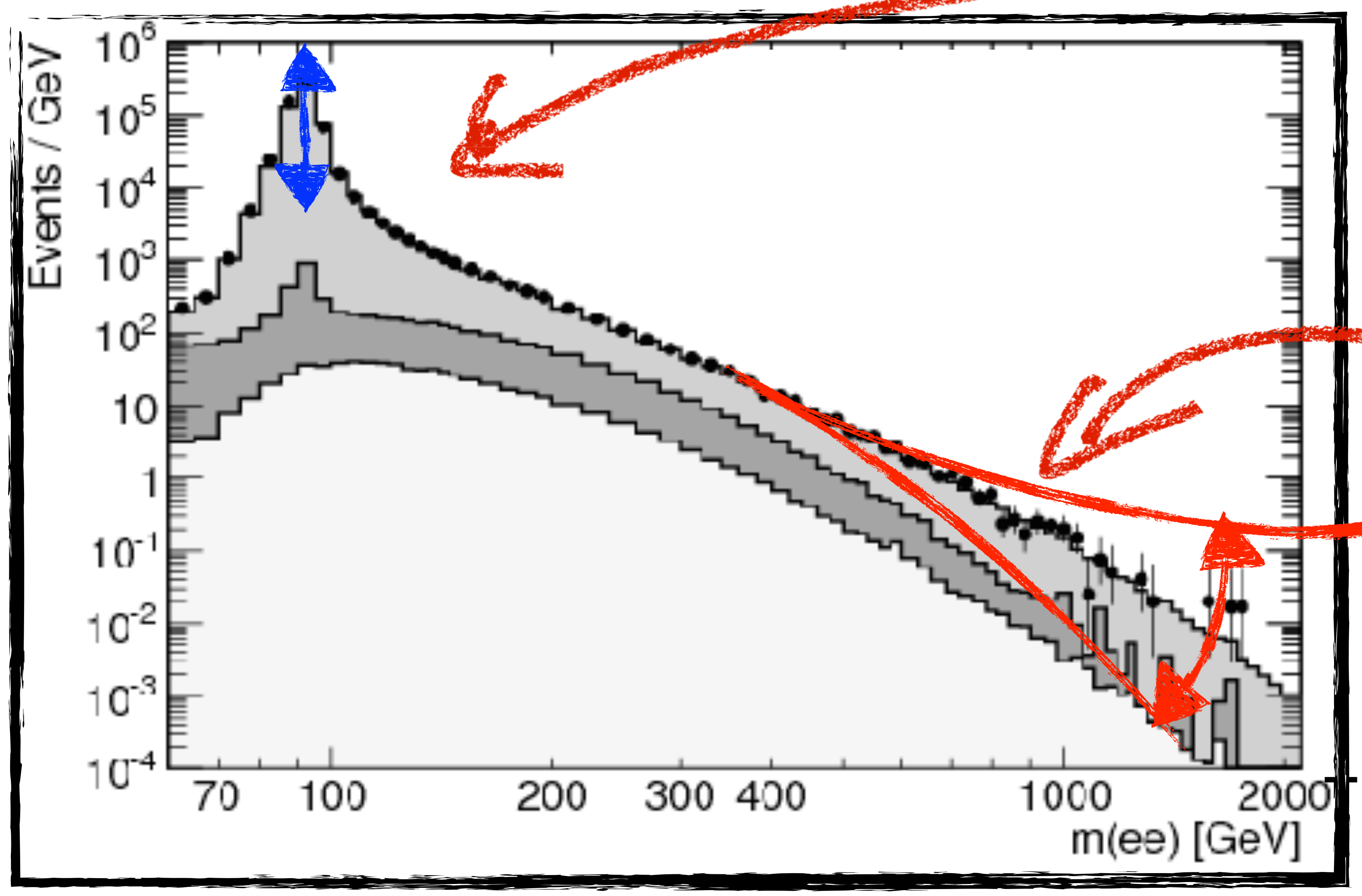

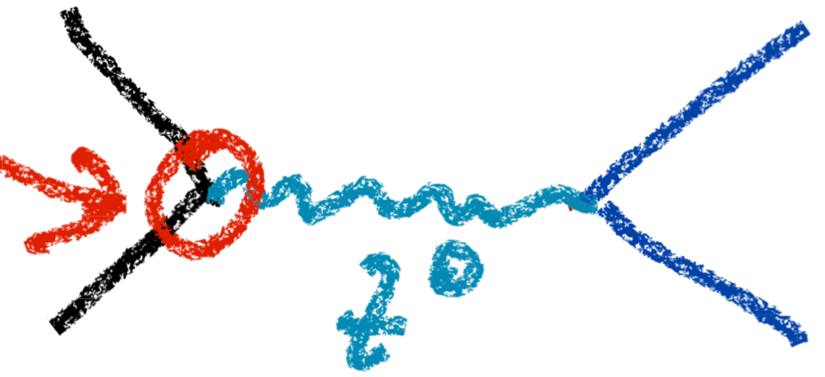

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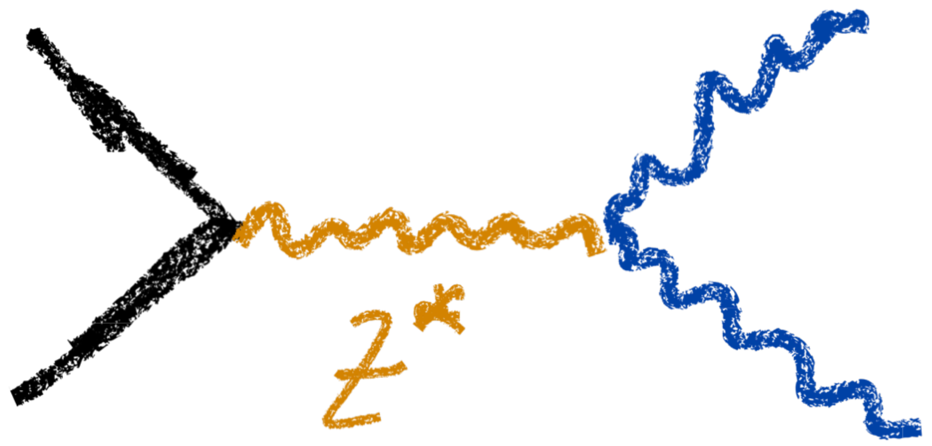

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Potential for direct production at highest energies - primarily hadron colliders, or 10+ TeV muon colliders

Conclusions

Wrapping up

Compelling Scientific Opportunities

Karlsruhe Institute of Technology

- An e^+e^- collider operating around 250 - 380 GeV will provide a model-independent, precise investigation of the Higgs sector, and studies of unprecedented precision of the top quark
- A revisit to the Z pole with much higher luminosity than LEP will enable to electroweak precision tests of the Standard Model at completely new levels. At the same time, this will also be a high-statistics flavour physics program.

- Scales in the TeV region and above can directly be probed by high-energy lepton colliders - CLIC, a (multi-)TeV ILC, and a muon collider. This also includes the measurement of the self-coupling of the Higgs.

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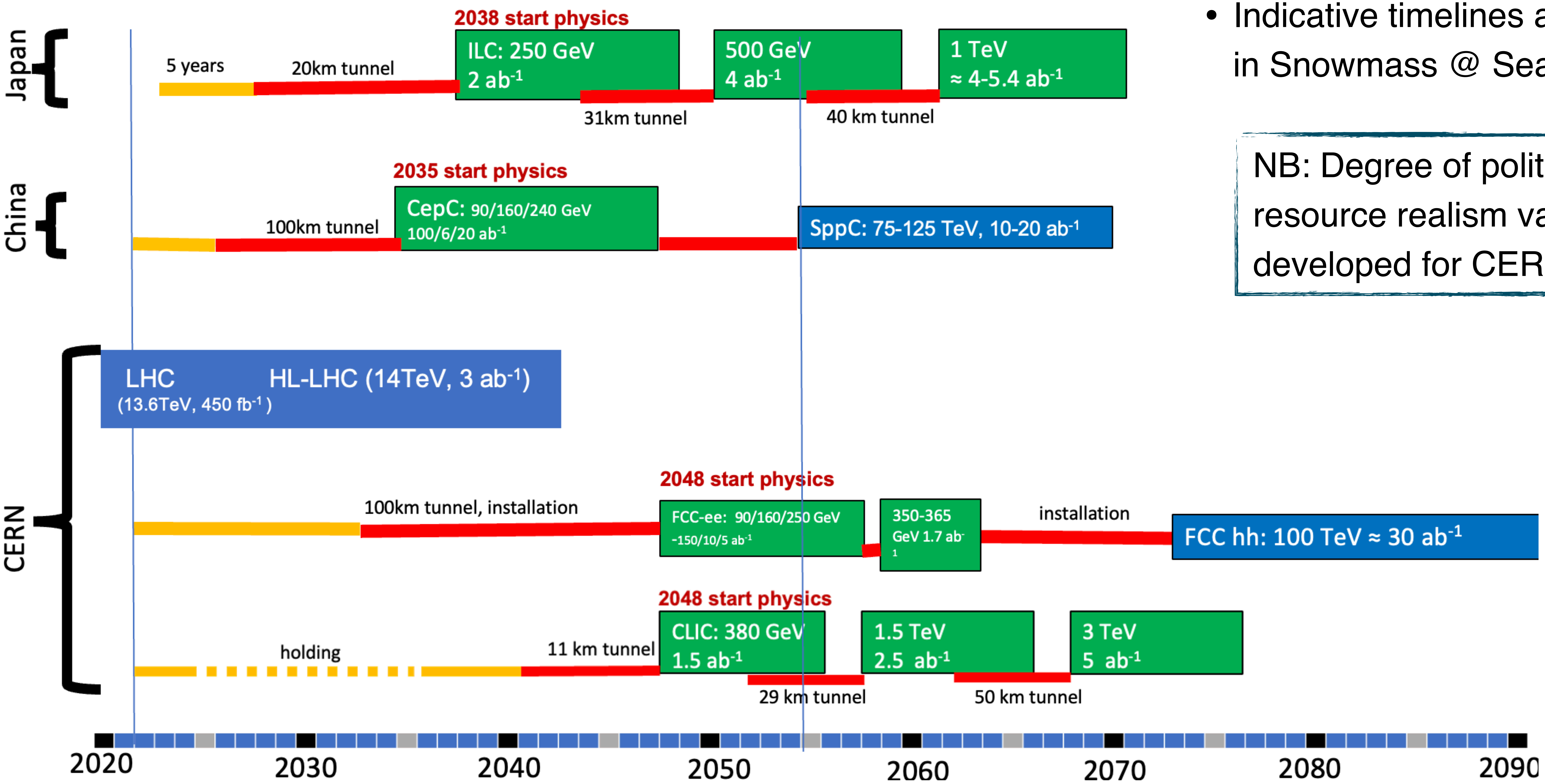
CERN is currently studying the feasibility of the **Future Circular Collider**:

- An e^+e^- machine running from the Z-pole up to 365 GeV - precision Higgs, Top, Electroweak.
- Followed by a ~ 100 TeV hadron collider - exploration of the highest energy scales, measurement of the self-coupling of the Higgs.

- **CLIC** is studied as “Option B” in case FCC cannot go forward.

The Way Forward

Strategies and Timescales - taken from 2022 Snowmass Meeting



- Indicative timelines as discussed in Snowmass @ Seattle

NB: Degree of political and resource realism varies - most developed for CERN projects

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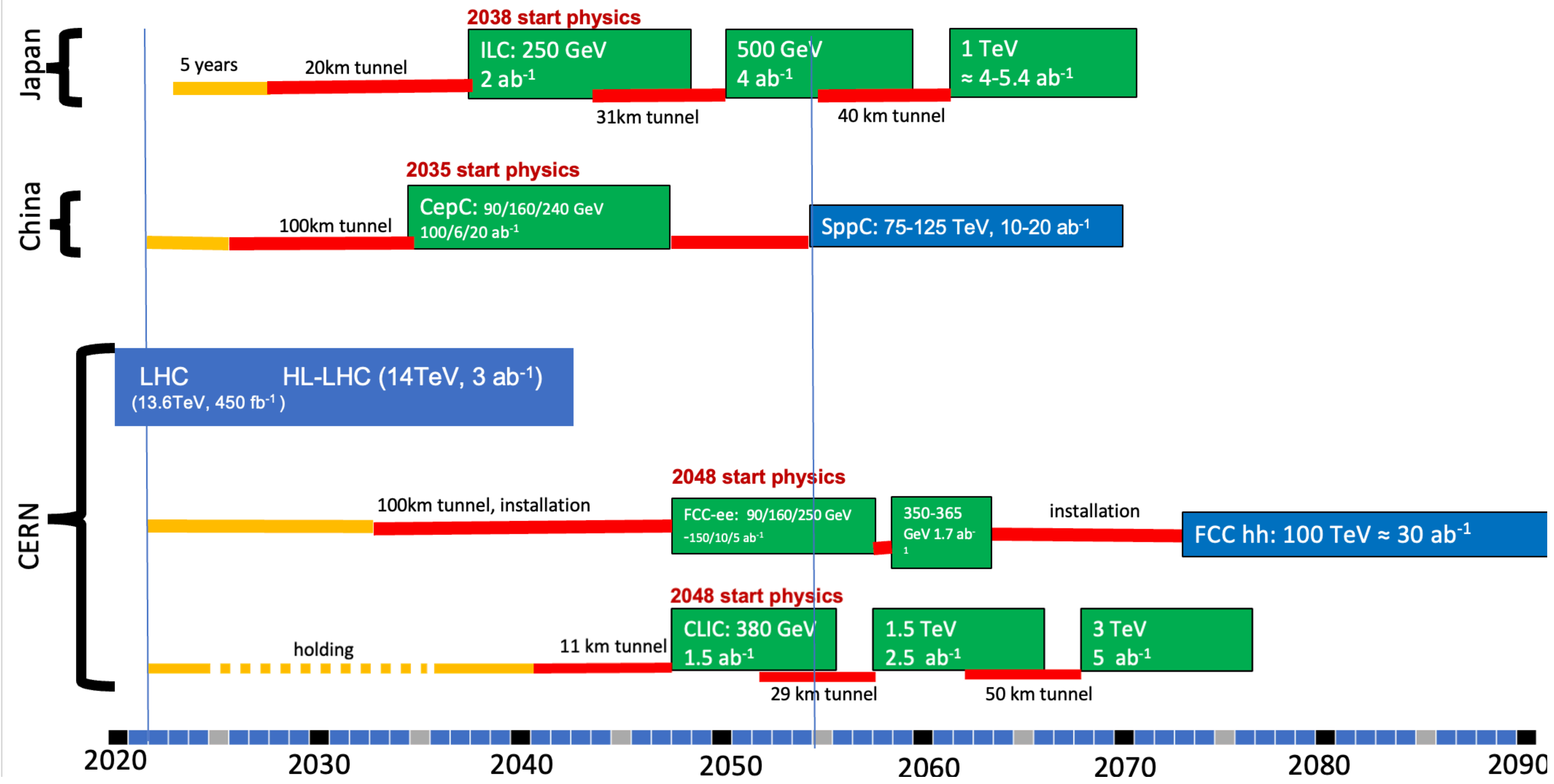

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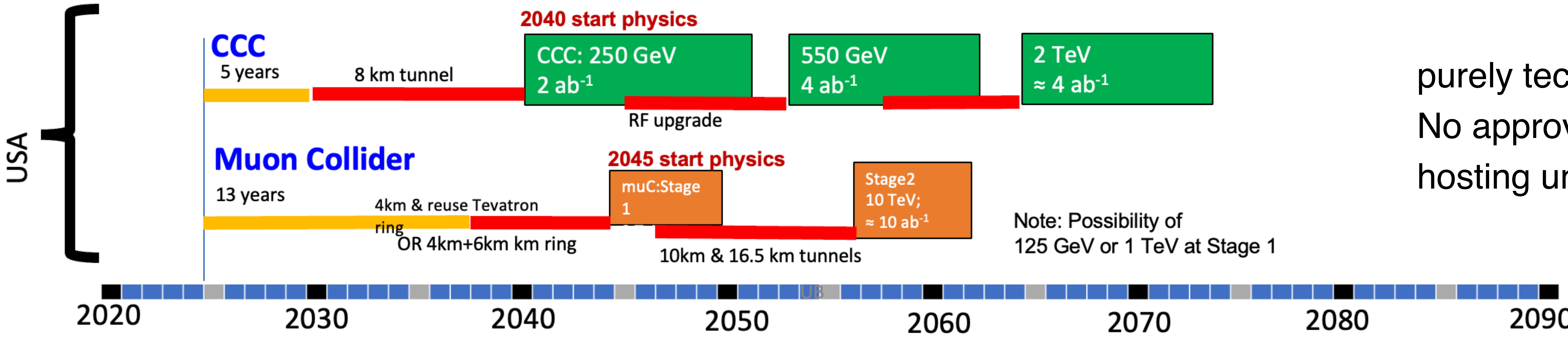
Proposals emerging from this Snowmass for a US based collider



purely technical!
No approval process yet, hosting unclear

Final Words

There are very exciting questions in high energy physics - a new e^+e^- collider may answer some of them!

Global large projects = long time scales - but contributions are needed now to make them happen.

This will be *your* HEP facility!