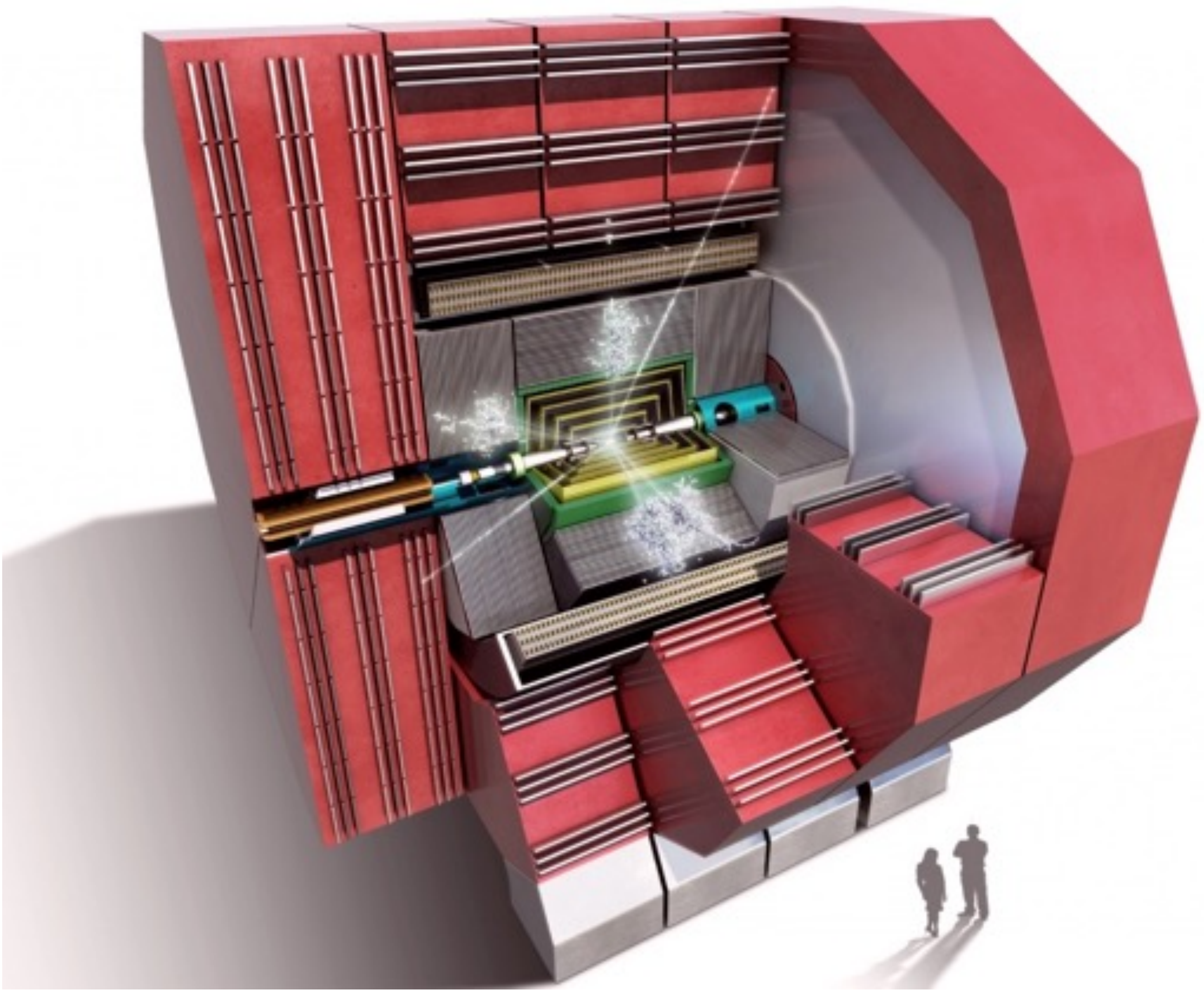
Impact of the Luminosity Spectrum on Top Mass Measurements at Linear Colliders



Miroslav Gabriel
Max-Planck-Institute for Physics

Young Scientist Workshop 2015, Ringberg Castle

Outline

1. Introduction to Future Linear Colliders
2. Top Quark Mass Measurement at e^+e^- Colliders
    - Reconstruction of the Invariant Mass
    - From a Threshold Scan
3. Influence of the Luminosity Spectrum
4. Reconstruction of the Luminosity Spectrum
5. Summary

Future Linear Colliders

Requirements:

- Precision physics and complement LHC → e+e- colliders
- Synchrotron radiation → Linear Collider
- High Luminosity

Two proposed concepts for future linear e^+e^- machines:

- Both deliver luminosity > 10^{34} $cm^{-2}s^{-1}$
- Both realised in staged design
- Similiar detector concepts

Experimental conditions:

- Highly focused beams at IP “nano-beams” → Rise to Beamstrahlung
- Very low background, mostly from $\gamma\gamma$ → hadrons
- Point particle collisions → precise initial & clean final states

International Linear Collider (ILC)

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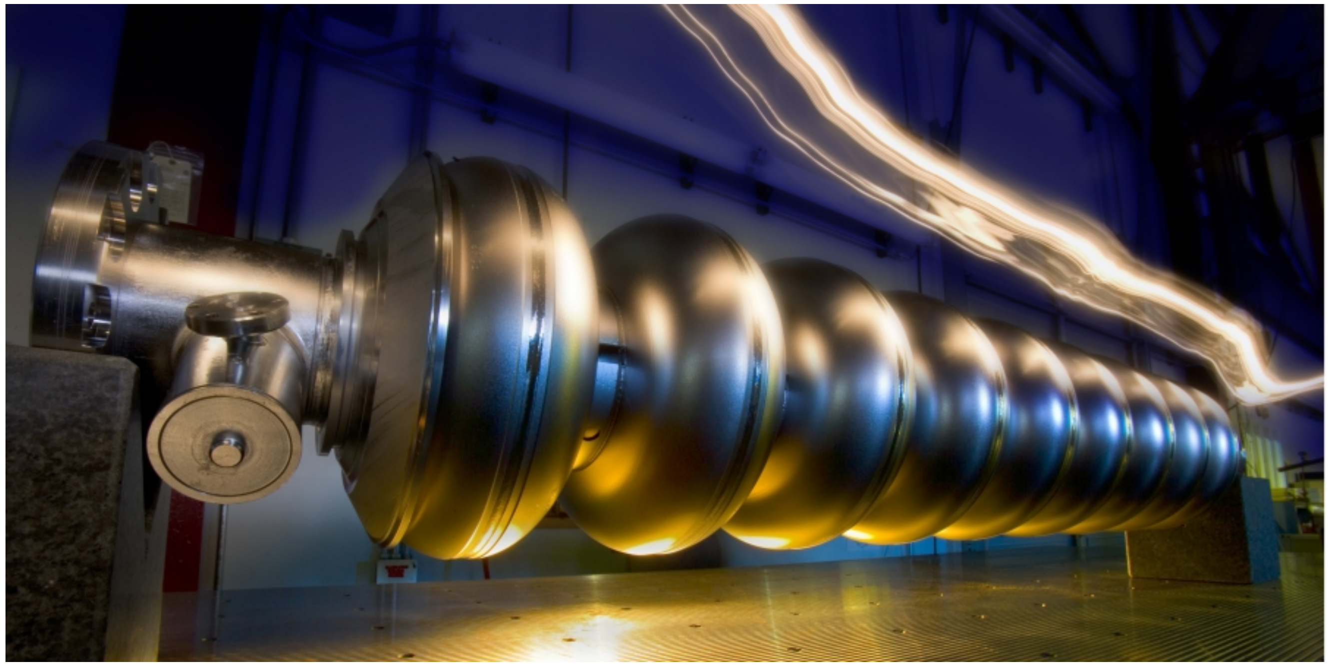


Future e^+e^- machine with Japan as potential host:

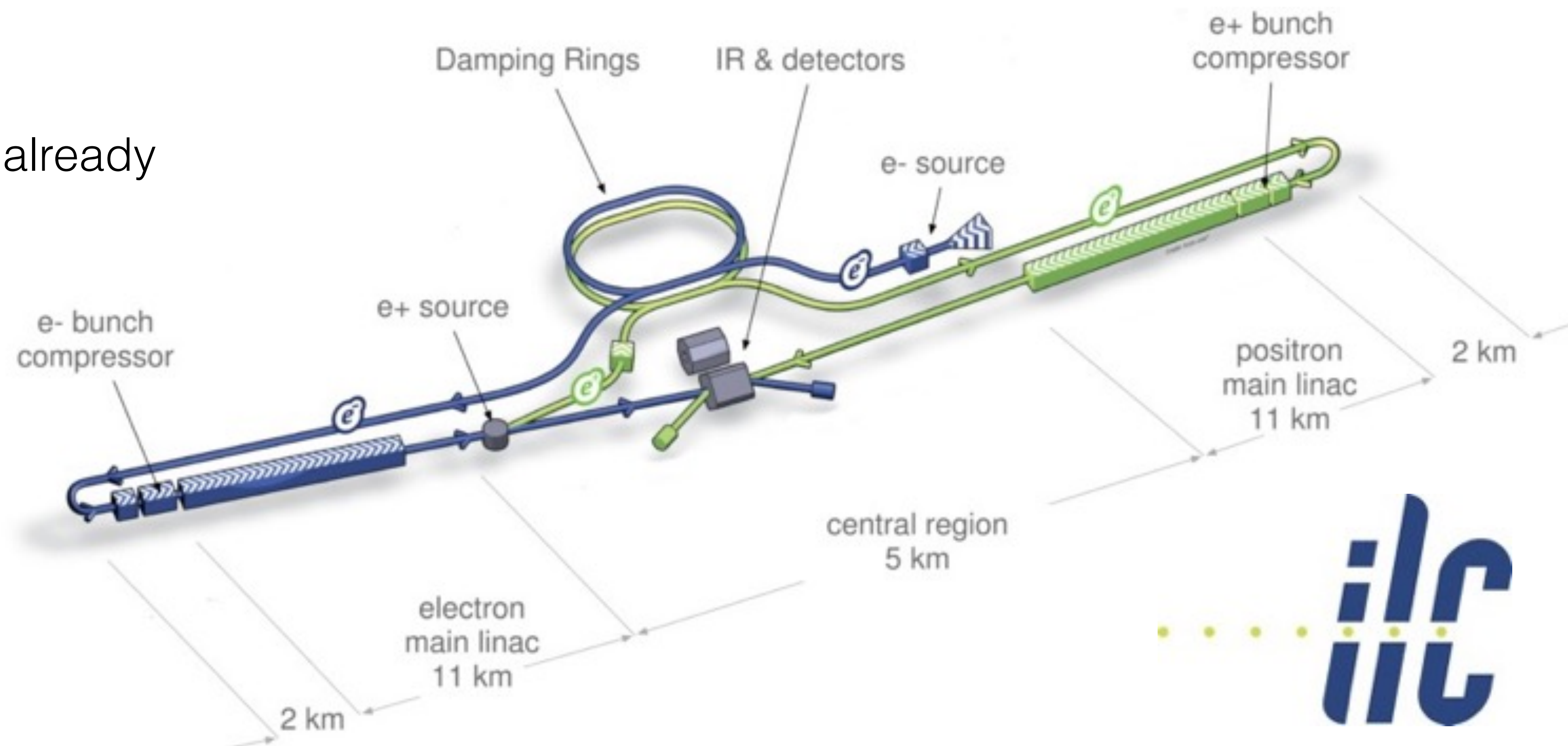
- Superconducting cavities ~ 30 MV/m
- 250 GeV, 350 GeV, 500 GeV, upgrade to 1 TeV
- 50 km long

Far advanced concept:

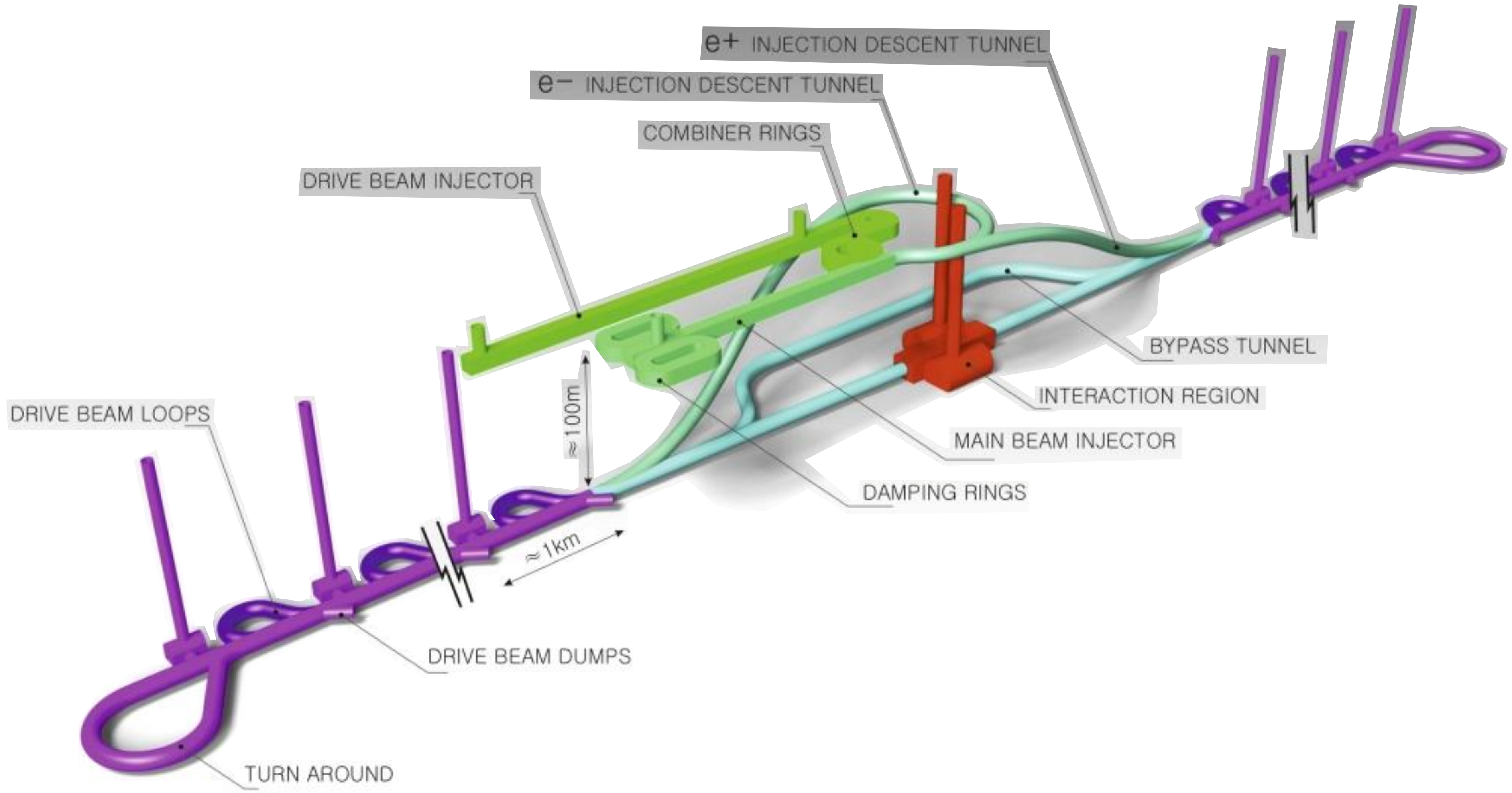
- TDR completed in 2012
- Accelerator technology already used for XFEL @ DESY
- Site selected (Kitakami)

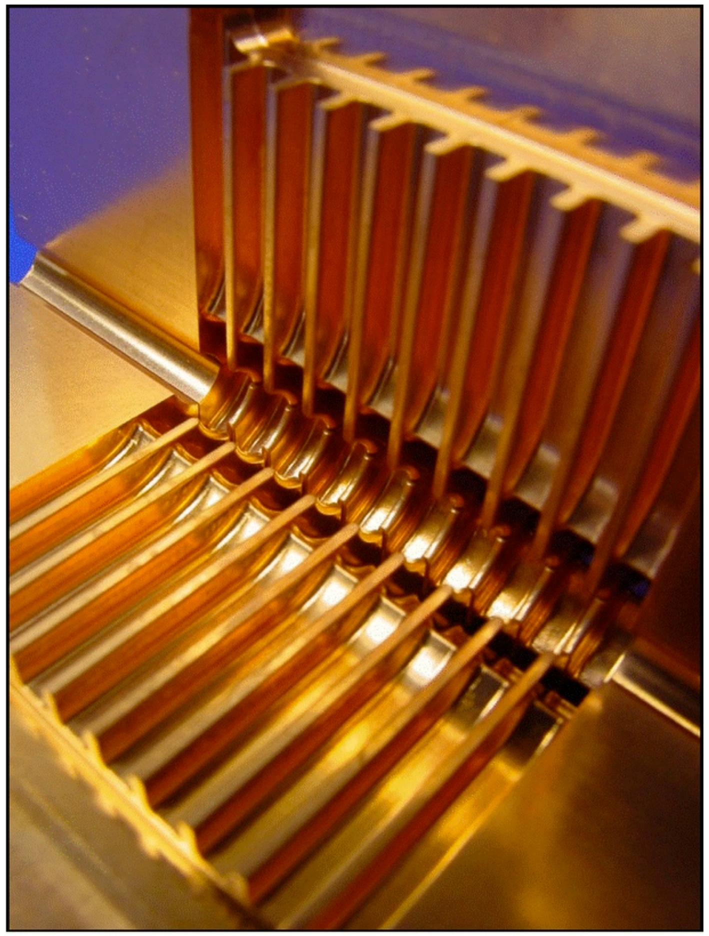
Timeline:

- Possible construction start ~ 2018



Compact Linear Collider (CLIC)





Future e^+e^- machine at CERN with 350 GeV, 1.4 TeV and ultimately 3 TeV:

- Two-beam acceleration scheme
- 50 km long
- Normal conducting RF cavities ~ 100 MV/m
- 0.5 ns bunch crossing, nanometer beams → most complicated luminosity spectrum

Timeline:

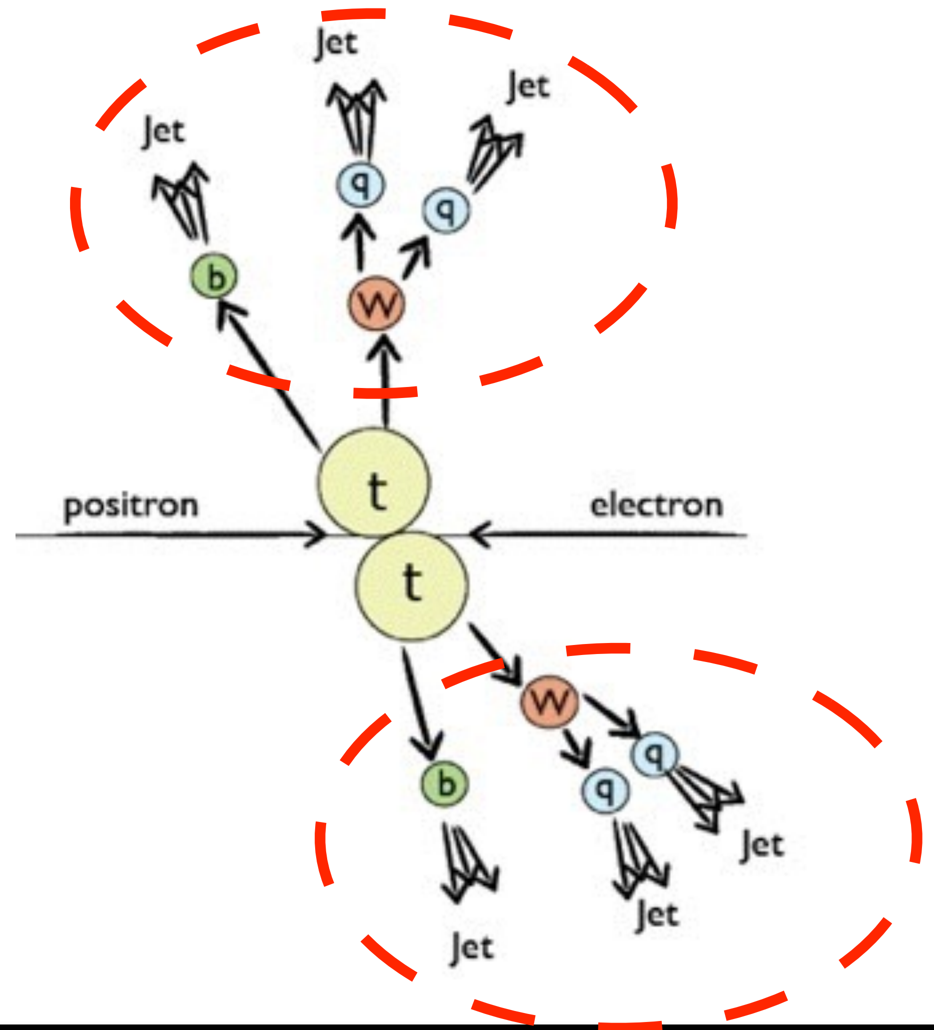
- CDR 2012, TDR ~ 2018, possible construction start 2025

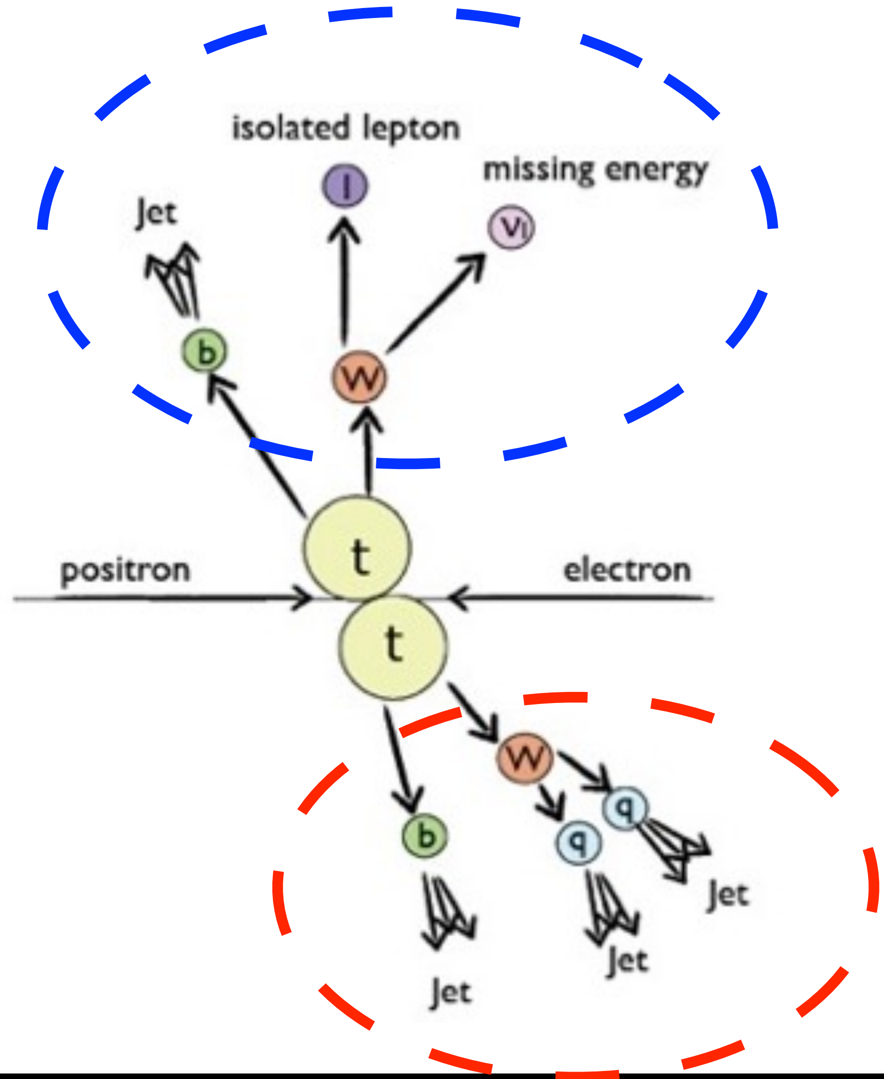
Top quark from e^+e^--annihilation at future Linear Colliders:

- Dominant production mechanism: Top Pair Production
- Top decay almost exclusive into W + b

} Talk by Andre Hoang

- **Different decay modes**:
  - **Fully-hadronic** ($e^+e^- \rightarrow t\bar{t} \rightarrow q\bar{q}bq\bar{q}\bar{b}$); Br: 46%
  - **Semi-leptonic** ($e^+e^- \rightarrow t\bar{t} \rightarrow q\bar{q}bl\nu\bar{b}$); Br: 15% per lepton flavour
  - Fully-leptonic ($e^+e^- \rightarrow t\bar{t} \rightarrow l\nu bl\nu\bar{b}$,) ; Br: 9%





Top mass at future Linear Colliders from top pair production:

- Very low background (mainly $\gamma\gamma\rightarrow$hadrons)
- Precise initial & clean final states

Two different measurement scenarios:

- **Direct Reconstruction of Invariant Mass (500 GeV):**
  - Mass in event generator “Pythia Mass” (Talk by Andre Hoang)
  - Arbitrary energies above threshold
  - High integrated luminosity
- **Threshold Scan (350 GeV):**
  - Dedicated measurement needed
  - Theoretically well understood (Talk by Andre Hoang)
  - Best mass measurement at LC

Invariant Mass (500 GeV)

Direct Reconstruction of Invariant Mass at 500 GeV:

- Full Detector Simulation (signal, detector model & background) including NNLO QCD calculations
- Reconstruction via:
  - fully hadronic
  - semi leptonic, excluding τ channel

Focus on quality of selected events:

- Lepton Collider ⇒ Very low non-$t\bar{t}$ background:

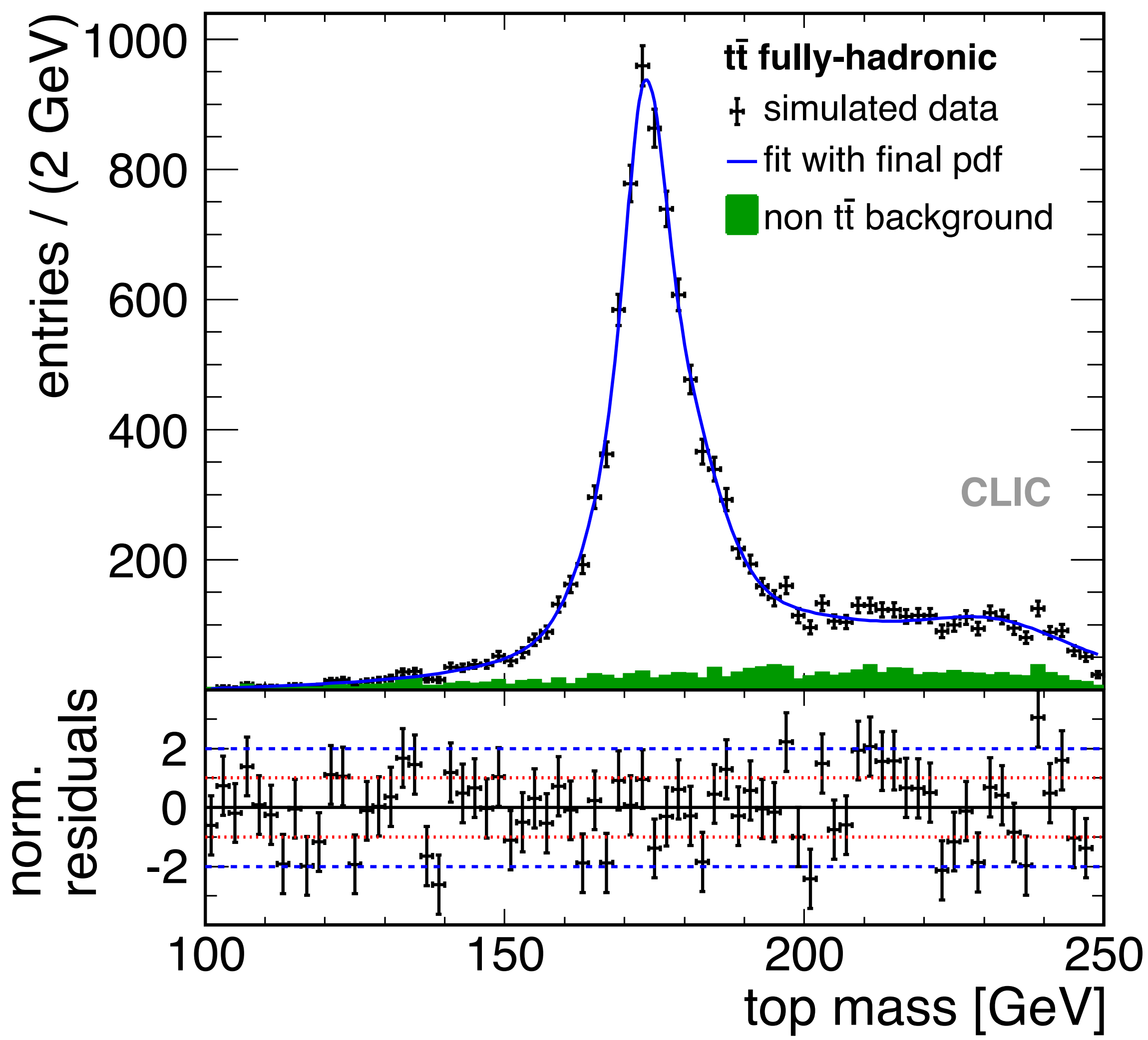
  S/B ~8.5 (12) for FH (SL) at 500 GeV
- High reconstruction efficiency:

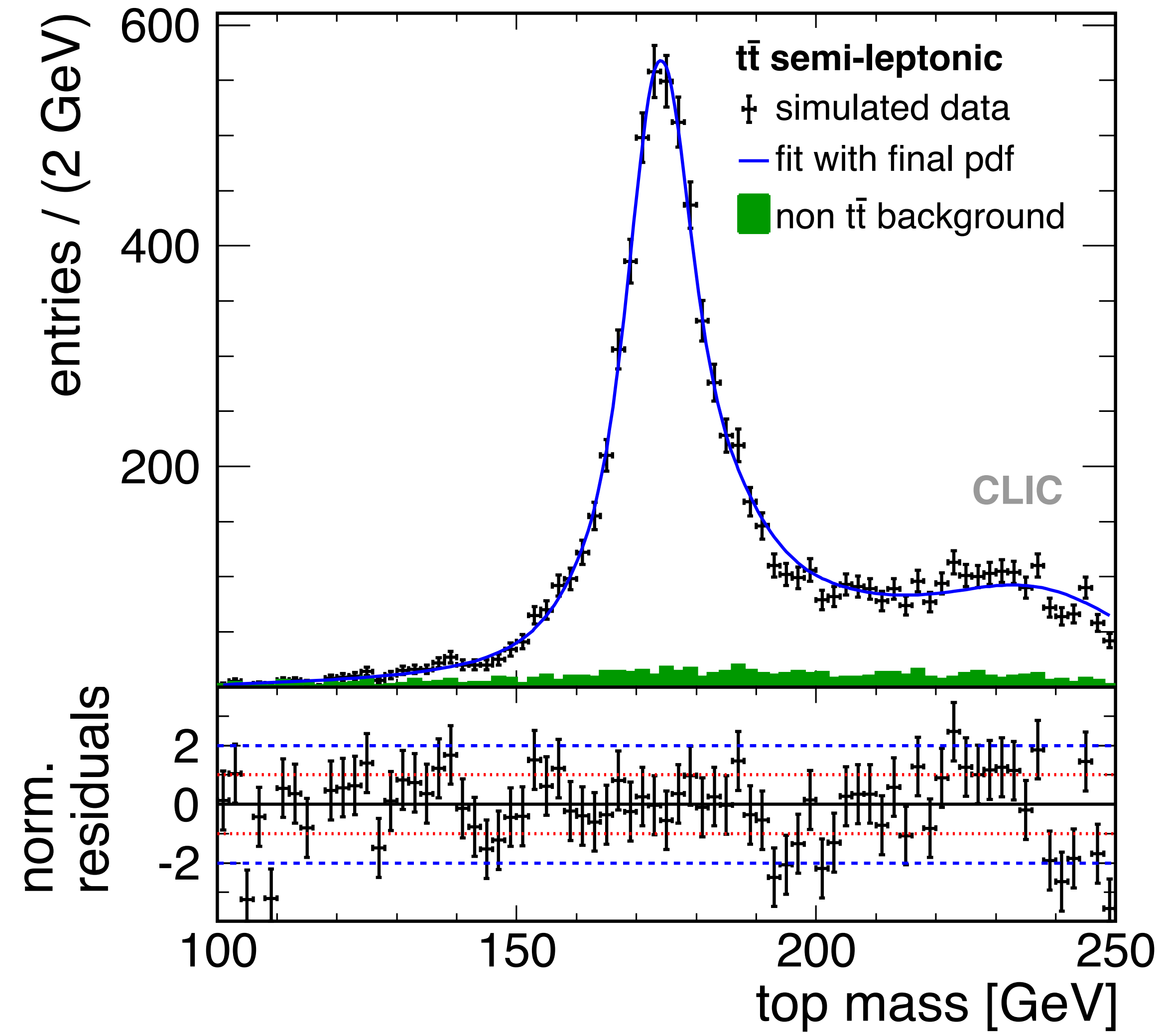
  34% (44%) for FH (SL) at 500 GeV

<u>Theoretically not well defined</u>

Invariant Mass (500 GeV)

EPJC 73: 2530 (2013)





Statistical Errors:

m_t: $\sigma_{stat.}$ = 80 MeV (FH + SL)

Γ_t: $\sigma_{stat.}$ = 220 MeV (FH + SL)

Systematic Errors:

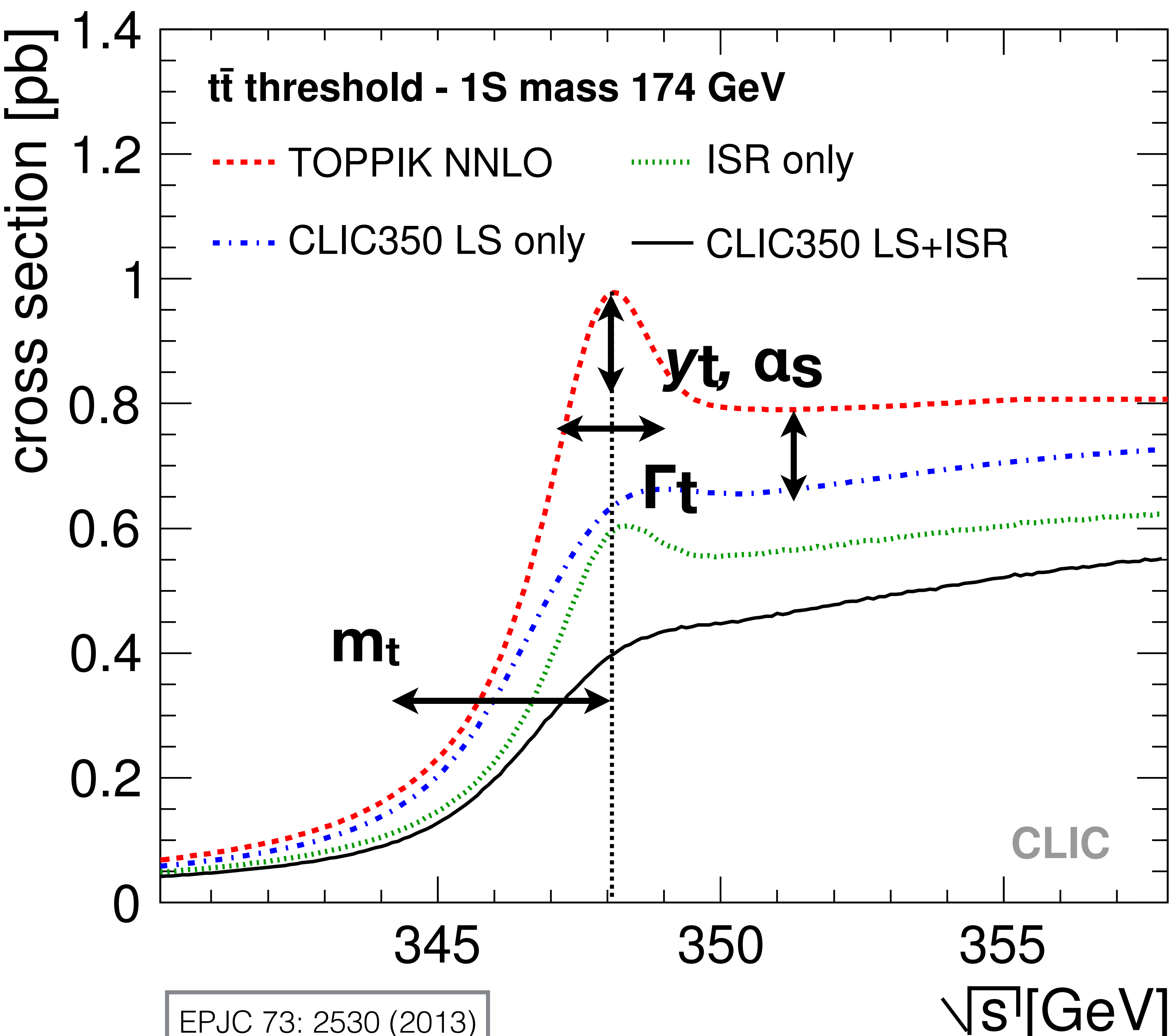
- exp. to be of similar order
- **Not included: Theory Error**

Top quark measurement at and above threshold at CLIC [EPJC 73: 2530 (2013)]

Threshold Scan in Theory

Top Threshold Scan:

- Measurement of top production cross section at the threshold
- Top mass affects rise of cross section
- Top mass extracted together with α_s
- α_s also from external input (LHC)
- Cross section connected to theoretically **well defined mass scheme** (here 1S)



EPJC 73: 2530 (2013)

Additional Access:

Γ_t, Y_t, electroweak couplings

Precision from Threshold Scan

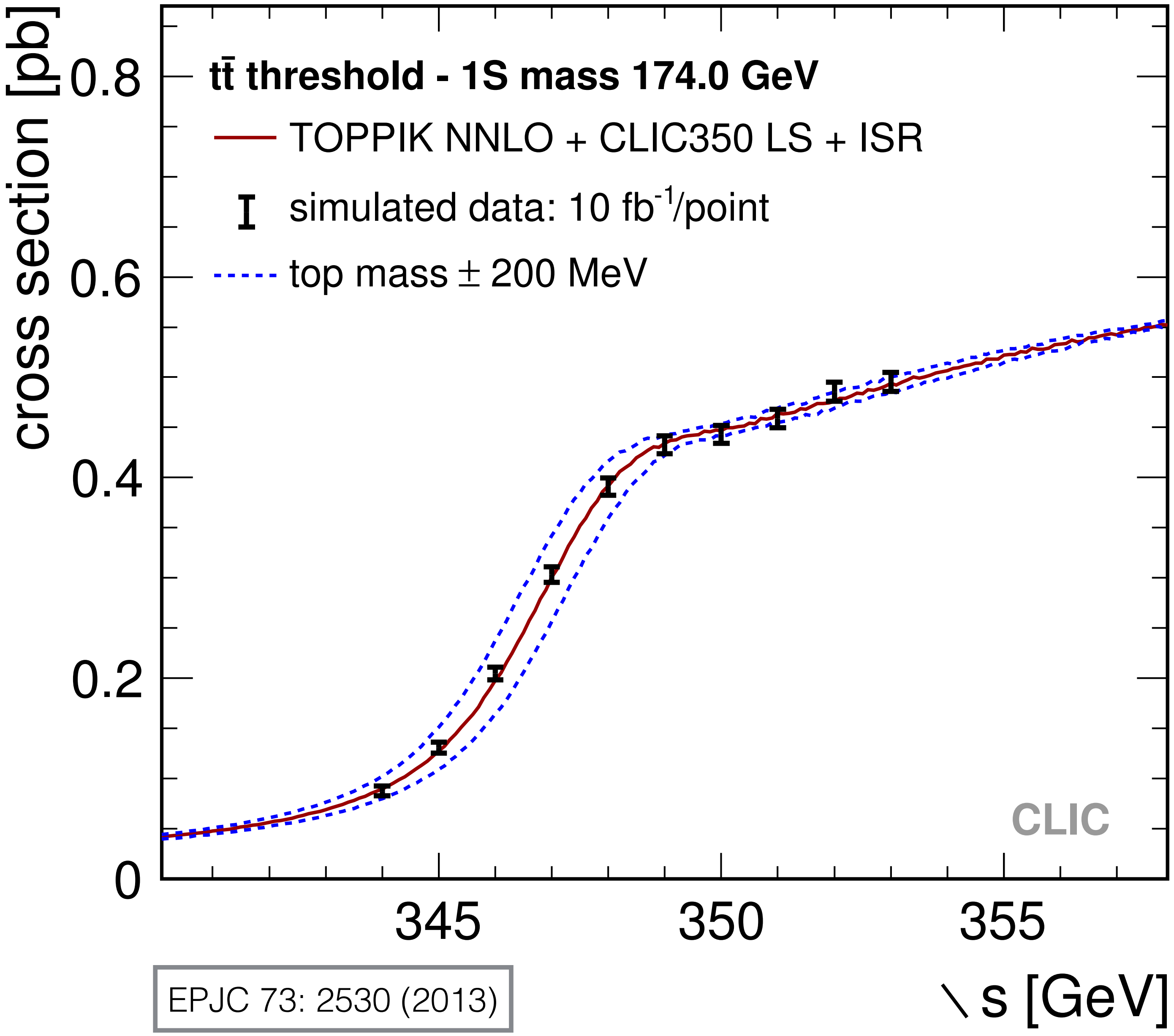
Procedure of the Threshold Scan:

- Measure σ at ten energies around 2x m_t
- Apply template fit to extract m_t
- Include of all relevant effects needed
- 100 fb^{-1} total

Analysis Focus on Selection Efficiency:

- Again fully hadronic and semi leptonic channels used
- S/B ~4.5 directly above threshold
- 70.2% efficiency including Br. (92% for selected decay modes)
- 99.8 % background rejection

Stat. uncertainty of Δm_t ~22 MeV



EPJC 73: 2530 (2013)

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Systematic Uncertainties

Measurements of the top mass will likely be limited by systematics.

Sources for Systematic Uncertainties on the Mass:

- Beam Energy ~ 30 MeV
- Selection efficiency and background rejection
- Theoretical uncertainties ~ 25-50 MeV
- Knowledge of the Luminosity Spectrum

Naiv study of the **impact** of accelerator specific **luminosity spectrum** on threshold scan:

- Assume 20% width of the peak of the luminosity spectrum

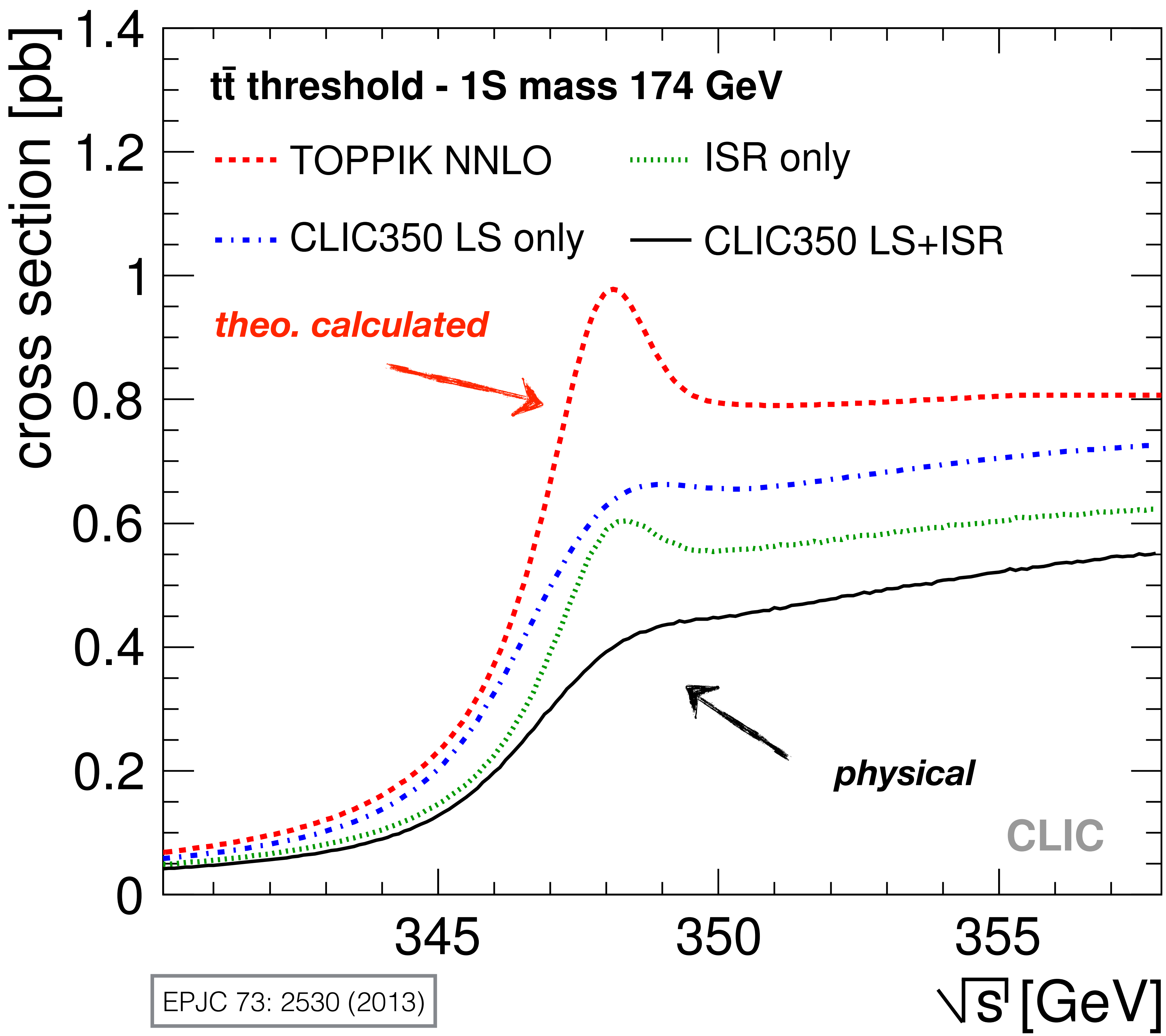
Syst. uncertainty of Δm_t ~ 75 MeV

Luminosity spectrum at CLIC 350 GeV has to be precisely know to estimate effect on threshold scan

Threshold Scan in Reality

Theoretically calculated σ varies from measurement. Affected by:

- **I**nitial **S**tate **R**adiation
- **L**uminosity **S**pectrum



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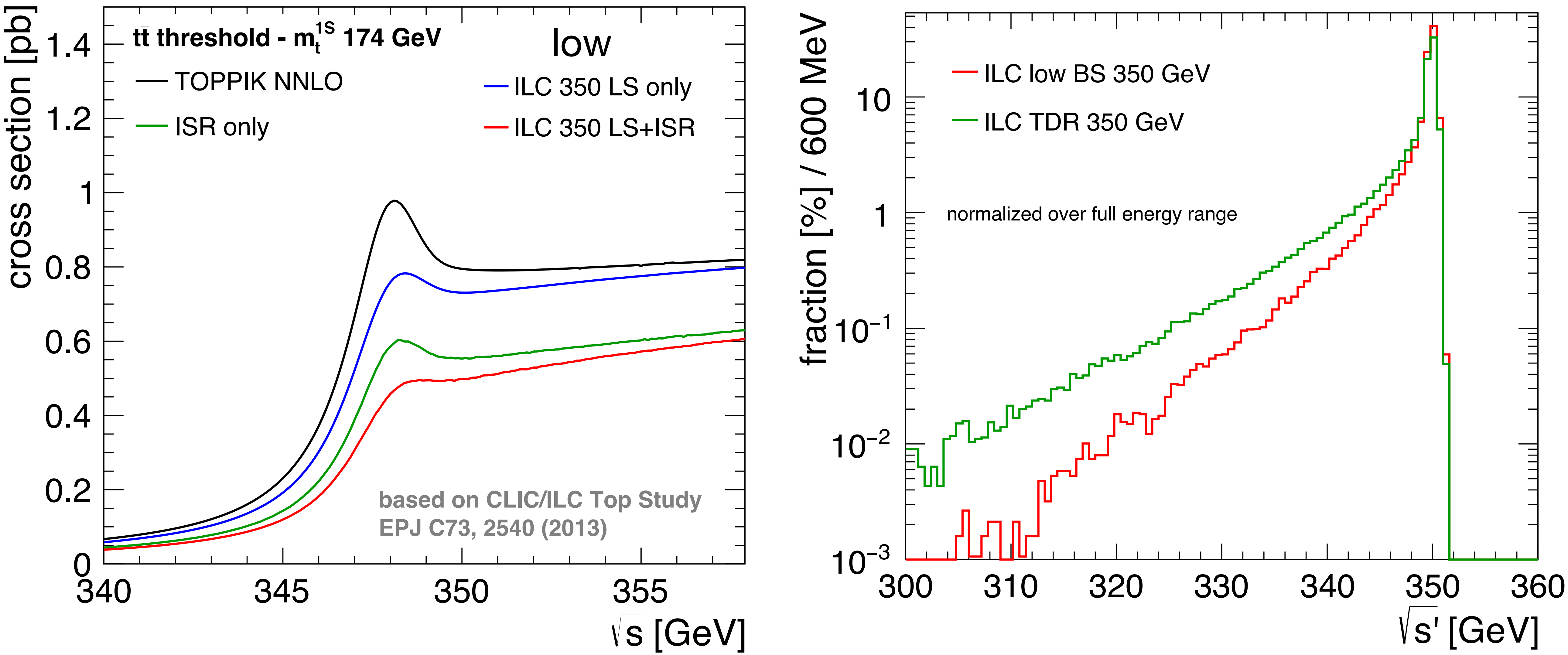
Example of Low Beamstrahlung option for ILC:



10% improvement in $\sigma_{stat.}$ vs. 50% less luminosity

Luminosity Spectrum and ISR

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Physics effects:

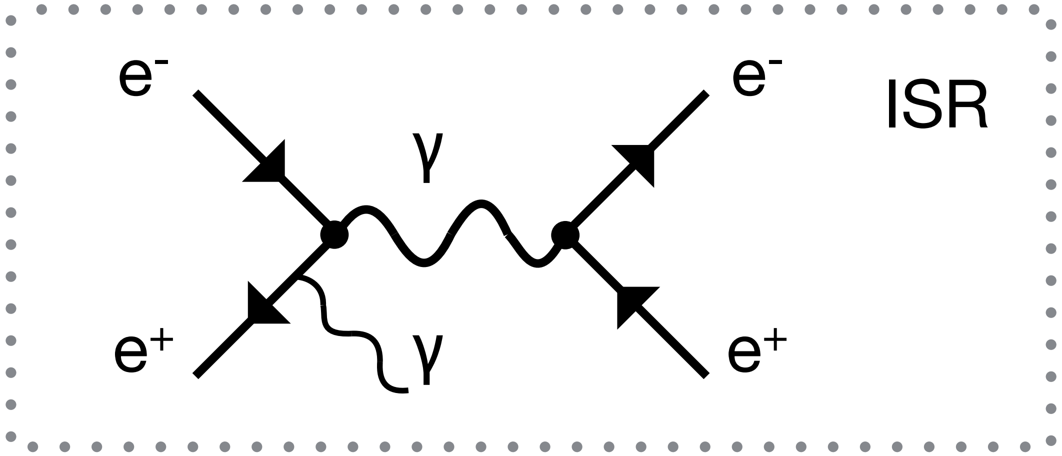
- **I**nitial **S**tate **R**adiation:
  - Theoretically well known
  - Leads to long tail

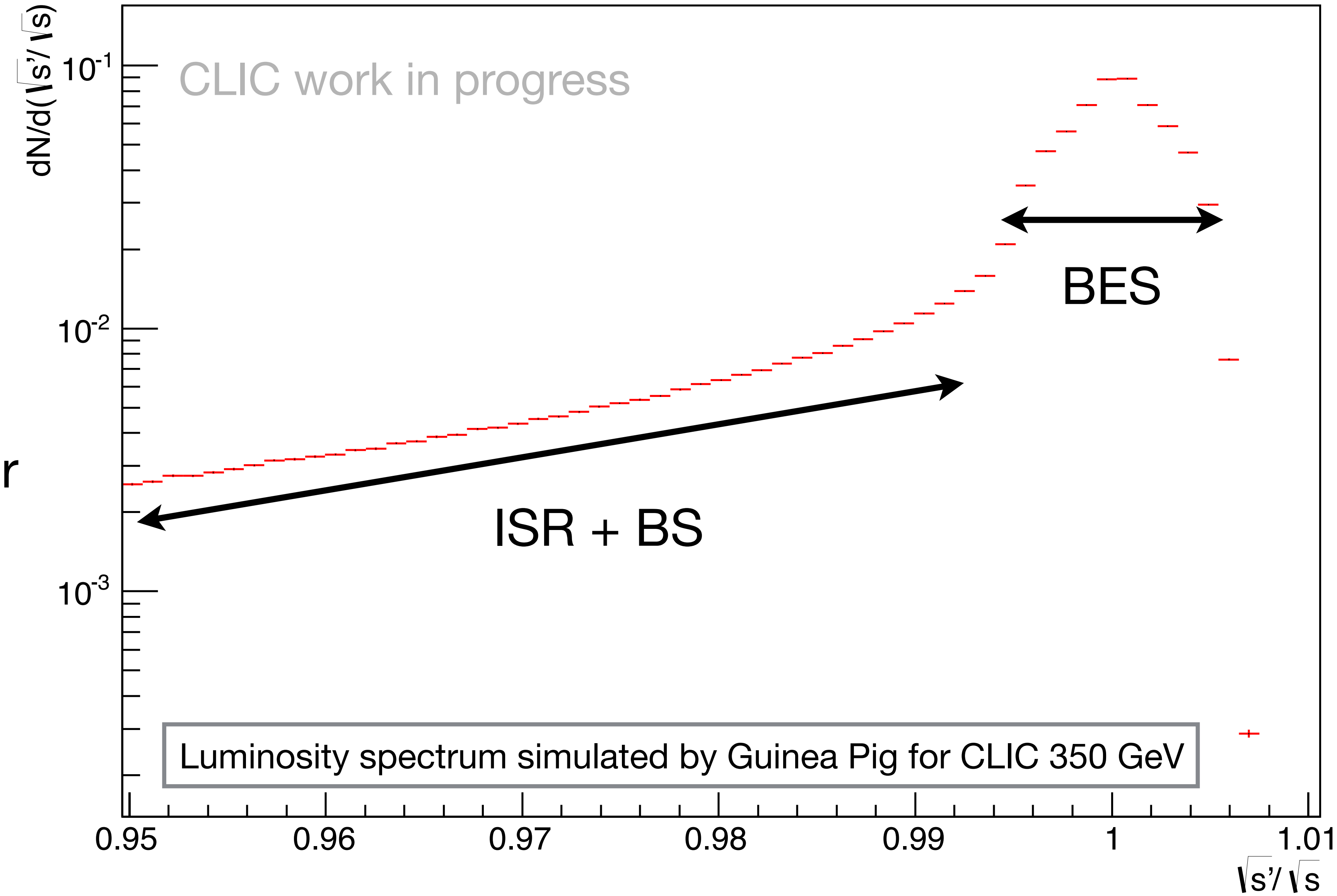
  → Emission of photons

Accelerator effects:

- **B**eam **E**nergy **S**pread:
  - Machine feature
  - Broadening of the peak
- **B**eam **S**trahlung
  - Strong focusing needed for high luminosity
  - Leads to long tail
  - Resulting fields affect e^-

  → Emission of photons





Obtaining the Lumi Spectrum

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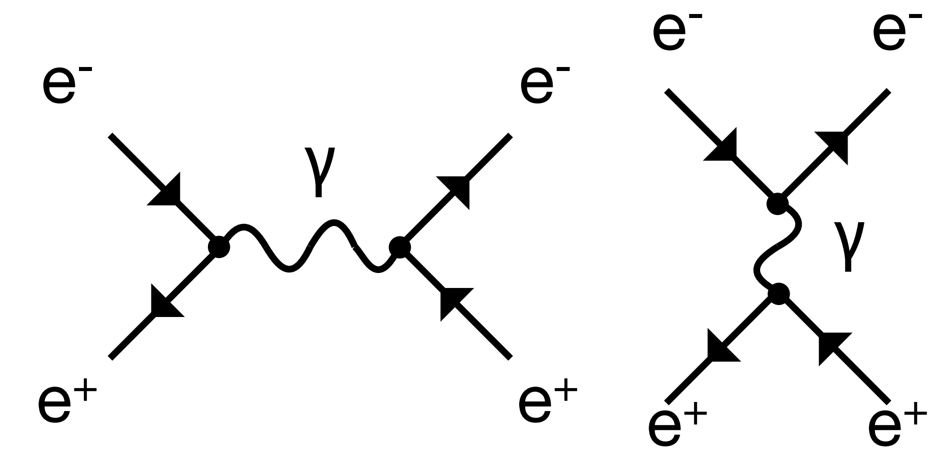
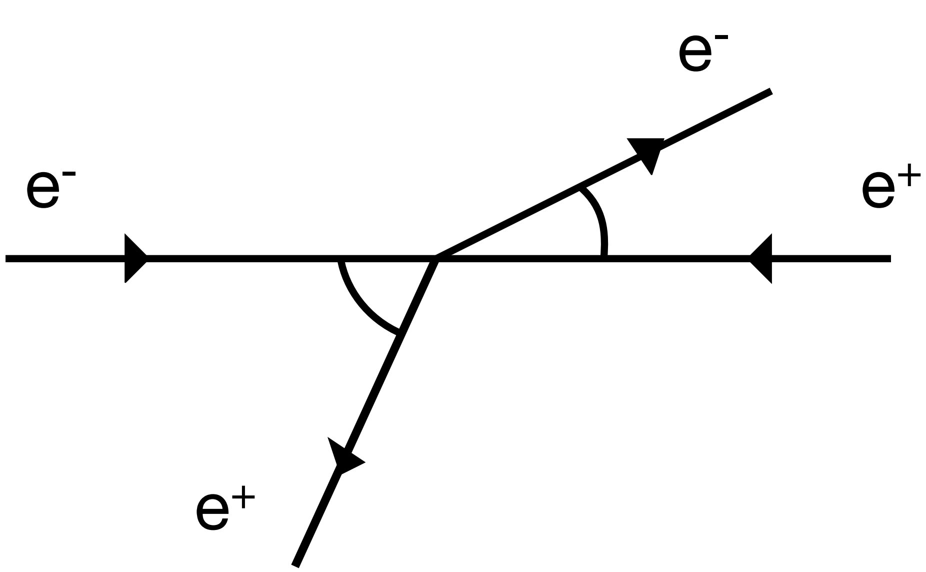
Following the approach of André Sailer and Stéphane Poss presented in:
Luminosity spectrum reconstruction at linear colliders for CLIC 3 TeV.
[Eur. Phys. J. C (2014) 74:2833]

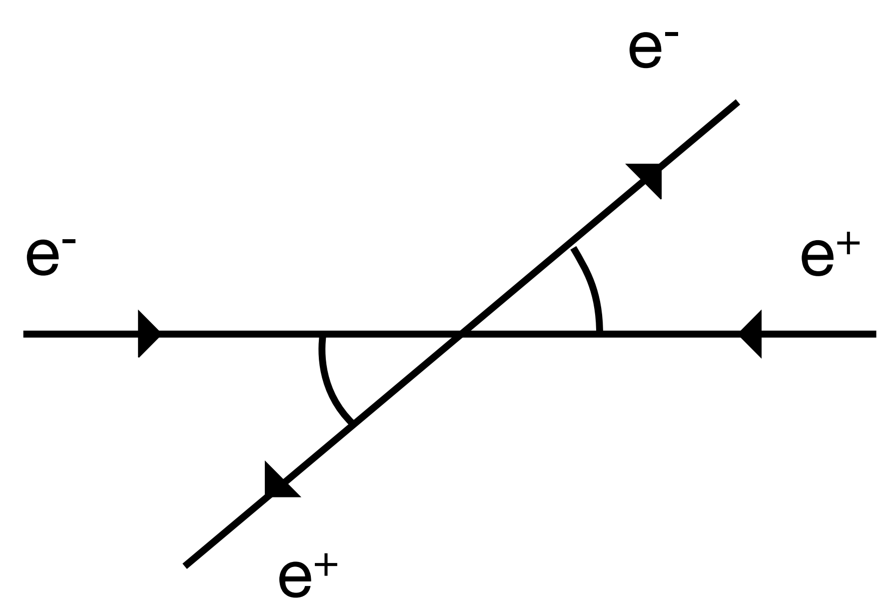
Luminosity spectrum can not be directly measured:

- Reconstruction from gauge process
- Large cross section process needed
  → Large angle **Bhabha scattering**
- Observables are $E_{electron}$, $E_{positron}$ and θ

e^+e^- scattering and annihilation:



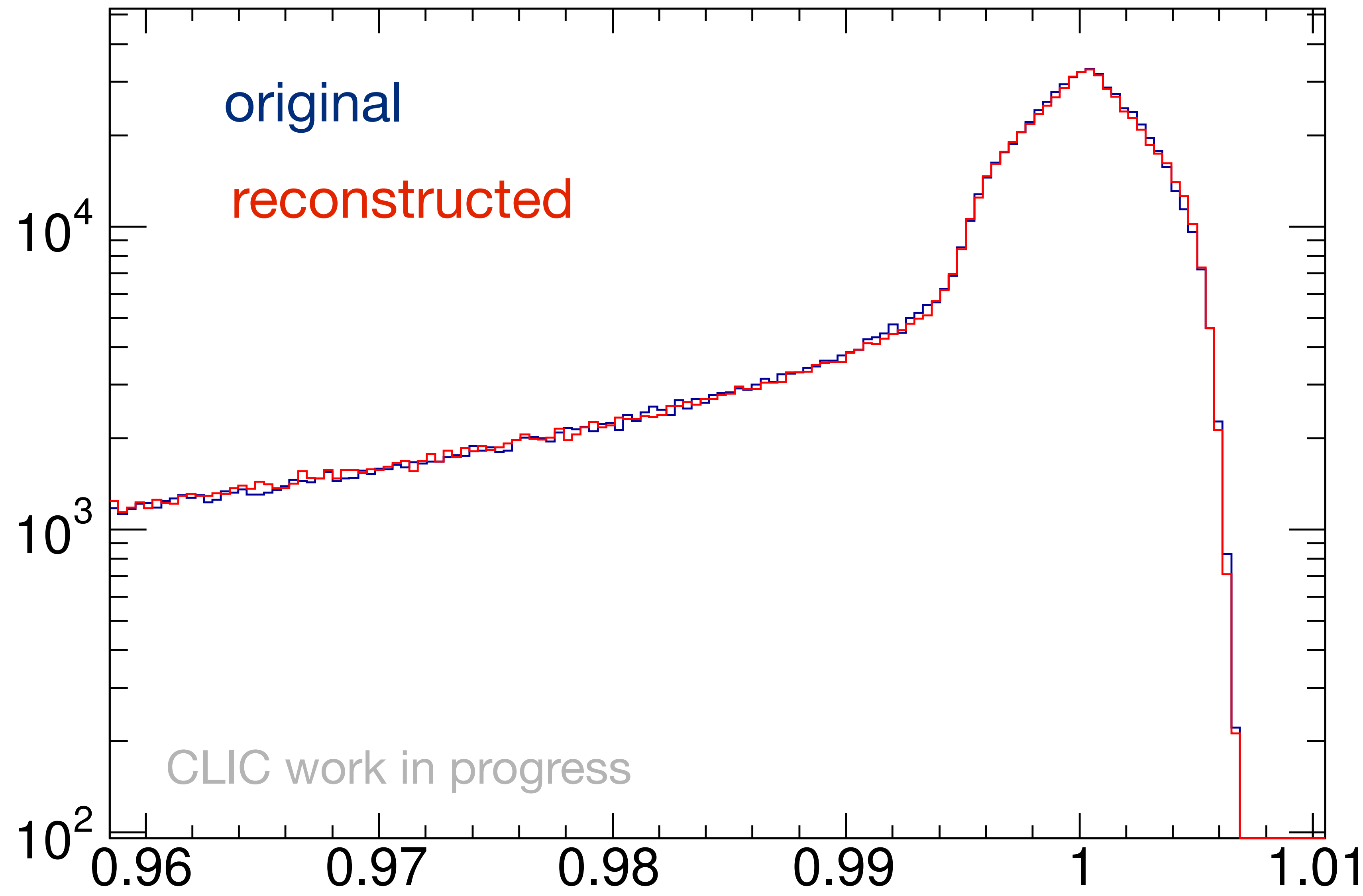




The Goal:
<u>Create minimal model to describe particle energy prior to collision and ISR</u>

Reconstruction of $L(E_1,E_2)$ in parameterised model:

- Get "real spectrum" from beam-beam simulation in Guinea Pig
- Extract energy and angular resolution from full detector sim
- Apply 3 stage reweighing fit to obtain model parameters

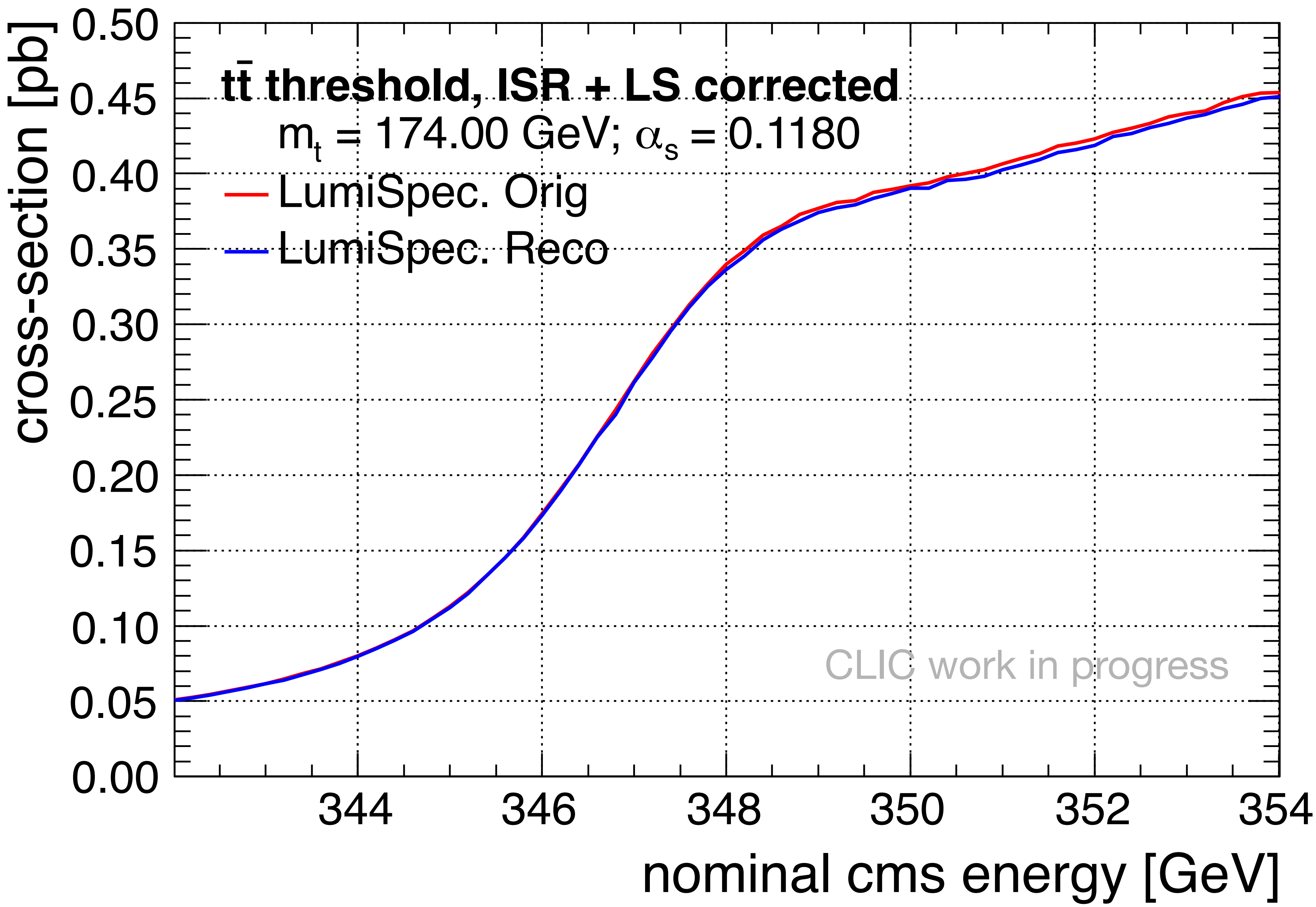


Model can successfully reconstruct real Lumi Spectrum

The Result

Current status:
Full studies for 350 GeV are still ongoing

For now first study:
Results from 3 TeV scaled down to 350 GeV



Syst. uncertainty of $\Delta m_t \sim$ 6 MeV

Goal:
Fully realistic reconstruction of the luminosity spectrum at 350 GeV

Summary

Future Linear e^+e^- Colliders:

- Two proposed concepts
- High luminosity high precision machines

Measurement of Top Mass at CLIC:

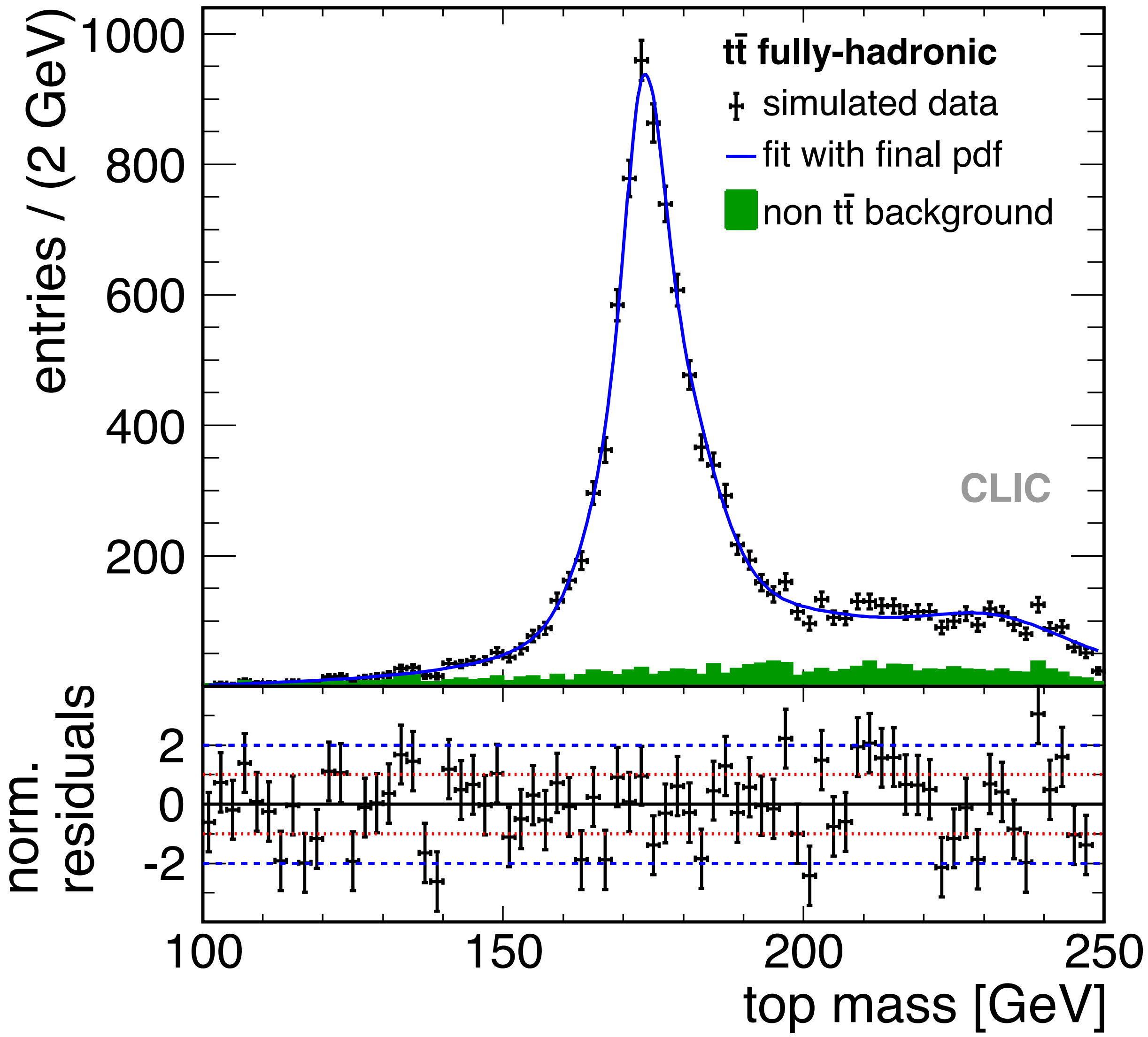
- Reconstruction of the invariant mass @ 500 GeV
- Threshold Scan:
  - Statistical uncertainties of ~ 20 MeV
  - comparable experimental systematics
  - Mass measurement in theoretically well defined setting

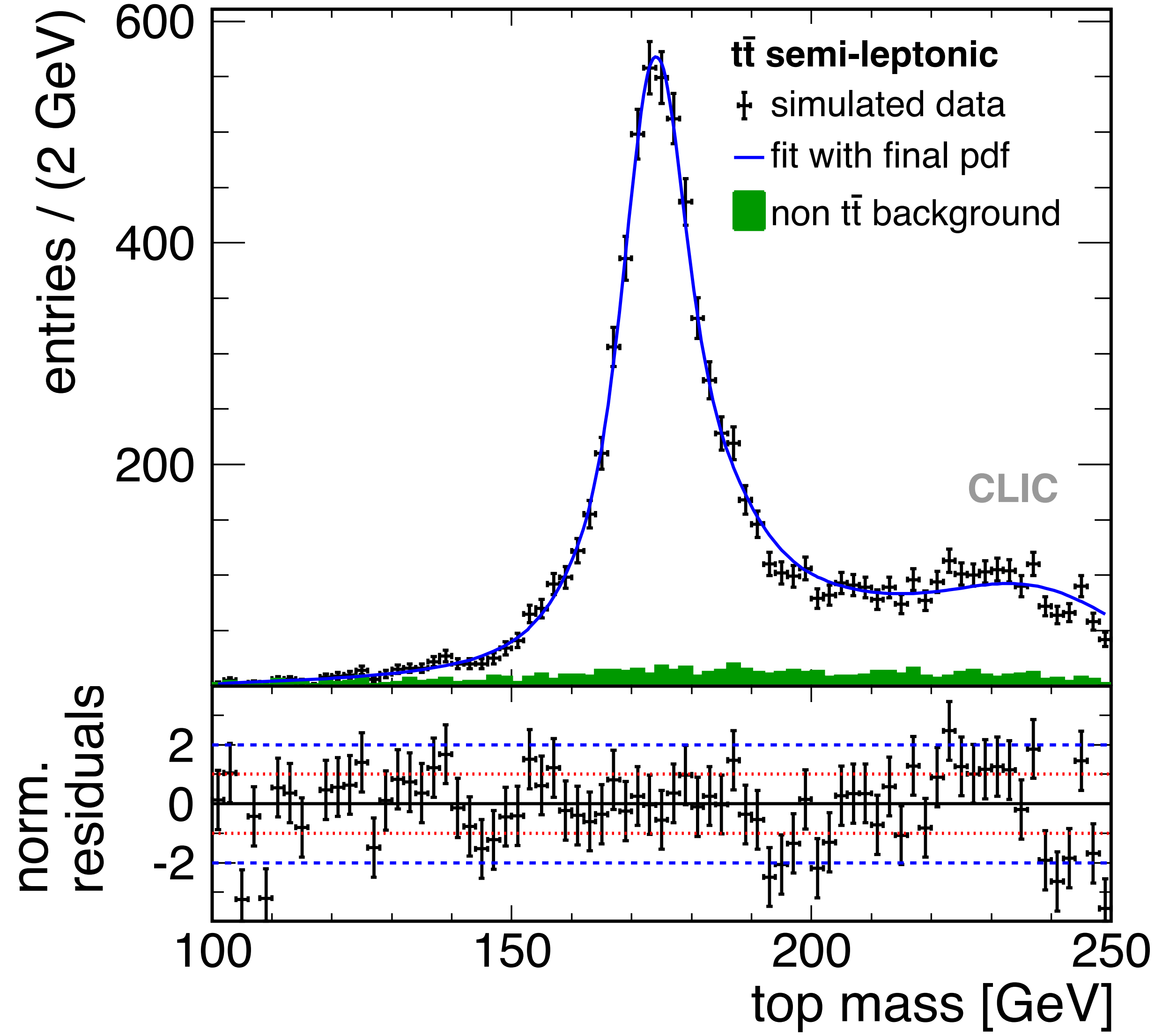
Luminosity Spectrum potential major contribution to uncertainty:

- Reconstruction with parametrised model based on analysis of Bhabha Scattering
- Scaling of 3 TeV results to the top threshold region indicate **syst. uncertainty Δm_t ~ 10 MeV**
- **Full studies** for 350 GeV CLIC **ongoing**

Backup

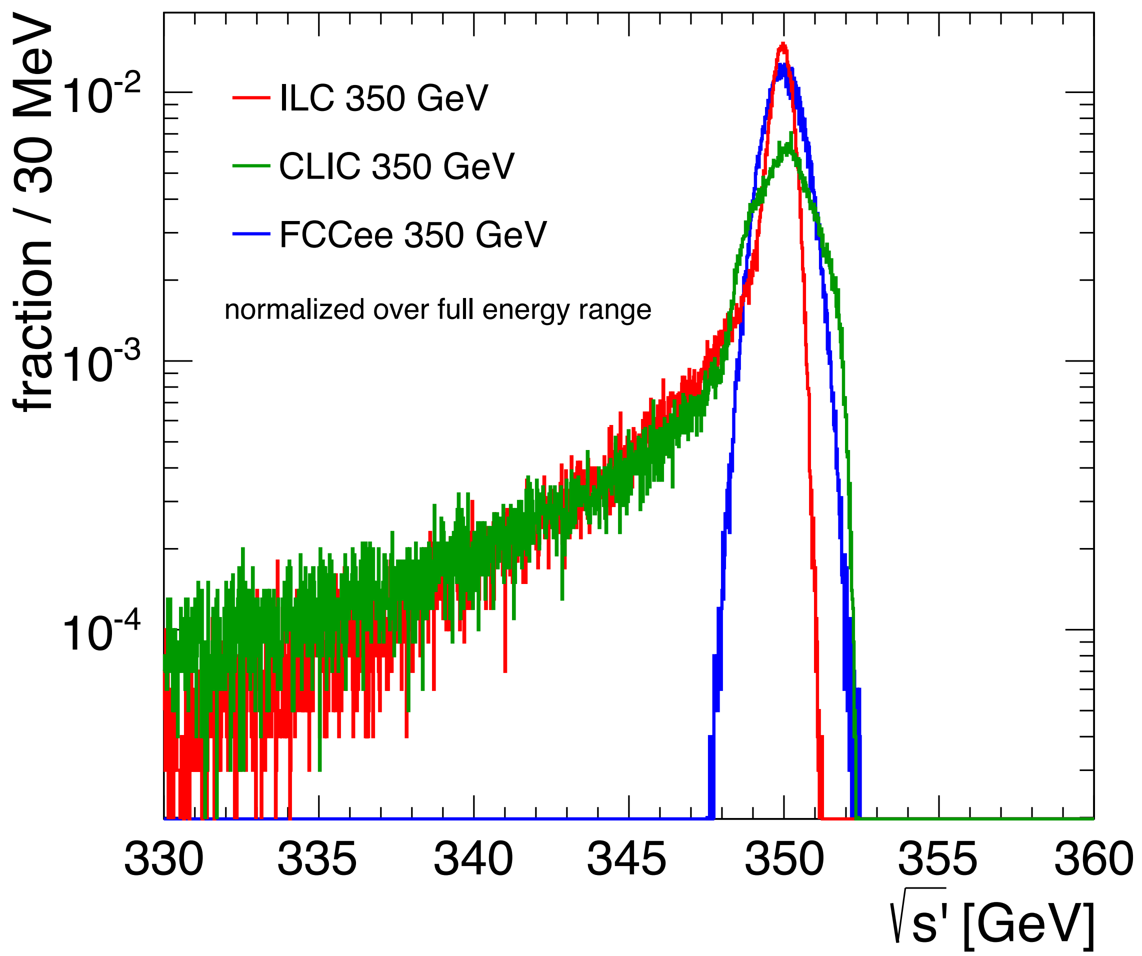
Mass Reconstruction Above Threshold

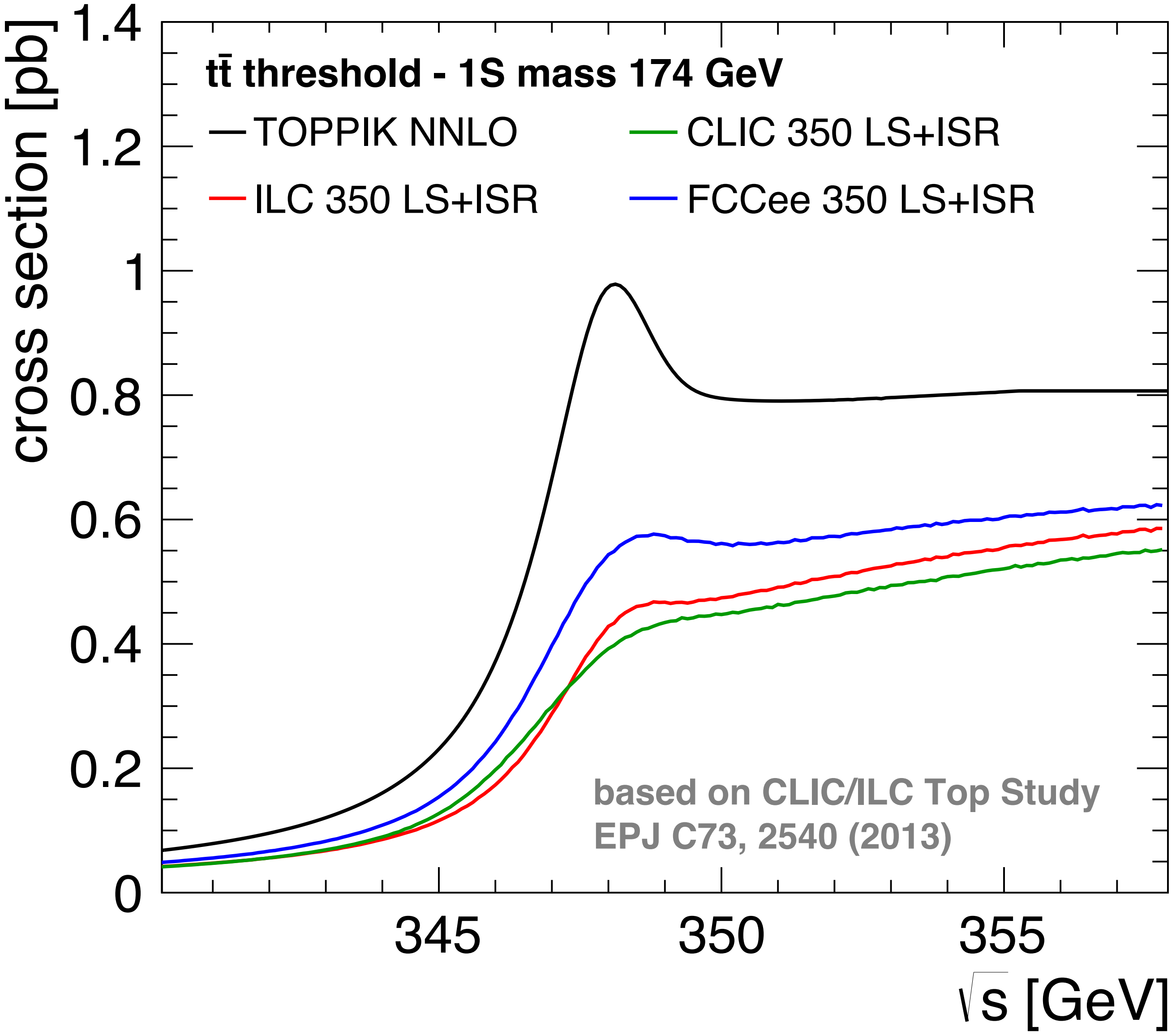




- Width less constrained than mass: substantial detector effects (peak width ~ 5 GeV compared to 1.4 GeV top width)

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



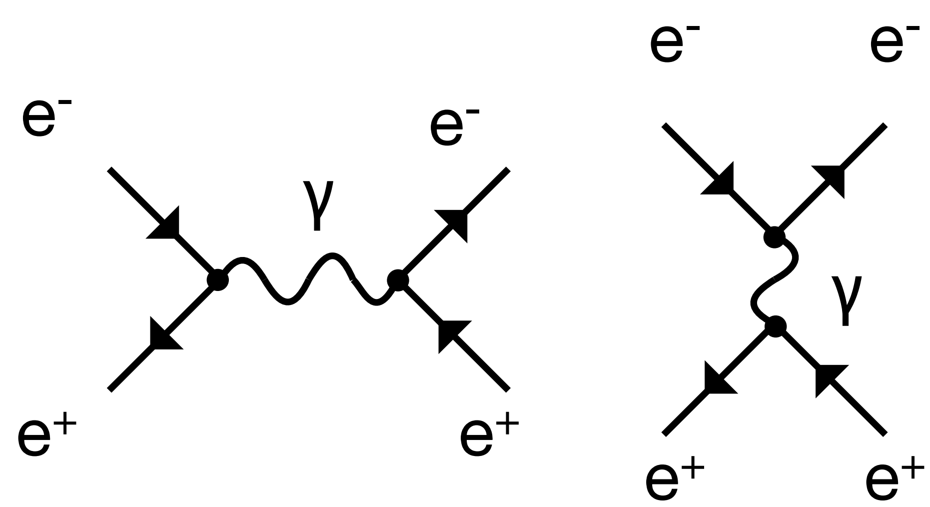


- Slight differences in statistics due to cross section, changes in sensitivity due to steepness of threshold turn-on
- For 100 fb^{-1}, no polarization, 1D mass fit:

16 MeV → 18 MeV → 21 MeV (stat)

FCCee ILC CLIC

Bhabha Scattering



Bhabha scattering:

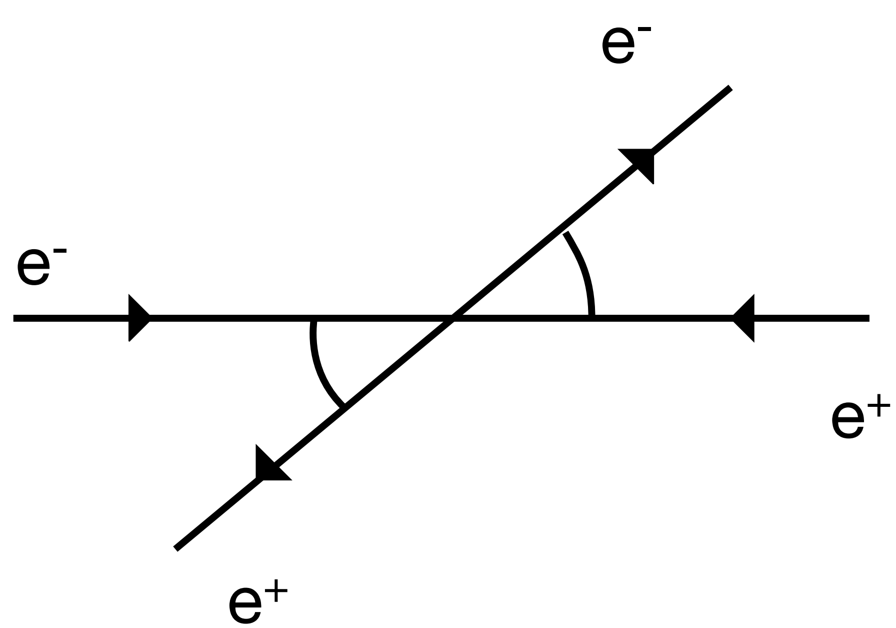
- Combination of scattering and annihilation

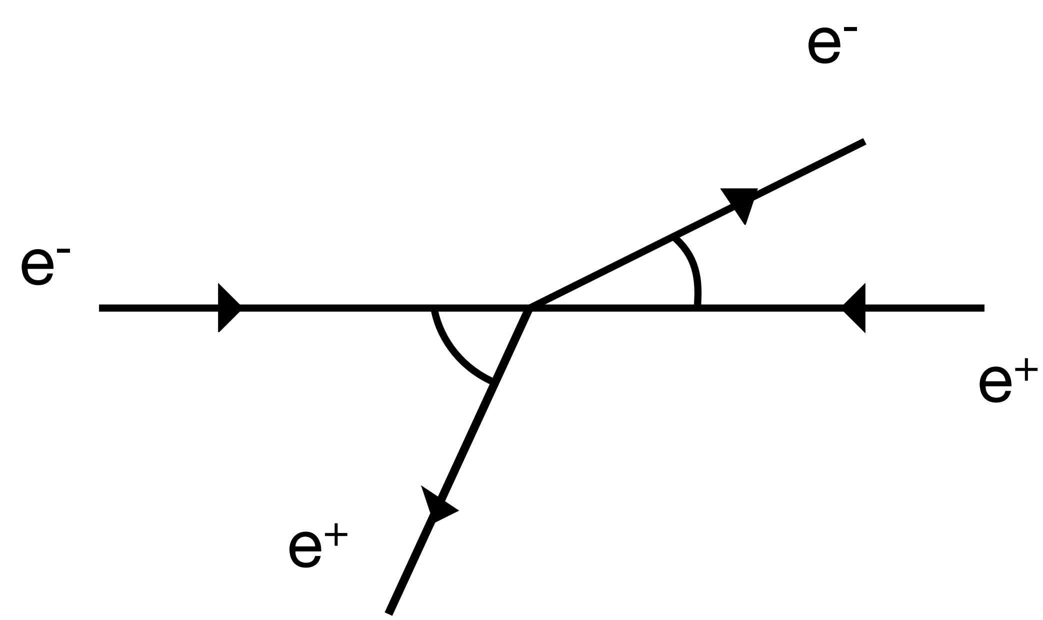
$$\frac{\sqrt{s'_{acol}}}{\sqrt{s_{nom}}} = \frac{\sqrt{sin(\theta_1) + sin(\theta_2) + sin(\theta_1 + \theta_2)}}{\sqrt{sin(\theta_1) + sin(\theta_2) - sin(\theta_1 + \theta_2)}}$$

$$\sqrt{s'_{acol}} = \sqrt{s'}$$

if only one electron emitted photons

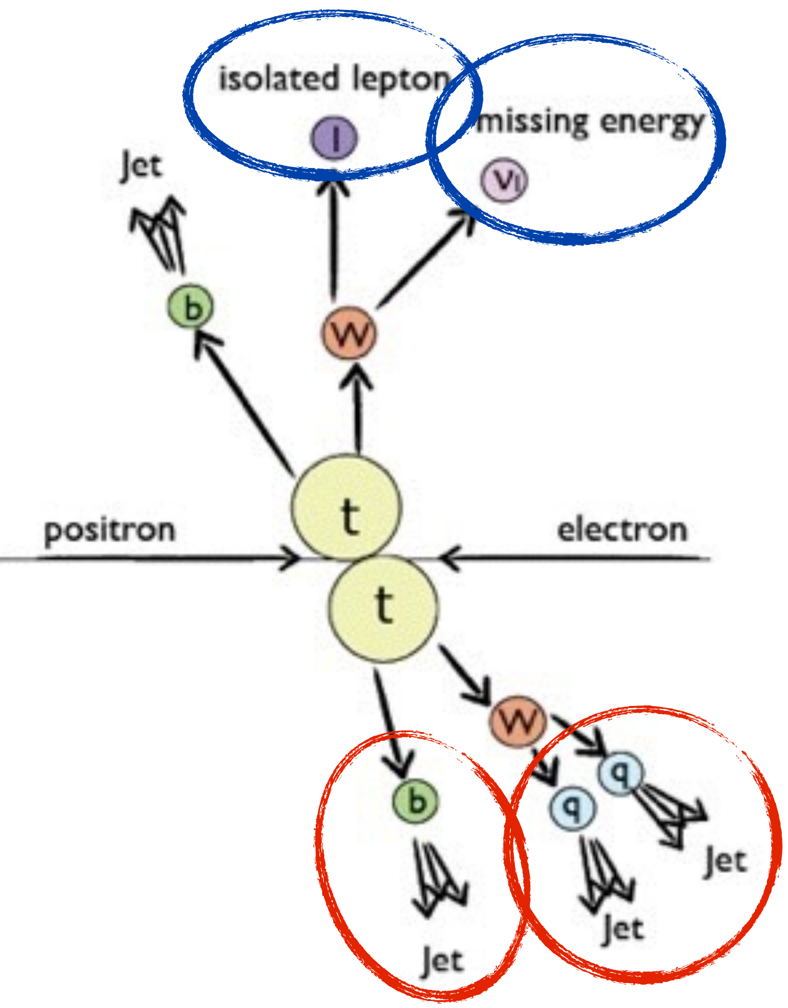
Measure angles and E_2 E_1





Identifying & Reconstructing Top Quarks

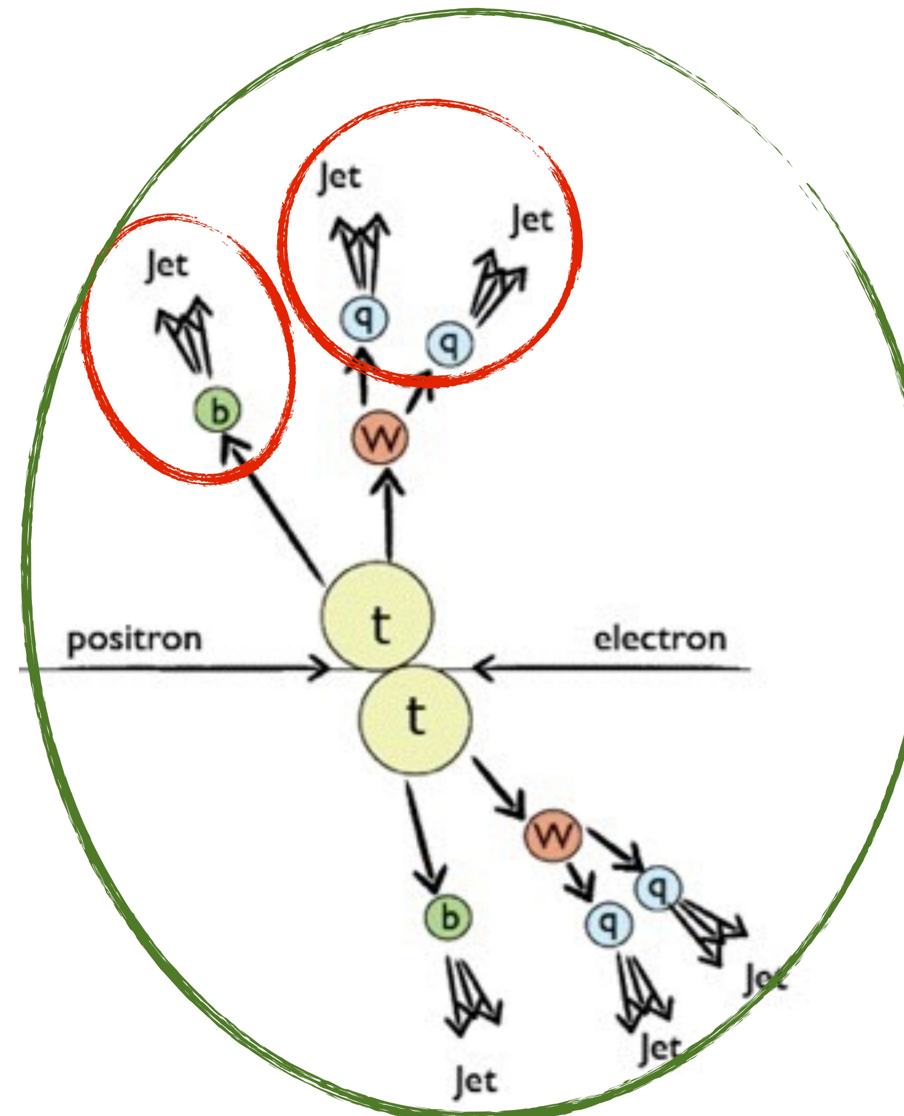
- Strategy depends on targeted ttbar final state



Semi-leptonic:
- isolated lepton ID, momentum measurement
  - provides t / tbar identification
- missing energy measurement

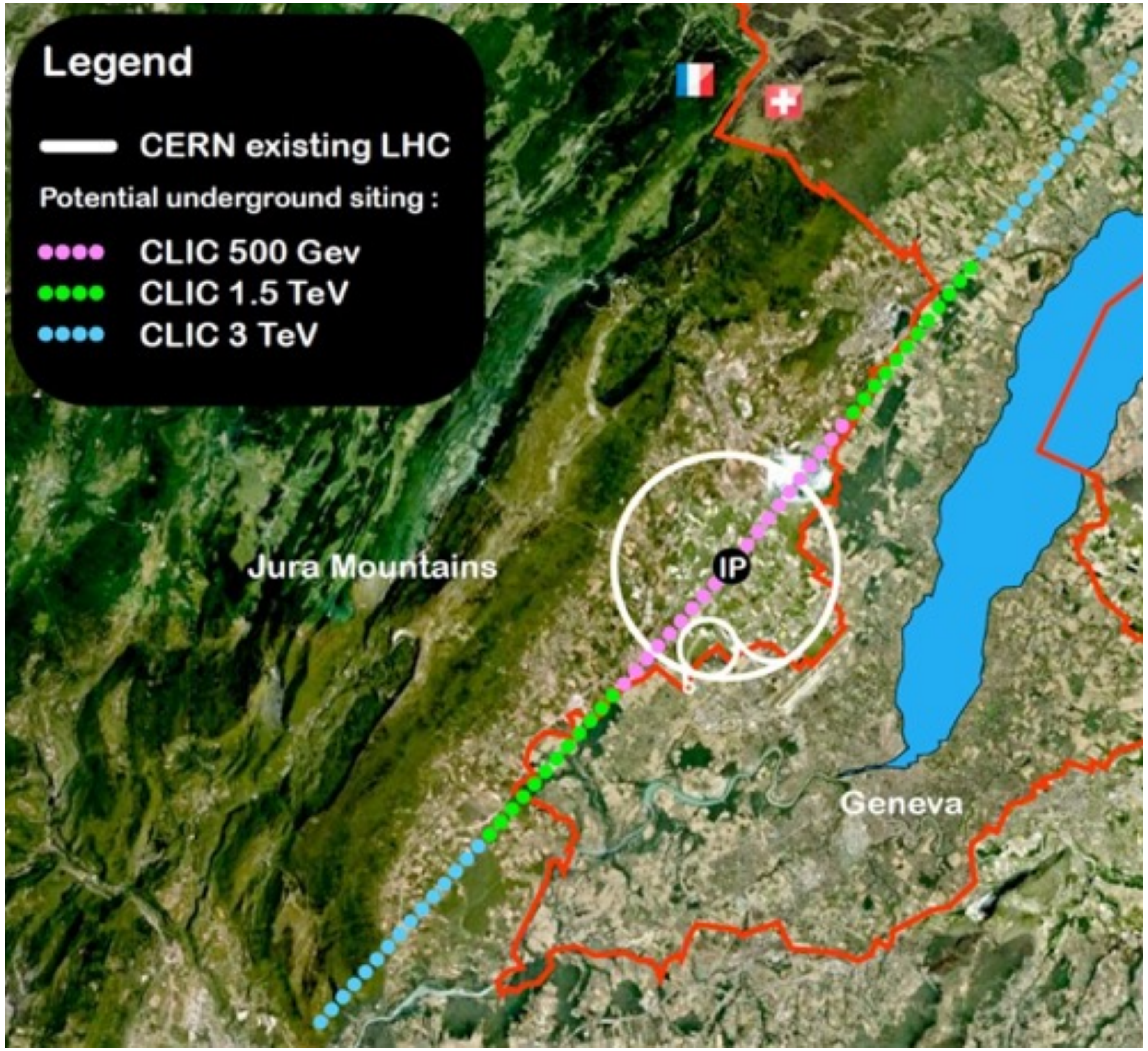
Universal
- Flavor tagging:
  - b - identification
  - b/c separation
- b-Jet energy measurement
- light Jet reconstruction & energy measurement

All-hadronic
- global hadronic energy reconstruction



Analysis Strategy

- Identify the type of top decay according to number of isolated leptons
  - all-hadronic (0 leptons), semi-leptonic (1 lepton), leptonic (>1 lepton) -> rejected
- Jet clustering (exclusive k_t algorithm) according to classification: 6 or 4 jets
- Flavor-tagging: Identify the two most likely b-jet candidates
- W pairing: Jets / leptons into W bosons
  - Unique in the semi-leptonic case: 1 W from two light jets, 1 W from lepton & missing Energy
  - 3 possibilities (4 light jets) in all-hadronic case - Pick combination with minimal deviation from nominal W mass
- Kinematic fit - Use Energy/momentum conservation to constrain event
  - Performs the matching of W bosons an b-Jets to t candidates
  - Enforces equal t and anti-t mass: Only one mass measurement per event
  - Provides already good rejection on non-tt background
- Additional background rejection with likelihood method based on event variables (sphericity, b-tags, multiplicity, W masses, d_{cut}, top mass w/o kin fit)


Legend
CERN existing LHC
Potential underground siting :
CLIC 500 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Jura Mountains
IP
Geneva

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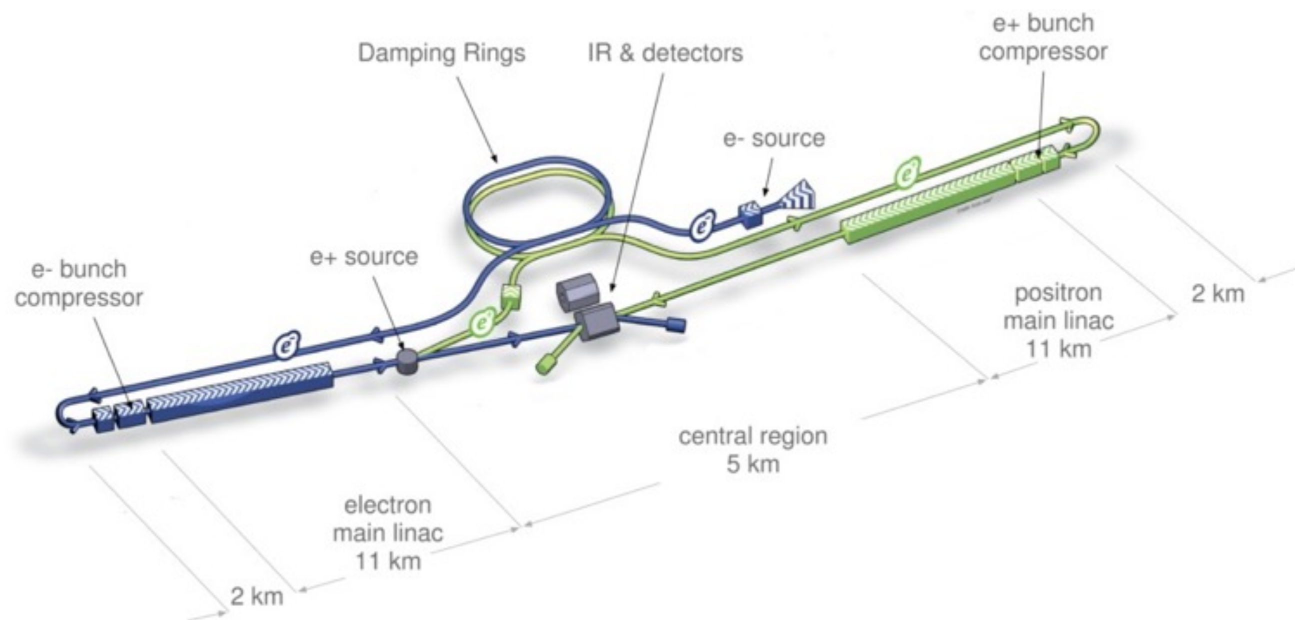
Two concepts e^+e^--colliders at the energy frontier:

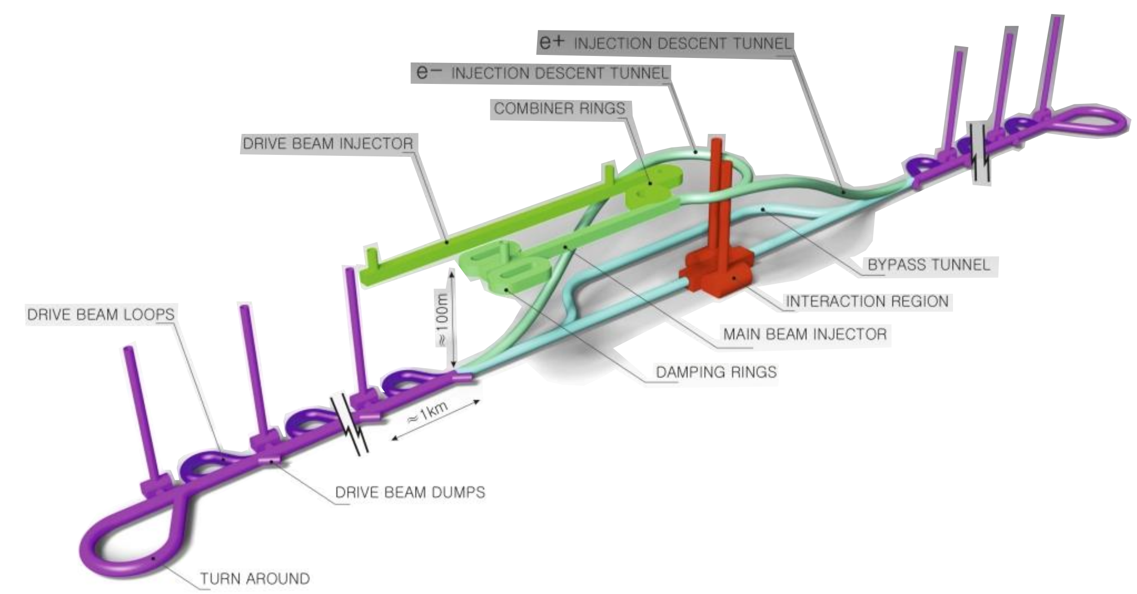


International Linear Collider:

- 250, 500 GeV, upgrade to 1 TeV
- SCRF with ~ 35 MV/m
- TDR completed

Compact LInear Collider:

- Three stages 350, 1400 and 3000 GeV
- Two-beam acceleration scheme
- Warm RF with ~100 MV/m
- Expected to reach maturity ~ 2018
- Focus of this talk



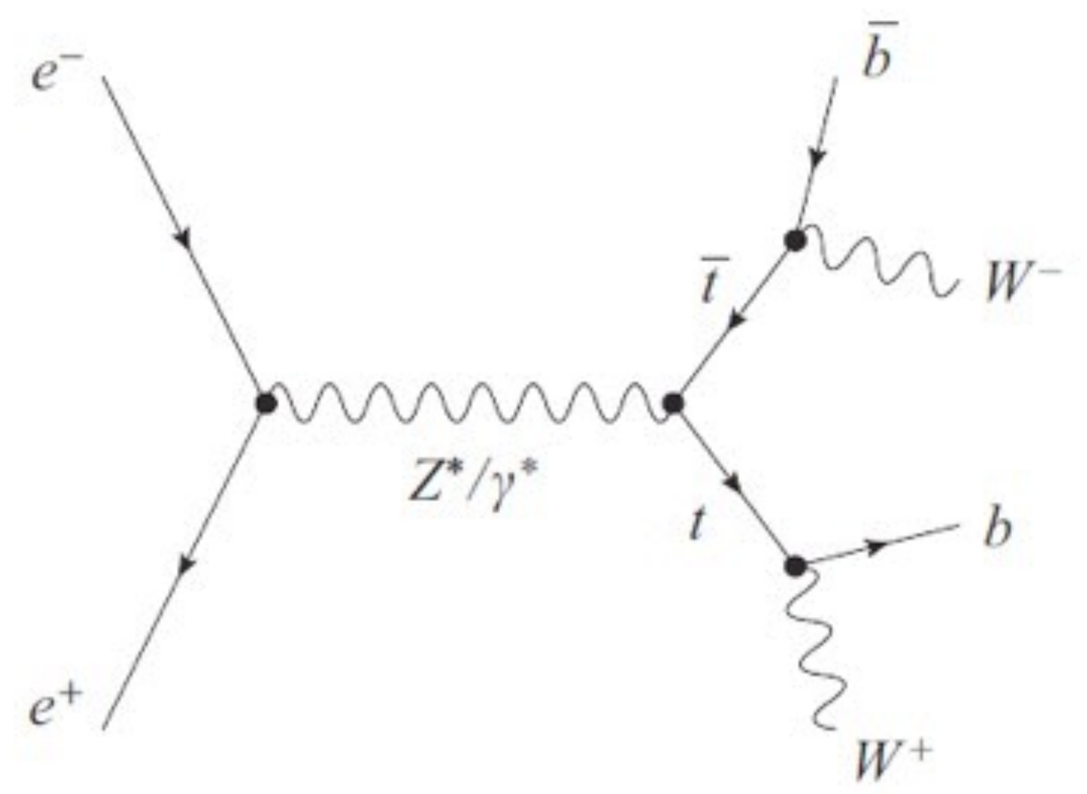
➤ Both provide **high luminosity** (1 - 2 x) & optional **beam polarization**

Top Precision Physics

Top mass measurement at LHC:

- Most precise measurement in template fits
- Actually measured: mass used in event generators for fit
- Connection to theoretically well defined mass scheme unclear,
uncertainty *O* (GeV)

Top production at and above 350 GeV at future e^+e^- linear colliders:



Dominant production process: Top pair production

Rich physics potential:

- Threshold Scan enables measurement of theoretically well defined top mass and other top properties
- Above threshold precision measurements of electroweak couplings:
Sensitivity to **New Physics**
- Precise initial & clean final states