Higgs Physics at Future Lepton Colliders

- with a slight emphasis on ILC -

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Max-Planck-Institute for Physics

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

- Higgs Production at Lepton Colliders
- Collider Options: Linear, Circular
- Higgs Measurements at e^+e^- Colliders: A Few Examples
- Interpretations: Fits, model discrimination & discovery

Will only discuss ***e^+e^- colliders***

[μ colliders provide the possibility for s-channel production (+ the same processes as e^+e^-), but are still (very) far off the real axis]

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A word on numbers:

Projected precisions in flux at present, with ongoing work towards the Update of the European Strategy for Particle Physics. Comparisons between different projects are highly non-trivial, and are not attempted here. In general:

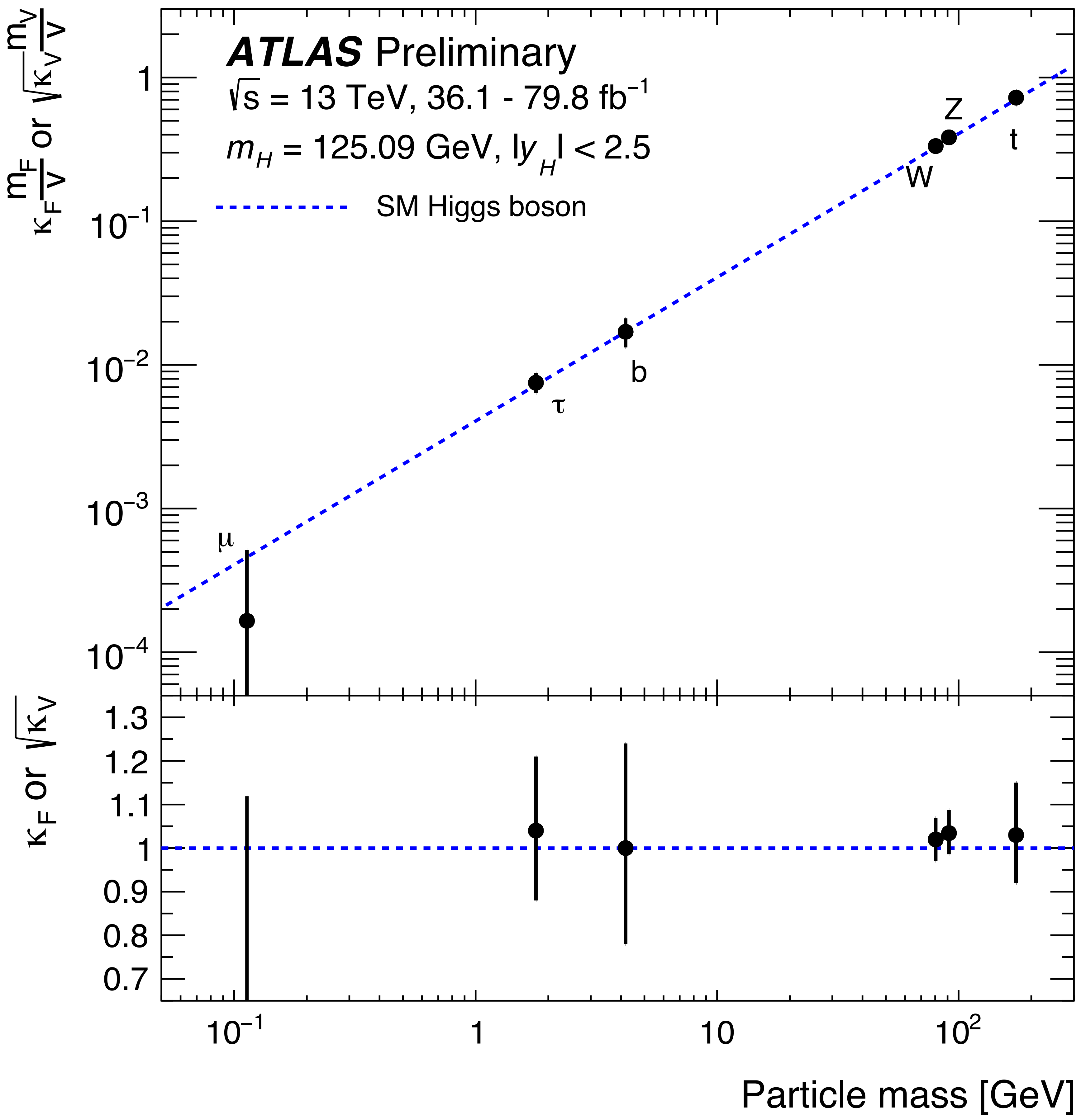
Linear Colliders: ILC & CLIC based on full simulations with realistic detector models, complete background and signal samples, uncheated reconstruction, event selection and analysis

Circular Colliders: FCCee using fast simulations and parametrized studies, CEPC full detector simulations with partial samples

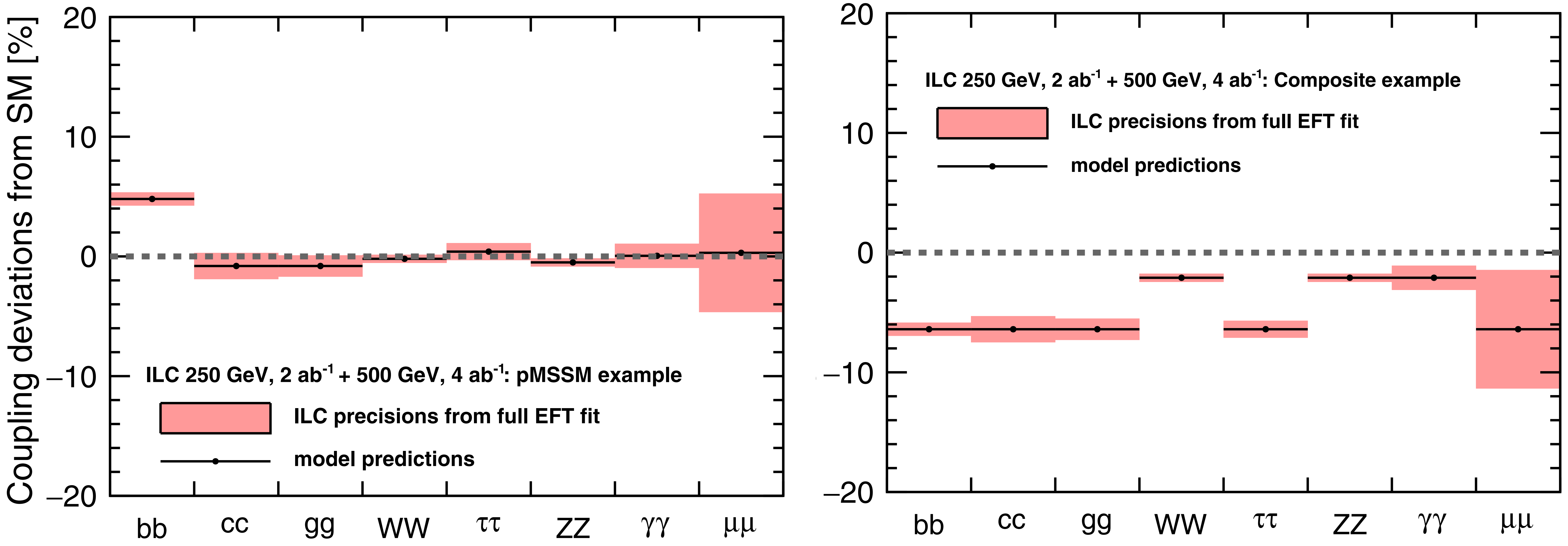
Motivation: Pushing the SM beyond its Breaking Point

Finding New Physics in the Higgs Sector

- The Standard Model makes unambiguous predictions about the couplings of the Higgs Boson, which are modified in many BSM models



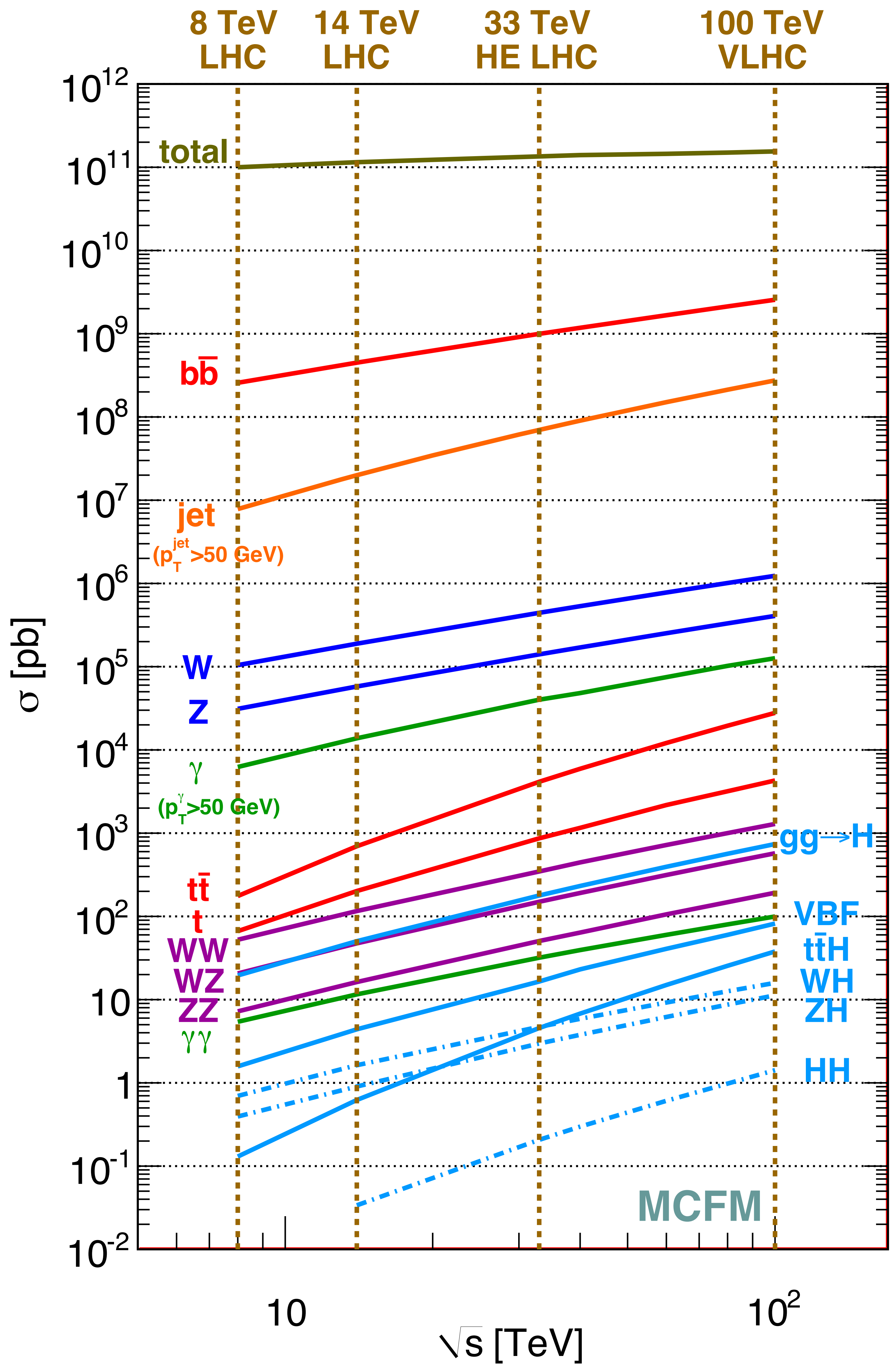
Examples from PRD 97, 053003 (2018)



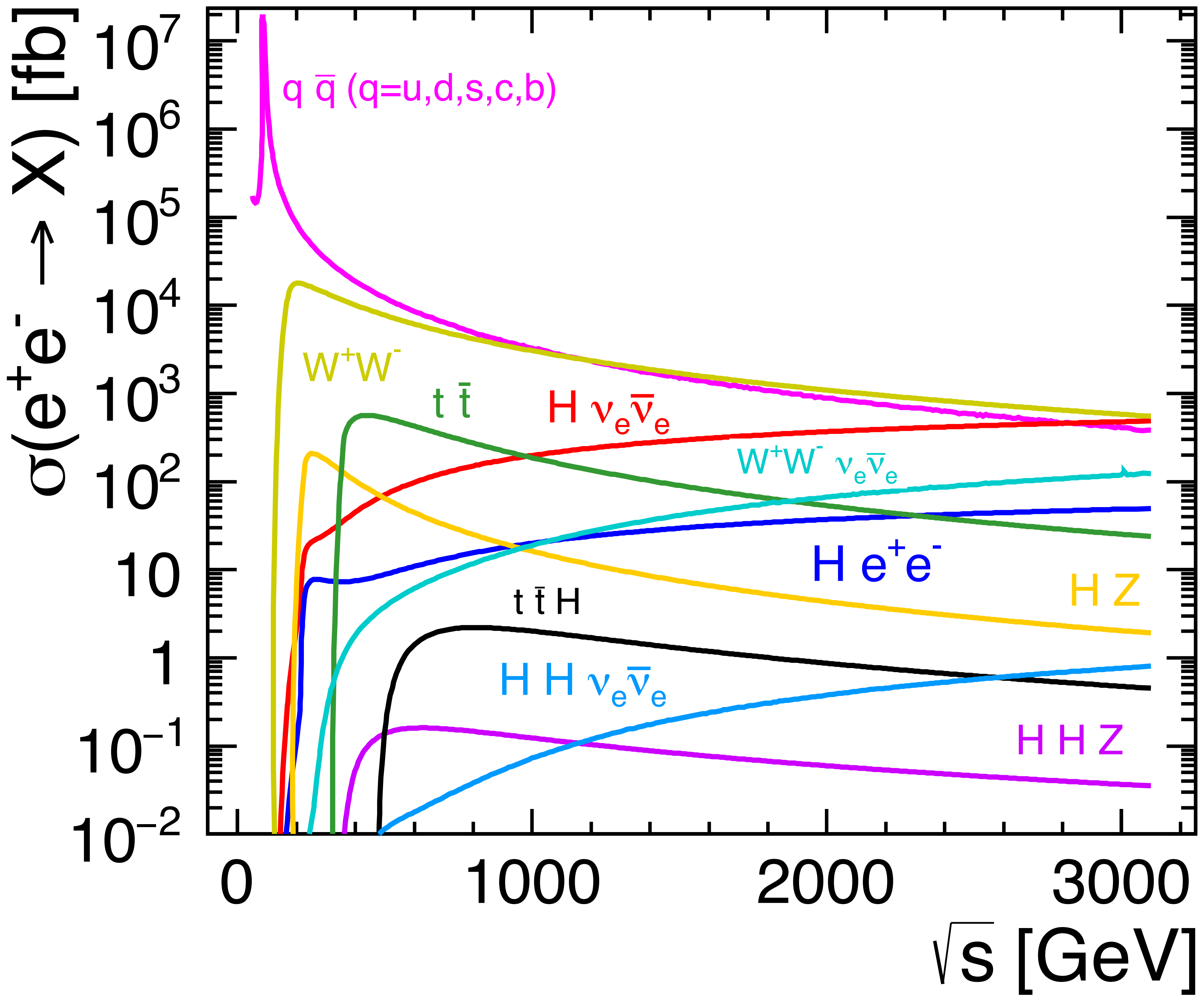
➩ %-level precision provides substantial discovery potential - how can this be achieved?

Lepton vs Hadron Colliders

A Question of Backgrounds



~ 9 orders of magnitude

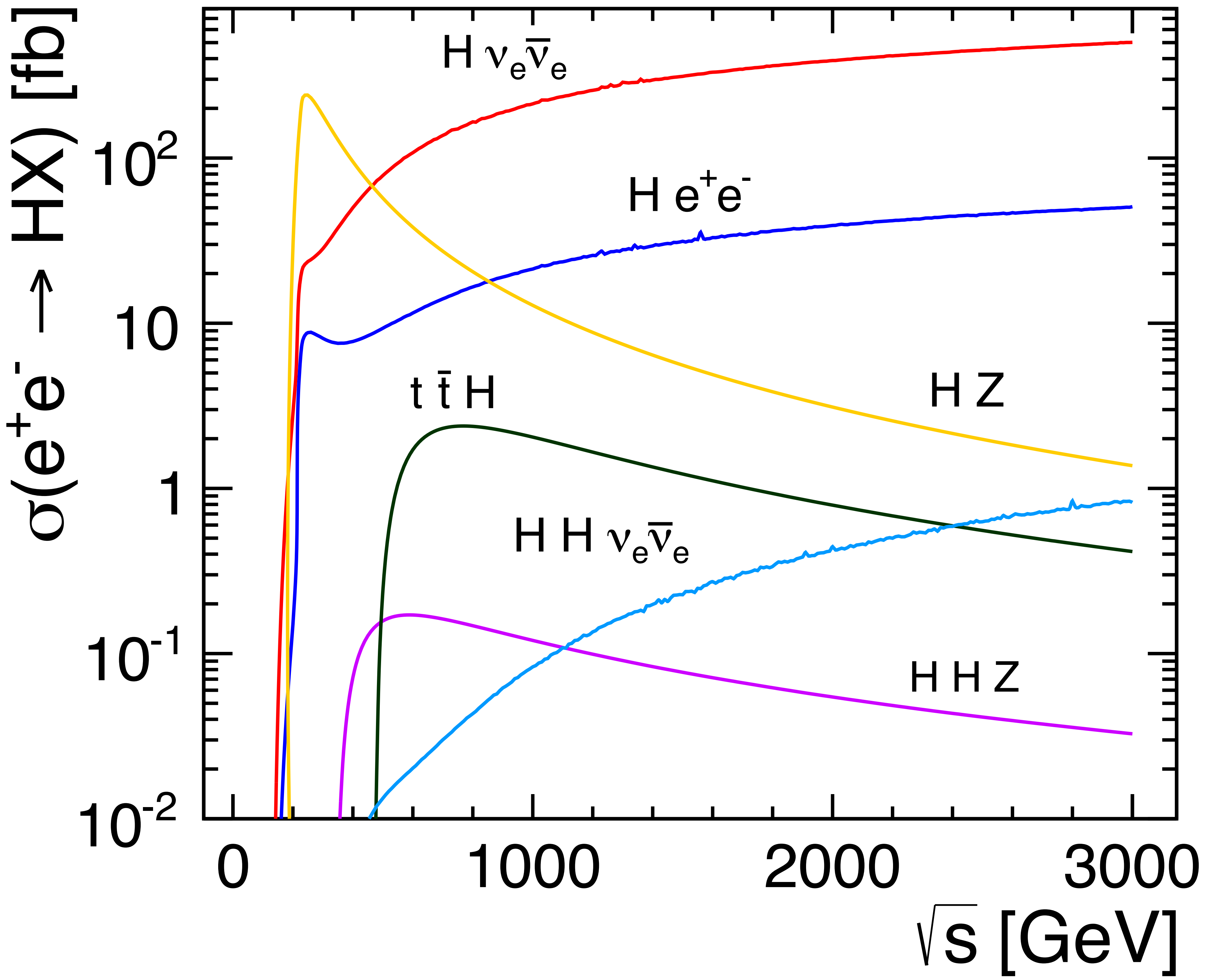


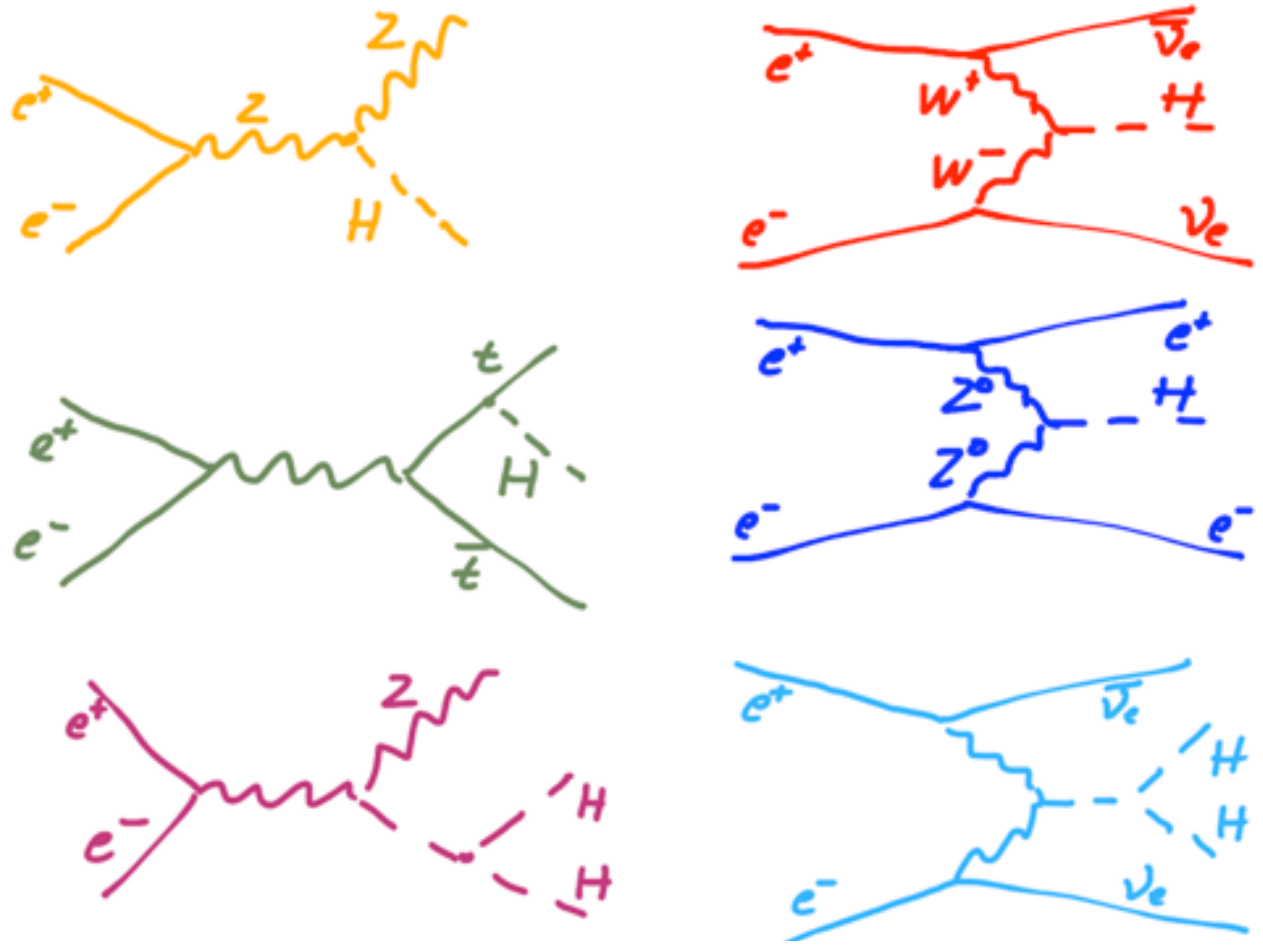
~ 2 orders of magnitude

- Higher cross section for Higgs production in pp (by ~ 2 orders of magnitude), but: very high background 10^9 x higher cross section
- In e^+e^-: background processes ~ 100 (or less) x higher cross section: high signal purity and efficiency possible

Higgs Production in e^+e^- Collisions

Evolution of Cross Sections with Energy





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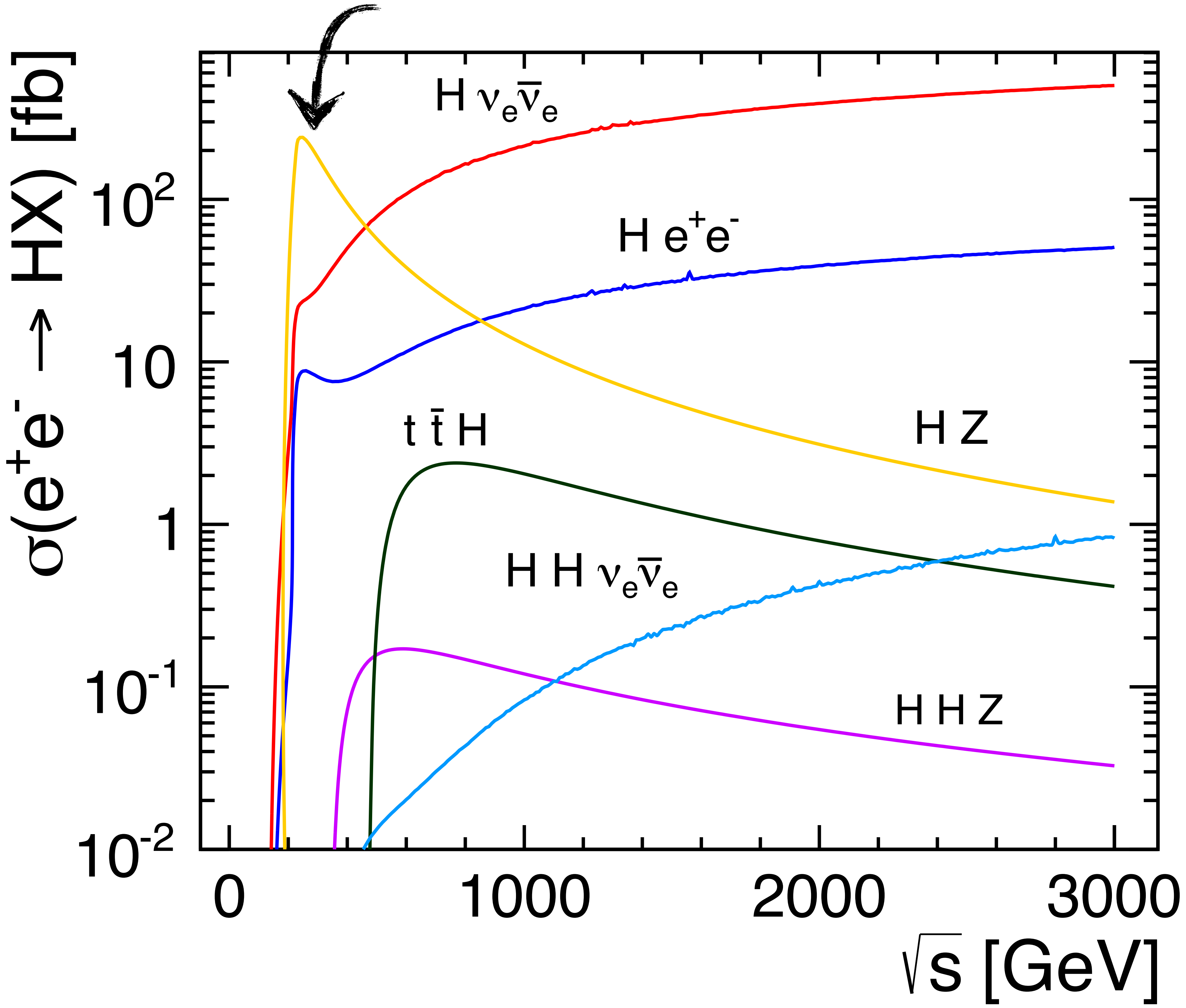

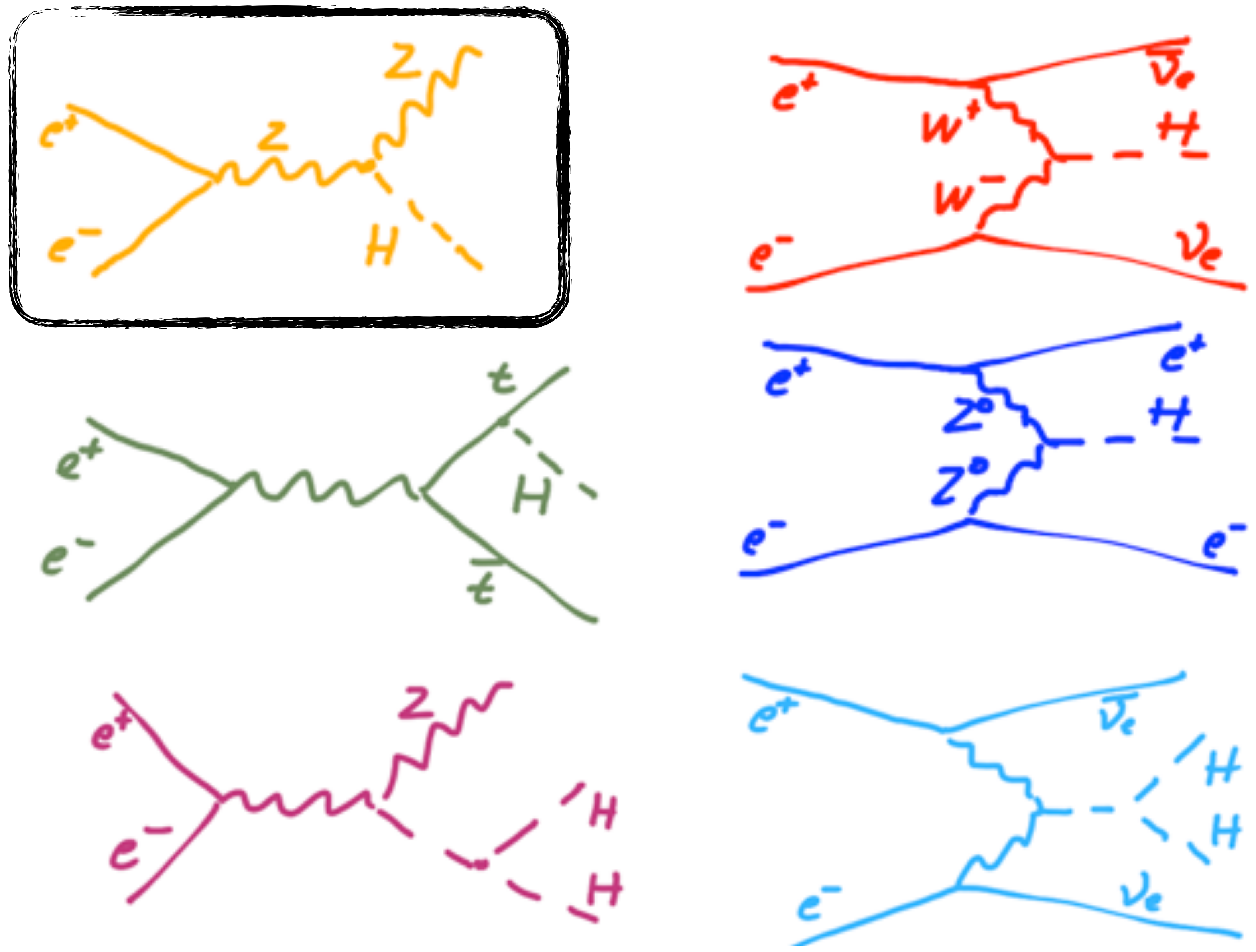

250 GeV:

Maximum of ZH production

Higgs Production in e+e- Collisions

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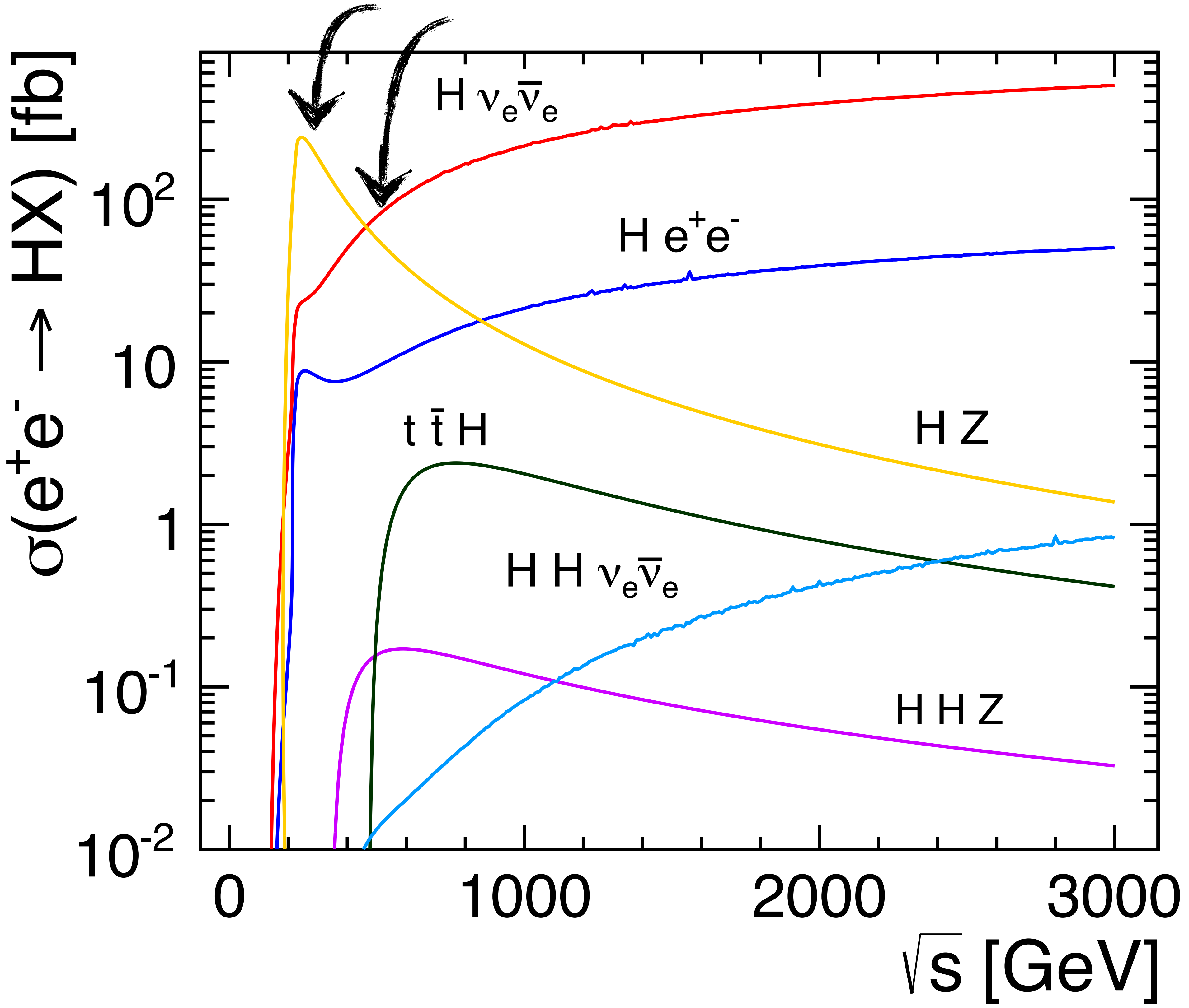

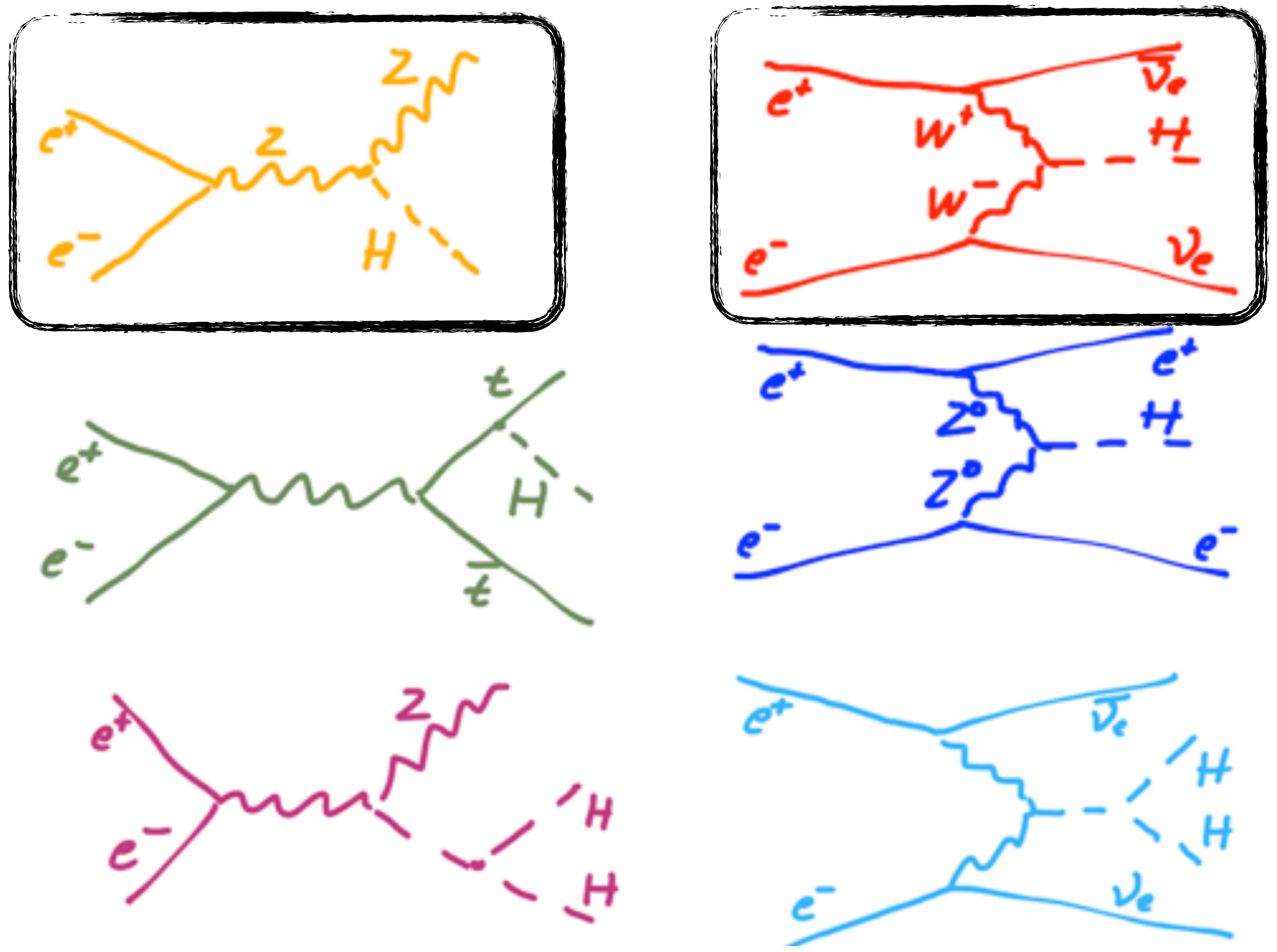

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(and top pair production)

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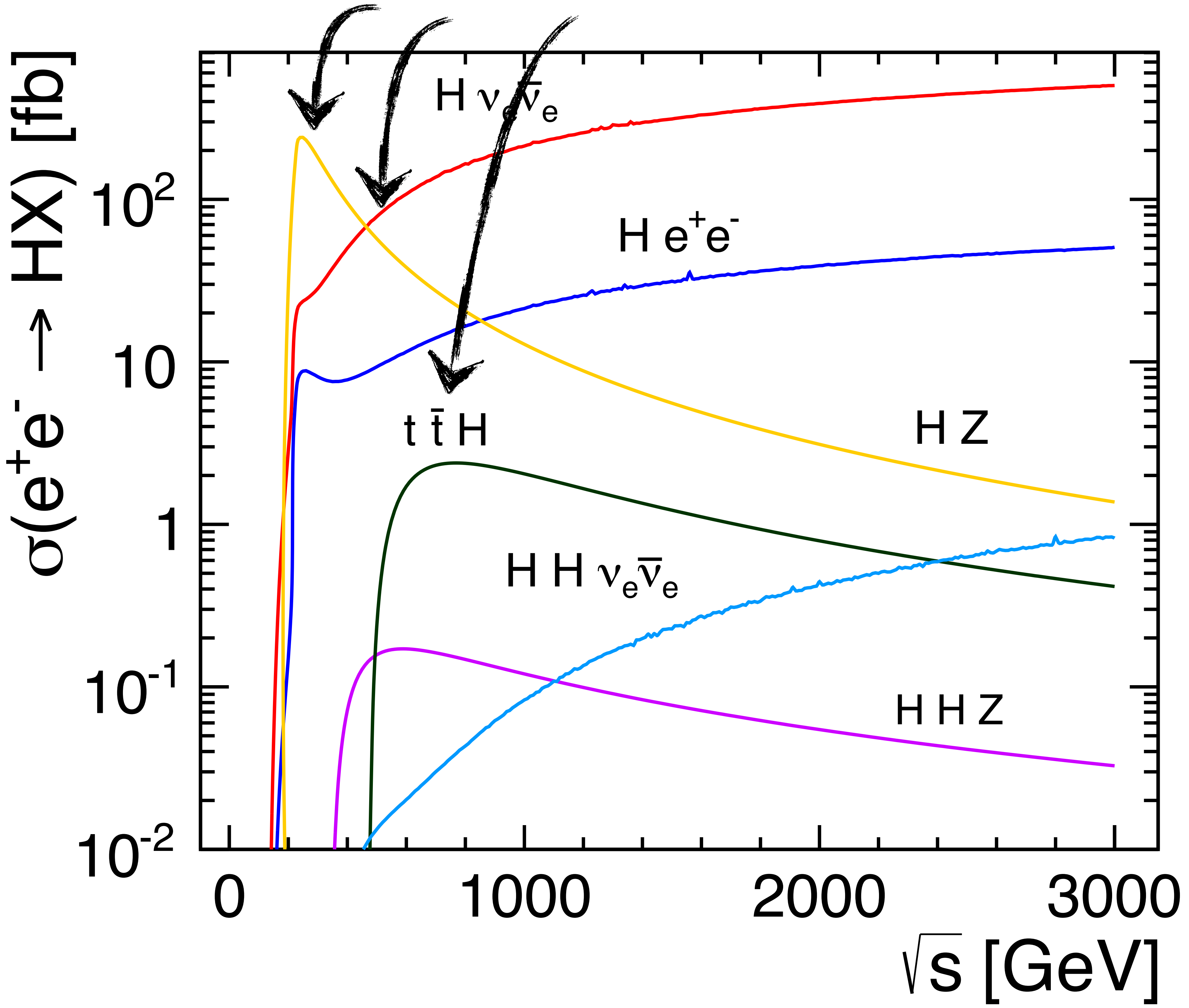

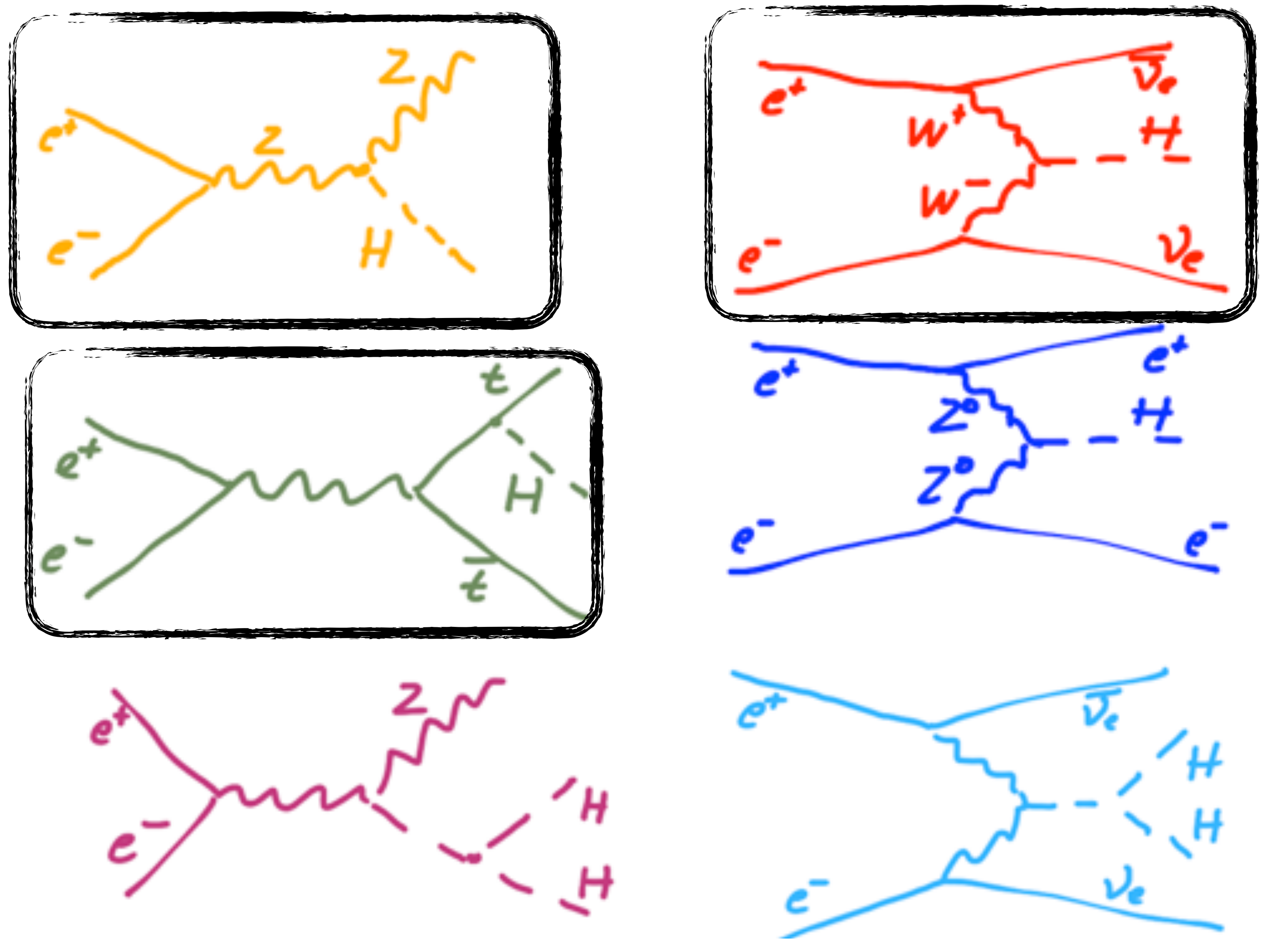

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ttH: direct access to top Yukawa coupling

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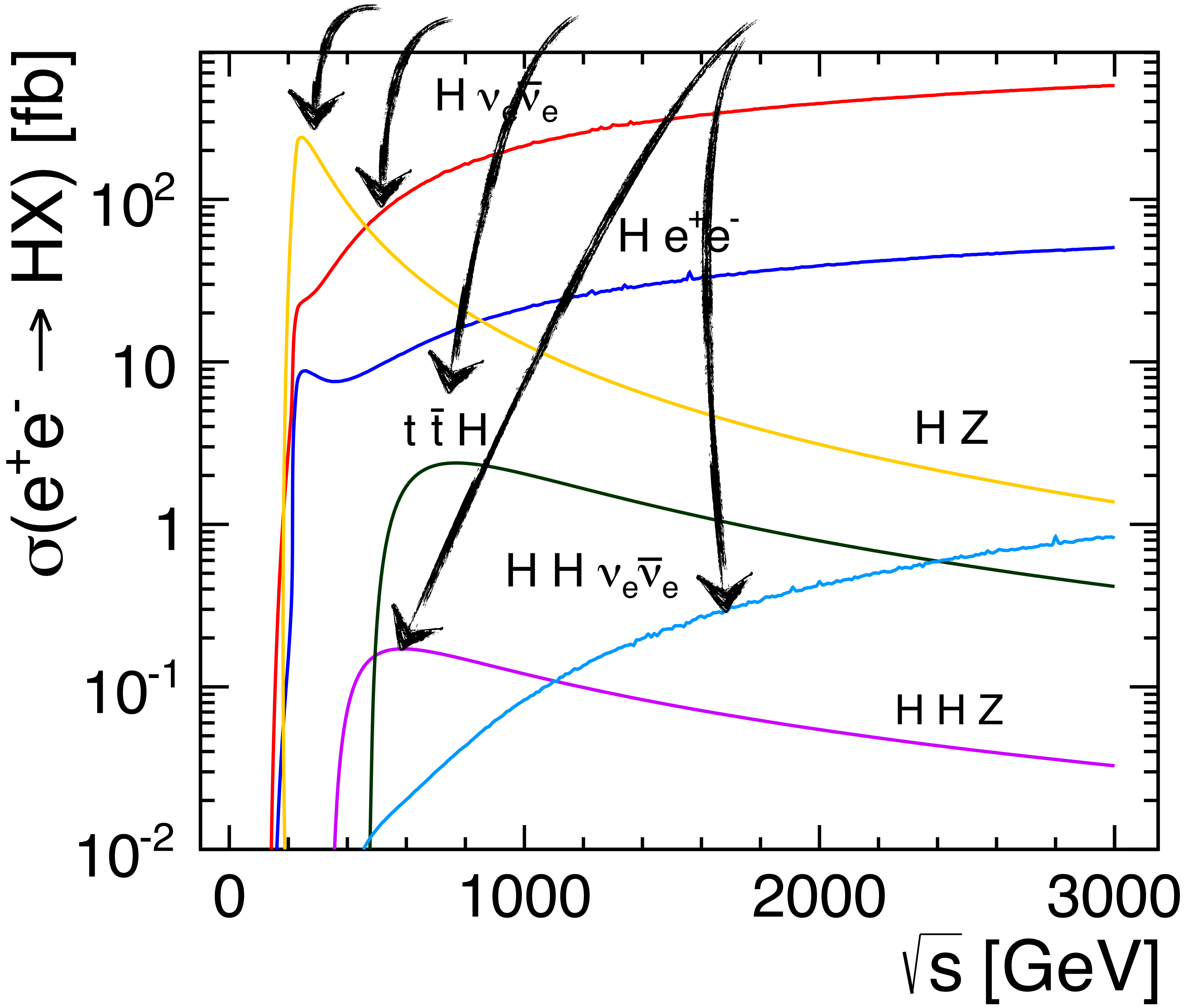

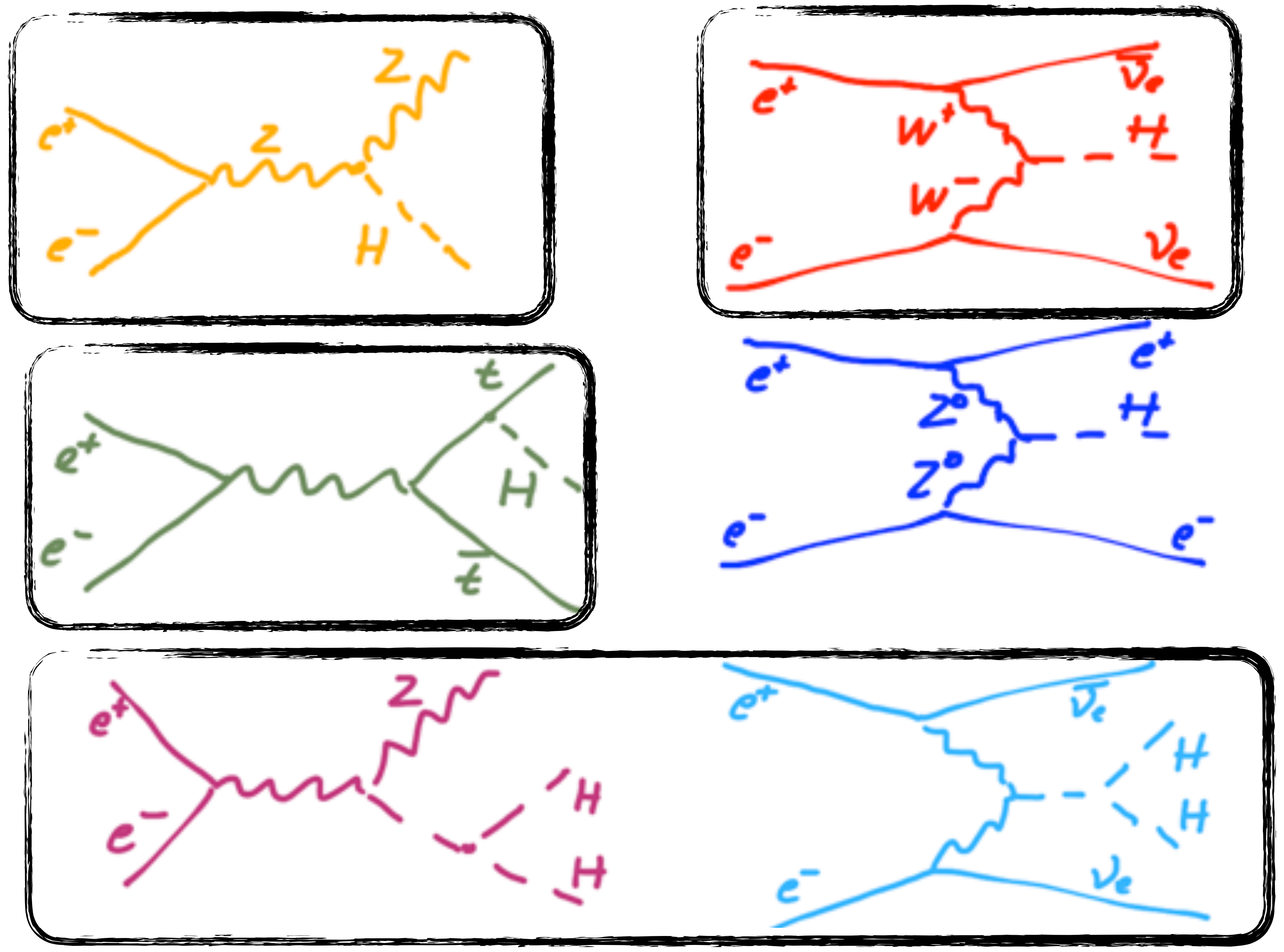

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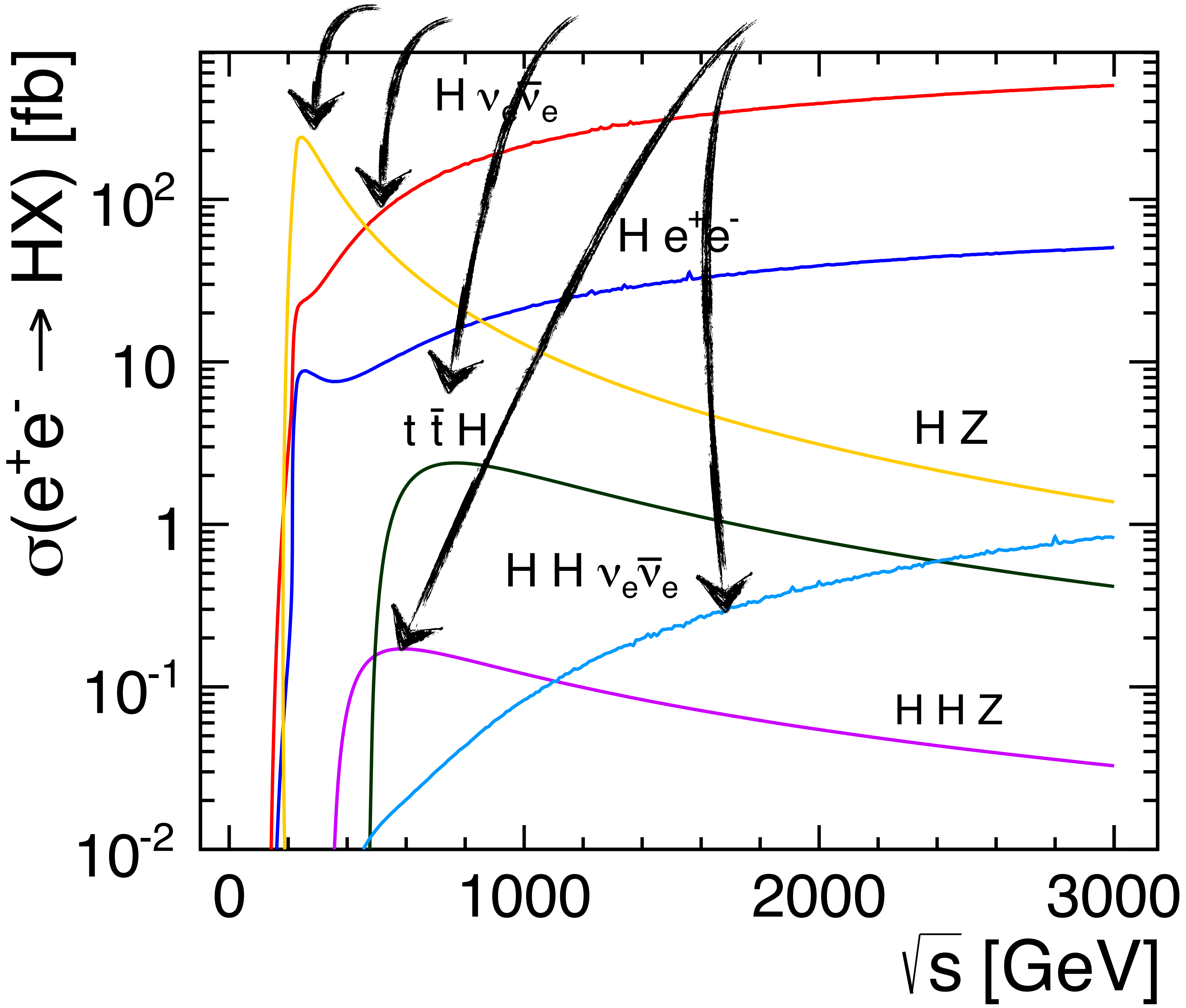

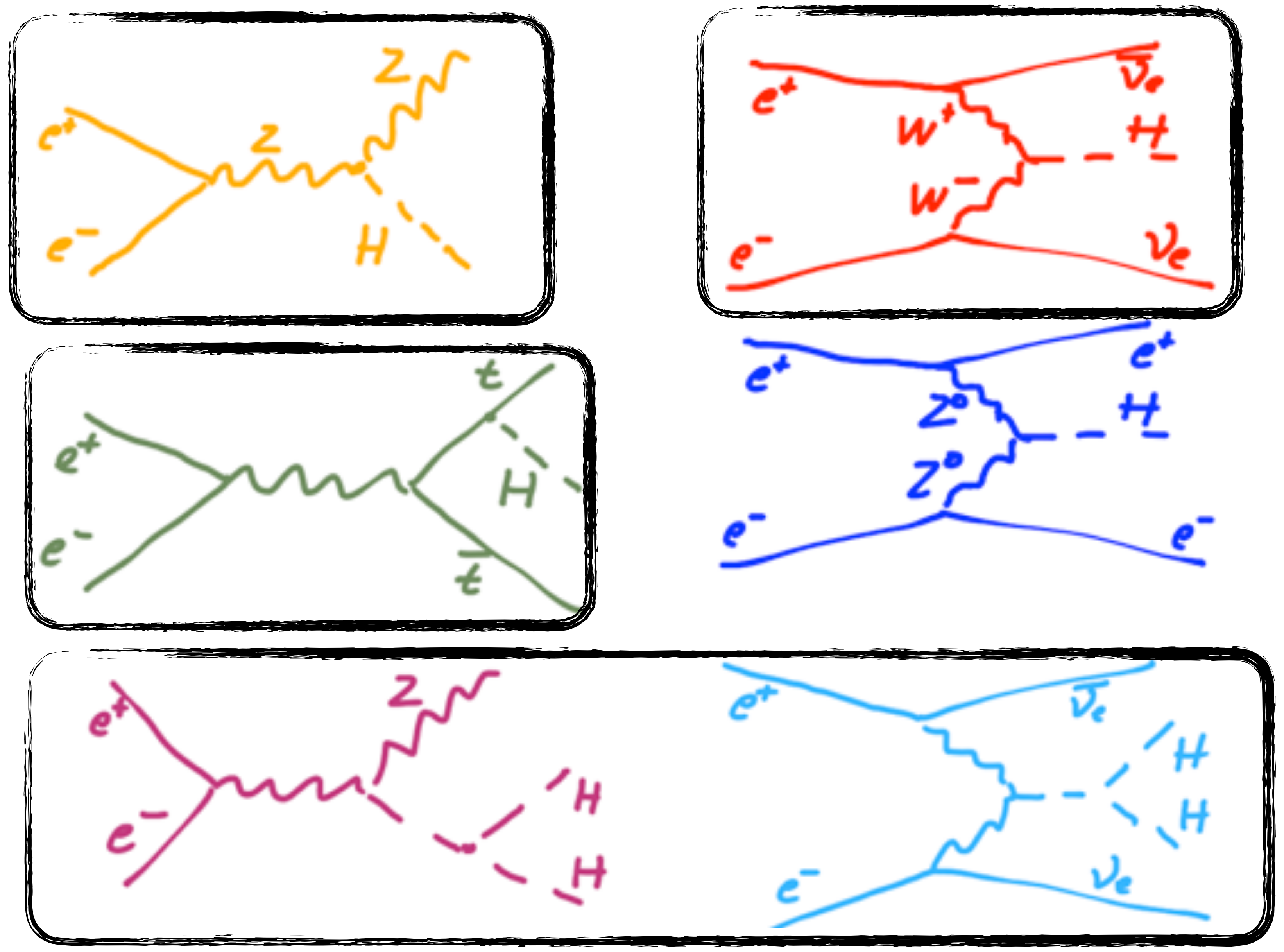

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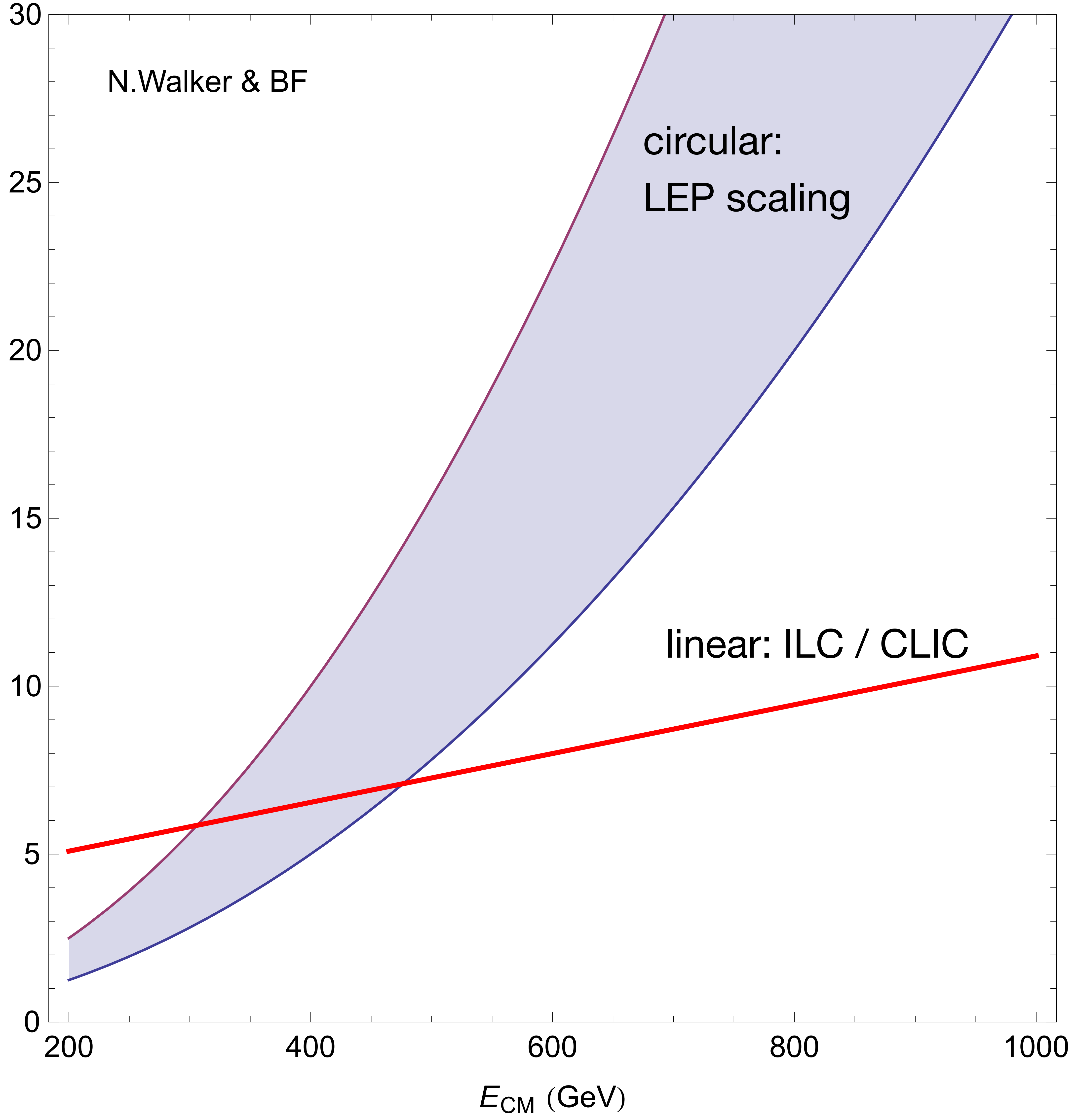
500 GeV; 1+ TeV:
Higgs self-coupling

- Polarisation plays a role as well:
  - Boosting of signal, reduction of background (or vice versa)
  - Adds key additional input for global fits & increases sensitivity to new phenomena

e^+e^- Colliders at the Energy Frontier

Constraints imposed by Physics



- Very simple cost model for storage rings:
  $a E^4/R + b R$
  (a and b taken from LEP - band using optimistic and pessimistic ways of calculating LEP costs)
  NB: Luminosity steeply drops with E in this scenario!
- Likewise for Linear Colliders:
  $c + d E$
  NB: Relative large offset due to complex infrastructure needed irrespective of final energy - this makes storage rings more efficient up to ~ 300 GeV

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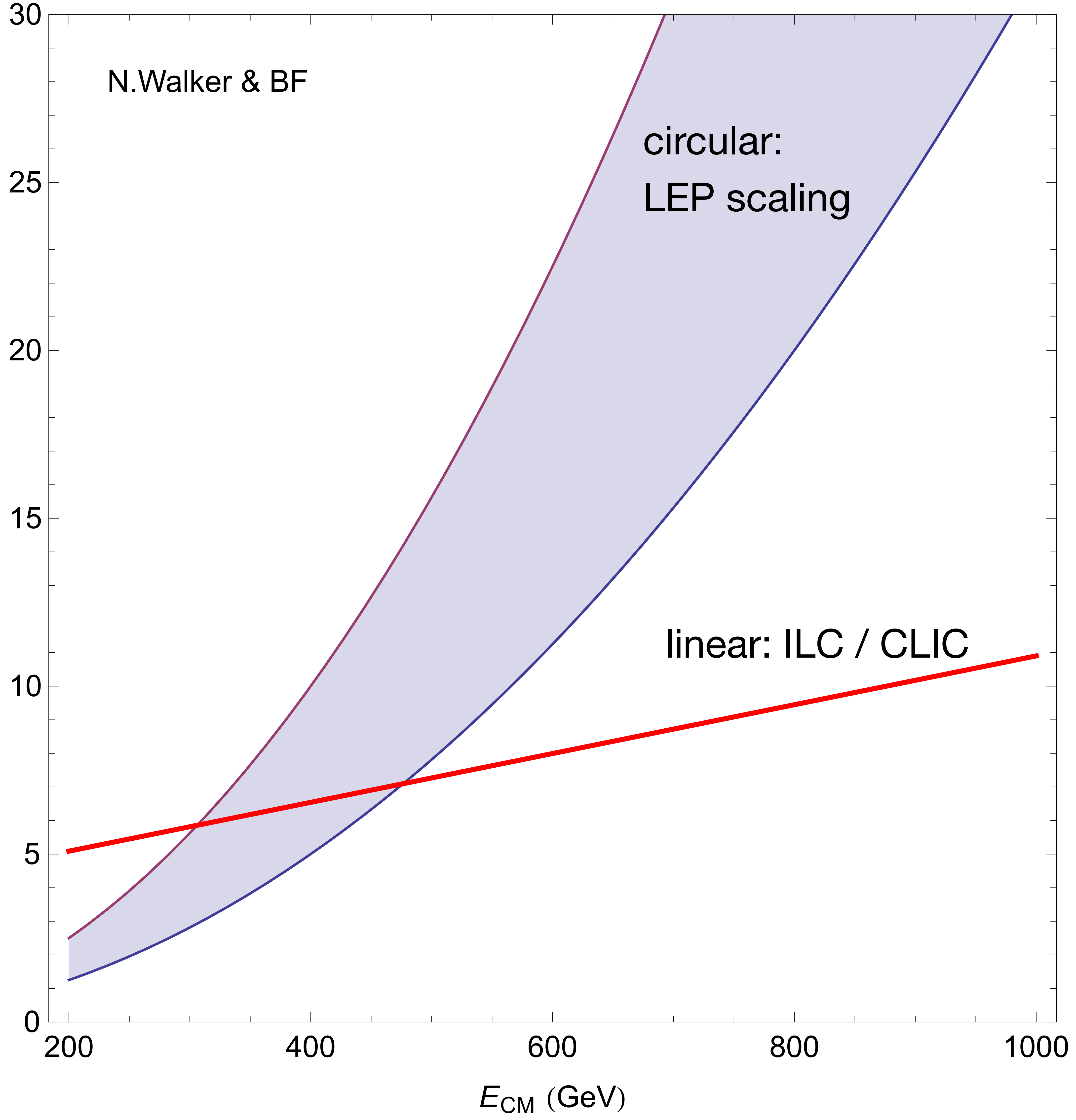

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Linear Colliders are high-energy machines!

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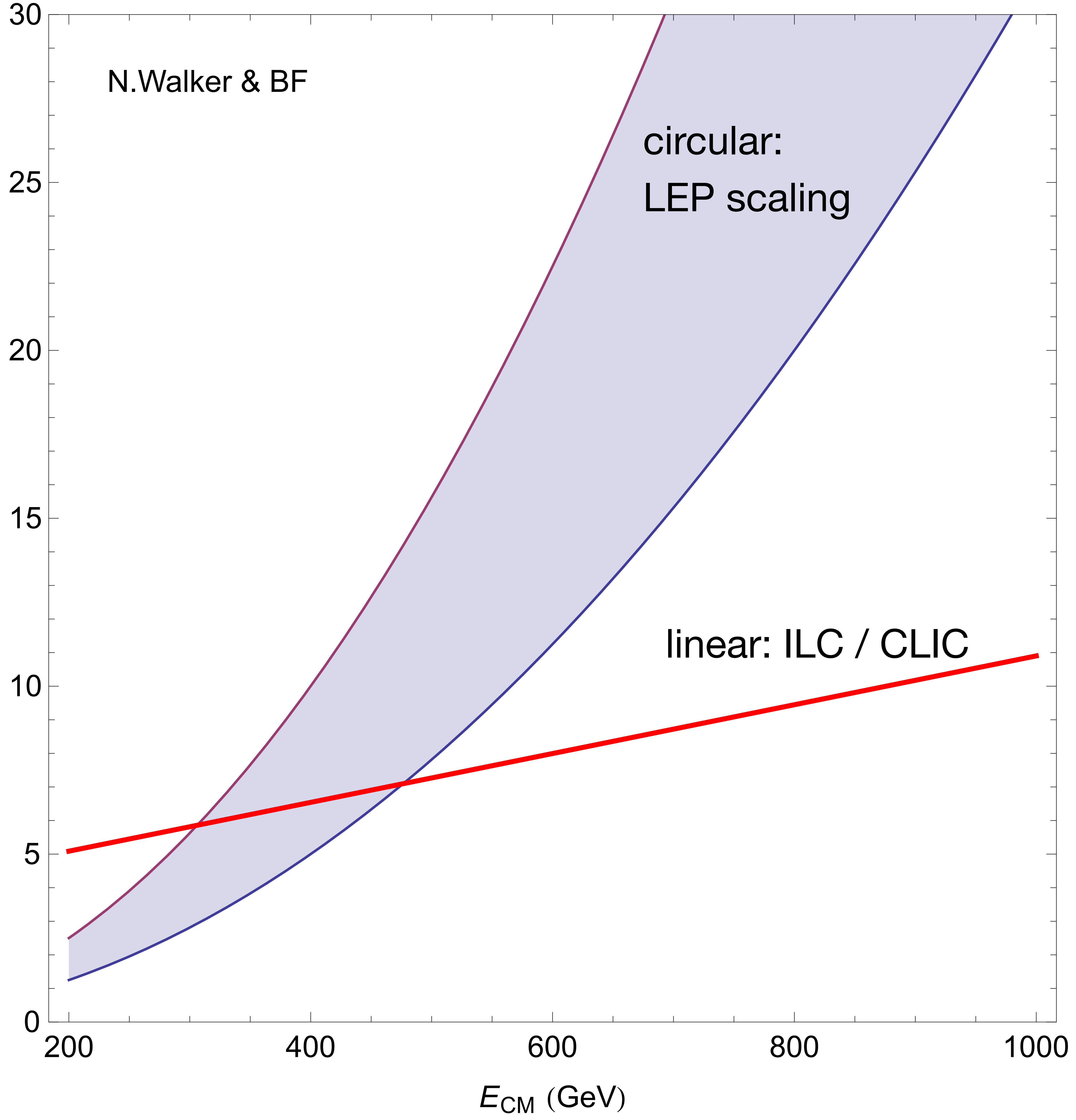

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Rings are impossible to beat at low energy,
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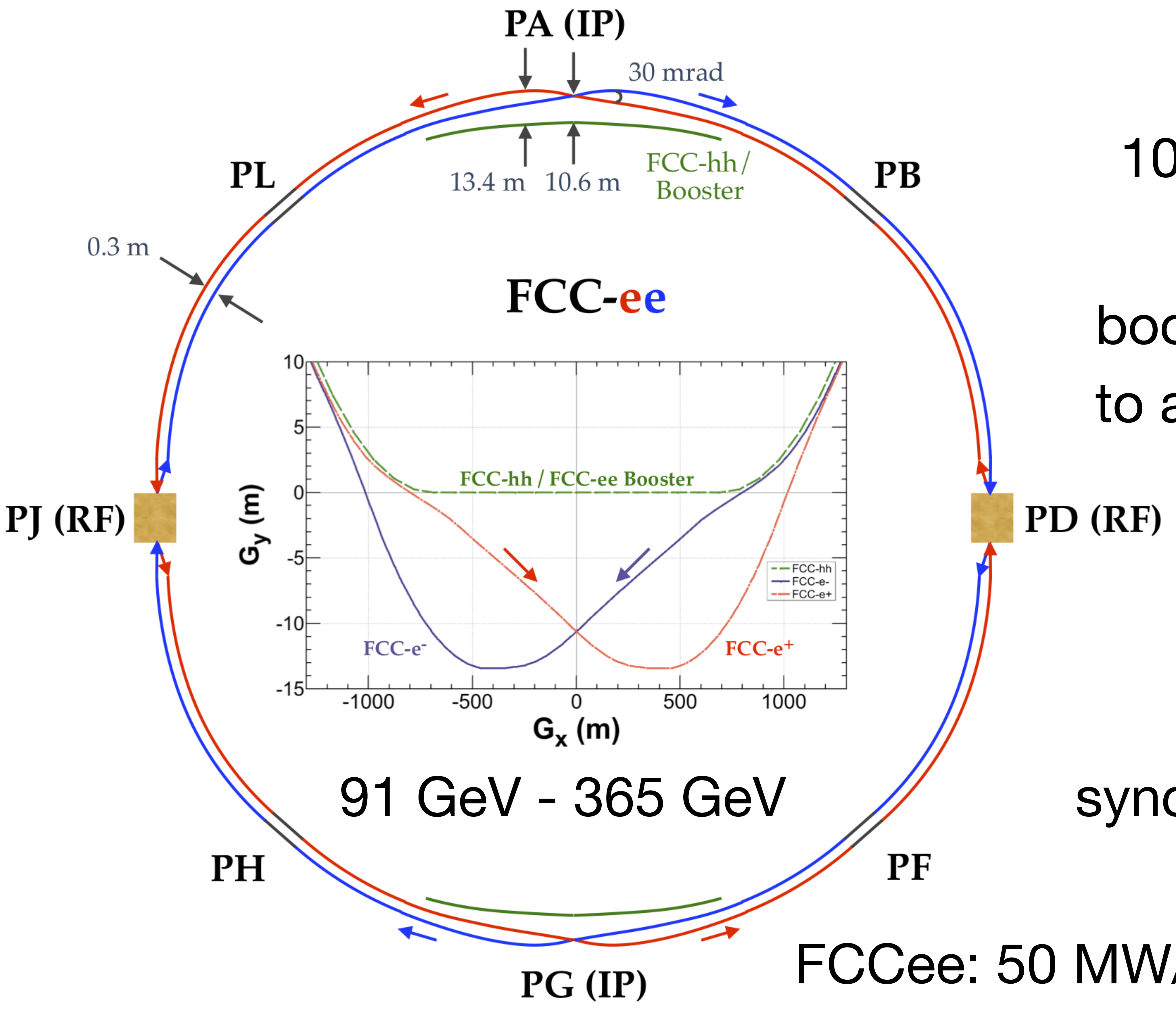
And it is not just about construction costs and energy:
Power consumption, capability for polarisation,…
⇨ Not a straight-forward optimisation!

The Facilities: Rings

FCCee, CEPC

- “Low tech”, large circumference accelerators - as a first stage of the scientific exploitation of a circular tunnel - later followed by a high-energy hadron collider
  - Add state-of-the-art ingredients: Nano-beams, high-gradient SCRF, …



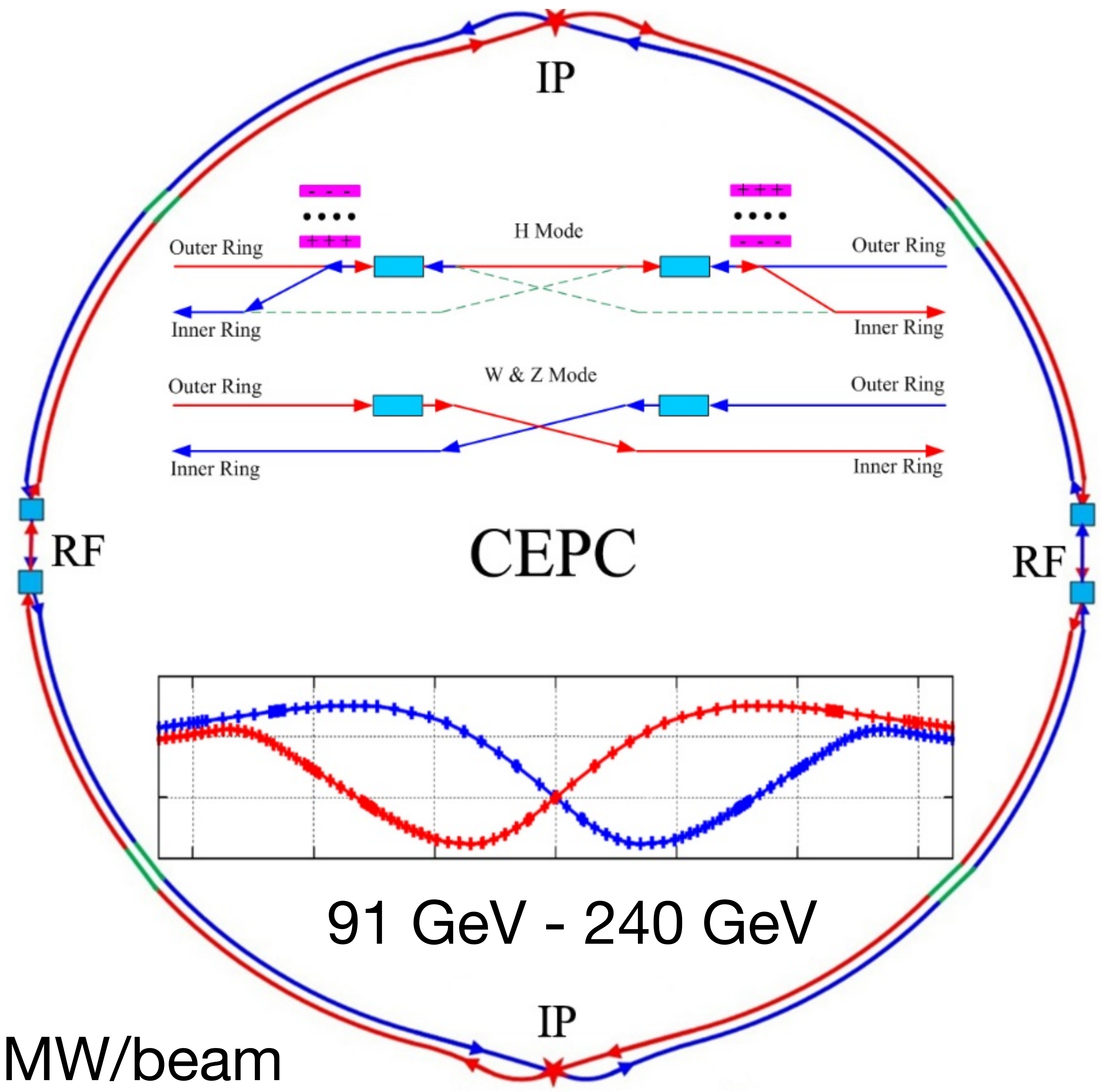
91 GeV - 365 GeV

100 km circumference

booster synchrotron required to achieve high luminosities

synchrotron radiation power:

FCCee: 50 MW/beam CEPC: up to 30 MW/beam



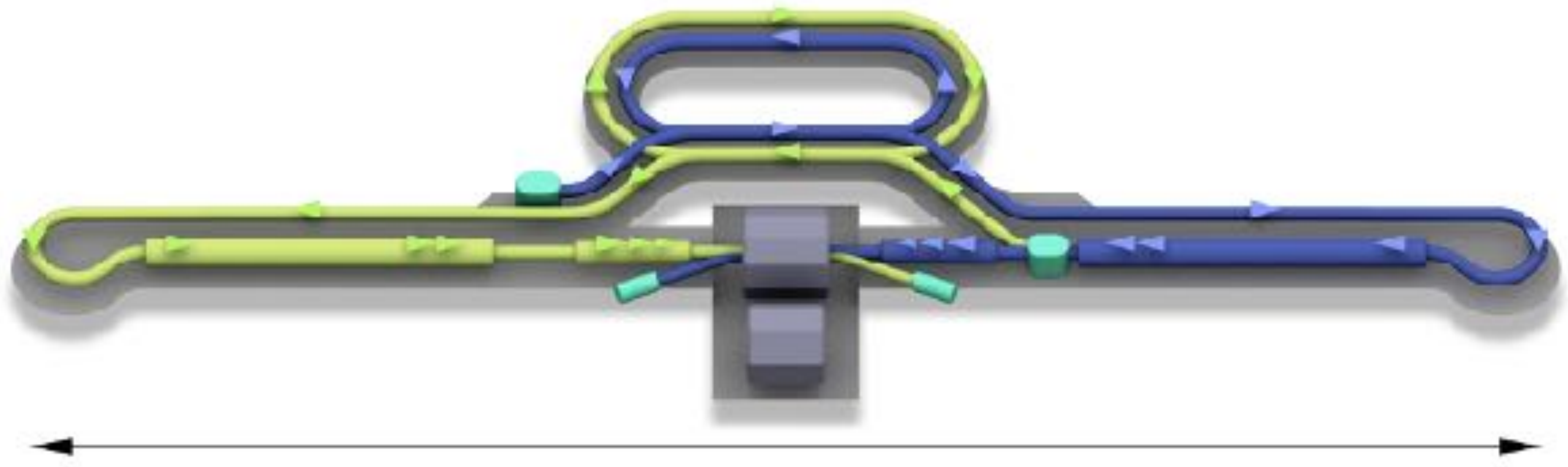
91 GeV - 240 GeV

The Facilities: Linear Colliders

ILC, CLIC

- High gradient linear accelerators - intrinsically upgradeable in energy (increase in length, higher-gradient acceleration technologies)

ILC (International Linear Collider)



~ 20 km for 250 GeV
~ 30 km for 500 GeV

superconducting RF

baseline 250 GeV, full TDR energy 500 GeV, potential to 1+ TeV

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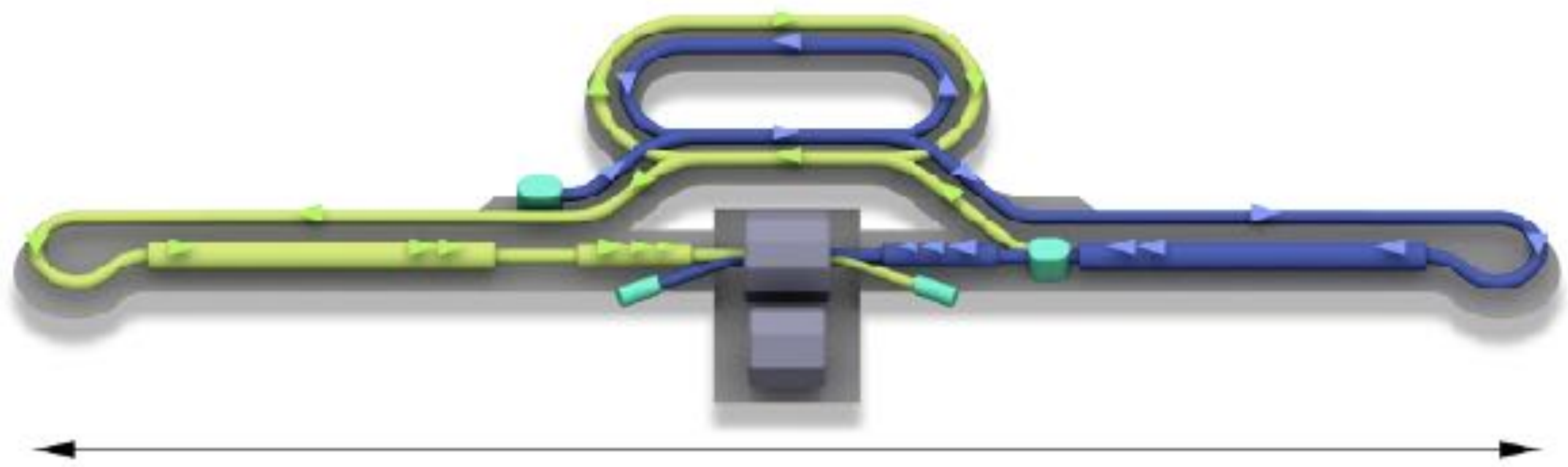

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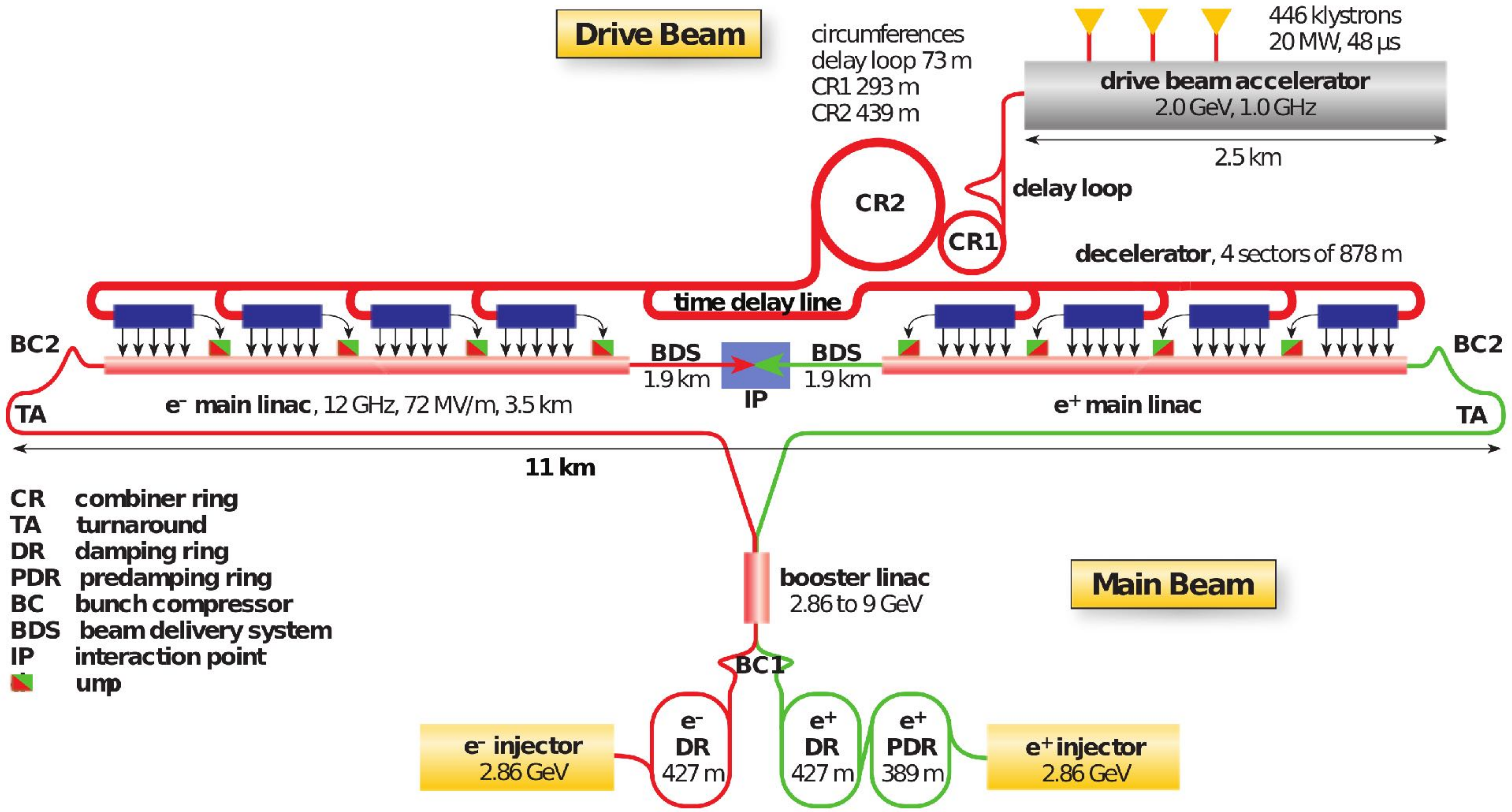
CLIC (Compact Linear Collider)



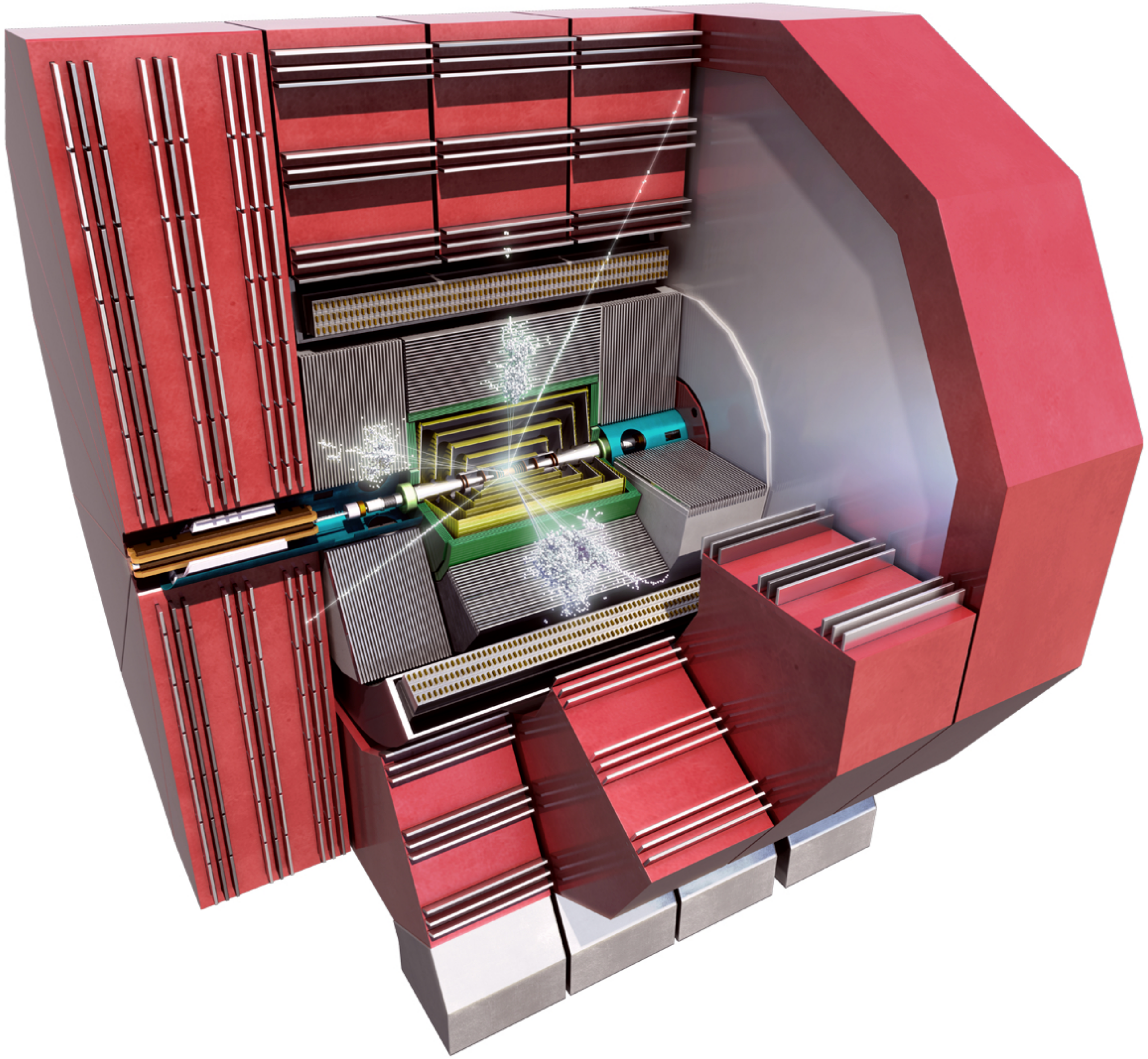
2-beam acceleration

three stages from 380 GeV (11 km) to 3 TeV (50 km)

Linear Collider Detectors

… similar for FCCee, CEPC

- Realistic detector concepts for Linear Colliders established over the last ~ 15 years
    - Capitalize on (and drive) technological advances
    - Exploit LC conditions: benign background levels, low event rates, collider time structure, …



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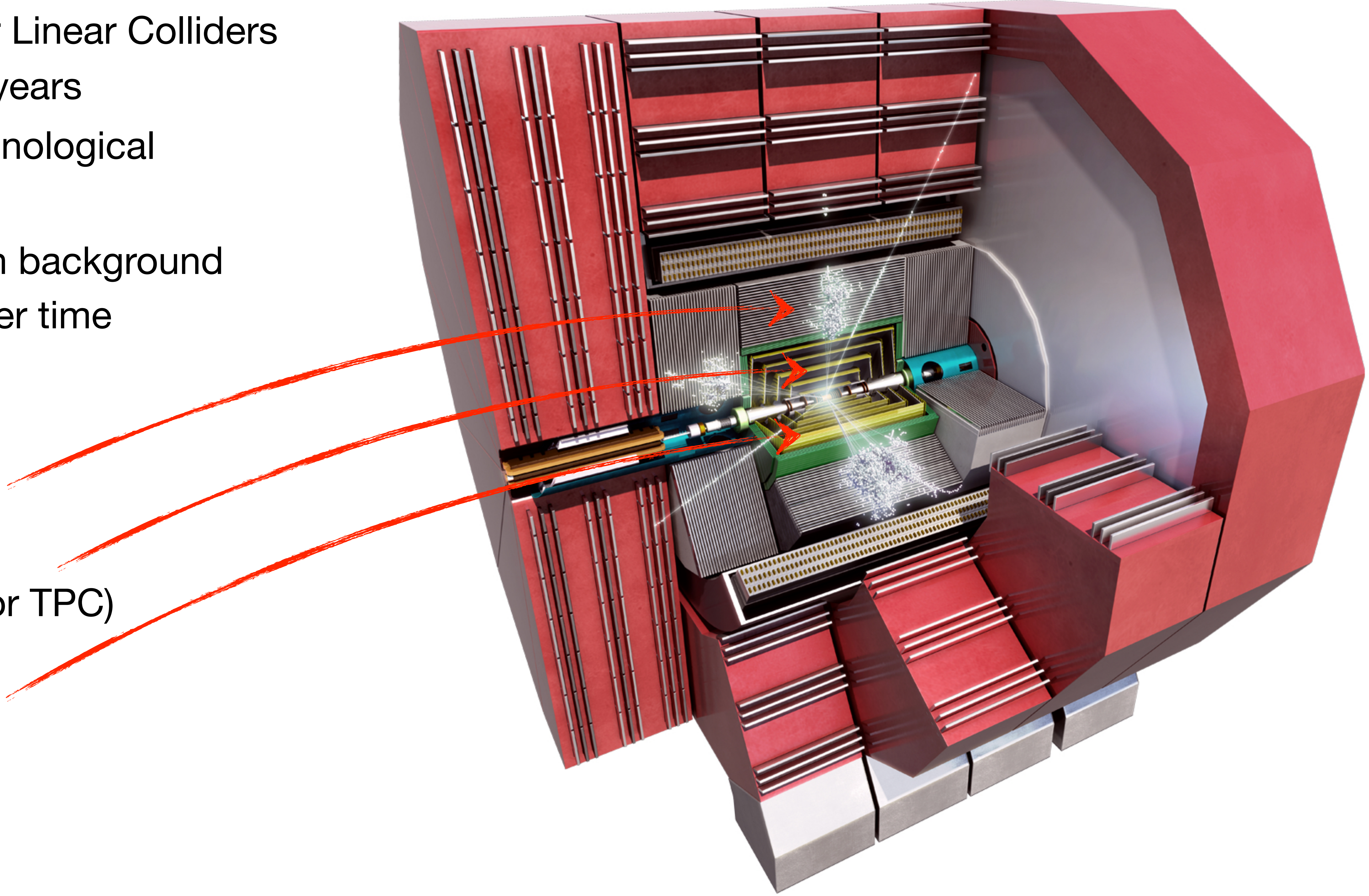

highly granular calorimeters & PFA reconstruction

low-mass tracking (all-silicon or TPC)

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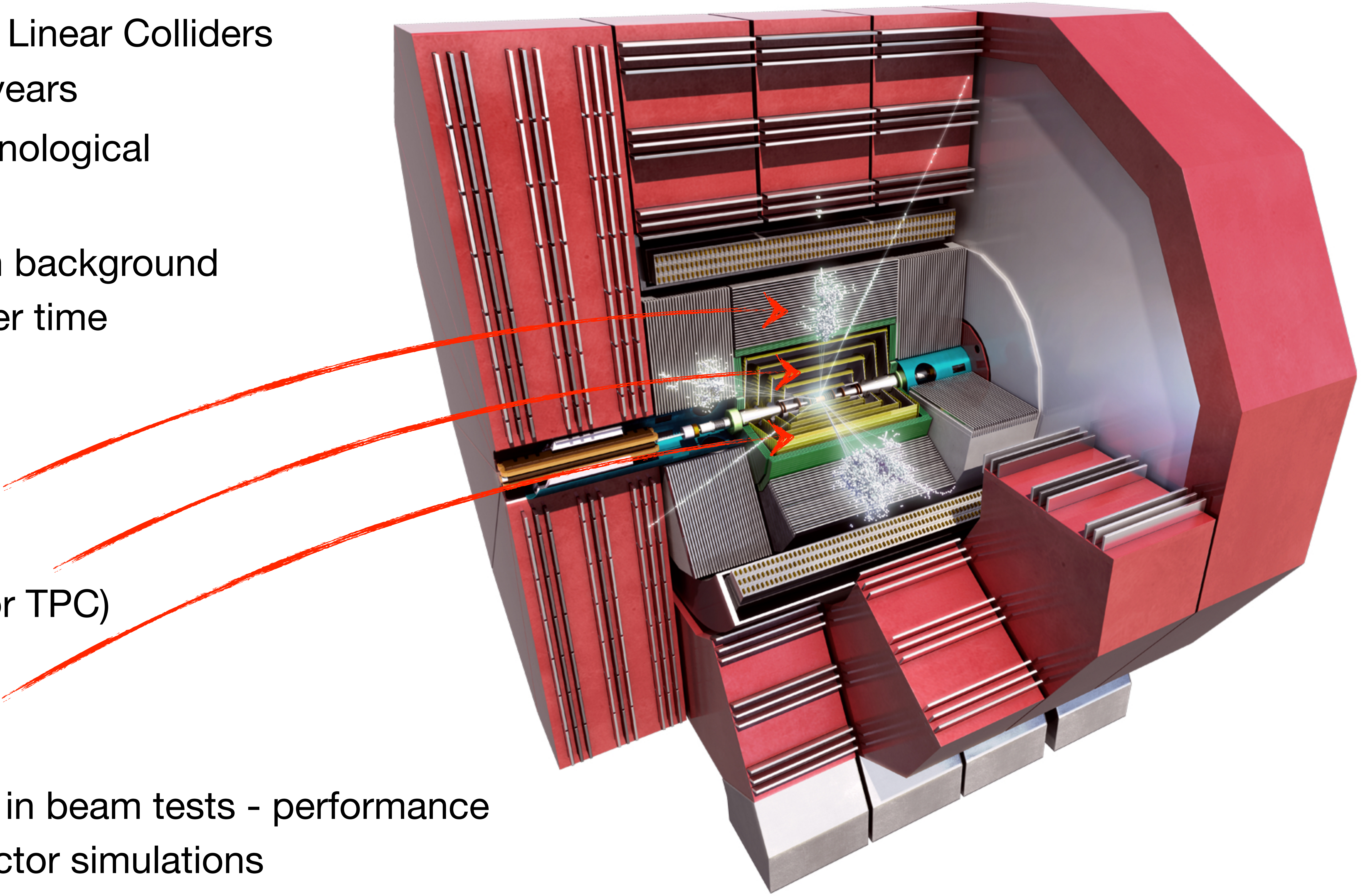

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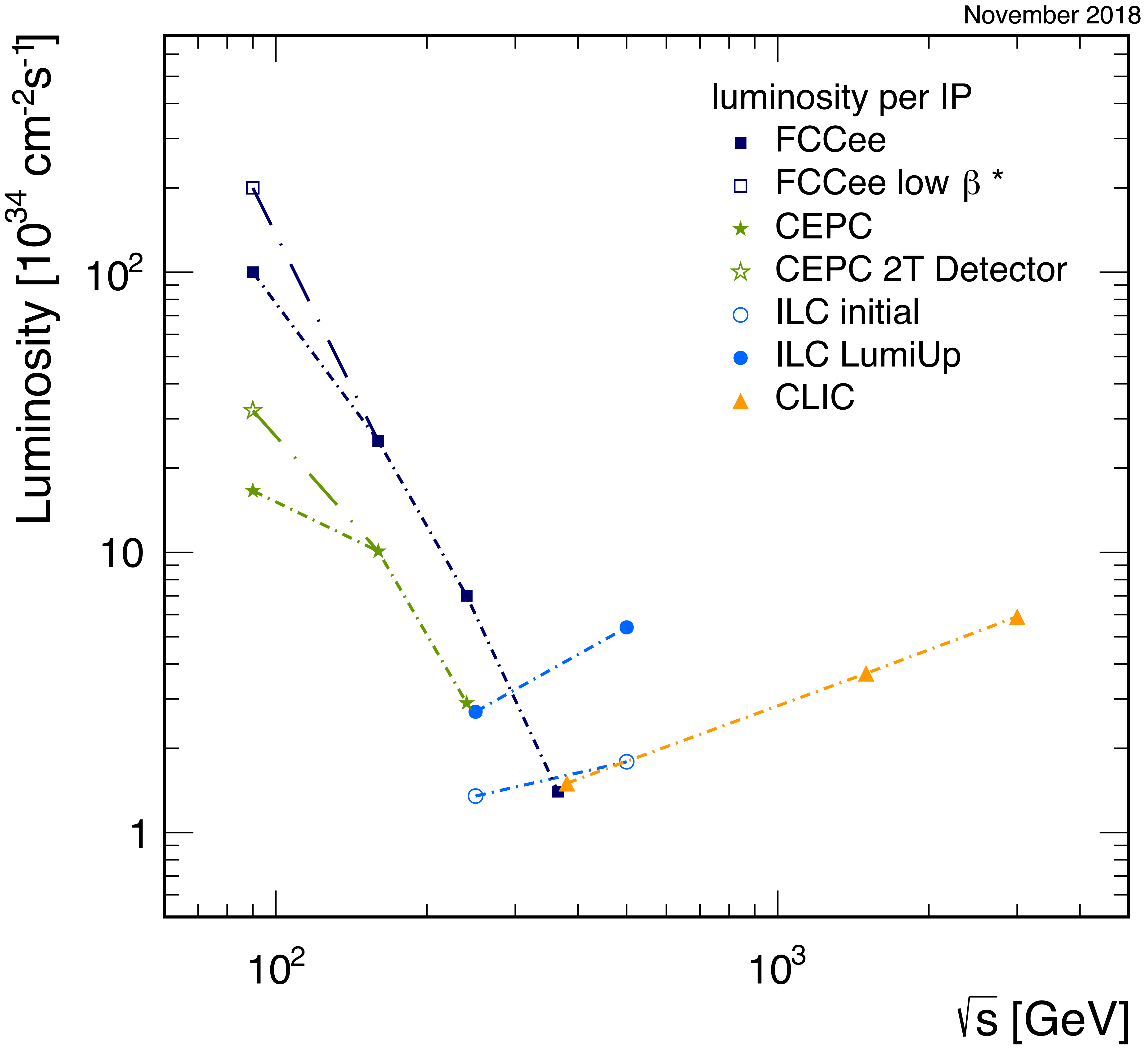
- Key technologies demonstrated in beam tests - performance results used to validate full detector simulations

e+e- Colliders: Luminosities

In Relation to the Higgs Program



- NB: Circular colliders can have more than one IP (default: 2), while for linear colliders several detectors do not result in an increase in statistics

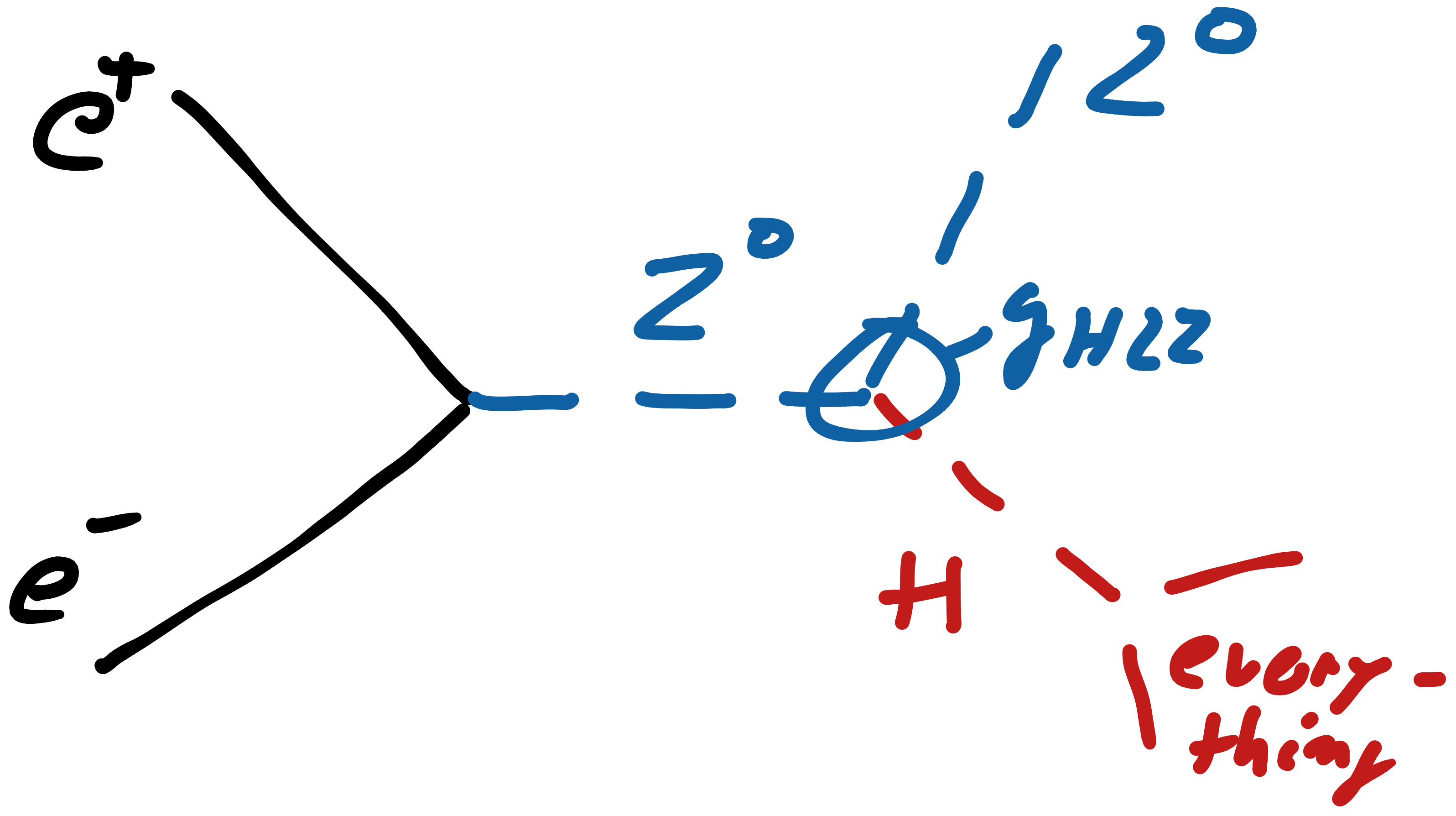
Cross-over of luminosity curves in the focus region of Higgs physics

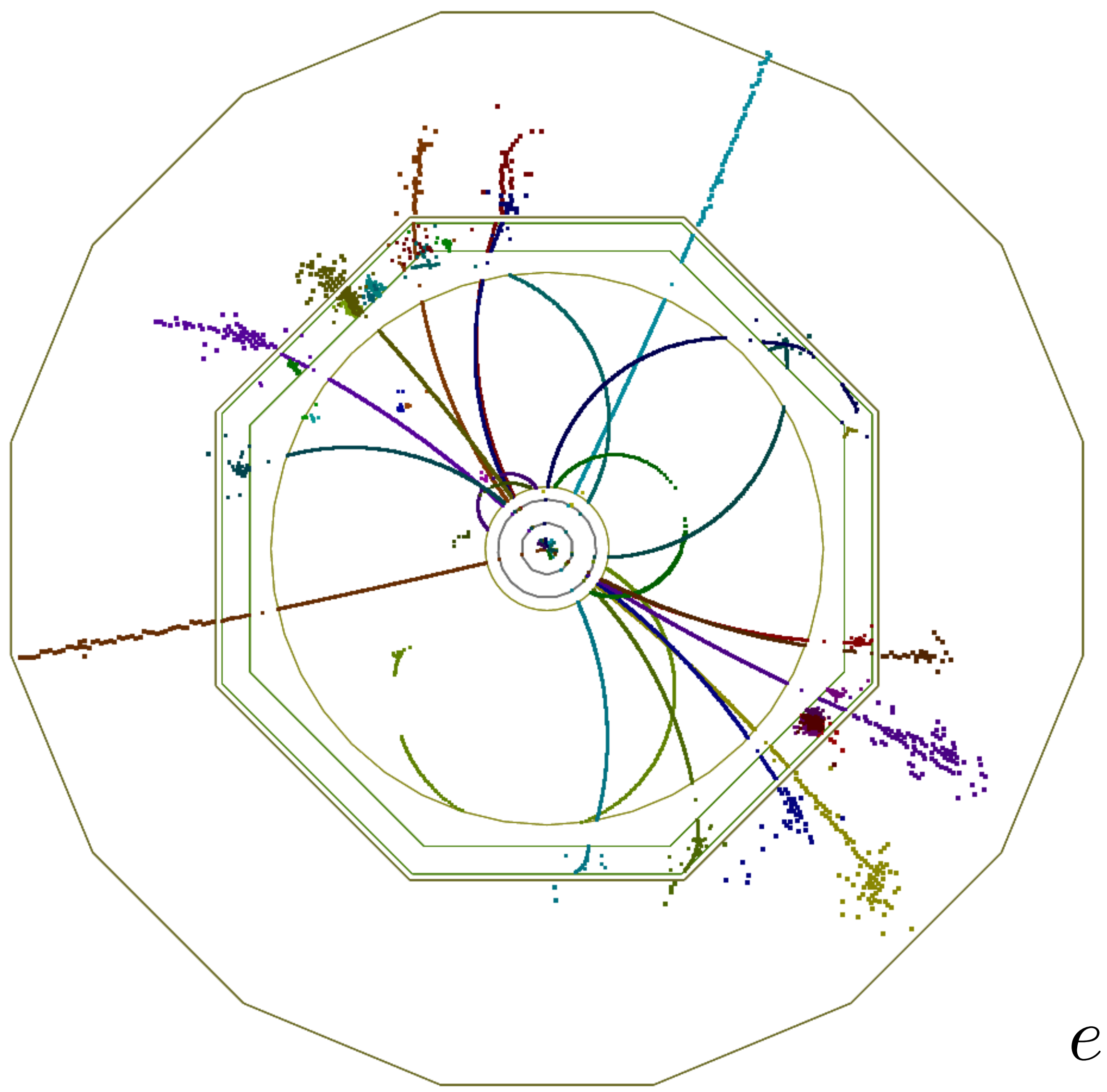
- Choice of collider energy reflects luminosity evolution with energy: For circular colliders, 240 GeV provides highest ZH statistics, for linear colliders 250 GeV is better

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

The ZH Higgsstrahlung Process

- What model independence means: Measure the coupling of the Higgs Bosons to elementary particles free from model assumptions (e.g. how it decays)
  - Requires: The “tagging” of Higgs production without observing the particle directly
    - Not possible at hadron colliders





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

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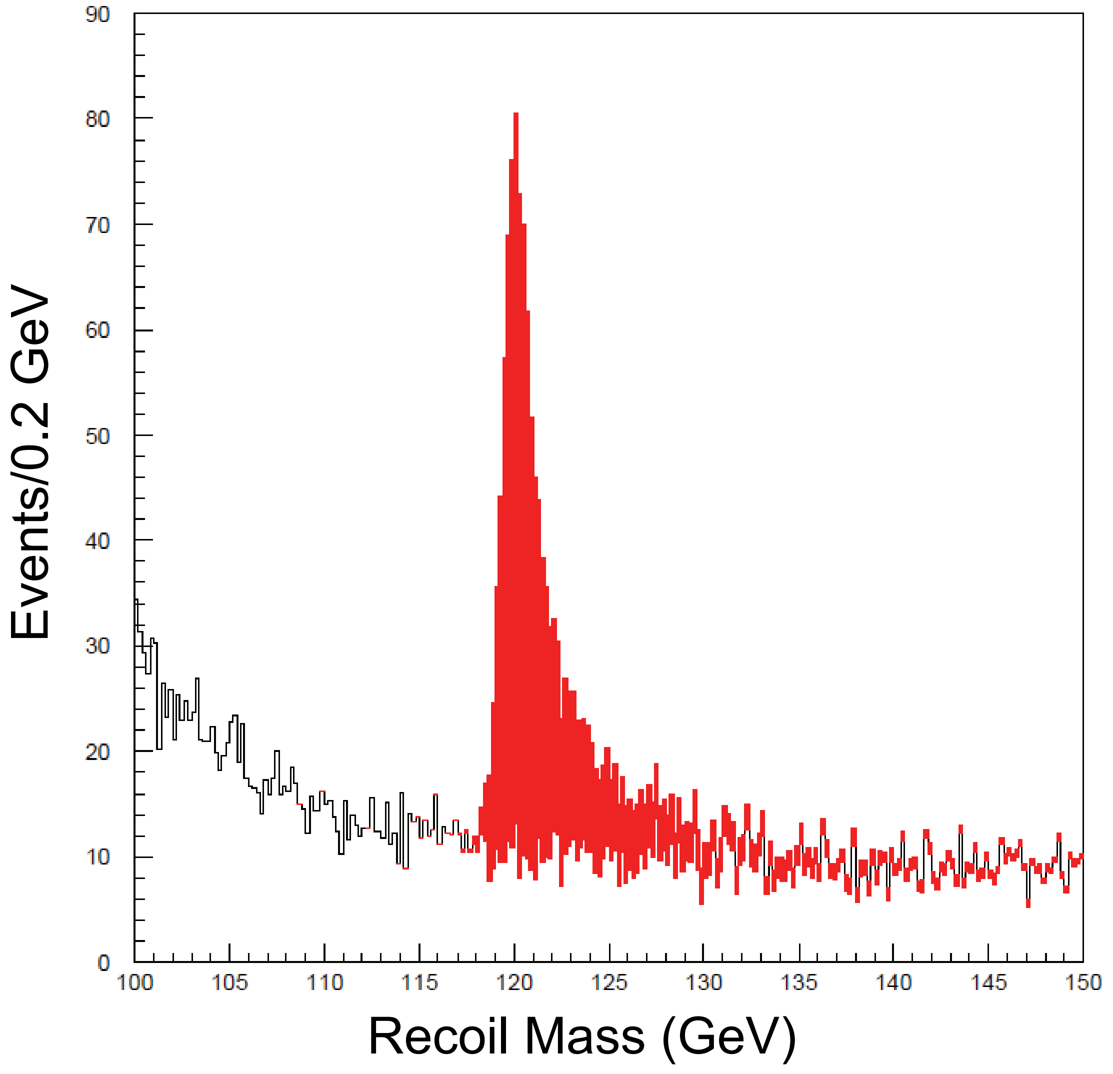
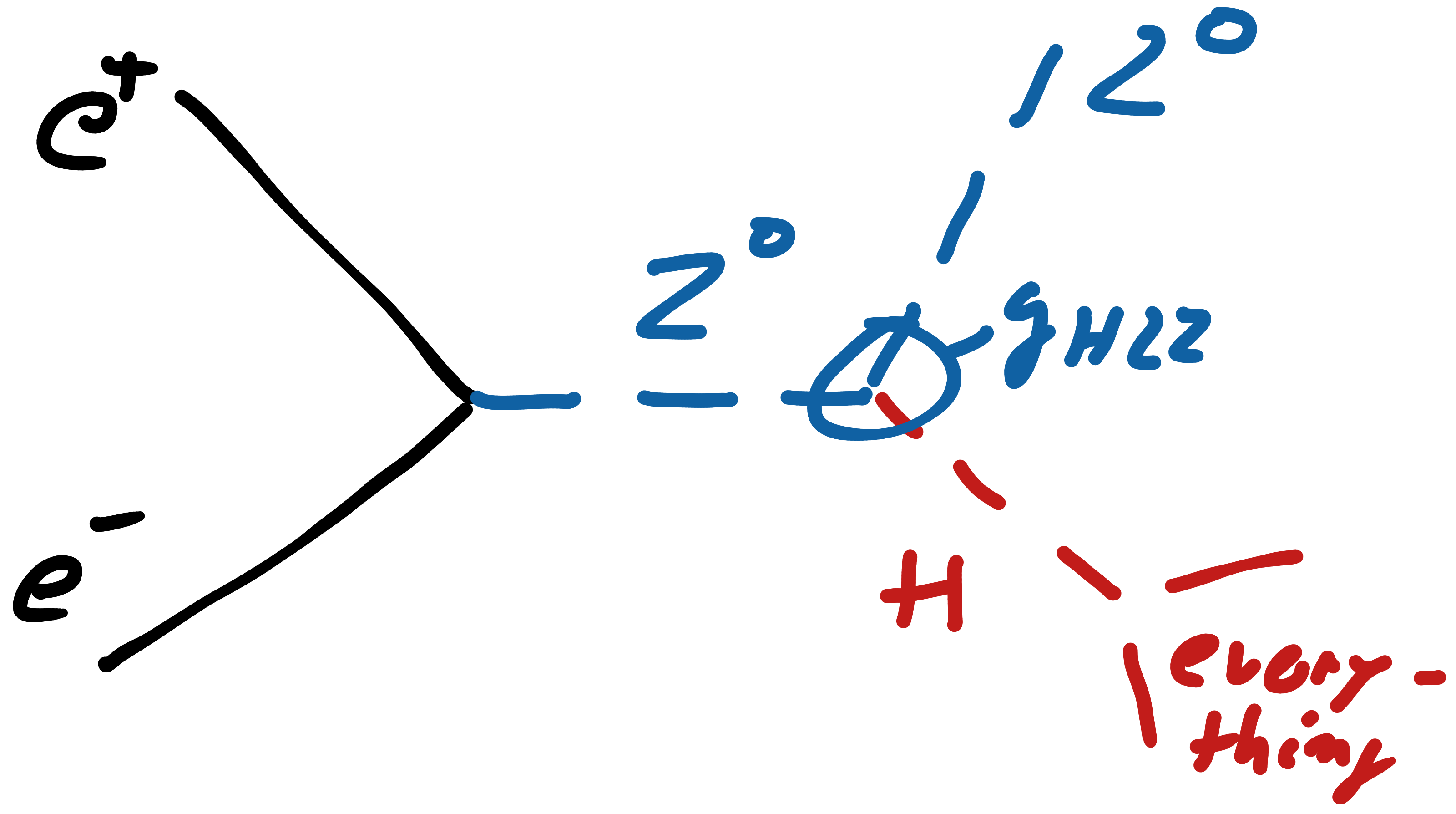
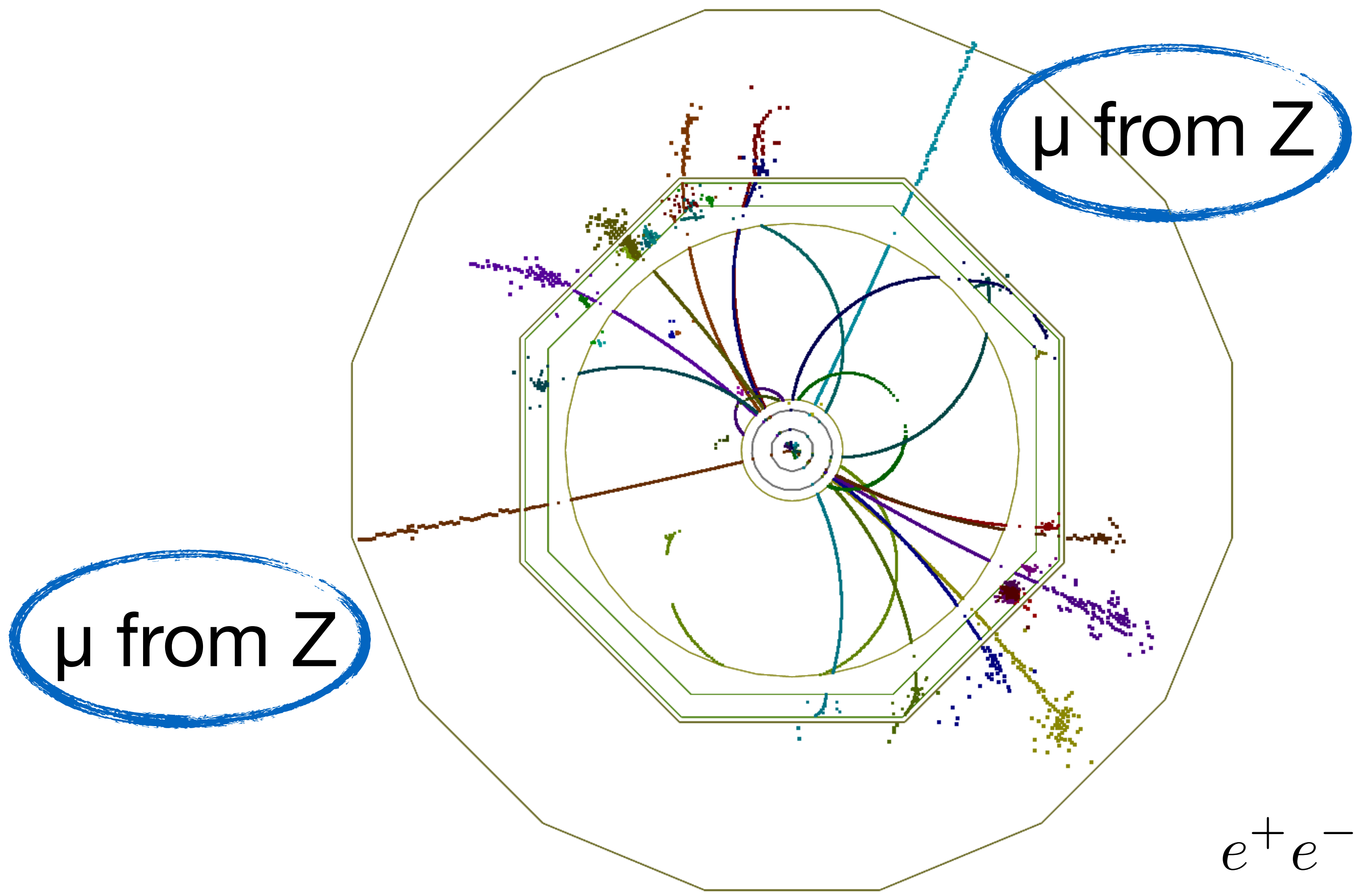
recoil mass:
measure only the Z!

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







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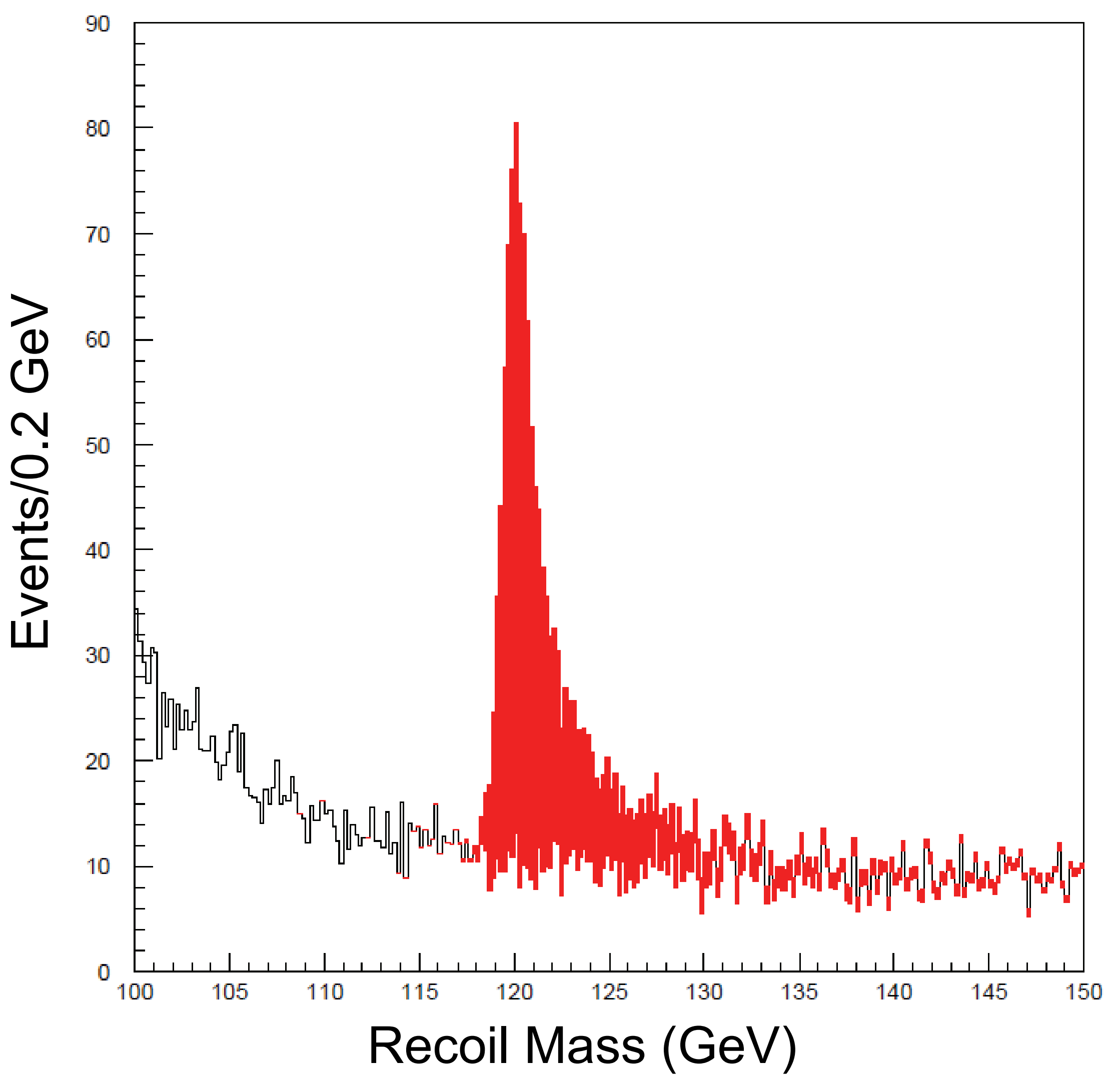

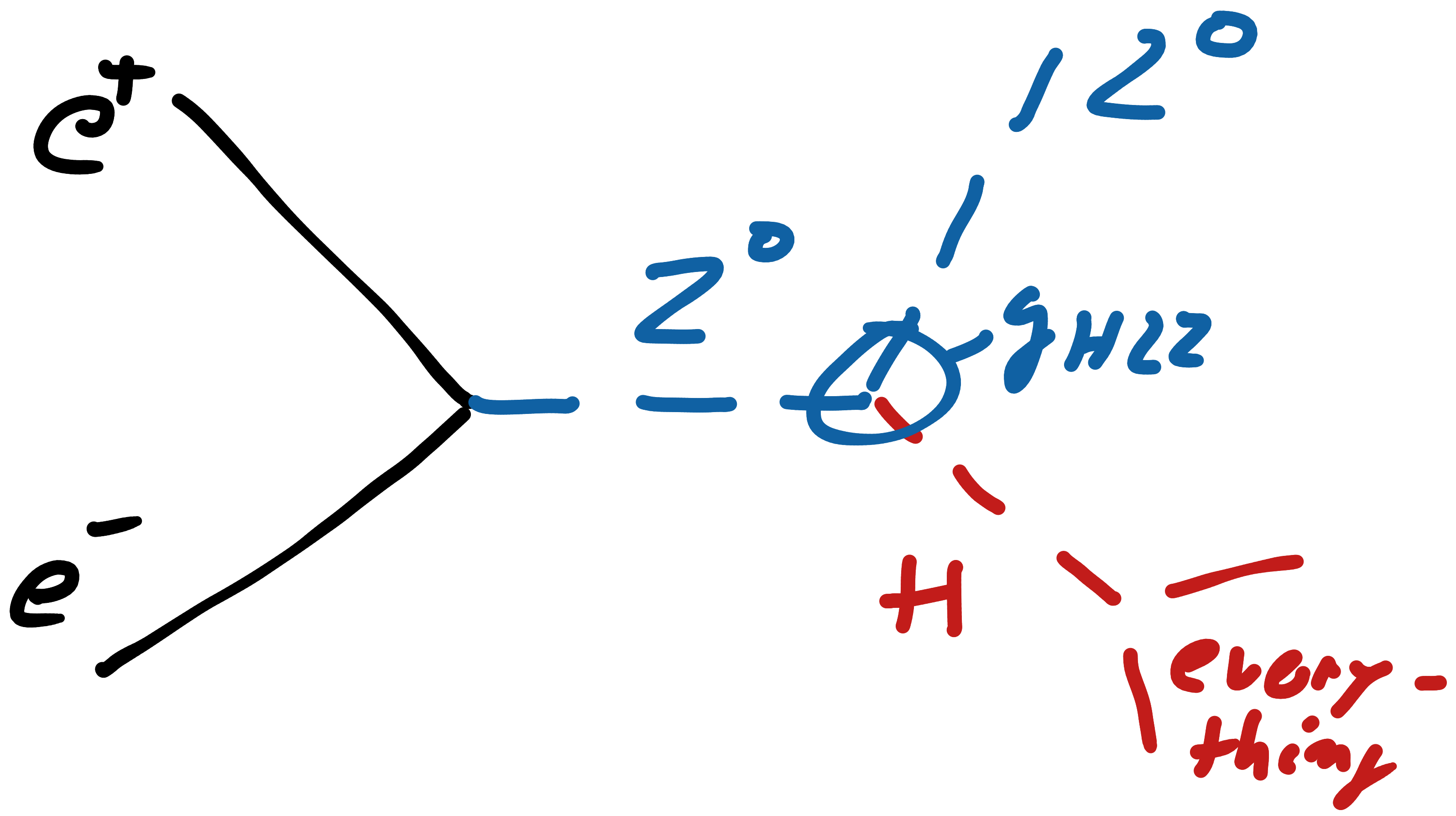

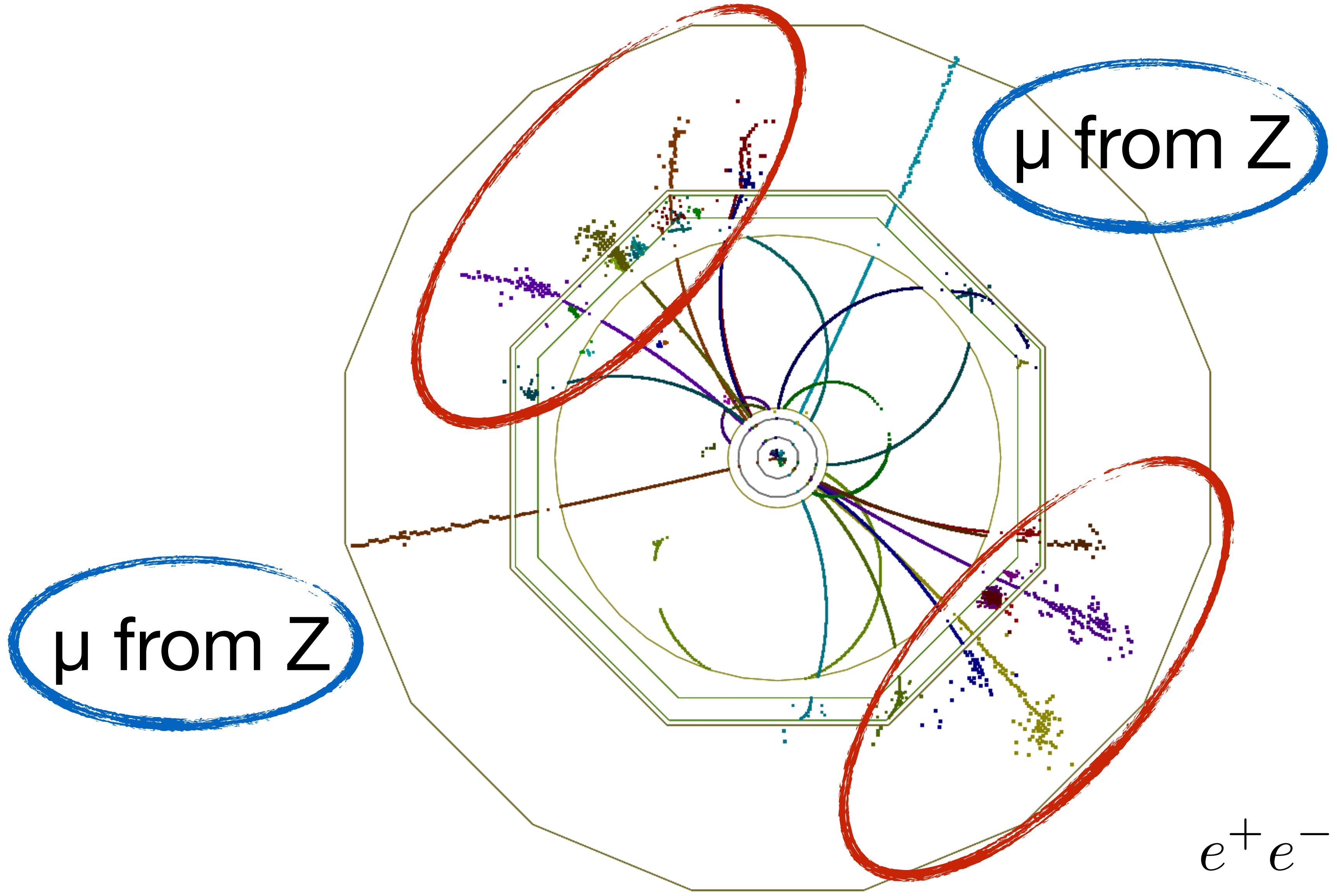

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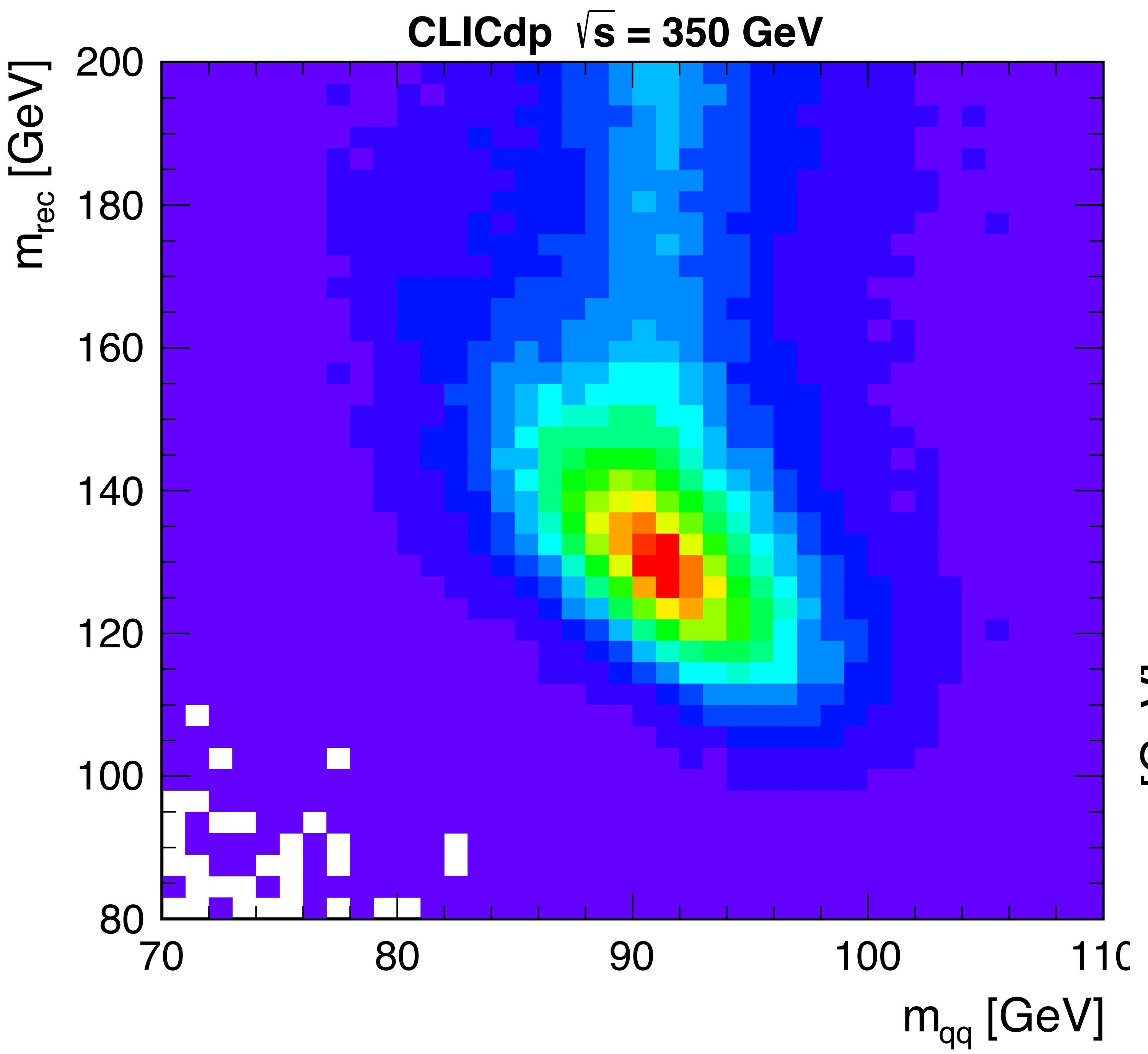
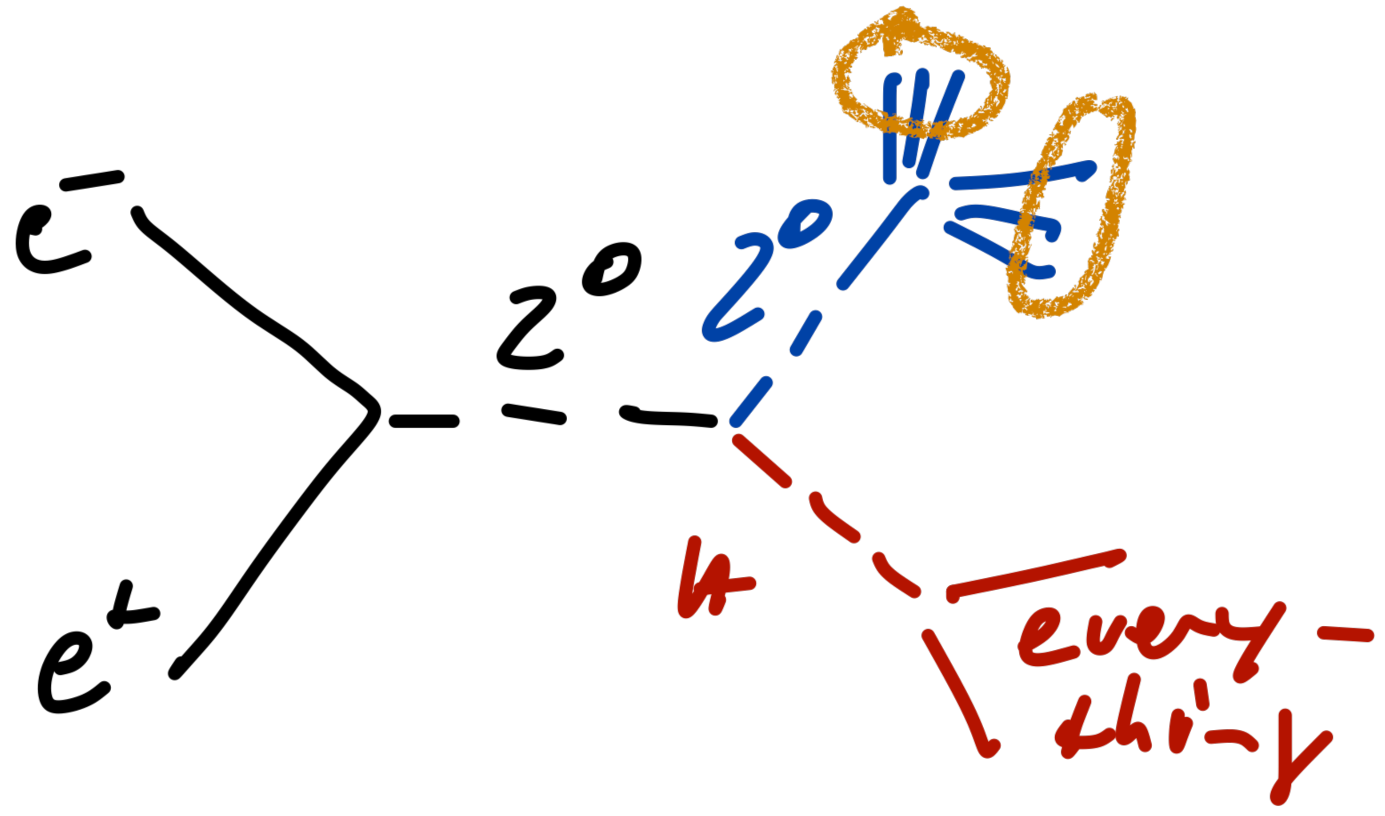
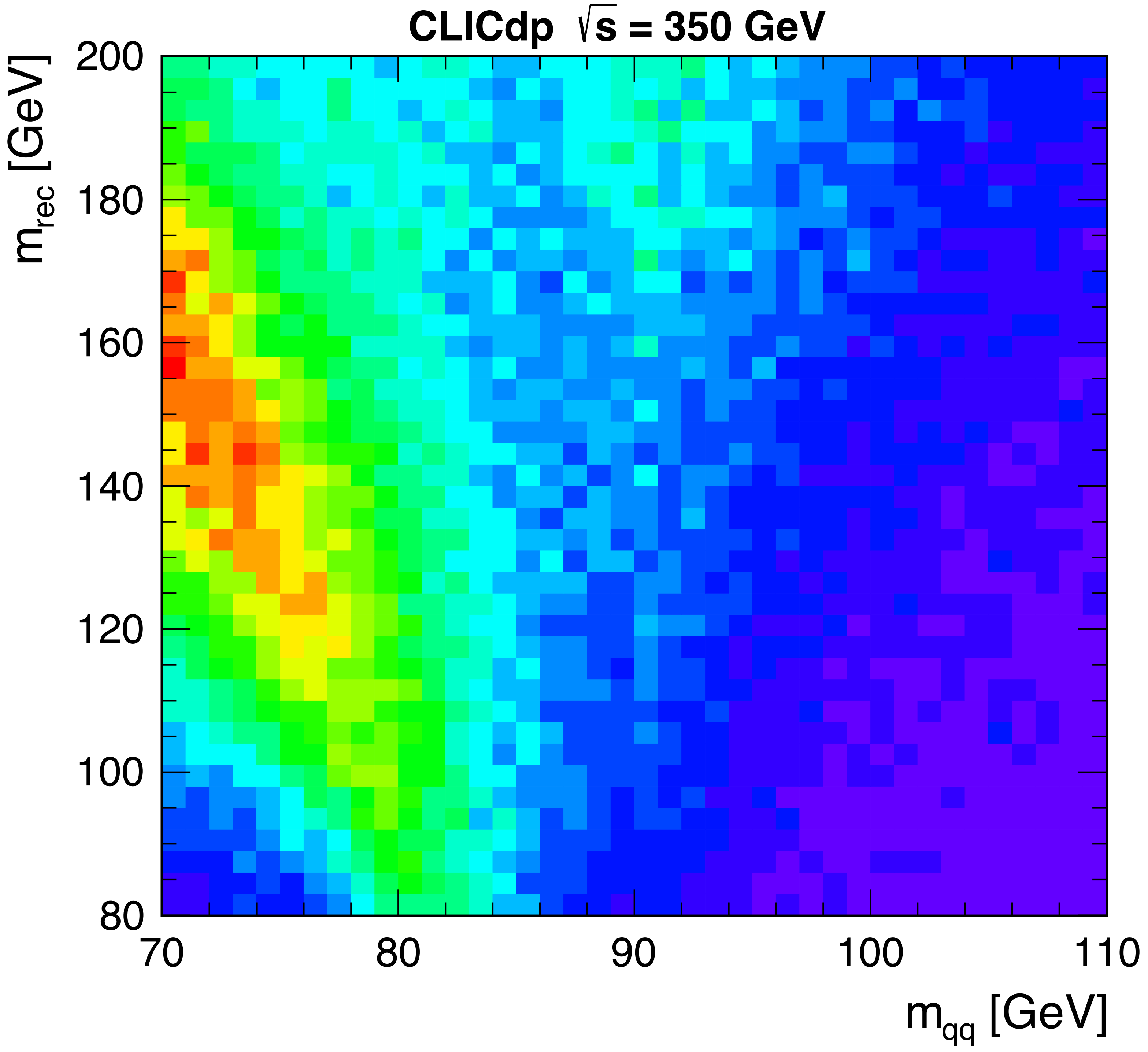
Hadronic Recoils & Invisible Decays

Fully exploiting Higgsstrahlung



- 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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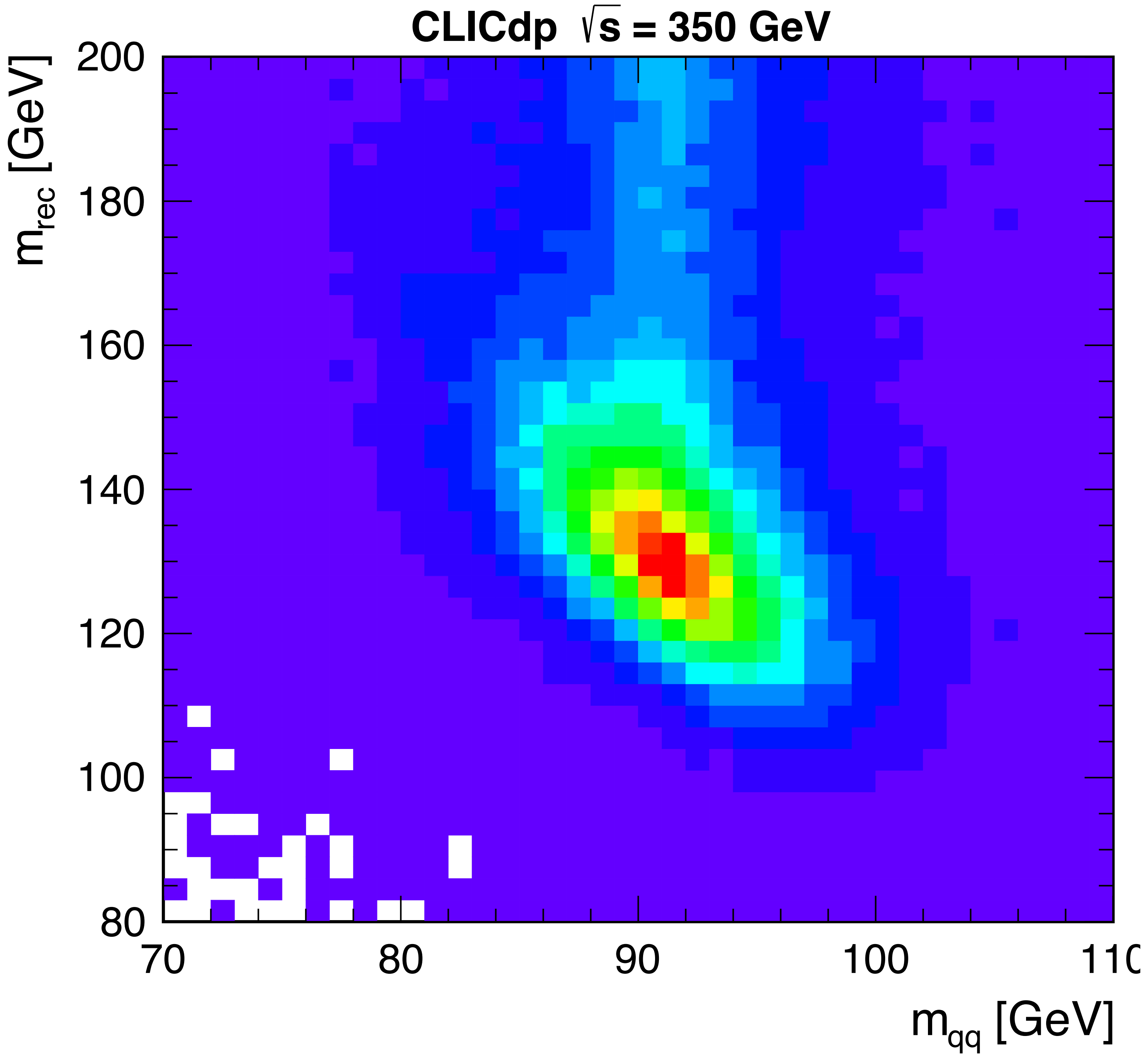

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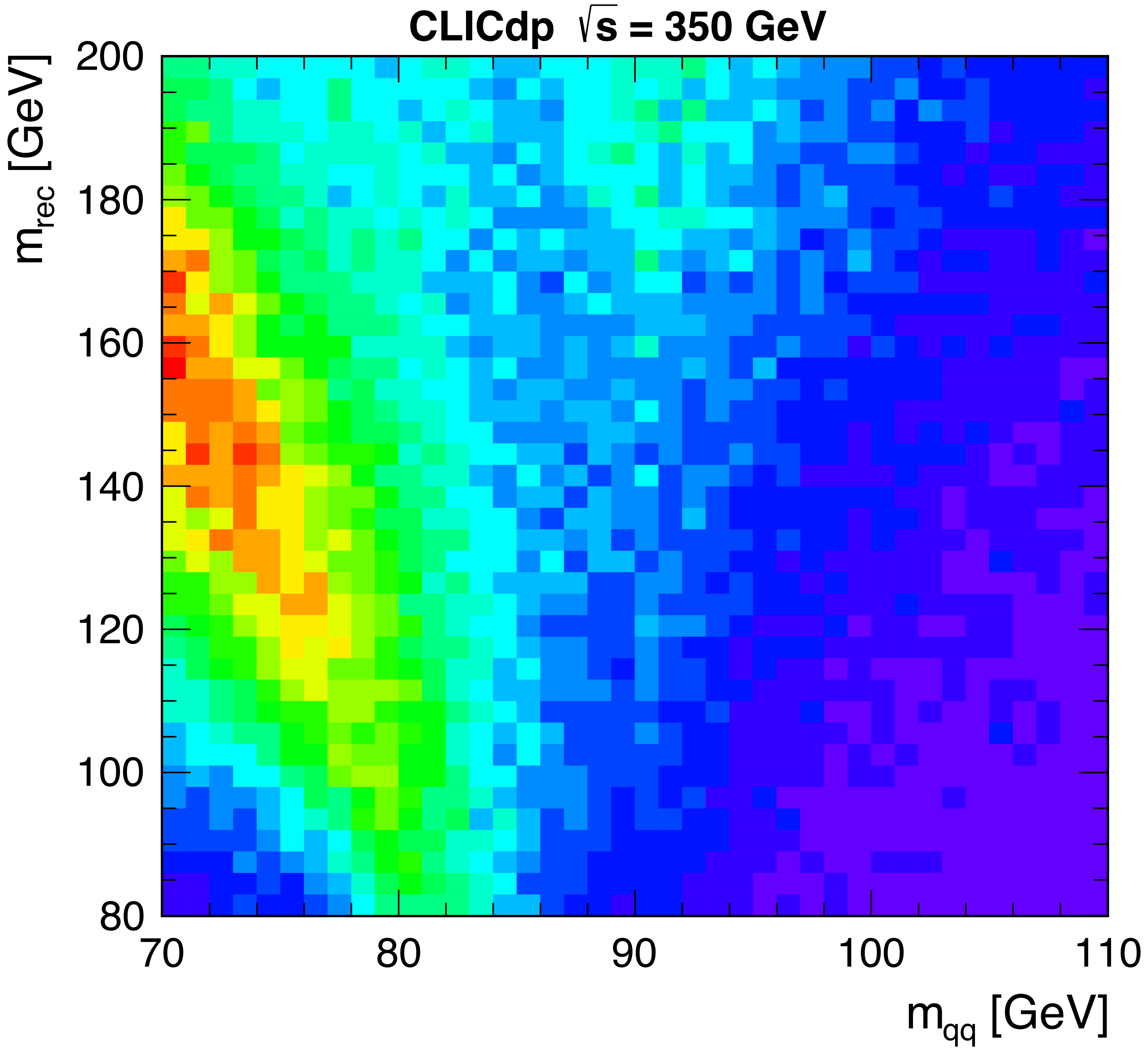
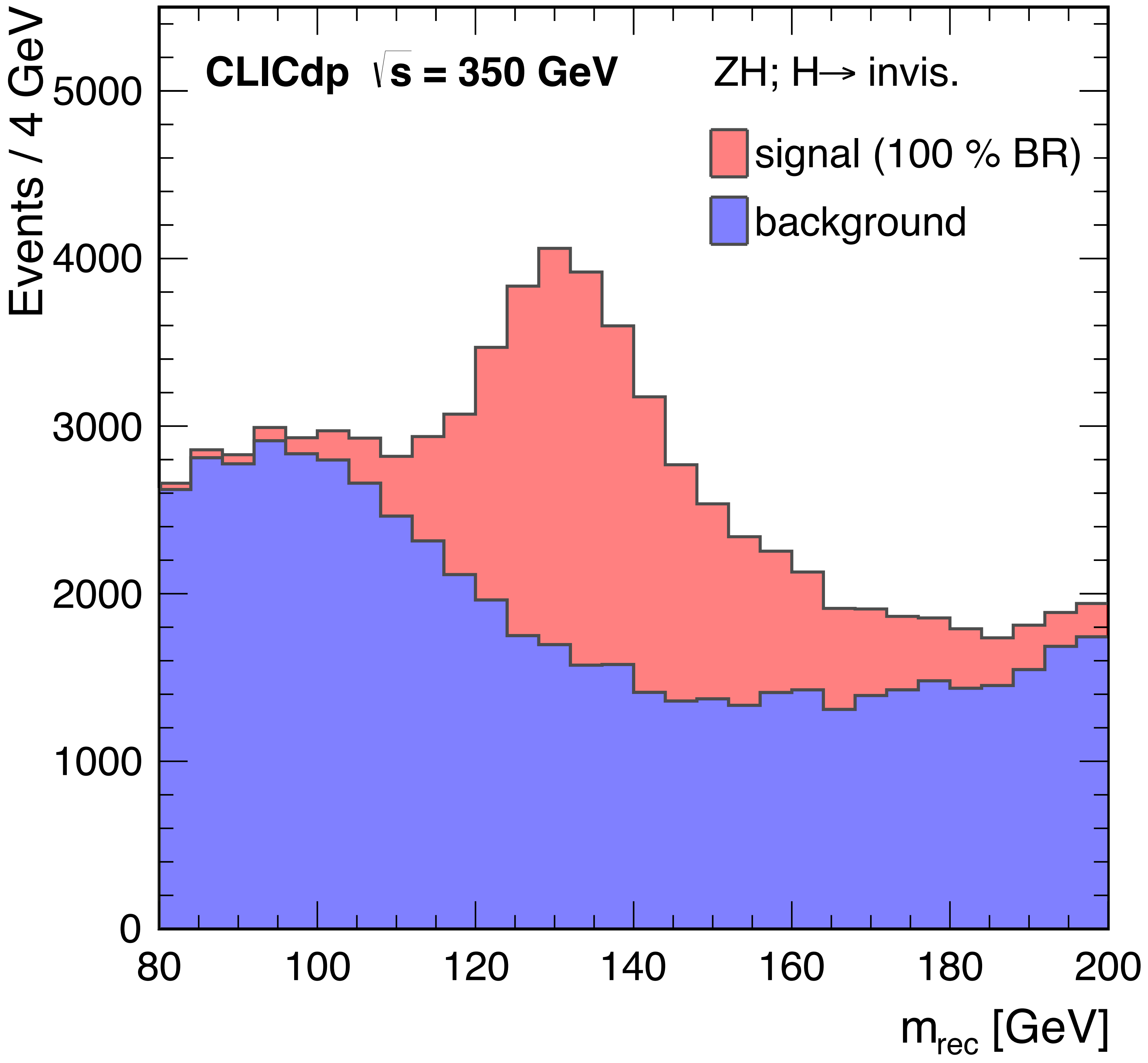
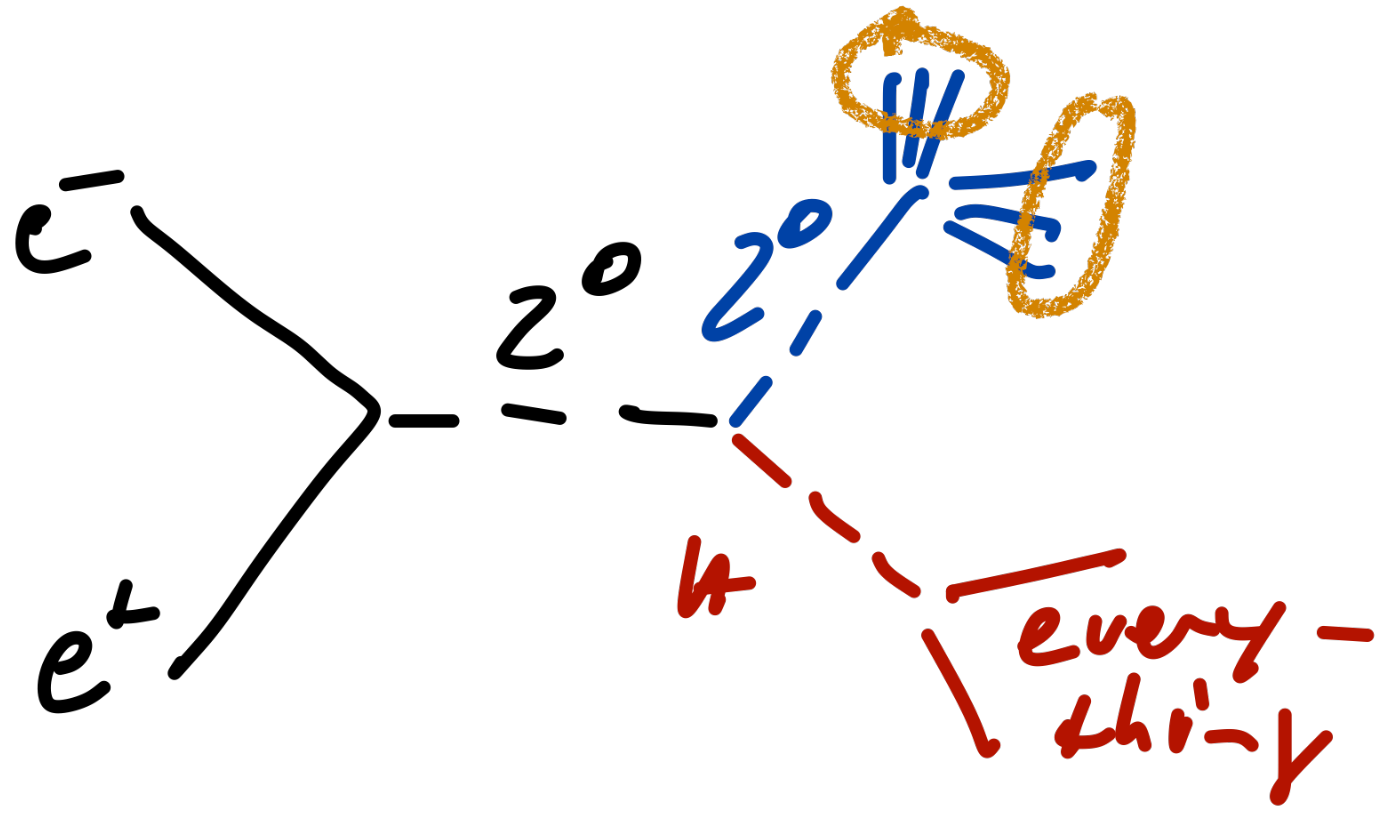






- HZ events can be used to constrain invisible Higgs decays: Limits on the few per mille level

example from CLIC

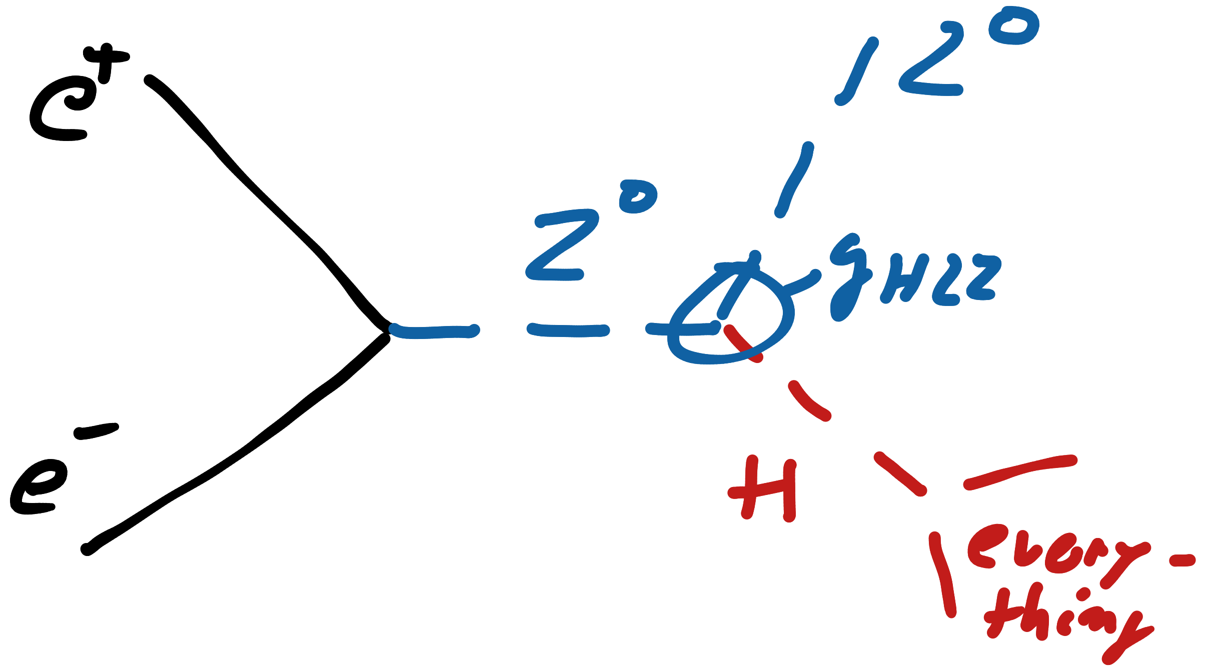
Precision Measurements of Couplings

Exploring the Higgs Sector

- The main measurements to make:

σ for Z recoil measurements

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



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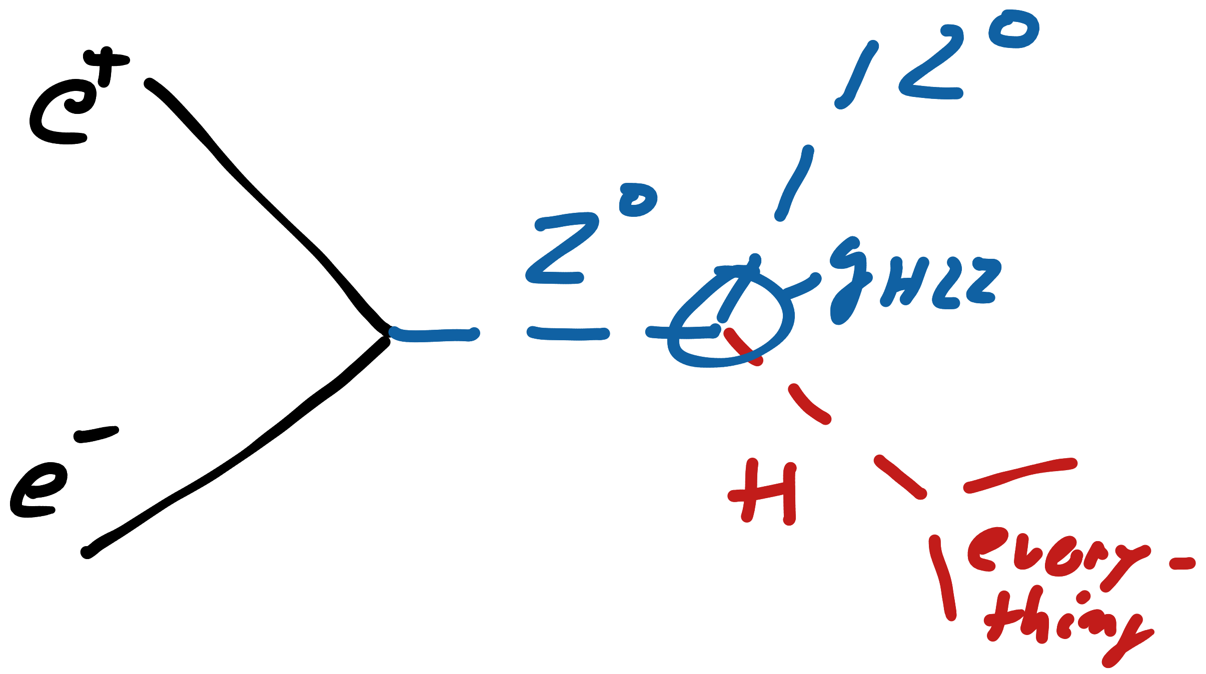

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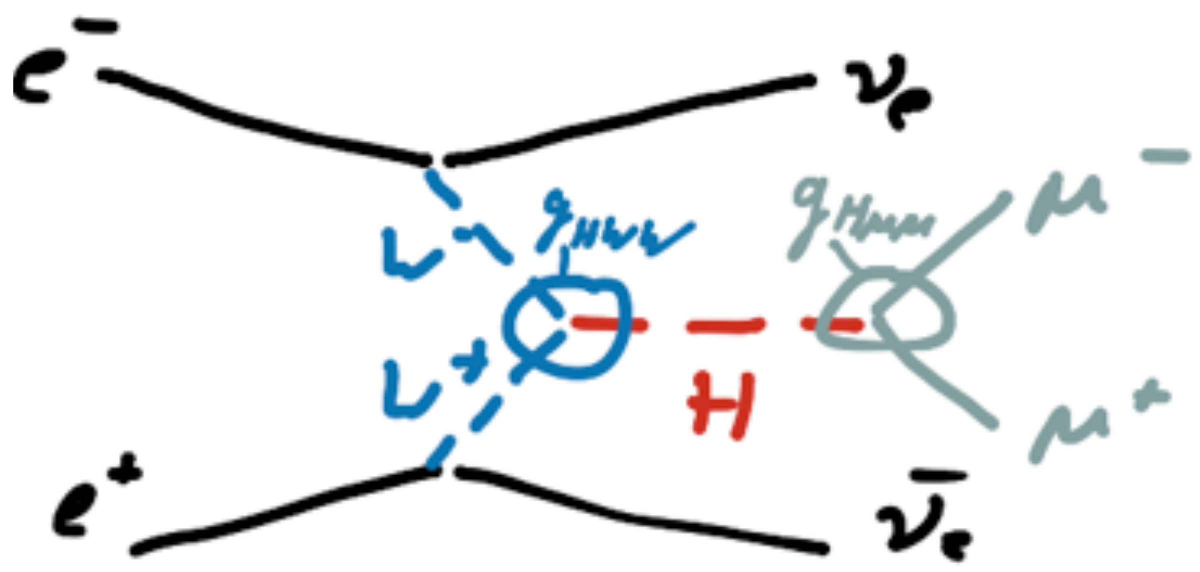
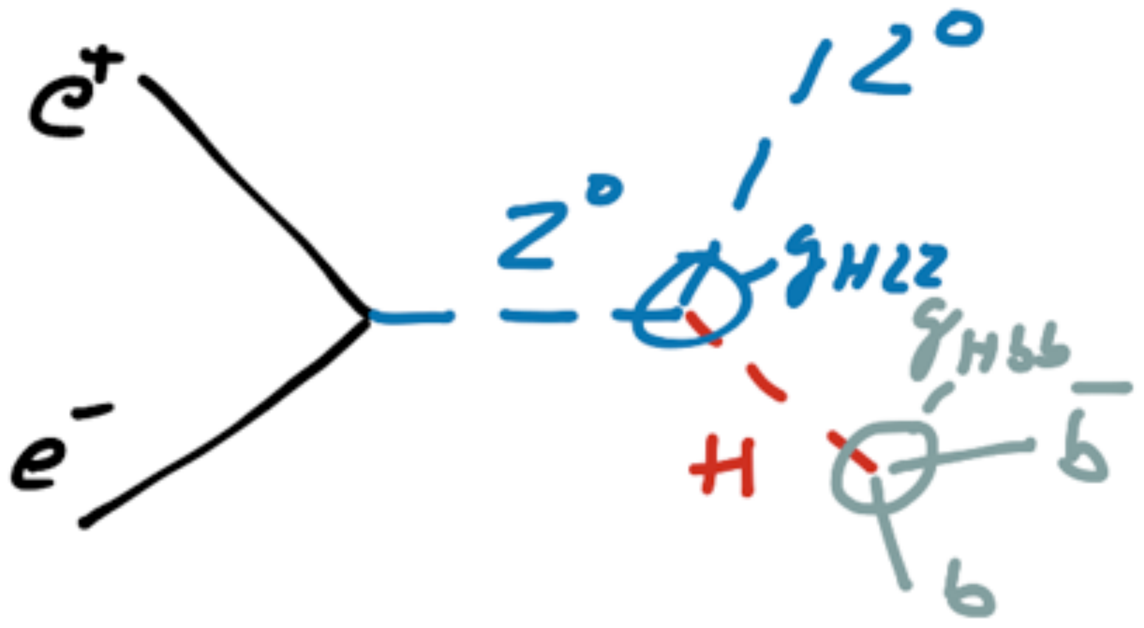
σ x BR for specific Higgs decays

$$\sigma \times \mathrm{BR}(\mathrm{H} \to \mathrm{ff}) \propto \frac{g^2_{\mathrm{Hii}} g^2_{\mathrm{Hff}}}{\Gamma_{\mathrm{tot}}}$$





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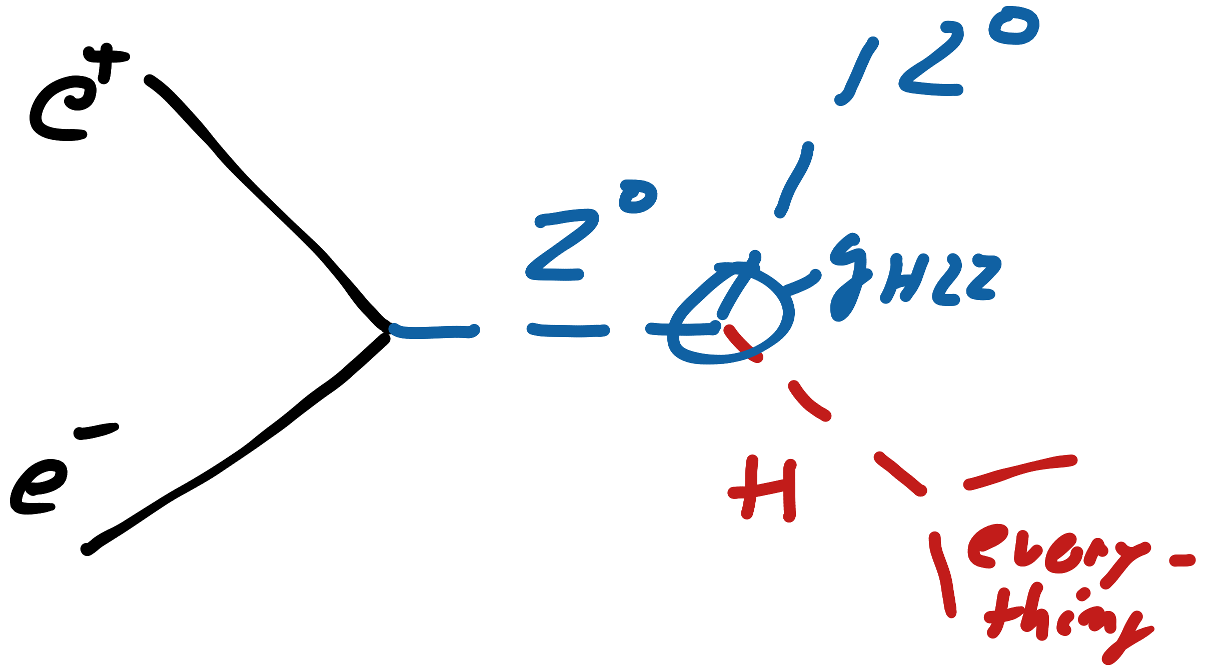

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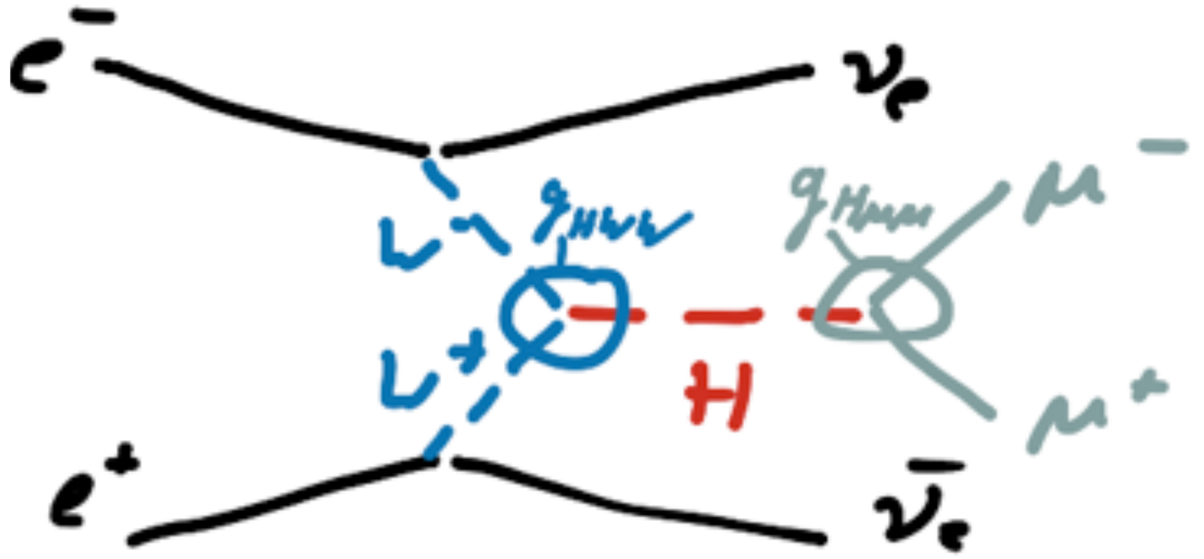
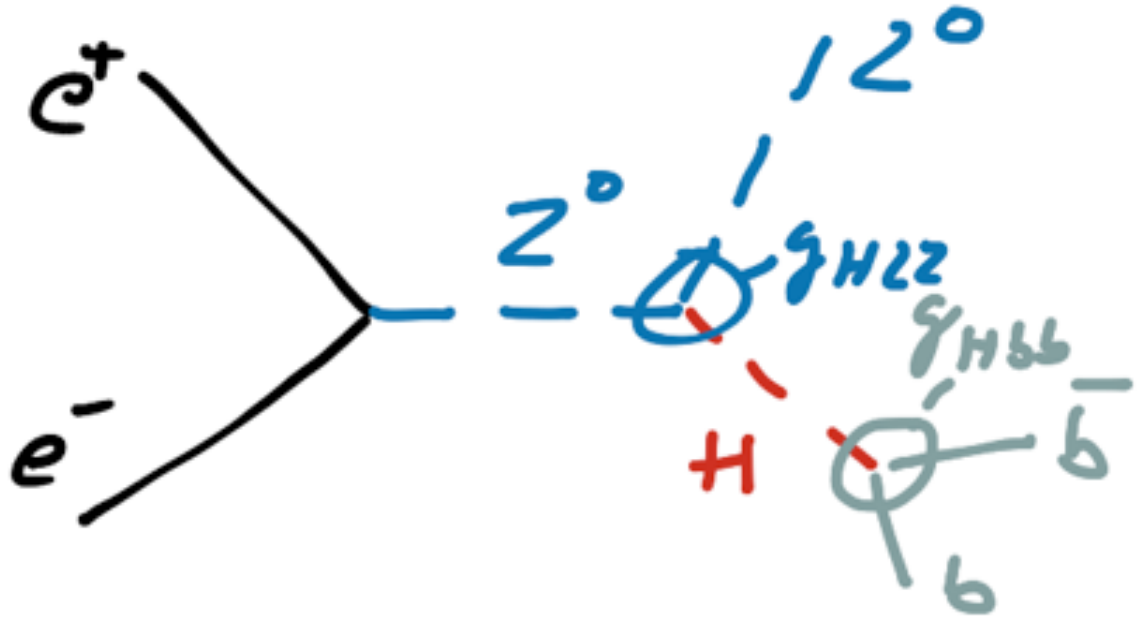
σ x BR for specific Higgs decays

$$\sigma \times \text{BR}(\text{H}\rightarrow \text{ff}) \propto \frac{g^2_{\text{Hii}}\, g^2_{\text{Hff}}}{\Gamma_{\text{tot}}}$$





measure couplings to fermions and bosons using production and decay

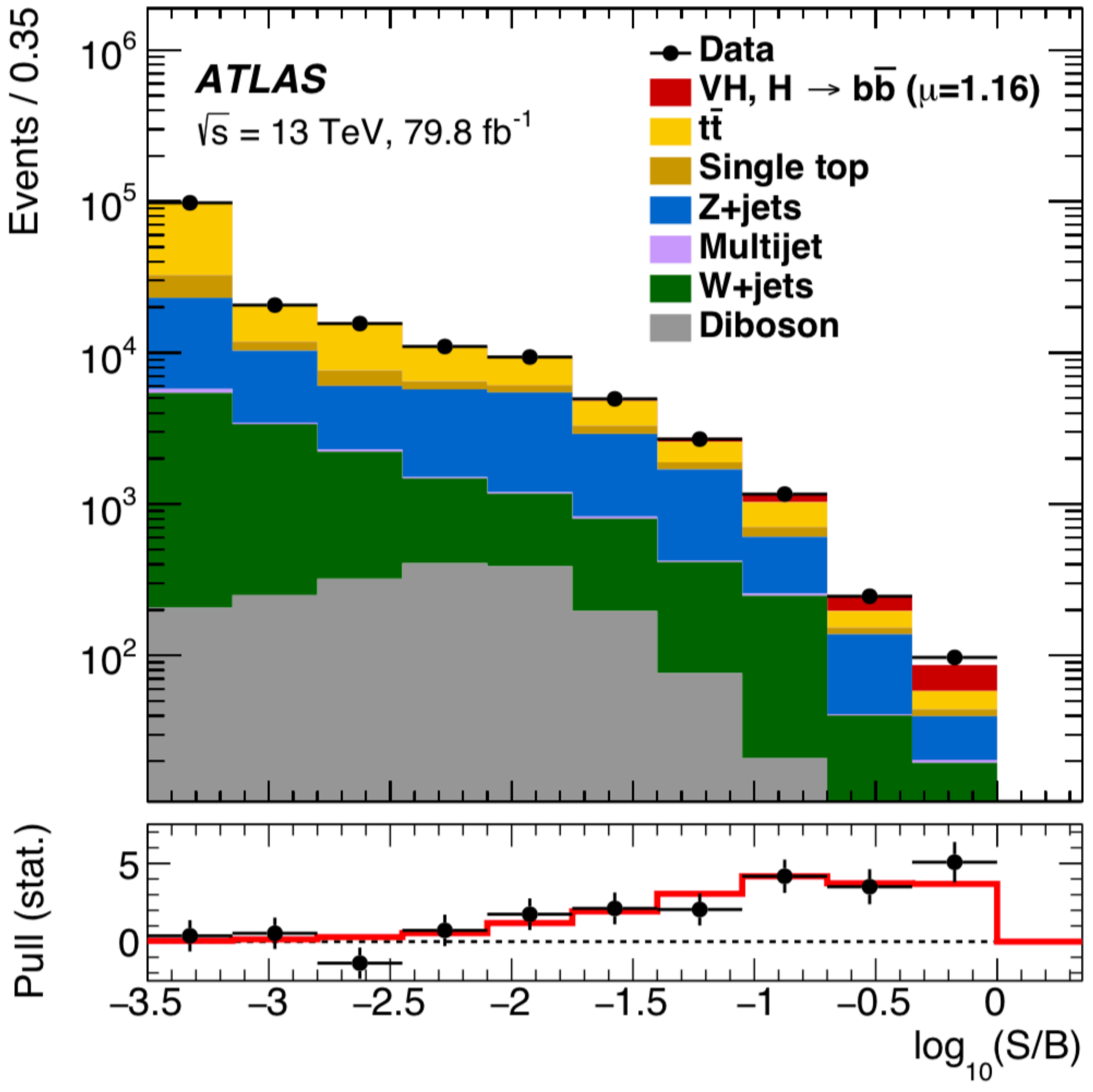
➯ can be made model-independent in combination with the measurement of the HZ coupling in recoil

Unique Measurements at Lepton Colliders

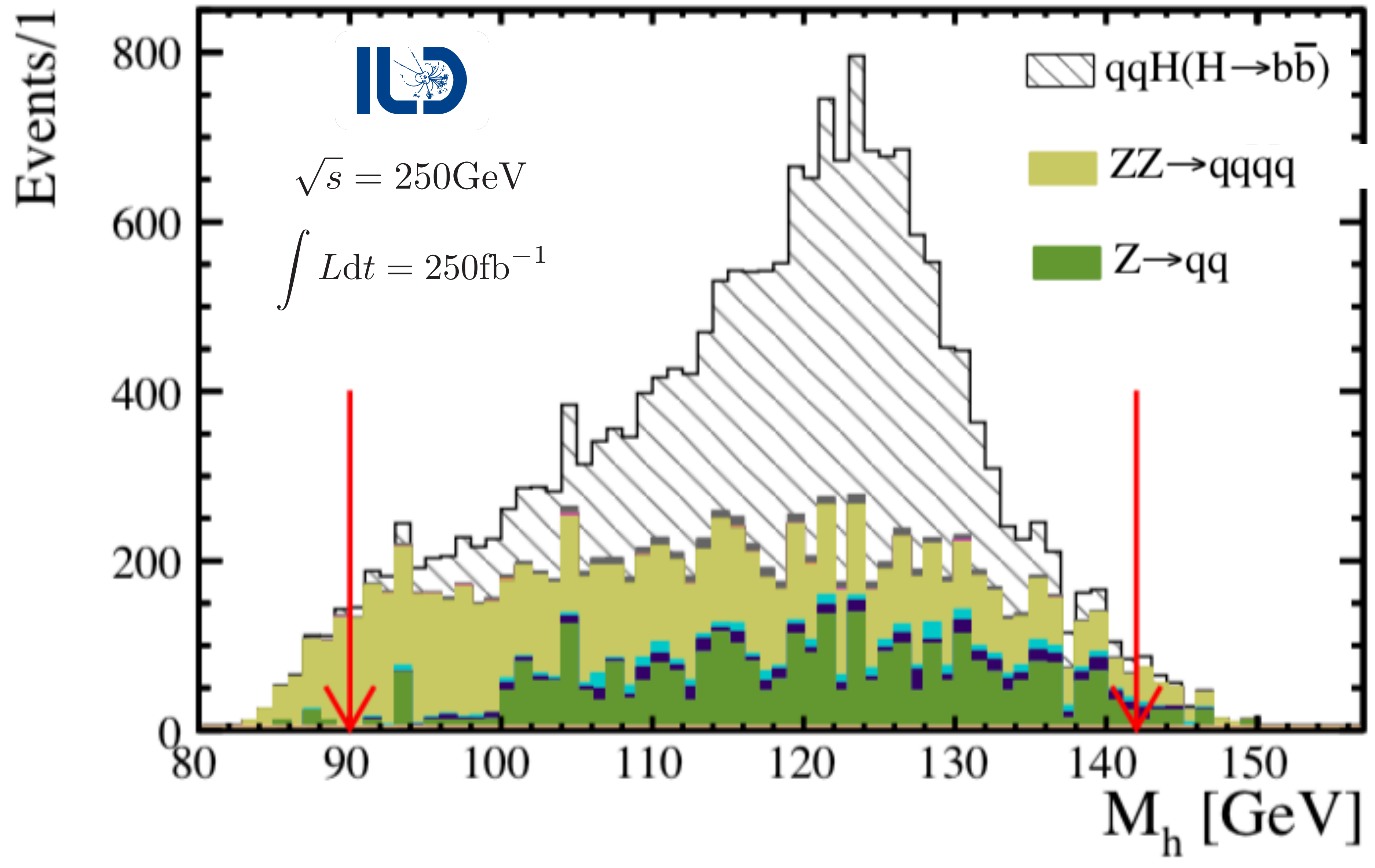
Enabled by the clean environment

- 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

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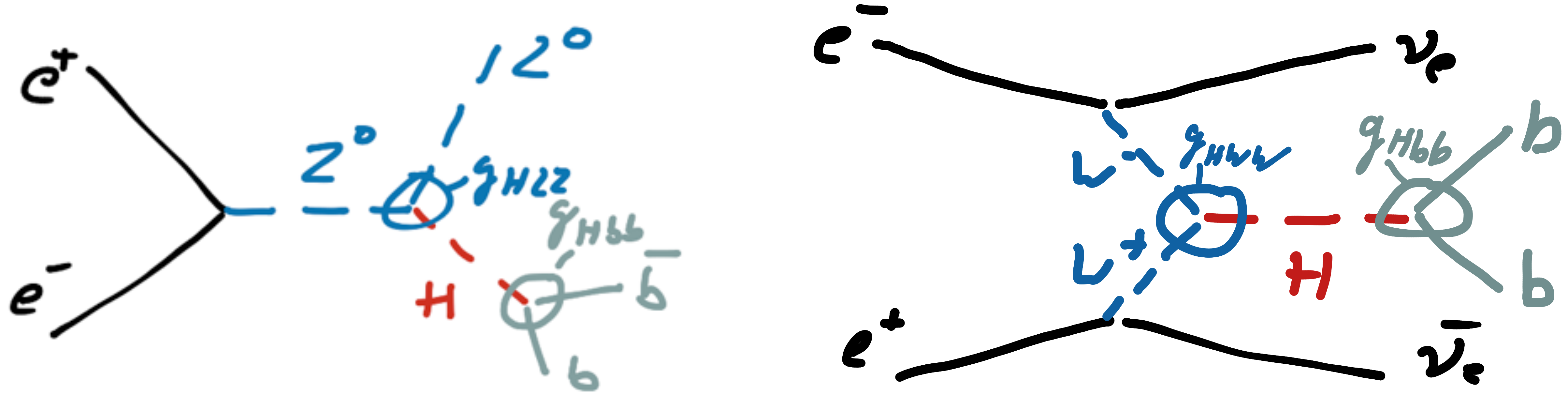
- Higgs decays to jets: difficult (or impossible) at hadron colliders

  Measurement of H->bb, cc, gg

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



example from CLIC

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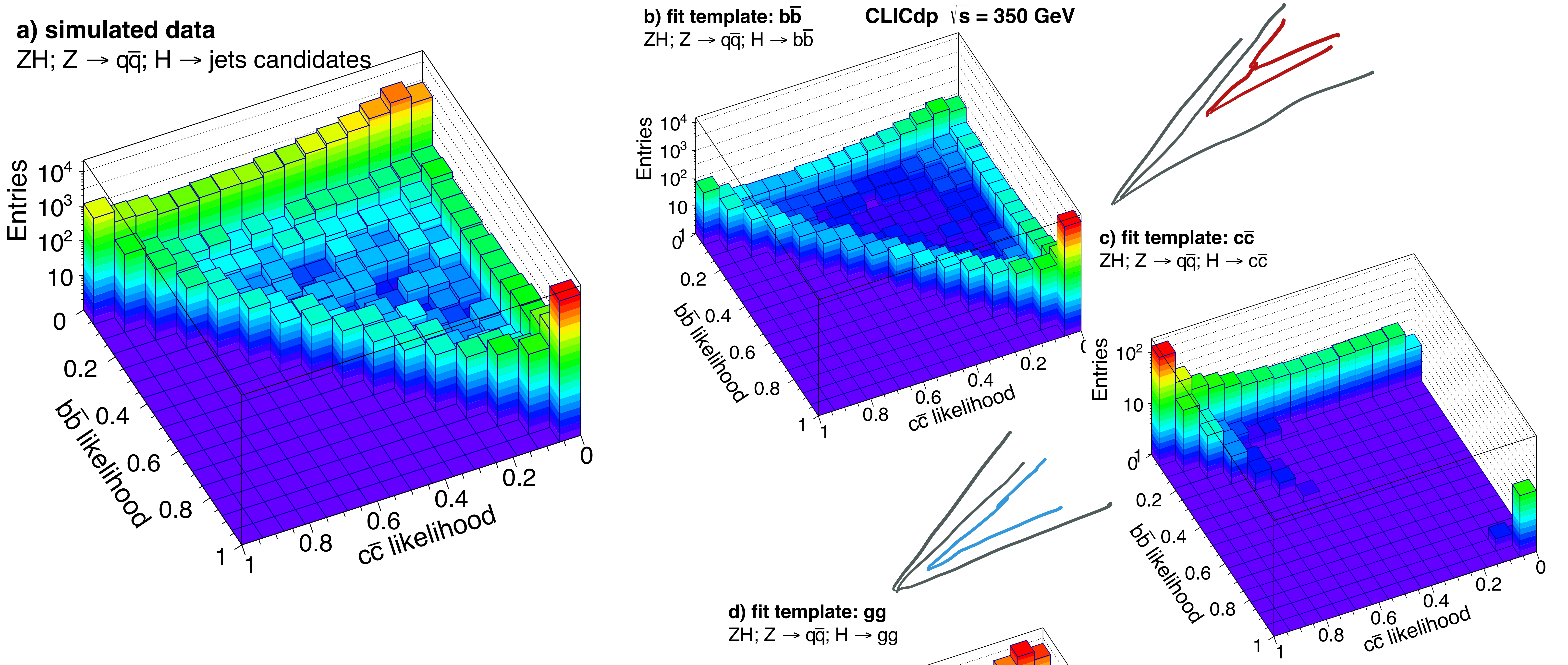

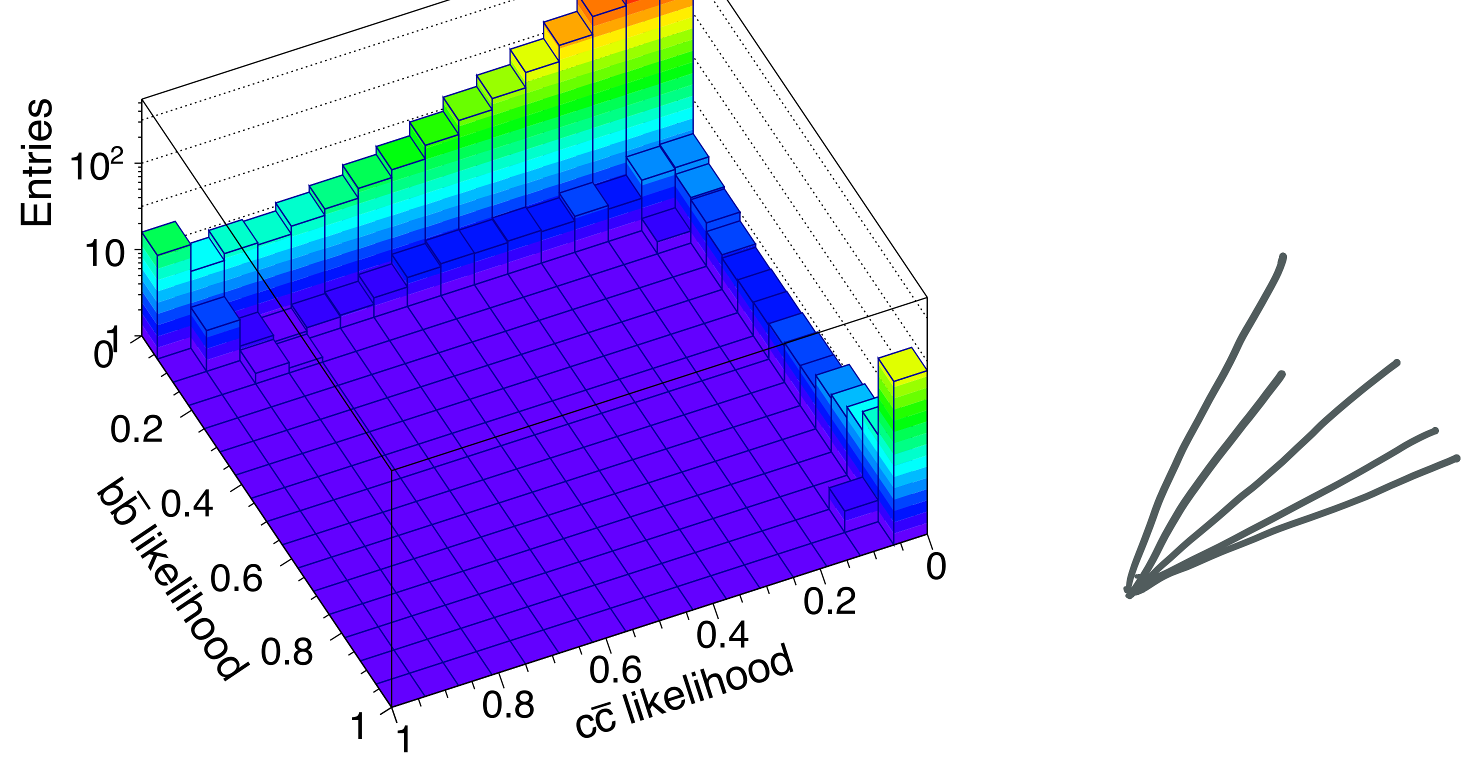

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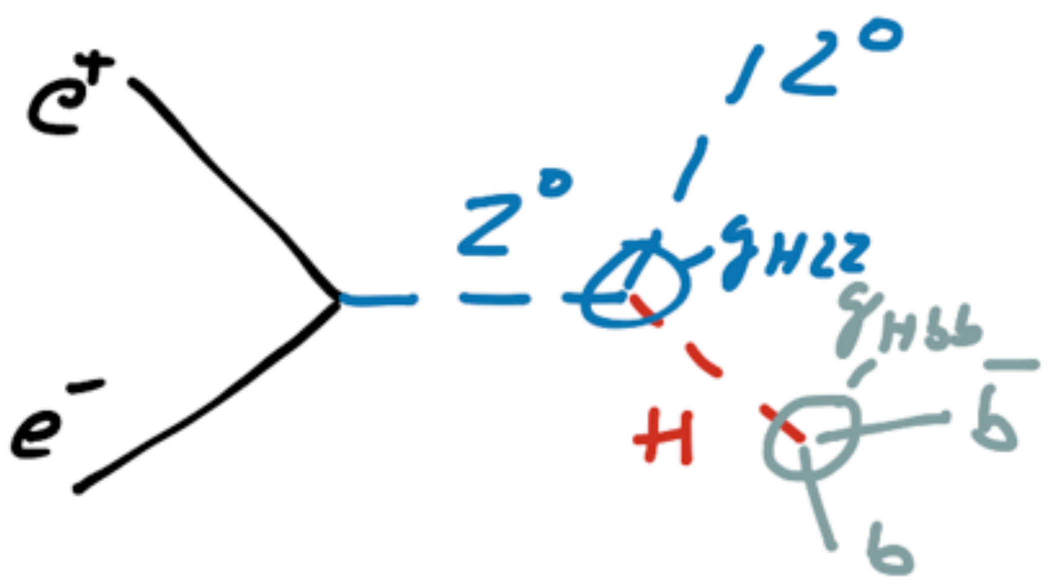
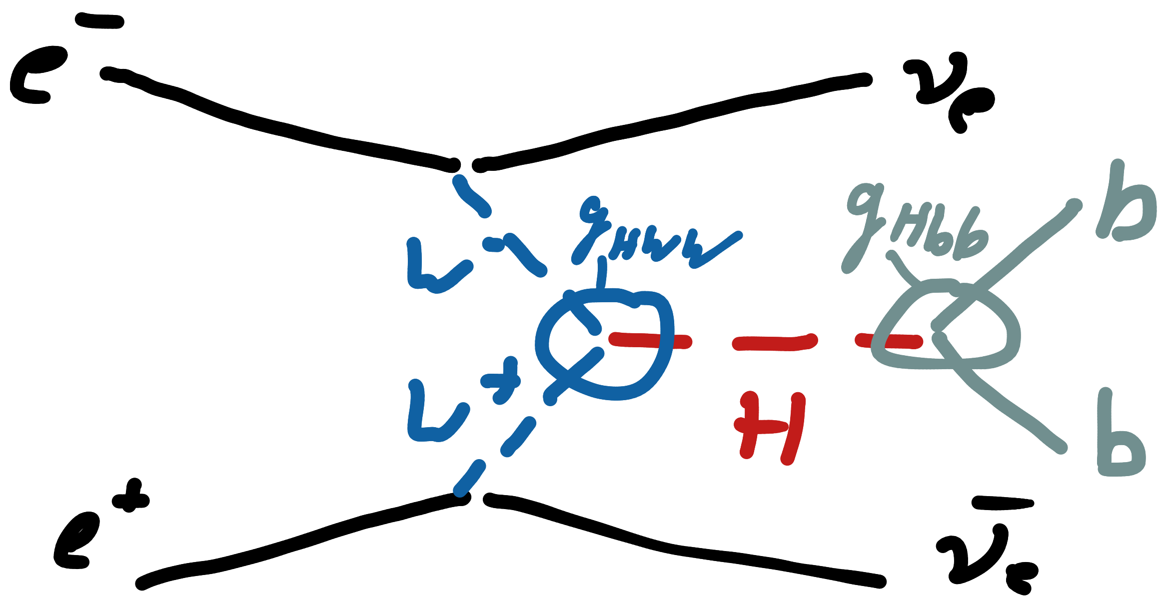
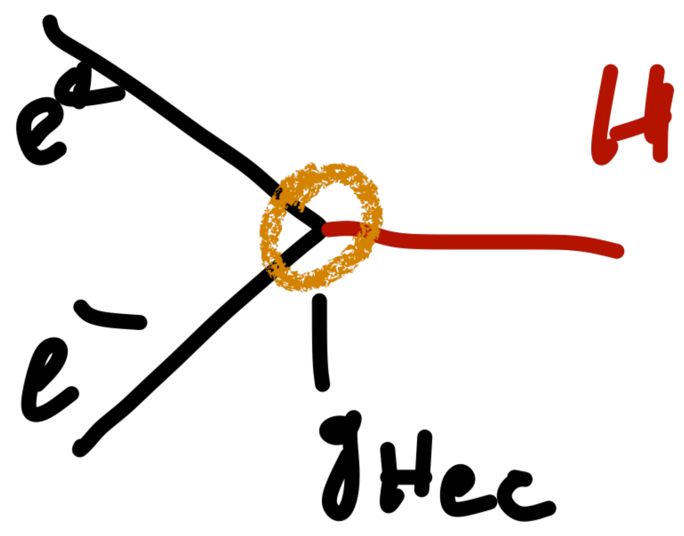


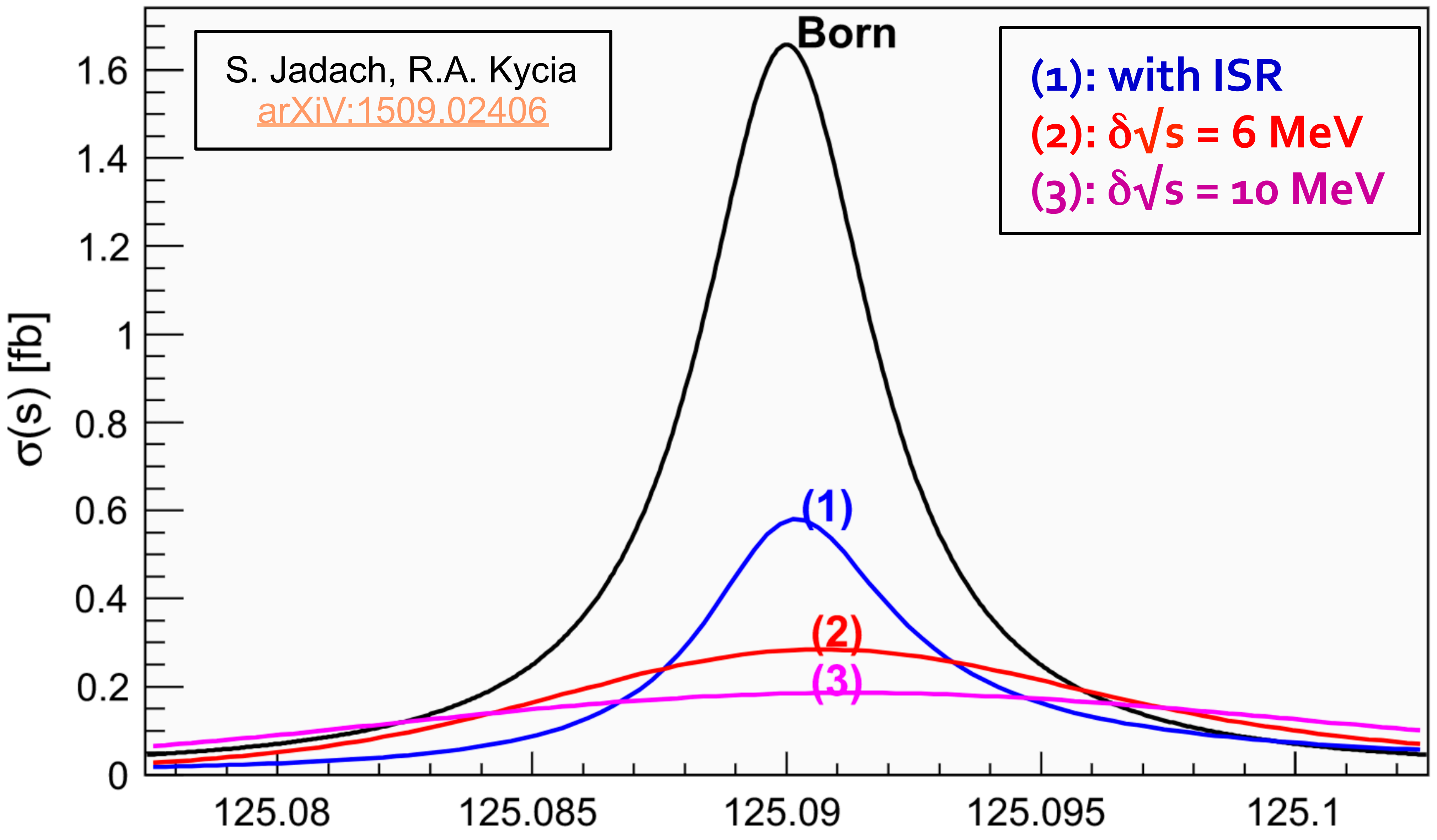


Accessing the Couplings to First Generation Leptons

A long shot - Requires extreme Luminosities

- 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





With special monochromatization setups for FCCee:
Energy spreads of 10 MeV / 6 MeV may be achievable, at significantly reduced luminosity (7 ab^{-1}/year / 2 ab^{-1}/year)

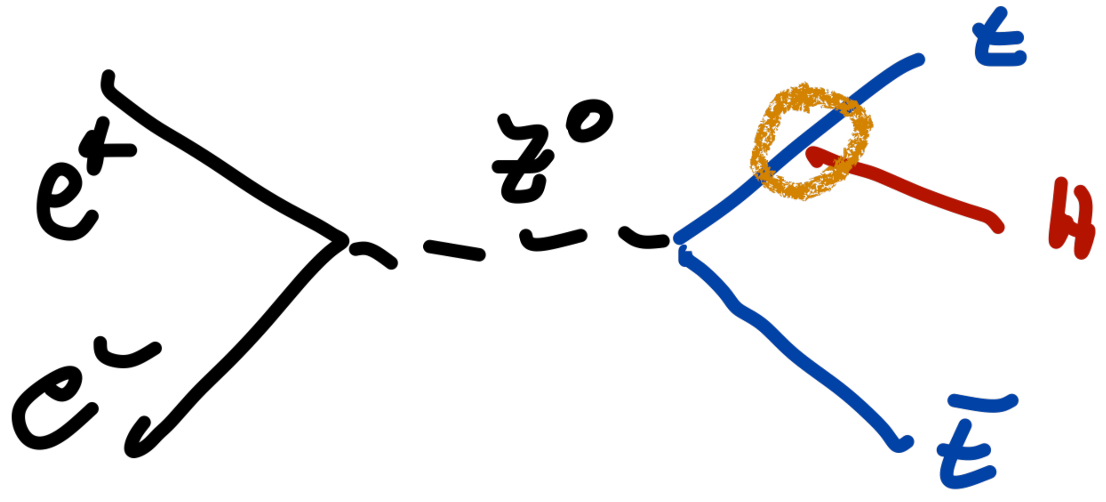
NB: signal sits on very large backgrounds

For both options of the energy spread: Expected signal significance ~ 0.4 σ / $\sqrt{t/[\text{years}]}$

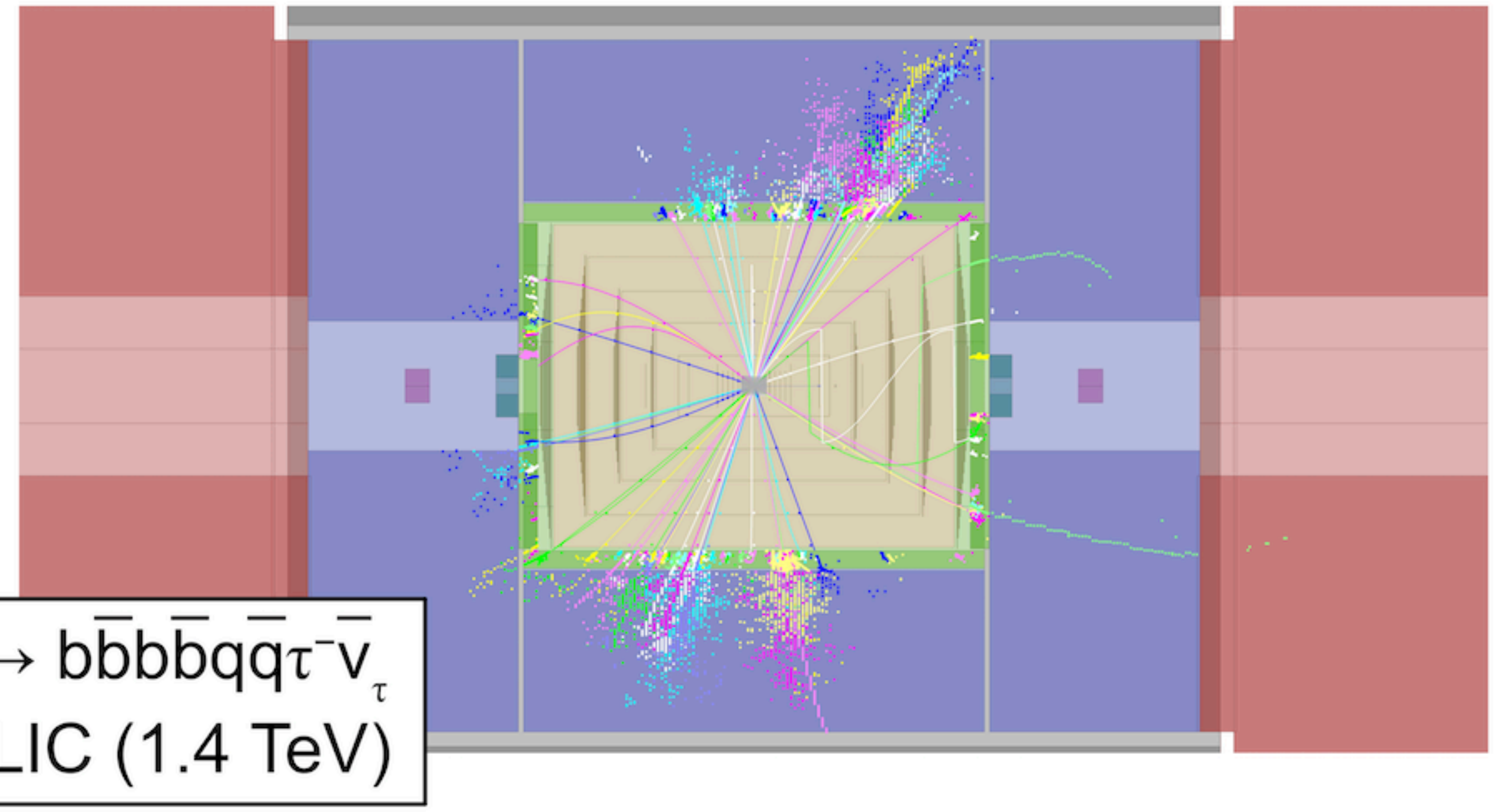
➯ Upper limit of 2.5 x SM at 95% CL reachable in ~ 5 years (one IP) of dedicated running

Directly measuring the Coupling to the Top Quark

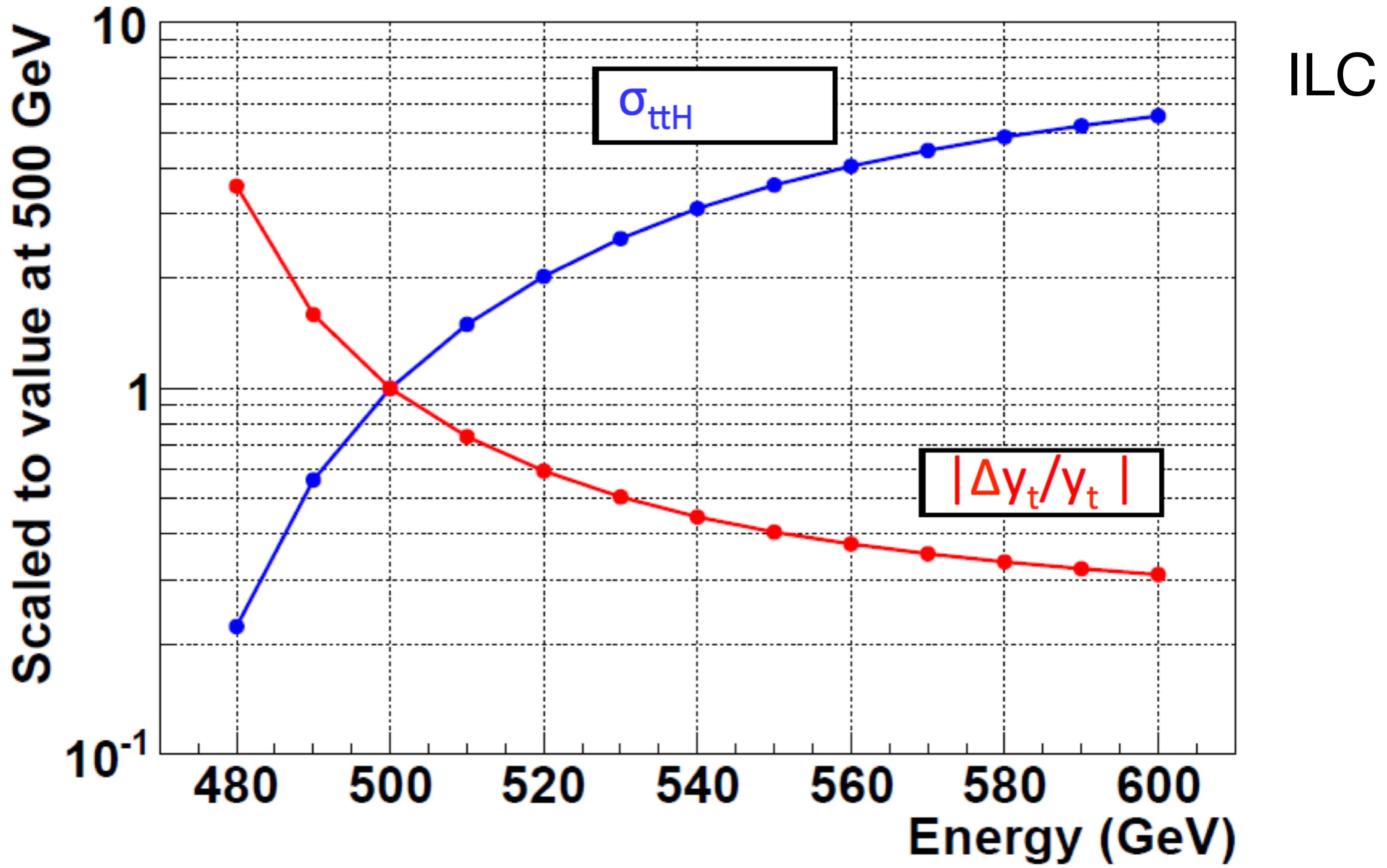
Requires higher Energies



- 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)



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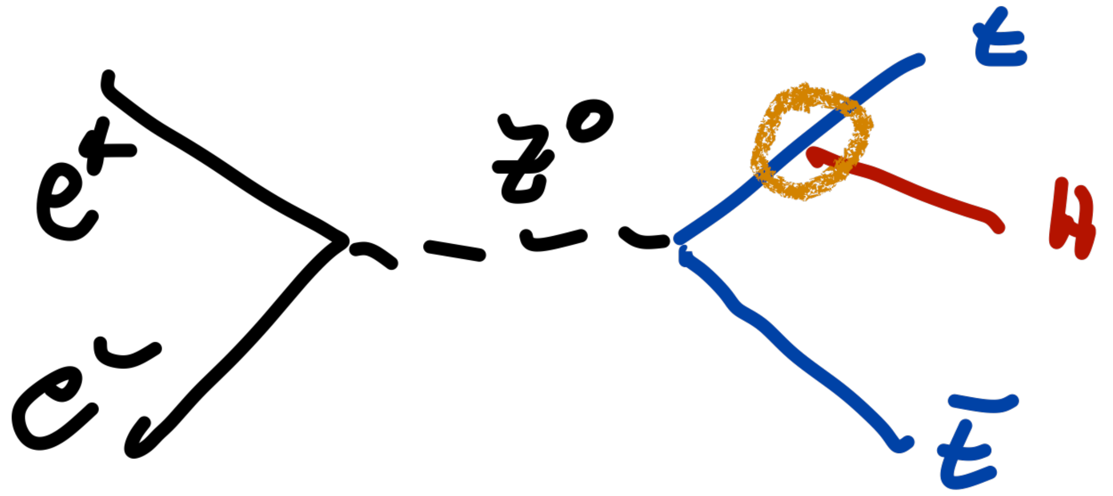

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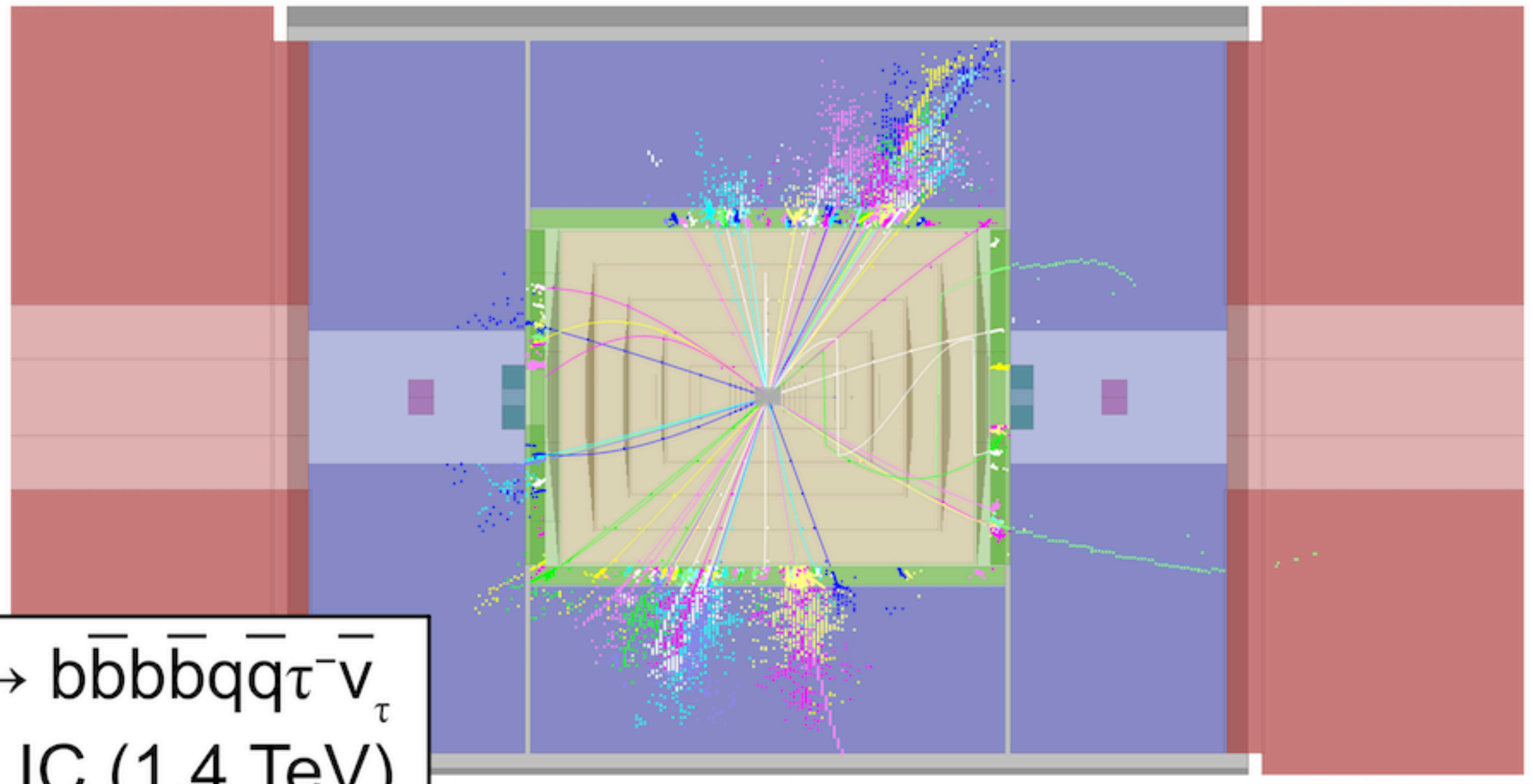

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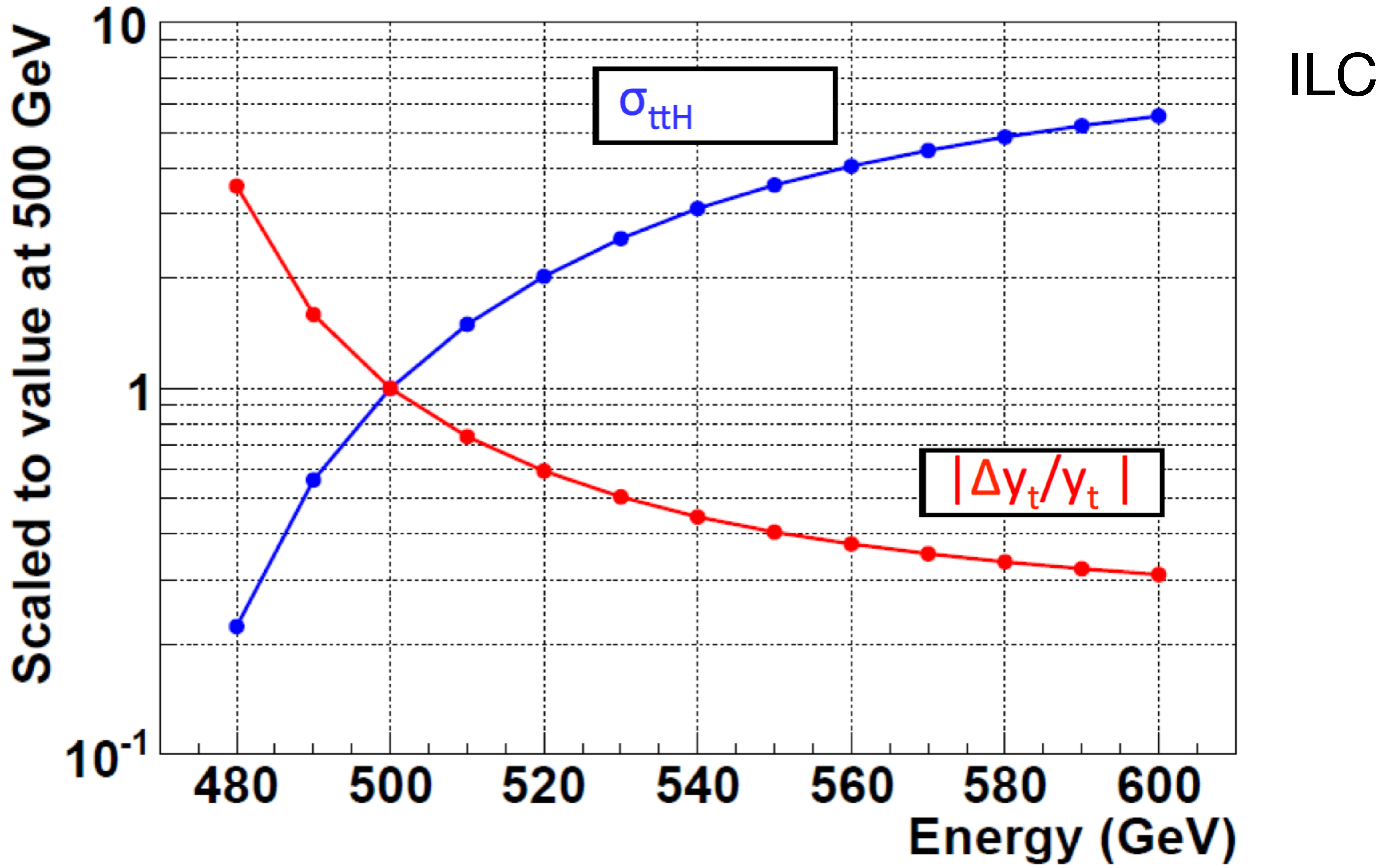


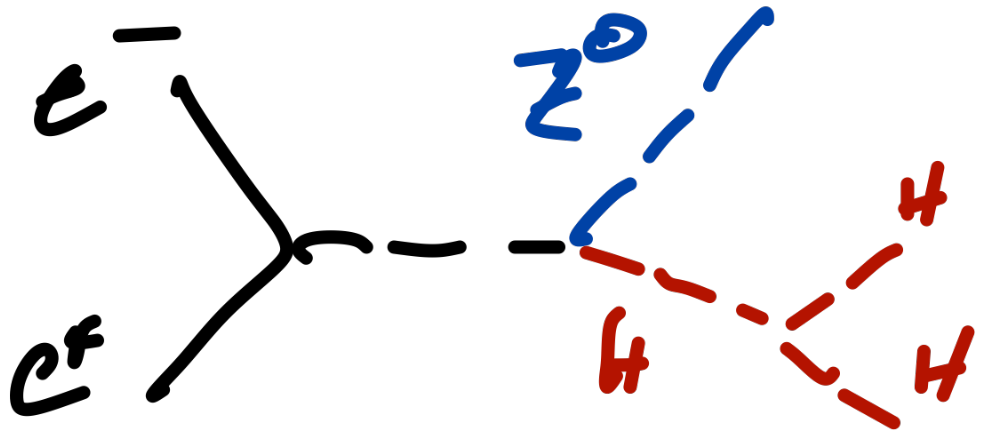
ILC: $\Delta g_{ttH}/g_{ttH}$ ~ 6.3% with 4 ab^{-1} @ 500 GeV
would be ~ 3% @ 550 GeV
(and ~ 13% @ 485 GeV: achieving design energy critical!)

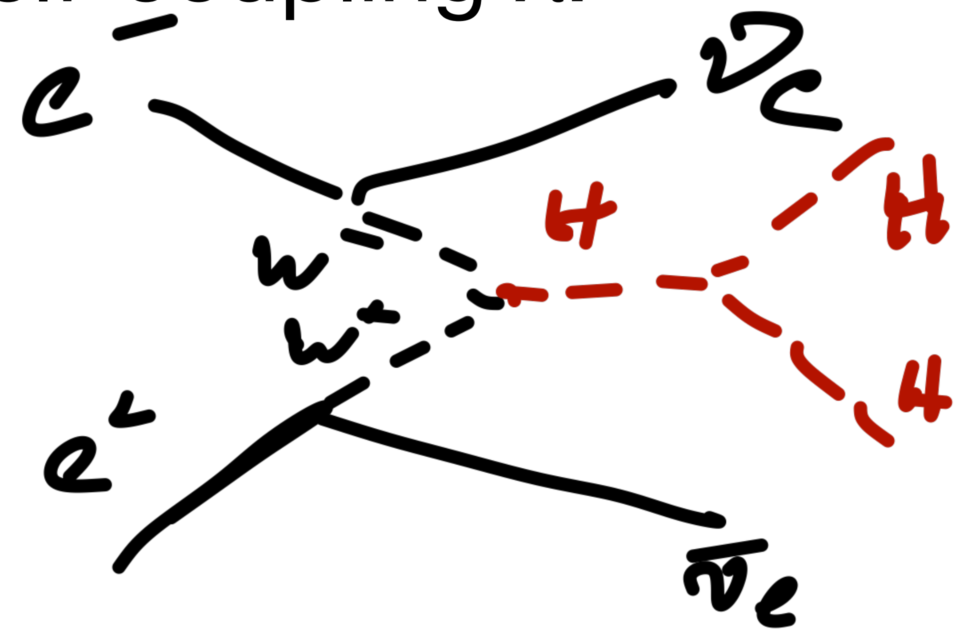
CLIC: $\Delta g_{ttH}/g_{ttH}$ ~ 2.9% with 2.5 ab^{-1} @ 1.4 TeV

Measuring the Higgs Self-Coupling

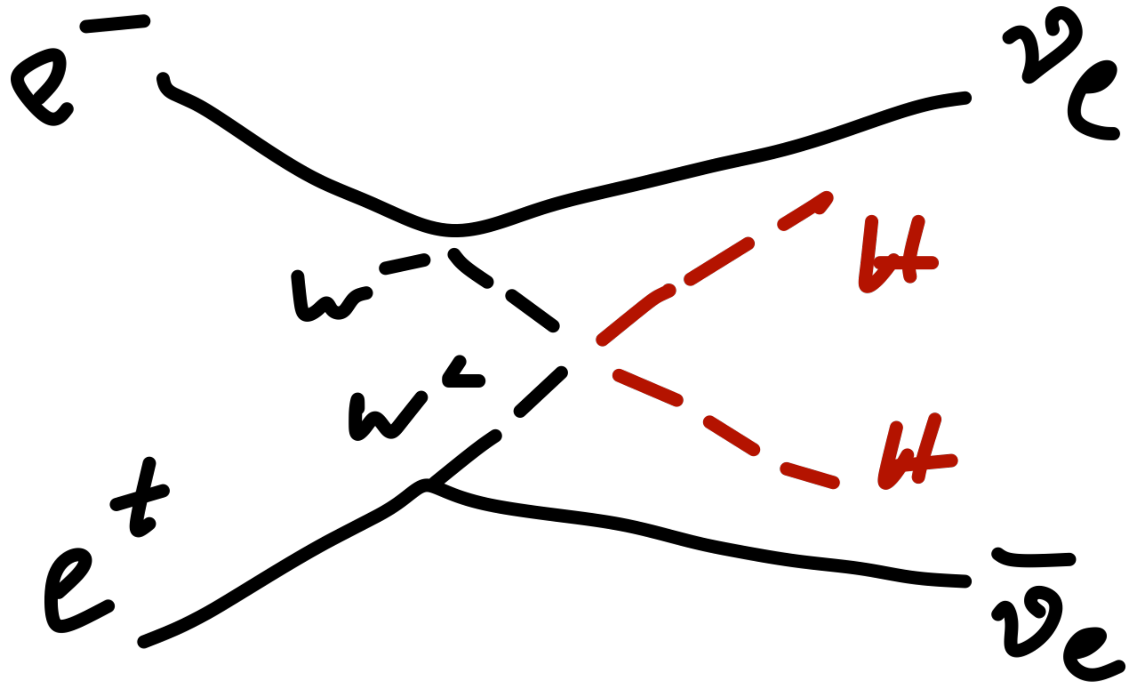
Requires higher Energies - may be the ultimate Challenge in Higgs Physics

- Two processes with double Higgs final states provide access to the self-coupling λ:





the final state also receives contributions from the quartic coupling



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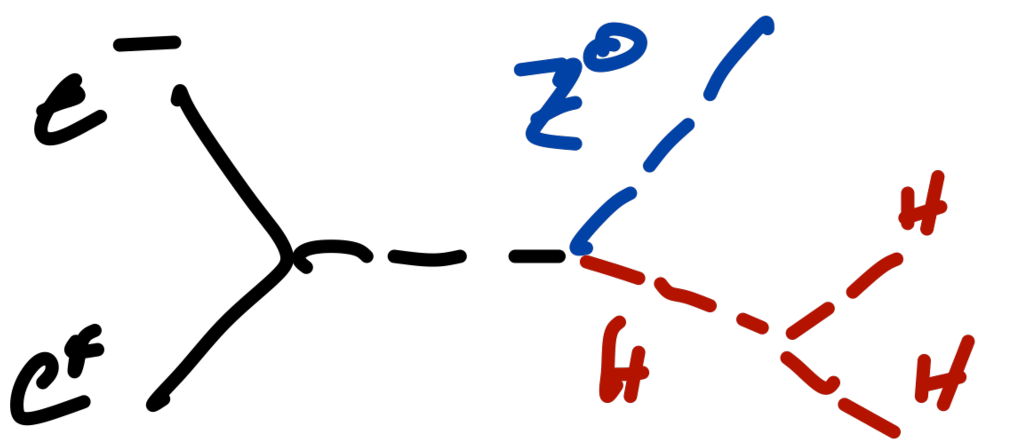

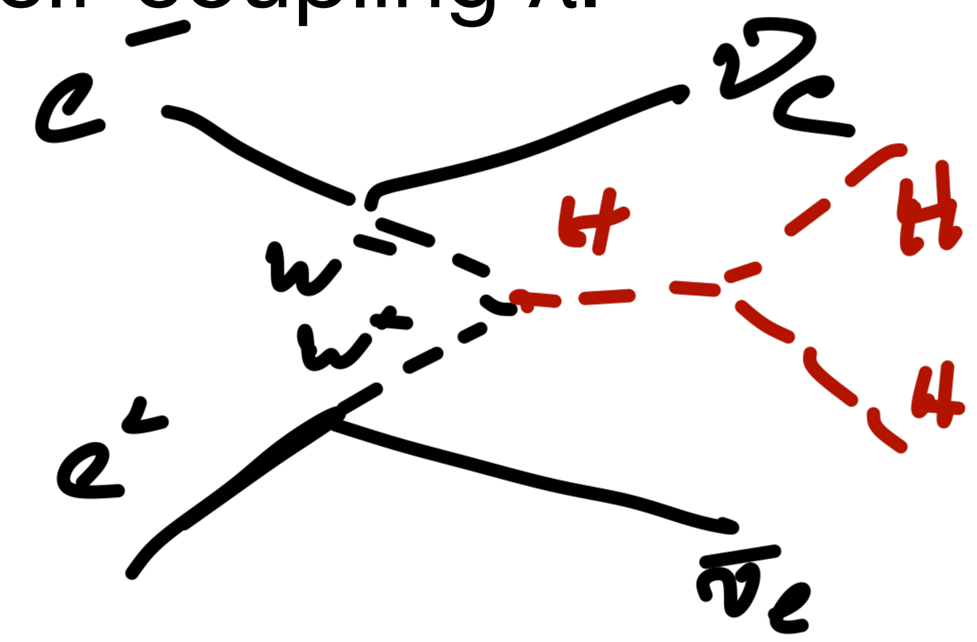

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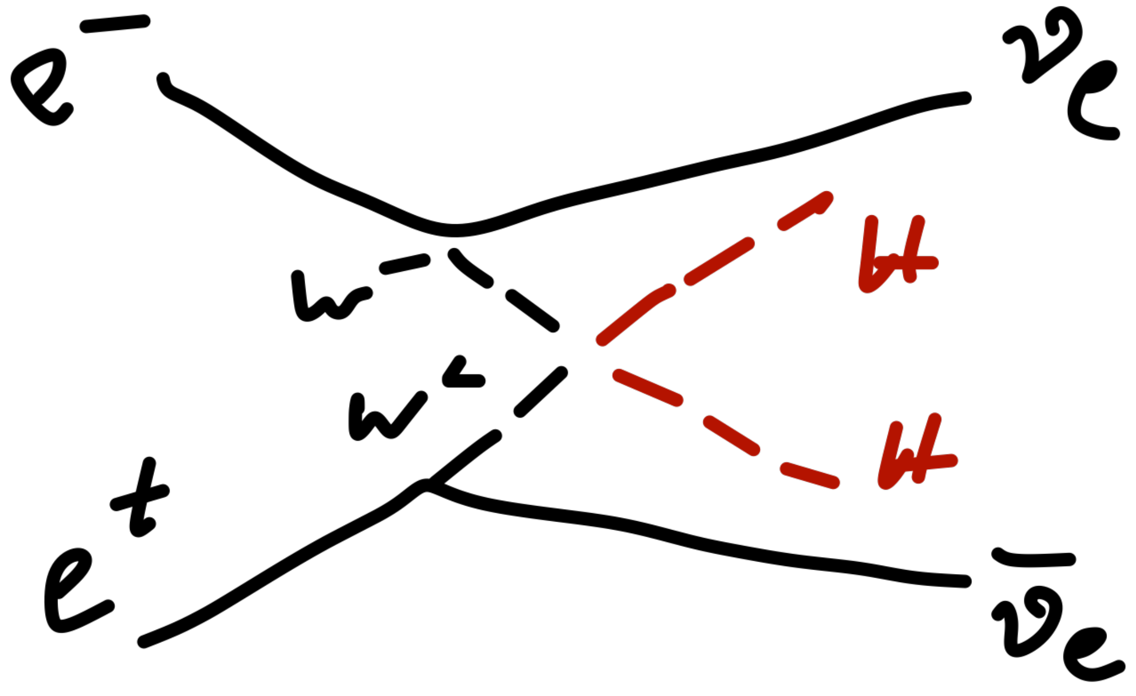
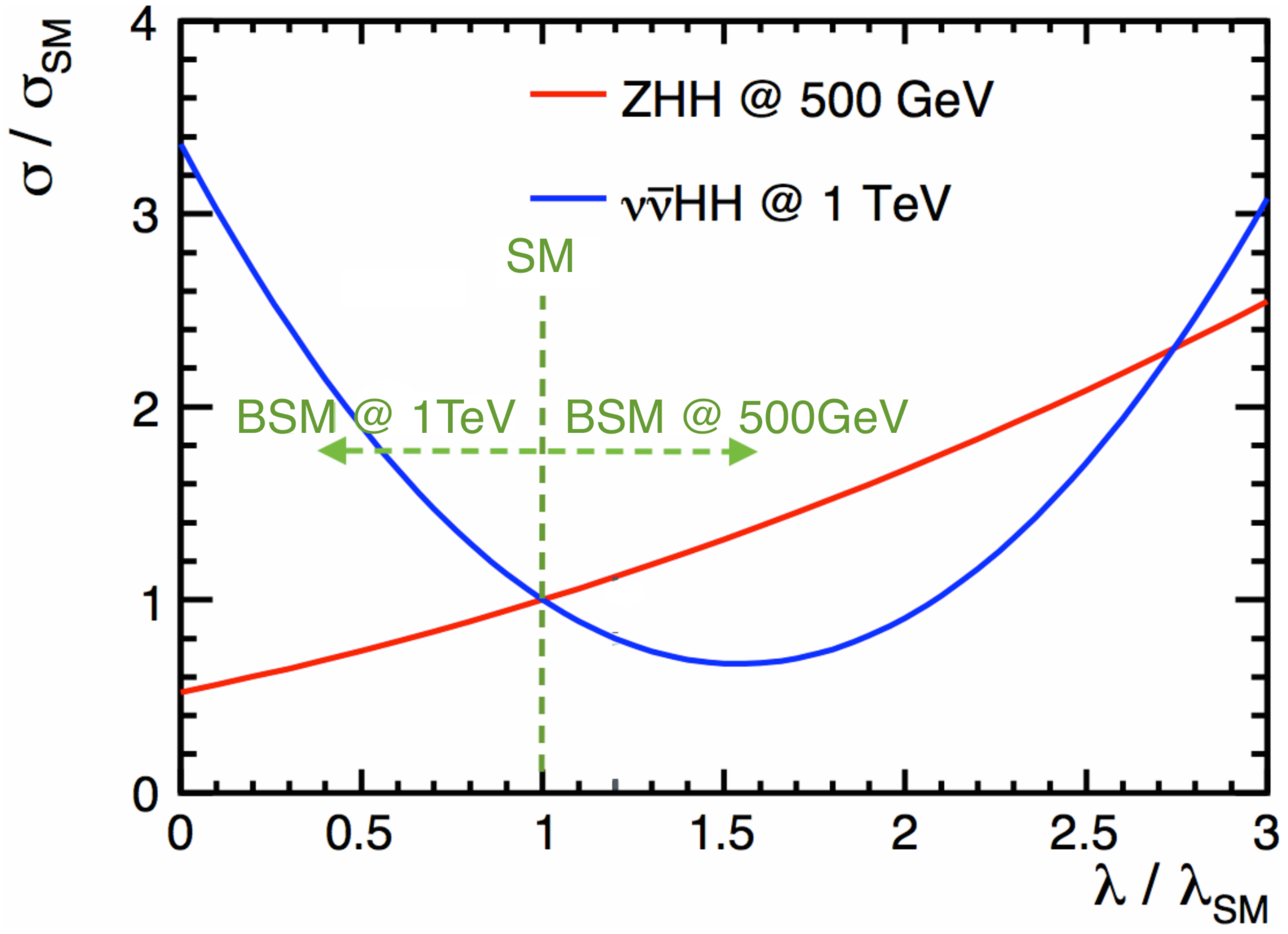


cross section depends non-linearly on λ, measurements at different energies / of different processes lift degeneracies



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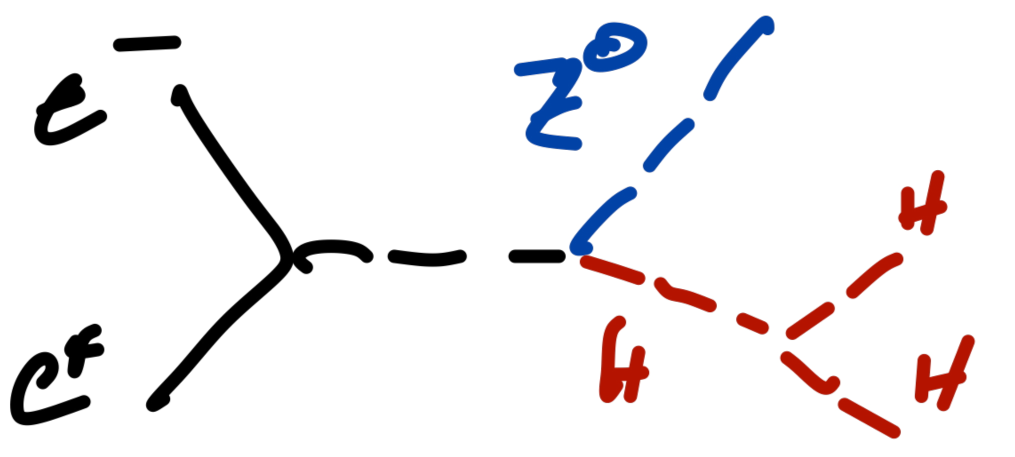

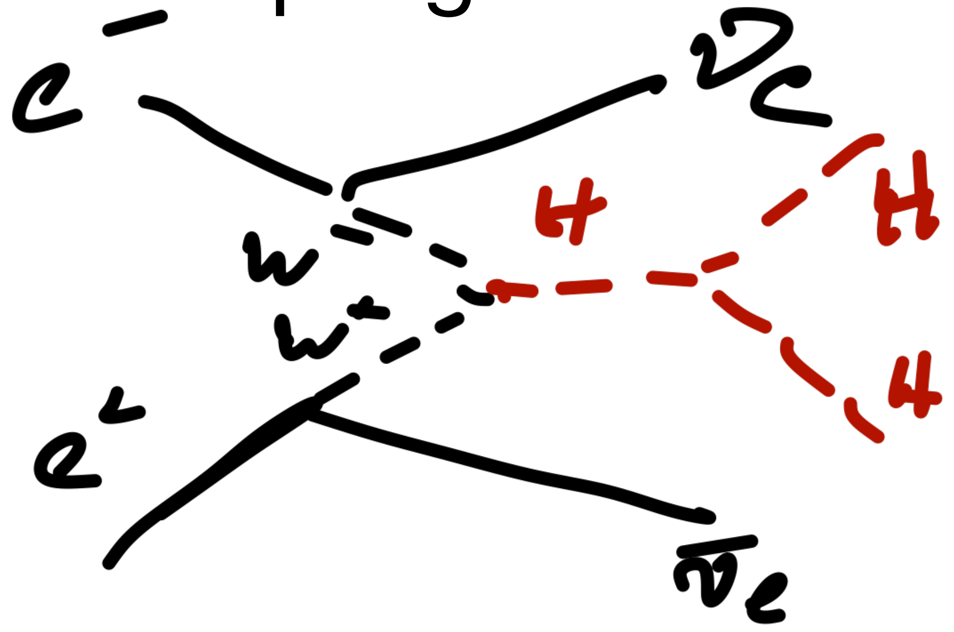

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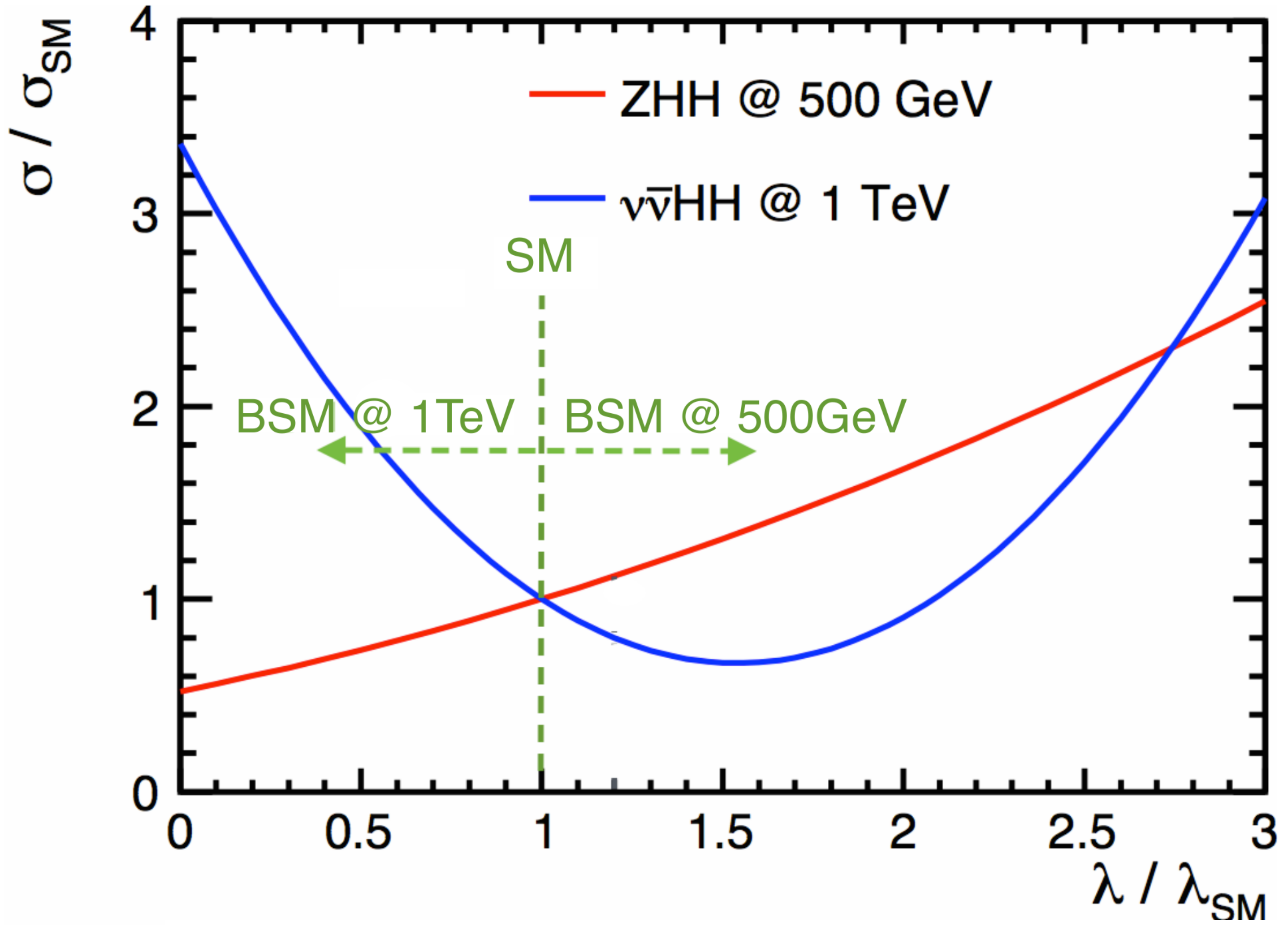

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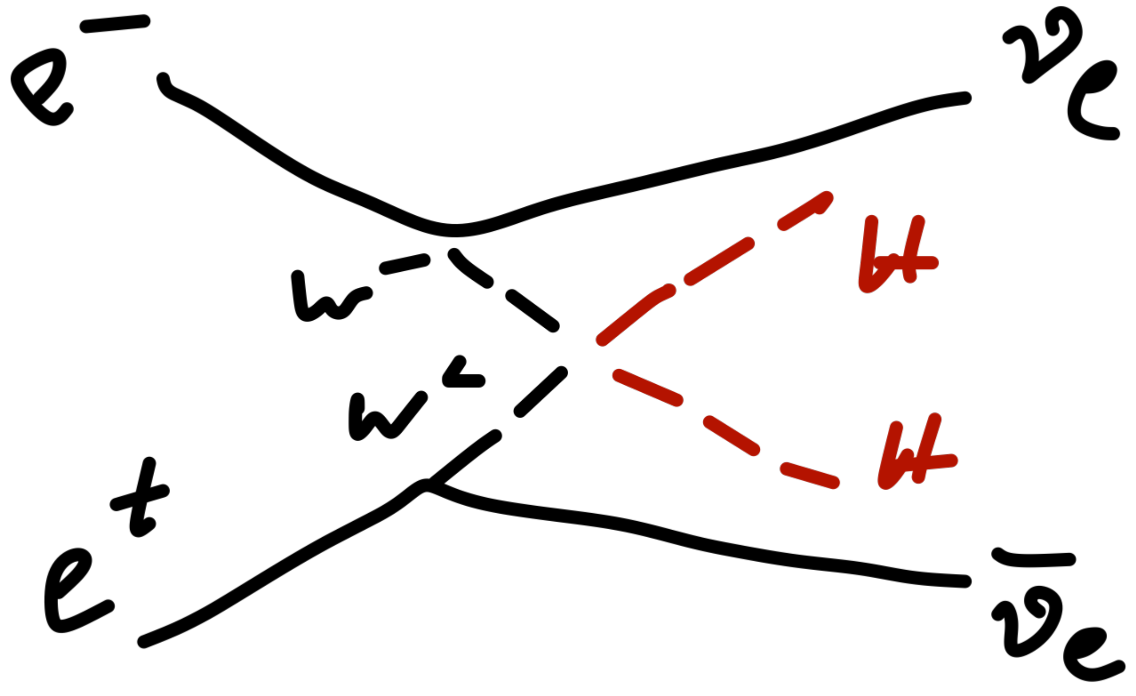


ILC: Using the ZHH process

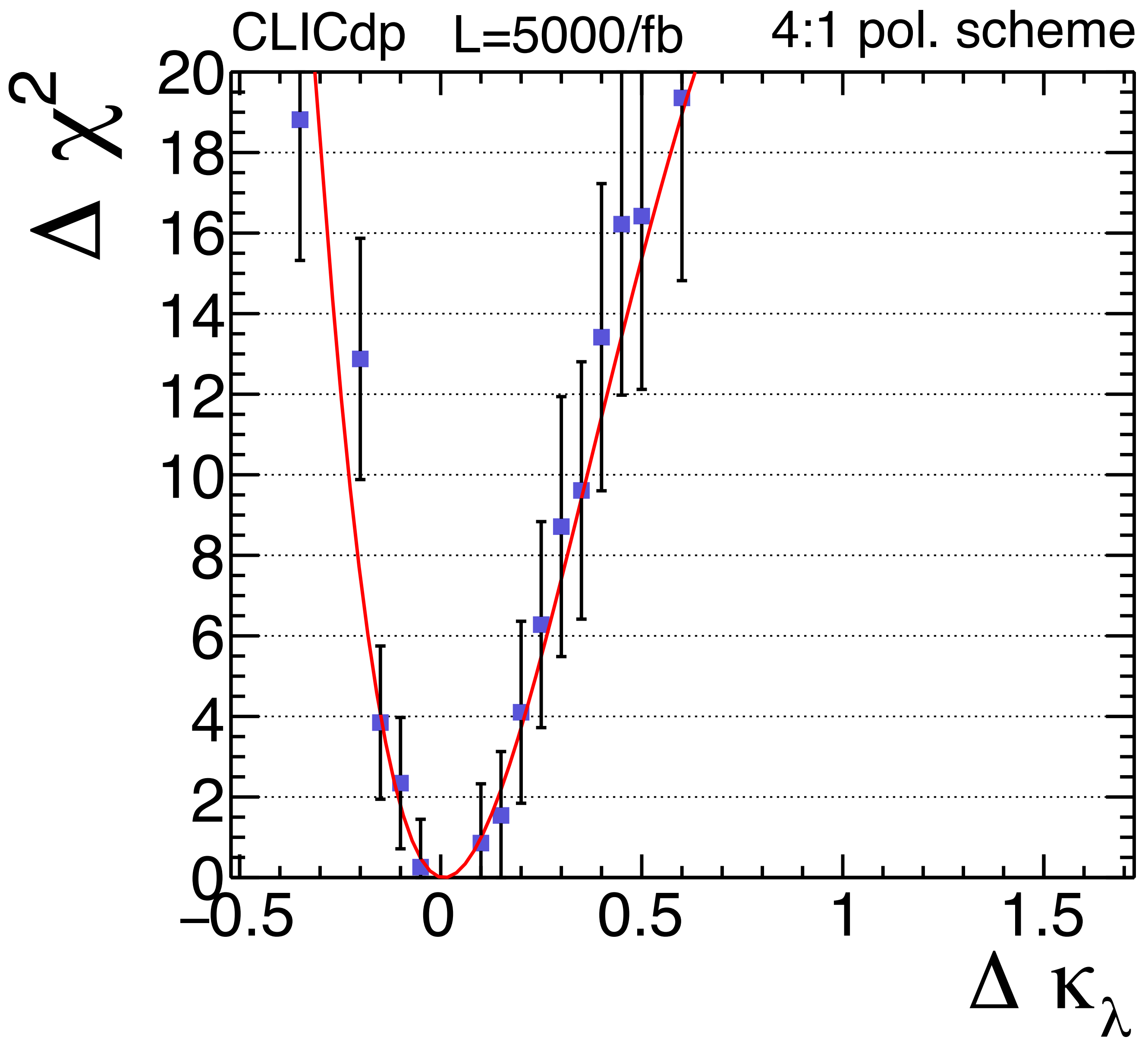
$\Delta\lambda/\lambda$ ~ 27% with 4 ab^{-1} @ 500 GeV

CLIC: A combination of ZHH (1.4 TeV) and ννHH (1.4 TeV + 3 TeV), combining cross section and M$_{HH}$ differential

$\Delta\lambda/\lambda$ ~[-7%, +11%] with

2.5 ab^{-1} @ 1.4 TeV, 5 ab^{-1} @ 3 TeV

➪ ~ 10% measurement feasible - but only at multi - TeV collider



Interpreting Higgs Measurements

A Word on Fits

- The Higgs coupling measurements at any present and future collider unfold their full potential in global fits of all observables - possibly beyond Higgs measurements alone
  - The evaluation of the potential of future colliders is based on such fits using projected precisions on various Higgs (and other) measurements as input

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Typical fits used in this context:

- **“Model-independent” fit**

minimize a χ² with all measurements:

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

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

$$C_{\mathrm{ZH,H}\to b\bar{b}} = \frac{g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hbb}}}{\Gamma_{\mathrm{H}}}$$

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ΔF$_i$: uncertainty of measurement (σ or σxBR)

total width as a free parameter: no constraints imposed on BSM decays

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

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

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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

Perspectives on Precision

Still in flux - Meant as a rough Guide

- Comparisons of the potential of different colliders are non-straightforward: The projections are based on different levels of realism / pessimism / optimism in detector modeling, analysis techniques, systematic uncertainties and machine parameters / running scenarios,…

  Here: Taking the "model independent" fit results - combine the projected uncertainties on σxBR

	ILC 250	ILC 500	CLIC 380	CLIC 3 TeV	CEPC	FCCee 240	FCCee 365
$\delta g_{HZZ}/g_{HZZ}$	0.38	0.30	0.6	0.6	0.25	0.25	0.22
$\delta g_{HWW}/g_{HWW}$	1.8	0.40	1.0	0.6	1.4	1.3	0.47
$\delta g_{Hbb}/g_{Hbb}$	1.8	0.60	2.1	0.7	1.3	1.4	0.68
$\delta g_{Hcc}/g_{Hcc}$	2.4	1.2	4.4	1.4	2.2	1.8	1.23
$\delta g_{Hgg}/g_{Hgg}$	2.2	0.97	2.6	1.0	1.5	1.7	1.03
$\delta g_{H\tau\tau}/g_{H\tau\tau}$	1.9	0.80	3.1	1.0	1.5	1.4	0.80
$\delta g_{H\mu\mu}/g_{H\mu\mu}$	5.6	5.1		5.7	8.7	9.6	8.6
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	1.1	1.0		2.3	3.7	4.7	3.8
$\delta g_{Htt}/g_{Htt}$	-	6.7	-	3.0	-	-	-
$\delta\Gamma_H/\Gamma_H$	3.9	1.7	4.7	2.5	2.8	2.8	1.6

ILC 250: 2 ab^{-1} @ 250 GeV
ILC 500: +0.2 ab^{-1} @ 350 GeV
+ 4 ab^{-1} @ 500 GeV

CLIC 380: 1 ab^{-1} @ 380 GeV
CLIC 3 TeV: + 2.5 ab^{-1} @ 1.5 TeV
+ 5 ab^{-1} @ 3 TeV

CEPC: 5.6 ab^{-1} @ 240 GeV

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FCCee 365: + 1.5 ab^{-1} @ 365 GeV

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$\delta g_{Hcc}/g_{Hcc}$	2.4	1.2	4.4	1.4	2.2	1.8	1.23
$\delta g_{Hgg}/g_{Hgg}$	2.2	0.97	2.6	1.0	1.5	1.7	1.03
$\delta g_{H\tau\tau}/g_{H\tau\tau}$	1.9	0.80	3.1	1.0	1.5	1.4	0.80
$\delta g_{H\mu\mu}/g_{H\mu\mu}$	5.6	5.1		5.7	8.7	9.6	8.6
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	1.1	1.0		2.3	3.7	4.7	3.8
$\delta g_{Htt}/g_{Htt}$	-	6.7	-	3.0	-	-	-
$\delta\Gamma_H/\Gamma_H$	3.9	1.7	4.7	2.5	2.8	2.8	1.6

ILC 250: 2 ab^{-1} @ 250 GeV
ILC 500: +0.2 ab^{-1} @ 350 GeV
+ 4 ab^{-1} @ 500 GeV

CLIC 380: 1 ab^{-1} @ 380 GeV
CLIC 3 TeV: + 2.5 ab^{-1} @ 1.5 TeV
+ 5 ab^{-1} @ 3 TeV

CEPC: 5.6 ab^{-1} @ 240 GeV

FCCee 240: 5 ab^{-1} @ 240 GeV
FCCee 365: + 1.5 ab^{-1} @ 365 GeV

Perspectives on Precision

Still in flux - Meant as a rough Guide

- Comparisons of the potential of different colliders are non-straightforward: The projections are based on different levels of realism / pessimism / optimism in detector modeling, analysis techniques, systematic uncertainties and machine parameters / running scenarios,…

Here: Taking the “model independent” fit results - combine the projected uncertainties on σxBR

	ILC 250	ILC 500	CLIC 380	CLIC 3 TeV	CEPC	FCCee 240	FCCee 365
$\delta g_{HZZ}/g_{HZZ}$	0.38	0.30	0.6	0.6	0.25	0.25	0.22
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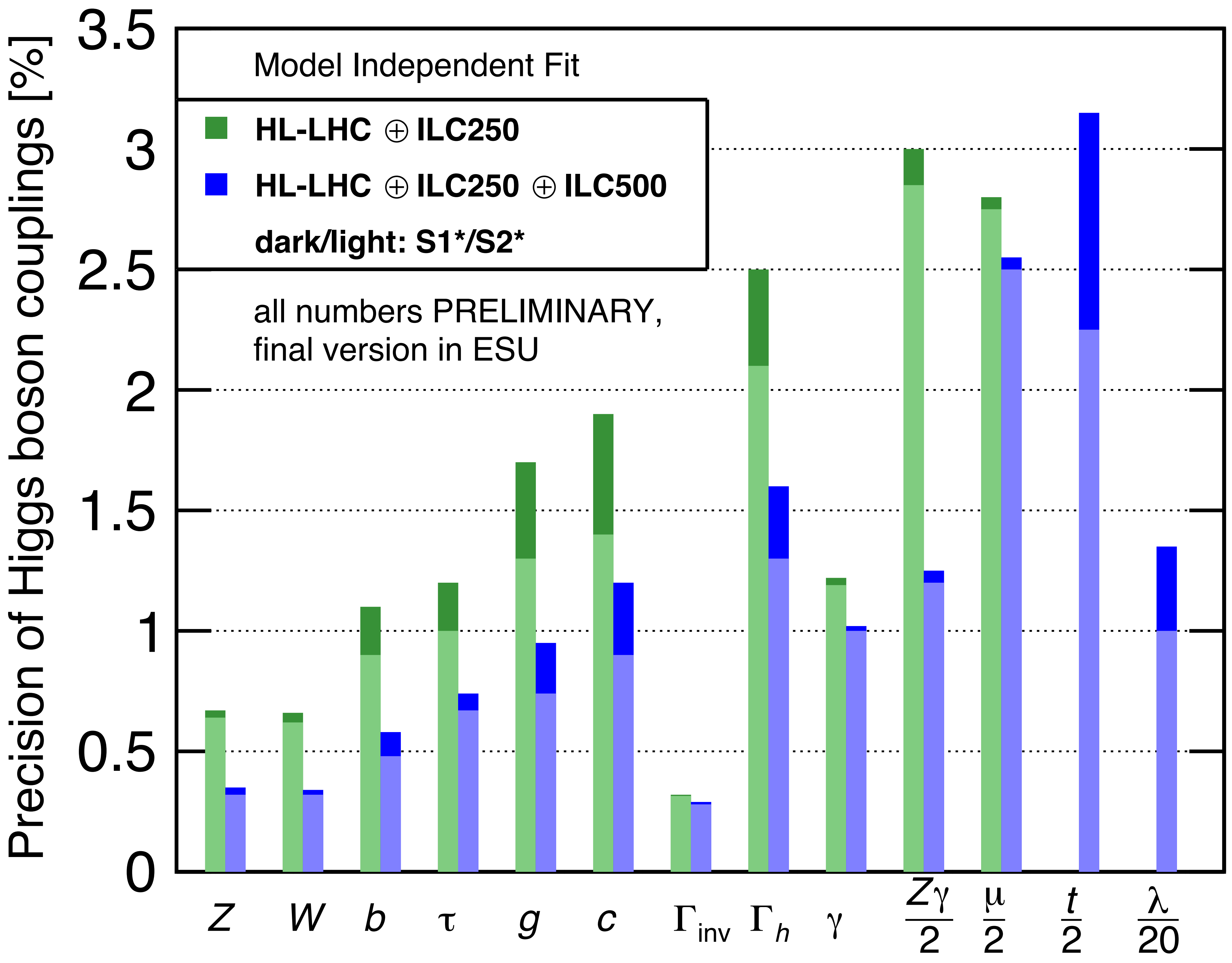
A Closer Look at ILC - in relation to LHC

Based on preliminary numbers in preparation for the ESU



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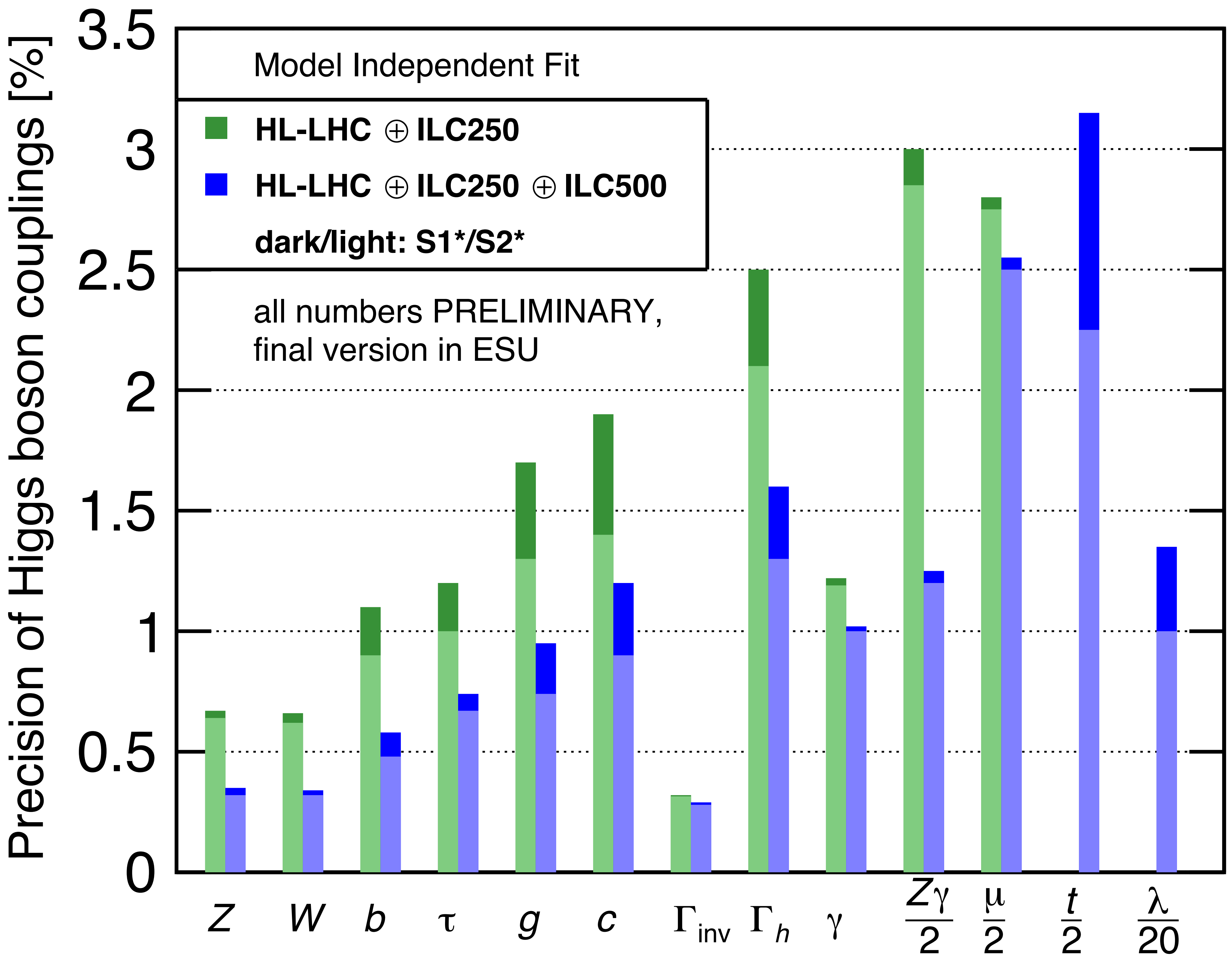
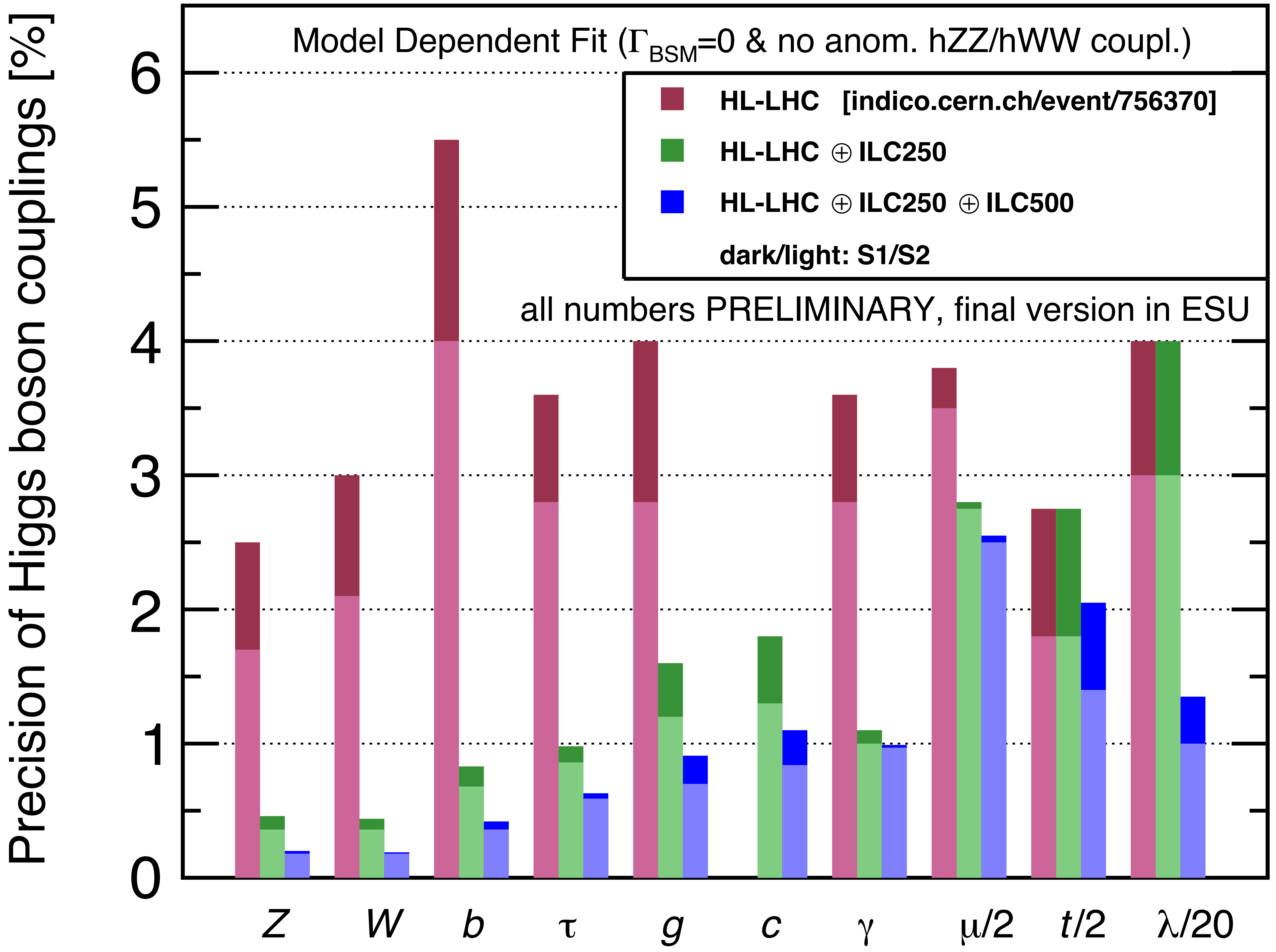


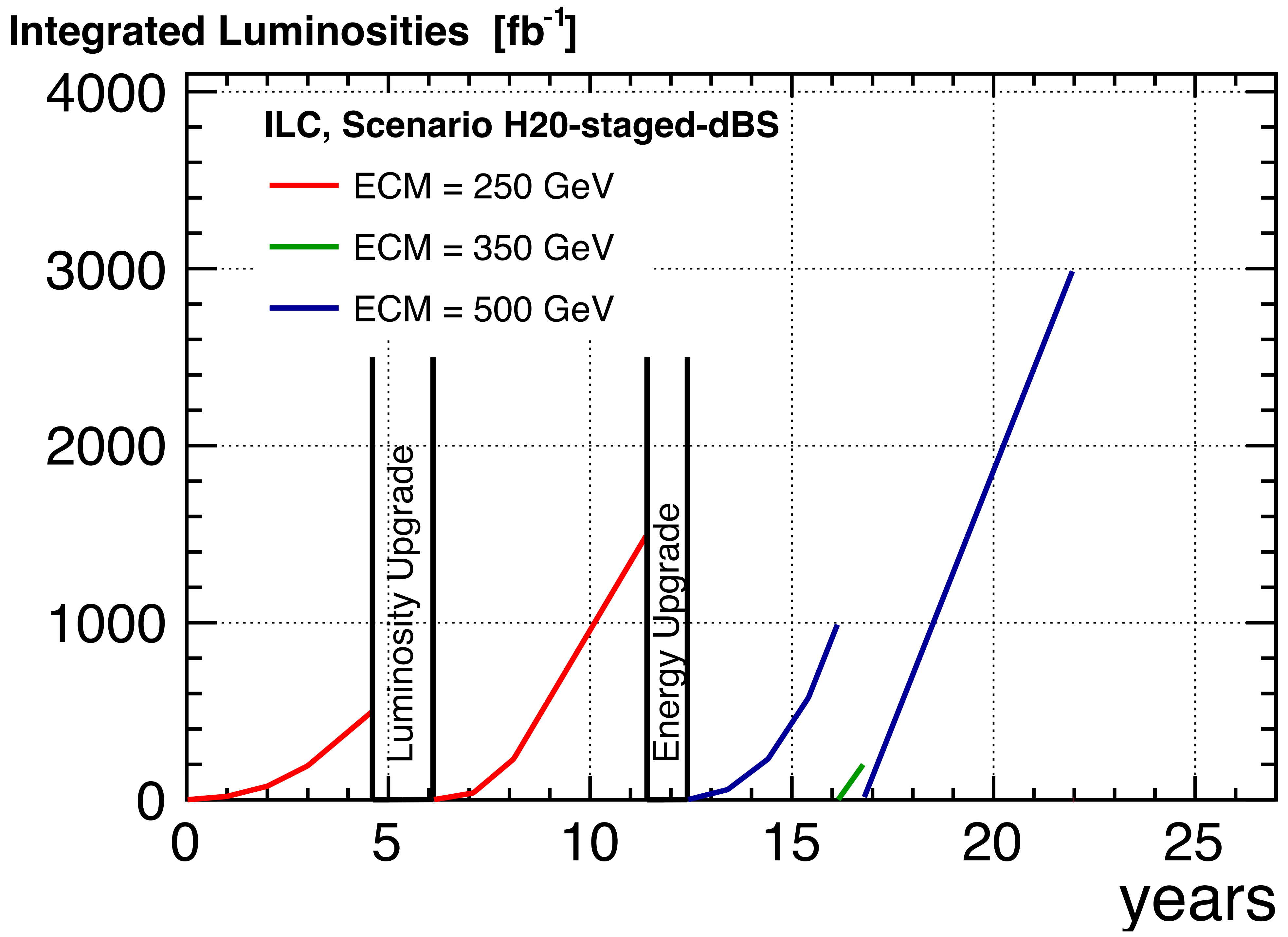
- ILC (and other e^+e^- colliders) provide model-independent measurements of couplings - can be used to extend model independence to LHC measurements

- ILC (and other e^+e^- colliders) go substantially beyond HL-LHC precision for a model-dependent analysis of Higgs results - 1 order of magnitude improvement in key channels



Discovery Stories in the Higgs Sector

An ILC Example



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

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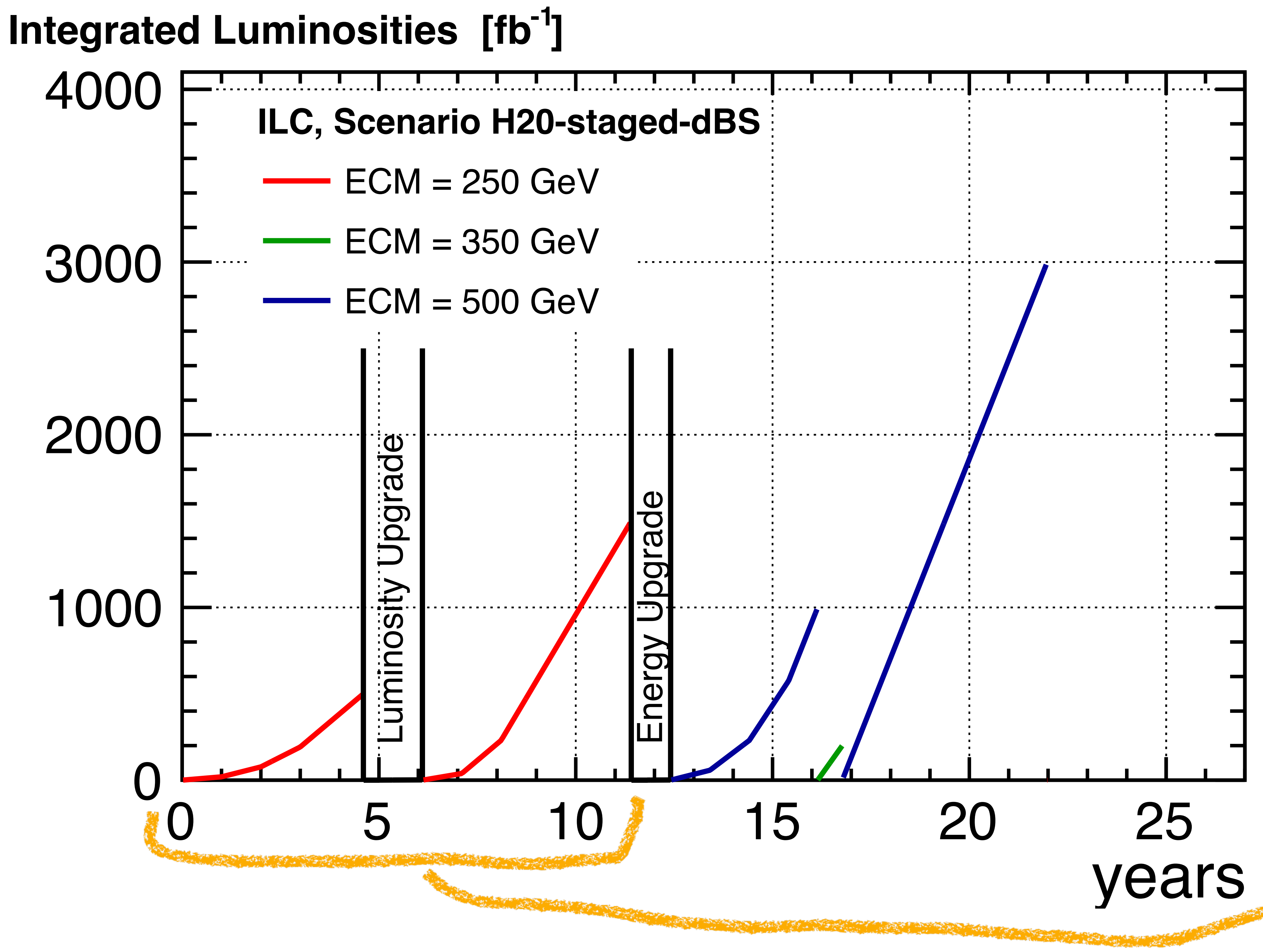

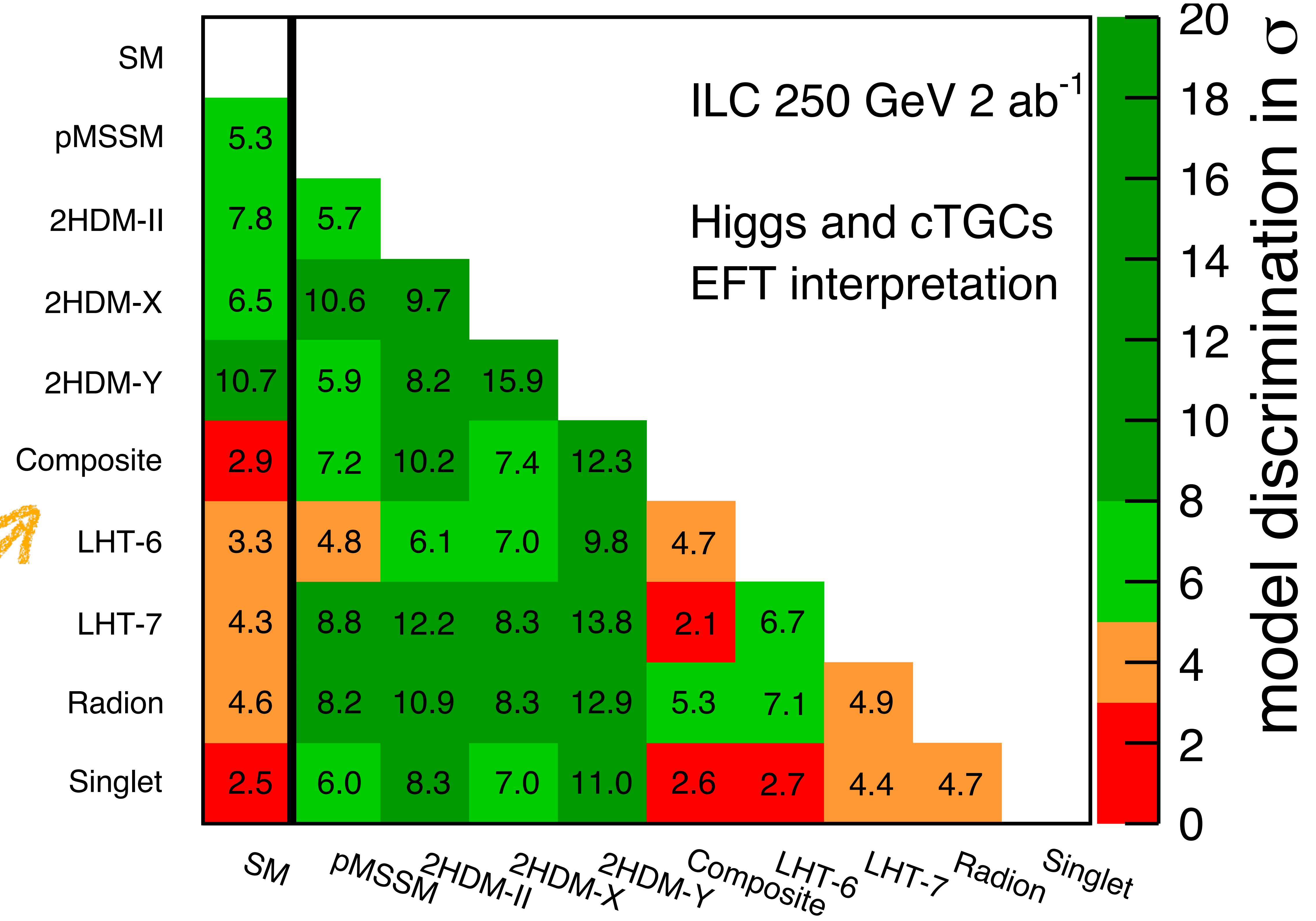

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.3									
2HDM-II	7.8	5.7								
2HDM-X	6.5	10.6	9.7							
2HDM-Y	10.7	5.9	8.2	15.9						
Composite	2.9	7.2	10.2	7.4	12.3					
LHT-6	3.3	4.8	6.1	7.0	9.8	4.7				
LHT-7	4.3	8.8	12.2	8.3	13.8	2.1	6.7			
Radion	4.6	8.2	10.9	8.3	12.9	5.3	7.1	4.9		
Singlet	2.5	6.0	8.3	7.0	11.0	2.6	2.7	4.4	4.7	

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- Discrimination power between models illustrated with EFT fit of ILC projections

arXiv:1708.08912
arXiv:1710.07621

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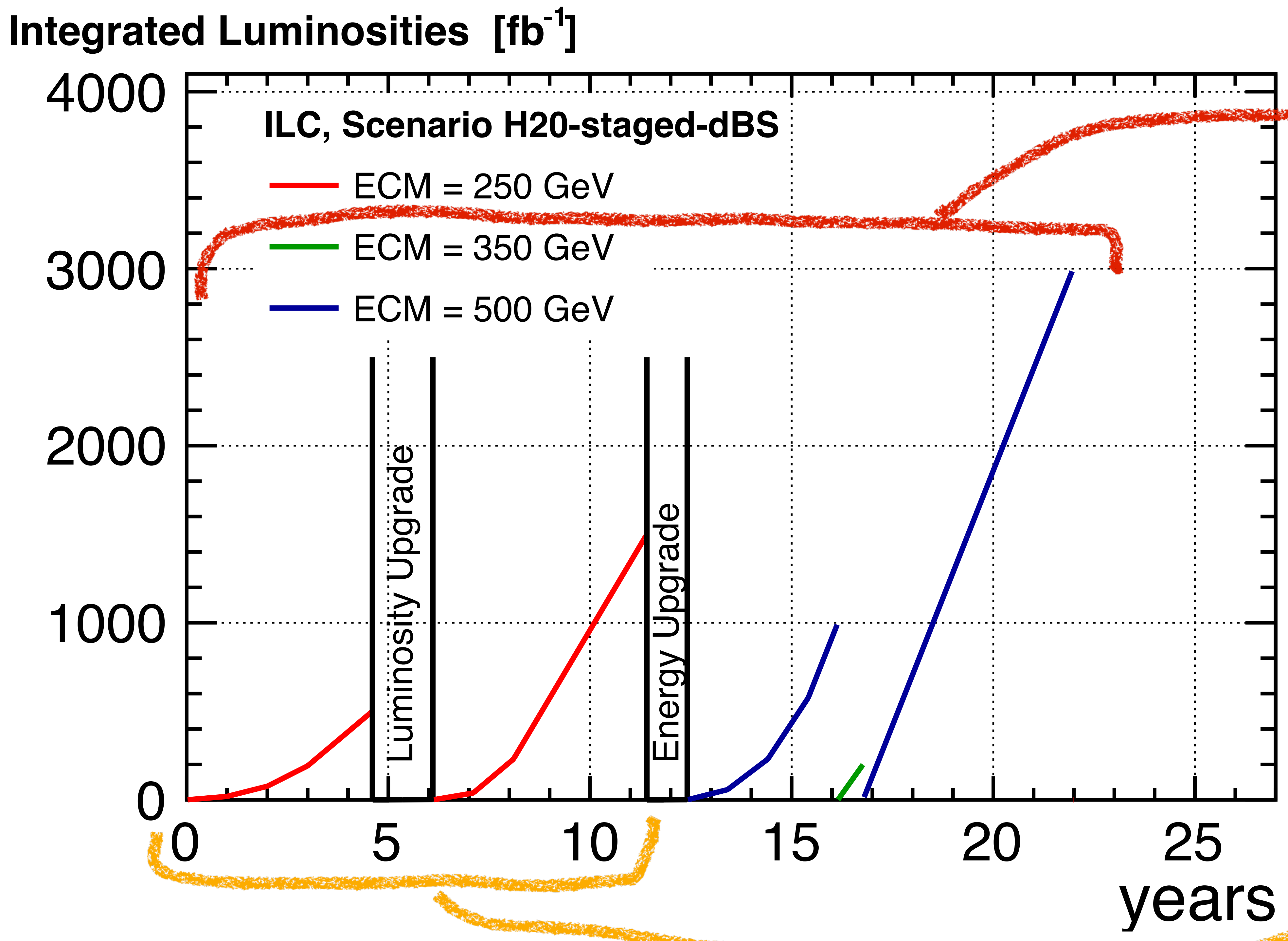

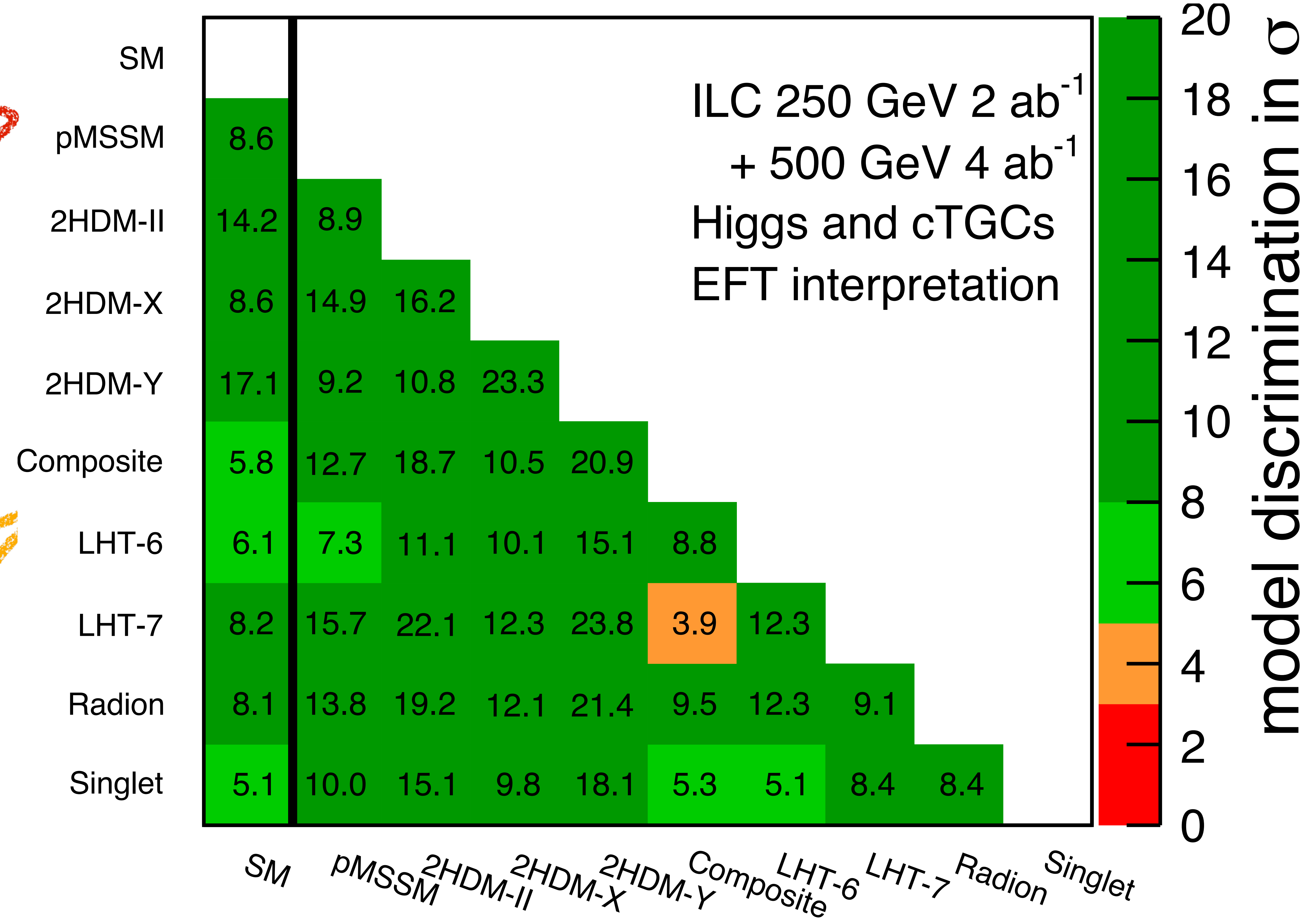

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SM										
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2HDM-II	14.2	8.9								
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Composite	5.8	12.7	18.7	10.5	20.9					
LHT-6	6.1	7.3	11.1	10.1	15.1	8.8				
LHT-7	8.2	15.7	22.1	12.3	23.8	3.9	12.3			
Radion	8.1	13.8	19.2	12.1	21.4	9.5	12.3	9.1		
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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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The Path towards the Real Axis

Waiting for Green Light… and for Strategies

- Decisions on next generation of facilities expected in the coming year(s):
    - Statement from Japan on ILC expected in coming weeks - possible site in Kitakami, north of Sendai
    - Update of European Strategy for Particle Physics: Towards the next project at CERN, but also with global consequences

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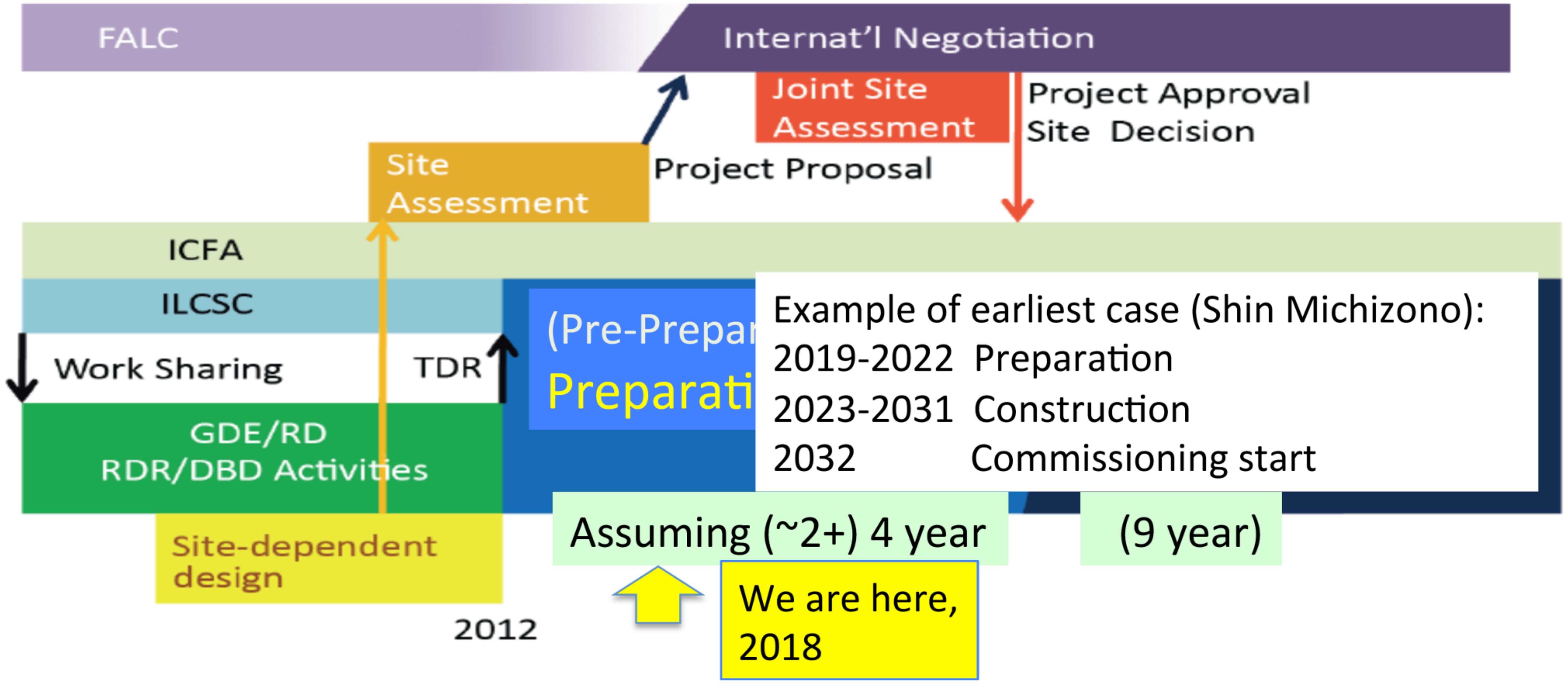
ILC Time Line: Progress and Prospect



Example of earliest case (Shin Michizono):
2019-2022 Preparation
2023-2031 Construction
2032 Commissioning start

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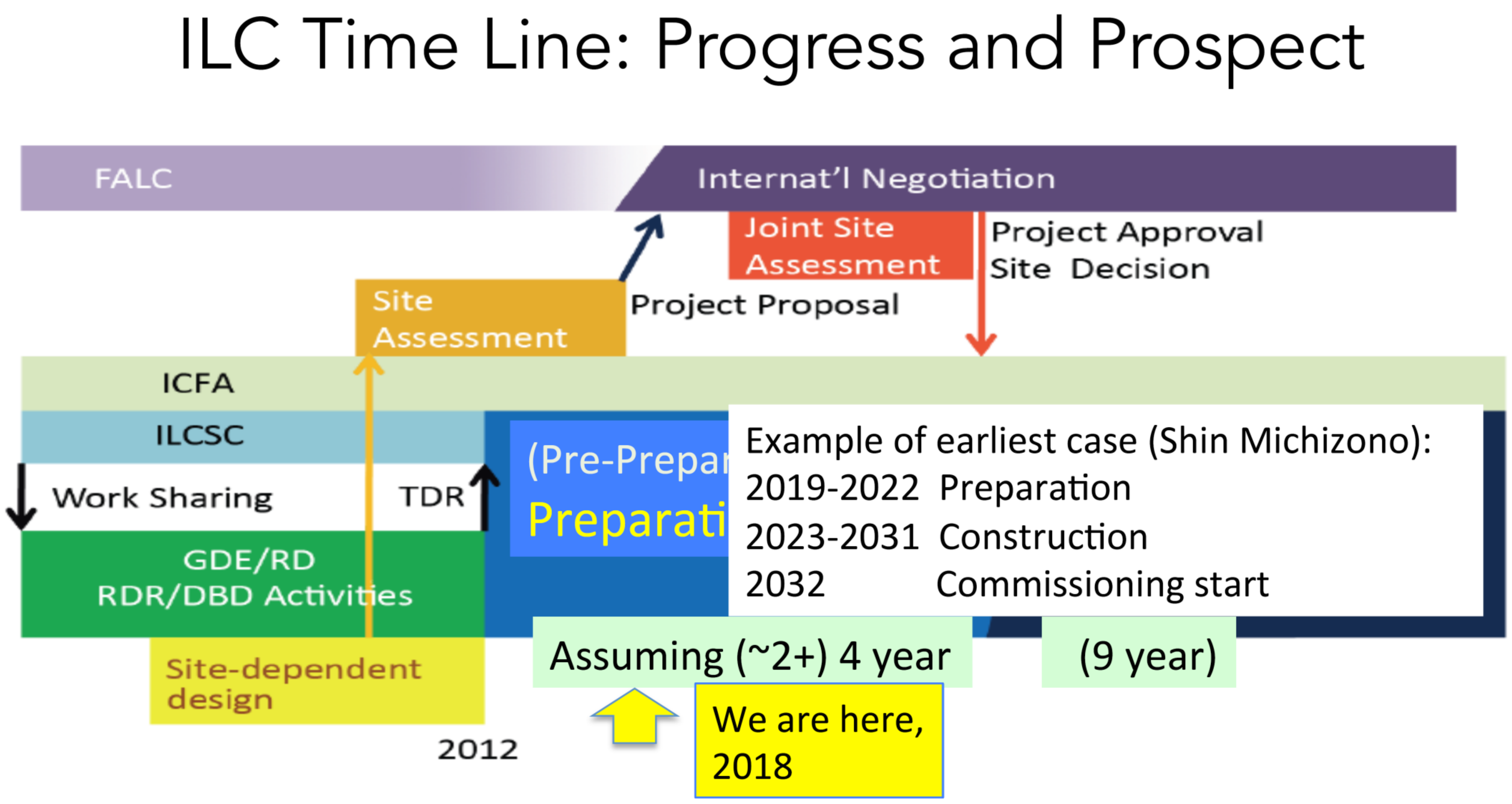
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2019-2022 Preparation
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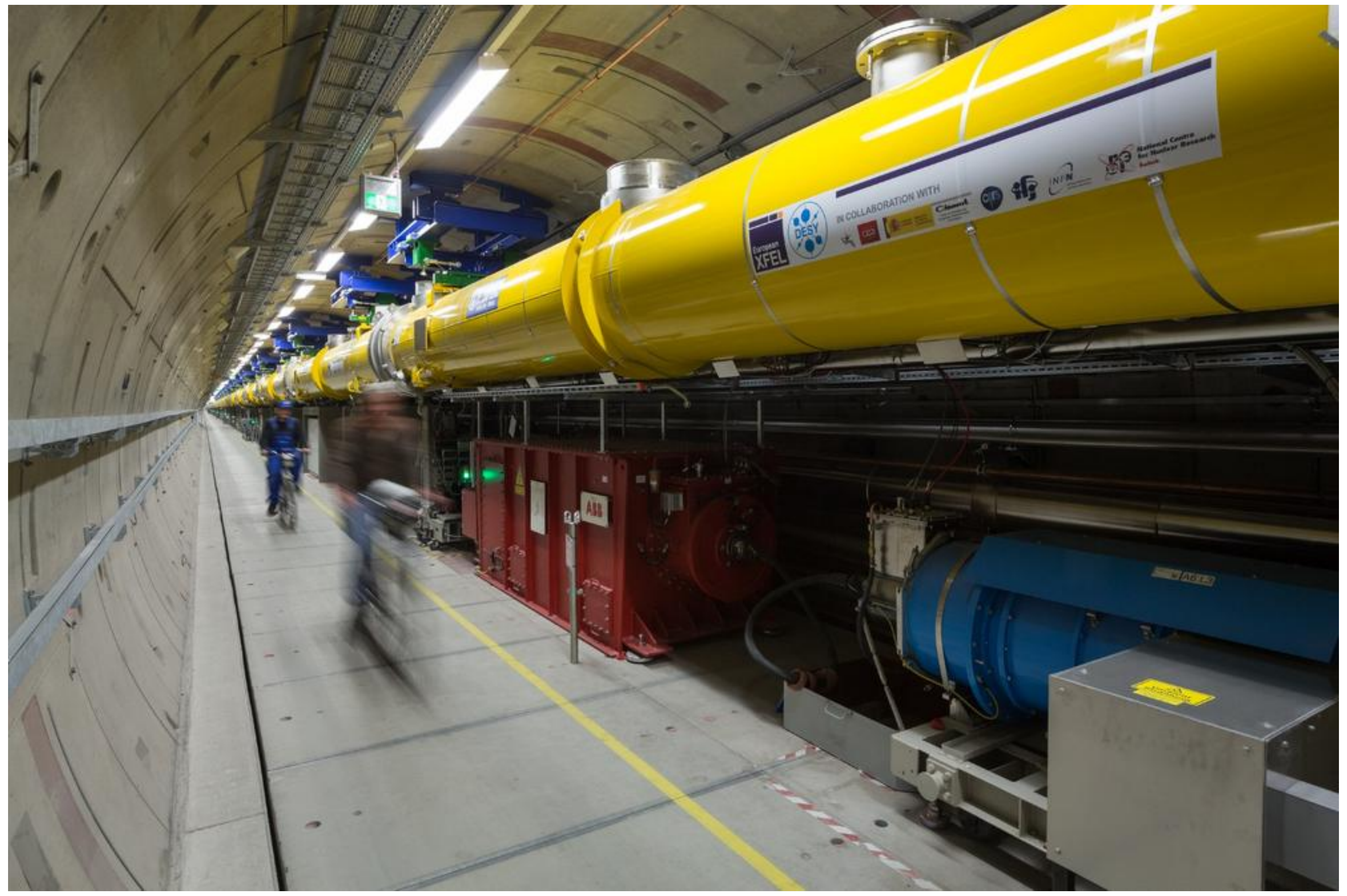
2032 Commissioning start

- ILC technology ready:
  European XFEL at DESY in operation, a 10% prototype of ILC main LINAC



Conclusions

- e^+e^- colliders provide the natural next step beyond HL-LHC for a thorough exploration of the Higgs sector:
  - Model-independent measurements of couplings and total width
  - Improvement of precision by up to an order of magnitude in many channels
  - Access to couplings difficult or impossible to measure at LHC

- Two classes of colliders under discussion:
  - Circular colliders FCCee, CEPC, with high luminosity for the ZH process and a maximum reach of 365 GeV
  - Linear colliders ILC and CLIC, with polarized beams and intrinsic energy upgradeability, currently up to 3 TeV
    - Uniquely capable of measuring the self-coupling - requires TeV+ energies for precision measurements

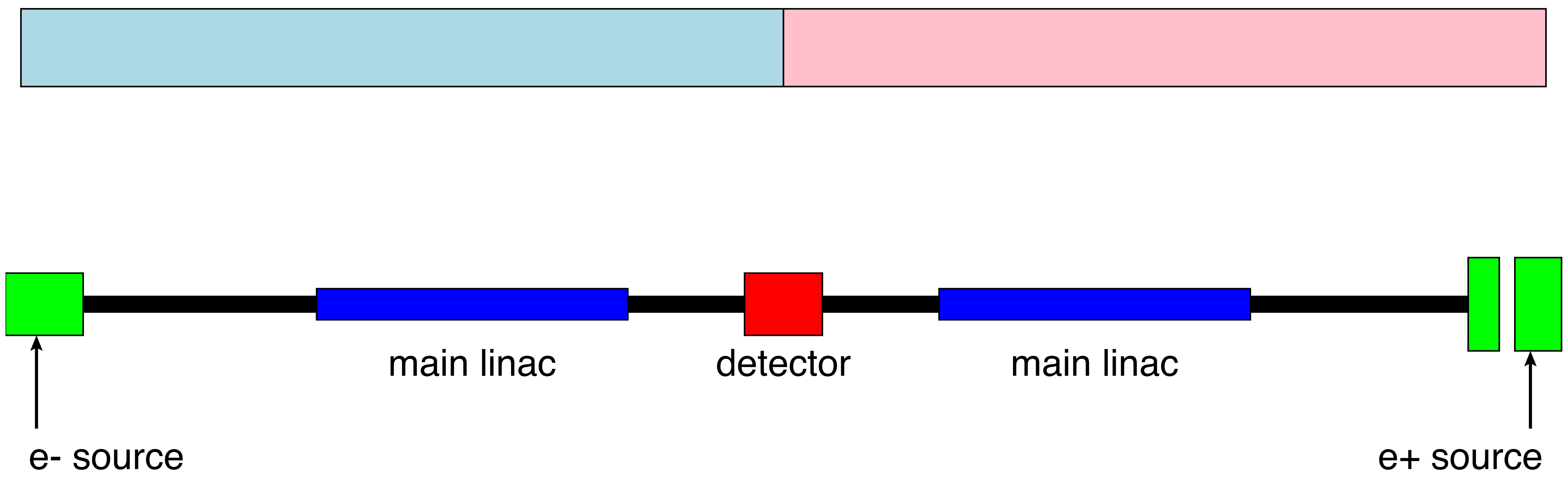
- It is decision time:
  - *Concrete* statement from Japan expected before the end of the year
  - Update of European Strategy for Particle Physics to set future directions at CERN (and elsewhere) in 2020
  - Progress in China towards CEPC / SppC

Extras

Linear Colliders

Key Elements & Performance Drivers

- Future e^+e^- colliders need:
  - High energy to explore the energy frontier
  - High luminosity to cope with falling cross sections, and to make precision measurements



For ***linear colliders***, this means:

- High acceleration gradient
- Extreme focusing of beams

Considerable complexity: “offset” in the costs in the “zero energy limit”

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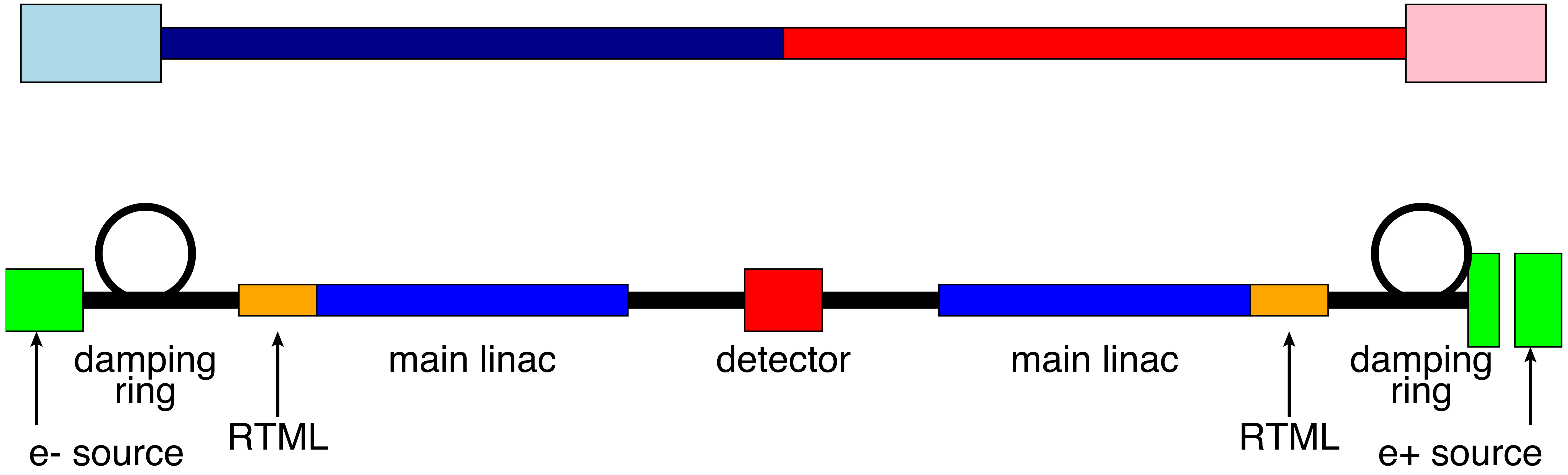

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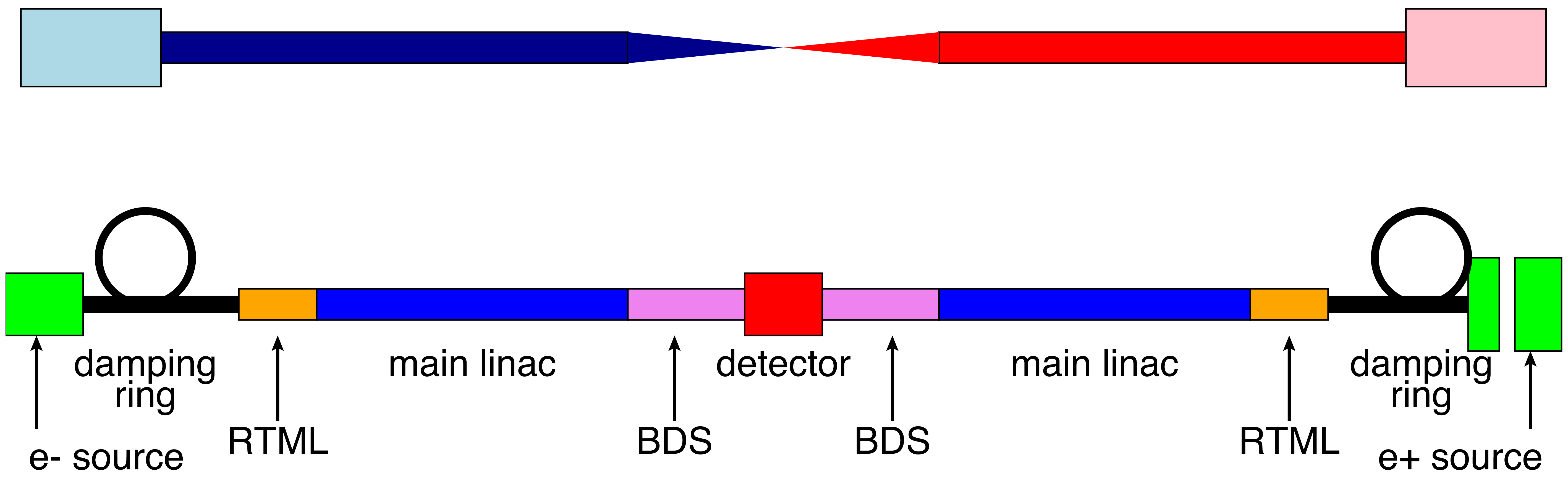

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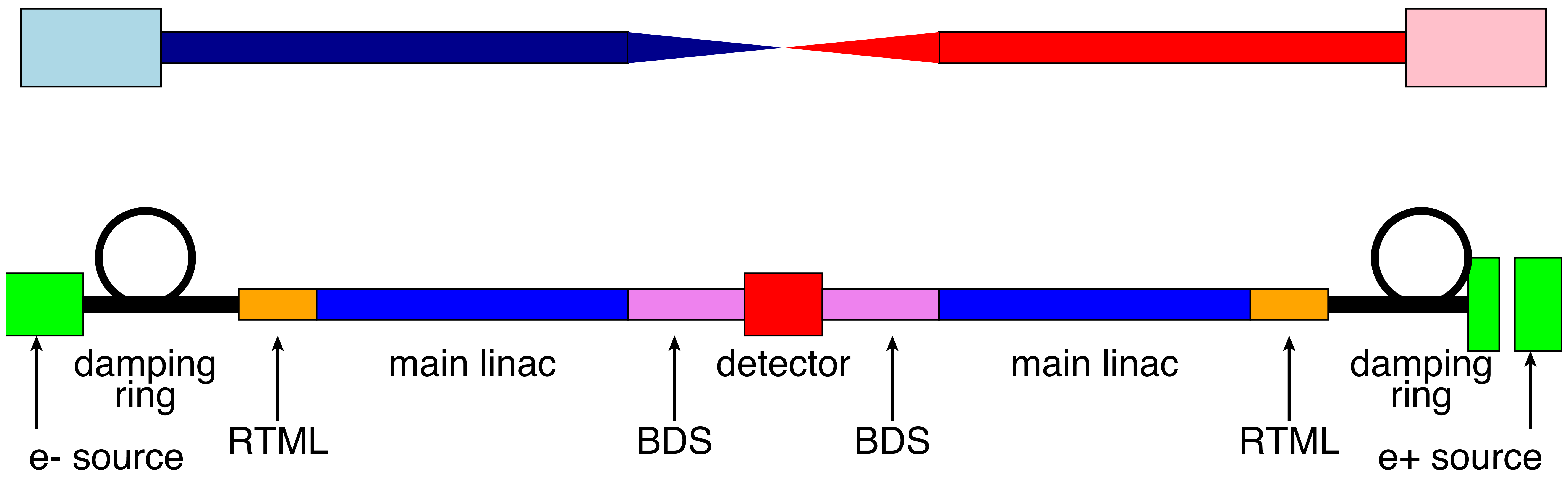

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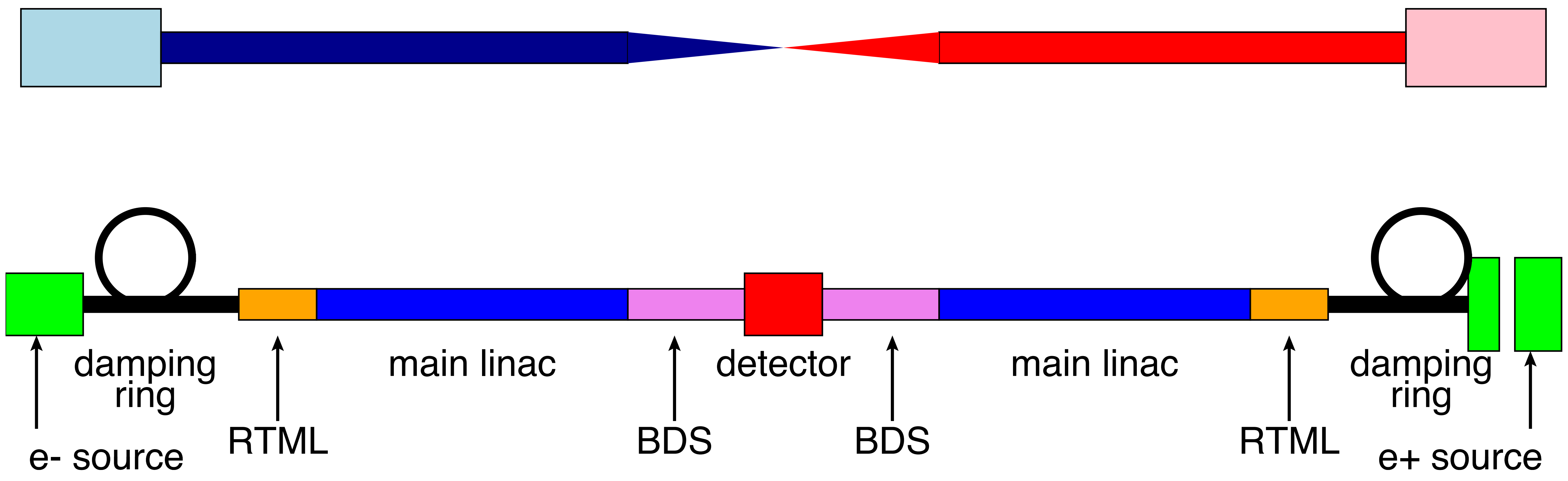

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➩ The linear layout provides a straight-forward energy upgrade path!

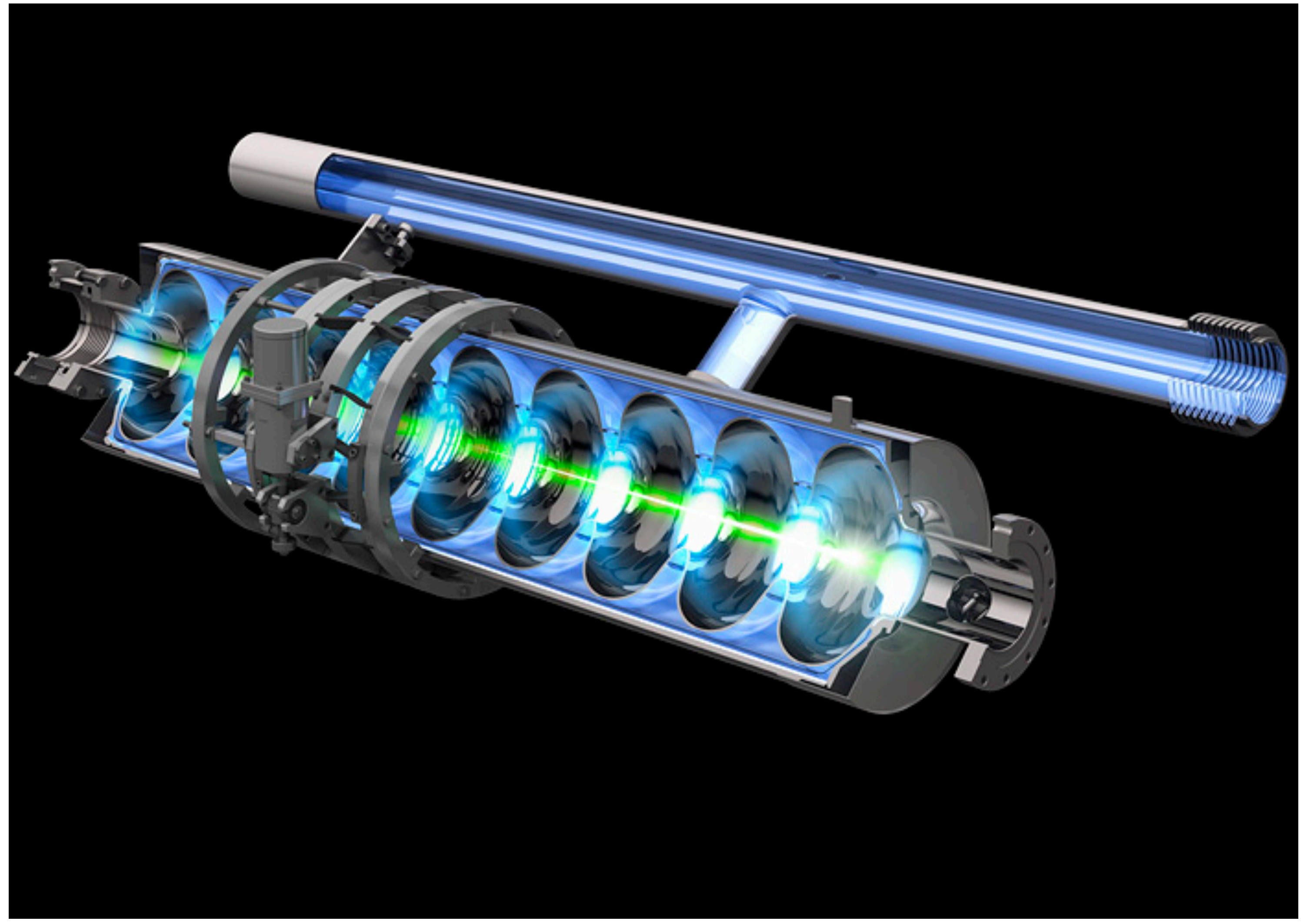
Linear Colliders

Main Technological Options

- Two collider concepts - based on different main linac technologies:

The **I**nternational **L**inear **C**ollider

- Superconducting RF structures, ~ 35 MV/m



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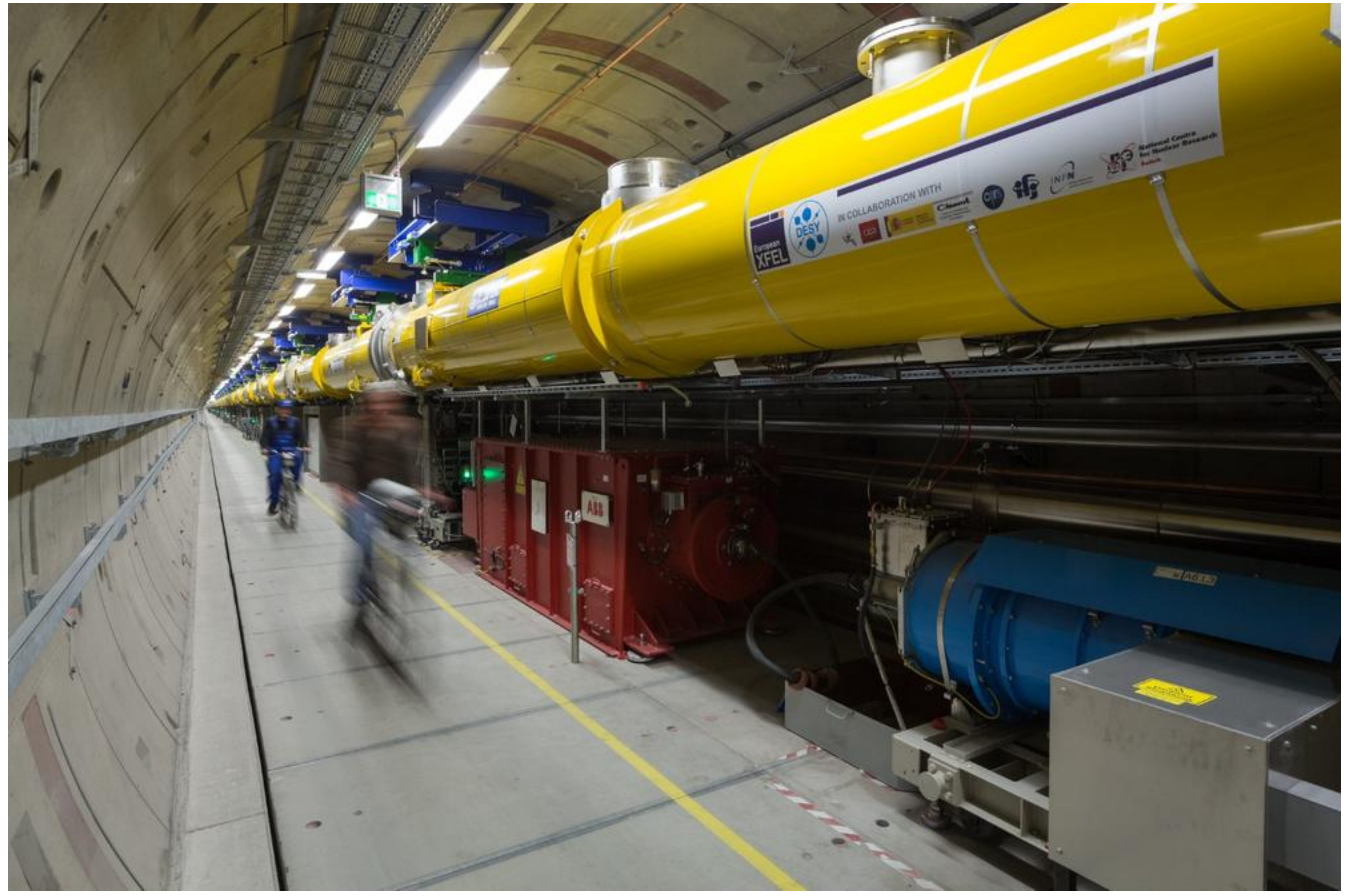

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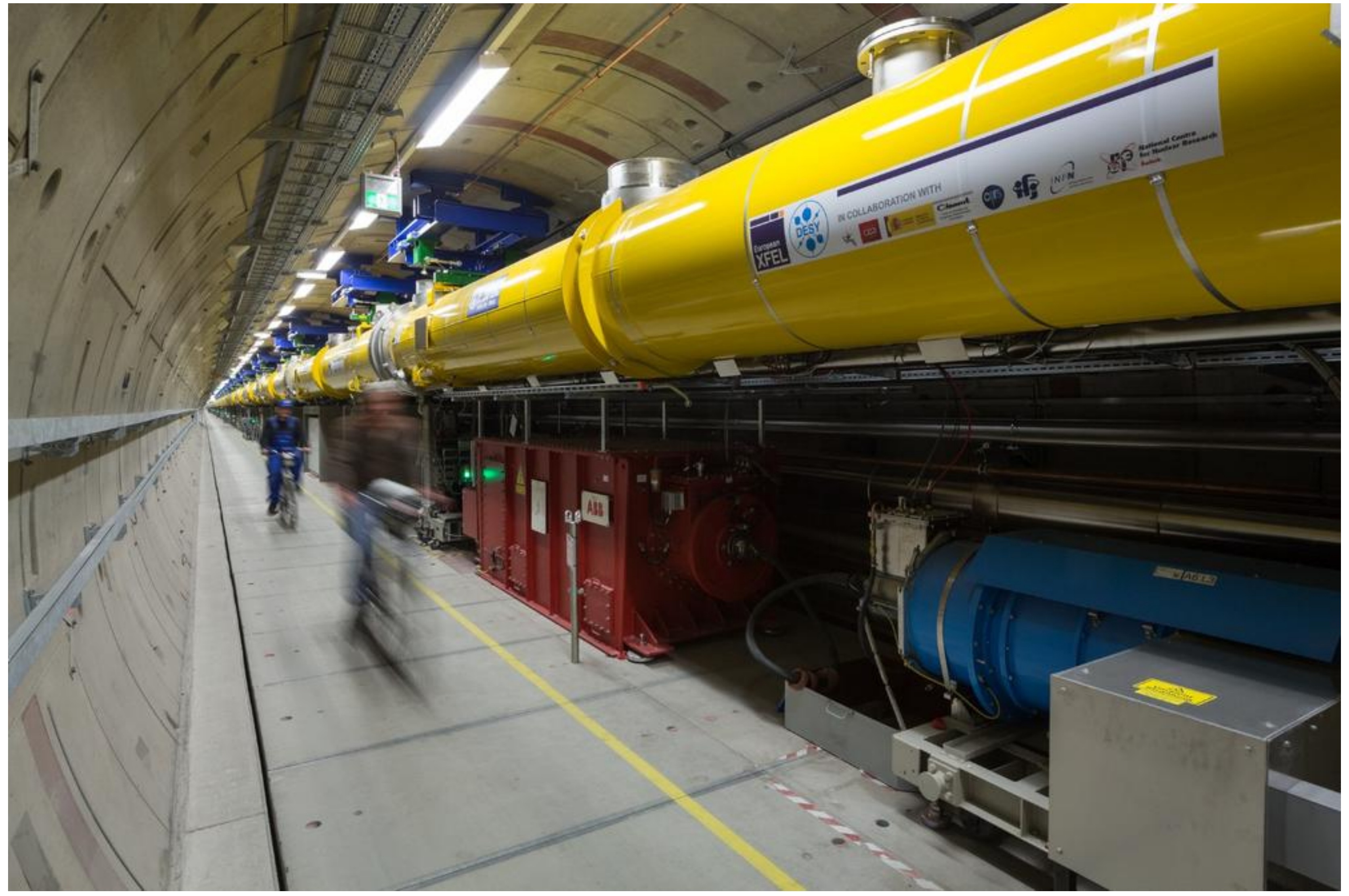

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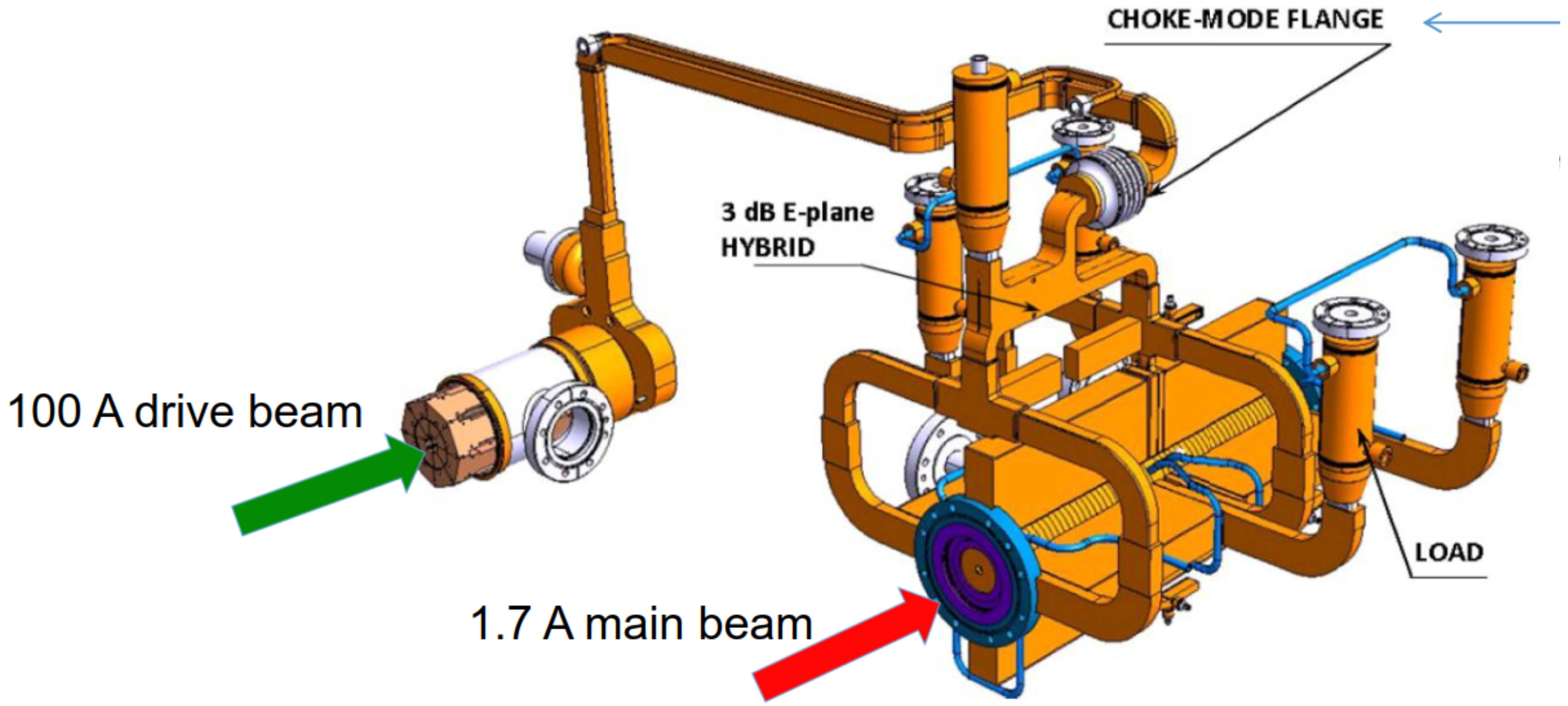
The **C**ompact **Li**near **C**ollider

- Warm structures, 2 beam acceleration, ~ 100 MV/m



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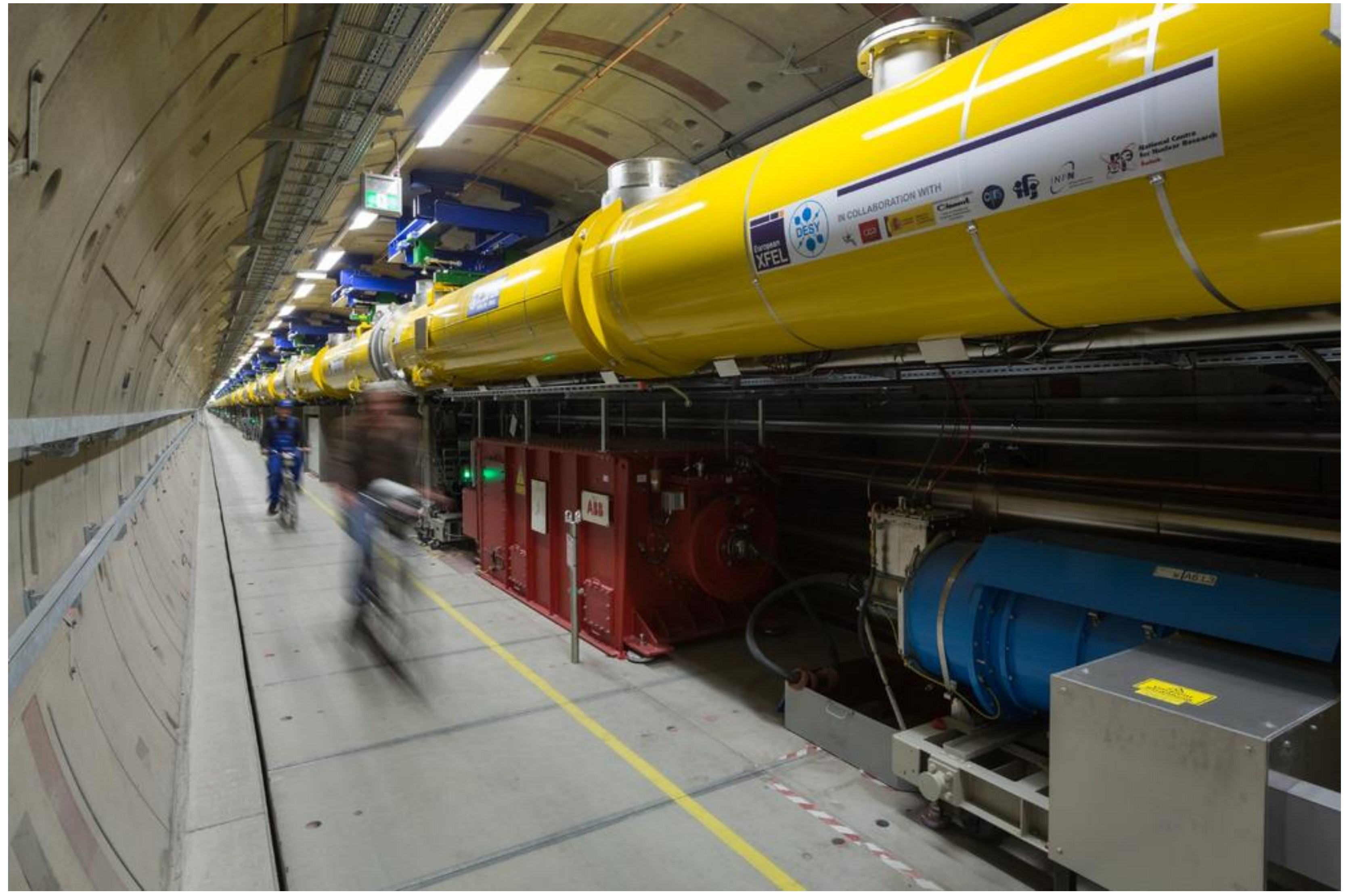

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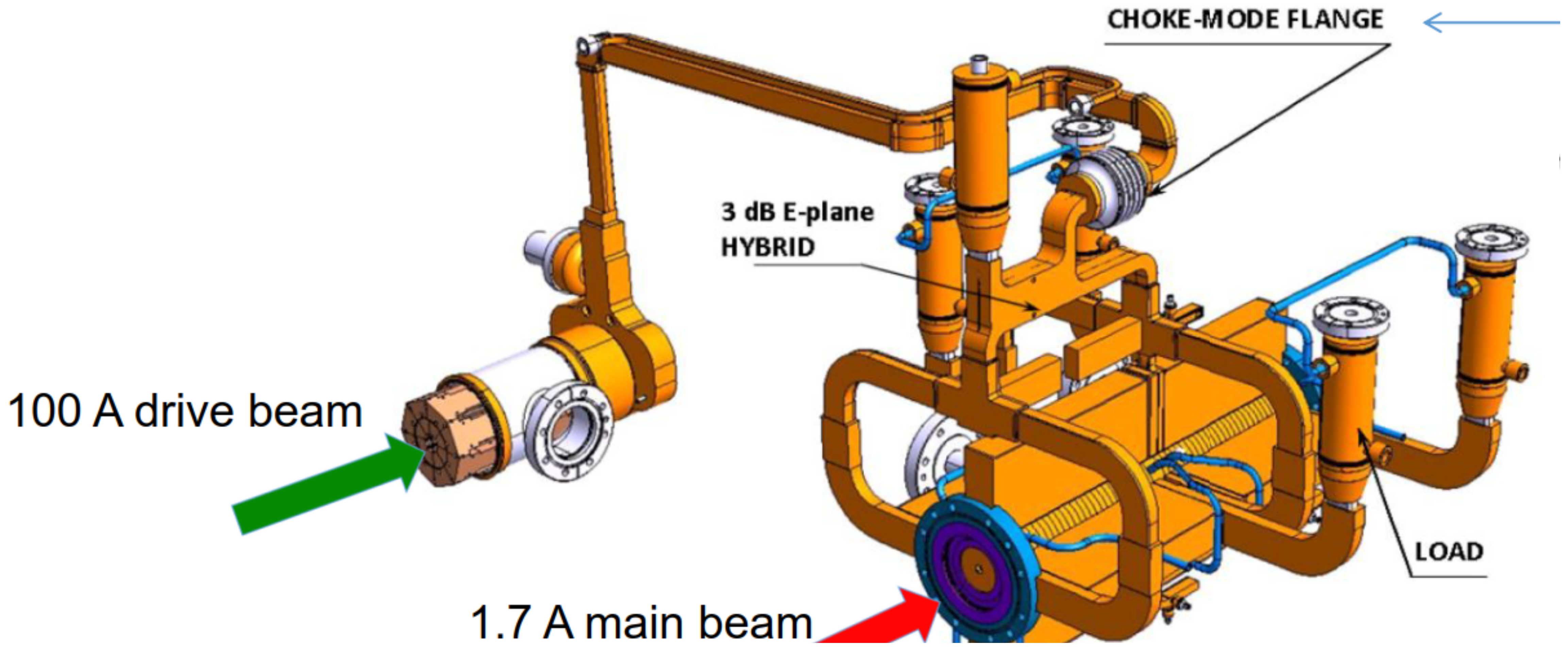


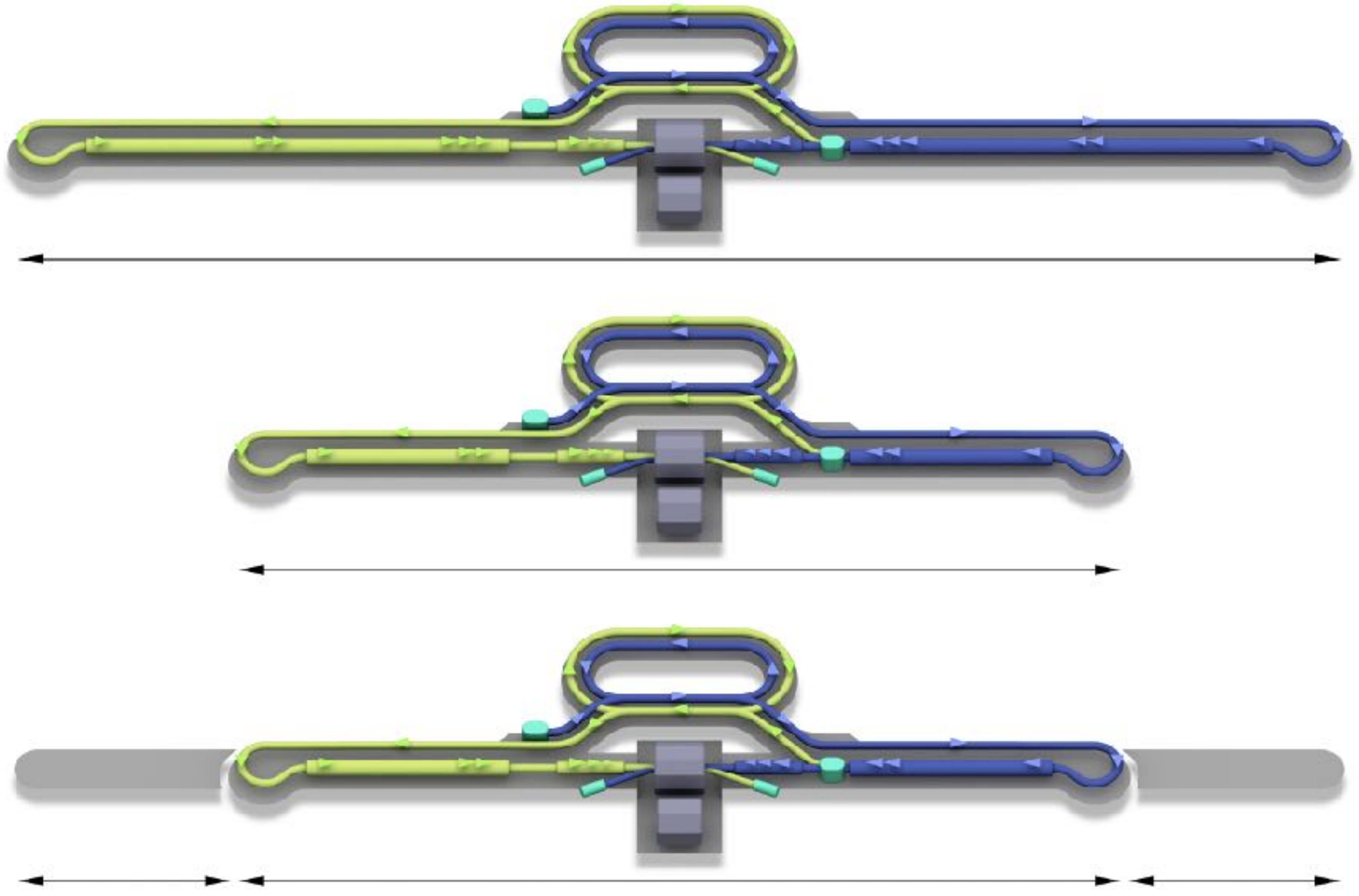
- All key steps successfully demonstrated: high-current drive beam, power transfer & acceleration, 100 MV/m gradient
- In progress: Industrialization, application in smaller facilities

Linear Colliders

Plans for Facilities

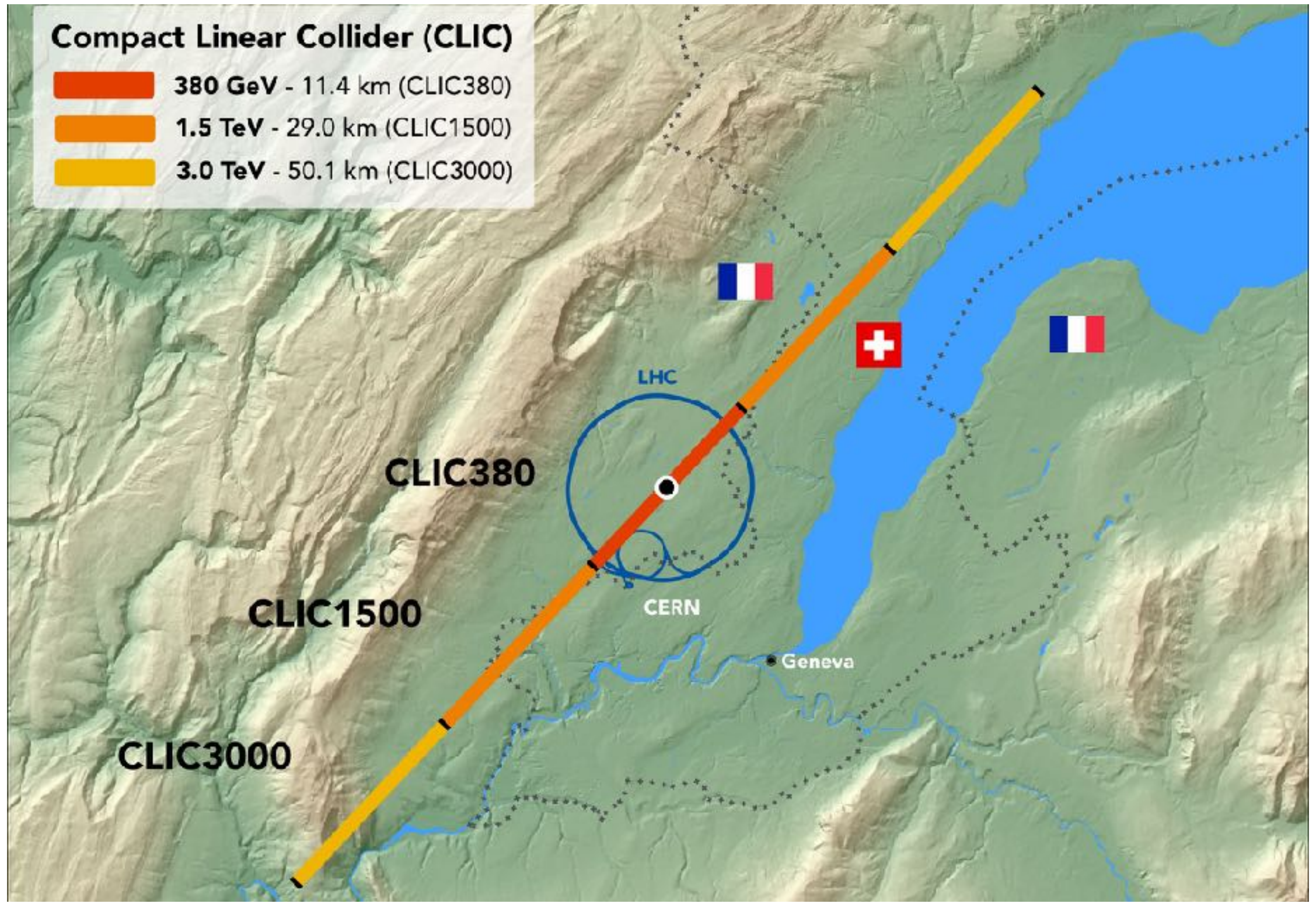
- Concrete worked-out designs for both facilities

- ILC: Technical Design Report in 2013



- Now proposed as a 250 GeV machine, upgradeable to 500 GeV, with ultimate potential to 1 - 1.5 TeV

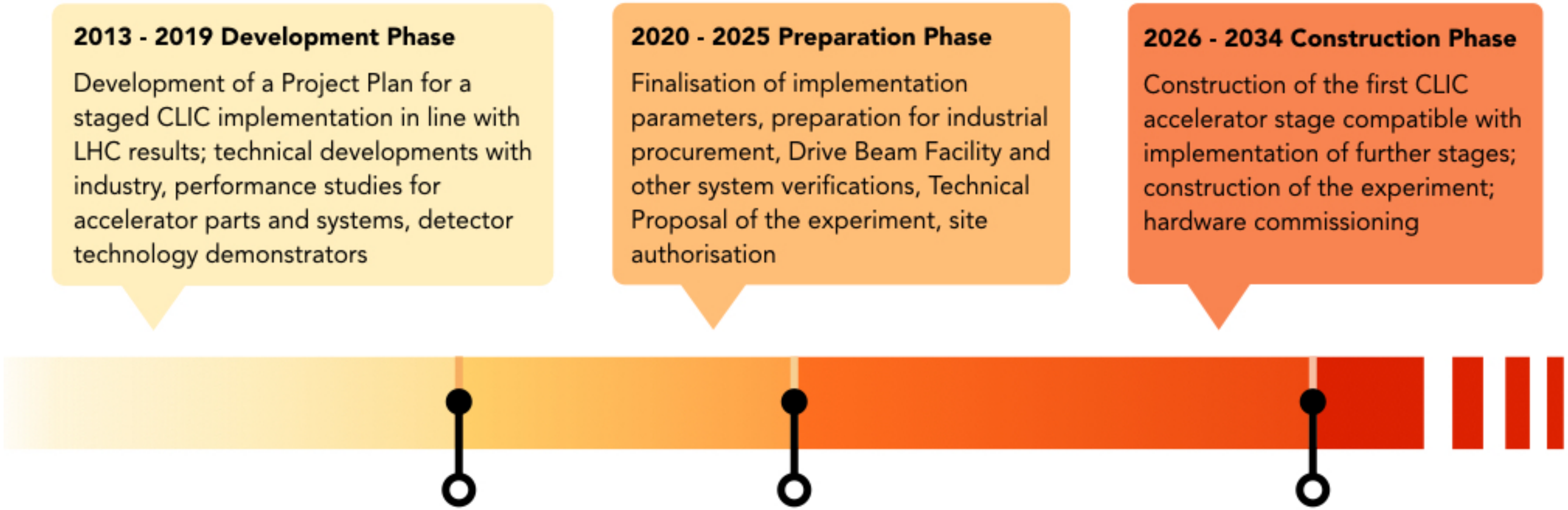
- CLIC: Conceptual Design Report in 2012



- A staged machine, with an initial energy of 380 GeV and ultimate energy of 3 TeV

Schedule: CLIC

The Road to Physics



2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion