Overview of New Physics Studies for CLIC

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on behalf of the CLIC Detector and Physics Study

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Outline

- Overview - BSM Studies at CLIC
- CLIC in Stages
- Making Measurement at CLIC
- Direct BSM Measurements
- Indirect Sensitivity in Precision Measurements
- Summary

References

- Brau et al., The physics case for an e^+e^- linear collider, arXiv:1210.0202
- CLIC CDR (#1), A Multi-TeV Linear Collider based on CLIC Technology, https://edms.cern.ch/document/1234244/
- CLIC CDR (#2), Physics and Detectors at CLIC, arXiv:1202.5904
- CLIC CDR (#3), The CLIC Programme: towards a staged e^+e^- Linear Collider exploring the Terascale, arXiv:1209.2543

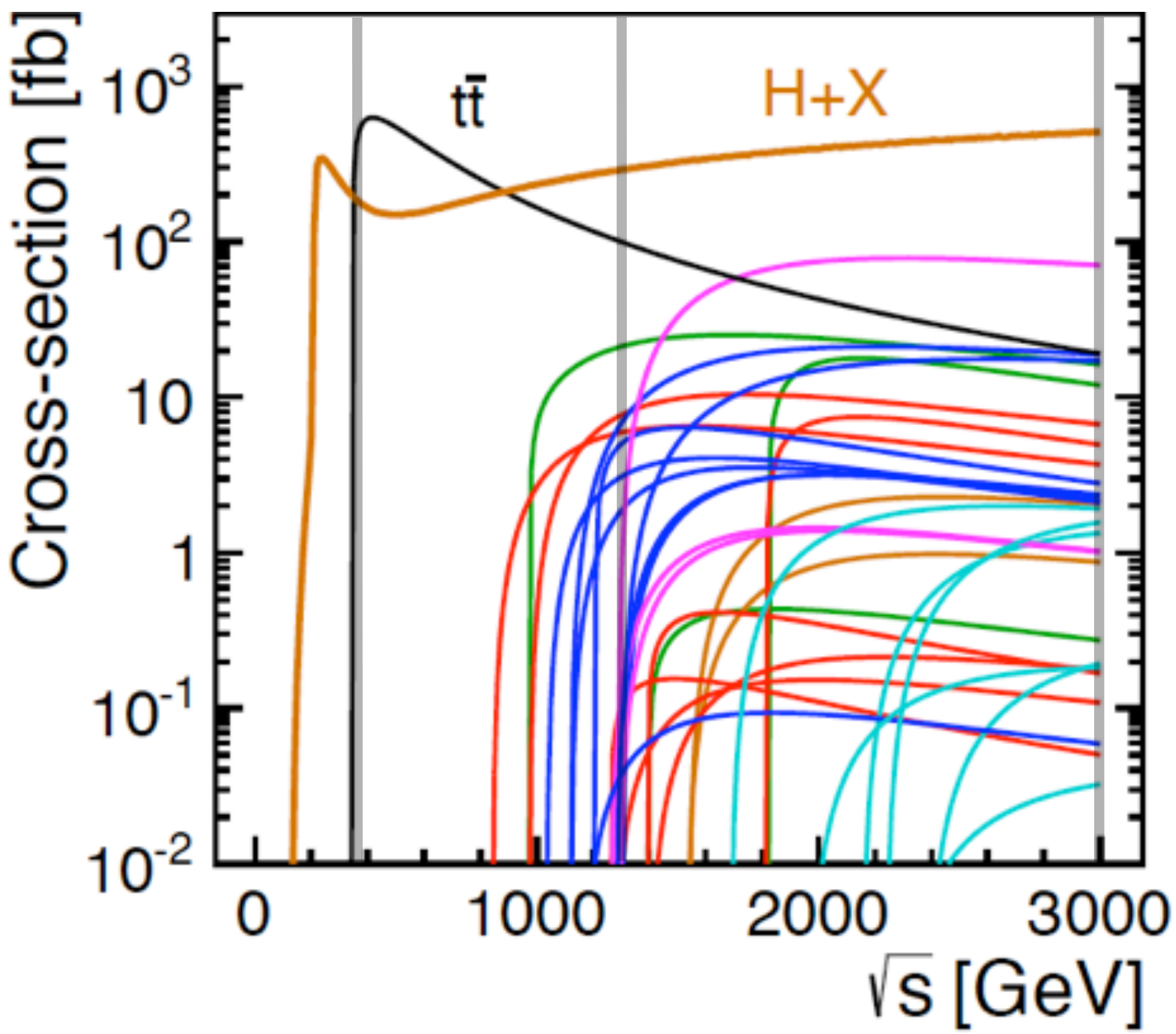
Overview - BSM Studies at CLIC

- We have many good reasons to expect New Physics in the TeV region - but up to now we have not seen anything: The energy scale and the nature of this New Physics is up to speculation
- Looked at two well-motivated scenarios:
  - SUSY - different models studied in the CDR phase, some are now under pressure from LHC
  - Indirect searches for a high-mass Z'

Many of the signatures studied are rather generic - even if a particular model gets excluded the results serve as an illustration of CLIC capabilities for a much wider range of searches.

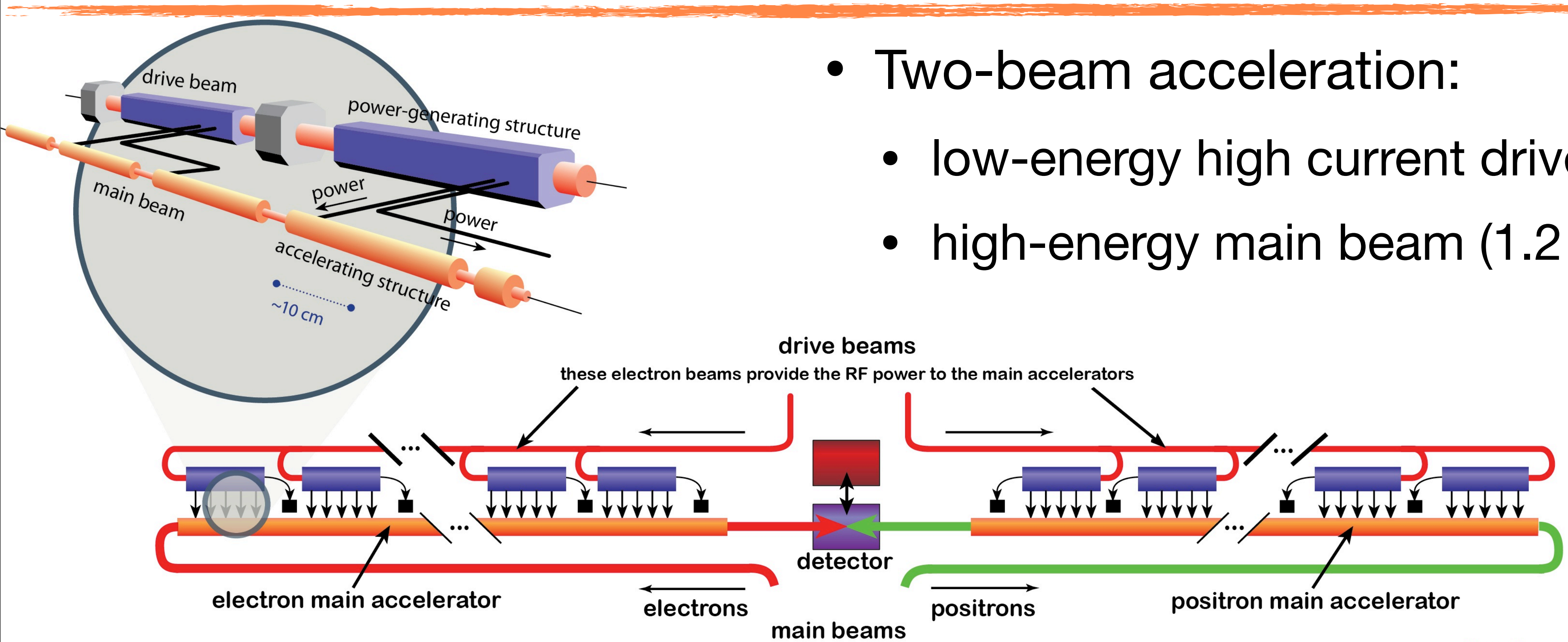
CLIC - A Staged Machine

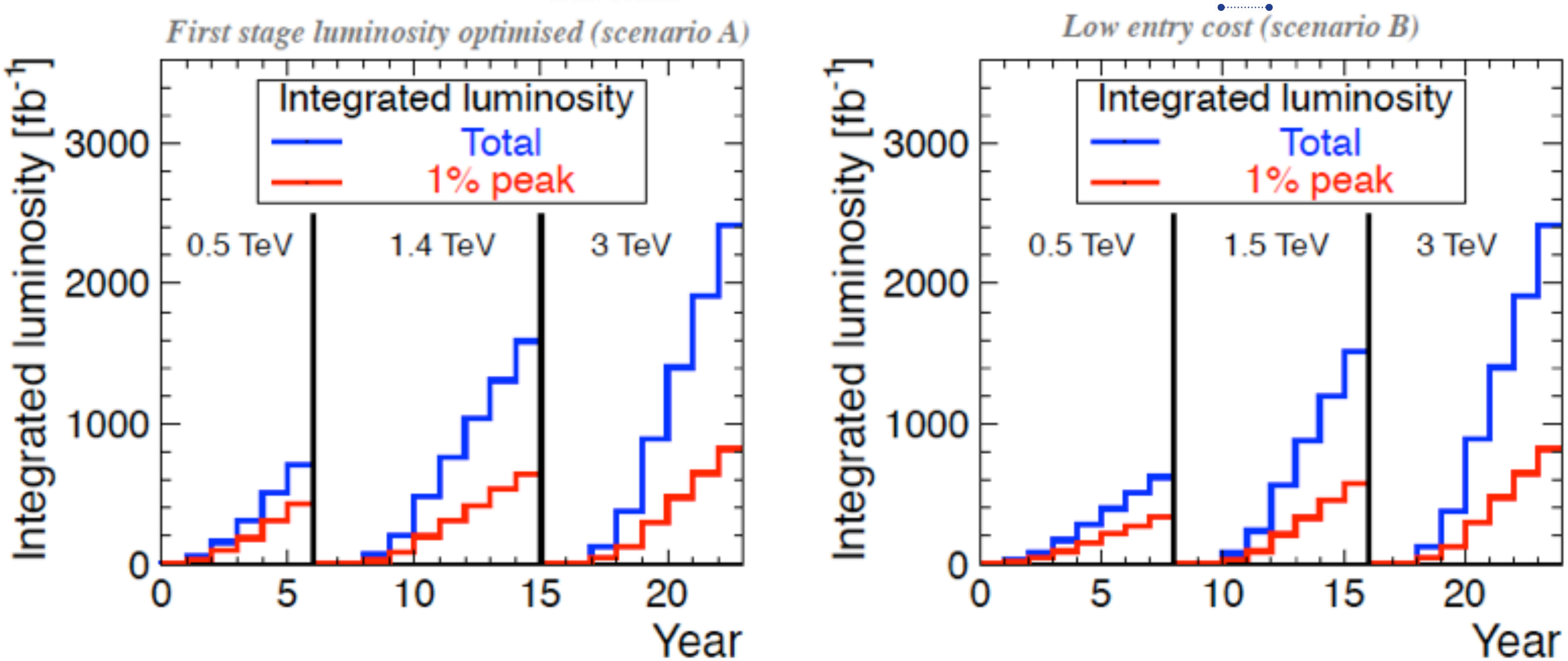
- CLIC will be implemented in stages: Optimized running conditions over a wide energy range
  - The best choice for the stages is defined by physics, with some additional technical considerations
    - May change with additional discoveries
- The current view: Three stages
  - 375 GeV, 500 fb^{-1},
    Focus on Higgs and Top
  - 1.4 TeV, 1.5 ab^{-1}
    BSM measurements - largest opportunities in weak sector
  - 3 TeV, 2 ab^{-1}
    Highest energy to maximize physics reach



CLIC - The Accelerator

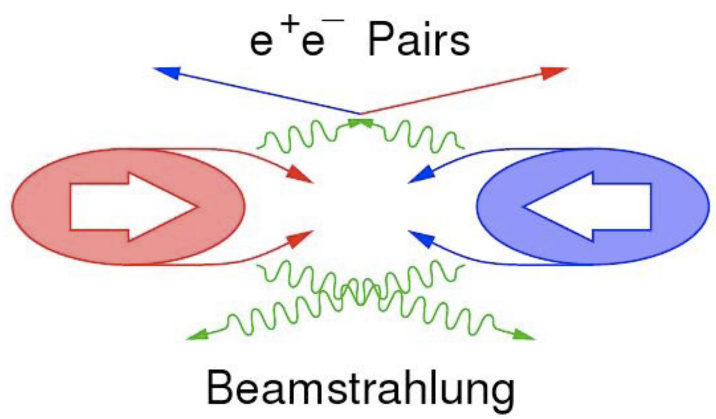
- Two-beam acceleration:
  - low-energy high current drive beam (2.4 GeV, 100 A)
  - high-energy main beam (1.2 A, 9 GeV - 1.5 TeV)



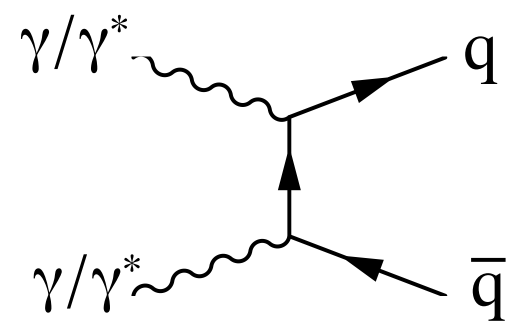


Making Measurements at CLIC - Environment

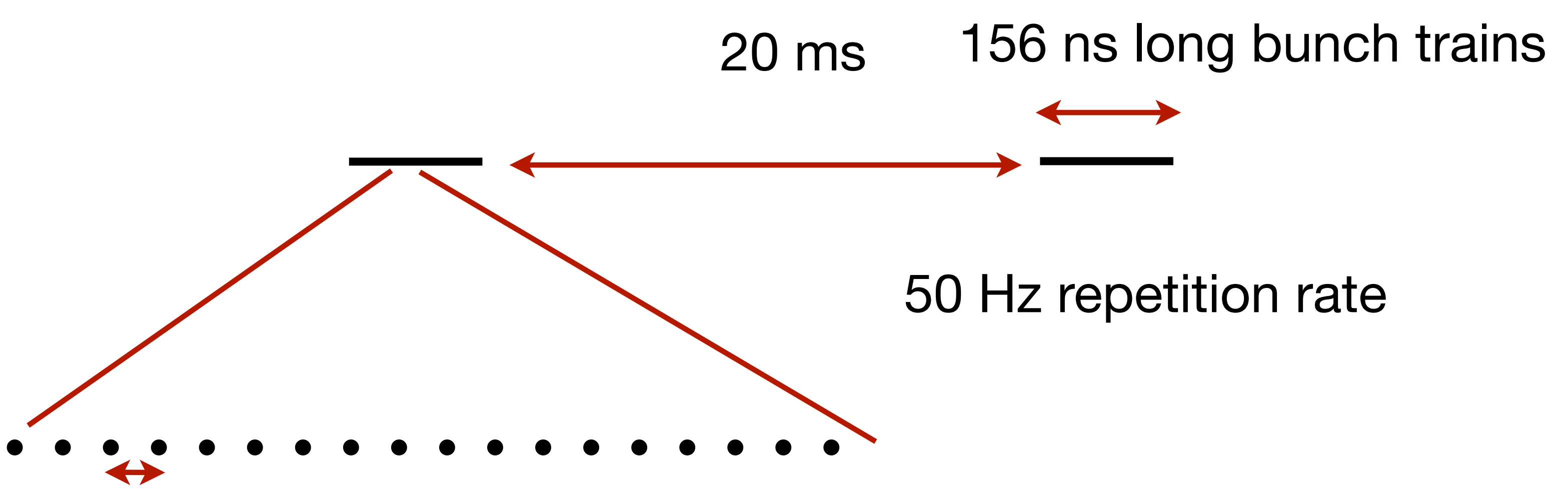
- The main challenge: High energy and high luminosity leads to high rates of photon-induced processes:



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



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

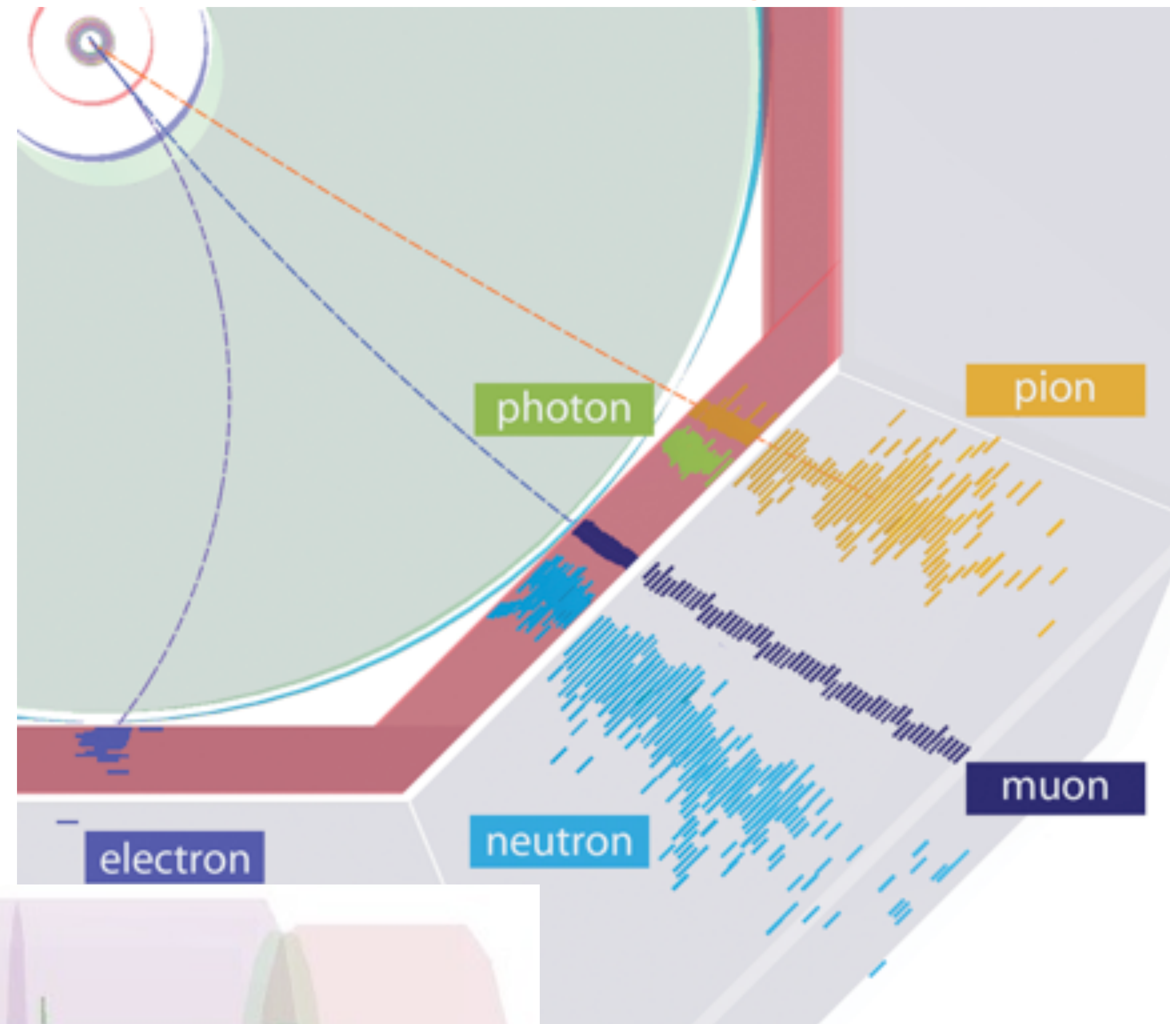


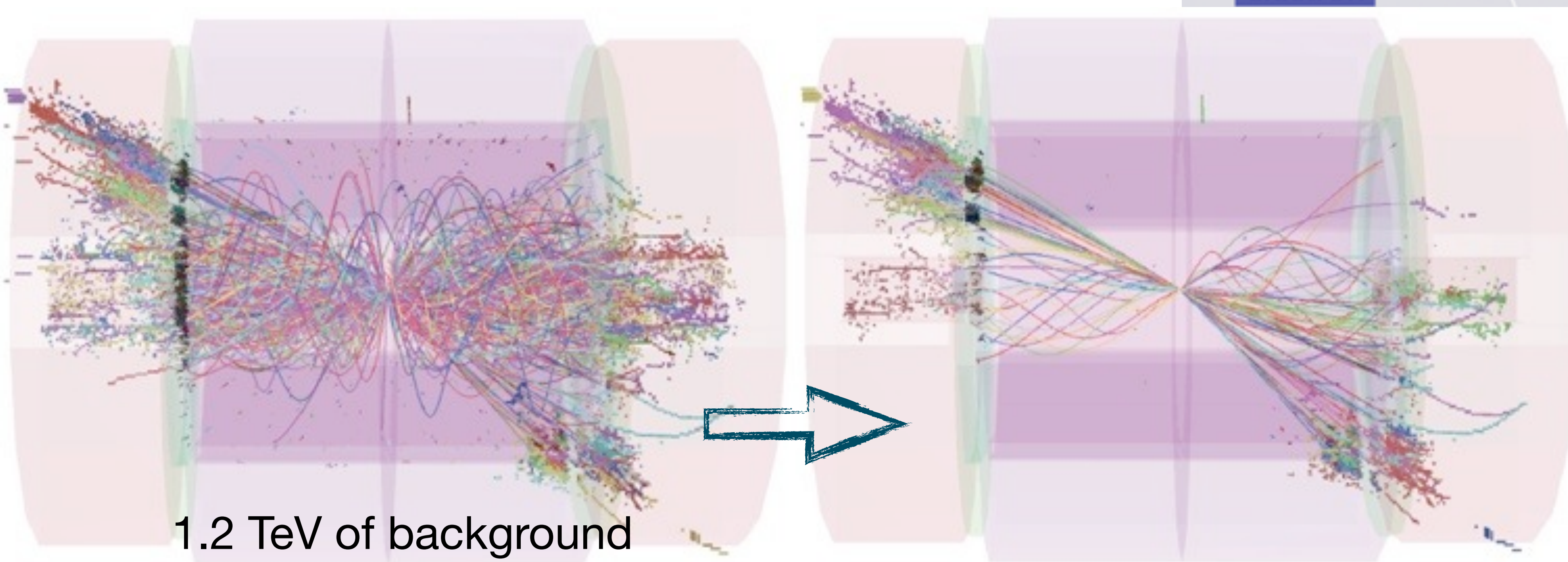
0.5 ns bunch to bunch spacing
312 bunches per train

Combined with bunch structure:
Pile-up of hadronic background:
~ 19 TeV in HCAL / bunch train
⇨ Needs to be rejected by reconstruction

Making Measurements at CLIC - Reconstruction

- 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



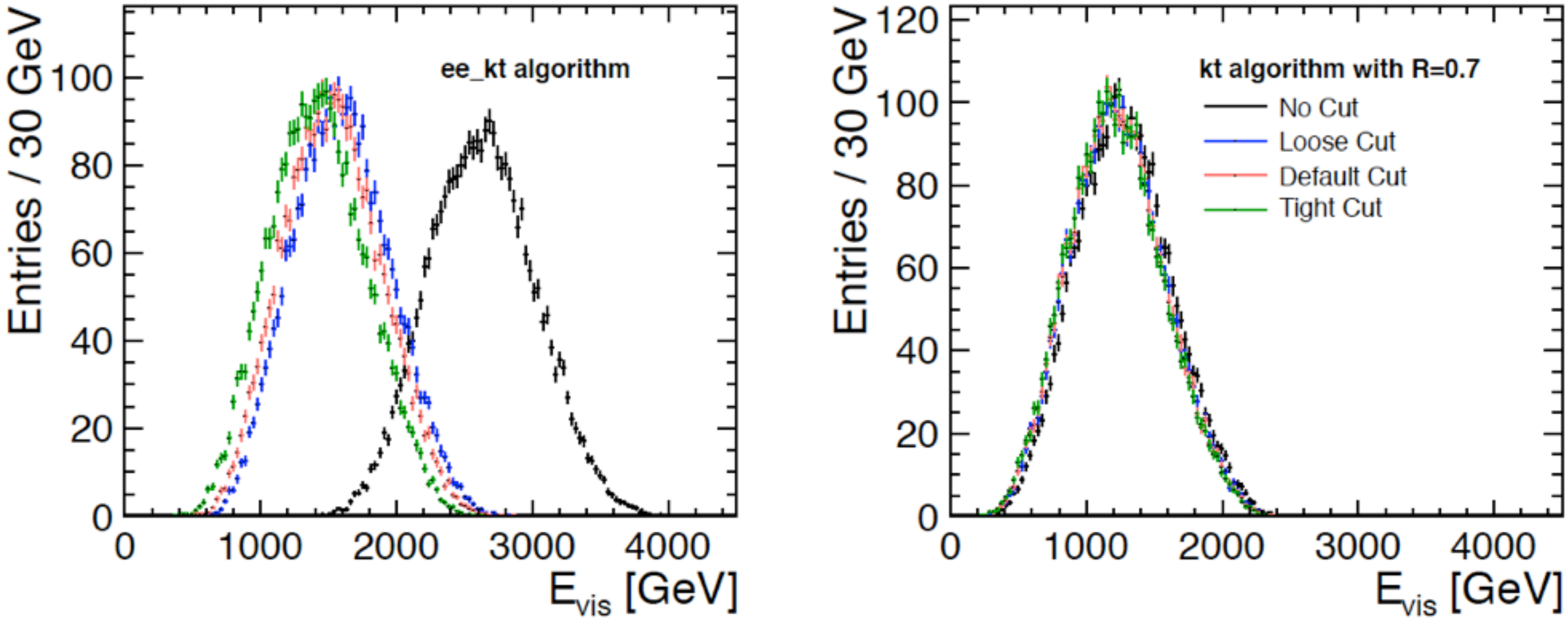


$$e^+e^- \rightarrow t\bar{t} \text{ @ } 3 \text{ TeV}$$

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

Mitigating Background: Jet Reconstruction

- Jet finding crucial for many analyses - and jets are particularly susceptible to γγ -> hadrons background
- Jet algorithms from hadron colliders (beam jets, η instead of θ) robust against forward-going background particles - Also well-suited for ILC!



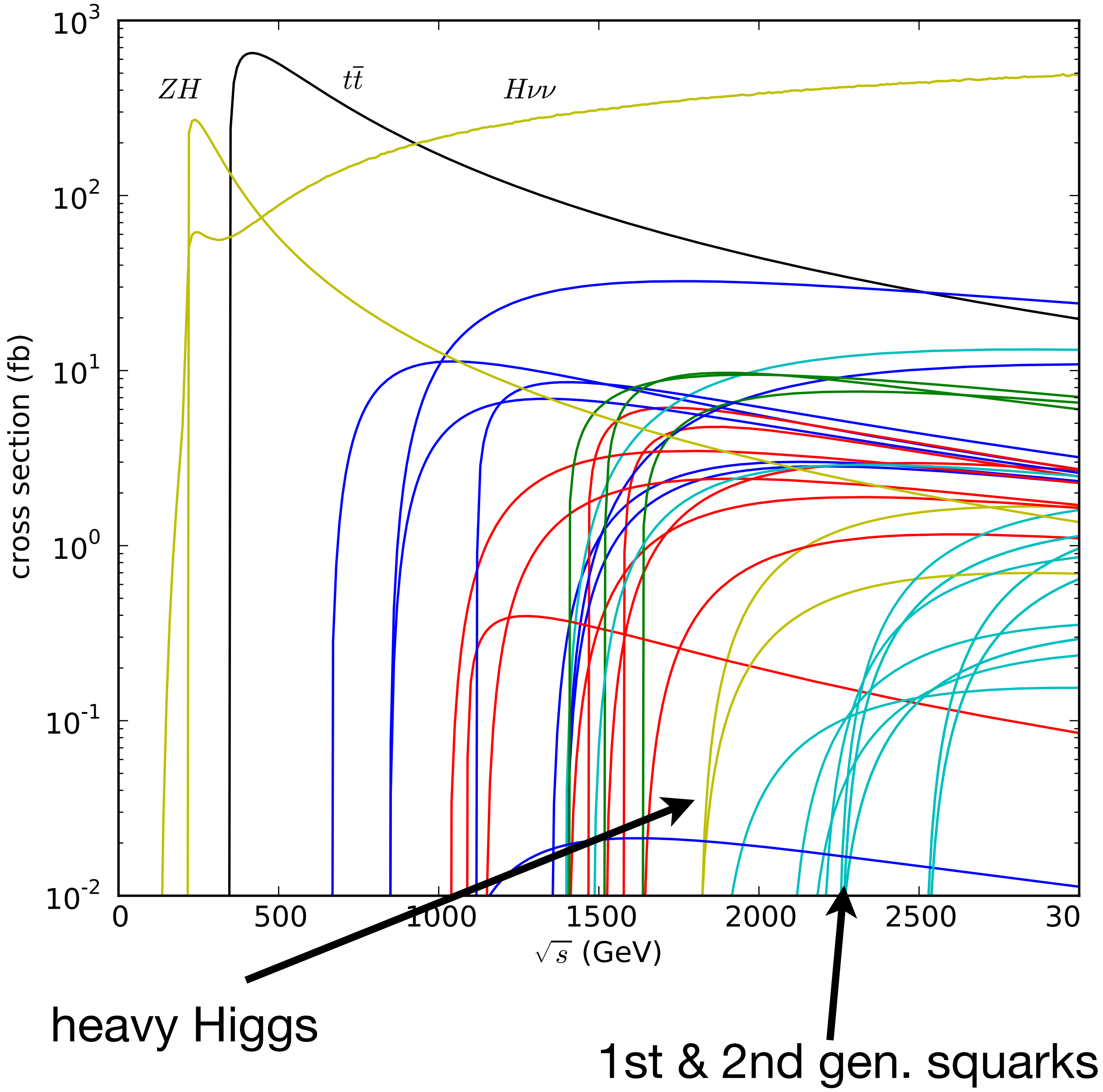
example from TeV-scale squark production at 3 TeV

SUSY Studies

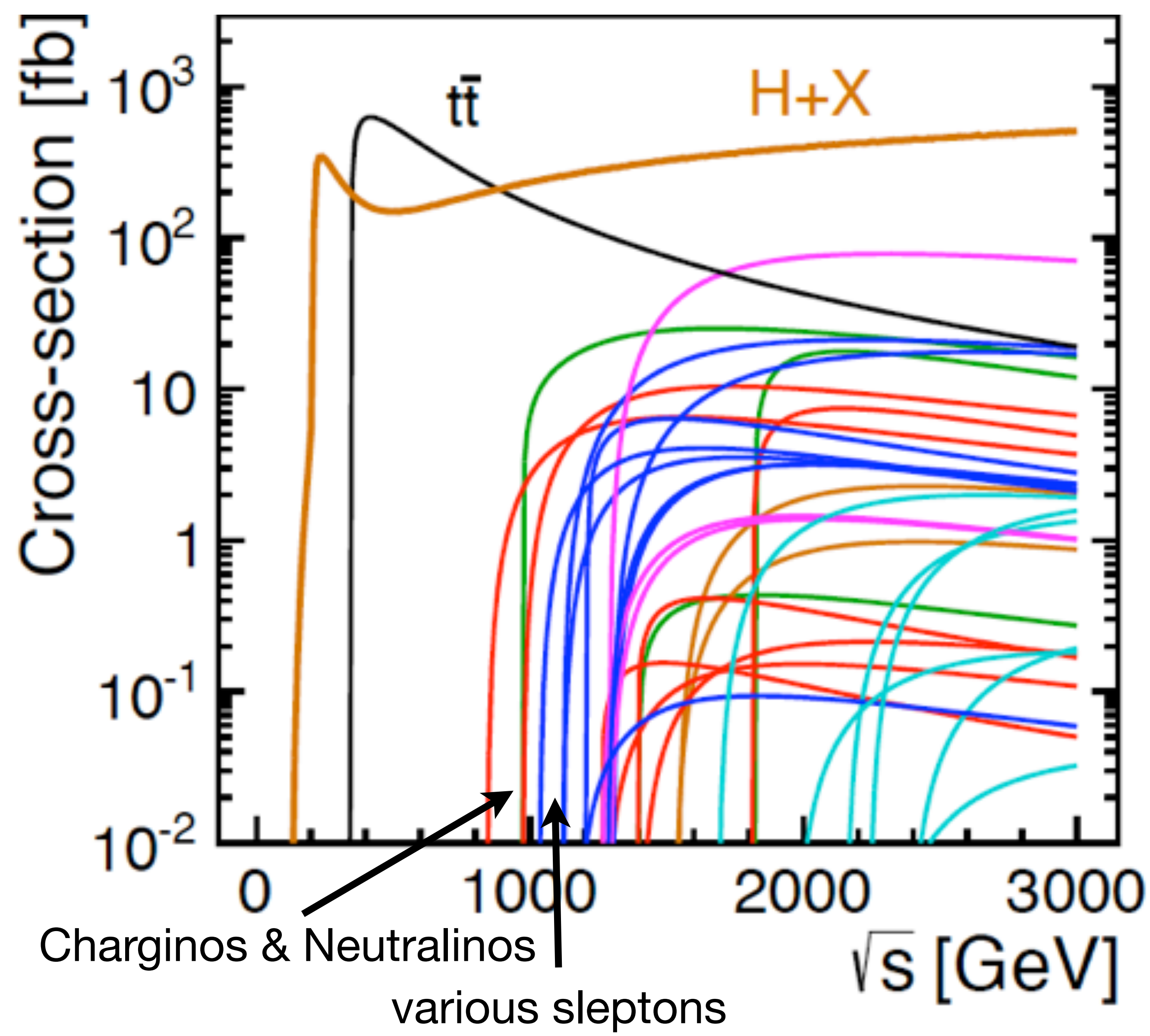
- Three different models have been investigated, selected to show performance for various different physics channels and at different energies

  Two examples:

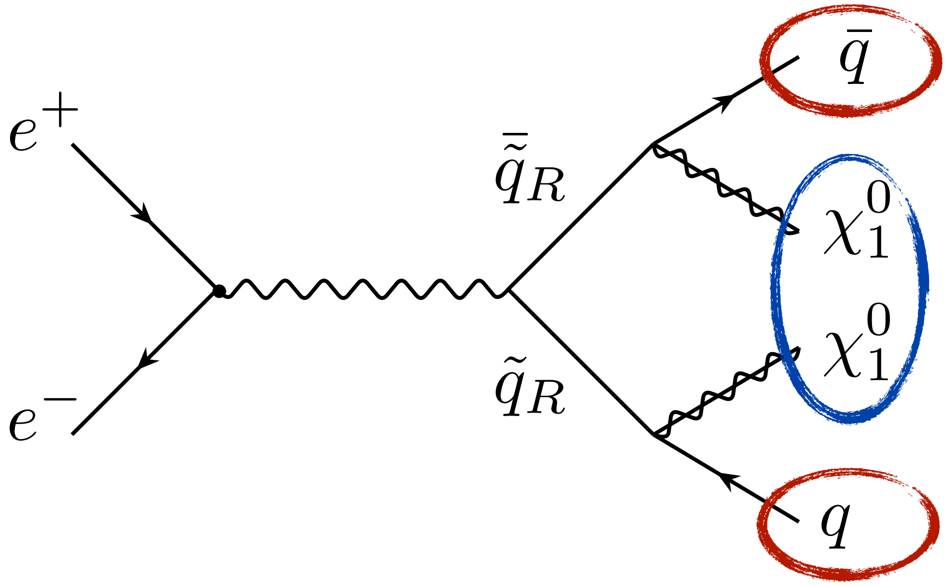
"Model 1" ➯ 3 TeV



"Model 3" ➯ 1.4 TeV



Light-flavored Squarks @ 3 TeV



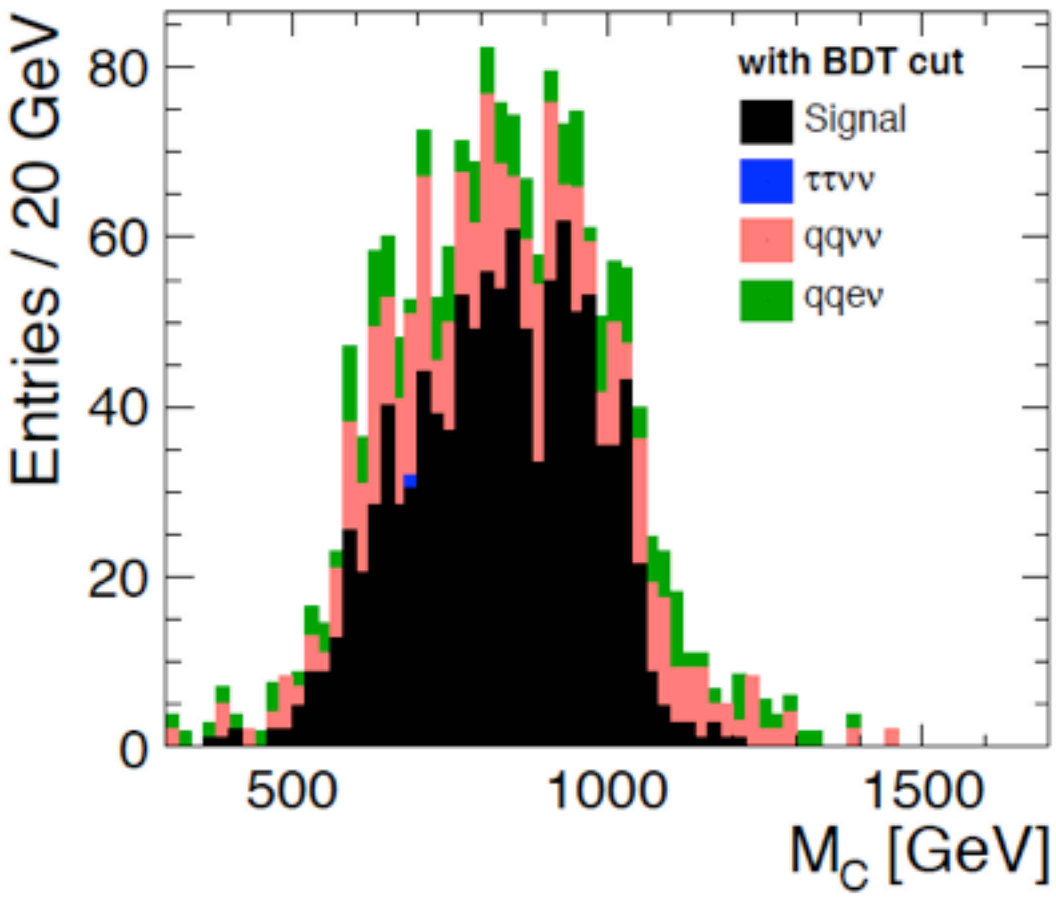
- Very generic new physics signature: **Two jets** + **missing energy**
- The concrete model:
  - Right-squark mass (u,d,s,c): 1.12 TeV
  - Neutralino mass: 330 GeV

Main analysis challenge: Low cross-section 1.5 fb, background 10^4 higher

Signal selection based on BDTs, requirement of MET

Mass measurement using M_C: independent of s, systematics from luminosity spectrum negligible

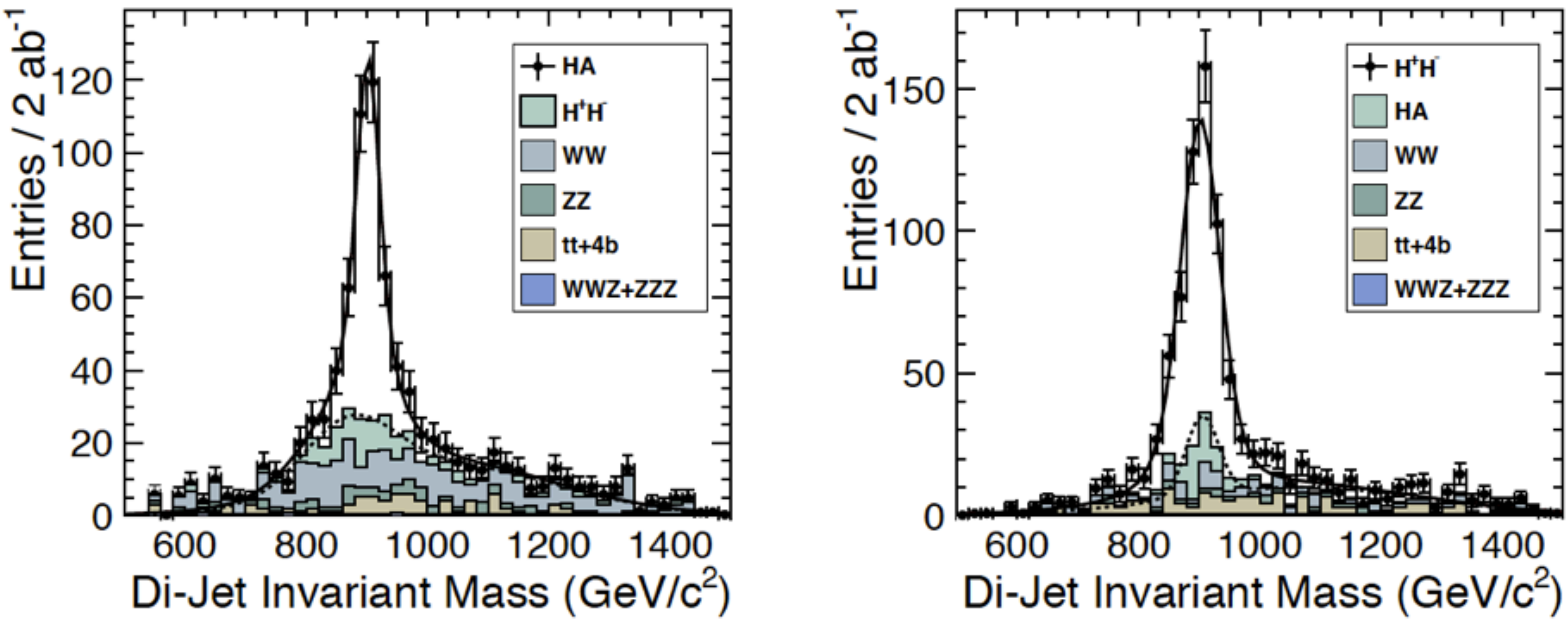
$$M_C = \sqrt{2(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2)}$$



Mass with a template fit: 0.5% (6 GeV) uncertainty

Probing Heavy SUSY Higgs @ 3 TeV

- Spectacular final states: four b-jets, and two tops + two b jets (8 jet final state)
  - The model: Mass scale for neutral and charged heavy Higgs H^0, A, $H^{\pm}$: 900 GeV

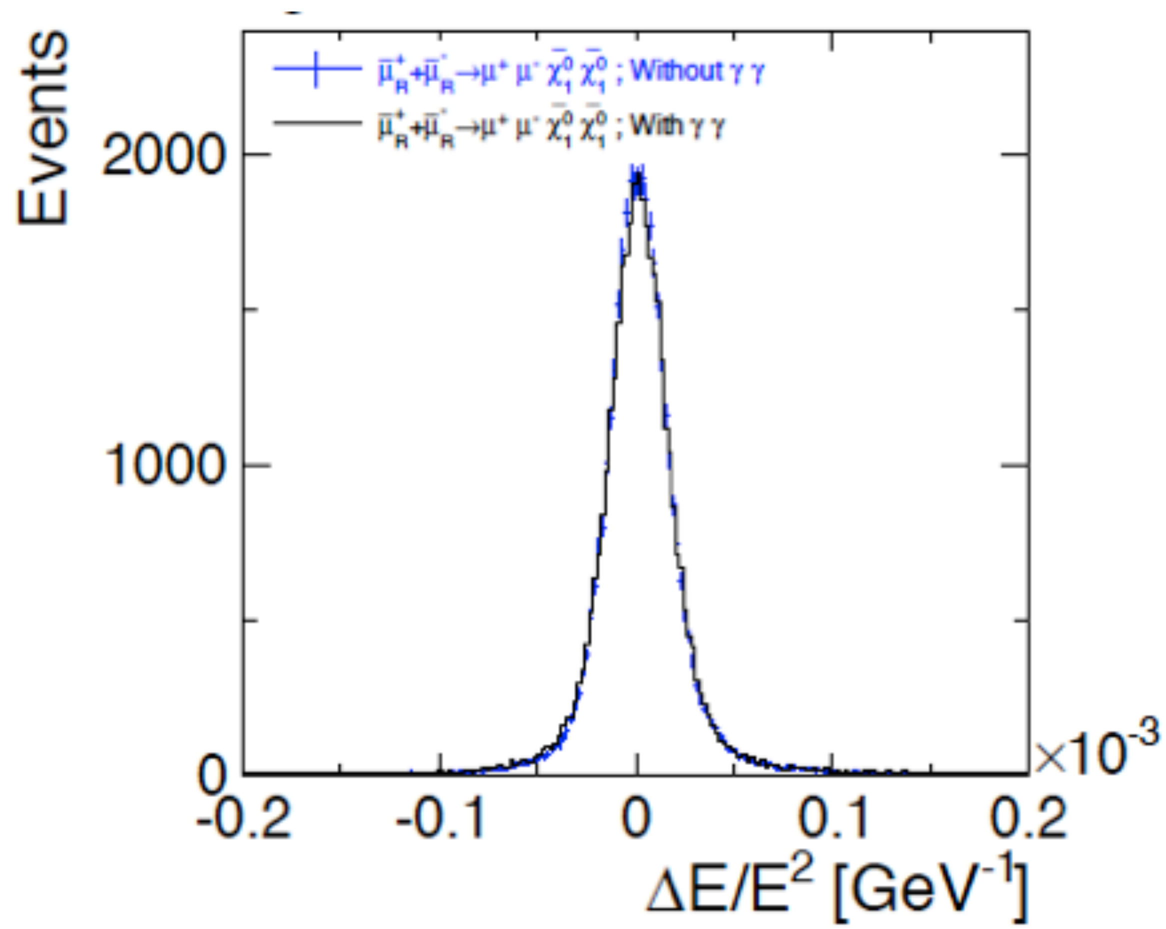


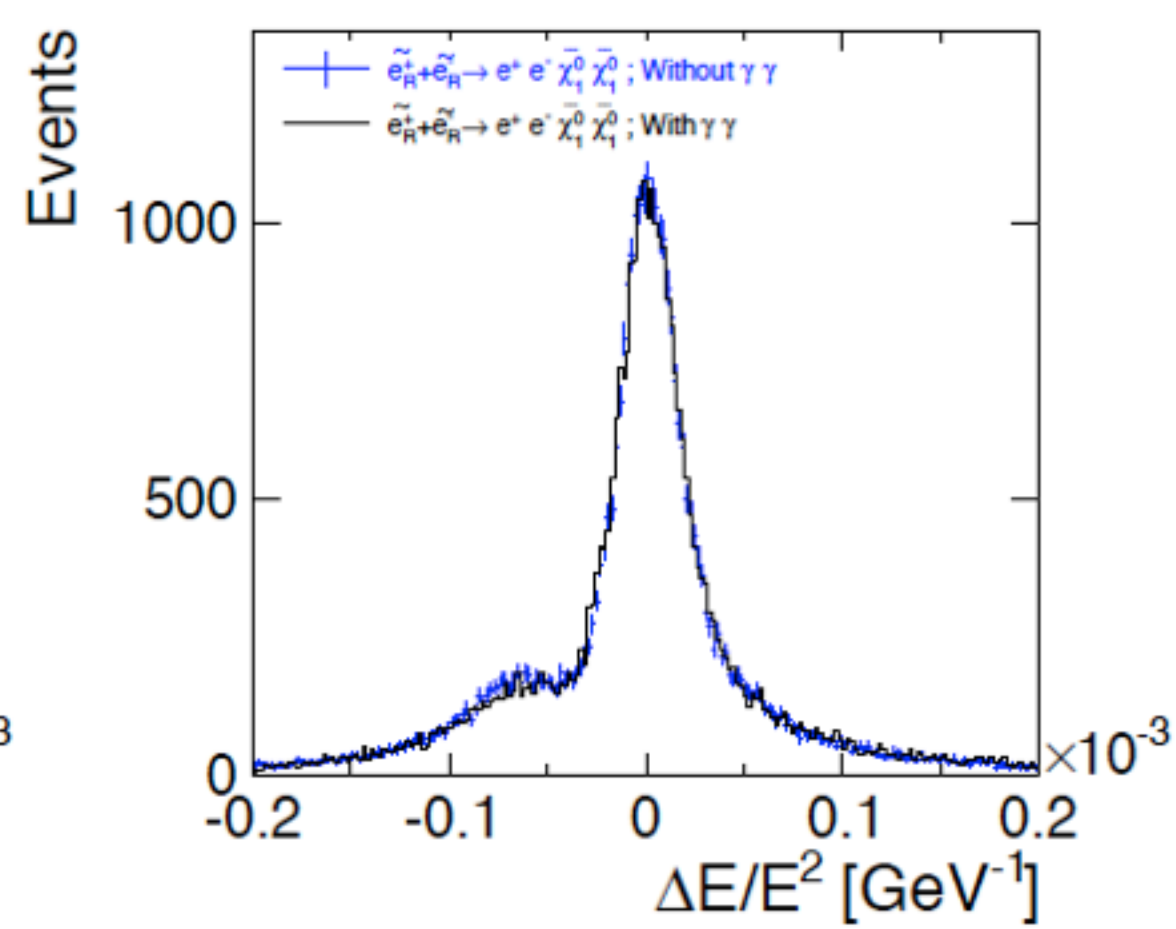
(a) $e^+e^- \rightarrow b\bar{b}b\bar{b}$ (b) $e^+e^- \rightarrow t\bar{b}b\bar{t}$

Masses can be determined with a statistical precision of 0.3% (2 GeV), the width on the 20% level (6 GeV)

1^{st} & 2^{nd} Generation Sleptons @ 1.4 TeV

- A classic measurement at lepton colliders: Excellent sensitivity
- Electron and muon final states easy to reconstruct also in CLIC environment:



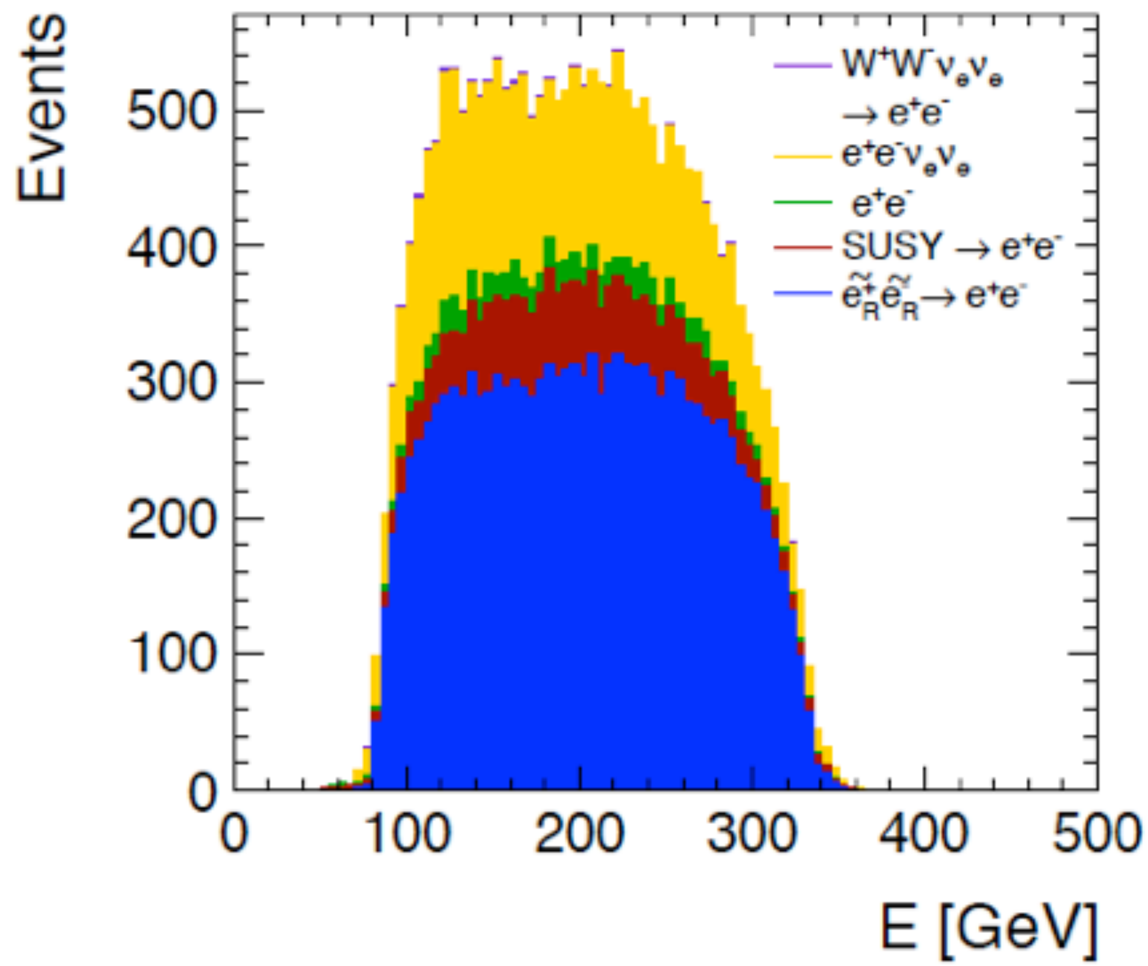


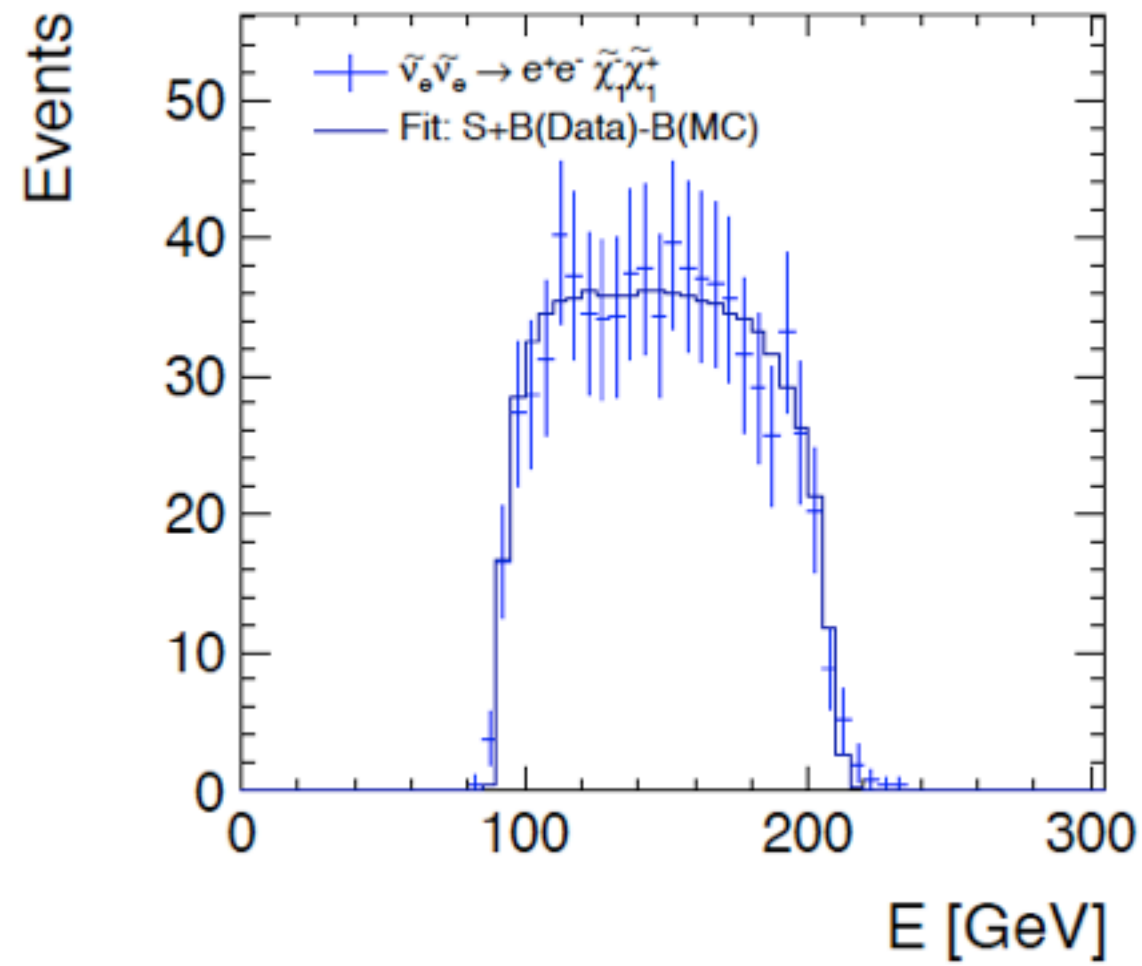
Studied Processes

$$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$
$$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$
$$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e \to e^+e^-\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \to e^+e^-W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

masses:
charged sleptons: 560 GeV
sneutrinos: 644 GeV

1st & 2nd Generation Sleptons @ 1.4 TeV





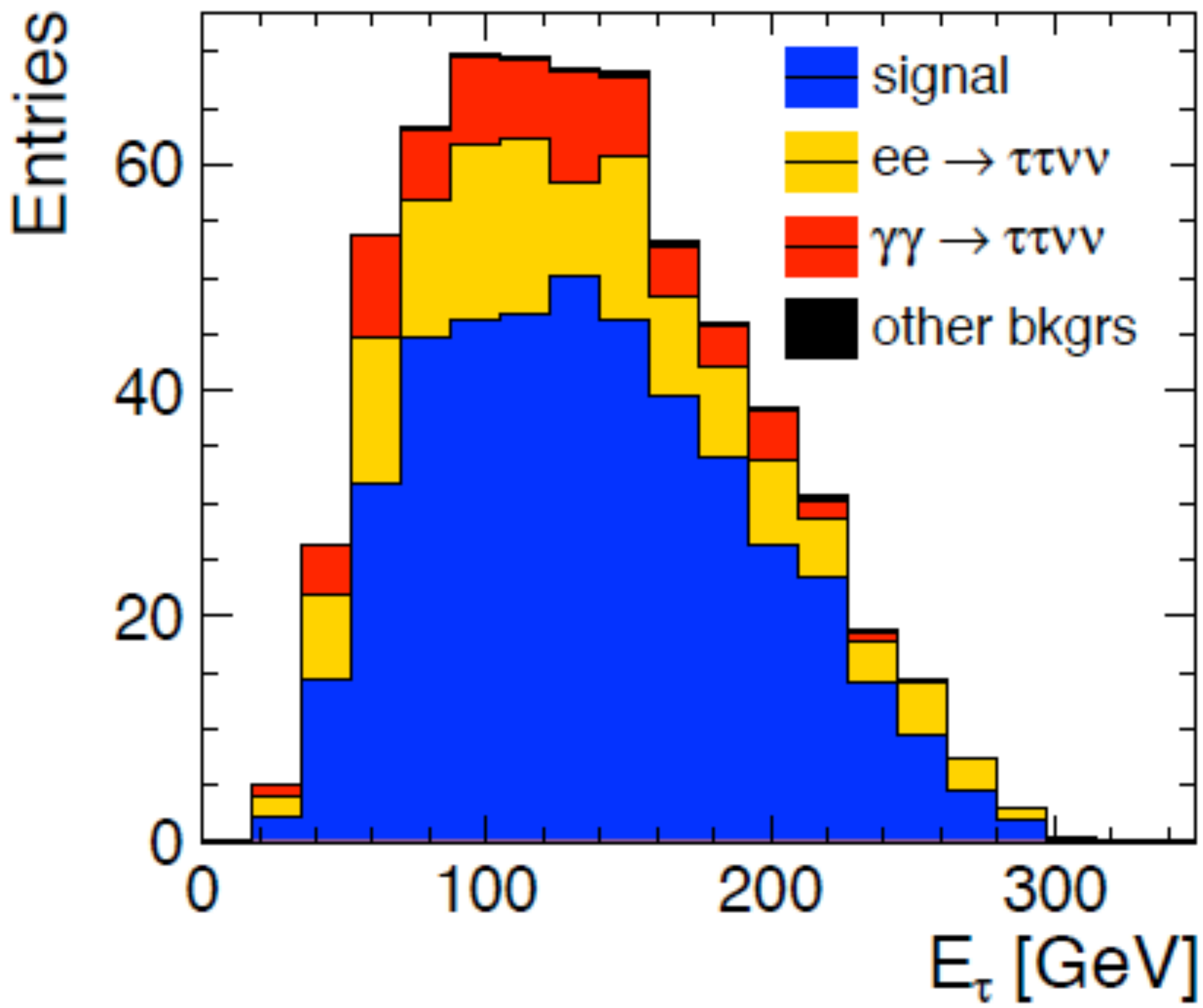
- Determination of slepton and neutralino/chargino masses from kinematic endpoints of the lepton (e, μ) energy distributions with analytic fit
  - 0.1% accuracy on slepton and neutralino masses
  - 2.5% accuracy on sneutrino and chargino masses

> Previous studies have demonstrated similar accuracies for TeV - scale particles at 3 TeV

Staus @ 1.4 TeV

- More challenging: Additional missing energy due to neutrino from tau decay

$$e^+e^- \rightarrow \tilde{\tau}\tilde{\tau} \rightarrow \tau^+\tau^-\chi^0\chi^0$$



The model:

- stau mass ~ 520 GeV
- neutralino mass ~ 360 GeV

- Only considering hadronic tau decay modes (~ 65% BR)
- Tau finding with seeded cone-based jet algorithm, background rejection with BDTs
- Mass measurement with template fit (fully simulated signal templates with different mass hypotheses) - Neutralino mass needed as input

Statistical precision on mass: 2.0%; on cross section 7.5% (systematics from BDT training 0.5% on mass)

Gauginos @ 1.4 TeV

- Another classic: CLIC reach extends substantially beyond LHC reach

$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow h(Z)h(Z)\tilde{\chi}_1^0\tilde{\chi}_1^0$$

95% (h) 5% (Z)

The model:

- Chargino mass ~ 490 GeV
- neutralino masses ~ 360 GeV, ~ 490 GeV

reconstructed in all-hadronic decay:
4 jets + missing energy

Key challenges: reconstruction of low-energy jets in background environment,
di-jet invariant mass resolution for boson identification

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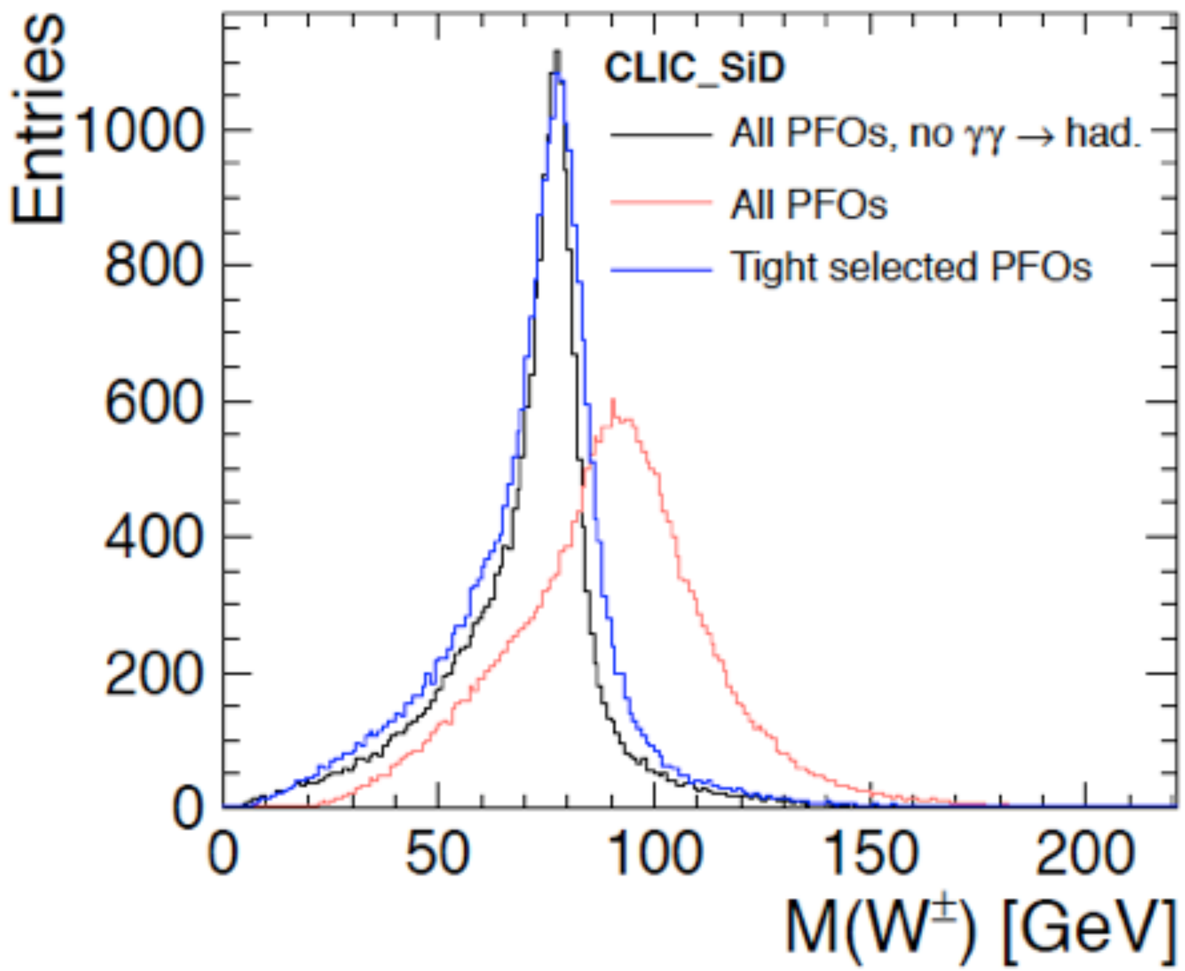
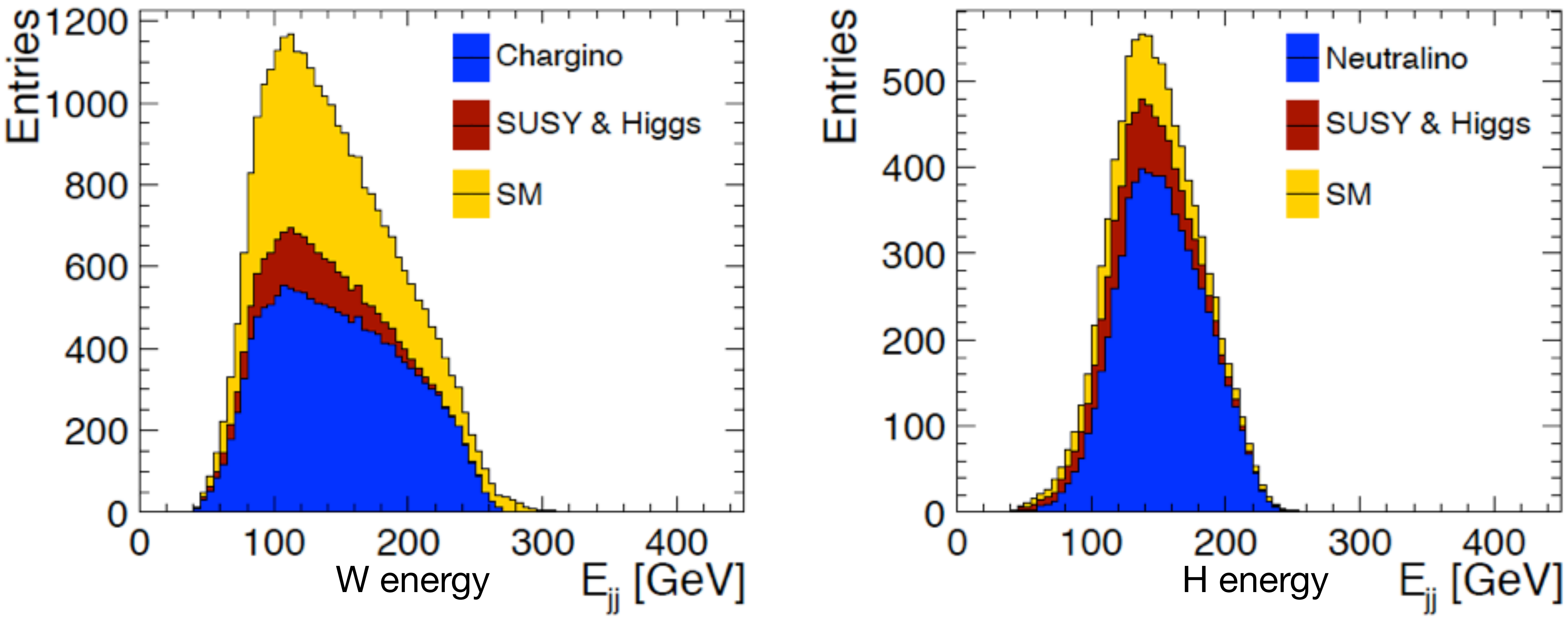
PFO selection cuts clean up invariant mass distributions very effectively



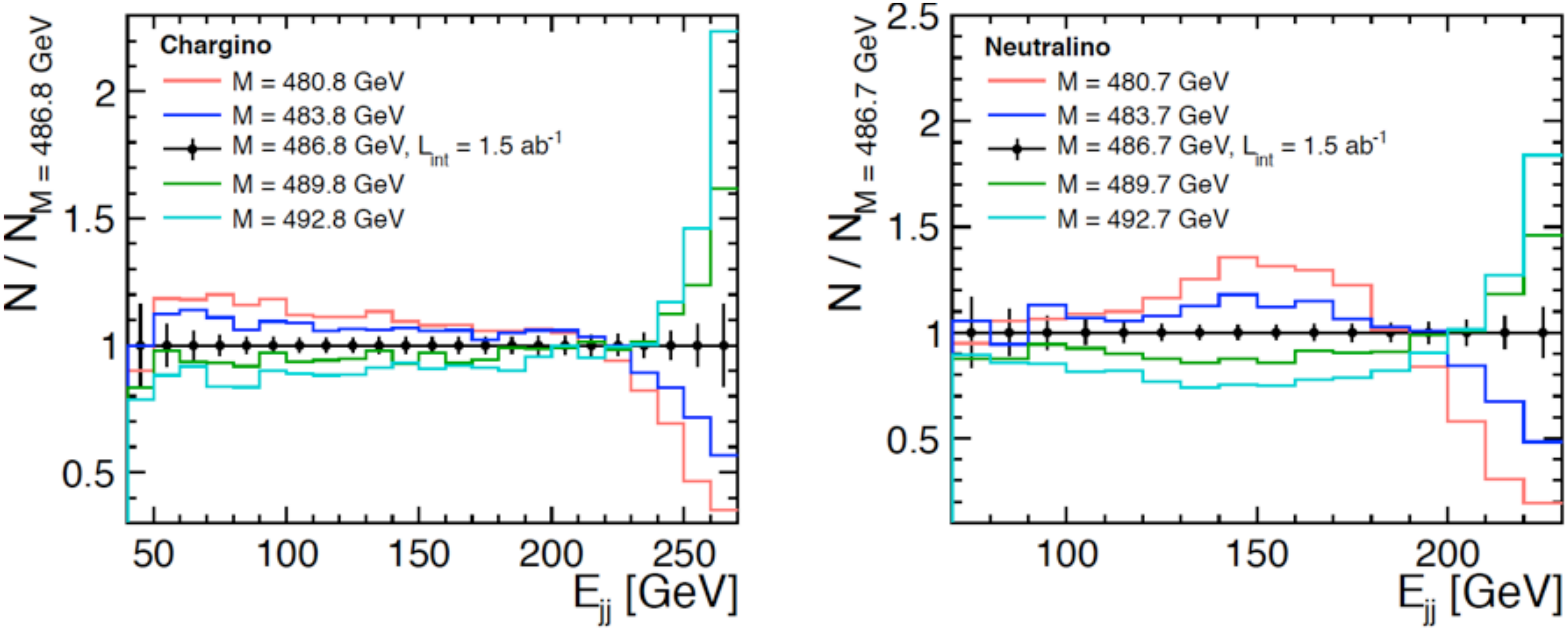
Gauginos @ 1.4 TeV

- Event selection and background rejection based on Boosted Decision Trees
  - efficiency 33% / 41% for Charginos / Neutralinos (including BRs)
- Mass (and cross section) measurement from reconstructed energy distribution of bosons - lightest neutralino mass needed as input



Gauginos @ 1.4 TeV

- Mass and cross-section obtained from template fit (simulated signal templates)



Statistical mass precision: 0.8 GeV / 0.2% (Chargino), 0.5 GeV/ 0.1% (Neutralino)

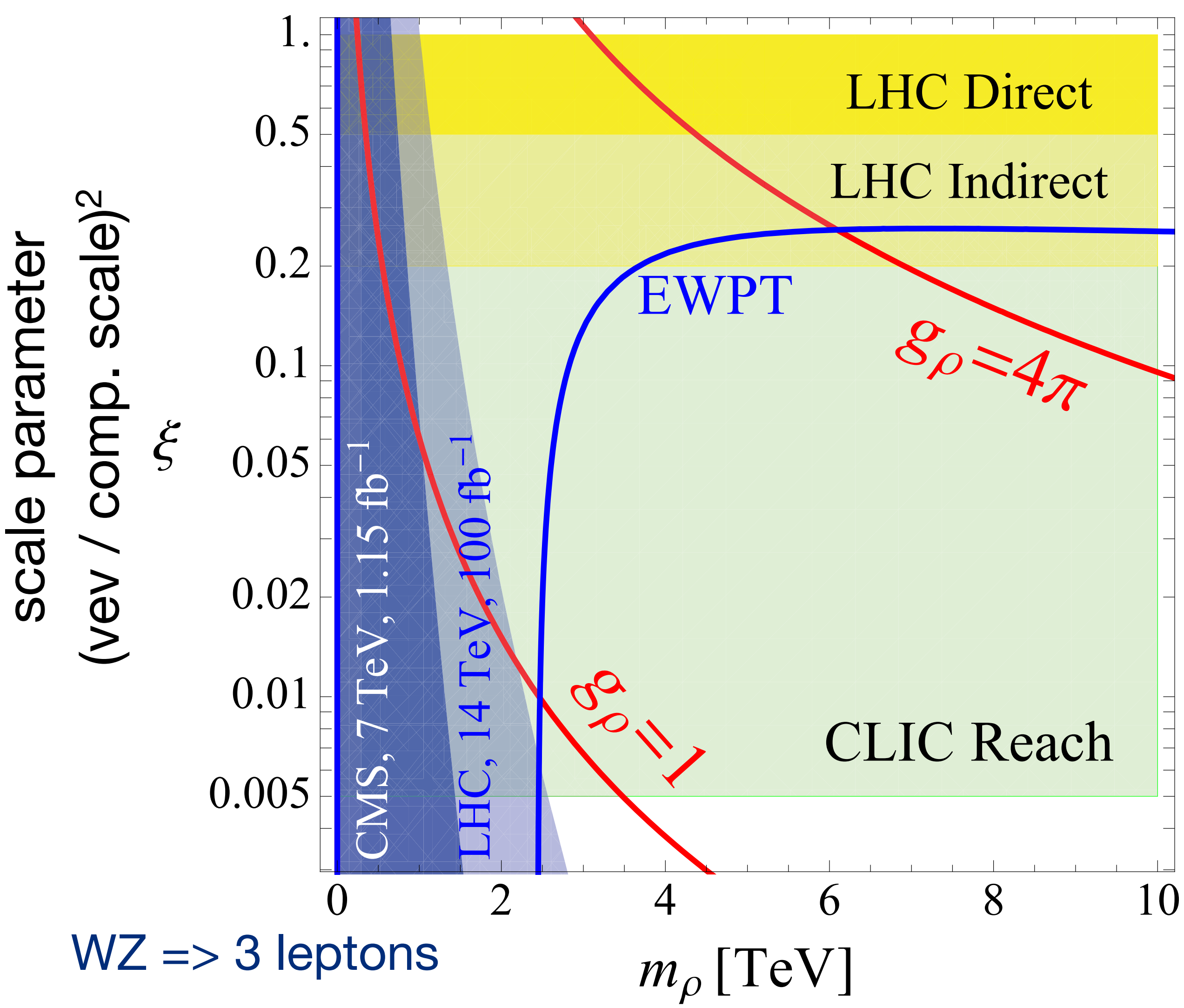
Cross section: 1.3%

Dominating systematics: JES on the 1 - 3 GeV level, Neutralino mass ~ 1 GeV

> Previous studies have demonstrated 1% accuracies for Gauginos with masses of ~650 GeV at 3 TeV

Indirect Probes for New Physics

- Precision measurements at lepton colliders provide sensitivity for beyond the direct reach given by the collision energy
- Many examples - Asymmetries in top production, Higgs measurements, di-lepton production,... With full studies at CLIC we have just barely started to scratch the surface



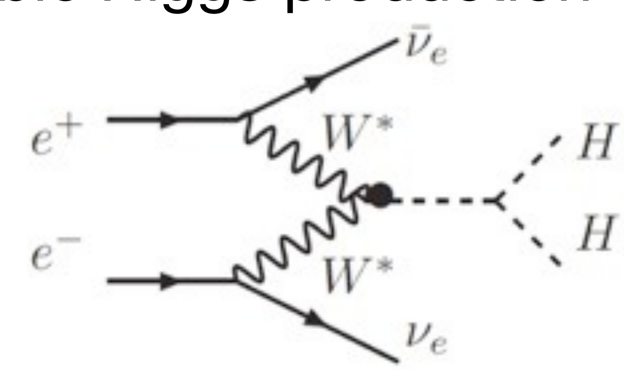
WW scattering, double H

single H

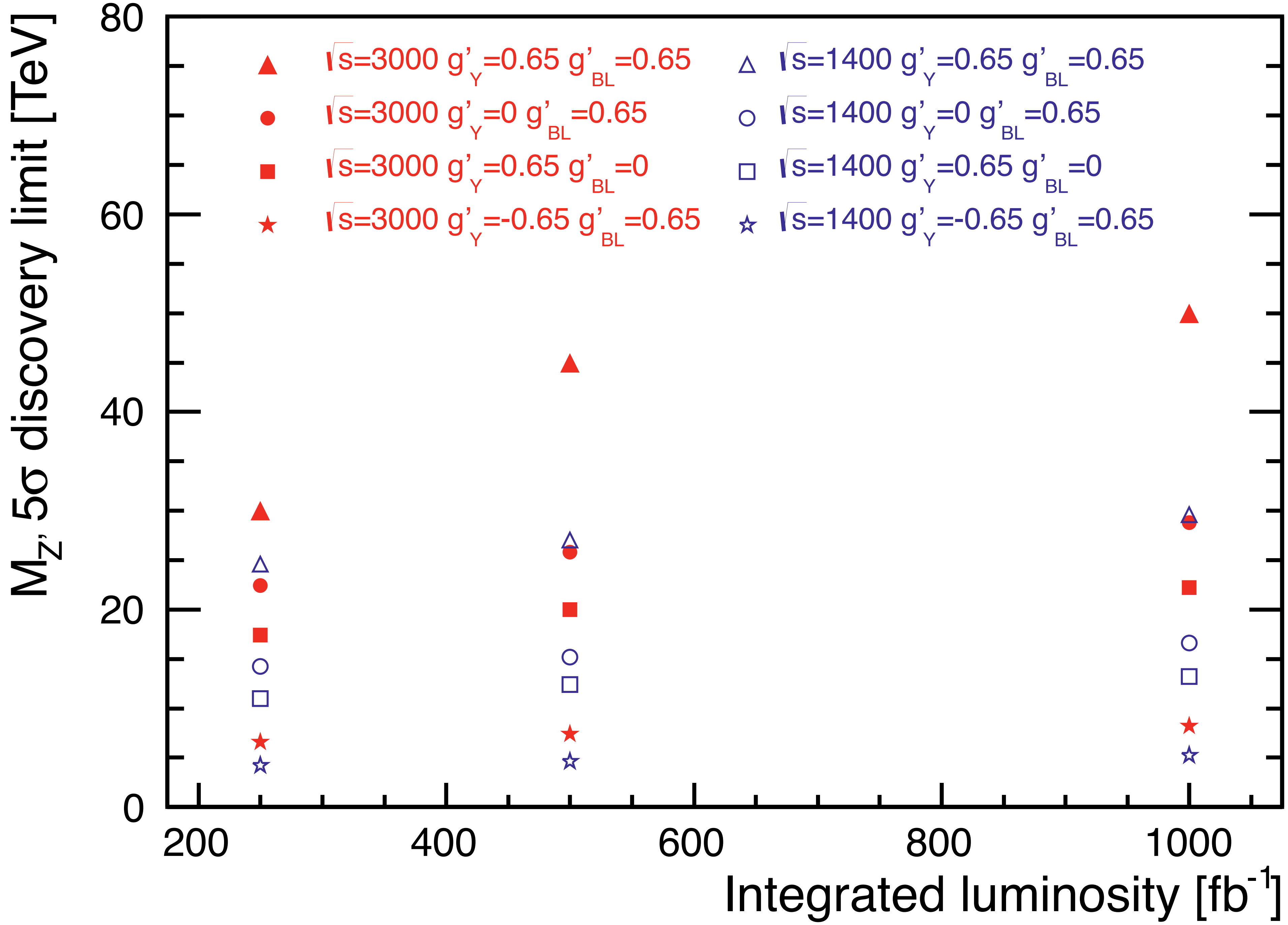
WZ => 3 leptons

One example: Higgs compositeness
- parametric study

CLIC reach: clean environment to study double Higgs production



Sensitivity to High-Mass Z'



di-muon events

3 TeV

1.4 TeV

- Sensitivity study of $e^+e^- \to \mu^+\mu^-$:
  (Model dependent) sensitivity to tens of TeV

Summary

- CLIC is a discovery machine for BSM physics at the energy frontier
- Direct sensitivity to strong and electroweak particles up to ~ 1.5 TeV
  - Studied example: SUSY - Measurement of most of the spectrum on the 1% or better level - A full summary is given in the CDRs
    - Many signatures are rather generic - CLIC sensitivity also applies to other models of new physics with directly accessible particles
- Indirect sensitivity through precision studies - Extends to several tens of TeV
  - Studies have barely started to scratch the surface:
    - Higgs compositeness in Higgs precision measurements
    - Heavy Z’ from di-lepton measurements
  - Many additional opportunities to be explored in the future: Top as a tool - asymmetries to probe extra dimensions, search for CP violation, ...

The CLIC Detector & Physics Study

- Pre-collaboration structure based on a light-weight "Memorandum of Cooperation": http://lcd.web.cern.ch/LCD/Home/MoC.html

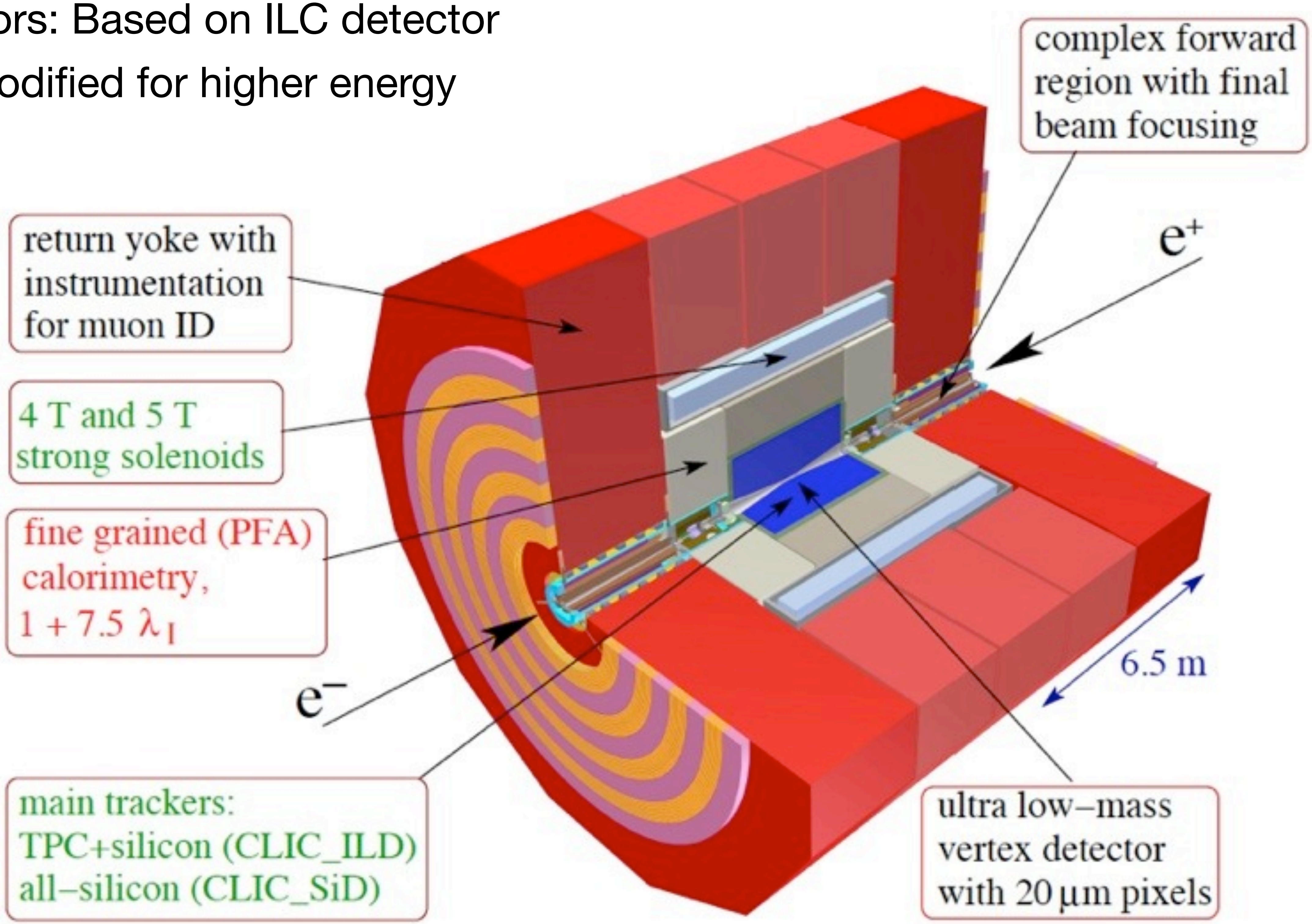
Australia: ACAS; Belarus: NC PHEP Minsk; Czech Republic: Academy of Sciences Prague; Denmark: Aarhus Univ.; Germany: MPI Munich; Israel: Tel Aviv Univ.; Norway: Bergen Univ.; Poland: Cracow AGH + Cracow Niewodniczanski Inst.; Romania: Inst. of Space Science; Serbia: Vinca Inst. Belgrade; Spain: Spanish LC network; UK: Birmingham Univ. + Cambridge Univ. + Oxford Univ.; USA: Argonne lab; + CERN

Additional members welcome!

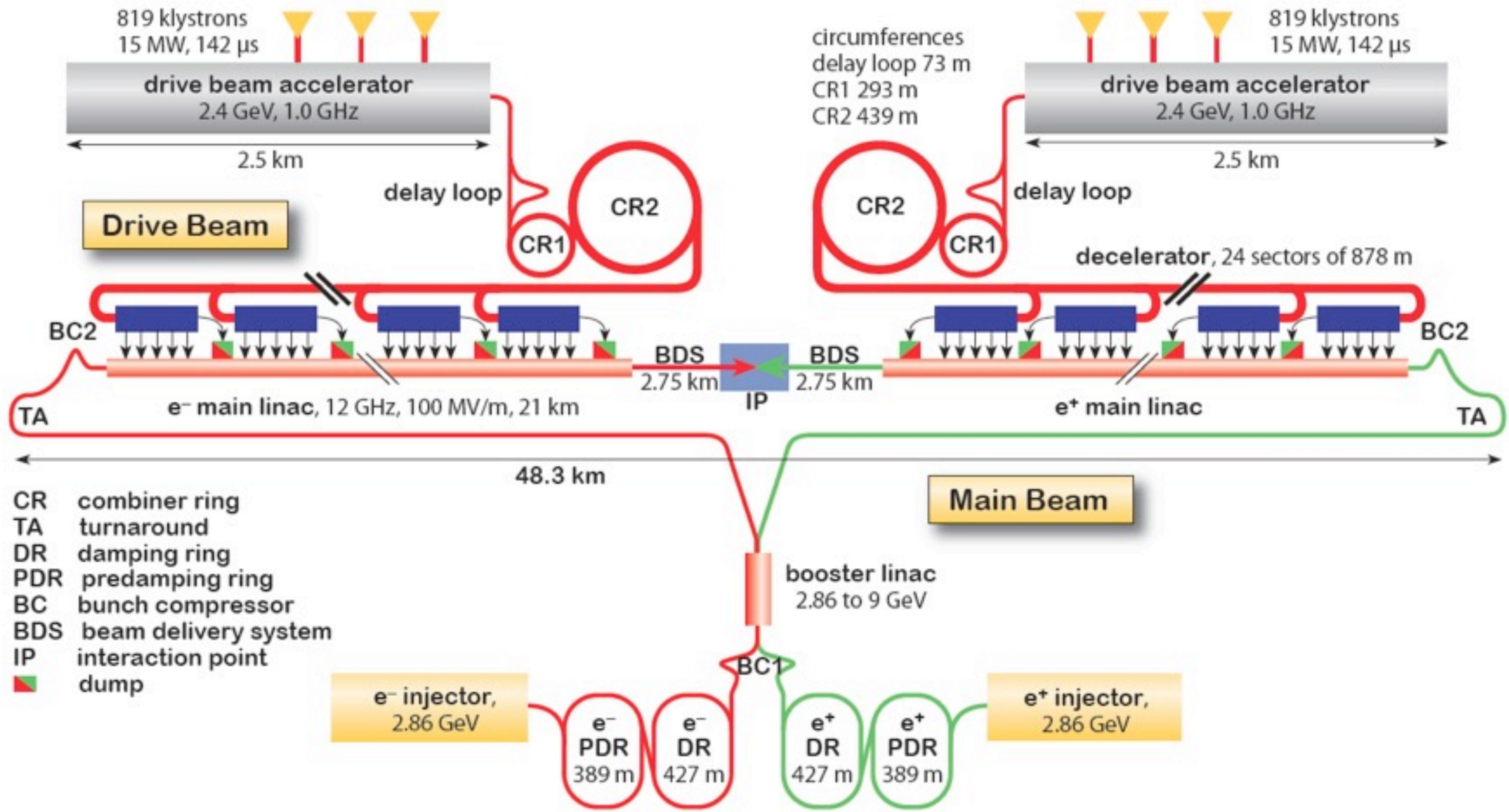
Backup

Making Measurements at CLIC - Detectors

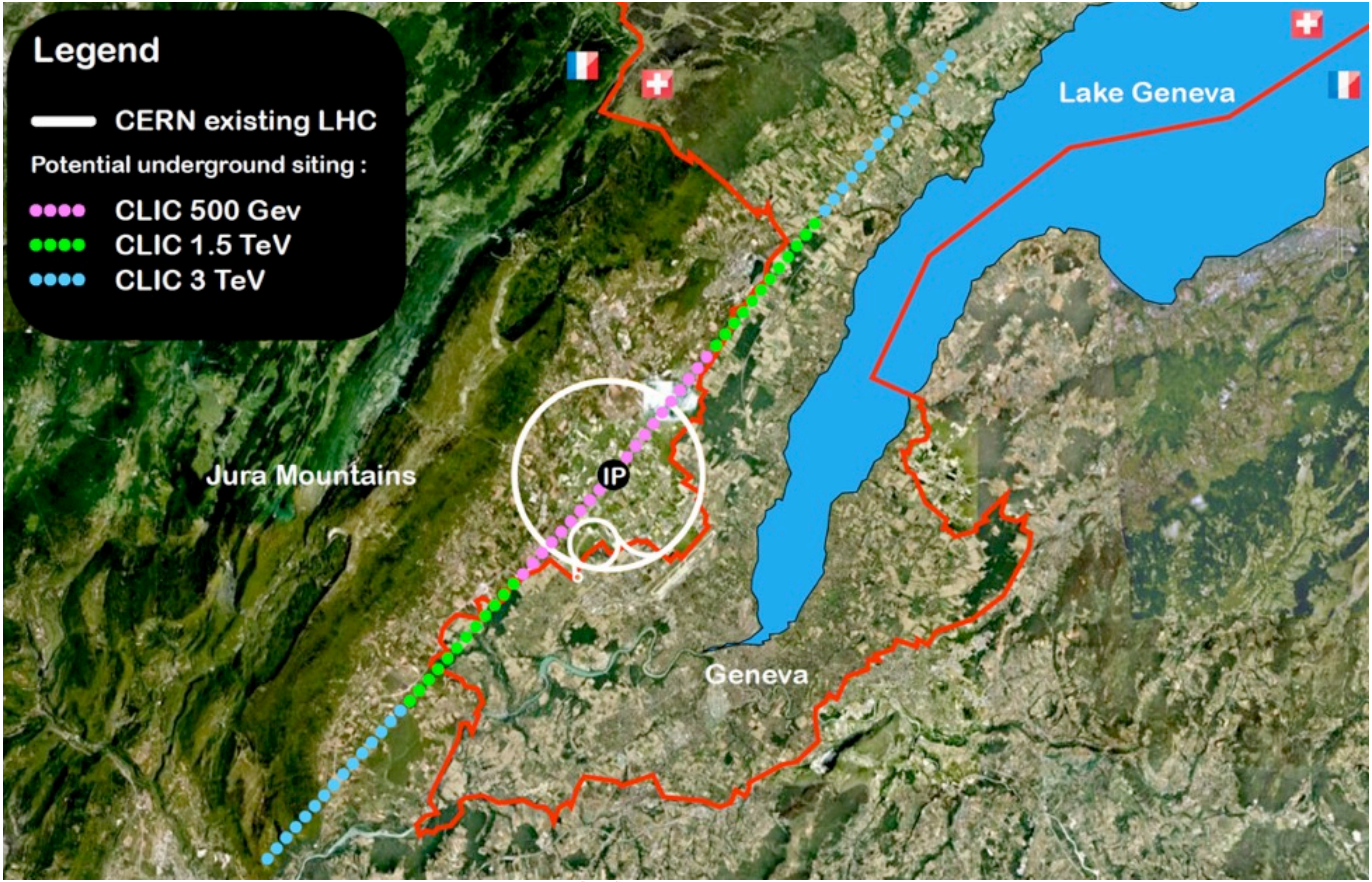
- CLIC detectors: Based on ILC detector concepts, modified for higher energy



CLIC - 3 TeV Layout



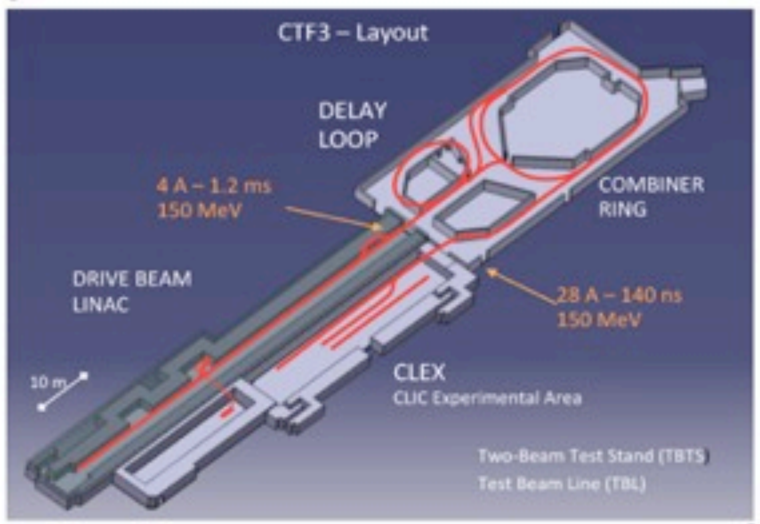
CLIC - Possible Implementation at CERN



CLIC - Towards Realization

2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



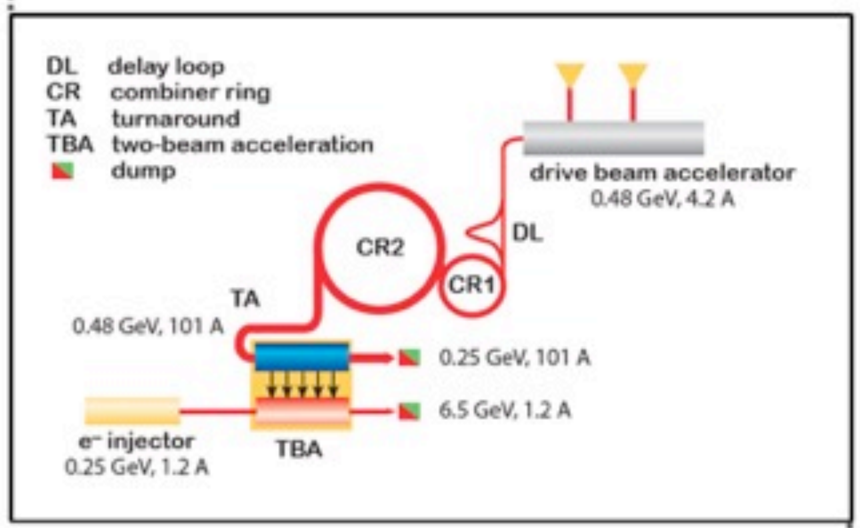
2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2017-22 Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



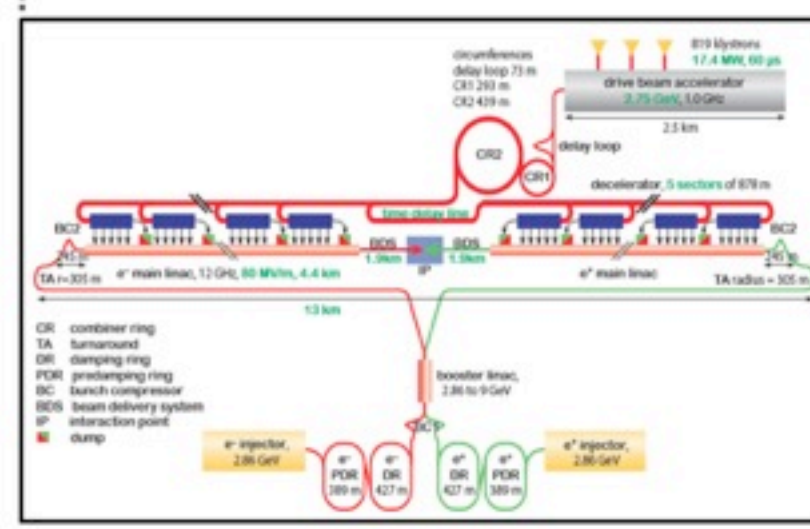
2022-23 Construction Start

Ready for full construction and main tunnel excavation.

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

> Faster implementation possible, for example with a klystron-based first stage as Higgs factory