Perspectives for Top Physics at the (I)LC

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Outline

- Introduction: Top Physics at Future Colliders
- Linear Colliders in brief
- Top quarks in e^+e^- collisions
- Top properties: Mass
- Top as a BSM probe: Electroweak couplings
- The Top Yukawa Coupling
- Summary

Top Physics at Future Colliders

- Key motivation for future energy frontier colliders after the Higgs discovery:
    - Full understanding of EWSB
    - Discovering / constraining New Physics to find the “breaking point” of the Standard Model - and to answer fundamental open questions

- As the heaviest SM particle, the Top plays an important role in this: Strongest coupling to the Higgs field, potential sensitivity to New Physics
    - The top mass is the leading uncertainty in the study of the vacuum stability of the SM
    - Deviations from the SM expectations in electroweak couplings could point to BSM physics at higher scales

Top physics will be a key component for any future collider

- Top is the only quark that has not yet been studied in e^+e^- collisions - will benefit substantially from further precision measurement

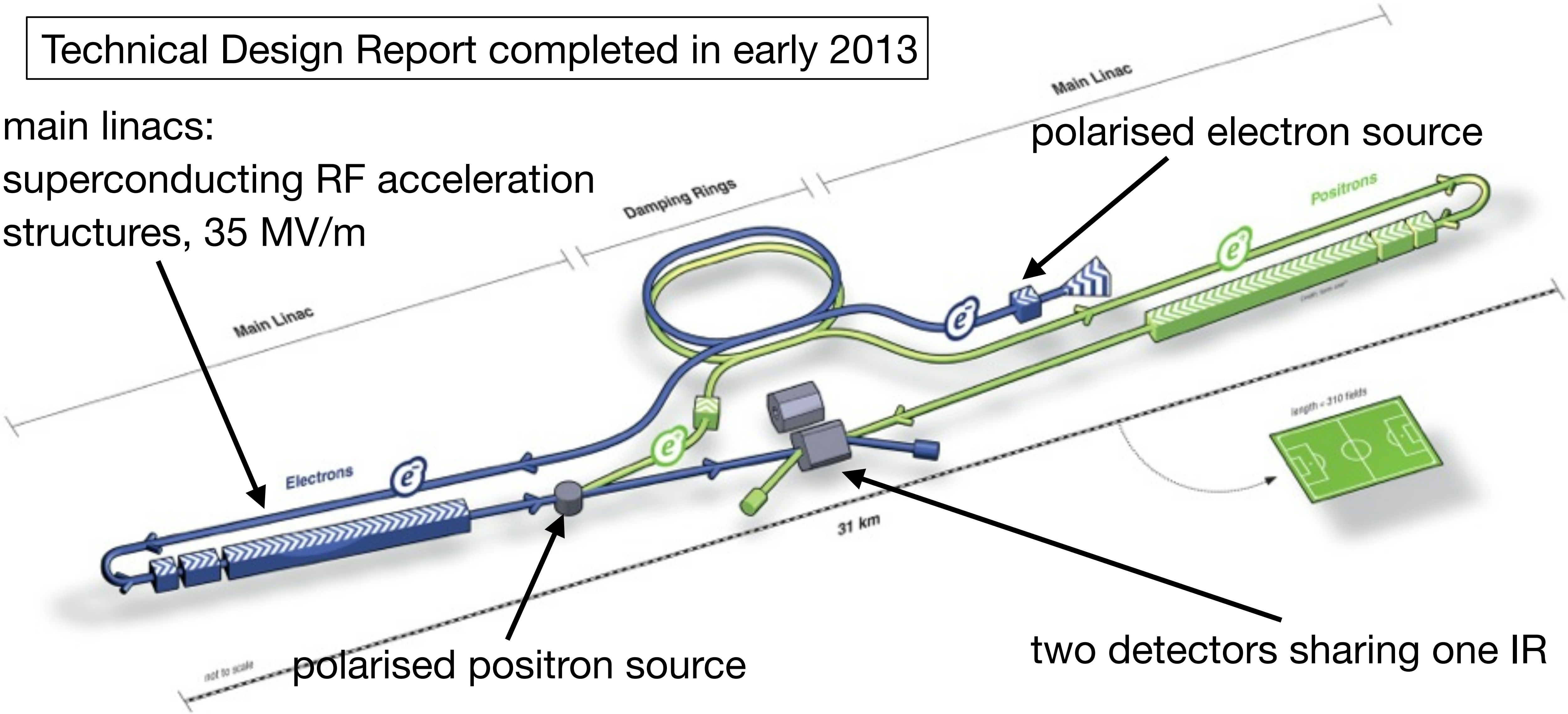
ILC - The International Linear Collider

- Currently the most advanced concept for a future energy frontier collider
  - e^+e^- collider, baseline energy 500 GeV, high luminosity: 2×10^{34} cm^{-2}s^{-1}
    - staged construction, starting from 250 GeV / 350 GeV
    - upgrade to 1 TeV possible (extension of linacs), luminosity upgrade by rate increase

Technical Design Report completed in early 2013

main linacs:
superconducting RF acceleration structures, 35 MV/m

polarised electron source

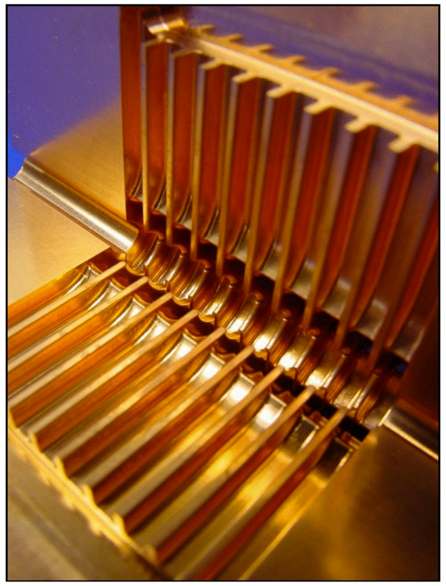


polarised positron source

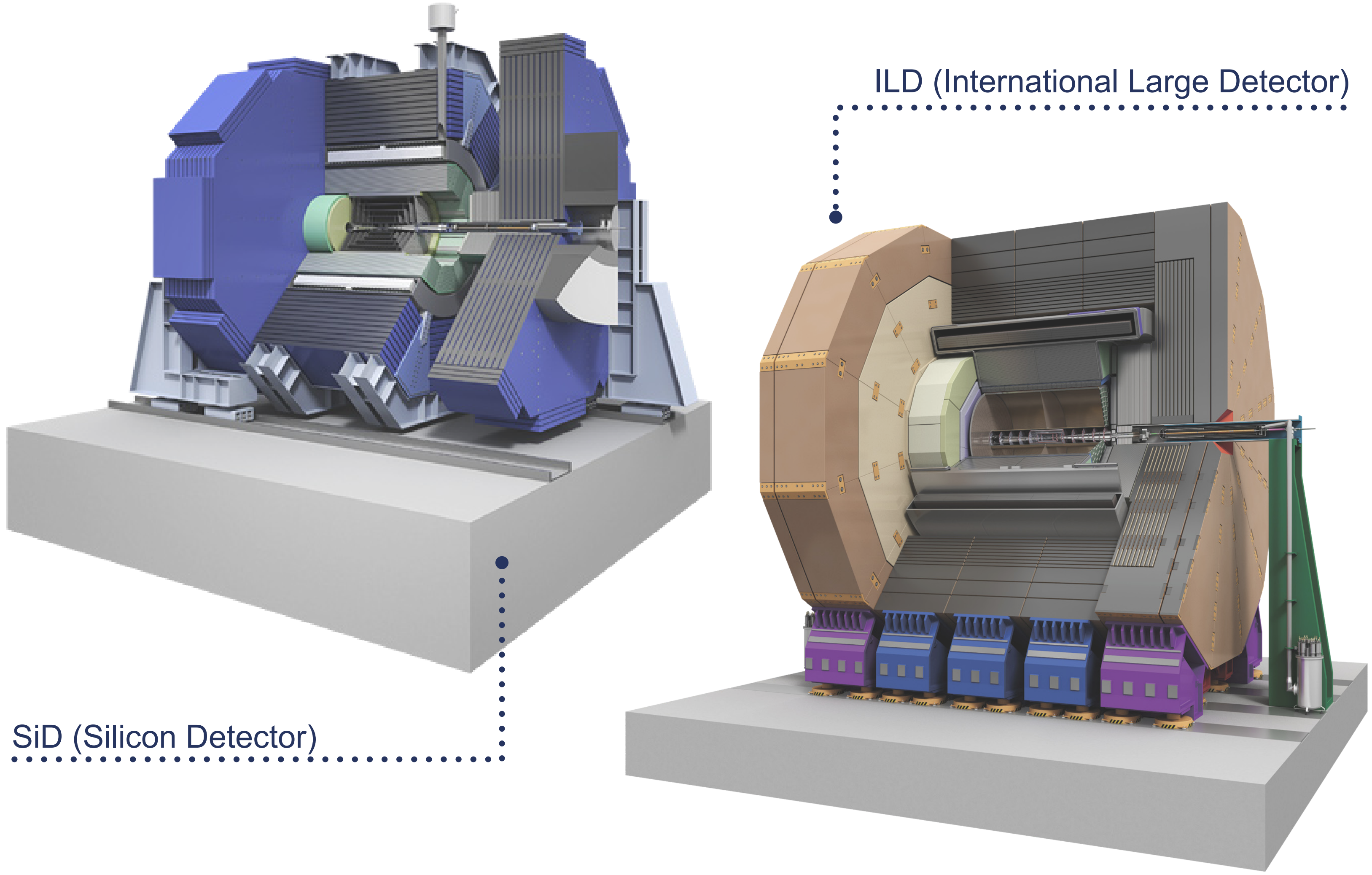
two detectors sharing one IR

CLIC - The Compact Linear Collider

- A possible future energy frontier collider at CERN
  - e^+e^- collisions at up to 3 TeV with high luminosity (~ 6 x 10^{34} $cm^{-2}s^{-1}$ at 3 TeV)
  - Staged construction 350 - 500 GeV, ~ 1.5 TeV, 3 TeV - detailed energies under study, based on physics and technical considerations
  - Based on two-beam acceleration: gradients of 100 MV/m
  - Development phase until ~2018 - CDR completed in 2012



Detector Systems at Linear Colliders



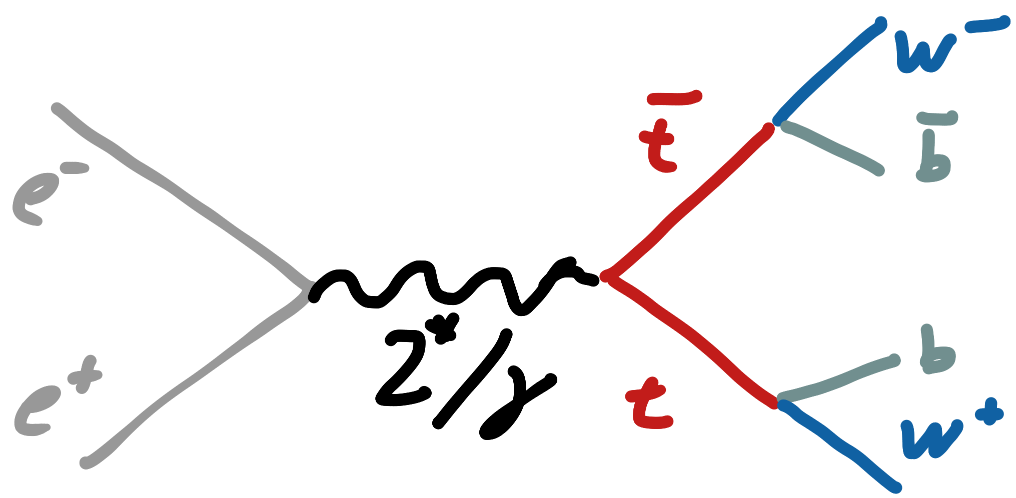
- Low-mass, high precision vertexing & tracking
- Highly granular calorimeters
- Particle flow event reconstruction

- CLIC detectors based on ILC concepts, with modifications in the calorimeters, vertex and forward regions to account for higher energy and higher backgrounds

- Detailed simulation models implemented in GEANT4
- Realistic event reconstruction including pattern recognition, tracking, PFA
- ▸ Full simulation studies used for all results presented here

Top Quark Physics at Linear Colliders

- The dominant production mechanism: Top pair production



- Rich physics opportunities:

Top Quark Physics at Linear Colliders

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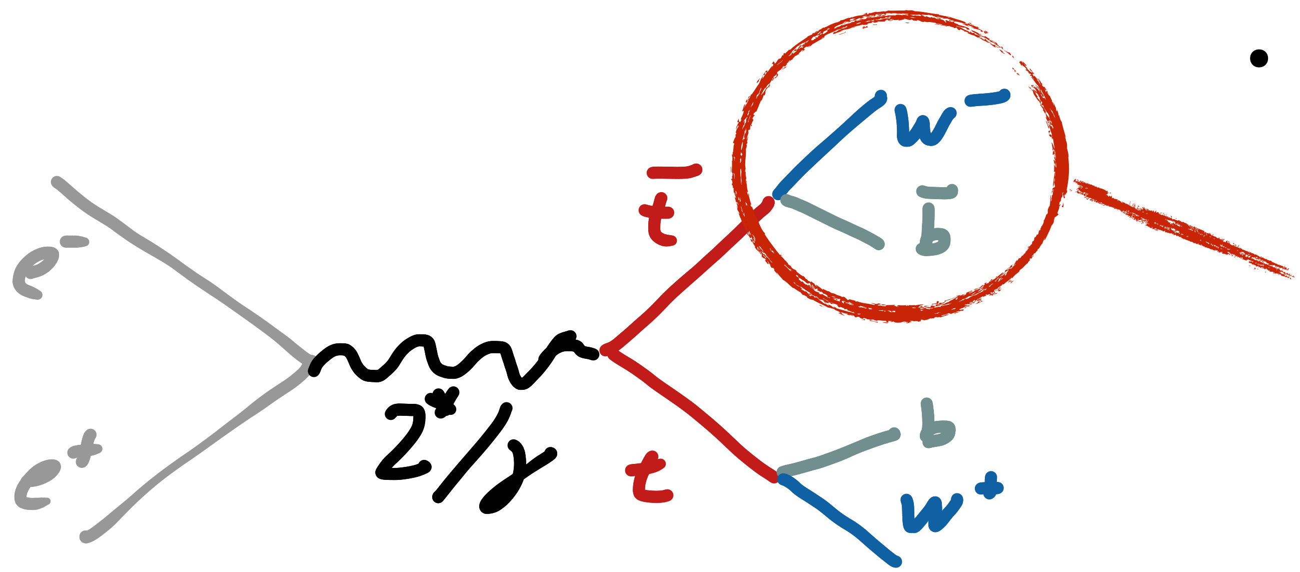

- Rich physics opportunities:
  - Top properties: **mass**, width, decay modes
  - BSM sensitivity: CP violation, flavor-changing decays,…

Top Quark Physics at Linear Colliders

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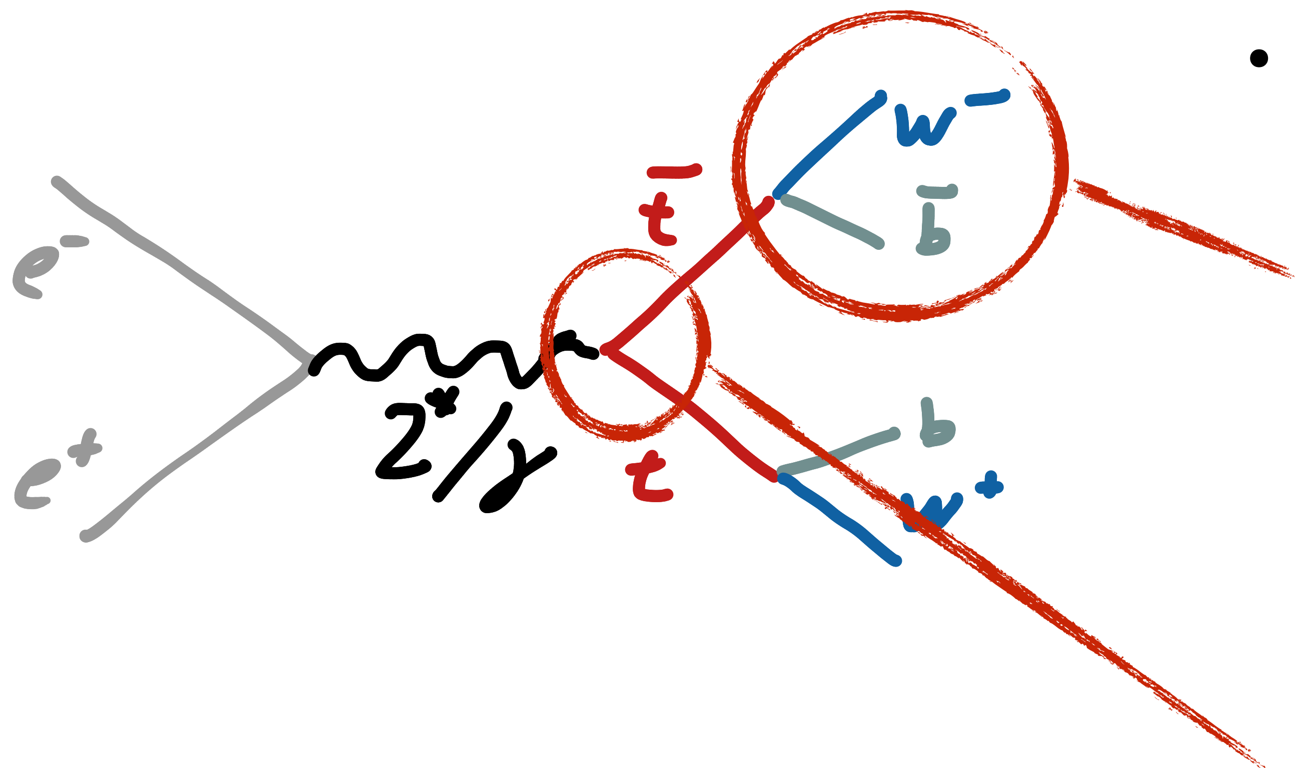

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  - Top properties: **mass**, width, decay modes
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  - Top properties: **mass**, width,
  - Yukawa coupling, strong coupling constant
  - **Electroweak couplings** - sensitivity to BSM physics

Top Quark Physics at Linear Colliders

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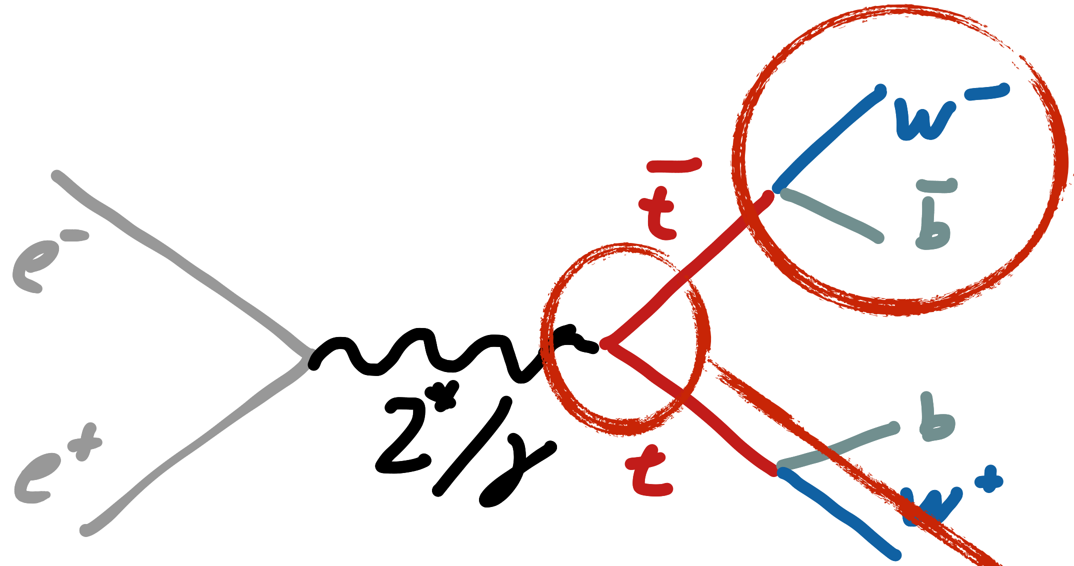

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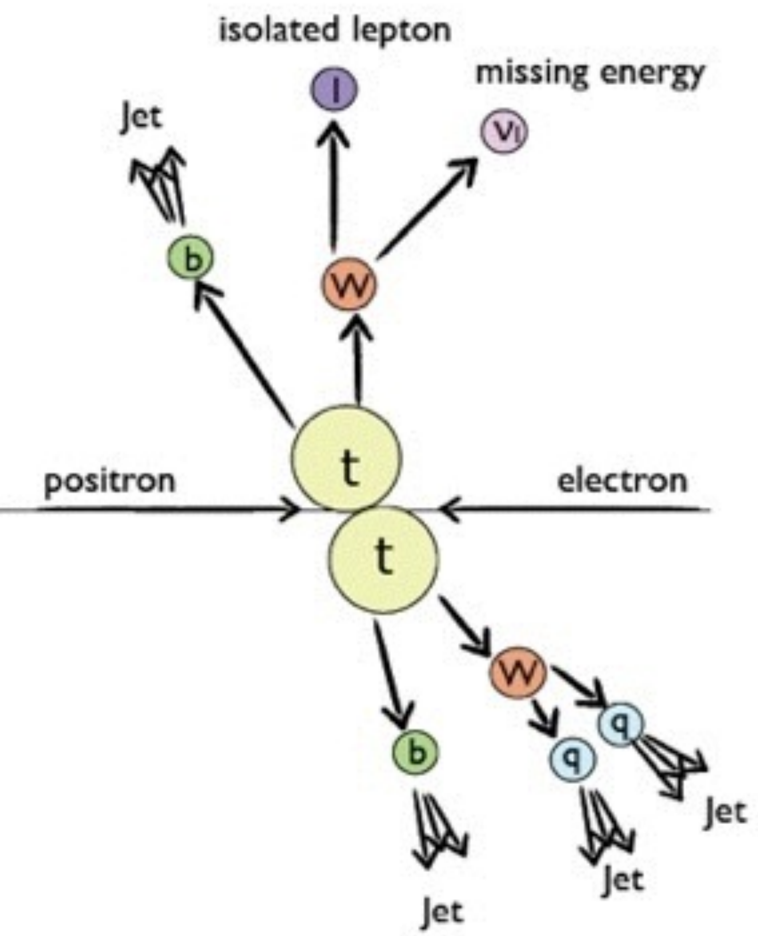
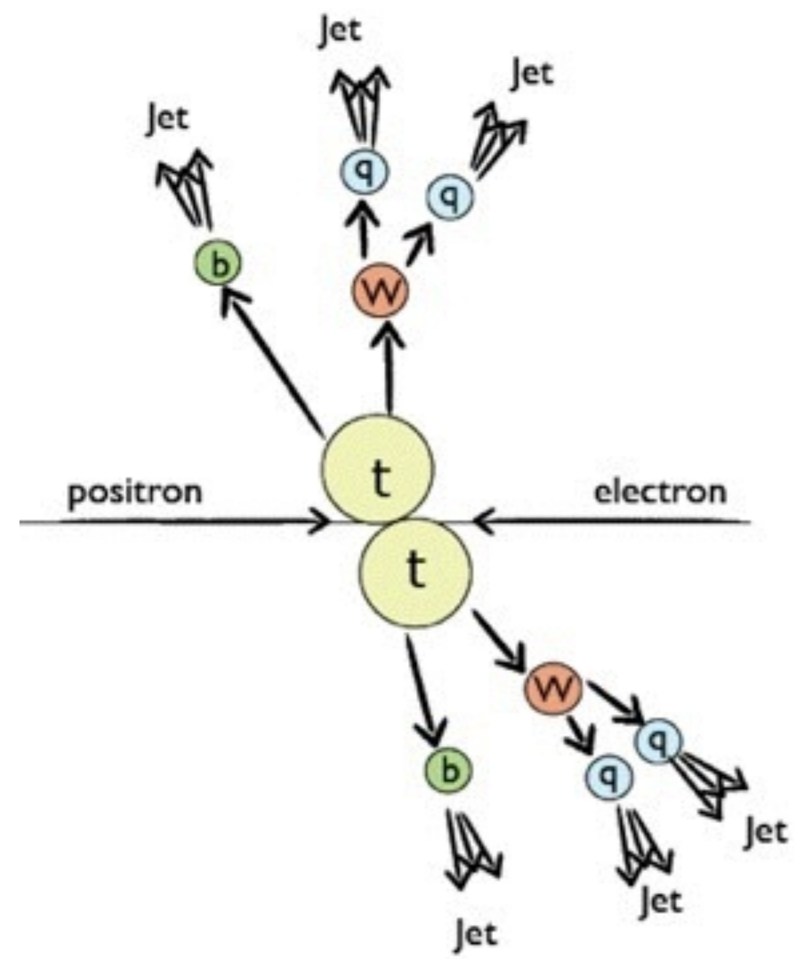
- Measurements enabled by
  - known initial state & clean final state
  - Possibility for polarized beams - crucial for coupling measurements

Identifying & Reconstructing Top Quarks

- Strategy depends on targeted ttbar final state





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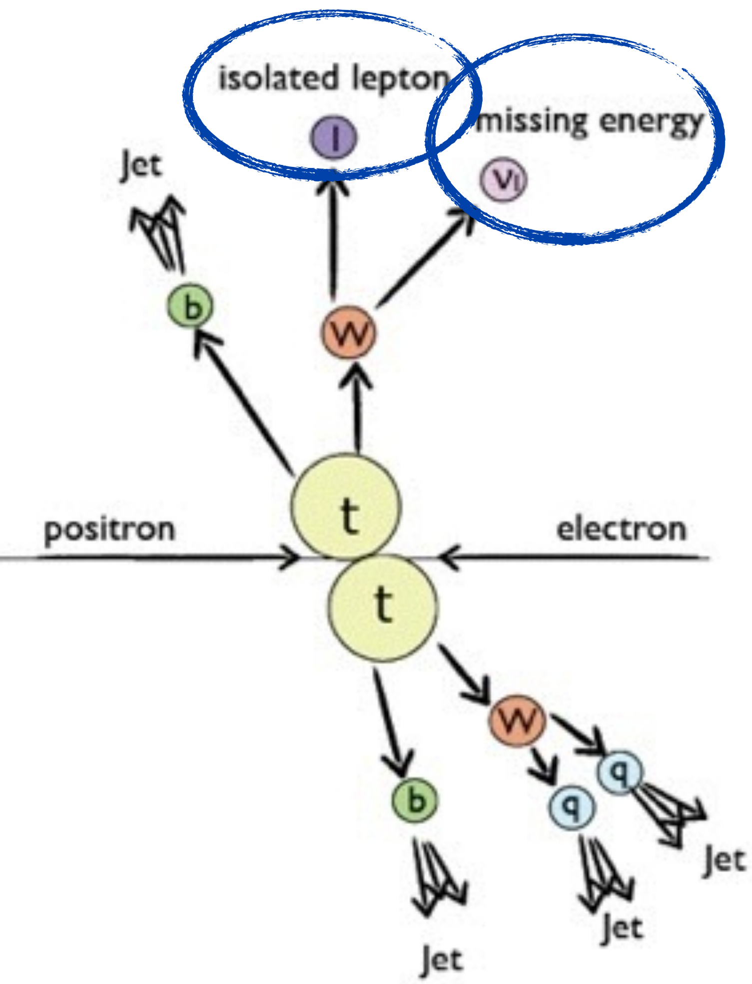
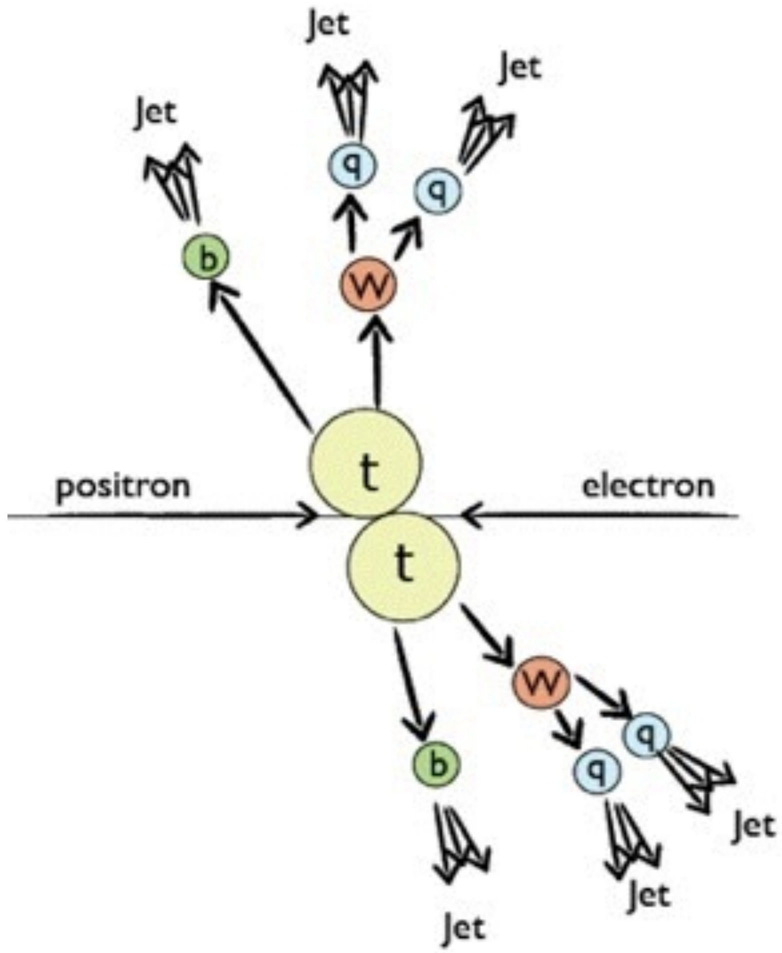


Semi-leptonic:
- isolated lepton ID, momentum measurement
  - provides t / tbar identification
- missing energy measurement



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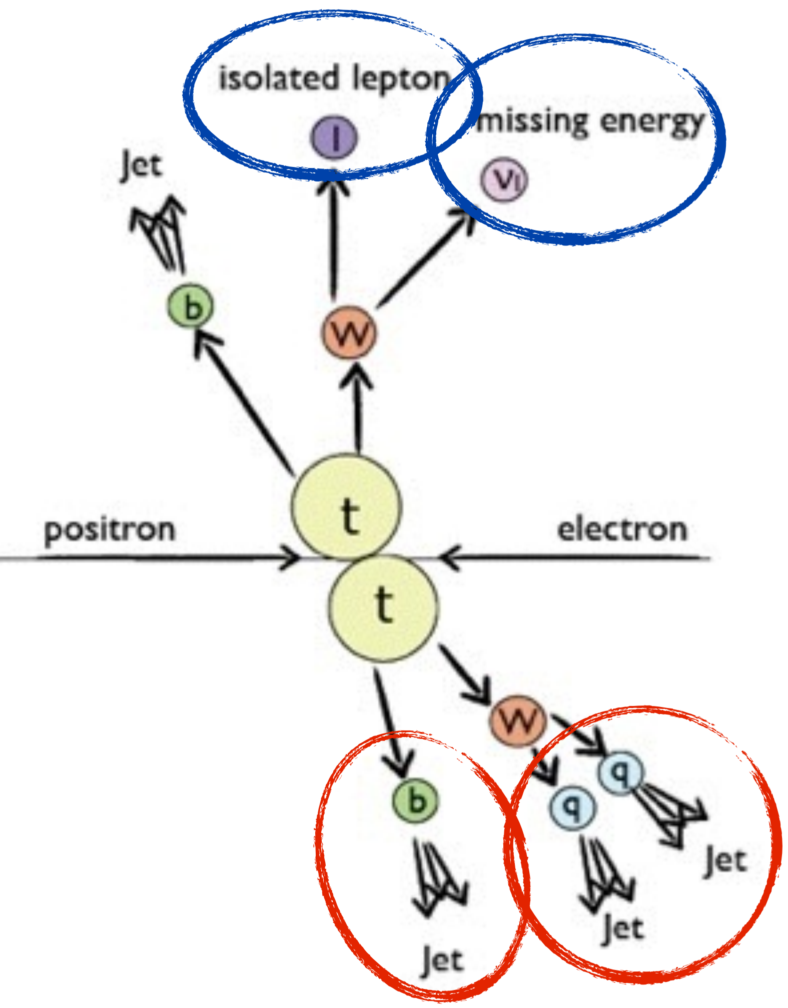

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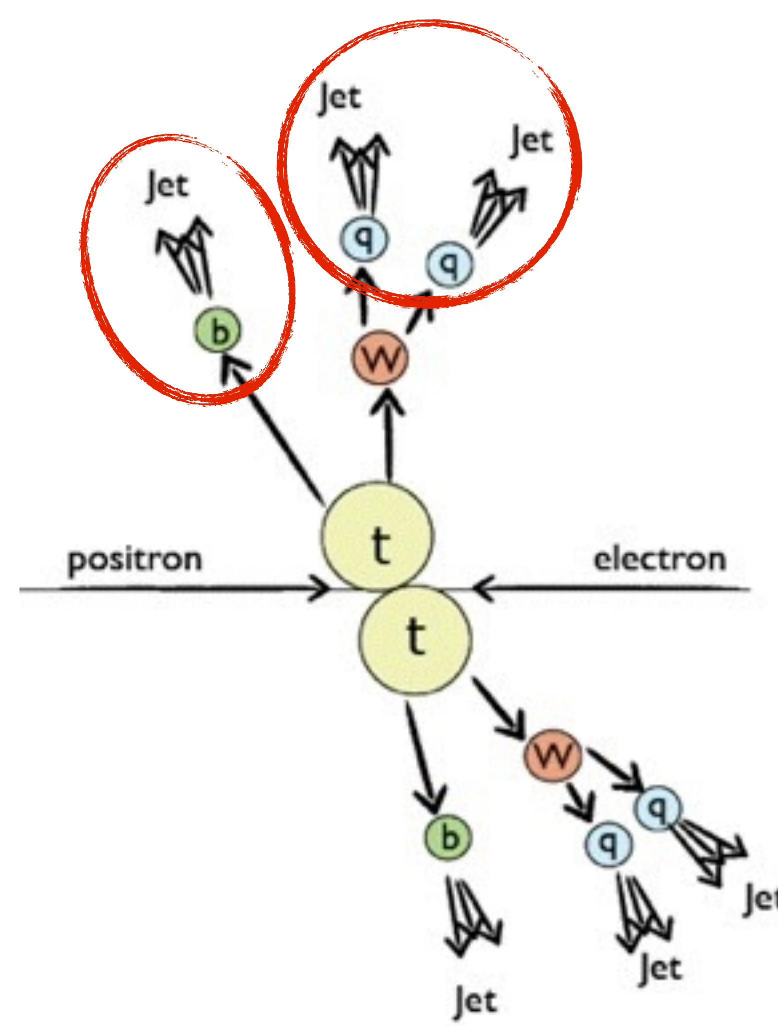
Universal
- Flavor tagging:
  - b - identification
  - b/c separation
- b-Jet energy measurement
- light Jet reconstruction & energy measurement



Identifying & Reconstructing Top Quarks

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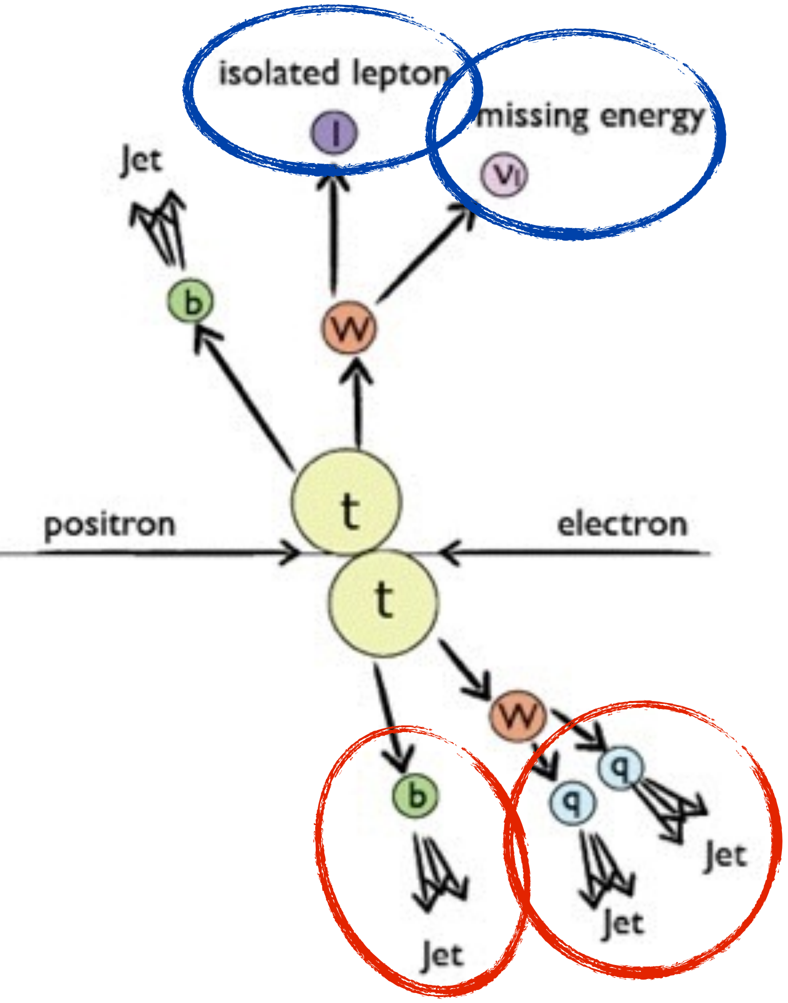

Semi-leptonic:
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Universal
- Flavor tagging:
  - b - identification
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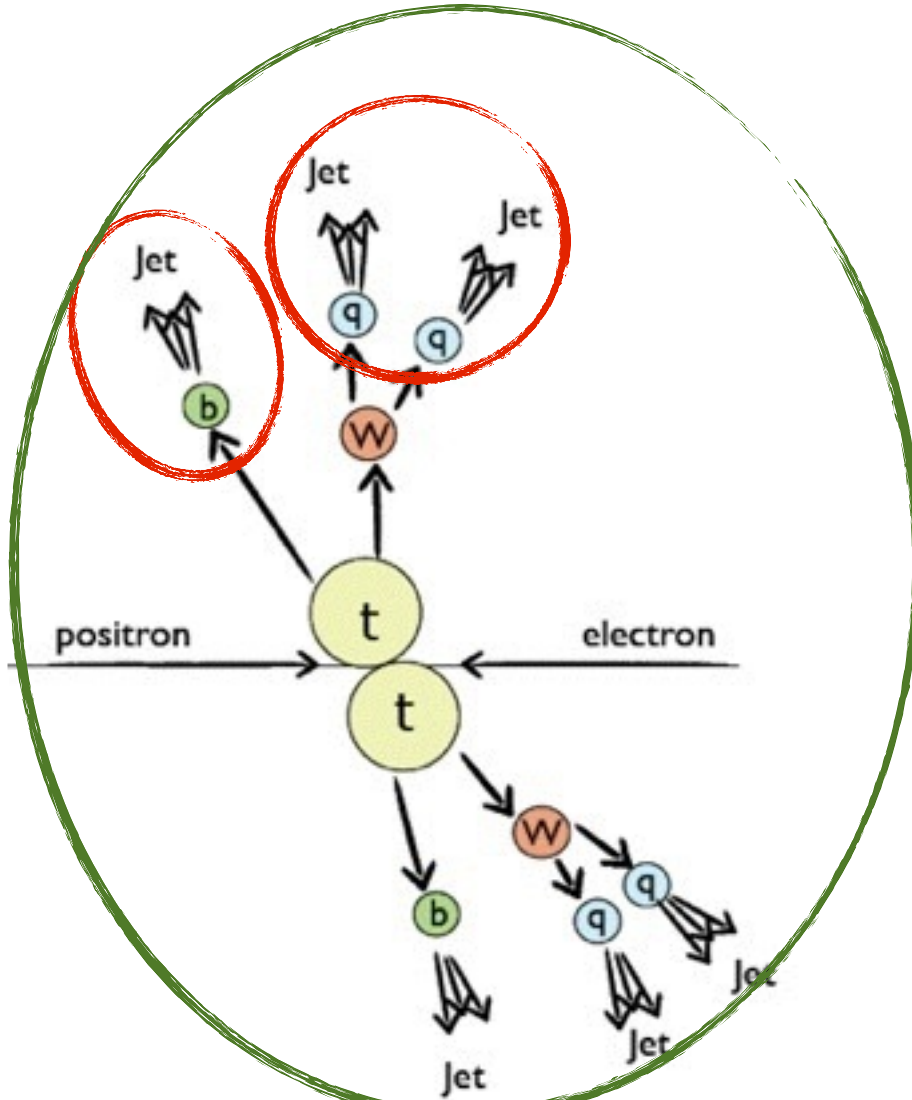
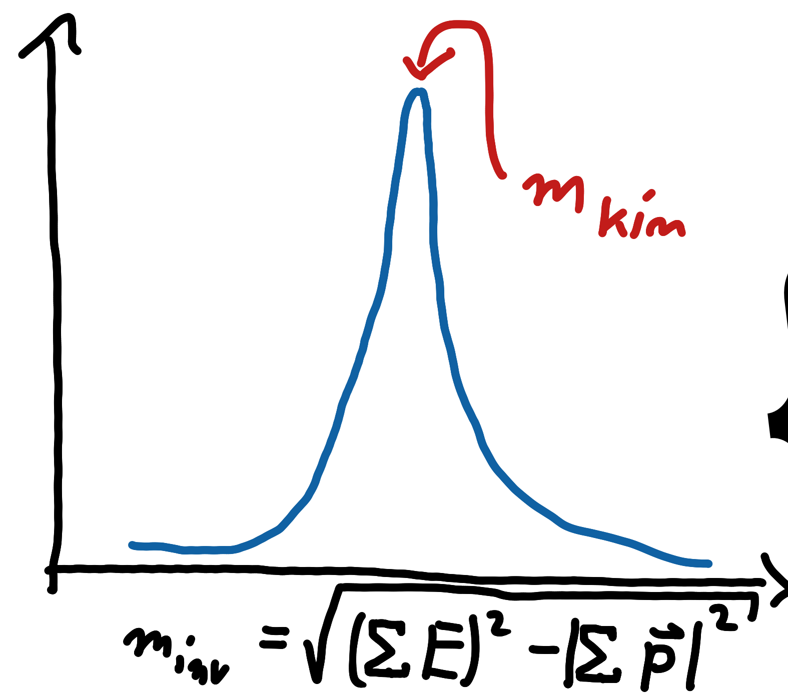
- light Jet reconstruction & energy measurement

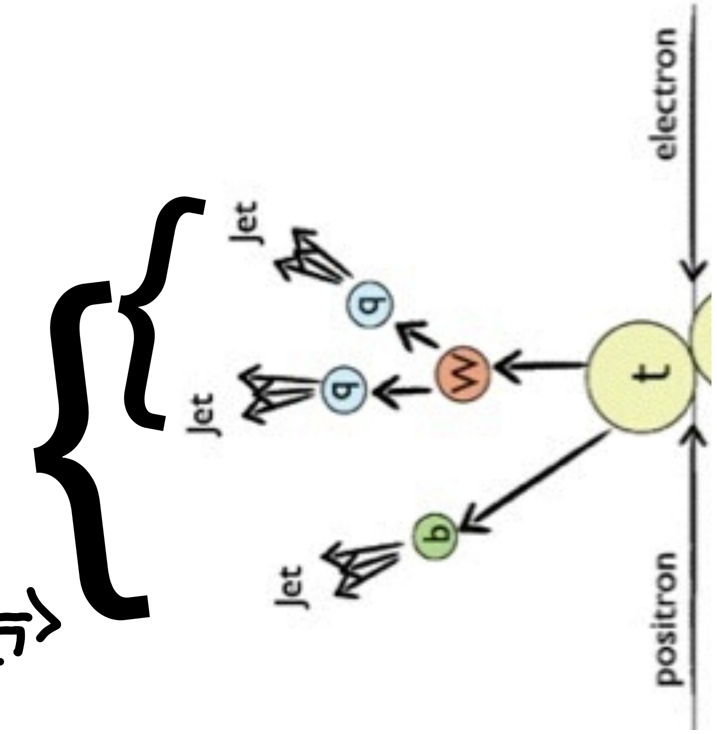
All-hadronic
- global hadronic energy reconstruction

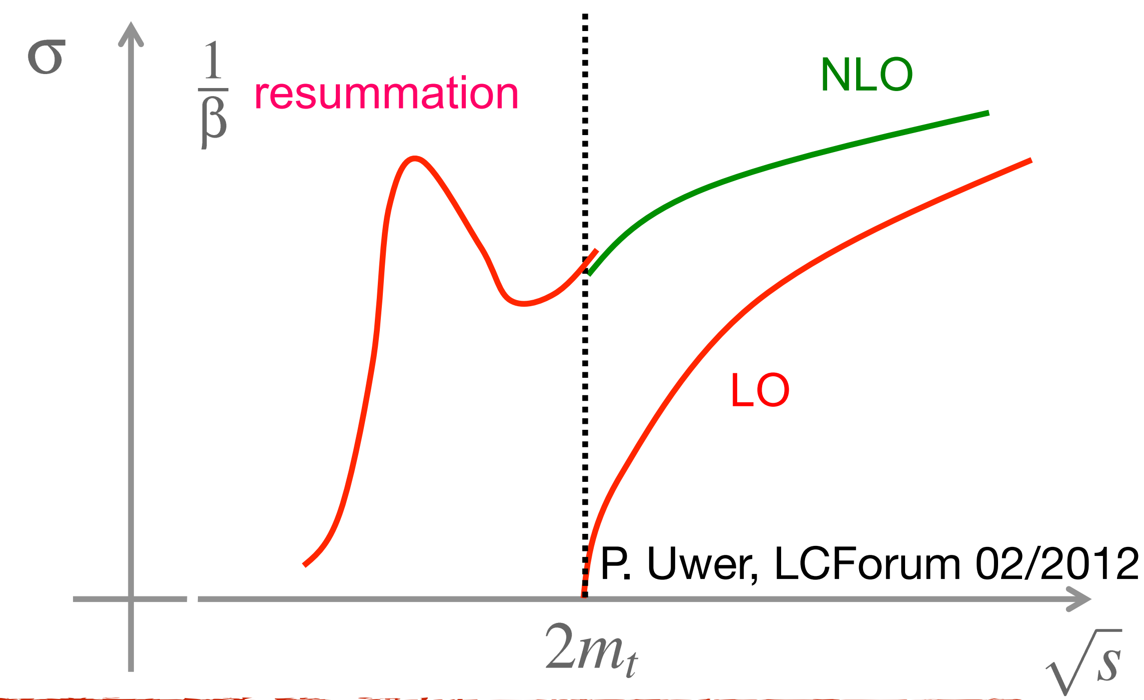


Top Mass at e^+e^- Colliders

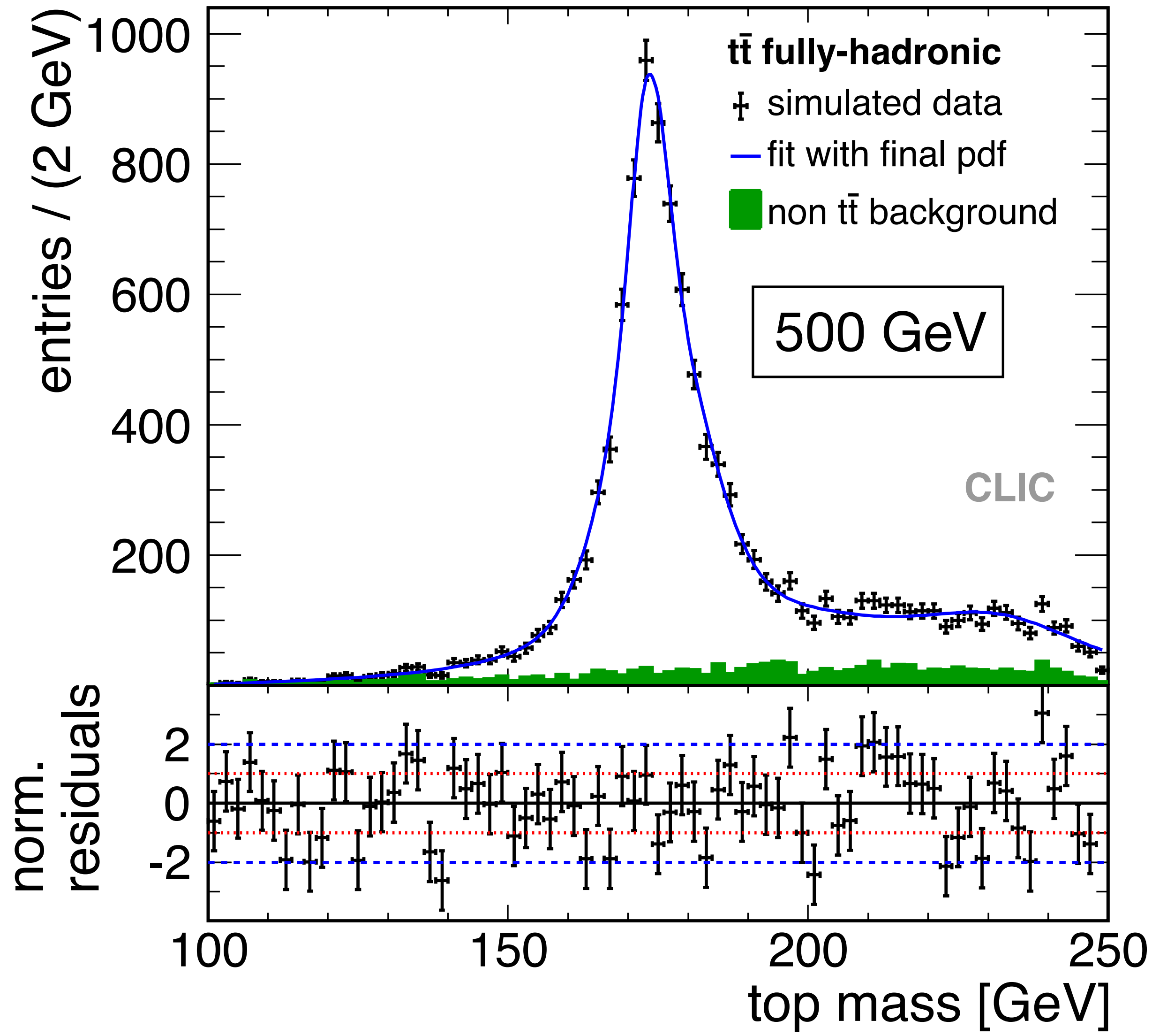
- Measurement in top pair production, two possibilities, each with advantages and dis-advantages:
  - Invariant mass
    - experimentally well defined (but not theoretically: “PYTHIA mass”)
    - can be performed at arbitrary energy above threshold: high integrated luminosity
  - Threshold scan
    - theoretically well understood, can be calculated to higher orders
    - needs dedicated running of the accelerator (but is also in a sweet spot for Higgs physics)
    - ‣ The “ultimate” mass measurement at a LC!







Reconstruction and kinematic Mass - Performance



- Very low non-ttbar background
  - S/B ~8.5 (12) for FH (SL) at 500 GeV
  - S/B ~4.5 directly above threshold
- High reconstruction efficiency
  - 34% (44%) for FH (SL) at 500 GeV
  - 92% for selected decay modes at threshold

Analysis at threshold optimized for significance, not highest reconstruction quality

Full simulations with a detailed detector model, signal, physics & machine backgrounds

Mass fit - Result:

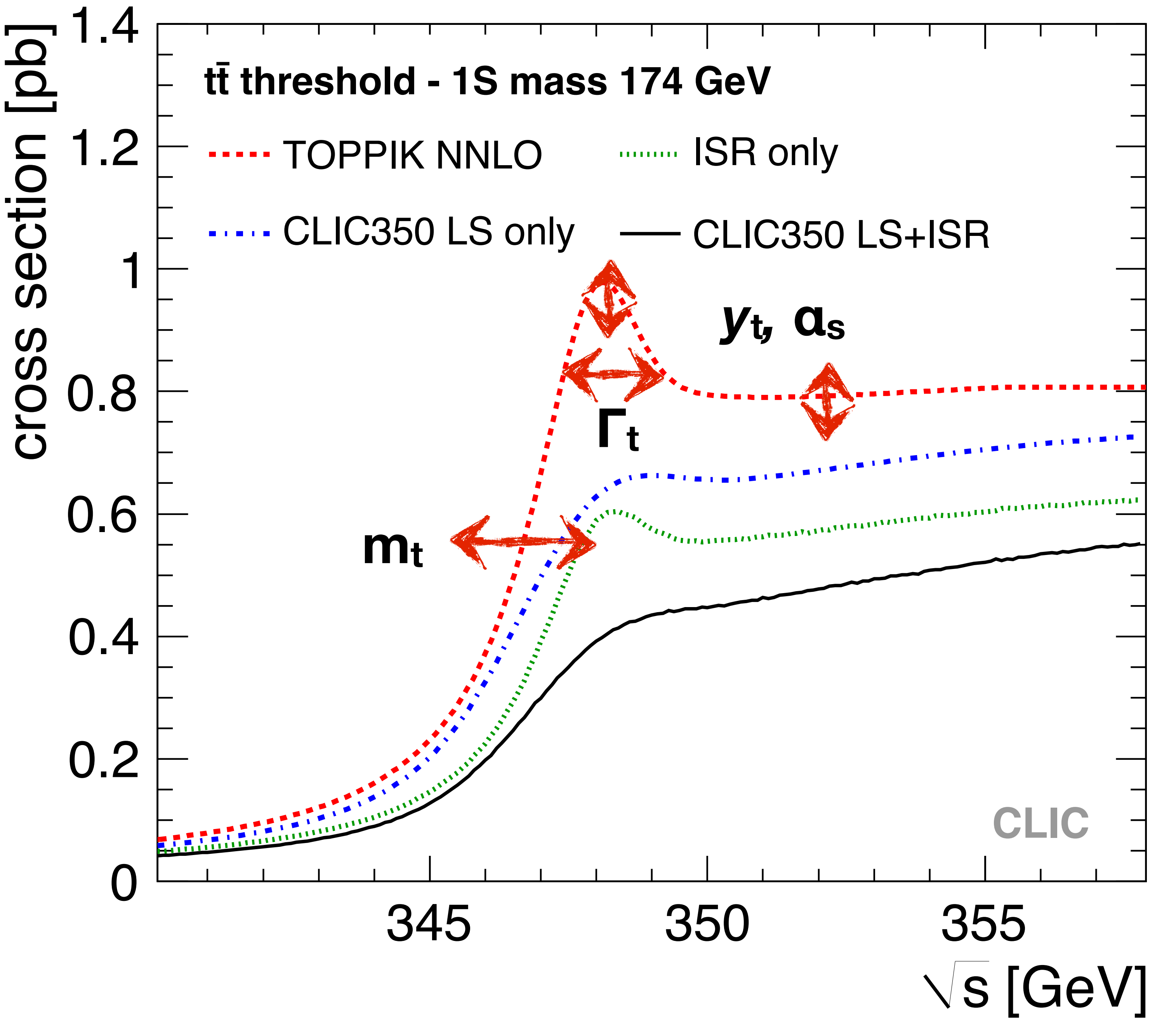
stat. uncertainty on m_t: 80 MeV (FH + SL) [100 fb^{-1}]

stat. uncertainty on Γ_t: 220 MeV (FH + SL)

exp. systematics of similar order

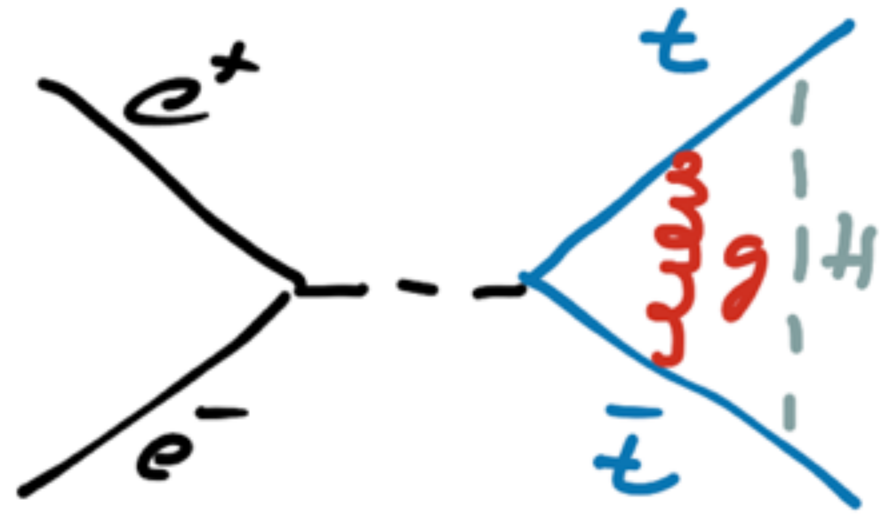
in addition: ***substantial*** theoretical / interpretation uncertainties

The Top Threshold - Ultimate Sensitivity



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

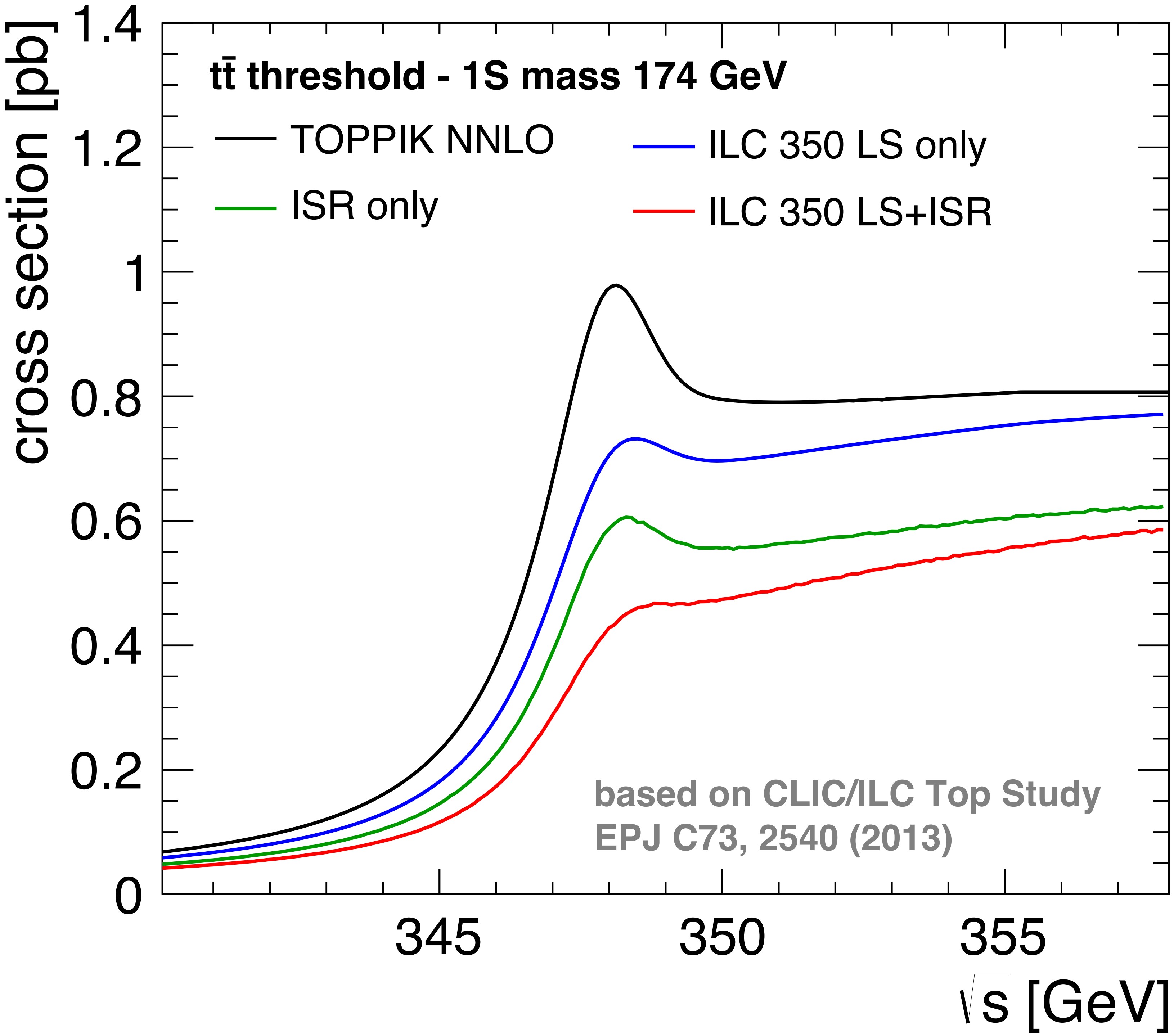


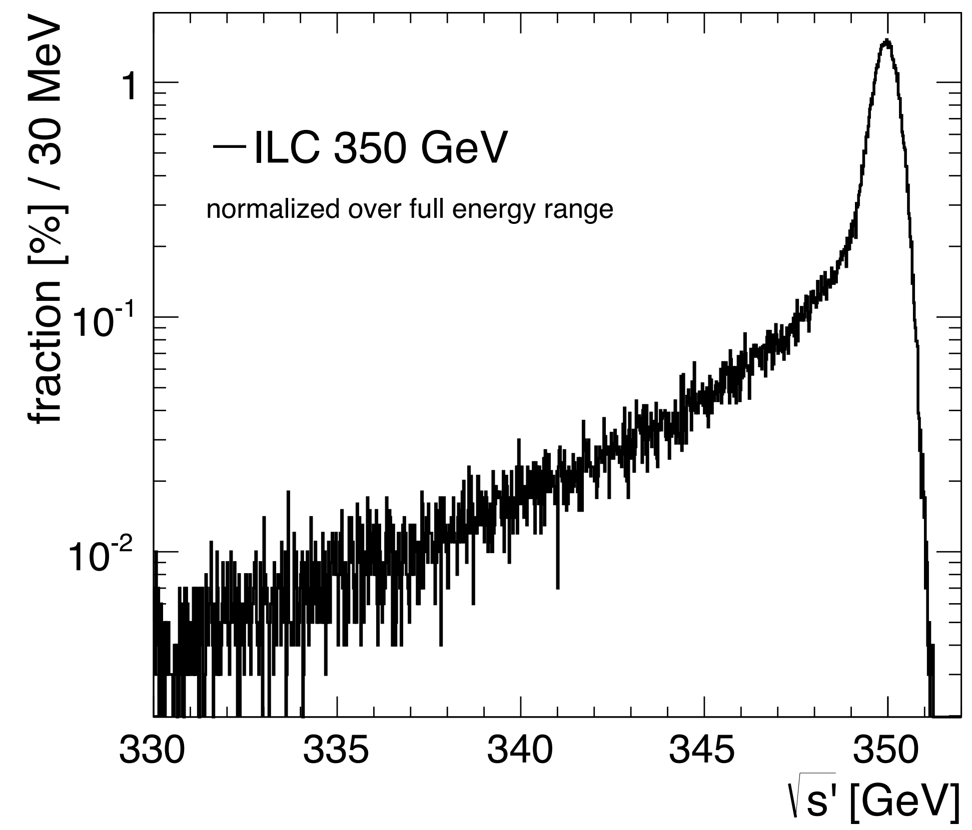
- Effects of some parameters are correlated; dependence on Yukawa coupling rather weak - precise external α_s helps

Here: Extract mass and α_s

From Theory to Experiment: Collider Effects

- The luminosity spectrum of the collider and ISR affect the shape of the threshold





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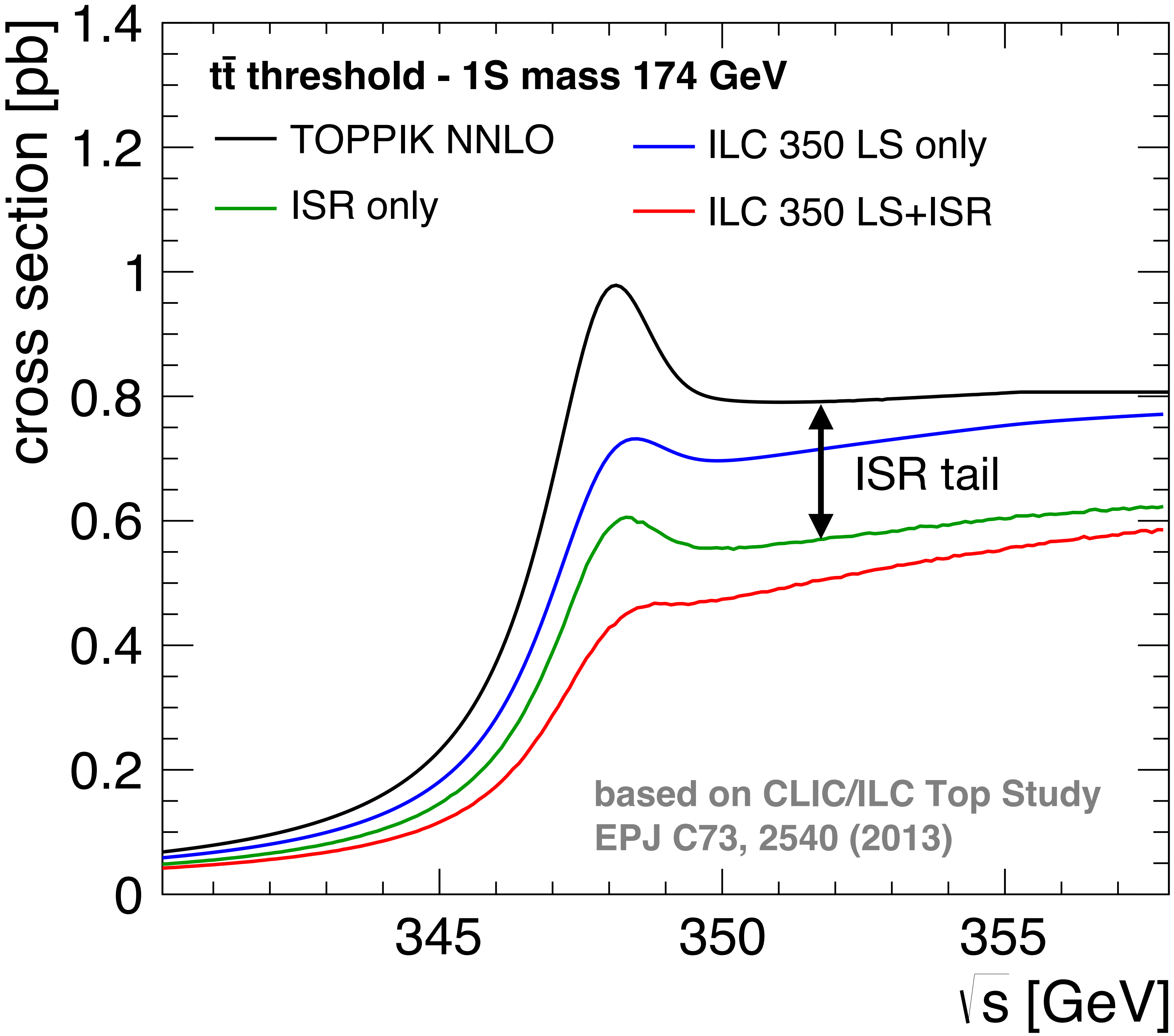

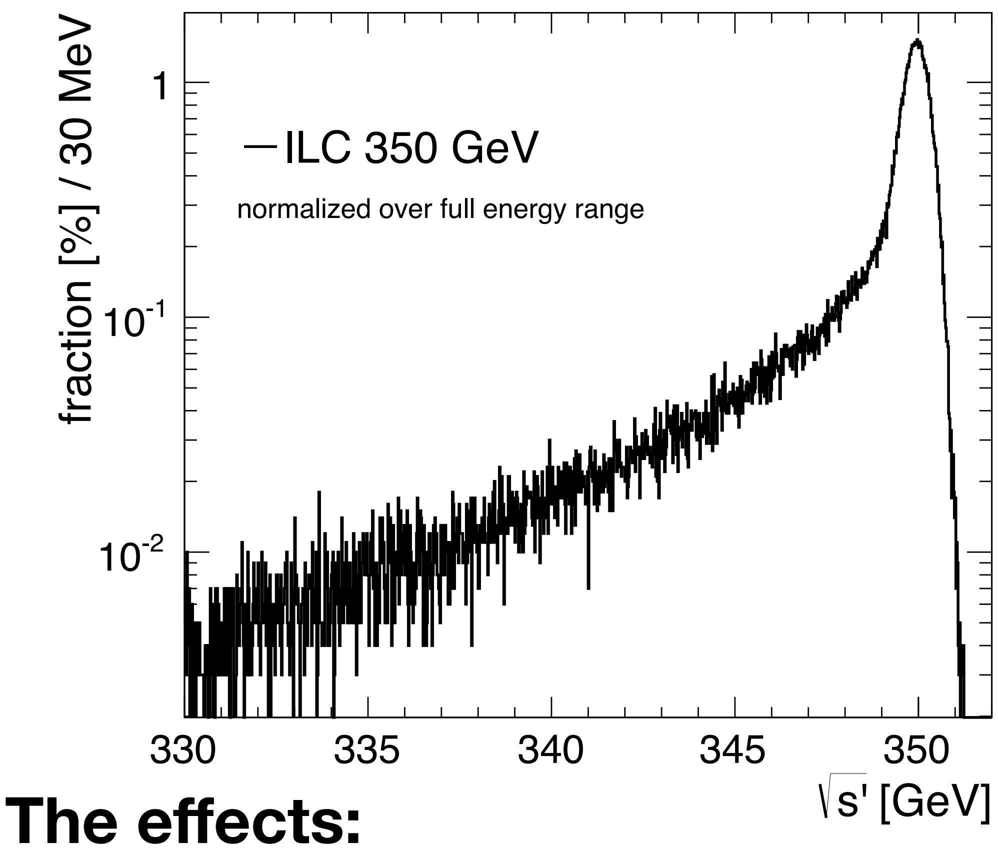

The effects:

- ISR tail: lowering of effective L at top energy

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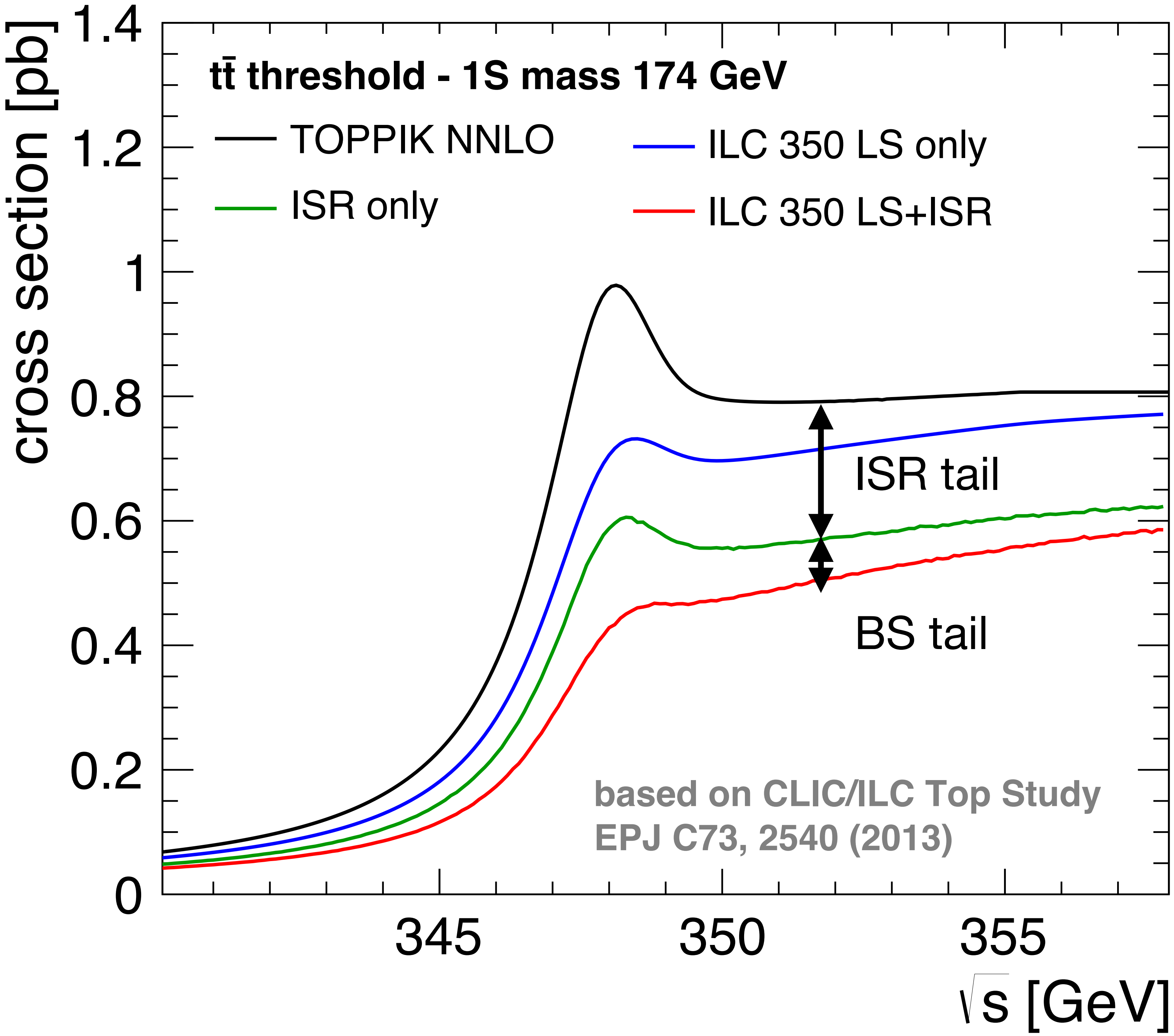
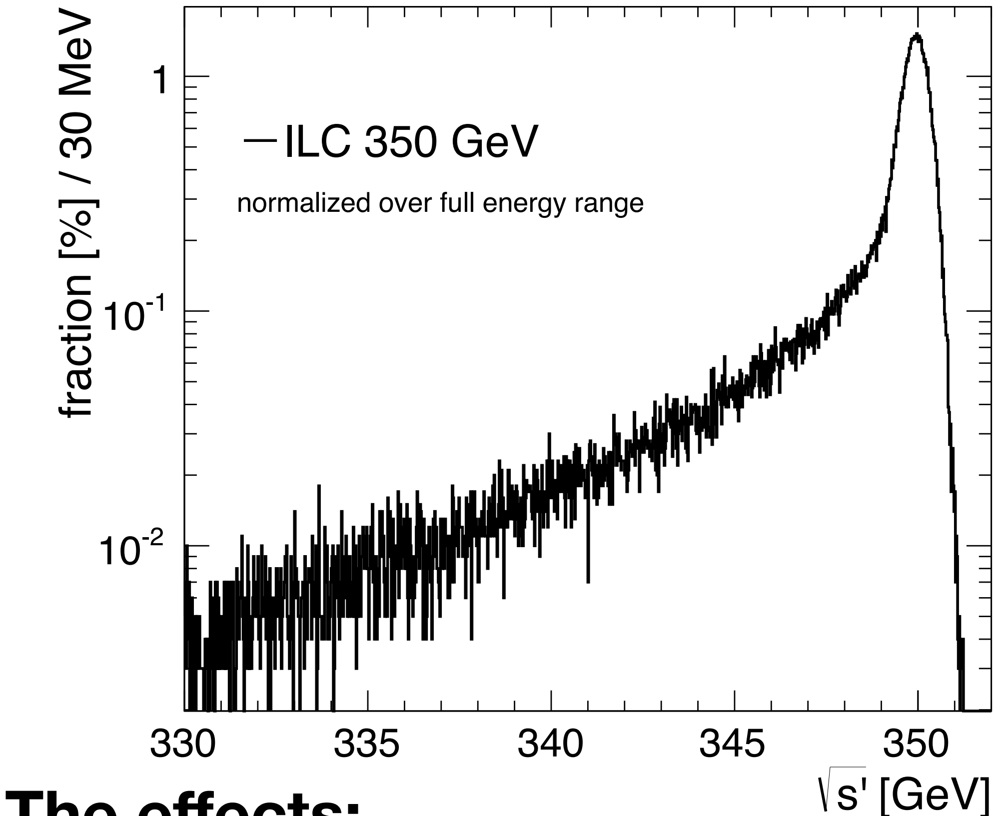


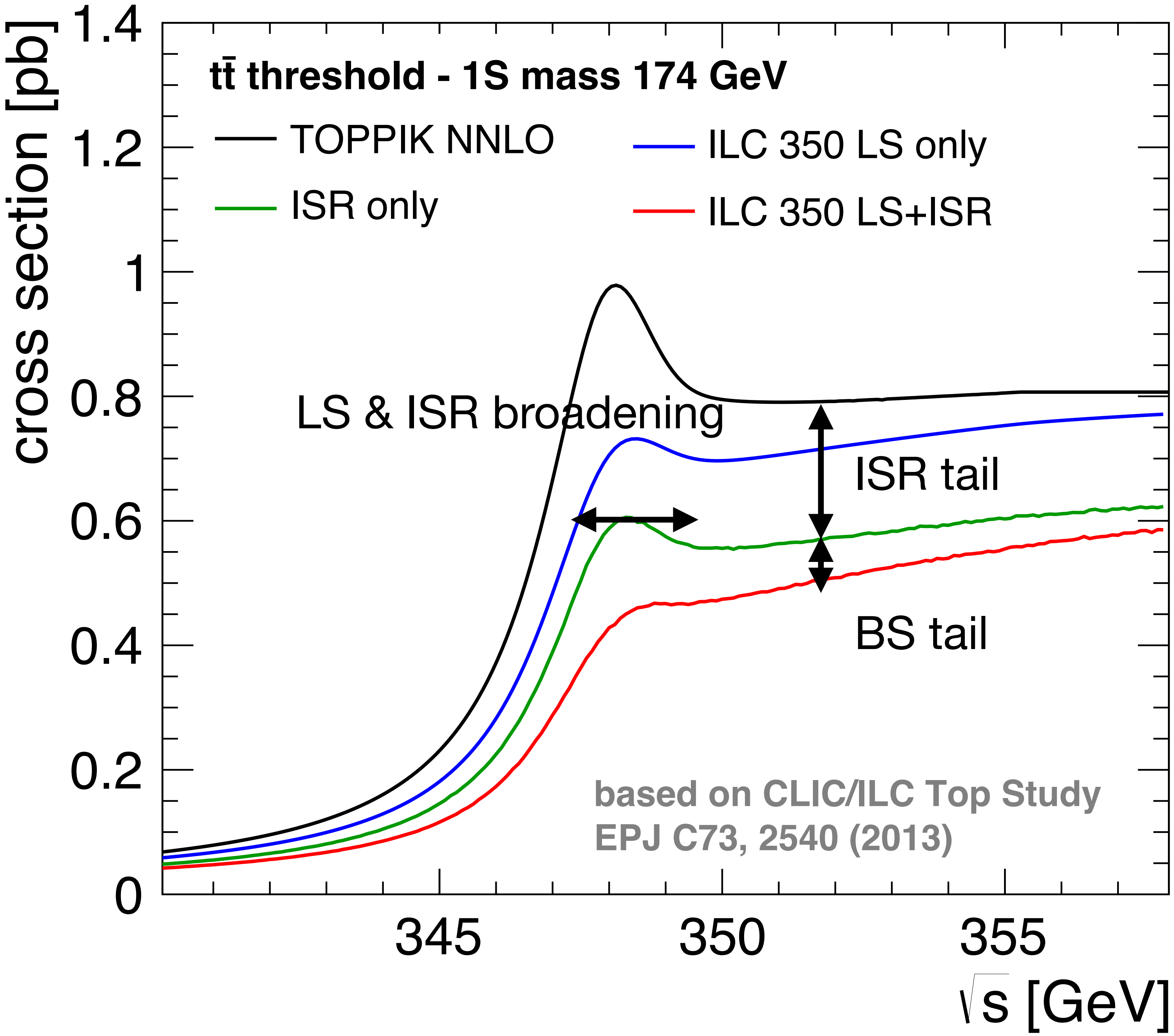


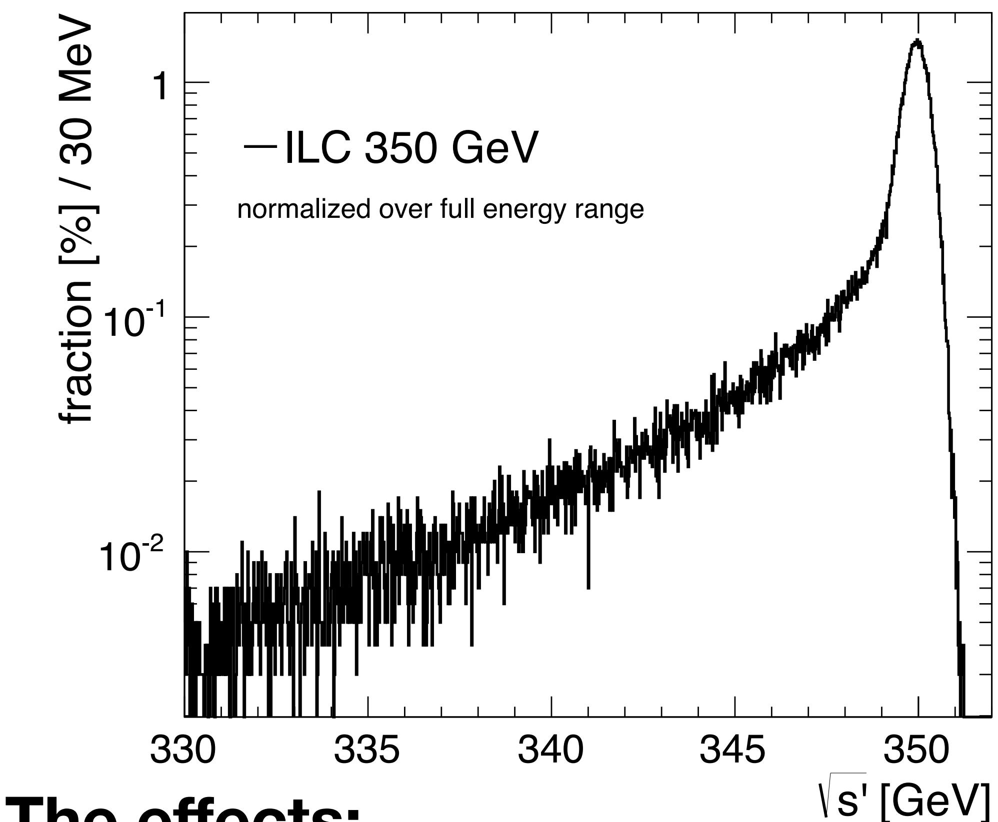
The effects:

- ISR tail: lowering of effective L at top energy
- BS tail: lowering of effective L at top energy

From Theory to Experiment: Collider Effects

- The luminosity spectrum of the collider and ISR affect the shape of the threshold

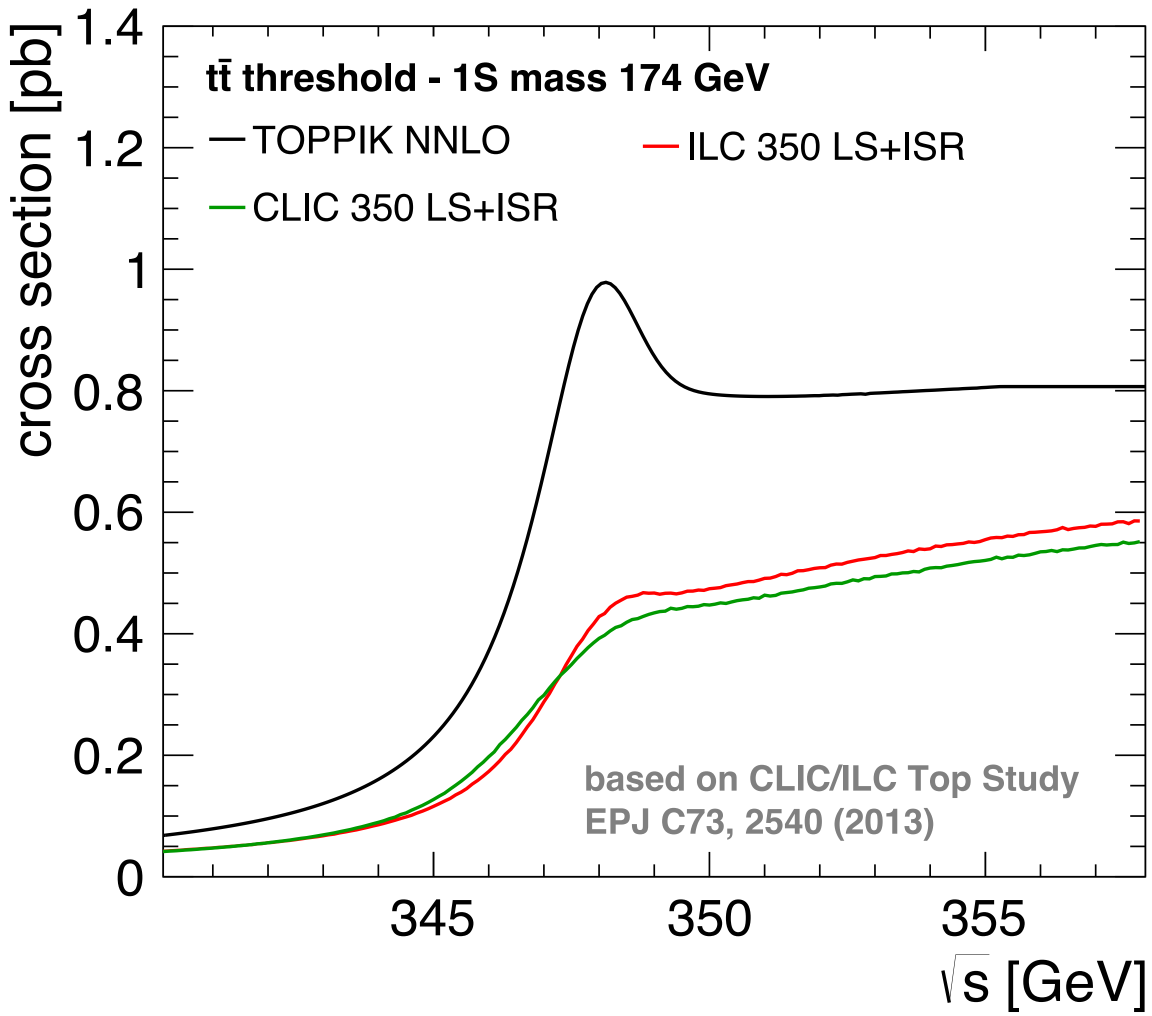




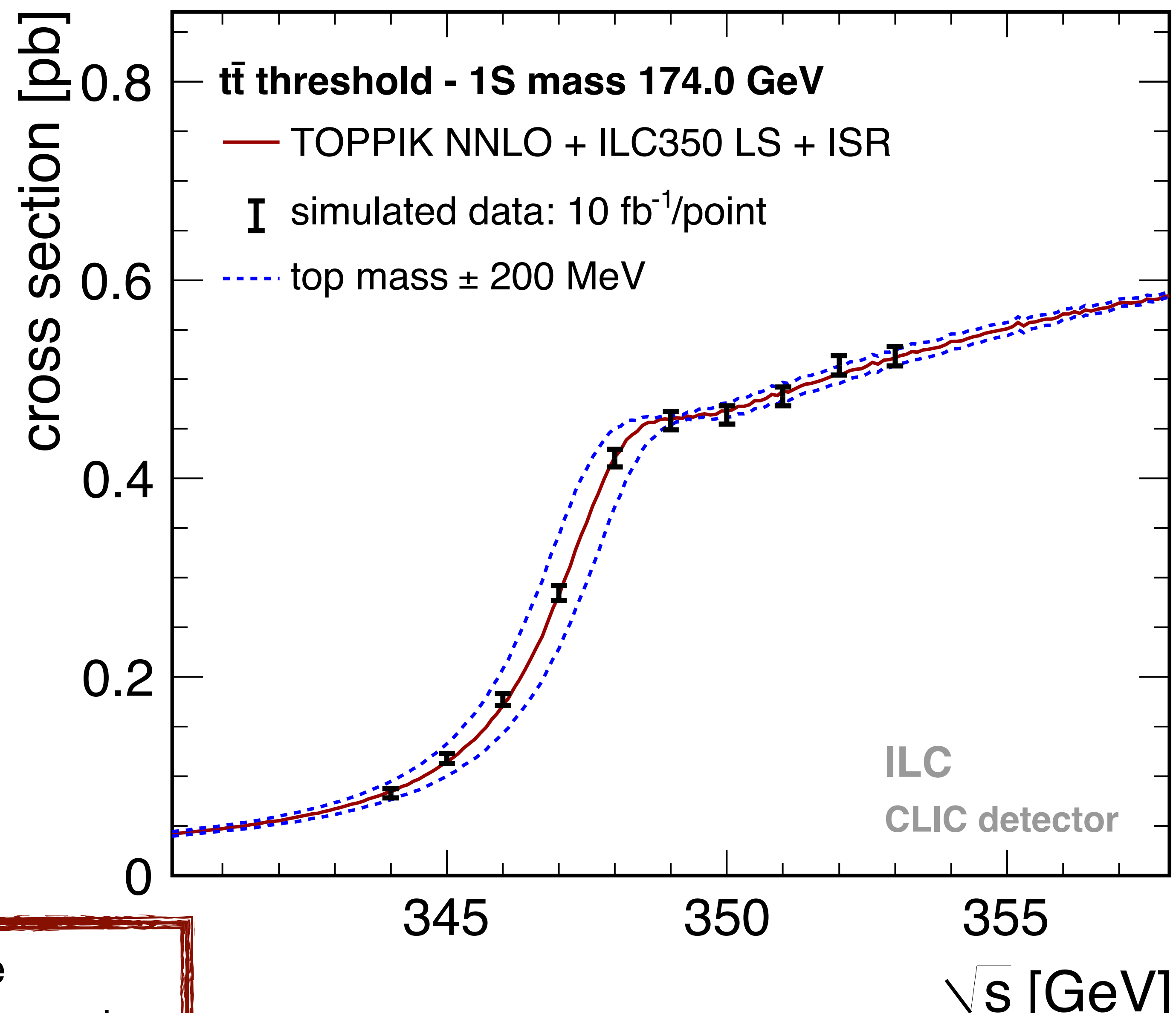
The effects:

- ISR tail: lowering of effective L at top energy
- BS tail: lowering of effective L at top energy
- LS & ISR broadening: smearing of Xsection due to beam energy spread, BS tail and ISR

Threshold Scans at Linear Colliders



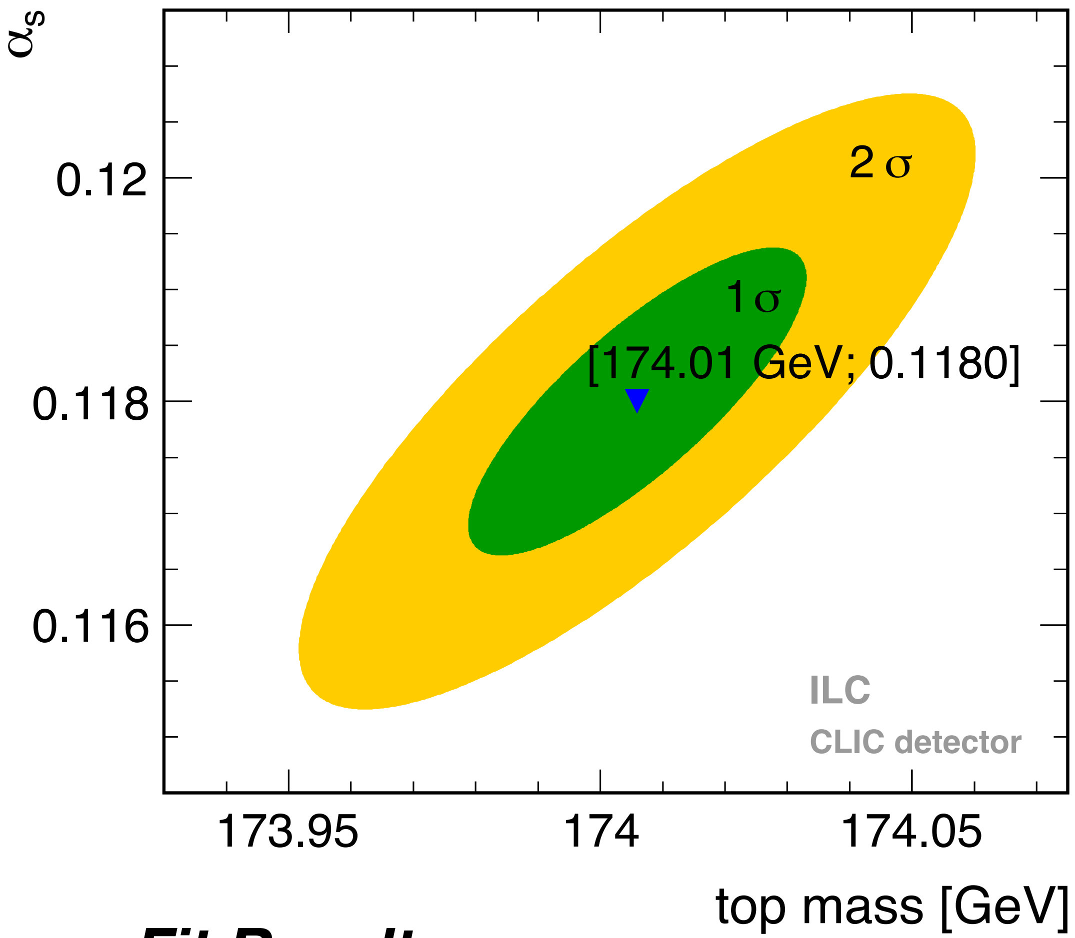
- The precise threshold shape depends on the collider
  - rather small differences between ILC and CLIC



- Assume an integrated luminosity of 100 fb^{-1}, equally spread over 10 points

NB: Assuming unpolarized beams - LC beams can be polarized, increasing cross-sections / reducing backgrounds

Statistical Precision from Threshold Scan



- Additional possibilities:
  - With high precision external α_s the Top Yukawa coupling can be measured with ~ 7% (stat) precision
  - The top width can also be included in the fit - uncertainties (stat) ~ 30 MeV

arXiv:1310.0563

Fit Results

[MeV]	Δm	theory 1%/3%	Δα	theory 1%/3%
ILC - 2D Fit	27	5/9	0.0008	0.0009/0.0022
CLIC - 2D Fit	34	5/8	0.0009	0.0008/0.0022

[MeV]	Δm	theory 1%/3%	α_s
ILC - 1D Fit	**18**	18/55	21
CLIC - 1D Fit	22	18/56	20

EPJ C73, 2540 (2013)

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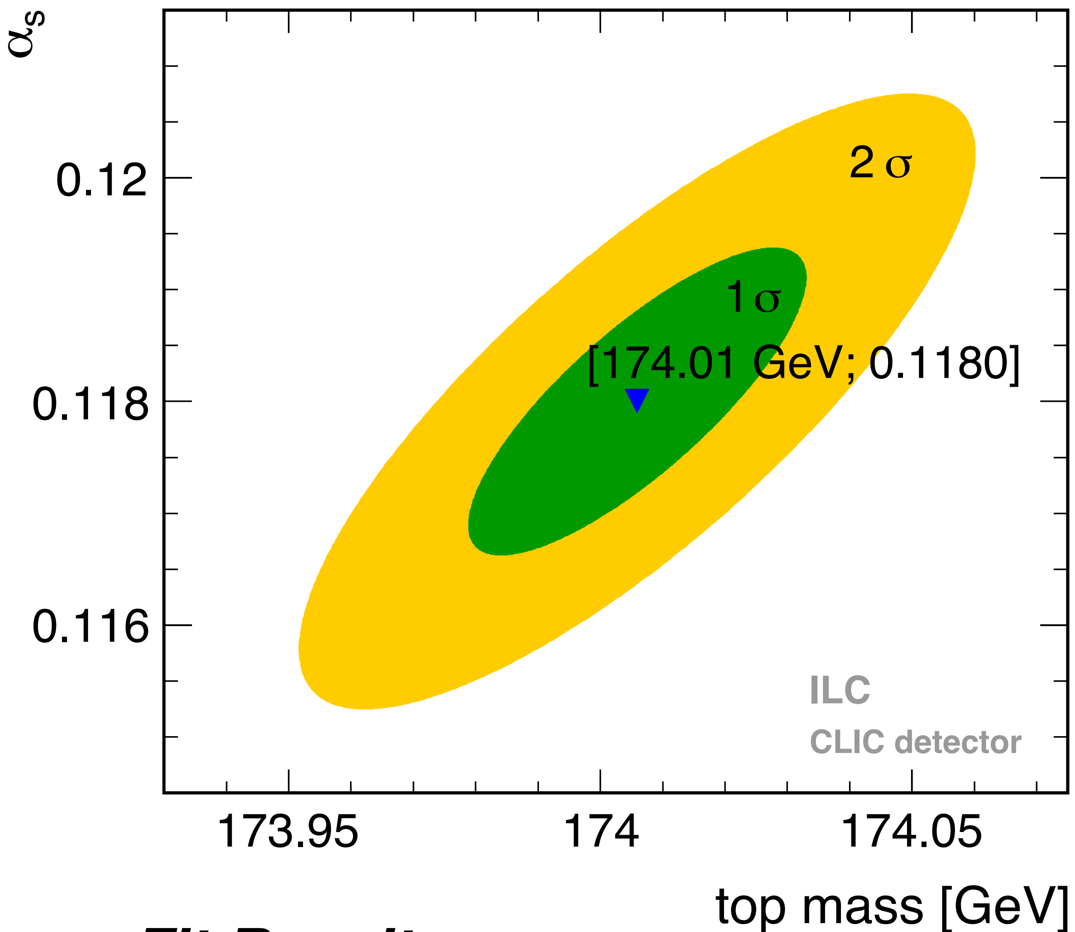

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naive assumption: global normalisation uncertainty of cross section

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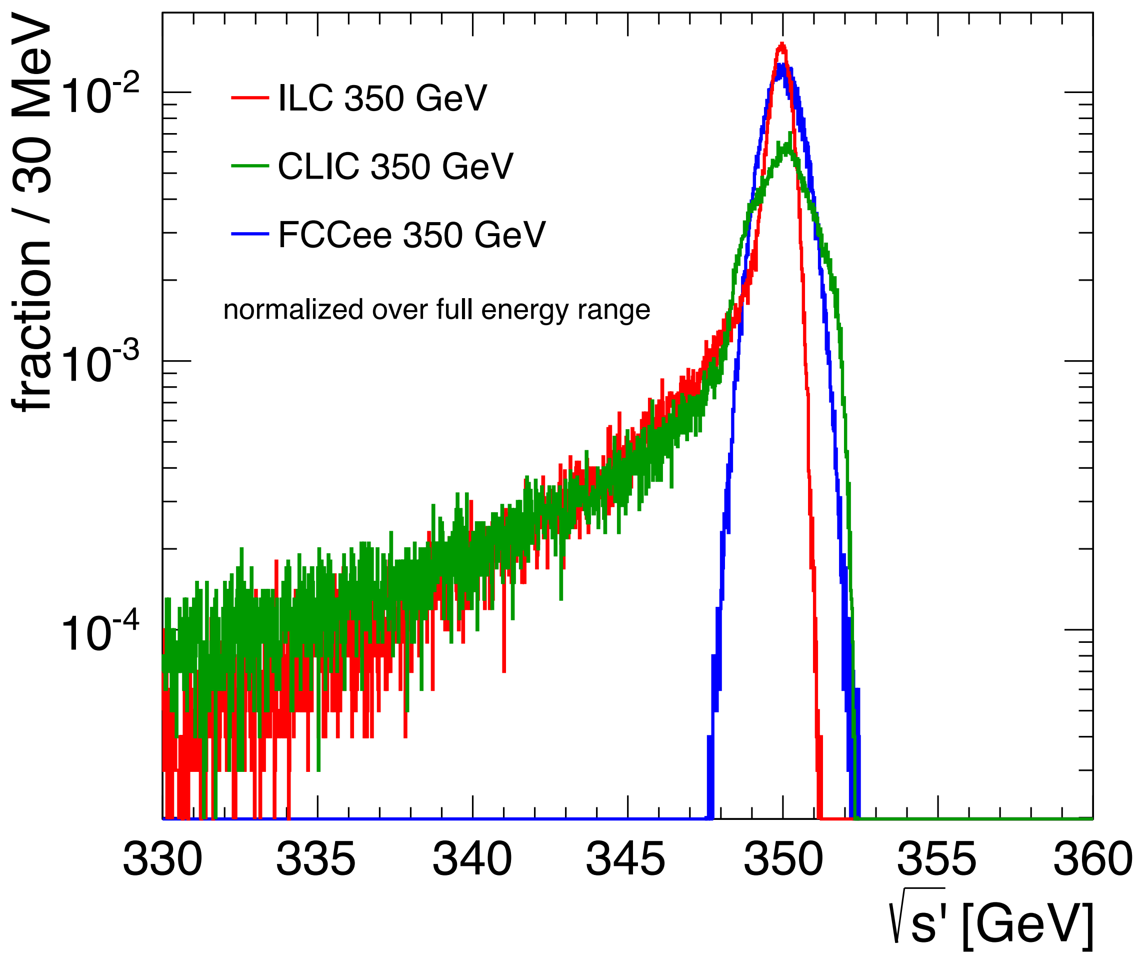
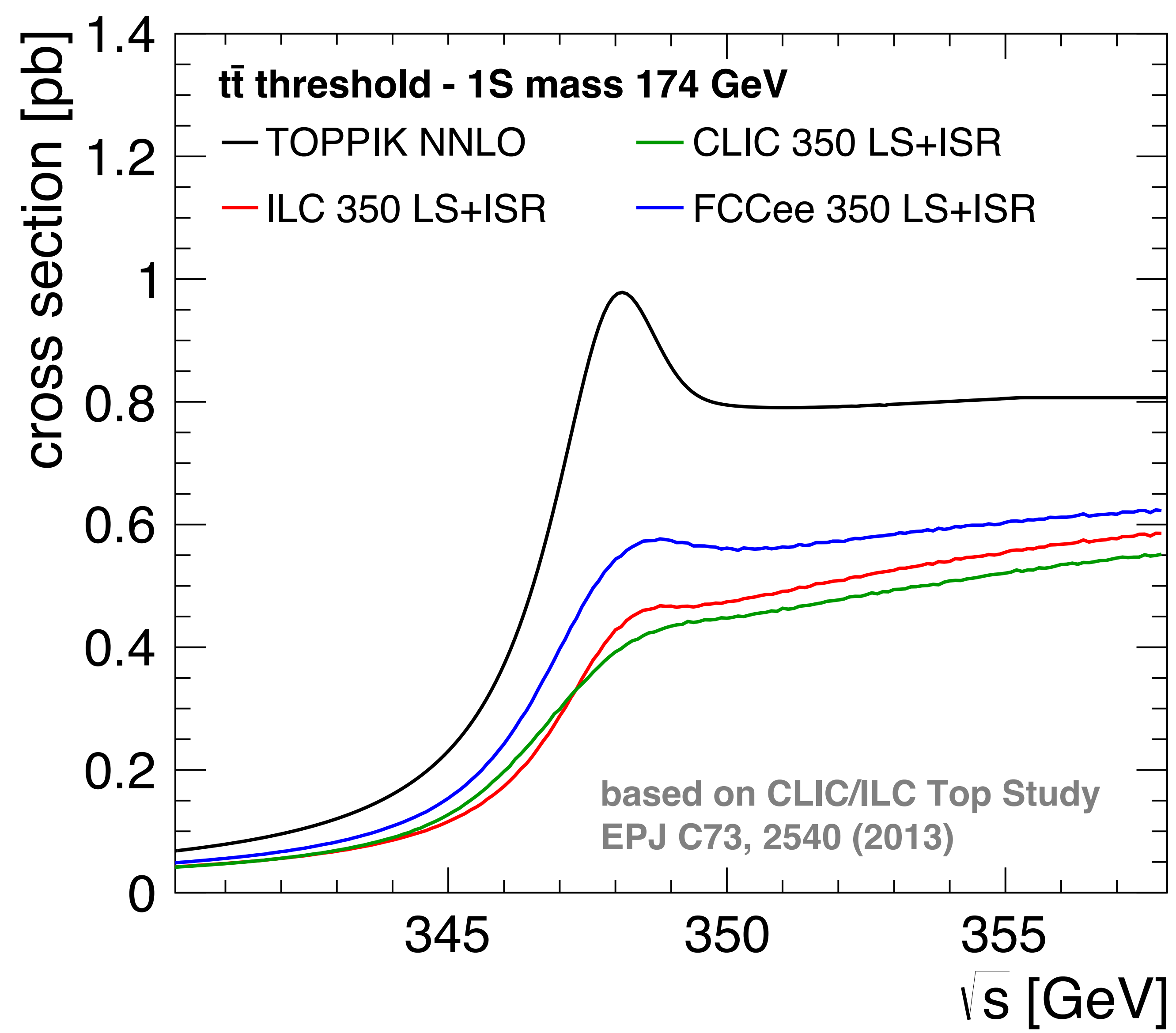
Side Remark - Threshold Scan at LCs and FCCee



- Somewhat different luminosity spectra for different machines:
  - no beamstrahlung tail in storage ring
  - sharper main peak at ILC, broader at CLIC



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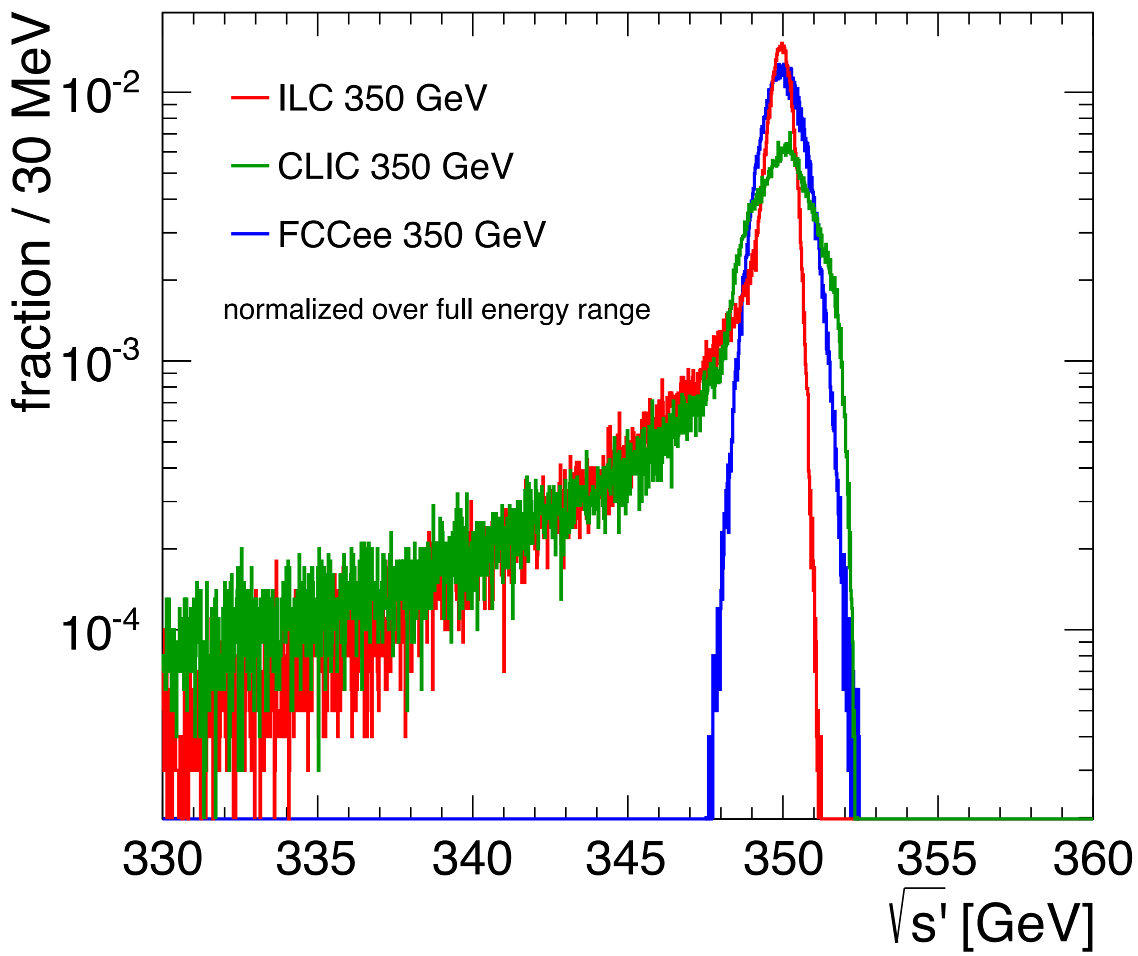

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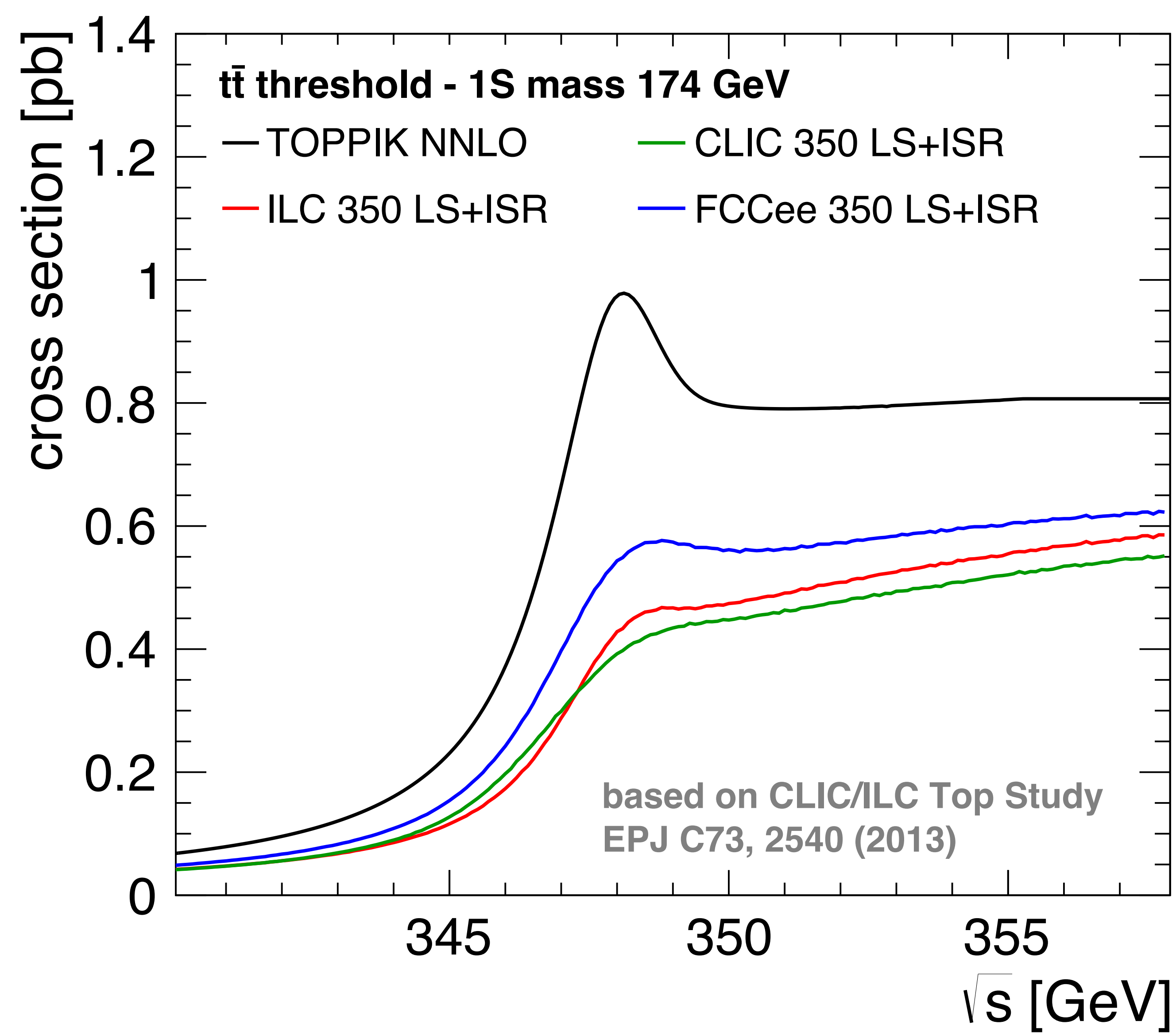
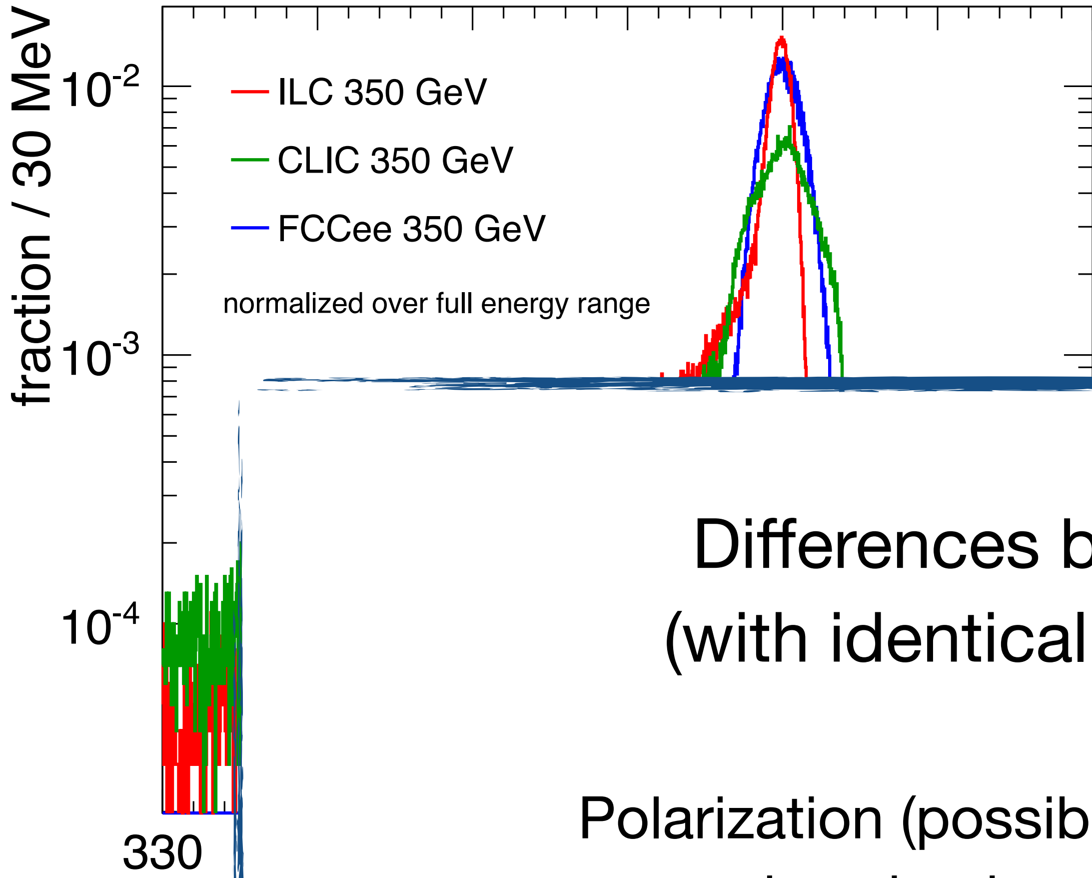


- Slight differences in statistics due to cross section, changes in sensitivity due to steepness of threshold turn-on
- For 100 fb^{-1}, no polarization, 1D mass fit:

16 MeV	→ 18 MeV	→ 21 MeV	(stat)
FCCee	ILC	CLIC	

Side Remark - Threshold Scan at LCs and FCCee



- Somewhat different luminosity spectra for different machines:
  - no beamstrahlung tail in storage ring
  - sharper main peak at ILC, broader at CLIC

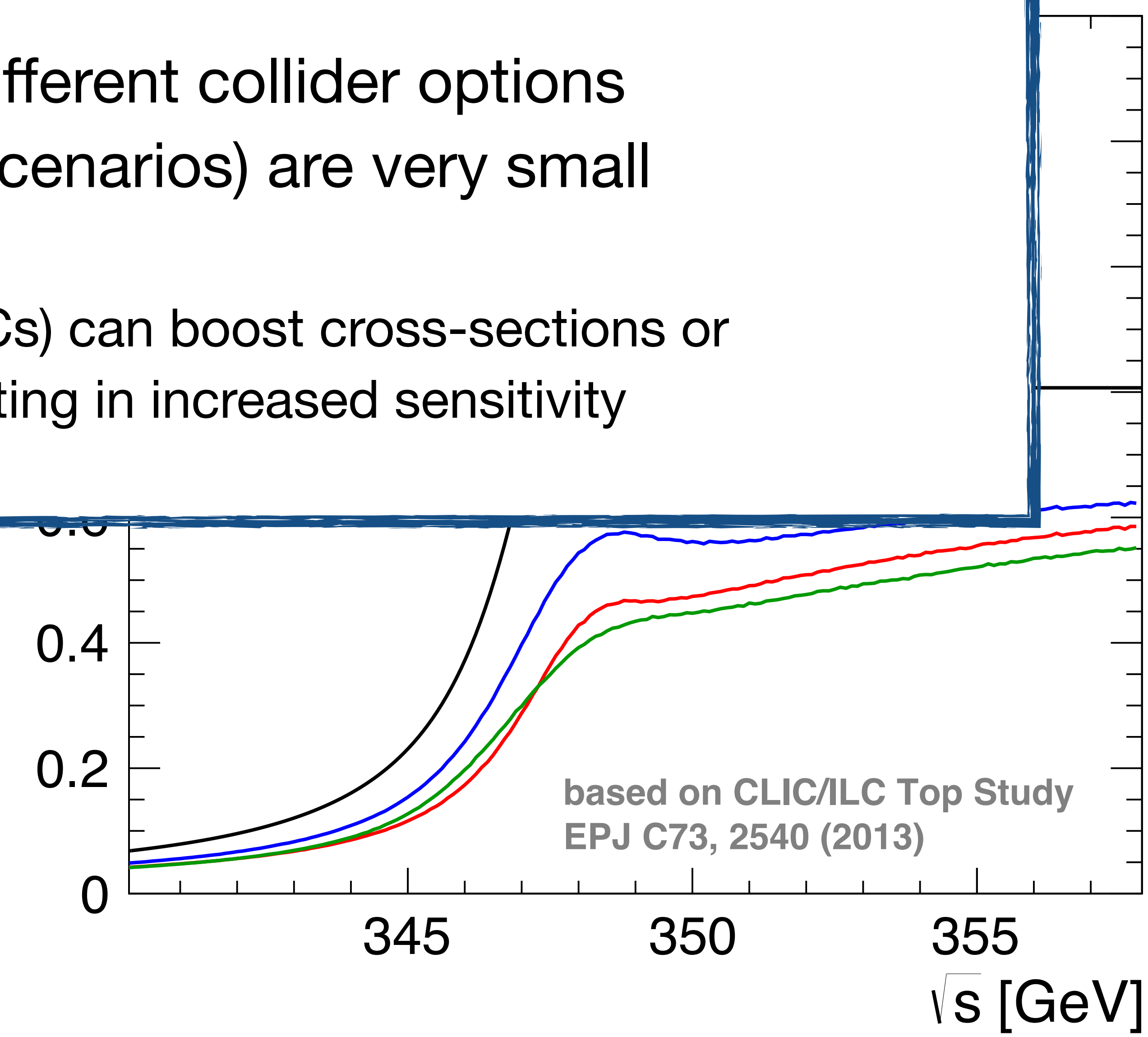
Differences between different collider options (with identical running scenarios) are very small

Polarization (possible only in LCs) can boost cross-sections or reduce backgrounds, resulting in increased sensitivity

- Slight
  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



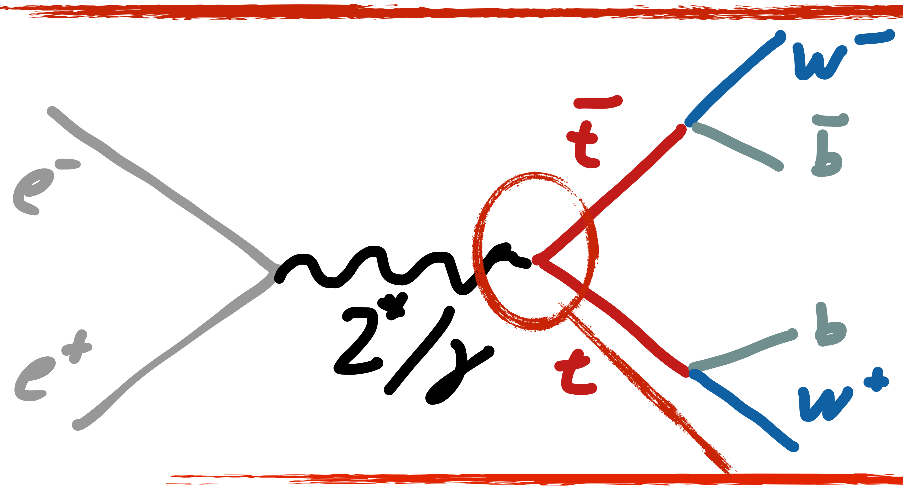
Systematics: First Studies

- Measurements at the top threshold will likely be systematics limited
  - first studies have been done, still incomplete

Mass:

- *Statistical* uncertainty for 100 fb^{-1} (reasonably modest program)
  ~ 20 - 30 MeV (stat)
- *Experimental* Systematics
  - Beam Energy: **~ 30 MeV** or lower
  - Non-ttbar background, selection efficiencies: **~ 10 MeV**
  - Luminosity Spectrum (studied for CLIC LS with reconstruction of spectrum via Bhabha scattering): **~ 6 MeV**
- *Theory* Systematics
  - Expected to be significant, naive estimates provide numbers of up to *O* 100 MeV - Requires a dedicated study - in progress for NNNLO calculations of cross-section at threshold

Electroweak Couplings of the Top Quark



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

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

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

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

$$F_{1V}^\gamma \quad \boxed{F_{1A}^\gamma} \quad F_{2V}^\gamma$$
$$F_{1V}^Z \quad F_{1A}^Z \quad F_{2V}^Z$$

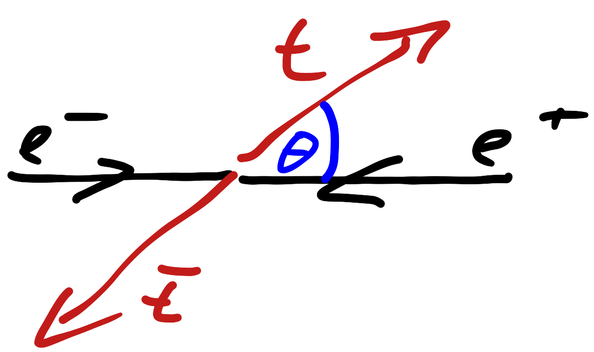
= 0 due to gauge invariance

- 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!

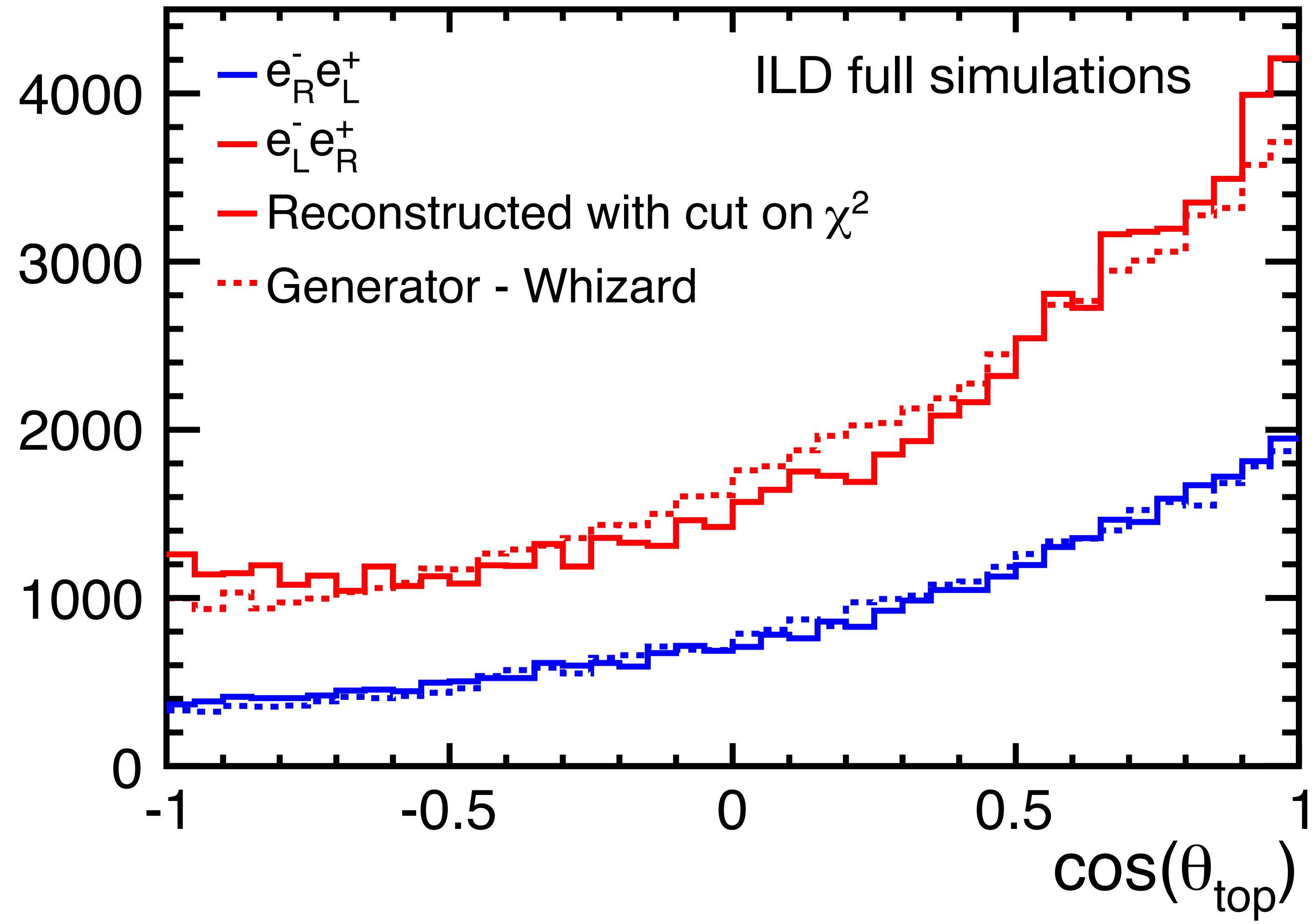
Accessing EW Couplings: Asymmetries & Angles

- Forward-backward asymmetry:

$$A^t_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$



- ILC, 500 GeV, 500 fb^{-1}
- Two polarisation configurations:
  - $e^-_R e^+_L$: P(e^-) -80%, P(e^+) +30%
  - $e^-_L e^+_R$: P(e^-) +80%, P(e^+) -30%



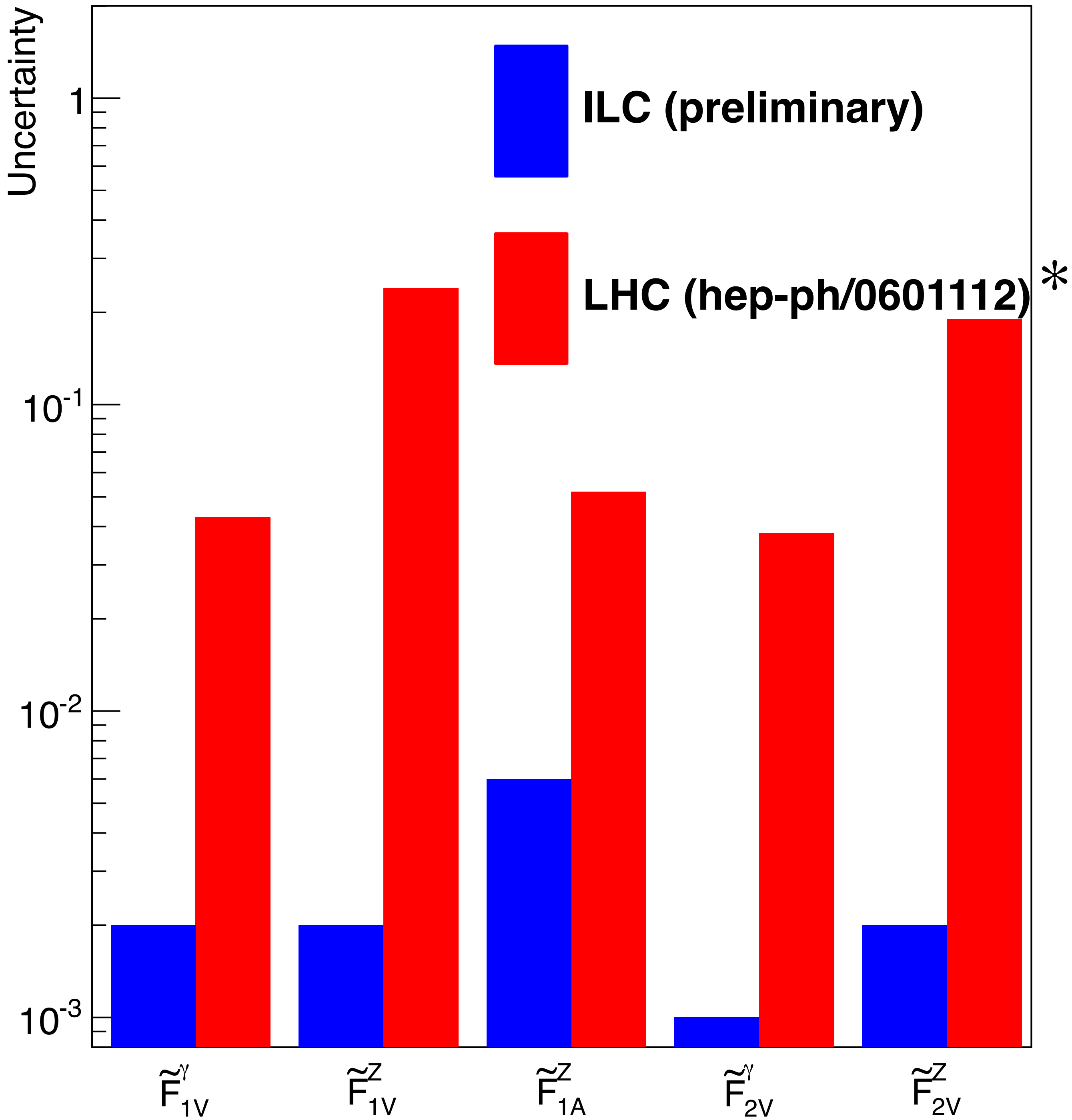
precision on asymmetry:
~2% (stat+ syst)

Electroweak Couplings: Expected Precision

precision on total cross-section:
~0.5% (stat+ lumi)

- The combination of polarised cross-section, asymmetry and helicity angle measurements gives access to all relevant couplings - with percent to permille - level precision

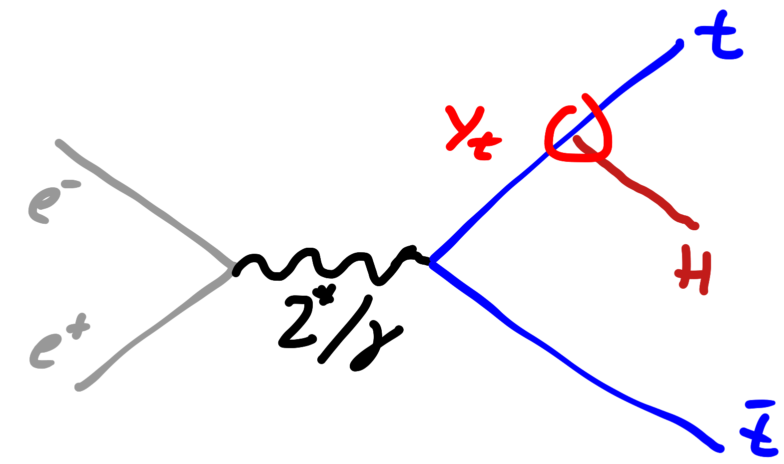
Additional potential may exist with additional measurements and higher energy - potentially further improved BSM sensitivities
Not studied yet...

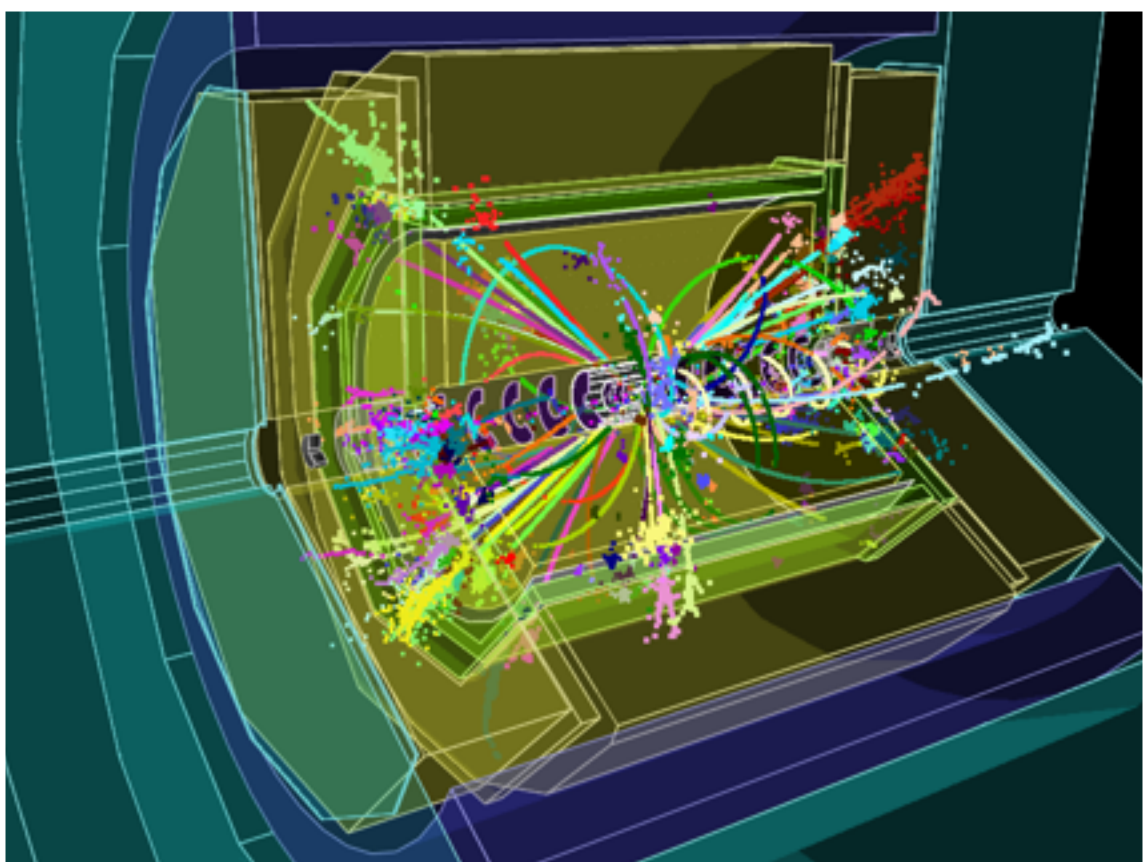


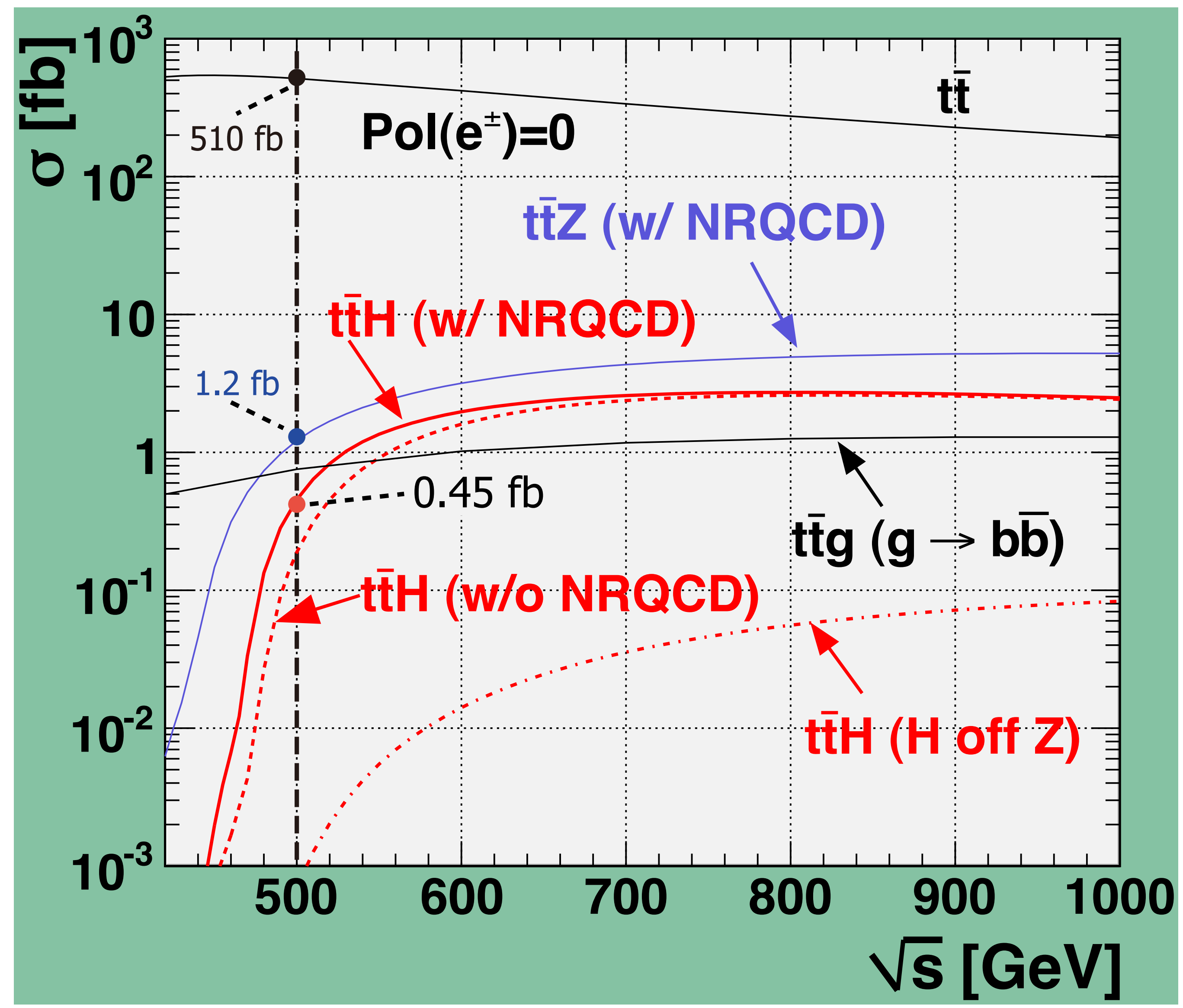
* Snowmass 2005 projection
LHC 14 TeV, 300 fb^{-1}

Direct Access to Top Yukawa Coupling

- Direct measurement of the top Yukawa coupling via the process ttH
  - complex final state, low cross-section
  - ~ 8% measurement of the cross section at 1 TeV: **4%** uncertainty on y_t for 1 ab^{-1}
  - First measurements at 500 GeV - slight energy boost to 550 GeV would help enormously - 6% on y_t with 1.6 ab^{-1}

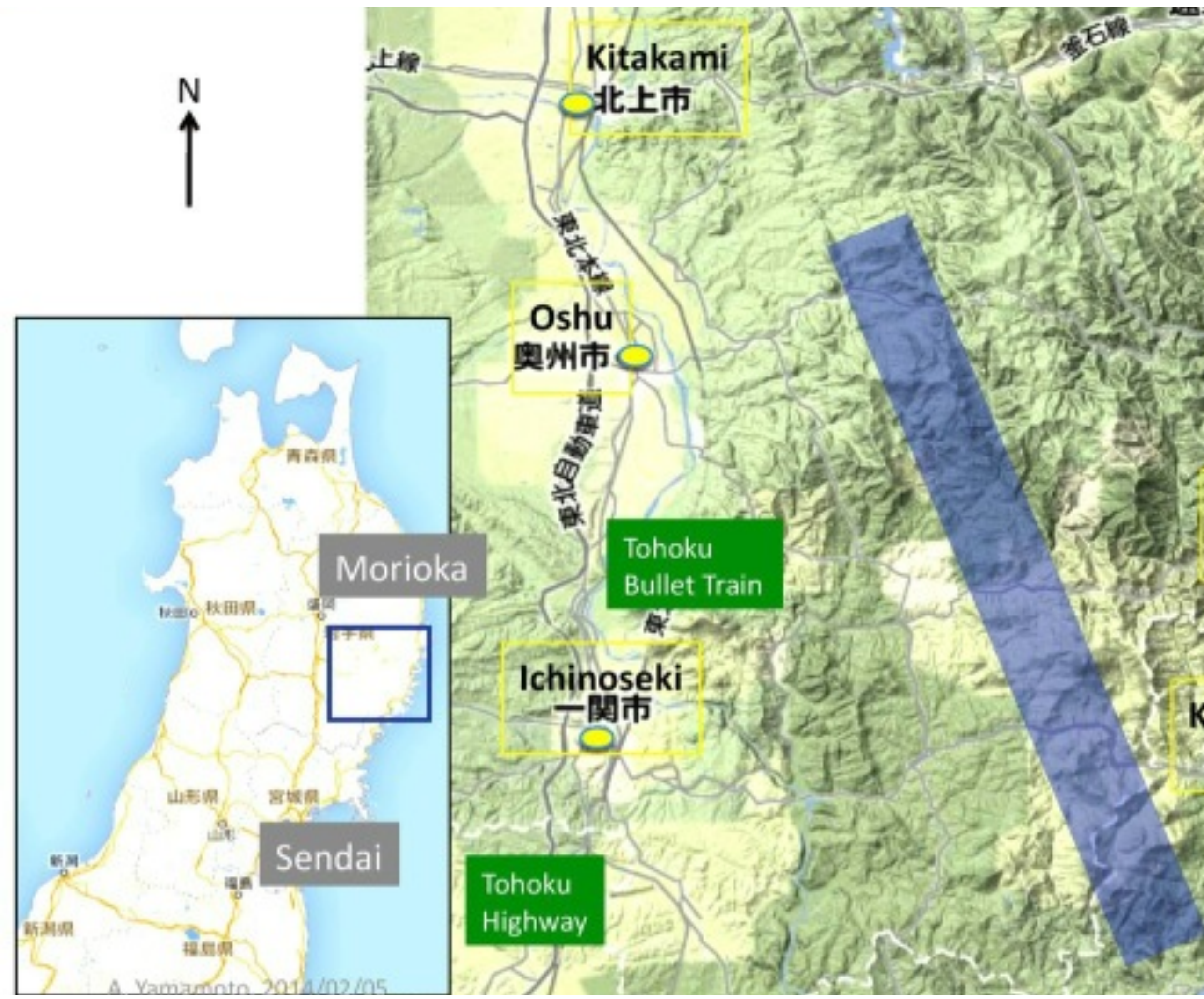






ILC (国際リニアコライダー) in Japan

- 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 choice 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

Summary

- Linear colliders will be capable of producing top quarks in a very clean environment: Excellent conditions for precision measurements of top quark properties and couplings

- The invariant mass can be reconstructed with an experimental precision of *O* 100 MeV (stat+ syst), but suffers from substantial theoretical uncertainties
- A threshold scan provides the ultimate mass precision in a theoretically well-understood setting: Statistical uncertainties on the **20 - 30 MeV** level, with comparable experimental systematics, studies of theoretical uncertainties ongoing

▸ Total uncertainty of ~ **100 MeV** or better in reach

- **Polarised beams** at linear colliders allow detailed measurements of top electroweak couplings with the separation of axial and vector and Z and γ contributions
    - accuracies on the percent to permille level expected

- A direct measurement of the top Yukawa coupling via the ttH process on the **2 - 4%** level (depending on integrated luminosity) at 1 TeV

Backup

Systematics on Mass - Details

- Incomplete - but looked at several key aspects:
  - Theory uncertainties currently based on simple scaling of cross section (1%, 3%) (10 MeV up to ~50 MeV, depending on fit strategy -> uncertainty mostly absorbed in α_s uncertainty for combined fits) - More sophisticated studies planned, based on results by Beneke *et al.*, see next talk
  - Non-ttbar background: 5% uncertainty results in 18 MeV uncertainty on mass (After selection, the non-ttbar background cross section is ~ 70 fb, so 5% uncertainty can be reached with ~ 6 fb^{-1} below threshold)
  - Beam energy: Expect 10^{-4} precision on CMS energy: ~30 MeV uncertainty on mass - potential for further improvement?
  - Luminosity spectrum - first study based on CLIC 3 TeV model (substantially more complicated than ILC): ~ 6 MeV uncertainty from fit of LS parameters

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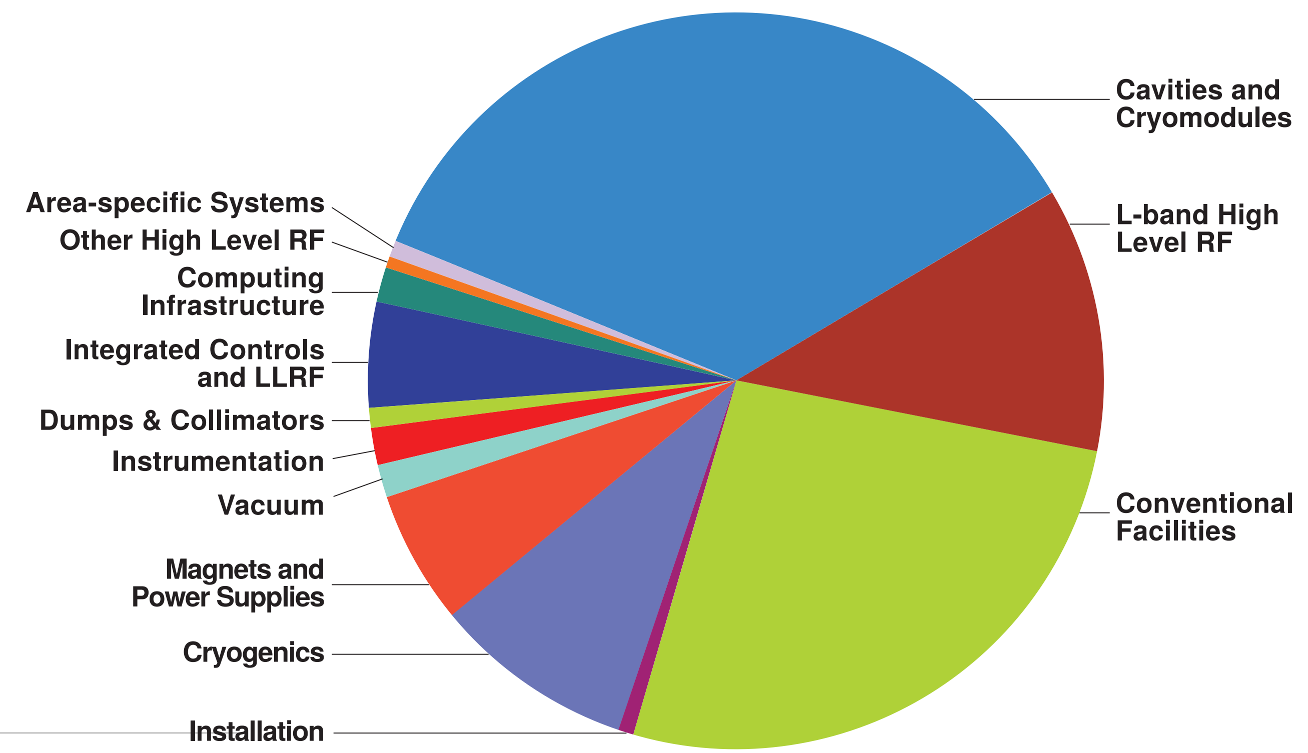
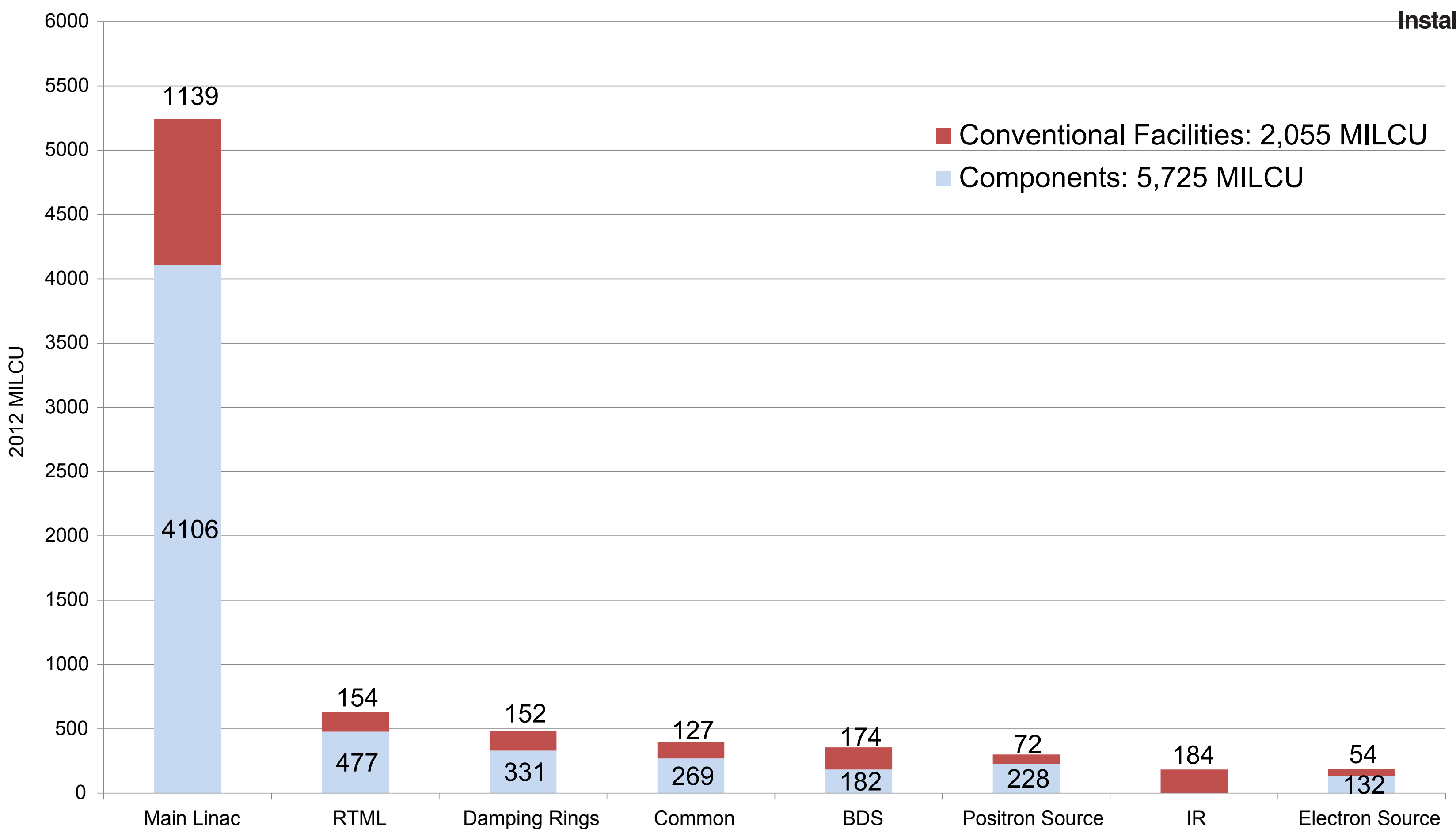
"Interpretation" uncertainty:
Theory uncertainties are incurred when transforming the 1S mass used to describe the threshold to the MSbar mass - currently *O* ~ 100 MeV, depending on α_s precision and number of orders - significant reduction possible when needed

ILC Cost

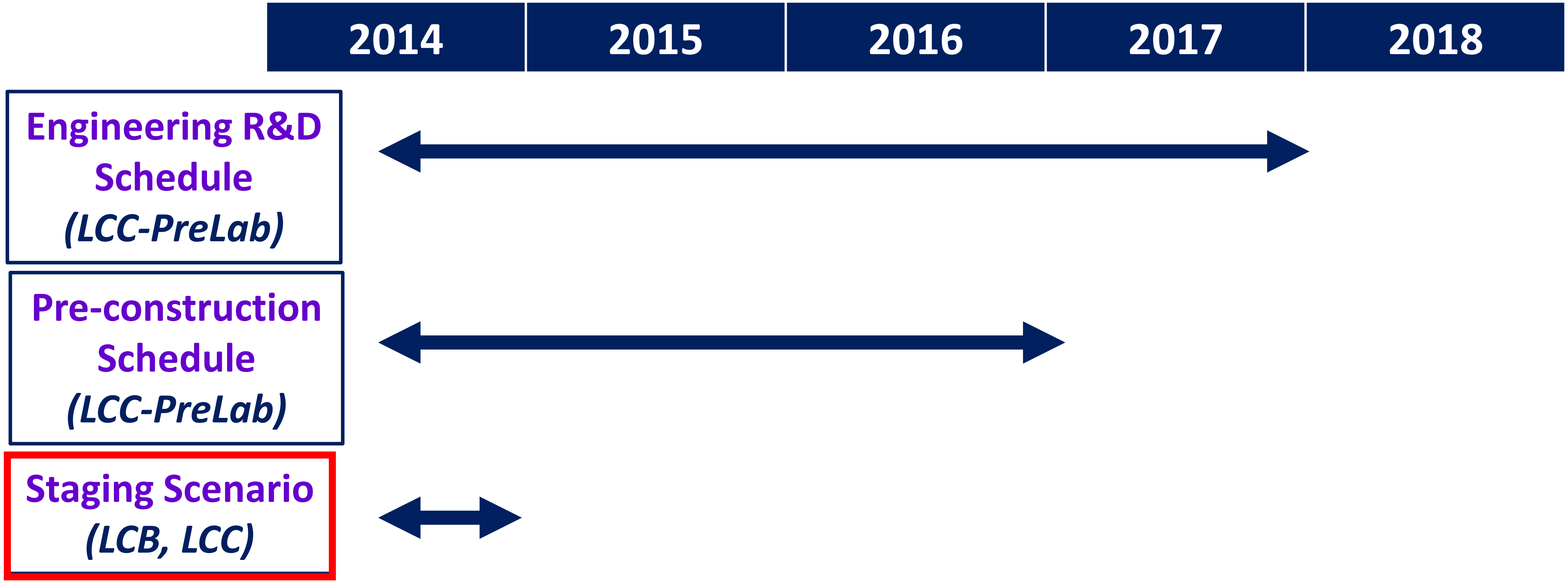
- Not surprising: An energy frontier collider is expensive
  - Rather solid cost estimate for the 500 GeV machine: ~ 8 Billion USD
  - Biggest component: Main linac, acceleration structures

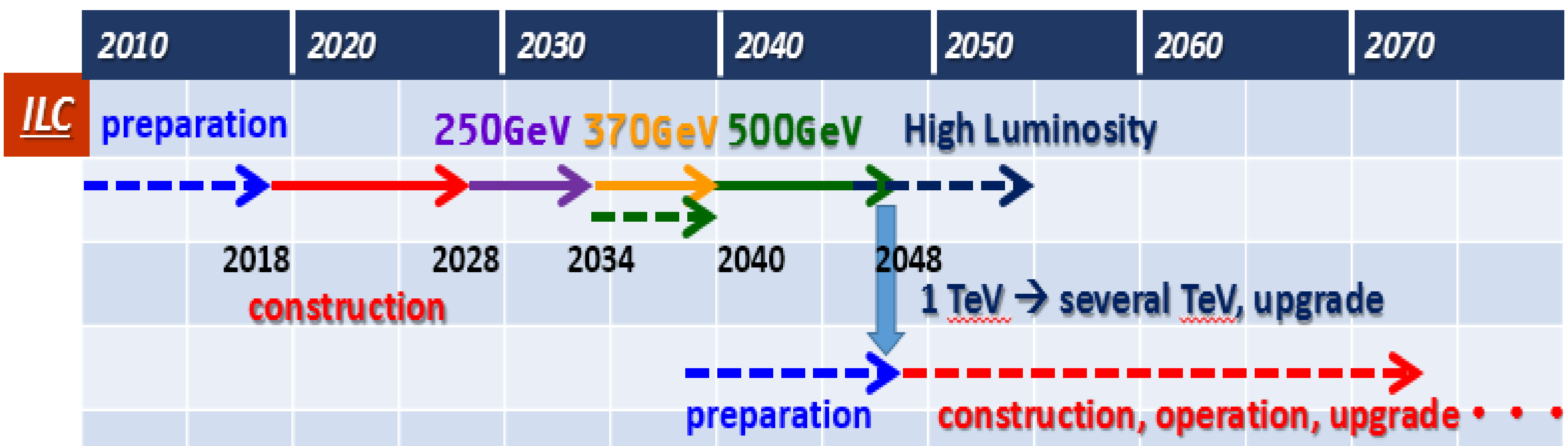




- The construction cost will be spread over ~ 10 years, and shared across the globe - details to be worked out!
- Many contributions expected “in kind”: production of components “at home”, installation in ILC

ILC - Current Schedule

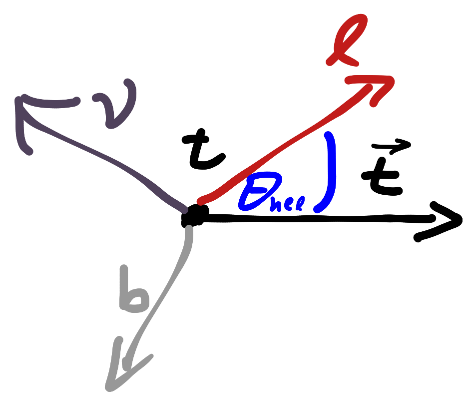


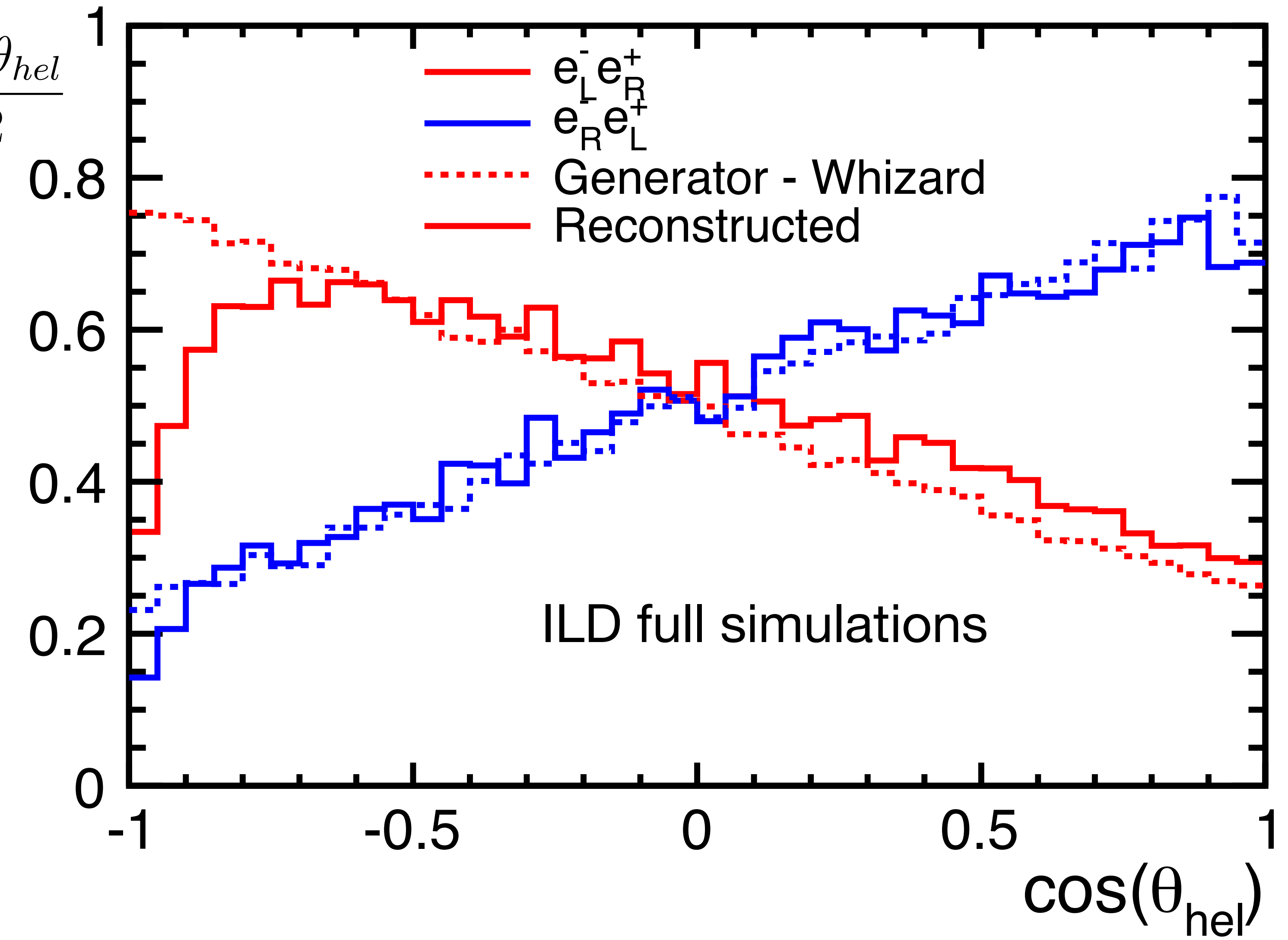


Accessing EW Couplings: Asymmetries & Angles

- Helicity Angle

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta_{hel}} = \frac{1+\lambda_t \cos\theta_{hel}}{2} = \frac{1}{2} + (2F_R - 1)\frac{\cos\theta_{hel}}{2}$$



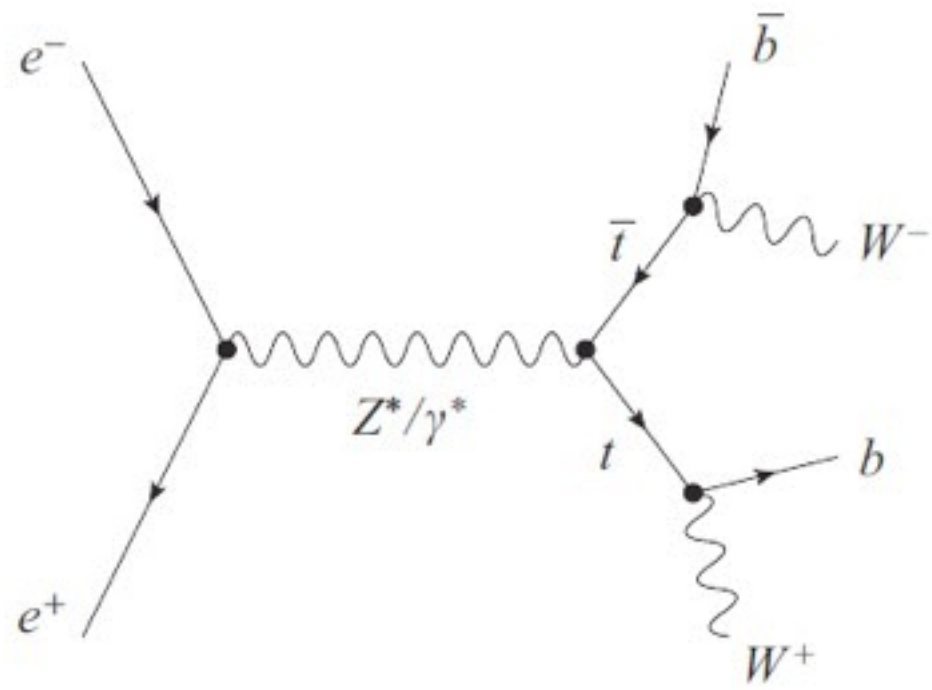


- ILC, 500 GeV, 500 fb^{-1}
- Two polarisation configurations:
  - $e^-_R e^+_L$: P(e$^-$) -80%, P(e$^+$) +30%
  - $e^-_L e^+_R$: P(e$^-$) +80%, P(e$^+$) -30%

precision on helicity angle:
~4% (stat+ syst)

Reconstructing Top Quarks at Lepton Colliders

- Driven by production and decay:
  - Production in pairs, decay to W and b



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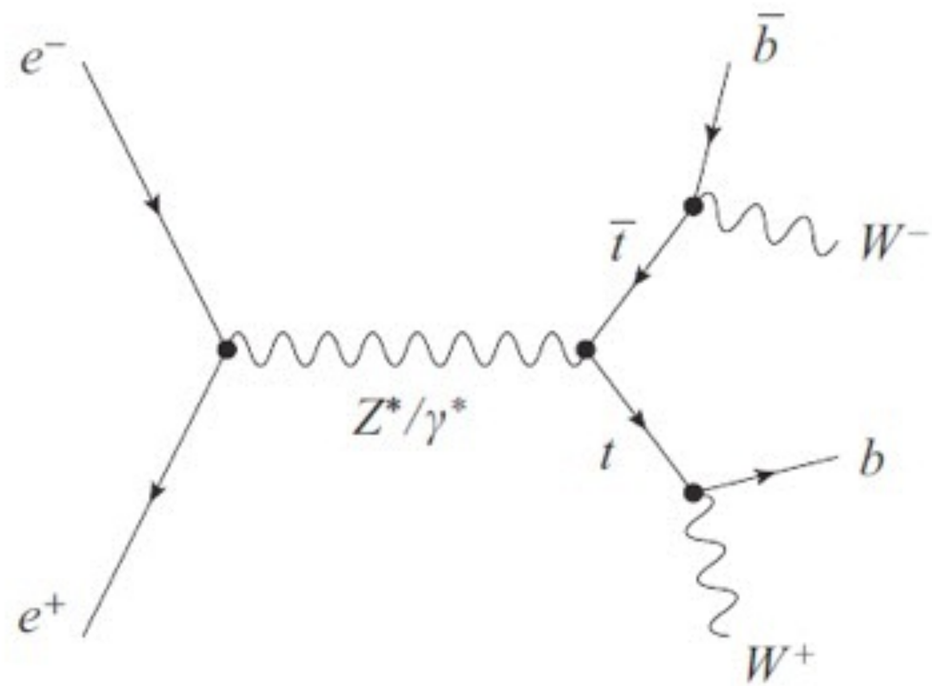
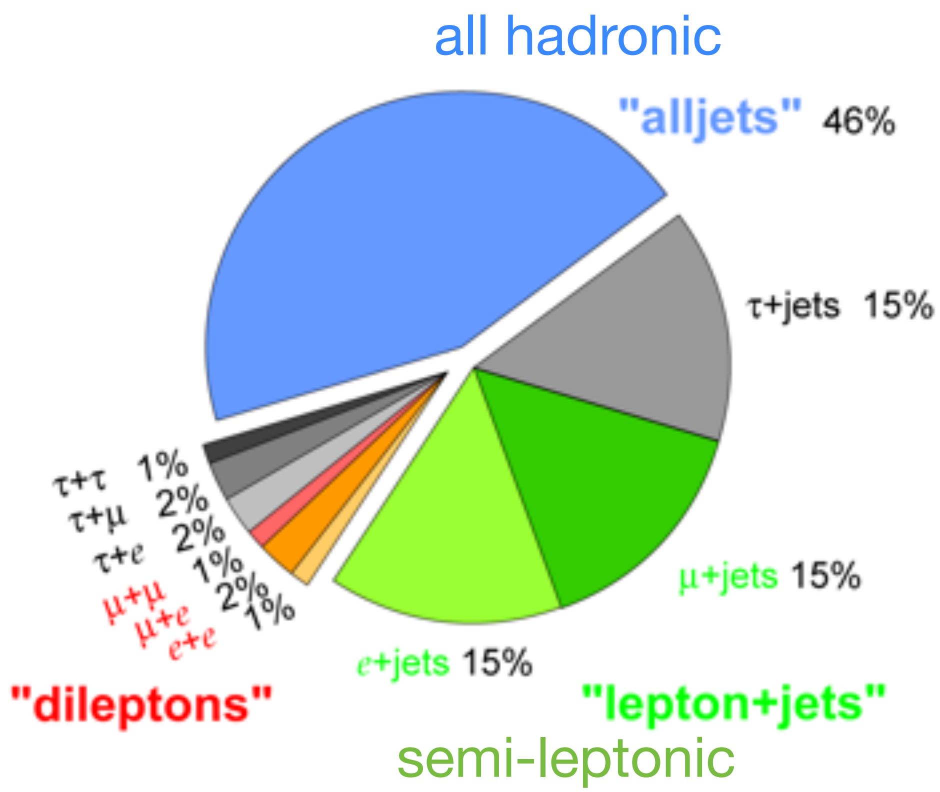


Event signature entirely given by the decay of the W bosons:



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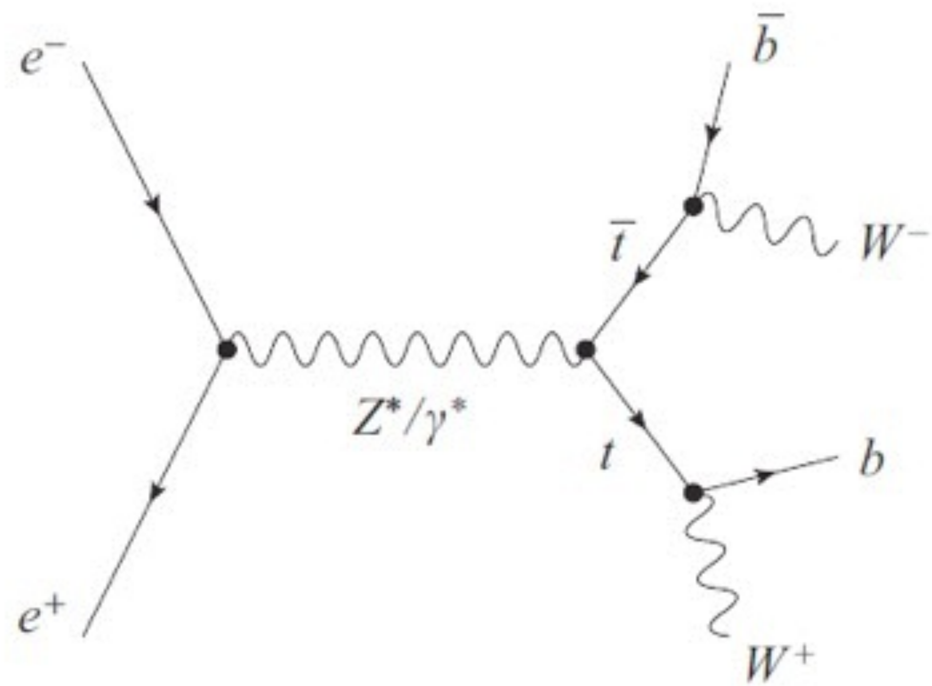

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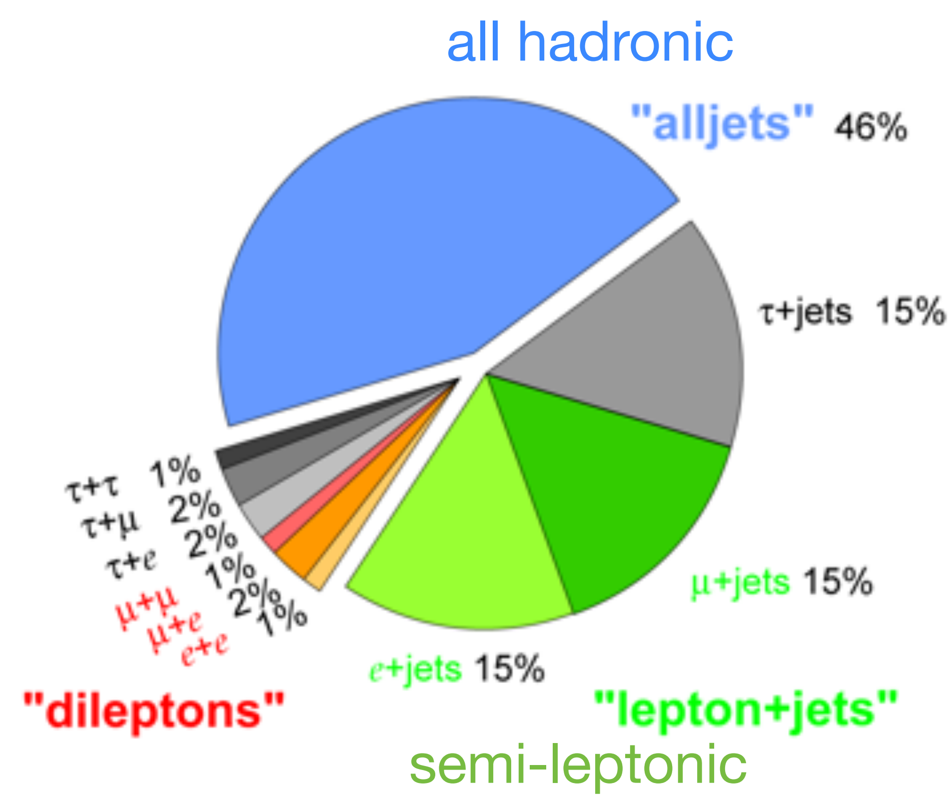


- At hadron colliders: Hard to pick out top pairs from QCD background - Use one and two-lepton final states
- At lepton colliders: Top pairs easy to identify, concentrate on large branching fractions and controllable missing energy (not more than one neutrino!)

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)

Analysis Challenges & Event Simulation - CLIC

- Key reconstruction challenge at CLIC: pile-up of γγ -> hadrons background, rejected with timing & p_t cuts and with jet finding based on k_t algorithm
  - Also relevant for ILC: No pile-up, but several γγ -> hadrons events / BX - Jet finding now follows CLIC experience

- Event generation with PYTHIA (for ttbar, LO) and WHIZARD, depending on final state
- Full GEANT4 detector simulation
- Reconstruction with PandoraPFA

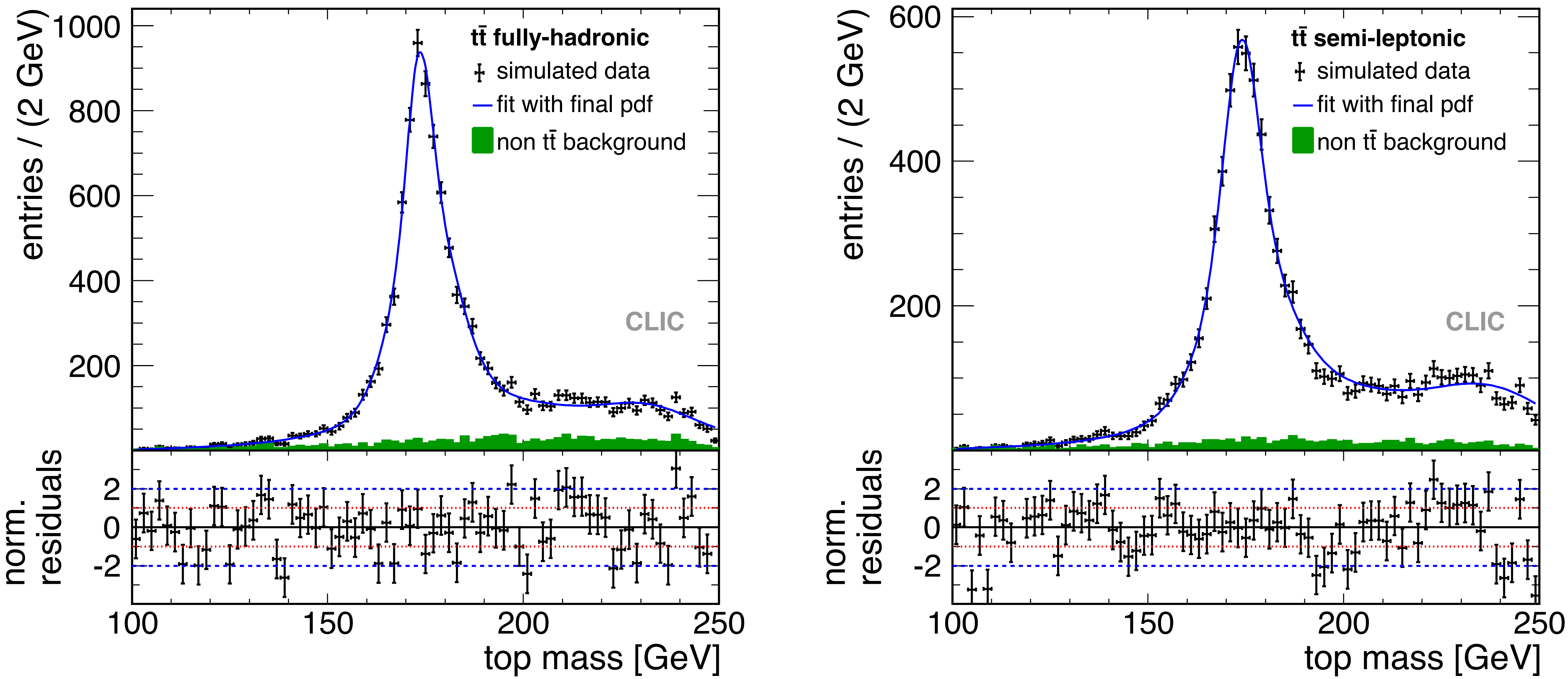
no direct simulation of threshold - currently using NNLO cross sections - *TOPPIK, Hoang & Teubner* -

type	final state	σ 500 GeV	σ 352 GeV
Signal (m_{top} = 174 GeV)	$t\bar{t}$	530 fb	450 fb
Background	WW	7.1 pb	11.5 pb
Background	ZZ	410 fb	865 fb
Background	$q\bar{q}$	2.6 pb	25.2 pb
Background	WWZ	40 fb	10 fb

both at and above threshold 100 fb^{-1} assumed

… in addition: single top may be worth considering

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

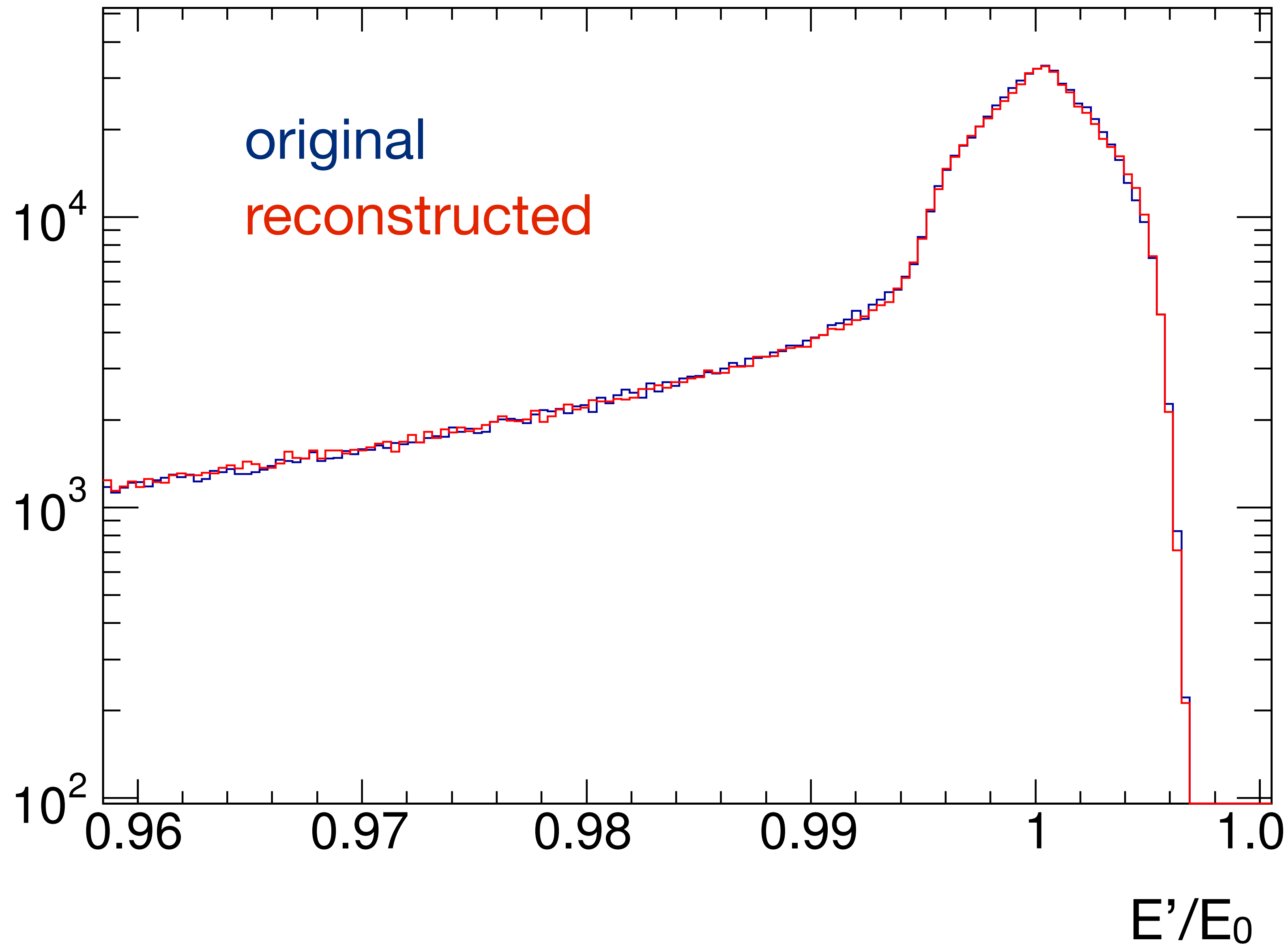
Systematics - Invariant Mass above Threshold

- Still incomplete, but some key issues were investigated:
  - Possible bias from top mass and width assumptions in detector resolution: Below statistical error, no indication for bias found
  - Jet Energy Scale: Reconstruction of W bosons can be used to fix this to better than 1% for light jets, assume similar precision for b jets from Z and ZZ events: Systematics below statistical uncertainties of the measurement
  - Color Reconnection: Not studied yet - depends on space-time overlap of final-state partons from t and anti-t decay - Expected to be less than in WW at LEP2: Comparable or smaller systematics on mass - less than 100 MeV

The key issue - and open question:
Above threshold the "PYTHIA mass" is measured - not well defined theoretically
➩ Substantial uncertainties in the interpretation of the measurements, far outweighs statistical uncertainties
➩ Some theory work in this direction already exists, but more is needed (also in in terms of connecting theory and experimental observables)

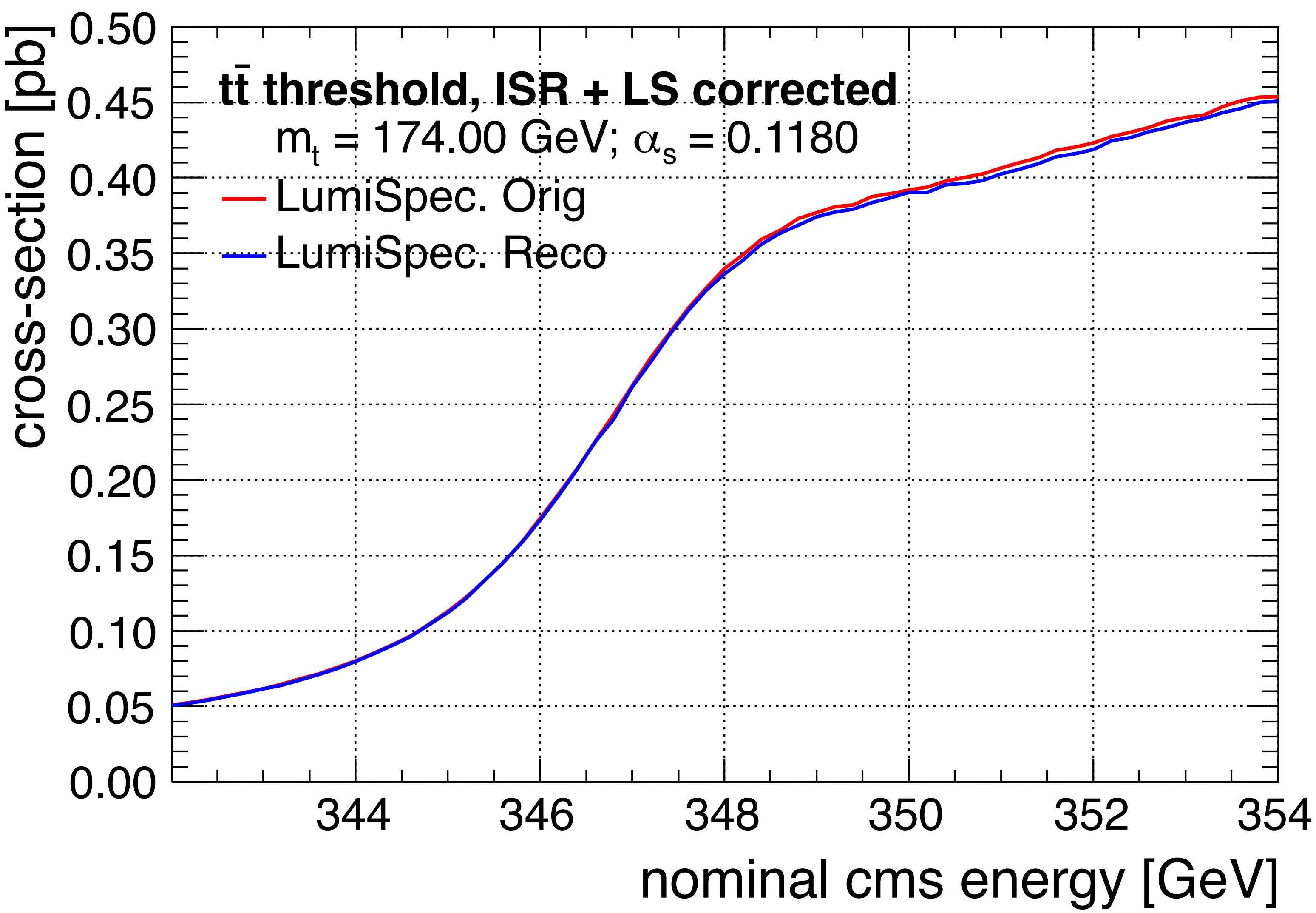
Systematics - Luminosity Spectrum

- Initial back-of-the envelope studies indicated possible systematics of 10s of MeV - mainly related to the shape of the main luminosity peak
- The challenge: Determining the shape (and normalization) of the luminosity spectrum from data
    - Accessible via energy and angle of $e^{\pm}$ from Bhabha events
    - Parametrized by a complex 19 parameter function, parameters determined from fits to Bhabha events (details: arXiv:1309.0372)



First CLIC study: application of 3 TeV model to 350 GeV - not yet full simulations, scaled uncertainties

Systematics - Luminosity Spectrum



- Impact of reconstructed luminosity spectrum on threshold behavior
  - Currently still a small bias: slightly reduced peak luminosity in model (0.7% too low)
    - Reason understood, straight-forward to correct

Global Results Summary - Luminosity Spectrum uncertainty for CLIC:

1D fit: Δm_t = (± 22 (stat) ± **5.3** (lumi parameters) - **22** (lumi reco)) MeV

2D fit: Δm_t = (± 34 (stat) ± **6.0** (lumi parameters) + **5.5** (lumi reco)) MeV

$\Delta\alpha_s$ = (± 9 (stat) ± **2.5** (lumi parameters) + **10** (lumi reco)) x 10^{-4}