ILC Top

Keisuke Fujii, KEK
on behalf of the HEP_01 team

ILC Top (HEP_01) Team

French Group

François Le Diberder

Sviatoslav Bilokin
Jeremy Hebinger
Emi Kou
Roman Pöschl
François Richard
Boris Tuchming
Viatcheslav Shavy
Paul Colas
Maxim Titov

Japanese Group

Keisuke Fujii

Akimasa Ishikawa
Yuichiro Kiyo
Masakazu Kurata
Yoshimasa Kurihara
Taikan Suehara
Yo Sato
Yukinari Sumino
Tomohiko Tanabe
Hitoshi Yamamoto

The ILC Top team is expanding!
There are new students not in this list.

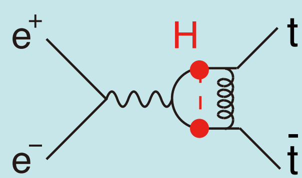
Areas of Current Activities

Key quantities: mt, tth and ttZ couplings

Top at Threshold

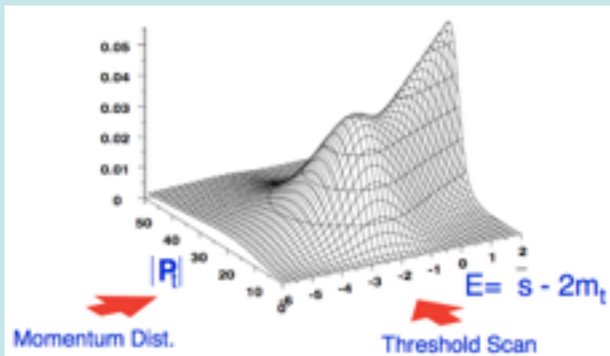
$m_t = g_{tth}\, v$

~10% effect



tth

The top mass is crucial to decide the fate of the SM vacuum!

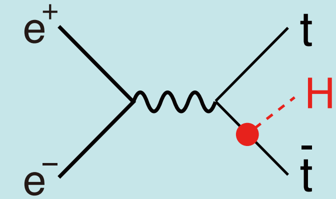


Strong team of QCD experts in Japan

Open Top Region

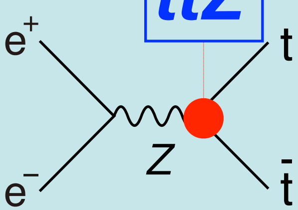
tth

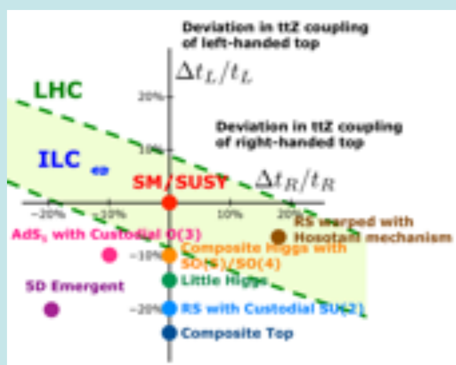
Japanese analysis team working on the tth coupling



Open Top Region

ttZ





Strong analysis team of both theorists and experimentalists in France.

GRACE *Sizable EW 1-loop effects!*

Higher order EW correction essential for BSM detection !

GRACE experts in Japanese Team!

Development of Analysis Techniques

Matrix Element Method

$$e^+e^- \to t\bar{t} \to \mu^+\mu^- b\bar{b}\,\nu_\mu\bar{\nu}_\mu$$

$$|\mathcal{M}|^2$$

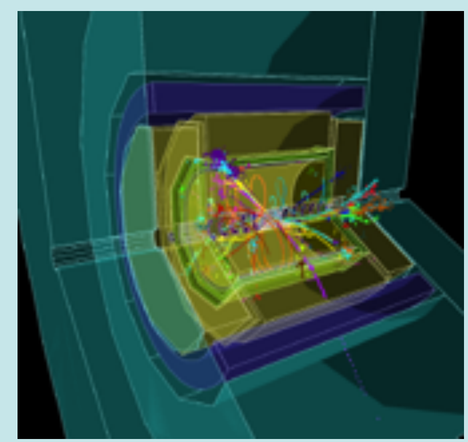
Full reconstruction of 2L+2b final states → full exploitation of available information

Expert in Matrix Element Method in French team

b-tagging and b-charge ID

Final state reconstruction uses all detector aspects

Proper top charge ID is essential, for which b-charge ID is very powerful if realized



In all of these analyses b-tagging and b-charge measurement essential !

Analysis experts in France

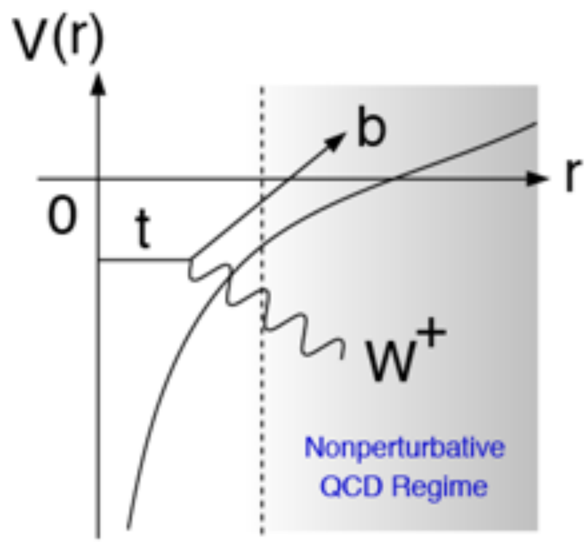
Experts of flavor tagging (LCFIPlus) in Japan

Highlights

Top at Threshold

Top at Threshold

The $t\bar{t}$ threshold is the ideal place to make a clean measurement of the top mass and the lowest energy place to access the tth coupling



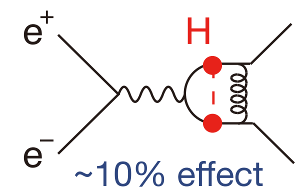
$\Gamma_t \approx 1.4$ GeV for $m_t = 175$ GeV

Because of this large width, the top and the anti-top pair created at r=0 decay before entering the non-perturbative QCD regime.

Γ_t acts as an infrared cutoff

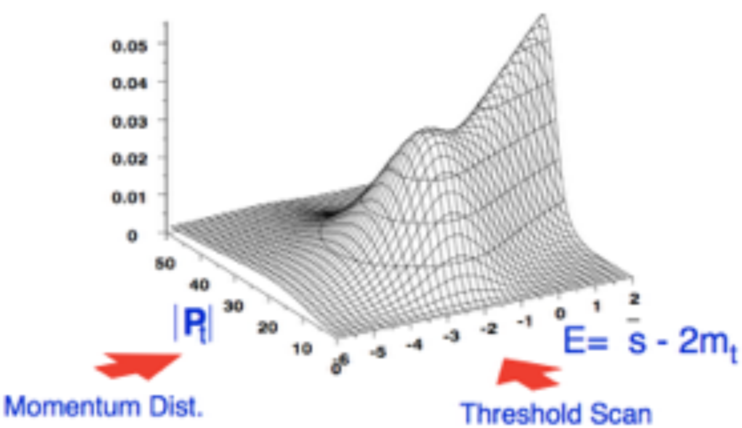
Reliable cross section calculation from first principle (perturbative QCD) even in the threshold region as first shown by Fadin-Khoze!

The reliable estimate of the QCD bound-state effects gives us the ***opportunity to access the tth coupling!***

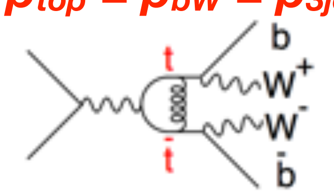


tth

More importantly the reliable estimate of the QCD bound-state effects allows us to extract ***the short-distance top quark mass in a theoretically very clean way!, which is crucial to decide the fate of the SM vacuum!***

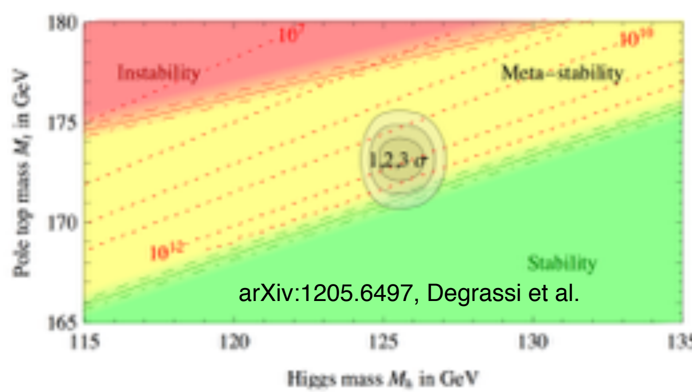


$p_{top} = p_{bW} = p_{3jets}$

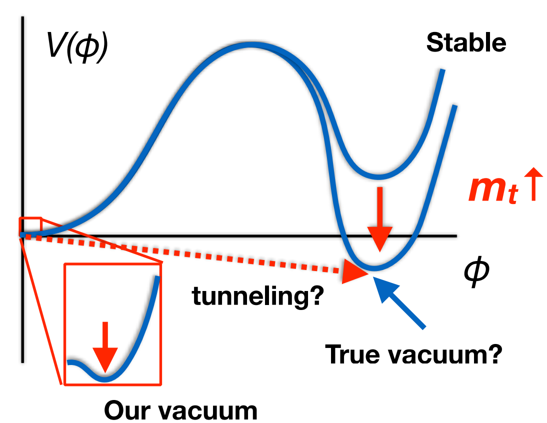


1S peak→m_t

$\sigma \rightarrow g_{tth}$



At LHC, theory error limits the top mass precision to ~500MeV.

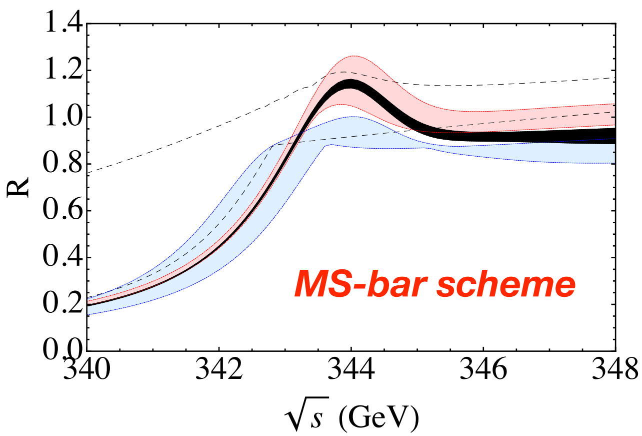


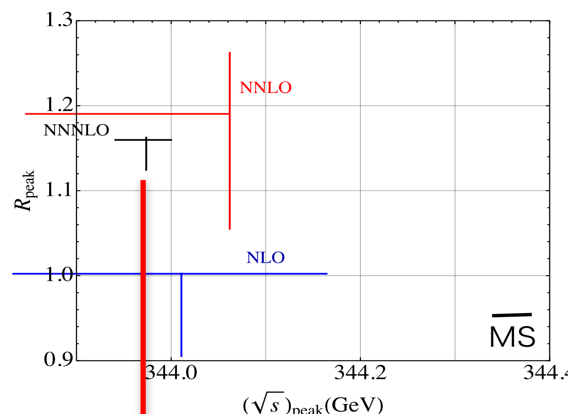
World experts of QCD (Y. Kiyo & Y. Sumino) in Japanese team

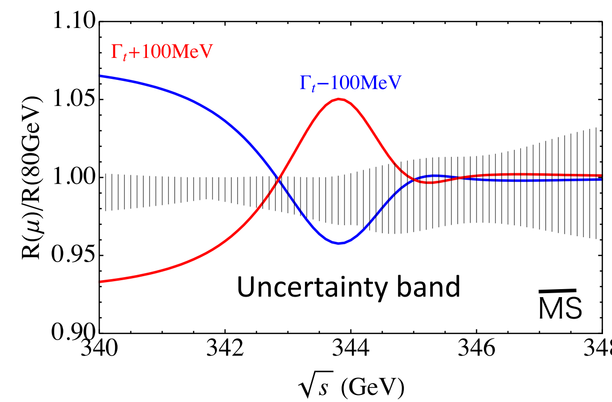
NNNLO top production near threshold

The state-of-the-art

NNNLO study for mt, Γt extraction in threshold scan with NNNLO cross section
(presented in TopLC15, IFIC Valencia, 30 June-2 July, 2015)







NNNLO scale dependence
(black band) in MS-bar scheme

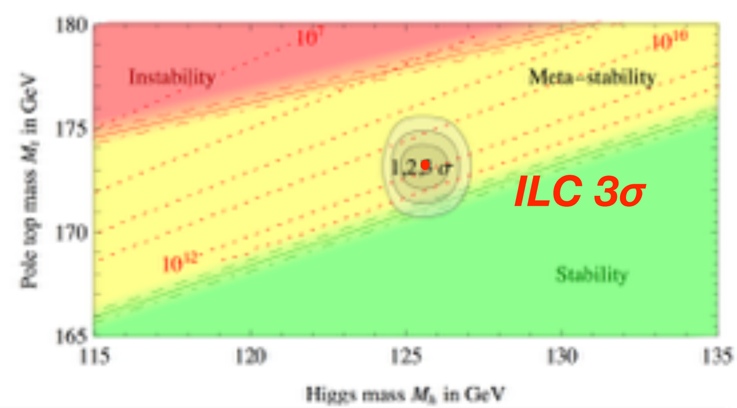
Uncertainty of peak position and magnitude $\Delta R_{peak} \sim 3\%$ $\delta E \sim \pm 30\mathrm{MeV}$

Sensitivity of Cross section for top width

With NNNLO threshold cross section, feasibility study for top properties (mass, width, Yukawa coupling with Higgs boson) had been started

- Precision of top mass determination, **Kiyo**-Mishima-**Sumino**(JHEP 1511(2015)084
- NNNLO QCD corrections, Beneke-**Kiyo**-Marquard-Penin-Piclum-Steinhauser, PRL115(2015)no.19, 192001

$$\Delta m_t(\overline{MS}) \lesssim 30\,\mathrm{MeV}$$
$$\Delta m_H = 15\,\mathrm{MeV}$$



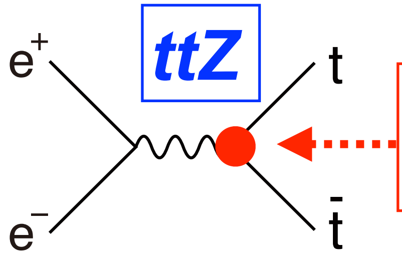
ILC pinpoints the vacuum location!

Open Top Region

In Search of Anomalous ttZ couplings

Top: **Heaviest in SM**→Must couple **strongly to EW symmetry breaking sector!**

→ ***Specific deviation pattern*** *expected in* ***ttZ form factors*** *depending on new physics.*



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

Key points

$\Gamma_t \approx 1.4$ GeV for $m_t = 175$ GeV

The top decays before forming a top hadron.

Top spin is measurable by ***angular analysis of decay products → ME***

+ Polarized beams to disentangle the left- and right-handed couplings

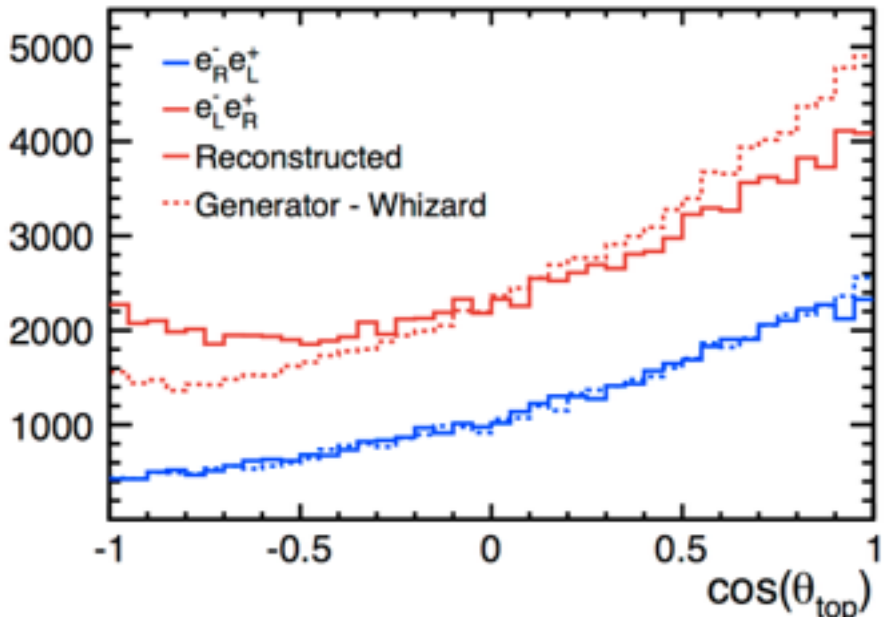
We are developing experimental technique for precision top quark reconstruction

b-tagging and b-charge measurement are essential!

Experts of event reconstruction in France
Experts of flavor tagging (LCFIPlus) in Japan

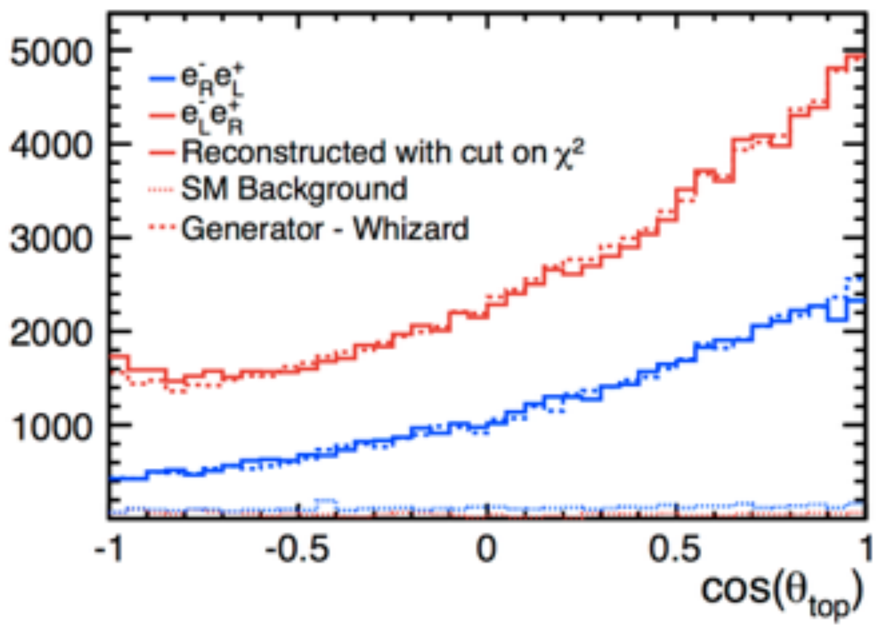
Semi Leptonic Analysis - Reconstruction of θ_{top} at $\sqrt{s}$=500 Gev

Arxiv:1505.06020
EPJC (2015) 75:512



Ambiguities in the case of left handed electron beams
Due to V-A structure at ttX vertex

Precise reconstruction of θ_{top} in case of right handed electron beams



Remedy to address ambiguities:
Select cleanly reconstructed events by χ^2 analysis
or
Reconstruction of b quark charge (New study)

Precise reconstruction for both beam polarisations

- Efficiency Penalty for e_L
- ε_{tot}: e_R~ 50%, e_L ~ 30%

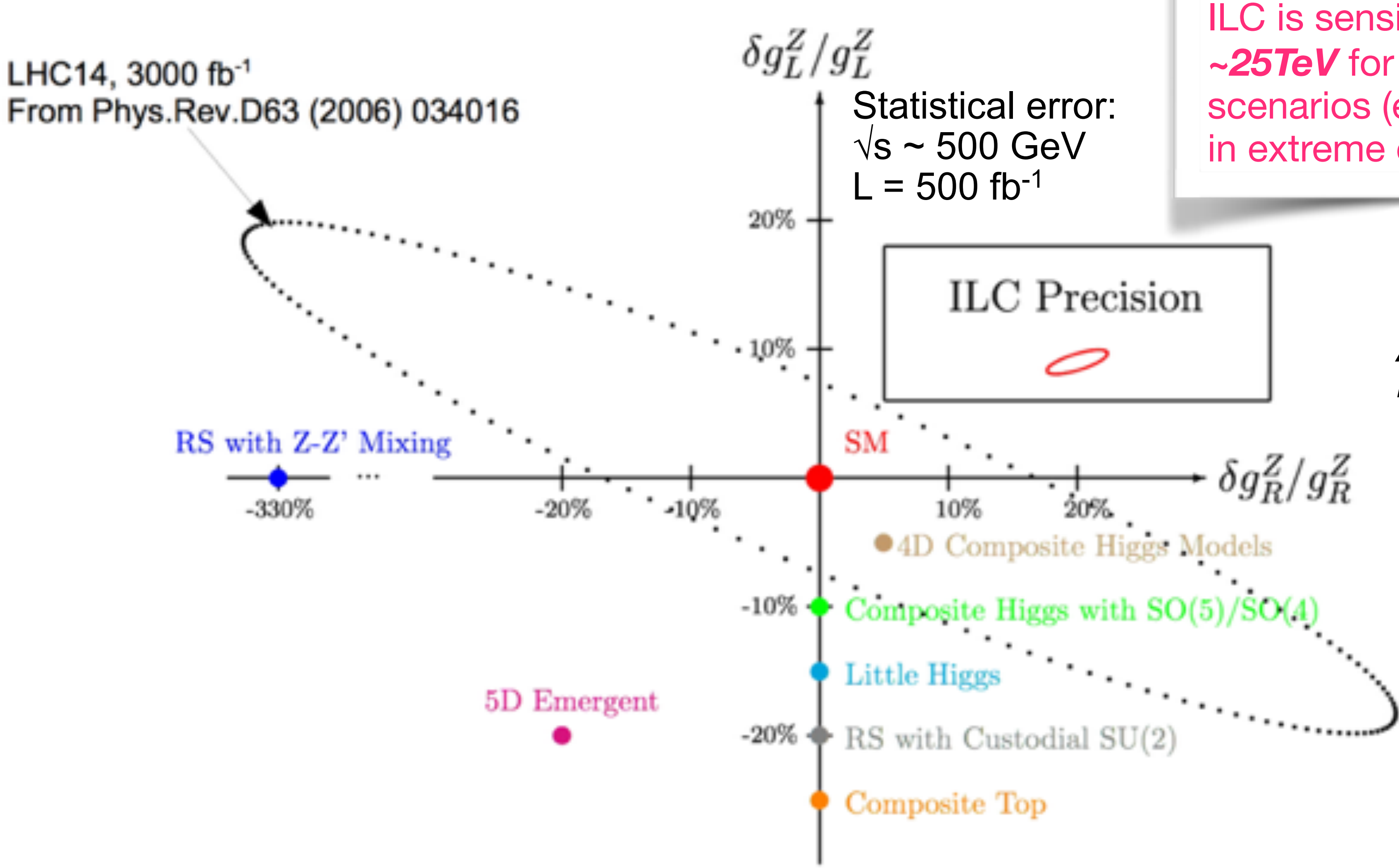
Low ε for e_L

Results:

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{stat.}$ [%]	$(\delta A^t_{FB}/A^t_{FB})_{stat.}$ [%]
$-0.8, +0.3$	0.47	1.8
$+0.8, -0.3$	0.63	1.3

Top is primary candidate to be a messenger new physics in many BSM models
Incorporating compositeness and/or extra dimensions

ILC is sensitive to ***M_{KK} up to ~25TeV*** for typical RS scenarios (even up to ~80 TeV in extreme cases)!



Arxiv:1505.06020
EPJC (2015) 75:512

Precision expected for top quark couplings will allow to distinguish between models
Remark: All presented models are compatible with LEP elw. precision data

Top quark charge reconstruction

To remedy low e_L efficiency and further improve sensitivities to NP

- Proper top quark charge measurement essential to **control migrations observed in semi-leptonic analysis**

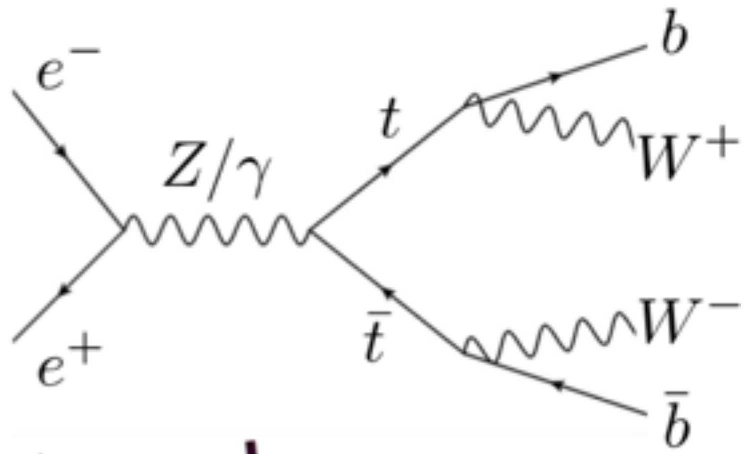
- Exploit properties of B-Mesons to **determine b-quark charge and hence top quark charge**

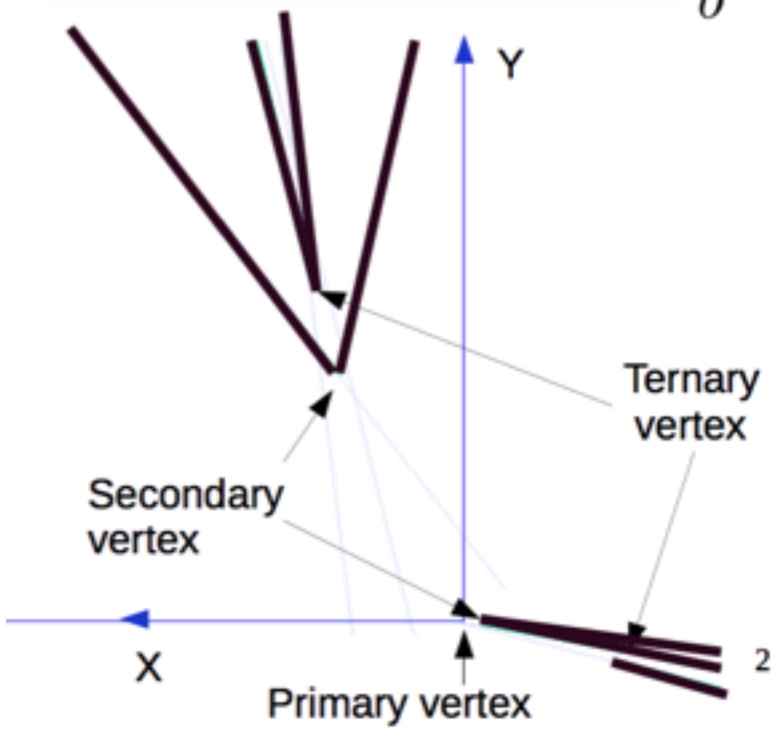
- Additionally **charged Kaons from a Ternary** carry the imprint of the original Top quark charge

- Developed algorithms:

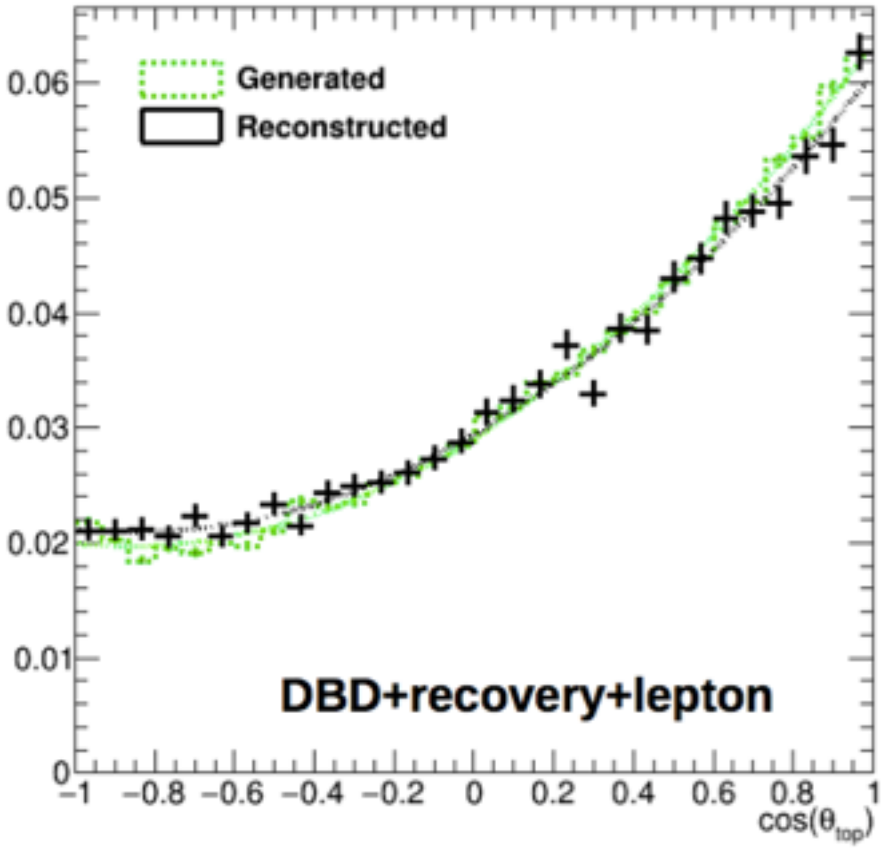
  - **TruthVertexFinder** for generated Secondary and ternary vertices
  - **VertexChargeRecovery** to collect And assign all tracks to their vertex

Both algorithms are part of ILD Software





Improvement of semi-leptonic analysis



$$A_{fb}^{rec}/A_{fb}^{gen} = 92.7\%$$

Efficiency 40%

- Event selection:
  a) Consistent b-charge and lepton charge
  or
  b) $\chi^2 < 15$

$$\chi_t^2 = (\frac{m_{rec} - m_t}{\sigma_m})^2 + (\frac{E_{rec} - E_{beam}}{\sigma_E})^2 + (\frac{p_{rec}^* - p_b^*}{\sigma_p^*})^2 + (\frac{cos\theta_{rec} - cos\theta_{bW}}{\sigma_{cos\theta_{bW}}})^2$$

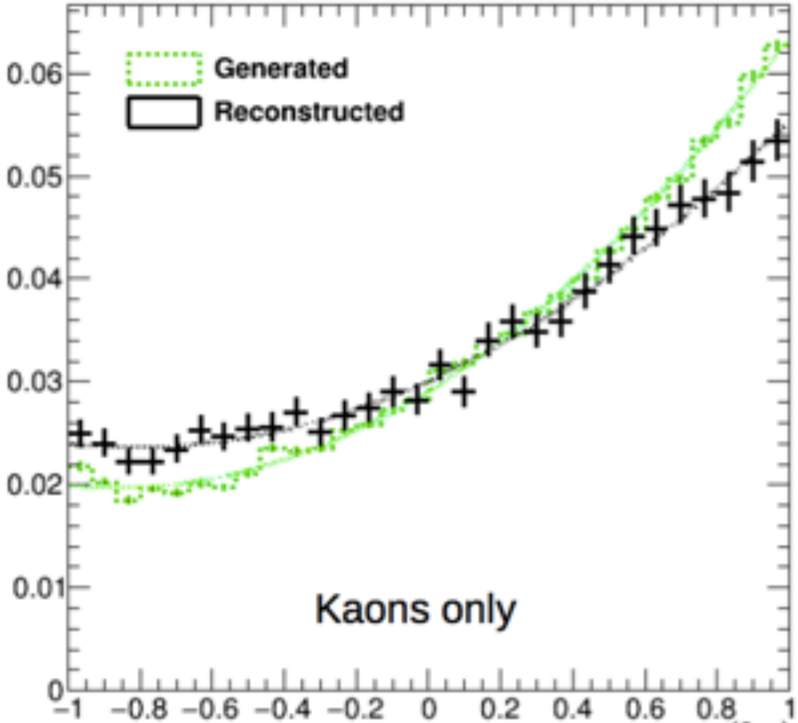
- Total efficiency is ~33% better than for Published result
  Arxiv:1505.06020, EPJC (2015) 75:512

Significant improvement w.r.t. published results (=ILD DBD)
33% better efficiency => ~17% less LC running time for same precision

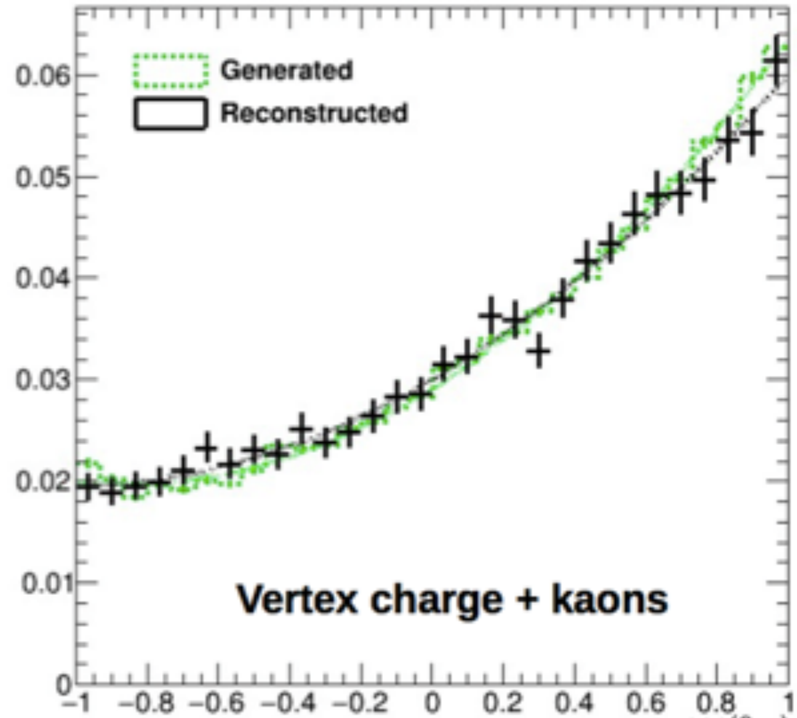
B-charge and Kaons

- top polar angle from vertex charge and Kaon charge (*still from generator information*)

=> Independent of top decay modes



$A_{fb}^{rec}/A_{fb}^{gen} = 72.8\%$



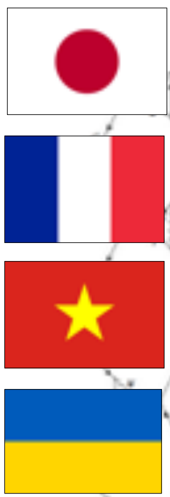
$A_{fb}^{rec}/A_{fb}^{gen} = 94.4\%$

- Clean reconstruction of top polar angle spectrum

- (Still) small efficiency of 15% due to very tight selection

Matrix Element Method

Based on GRACE software

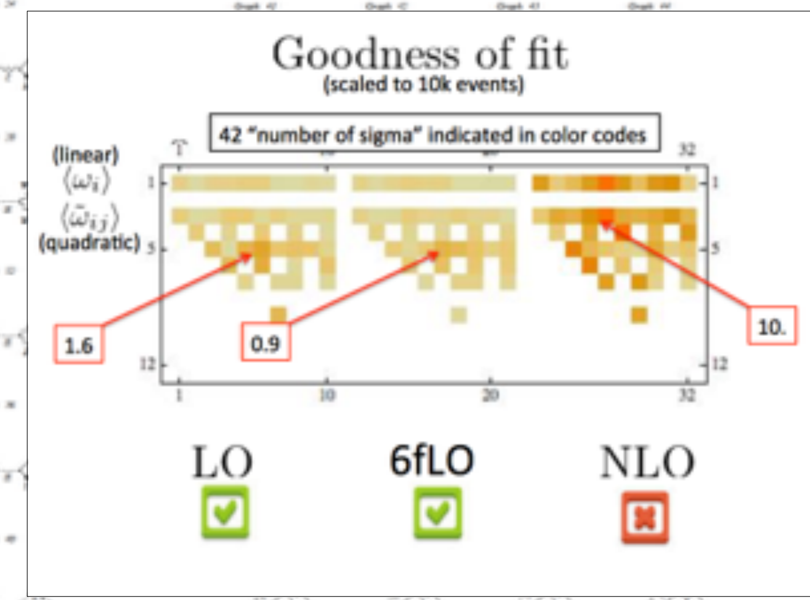


team

P. Khiem
B. Knysh
E. Kou
Y. Kurihara
F. Le Diberder
T. Moskalets
N. Quach

+ Close future
Y. Sato
H. Yamamoto
R. Poeschl
CEA physicists

NLOew-Data



Simple LO ME can handle LO and 6f-LO MC data but not NLOew MC data because of significant NLOew effects.

NLOew MC data requires NLOew ME!

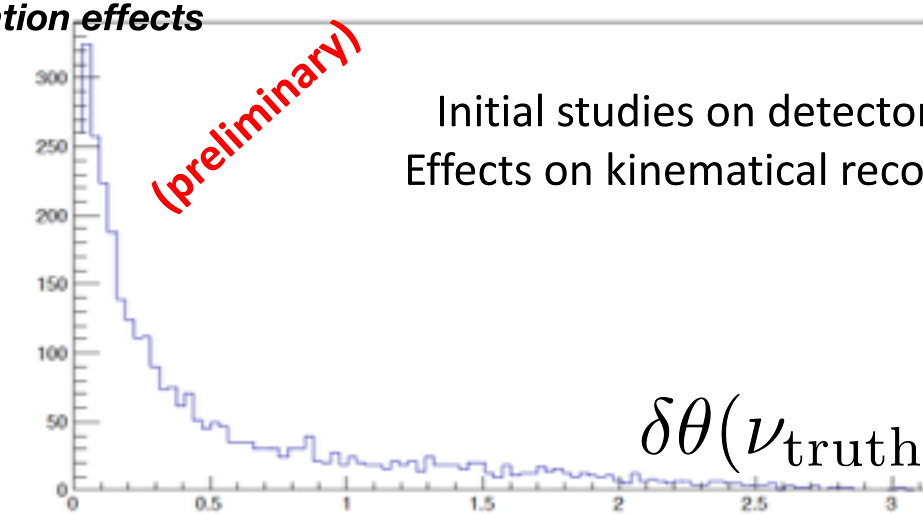
arXiv : 1503-.04247
Trento **: Frascati Phys.Ser. 61 (2016) 72-78**
LCWS2015 ; eLCWS2016

Generator-level study

To include detector/hadronization effects

B. Knysh
Master student
Kiev, Ukraine

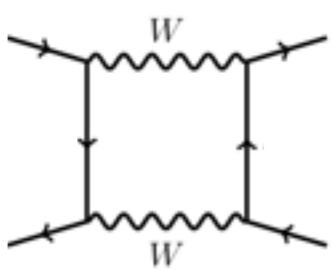
will be followed up by
Y. Sato (Tohoku student)
in FY2016



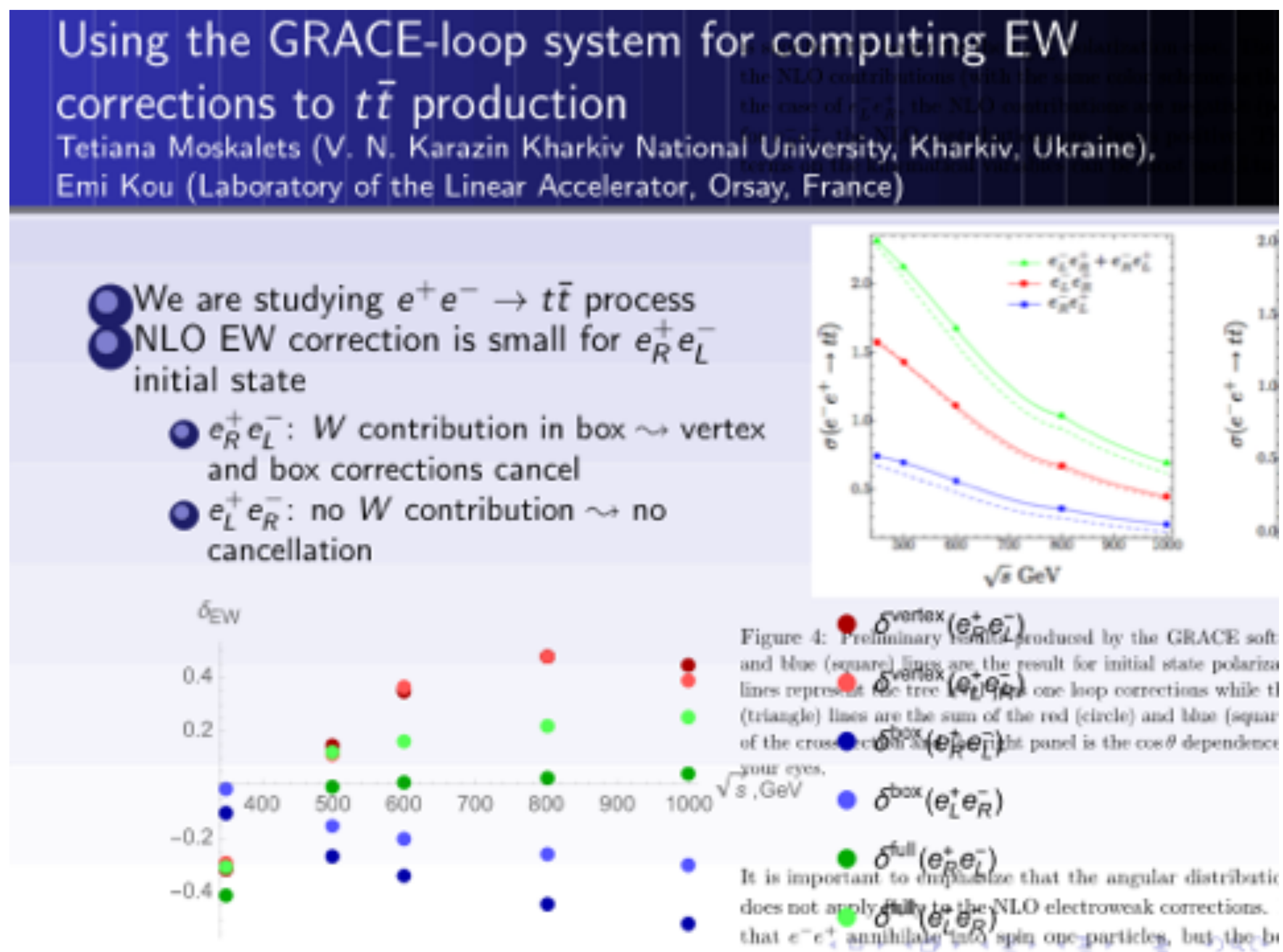
Initial studies on detector/physics
Effects on kinematical reconstruction

$$\delta\theta(\nu_{\mathrm{truth}} - \nu_{\mathrm{reco}})$$

W*here does the correction come from?*



Key role of W box diagram



Summary

- We made a significant theoretical progress in the threshold top pair production and the extraction of the short-distance top mass.

- Successful development of algorithms for reconstruction of vertex charge.

    - Clean top polar angle spectrum for semi-leptonic top decays
      33% increase of efficiency w.r.t. Paper and ILD DBD

    - Clean polar angle spectrum when using vertex charge and Kaon charge

- **Planned research stay in Japan by Sviatoslav Bilokin to work on new vertexing Algorithm in FY2016.**

    - Higher efficiency of secondary vertices (not shown today)
    - Improved particle identification

- Application of algorithms to ee-> bb final states.

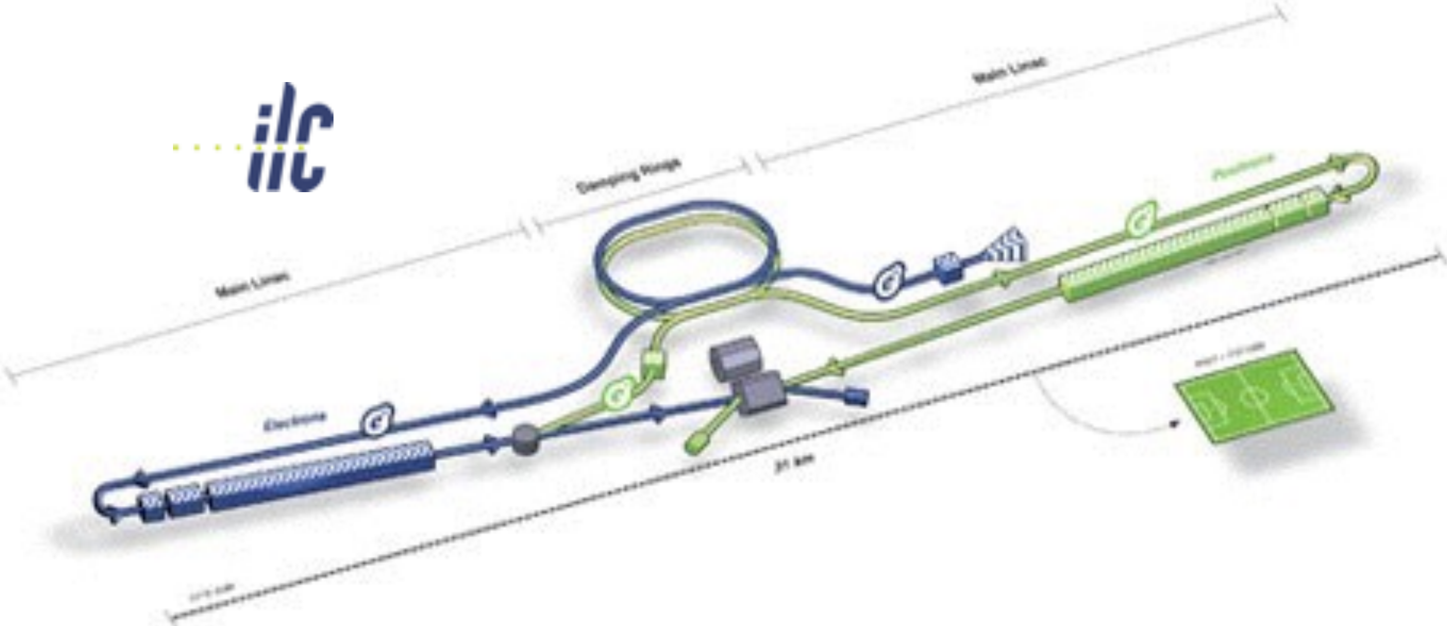
- Matrix Element Method needs proper 1-loop corrections.

- Found the key role played by the W box diagram using GRACE.

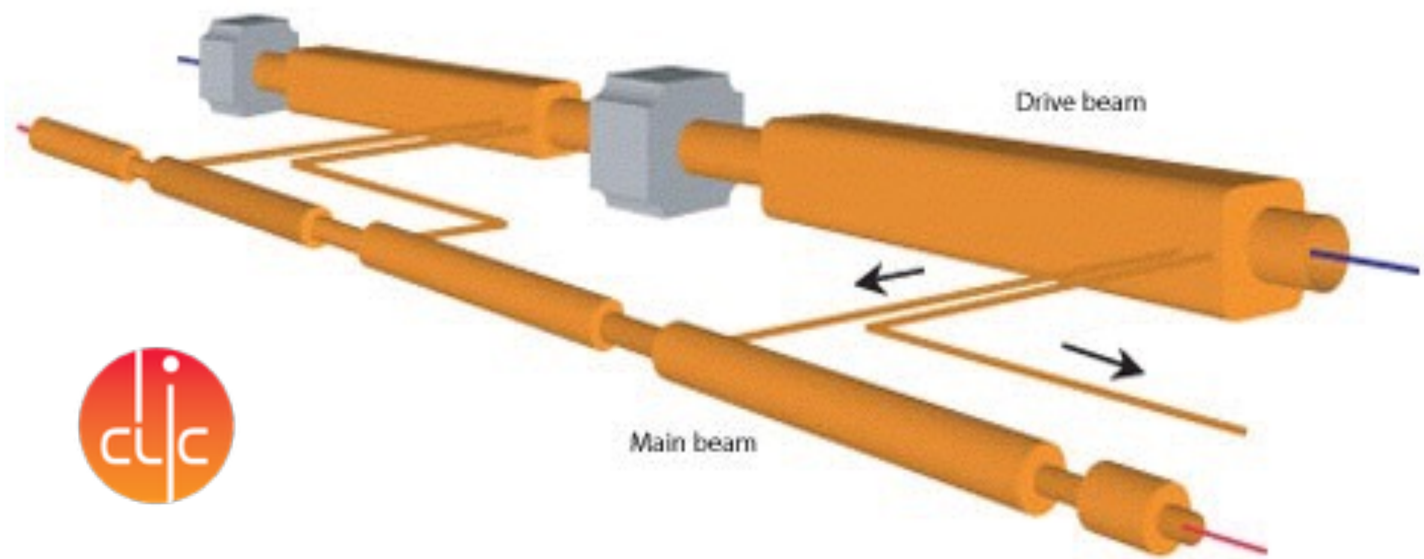
- **Planned research stay in France by Yo Sato to work on ME analysis in FY2016**.

Backup

Future Linear Electron-Positron Colliders



Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors



Energy: 0.5 - 3 TeV

CDR in 2012

Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[GeV]\sin^{3/2}\theta)]$ μm(1/3 x SLD)

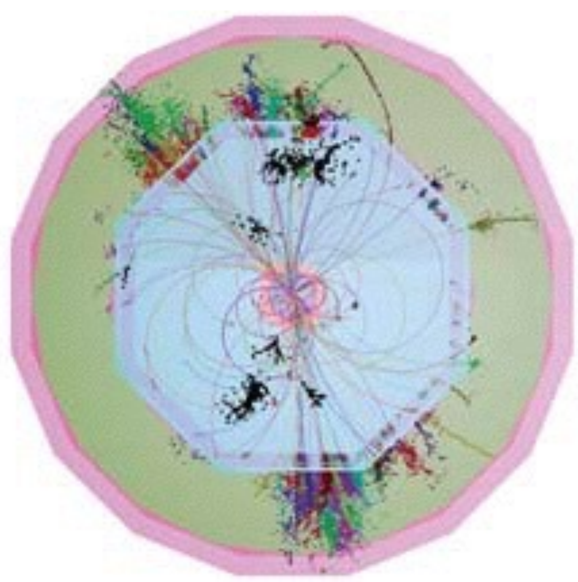
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(GeV))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : θ_{min} = 5 mrad

(for events with missing energy e.g. SUSY)



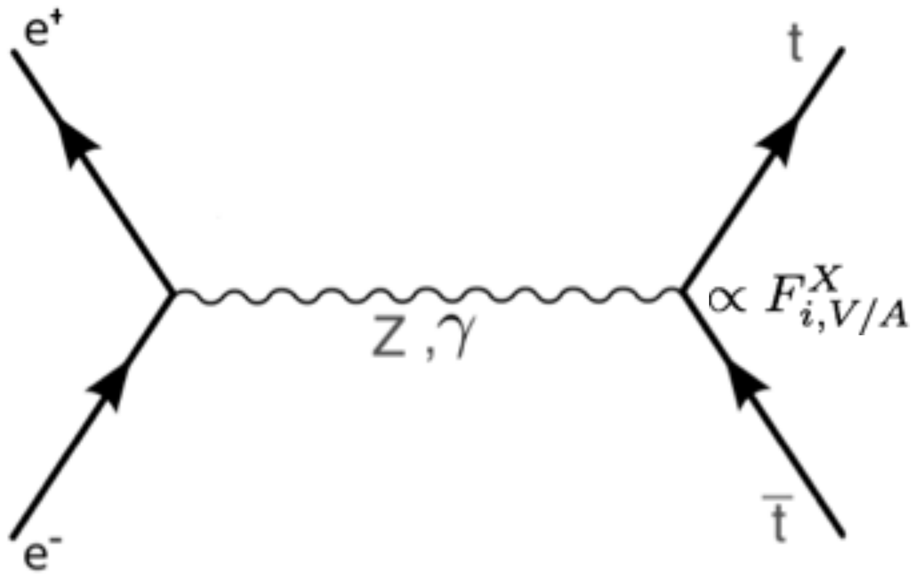
Final state will comprise events with a large number of charged tracks and jets(6+)

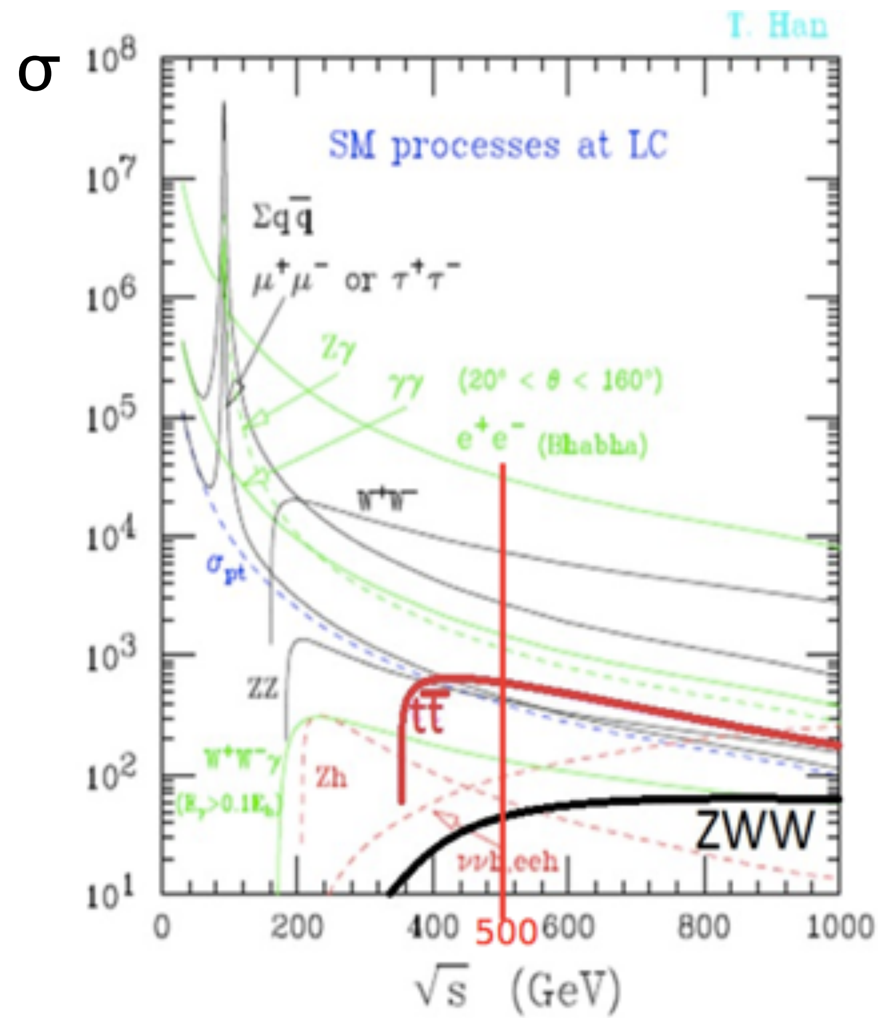
- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Detector concepts ILD and SiD

Top Quark Physics at Electron-Positron Colliders





- Top quark production through electroweak processes
  no competing QCD production => Small theoretical errors!

- High precision measurements
  - Top quark mass at ~ 350 GeV through threshold scan
  - Polarised beams allow testing chiral structure at ttX vertex
    => Precision on form factors F and couplings g

Disentangling

At ILC **no** separate access to ttZ or ttγ vertex, but ...

ILC 'provides' two beam polarisations

$$P(e^-) = \pm 80\%$$

$$P(e^+) = \mp 30\%$$

There exist a number of observables sensitive to chiral structure, e.g.

$$\sigma_I$$

x-section

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

Forward backward asymmetry

$$(F_R)_I = \frac{(\sigma_R)_I}{\sigma_I}$$

Fraction of right handed top quarks

⇩

Extraction of relevant unknowns

$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$
$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

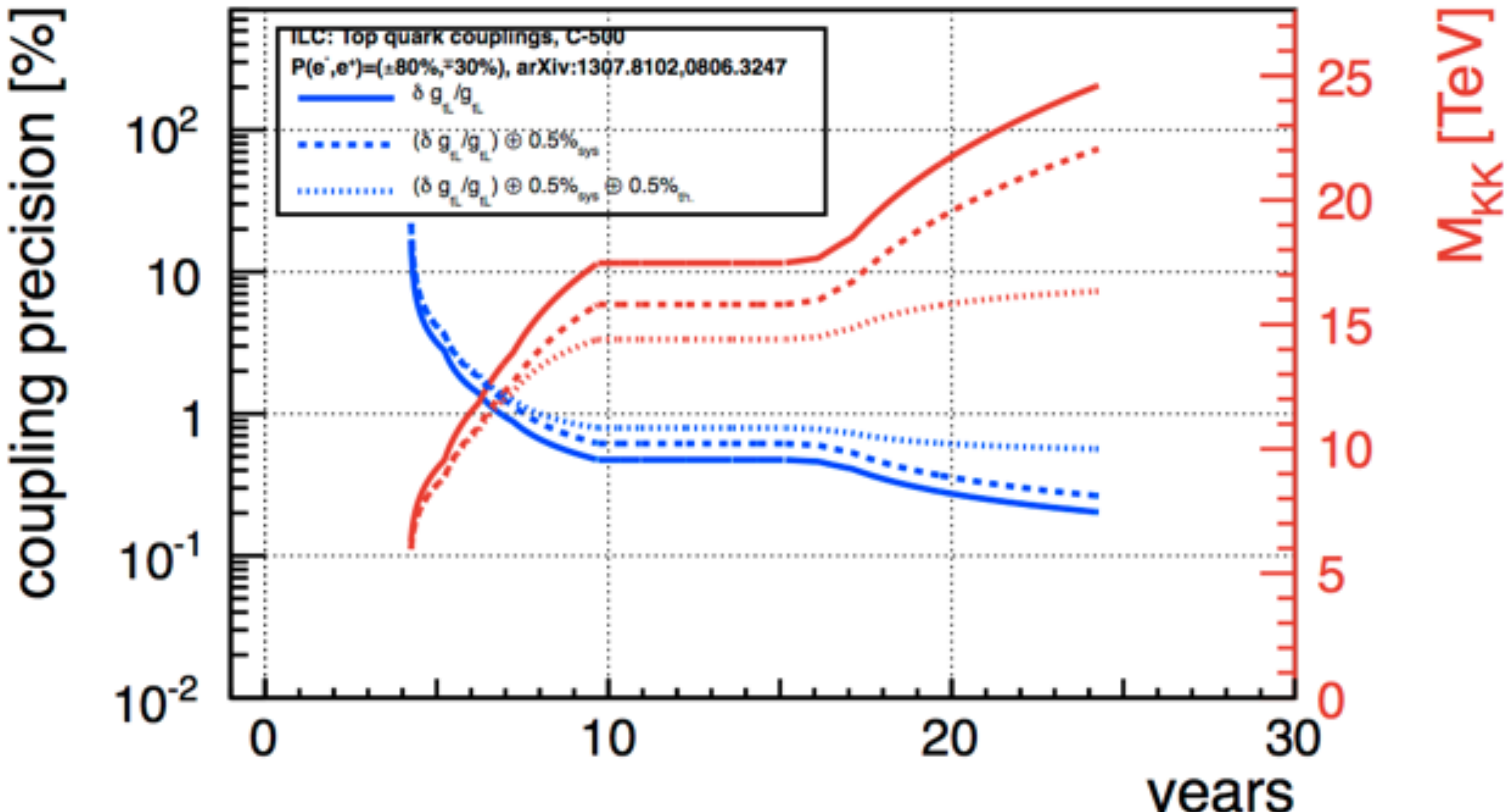
or equivalently

$$g^{\gamma}_{L},\quad g^{\gamma}_{R},\quad g^{Z}_{L},\quad g^{Z}_{R}$$

Example for physics reach

New physics reach for typical BSM scenarios with composite Higgs/Top and or extra dimensions

Based on phenomenology described in Pomerol et al. arXiv:0806.3247

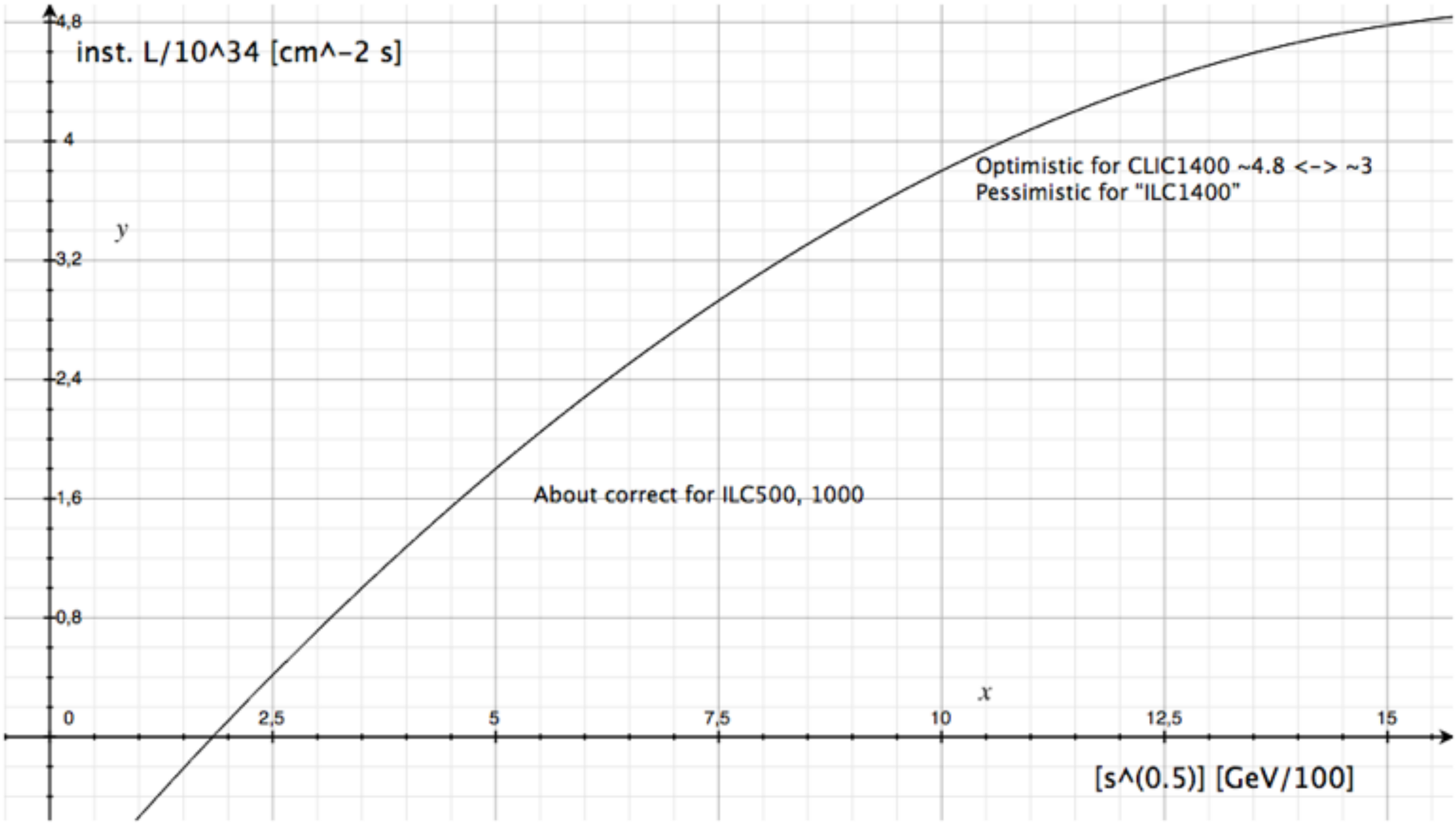


Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 TeV for extreme scenarios)

=> Important guidance for e.g. 100 TeV pp-collider

Assumptions for Lumi scaling

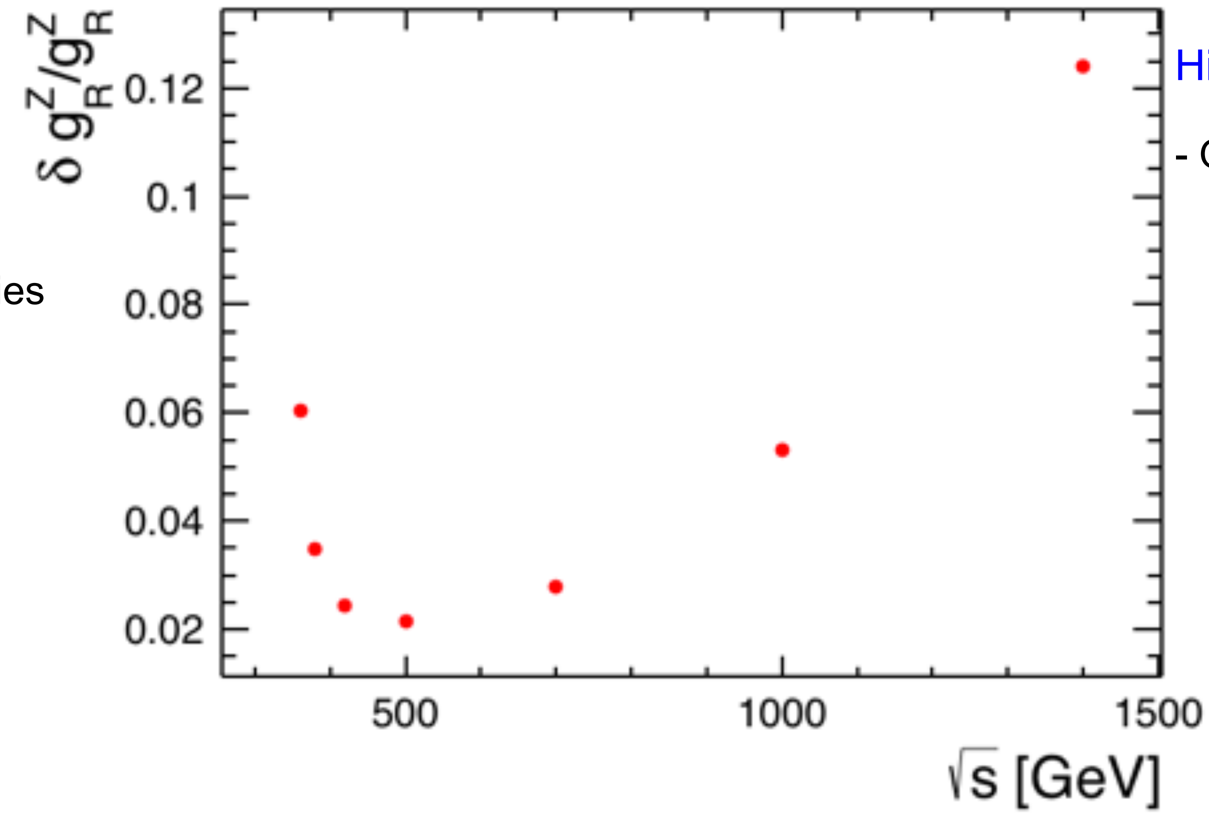


Different centre of mass energies I

... simplified discussion for gRZ

Small cms energies:

- Vanishing axial vector coupling
- On top (not shown) large QCD uncertainties



High cms energies:

- Quickly decreasing cross section

Broad minimum between 400 and 700 GeV

$\sqrt{s}$ ~ 500 GeV is "sweet spot" for coupling measurements

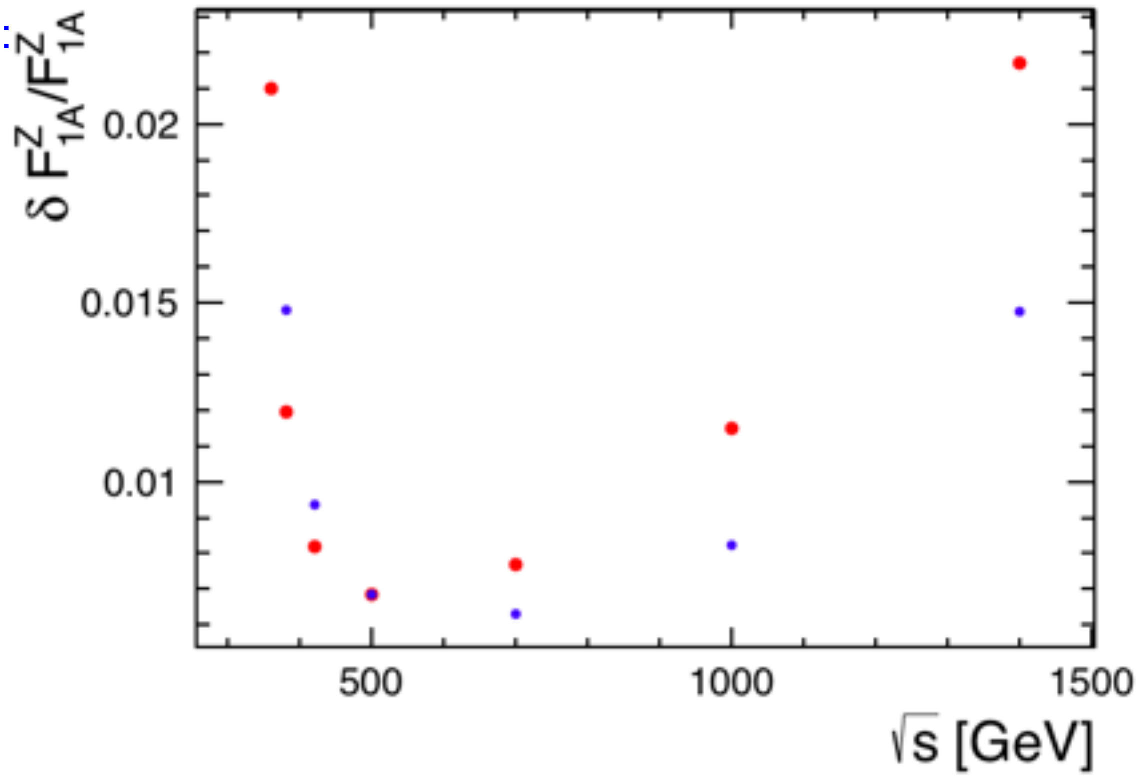
However:
- Sensitivity to CP violating Higgs at smaller cms energies
- New physics at higher energies may increase cross section

Different centre of mass energies II

... influence of different instantaneous luminosities
(Assumption caveats, see backup)

Small cms energies:

- Vanishing axial vector coupling
  +
- Lumi decreases at linear colliders



High cms energies:

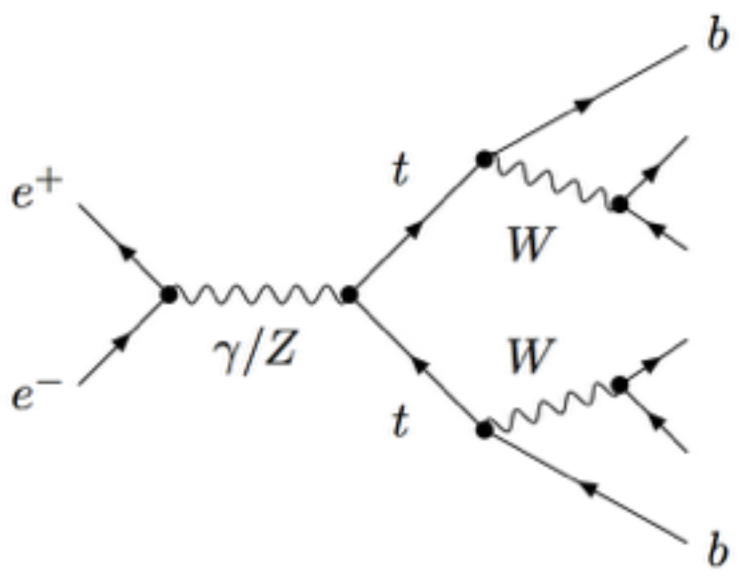
- Quickly decreasing cross section
- ... partially compensated by increasing luminosity

Broad minimum between 400 and 700 GeV

√s ~ 500 GeV is "sweet spot" for coupling measurements
However:
- F1AZ would profit from somewhat higher energies (beta dependence)
- Remark: Full disentangling for F1VZ and F2VZ at ~1 TeV

√s ~ 1 TeV attractive option

Trends in upcoming studies



Top pair production is effectively ee->6f process

- Role of (indistinguishable) single top production (Eur. Phys. J. C (2015) **75**: 223)
  Only relevant for e_L

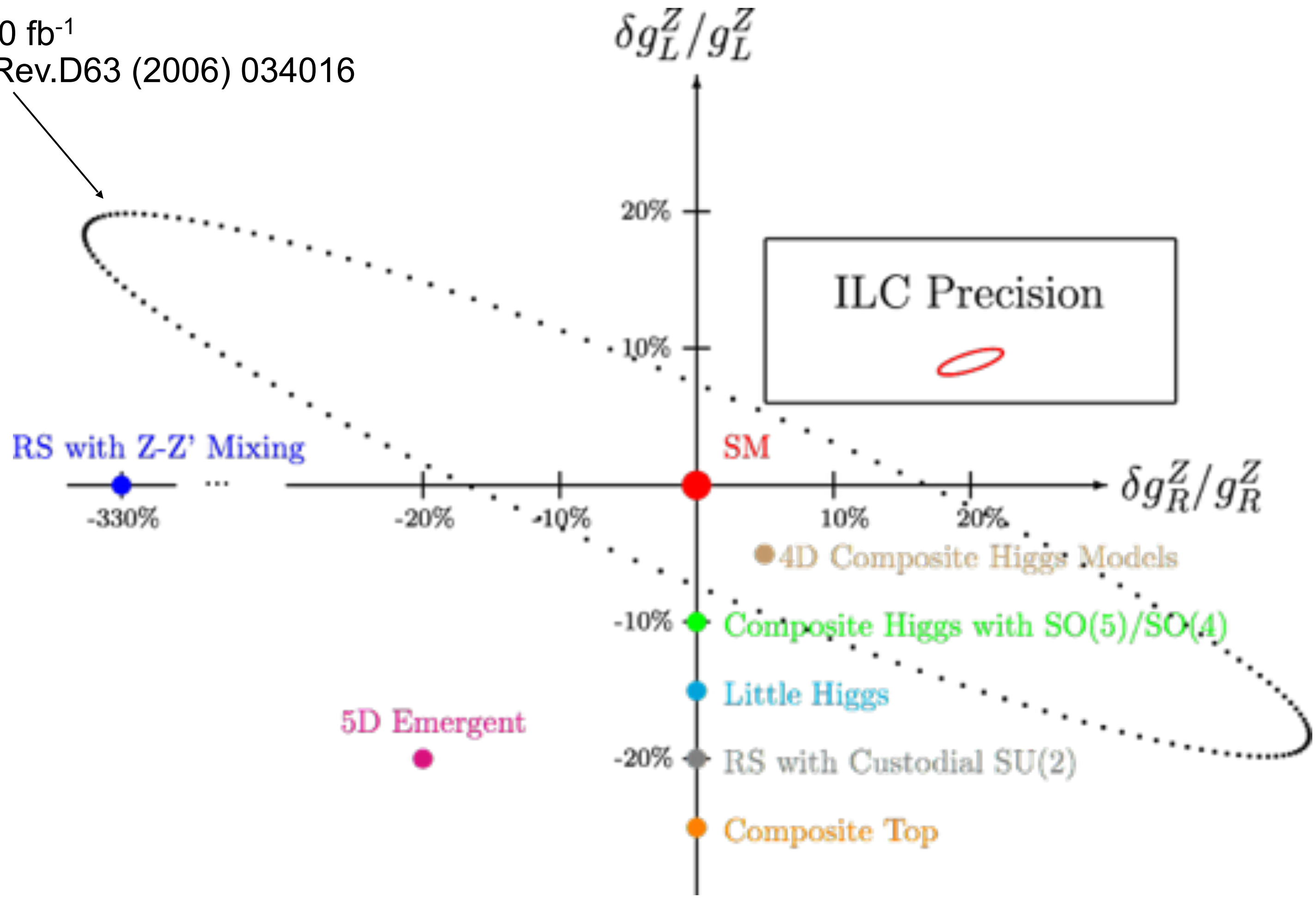
- Effective filed theory approaches w.r.t. full models

- Exploitation of information of final state by matrix element method (arxiv: 1503.04247)
  Unbiased access to tensorial CP violating form factors !?

- Exotic decays as e.g. t->ch

What about LHC perspectives?

LHC14, 3000 fb^{-1}
From Phys.Rev.D63 (2006) 034016

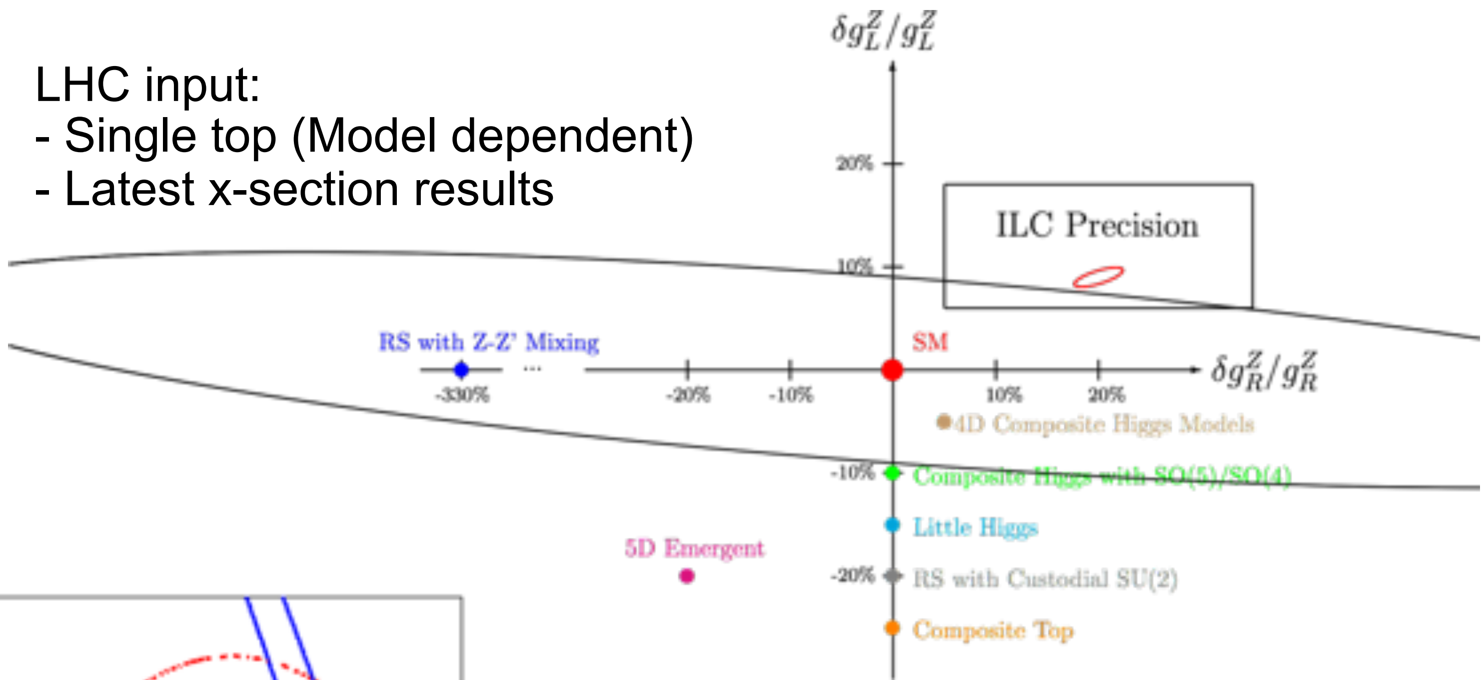


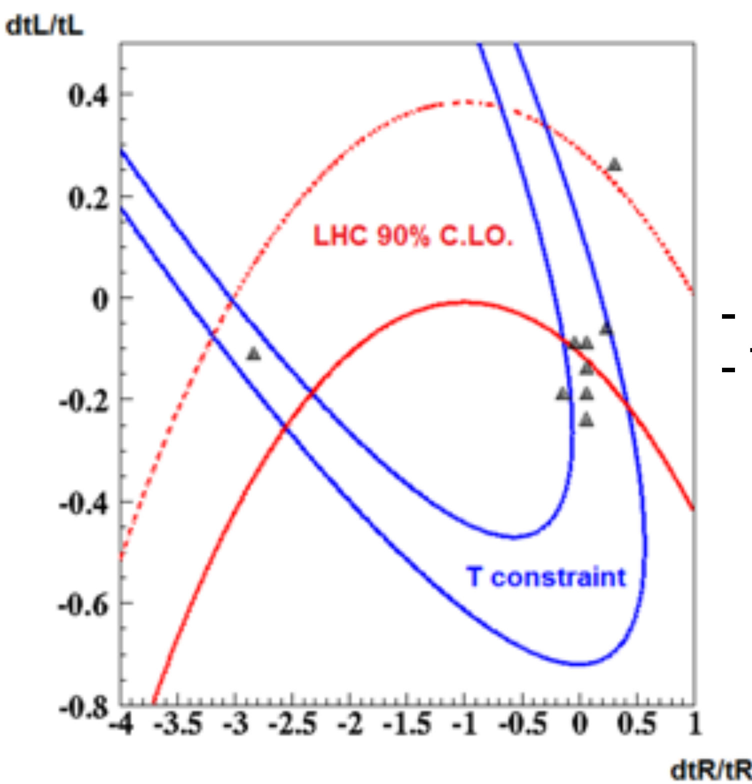
Linear Collider will outperform LHC results

- Particular poor constraint on g_R (this holds also for flavor physics results)
- LHC LO QCD analysis, ~30% improvement through NLO QCD
- LHC may still be capable to exclude models

Comparison with current LHC results

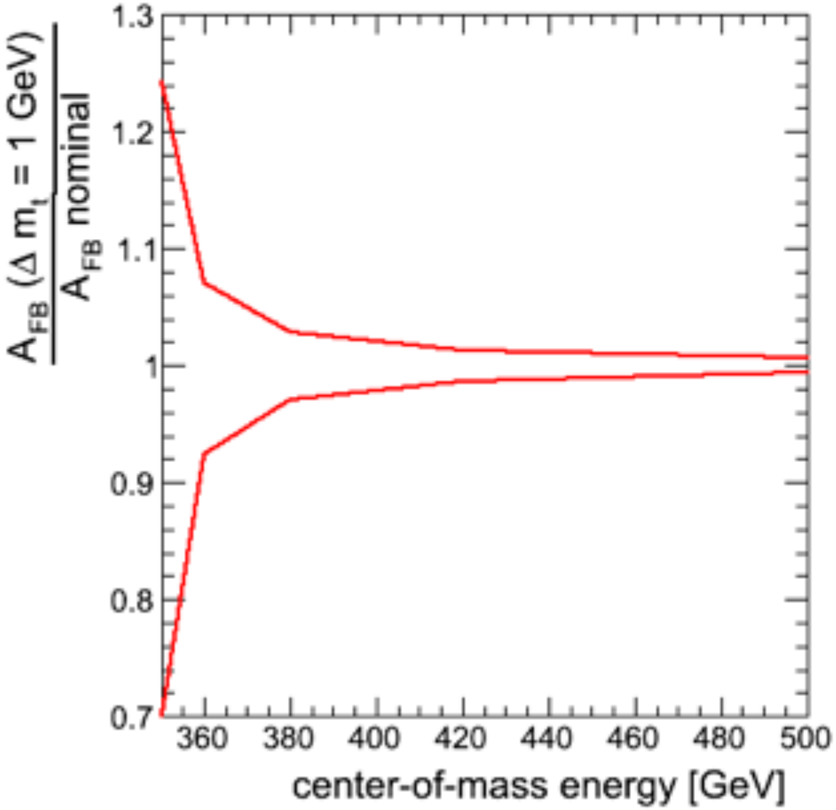
LHC input:
- Single top (Model dependent)
- Latest x-section results





- Result based on latest x-section results
- Takes into account possible sign flip of couplings

From threshold to continuum



Influence of the top quark mass on x-sec and A_{FB}

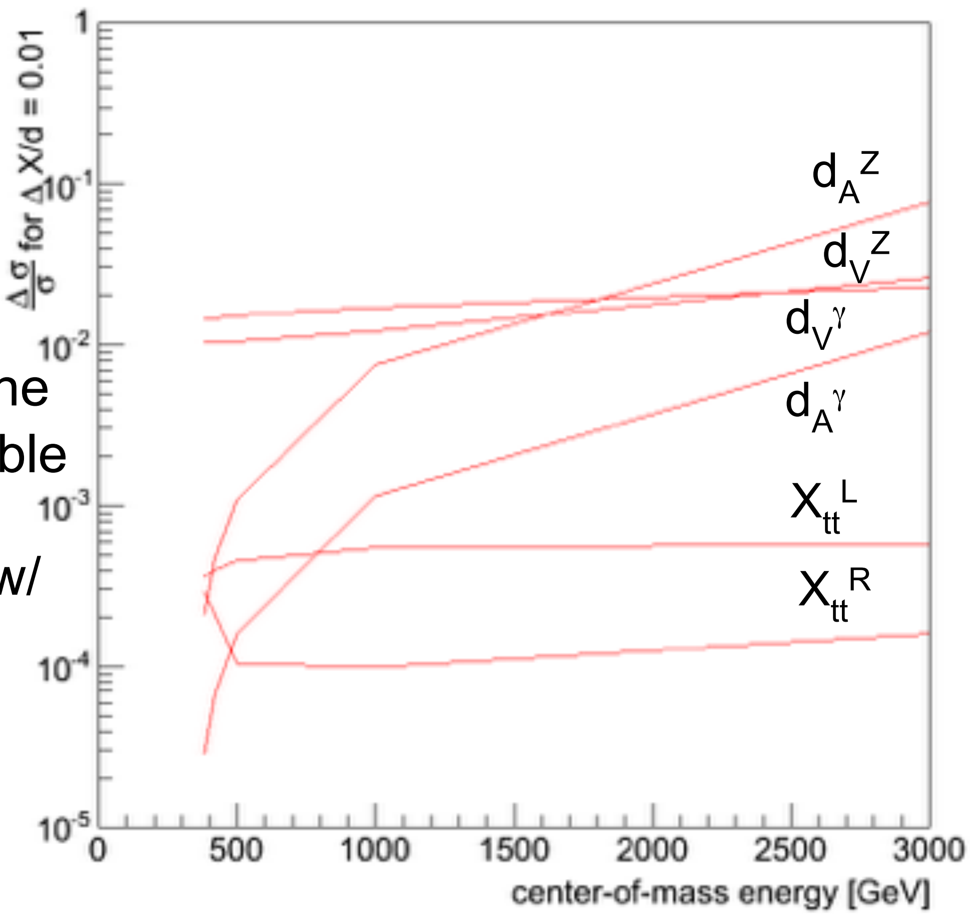
- very pronounced below √s = 360 GeV
- 2.9%/GeV at √s = 380 GeV
- 1.3%/GeV at √s = 420 GeV
- 0.6%/GeV at √s = 500 GeV

With the assumption of a 100 MeV pole mass measurement at threshold, the remaining uncertainty is one per mil or less above 420 GeV

Dimension 6 effective operators
(~equivalent role to anomalous form factors)
have been implemented in WHIZARD...

Allow to map the dependence on √s of the impact of new physics on given observable

May help to explore the sensitivity of new/ additional observables



Potential systematic uncertainties

- Luminosity: Critical for cross section measurements
  Expected precision 0.1% @ 500 GeV

- Beam polarisation: Critical for asymmetry measurements
  Expected to be known to 0.1% for e- beam
  and 0.35% for e+ beam

- Migrations/Ambiguities: Critical for A_{FB}:
  PFLOW important for selection of 'clean events' but maybe subleading w.r.t. jet clustering
  Control of b charge is most relevant topic !!!!

- Other effects: b-tagging, passive material etc.
  LEP1 claims 0.2% error on R_b -> guiding line for LC

Under discussion with theory groups:

- Consideration full 6f final state (Interference with single top and ZWW)
- Electroweak NLO predictions (Correction LO → NLO ~ 15%)
- Update and maintenance of event generators (WHIZARD, MADGRAPH etc.)