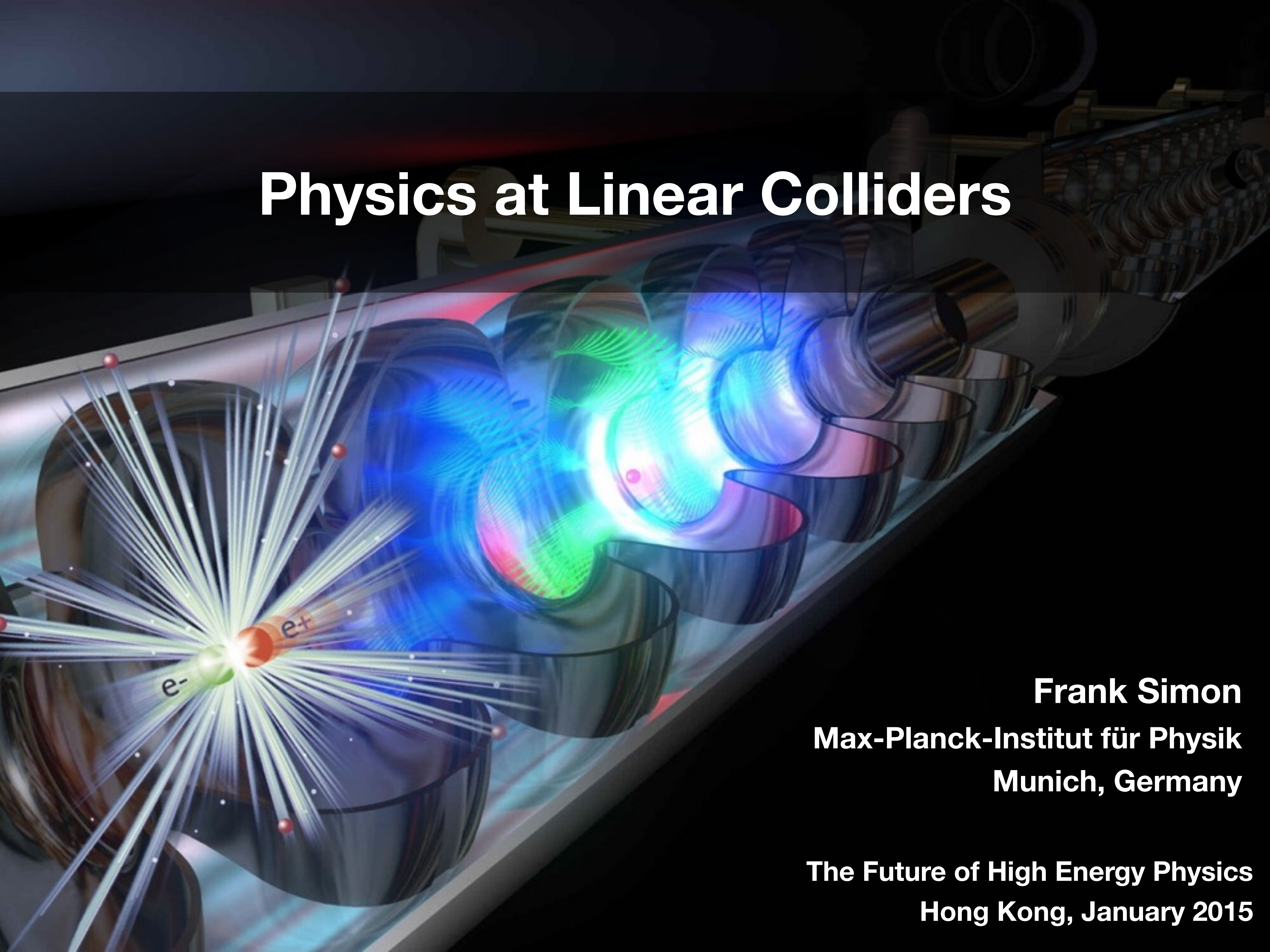

Physics at Linear Colliders

Frank Simon
Max-Planck-Institut für Physik
Munich, Germany

The Future of High Energy Physics
Hong Kong, January 2015

The Role of Linear Colliders at the Energy Frontier

- The discovery of the Higgs particle at the LHC is a milestone in particle physics: With it the complete spectrum of particles in the Standard Model is in hand, a theory which could in principle be valid to energies 13 orders of magnitude higher than those probed in present experiments. Yet it has its shortcomings - among them:
    - It does not explain *why* the Higgs field gives mass to all particles
    - It does not provide a particle or particles that could explain dark matter
    - It does not explain the asymmetry between matter and antimatter observed in the Universe

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LHC gives access to very high energies, but high-energy e^+e^- colliders provide a high degree of complementarity to the LHC (and future p+p colliders):

- Equal sensitivity to electroweak and strongly interacting particles
- Background levels are low, allowing the study of all decay modes of heavy particles and precision measurements giving indirect access to high scales

The Pillars of the Linear Collider Physics Program

- Measurement of the properties of the newly-discovered Higgs boson with very high precision
- Measurement of the properties of the top quark with very high precision
- Searches for and studies of new particles expected in models of physics beyond the SM at the TeV scale

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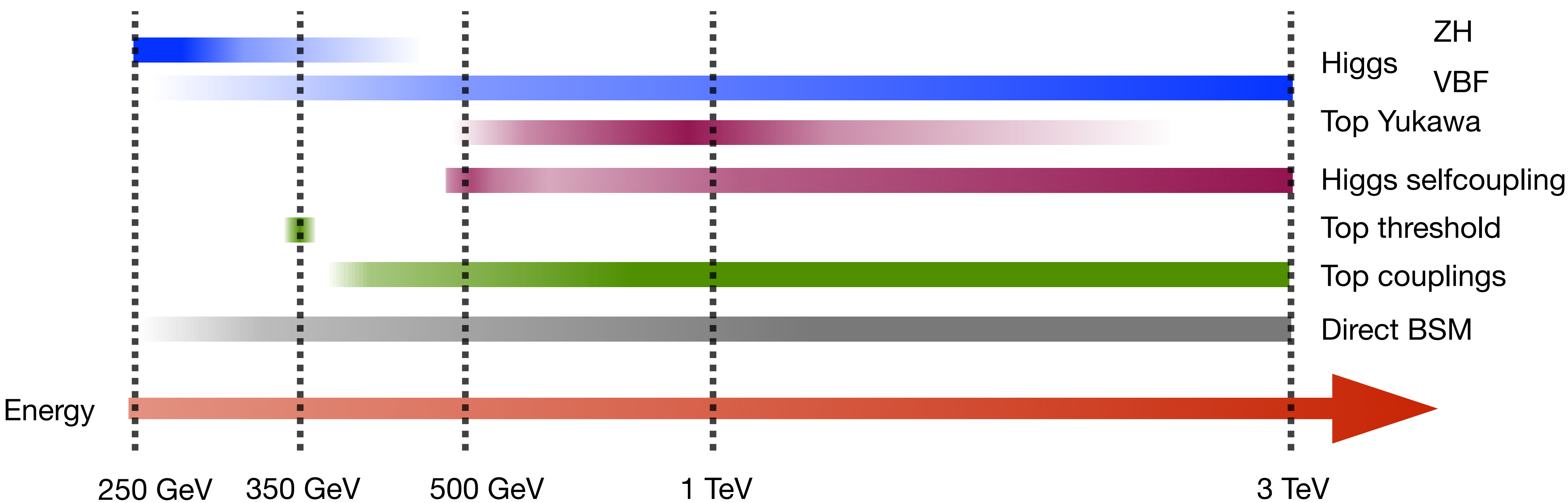
This program defines the energy range:



Overview

- Linear Colliders
  - ILC & CLIC
  - Experimental Conditions & Detectors
  - Staged Running Scenarios

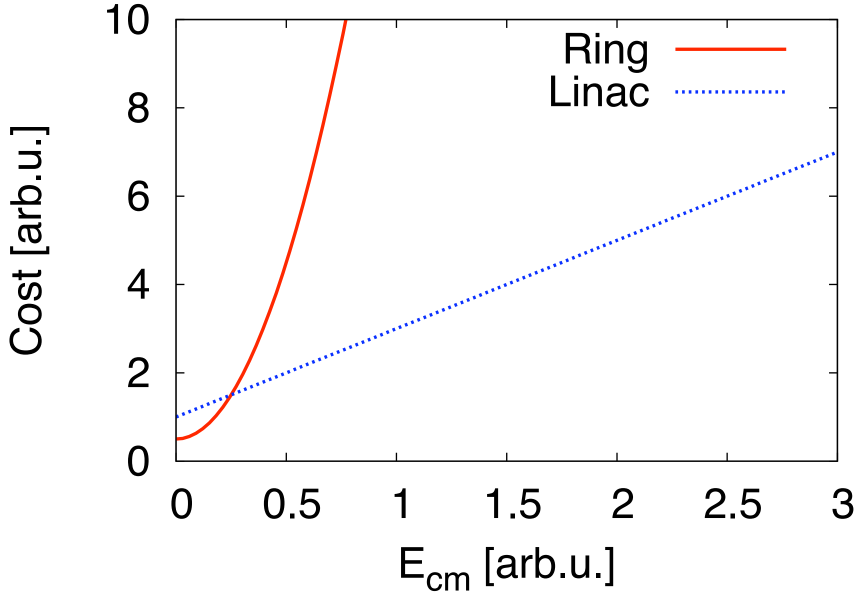
- Linear Collider Physics
  - Higgs
  - Top
  - BSM

- Outlook, Summary

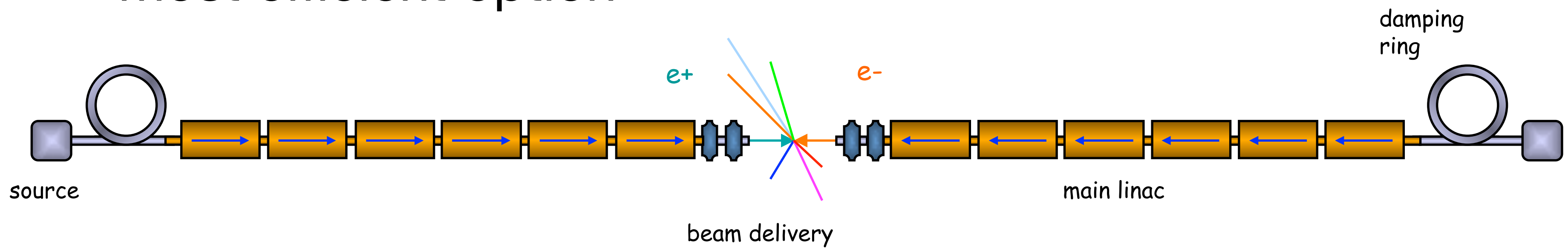
Linear Colliders

Requirements for high-energy e^+e^- Collisions

- Need high energy ***and*** high luminosity
  - synchrotron radiation in circular machines (~ E^4) sharply limits maximum energy



- For energies > ~ 300 - 400 GeV linear colliders are the most efficient option



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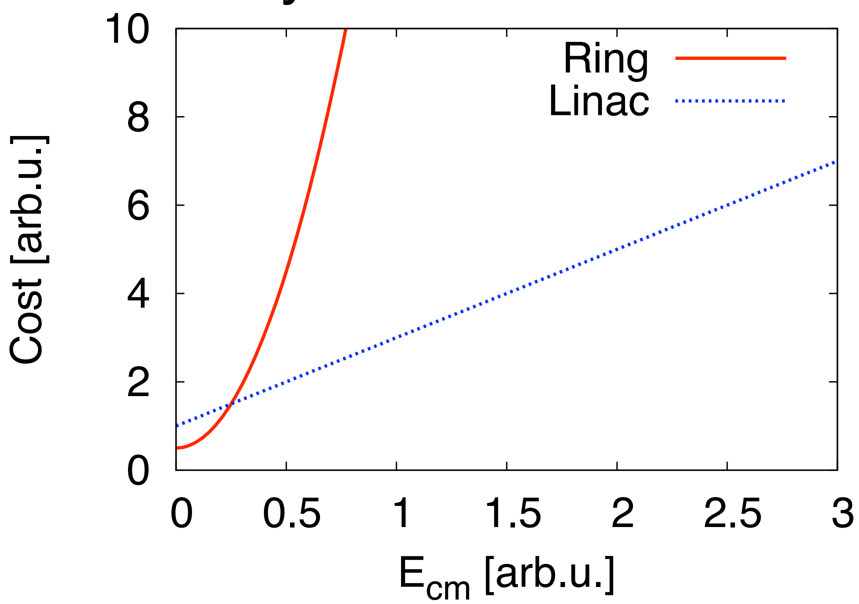

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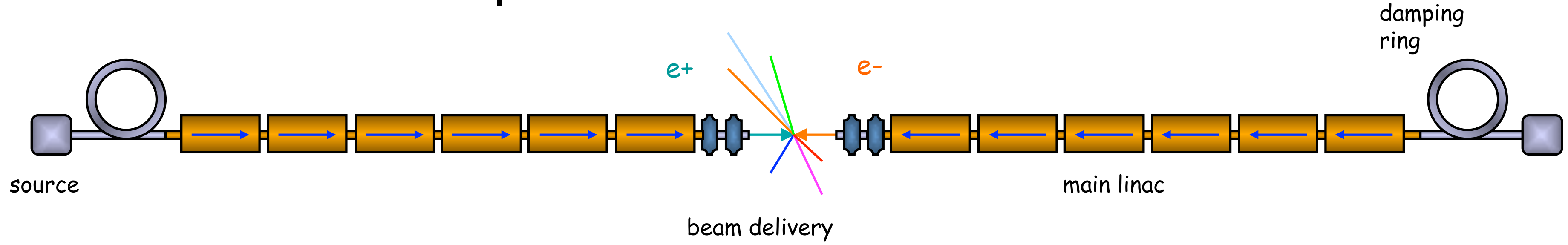
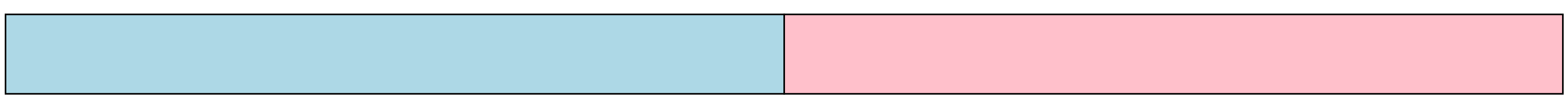
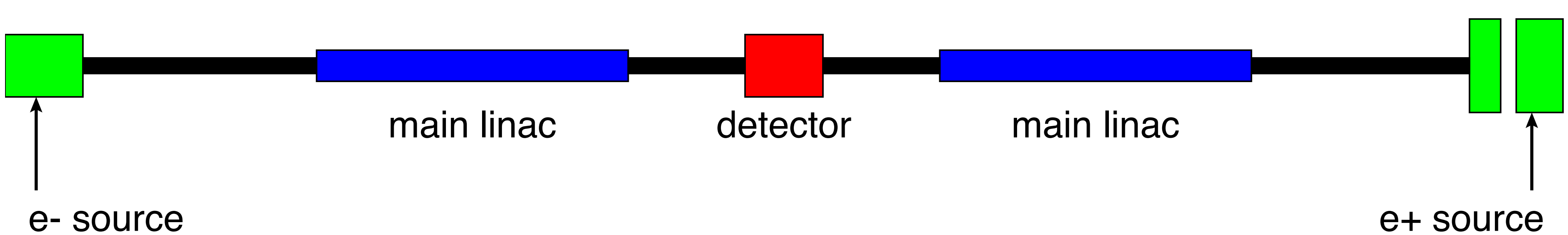


- High energy requires high gradients, high luminosity requires low emittance and very small beam size at IP (“nano-beams”)





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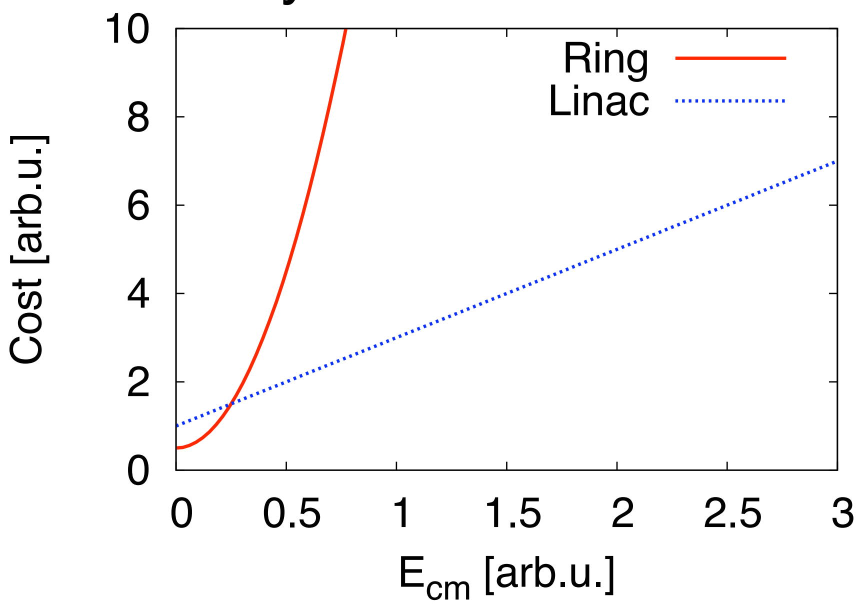

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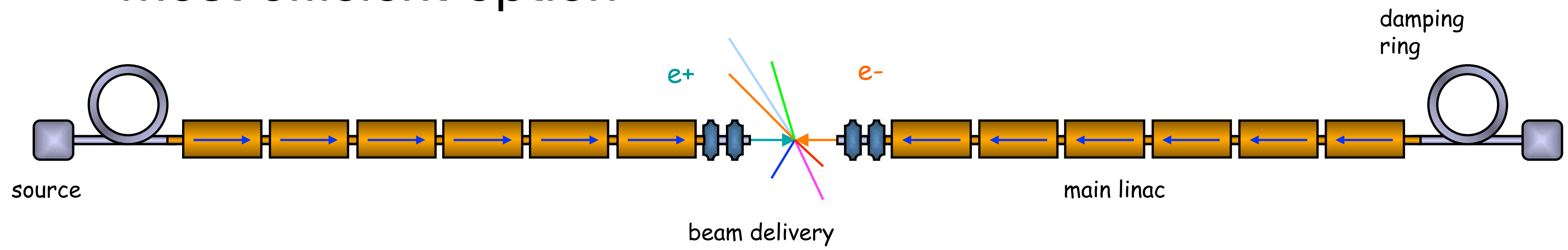

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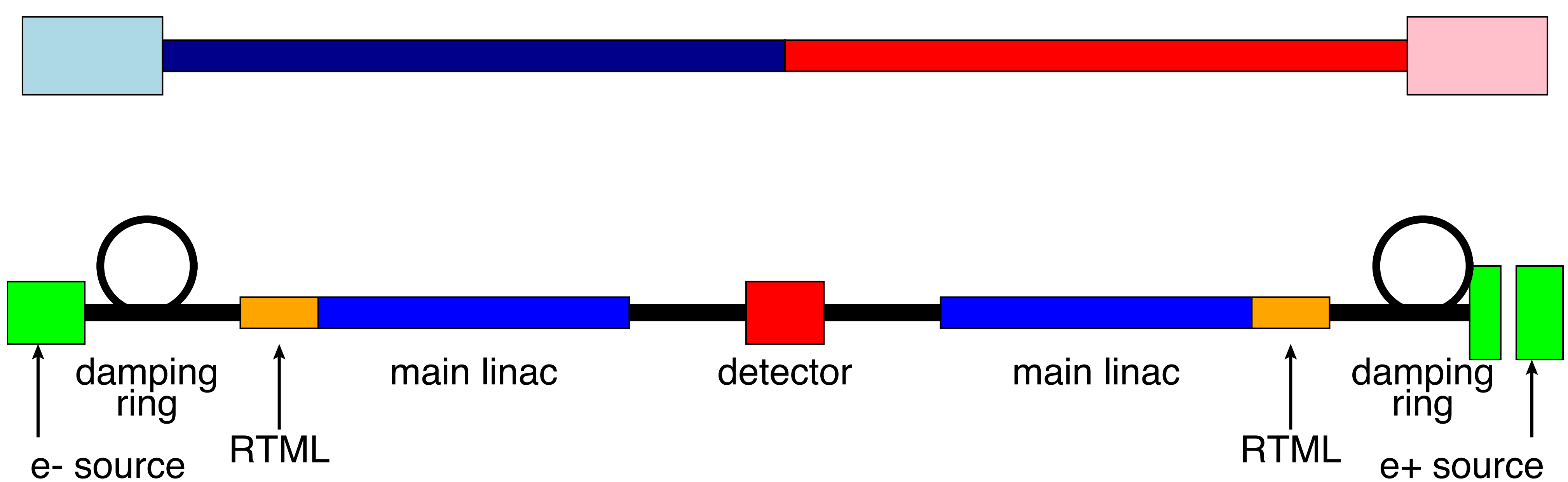

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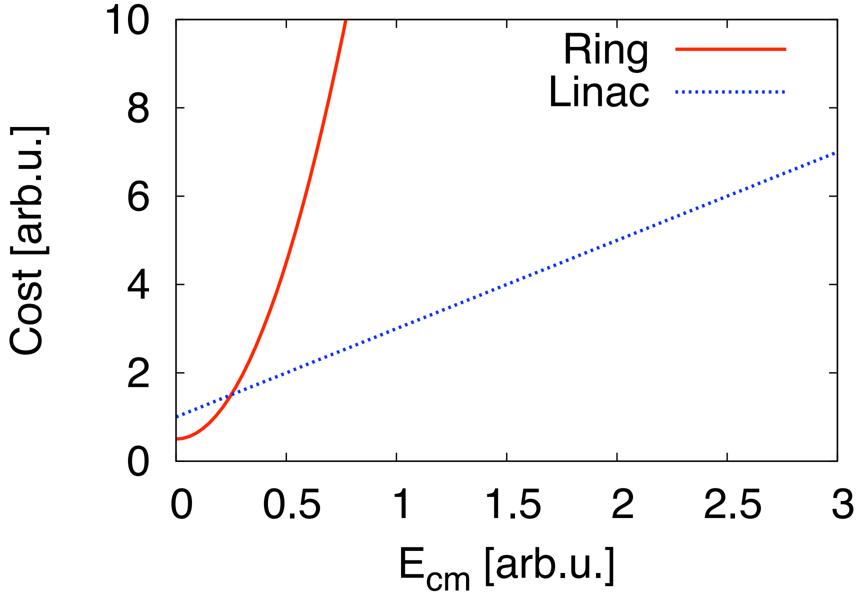

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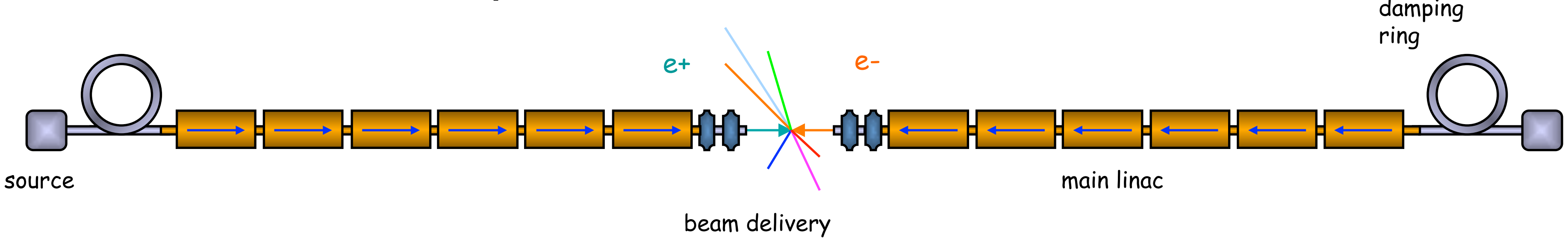

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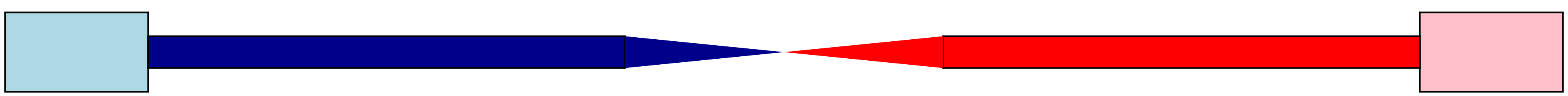
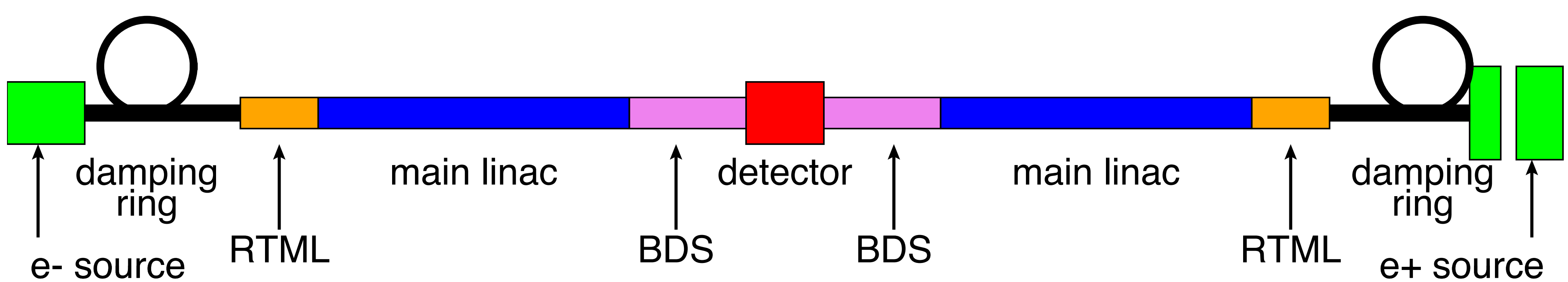
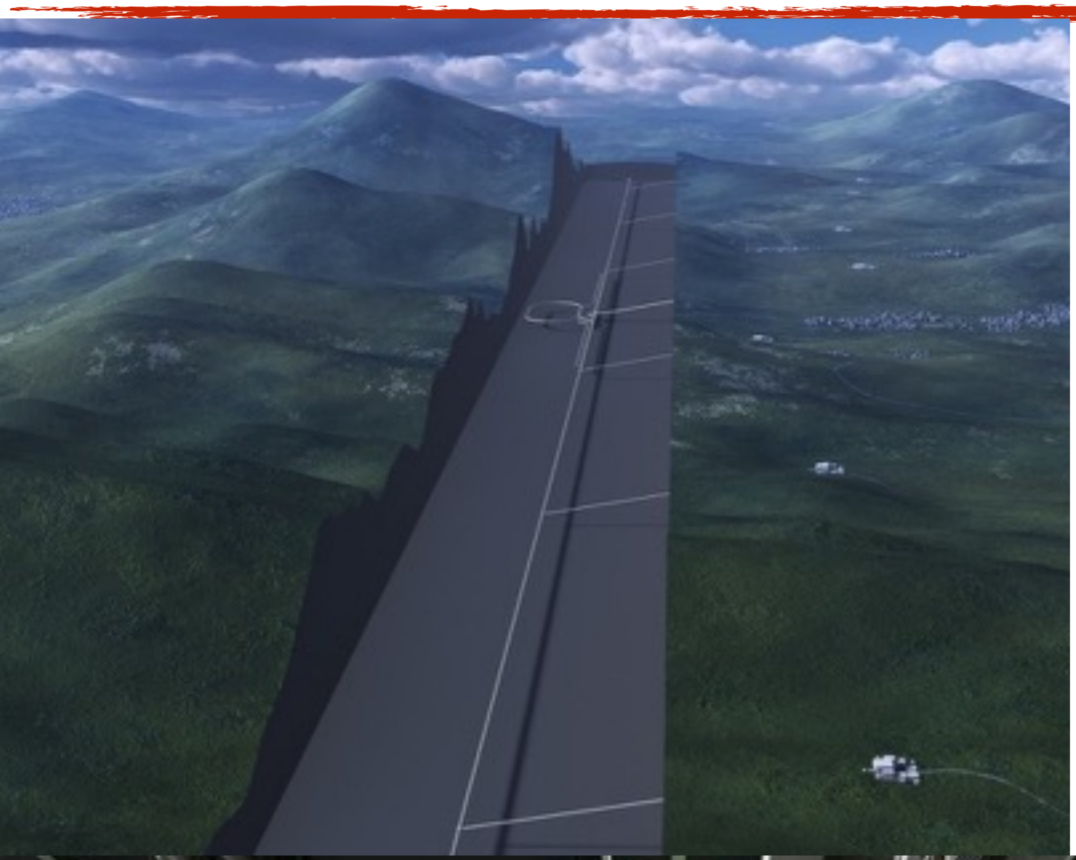




Linear Colliders - The Line-Up: ILC

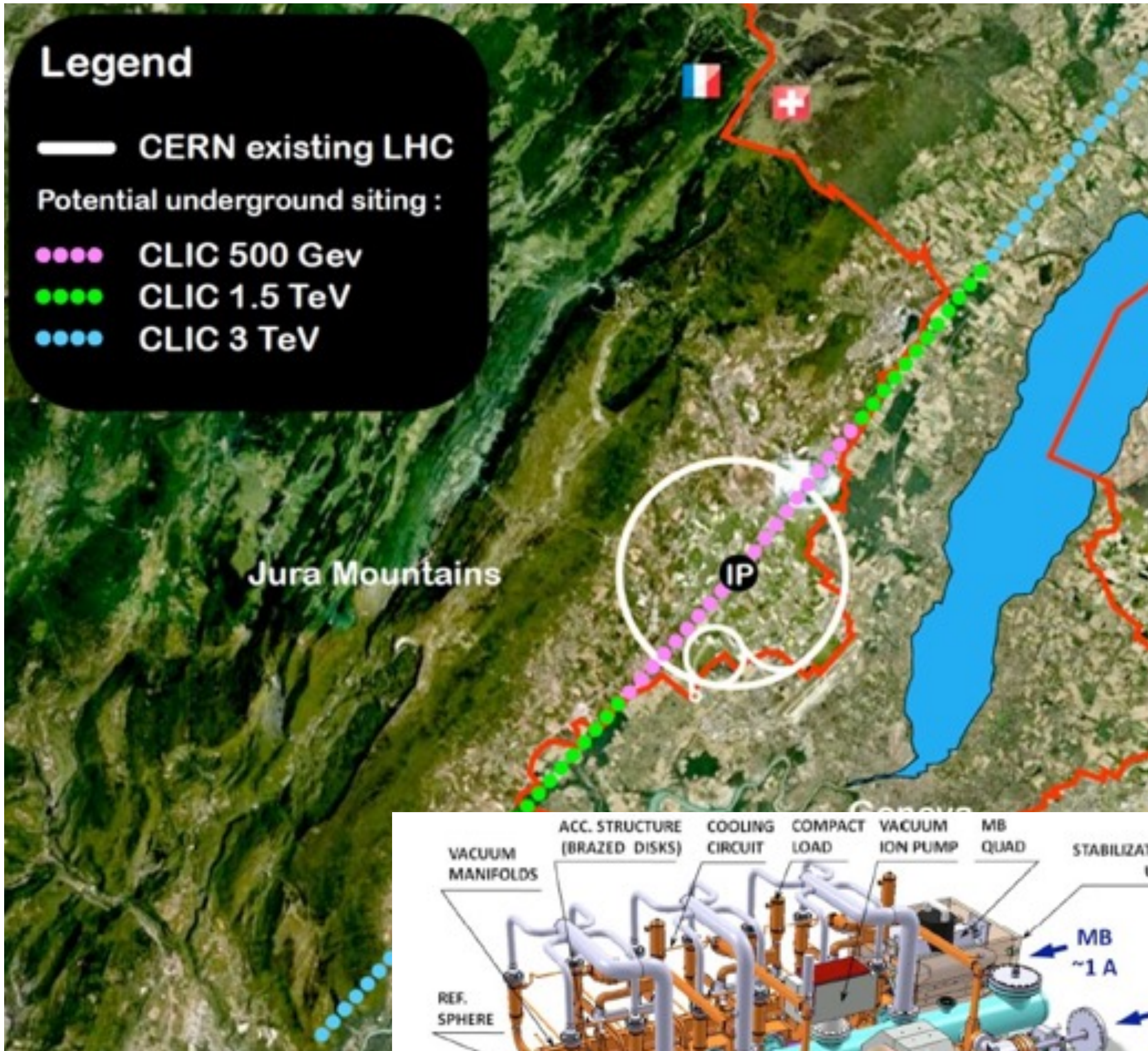


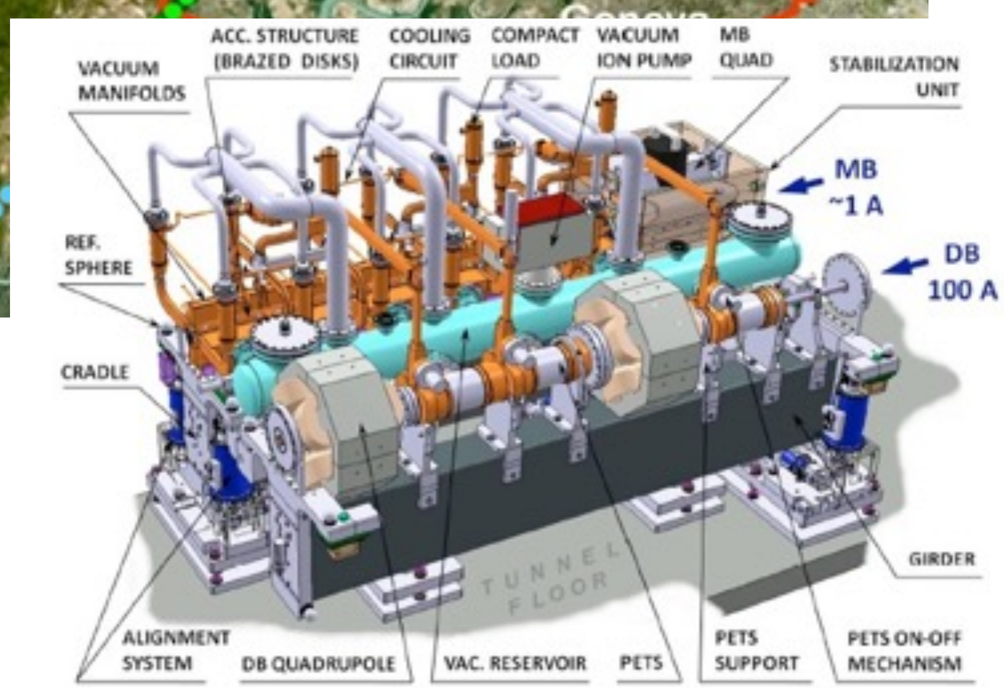
- The **I**nternational **L**inear **C**ollider: a 30 - 50 km long linear tunnel
  - e^+e^- collisions up to 500 GeV / 1 TeV for Higgs, Top, BSM
  - Superconducting acceleration structures, ~ 30 MV/m
  - Technologically far advanced: Technical design report completed in 2012, ILC technology is being used for XFEL construction at DESY
  - Japan as potential host - Possible site north of Sendai (Kitakami)

Current time line

- Construction starting in 2018, physics 2027

Linear Colliders - The Line-Up: CLIC





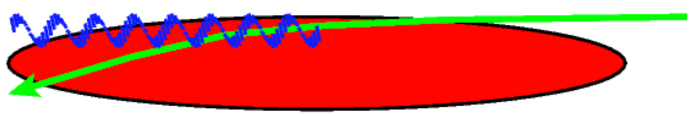
- The **C**ompact **Li**near **C**ollider: A 50 km long linear tunnel as one of CERNs future options
  - e^+e^- collisions up to 3 TeV for Higgs, Top, BSM
  - Two-Beam acceleration, 100 MV/m
  - Main technological issues demonstrated, Conceptual Design report published in 2012

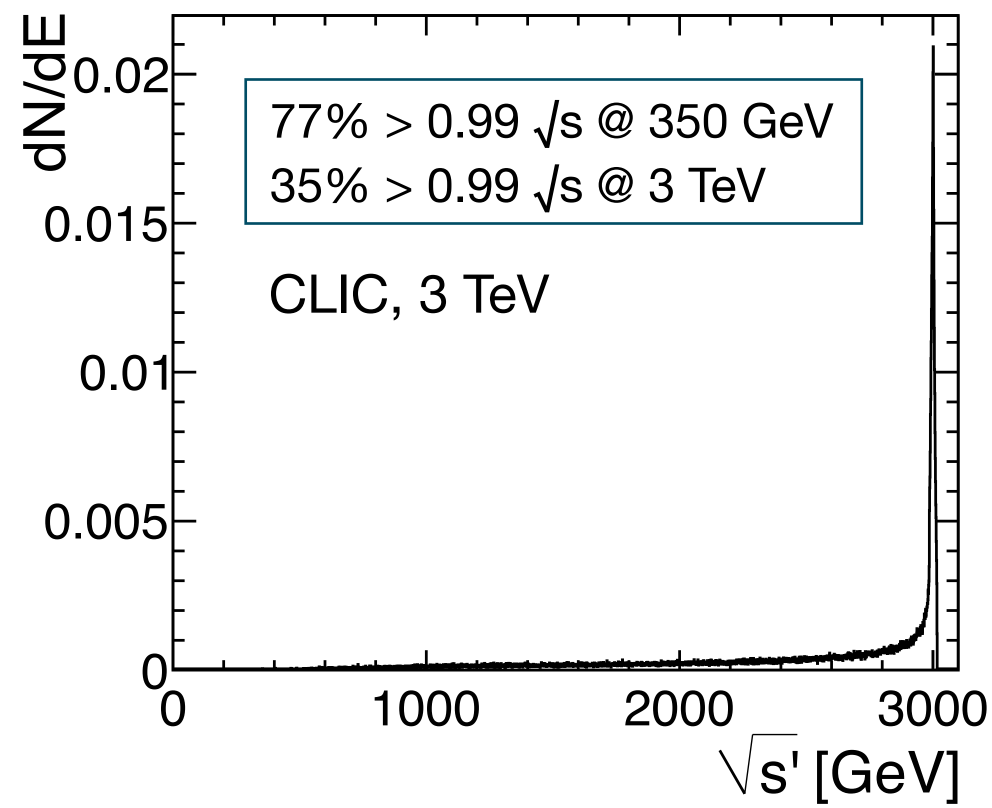
Current time line

- Technical Design by 2018
- Construction could start in 2025, physics by 2035

Experimental Conditions at Linear Colliders

- High luminosity requires very strong focussing - leads to the emission of Beamstrahlung





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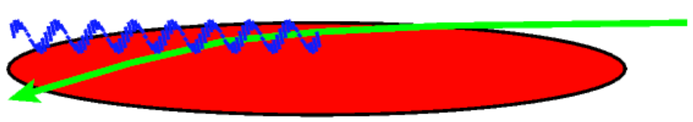
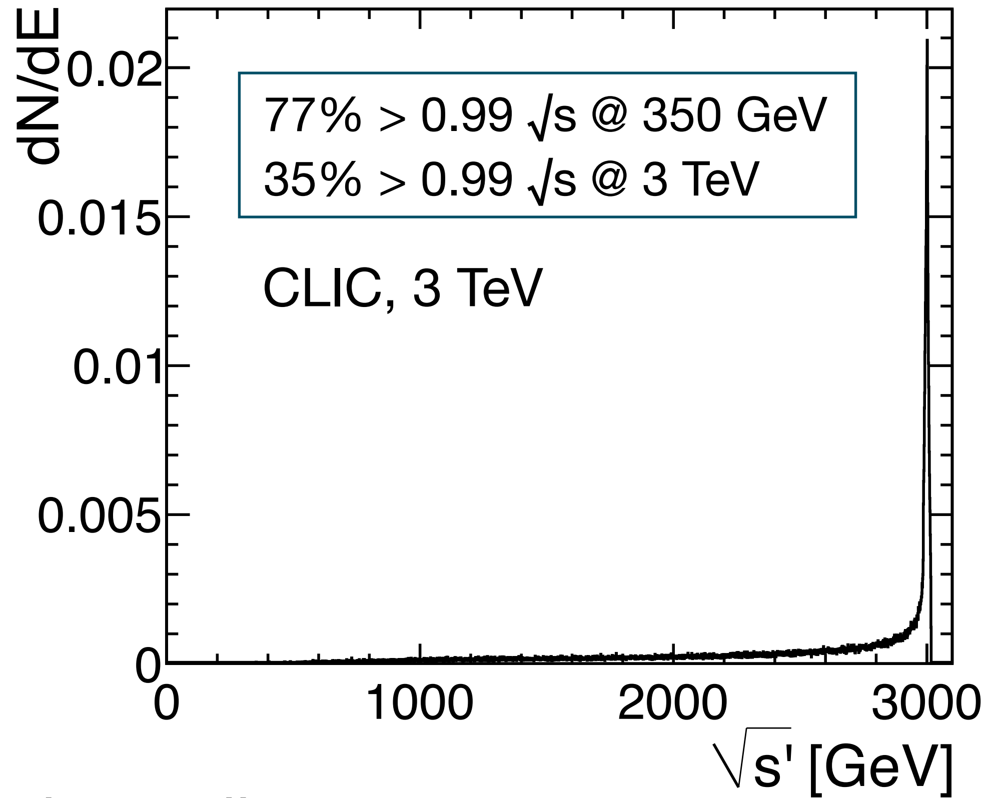
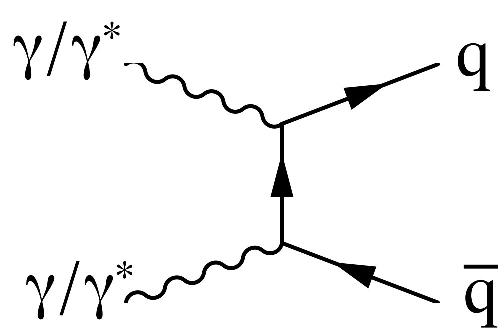




- Photons result in mini-jet production at LC energies:



➩ hadronic background, depending on energy and luminosity per BX (higher at ILC than at CLIC) up to a few events per BX

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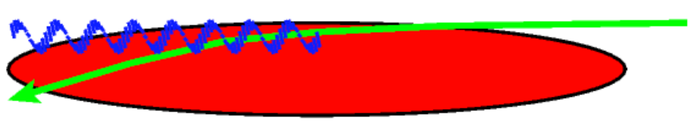

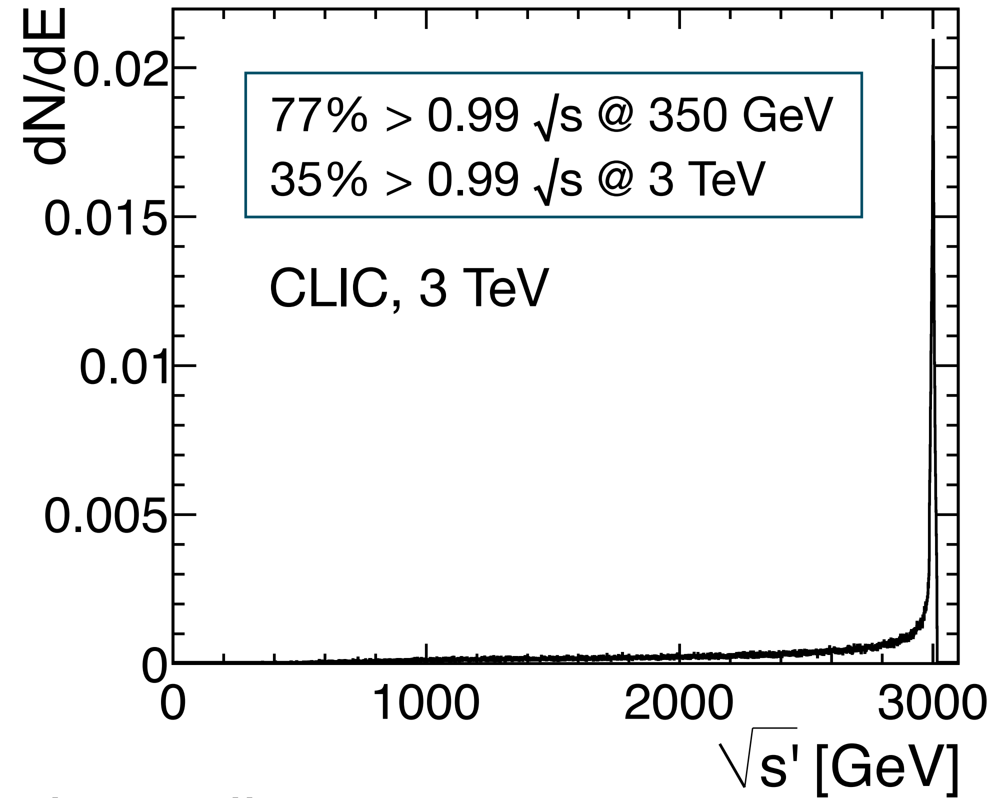

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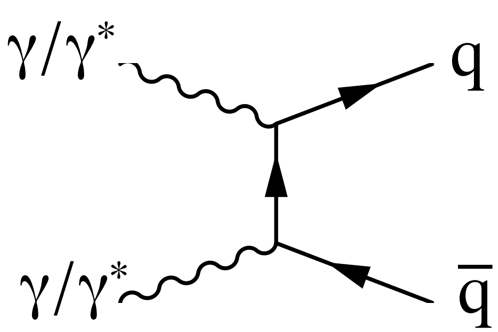

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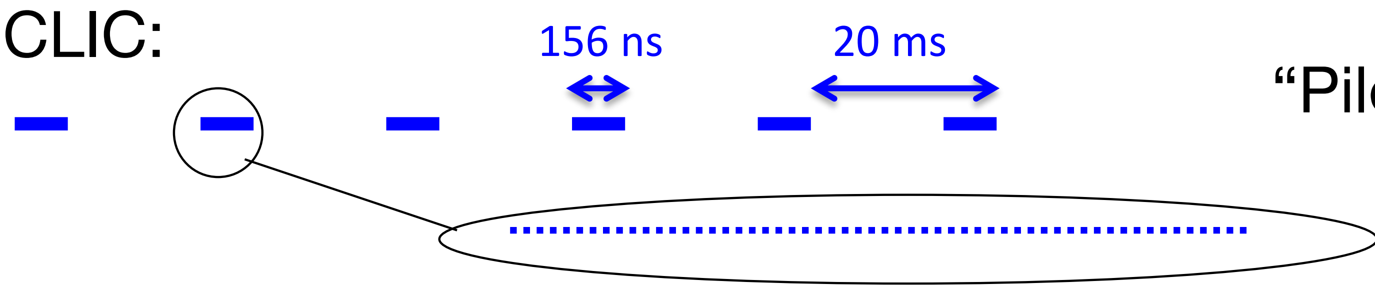
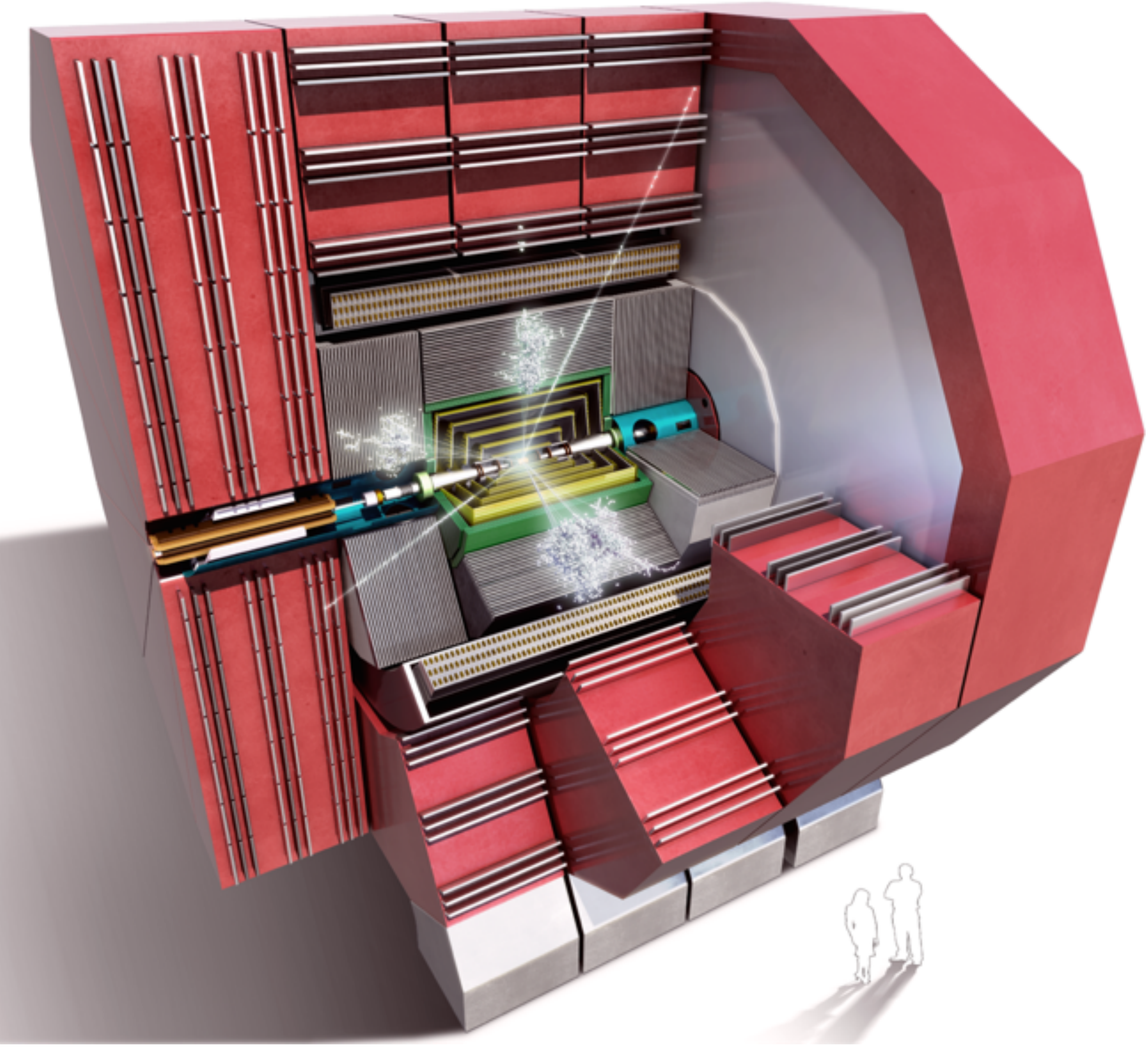
At CLIC:



312 bunches per train, separated by 0.5 ns

"Pile-up" of γγ -> hadrons background

Detectors at Linear Colliders



- General purpose detectors (ILD, SiD at ILC, CLIC detector concept derived from those, currently being optimised)
  - almost hermetic coverage
  - precise vertexing & tracking
  - highly granular calorimeters for Particle Flow event reconstruction

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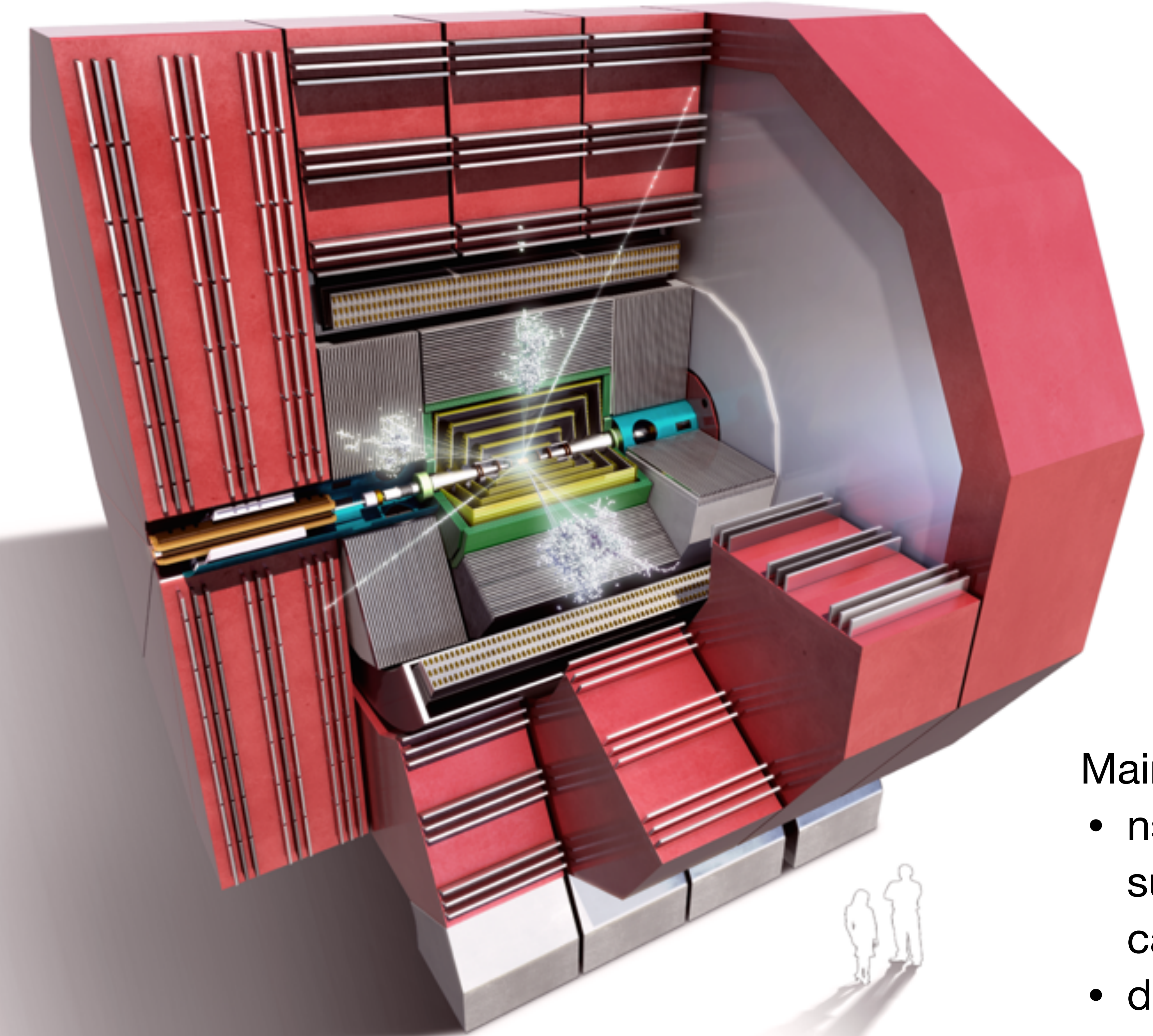

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  - almost hermetic coverage
  - precise vertexing & tracking
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Main additional CLIC features:
- ns-level time stamping in most sub detectors in particular in the calorimeters to reject background
- deeper calorimeters for higher energies

Running Scenarios: Staged Programs

- Linear Colliders lend themselves to a staged implementation
  - Start with a shorter, lower energy collider, extend in several steps to full energy

NB: Details on staged implementation depend on acceleration technology, physics goals, funding considerations, …

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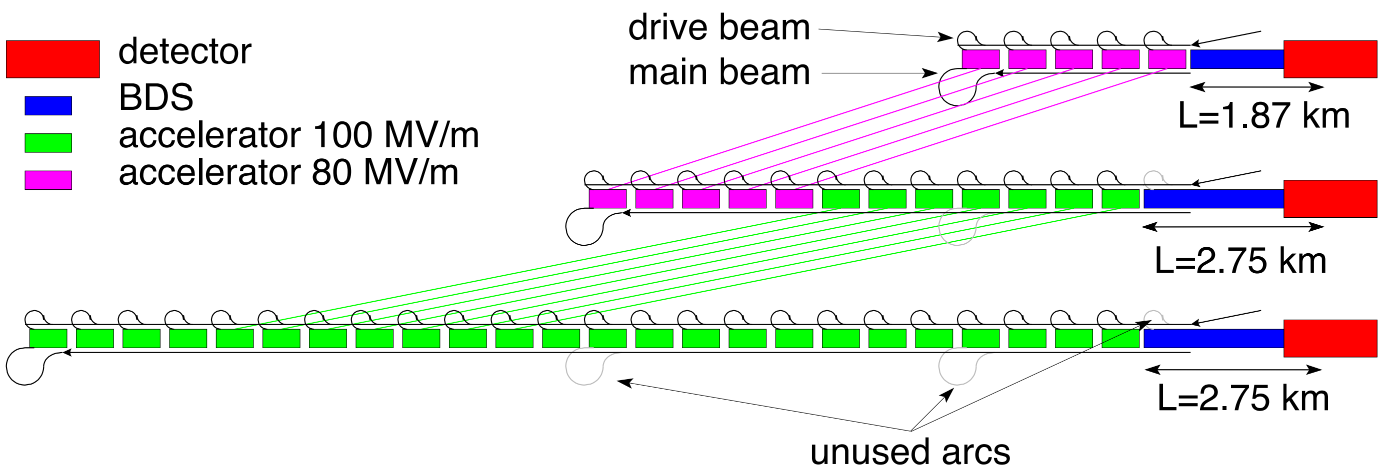
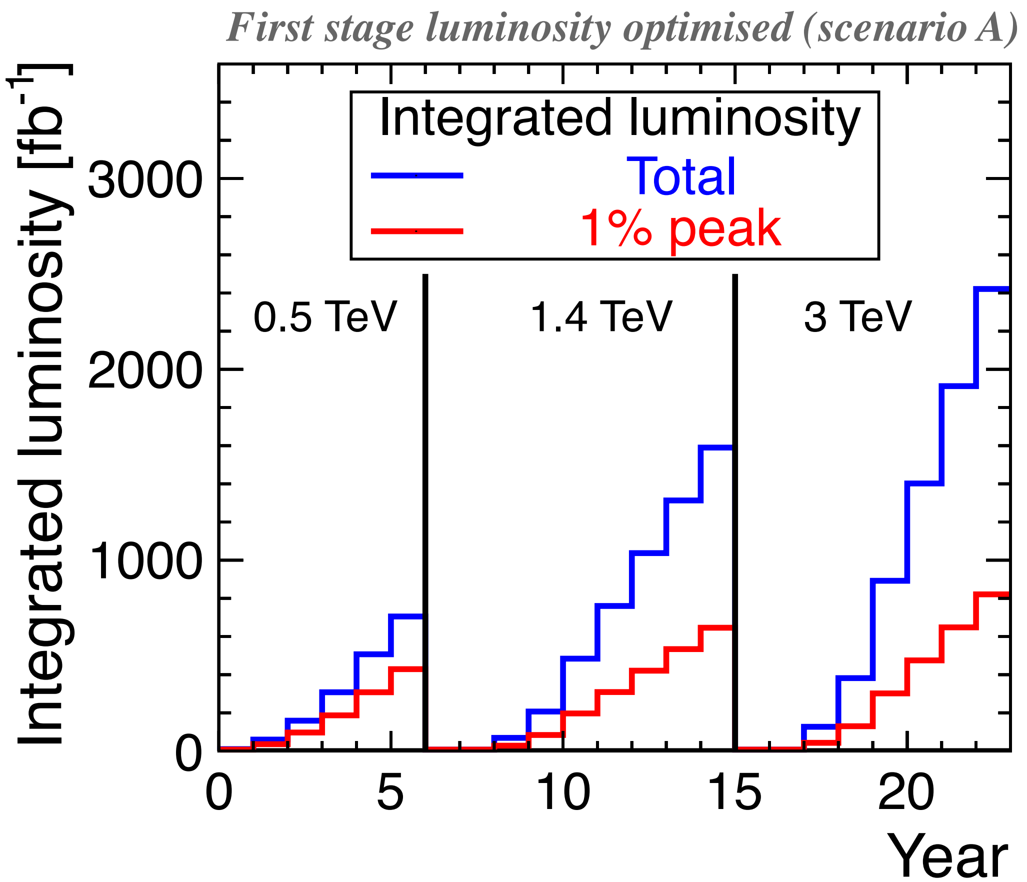
Illustration for CLIC





3 stages: 350 GeV, 1.4 TeV, 3 TeV
each with its own significant physics program

Physics Highlights at Linear Colliders

Before we begin: A Word about the Studies

- Most of the projections shown in the following slides are based on full detector simulations
  - realistic detector models
  - full reconstruction code, including tracking and particle flow algorithm
  - full set of signal and background processes, including beam-induced backgrounds

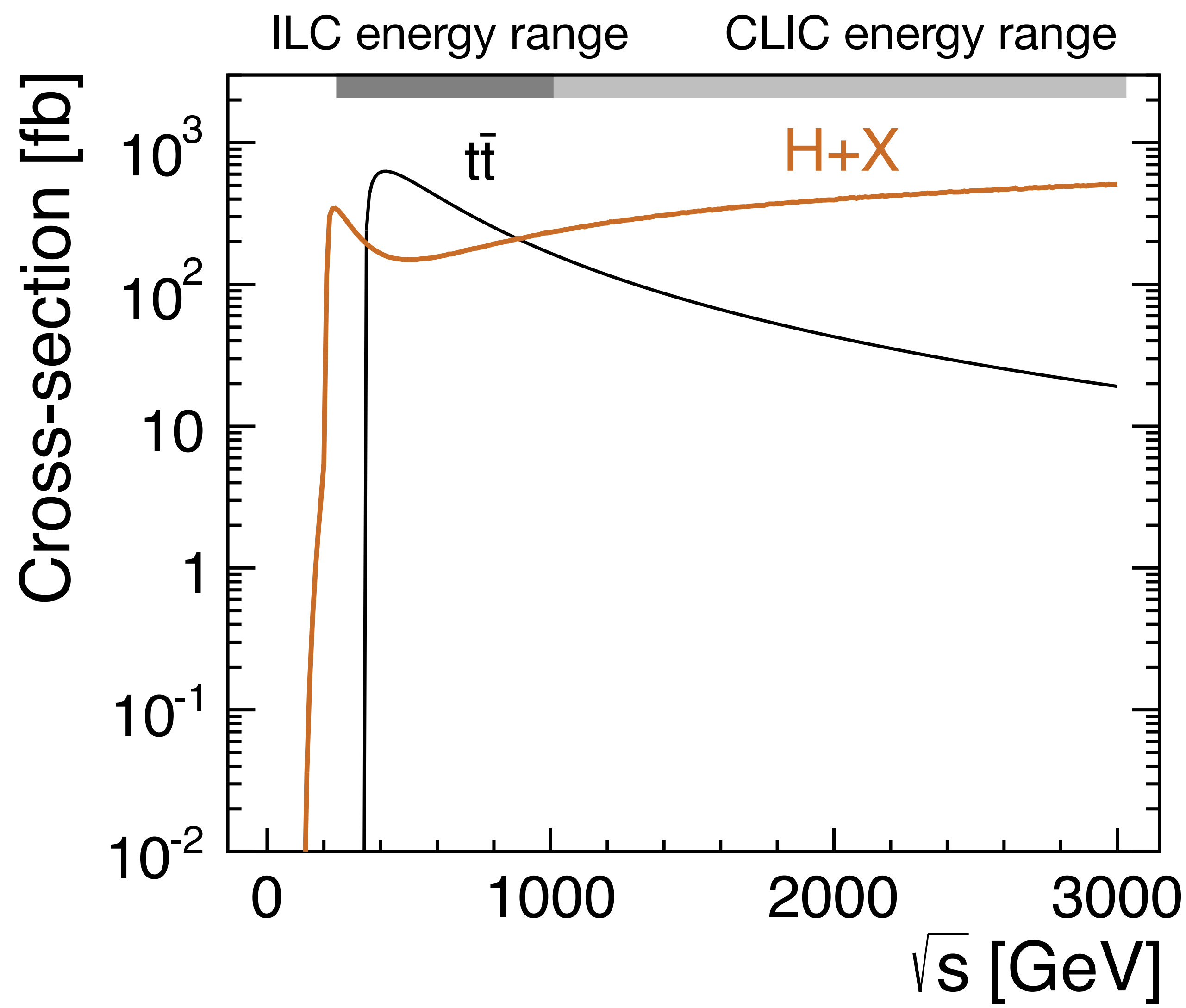
- Based on ILC TDR / DBD, CLIC CDR studies as well as ongoing studies and updates

- Quite a few of the assumptions on detector performance are proven with prototypes
  - Highly granular calorimeters,
    validation of two-particle separation with PFA
  - TPC with MPGD readout
  - Vertex detectors, including potential for very low material
  - …

The LC Physics Landscape

… a combination of certainty and speculation:

- Excellent physics program guaranteed:
  - Higgs physics - mass, couplings, potential, …
  - Top physics - properties (mass, width,…), top as a probe for New Physics
  - Precision physics - electroweak measurements, QCD, …



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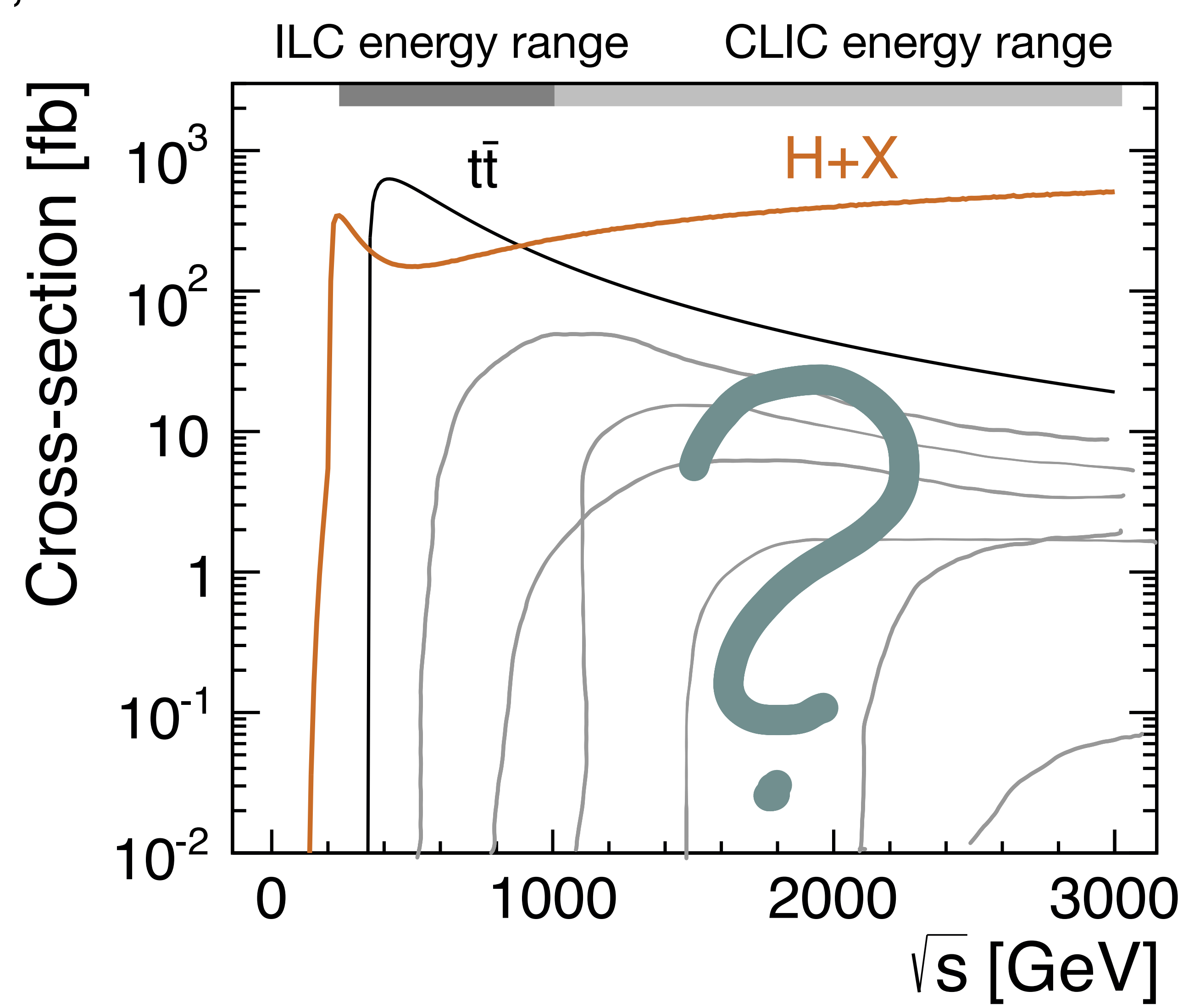
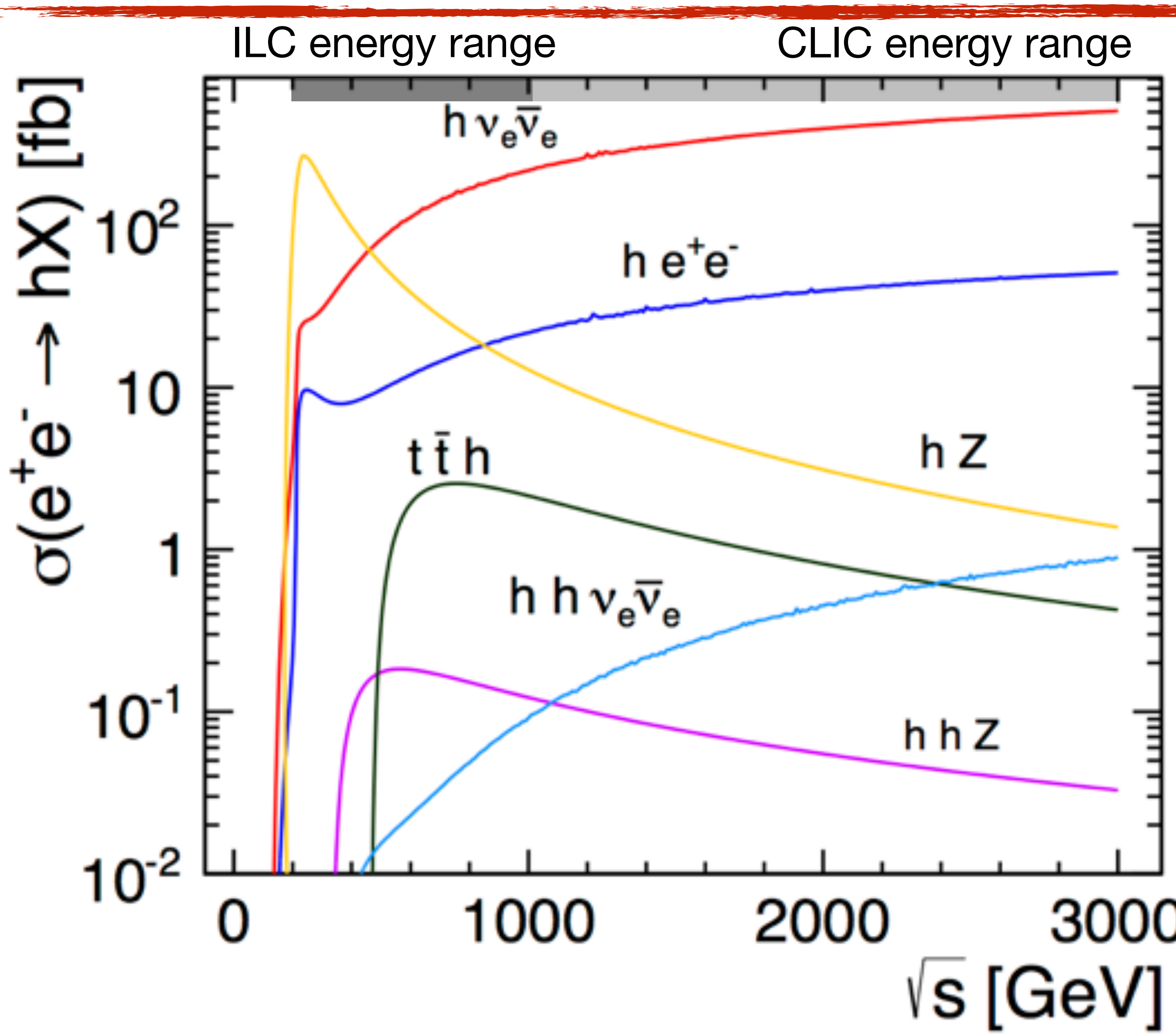
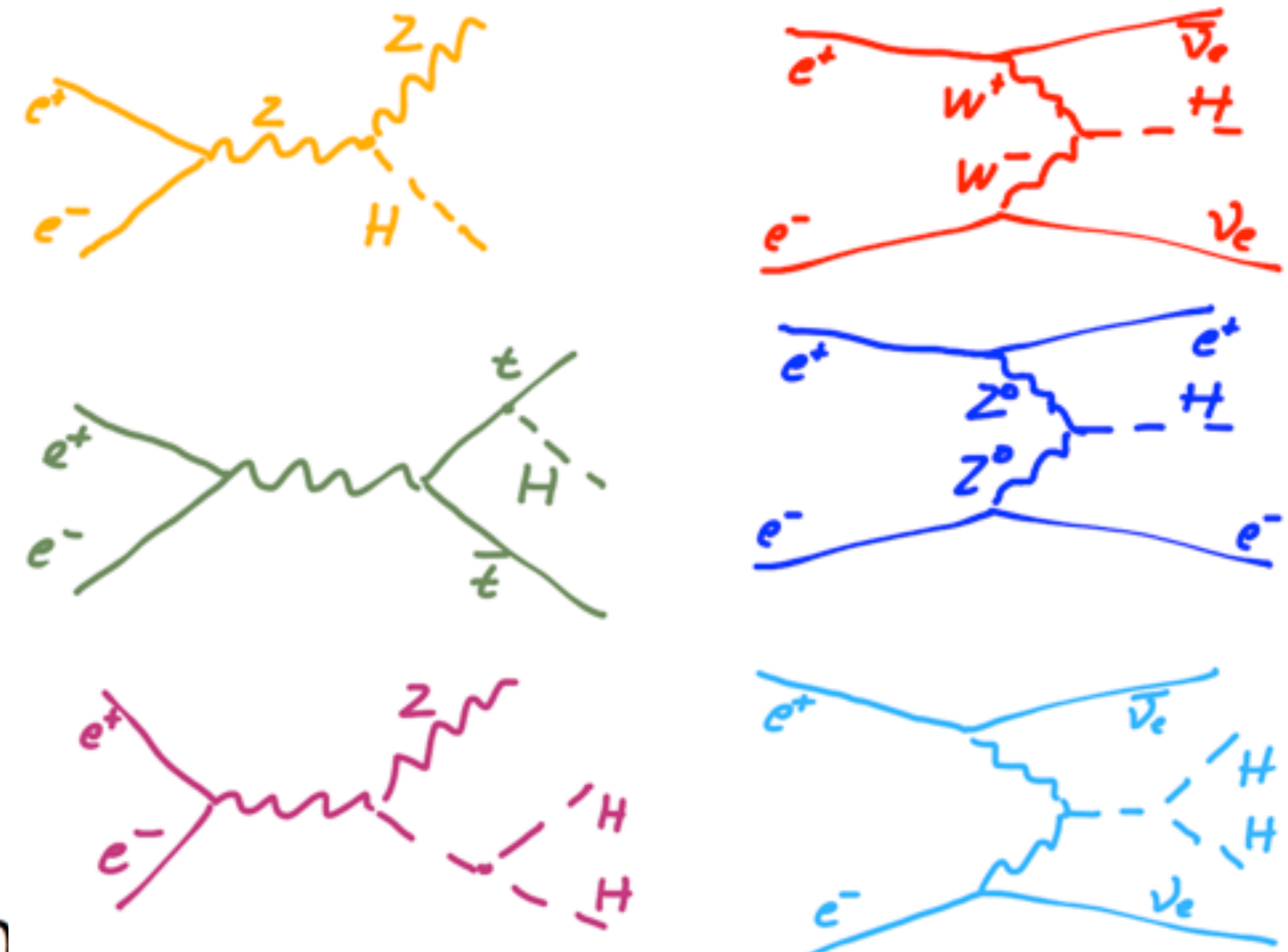


- Discovery potential for New Physics
  - Direct production of new particles - Mass reach up to $\sqrt{s}/2$ for (almost) all particles
    - Spectroscopy of New Physics
  - Indirect (model-dependent) search for New Physics extending far beyond $\sqrt{s}$

A Closer Look at Higgs Production





- Several different Higgs production mechanisms
  - Access to various Higgs properties
  - Different energy to access different processes - from **250 GeV** to **1 TeV** and beyond

Precision Measurements at Linear Colliders

- A flagship measurement: Model-independent Higgs couplings
  What it means: Measure the coupling of the Higgs to bosons and fermions 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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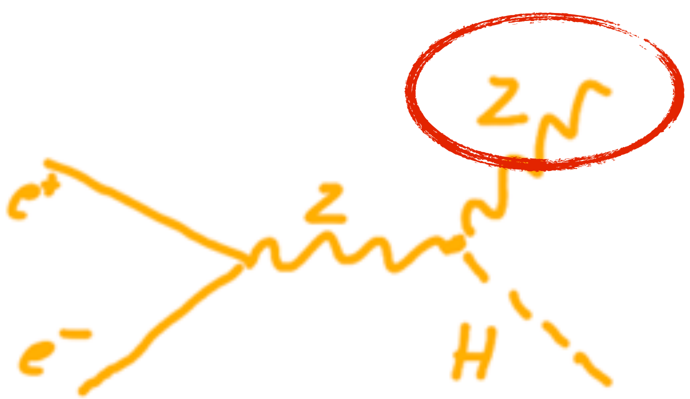
The strategy in e^+e^- collisions:

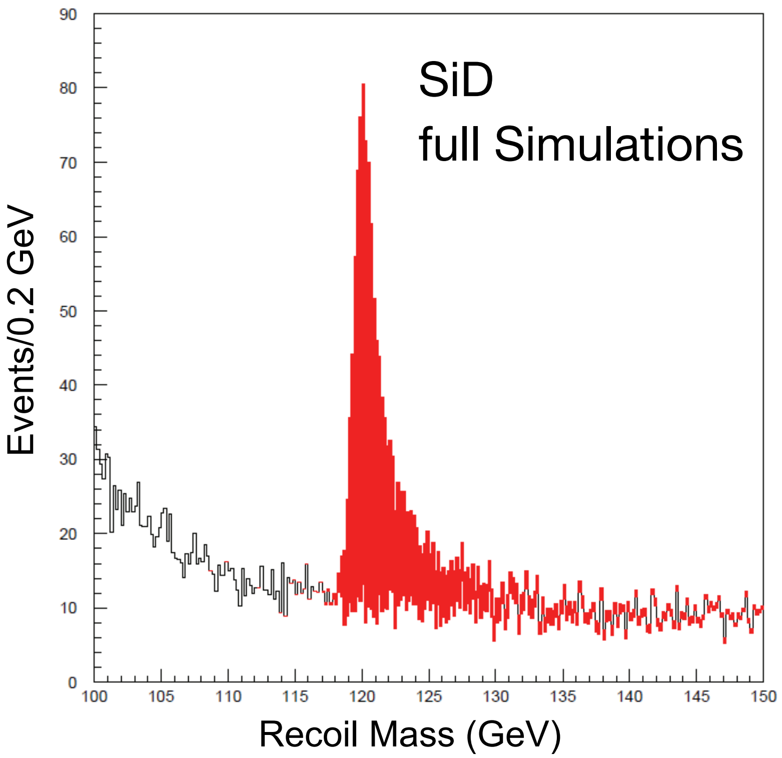


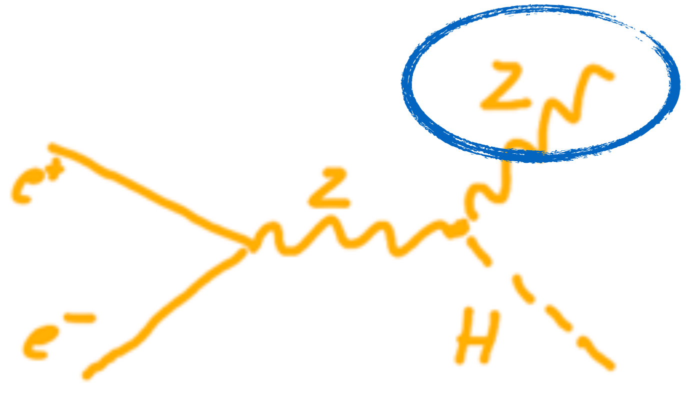
measure ***only*** the Z boson
from the known e^+e^- center-of-mass energy, calculate the “recoil mass”:

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

Exploits: known initial state in e^+e^-
Requires: Identification of Z independent of decay mode of H (or any other particle)
➩ Best results for Z -> μμ, but (almost) model-independent measurements also possible in Z -> qq

Model-Independent Measurement of H Production





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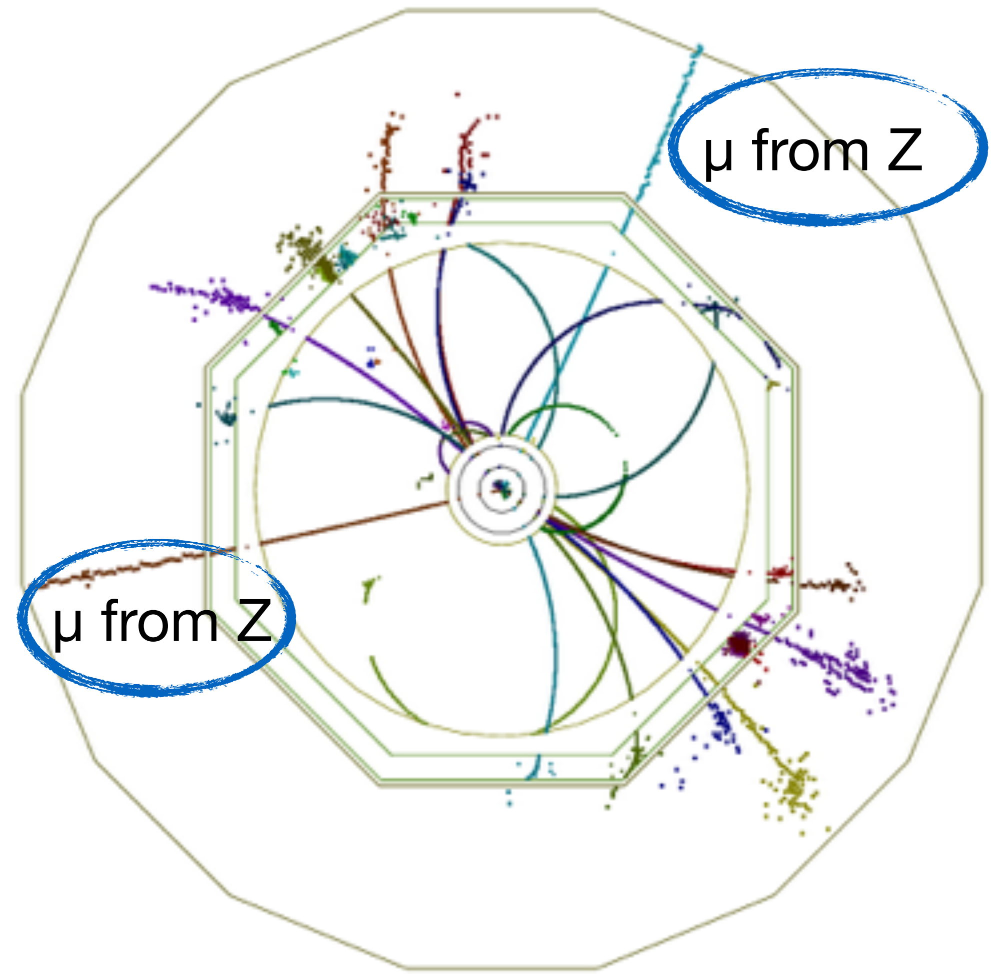

$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

What this provides: Total ZH cross section, and with coupling of H to Z

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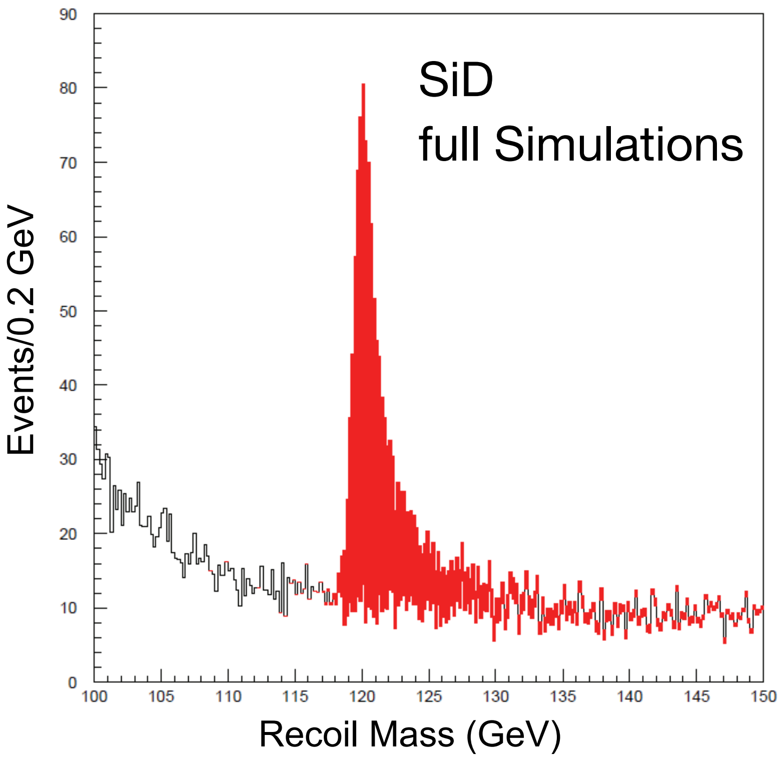

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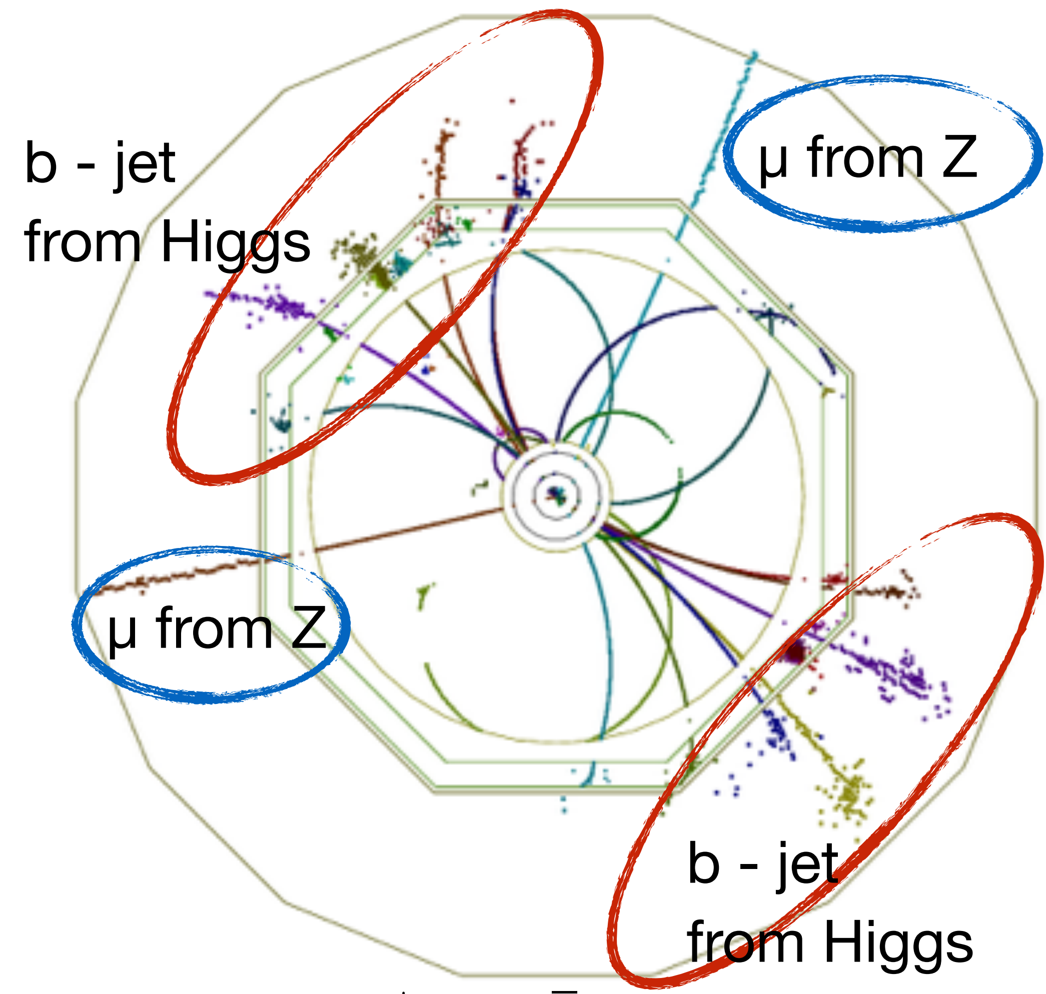

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What this provides: Total ZH cross section, and with coupling of H to Z

- In addition: Reconstruction of specific final states provides access to couplings to fermions and bosons via Higgs decay
  - Makes use of “clean” e^+e^- environment - also allows the reconstruction of final states which are not accessible at hadron colliders: cc, gg

Getting the Global Picture: All Couplings

- The measurements we are making are:

σ x BR (for specific Higgs decays)
σ (for model-independent recoil mass analysis)

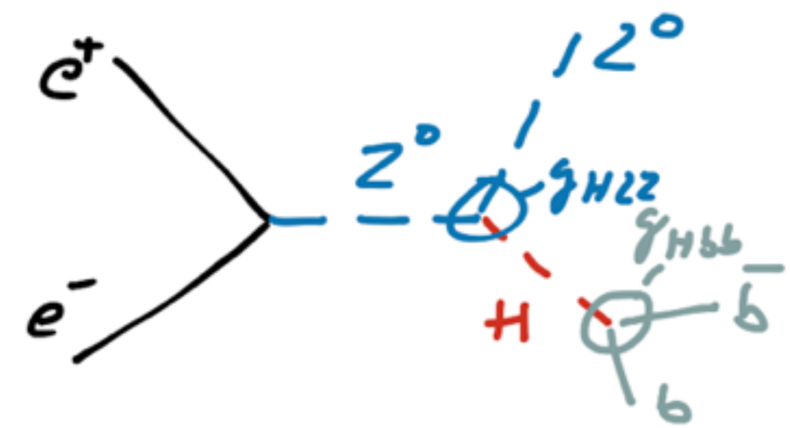
Both are sensitive to the Higgs couplings to the producing particles and to the final state:

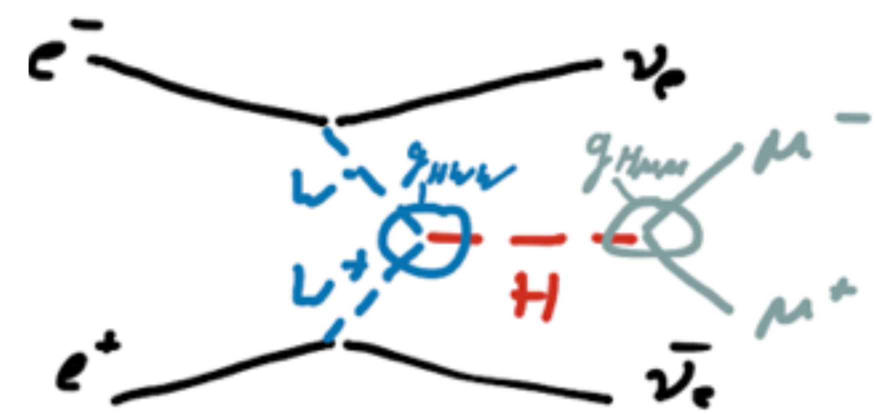
$\sigma_{\mathrm{recoil}} \propto g^2_{\mathrm{HZZ}}$ (NB: final state not considered!)

coupling in production coupling in decay

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

total width





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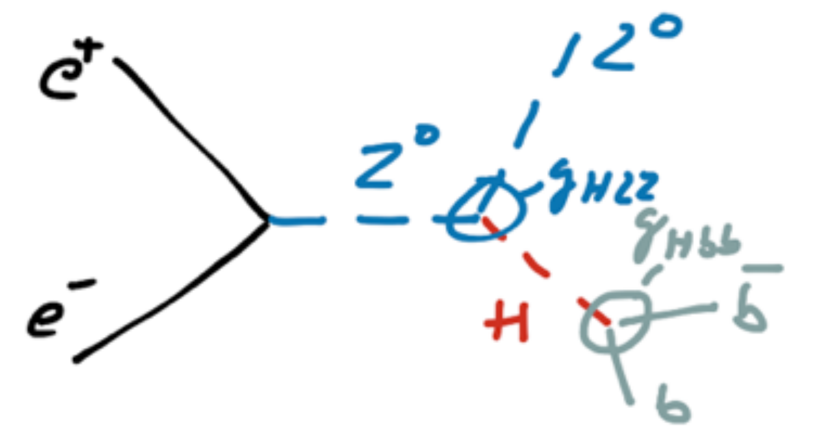

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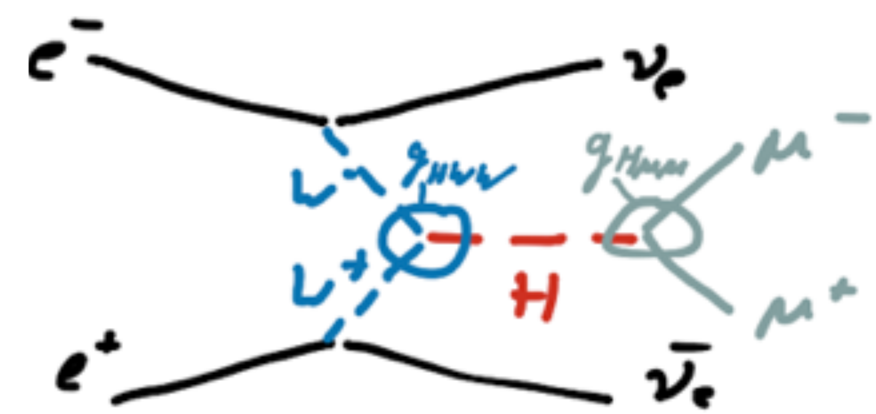

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coupling in production   coupling in decay

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total width

total width best measured in a combination of ZH and WW fusion final states - requires energy of ~ 350+ GeV

Global Fits: Putting it all together

- In the end you don't learn too much from a single measurement - a combination of all results gives a full picture of the couplings of the Higgs, and allows to detect deviations from the SM expectations, potentially pointing at a non-standard Higgs sector

The "simple" approach: Construct a χ^2 with all measurements, perform a global minimization

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

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

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

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

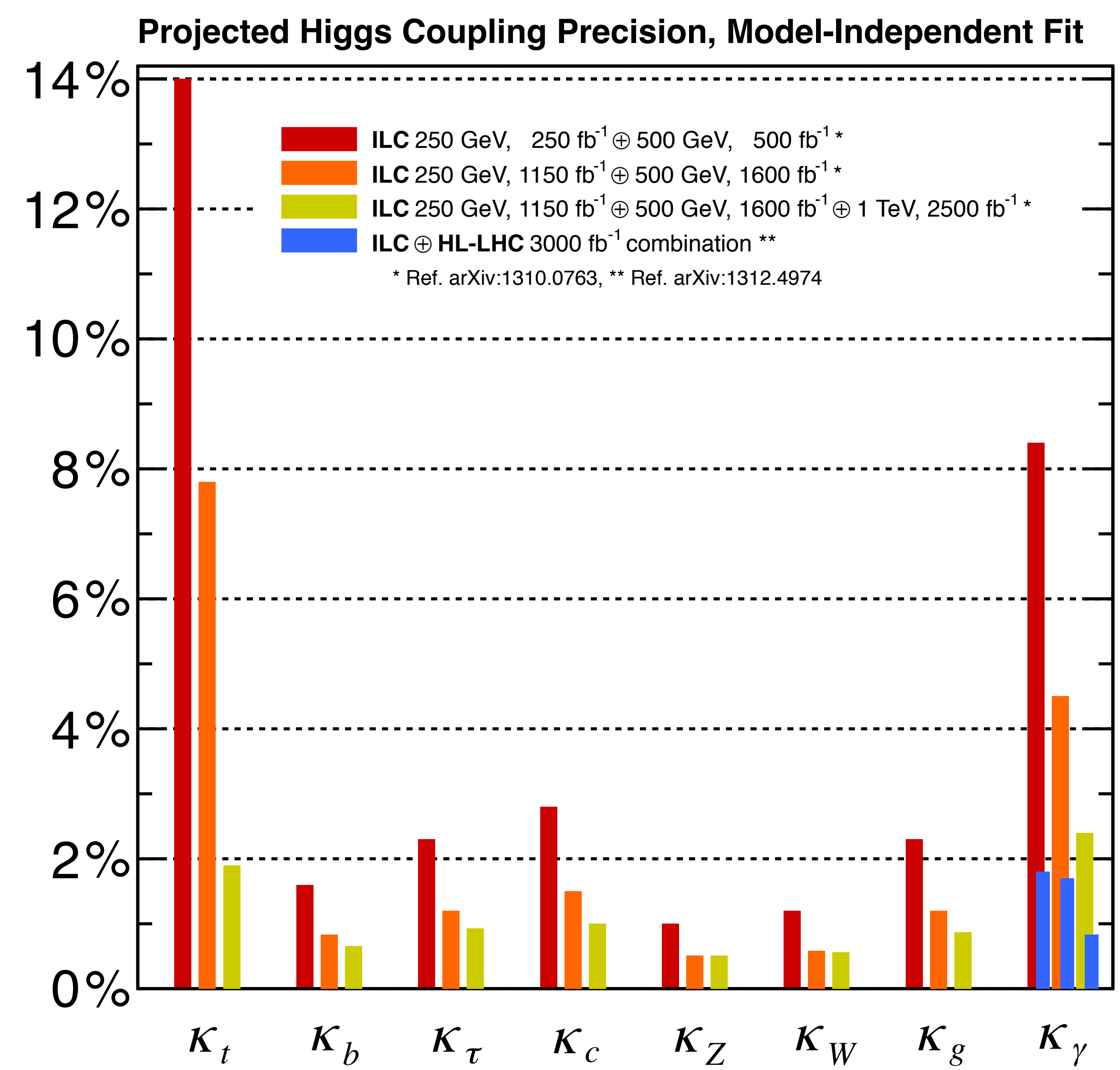
$$C_{\mathrm{H}\nu_e\bar{\nu}_e,\mathrm{H}\to b\bar{b}} = \frac{g^2_{\mathrm{HWW}} g^2_{\mathrm{Hbb}}}{\Gamma_{\mathrm{H}}}$$

...

As usual the devil is in the details: need to account for correlations between measurements, find a consistent way of quantifying and treating theoretical uncertainties when comparing to the SM, …

Higgs: The Global Picture

- Fully model-independent measurements of most couplings at the sub-1% to 2% level
- Deviations from the SM can be detected on the per mille level in some cases (model-dependent approach, comparable to LHC)



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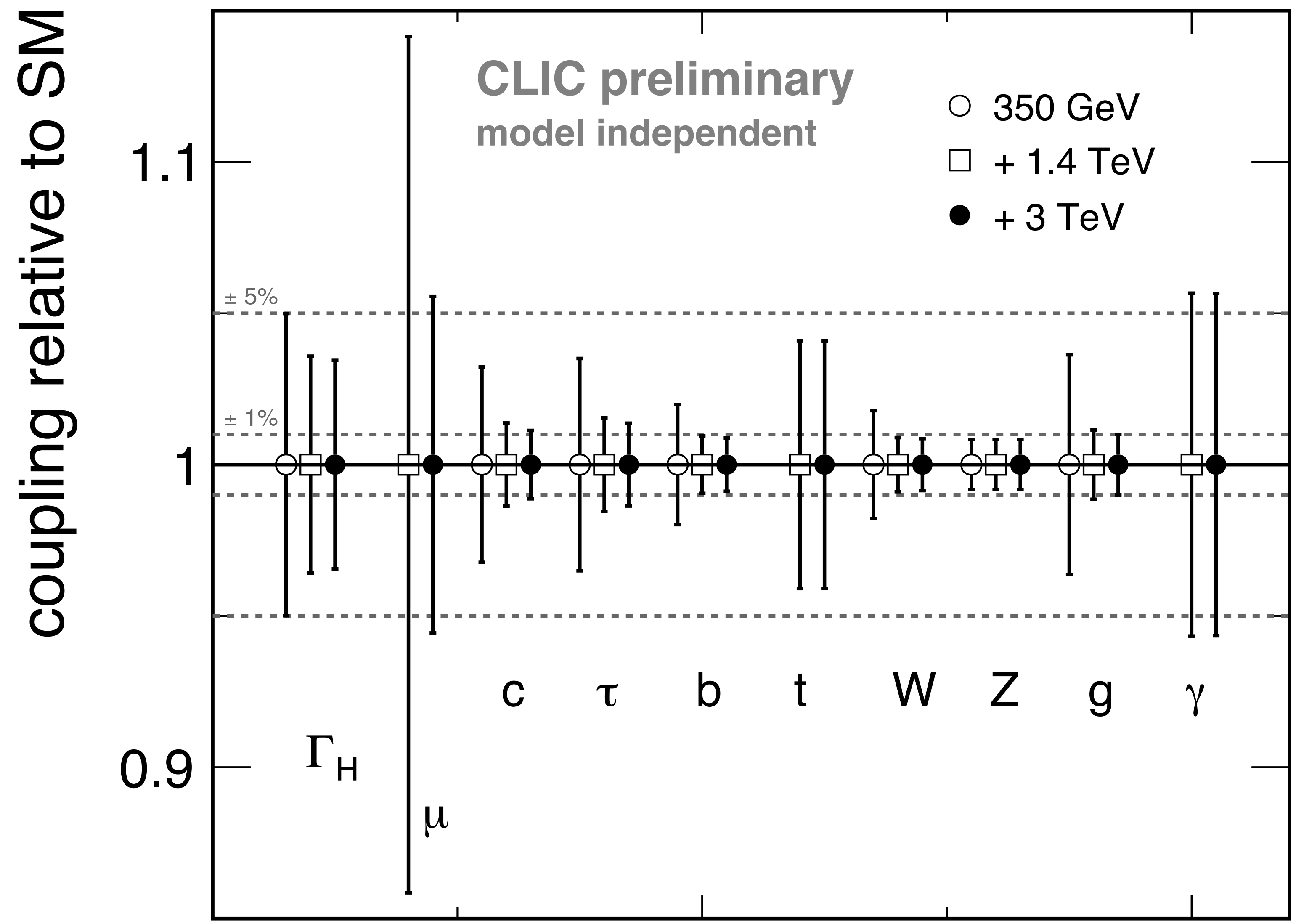

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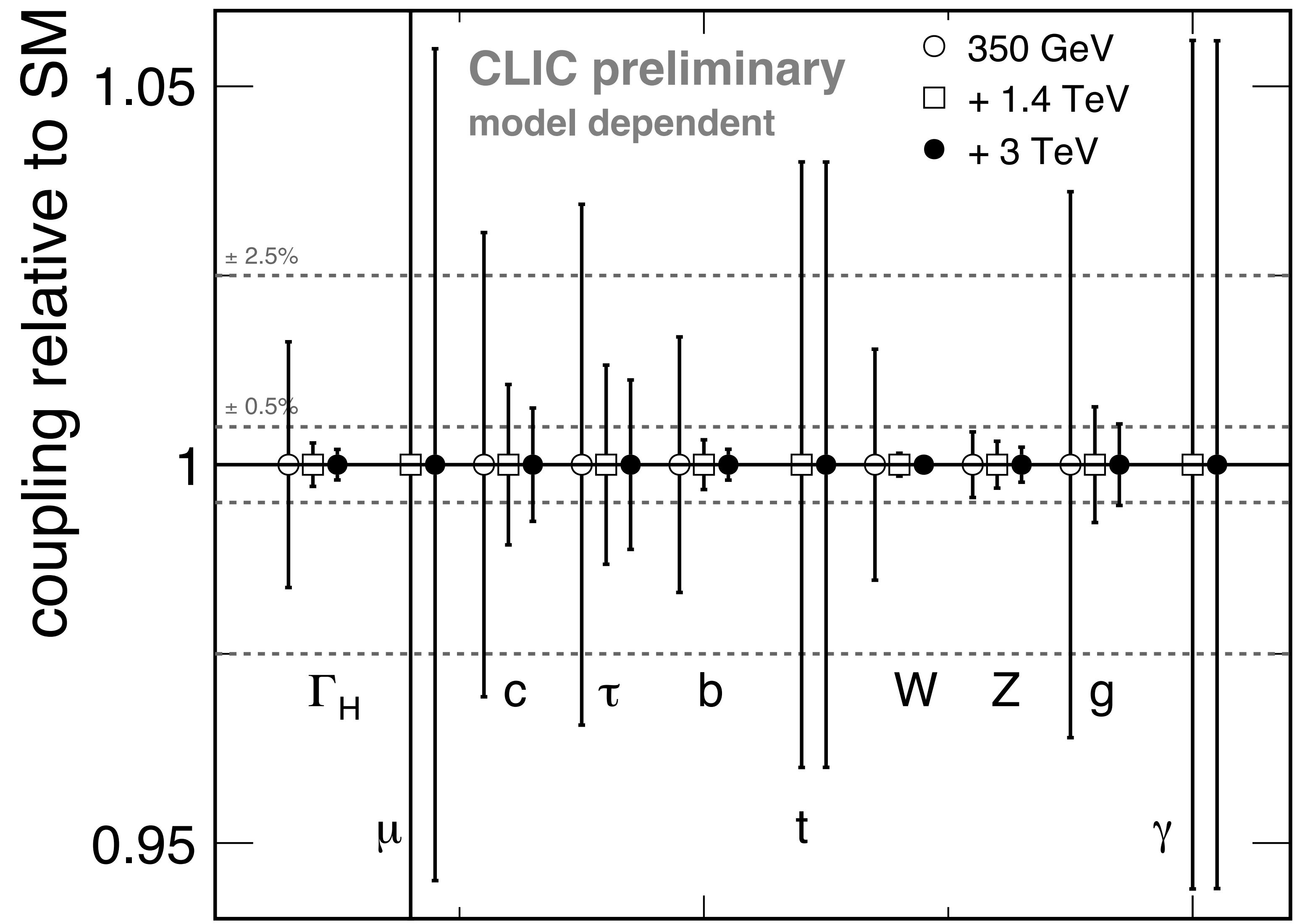
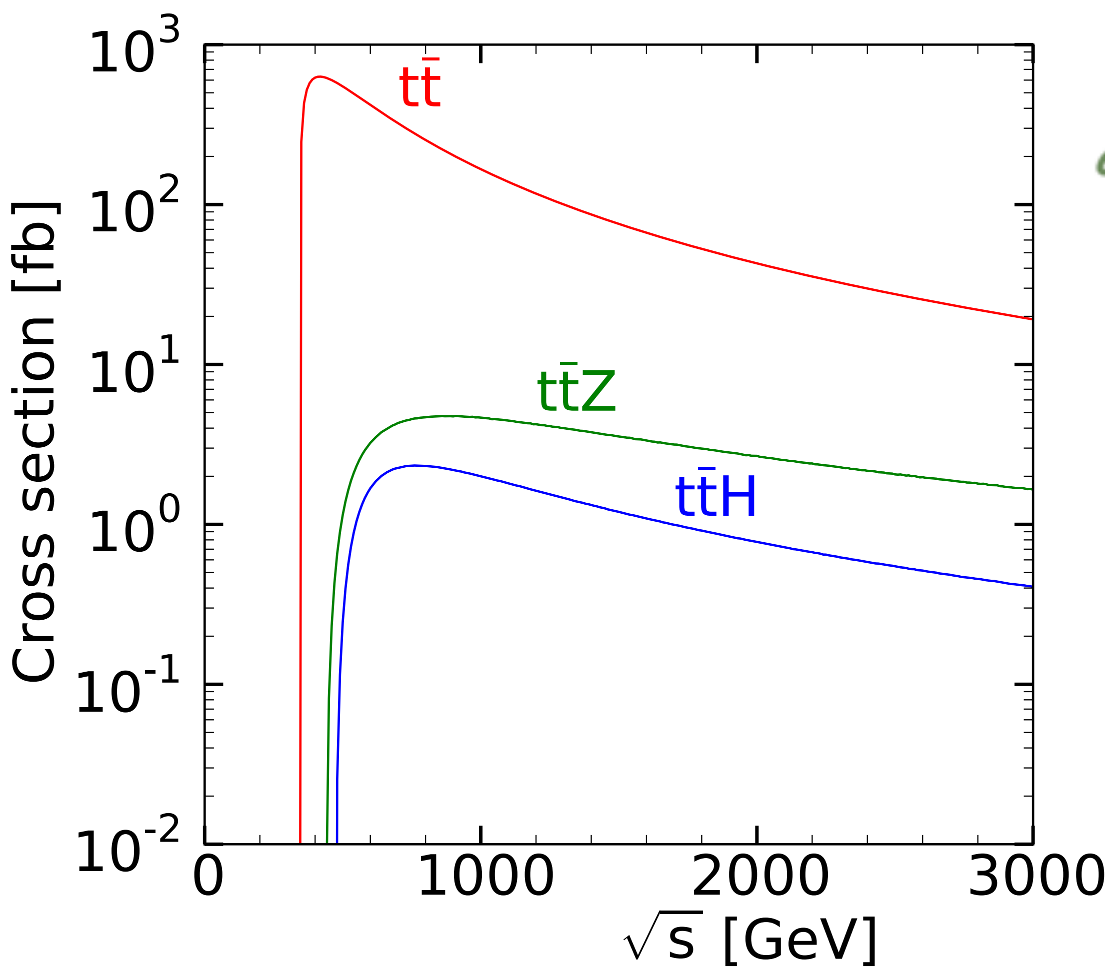


- Limit by ZH recoil removed for model-dependent fit (assuming no non-SM decays)

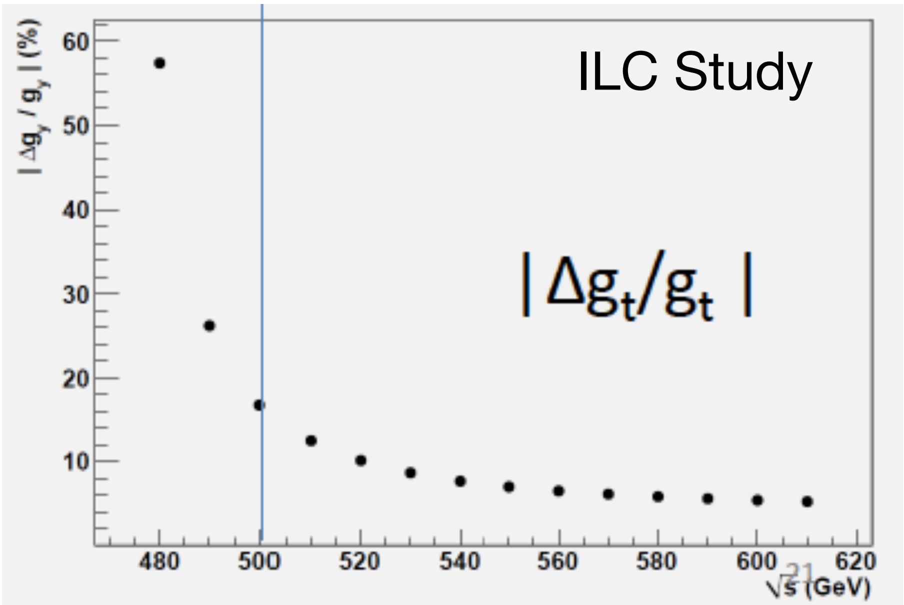
Direct Measurement of the Top Yukawa Coupling

- Direct measurement of the top Yukawa coupling possible at energies of ~ **500 GeV** and above



- Close to threshold, QCD effects lead to an enhancement of the cross section
  - Maximum around 800 GeV, somewhat higher energies compensated by higher luminosity

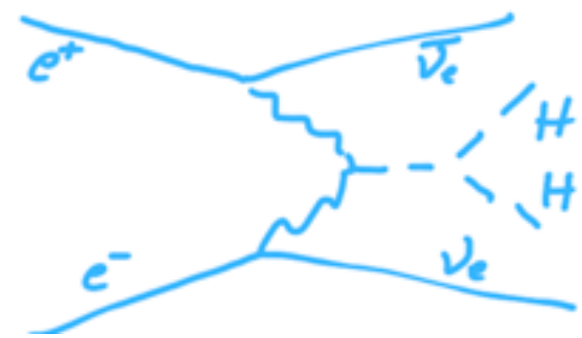
- Going a bit above threshold has substantial benefits: At ILC, the change from 500 GeV to 550 GeV results in > x2 improvement (14% -> 6% for 500 fb^{-1})



The Ultimate Challenge: Self-coupling

- At present e^+e^- colliders seem to be the only possibility for a significant measurement of the self-coupling of the Higgs
  - Provides a direct probe for the Higgs potential: Highly interesting and important!

σ_{max} at ~ 500 GeV



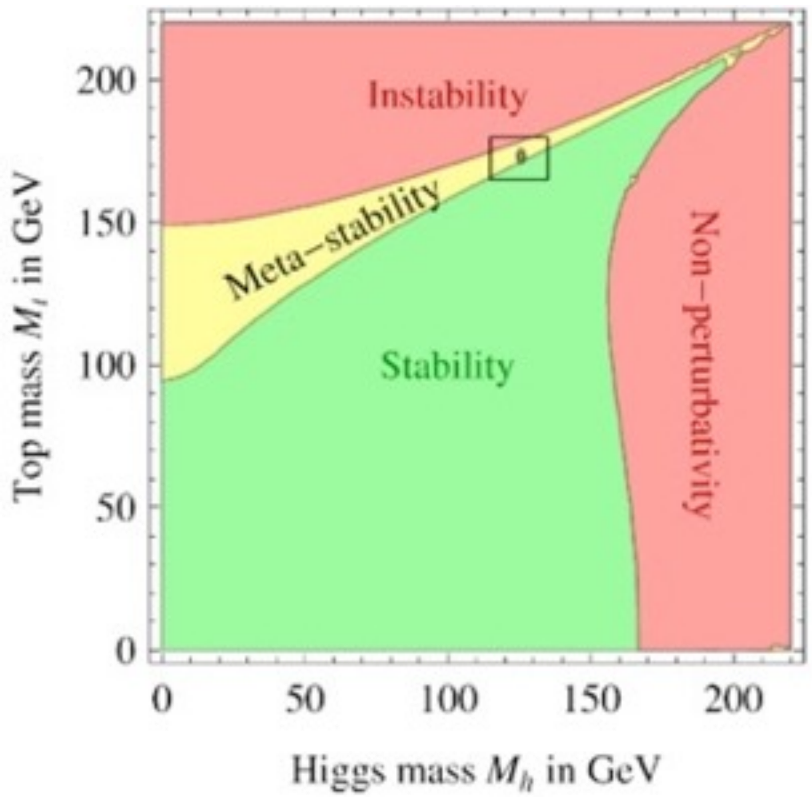
σ increasing with energy, significant from 1 TeV on

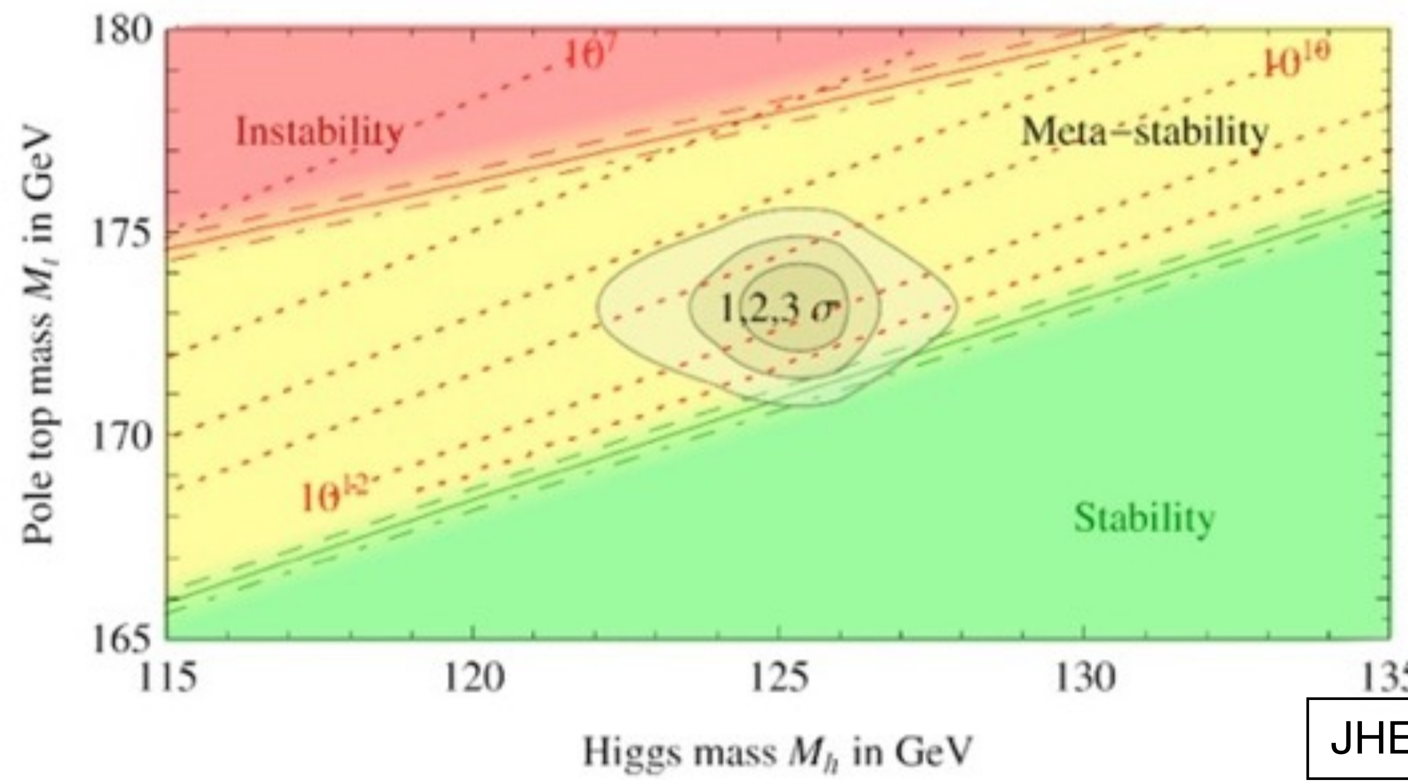
Two processes with two-Higgs final states - low cross-section
➩ separation from background a challenge!

Requires high integrated luminosities in both cases - best prospects at energies of 1(+) TeV, prospects for 10% measurement at CLIC (assuming 80% polarized electrons, 1.5 ab^{-1} at 1.4 TeV, 2 ab^{-1} at 3 TeV)

Pinning Down the Top Quark

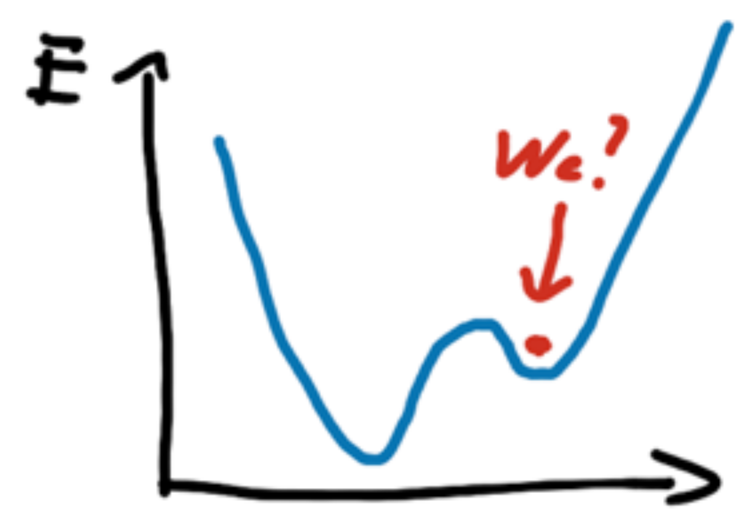
- As the heaviest SM particle, the Top plays an important role: Strongest coupling to the Higgs field, potential sensitivity to New Physics
  - One example: “The fate of the Universe”





JHEP 08, 98 (2012)

- Top mass, together with Higgs mass, provides information on the stability of the SM vacuum at higher scales
  - Possible validity of the SM up to the Planck scale?
  - Impact on evolution of the early universe



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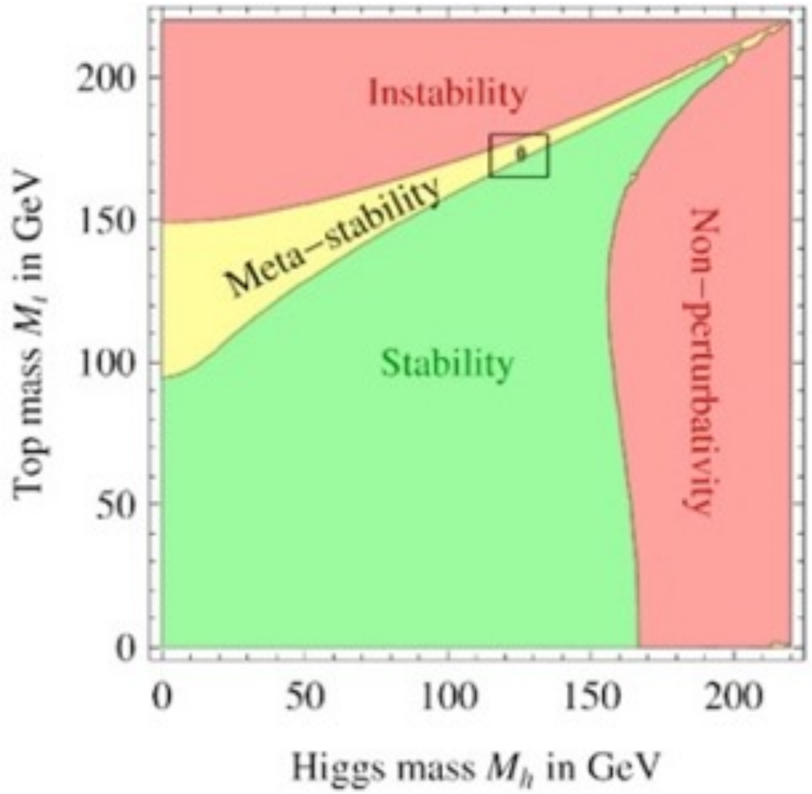

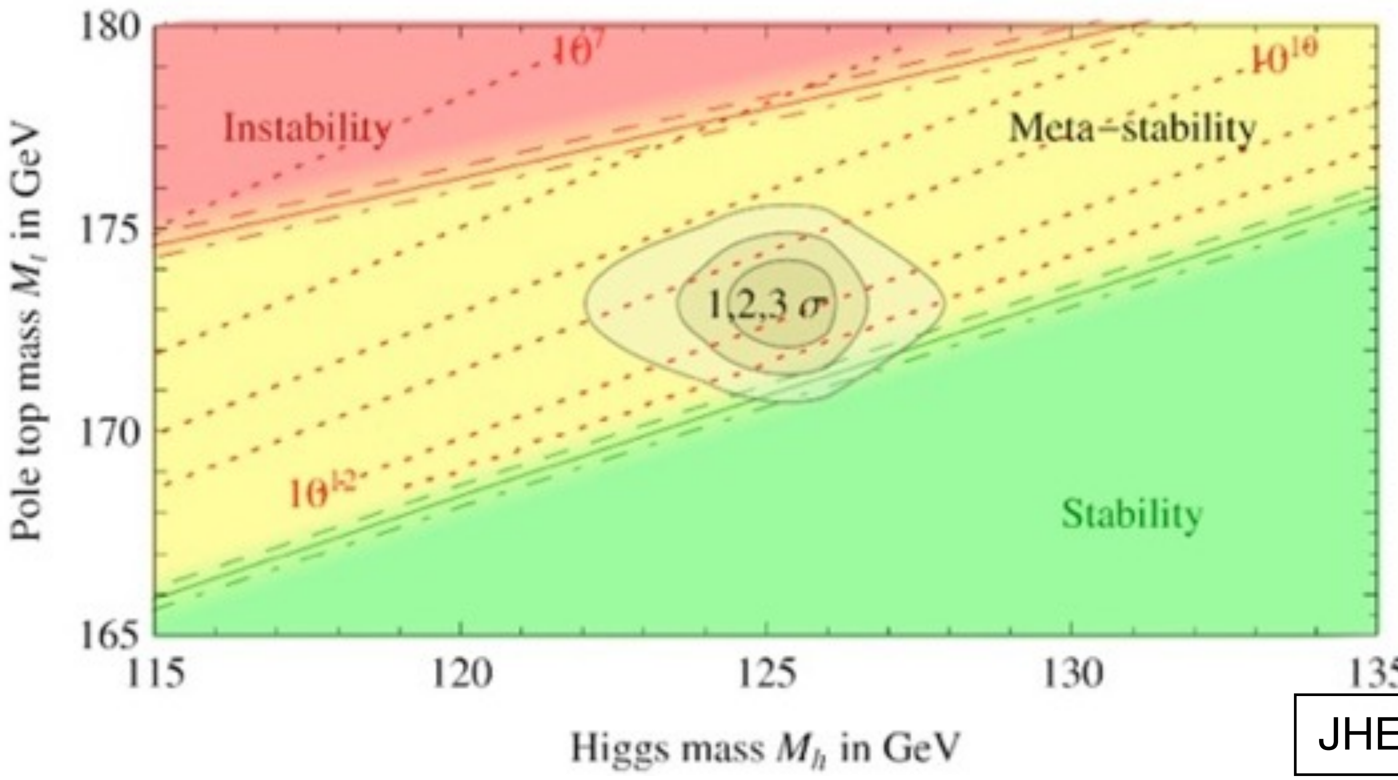

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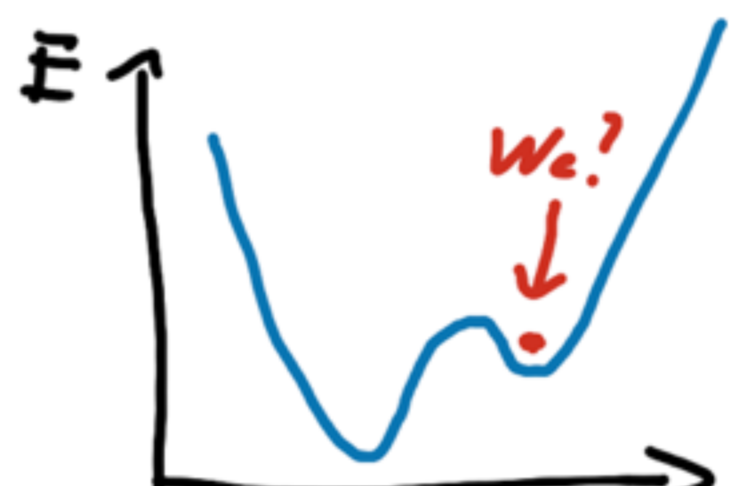
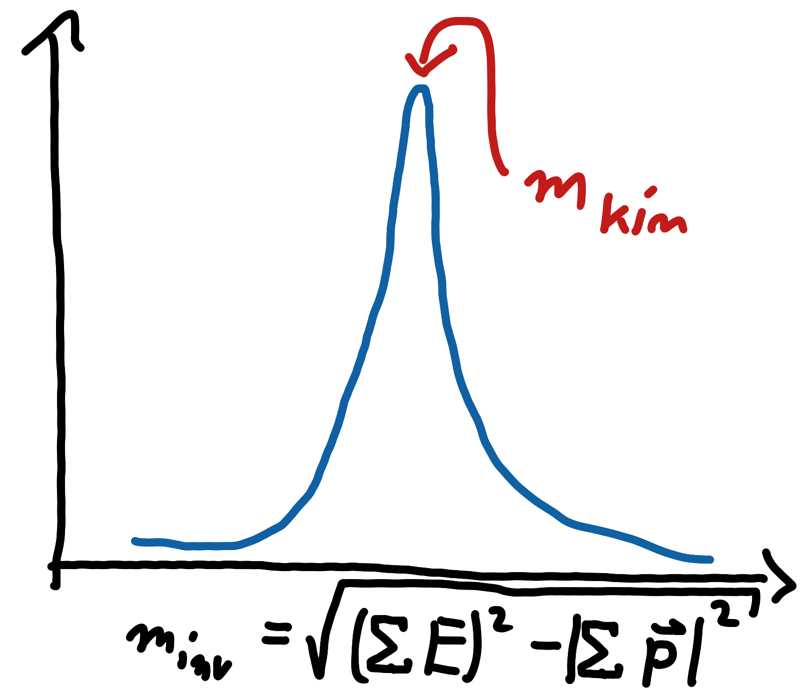


Leading uncertainty: Top Mass!

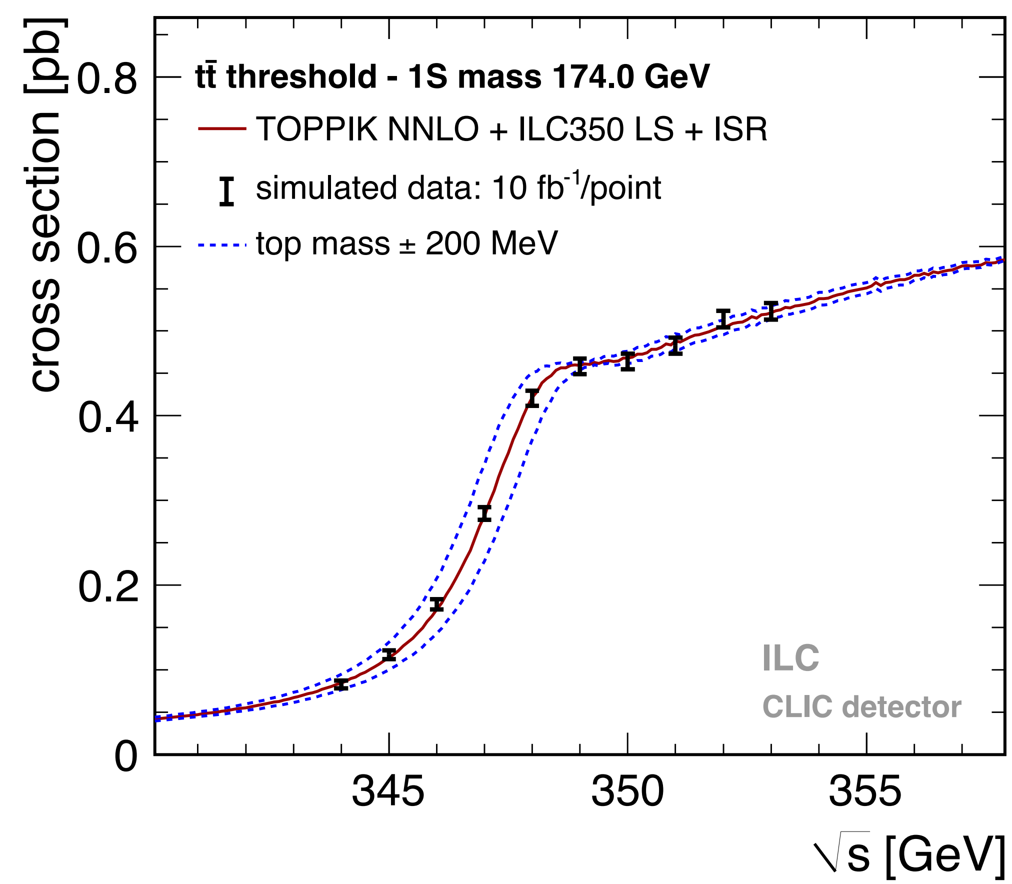
Measuring the Top Mass

- So far the top quark has only been produced at hadron colliders - Standard mass measurement by kinematic reconstruction
  - suffers from large (*O* GeV) theoretical uncertainties
- e^+e^- collisions allow the measurement of top properties with substantially reduced uncertainties - Smaller QCD effects, precise calculations of cross section in threshold region

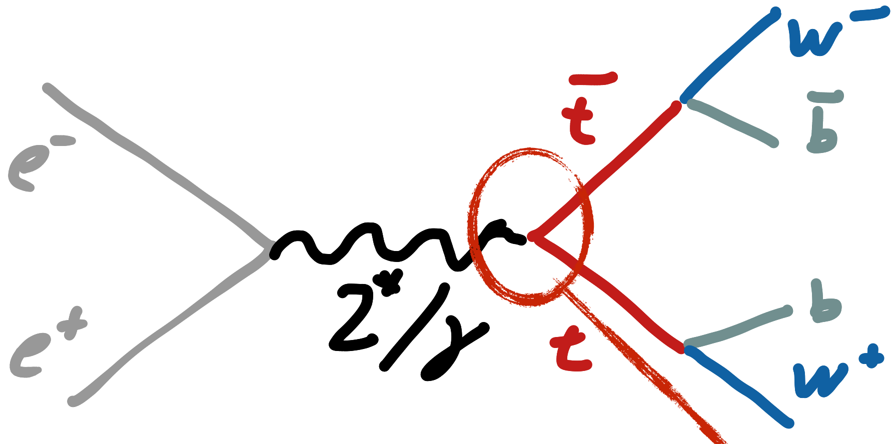


~ 100 MeV total uncertainty achievable - in a theoretically well-defined mass scheme - dominated by theoretical uncertainties (evaluation ongoing)

~ 1 order of magnitude better than LHC



Using the Top as a Tool to Explore New Physics



- The production of top pairs provides direct access to electroweak couplings - axial and vector form factors

$$\boxed{\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2)\right)\right\}}$$

X: Z, γ   *A*: axial coupling   *V*: vector coupling

- In total: 5 non-trivial CP-conserving form factors:

$$\begin{array}{ccc} F_{1V}^{\gamma} & \boxed{F_{1A}^{\gamma}} & F_{2V}^{\gamma} \\ F_{1V}^{Z} & F_{1A}^{Z} & F_{2V}^{Z} \end{array}$$

= 0 due to gauge invariance

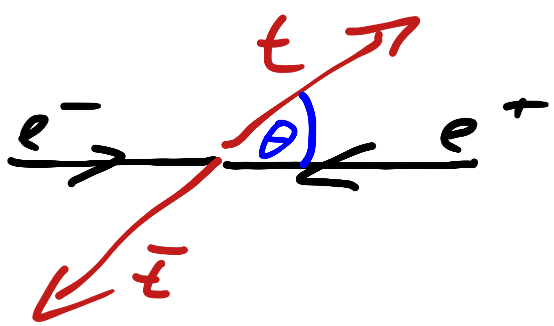
- Accessible through measurements of:
  - ***Total cross-section***
  - ***Forward-backward Asymmetry A_{FB}***
  - ***Helicity Angle λ*** distribution (related to fraction of left- and right-handed tops)
- For each: Two polarizations e^-_L - e^+_R, e^-_R - e^+_L

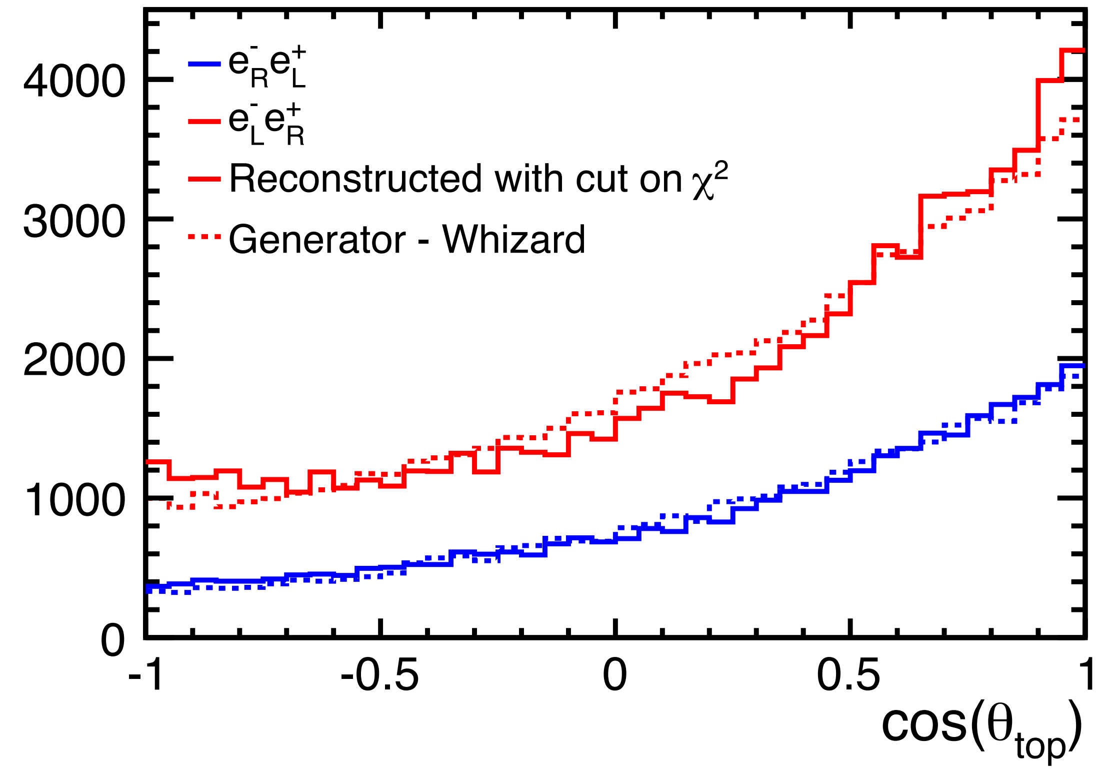
⇨ LC polarised beams crucial!

Using the Top as a Tool to Explore New Physics

- Asymmetry and angle measurements profit from higher energy: Larger signals, clean separation of top and anti-top and reconstruction of flight direction

example: A_{FB} - measured with 2% precision





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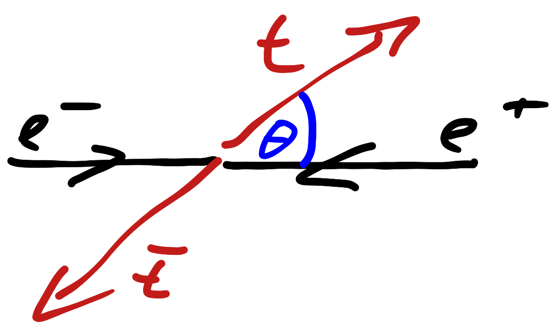
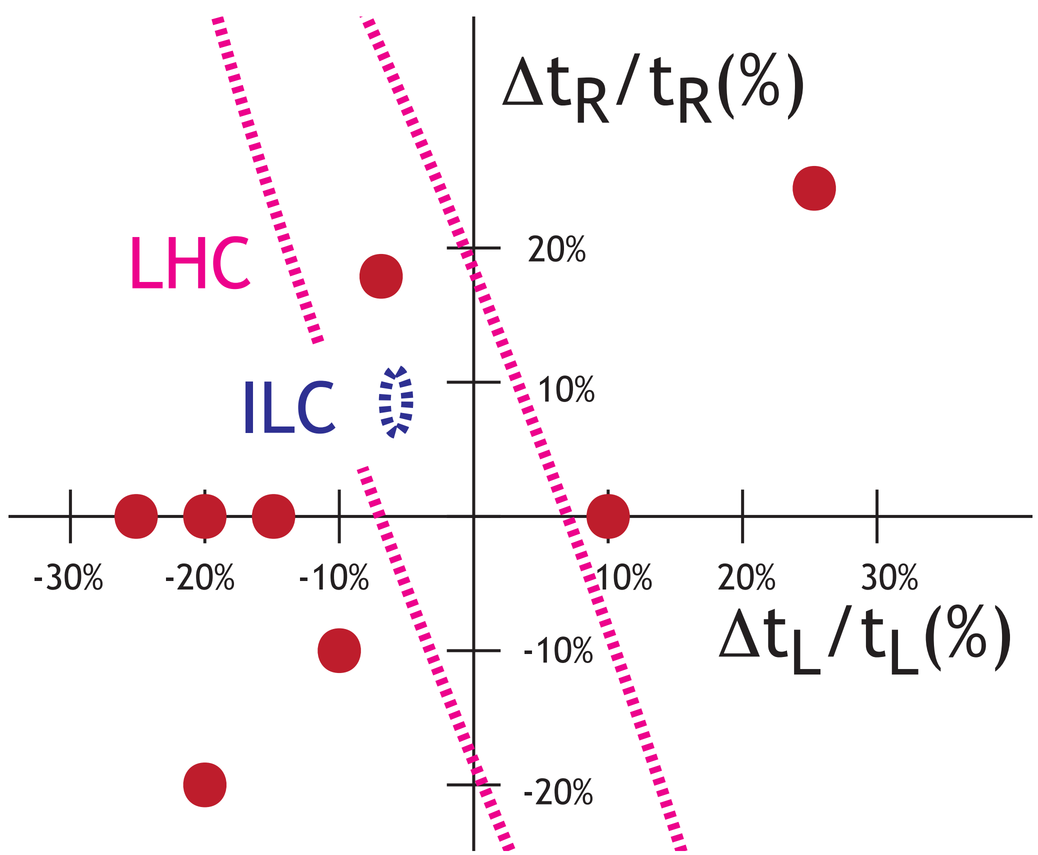
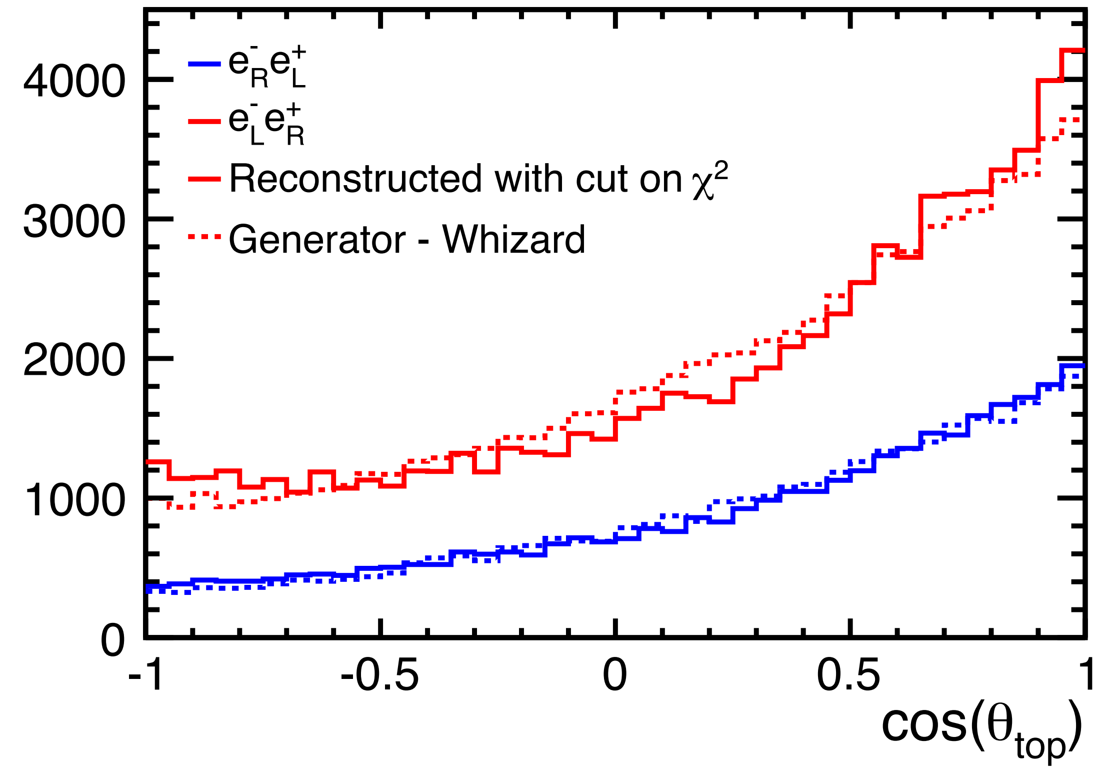




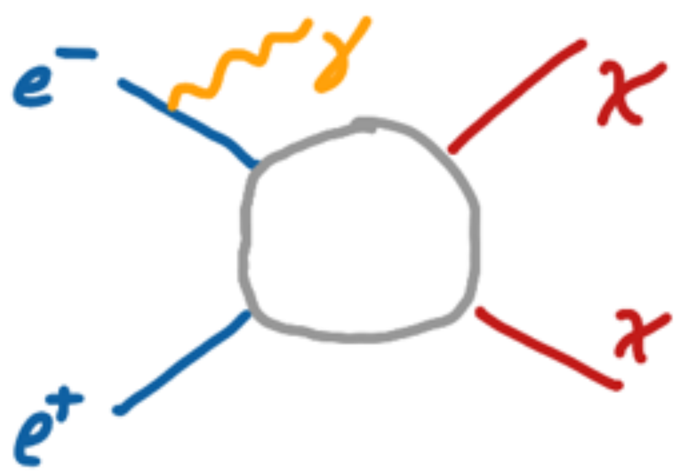


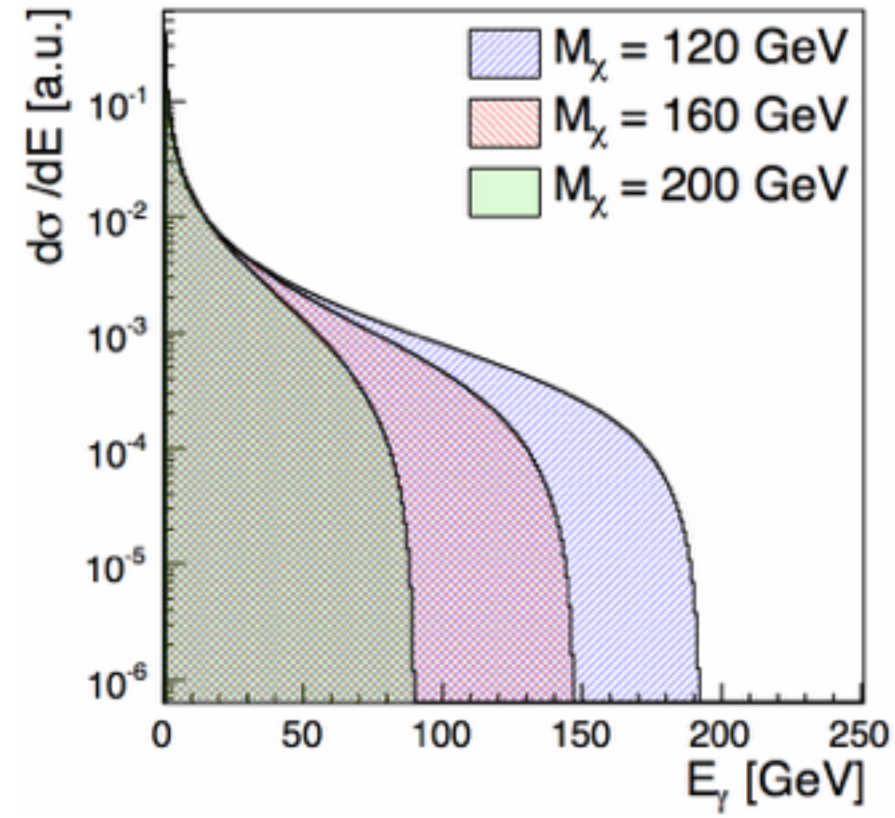
- Precise extraction of left- and right-handed coupling of top quarks to the electroweak interaction
  - Illustrated with deviations expected for a few different BSM models

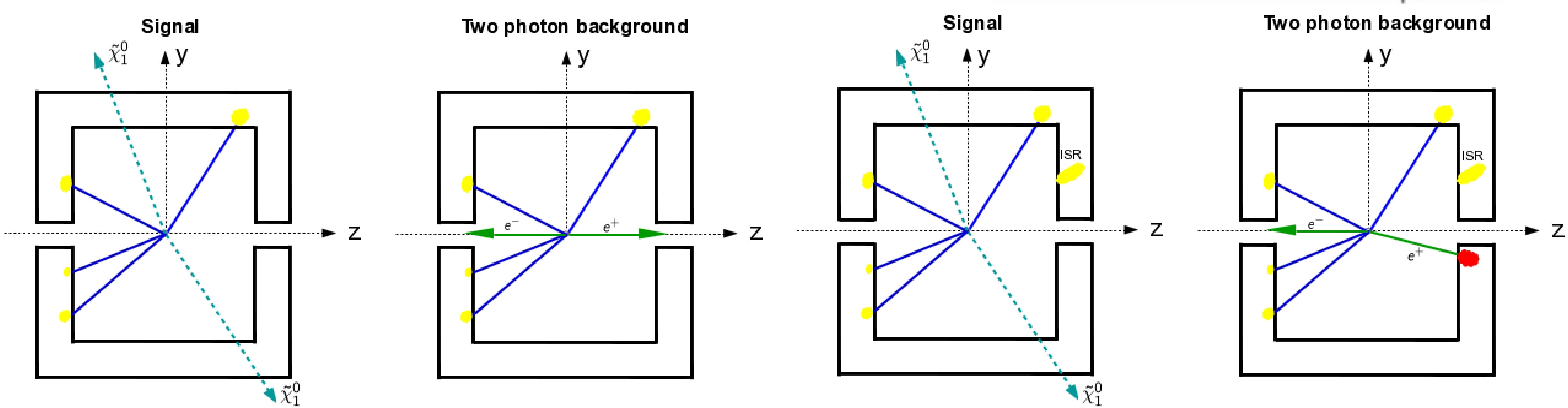
Discovery Potential for New Physics

- The ultimate motivation for a new collider - But entirely based on (more or less well founded) speculations)

  A key goal: Studying dark matter at colliders

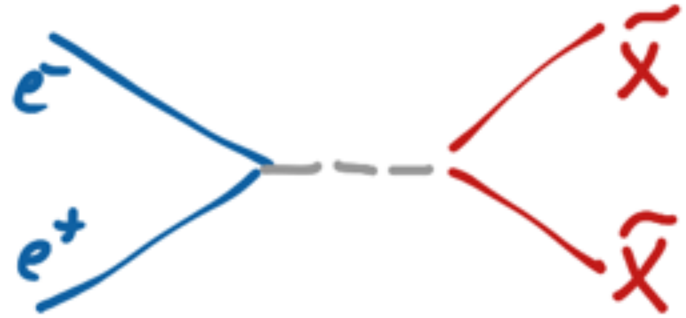






Discovery Potential for New Physics

- In general: Discovery and exploration of BSM physics



Discovery limit ~ $\sqrt{s}$ / 2 for (almost) any type of particle - particular strength (compared to LHC) in electroweak sector - gauginos, sleptons

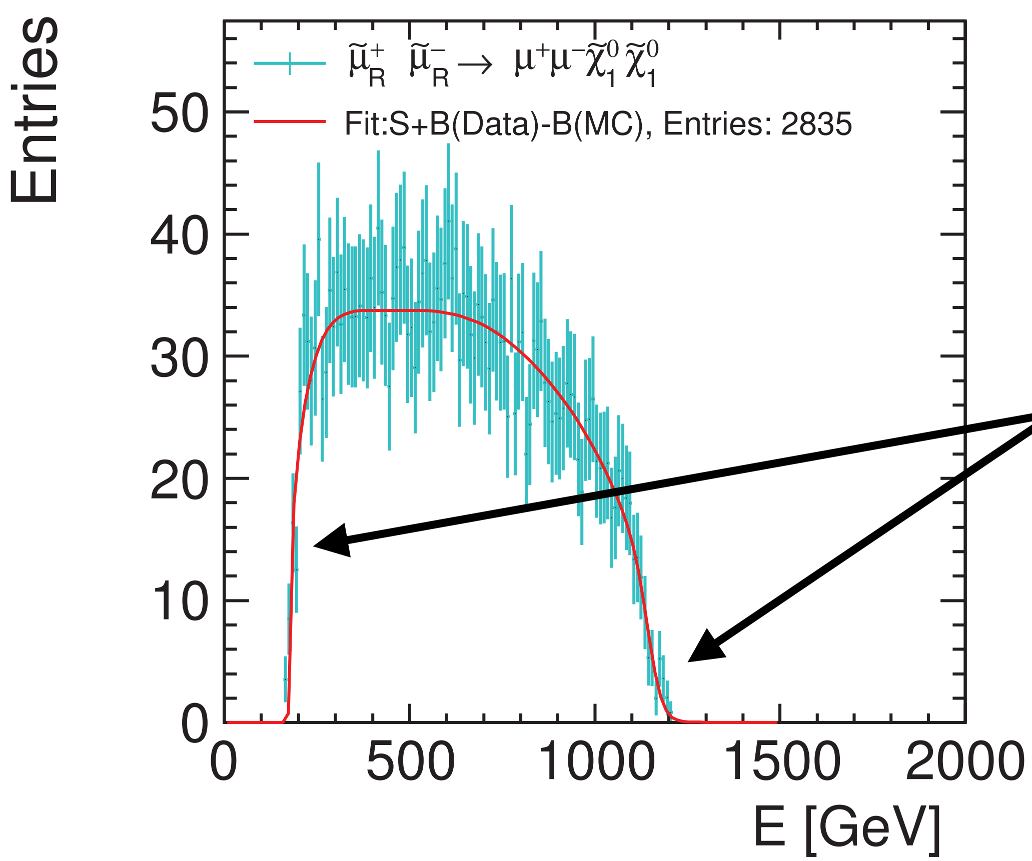
➫ Can fill in holes hadron colliders cannot cover (due to trigger requirements, high backgrounds, ...)

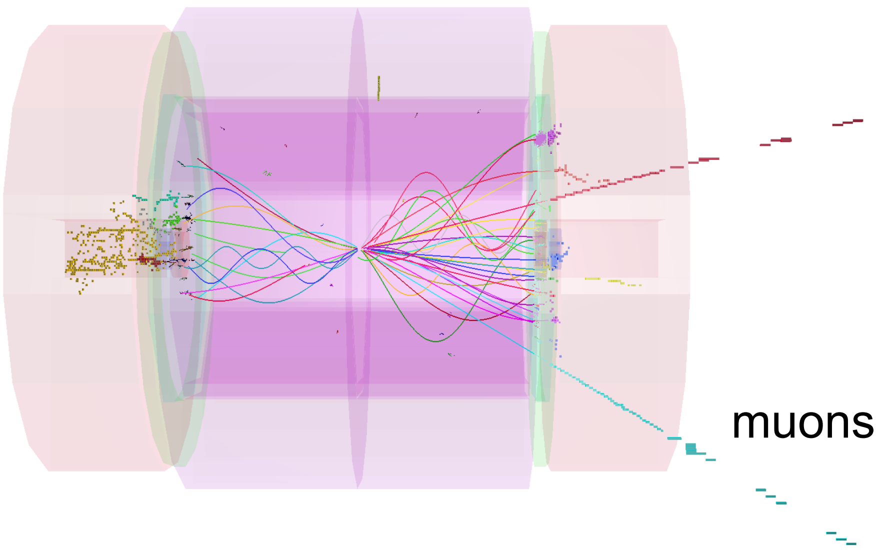
- Rich possibility for indirect searches:
  - Precision measurements of SM processes, compared with theoretical calculations, can provide indications for New Physics far beyond the energy scale directly accessible at the collider
    - Profits from the possibility for precision calculations of e^+e^- processes
    - Typical example: Z' detection in e^+e^- -> $\mu^+\mu^-$ - reach to 10s of TeV at CLIC

Brief Example: SUSY at CLIC

- The “simple” case: TeV-scale smuons

$$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \tilde{\chi}_1^0\,\tilde{\chi}_1^0$$





masses from end-points of muon energy distribution
a few GeV precision on particle masses:
0.5% for smuons, ~ 1% for neutralino (~ 350 GeV)

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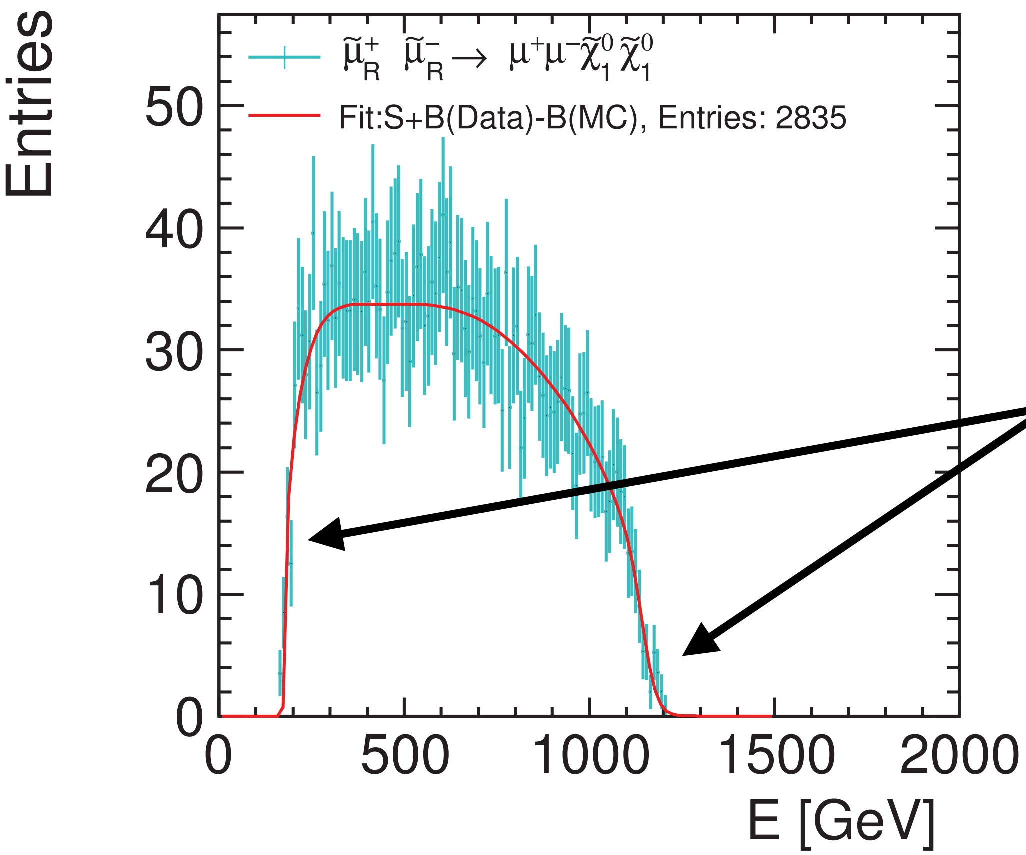

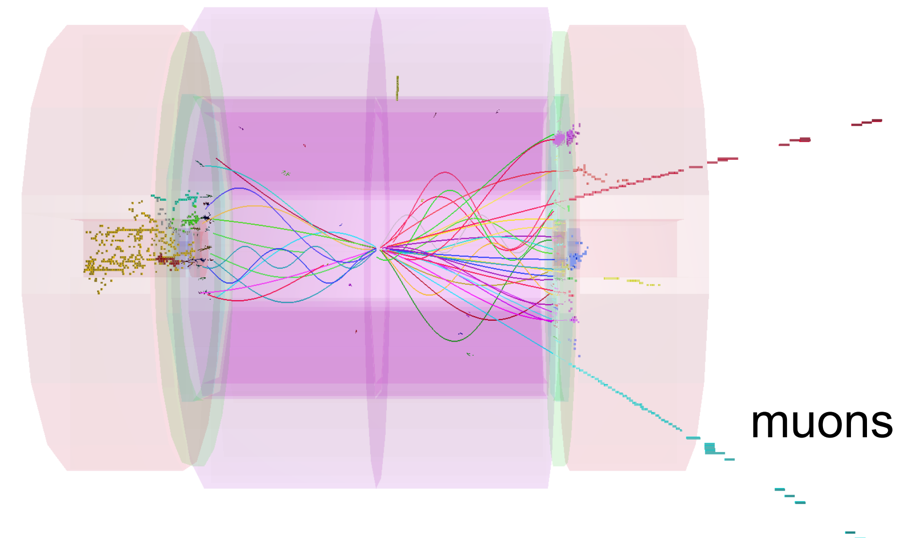

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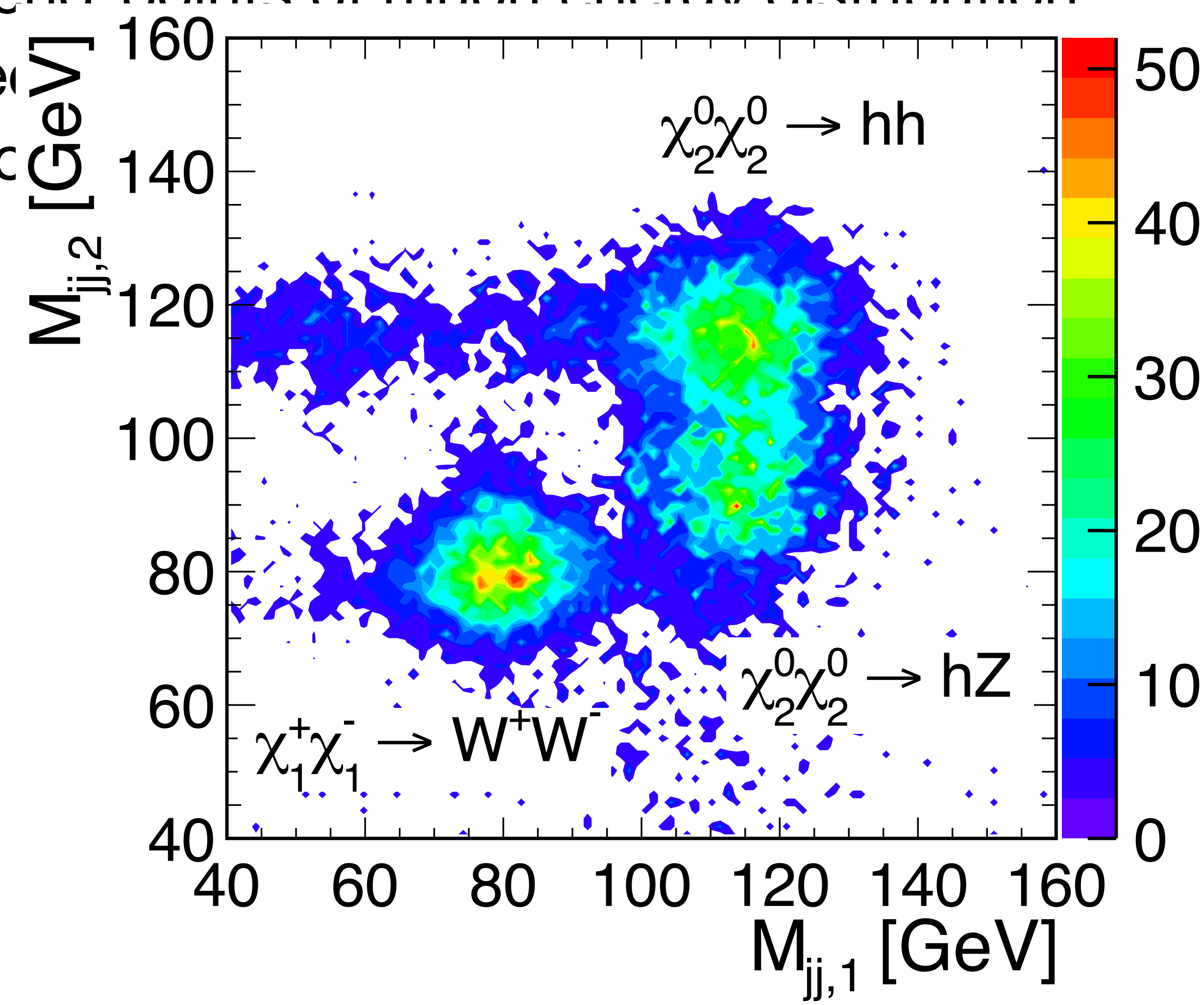
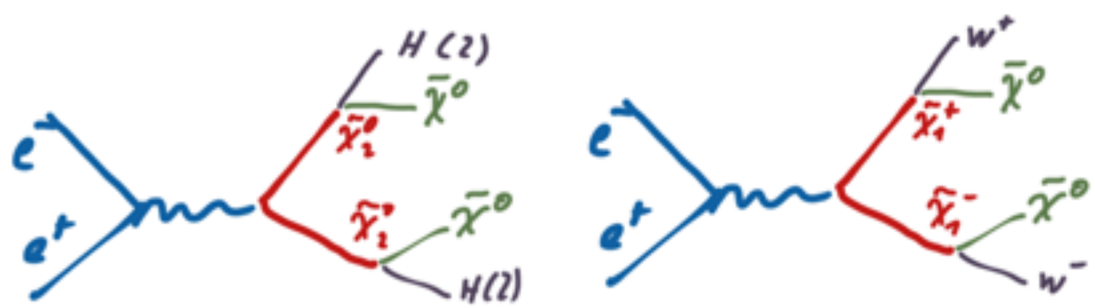


650 GeV gauginos measured via hadronic boson decays: 1% mass measurement for gauginos, LSP



Outlook, Summary

Linear Collider Projects - The Status

- The ILC and CLIC accelerator studies are organised under the heading of LCC with goals:
  - Strongly support the Japanese initiative to construct a linear collider as a staged project in Japan
  - Prepare CLIC machine and detectors as an option for a future high-energy linear collider at CERN
  - Further improve collaboration between CLIC and ILC machine experts

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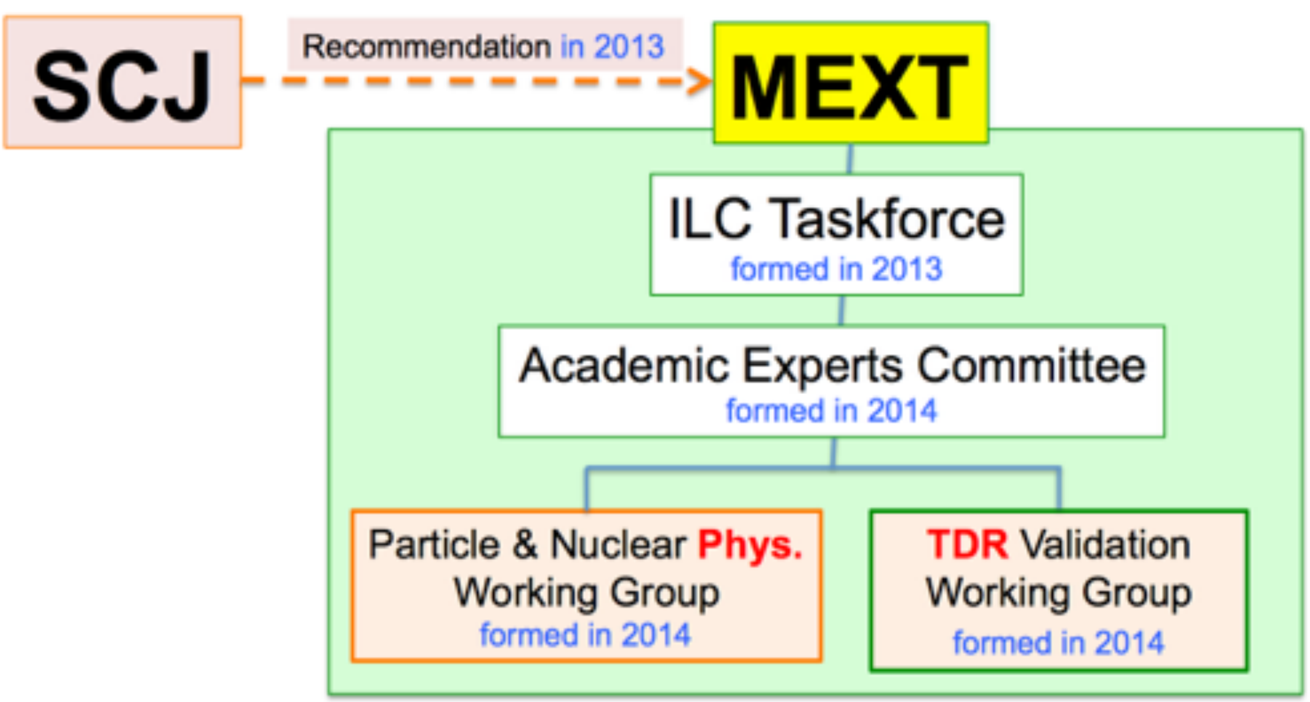
- Ongoing evaluation of ILC by committees established by MEXT, in parallel discussions on political levels



expect a conclusion in early 2016

Summary

- Linear Colliders cover the full spectrum of e^+e^- physics by providing energies from the ZH threshold into the TeV region with polarised beams
  - Precision Higgs measurements
  - Direct measurement of the Top Yukawa coupling and the Higgs selfcoupling
  - Precision measurements of top properties and couplings

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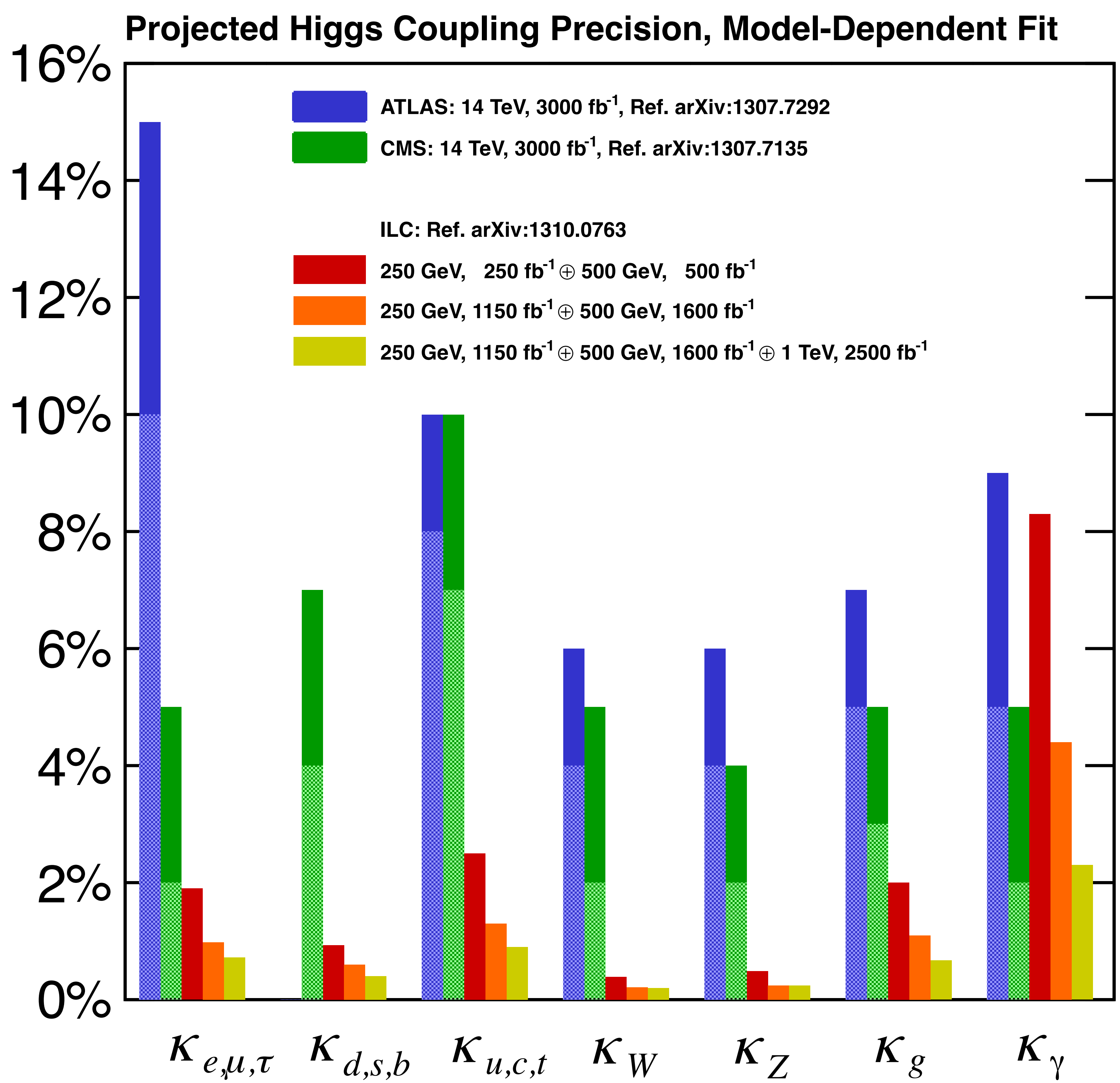
ILC is on the table now - decision expected in the next ~ 2 years
CLIC provides a credible future option to reach the multi-TeV regime

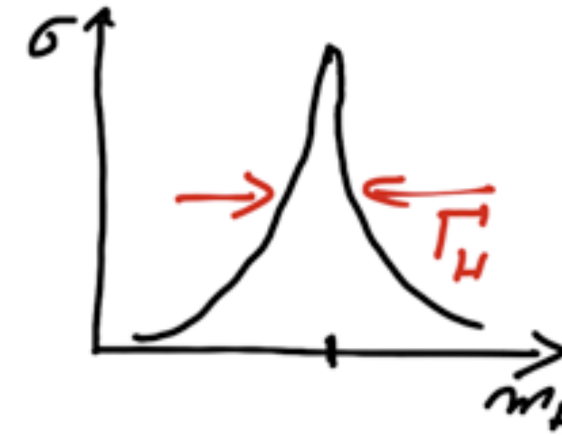
Backup

Higgs Couplings - ILC vs LHC



Measuring the Total Width

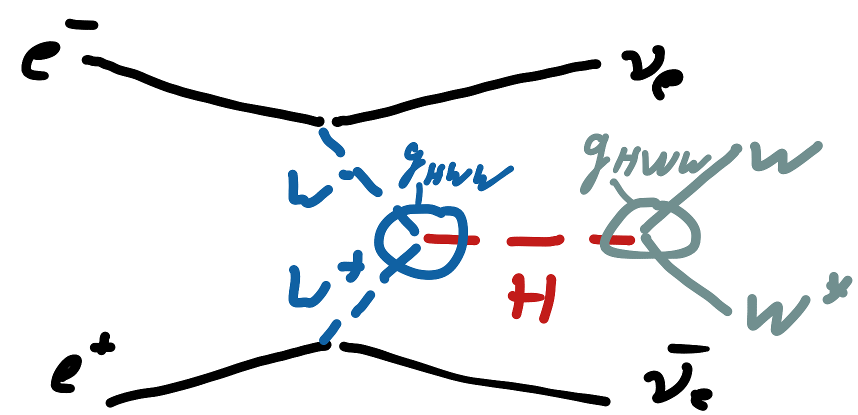
- The total width of a 125 GeV SM Higgs is ~ 4 MeV - no chance to measure directly (apart maybe from a μ collider) - use other “tricks”
  - e^+e^- offers an (almost) model-independent way (in contrast to techniques at hadron colliders, which always use strong assumptions…):



measure production and decay in the same channel - works for ZZ and WW
but: BR(H->ZZ) ~ 2.8%, BR(H->WW) ~ 22.3% => use:

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

in itself not model-independent (requires H reconstruction)



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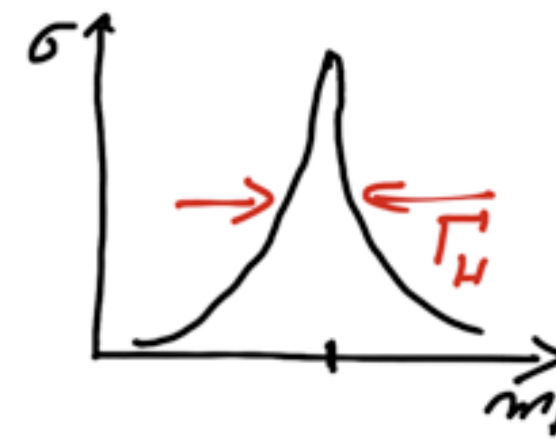

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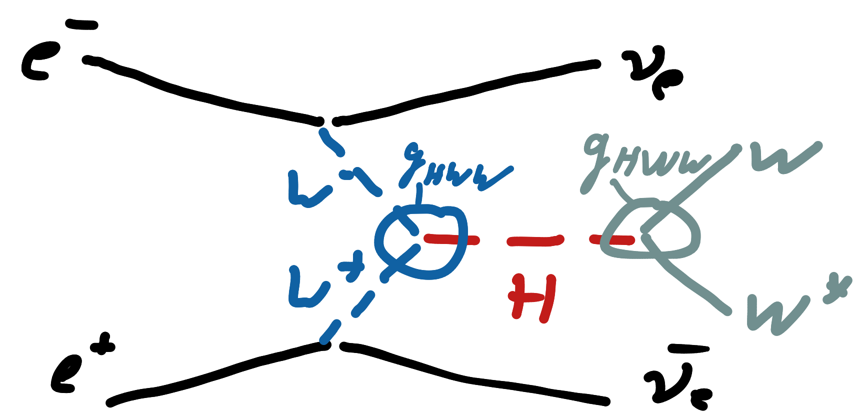

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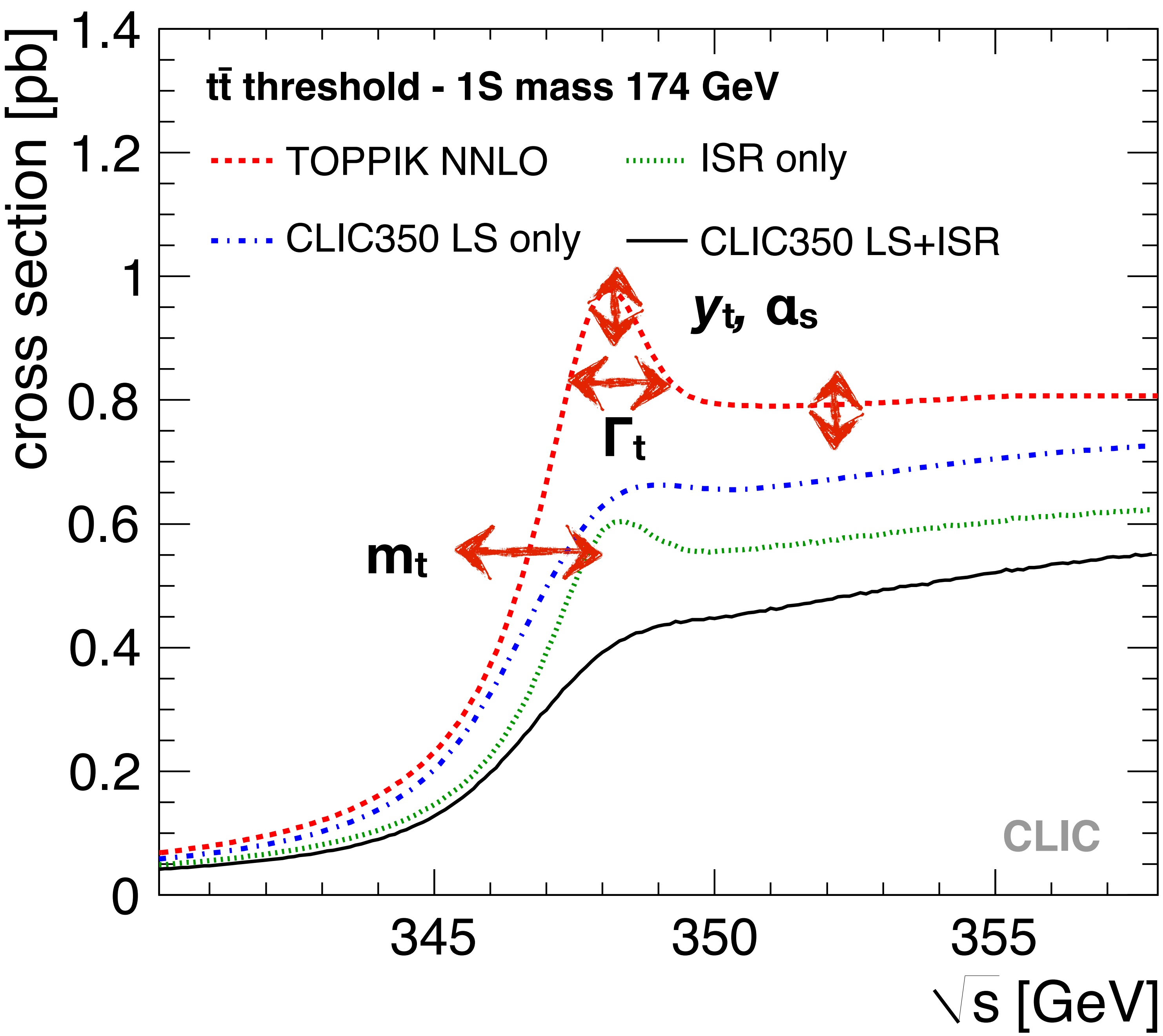
$$\frac{\sigma(e^+e^- \to \mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})}{\sigma(e^+e^- \to \mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})} \propto \frac{g^2_{\mathrm{HZZ}}}{g^2_{\mathrm{HWW}}}$$

g_{HWW} pinned down with model-independent g_{HZZ} and high-BR H->bb decay

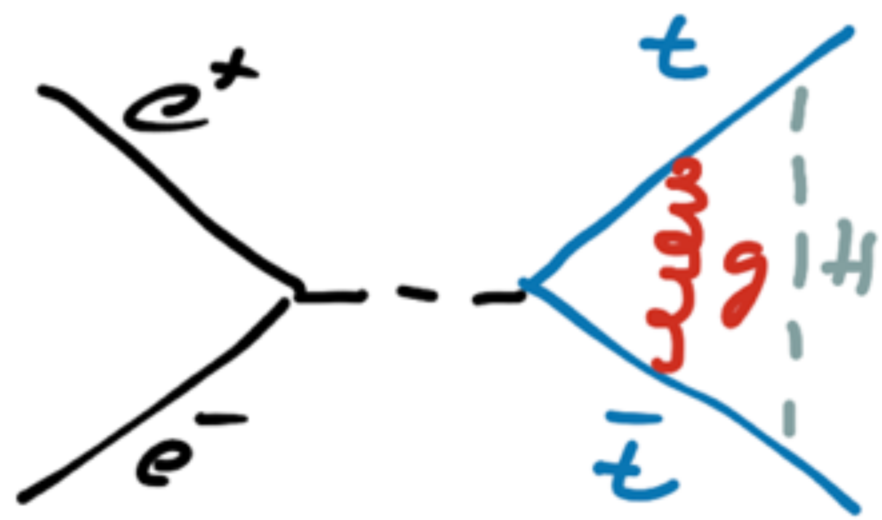
Top Threshold Scan - Sensitivities



- Effects of some parameters are correlated; dependence on Yukawa coupling rather weak => Needs further study!

The cross-section around the threshold is affected by several properties of the top quark and by QCD

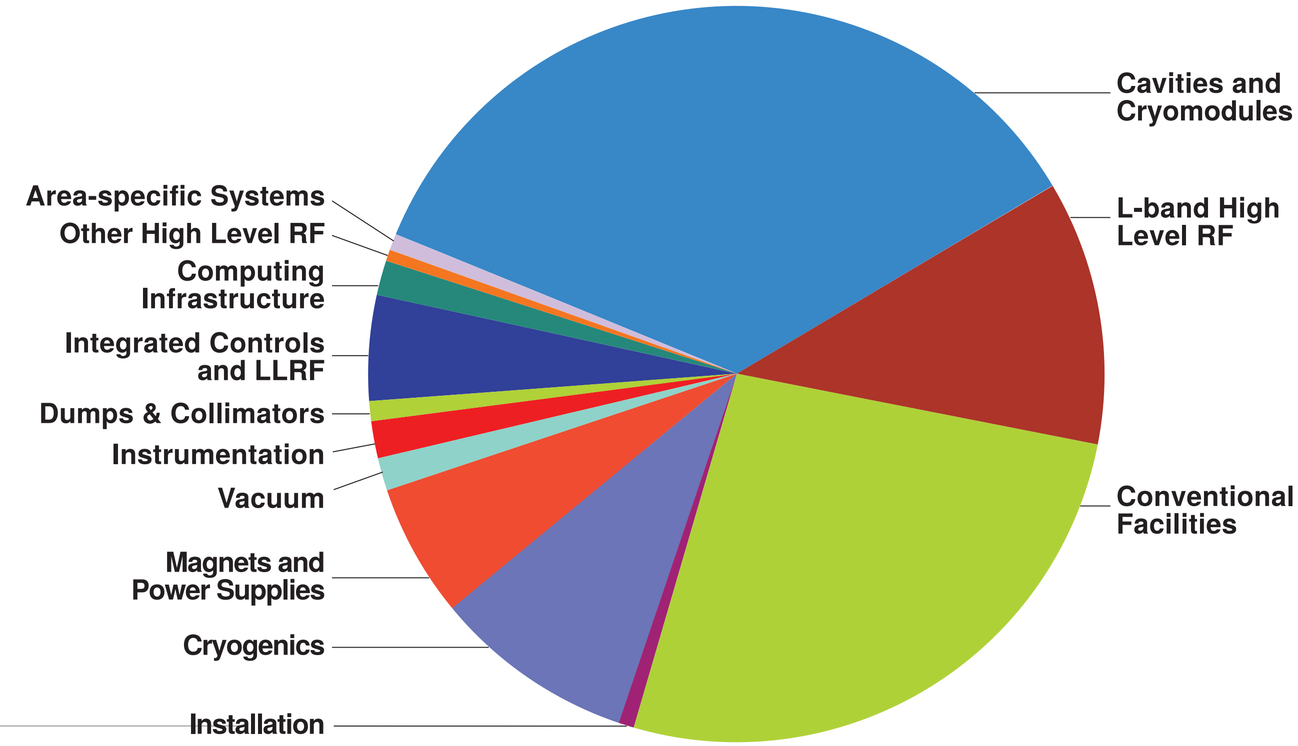
- Top mass, width, Yukawa coupling
- Strong coupling constant

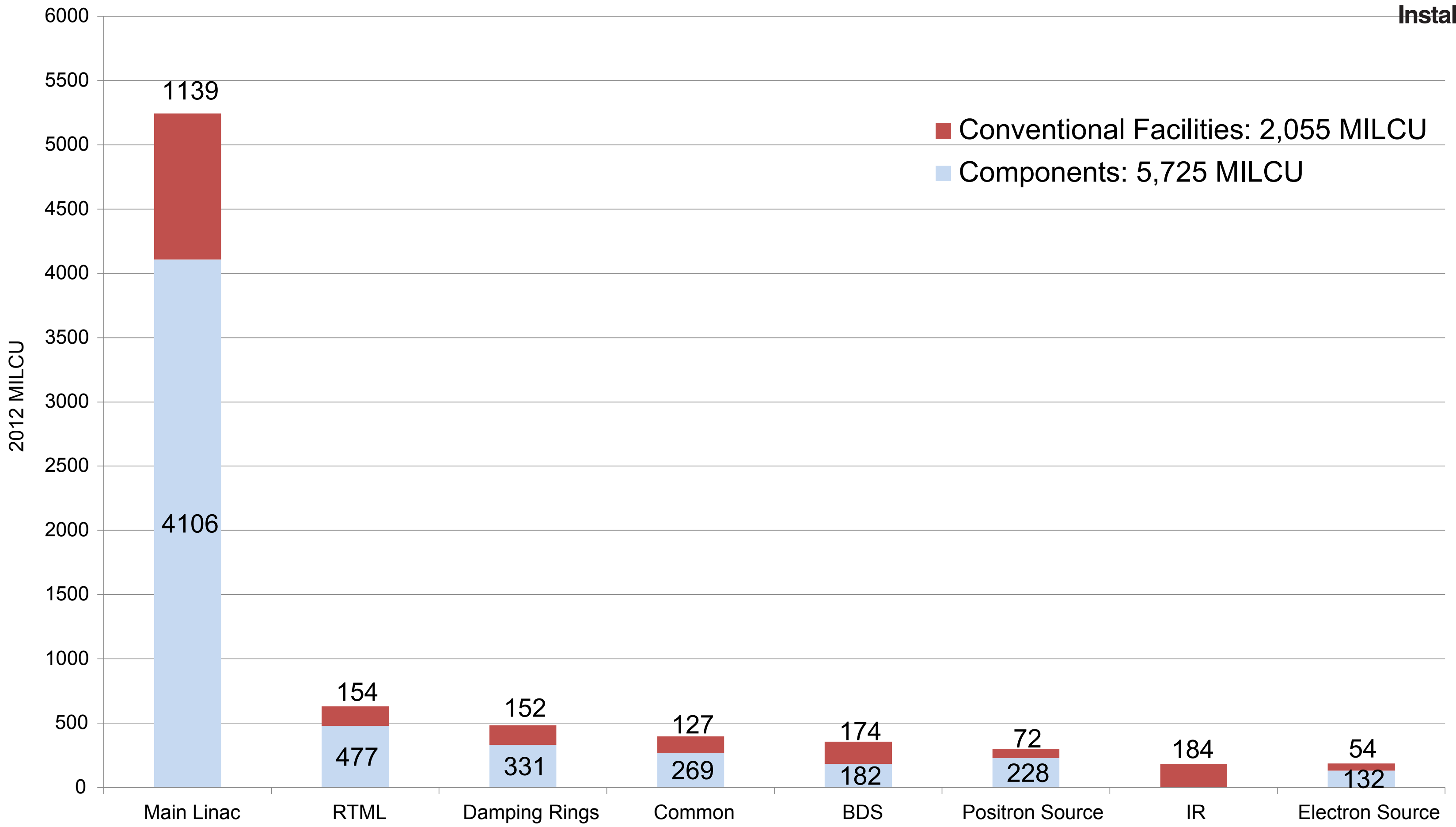


Here: Extract mass and α_s

ILC Cost

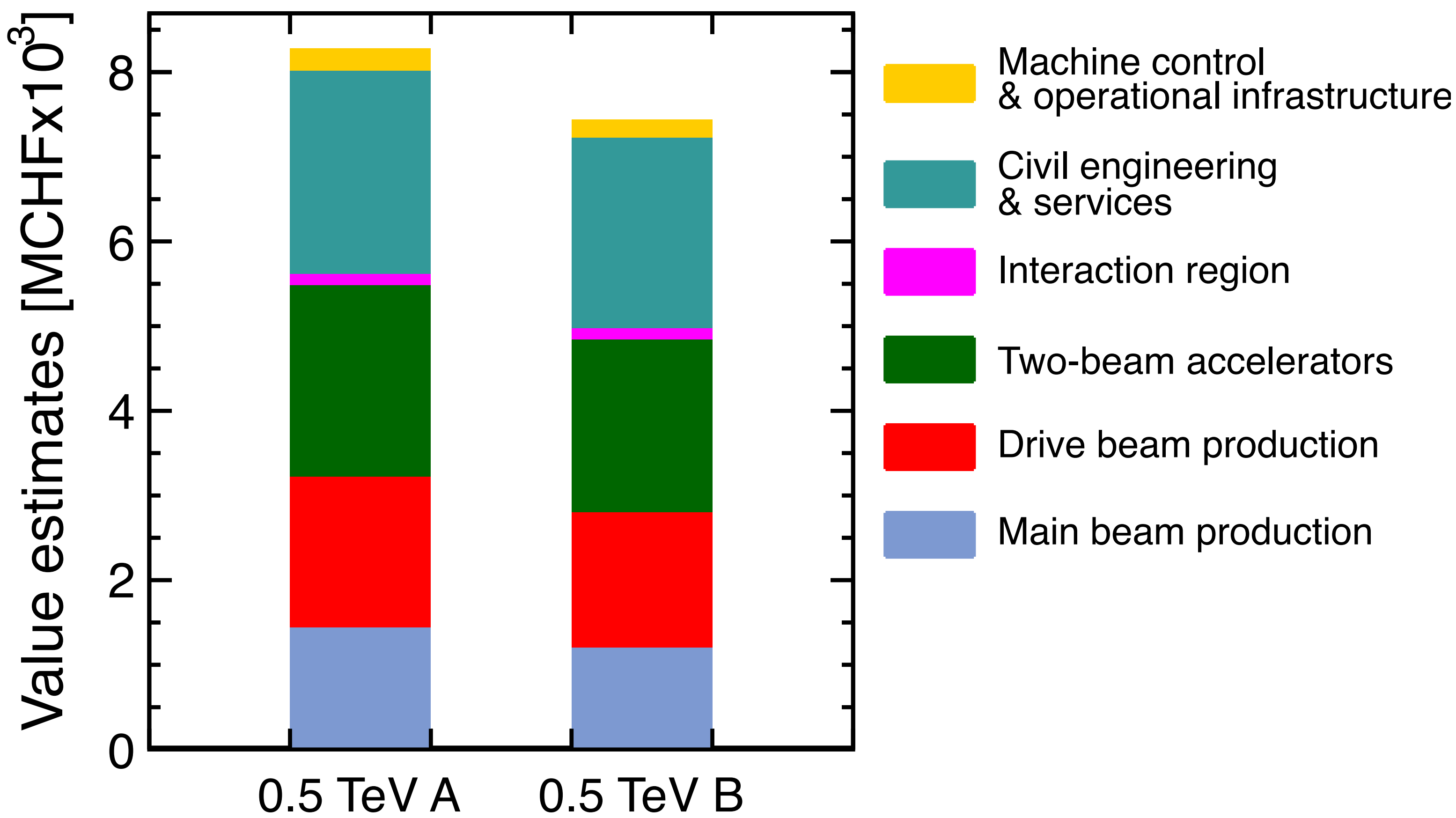
- From ILC TDR
  - Rather solid cost estimate for the 500 GeV machine: ~ 8 Billion USD (500 GeV version of CLIC similar)
  - Biggest component: Main linac, acceleration structures





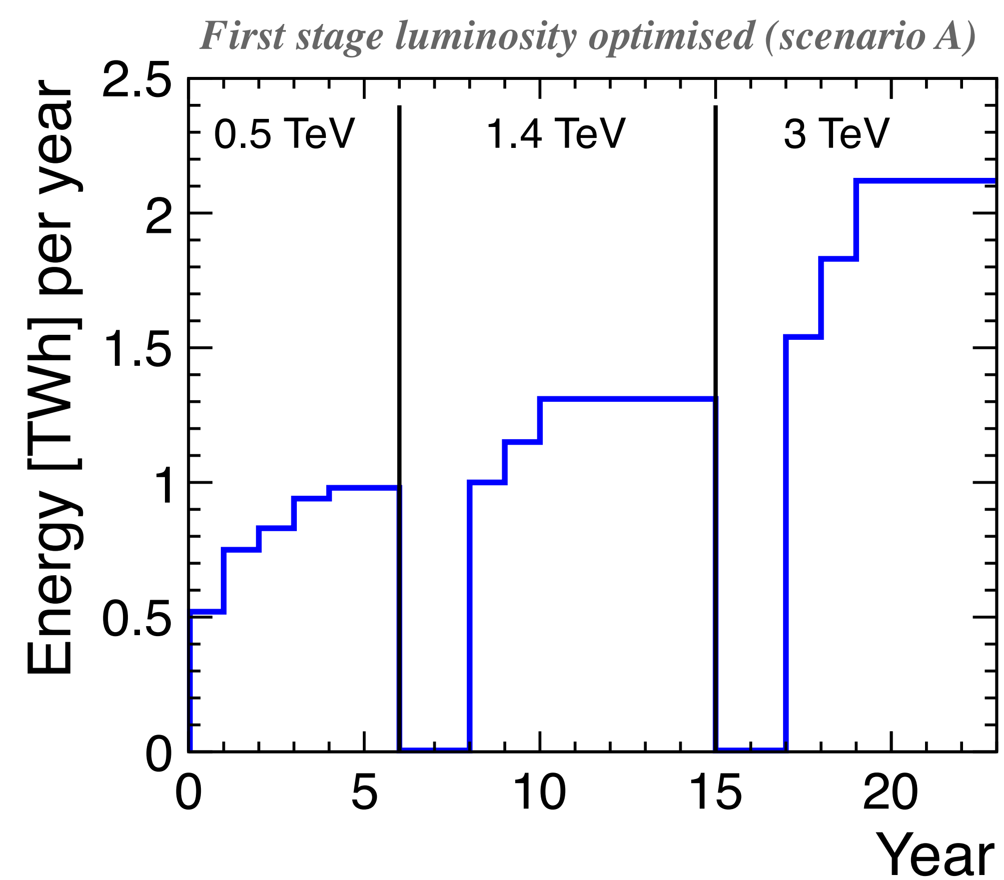
- The construction cost will be spread over ~ 10 years, and shared across the globe - details to be worked out!
- Many contributions expected “in kind”: production of components “at home”, installation in ILC

CLIC Cost and Power Budget

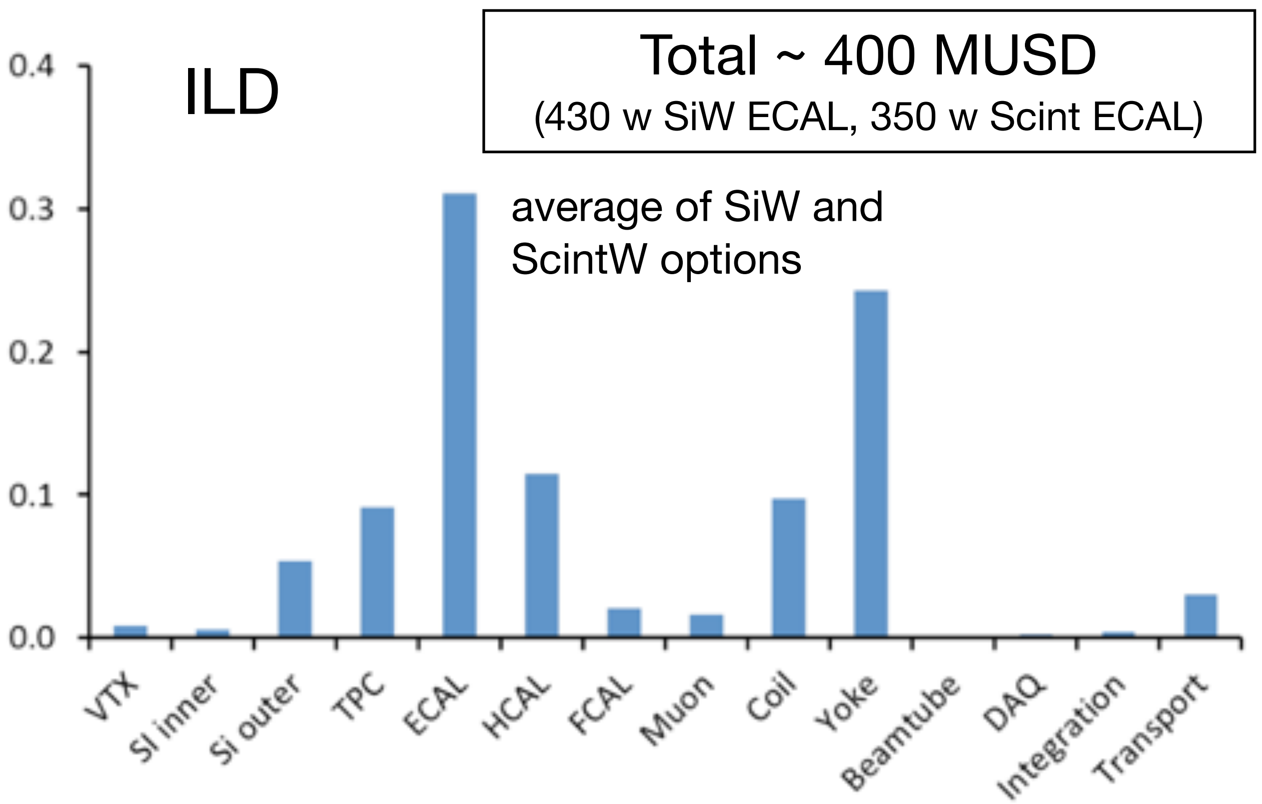


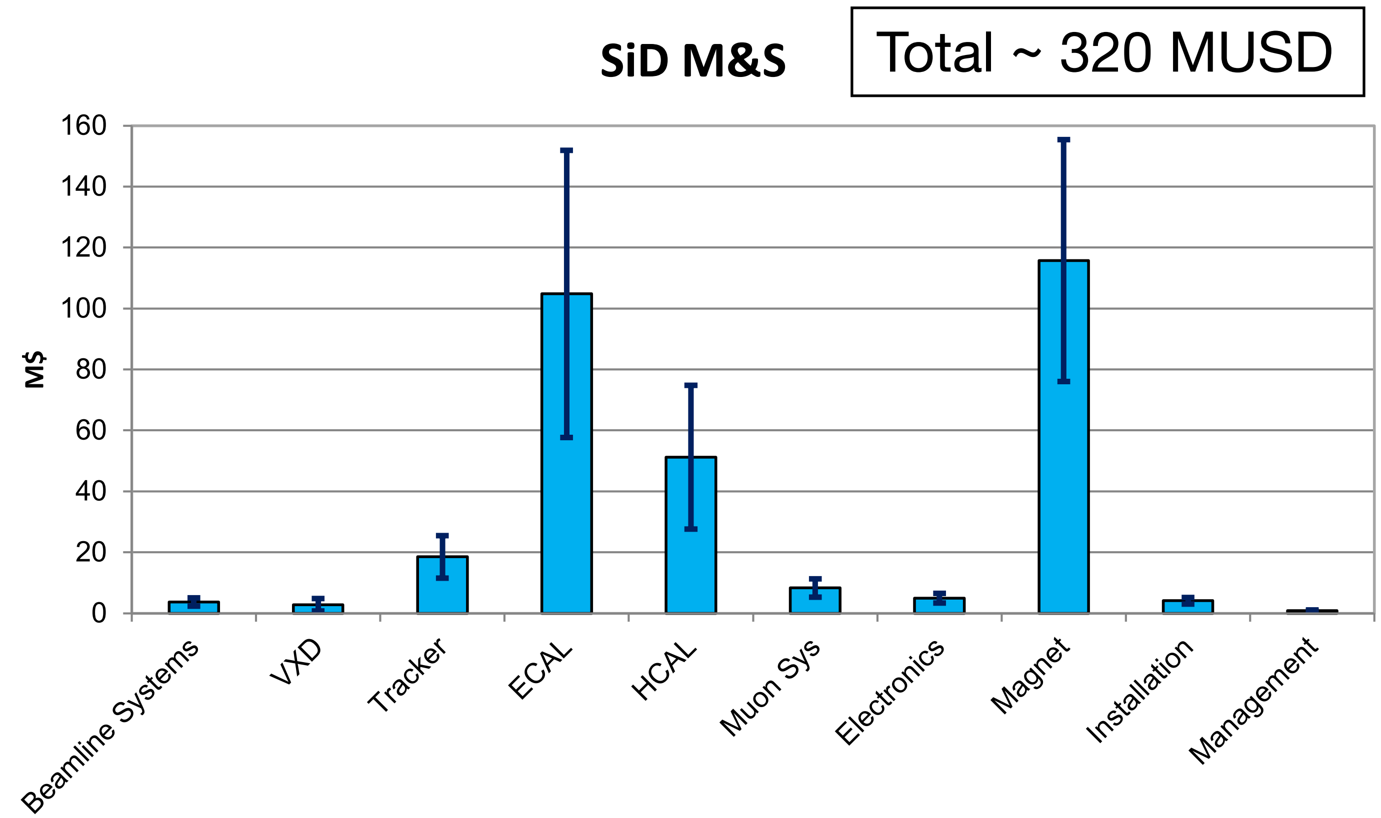
incremental cost for second stage: ~ 4 MCHF/GeV
(=> Initial cost quite high!)

Staging scenario	$\sqrt{s}$ (TeV)	$\mathscr{L}_{1\%}$ (cm^{-2}s^{-1})	$W_{main\ beam}$ (MW)	$P_{electric}$ (MW)	Efficiency (%)
A	0.5	$1.4 \cdot 10^{34}$	9.6	272	3.6
	1.4	$1.3 \cdot 10^{34}$	12.9	364	3.6
	3.0	$2.0 \cdot 10^{34}$	27.7	589	4.7
B	0.5	$7.0 \cdot 10^{33}$	4.6	235	2.0
	1.5	$1.4 \cdot 10^{34}$	13.9	364	3.8
	3.0	$2.0 \cdot 10^{34}$	27.7	589	4.7



ILC Detector Cost



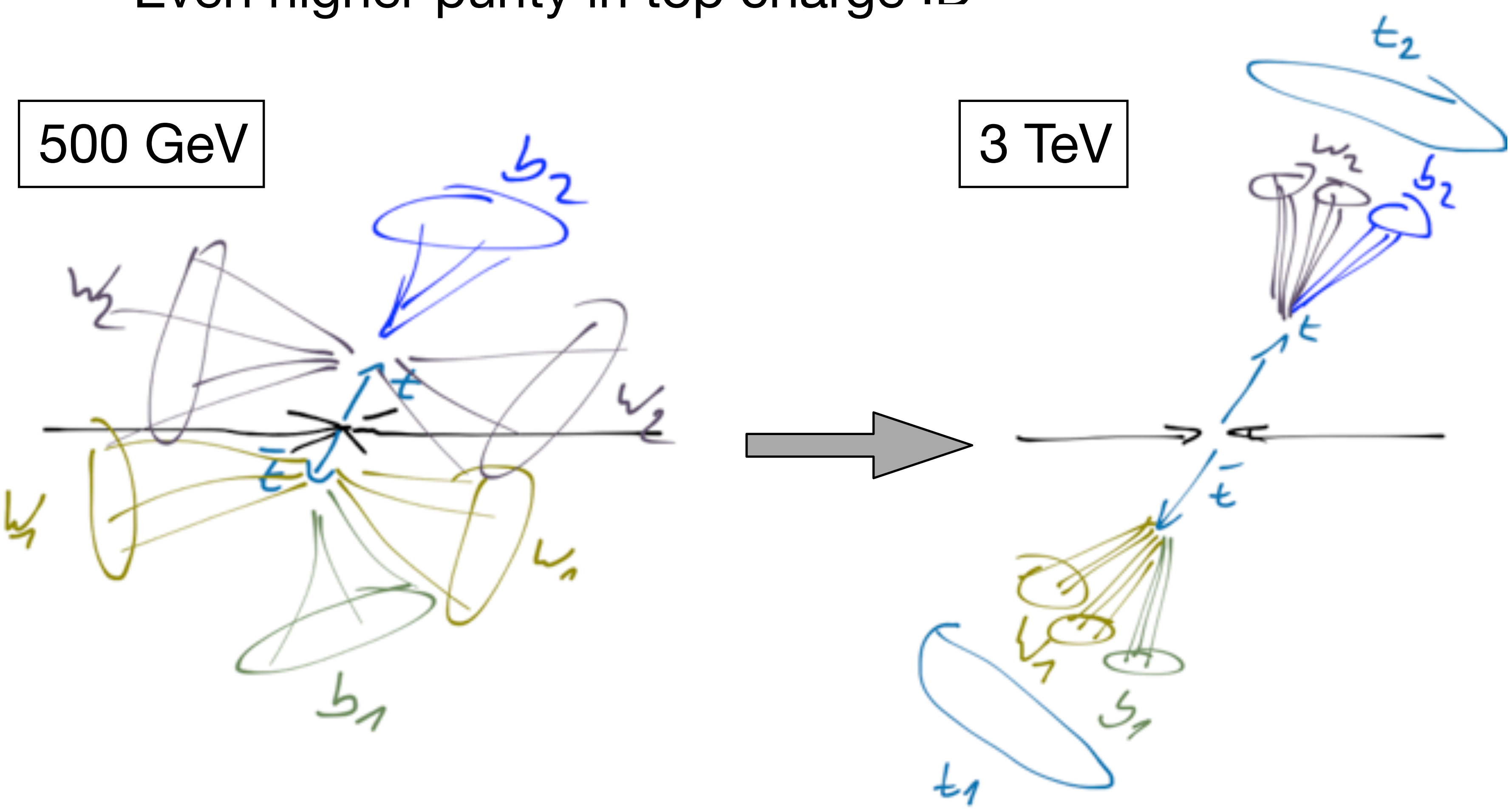


- First estimate of cost (excl. labor) - for the some of the more expensive systems already quite detailed (NB: on some items the cost models of ILD and SiD are different)
  - Clearly reflects the design for PFA: ~ 50% of the total cost is in the calorimeters
  - Shows SiD optimization with cost-effectiveness in mind

Studies to evaluate the cost and performance impact of parameter changes are ongoing

Top as a Tool at High Energy

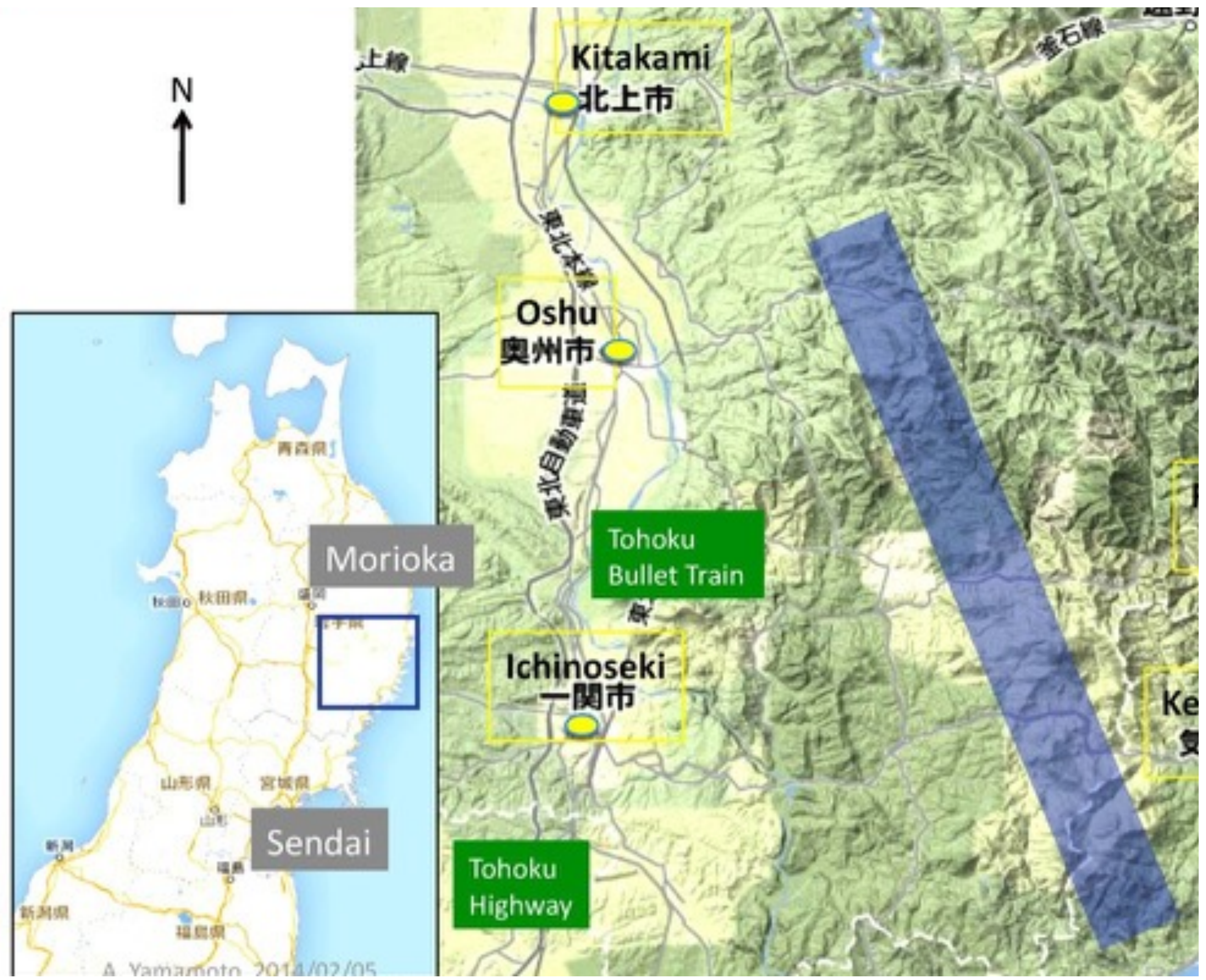
- The unique feature of CLIC: Collisions up to 3 TeV
  - Excellent sensitivity to New Physics: Effects in indirect searches often scale as E^2/Λ^2 => Benefit of high energy!
    - Well-demonstrated physics potential for ILC at 500 GeV: Measurement of ttbar asymmetries (forward-backward, left-right)
    - Higher energy improves unique assignment of final-state particles to top, anti-top: Even higher purity in top charge ID



Requires reconstruction of top quarks as highly boosted objects: Techniques well established at LHC, Potential benefits from PFA

ILC (国際リニアコライダー) in Japan?

- Japan has expressed interest to host ILC - with the goal of a global project with substantial financial contributions from outside, and the establishment of an “international city”
  - A site recommendation has been made: 北上市 (Kitakami) in Northern Japan



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- Strong support by local government and population
- Over the next ~ 1.5 years, a review process with committees by the Japanese science ministry MEXT is taking place - physics case and technical issues
- First contacts on government level about international participation have started

Possible ILC Schedule