Physics at CLIC

Frank Simon
Max-Planck-Institute for Physics

on behalf of the
CLIC Detector and Physics Study

CLIC Workshop
CERN, February 2014

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

Outline

- Introduction
- The CLIC Physics Landscape
- Experimental Conditions at CLIC

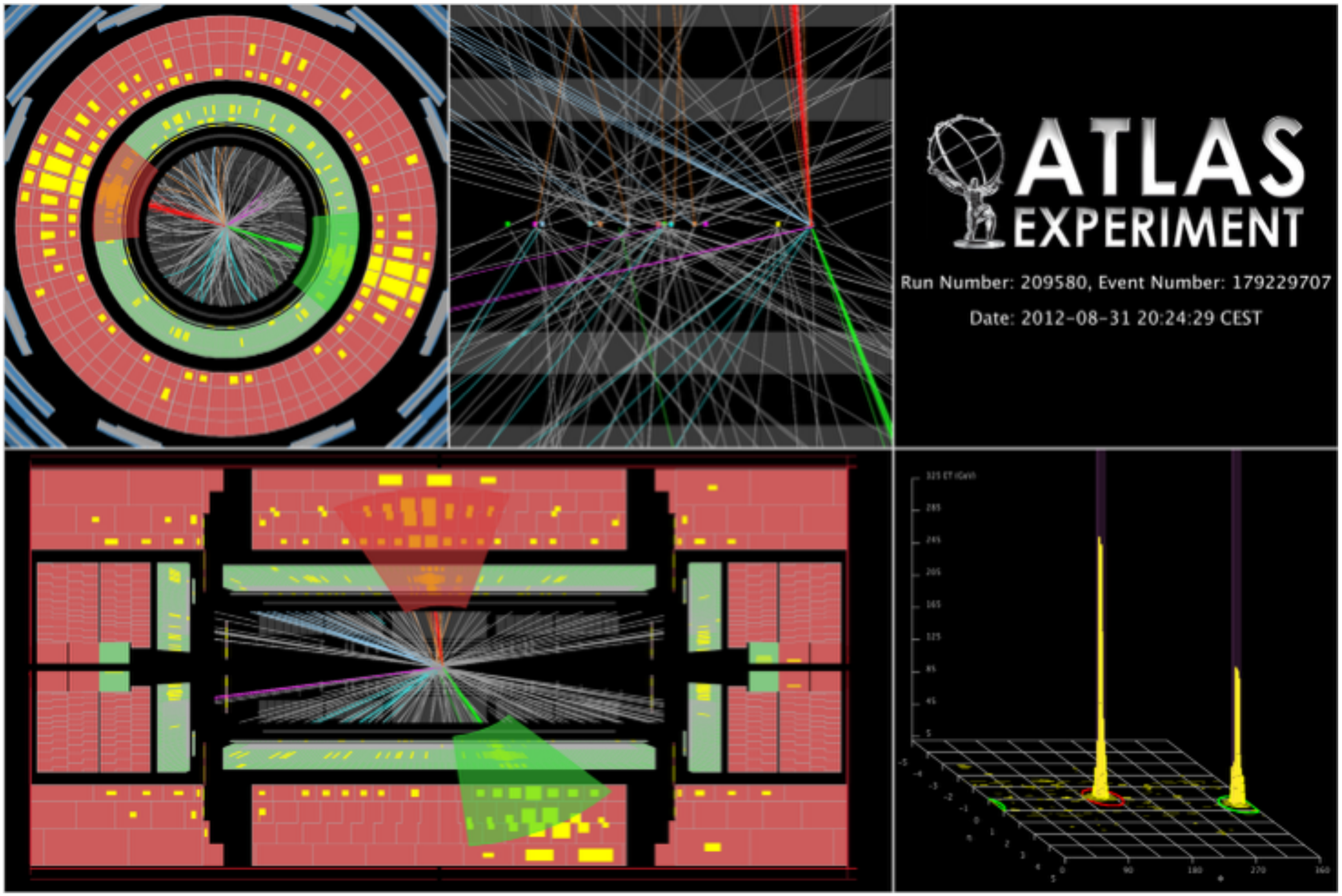
- The CLIC Physics Potential
  - Higgs Physics
  - Top & Electroweak Precision Physics
  - Beyond the Standard Model

- Conclusions

Introduction: e^+e^- Physics at the Energy Frontier

- Today, physics at the highest energy scales happens at the LHC

  fantastic energy reach: - here $\sum E_T \sim 4.9$ TeV



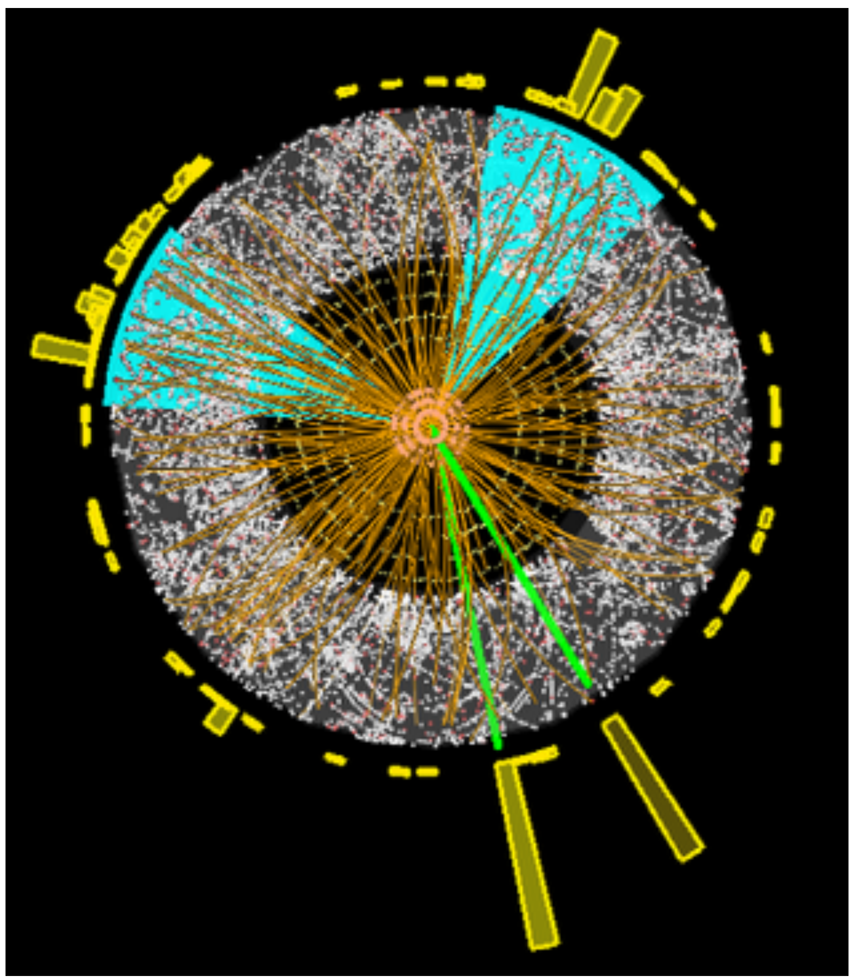
But there is a price:

High background levels and particle multiplicities

Unknown initial state

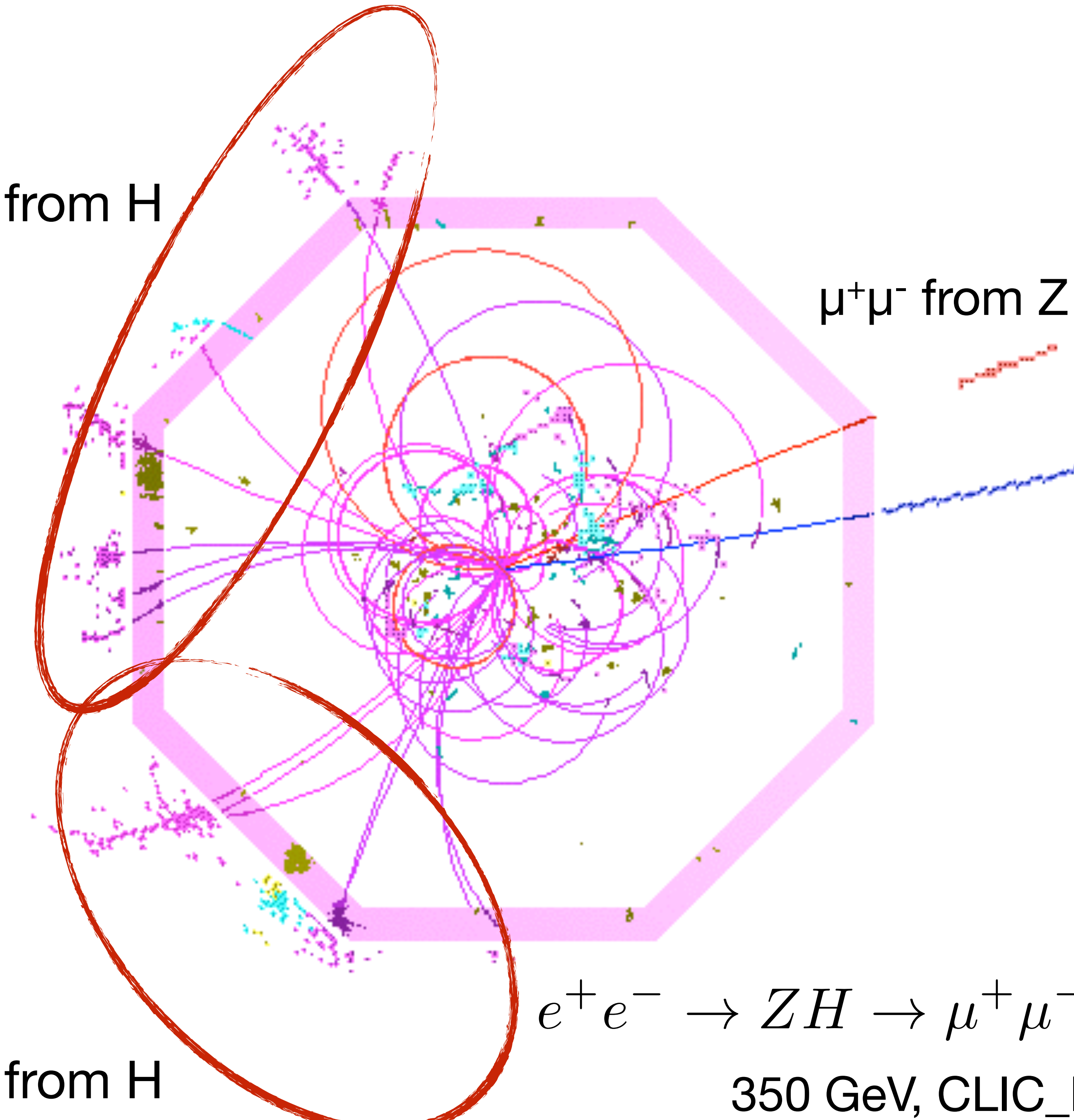
Introduction: e^+e^- Physics at the Energy Frontier

- Clean environment in e^+e^- collisions - observed final state corresponds to underlying fundamental interaction: allows precision measurements, "easy" identification of hadronic final states



$$pp \rightarrow ZH + X \rightarrow e^+e^- b\bar{b} + X$$

(candidate event)

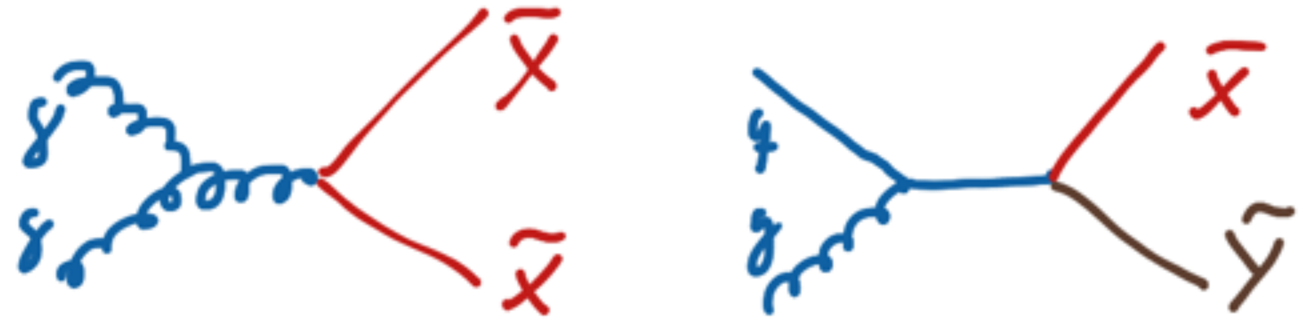


$$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b}$$

350 GeV, CLIC_ILD

pp and e^+e^-: A perfect Match

- Particle production at LHC dominated by gluon and quark-gluon interactions via strong interaction



- ▸ High cross-section and very high mass reach for strongly interacting states
- ▸ Hadronic final states often get lost in background

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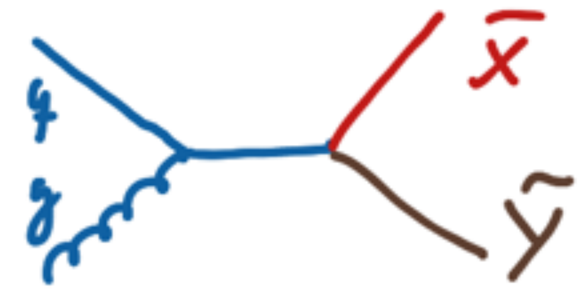

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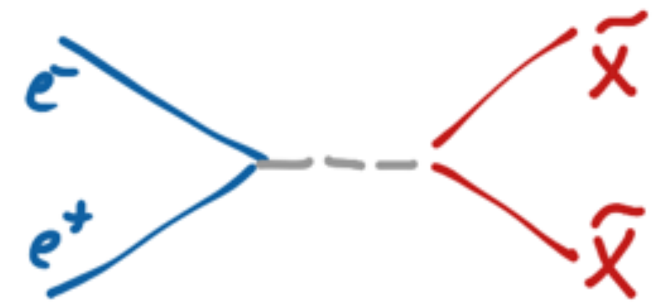
- At CLIC particles are produced via electroweak interactions



  - ▸ Typically smaller cross sections, comparable mass reach for ew and strong states
  - ▸ Precision measurements also in hadronic processes

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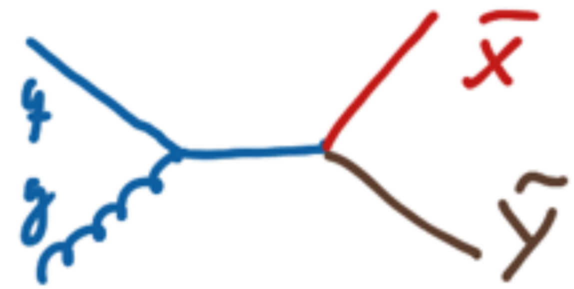

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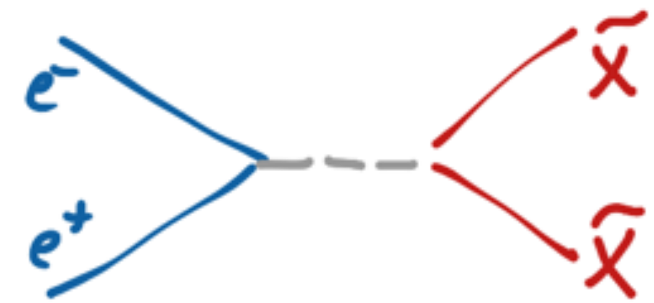


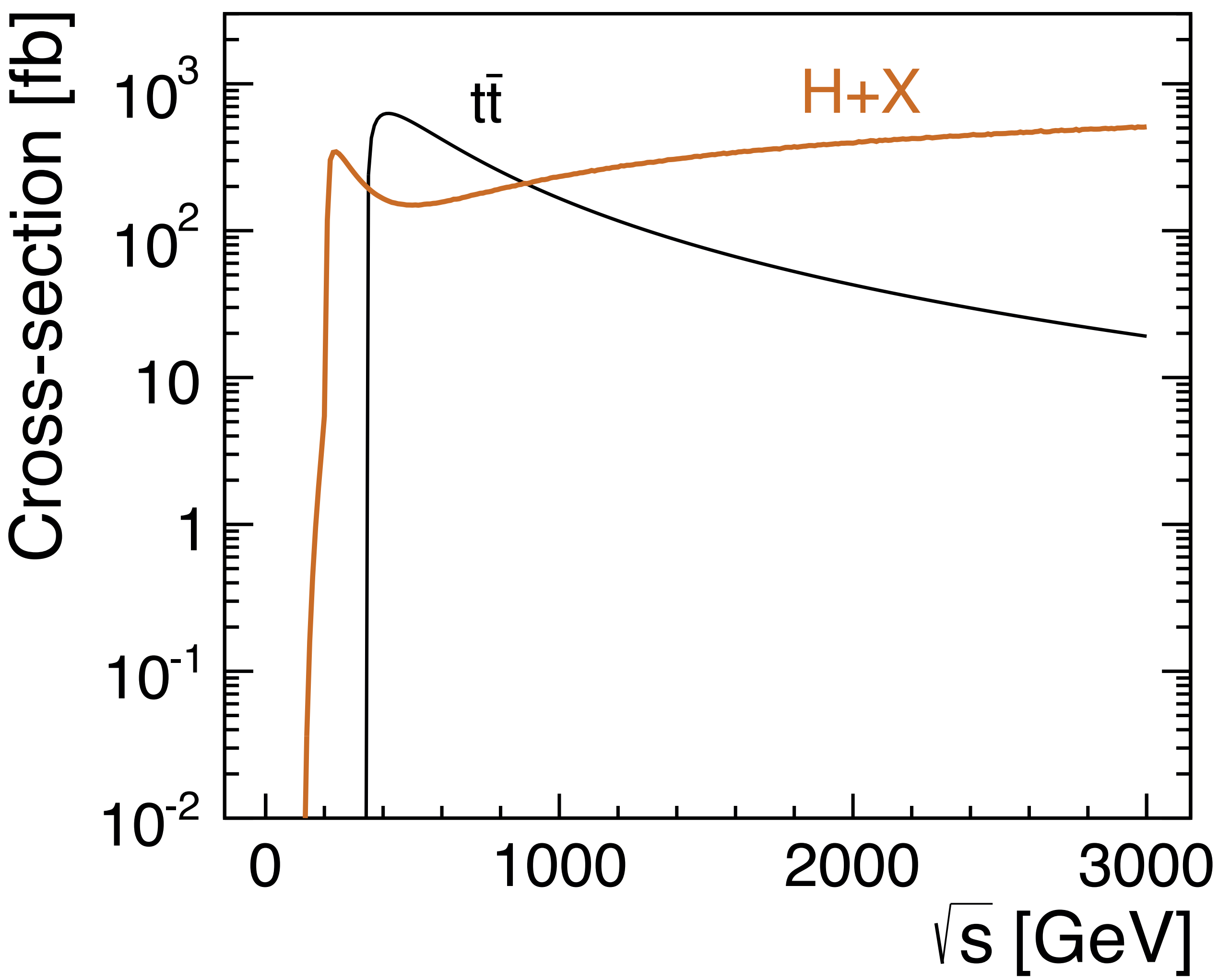
- ▸ Typically smaller cross sections, comparable mass reach for ew and strong states
- ▸ Precision measurements also in hadronic processes

➯ Highly complementary physics potential!

The CLIC Physics Landscape

… a combination of certainty and speculation:

- Guaranteed physics program:
  - 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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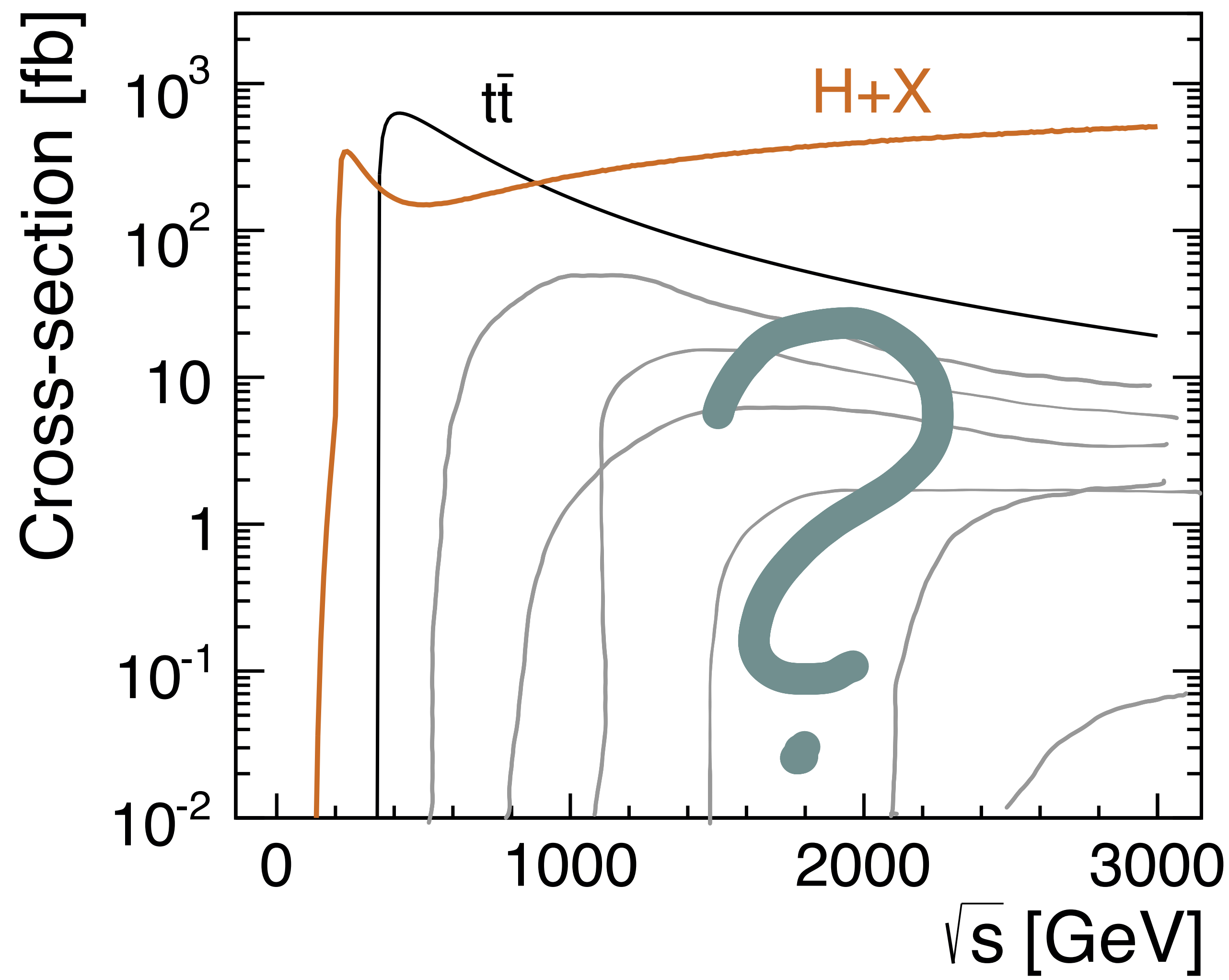
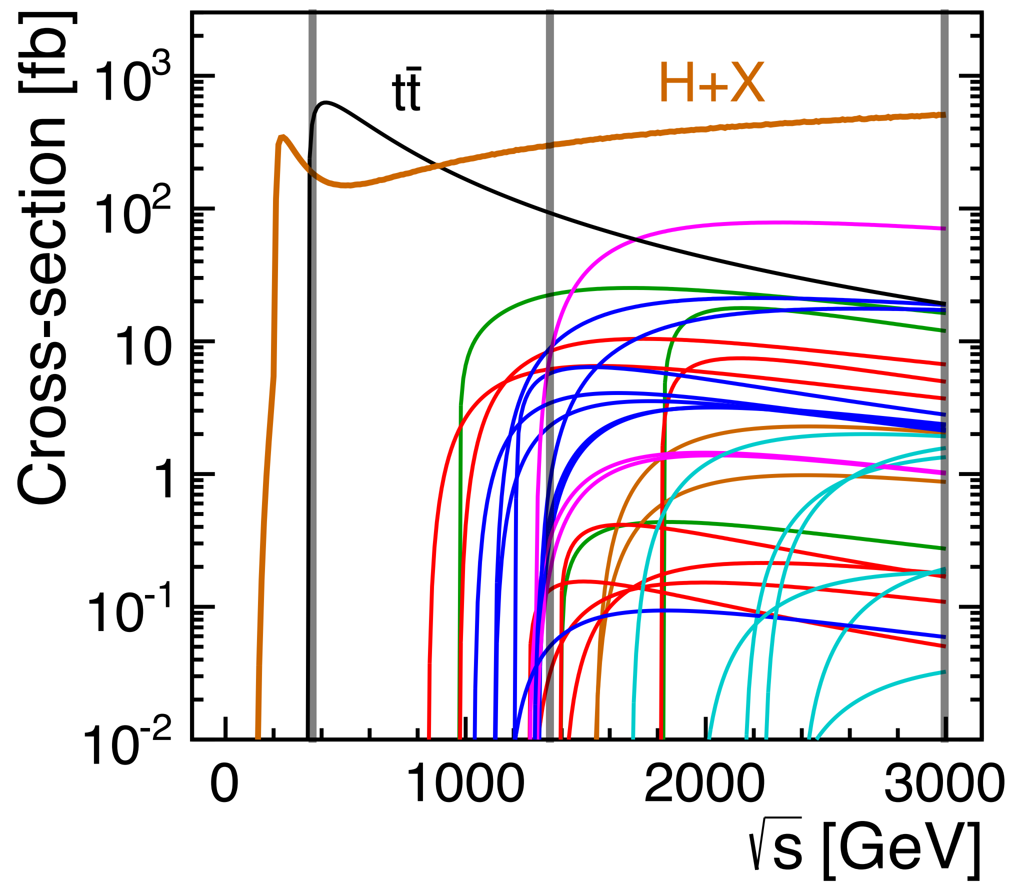
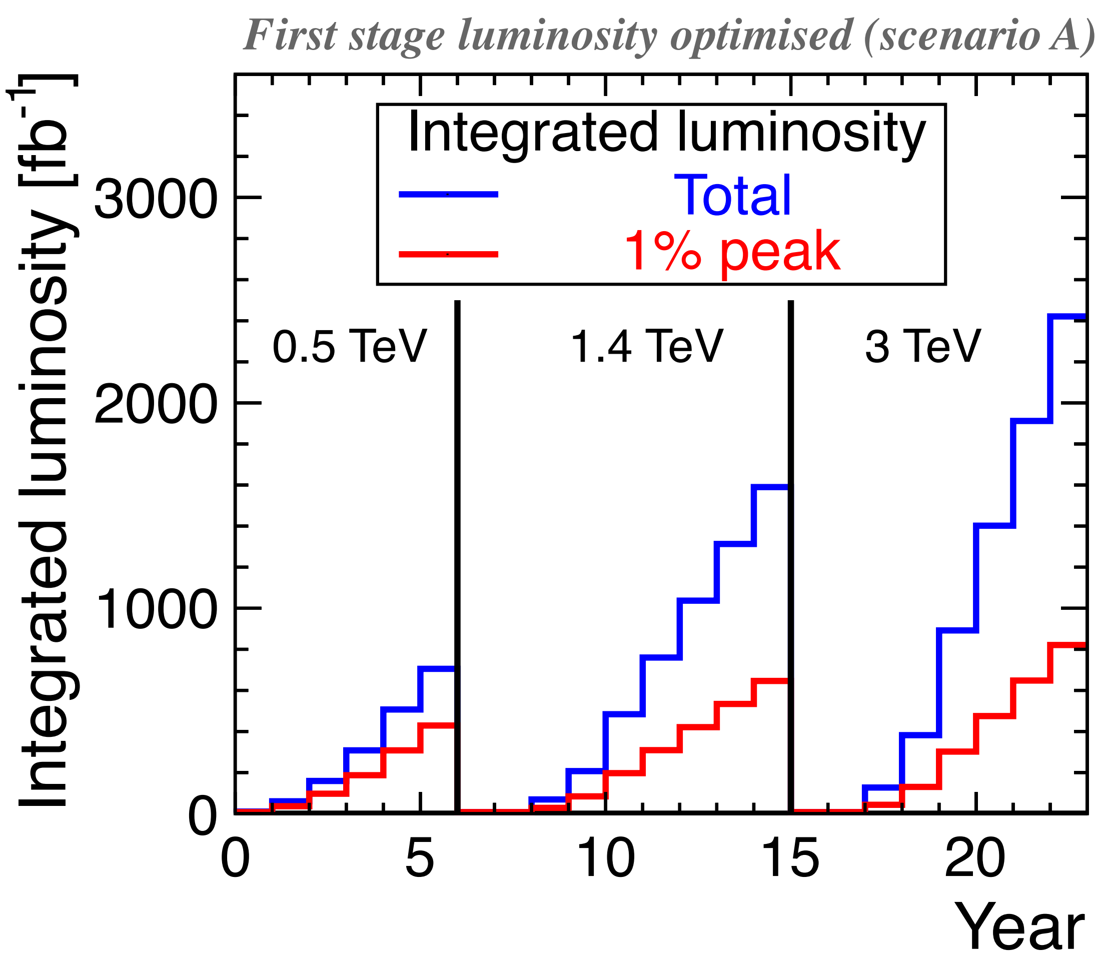


- Discovery potential for New Physics
  - Direct production of new particles - Mass reach up to √s/2 for (almost) all particles
    - Spectroscopy of New Physics
  - Indirect (model-dependent) search for New Physics extending far beyond √s

A Staged Program to maximize Physics Potential

- For optimal luminosity, the energy of a collider based on CLIC technology can only be varied within a factor of ~ 3: Staged construction of the machine





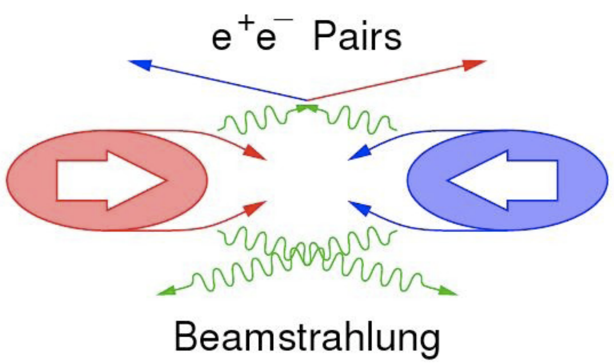
Provides:

- earlier start of physics
- optimal use of physics potential

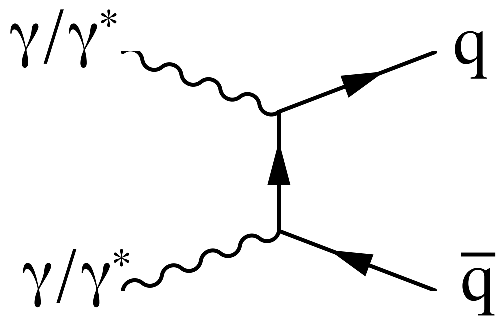
- Precise energy of the stages depends on physics - with considerations for technical constraints:
  - Possible scenario: ~375 GeV, 1.4 TeV, 3 TeV

Experimental Conditions at CLIC

- The main challenge: High energy and high luminosity leads to high rates of photon-induced processes:



e^+e^- pairs drive crossing angle & vertex detector radius



$\gamma\gamma \rightarrow$ hadrons interactions:
3.2 / bunch crossing @ 3 TeV

Combined with bunch structure (0.5 ns between BX):
Pile-up of hadronic background:
~ 19 TeV in HCAL / bunch train
➯ Needs to be rejected by reconstruction

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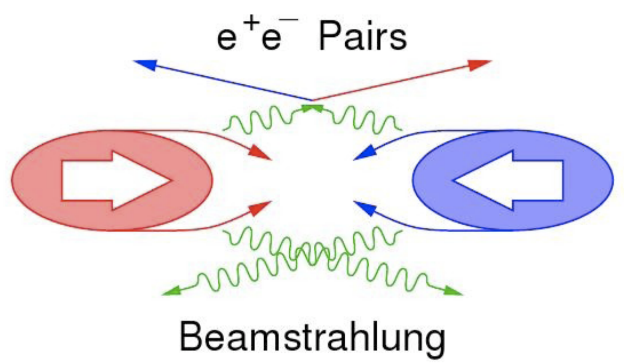

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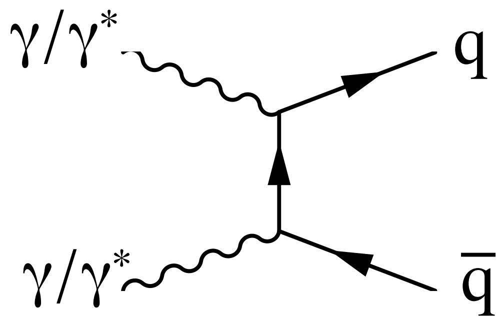

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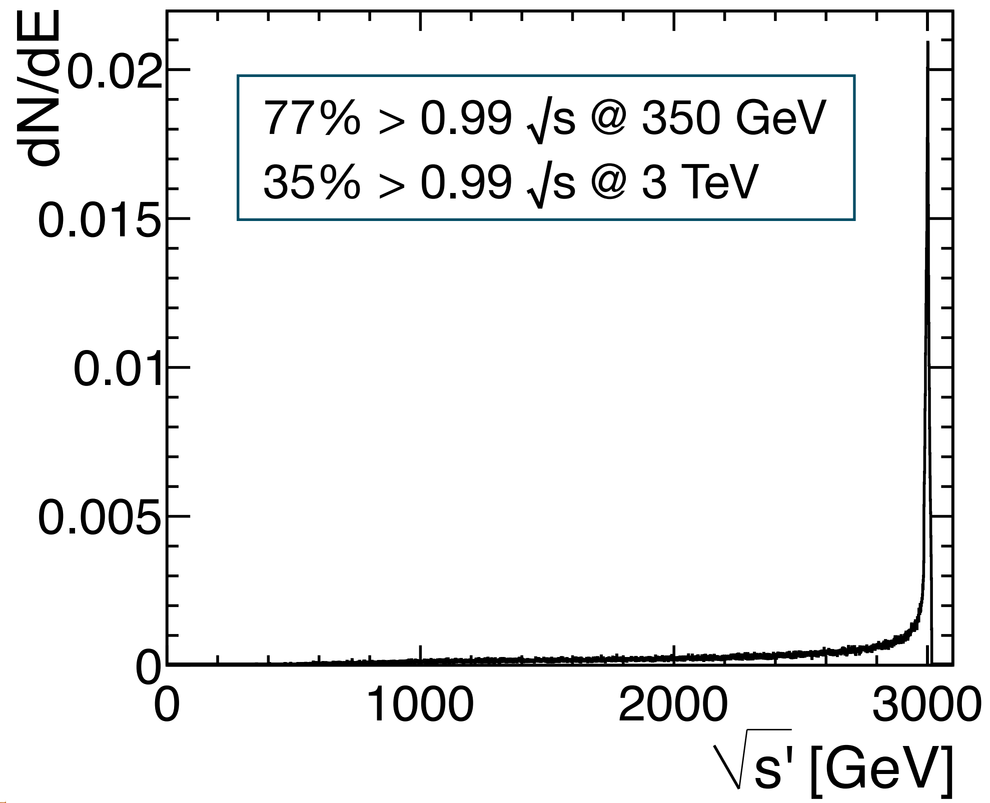
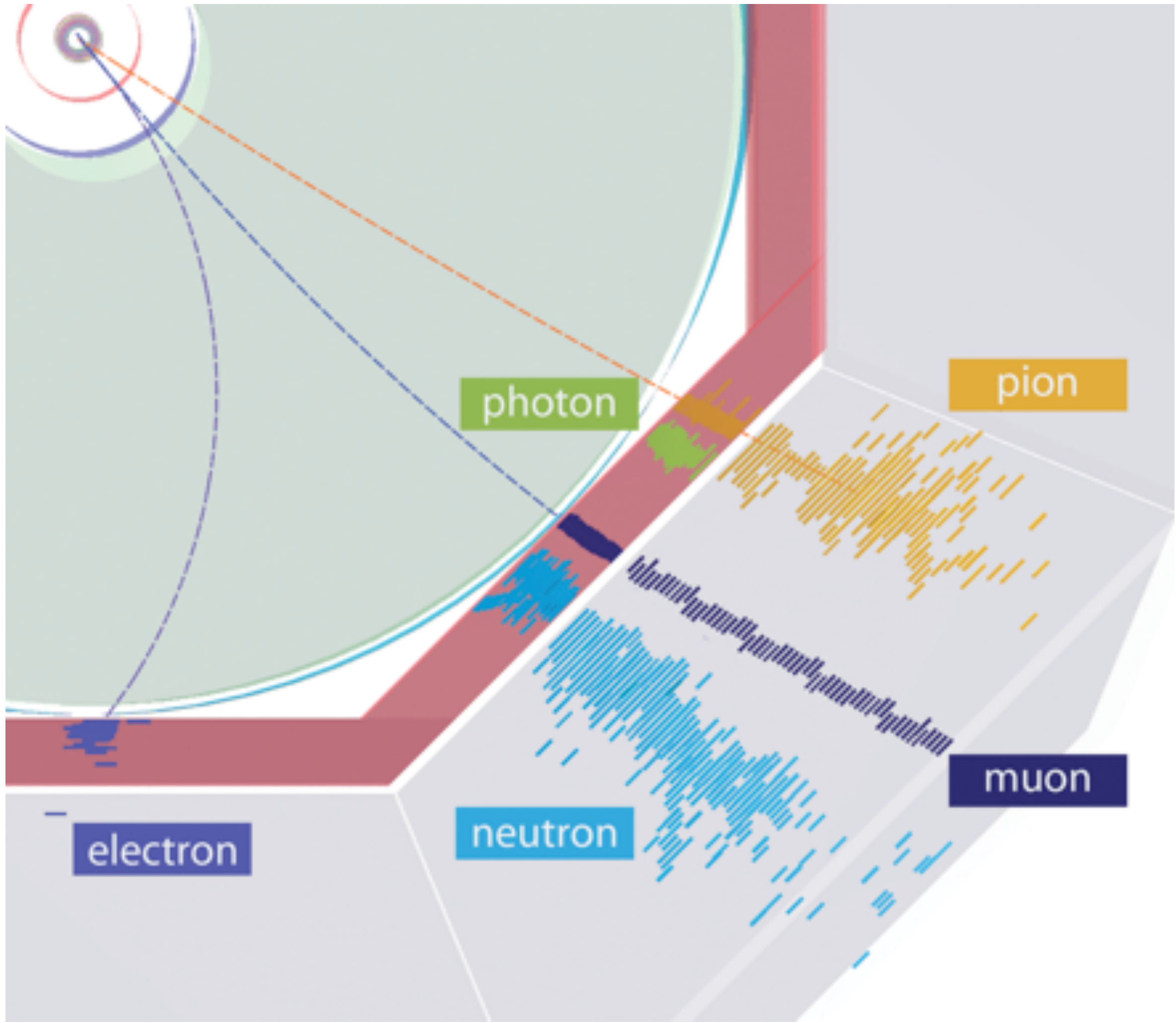
A further consequence of radiative losses: The luminosity spectrum - characterized by a main peak and a tail to lower energies



Reconstruction at CLIC

- Event reconstruction based on Particle Flow Algorithms
  - Provides optimal jet energy reconstruction
  - When combined with ns-level timing in the calorimeters: A powerful tool for the rejection of $\gamma\gamma \rightarrow$ hadrons background



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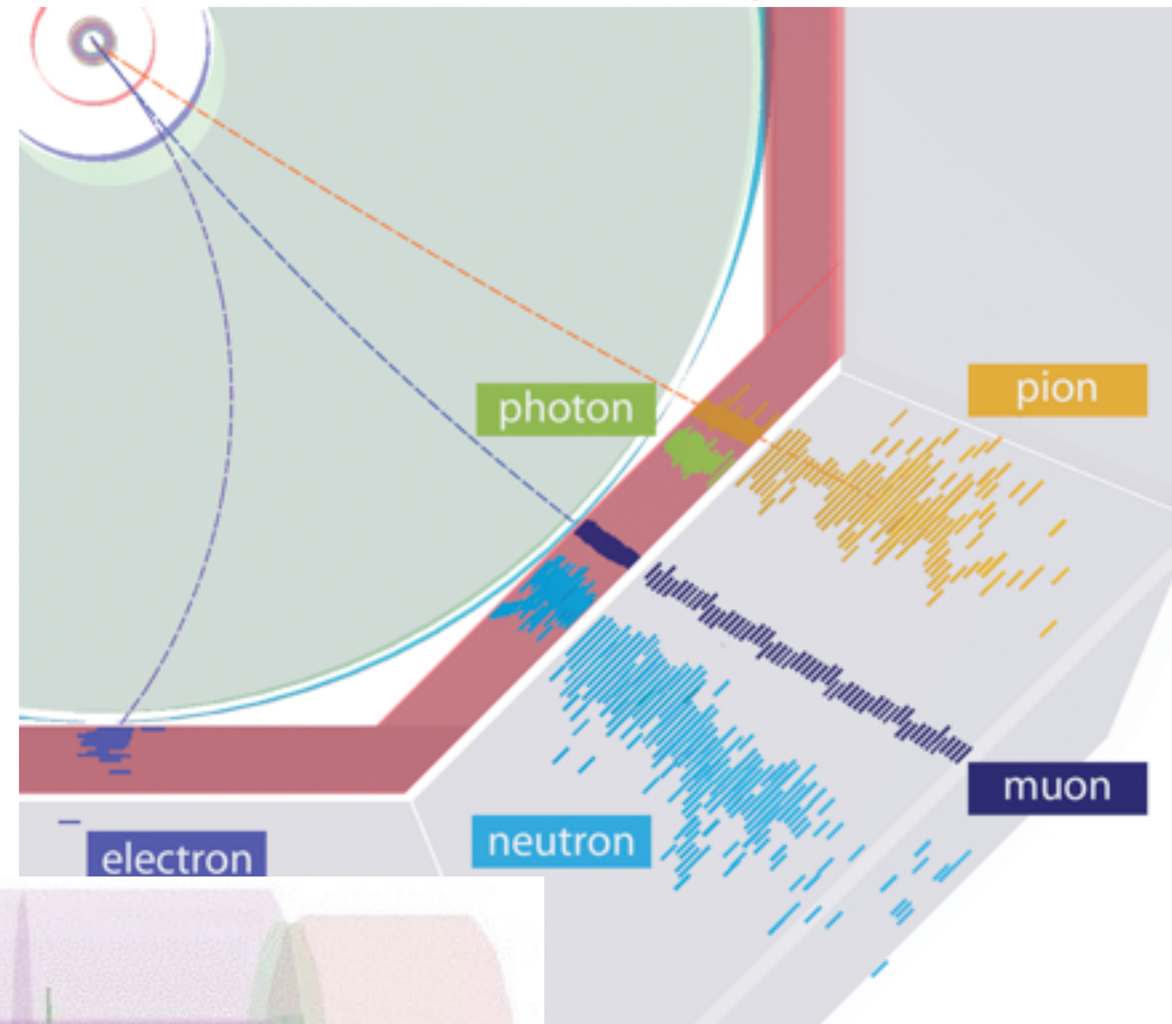
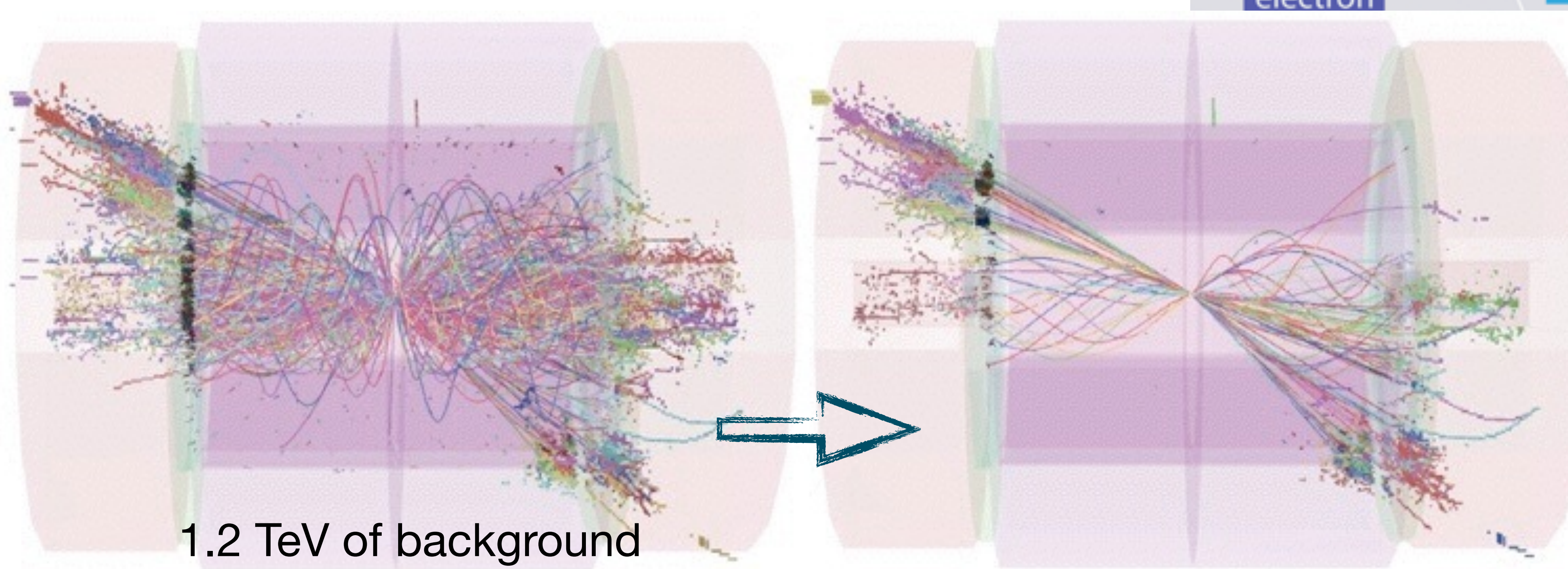




$$e^+e^- \to t\bar{t} \ @ \ 3 \ \mathrm{TeV}$$

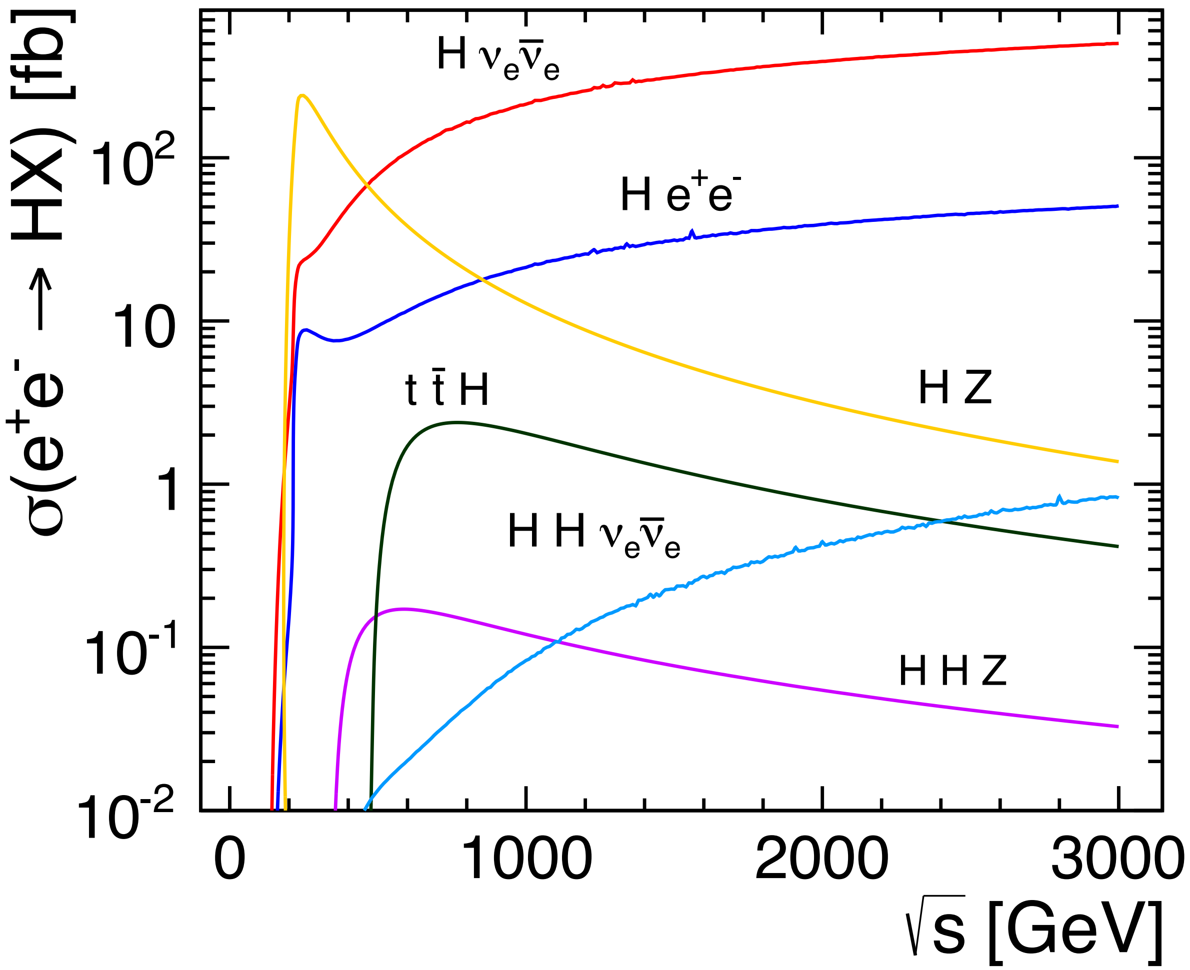
Reduction of background from 19 TeV to 100 GeV: Challenging CLIC environment under control!

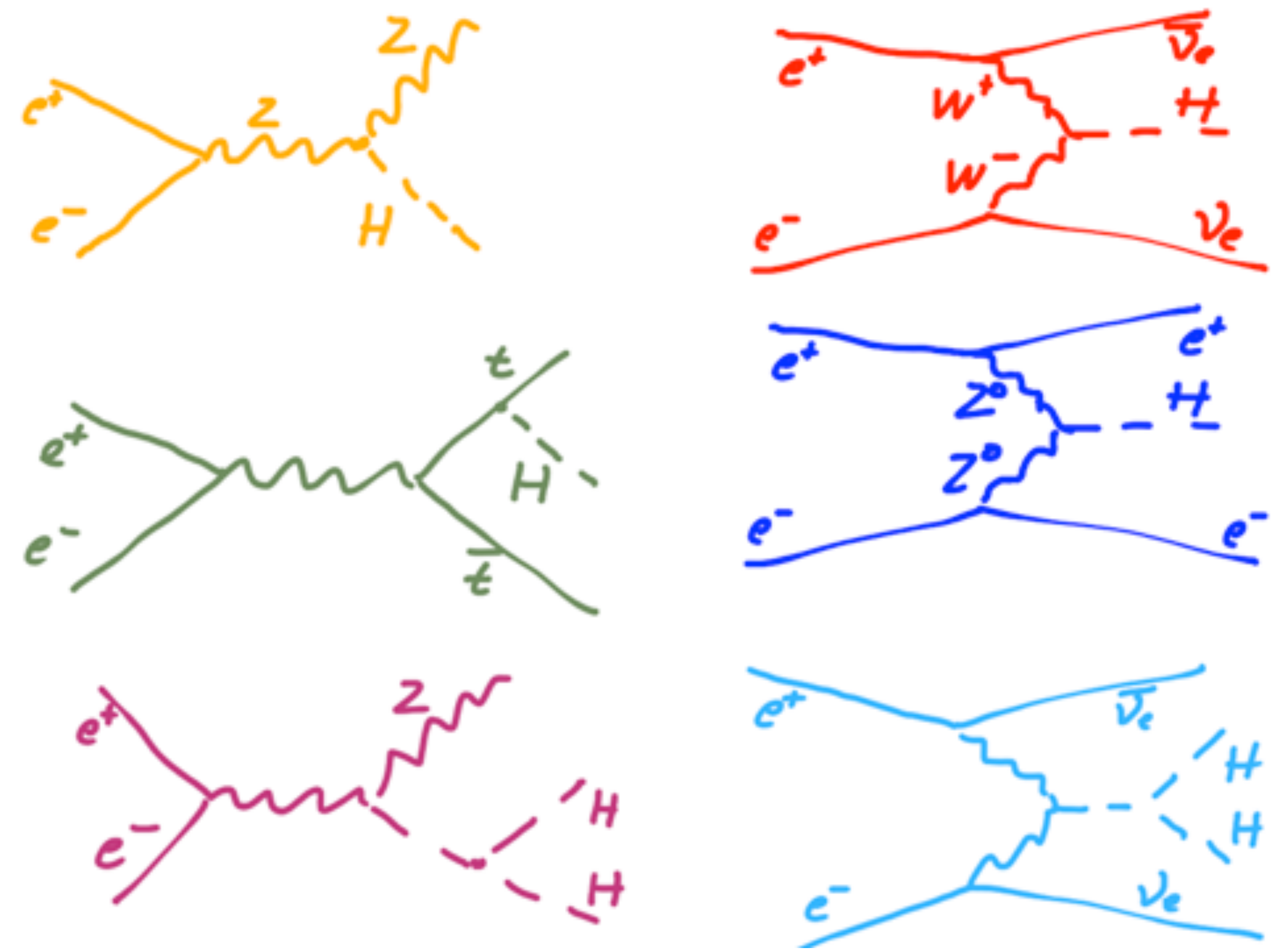
The Physics Potential

Based on studies using full GEANT4 simulations and reconstruction with realistic detector models, including machine-induced and physics backgrounds

Higgs Physics at CLIC

- Now a guaranteed physics program - Profits from the wide energy reach of CLIC





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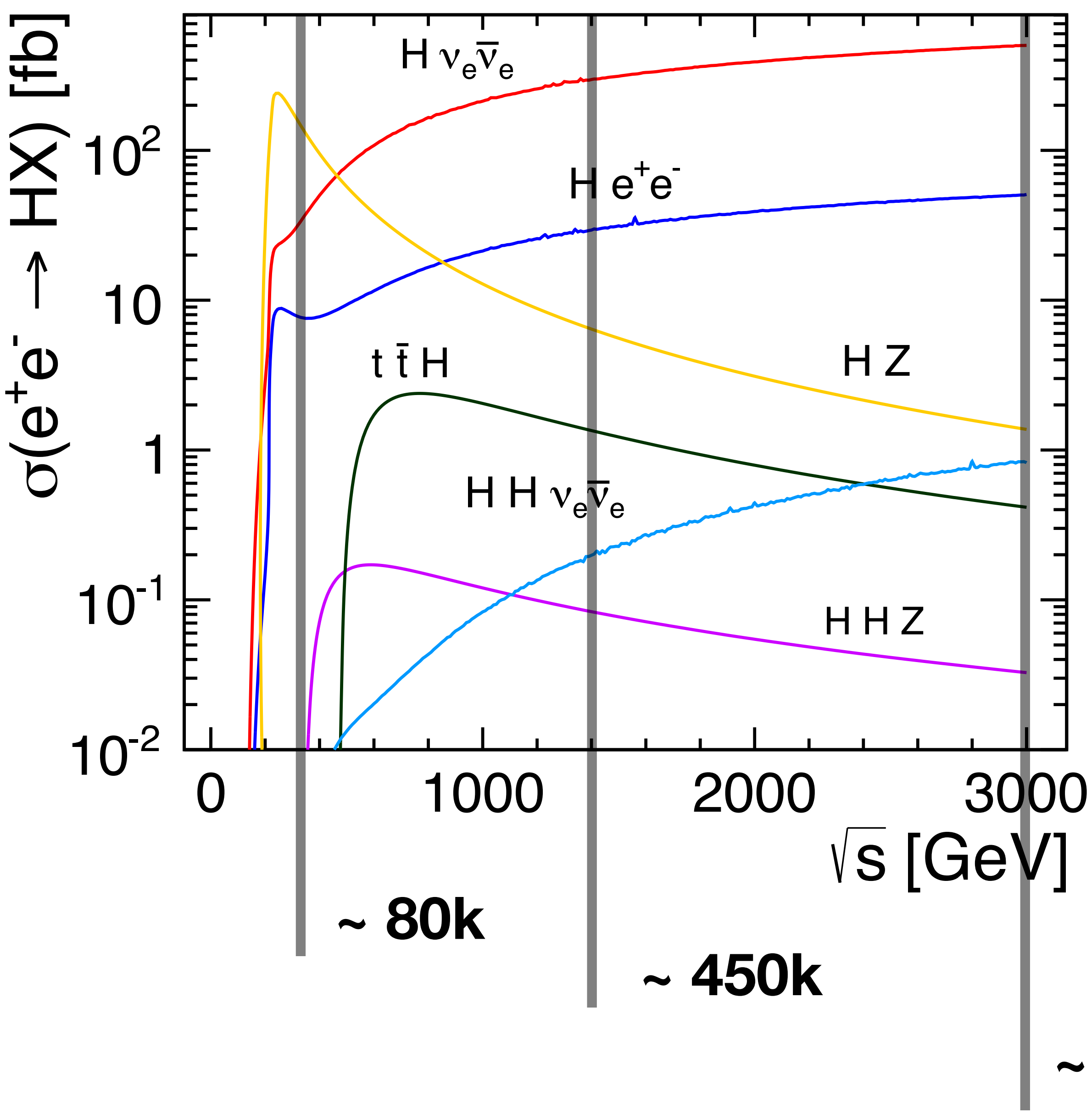

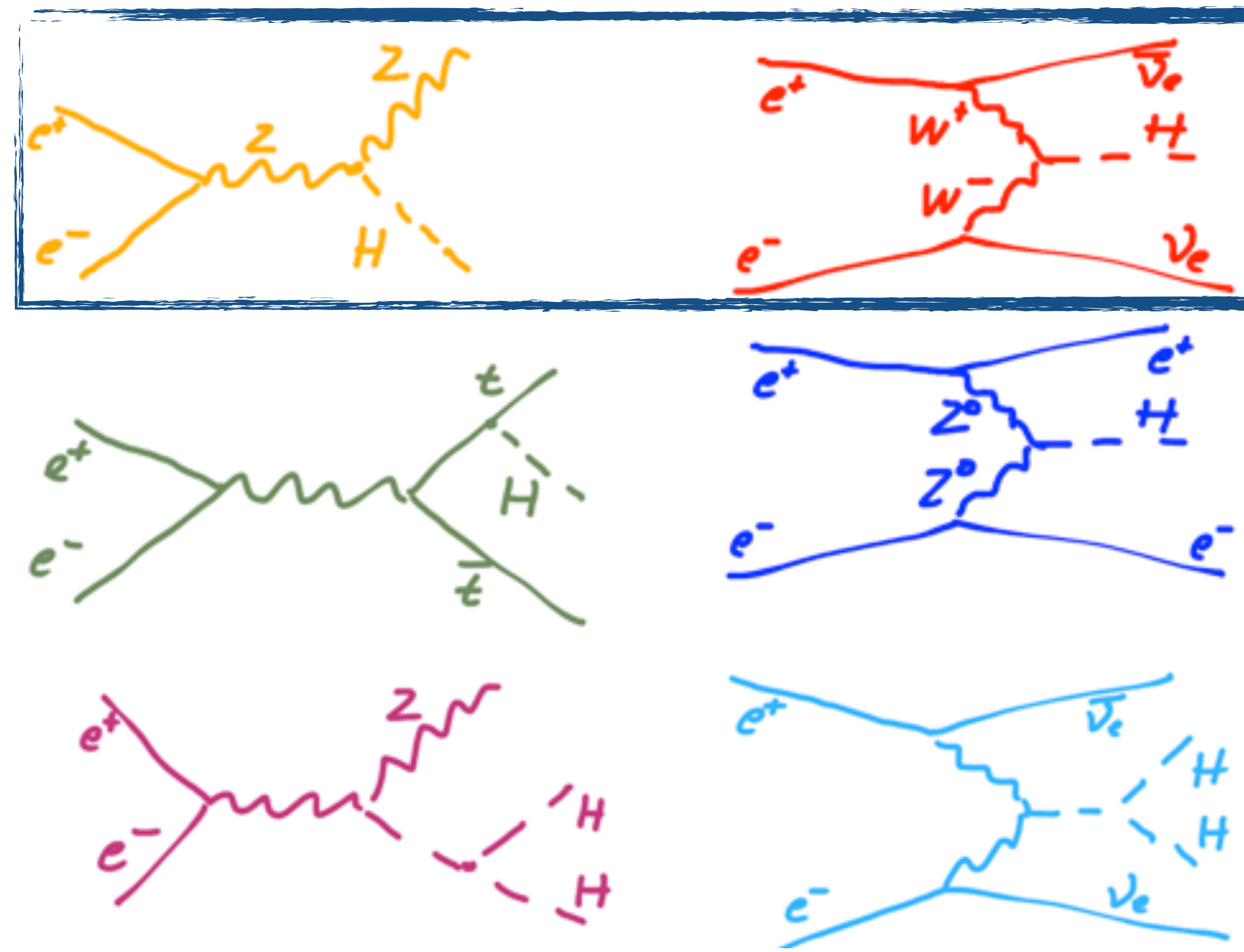

Higgs bosons per stage (w/o polarization)
(NB: Very high reconstruction efficiency!)

Main production modes - give access to couplings and total width

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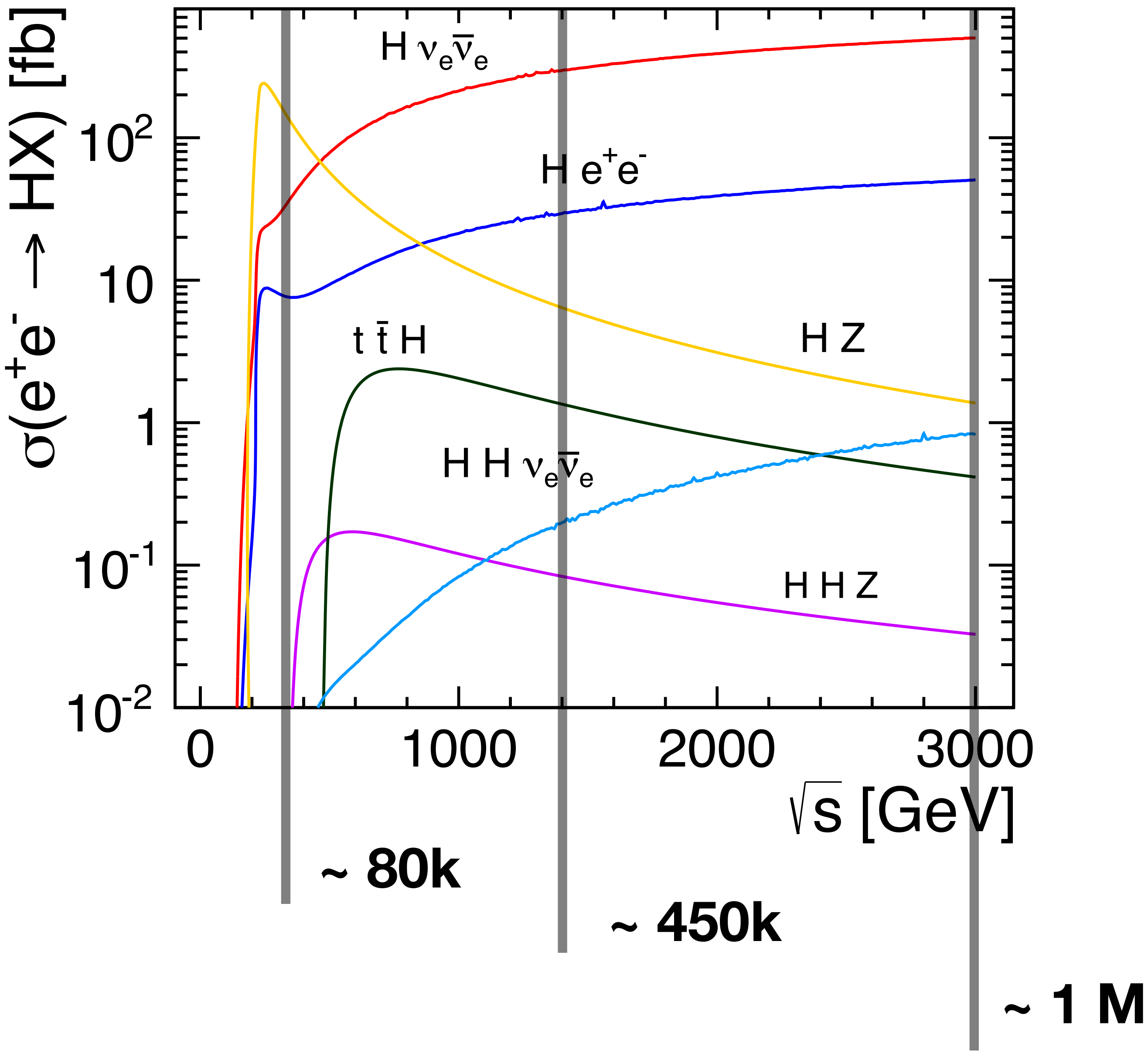
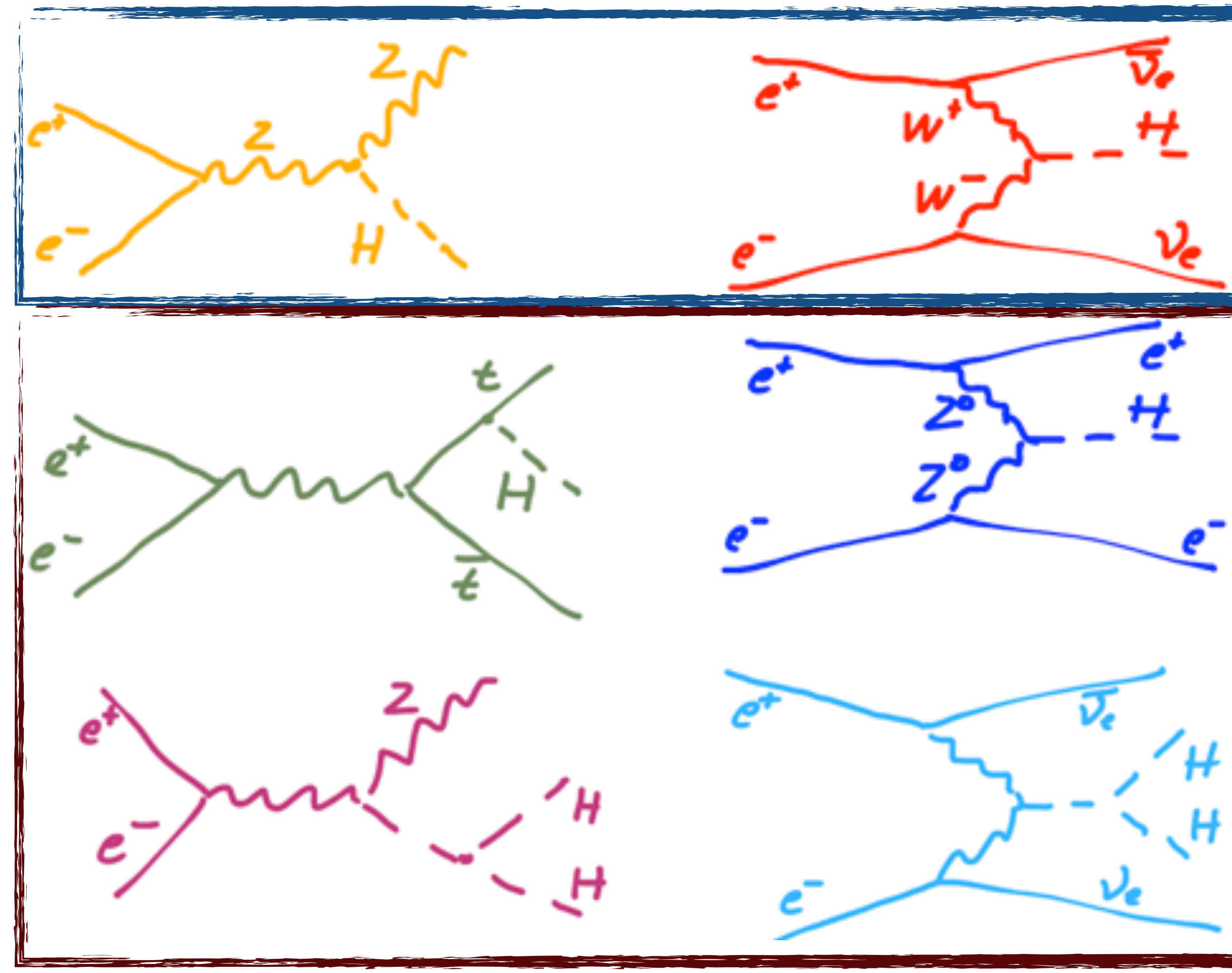




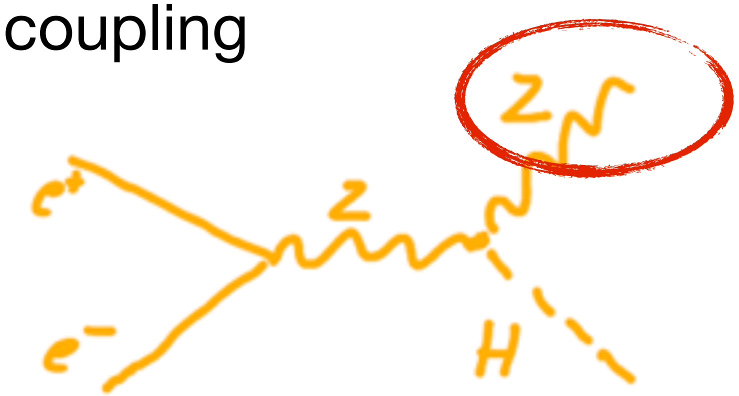
Higgs bosons per stage (w/o polarization)
(NB: Very high reconstruction efficiency!)

Main production modes - give access to couplings and total width

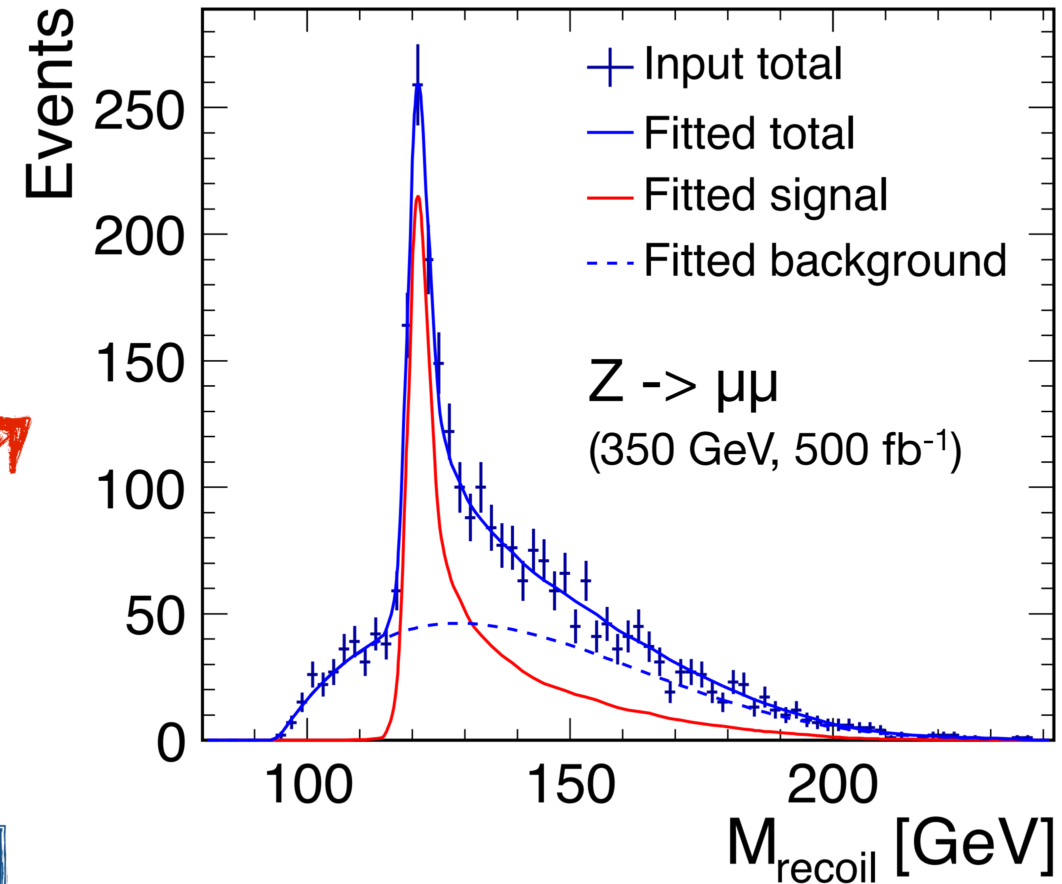
Rarer Processes - ZZ fusion, direct access to top Yukawa, self-coupling

Model-Independent Measurements of Couplings

- A unique features of lepton colliders: model-independent measurement of HZZ coupling



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



Absolute measurement of HZ cross section:
~ **4.2%** (stat) for leptonic Z decays at 350 GeV

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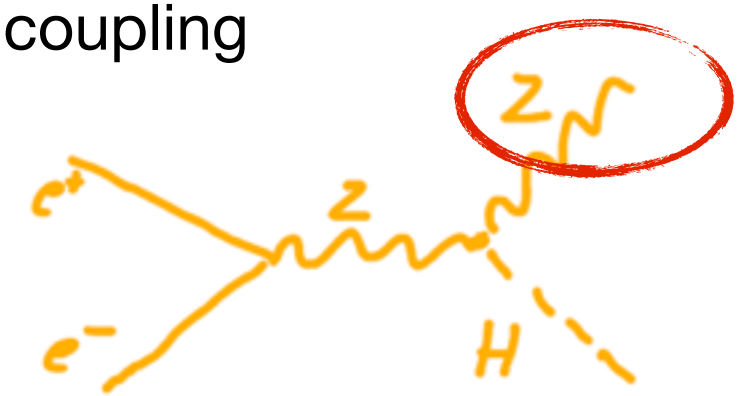

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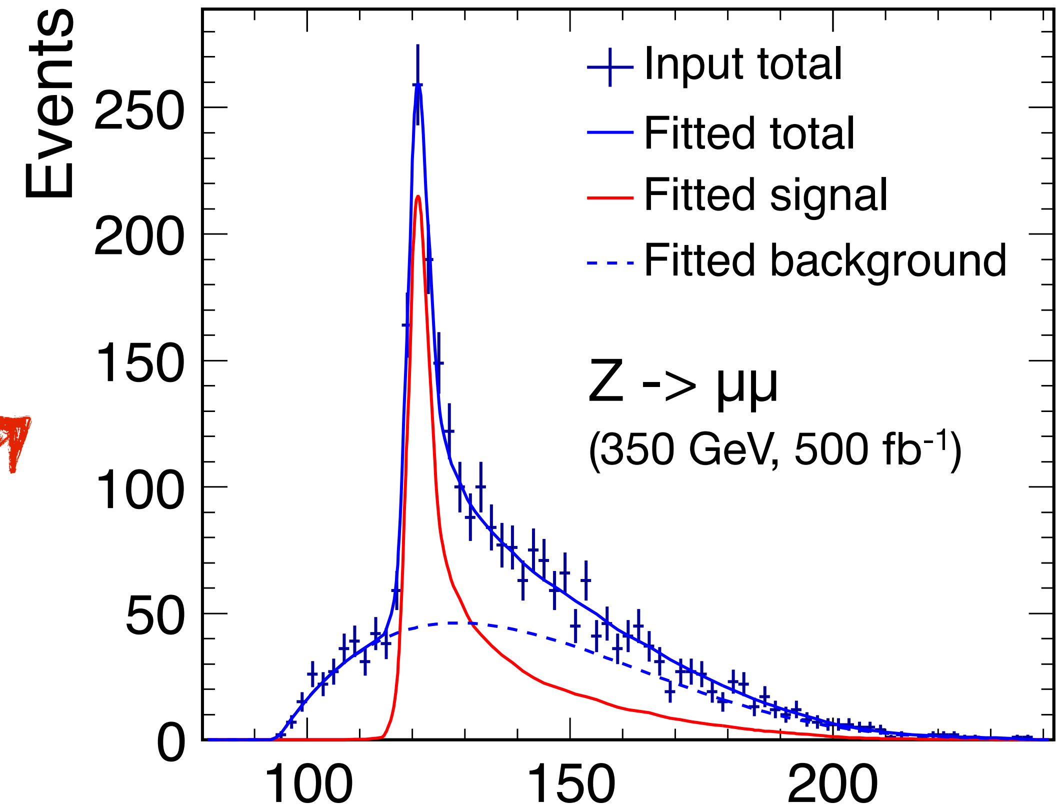

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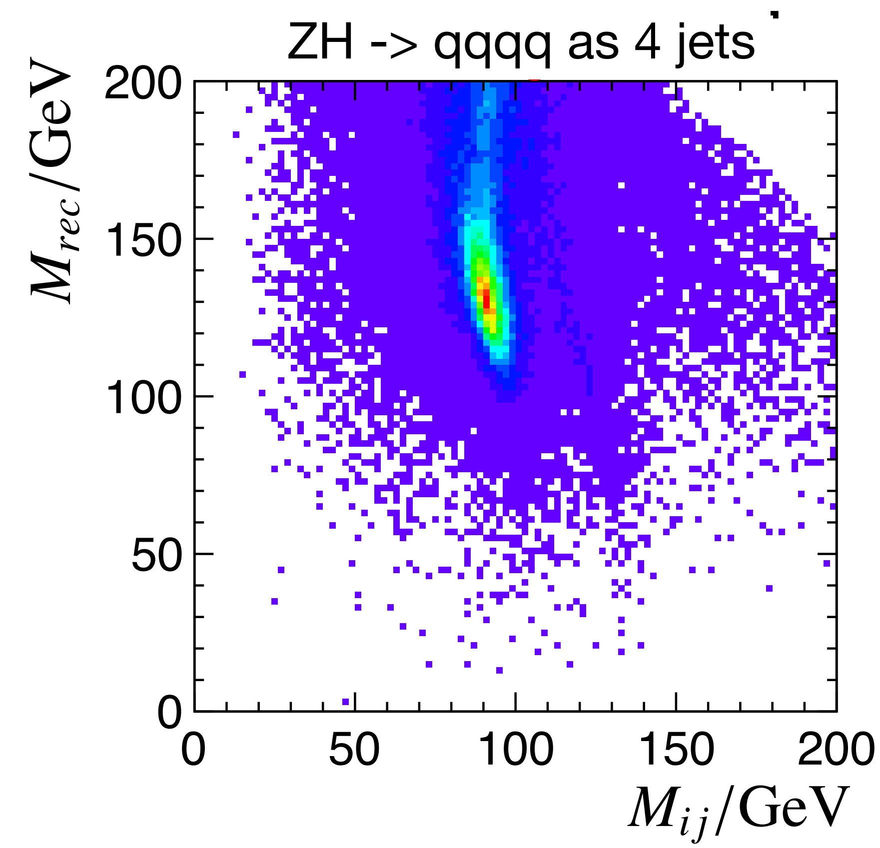
Potential for substantial improvement when also using hadronic Z decays

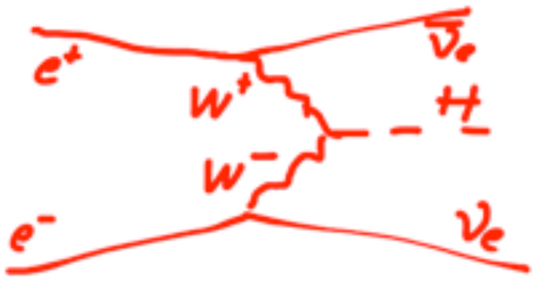
- The challenge: Z->qq reconstruction and event identification may depend on H decay mode
  - Ongoing study, bias seems to be very small

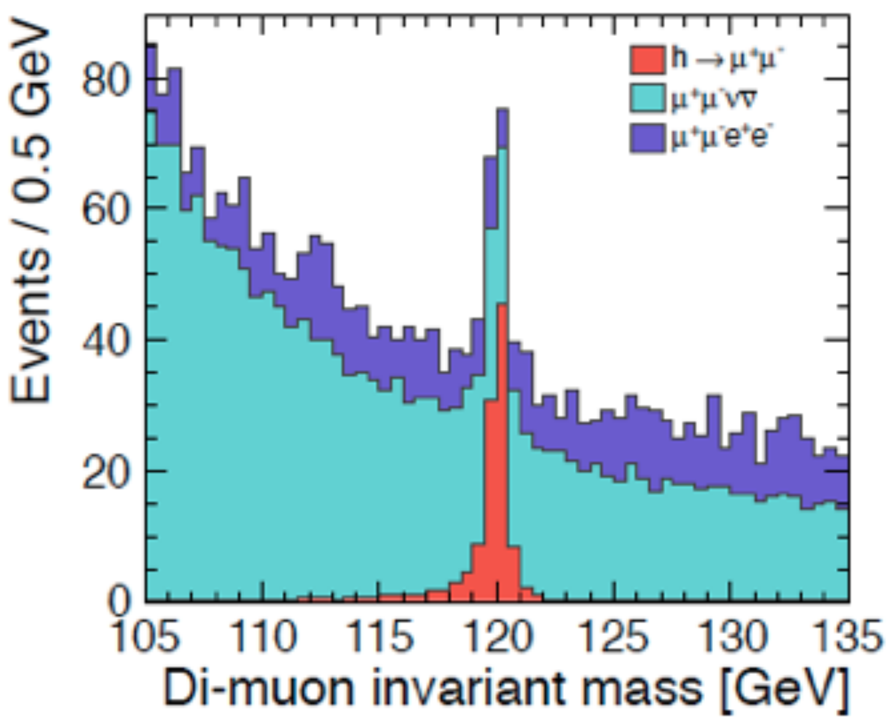


Including hadronic Z decays: Δσ/σ(HZ) = **2%** (stat)

Higgs Measurements at Higher Energy

- Increasing cross section of WW fusion provides high statistics at high energy: ~ 1M H at 3 TeV
  - Possibility to access rare H decays





σ x BR of H->μμ with ~ **15%** (stat)
σ x BR of H->bb with ~ **0.2%** (stat)
σ x BR of H->cc with ~ **2.7%** (stat)
σ x BR of H->gg with ~ **1.8%** (stat)

for 2 ab^{-1} at 3 TeV

σ x BR of H->ττ with ~ **3.7%** (stat) for 1.5 ab^{-1} at 1.4 TeV

Higgs mass at the 30 MeV level from direct reconstruction of H->bb

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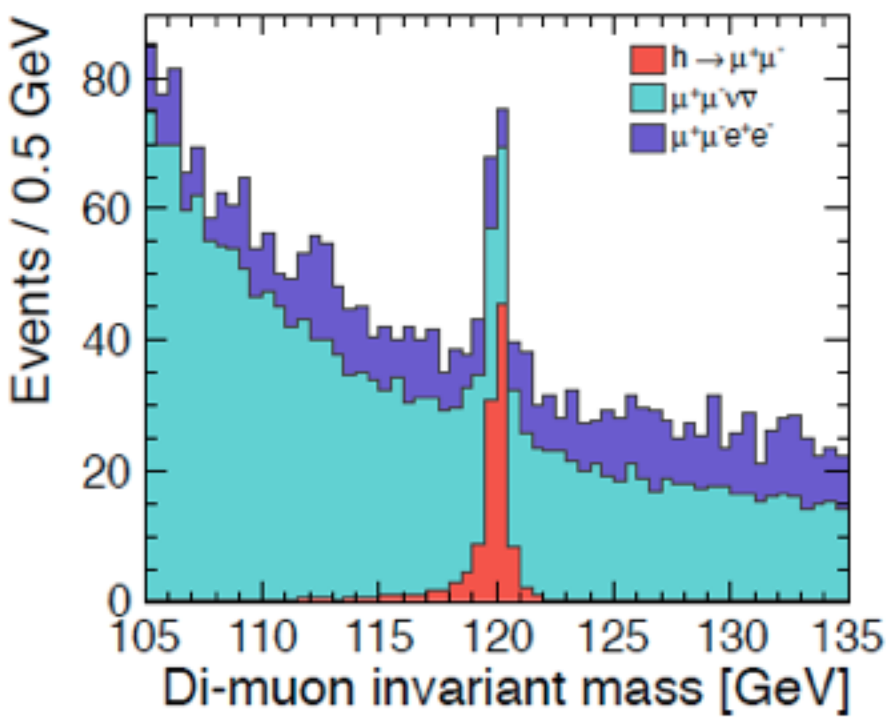

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Direct access to the top Yukawa coupling

Reconstruction via H->bb:

σ x BR ~ 8% for 1.5 ab^{-1} at 1.4 TeV

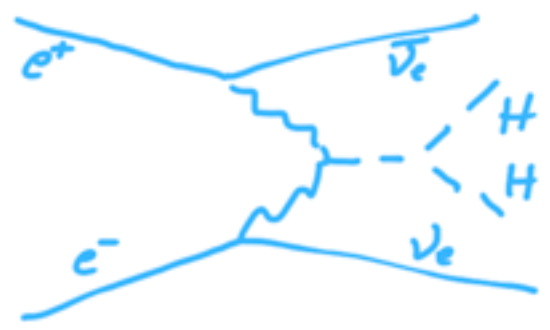
(substantially lower precision at 3 TeV due to low cross-section)

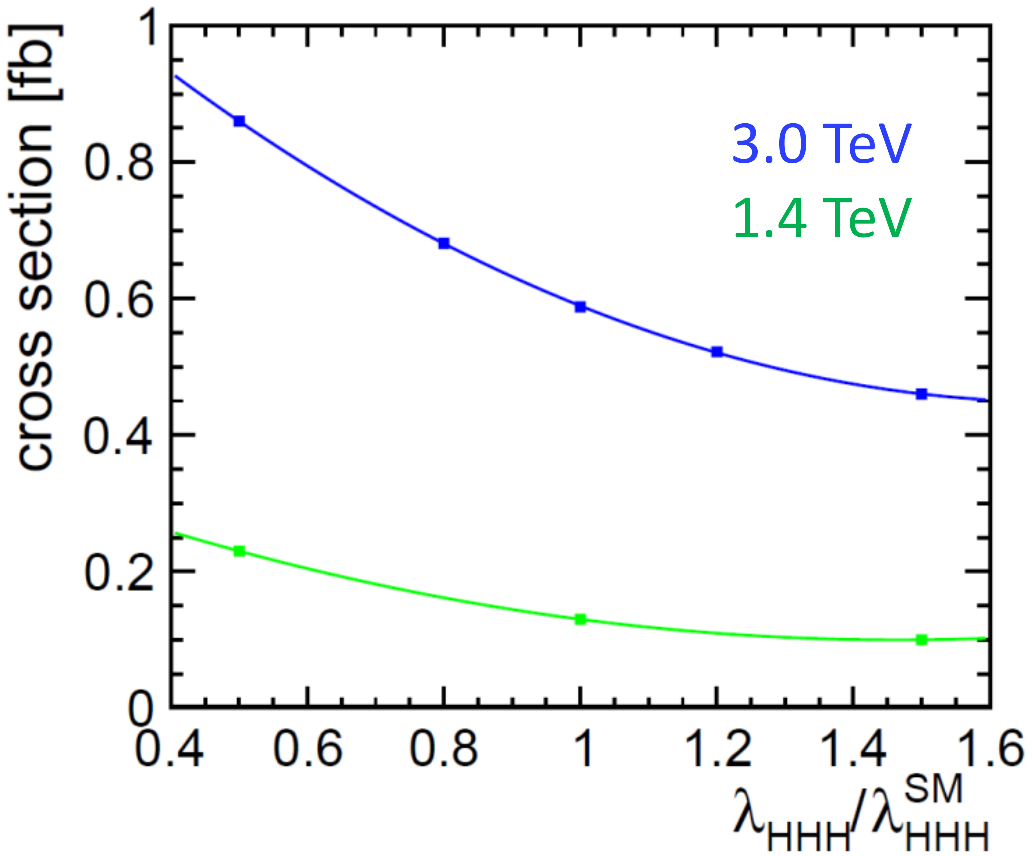
Measuring the Higgs Self-Coupling

- The ultimate challenge in Higgs physics: Direct access to the Higgs potential

At CLIC: Measurement in WW fusion - increasing cross-section at high energies

0.16 fb at 1.4 TeV, 0.63 fb at 3 TeV
(increases by 1.8 for 80% e^- polarization)





Cross section of HHνν final state depends on self-coupling (with a "dilution" by other processes)

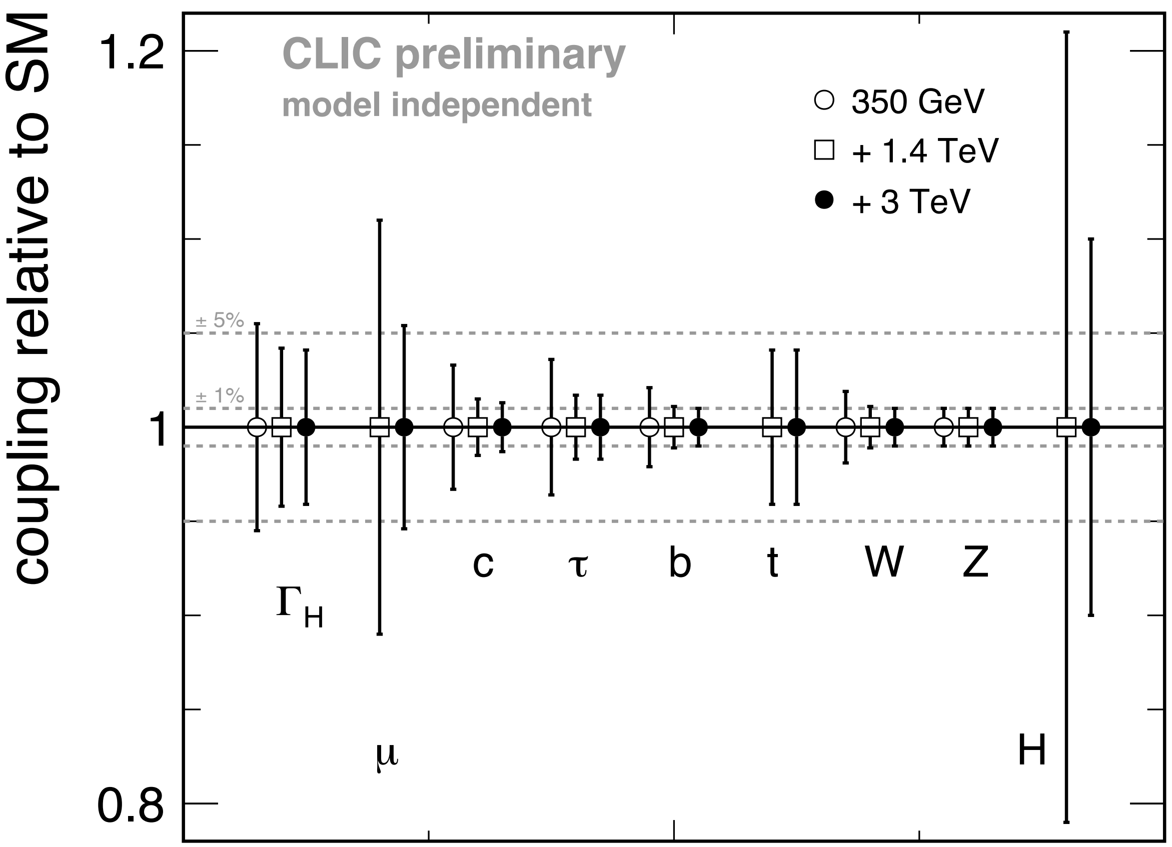
$\Delta\lambda_{HHH}$ ~ 28% (stat) with 1.5 ab^{-1} at 1.4 TeV
$\Delta\lambda_{HHH}$ ~ 16% (stat) with 2 ab^{-1} at 3 TeV
unpolarized

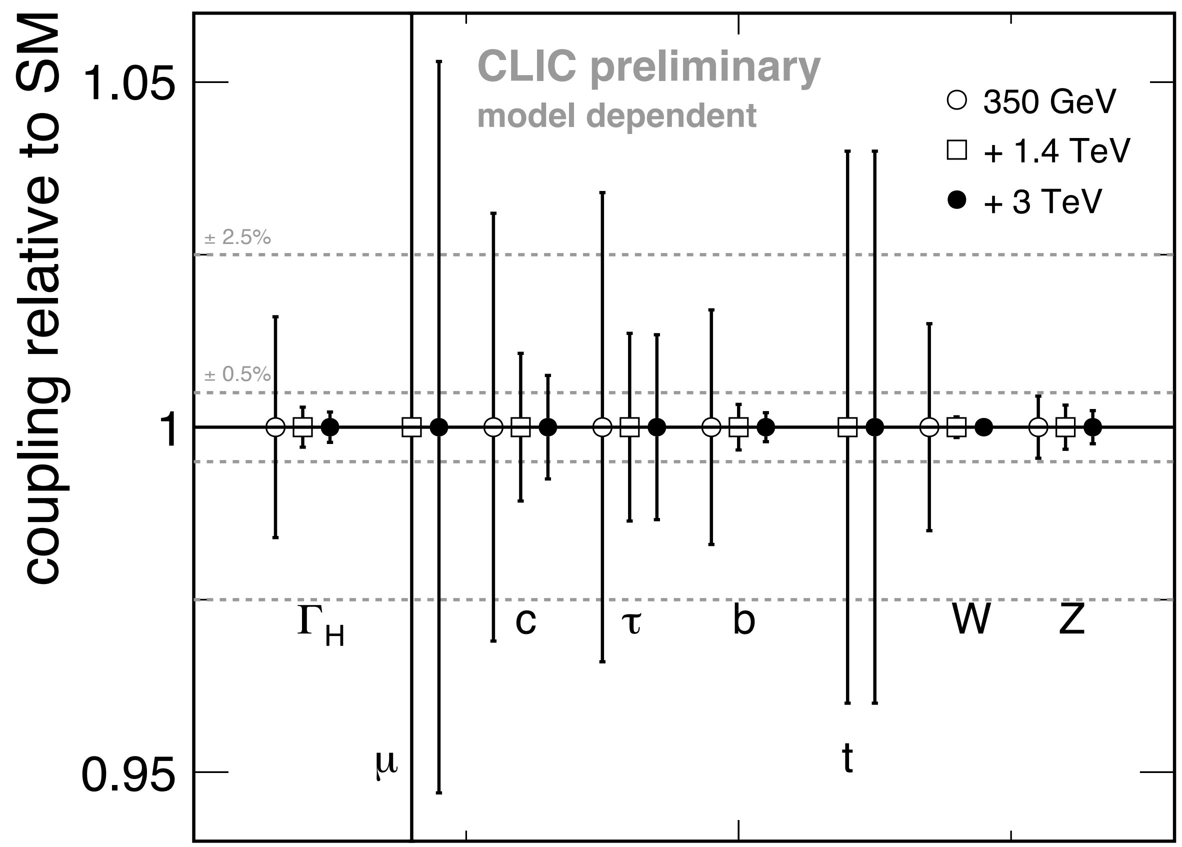
$\Delta\lambda_{HHH}$ ~ **21%** (stat) with 1.5 ab^{-1} at 1.4 TeV
$\Delta\lambda_{HHH}$ ~ **12%** (stat) with 2 ab^{-1} at 3 TeV
80% e^- pol.

~10% accuracy of self-coupling with the full (polarized) CLIC program

Precision Higgs Physics at CLIC: Global Picture

- From individual measurements of σ and σ x BR couplings are determined via a global fit using $$\sigma_{vis} = \sigma_{prod}(\mathrm{ii} \to \mathrm{H}) \times BR(\mathrm{H} \to \mathrm{f\bar{f}}) \sim \frac{g^2_{\mathrm{Hii}} g^2_{\mathrm{Hff}}}{\Gamma_{\mathrm{H}}}$$
  - model-independent: width as a free parameter
  - model-dependent: width constrained - Assuming only SM decays, with perturbations of SM BRs parametrized by κ parameters (LHC-like approach)





including preliminary results of hadronic Z decays in HZ cross-section measurement

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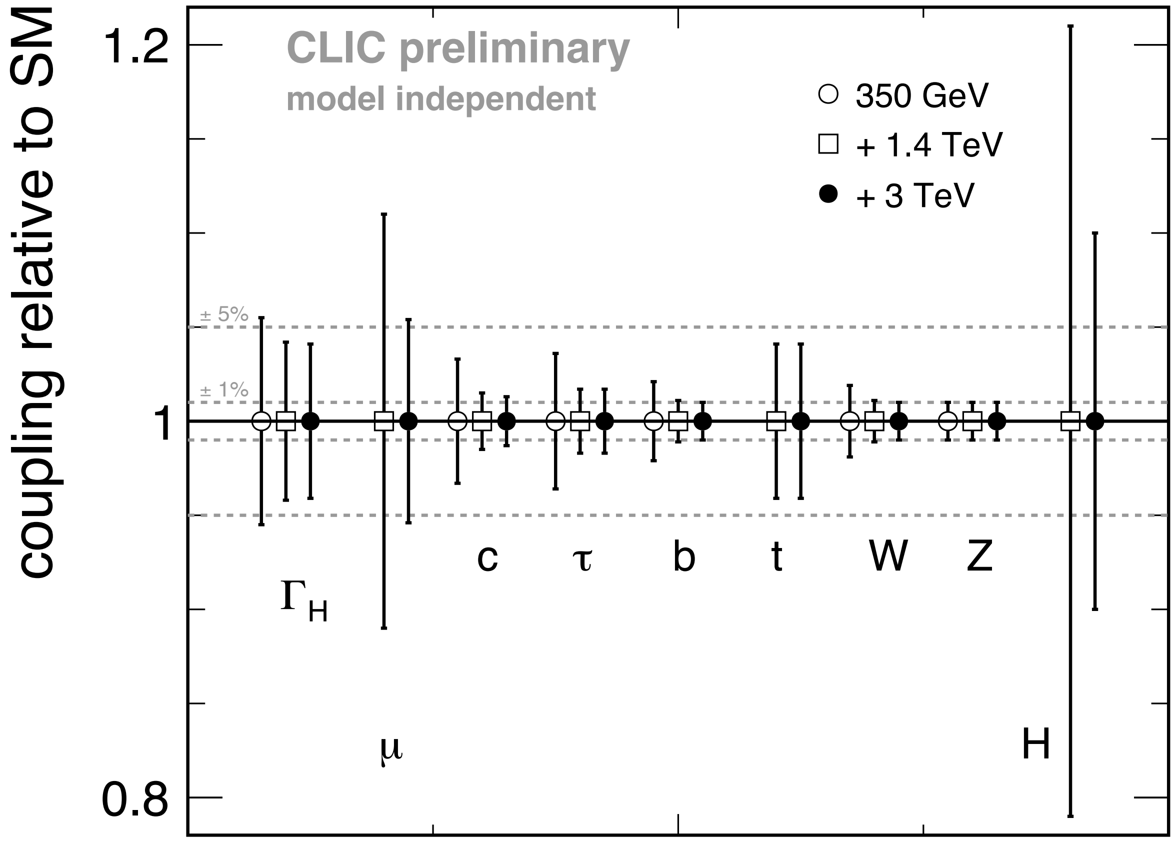

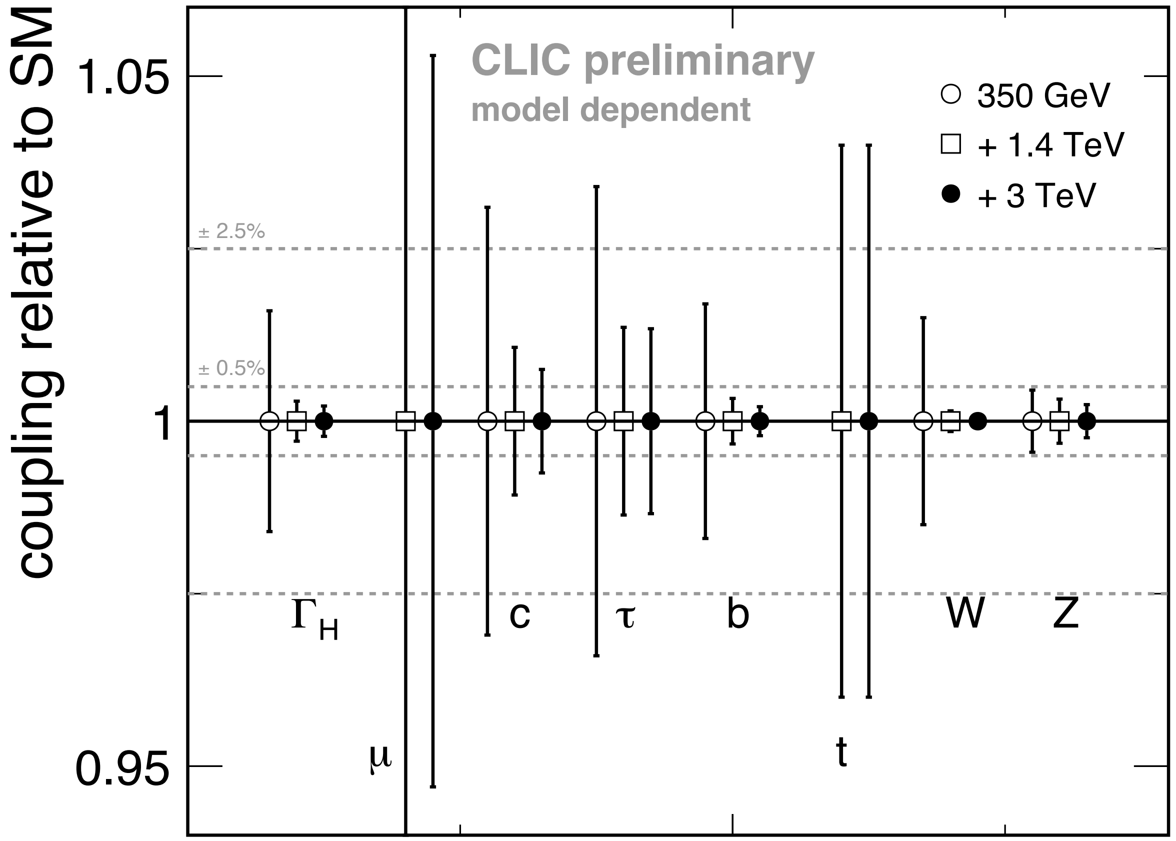

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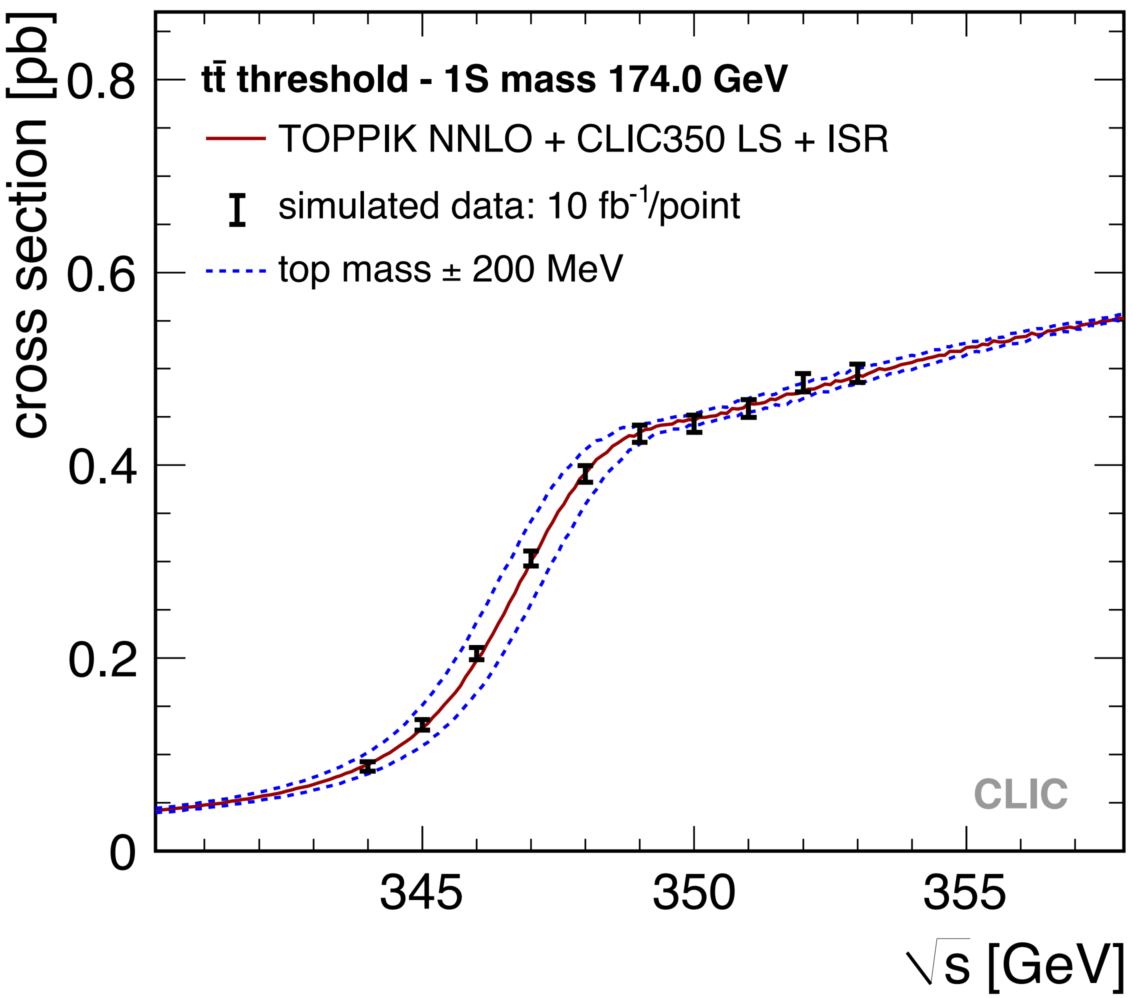
➯ model-independent 1% - level determination of most couplings in full program
➯ 1% to few ‰ with model-dependence

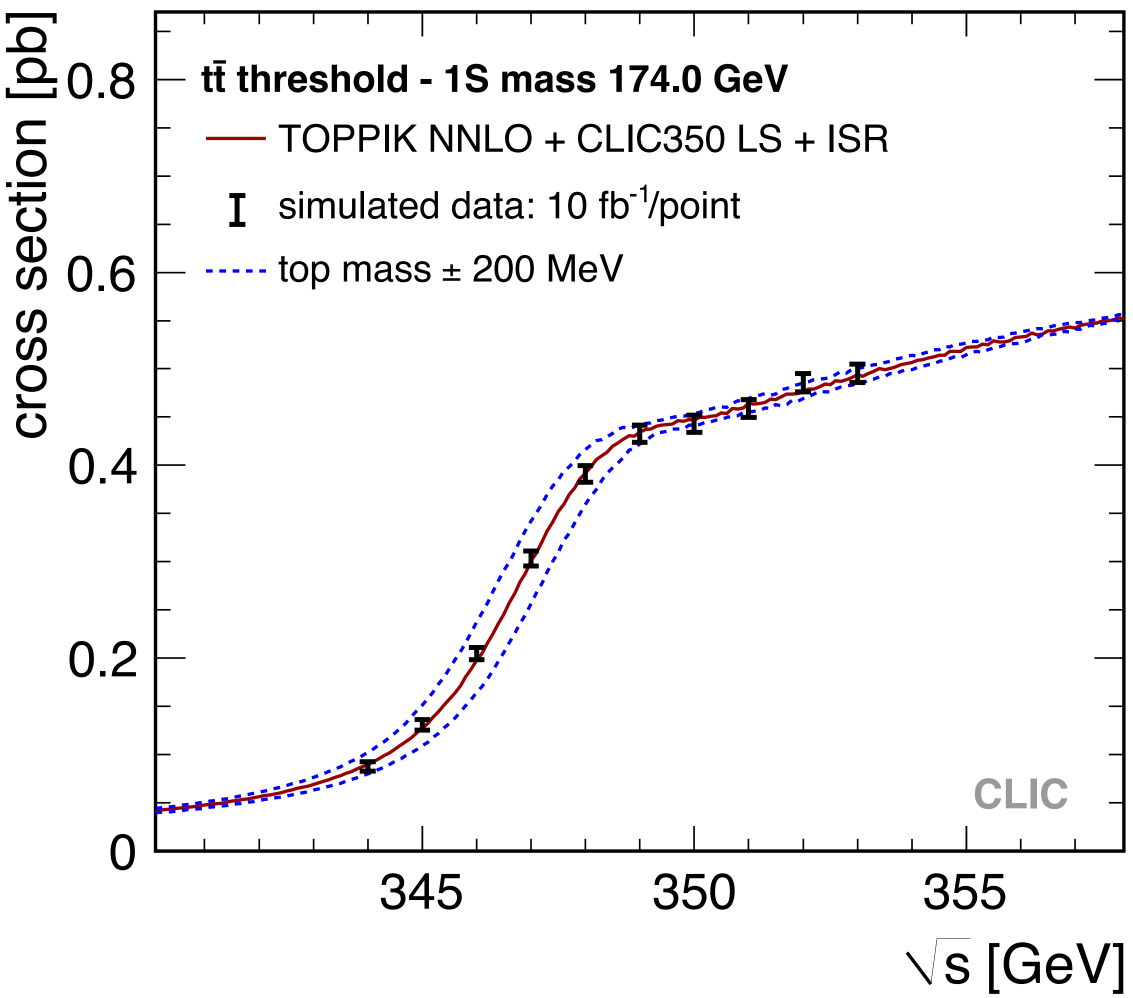
Top & Electroweak Precision Physics



- Precise and theoretically clean measurement of the top quark mass in a threshold scan
  - Statistical uncertainty on m_t: **30 MeV** for 100 fb^{-1}
  - Experimental systematics on a similar level, including ~ **6 MeV** from the measurement of the luminosity spectrum

Total uncertainty ~ **100 MeV** including theory uncertainties

Top & Electroweak Precision Physics



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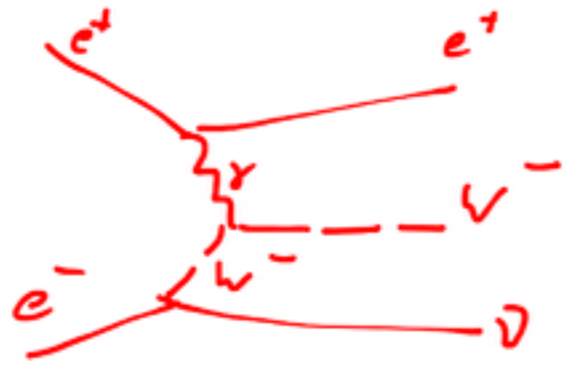
- Many other opportunities - one example: Measurement of W boson properties:
  - Large single W cross section at high energy: => 20 million Ws at 1.4 TeV, 45 million at 3 TeV
  - Good prospects for a precise mass measurement by direct reconstruction - detailed studies to be done

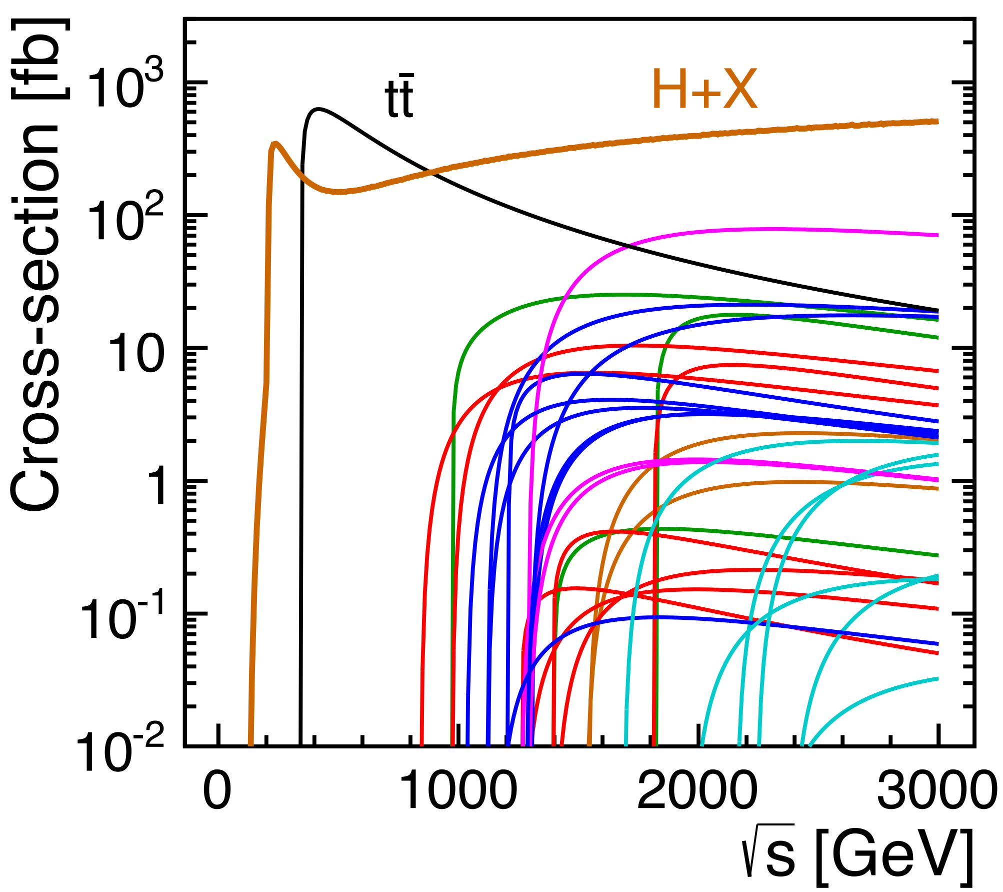


Beyond the Standard Model

- Two complementary approaches:
  - Direct measurement of new particles
  - Indirect evidence for new physics in precision observables

Potential for direct measurements studied with concrete SUSY models as examples:

“Model III” from CLIC CDR



- Three models with somewhat different mass scales to explore the physics potential of the 1.4 TeV and 3 TeV stages:
  - lightest neutralino ~ 350 GeV
  - heavier neutralinos / charginos ~ 480 - 650 GeV
  - Charged sleptons ~ 550 GeV - 1.1 TeV
  - Light-flavored squarks ~ 1.1 TeV
  - …

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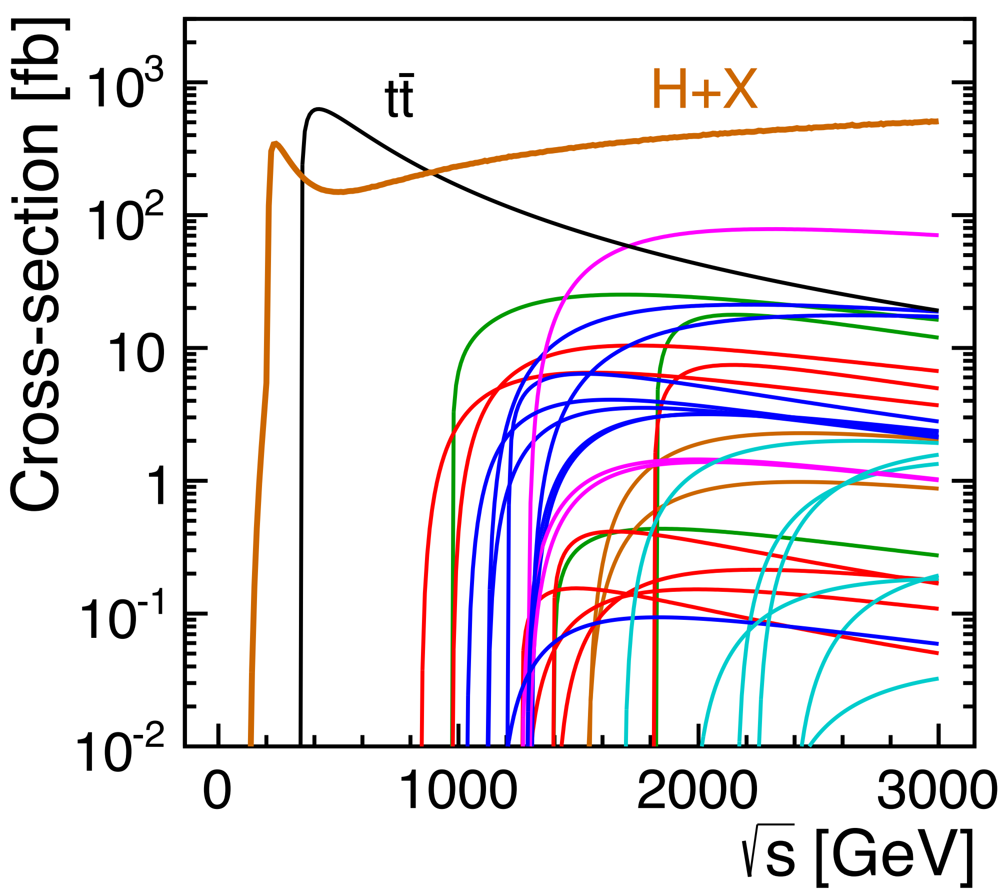

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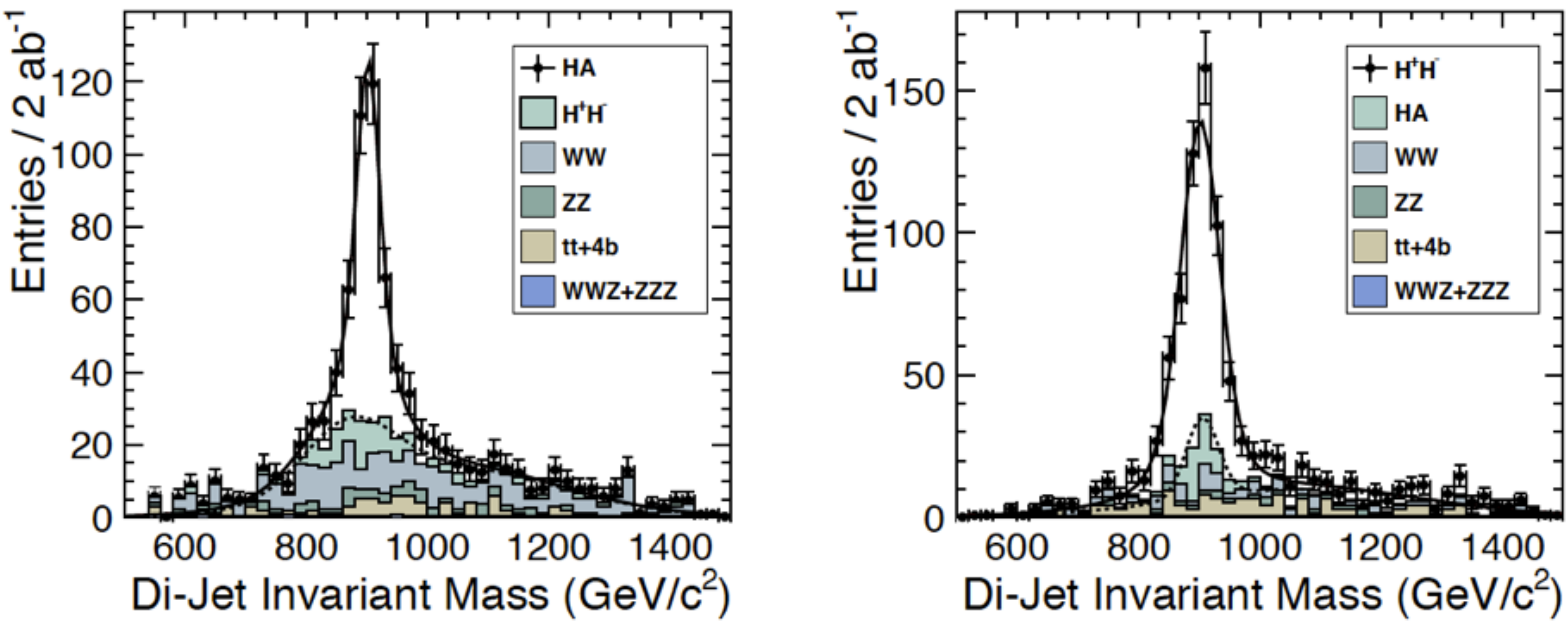
Studies in general serve as an illustration of capabilities independent of a concrete New Physics model

Extended Higgs Sectors

- Heavy Higgs bosons - for example H^0, A^0 and $H^{\pm}$ in SUSY - can be reconstructed with high precision

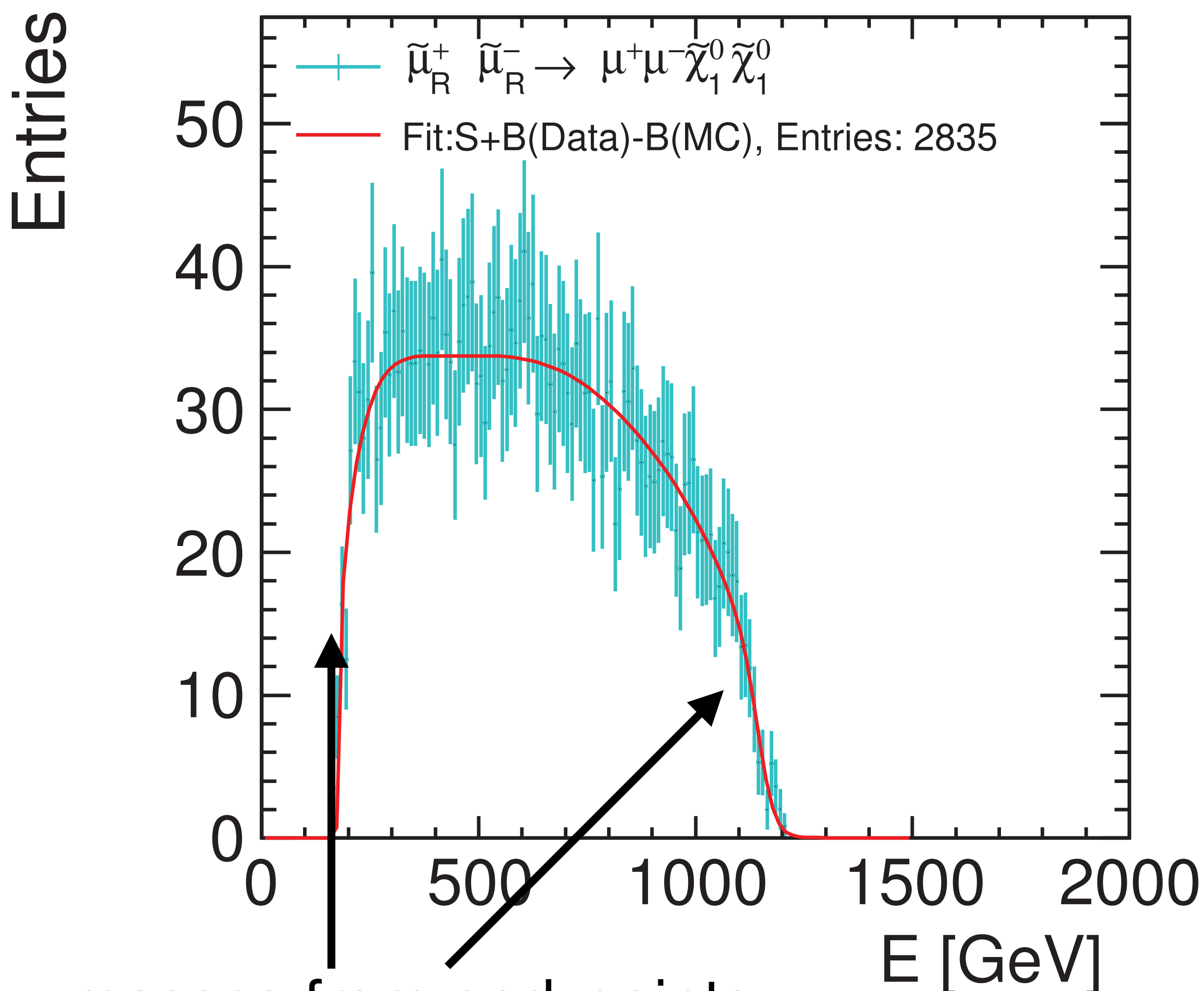


(a) $e^+e^- \to b\bar{b}b\bar{b}$

(b) $e^+e^- \to t\bar{b}b\bar{t}$

- For TeV-scale bosons the mass can be measured at the 3 GeV level, a direct measurement of the width is expected with 20% - 30% accuracy

TeV Scale Sleptons



masses from end-points
of muon energy distribution

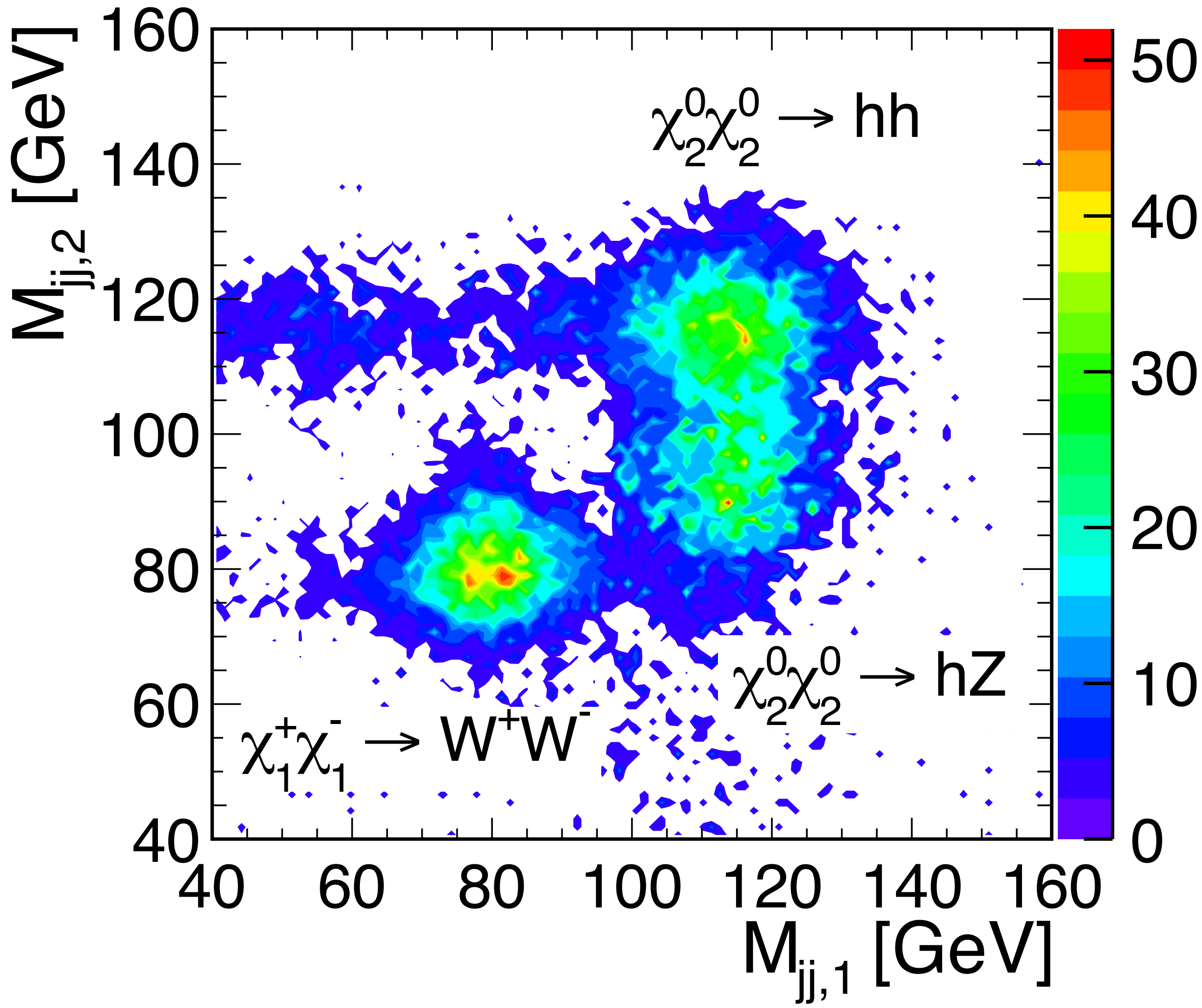
- A “classic” lepton collider measurement: electroweak particles with high mass

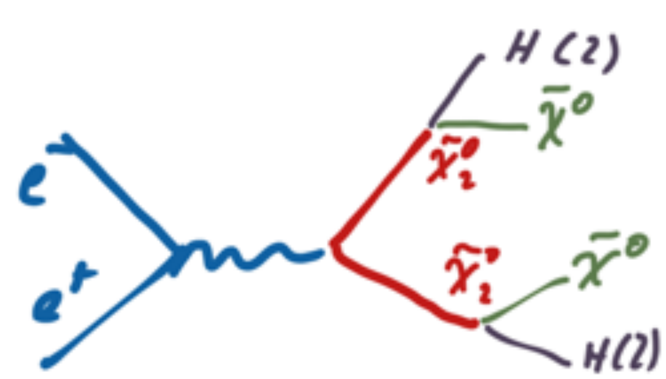
m_{smuon} = 1.01 TeV
$m_{neutralino}$ = 340 GeV

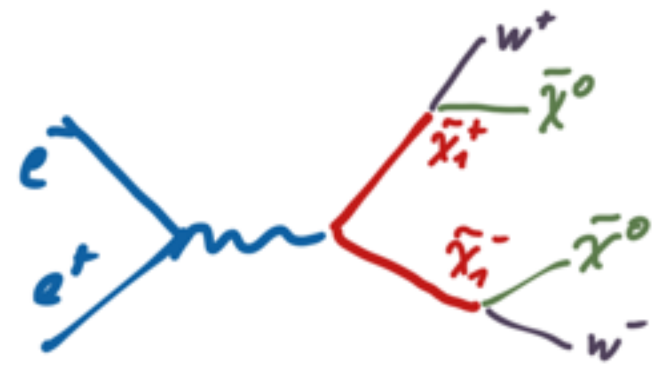
With 2 ab^{-1} at 3 TeV:
Δm_{smuon} = 5.5 GeV (stat)
$\Delta m_{neutralino}$ = 6.4 GeV (stat)

- Ideal “box shape” is distorted by luminosity spectrum (and momentum resolution)
- ▸ Requires knowledge of luminosity spectrum - can be precisely measured by reconstruction of Bhabha events. Resulting systematic uncertainty from spectrum parameter reconstruction ~ **40 MeV**, model biases < ~ 300 MeV

The Gaugino Sector







mass-degenerate charginos / neutralinos, $m_{gaugino}$ ~ 650 GeV (3 TeV benchmark)

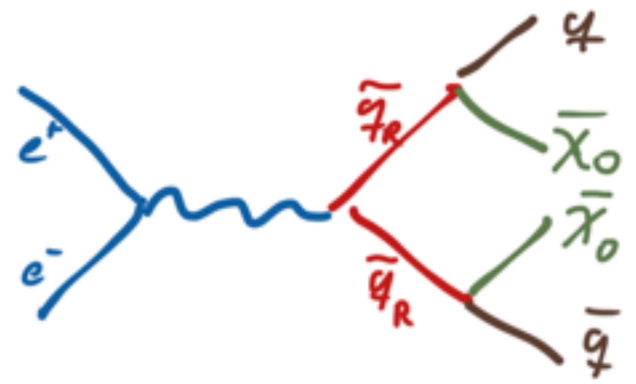
- A perfect test for jet energy reconstruction: Multi-jet final states of pairs of bosons and missing energy

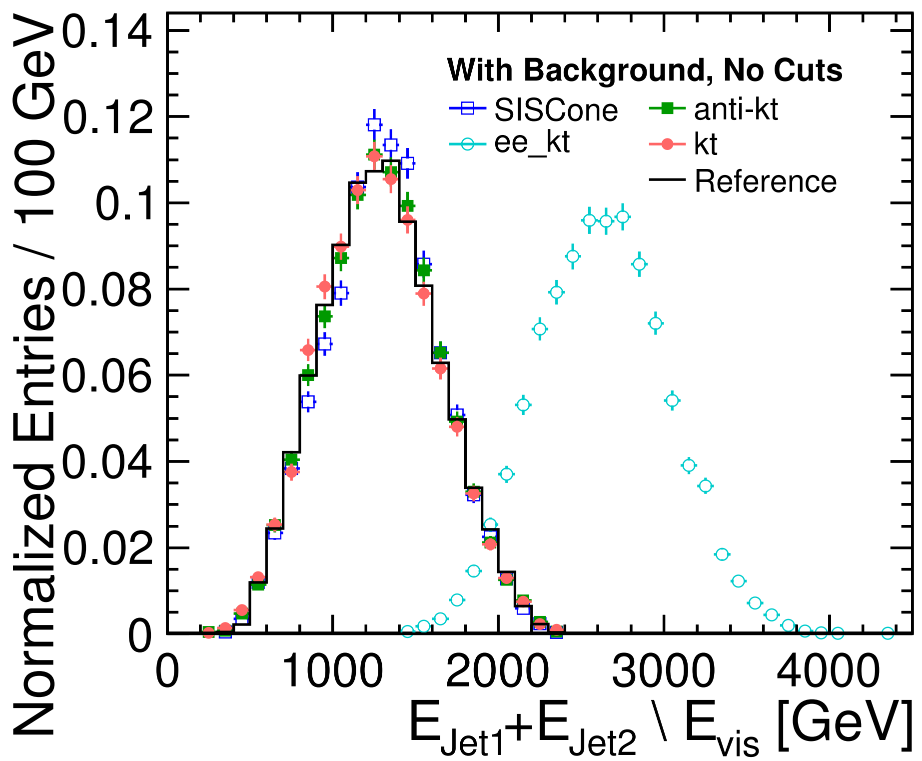
Mass measurement via template fit to reconstructed boson energy distribution (comparable in technique to slepton measurements, adapted to poorer energy resolution in hadronic final states)

$\Delta m_{gaugino}$ = ~ 6 - 7 GeV, Δm_{LSP} = 3 GeV (stat, m = 650 GeV)

TeV-Scale Squarks

- Light-flavored right-squarks at 1.1 TeV as a case for a high-energy, low jet-multiplicity final state with missing energy



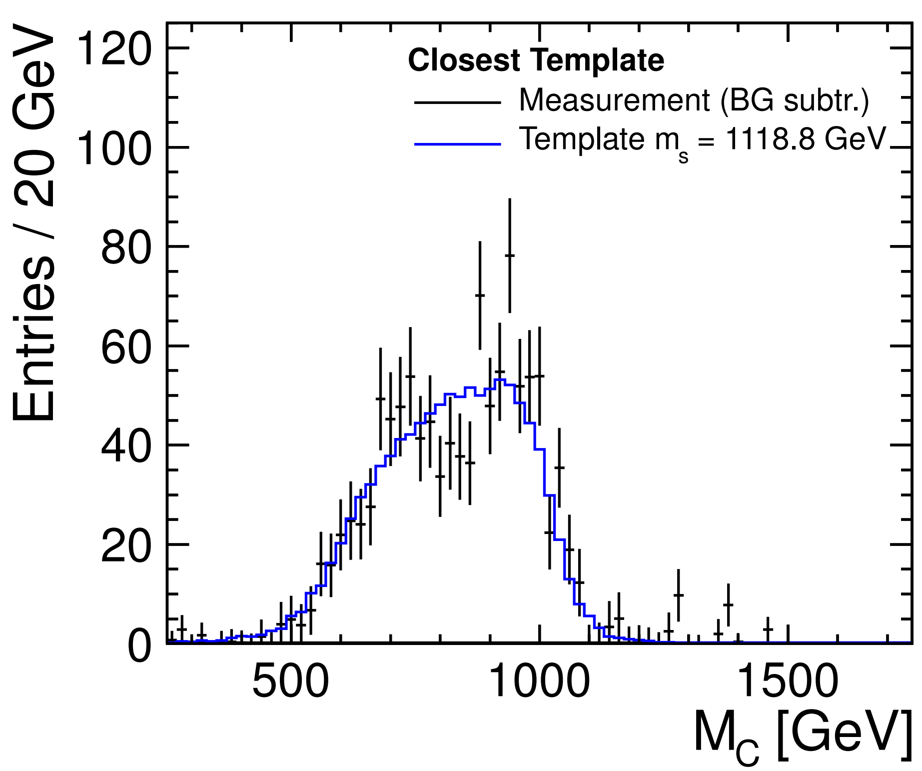


Stress-test jet finding in an environment with hadronic background: k_t algorithm (as used at LHC) provides substantially better performance than standard e^+e^- algorithms - now used as default for all linear collider (including ILC) studies

Mass measurement based on reconstructed energy of two final-state jets - needs neutralino mass as input

$$M_C = \sqrt{2(E_1E_2 + \vec{p}_1 \cdot \vec{p}_2)}$$

(no dependence on s)

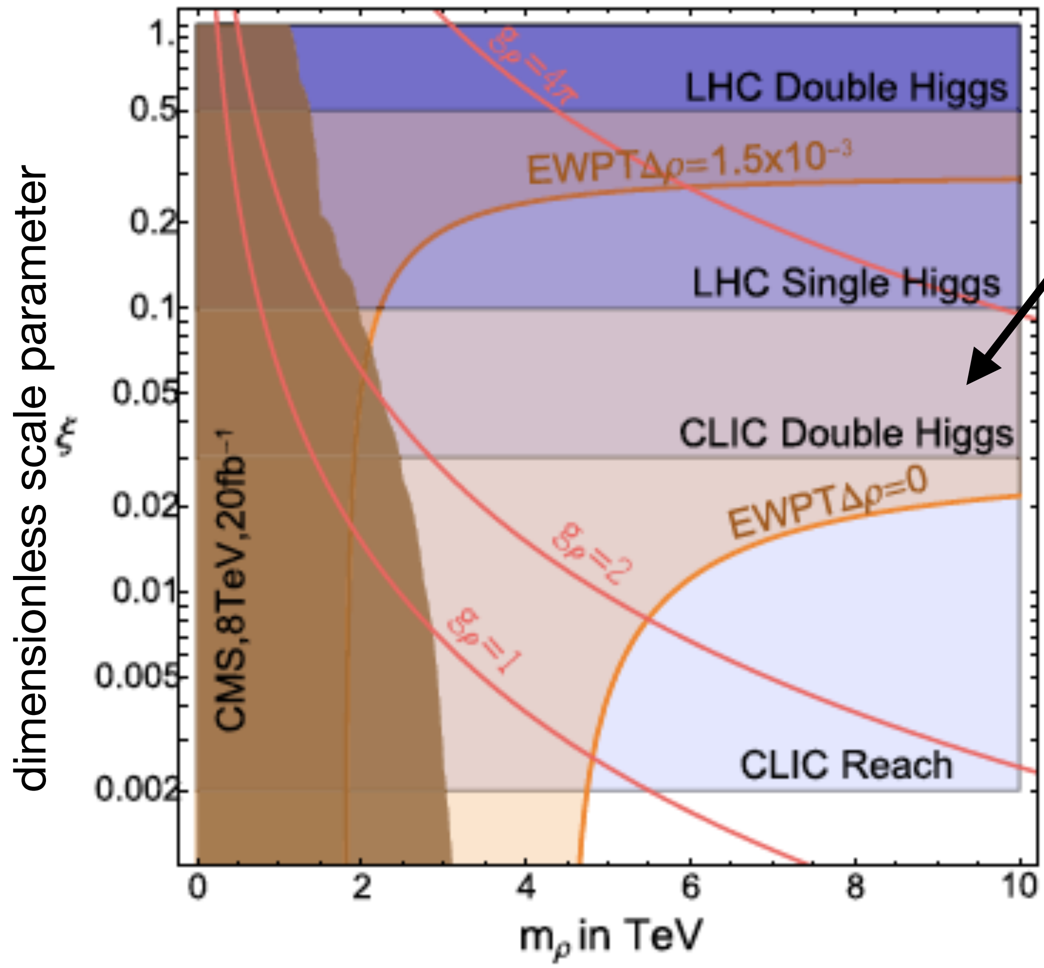


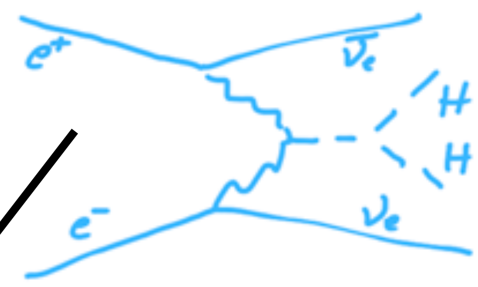
For m_s ~ 1.1 TeV: Δm ~ **6 GeV** (stat)

Indirect Sensitivity

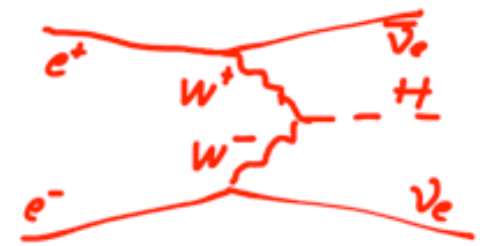
- Model-dependent search for New Physics by deviations in precision observables

Higgs Compositeness





further sensitivity boost:

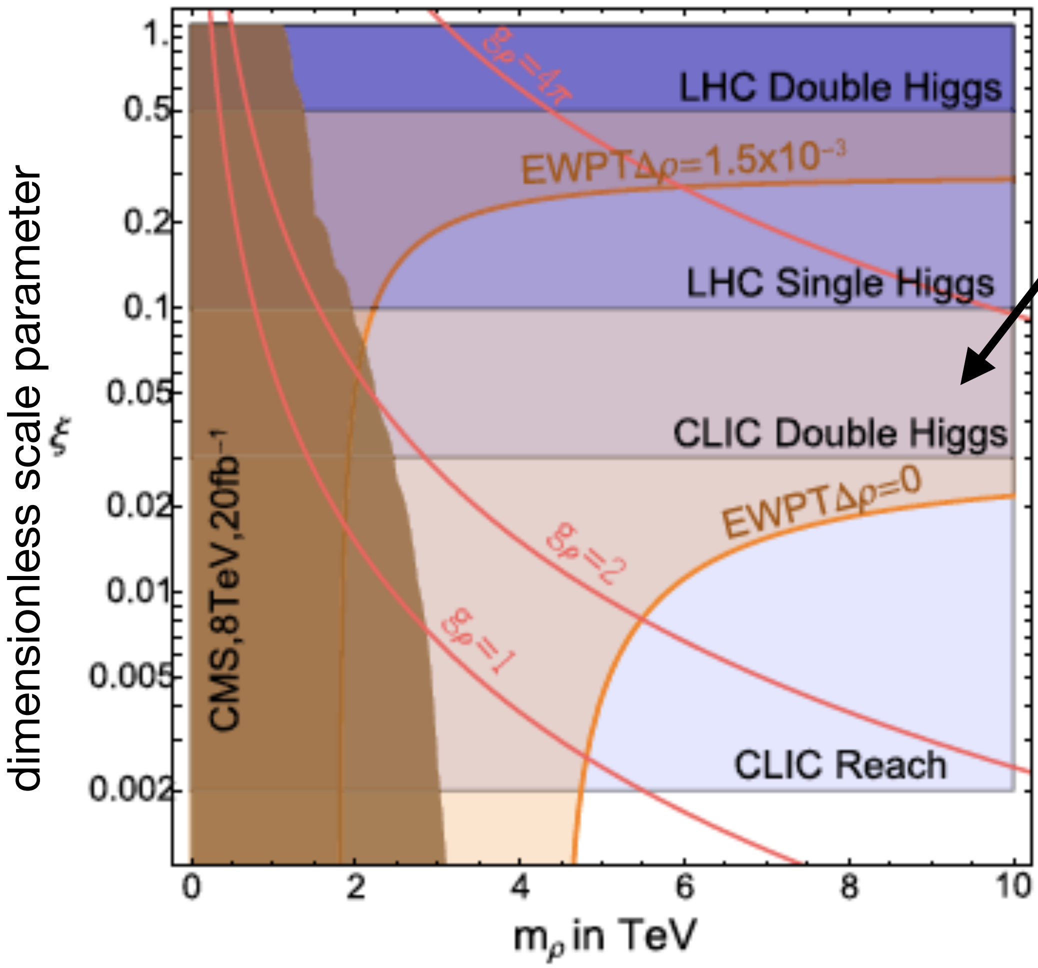


70 TeV reach for compositeness scale with 2 ab^{-1} @ 3 TeV using single and double Higgs production

Indirect Sensitivity

- Model-dependent search for New Physics by deviations in precision observables

Higgs Compositeness



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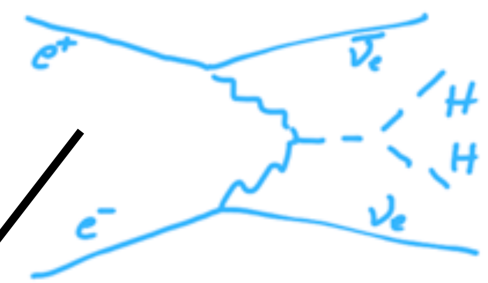
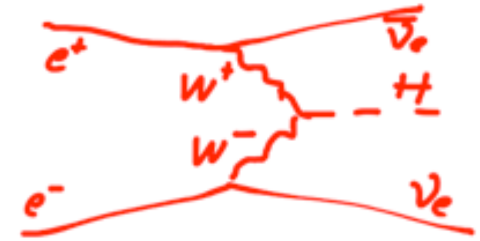
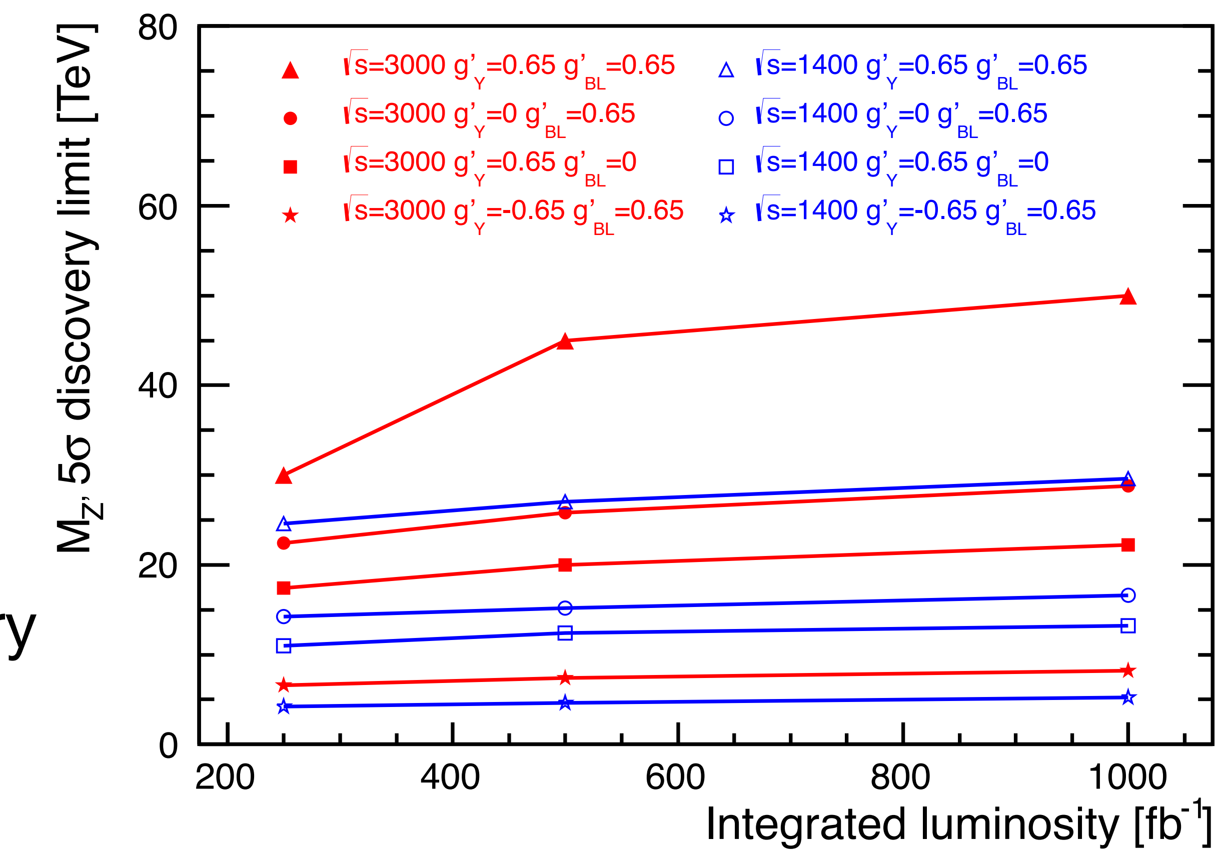




70 TeV reach for compositeness scale with 2 ab^{-1} @ 3 TeV using single and double Higgs production



Sensitivity to high-mass Z':
Cross section and forward-backward asymmetry in e^+e^- -> $\mu^+\mu^-$ with polarized electrons
Sensitivity up to 50 TeV with 1 ab^{-1} @ 3 TeV

BSM Sensitivity - Summary

- CLIC combines a large mass reach for new particles with the capabilities for precision measurements:
  - Mass reach close to $\sqrt{s}/2$ for strongly and electroweakly interacting particles (for example squarks, sleptons)
  - Mass measurements on the % level or better for most particles in accessible SUSY scenarios

- Indirect sensitivity to a large variety of new physics at high scales beyond direct reach:
  - Higgs compositeness scale ~ 70 TeV
  - Z’ (SM couplings) ~ 20 - 50 TeV
  - 2 extra dimensions M_D ~ 20-30 TeV
  - …

Summary and Outlook

- The CLIC physics program
  - Extends and complements the LHC program
    - Precision measurements & model-independence beyond the capability of hadron colliders
    - Complementary sensitivity to New Physics - reach to high mass scales
  - Maximized physics potential by a staged construction:
    - ~ **350 GeV**: Higgs (model-independent couplings) & Top
    - ~ **1.5 TeV**: BSM, Higgs - rare decays, top Yukawa, (self-coupling)
    - ~ **3 TeV**: BSM, Higgs - rare decays, self-coupling

- The physics potential and the experimental capabilities have been demonstrated with full simulations including machine-induced and physics backgrounds

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- The physics potential and the experimental capabilities have been demonstrated with full simulations including machine-induced and physics backgrounds

CLIC is an exciting and realistic option for a future collider at the energy frontier!

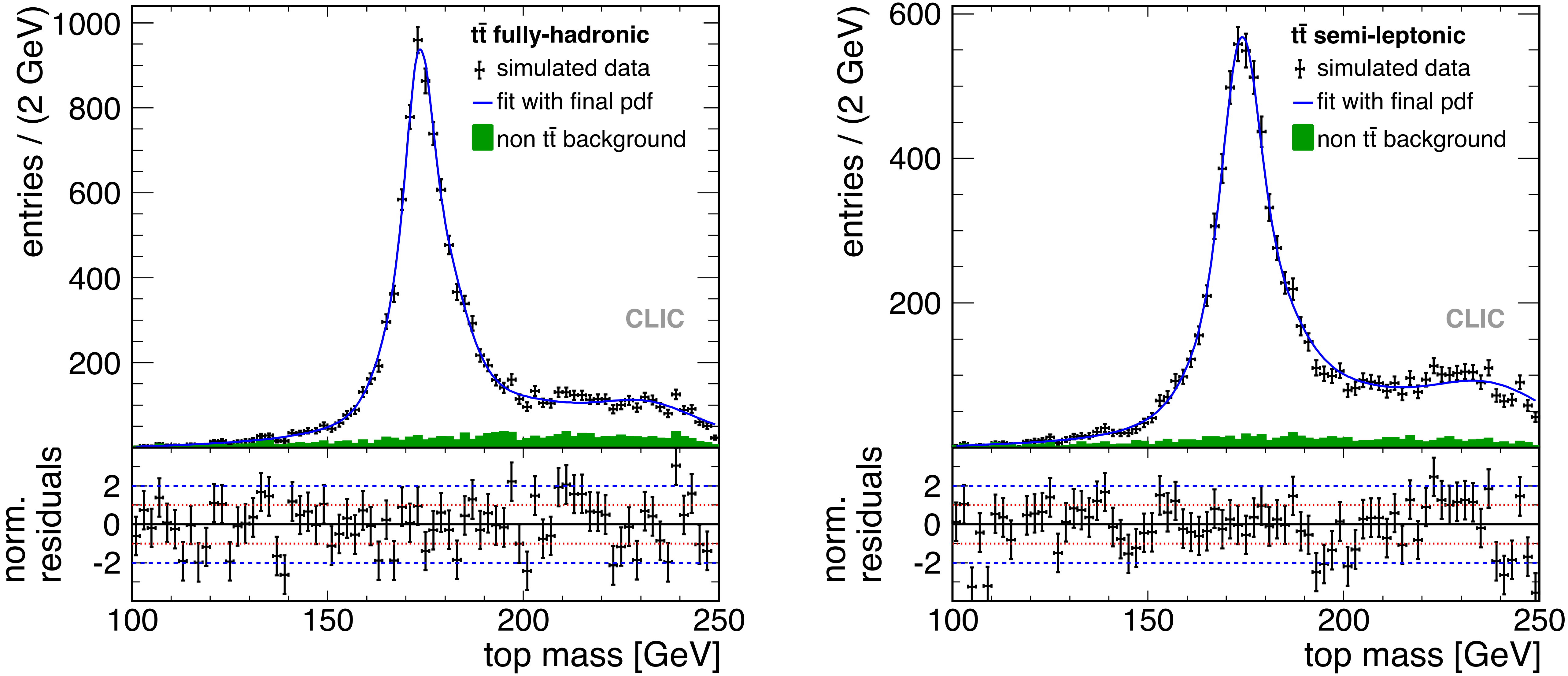
Backup

CLIC SUSY Benchmark Performance

Table 9: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [24, 25, 26, 27, 28, 29, 30].

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
	Neutralino	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
	Neutralino	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

Mass Reconstruction Above Threshold

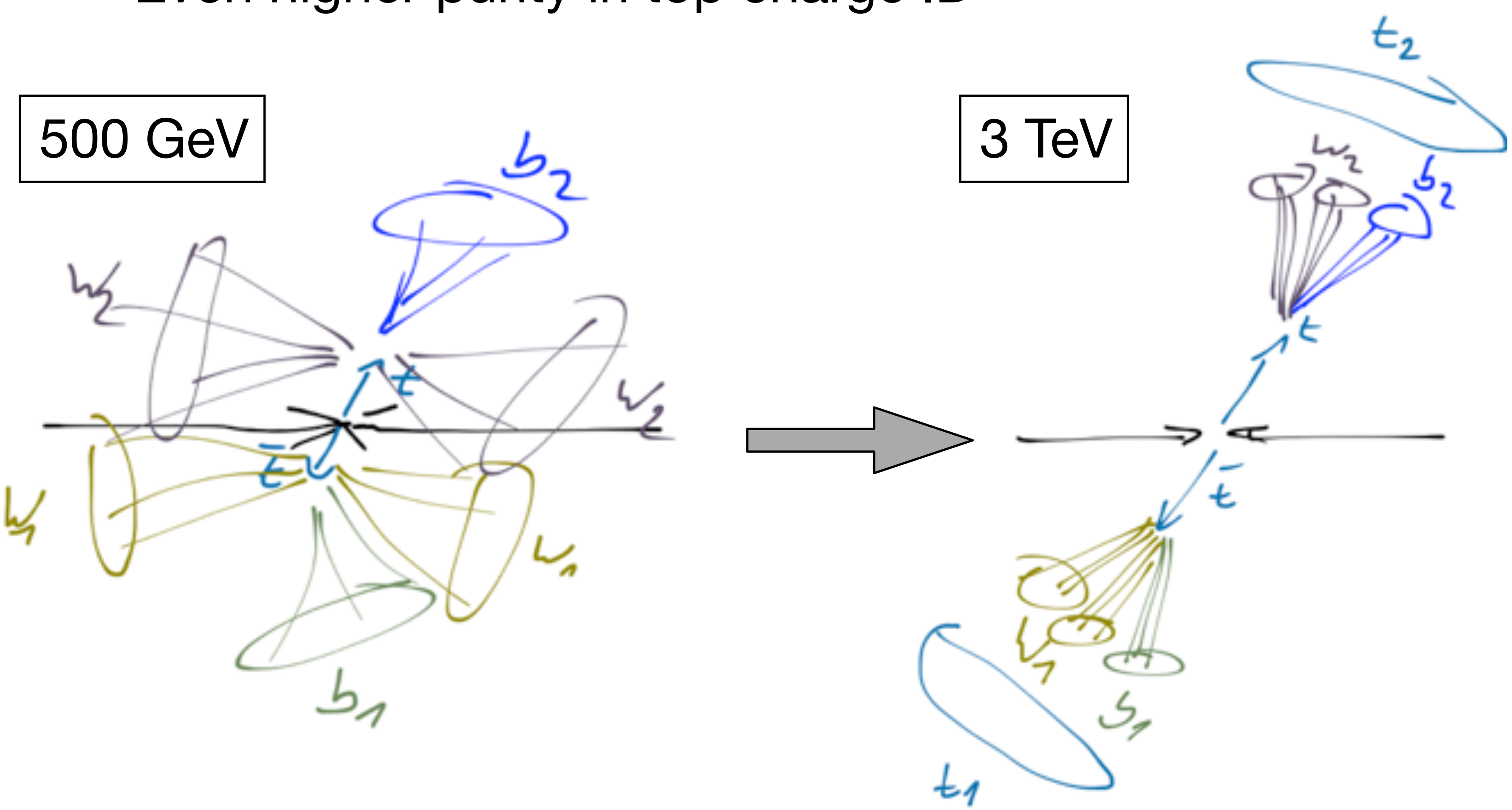


- Width less constrained than mass: substantial detector effects (peak width ~ 5 GeV compared to 1.4 GeV top width)

channel	m_{top}	Δm_{top}	Γ_{top}	$\Delta\Gamma_{top}$
fully-hadronic	174.049	0.099	1.47	0.27
semi-leptonic	174.293	0.137	1.70	0.40
combined	174.133	0.080	1.55	0.22

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