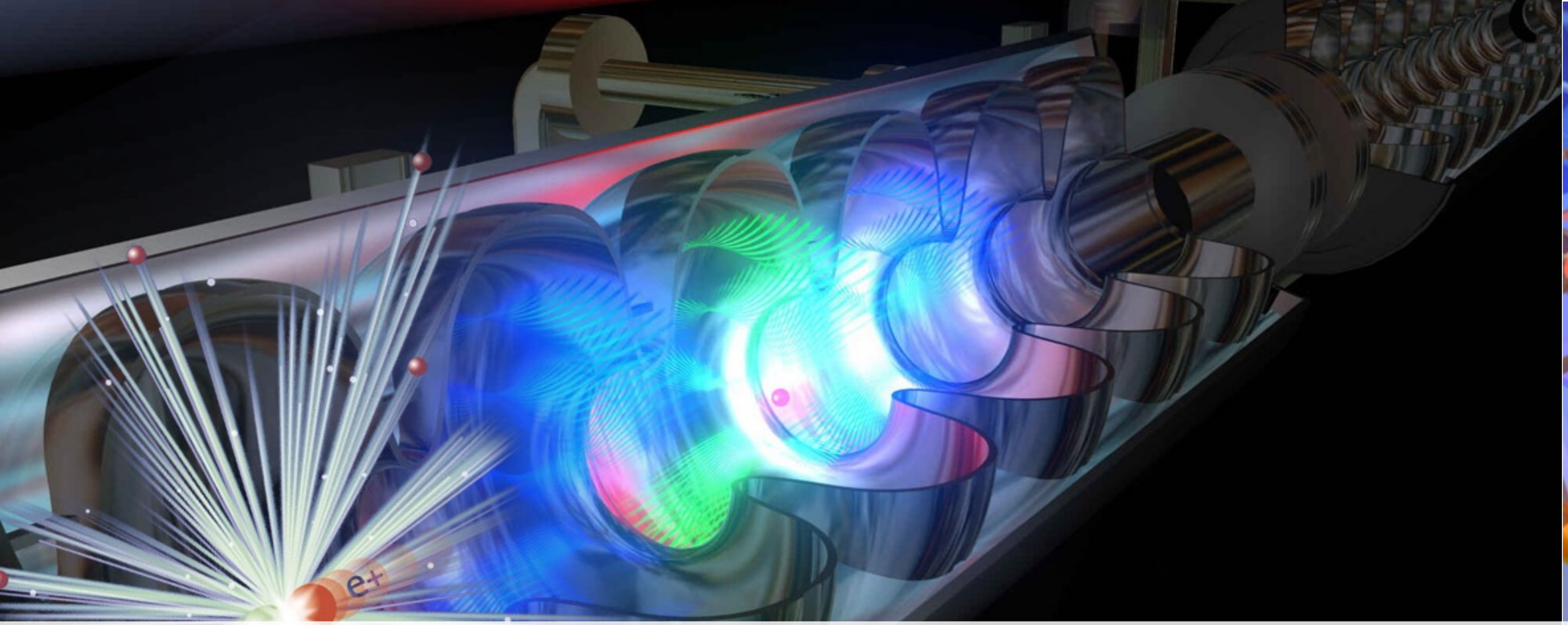


Experimental Physics at Lepton Colliders

Karlsruhe Institute of Technology

Frank Simon

@ Summer Student Lectures

CERN - July 2023

Institute for Data Processing and Electronics

Part II

Overview

A two-part story

- Part 1:
  - Scientific motivation
  - Future e^+e^- colliders in broad strokes
  - Detectors at future e^+e^- and $\mu^+\mu^-$ colliders
- **Part 2:**
  - Higgs physics
  - Electroweak precision
  - Top quark physics
  - 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

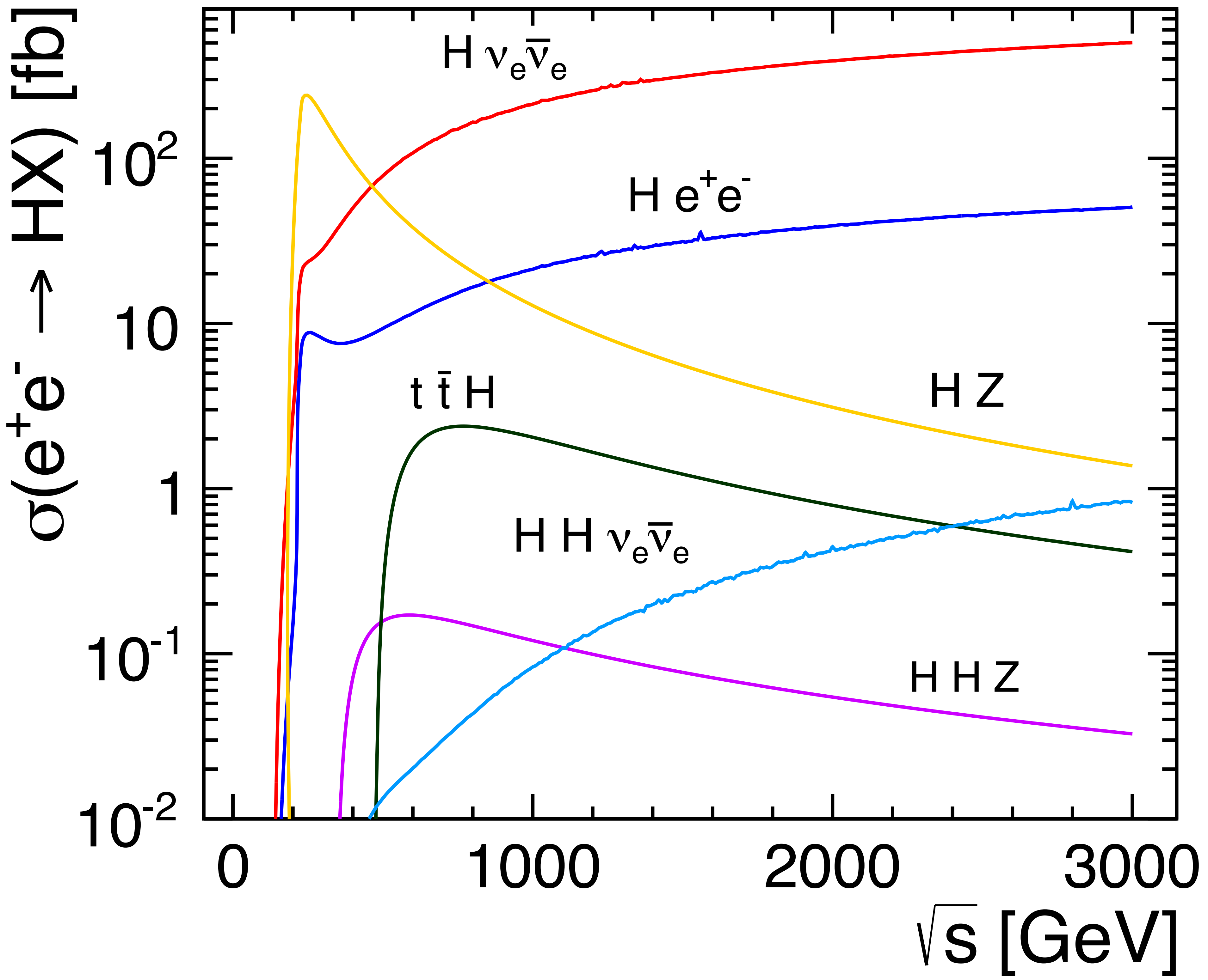
- I am focussing on e^+e^- colliders, only few remarks about $\mu^+\mu^-$

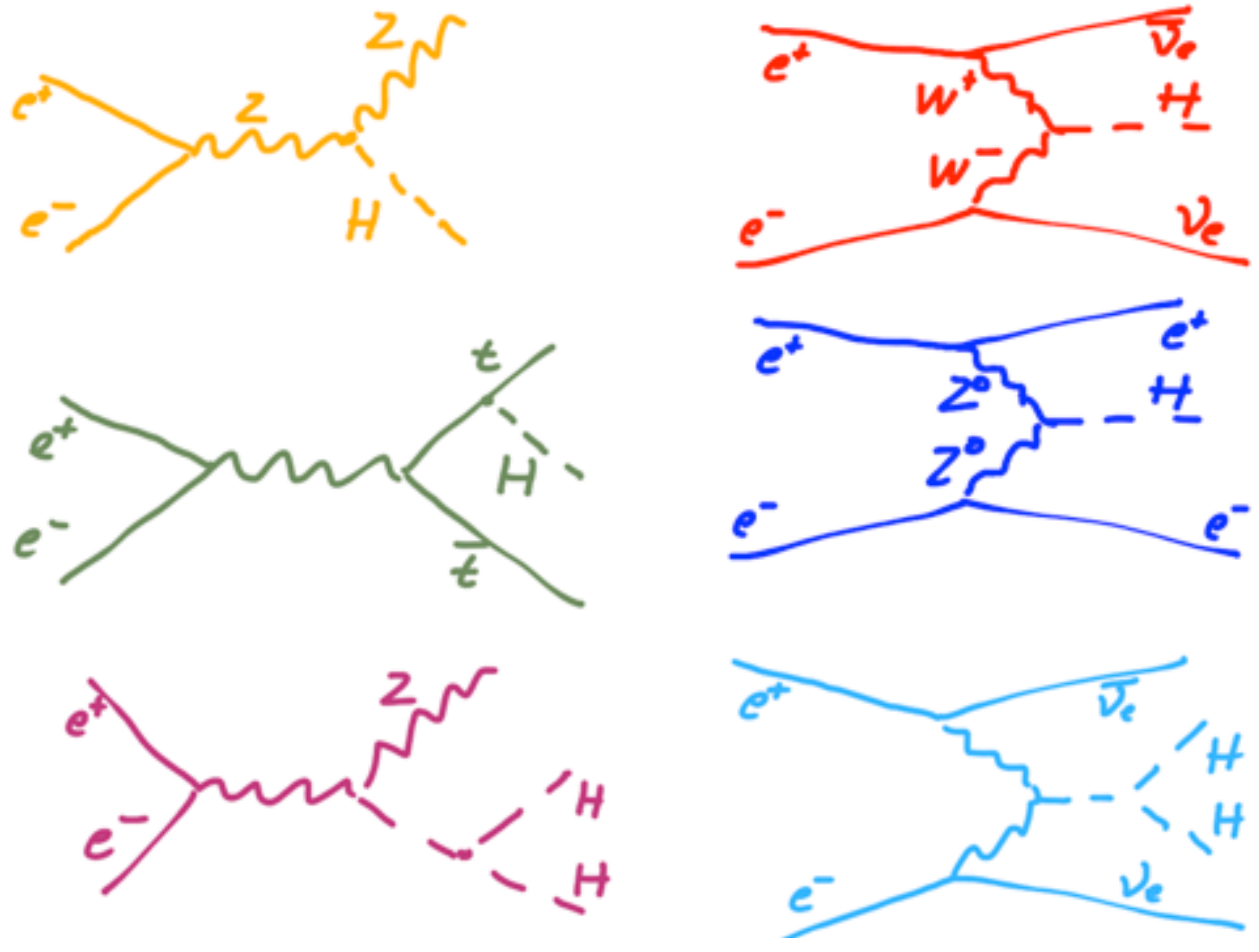
Precision Higgs Measurements

Higgs Factories and beyond

Higgs Boson Production in e^+e^-

A rich field to explore





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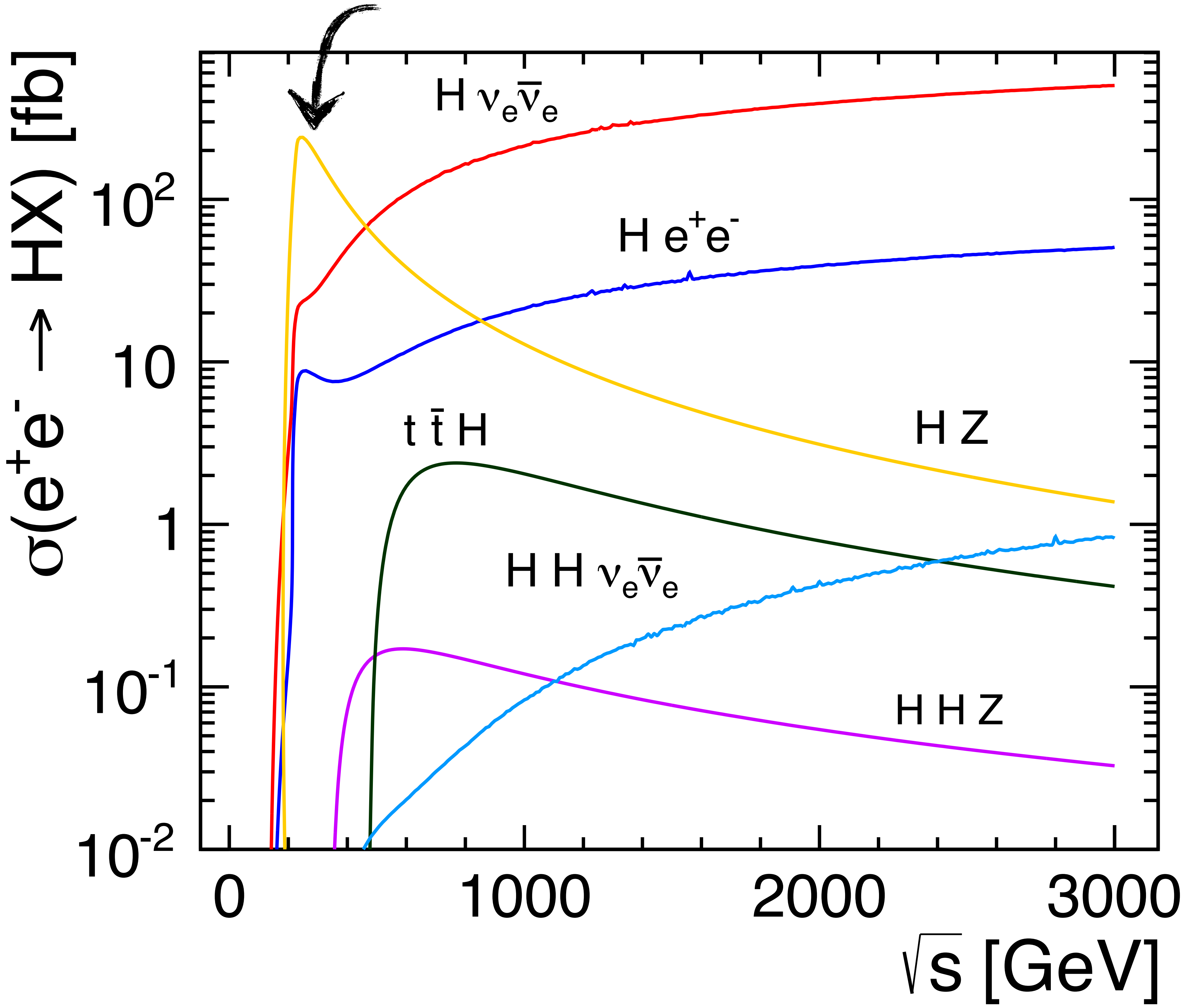

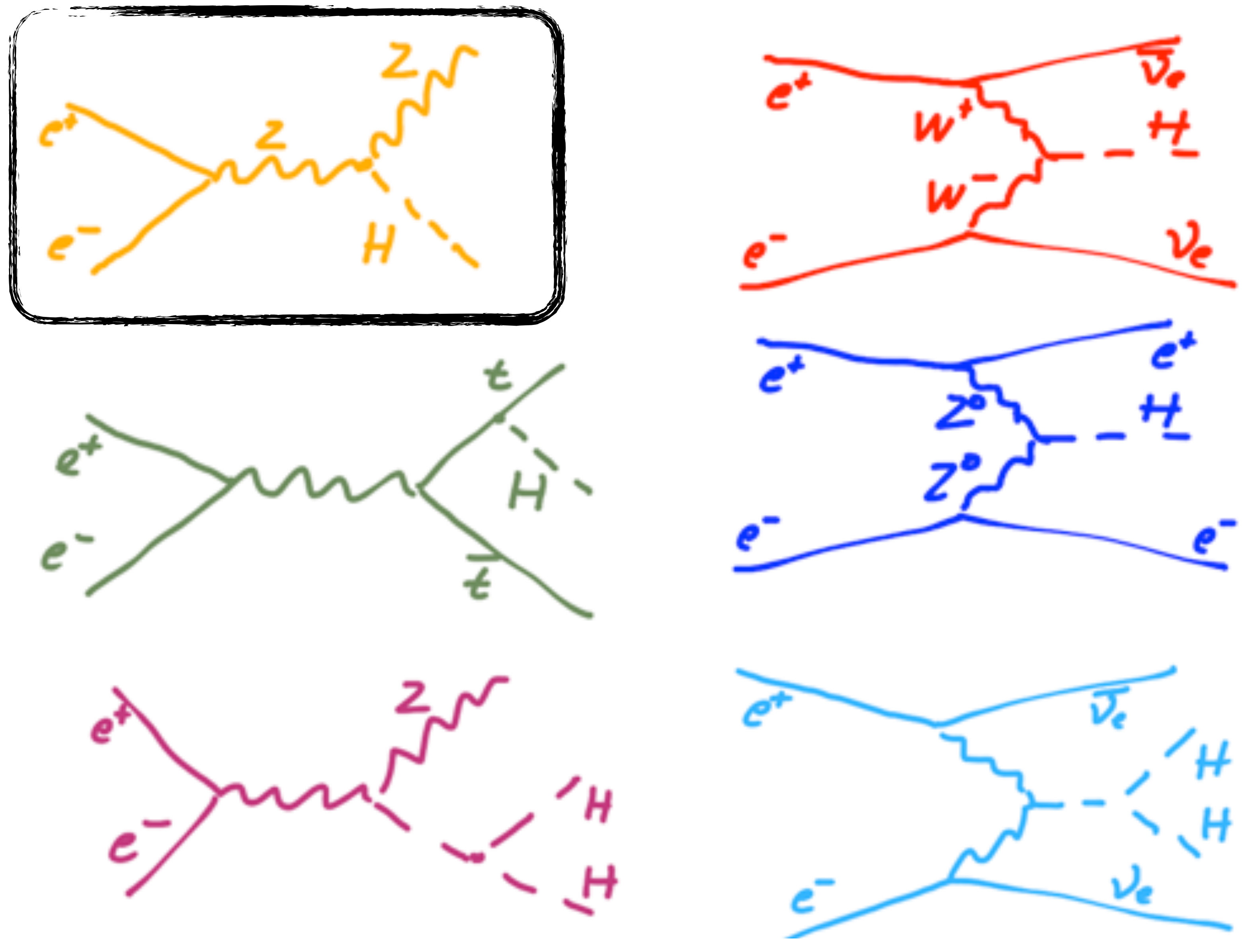

250 GeV:

Maximum of ZH production

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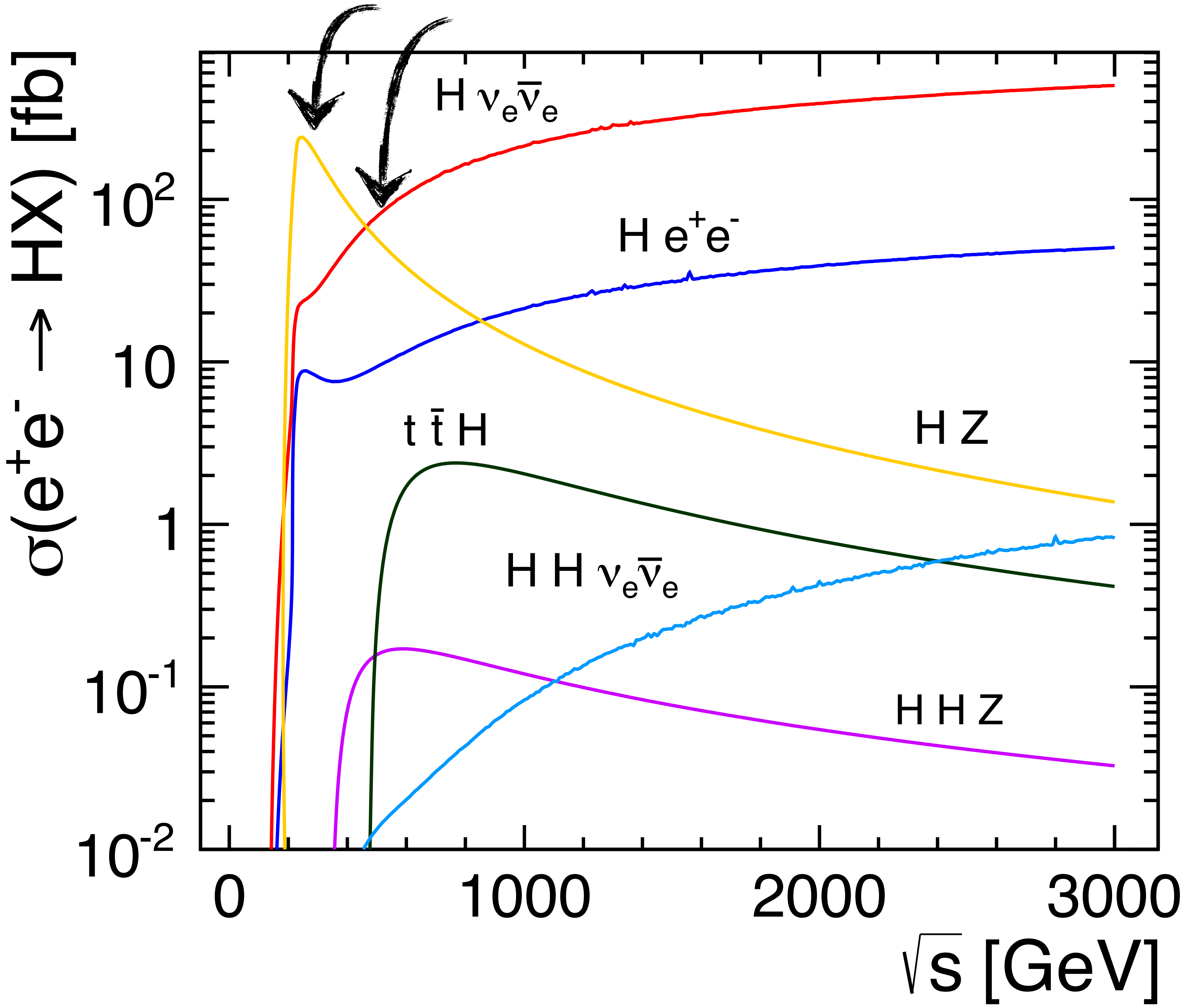

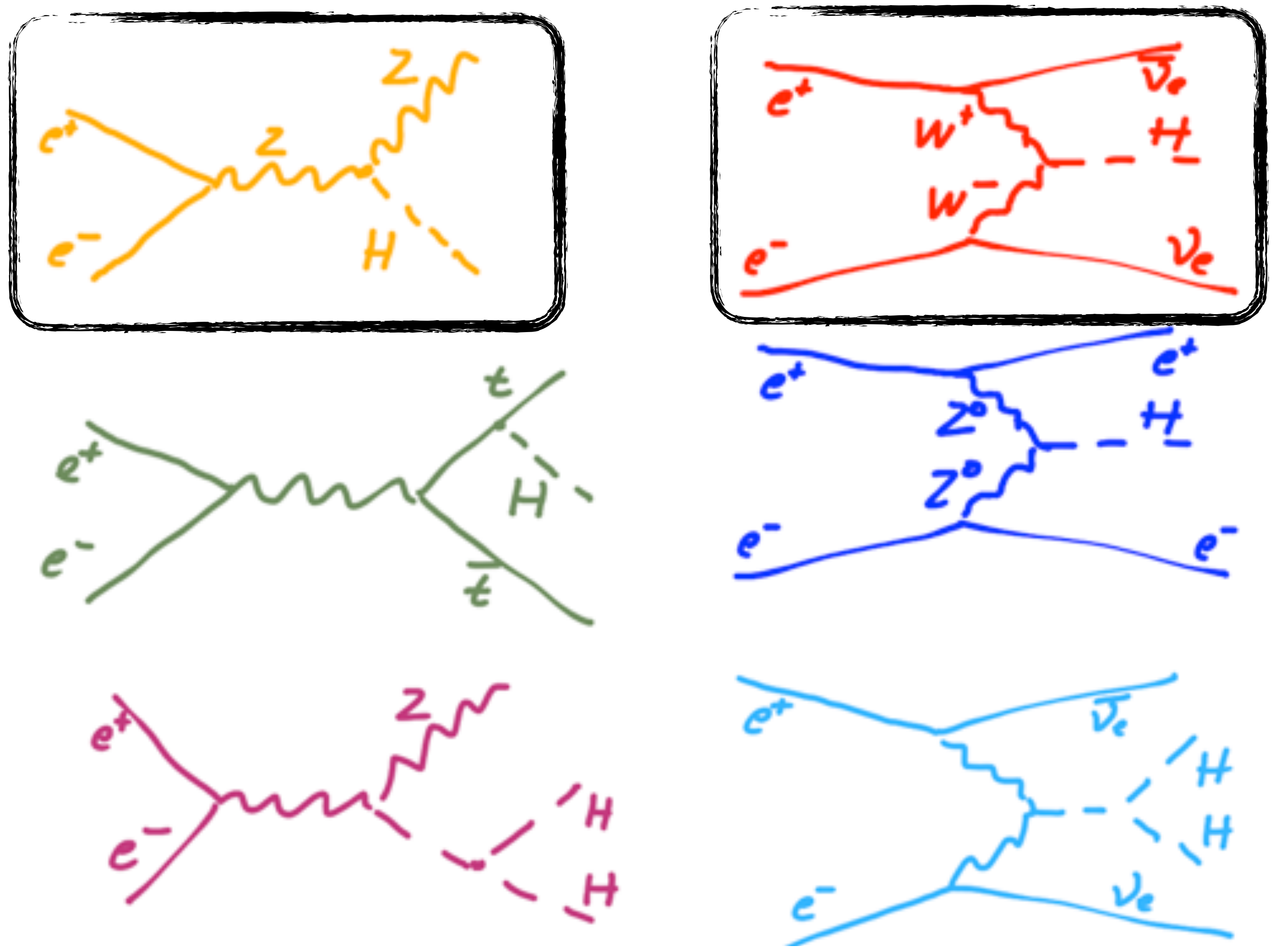

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WW fusion kicks in

(and top pair production)

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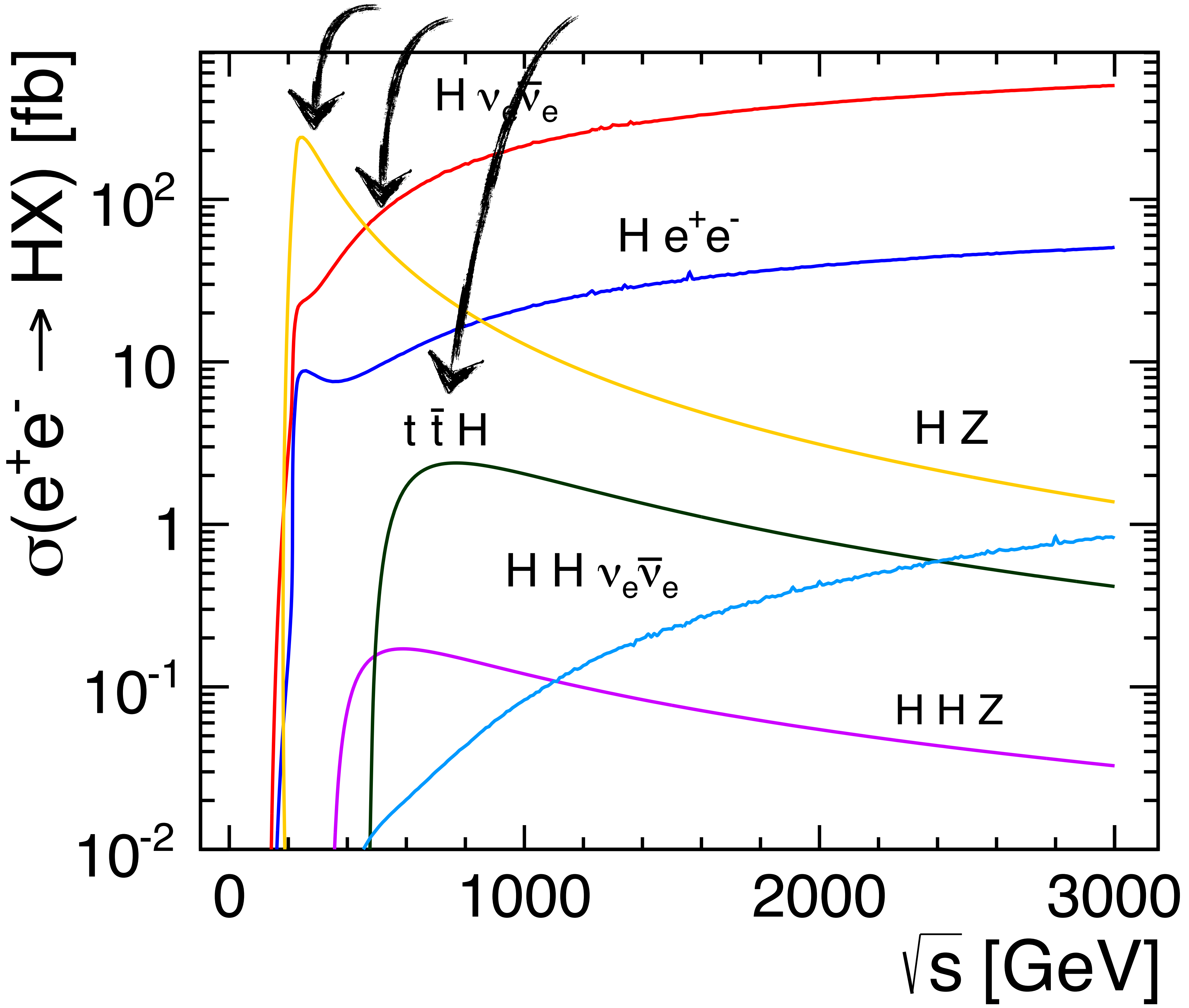

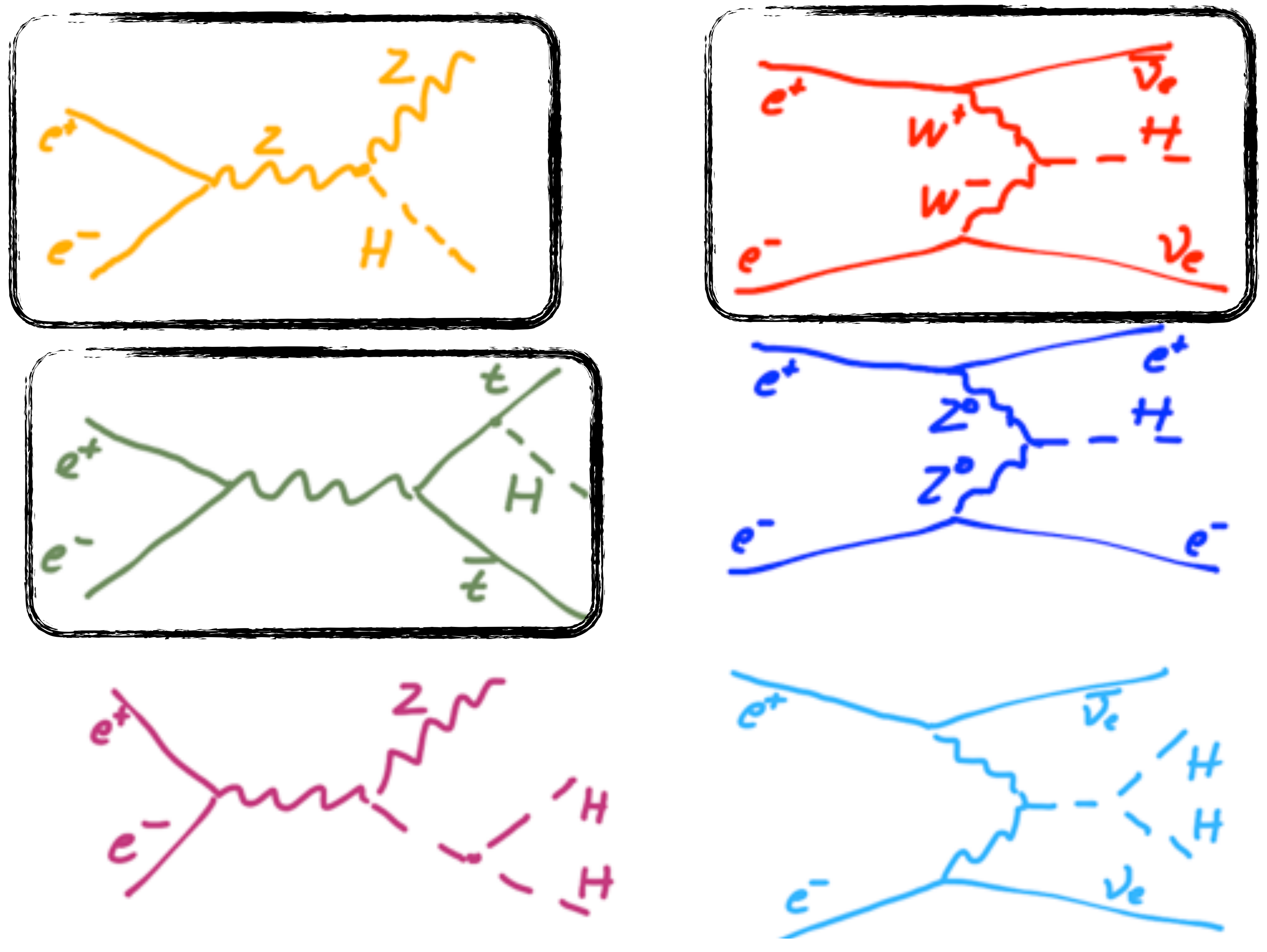

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ttH: direct access to top Yukawa coupling

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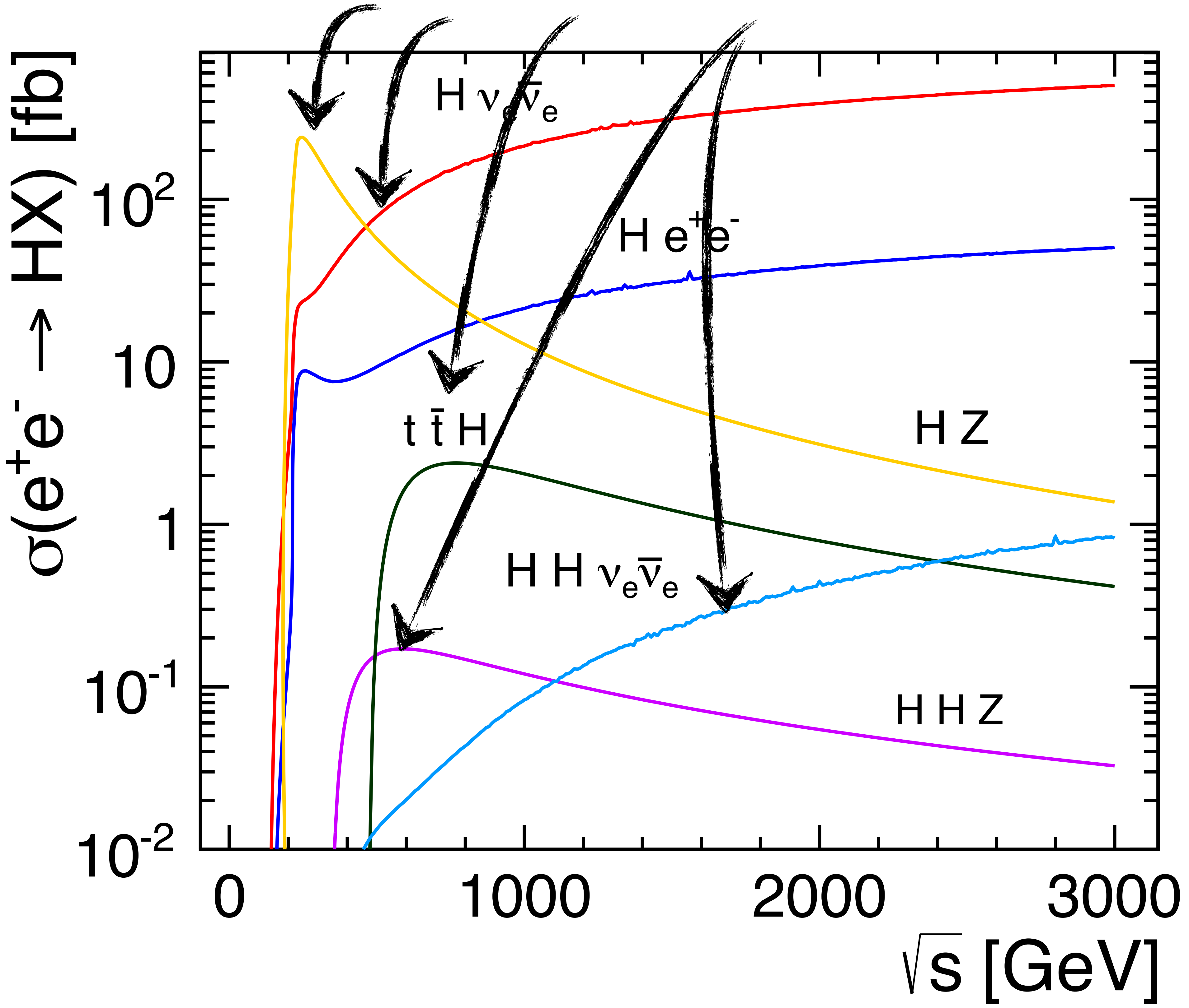

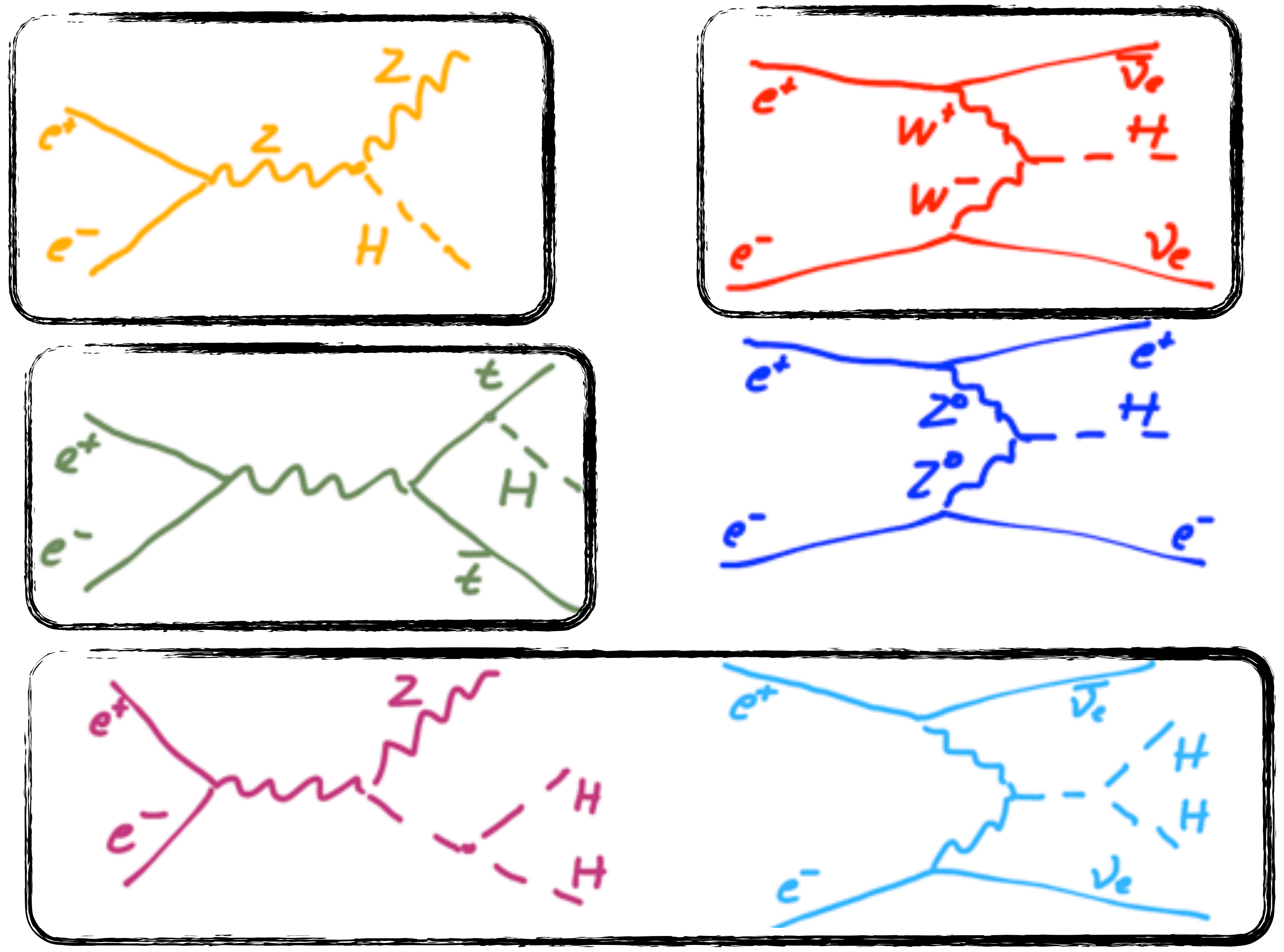

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500 GeV; 1+ TeV:

Higgs self-coupling

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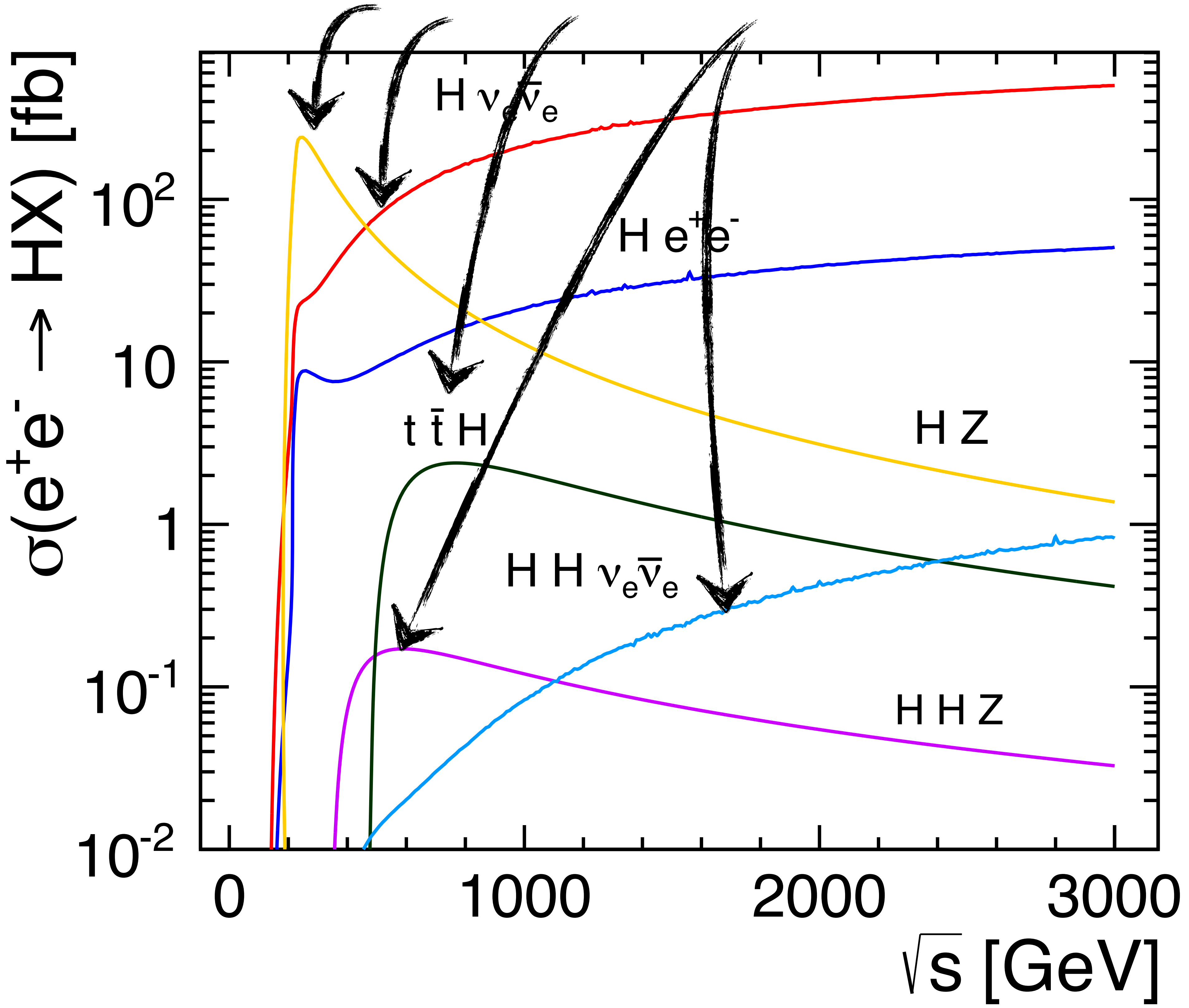

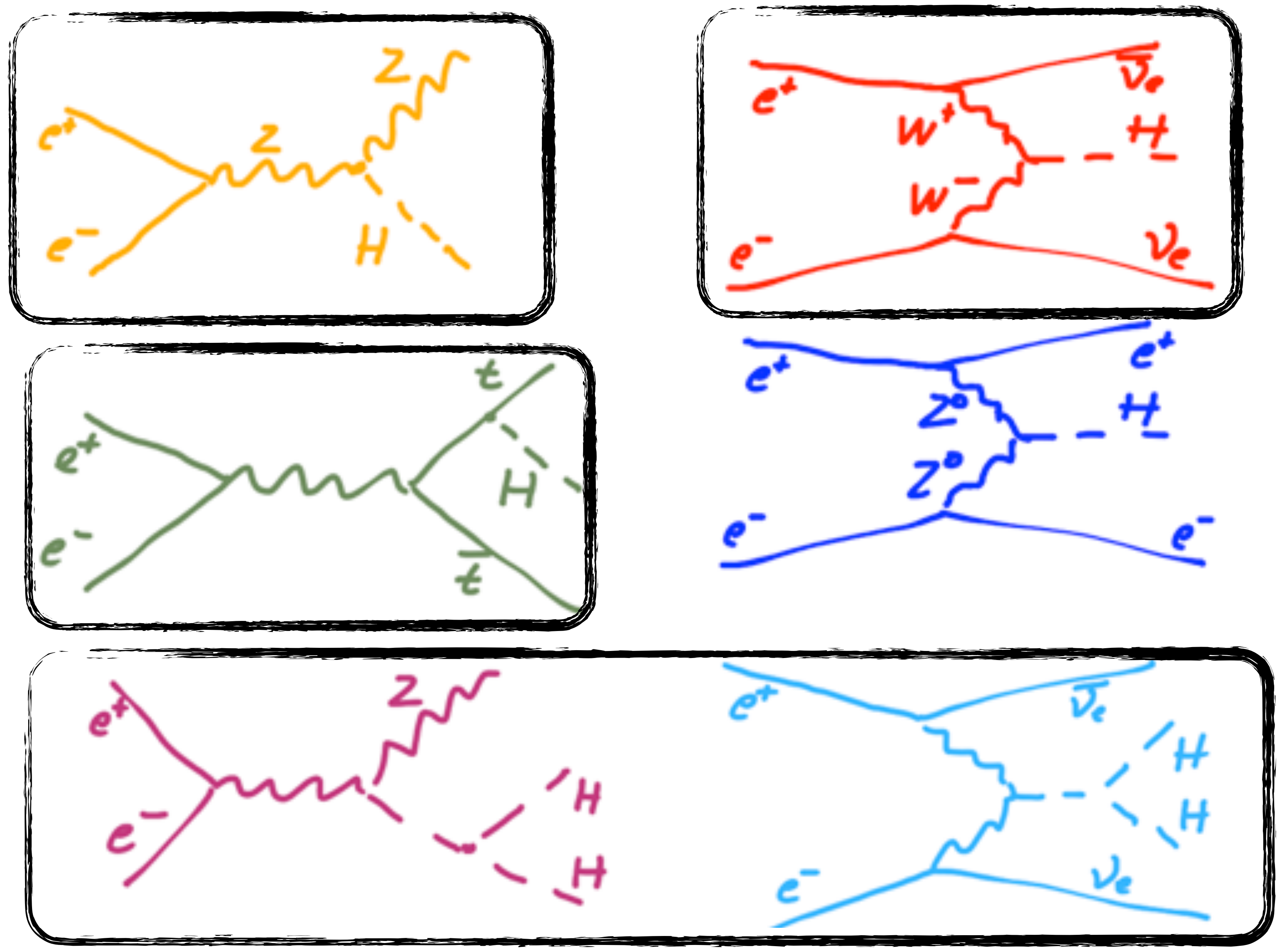

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500 GeV; 1+ TeV:
Higgs self-coupling

- 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
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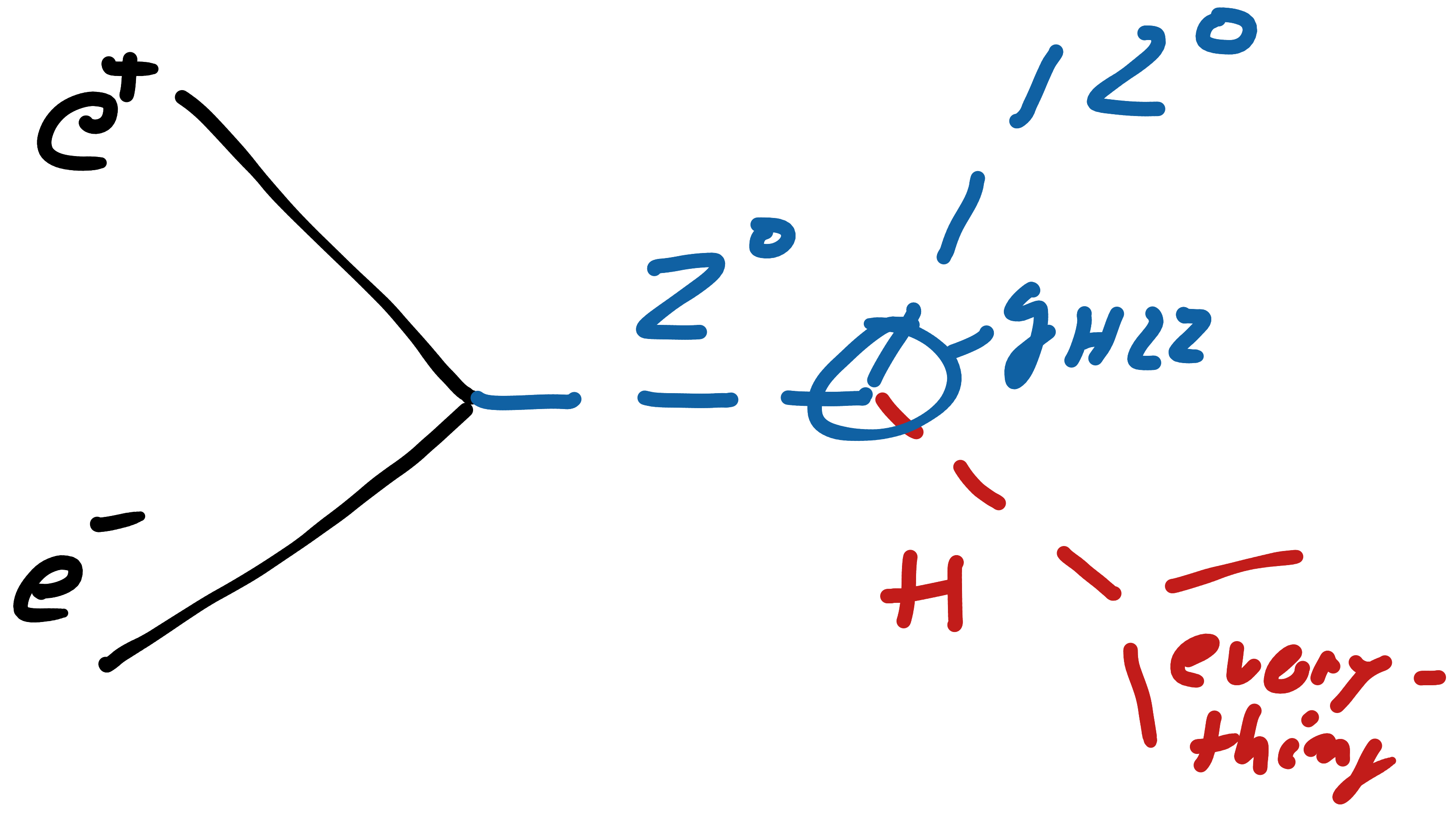

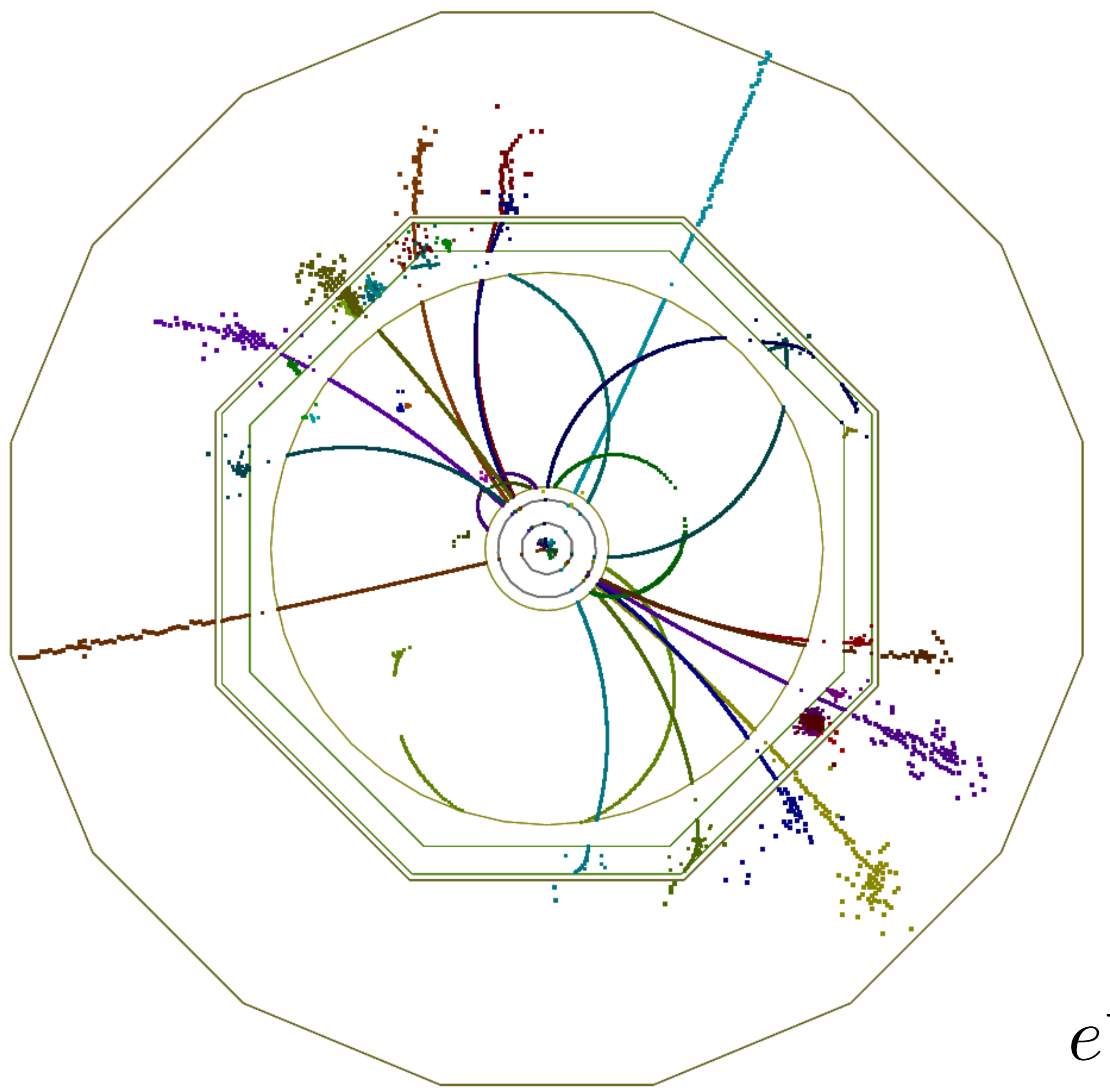

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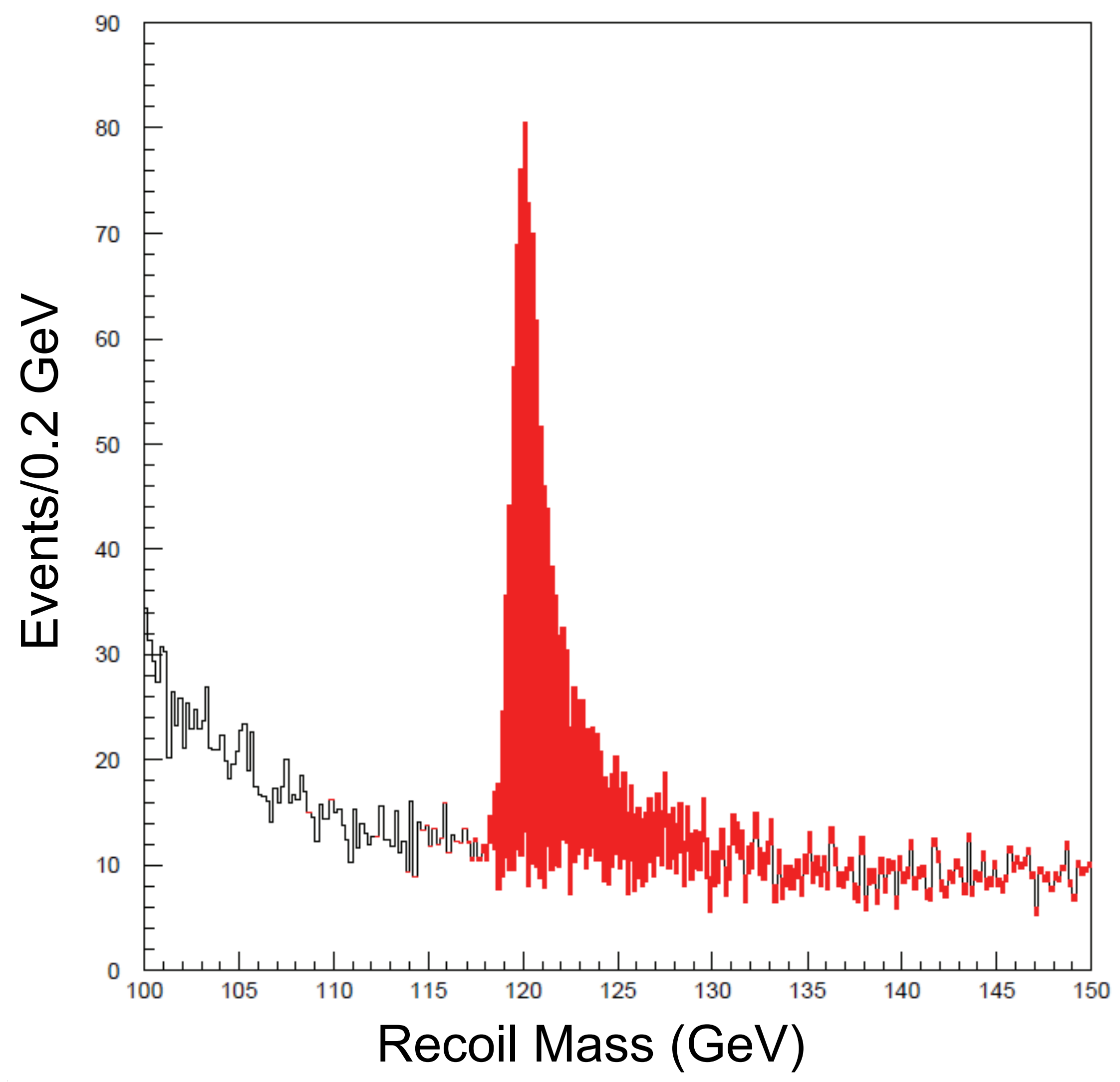
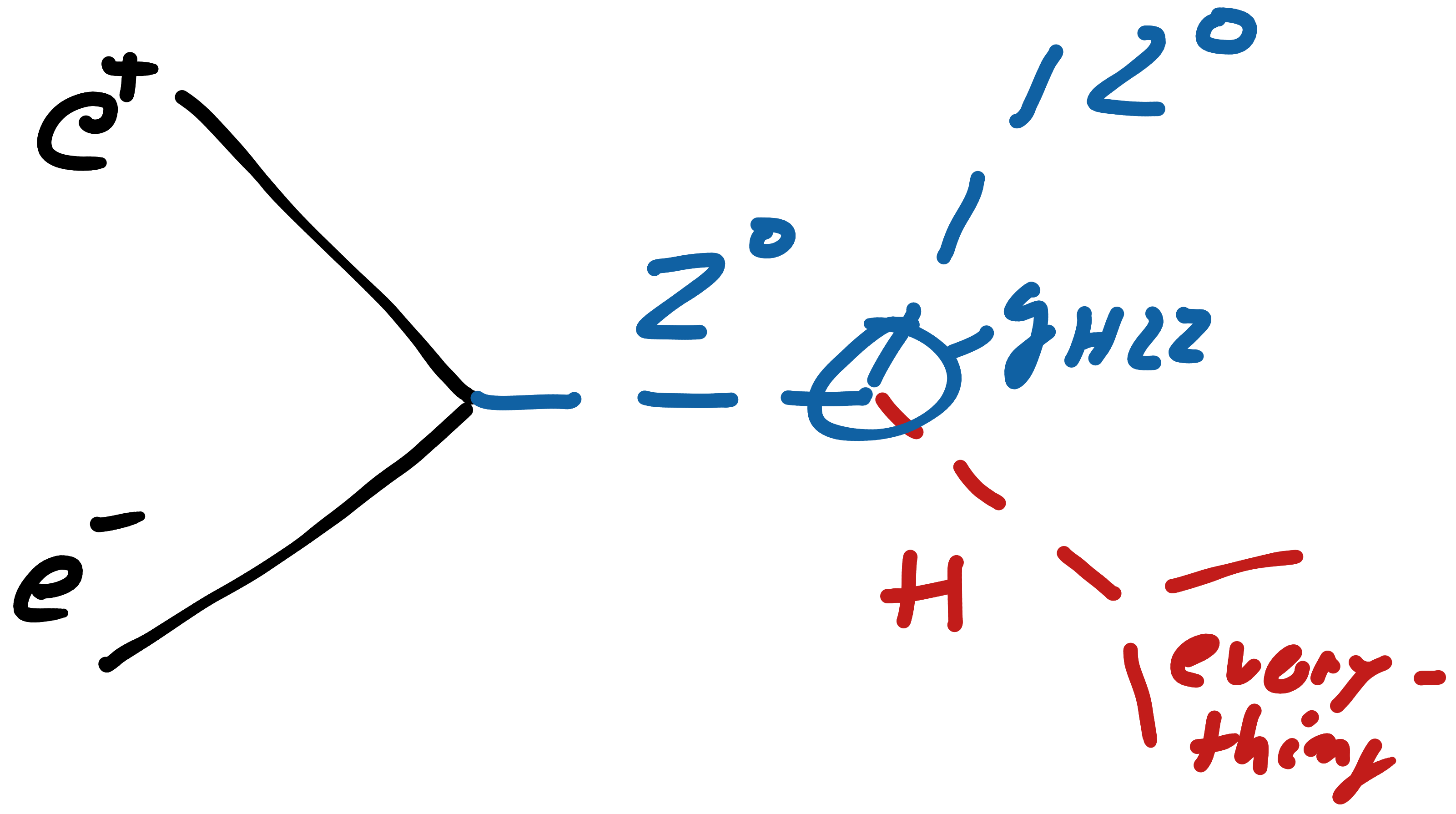
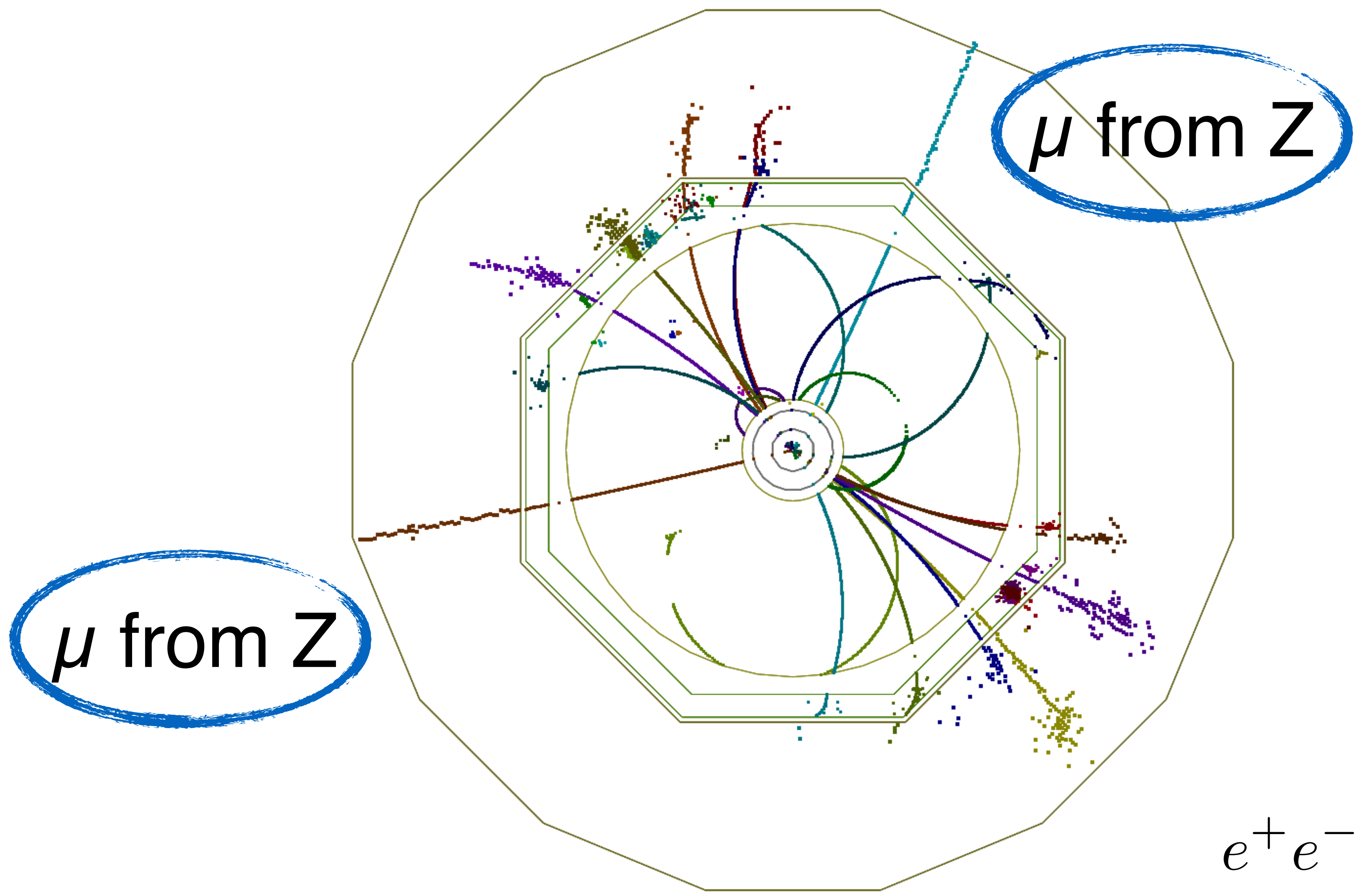
measure only the Z!

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







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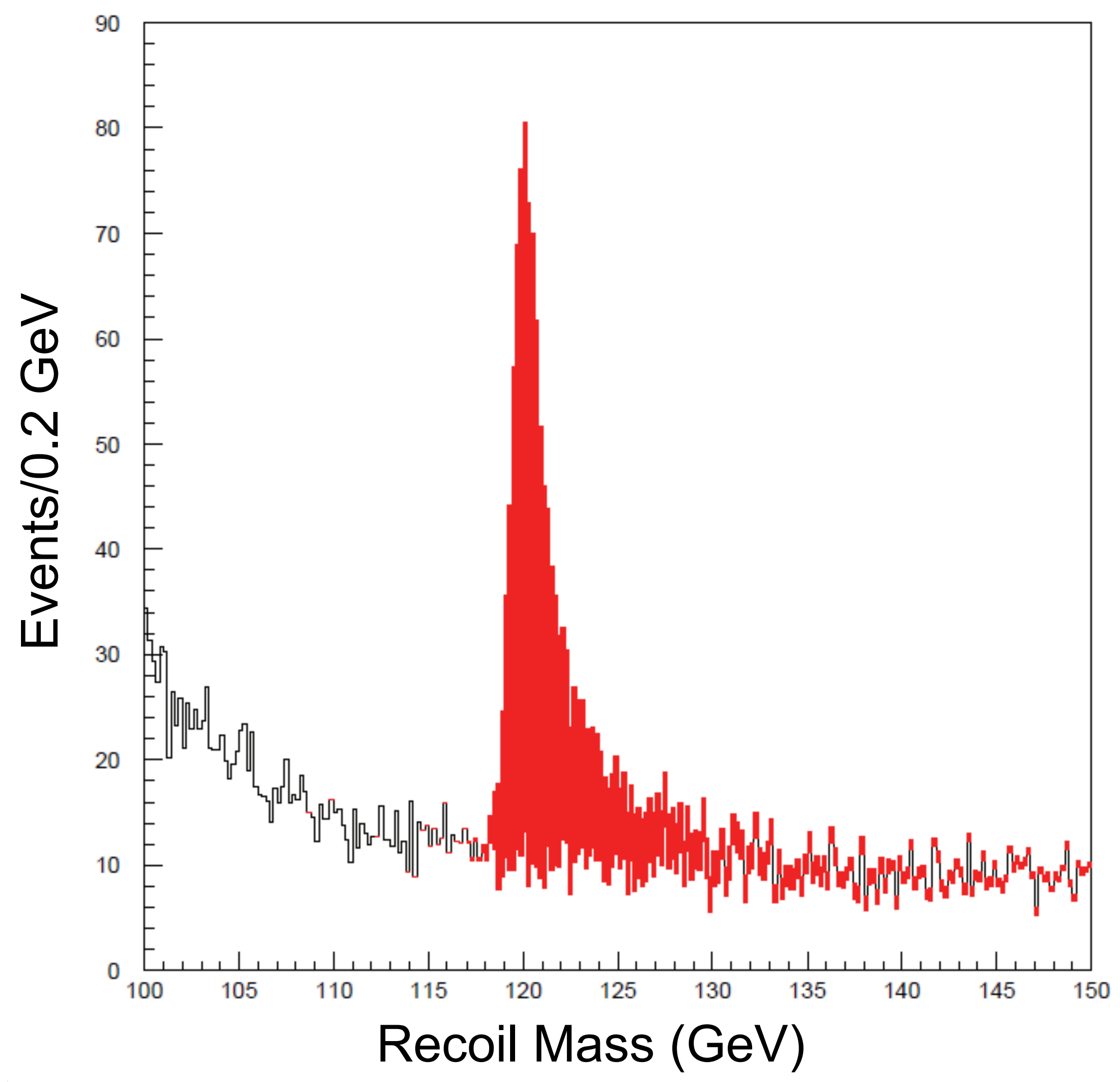

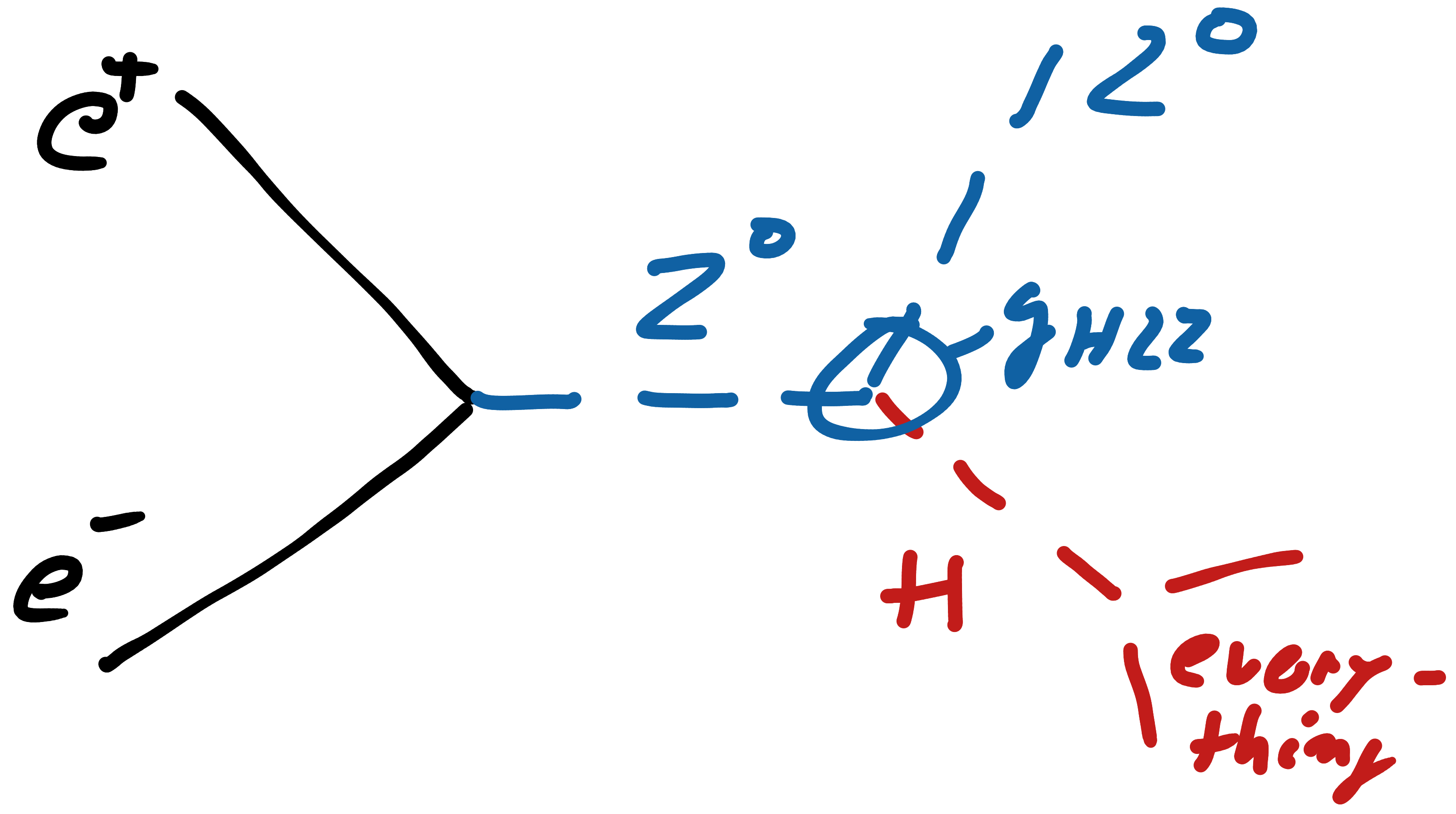

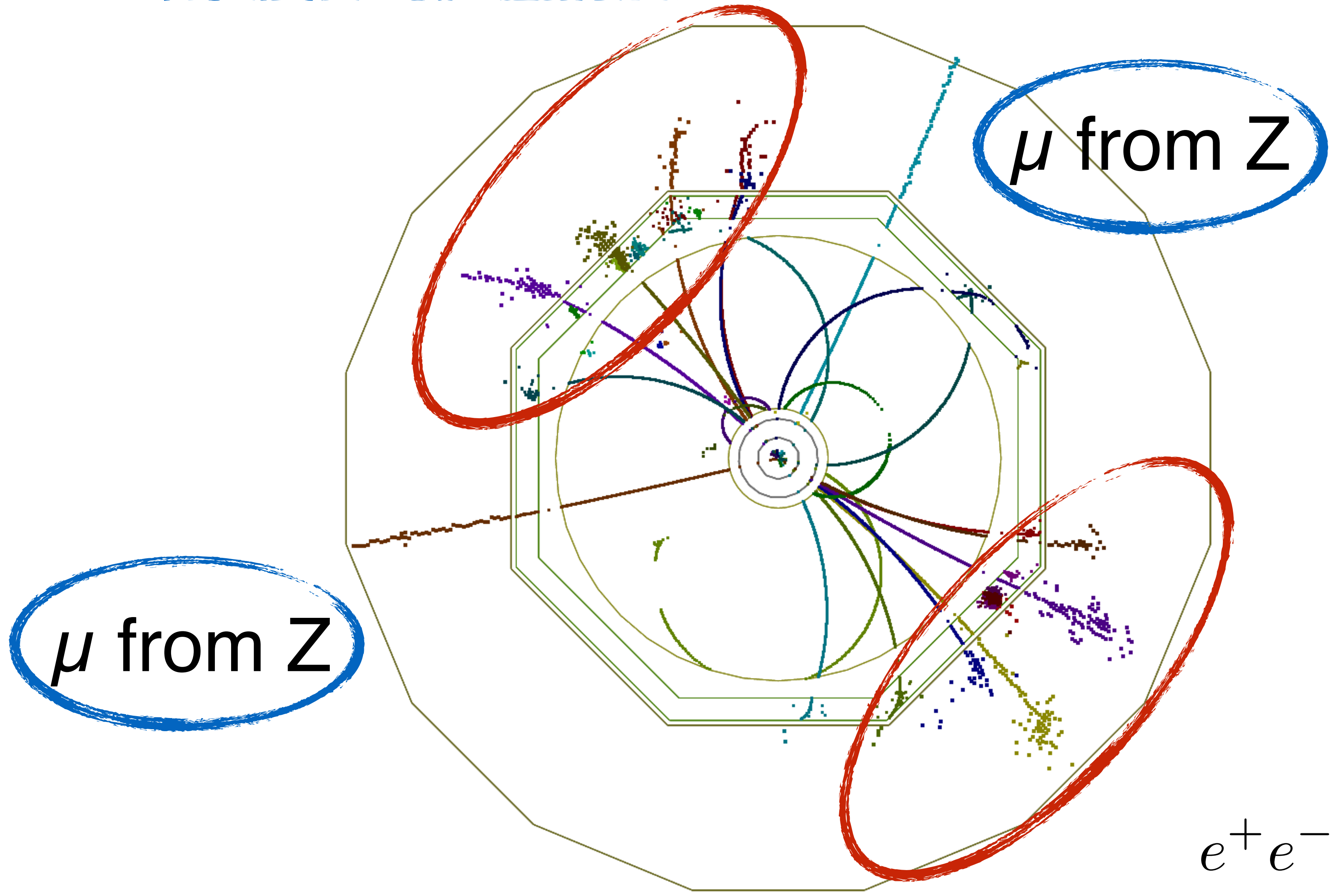

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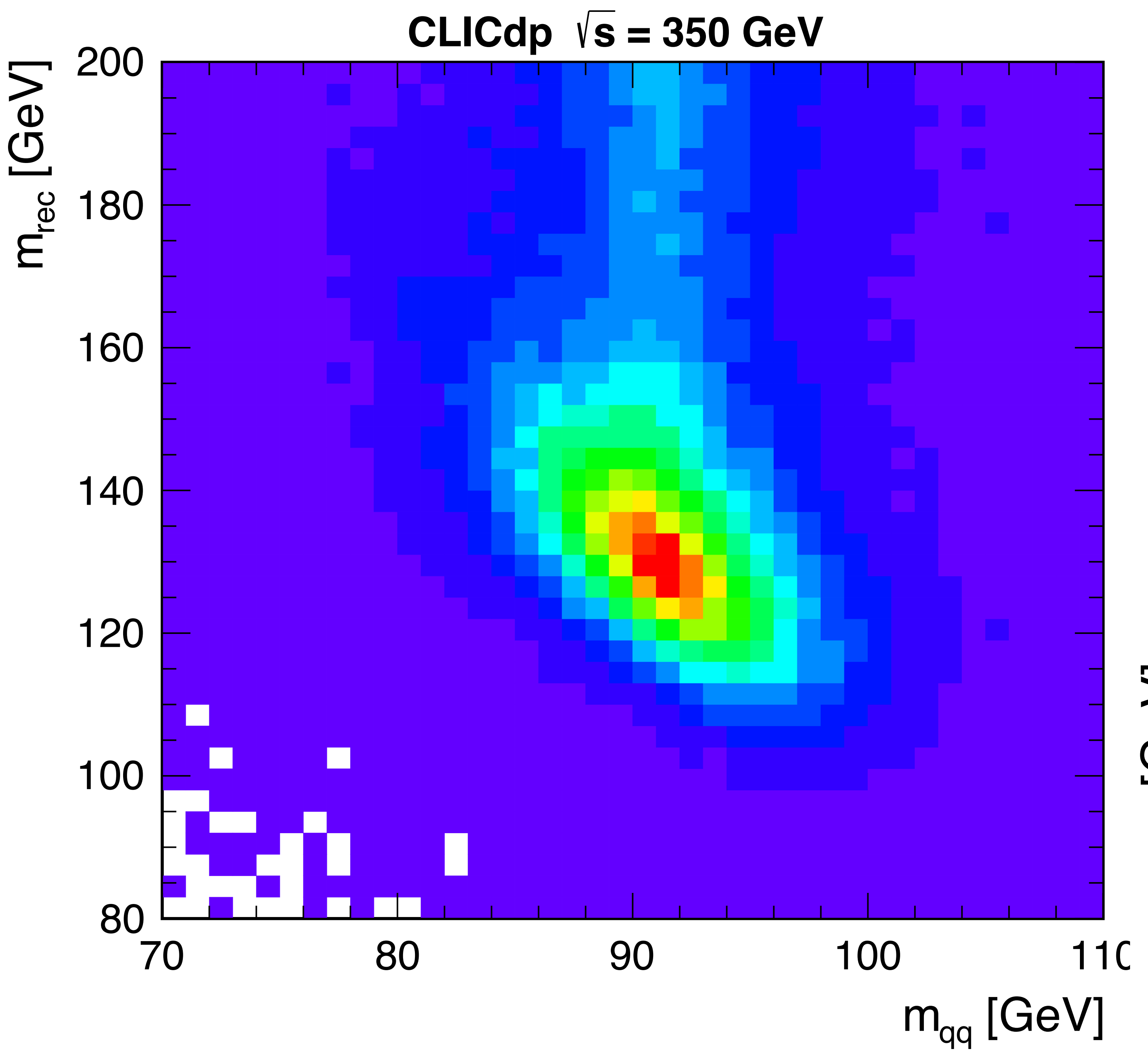
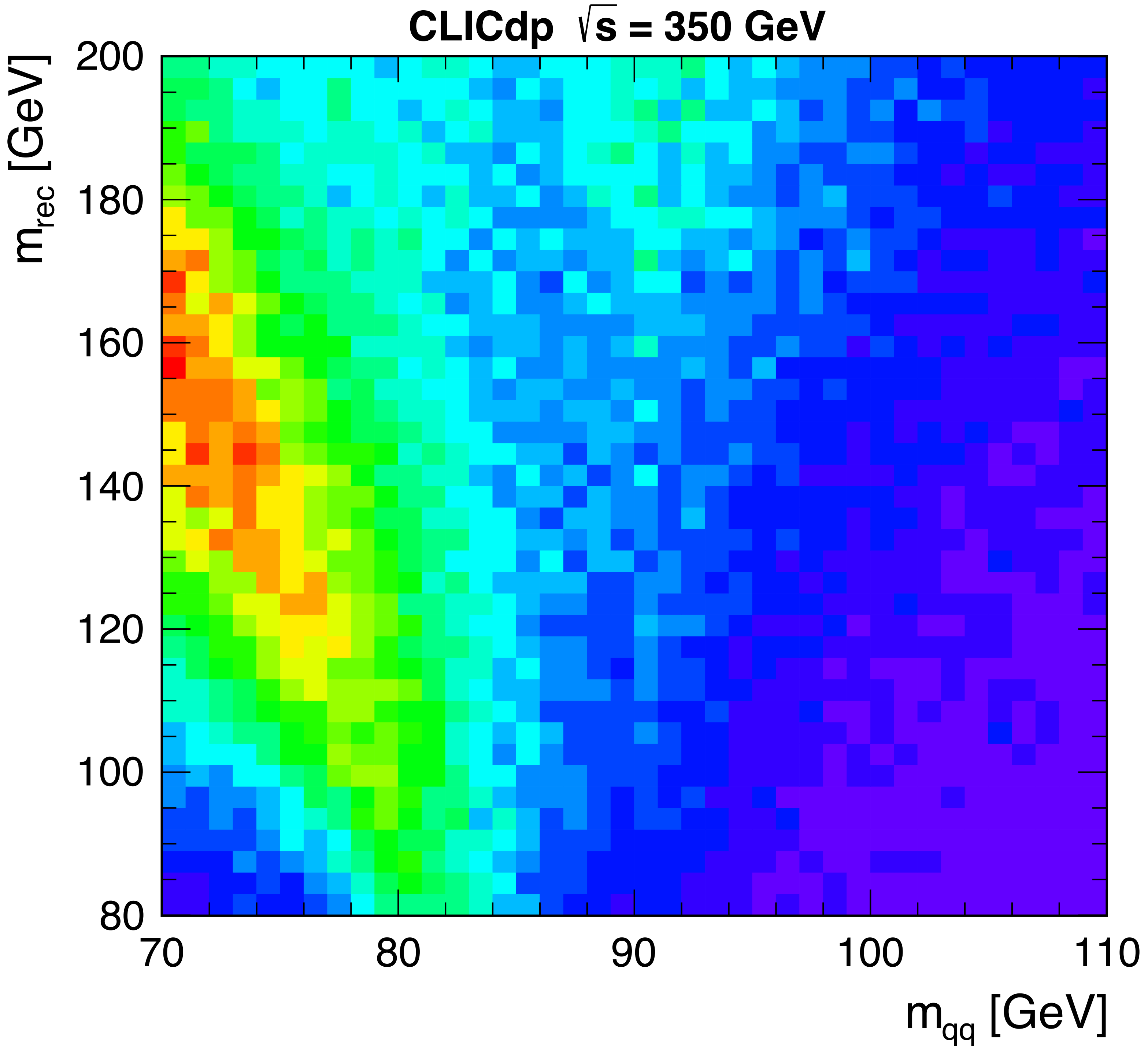
Hadronic Recoils & Invisible Decays

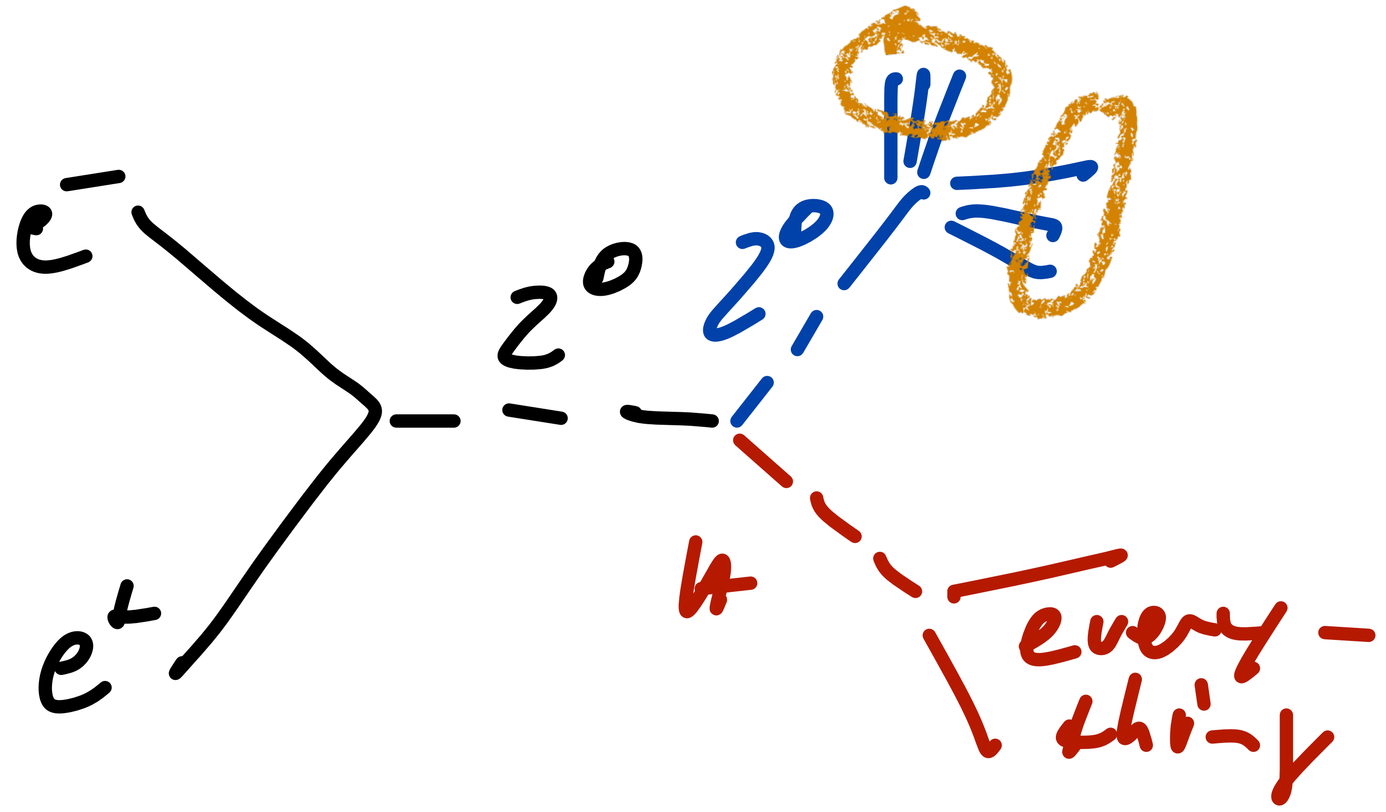
Fully exploiting Higgsstrahlung

Karlsruhe Institute of Technology



- 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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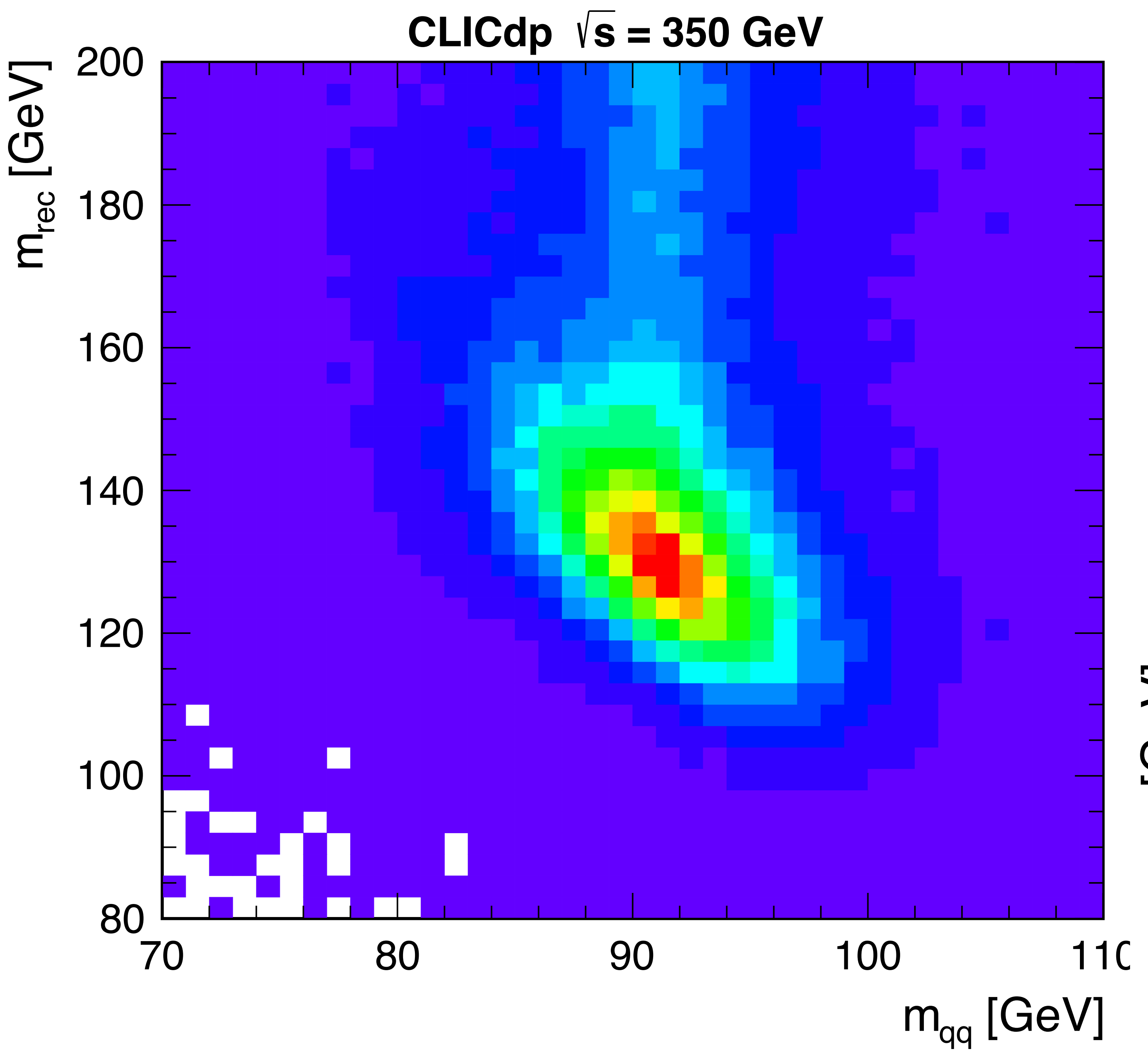

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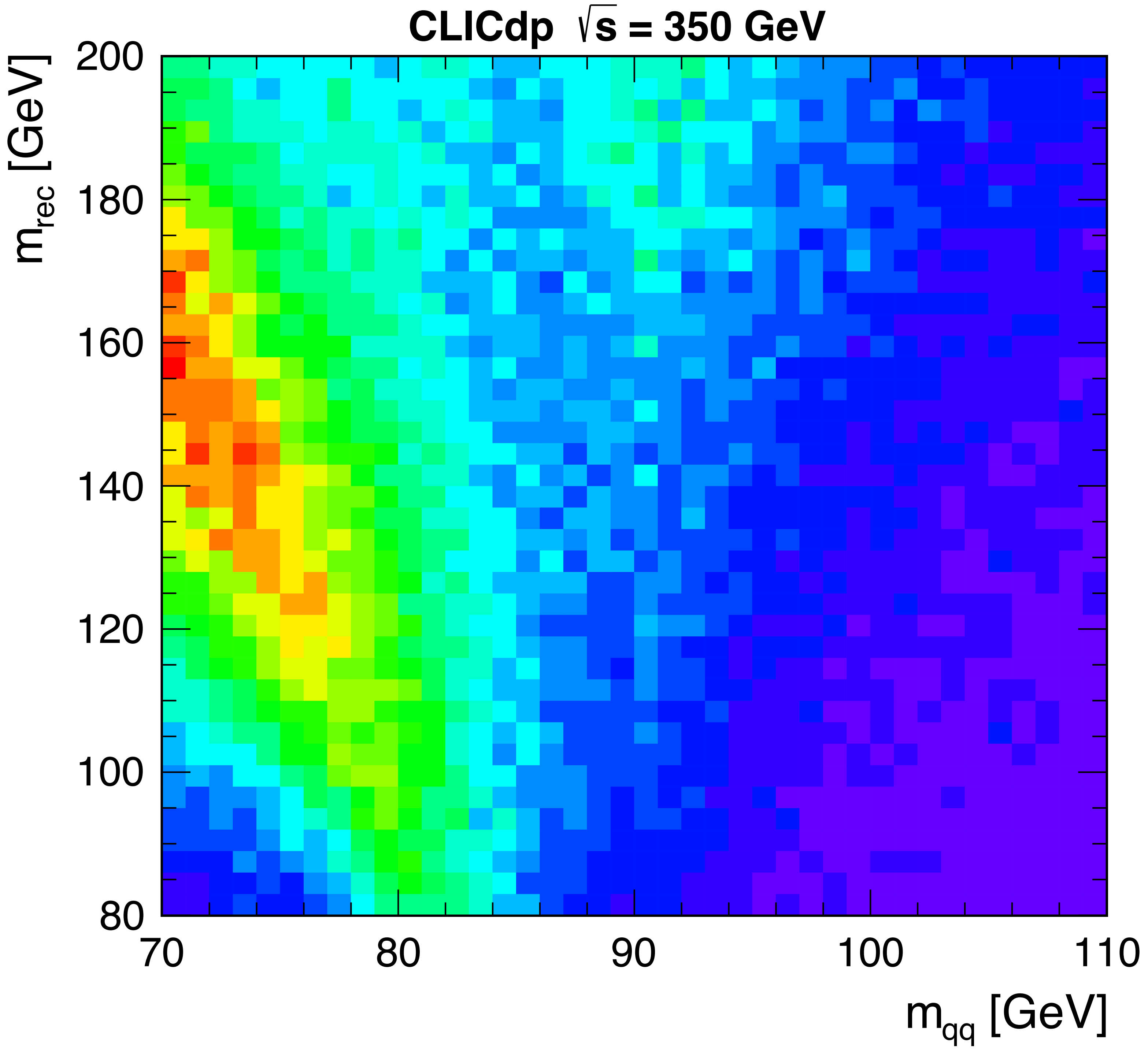
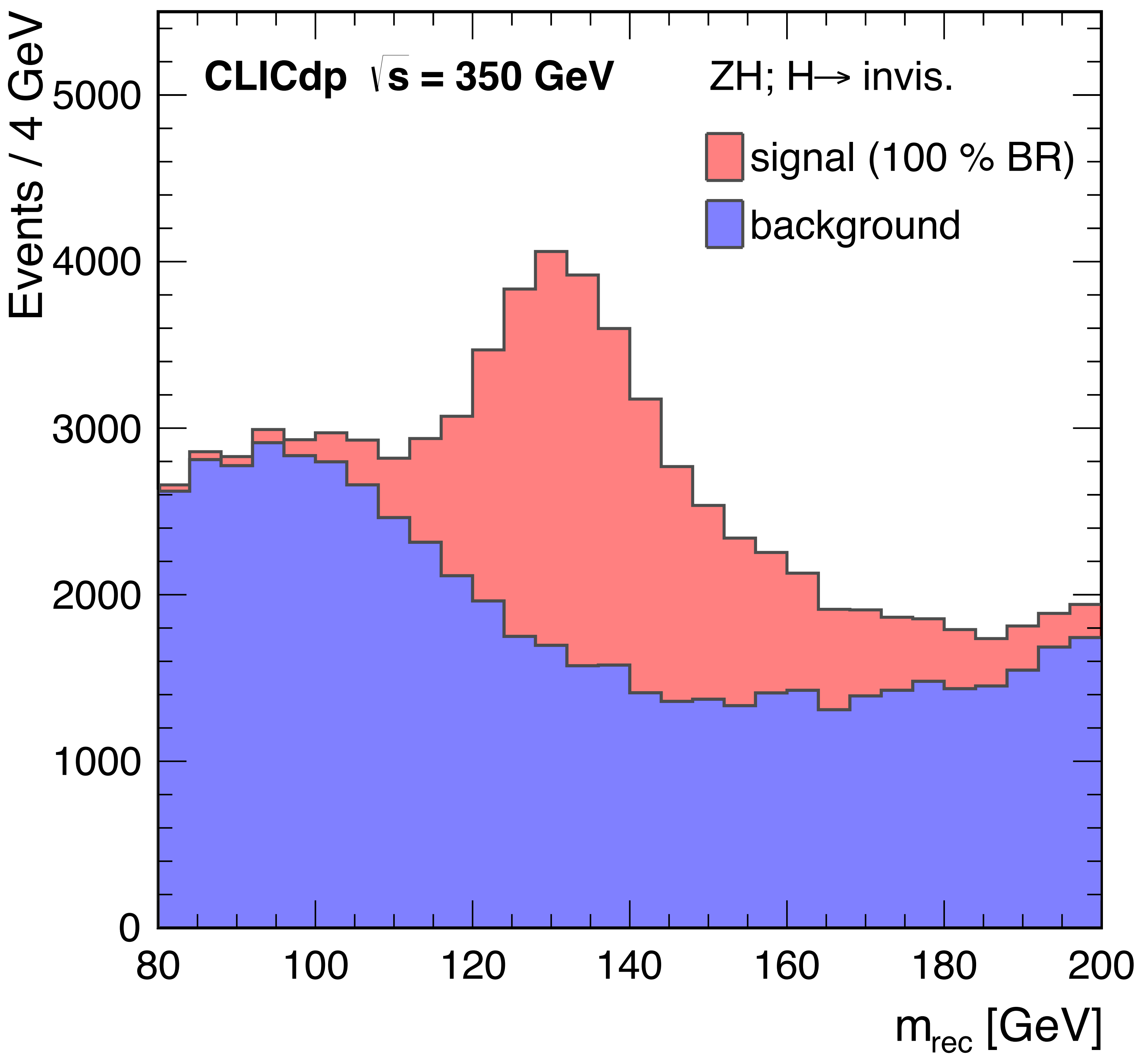
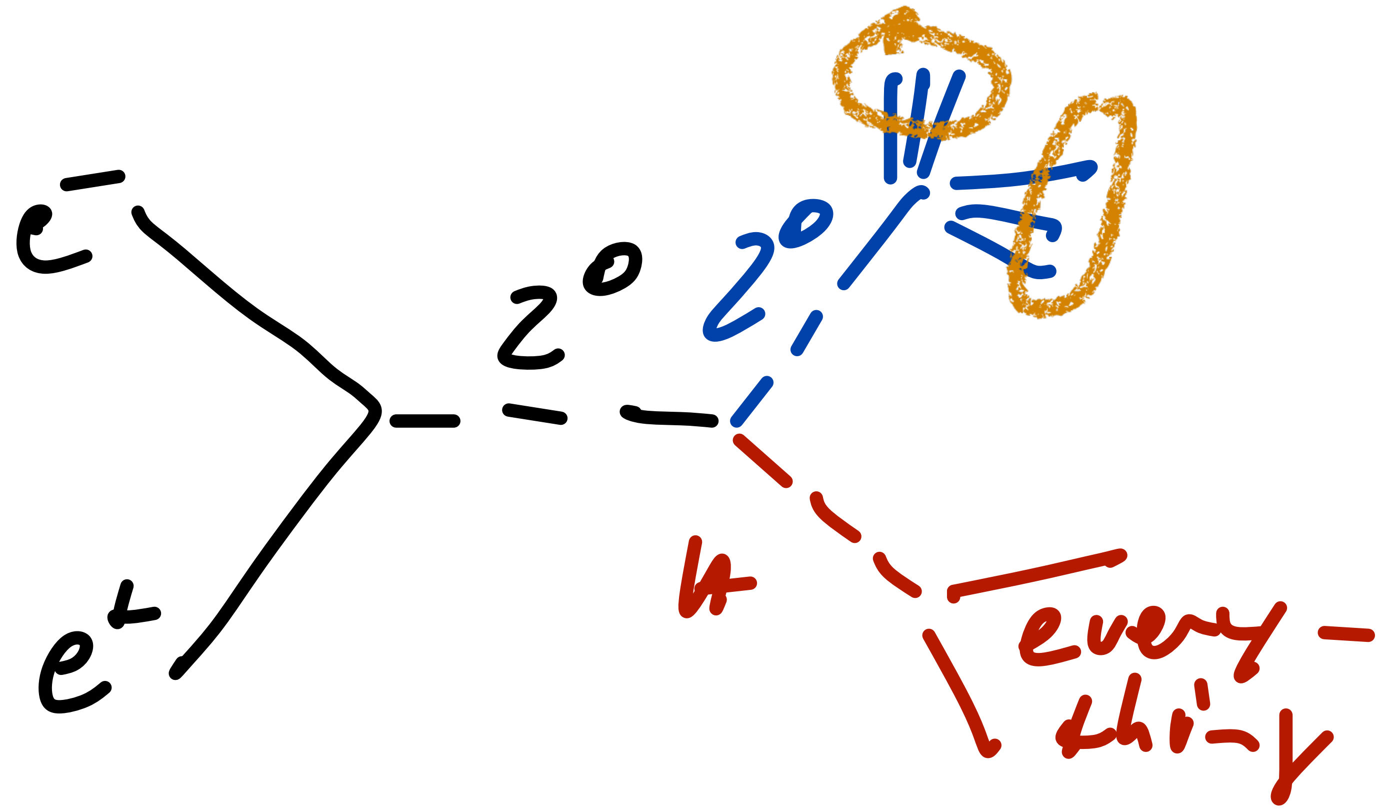






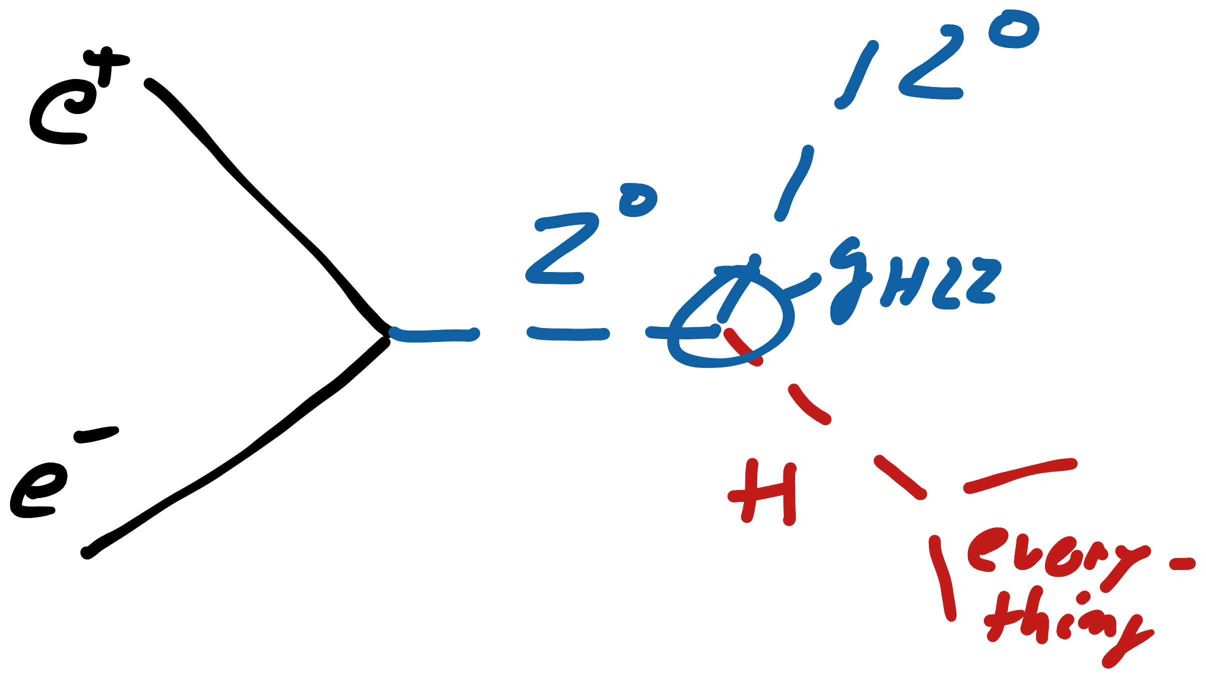
- HZ events can be used to constrain invisible Higgs decays: Limits on the few per mille level

example from CLIC

- The main measurements to make:

  σ for Z recoil measurements

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



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

Precision Measurements of Couplings

Exploring the Higgs Sector

Karlsruhe Institute of Technology

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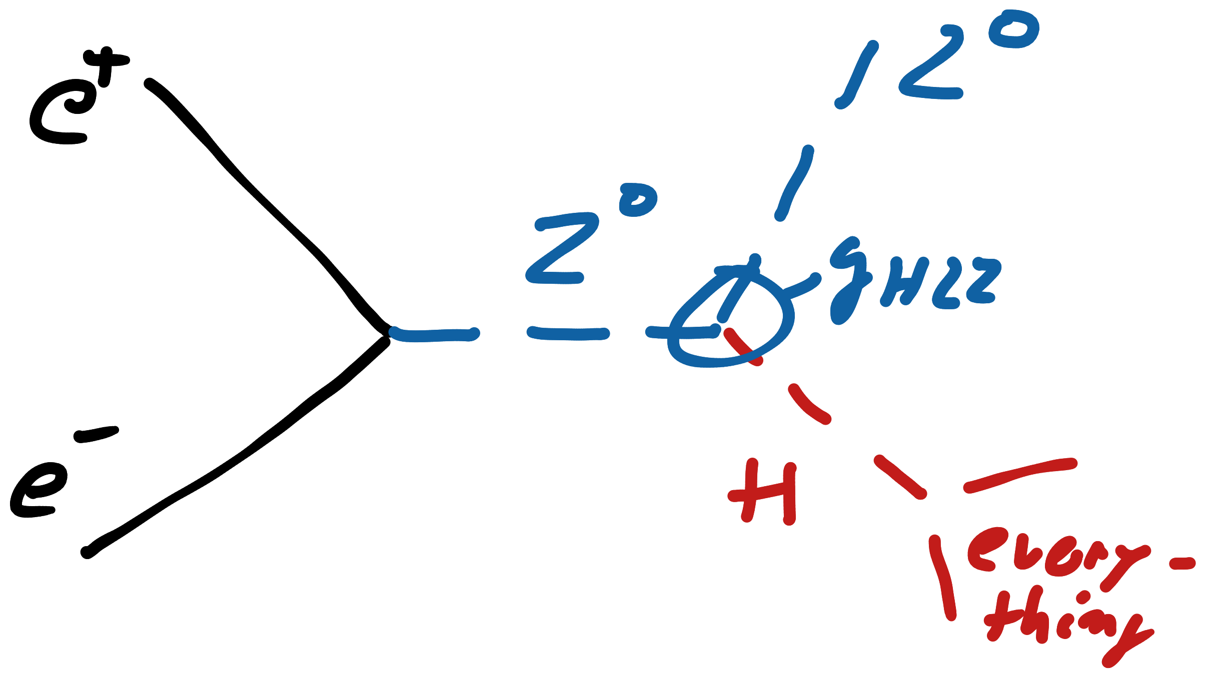

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σ x BR for specific Higgs decays - here the mass of 125 GeV is giving us many possibilites

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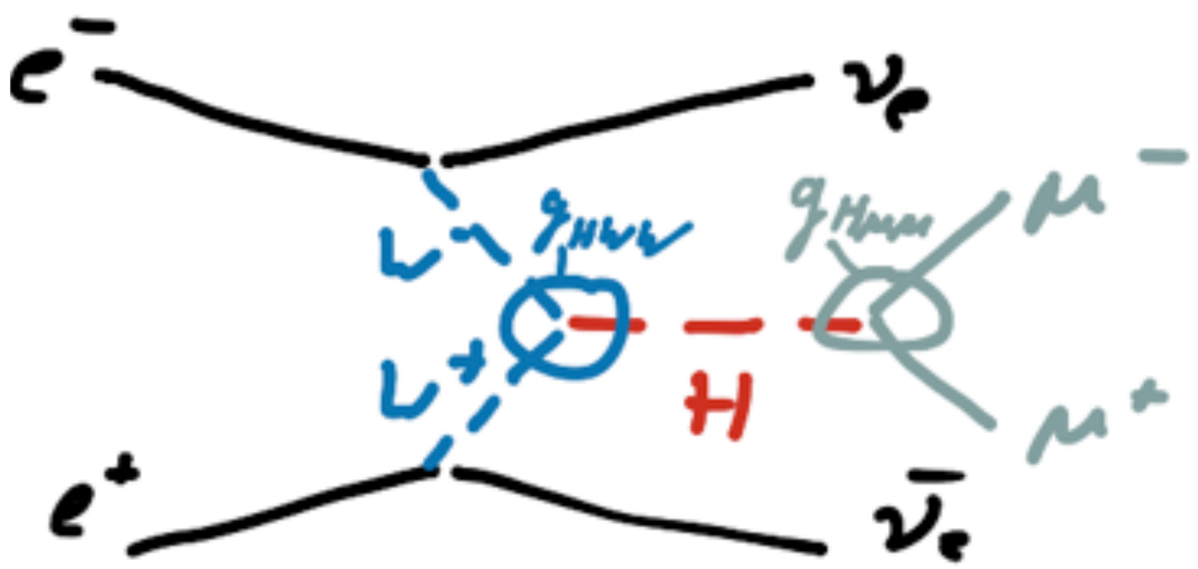

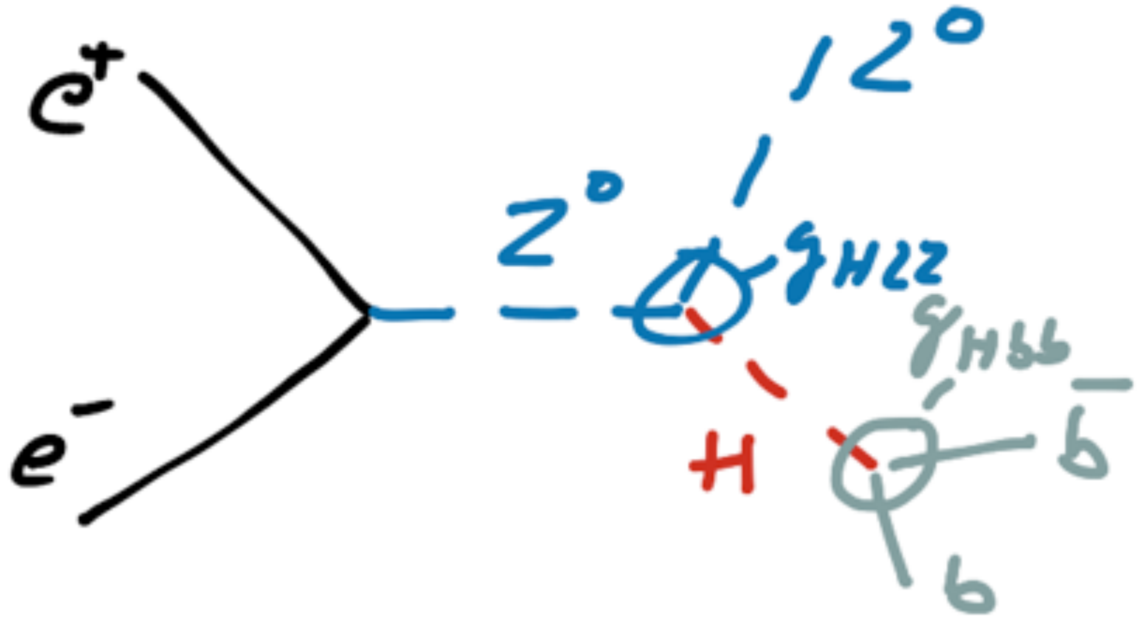

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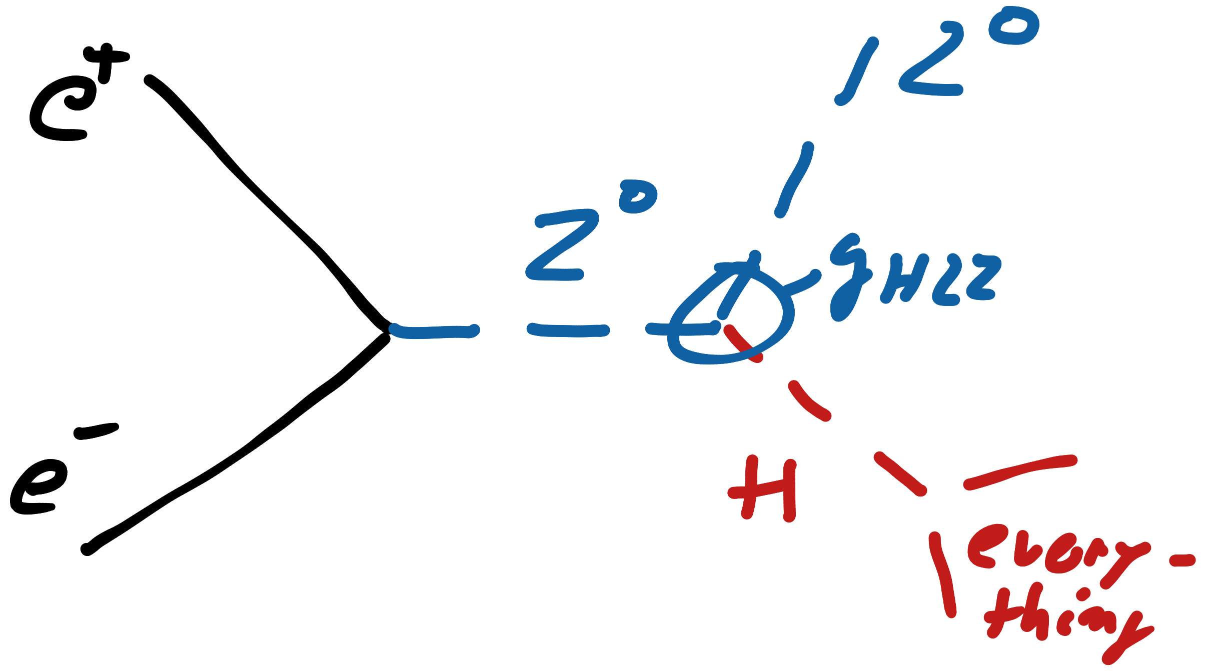

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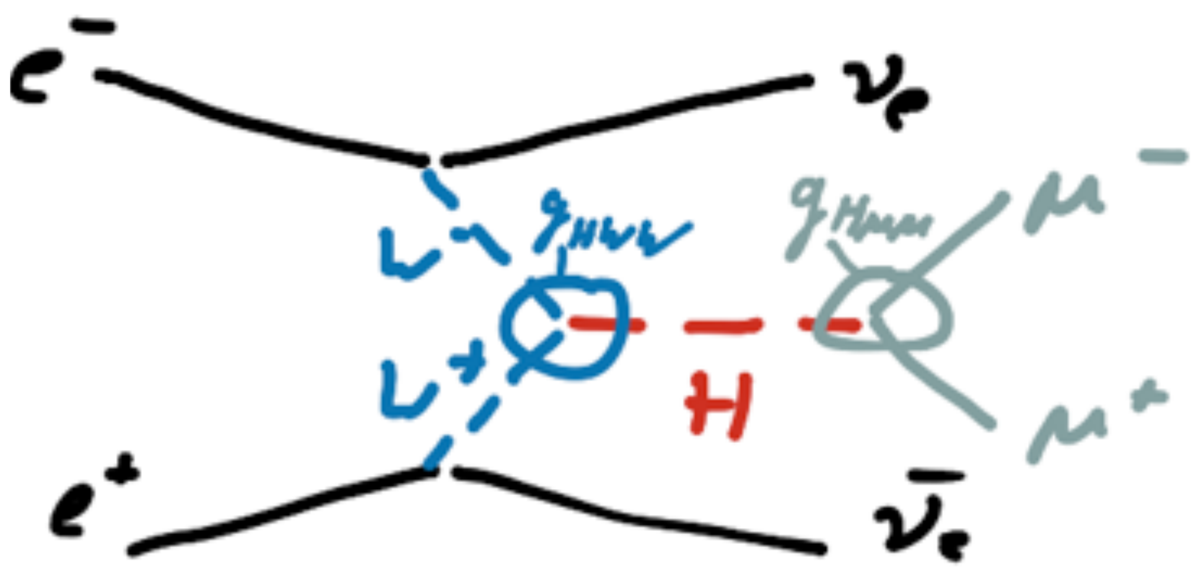
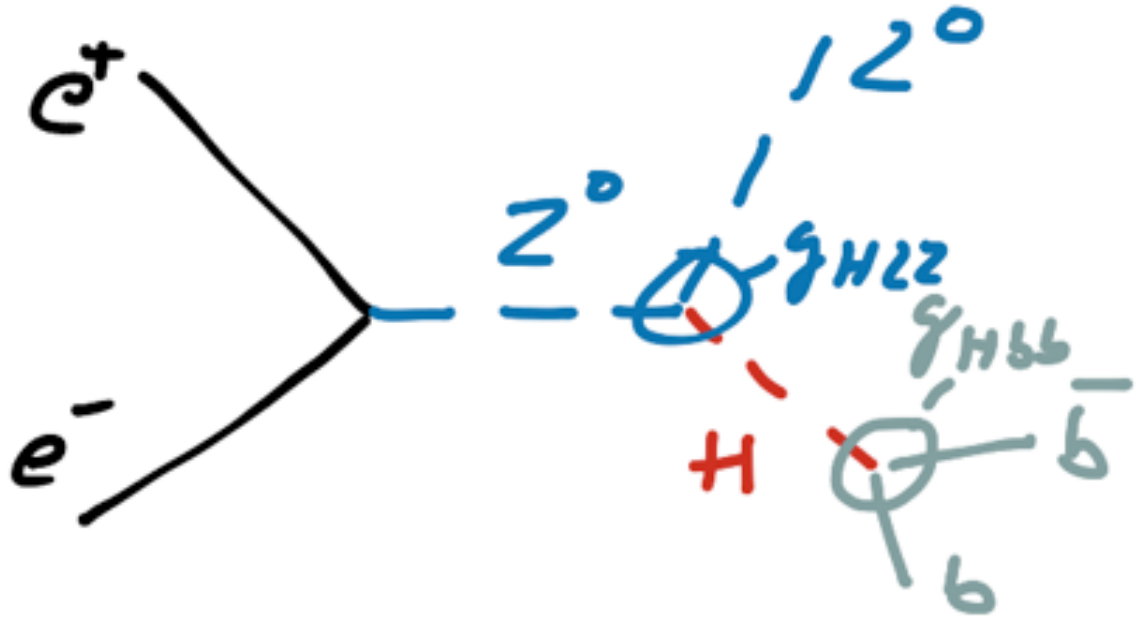




measure couplings to fermions and bosons using production and decay

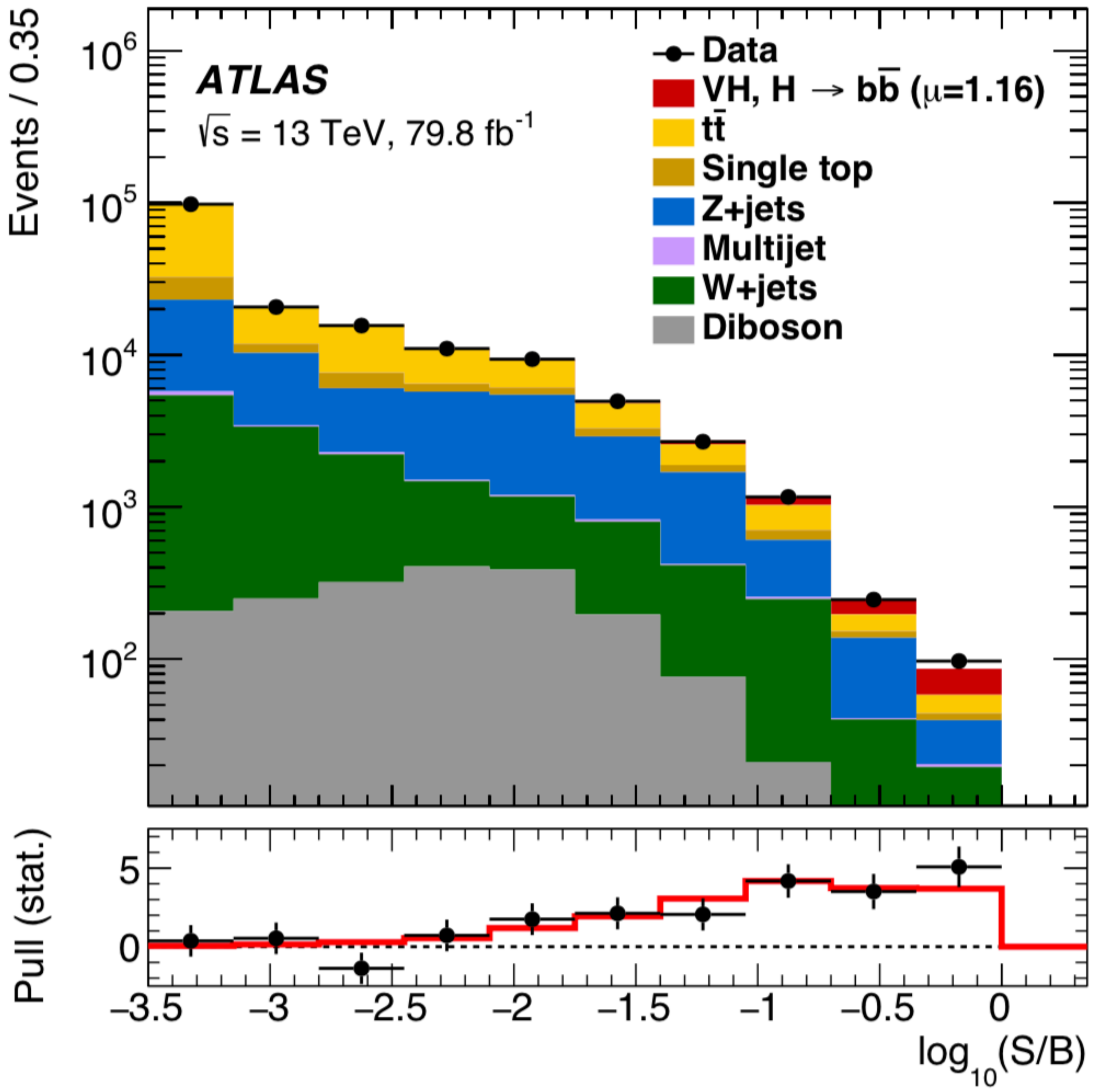
➩ can be made model-independent in combination with the measurement of the HZ coupling in recoil

Unique Measurements at Lepton Colliders

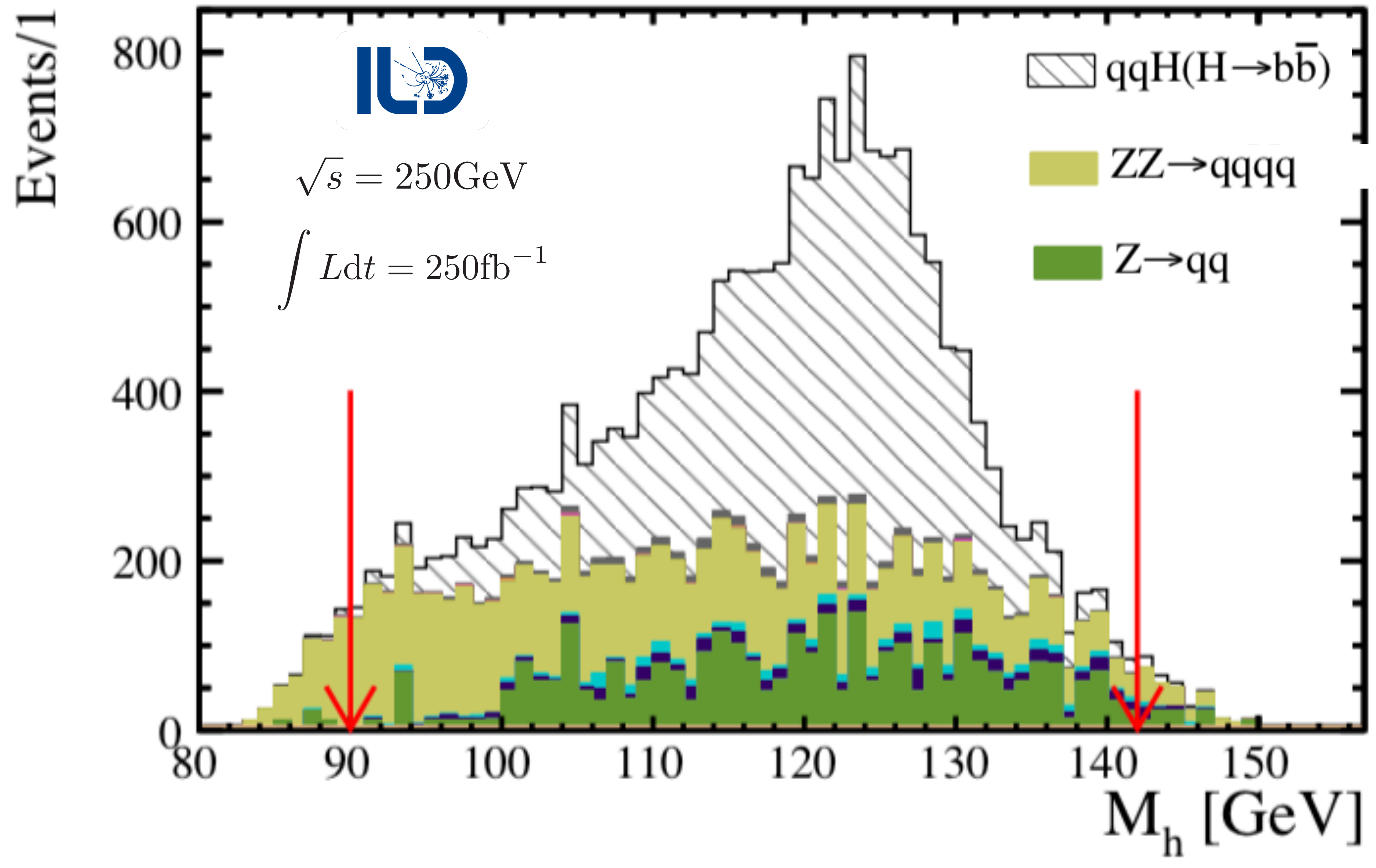
Enabled by the clean environment

- 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

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

	at LHC	at e+e-
# 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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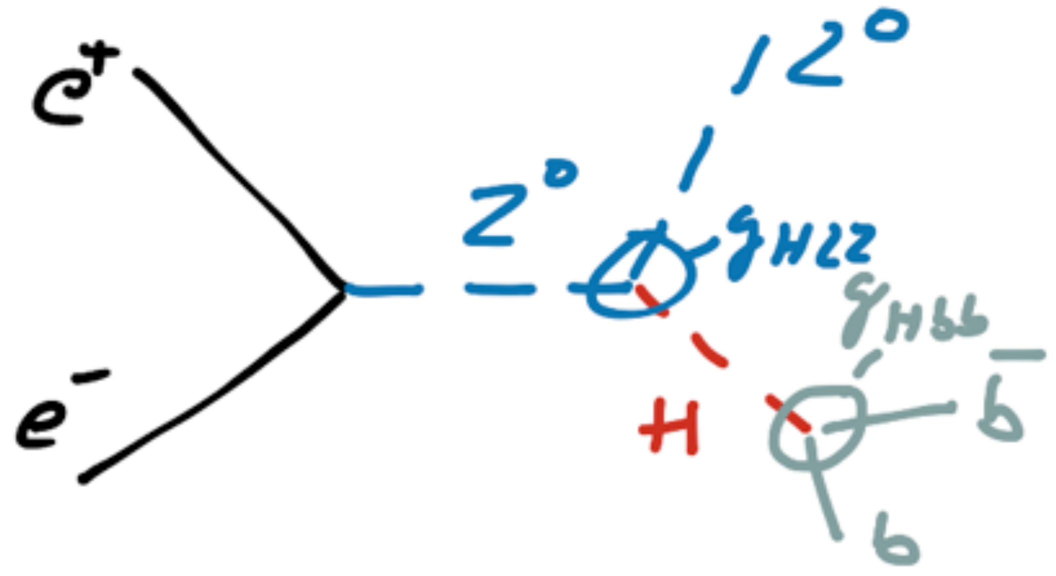
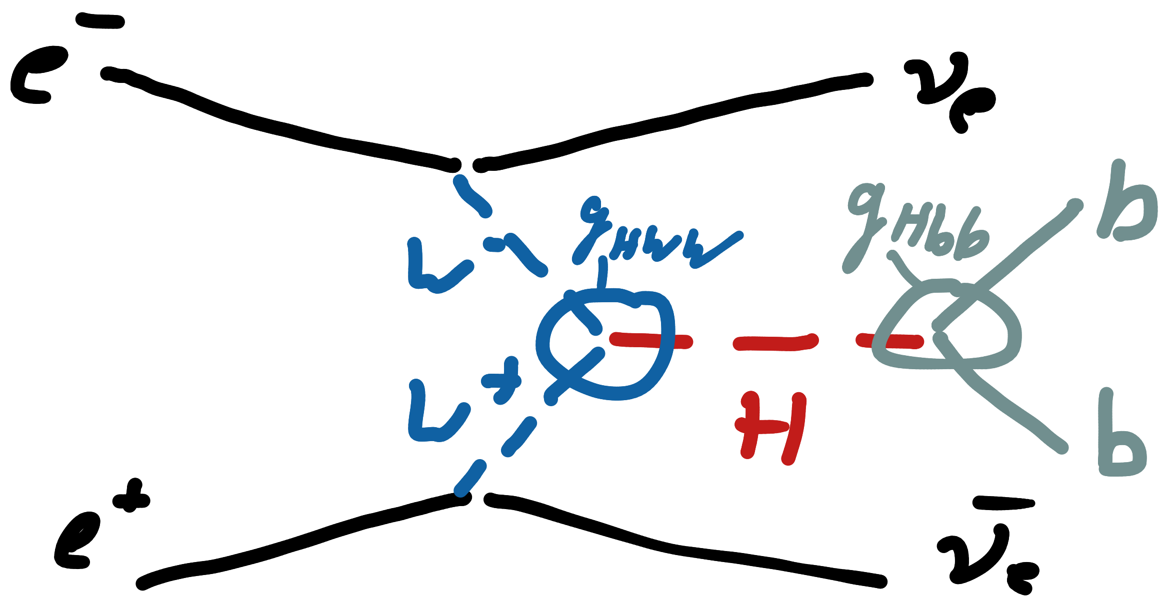
  Measurement of H->bb, cc, gg

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





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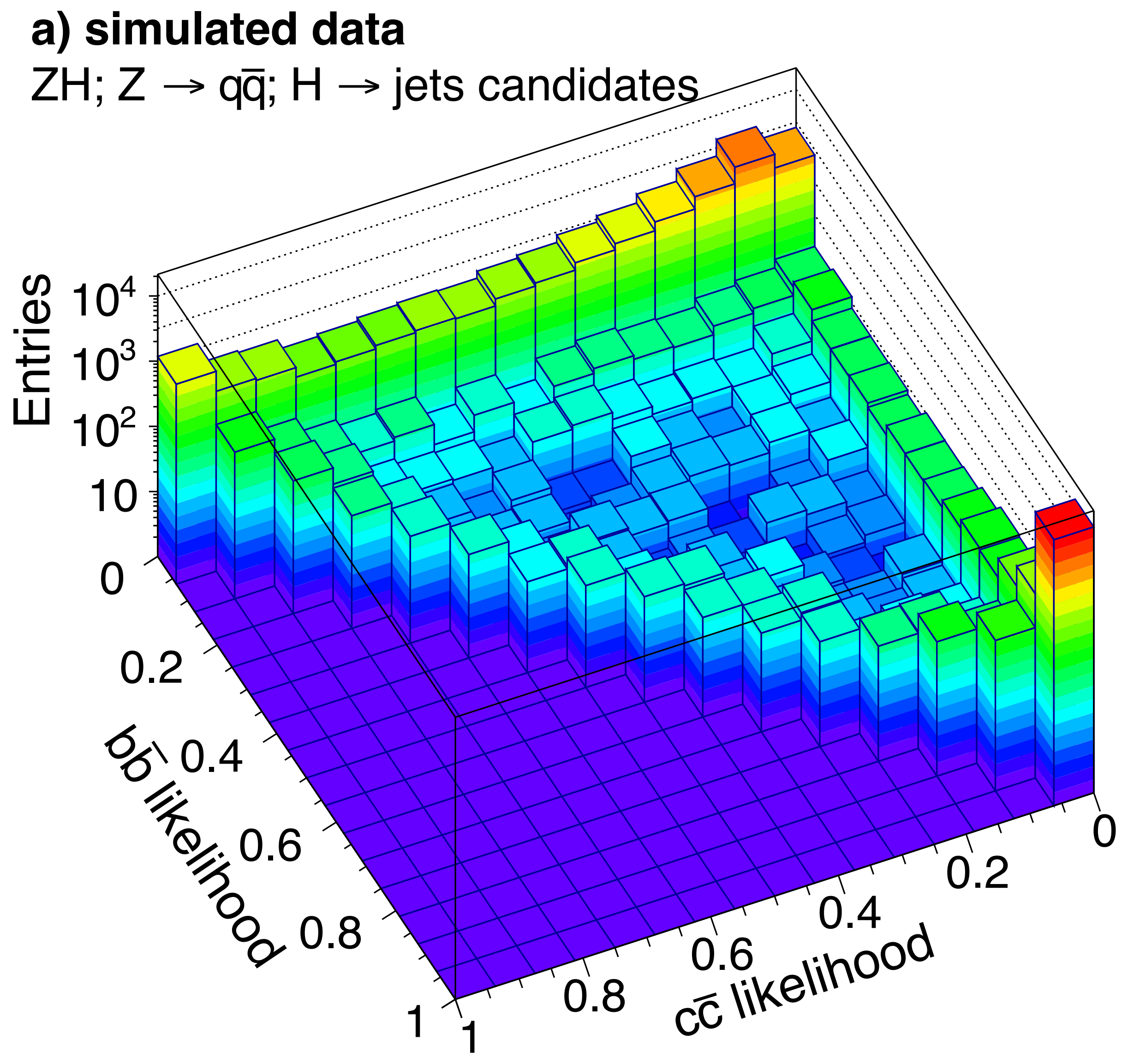

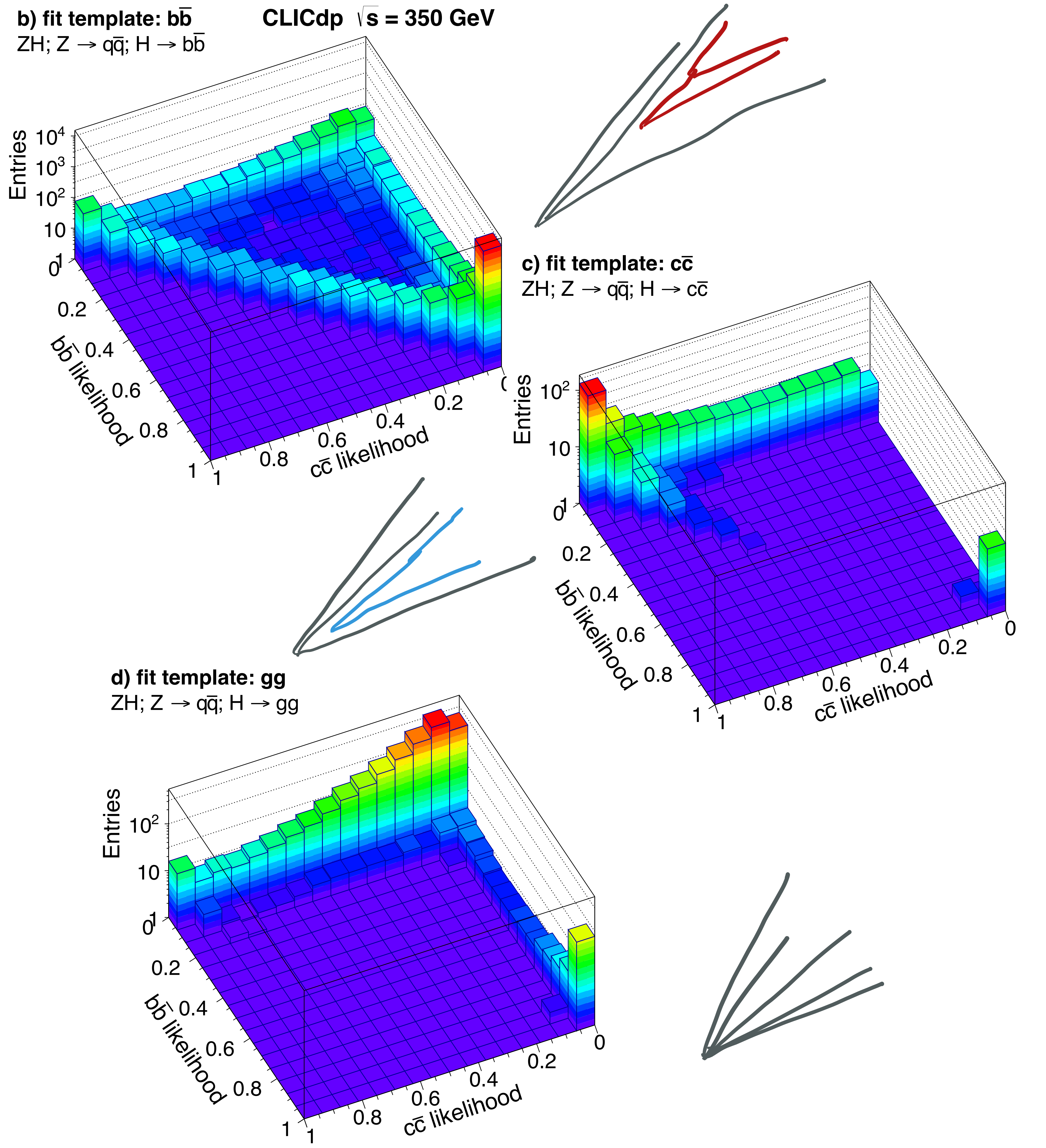

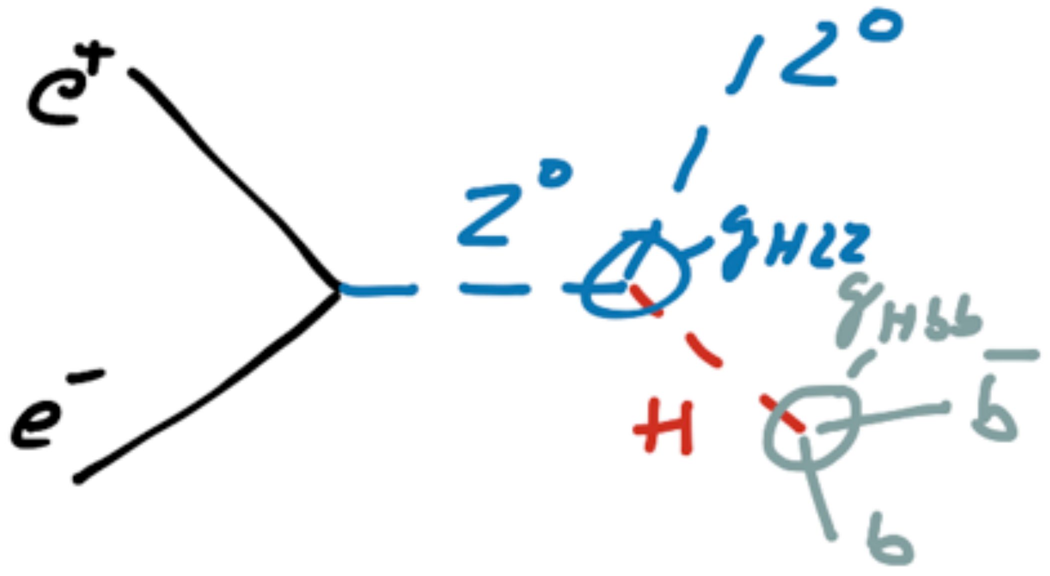

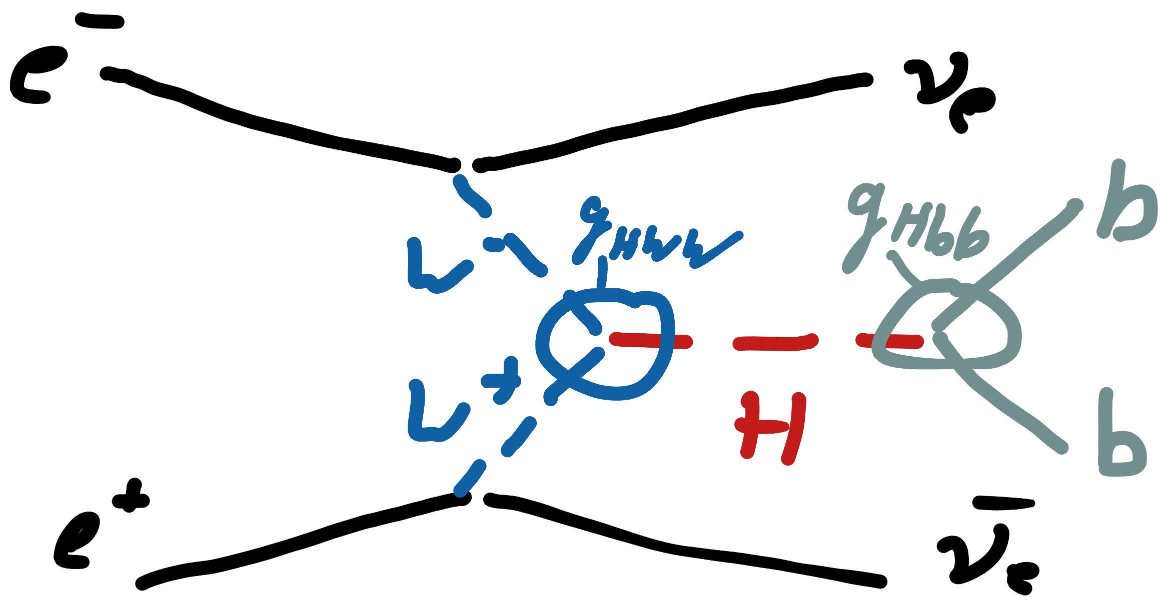

Interpreting Higgs Measurements

A Word on Fits

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Typical fits used in this context:

- **“Model-independent” fit**

minimize a χ^2 with all measurements:

$$\chi^2 = \sum_i \frac{(C_i - 1)^2}{\Delta F_i^2}$$

$$C_{\mathrm{ZH}} = g^2_{\mathrm{HZZ}}$$

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N.B.: Not fully model independent, does not account for certain possible BSM features of HV couplings

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- **"Model-independent EFT" fit**

  A global fit of Higgs and other EW observables parametrizing deviations from the SM by various operators - allows for couplings not included in κ fit, includes connections between W and Z couplings

Extracting the Total Width

Model independent measurement at high precision

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$$\sigma(\mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) \propto \frac{g_{HZZ}^4}{\Gamma_{\mathrm{tot}}} \quad \text{and} \quad \sigma(\mathrm{ZH}) \propto g_{HZZ}^2$$

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

$$\sigma(\mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to \mathrm{WW}^*) \propto \frac{g^4_{\mathrm{HWW}}}{\Gamma_{\mathrm{tot}}}$$

$$\frac{\sigma(e^+e^- \to \mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})}{\sigma(e^+e^- \to \mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})} \propto \frac{g^2_{\mathrm{HZZ}}}{g^2_{\mathrm{HWW}}}$$

need the "model-independent anchor" of the ZH measurement

Extracting the Total Width

Model independent measurement at high precision

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

- In the “model-independent fit” framework the total width is obtained from production and decay of the Higgs:

$$\sigma(\mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) \propto \frac{g^4_{HZZ}}{\Gamma_{\mathrm{tot}}} \quad \text{and} \quad \sigma(\mathrm{ZH}) \propto g^2_{HZZ}$$

➯ The low BR of H->ZZ and correspondingly large uncertainties make this determination relatively imprecise

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

$$\sigma(\mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to \mathrm{WW}^*) \propto \frac{g^4_{\mathrm{HWW}}}{\Gamma_{\mathrm{tot}}}$$

$$\frac{\sigma(e^+e^- \to \mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})}{\sigma(e^+e^- \to \mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})} \propto \frac{g^2_{\mathrm{HZZ}}}{g^2_{\mathrm{HWW}}}$$

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

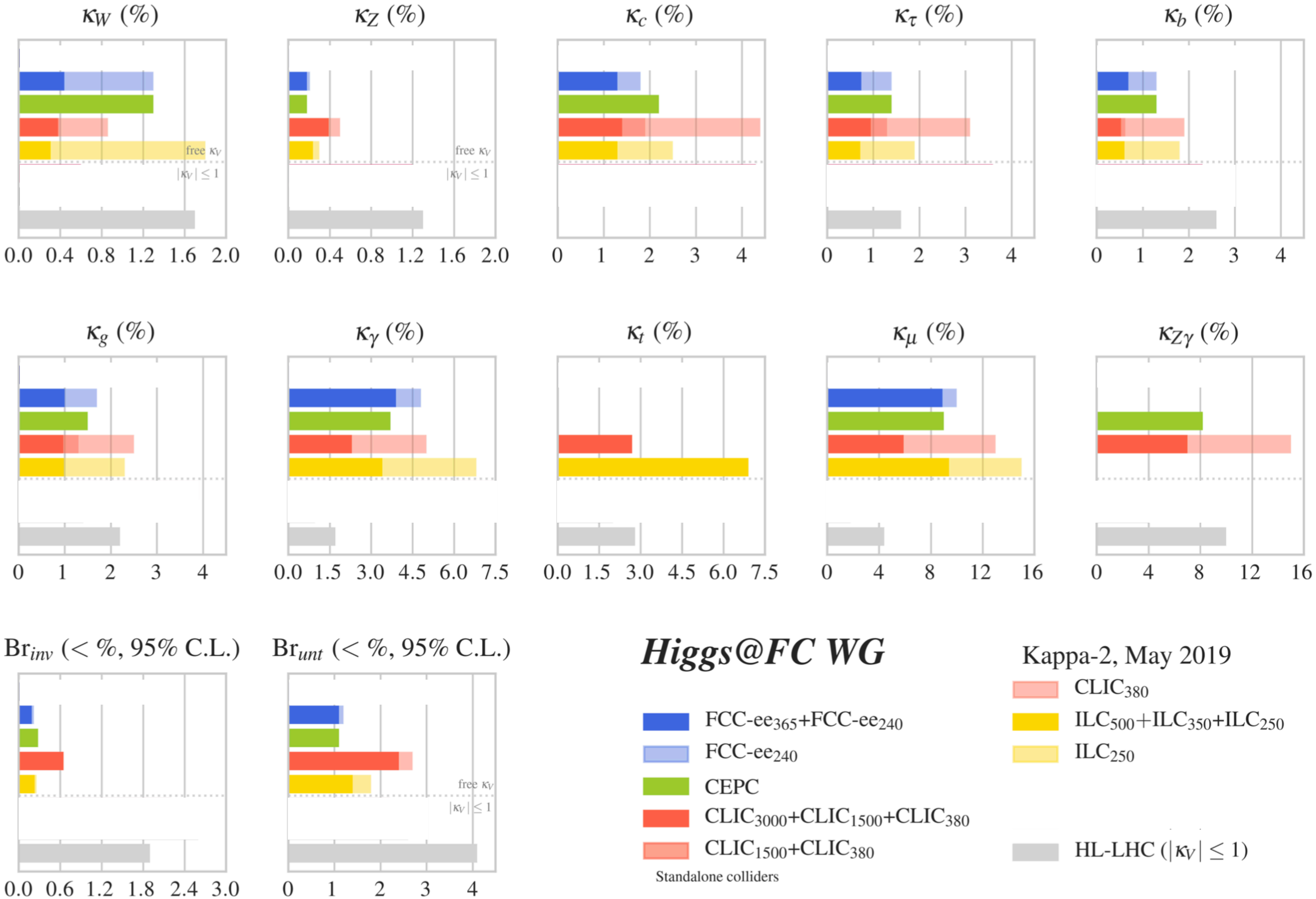
Perspectives on Precision

Illustrating Interplay and Reach

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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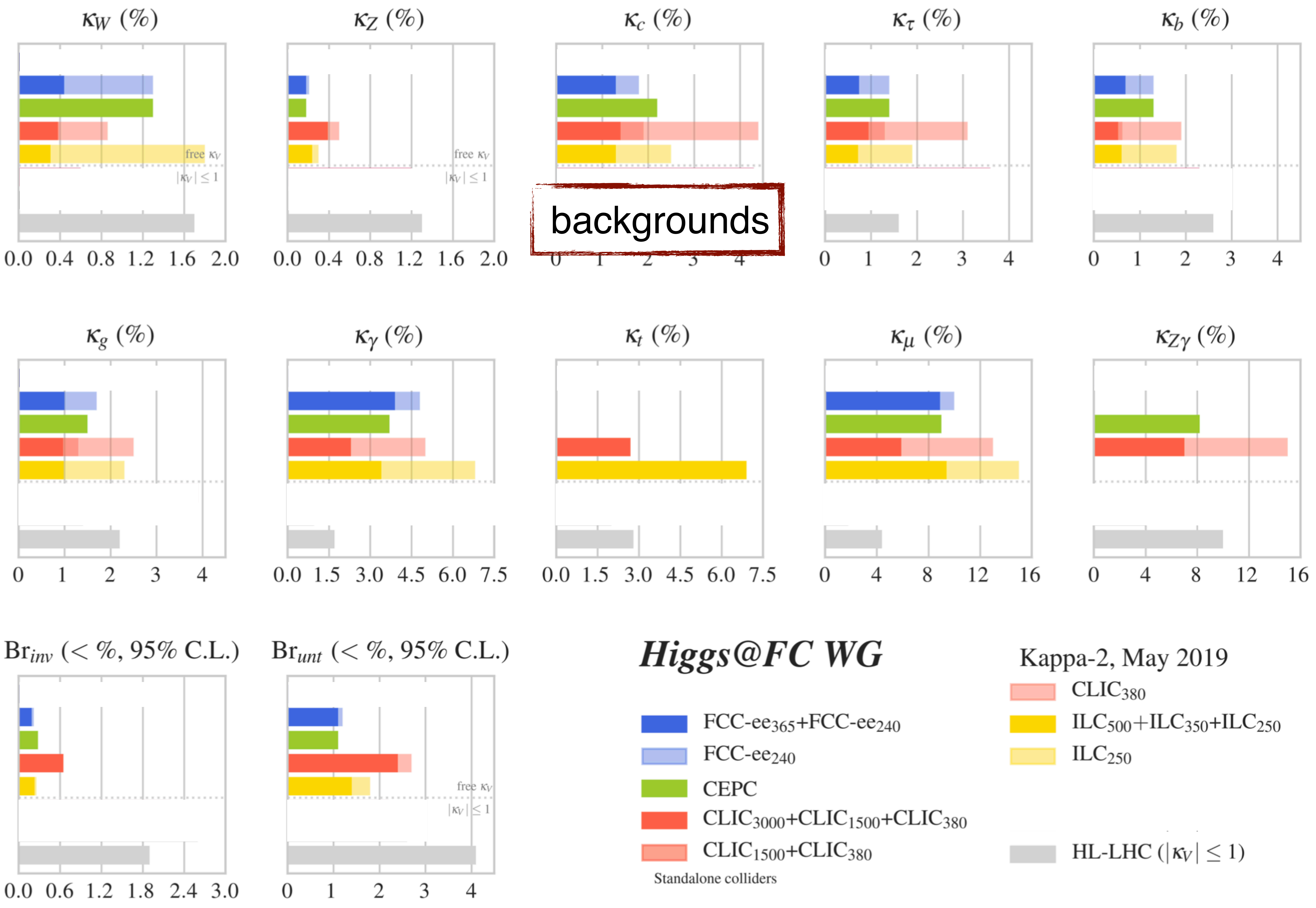

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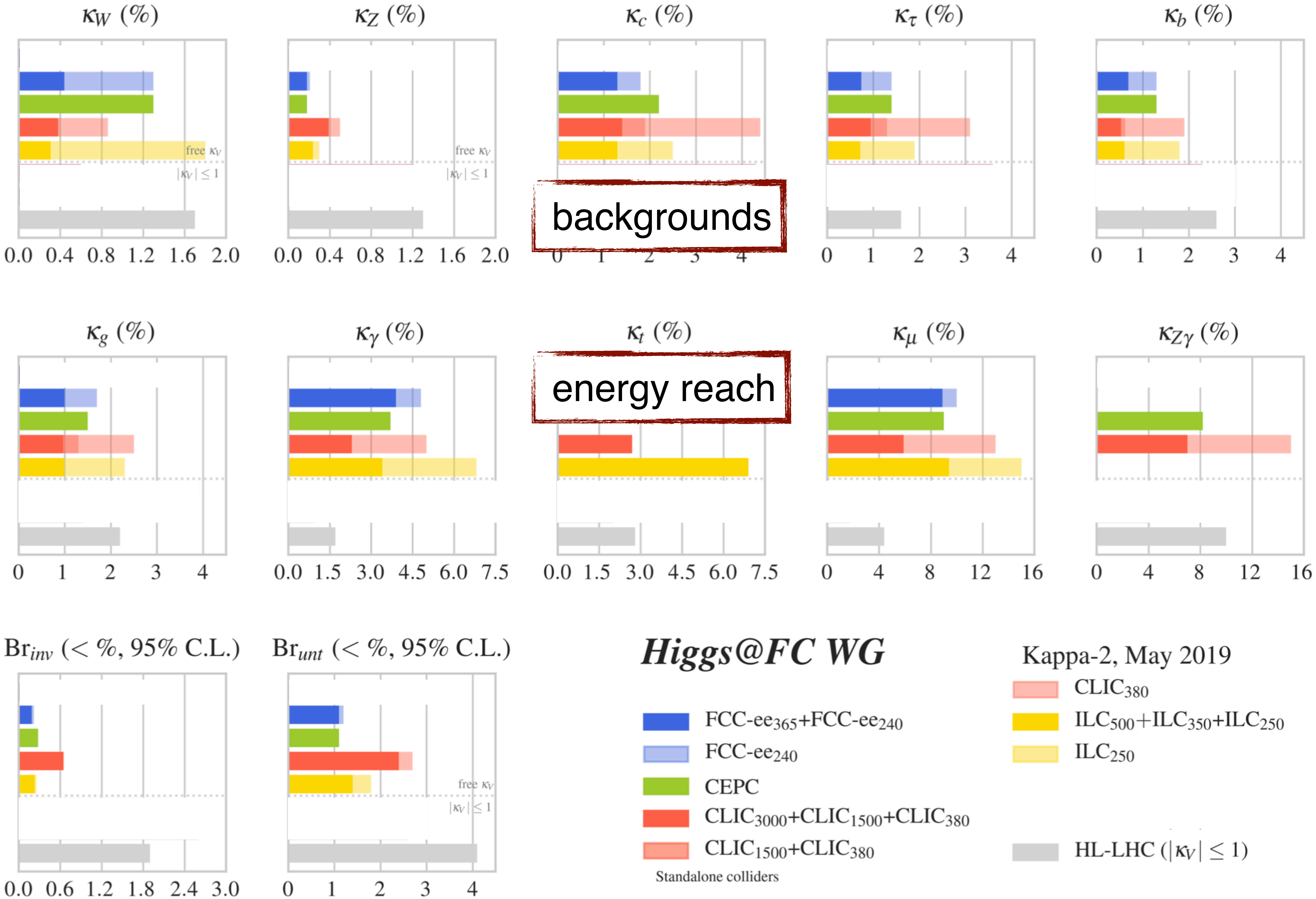


Perspectives on Precision

Illustrating Interplay and Reach

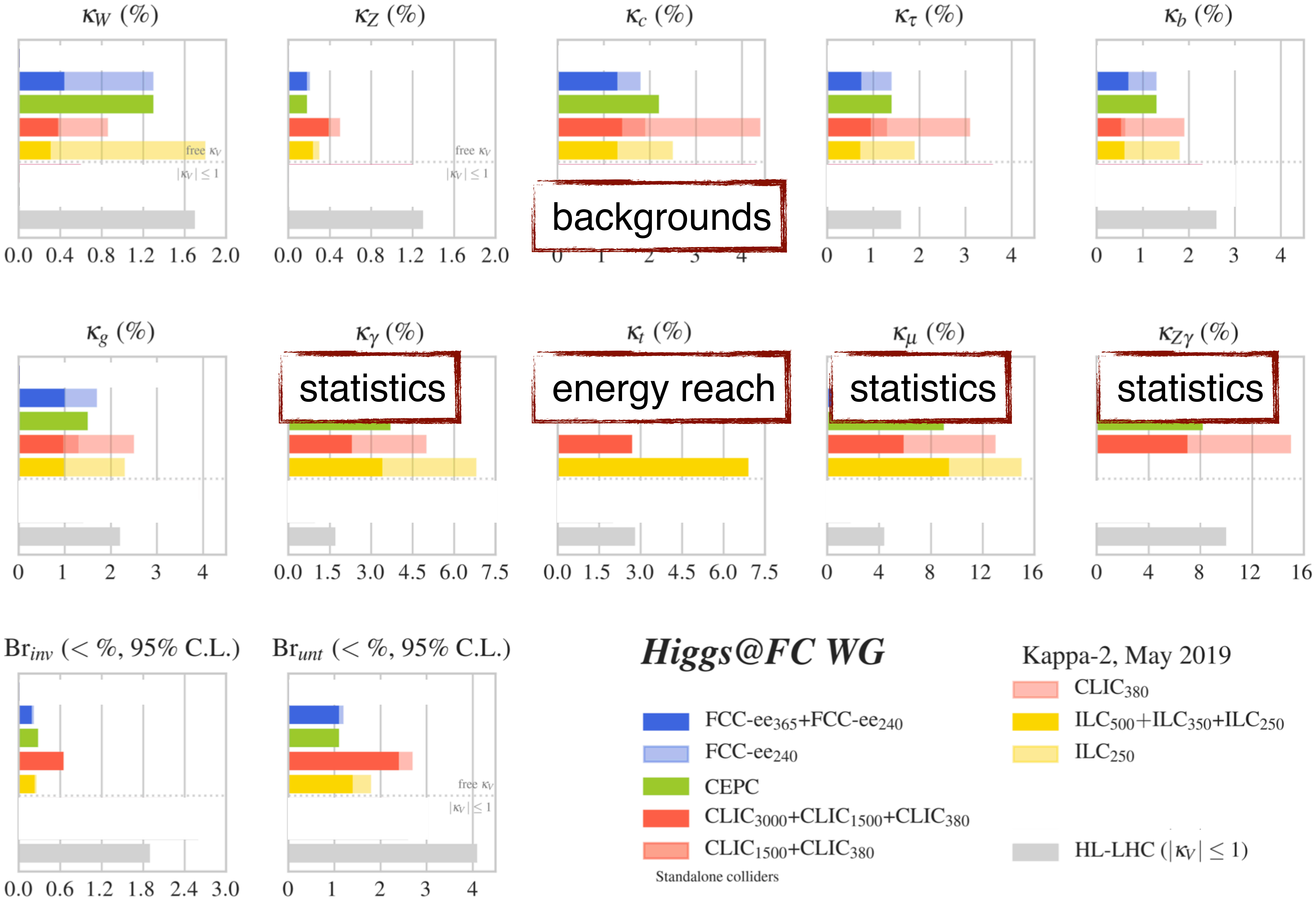
Karlsruhe Institute of Technology

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. $\kappa_V \leq 1$

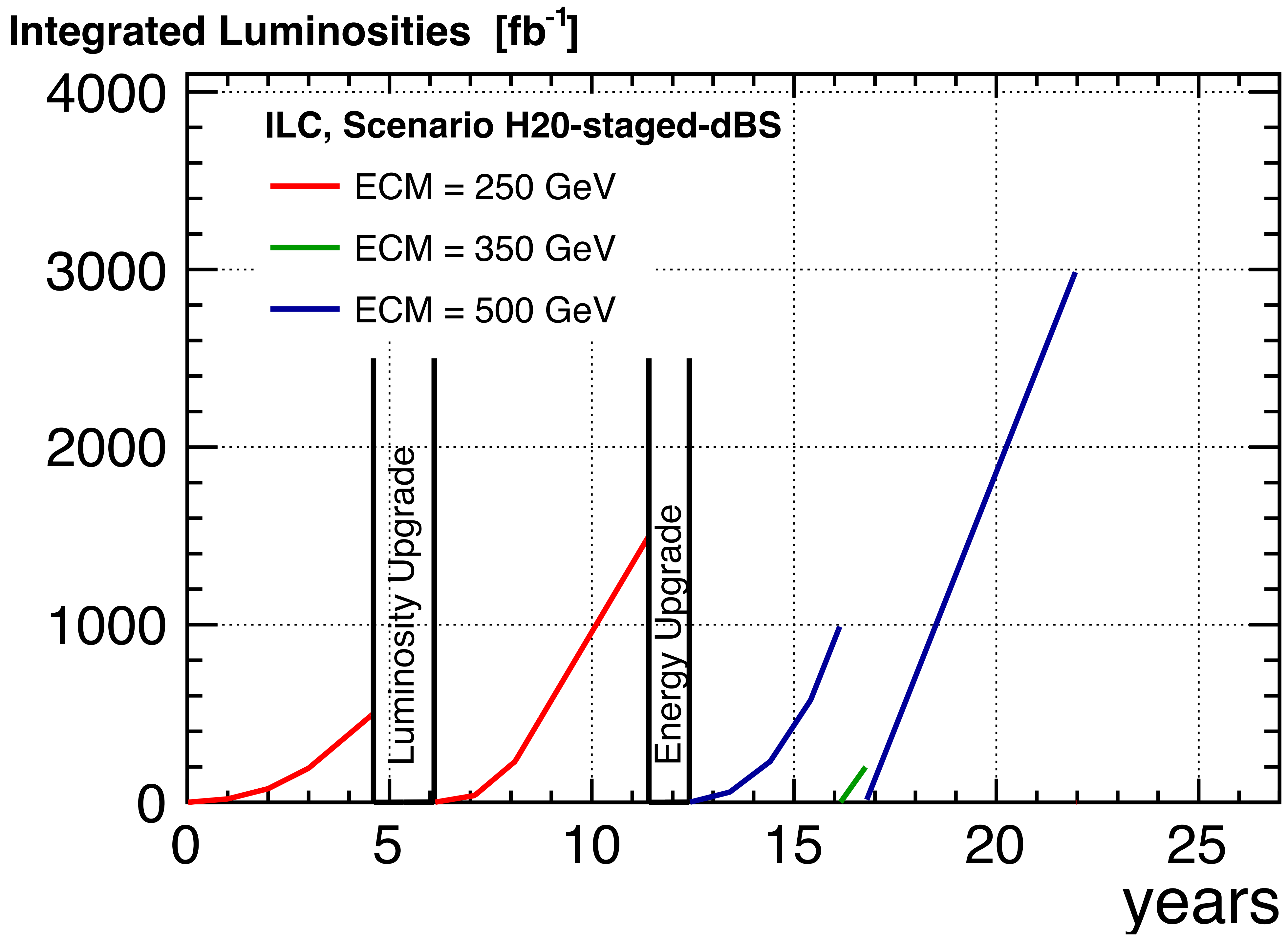
e+e- standalone

not showing HE-LHC, LHeC, FCC-hh



The Relevance of Higgs Coupling Measurements

One EFT Example for ILC



- Precision measurements of couplings may show deviations from the Standard Model
  - “Fingerprinting” of deviation pattern reveals underlying mechanisms

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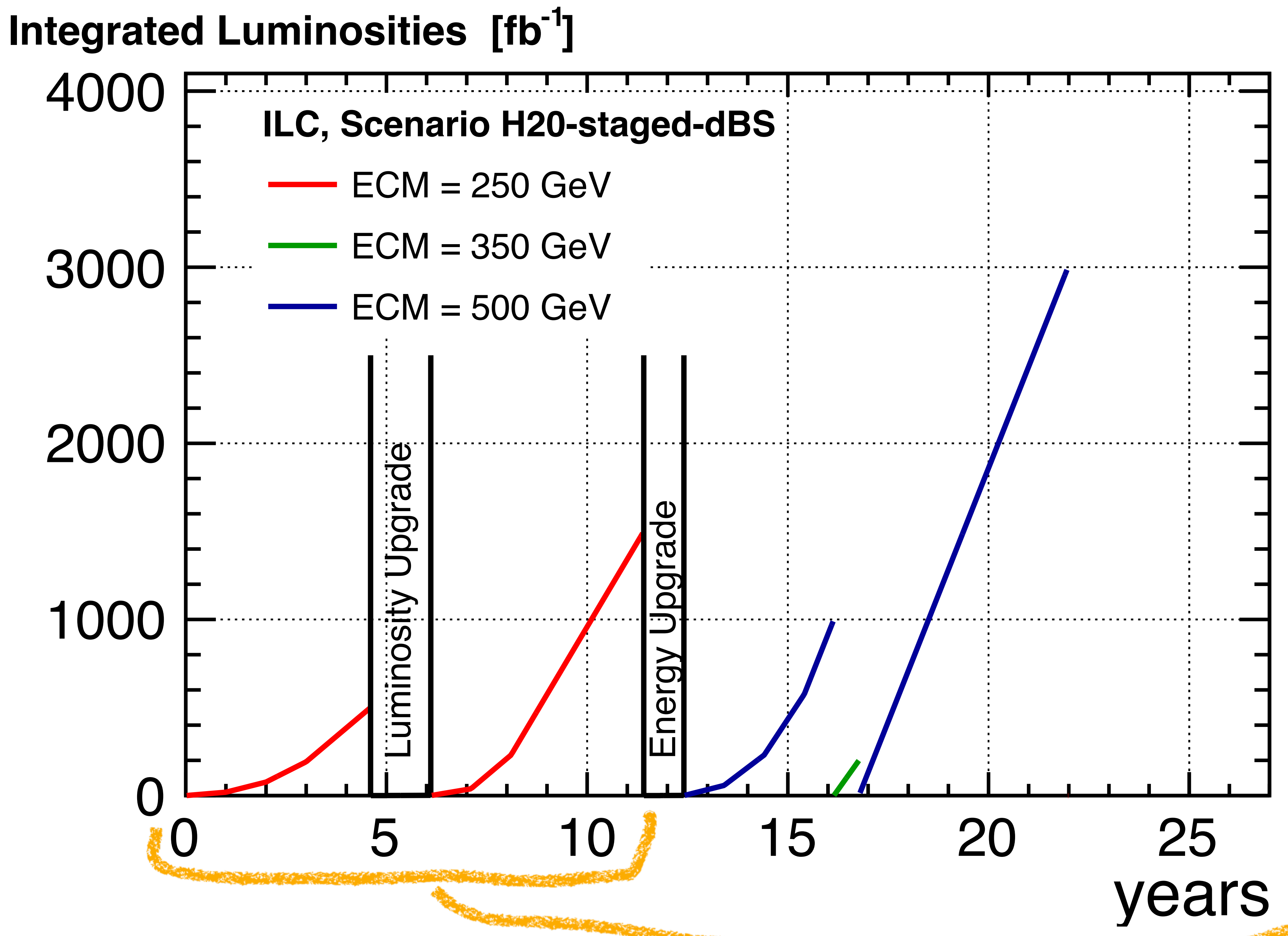

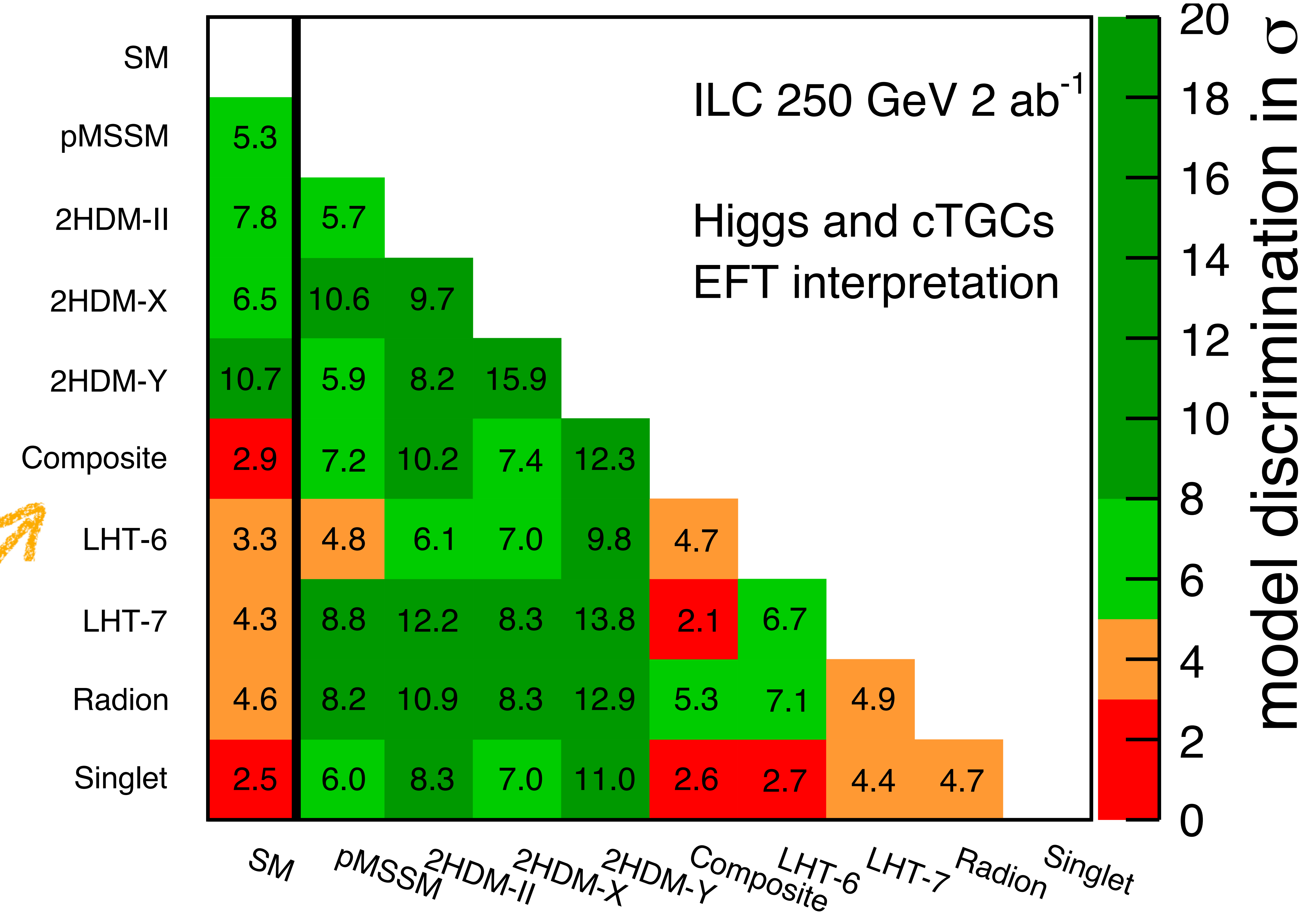

- Precision measurements of couplings may show deviations from the Standard Model
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arXiv:1708.08912

arXiv:1710.07621

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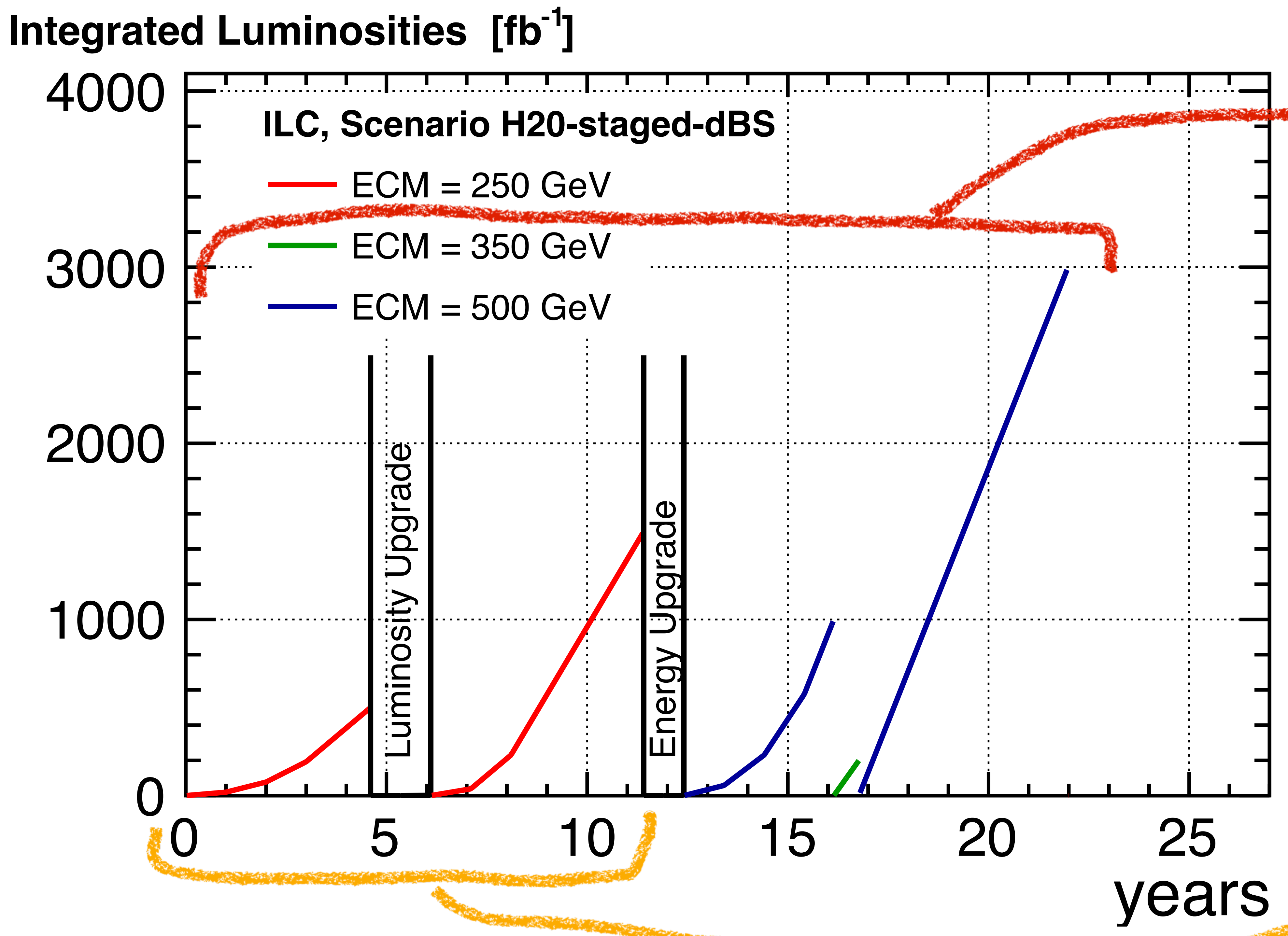

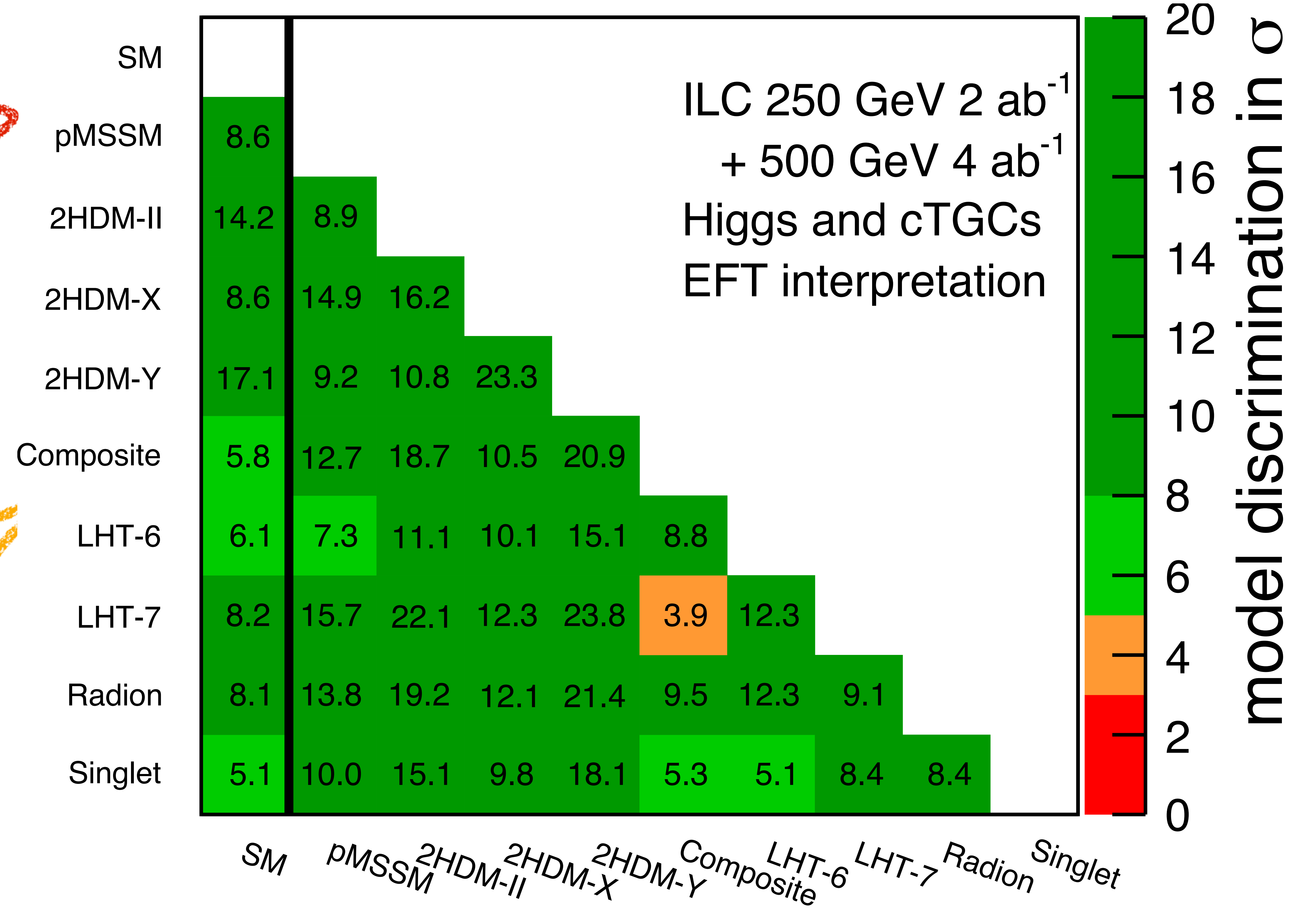

- Precision measurements of couplings may show deviations from the Standard Model
  - “Fingerprinting” of deviation pattern reveals underlying mechanisms
- Discrimination power between models illustrated with EFT fit of ILC projections
  - higher energy may be decisive

arXiv:1708.08912

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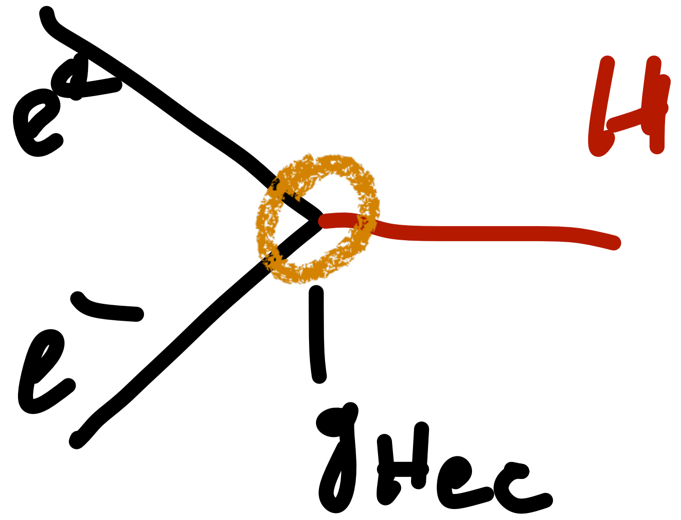
Accessing the Couplings to First Generation Leptons

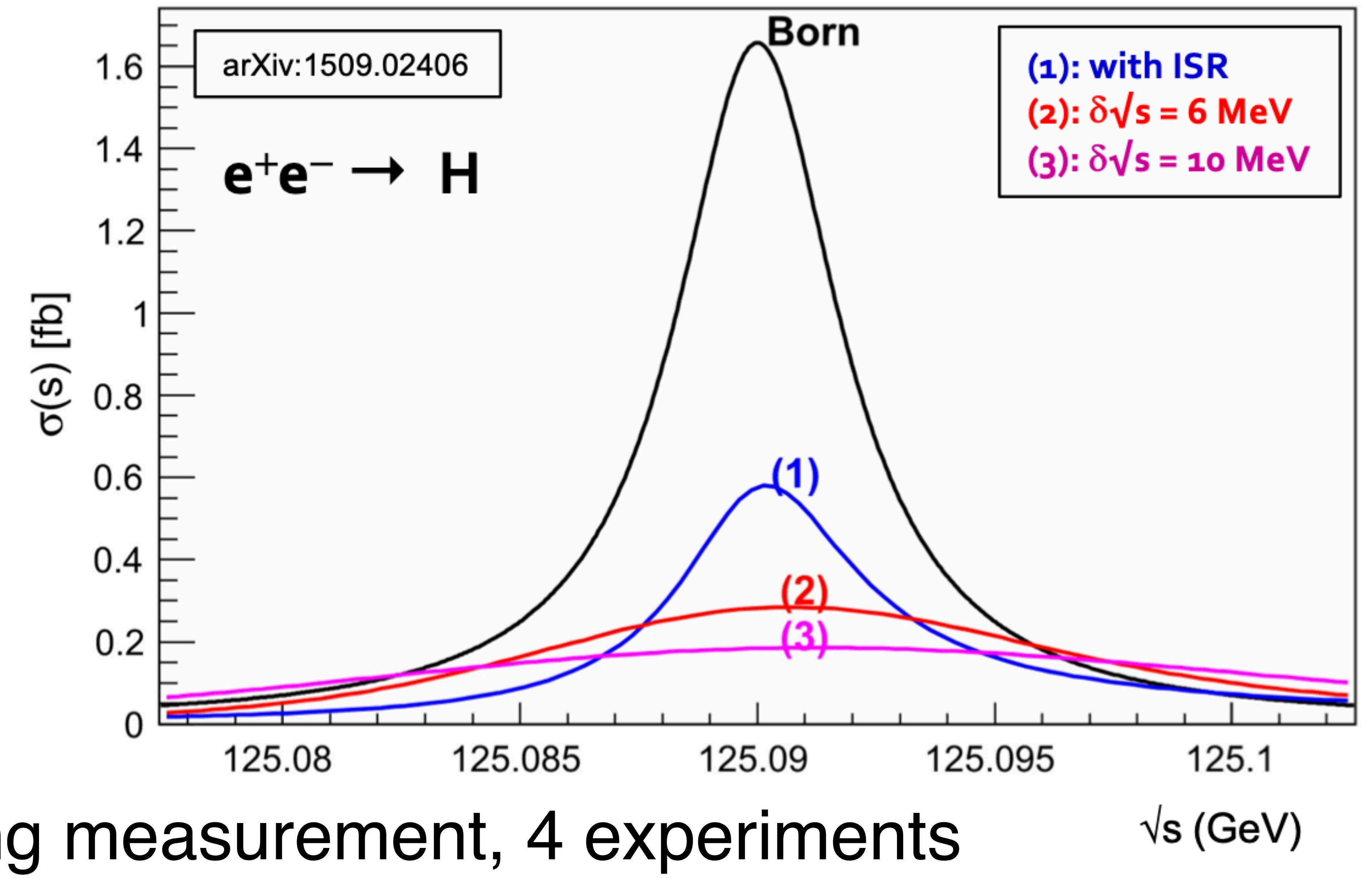
Requiring extreme luminosities of circular colliders

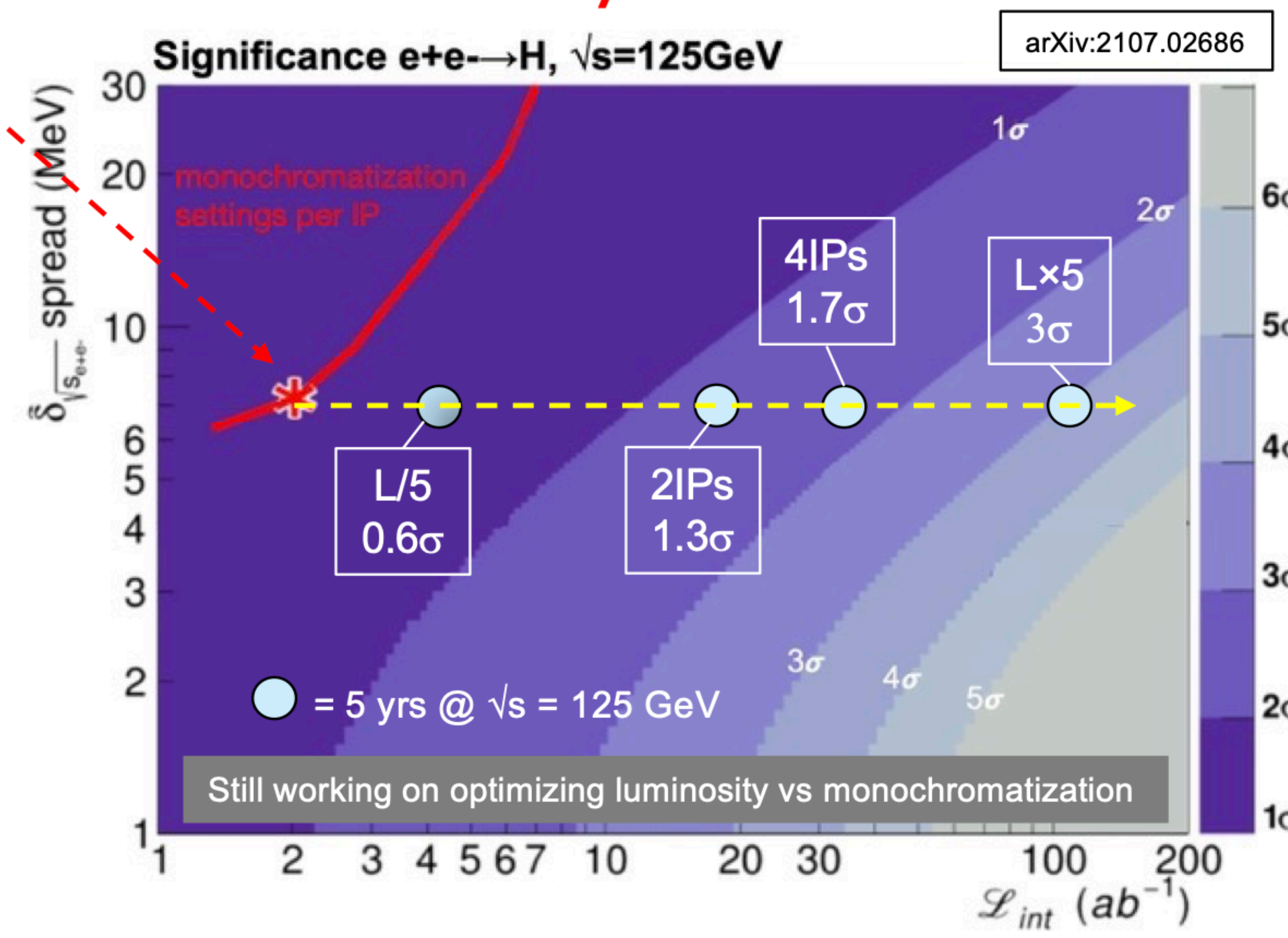
- The only chance to access couplings to first generation: Study of s-channel Higgs production in e^+e^- collisions
  - Requires high luminosities and very small energy spread at 125.1 GeV

Requires special monochromatization to



❑ **First studies indicate a significance of 0.4σ with one detector in one year**

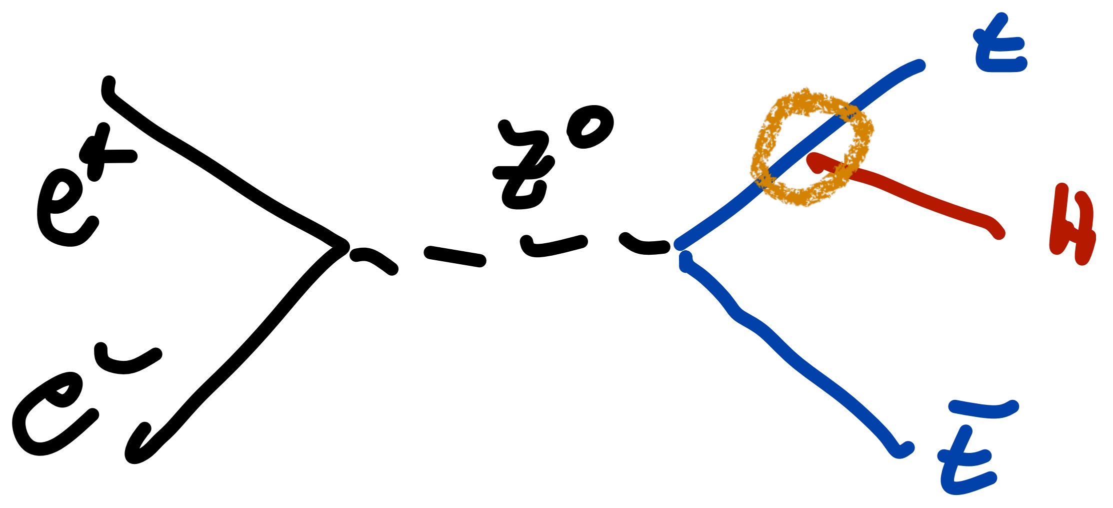




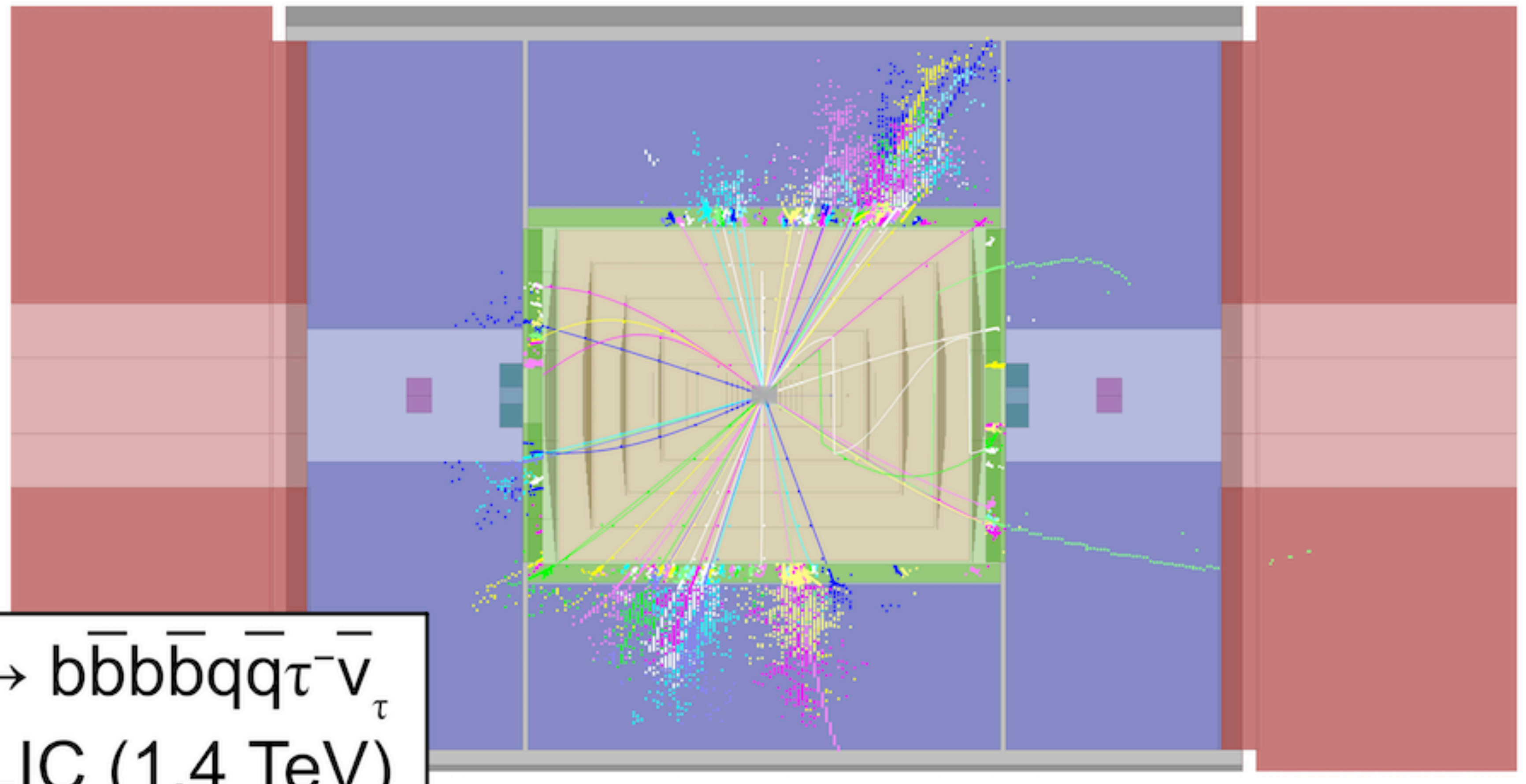
➯ A very challenging measurement, 4 experiments and 3 years may reach a result

Directly measuring the Coupling to the Top Quark

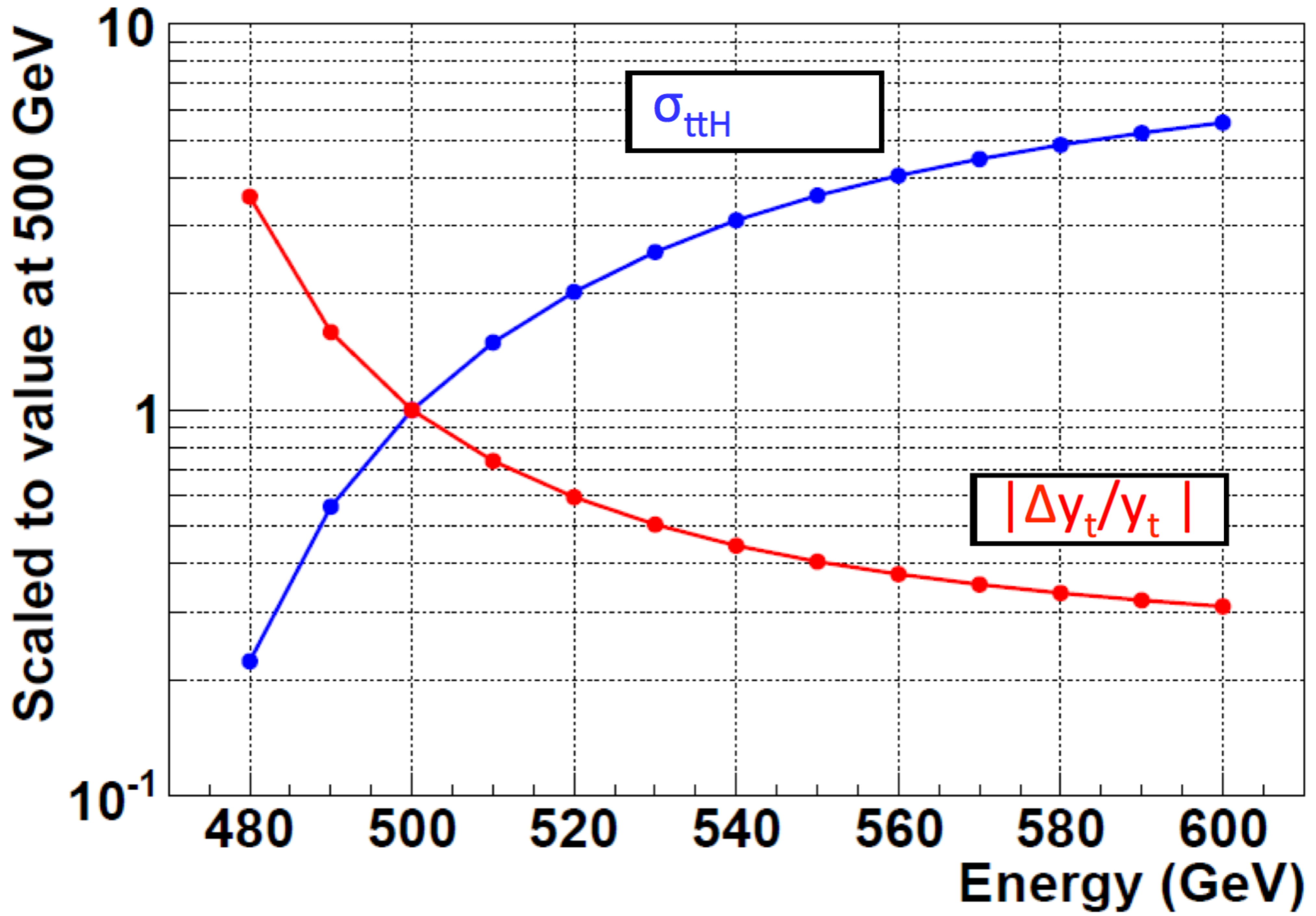
A higher-energy exclusive



- Direct access to the top Yukawa coupling provided by ttH final state: requires energy ≥ 500 GeV (ideal ~ 550 GeV - 1.5 TeV)



$t\bar{t}H \rightarrow b\bar{b}b\bar{b}q\bar{q}\tau^{-}\bar{\nu}_{\tau}$ at CLIC (1.4 TeV)



ILC

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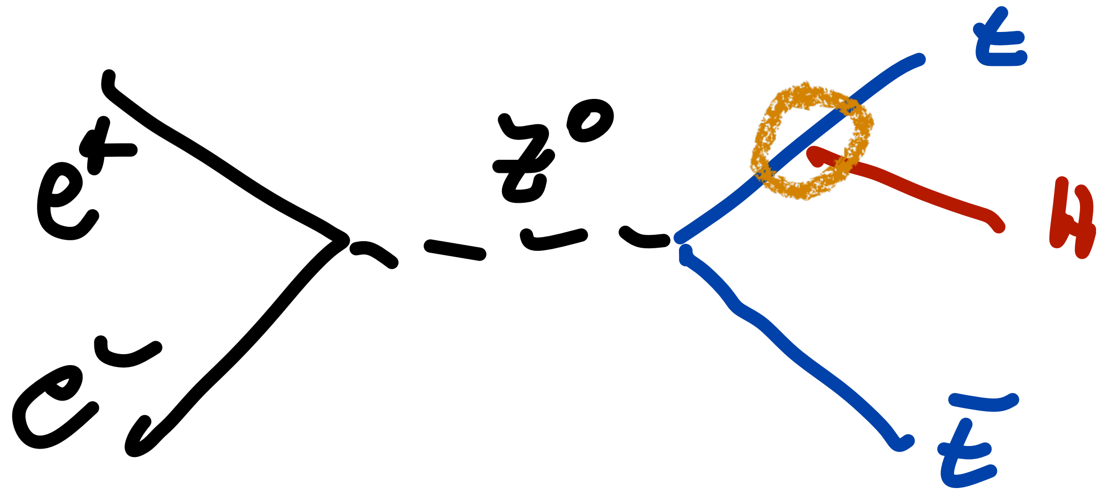

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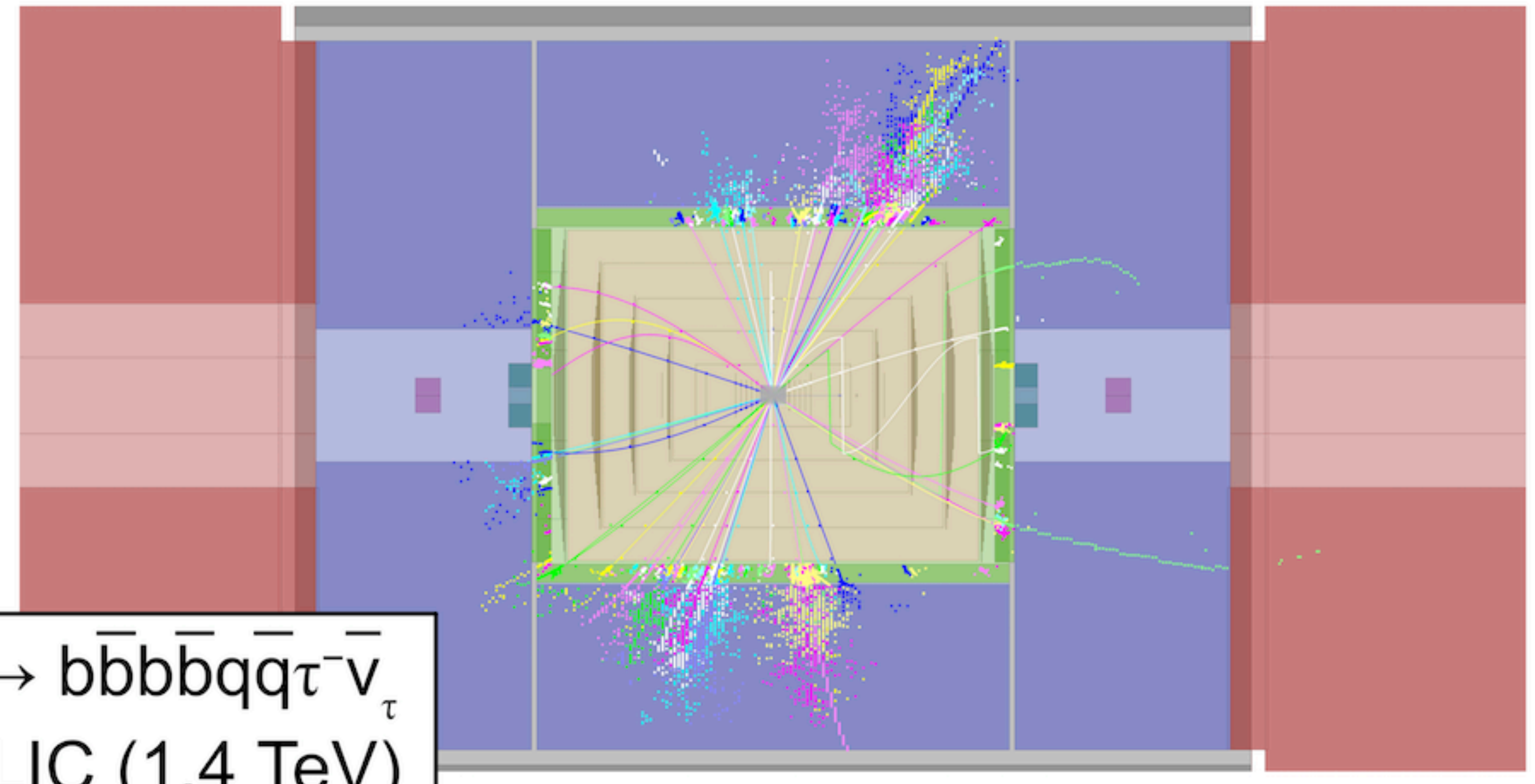

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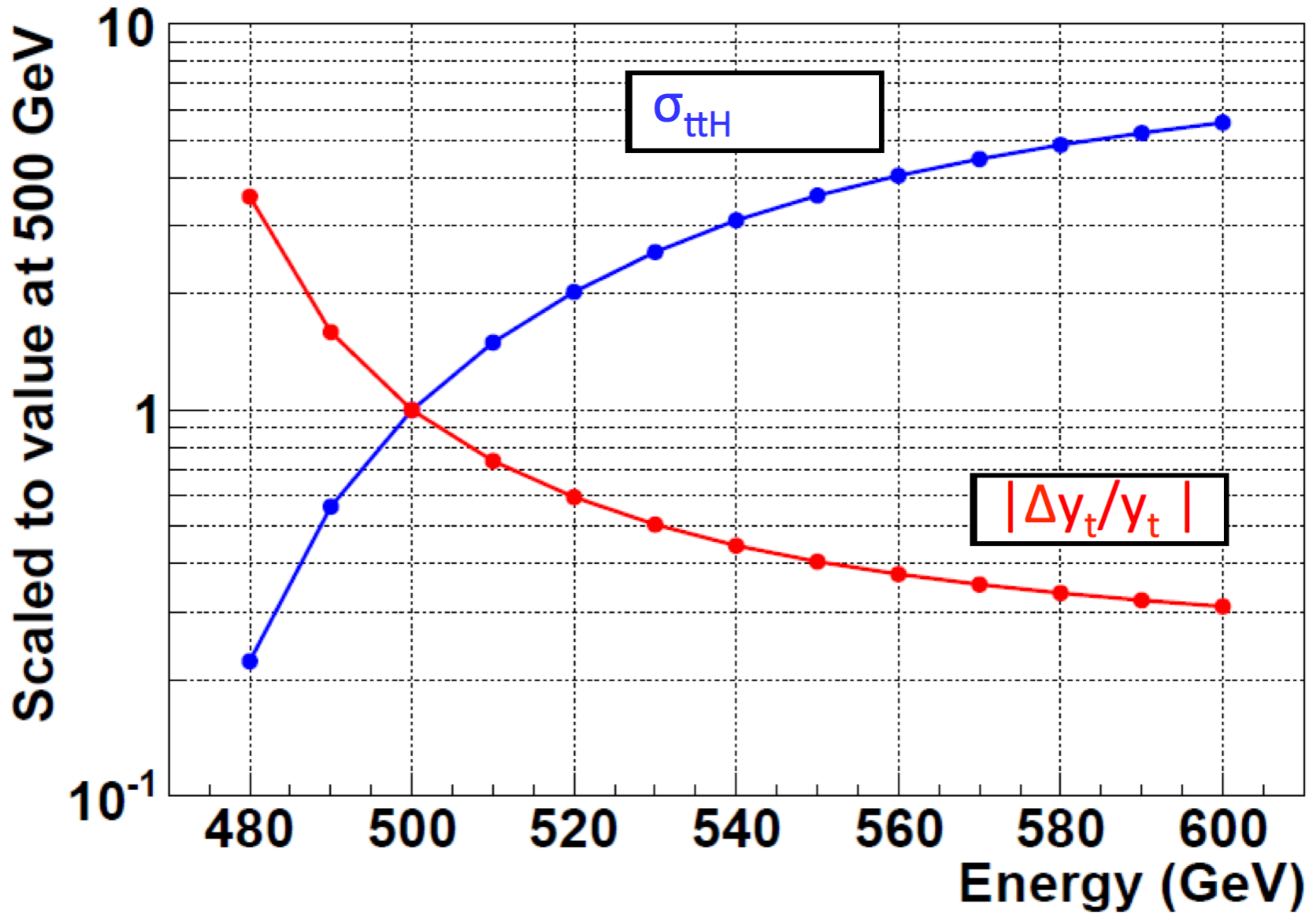


ILC

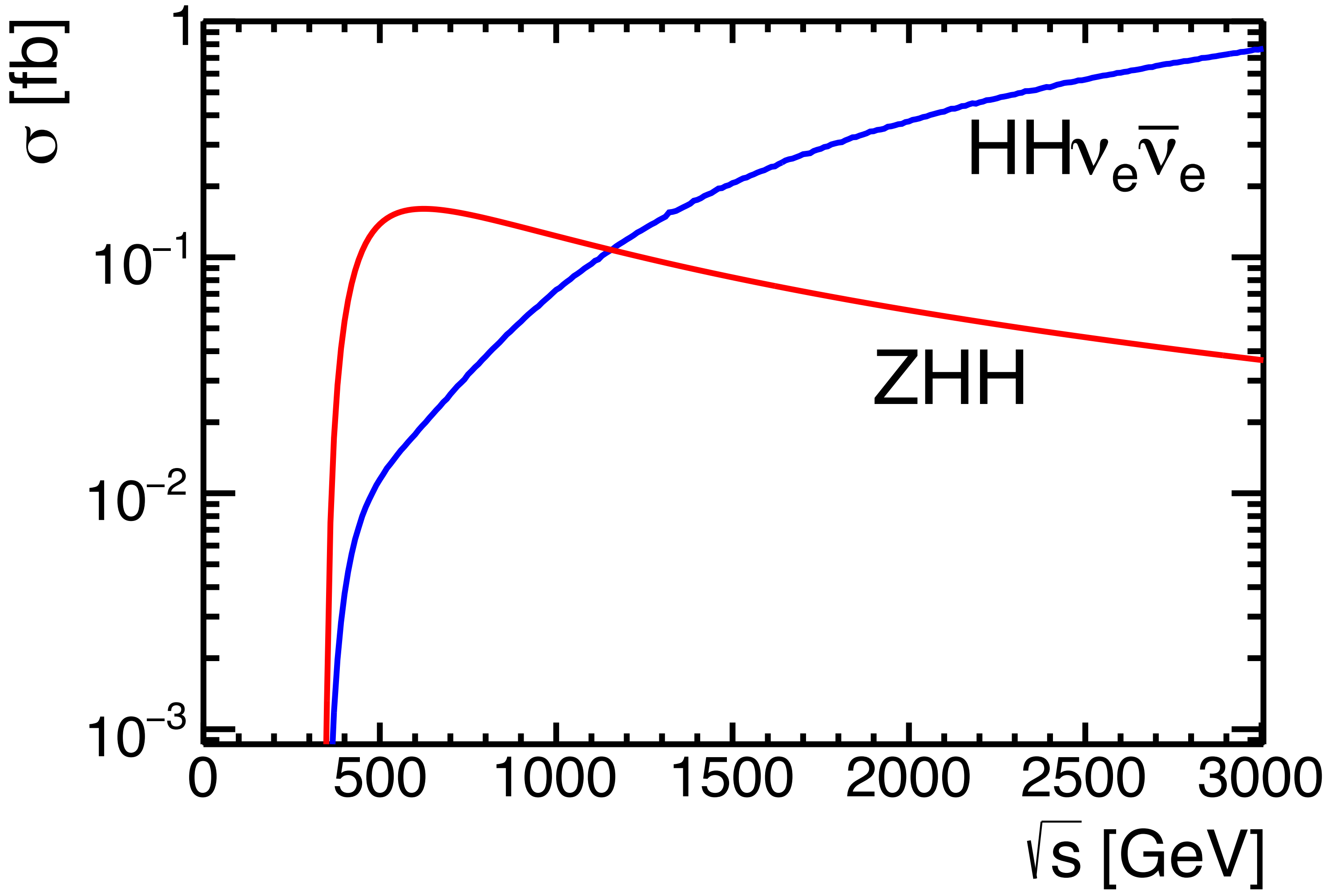
ILC: $\Delta g_{ttH}/g_{ttH}$ ~ 6.3% with 4 ab^{-1} @ 500 GeV
would be ~ 3% @ 550 GeV
(and ~ 13% @ 485 GeV: achieving design energy critical!)

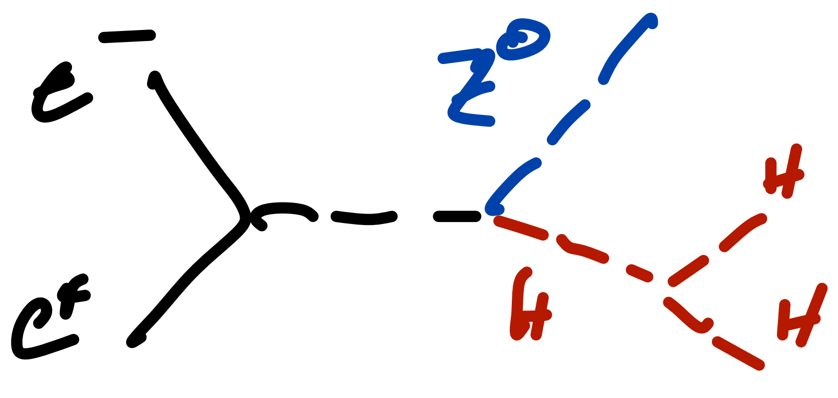
CLIC: $\Delta g_{ttH}/g_{ttH}$ ~ 2.9% with 2.5 ab^{-1} @ 1.4 TeV

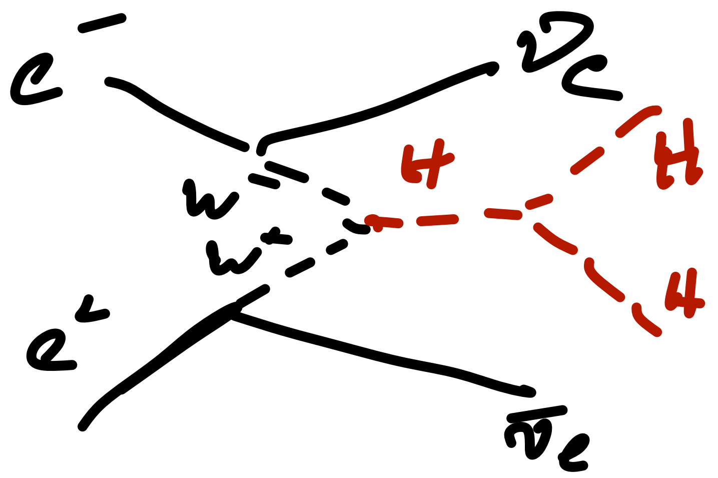
The Higgs Self-Coupling

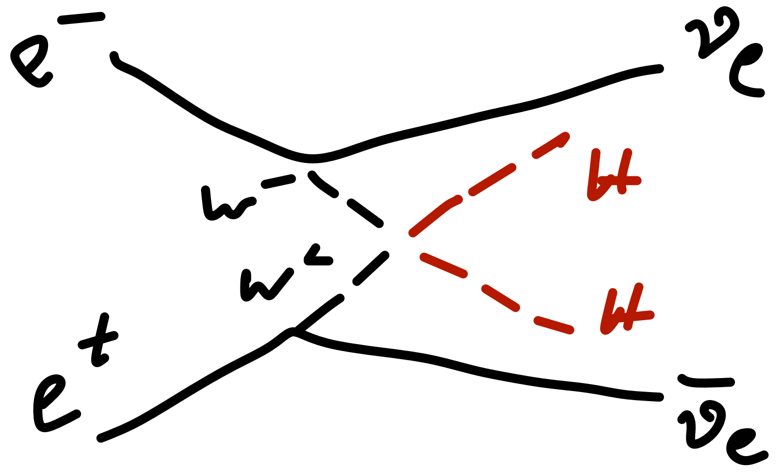
Requires higher energy - one of the key challenges of HEP

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









the final state also receives contributions from the quartic coupling

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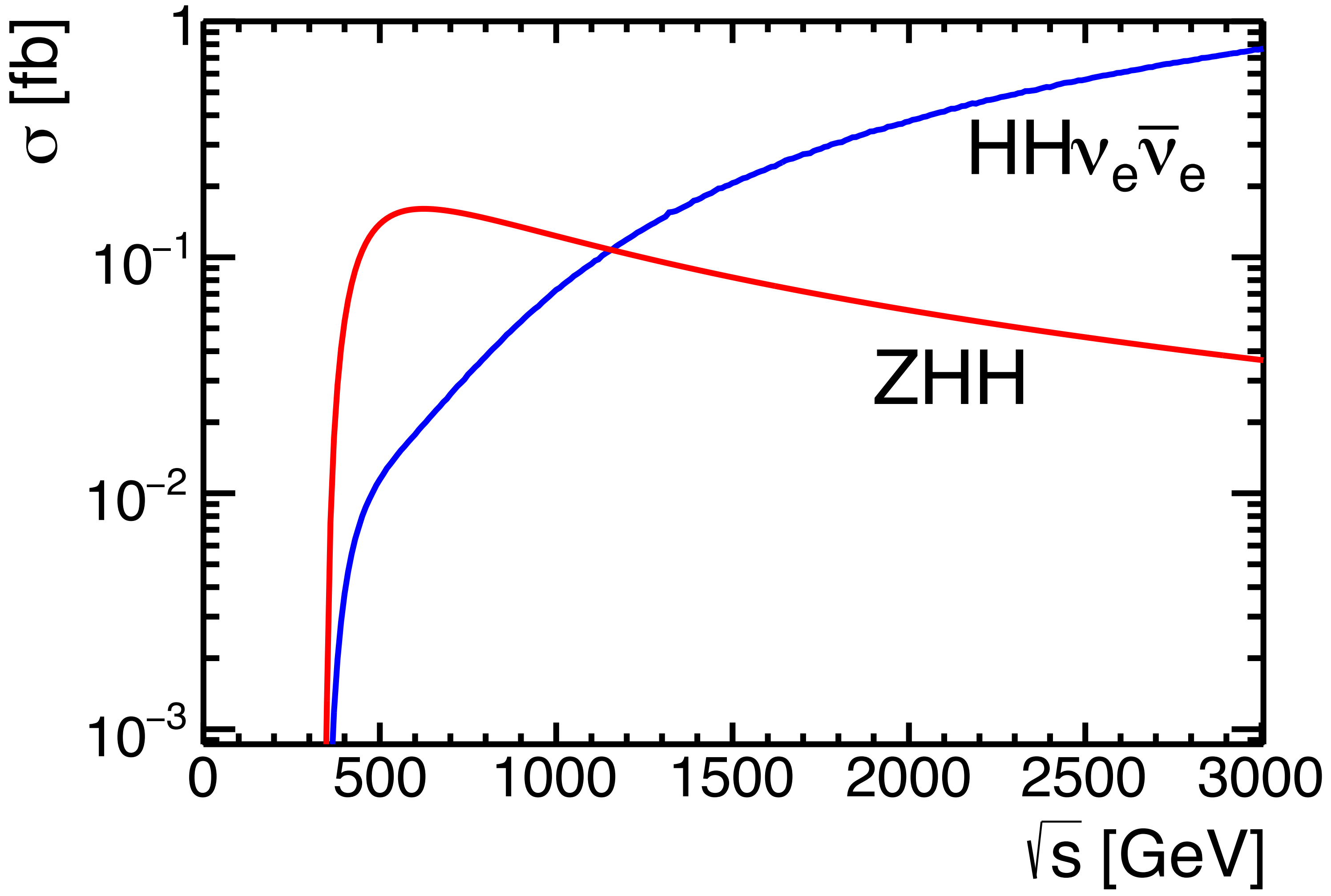
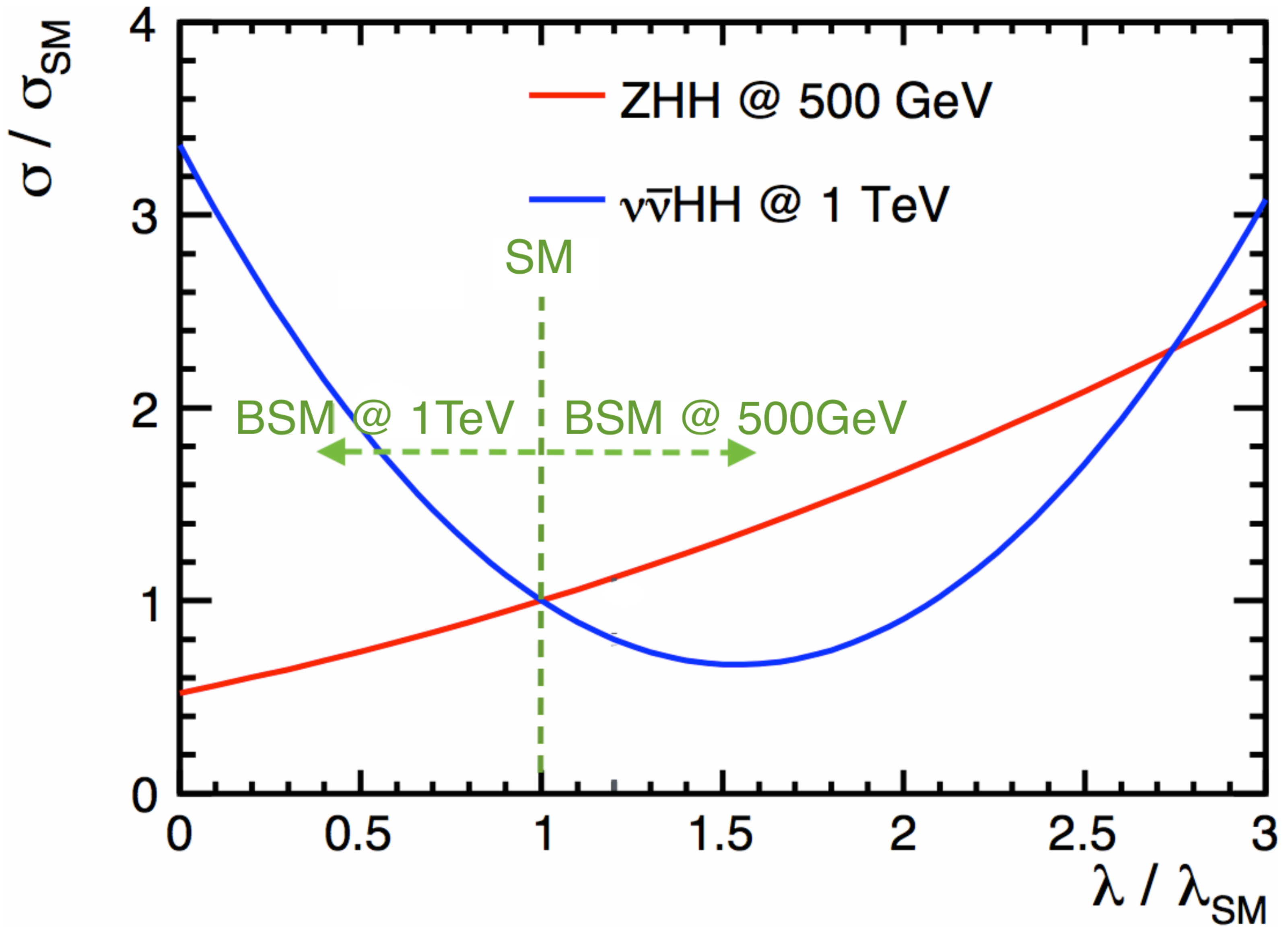
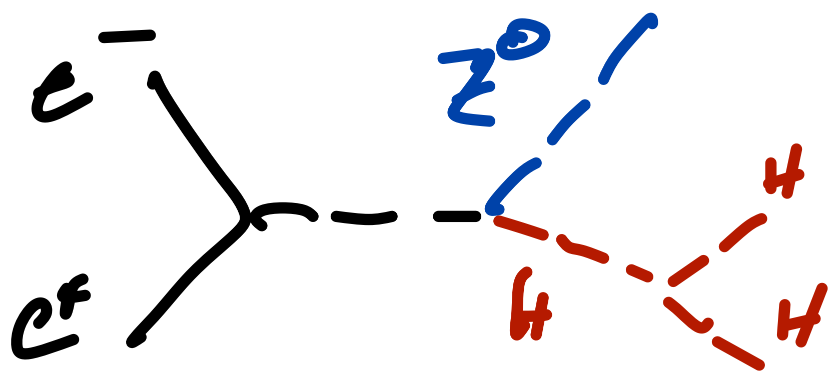
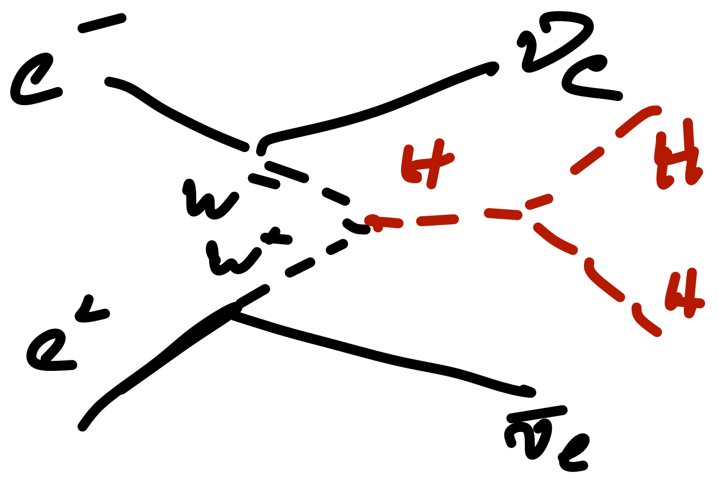
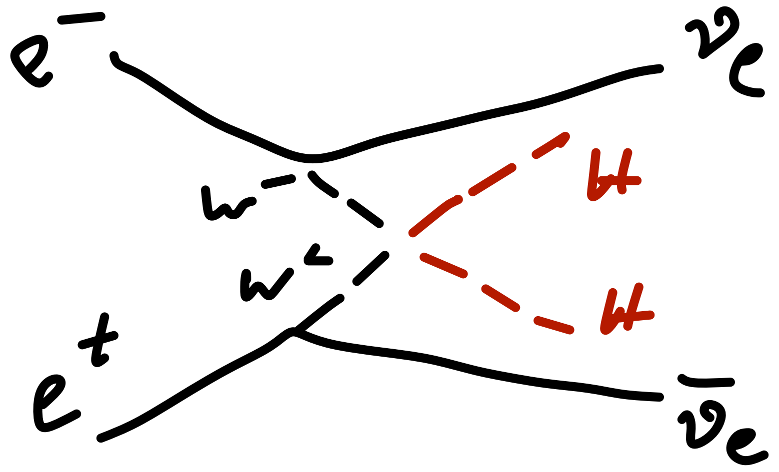


cross section depends non-linearly on λ, measurements at different energies / of different processes lift degeneracies









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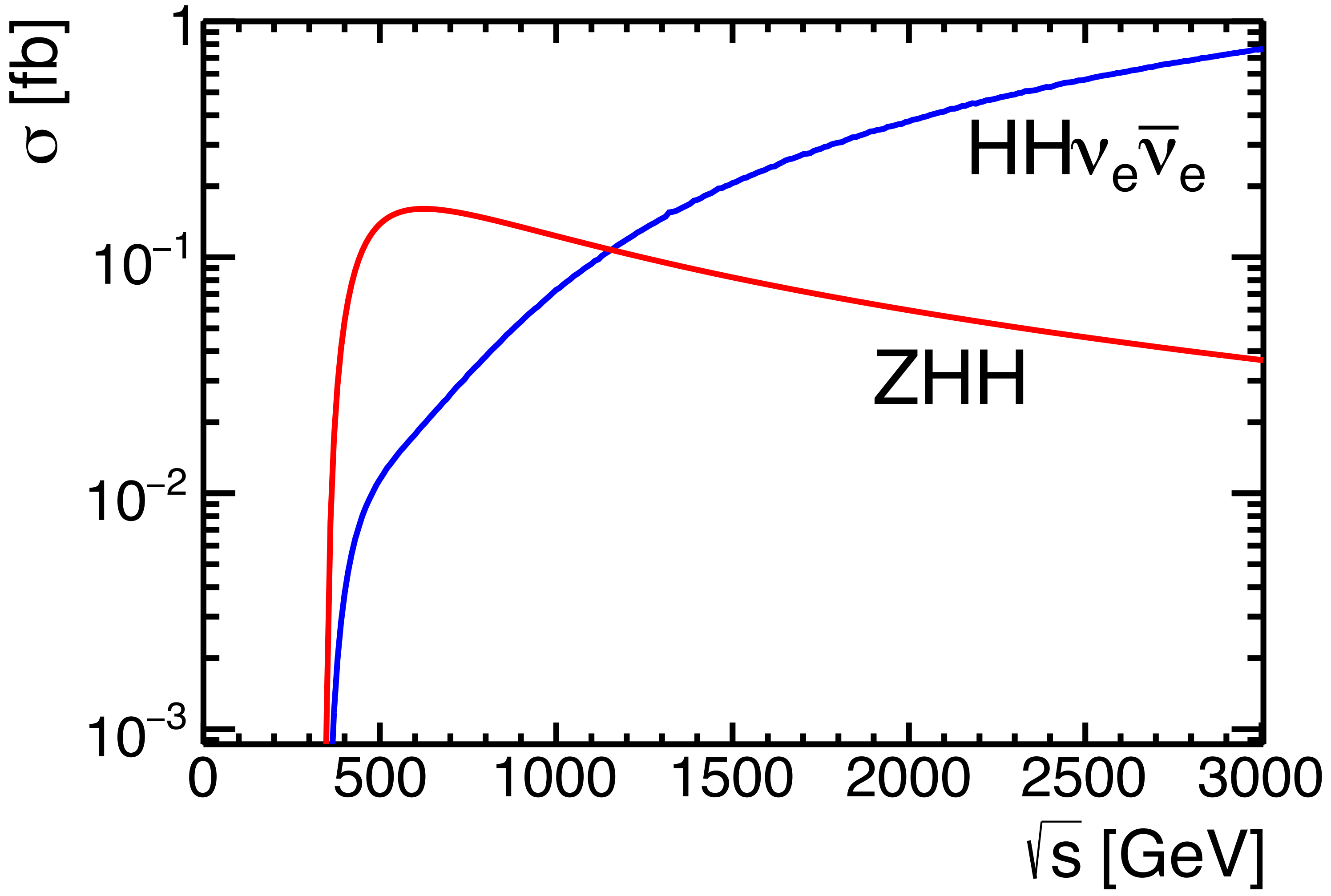

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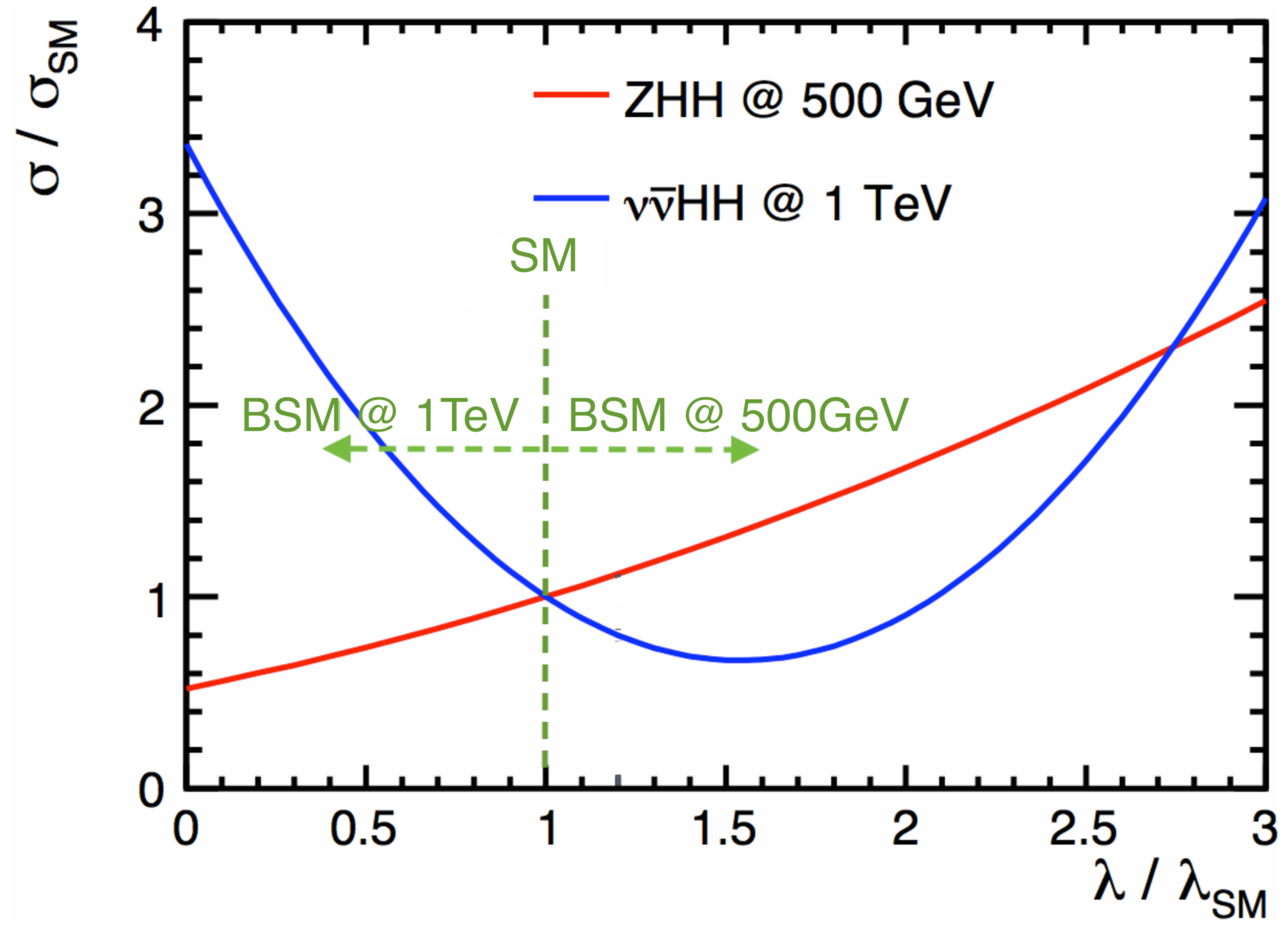
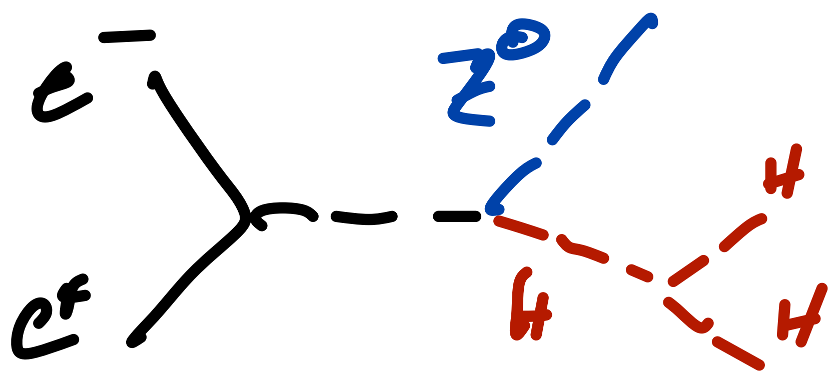
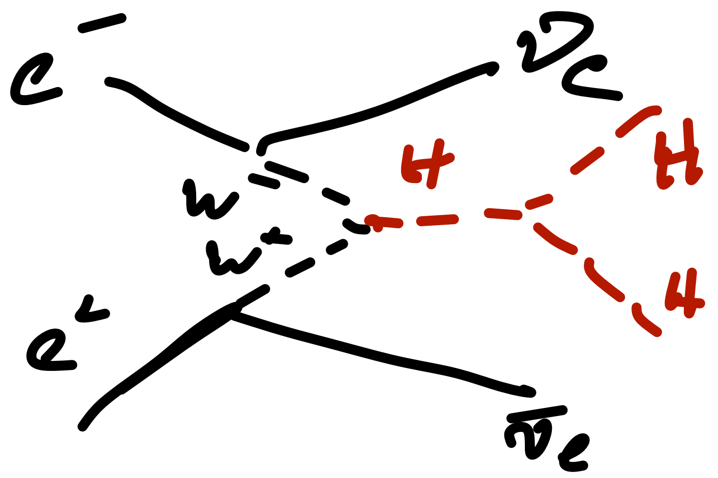
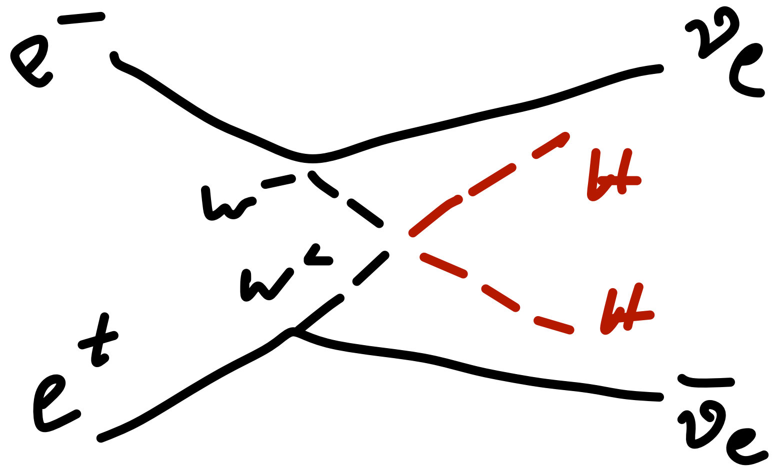






Full potential unfolds in the multi-TeV region through growing σ of VBF process:

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



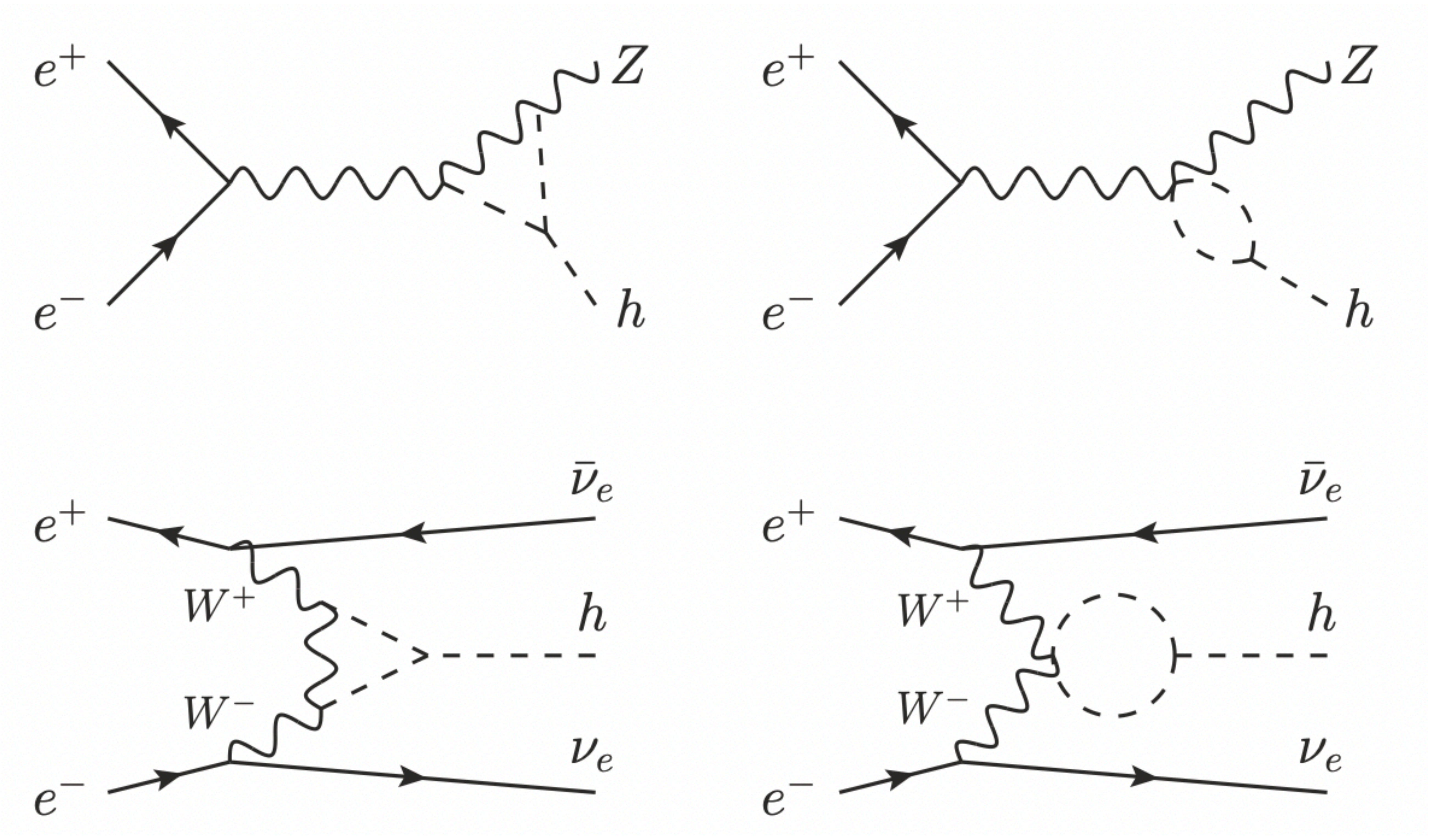
the final state also receives contributions from the quartic coupling

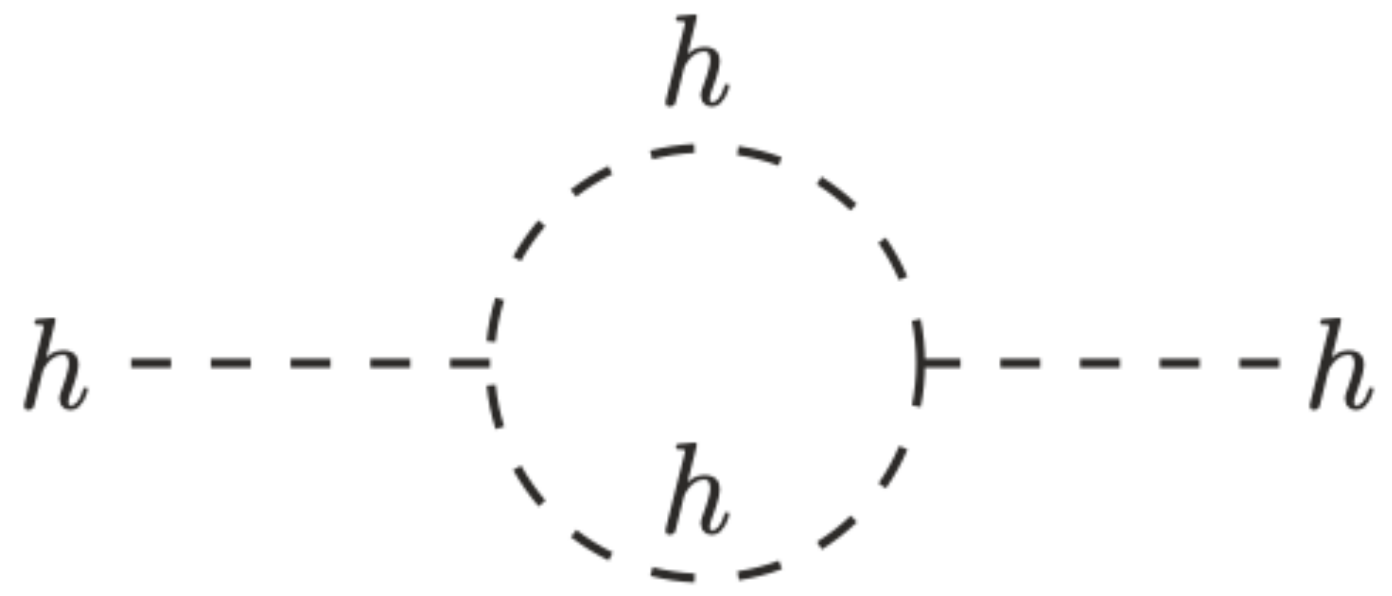
Frank Simon (frank.simon@kit.edu)

Indirect Measurement of the Self Coupling

Accessible via particle loops

- The self-coupling also influences single Higgs production:





Model-dependent: assumptions required for interpretation!

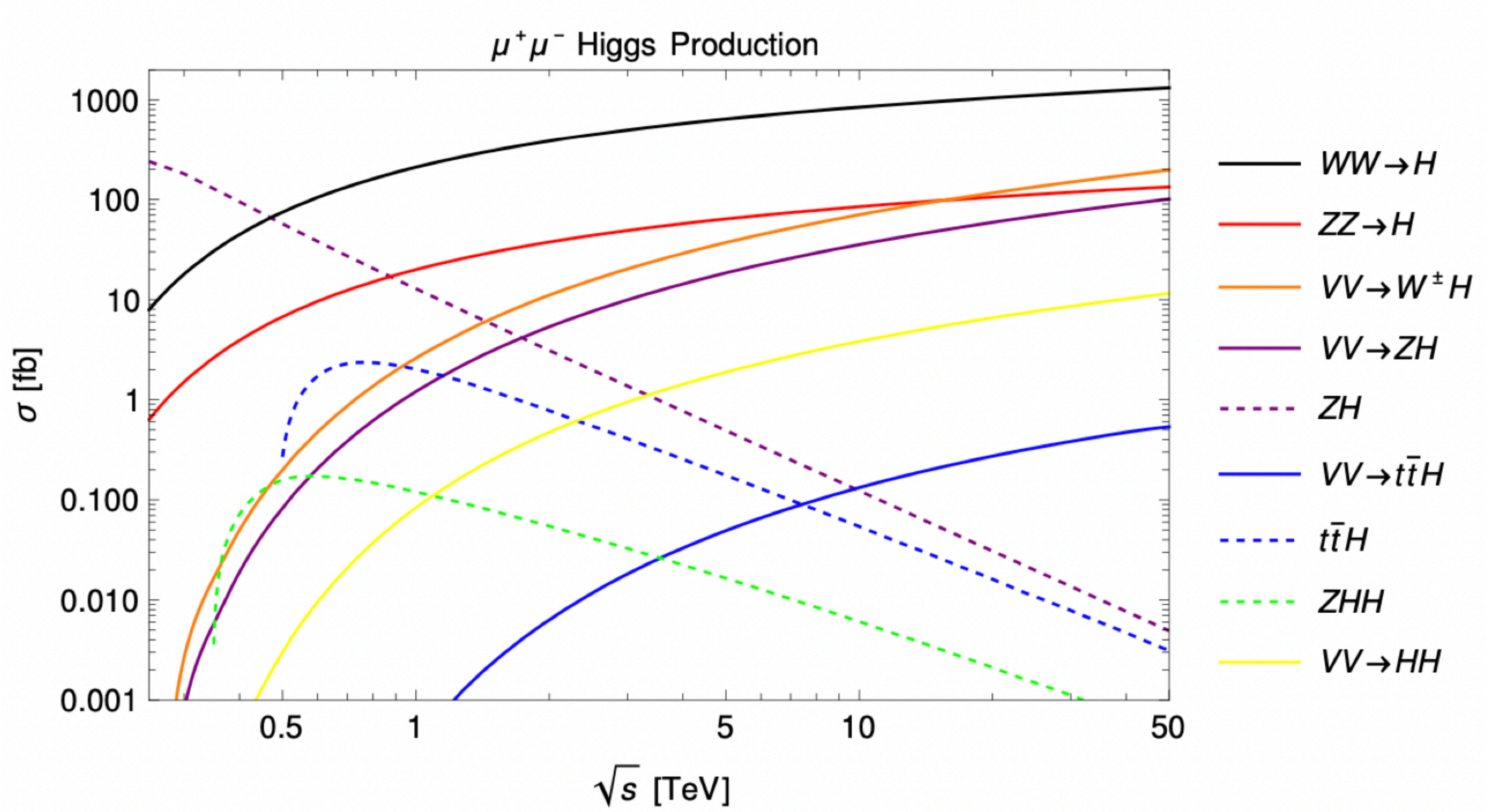
Overall precision limited, ~ 33% at FCC-ee combined with HL-LHC (which provides ~ 50%)

Interplay of different energies key. With optimised running, and increased L_{int} at 240 GeV and 365 GeV 20% may be doable.

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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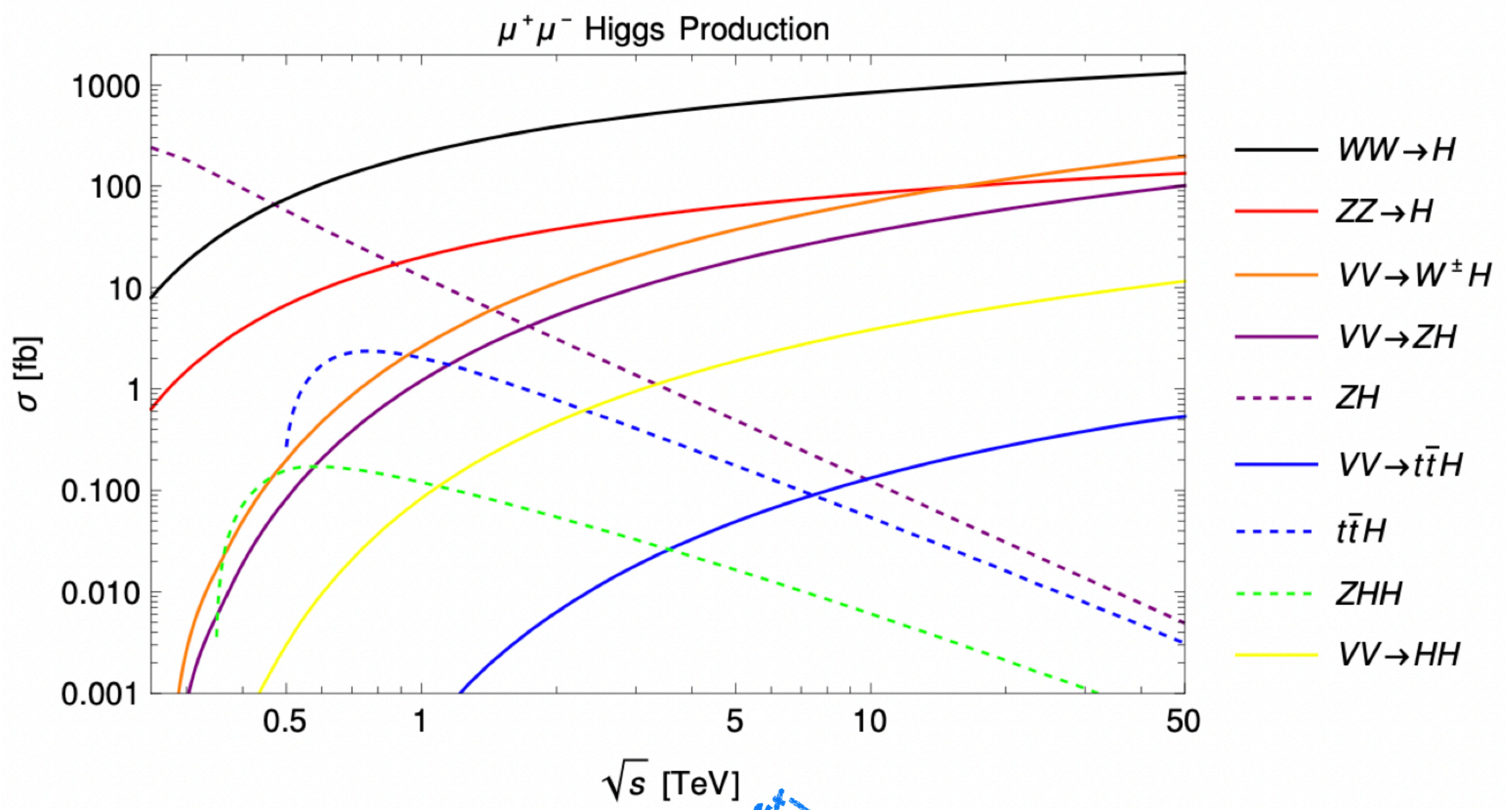
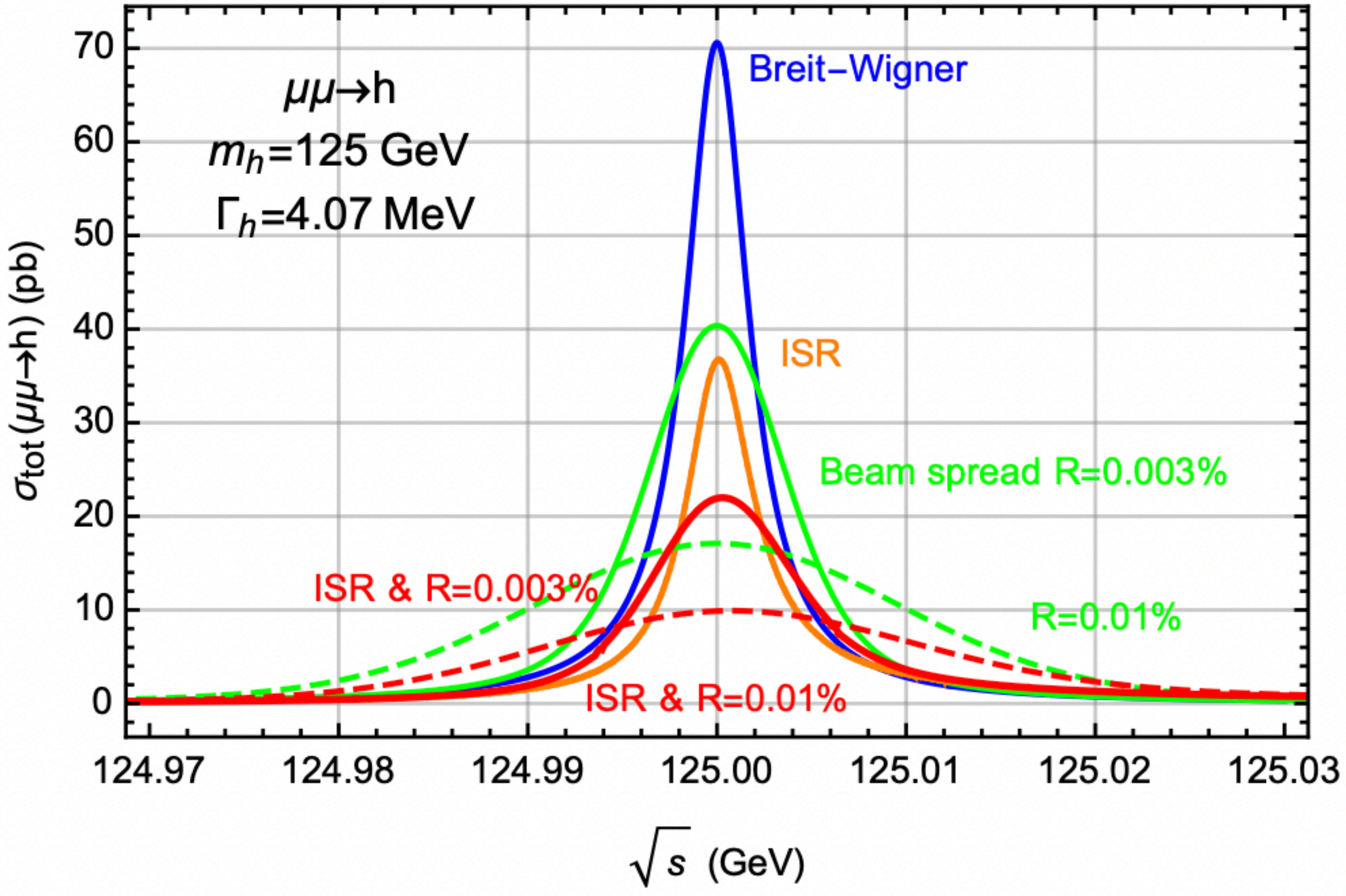
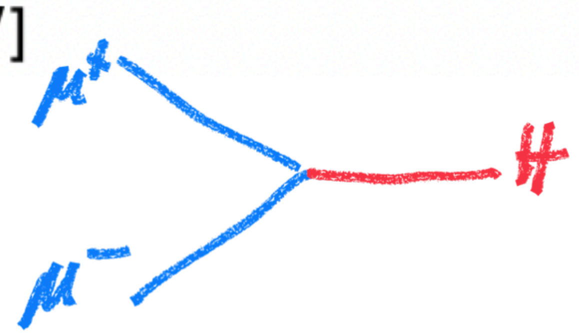






s-channel production at 125 GeV:

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

Overall Precision Perspective

Including muon colliders

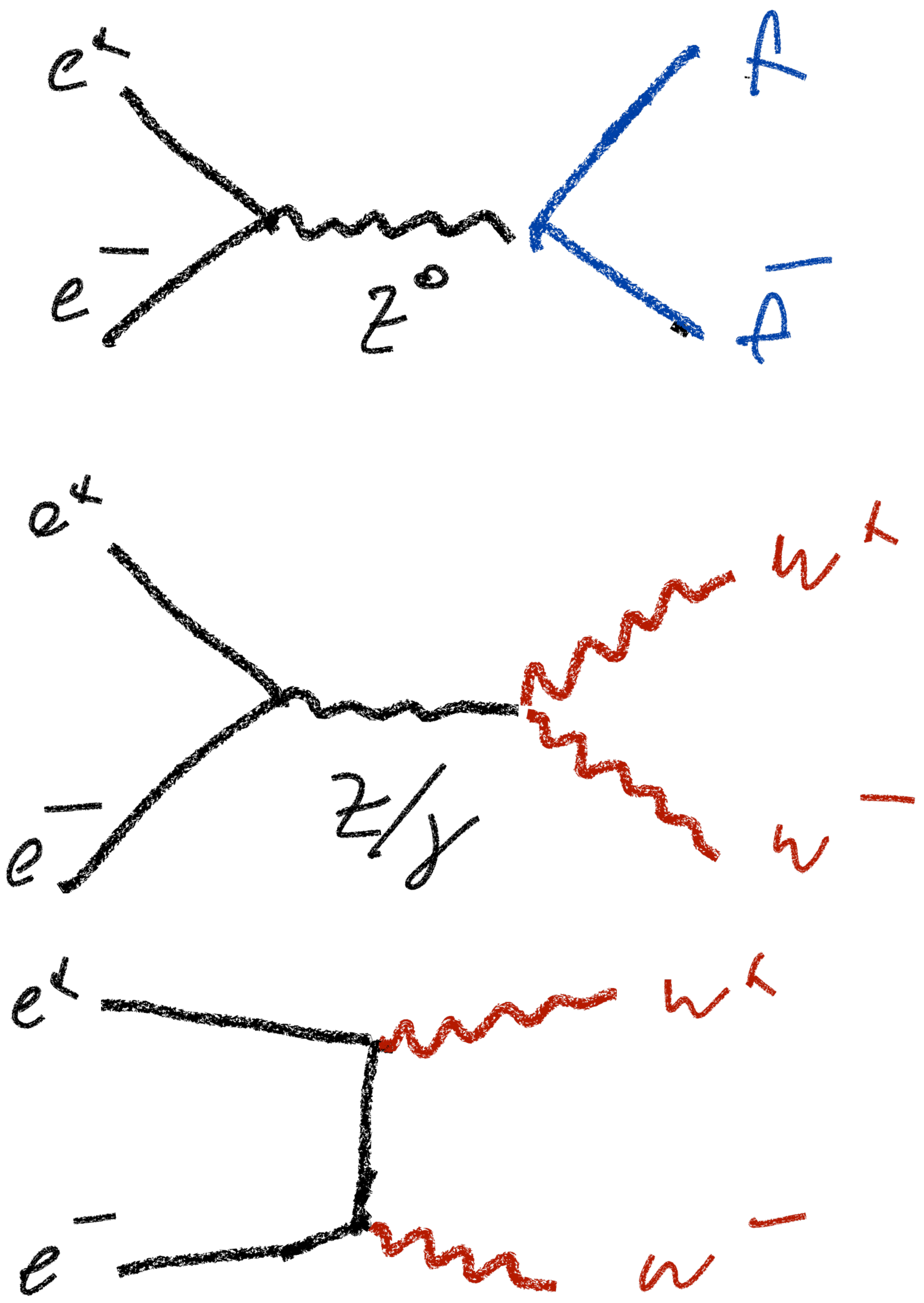
- An EFT fit, performed for Snowmass

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.

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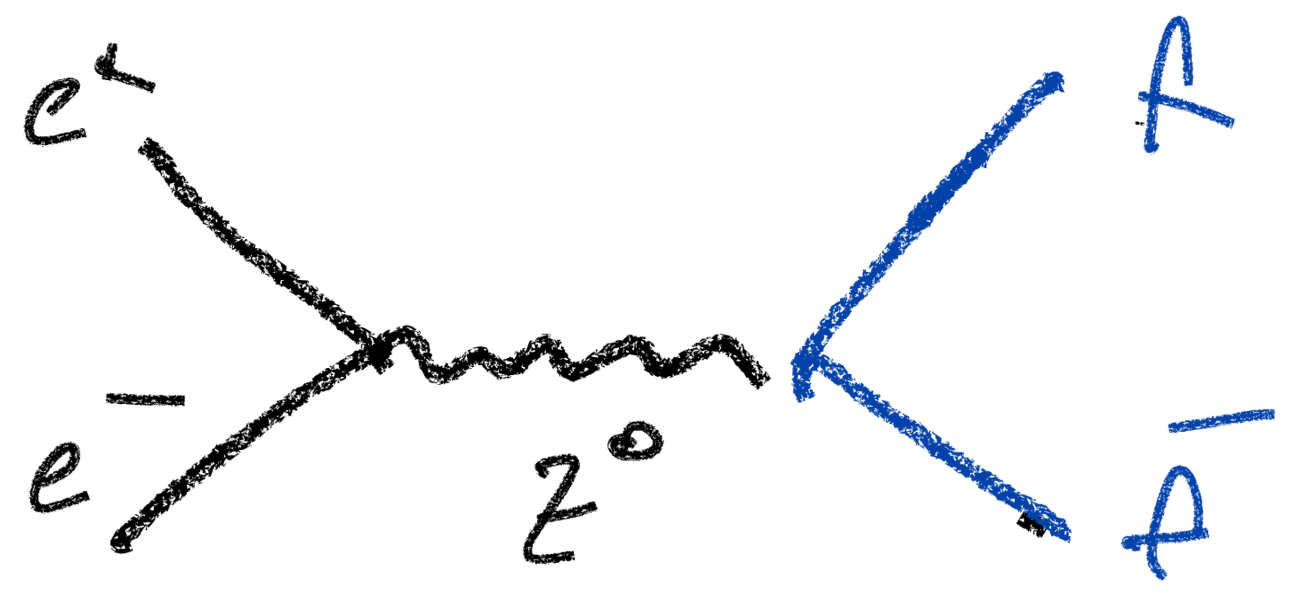

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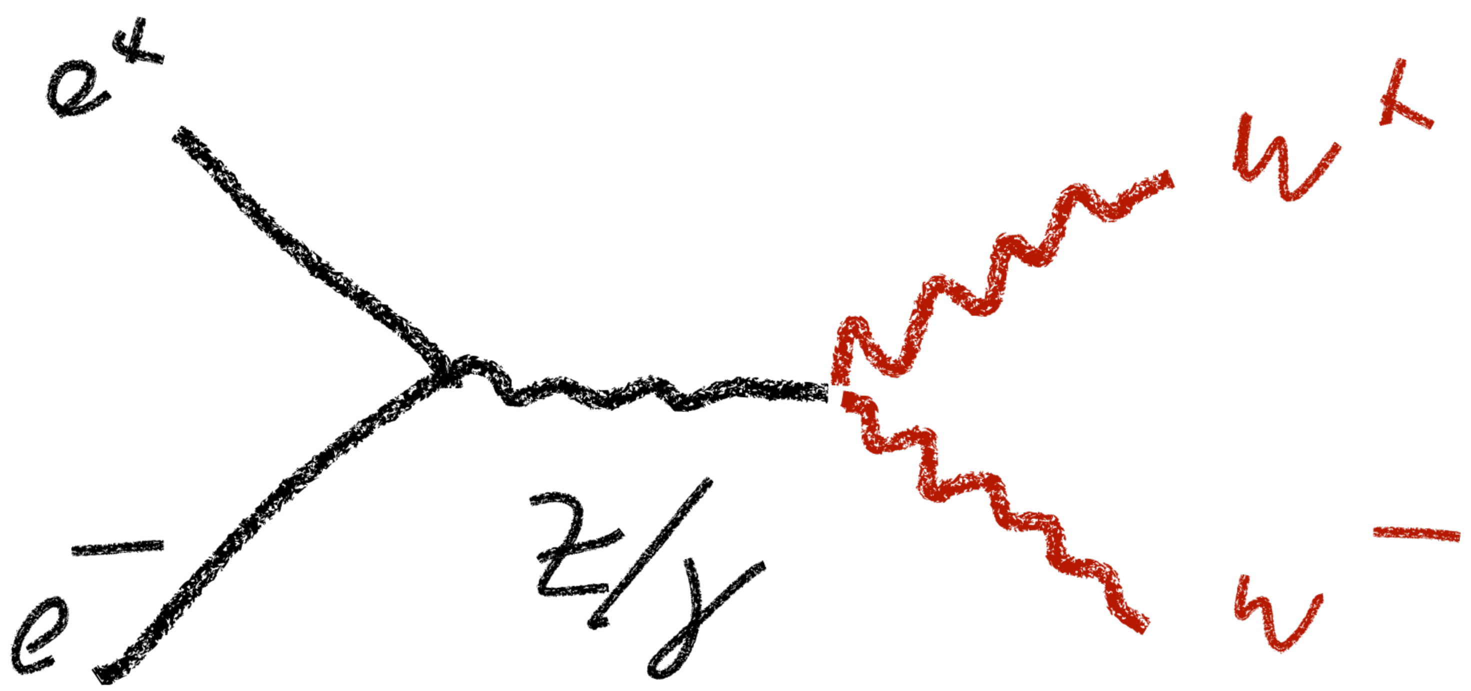
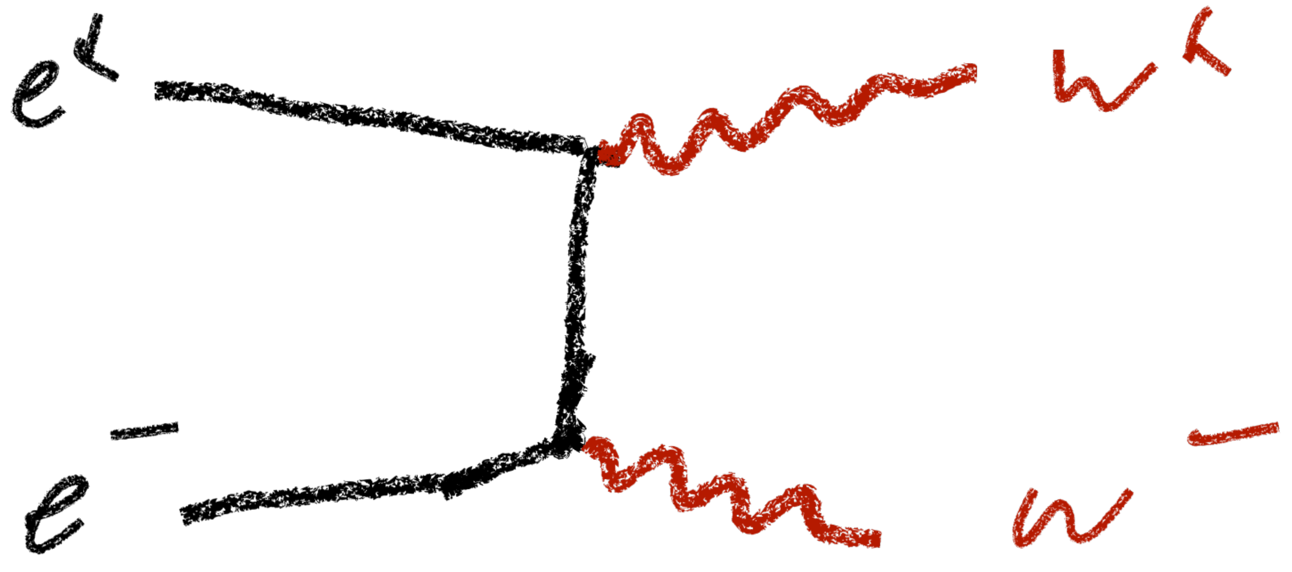


➯ Improving electroweak precision observables, enter into global fits

➯ Indirect searches for New Physics



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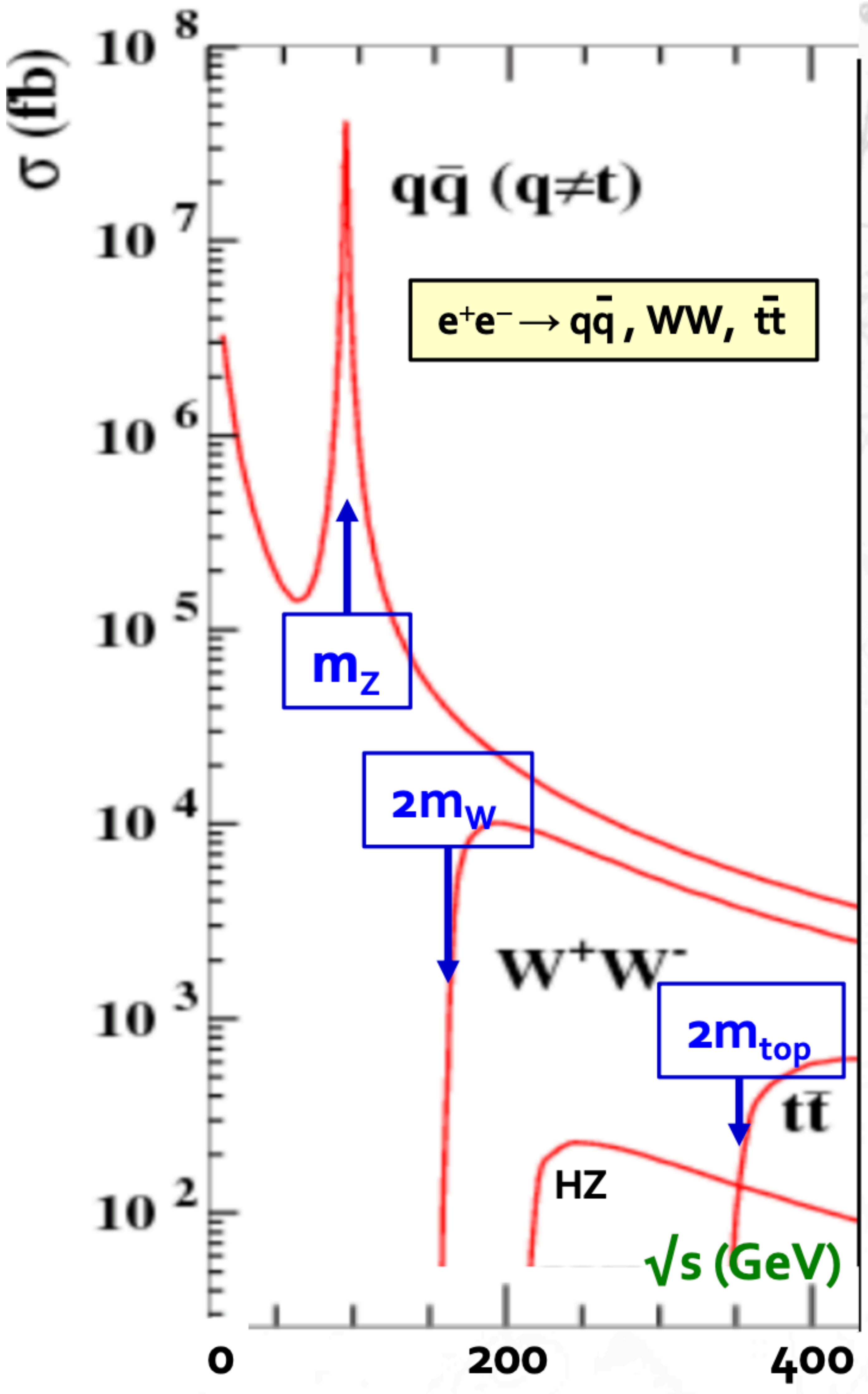
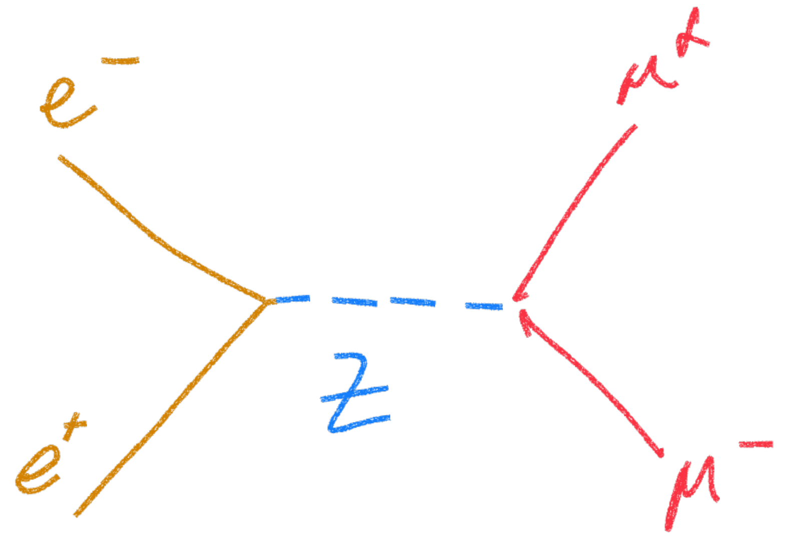
Electroweak Measurements

Cross sections and asymmetries





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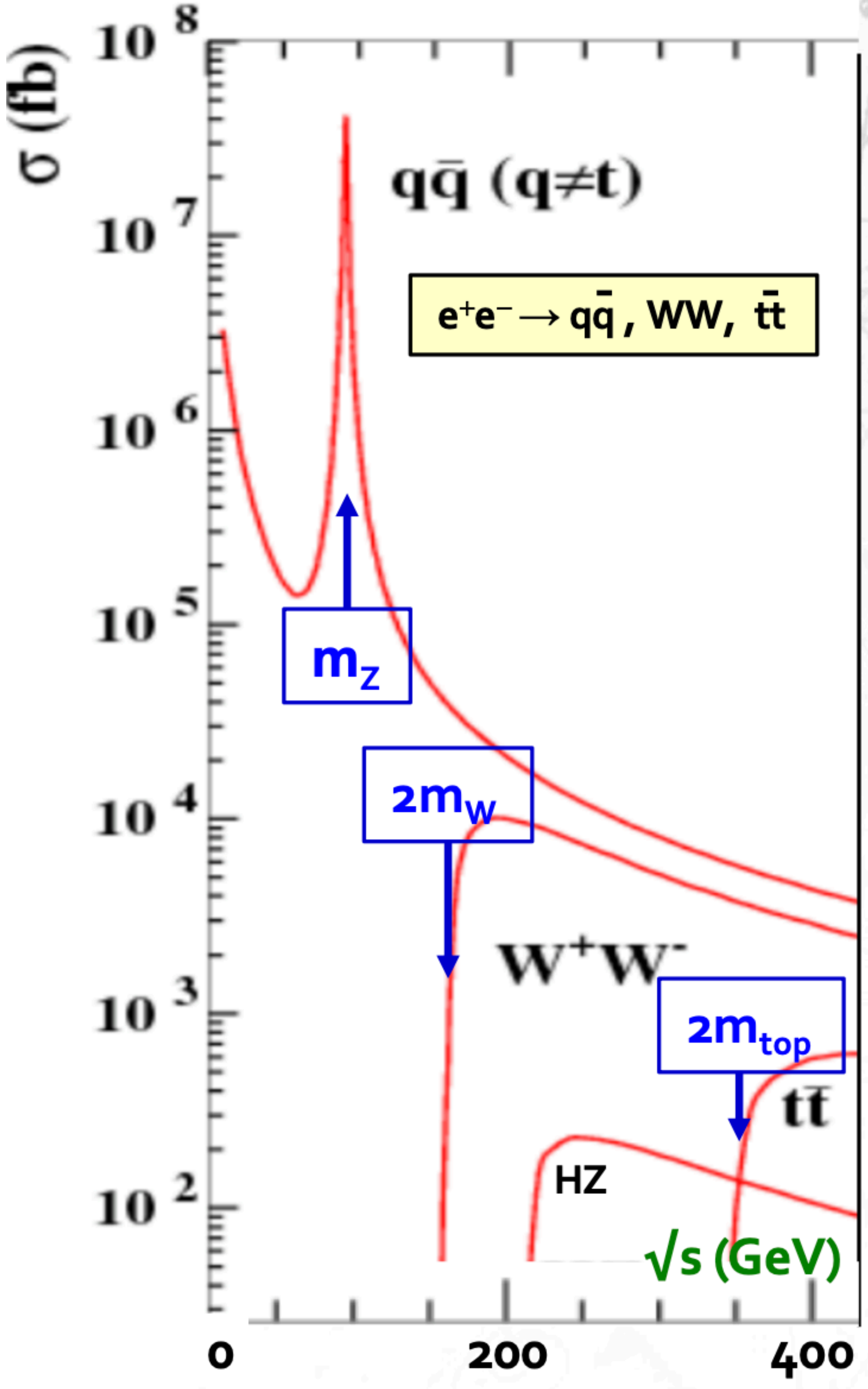
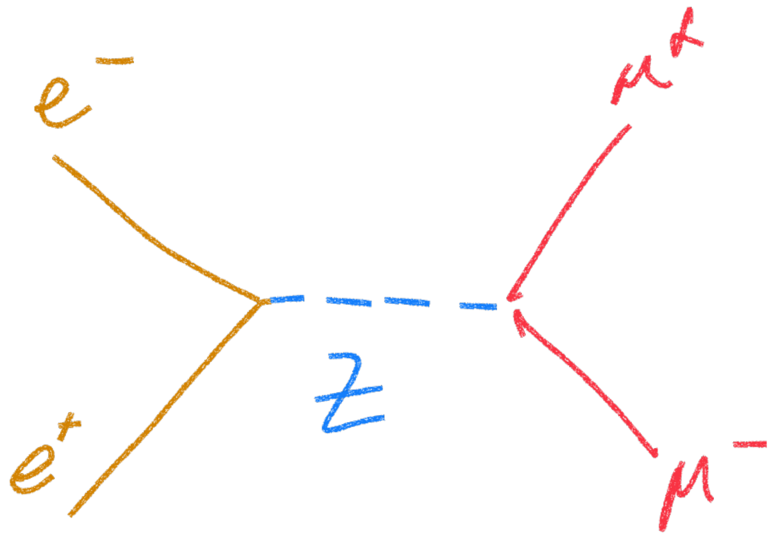
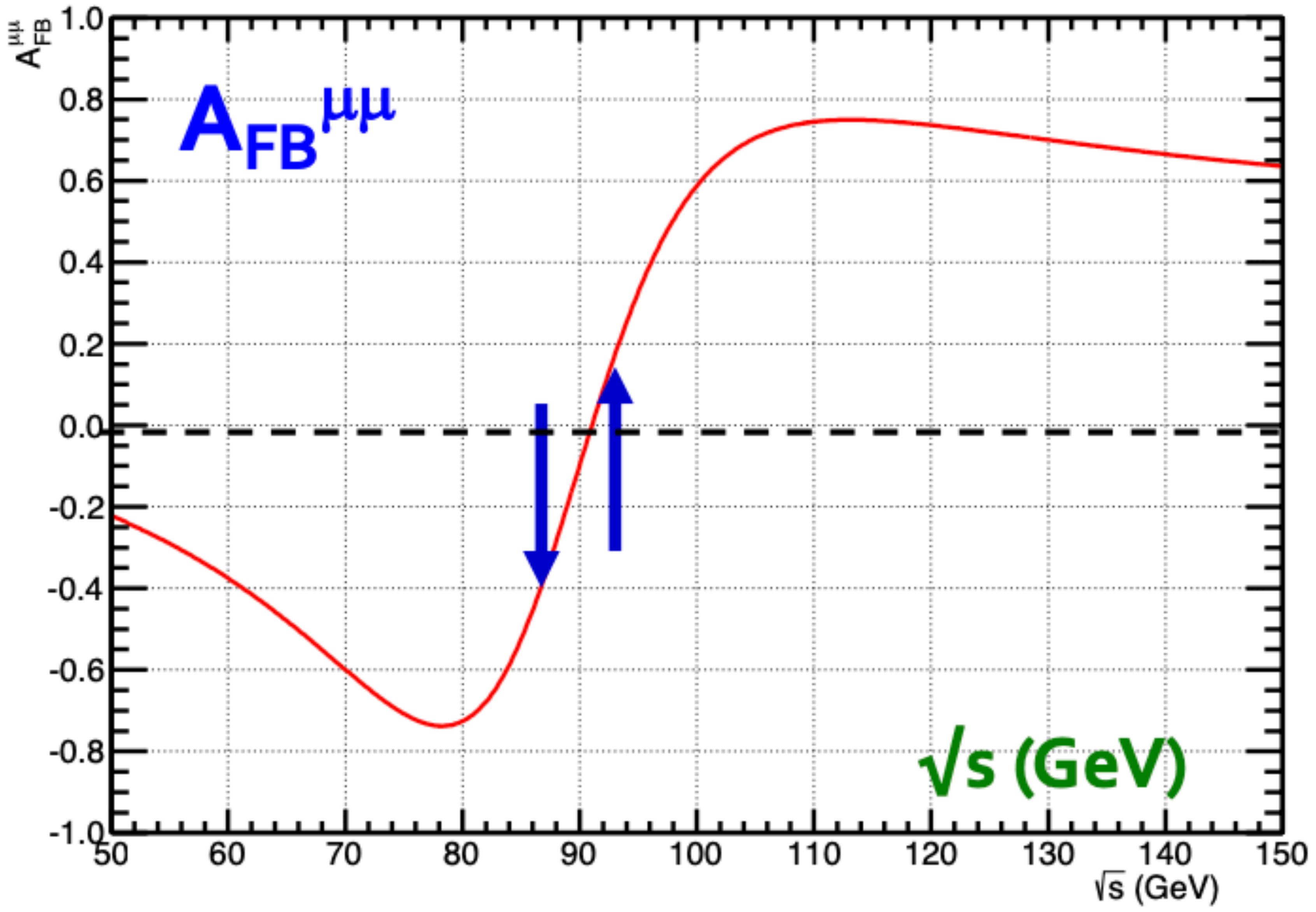
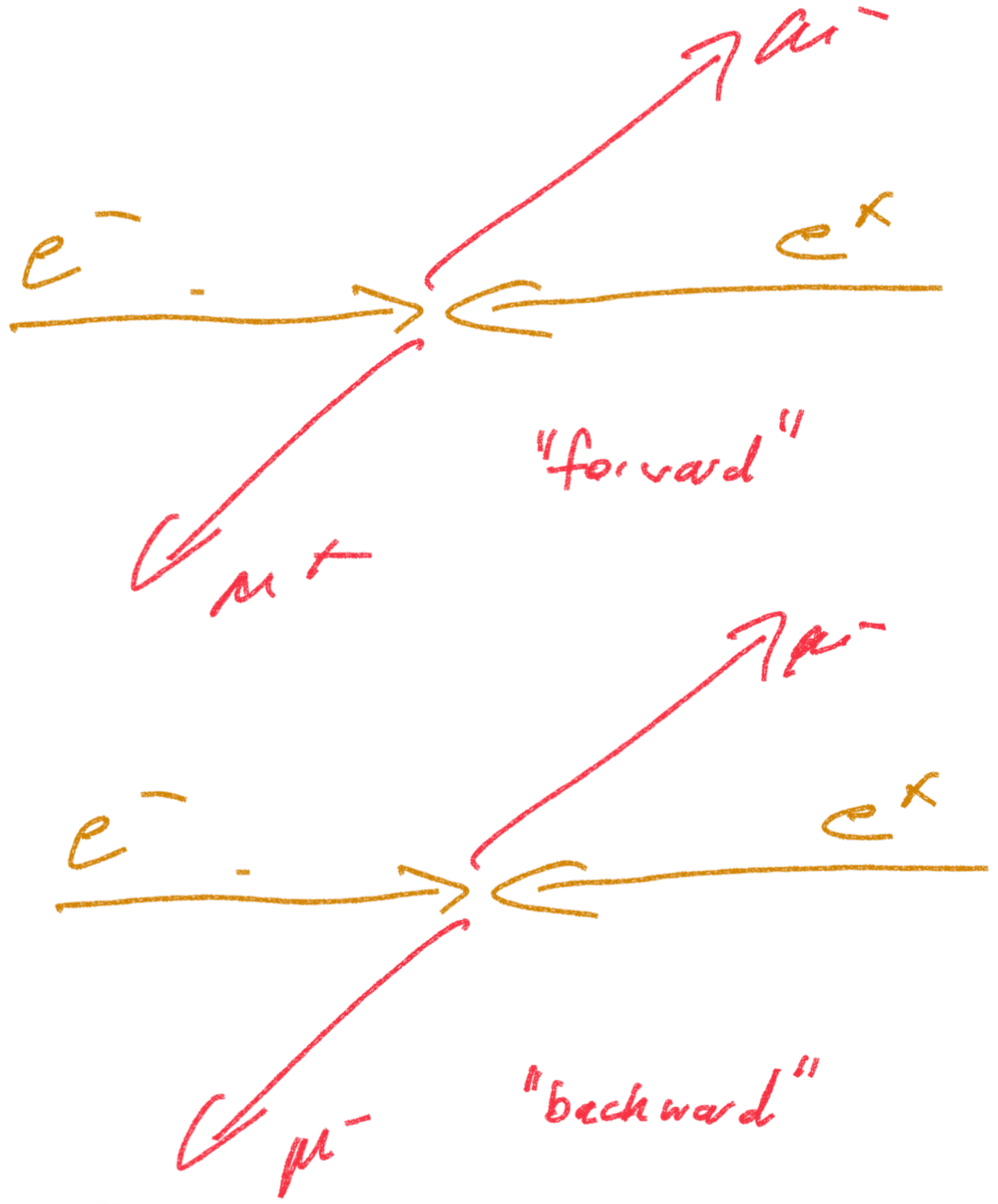






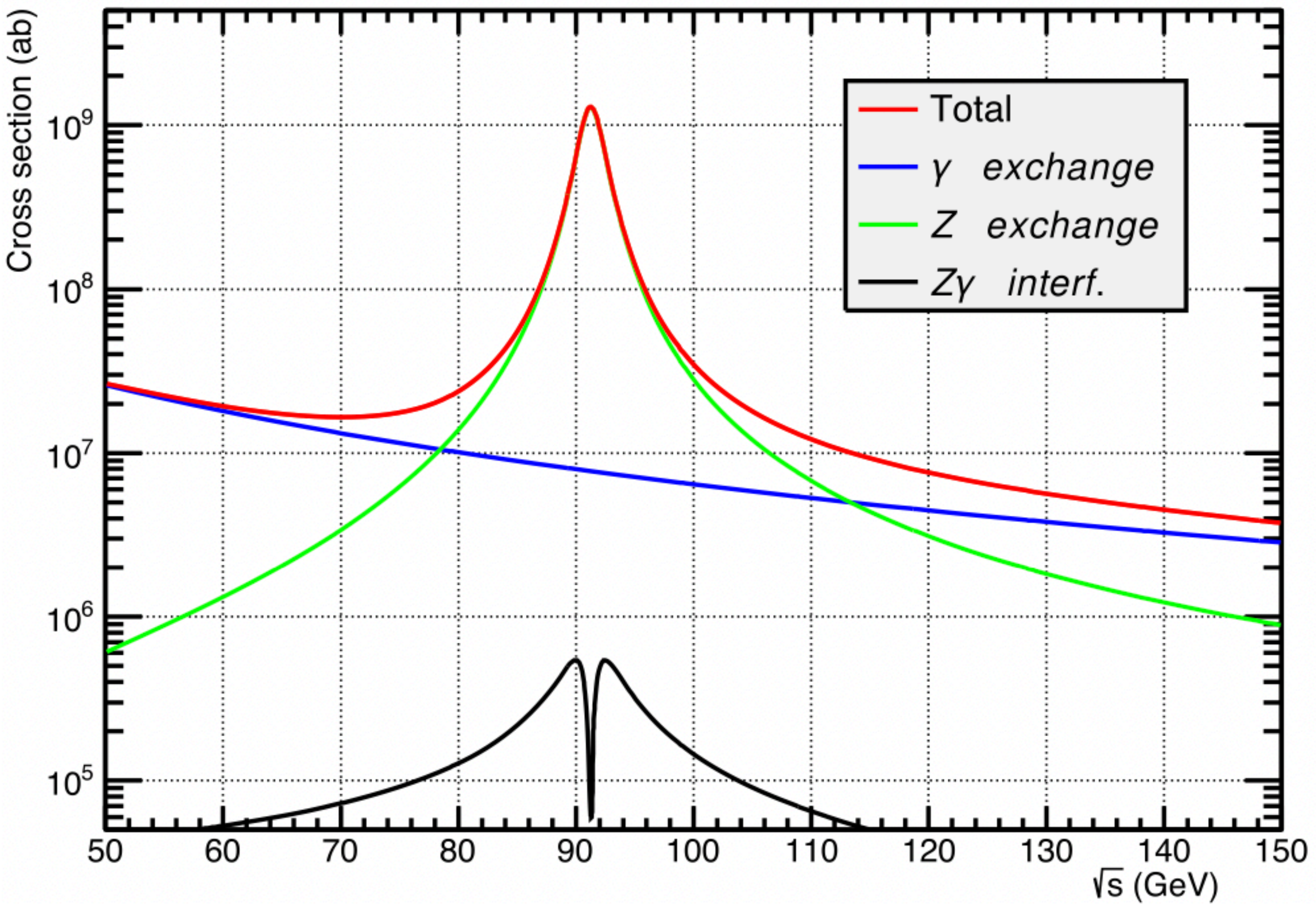


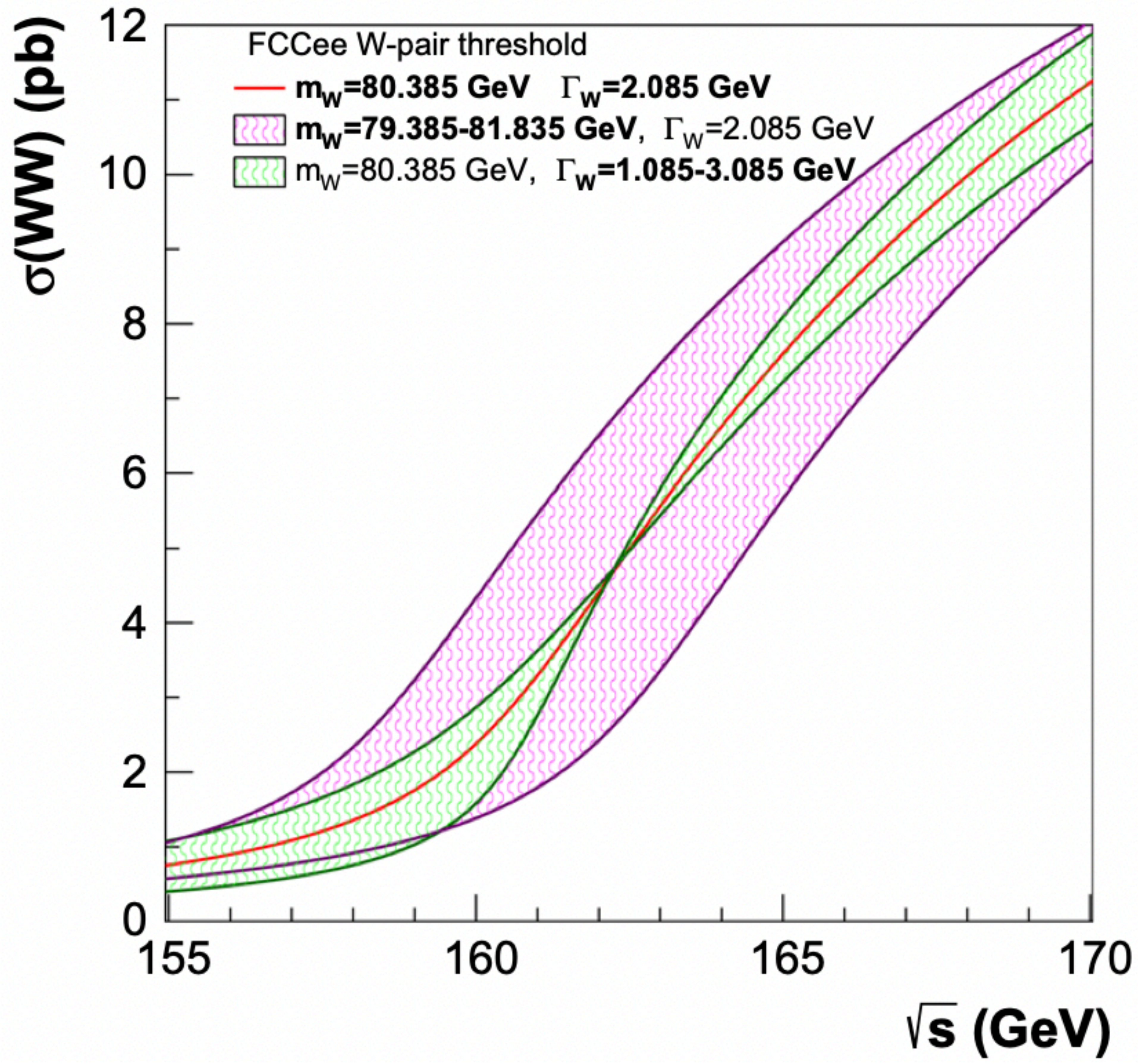
$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2 \vartheta_W^{eff}) + \alpha_{QED}(s)\frac{s - m_Z^2}{2s} g(\sin^2 \vartheta_W^{eff})$$

- Measure $\sin^2\Theta_W$ via A_{FB} at $\sqrt{s} = m_Z$
- Measure $\alpha_{QED}(m_Z)$ via A_{FB} slightly below and above resonance

Lineshapes and Thresholds

The things to explore





- Lineshapes, cross sections, asymmetries provide access to a wide range of electroweak precision measurements, putting the Standard Model to extremely stringent tests

FCC-ee Electroweak Projections

Summary

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2 – 1.0	Ratio of hadrons to leptons; acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	0.4 – 1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{\text{pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

Flavour Physics

Increasing interest

- 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

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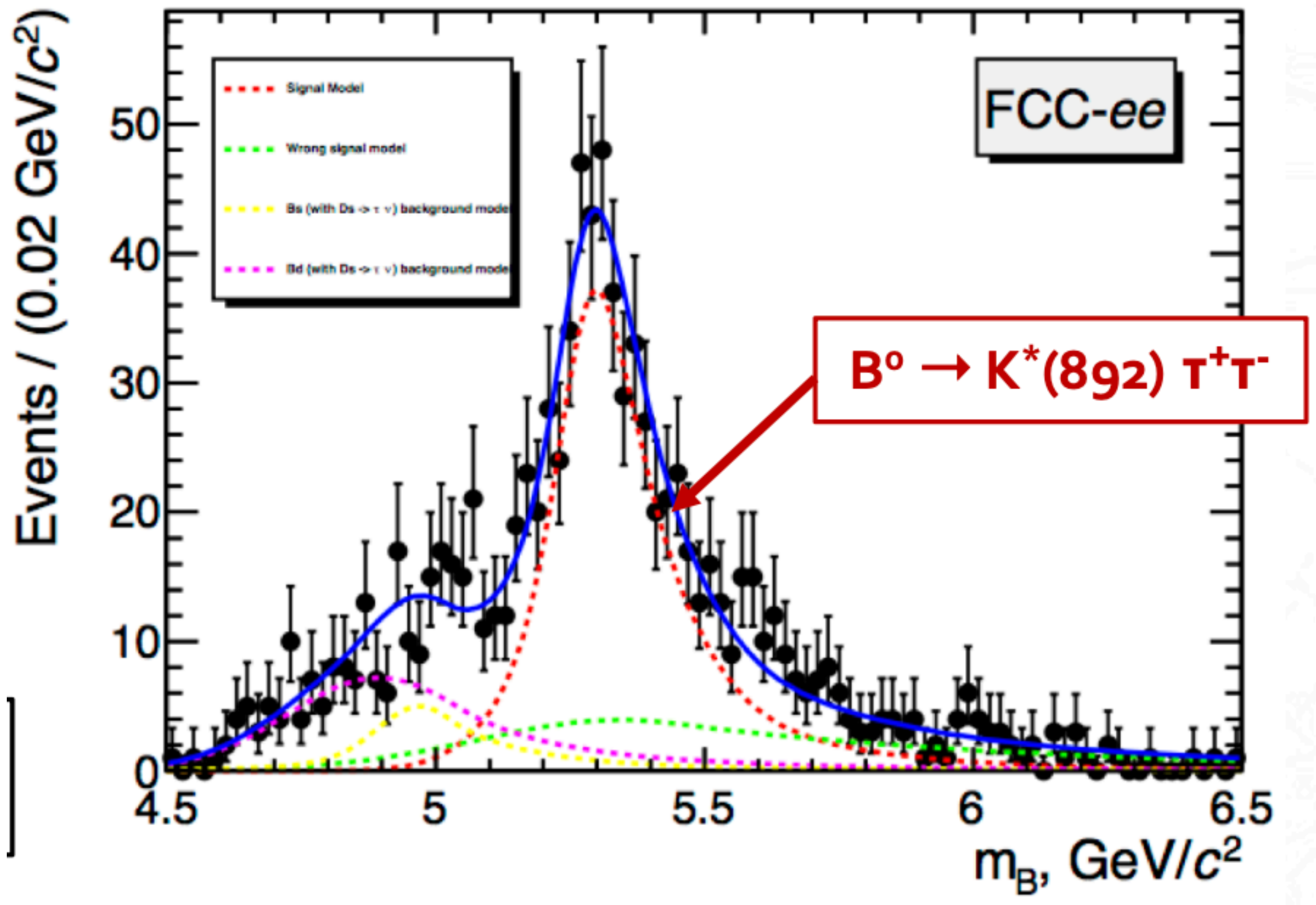
High-statistics measurements to follow up on hints for Lepton Flavour non-universality seen in b->sll transitions



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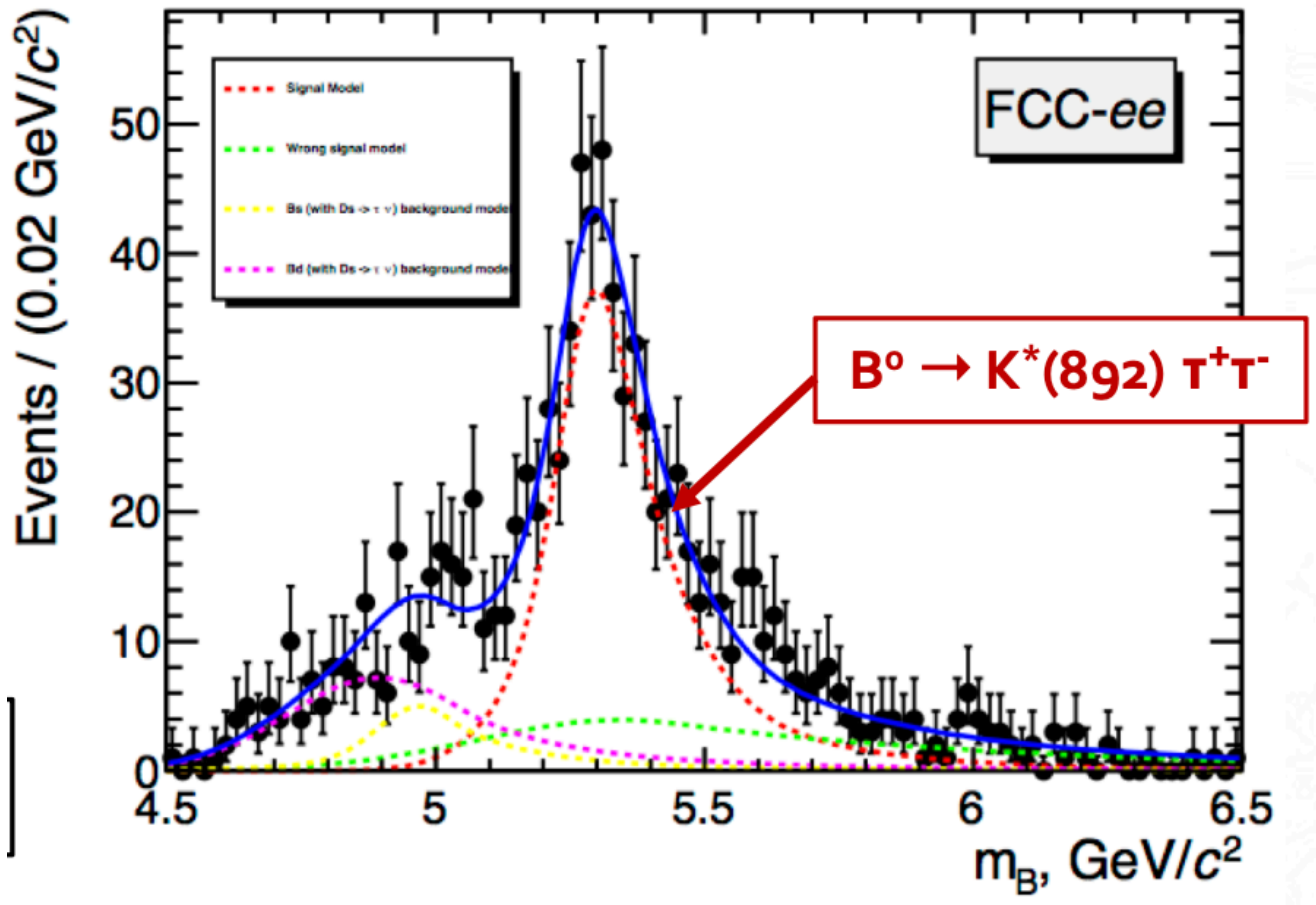
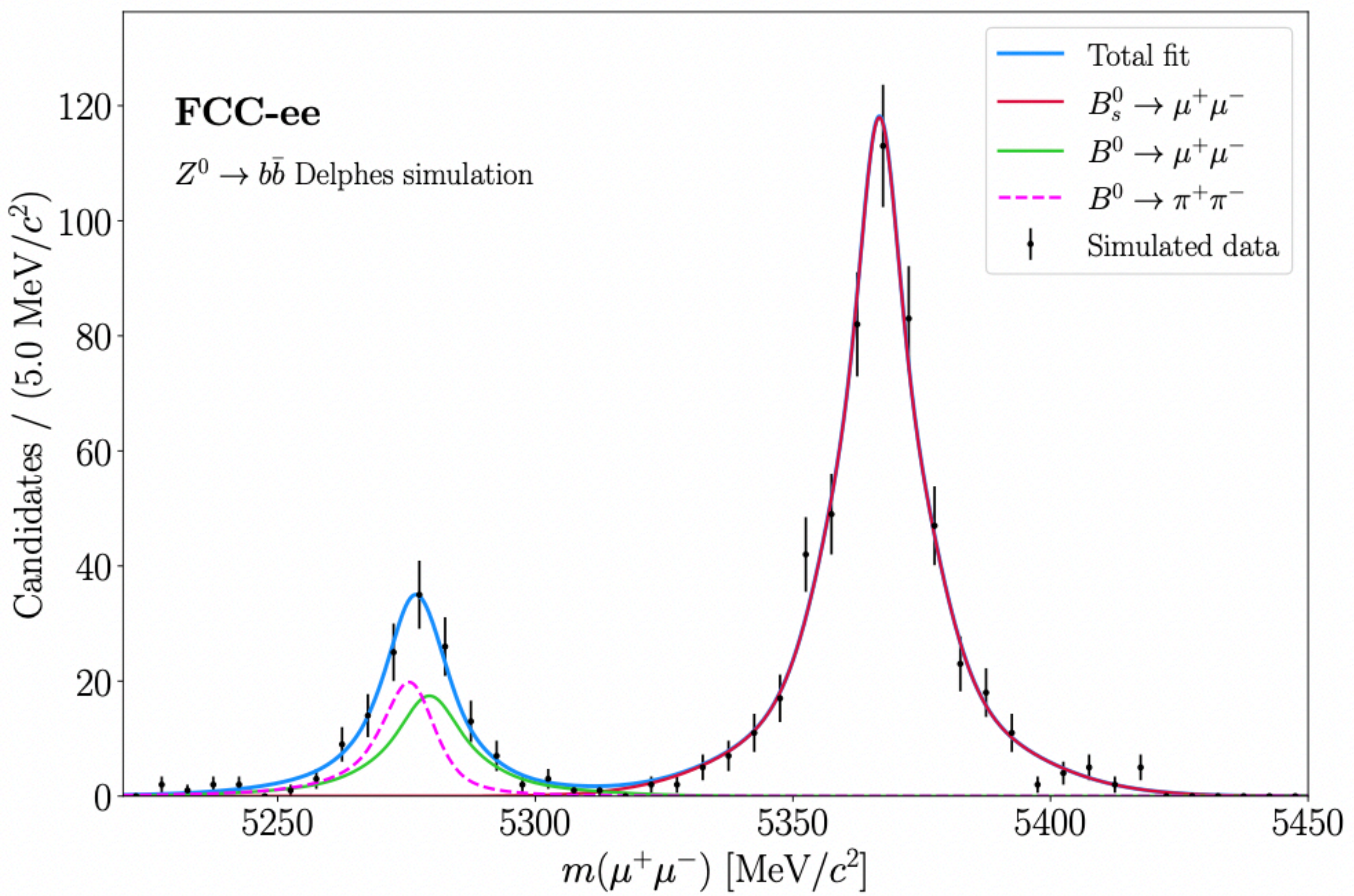


Explore rare be decays with unprecedented precision.

Study of CP violation, the CKM matrix, …



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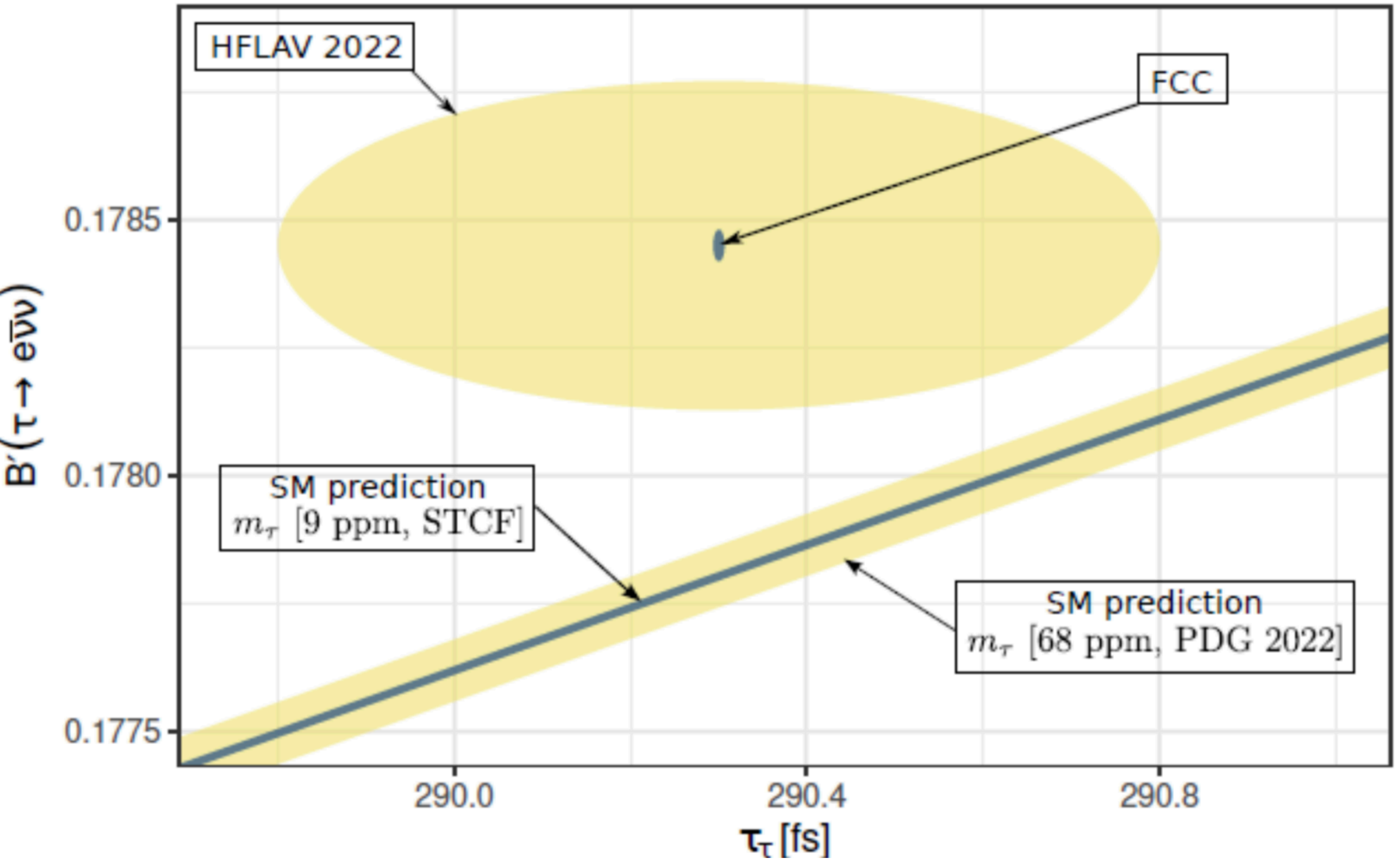
Canonical Tau Lepton Universality test
HFLAV 2022 in yellow, FCC estimates in blue



A precise study of the τ - extending beyond Belle II now beginning

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**
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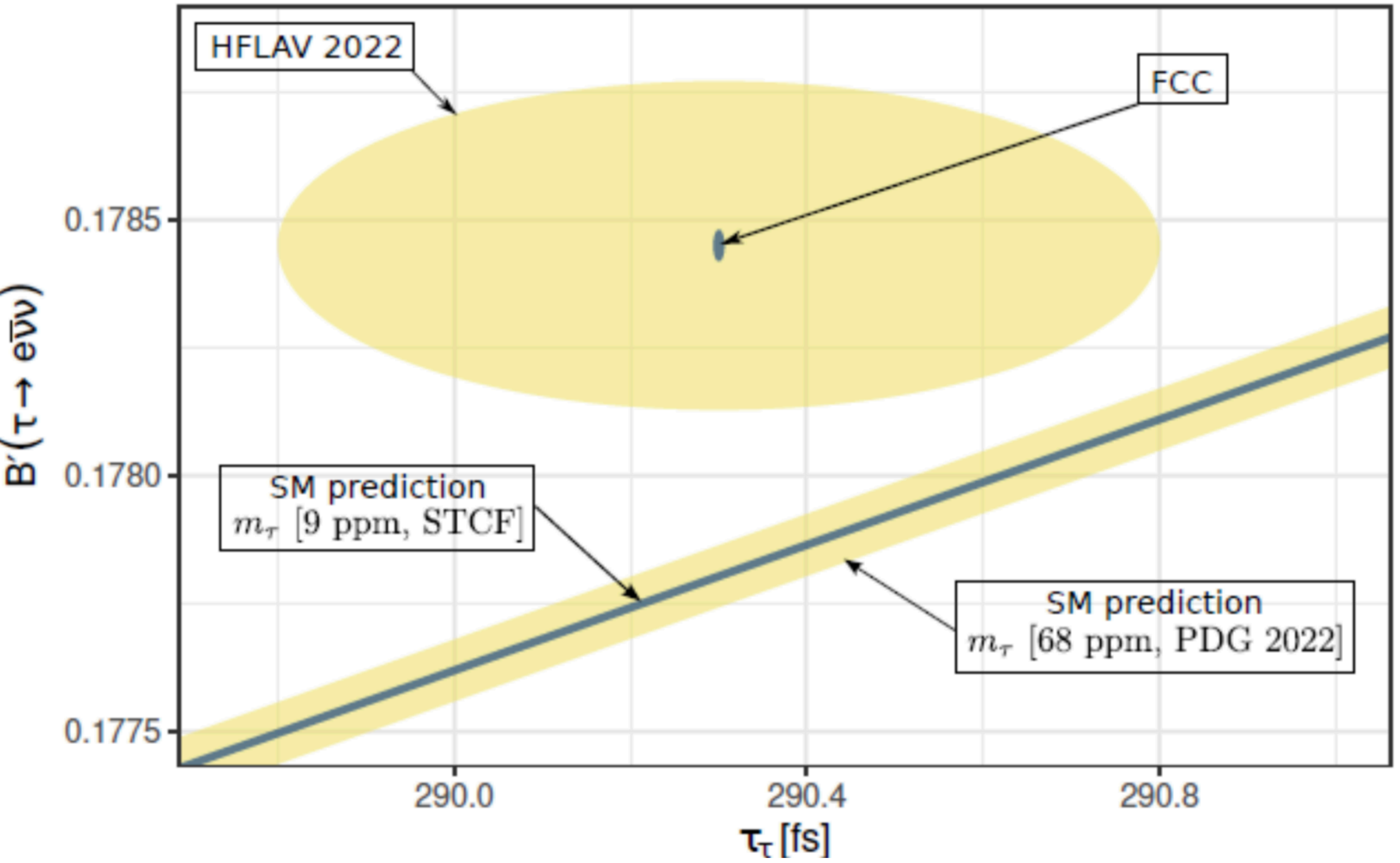

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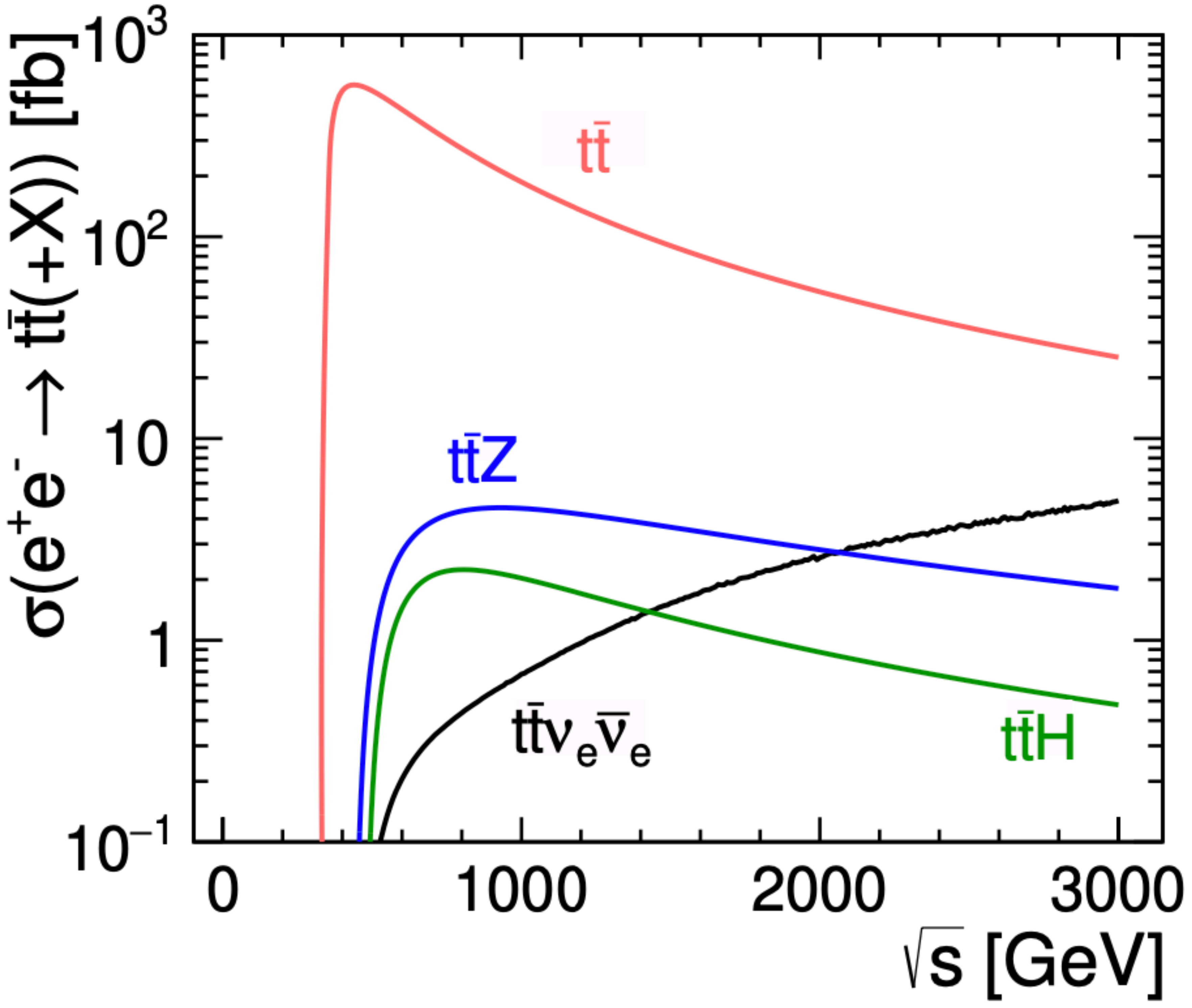
N.B.: Flavour physics introduces specific detector requirements such as PID, typically not front-and-center in Higgs Factory detector designs

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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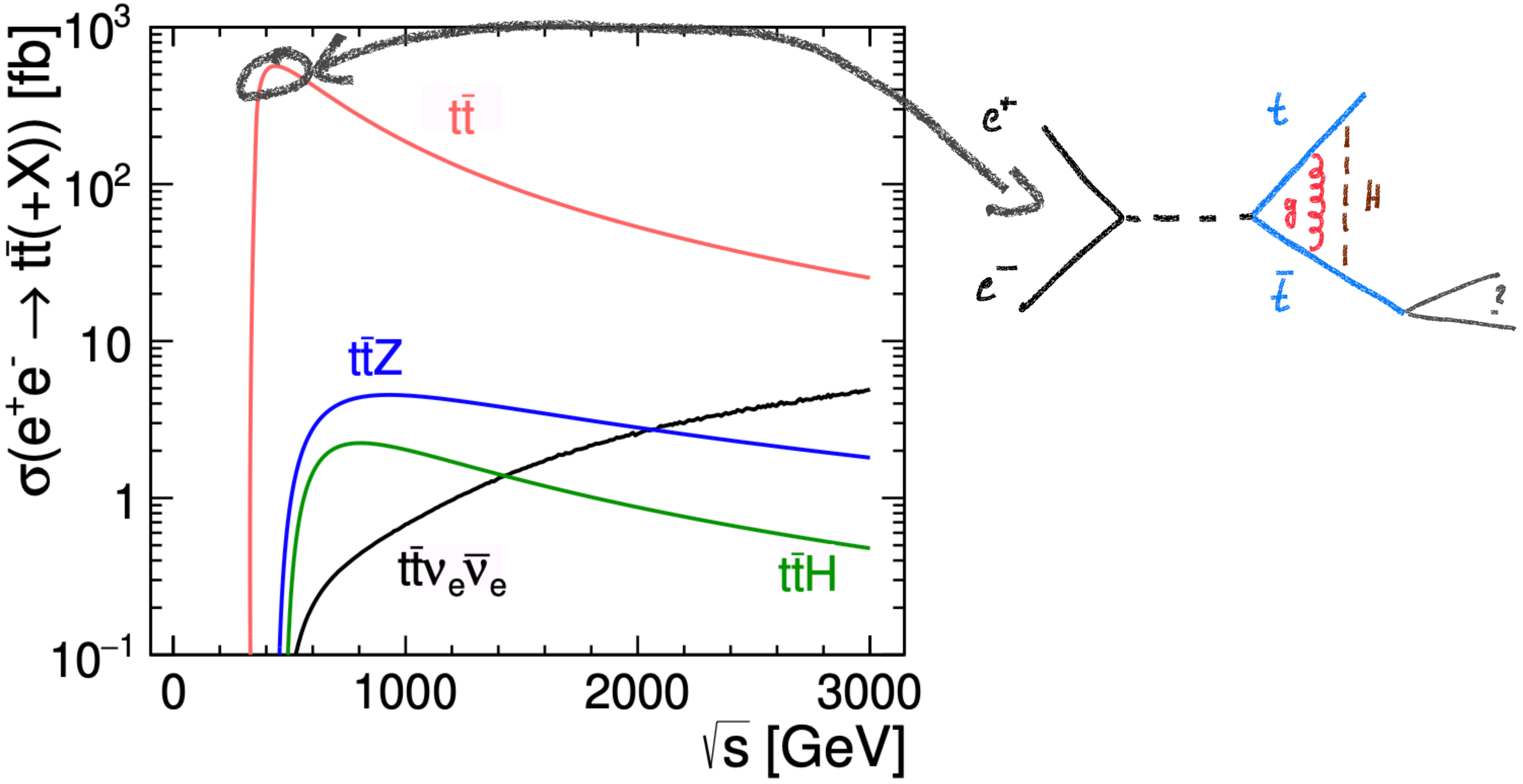

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- Search for BSM decays in clean environment

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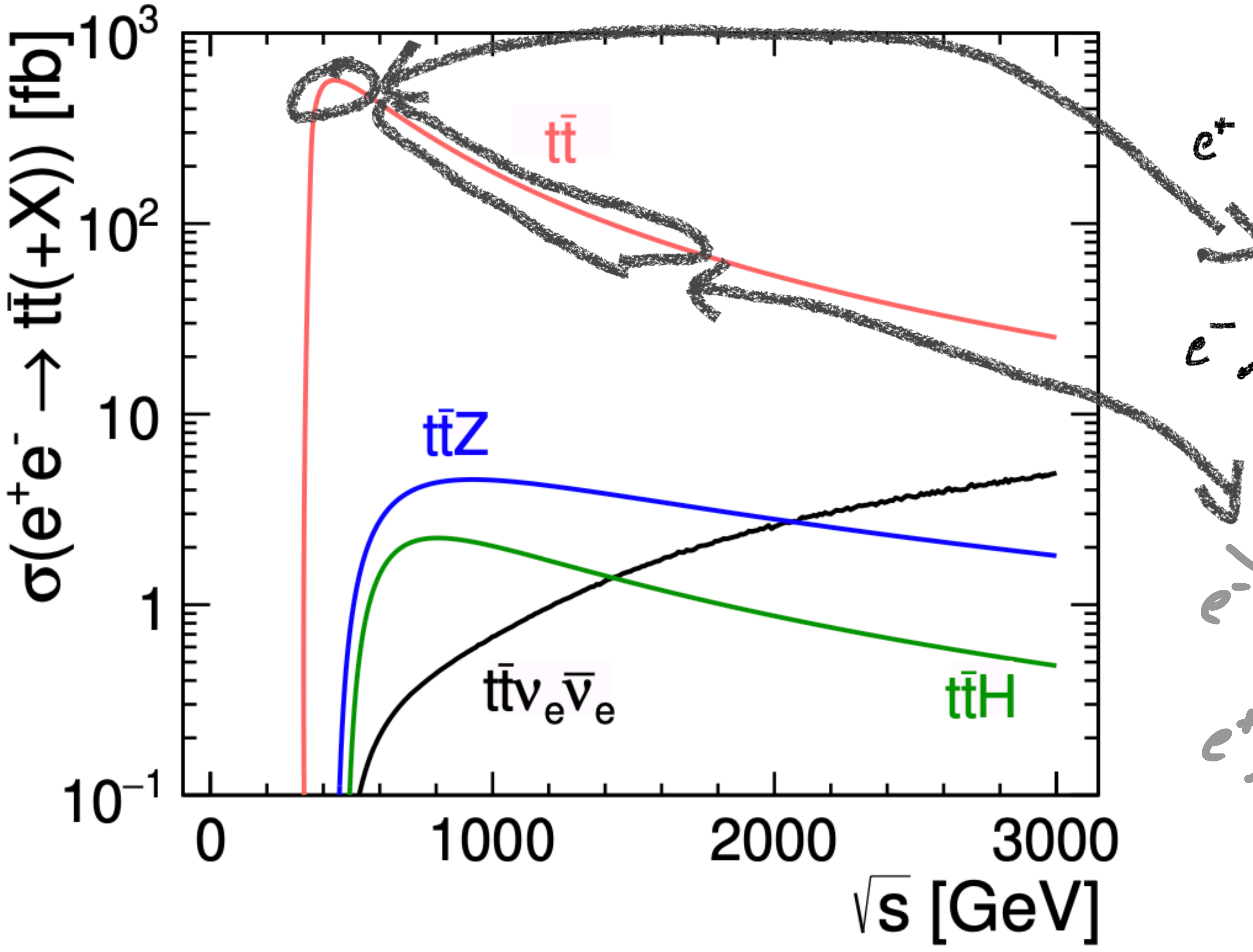

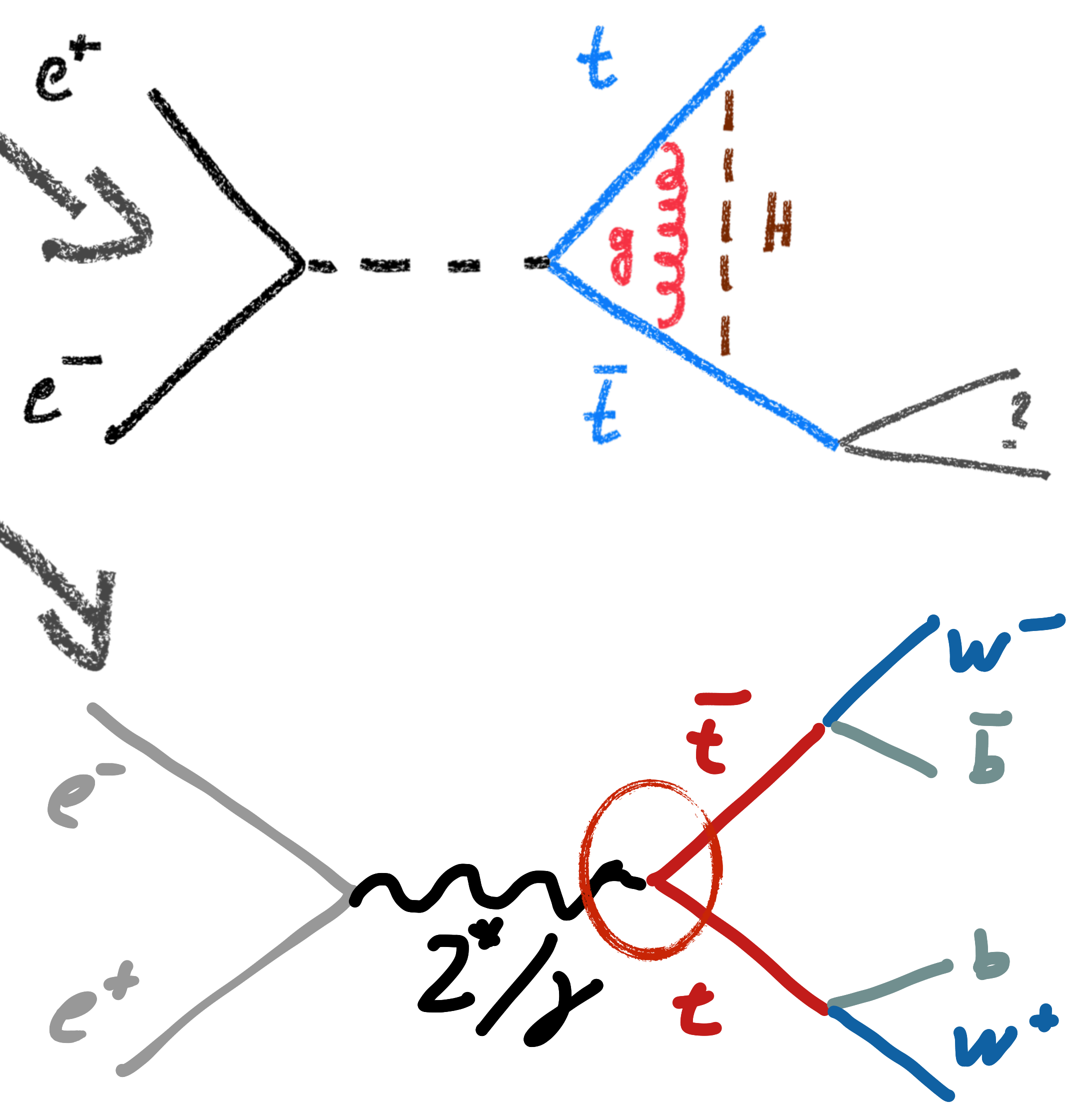

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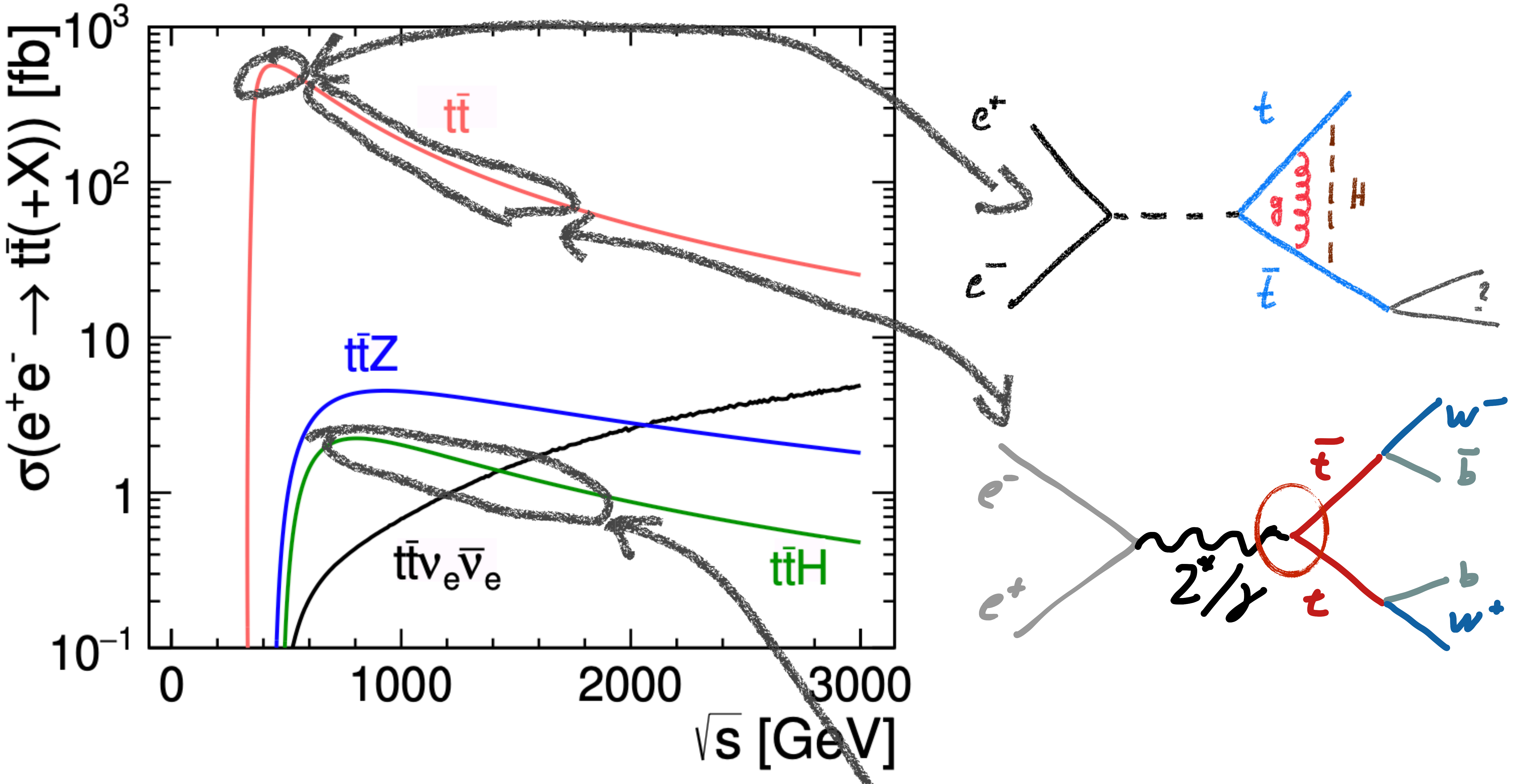

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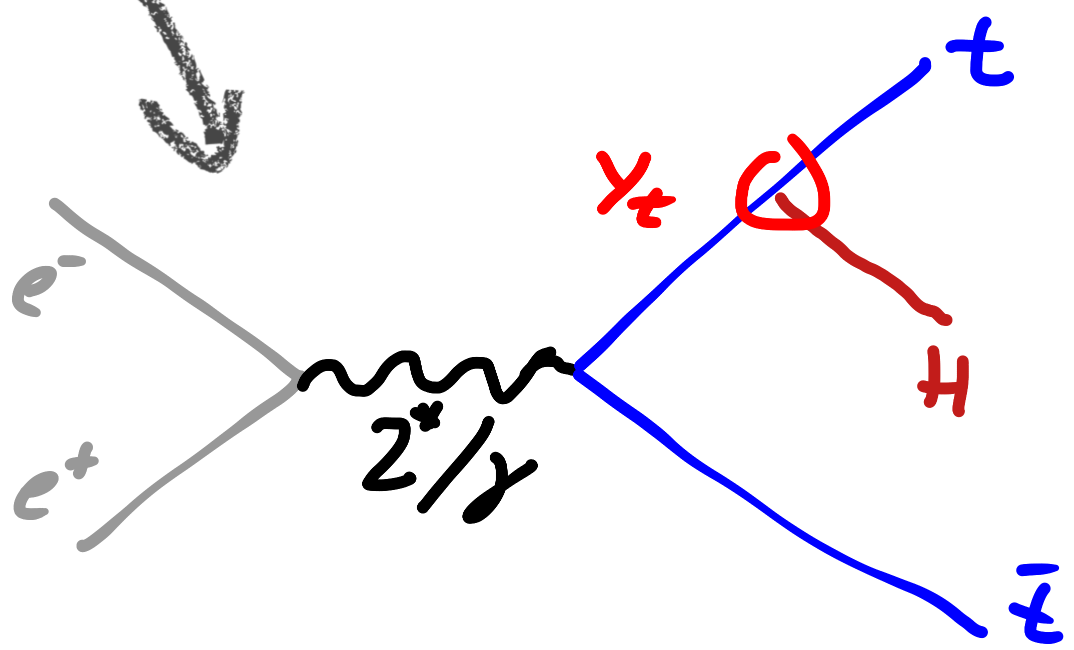


- Direct measurement of the top Yukawa coupling, ultimate potential of 2%
  [requires > 500 GeV, full scope assumes ~ 1 TeV]

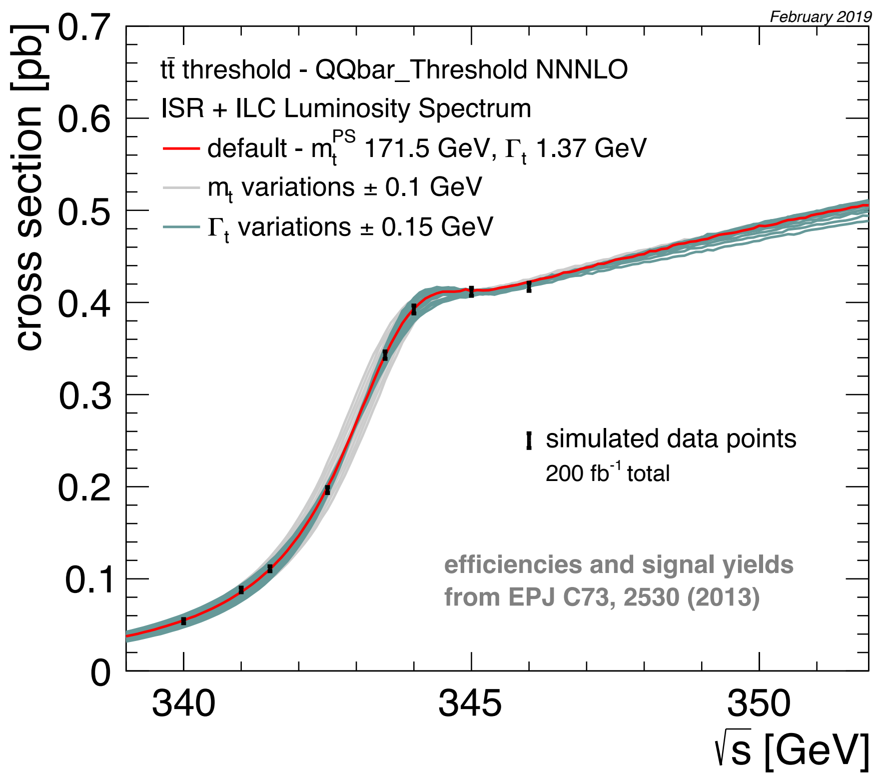
The Top Quark Mass (and other parameters)

Possibilities & Precision

- The accelerator side: Requires sufficient collision energy for top pair production
  - So far thoroughly studied for ILC, CLIC, threshold studies common for CLIC, FCC-ee, ILC

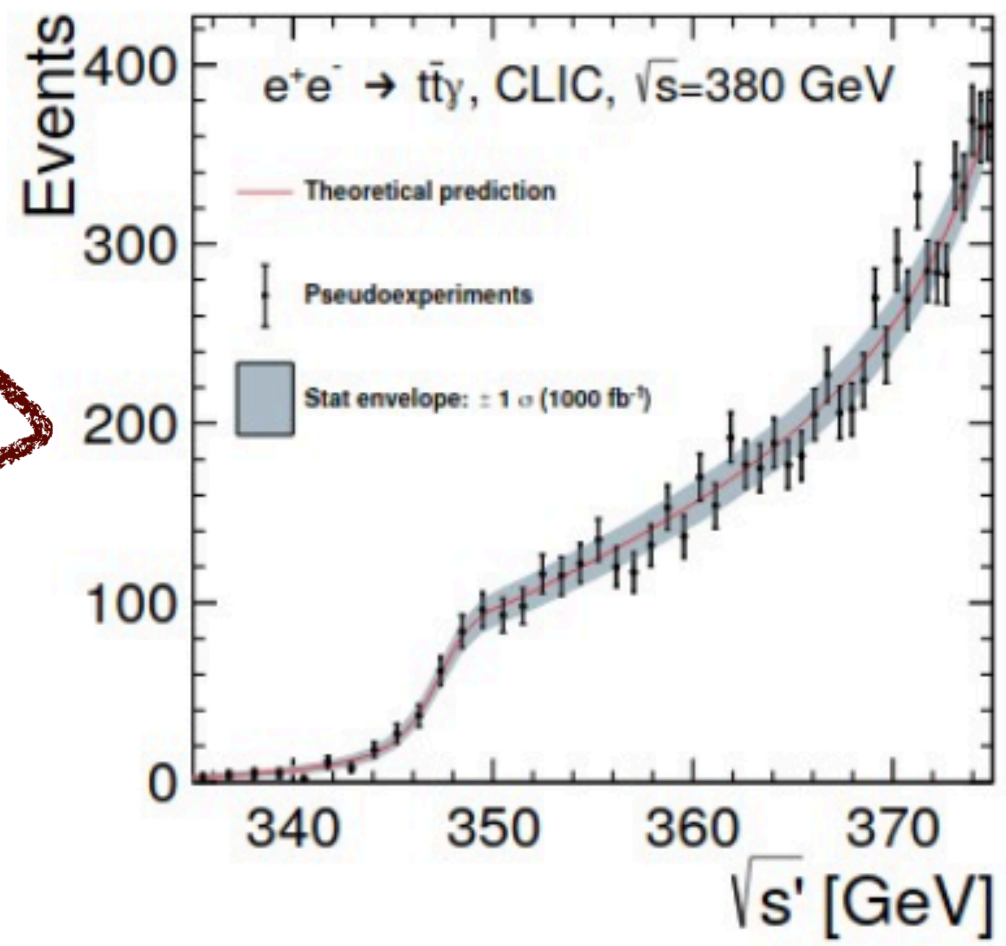
Three approaches to the top mass

The threshold scan around 350 GeV

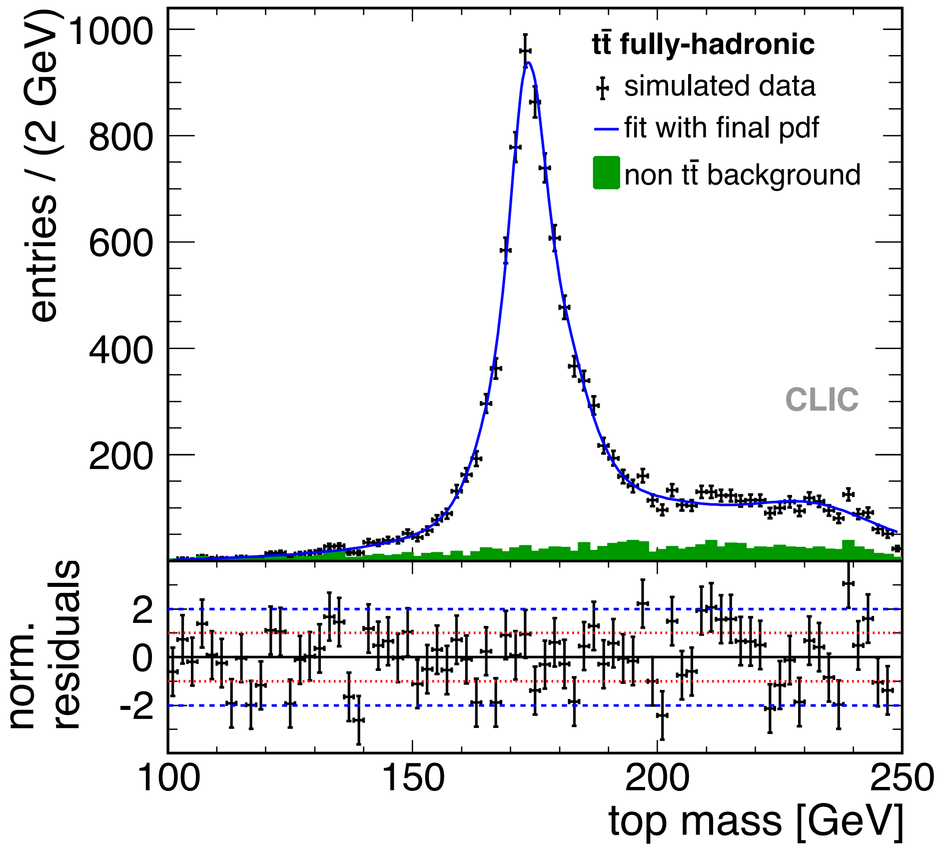


Extraction of the mass in theoretically well-defined mass definition (1S, PS): can directly be used in precision calculations, minimal conversion uncertainties to MSbar mass etc.

The top mass from radiative events



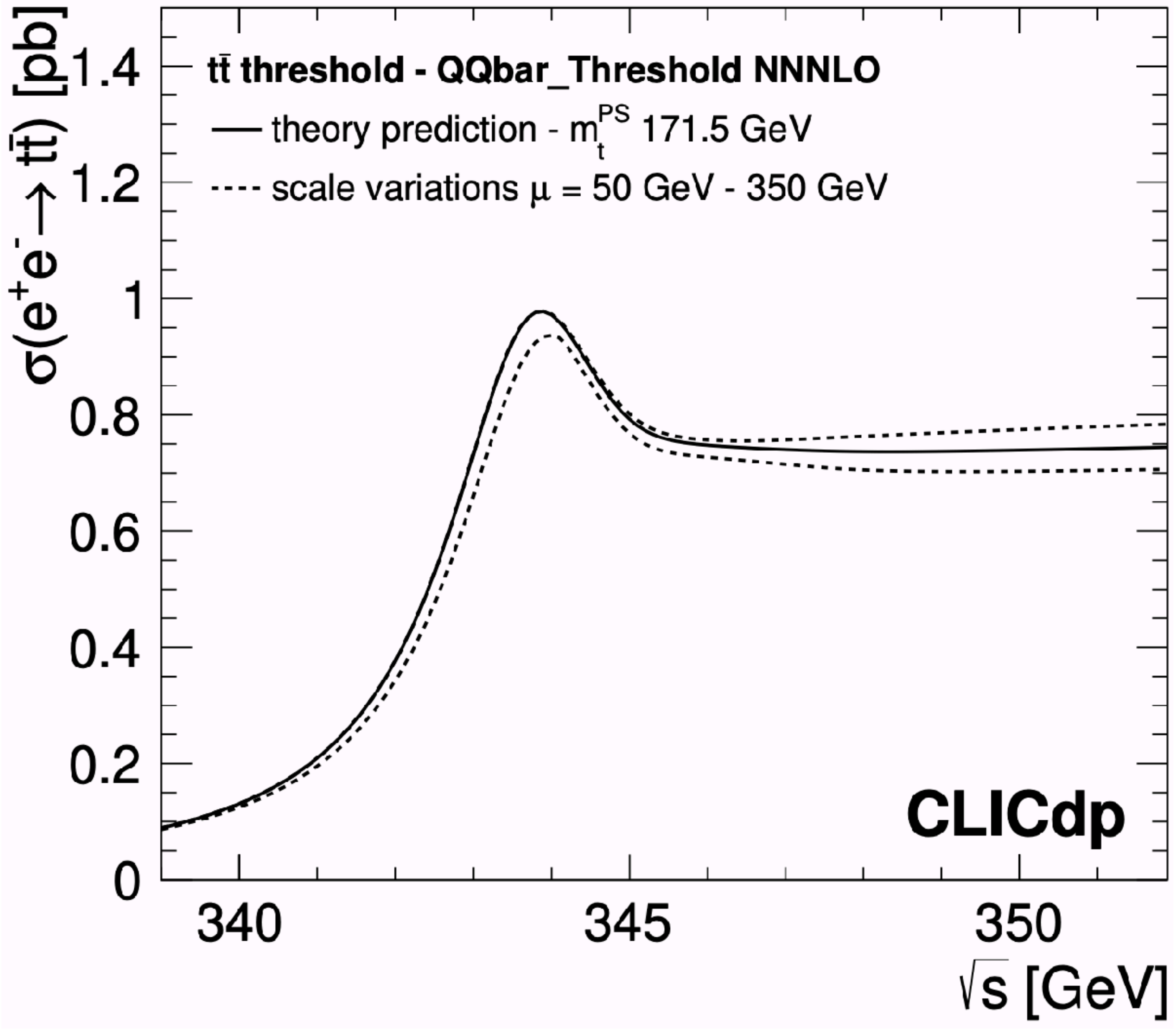
Direct kinematic reconstruction



measurement of a “MC mass”: Interpretation uncertainties of several 100 MeV

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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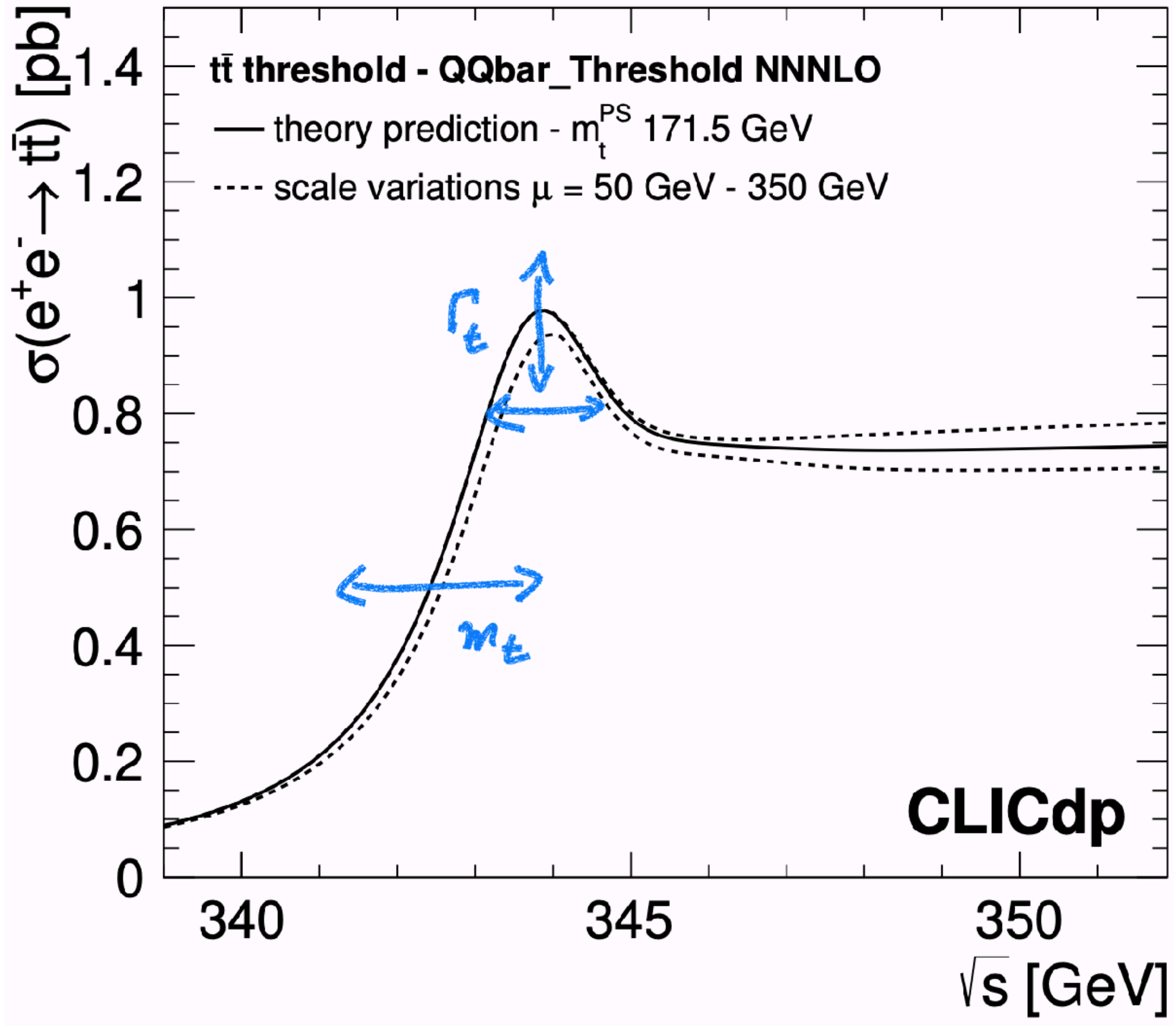

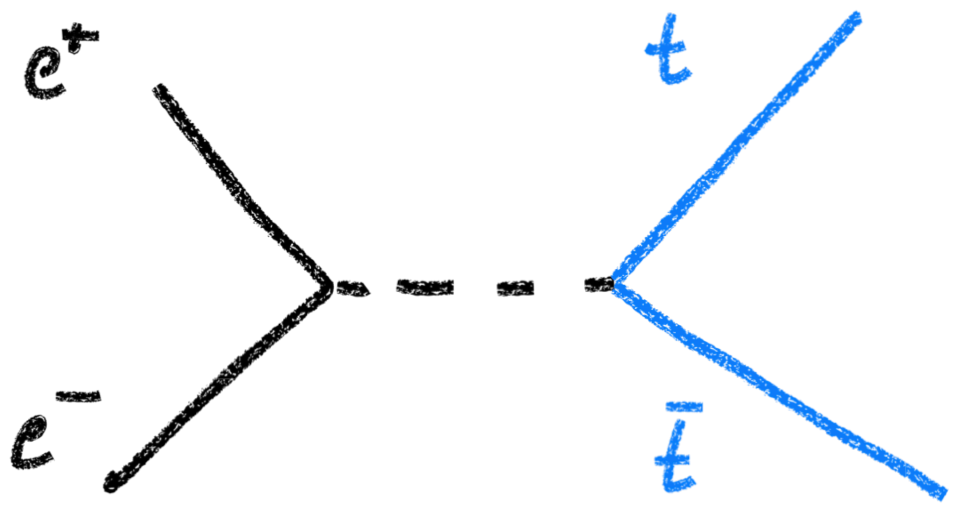

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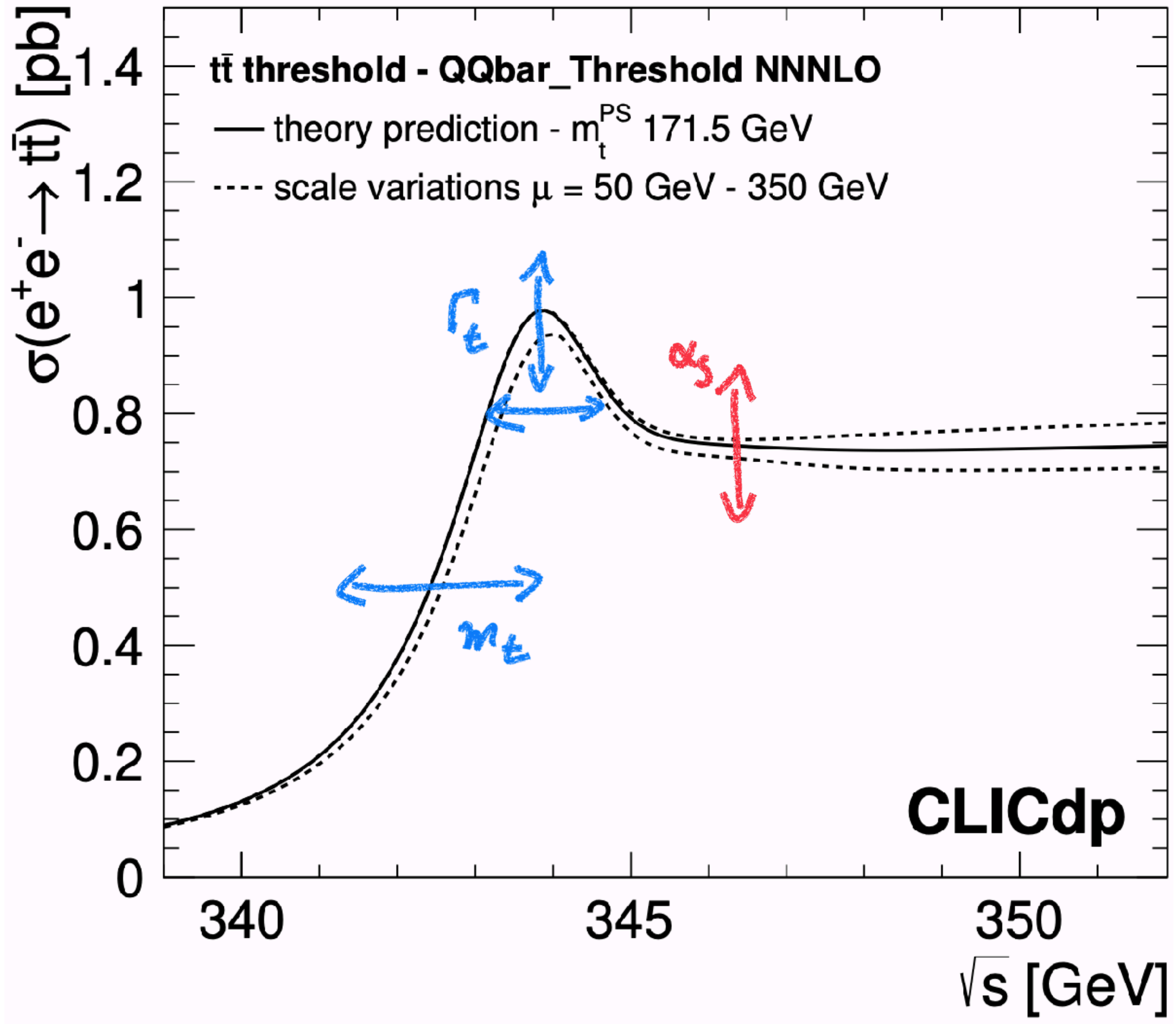

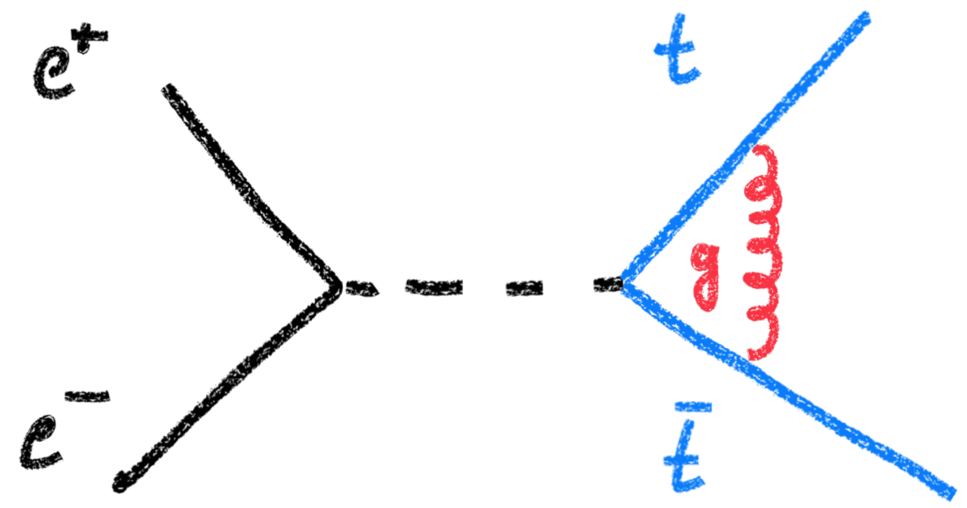

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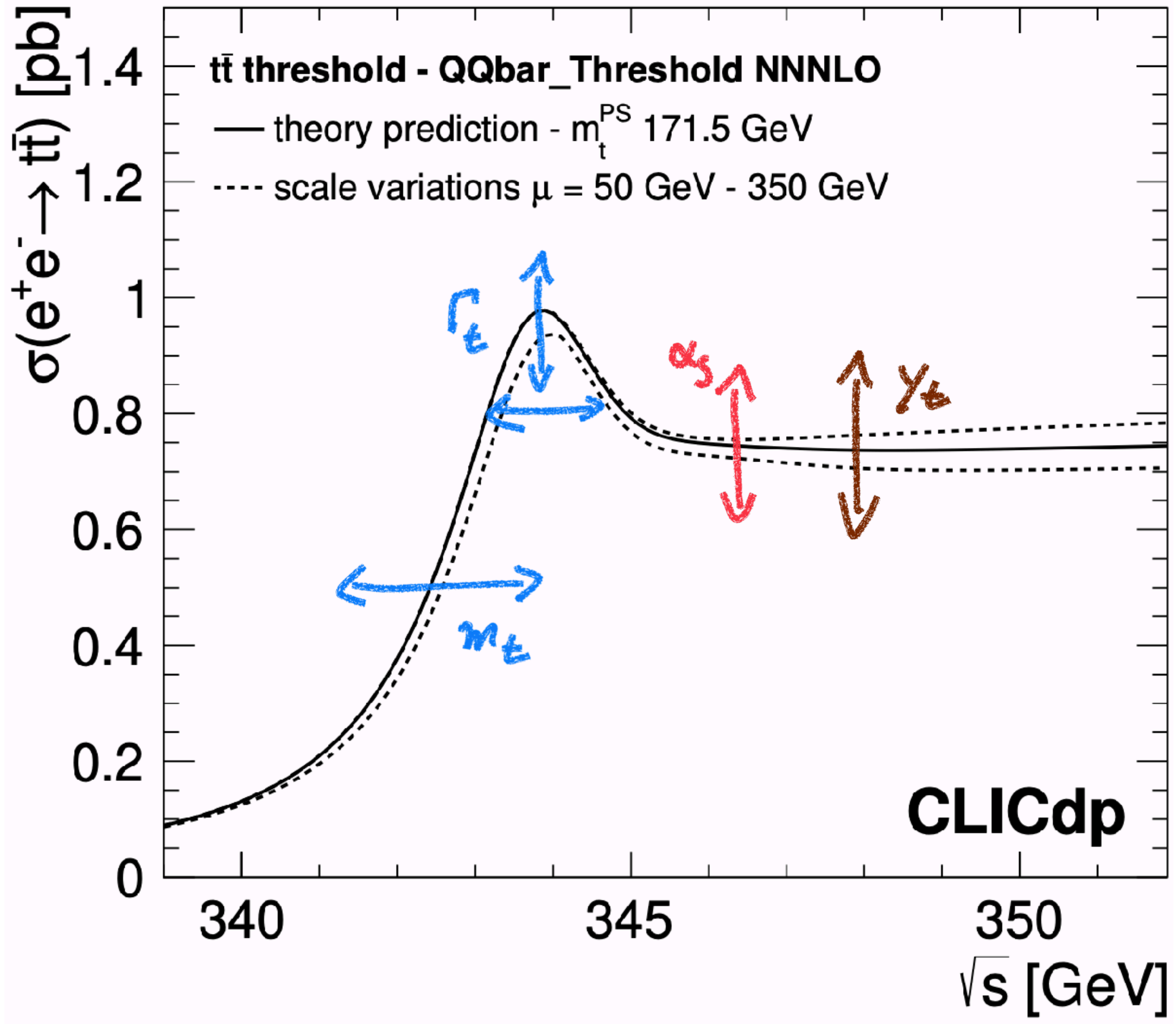

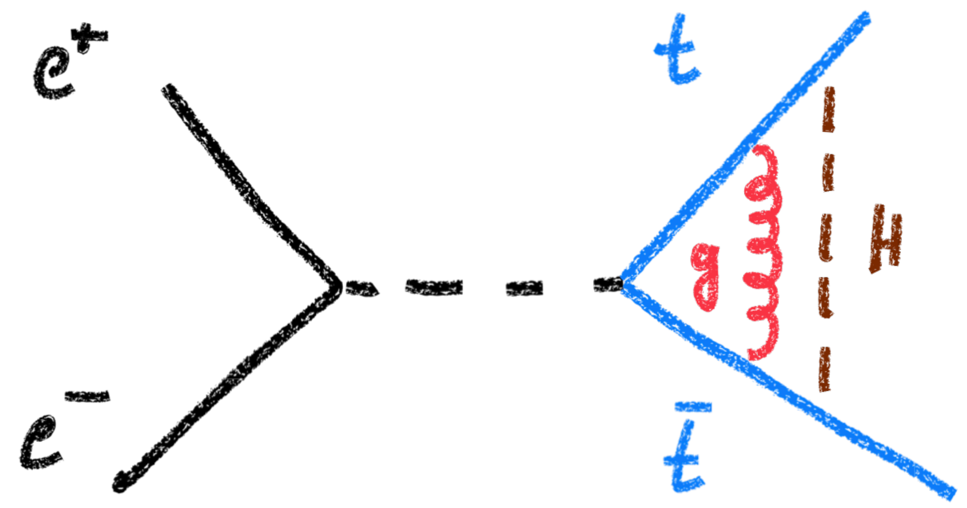

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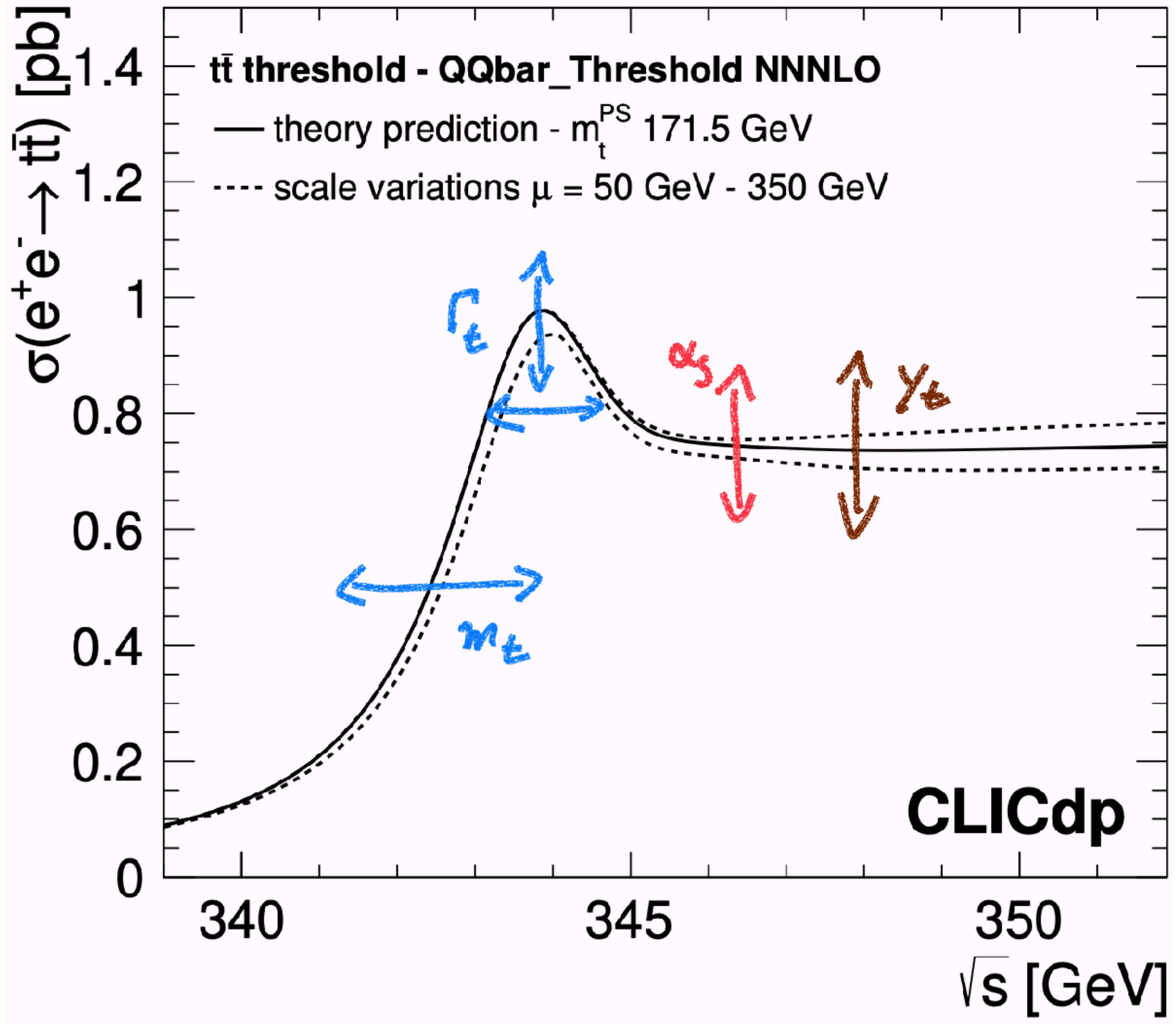

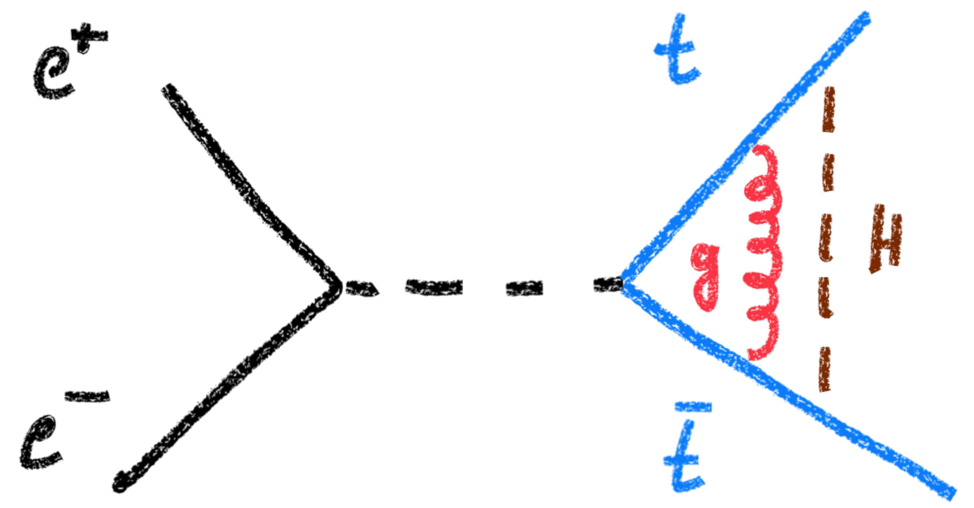

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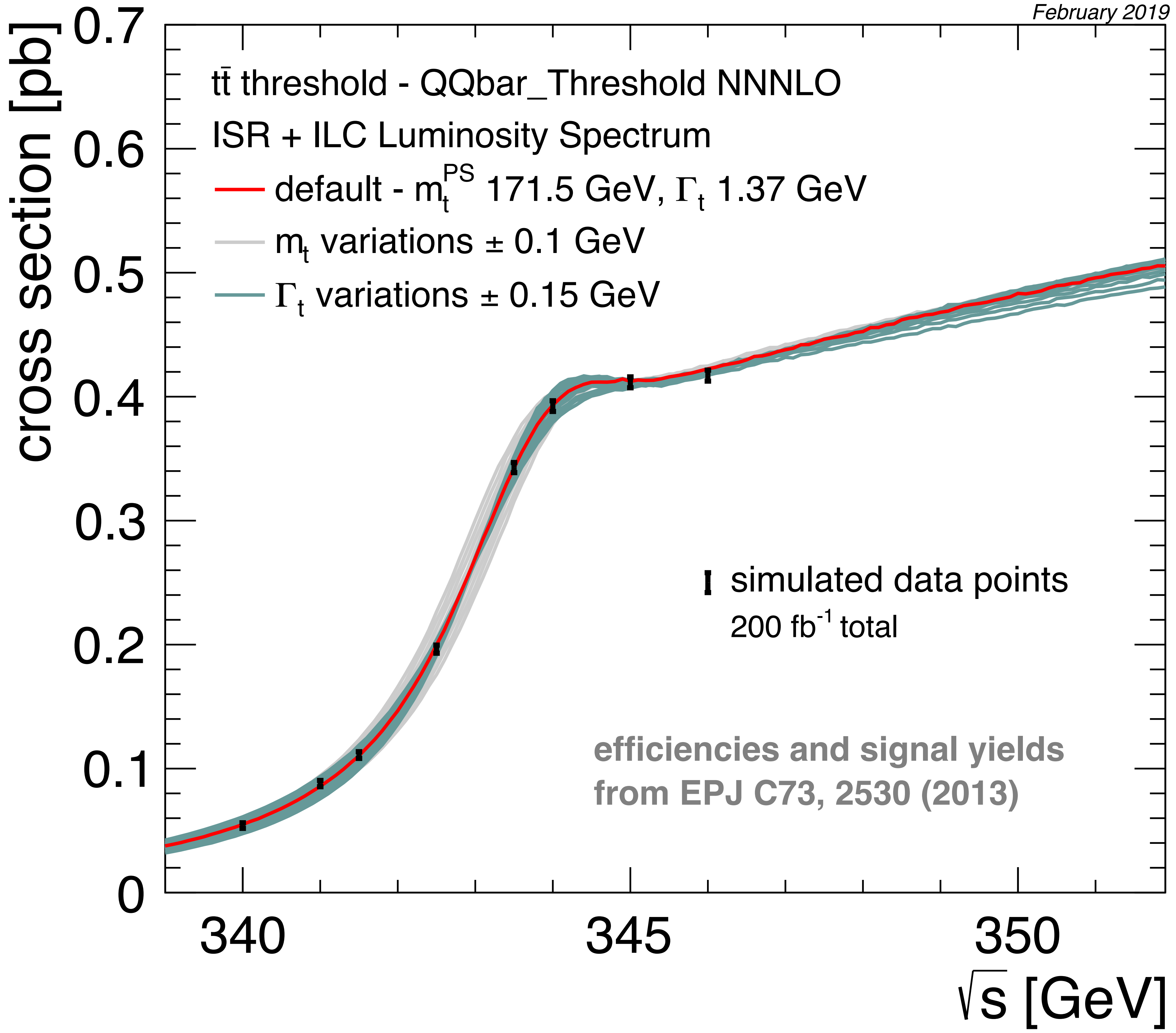
ISR, luminosity spectrum, reconstruction

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



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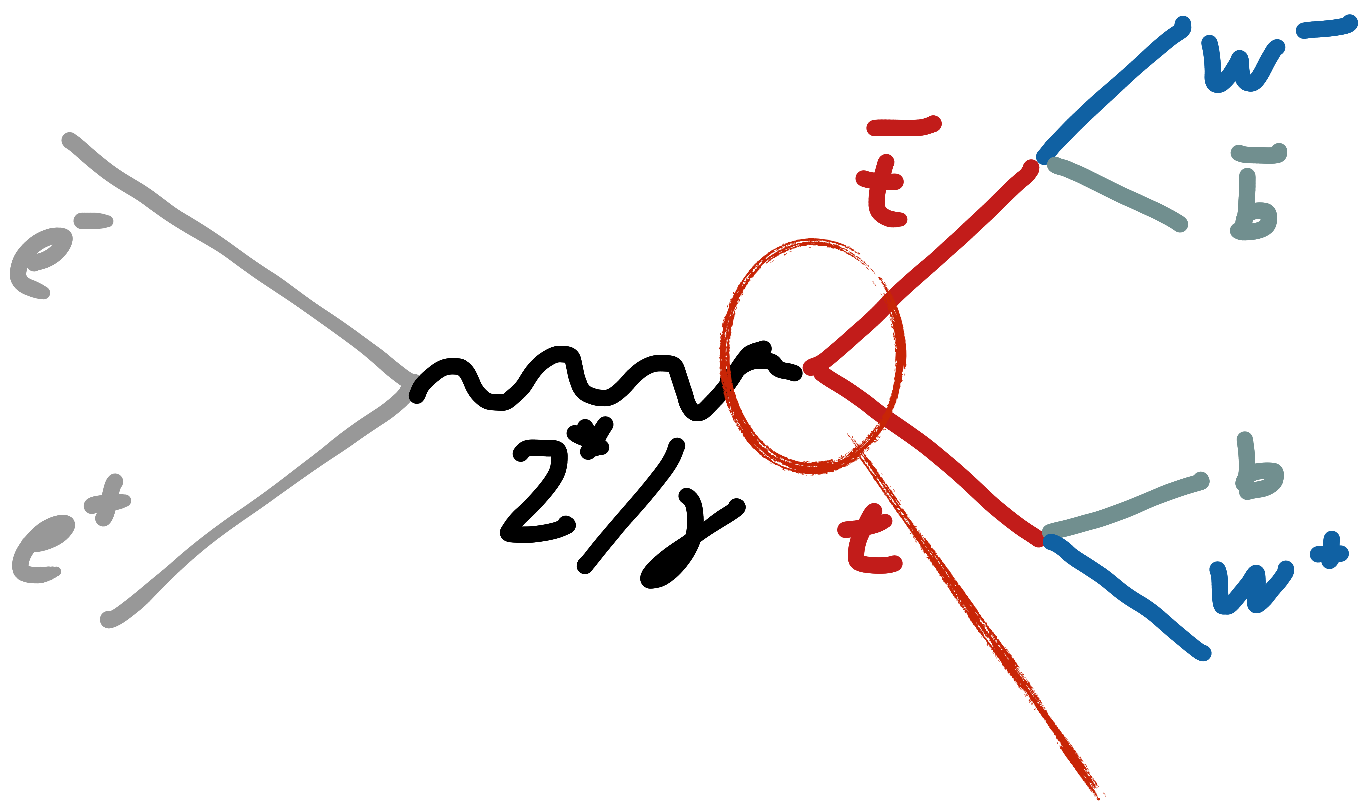
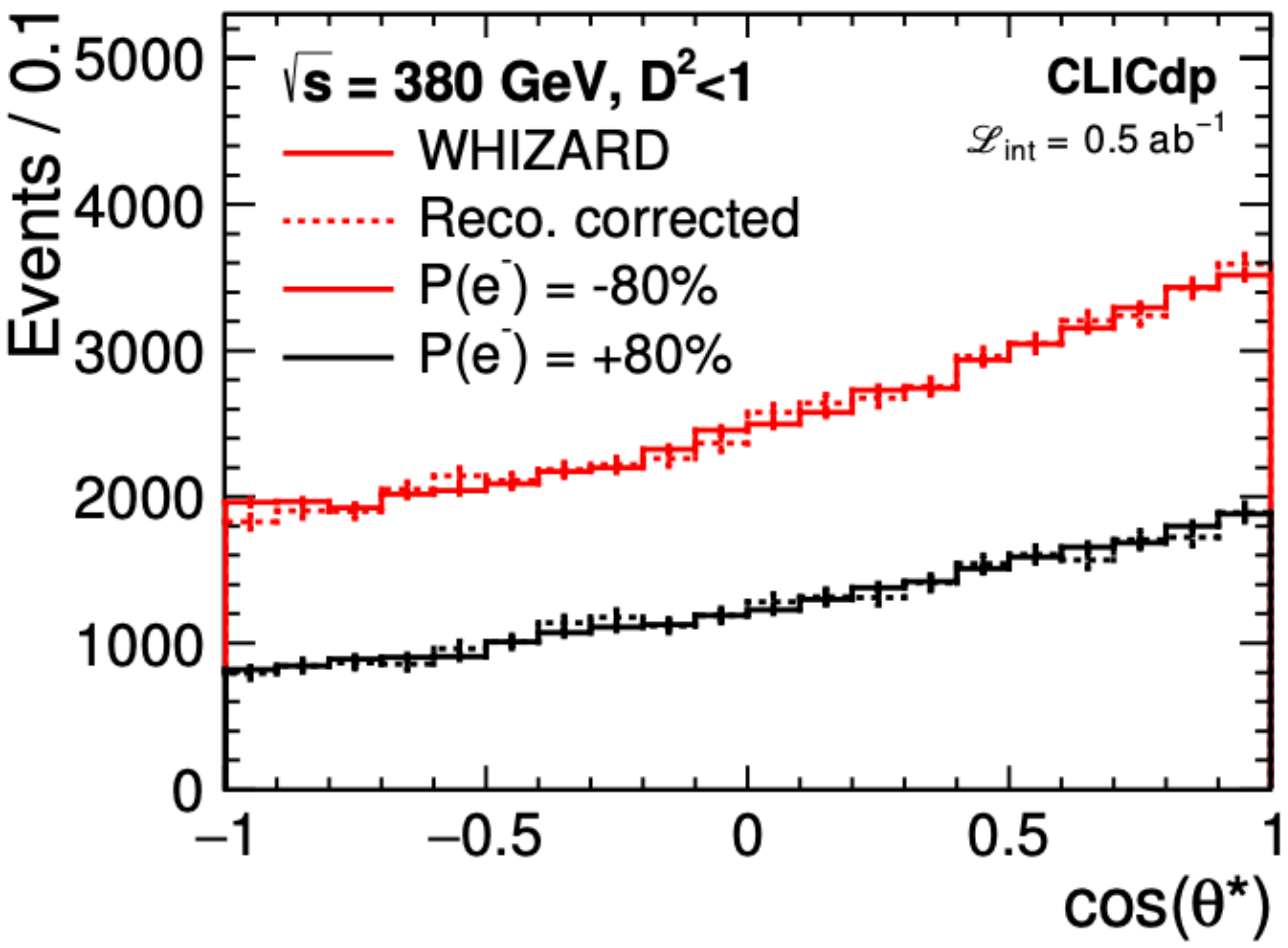
Electroweak Couplings of the Top Quark

Access via cross section and asymmetries



Accessing electroweak couplings in ttbar



- At Linear Colliders:
  - Using different beam polarisations
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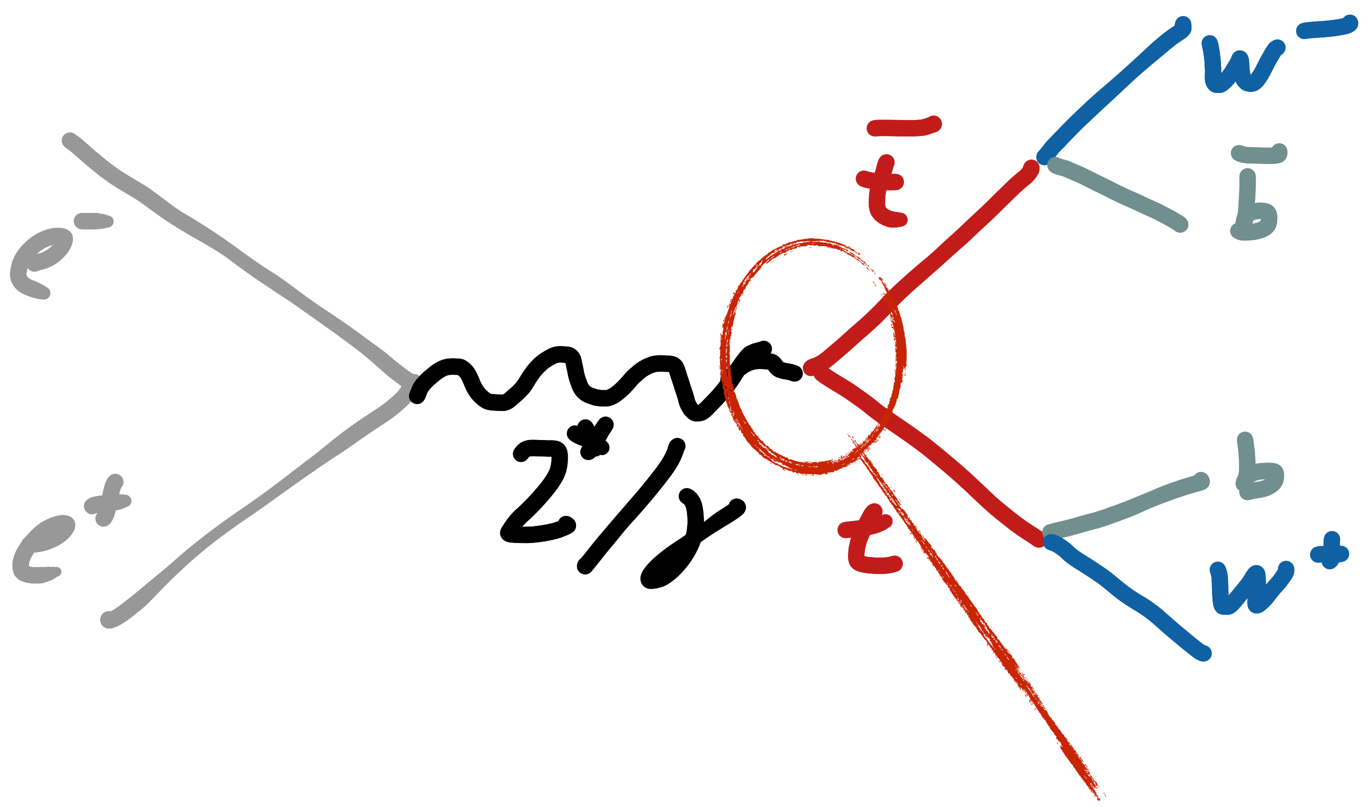

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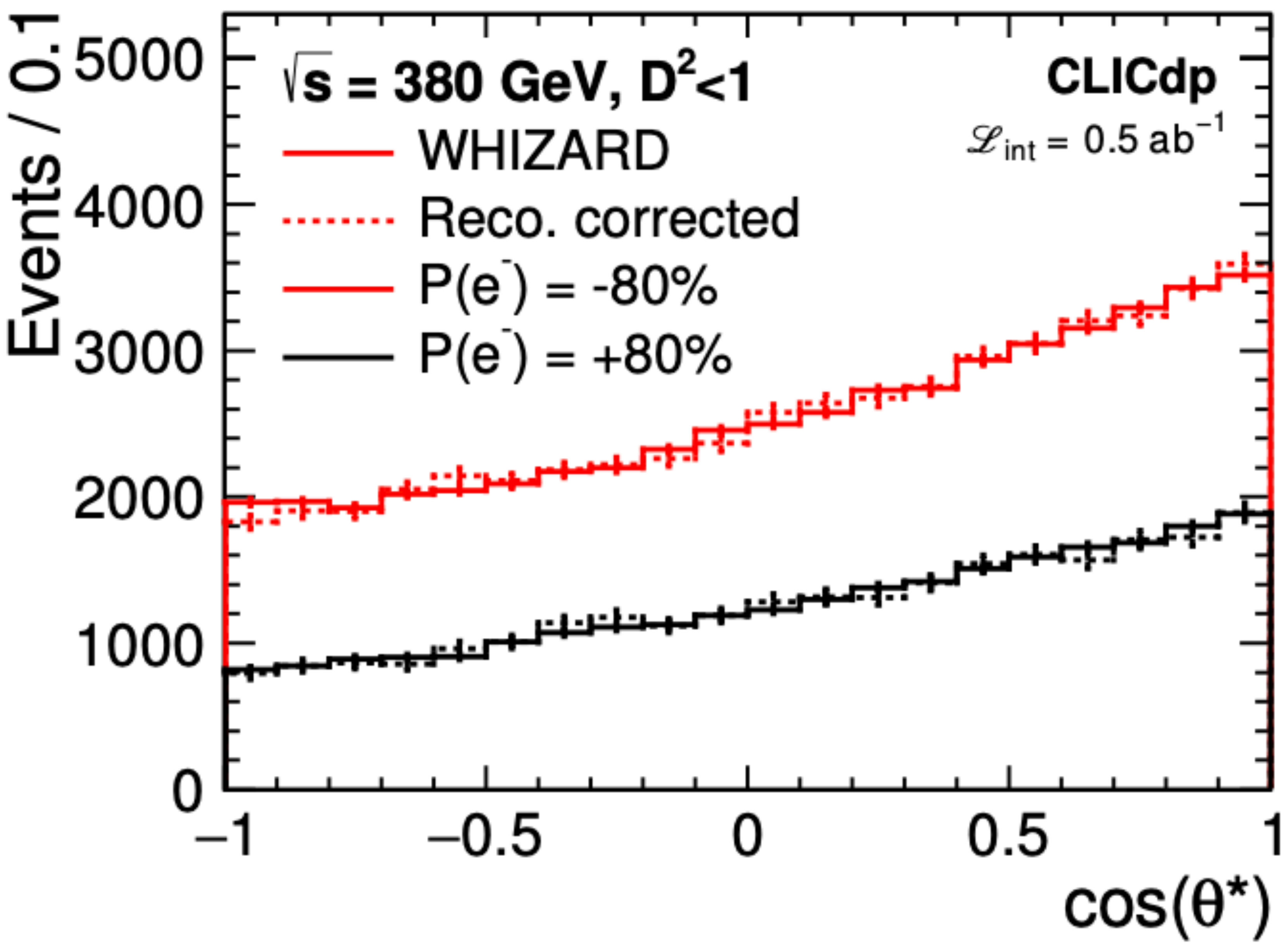
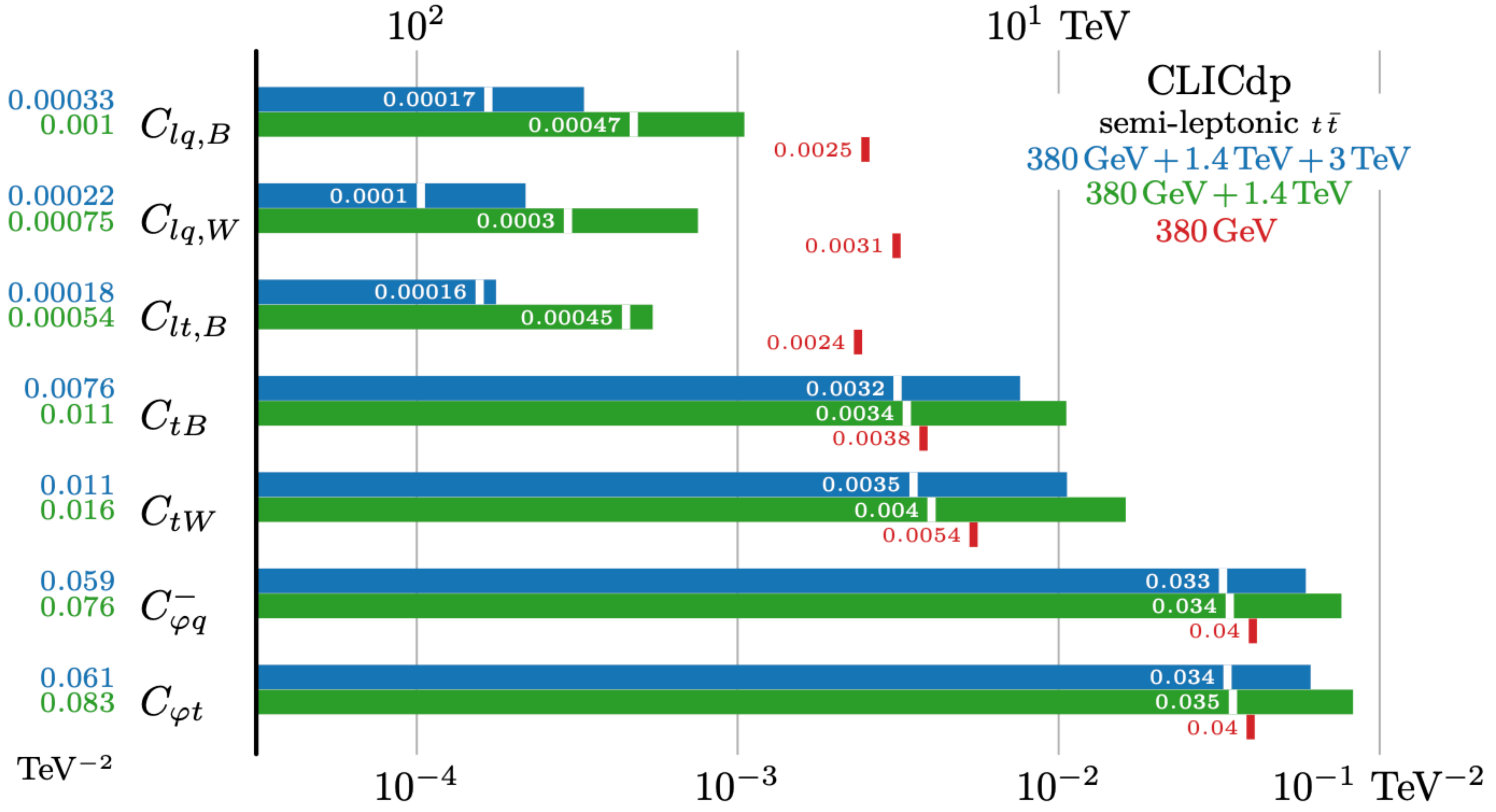


As an example: CLIC EFT-interpretation -> Reach up to 100 TeV

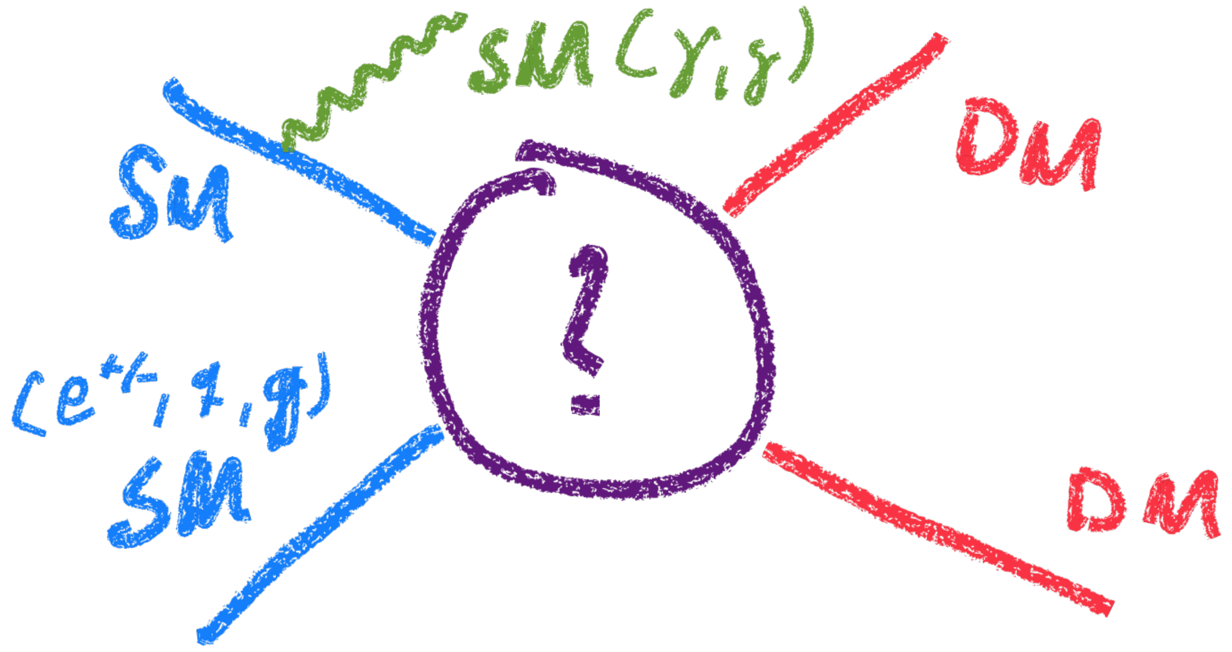


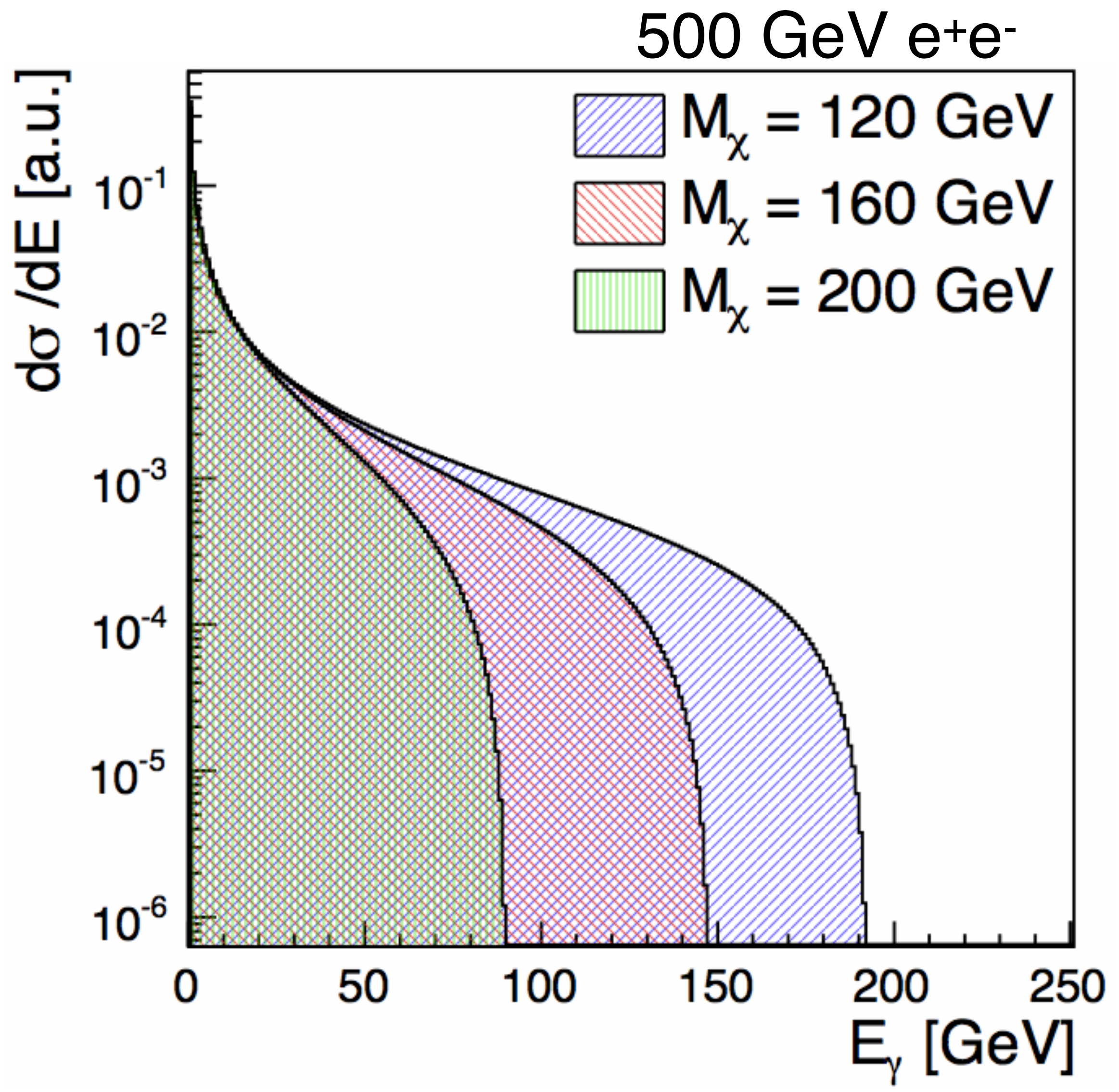
Into the Unknown

Searching for New Physics

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

Search for Dark Matter





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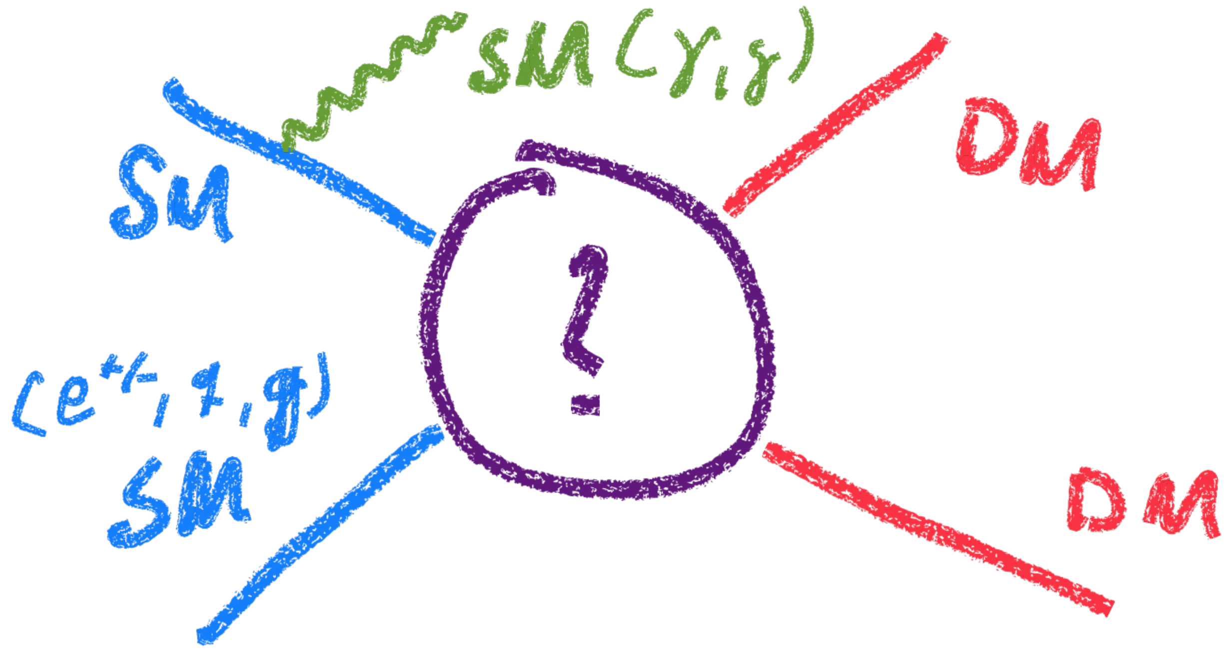

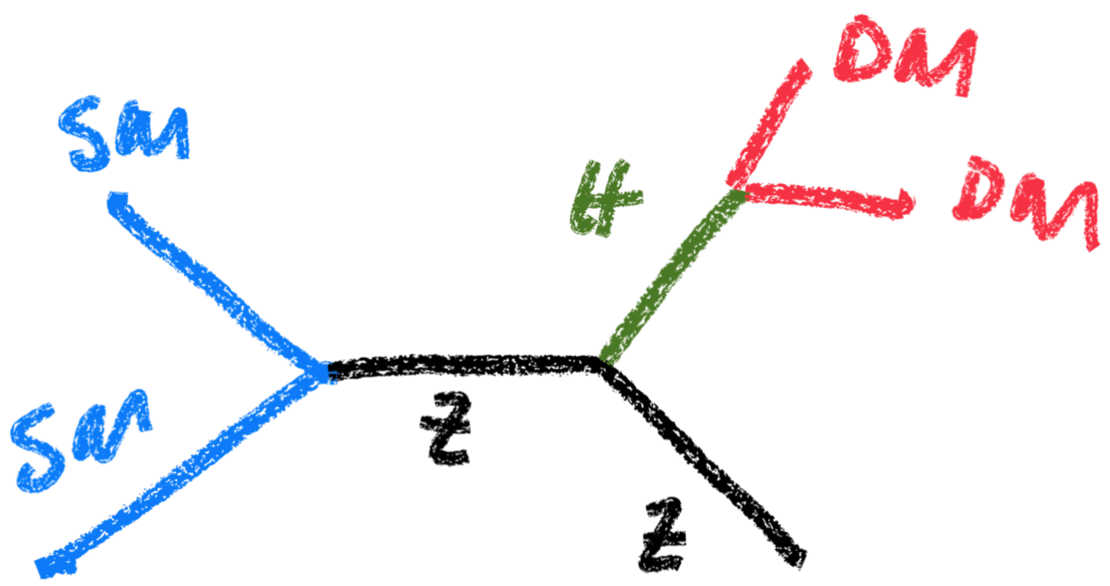

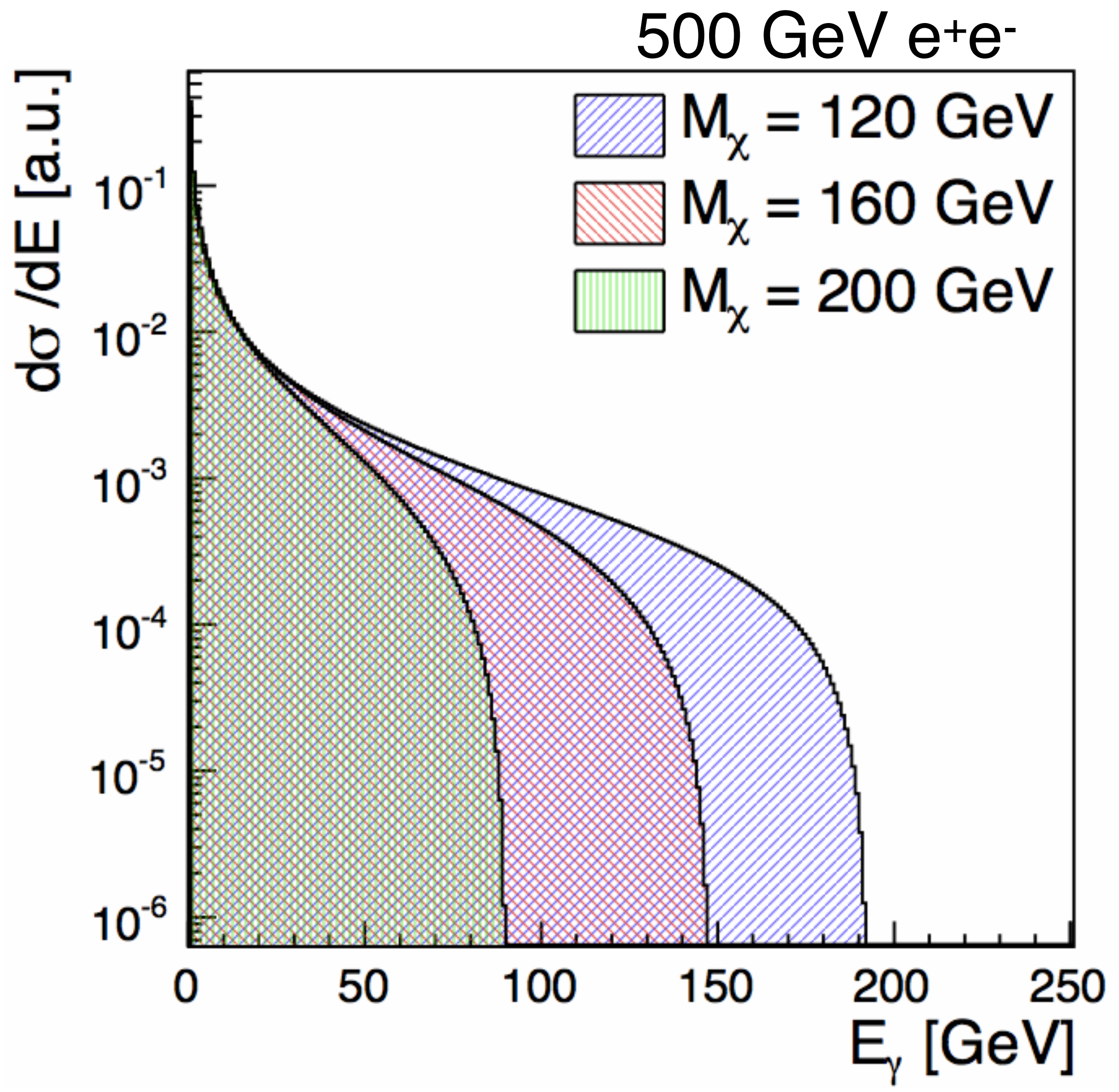

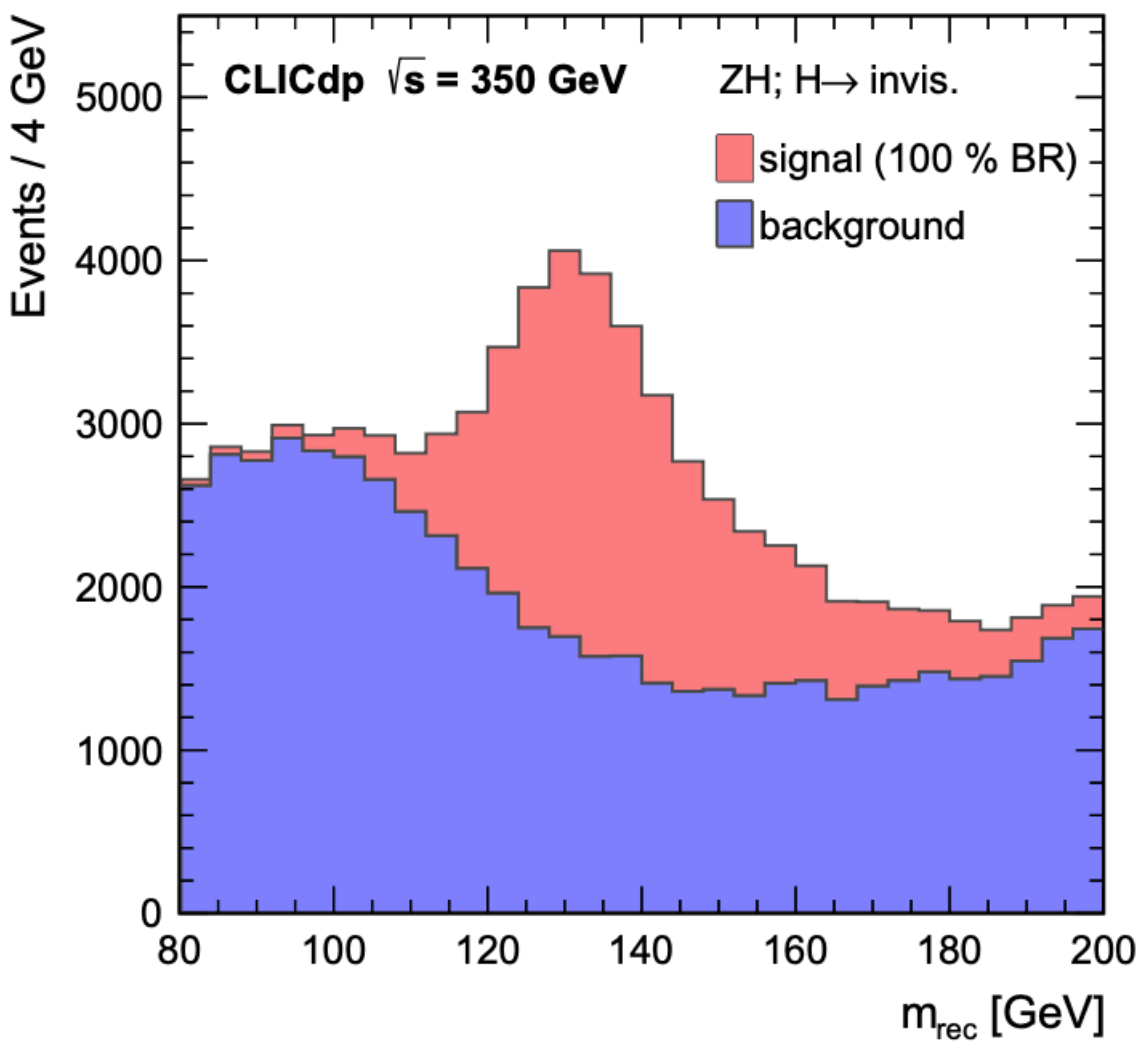

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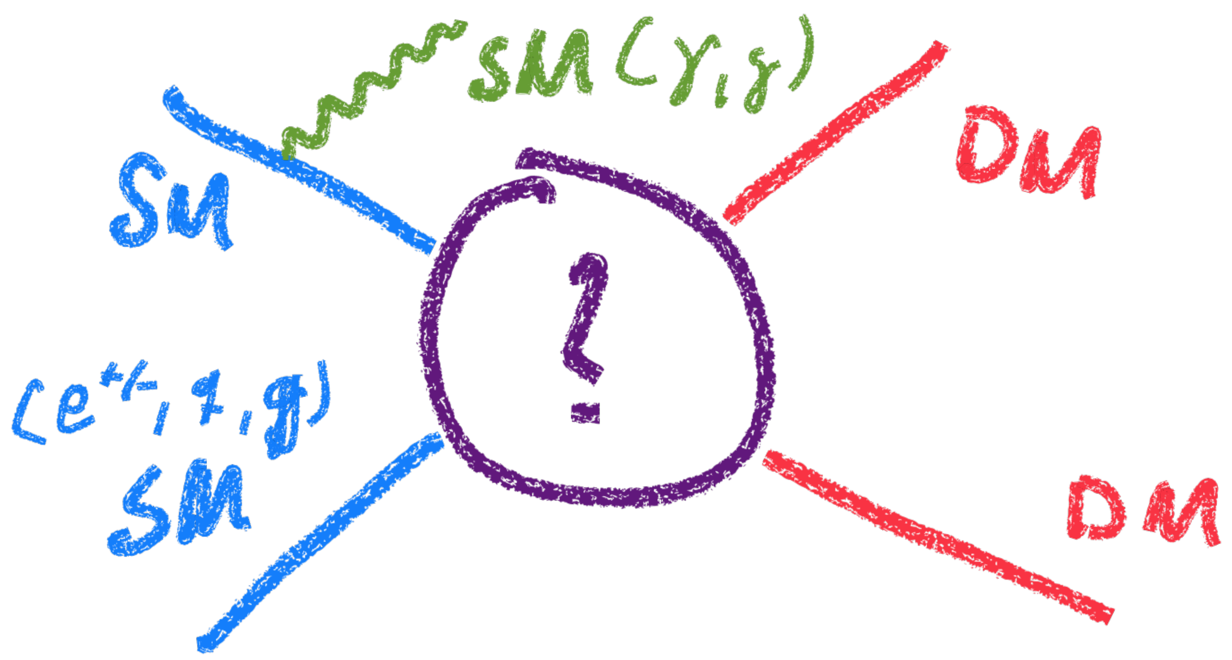
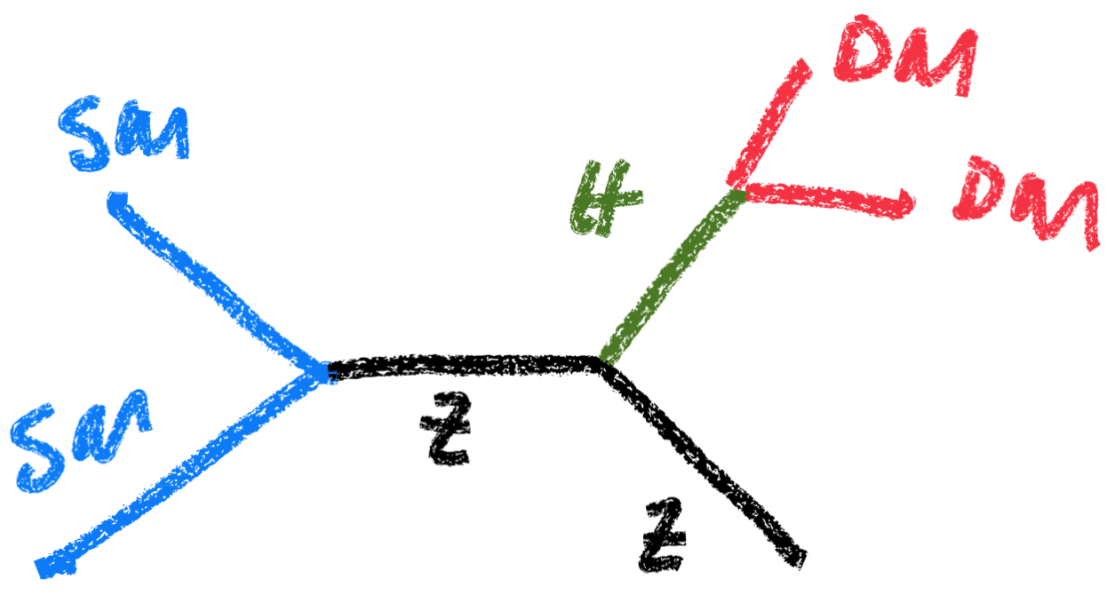
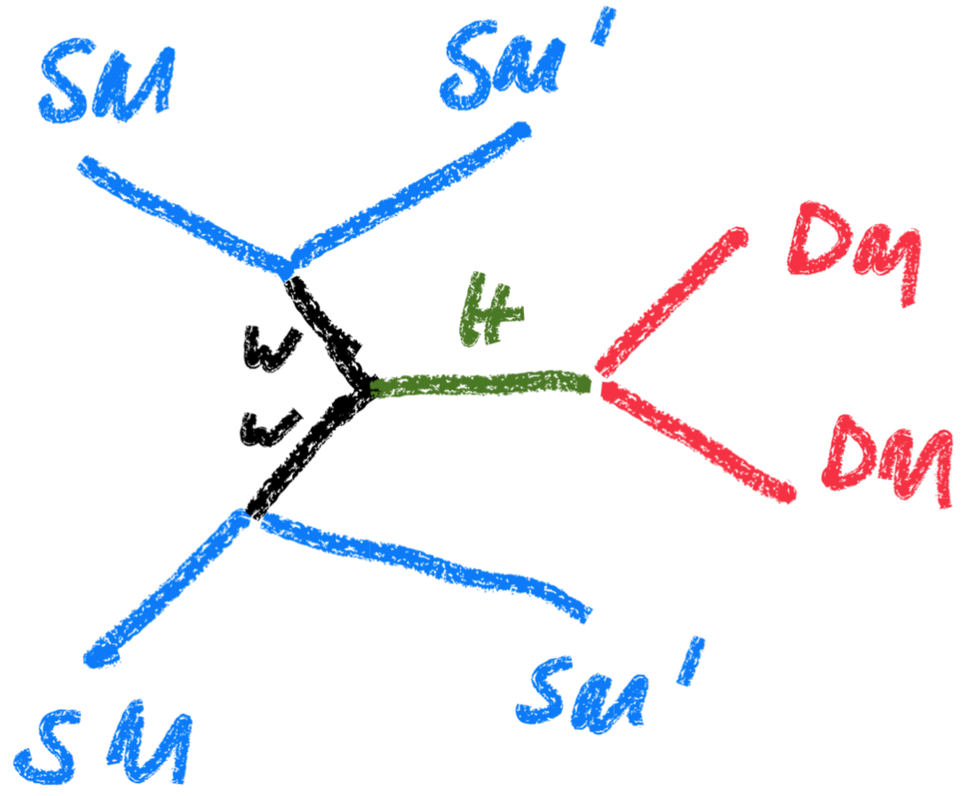
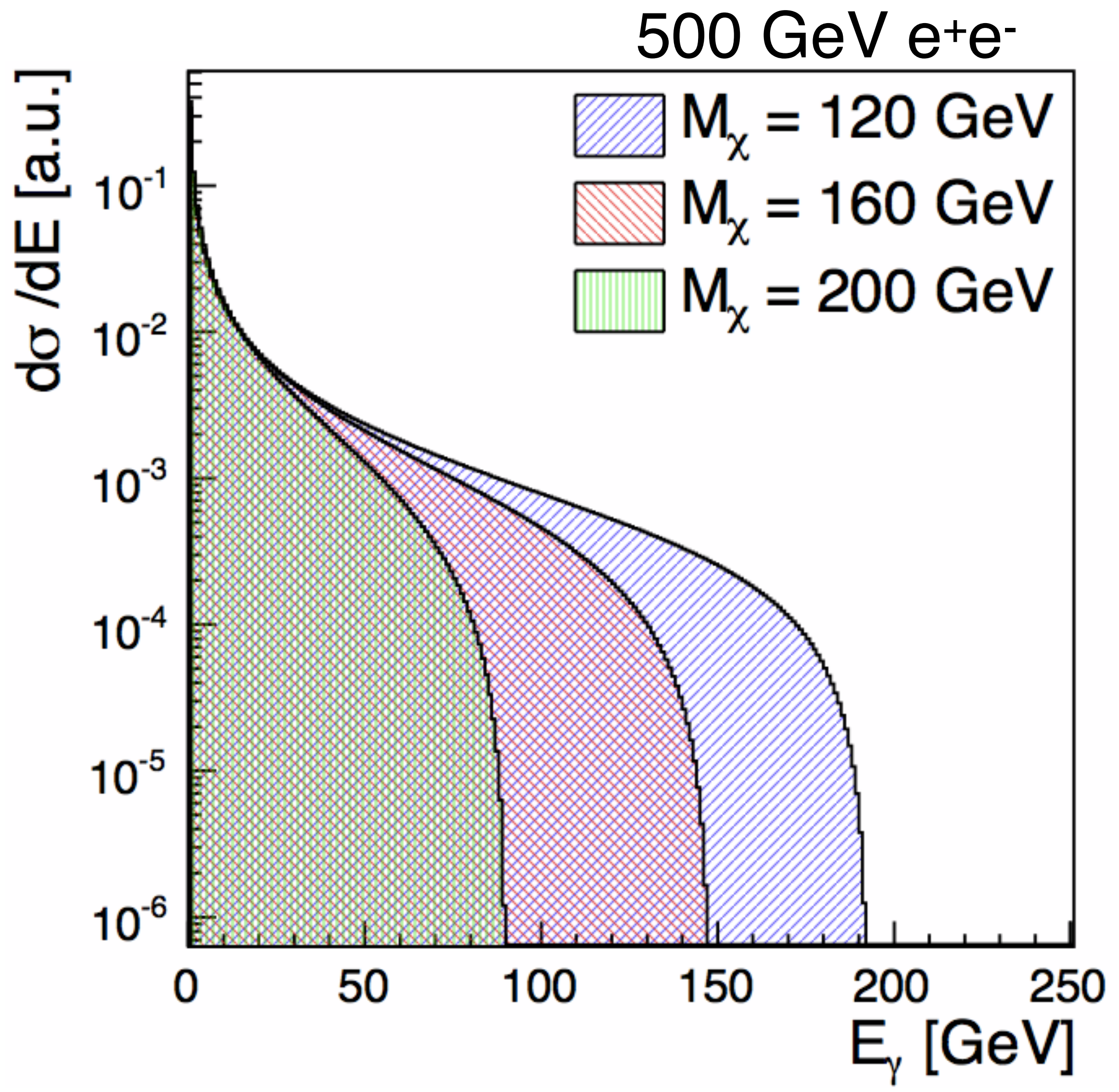
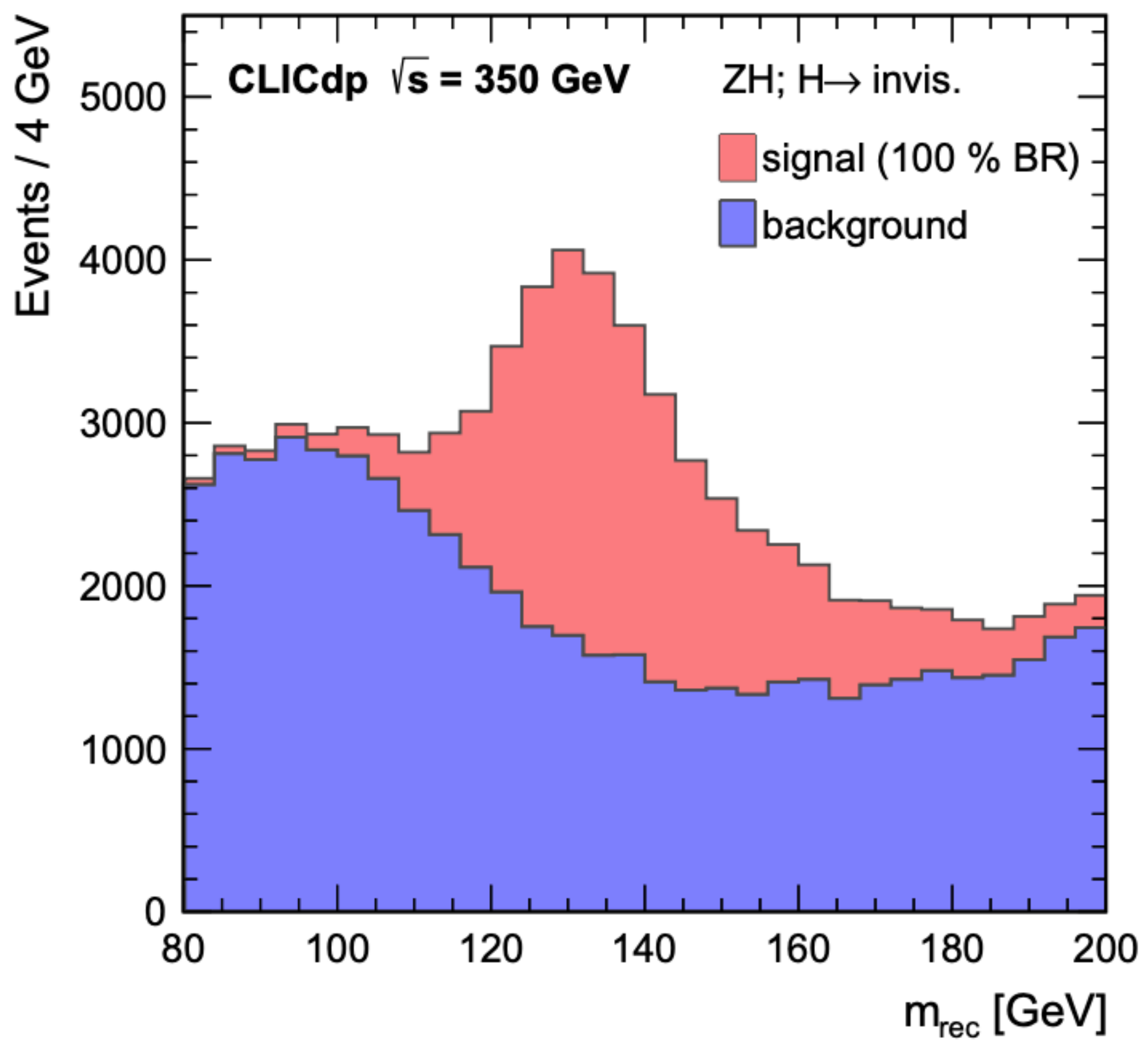




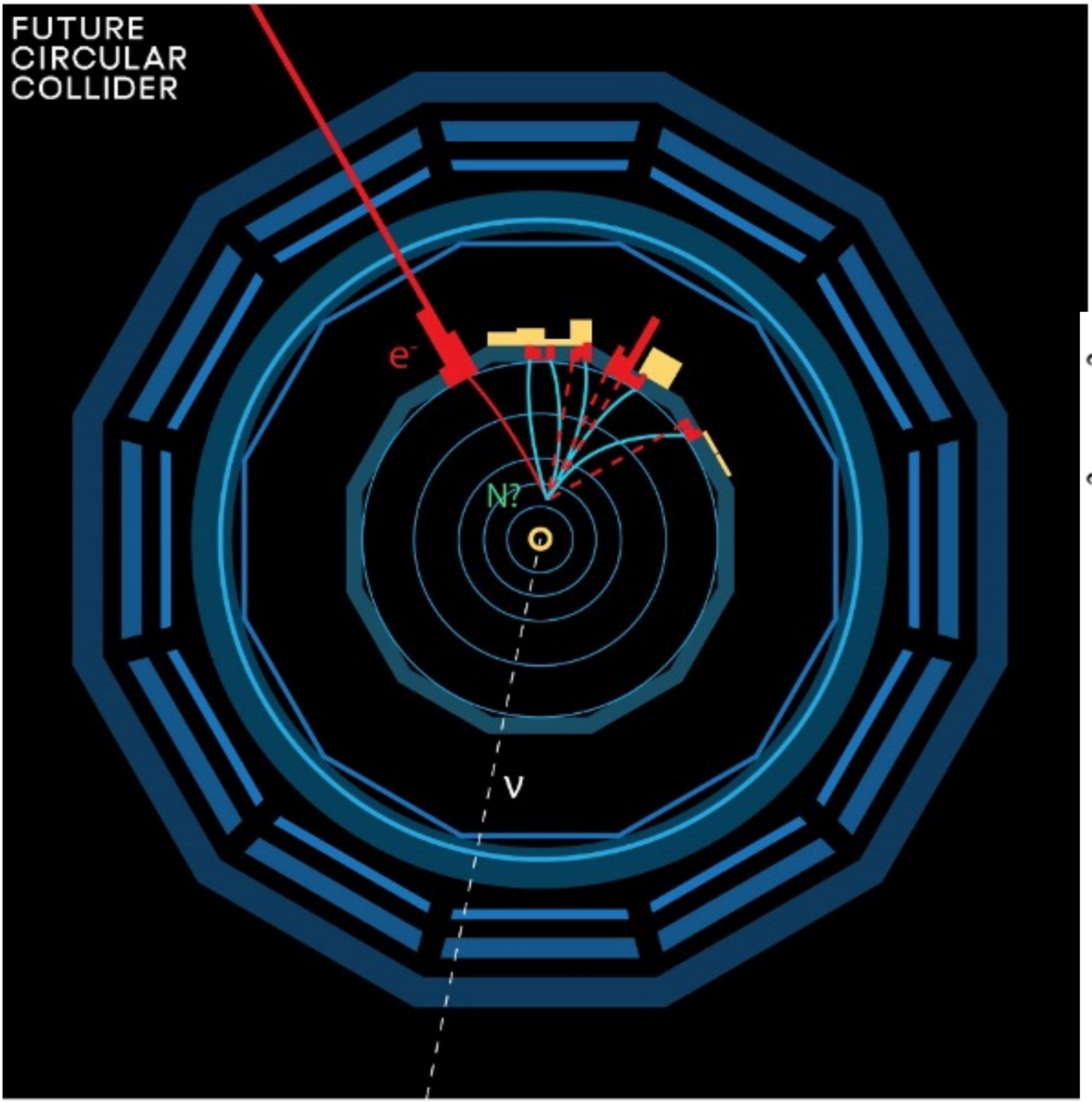




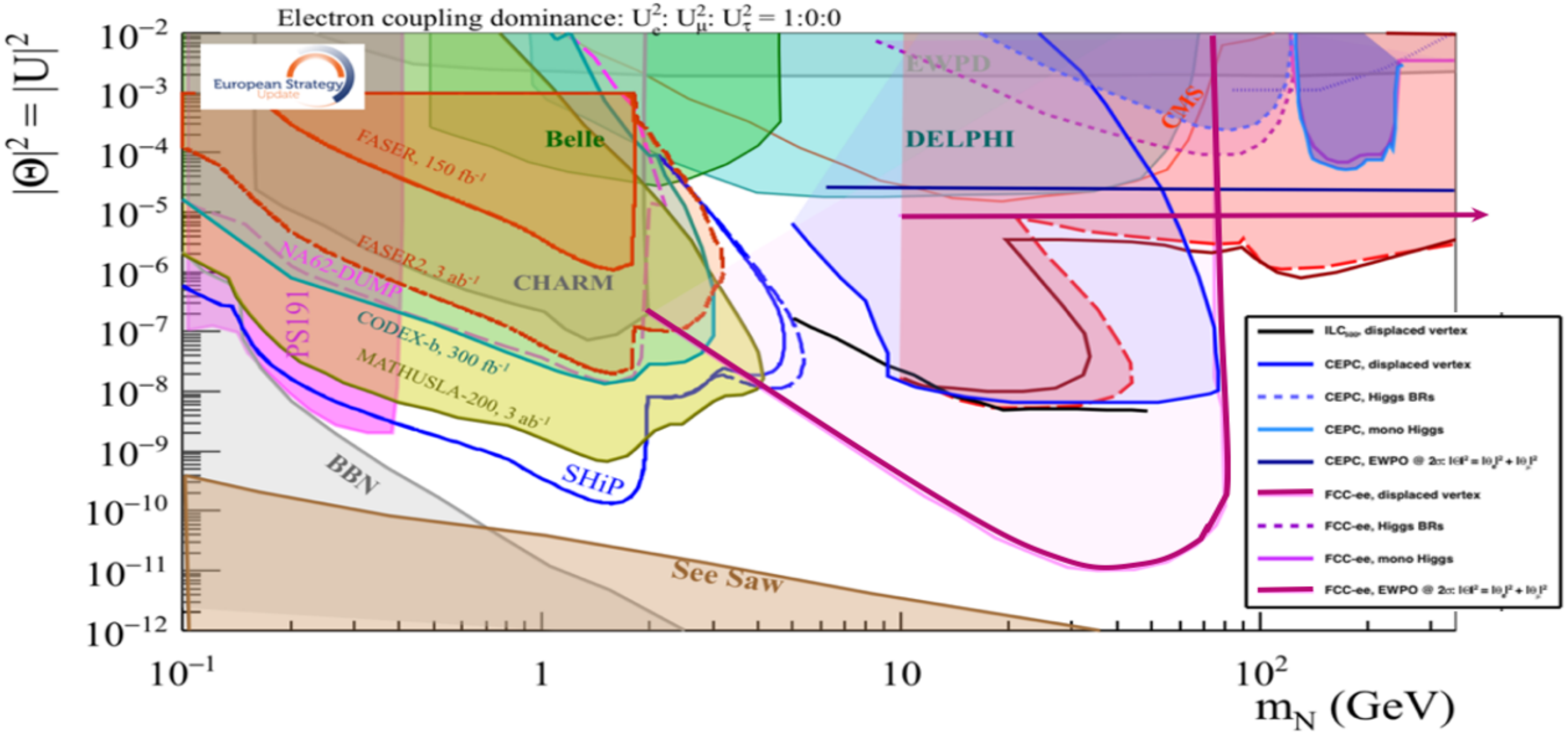


Sensitivity depends on

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



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



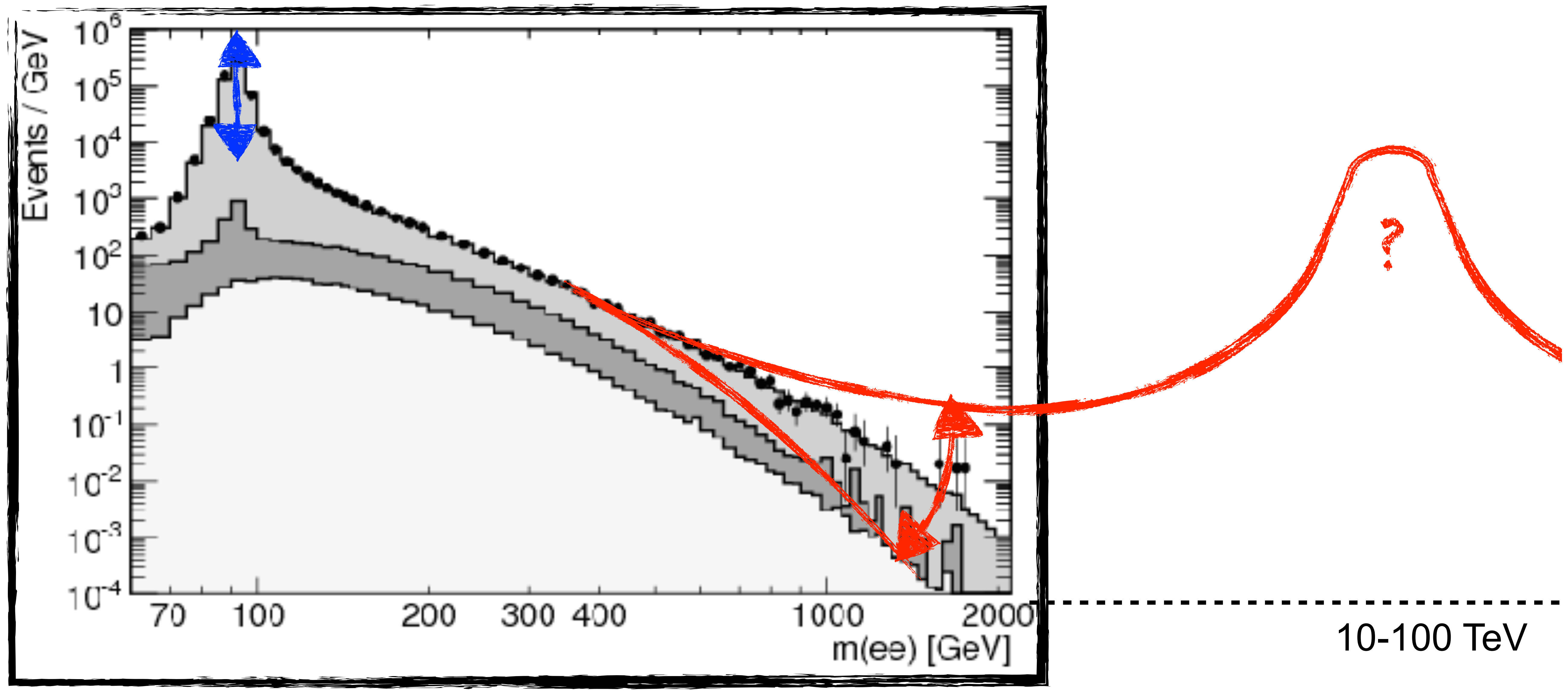
mass vs mixing² - unique phase space covered by FCC-ee

Into the Unknown

Indirect and direct exploration of the highest energy scales

Karlsruhe Institute of Technology

- Indirect probes with lepton colliders



For many generic models & new interactions:

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

➯ Sensitivity grows with s

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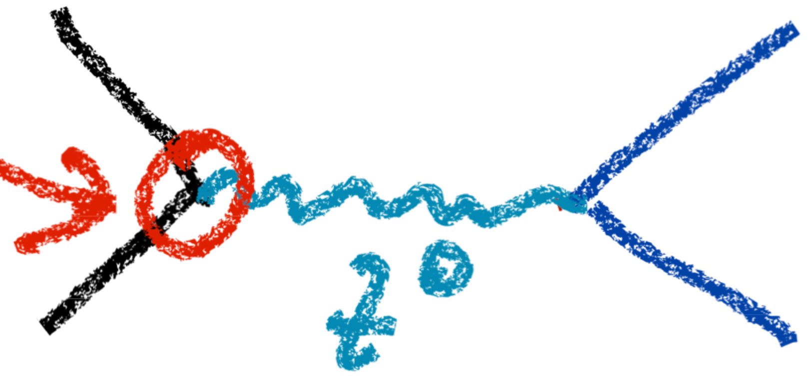
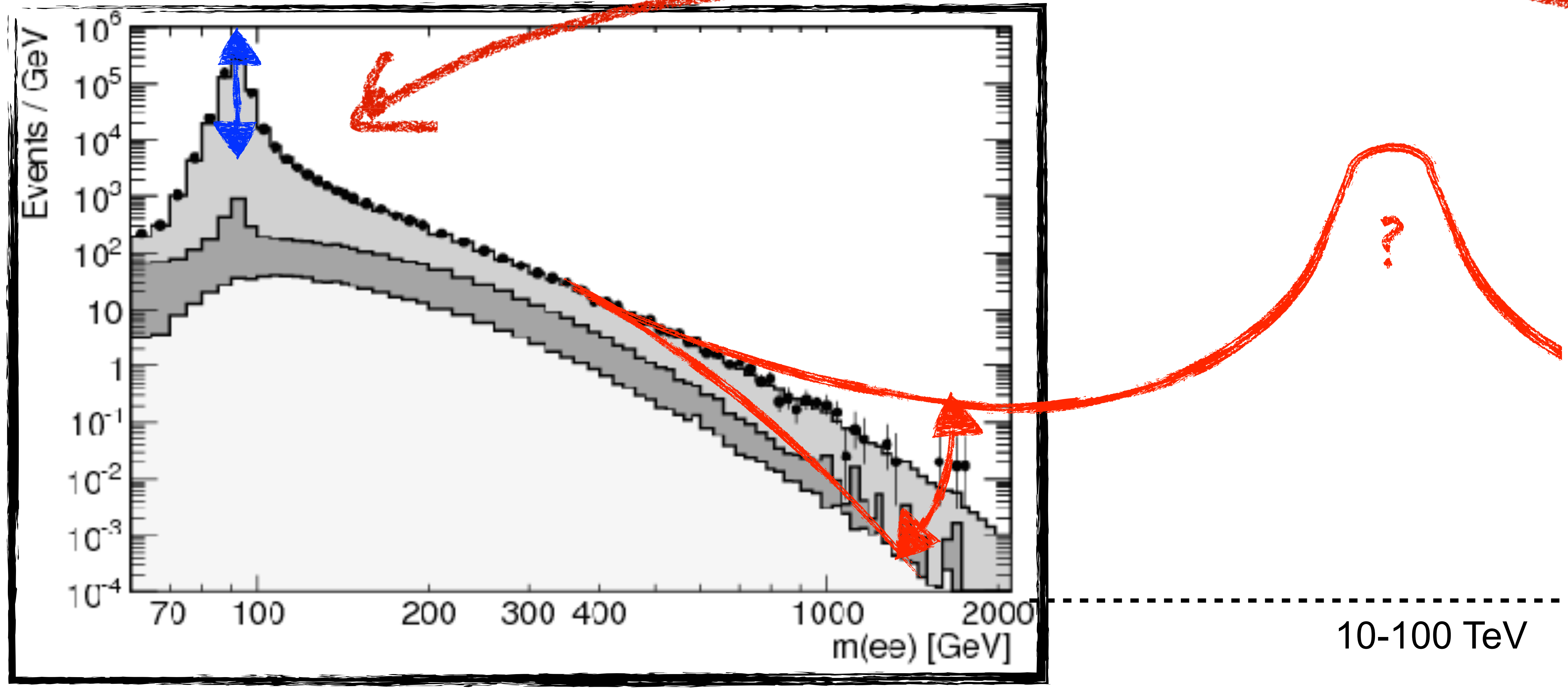
extreme precision with Z-pole programs

(and other measurements we talked about)





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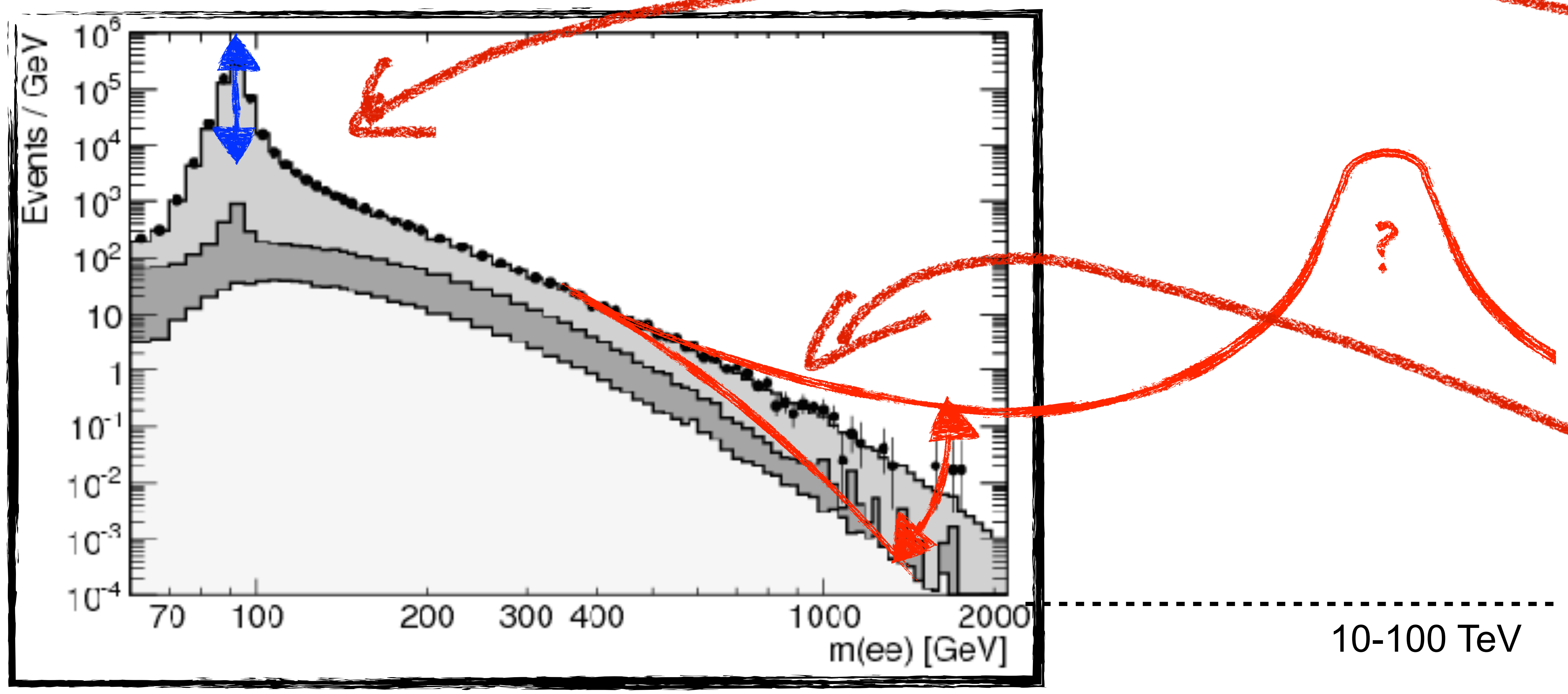

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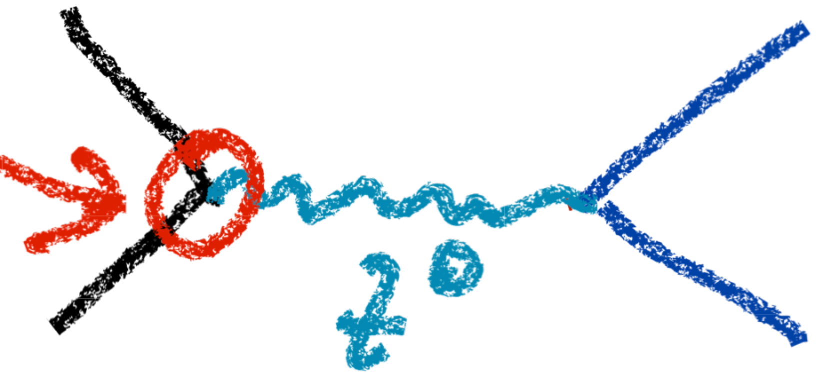
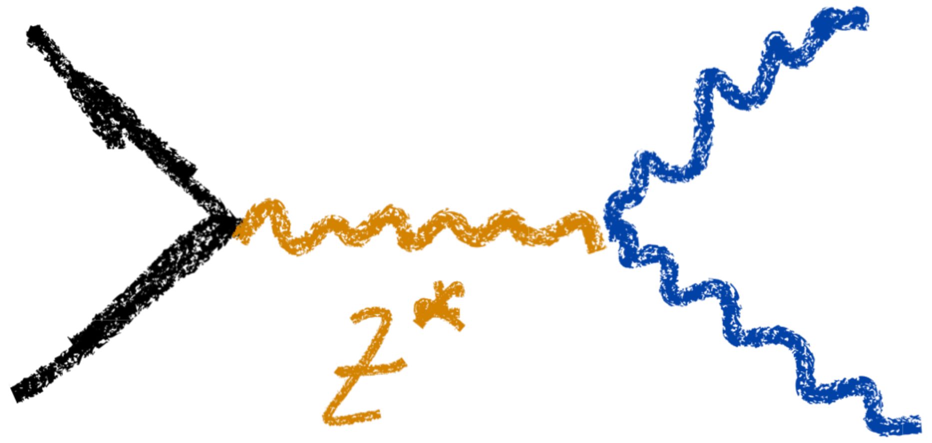


larger effects at higher energies



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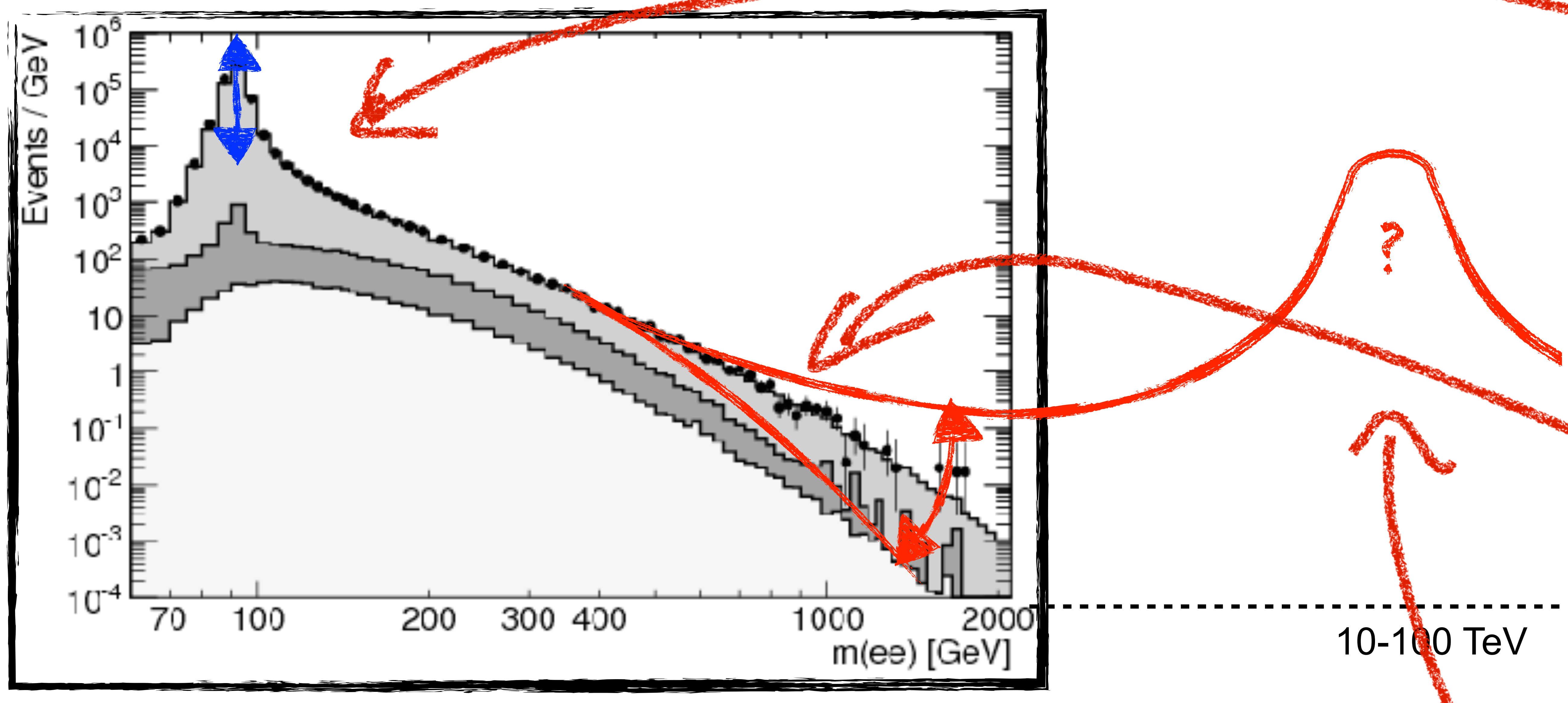

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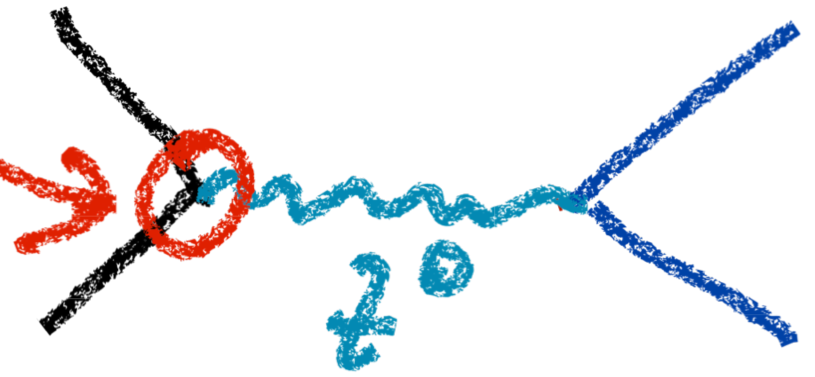
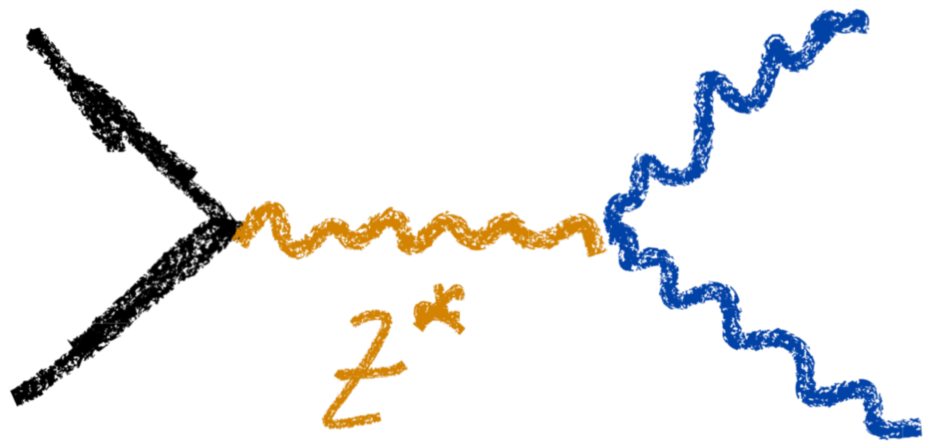


larger effects at higher energies



For many generic models & new interactions:

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

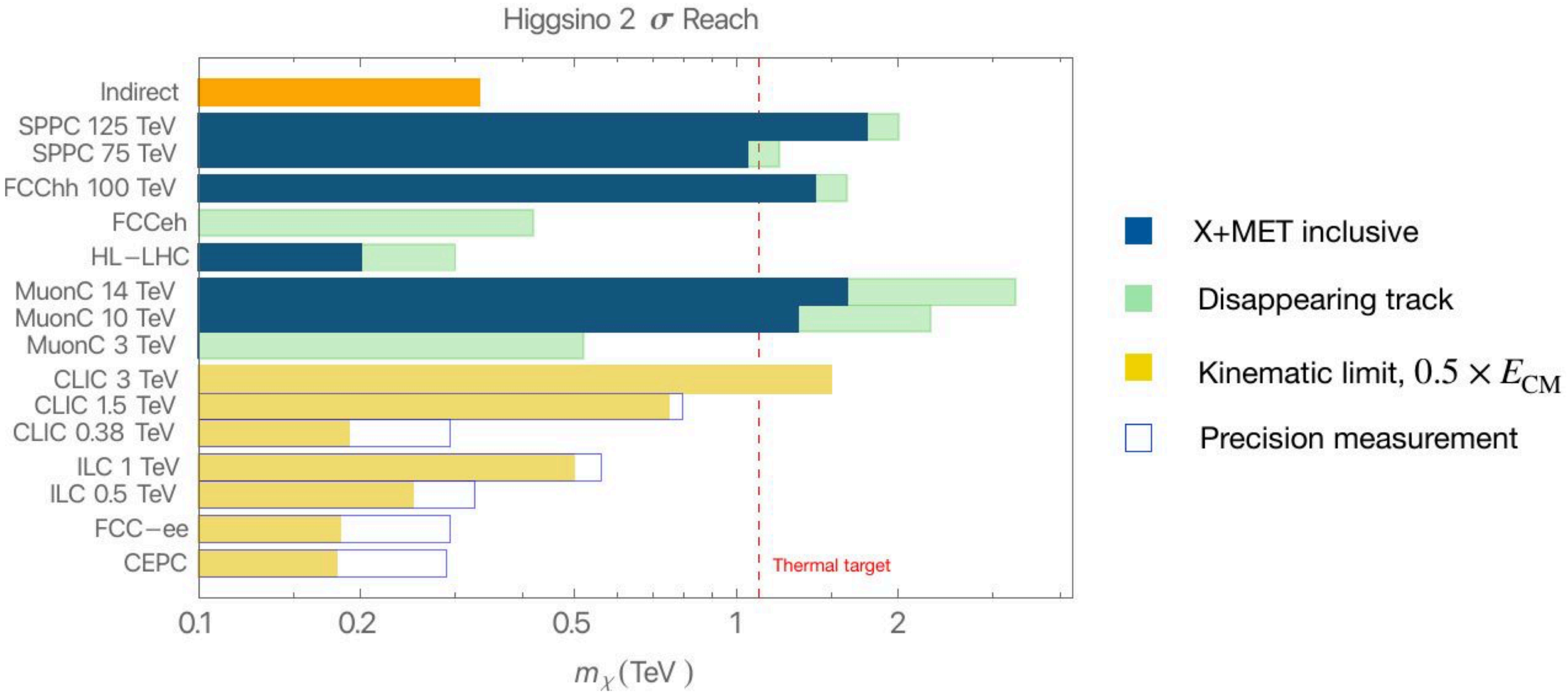
➯ Sensitivity grows with s

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

Sensitivity to High Scales

The Strength of CLIC and Muon Colliders

- Pushing limits on dark matter



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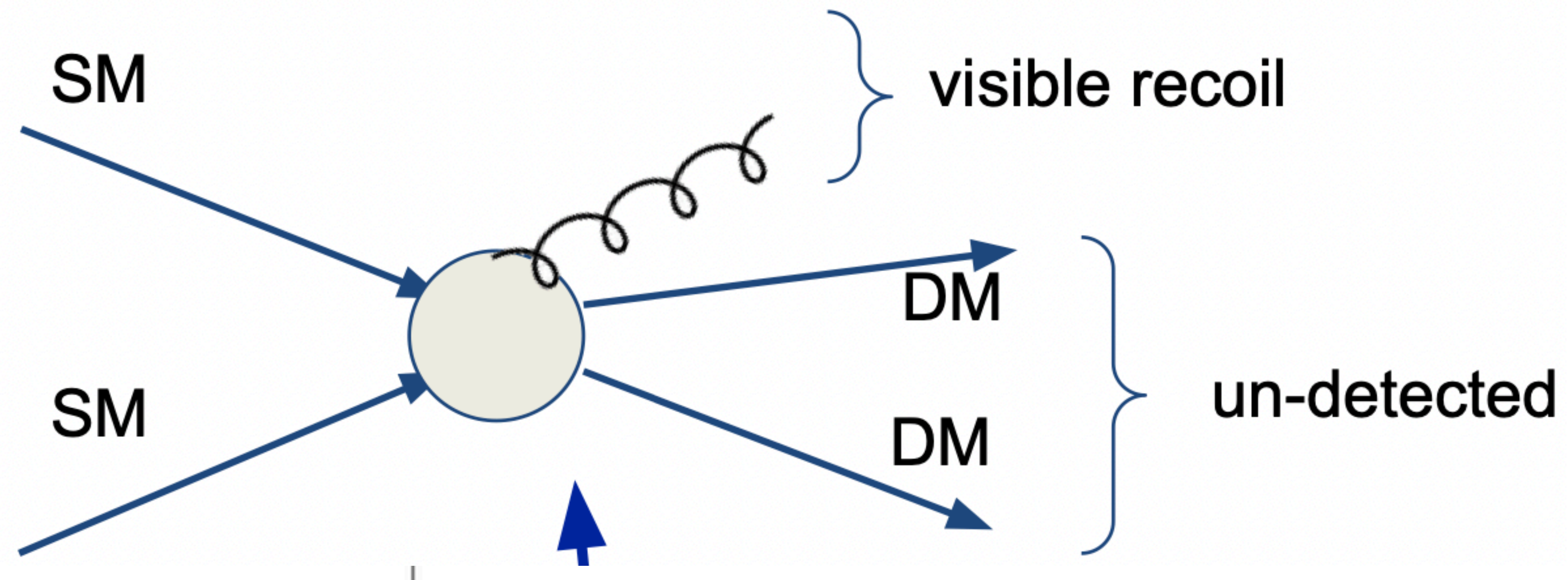

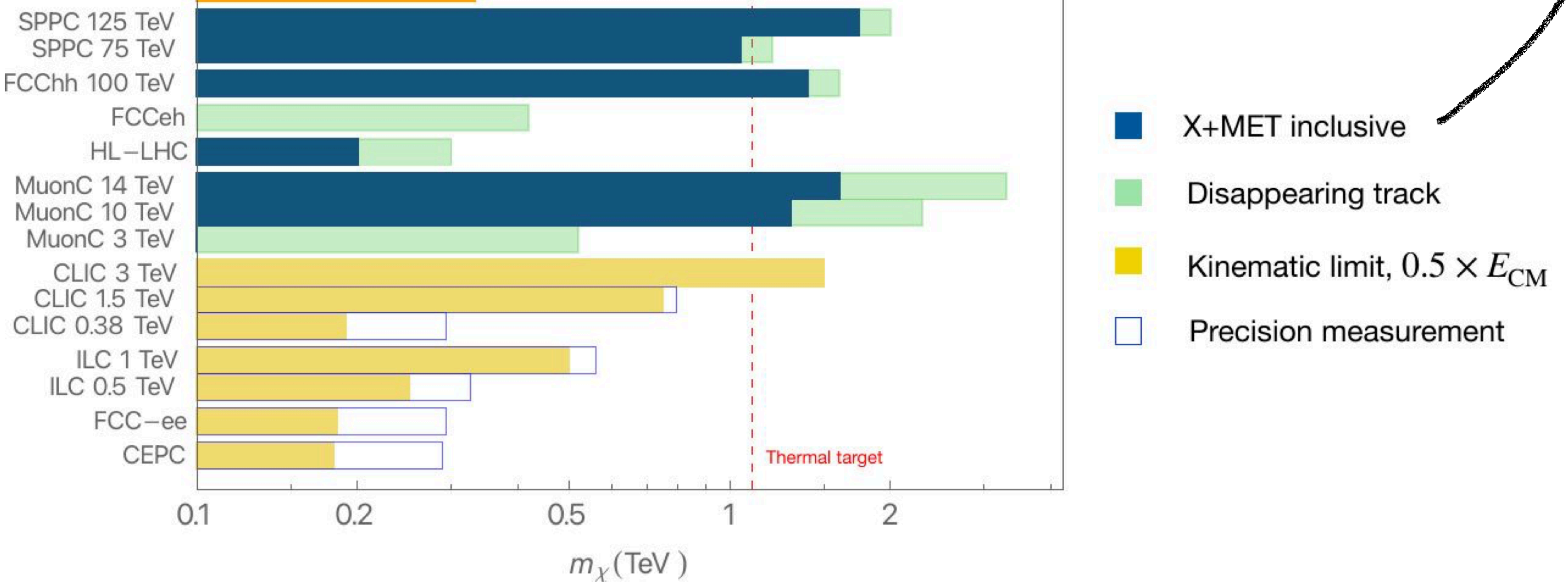

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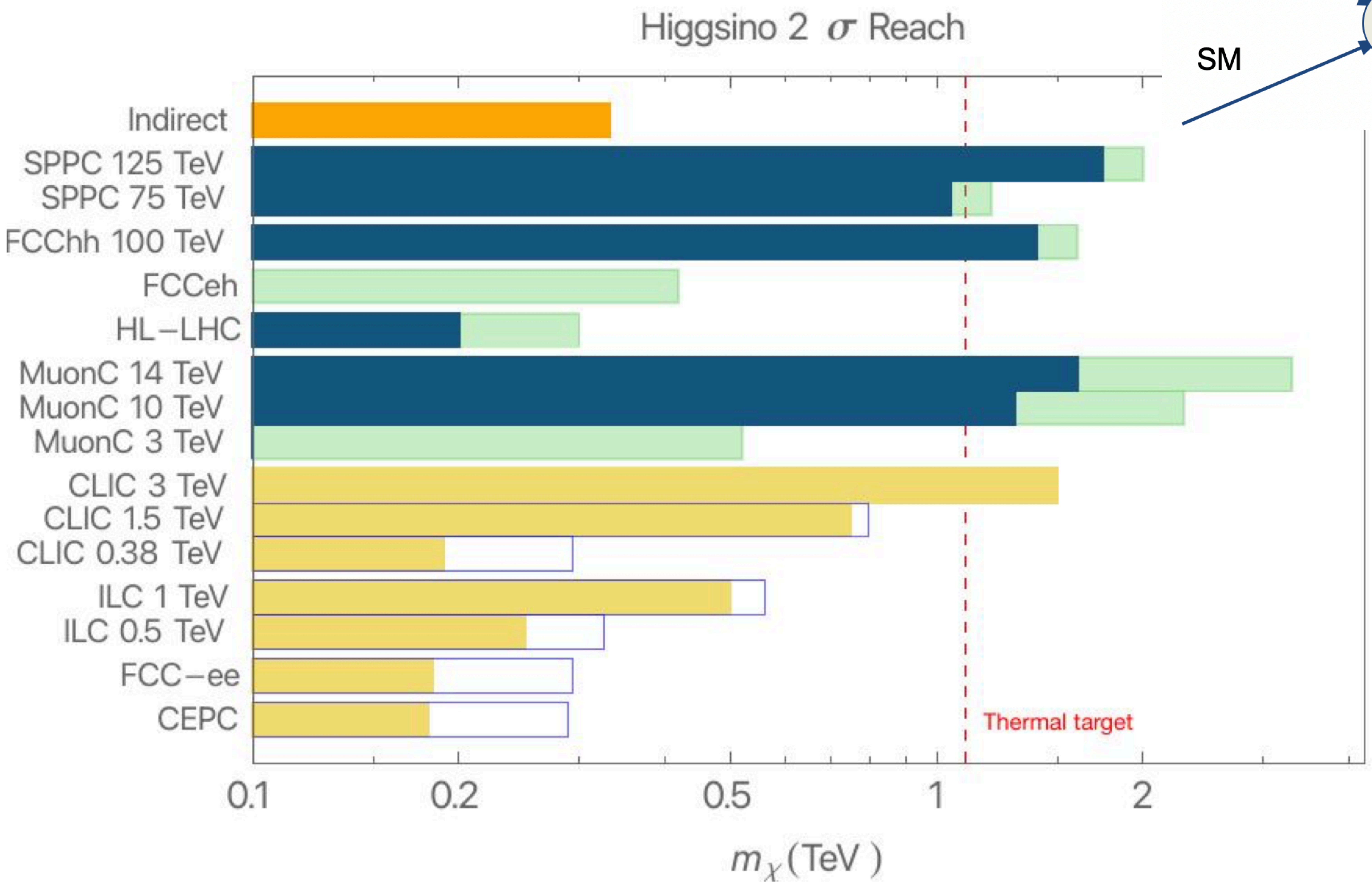
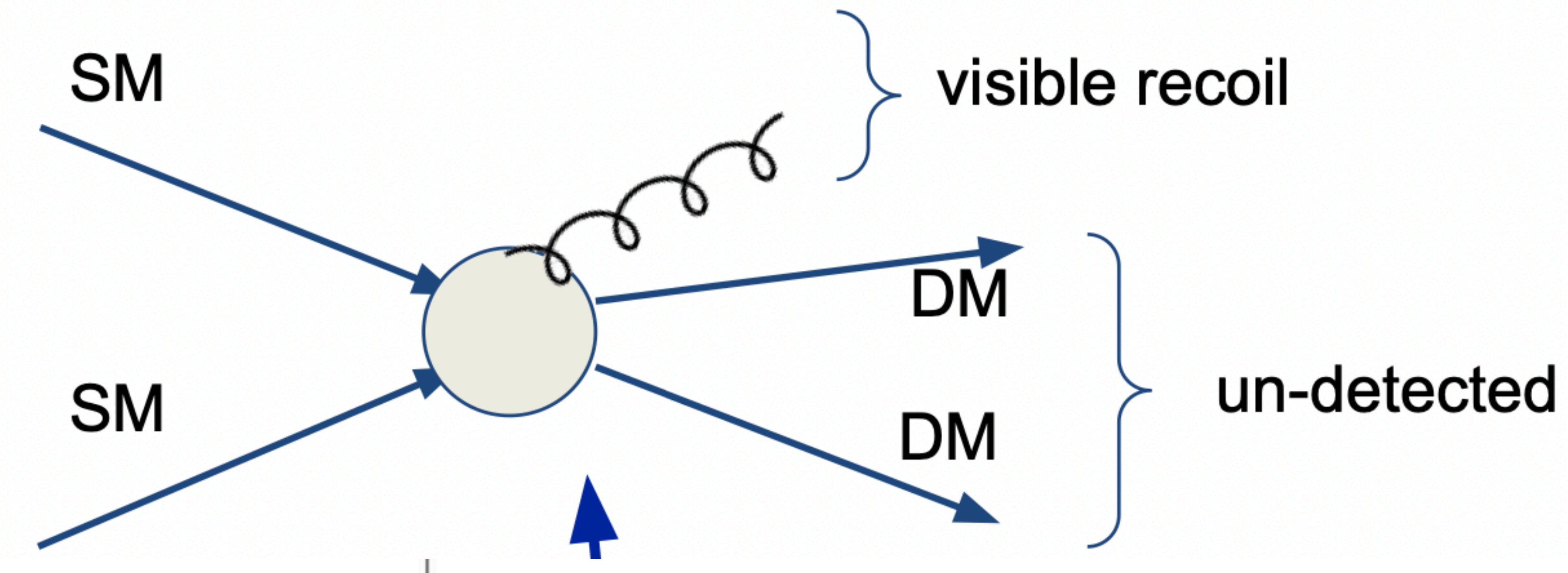


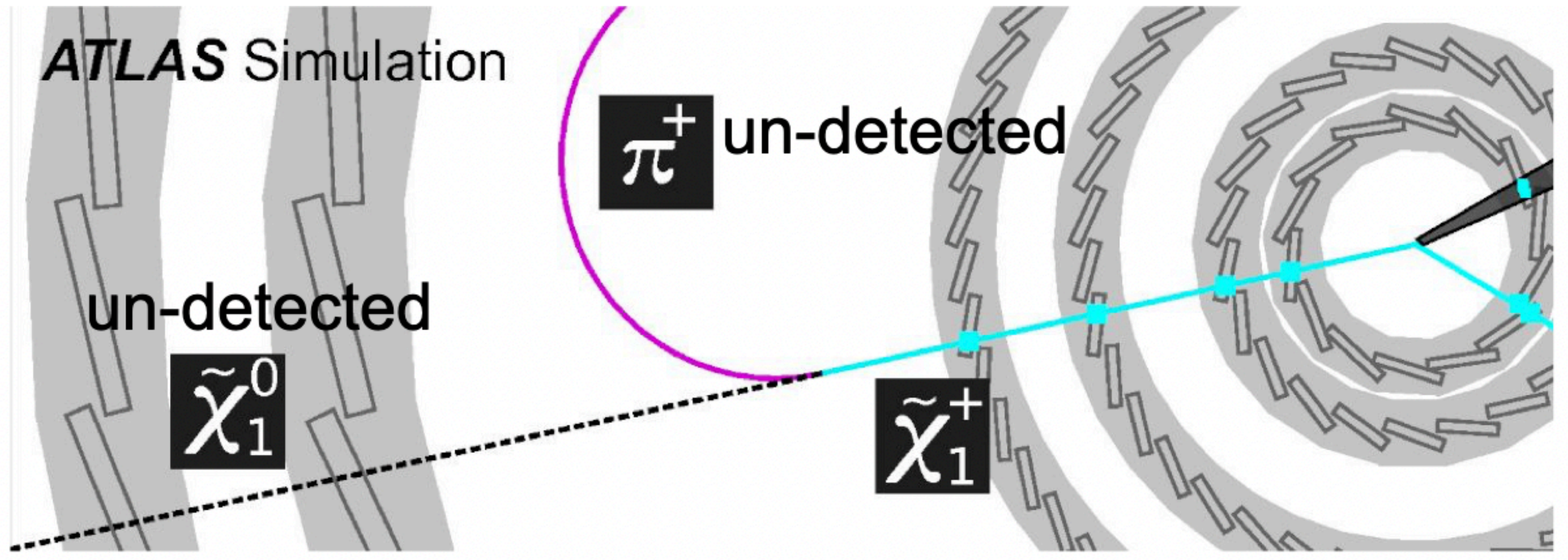


X+MET inclusive

Disappearing track

Kinematic limit, $0.5 \times E_{CM}$

Precision measurement



Sensitivity to High Scales

The Strength of CLIC and Muon Colliders

- Discovery potential for new particles - SUSY as an example

Lepton colliders: Full collision energy available for new particles -> Sensitivity up to kinematic limit.

Conclusions

Wrapping up

Compelling Scientific Opportunities

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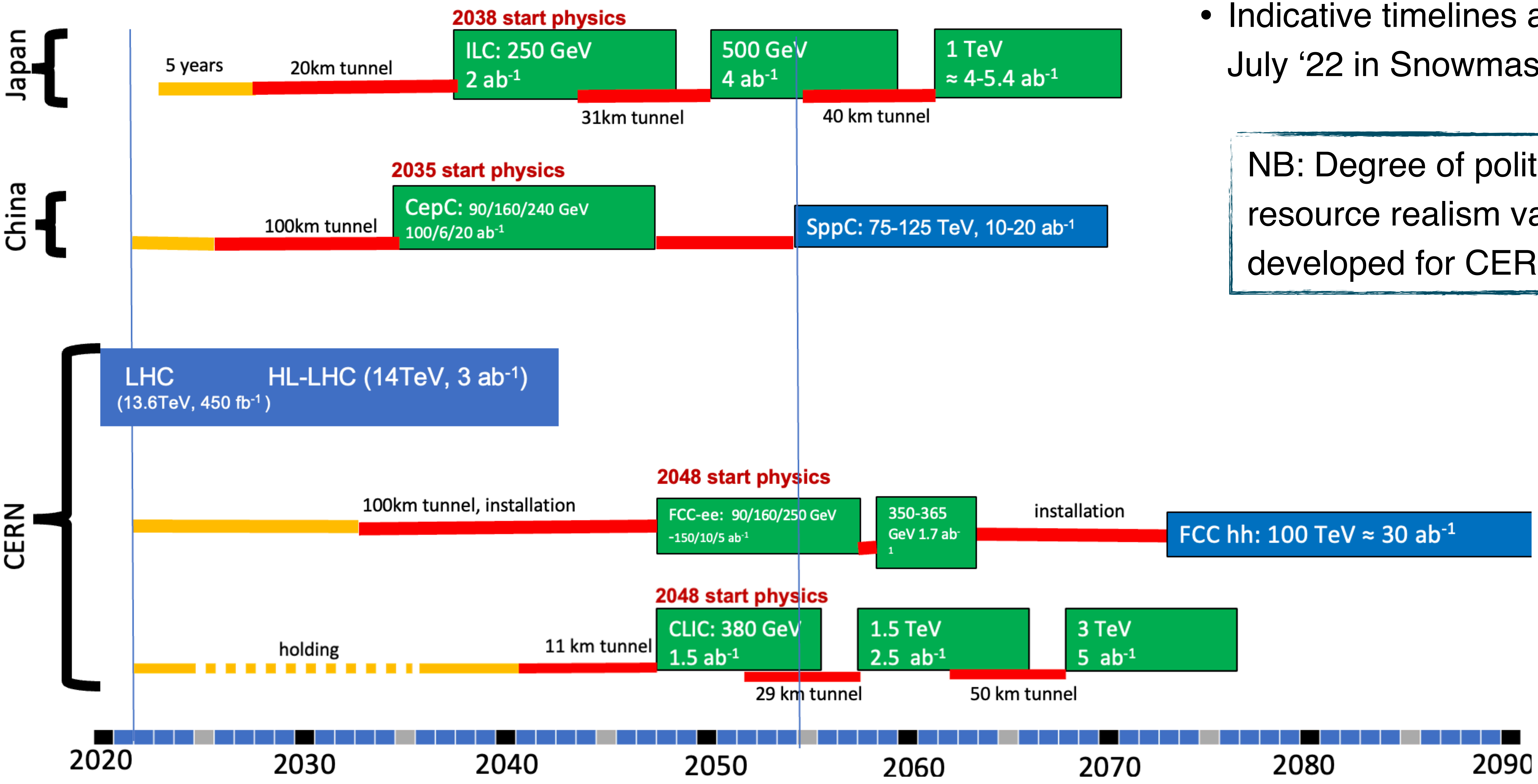
CERN is currently studying the feasibility of the **Future Circular Collider**:

- 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 last year's Snowmass Meeting



- Indicative timelines as discussed July '22 in Snowmass @ Seattle

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

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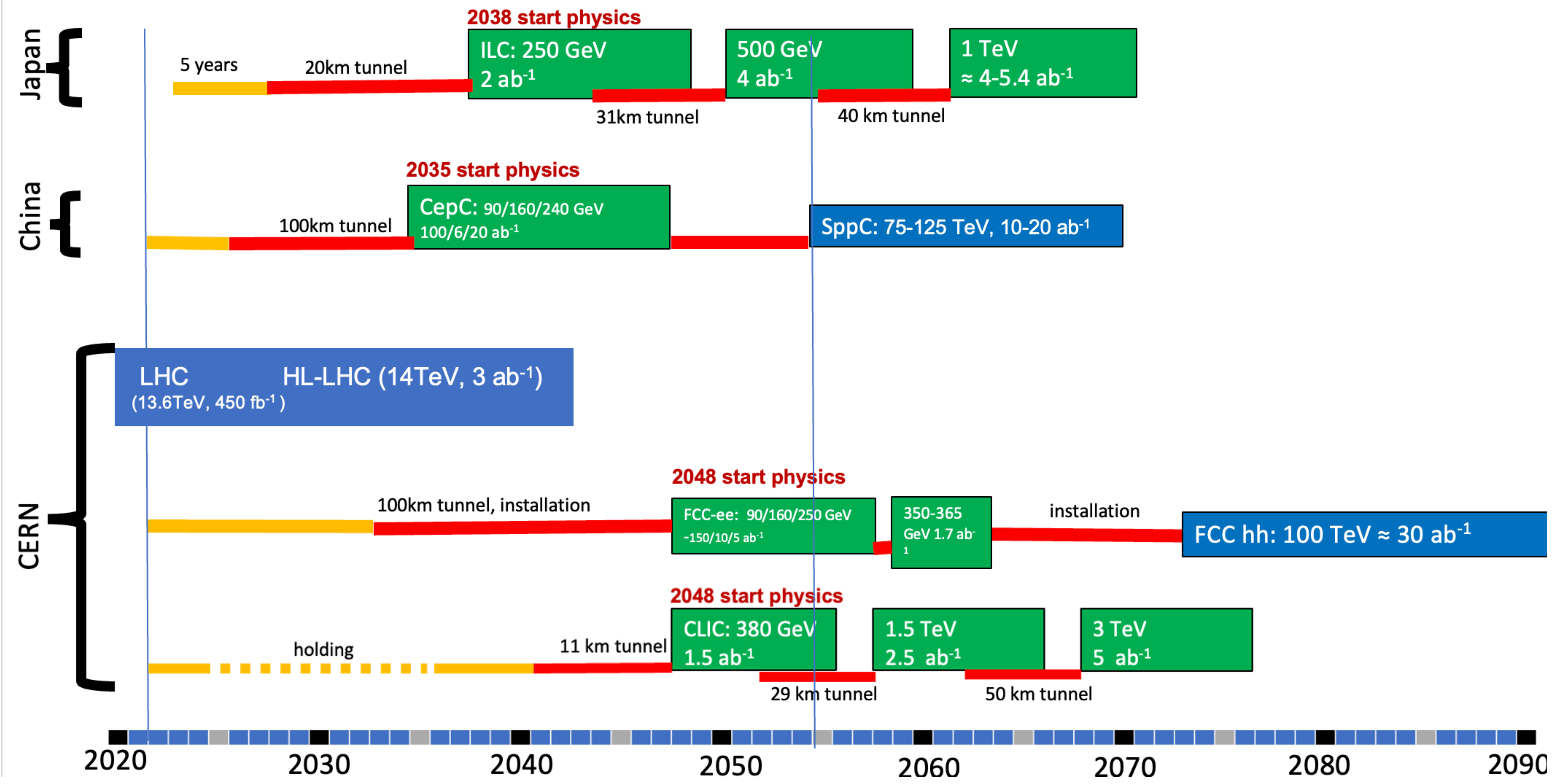

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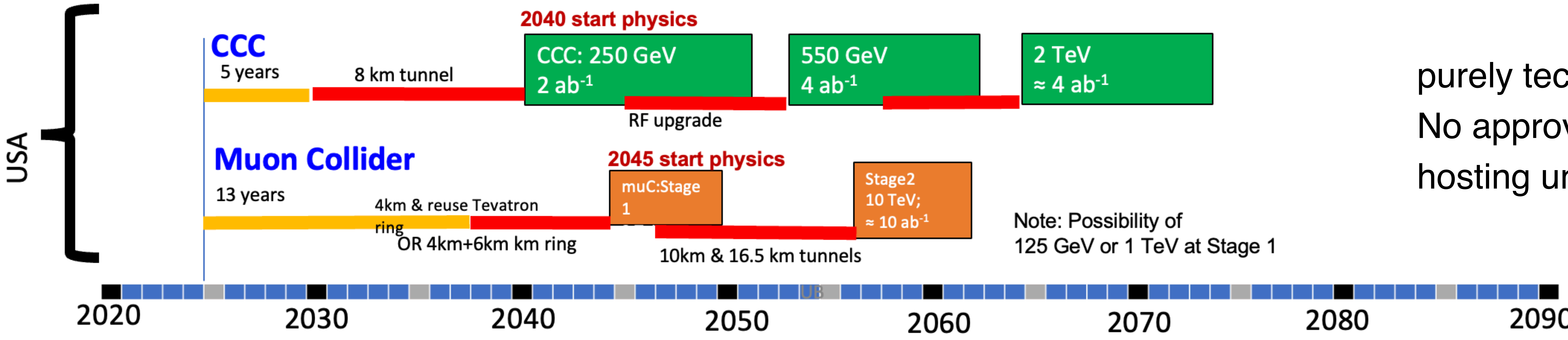
Proposals emerging from this Snowmass for a US based collider



purely technical!

No approval process yet, hosting unclear

Final Words

Karlsruhe Institute of Technology

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!

Extras Lecture 2

FCC-ee Time Line to Physics

Making a new facility happen