
# Precision top physics at a linear $e^+e^-$ collider; prospects for the measurement of the electro-weak couplings of the top quark

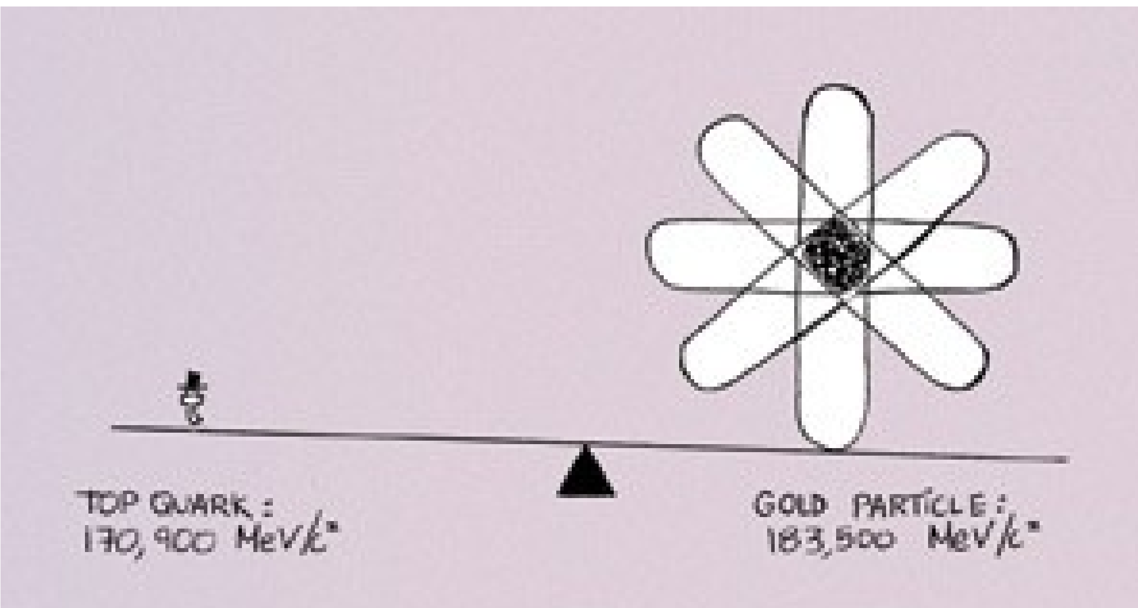
*Marcel Vos*
*IFIC (U. Valencia/CSIC)*

*M.S. Amjad, R. Poeschl, F. Richard, J. Rouëné, LAL Orsay, France*
*I. García García, E. Ros, P. Ruiz Femenia, M. Vos, IFIC Valencia*

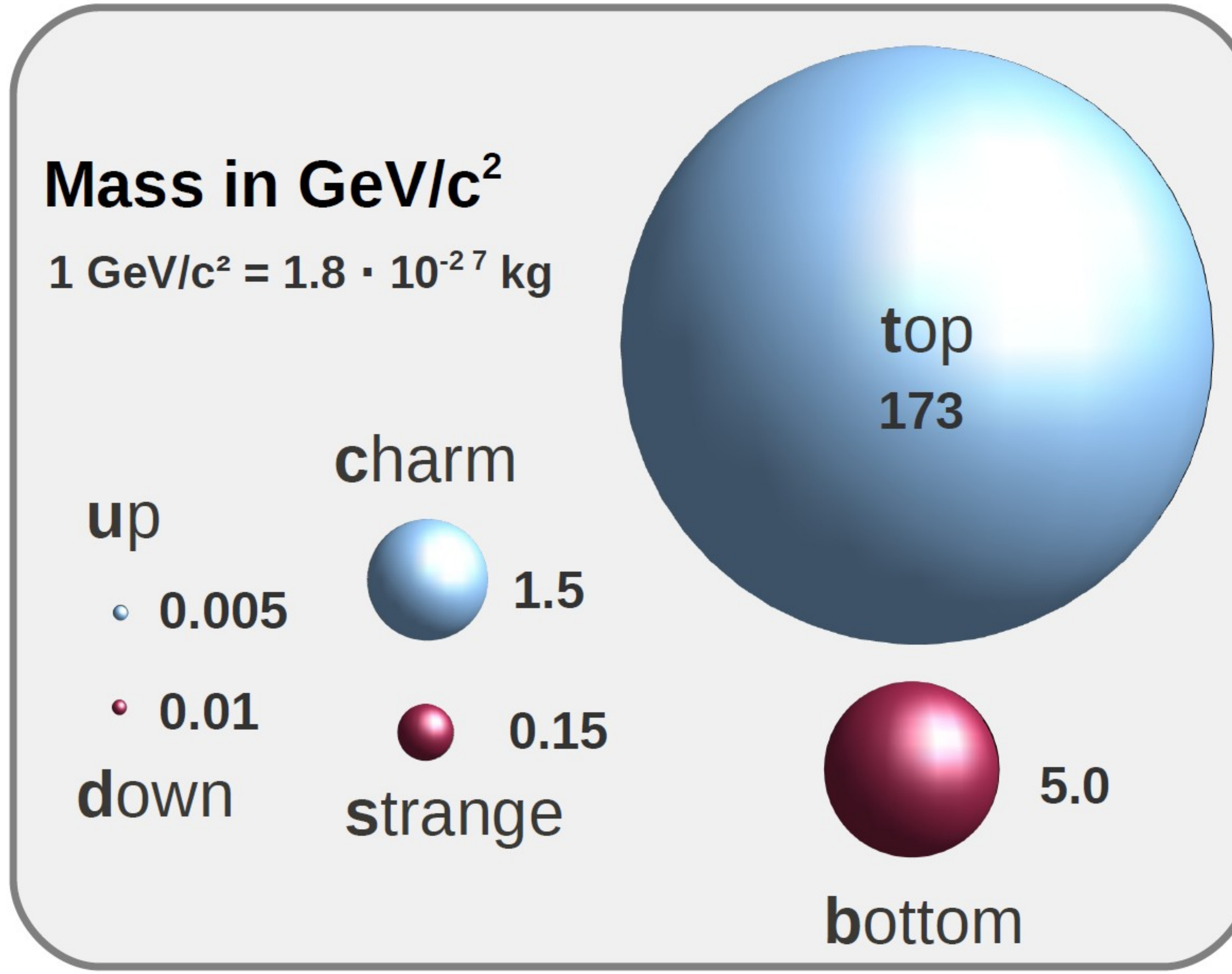
**LCWS13, Tokyo, November 2013**

## The top quark

The heaviest particle in the Standard Model




The Golden particle




We don't know why the SM fermions have the masses they have. The top quark has a mass of ~173 GeV. What does that number come from? In the SM it's the result of the Yukawa coupling of the top quark to the Higgs boson. But what does the number come from? We have been worrying about this for 45 years and we haven't made any progress!

Steve Weinberg, public lecture UTA, 24/10/2012

## The top quark: structure


What do we really know about the internal structure of the top quark?

***Not much, according to PDG2012***

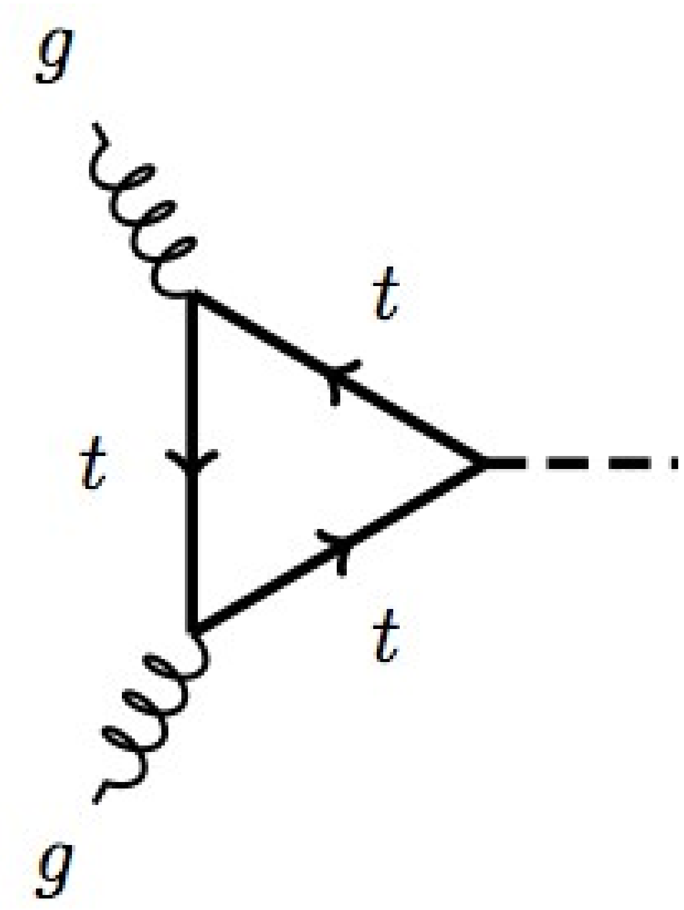
*Searches for contact interaction or exicted states of quarks and leptons yield limits on compositeness (from **PDG2012**)*

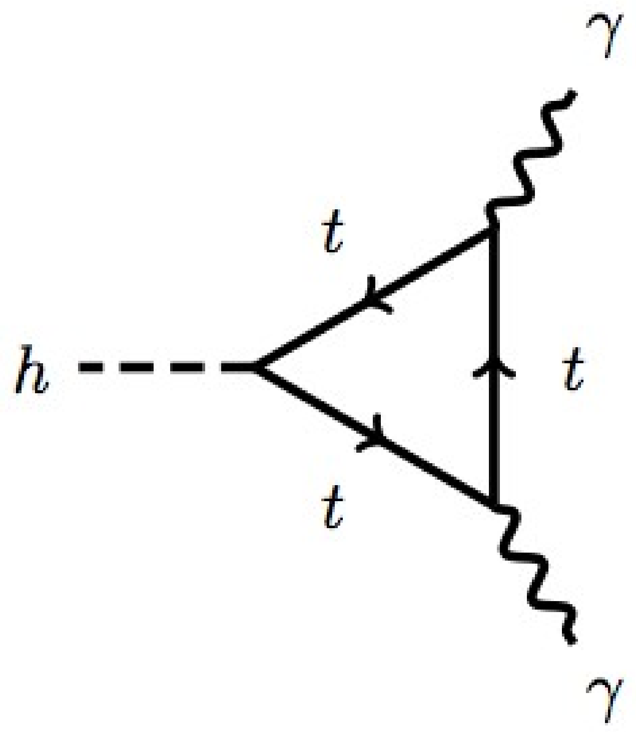
| observable | Compositeness scale reached [TeV] |
|---|---|
| L (eeee) | O(10) (LEP) |
| L (eeqq) | O(10) (LEP) |
| L (qqqq) | 2.9 (D0) 3.4 (ATLAS) 5.6 (CMS) |
| e* → e γ | 1 (CMS) |
| q* → q g | 2.5 TeV (CMS), 1.3 TeV (ATLAS 2010) |

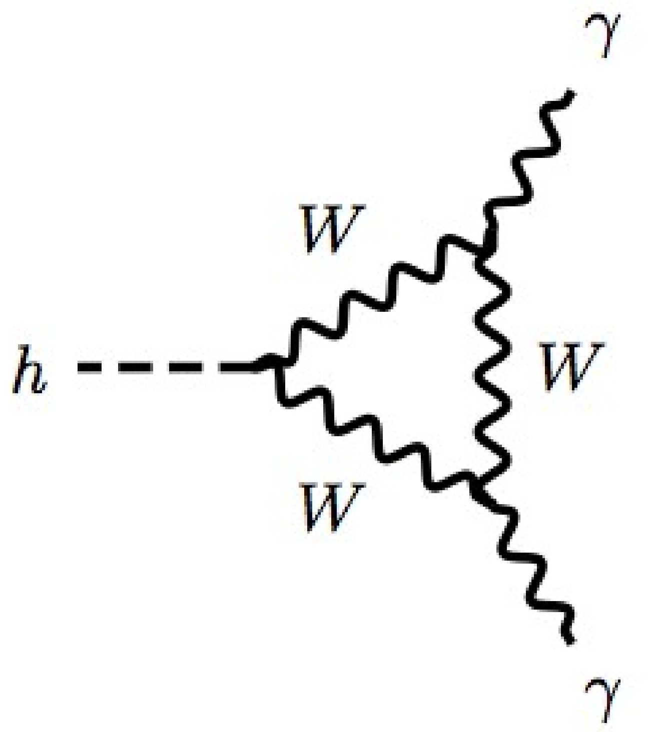
LHC is able to study top compositeness to some extent: *Englert, Freitas, Spira, Zerwas, Constraining the Intrinsic Structure of Top-Quarks, Phys.Lett. B721 (2013) 261-268*

## Tops, gauge bosons and loops

The top quark loves loops and loops love the top quark. Our favourite Higgs decay wouldn't work without heavy objects, nor would the dominant production mode.



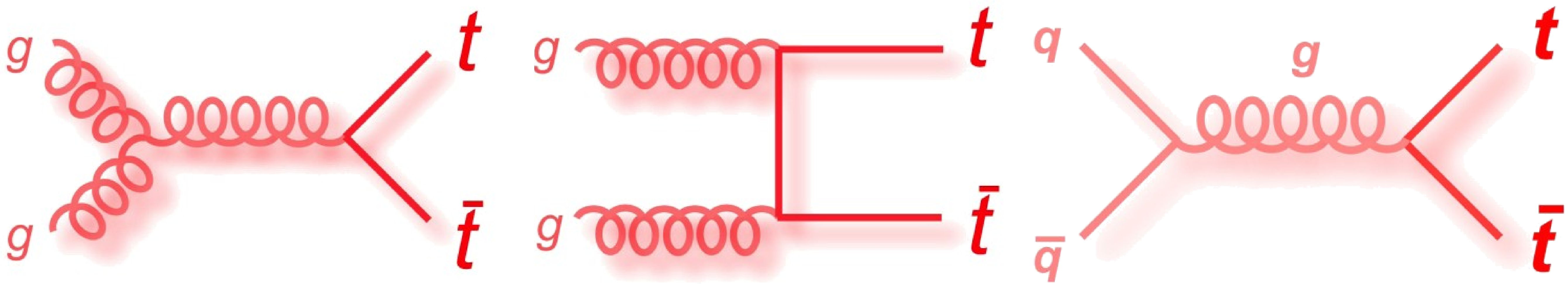
# Top at LHC

# Top quark production at hadron colliders

| Collider (energy) | process | approx σ | lumi (deliv/on tape) | # of ev |
|---|---|---|---|---|
| Tevatron $p\bar{p}$ (run II 1.96 TeV) | $t\bar{t}$ | ~7 pb | 12/10 $fb^{-1}$ | ~70 K |
| LHC pp (7 TeV) | $t\bar{t}$ | ~165 pb | 5.7/5 $fb^{-1}$ | ~800 K |
| LHC pp (8 TeV) | $t\bar{t}$ | ~235 pb | 23/22 $fb^{-1}$ | ~5 M |

**$t\bar{t}$: strong interaction**

Electroweak pair production is present, but not accessible as it's rate is several orders of magnitude below QCD pair production

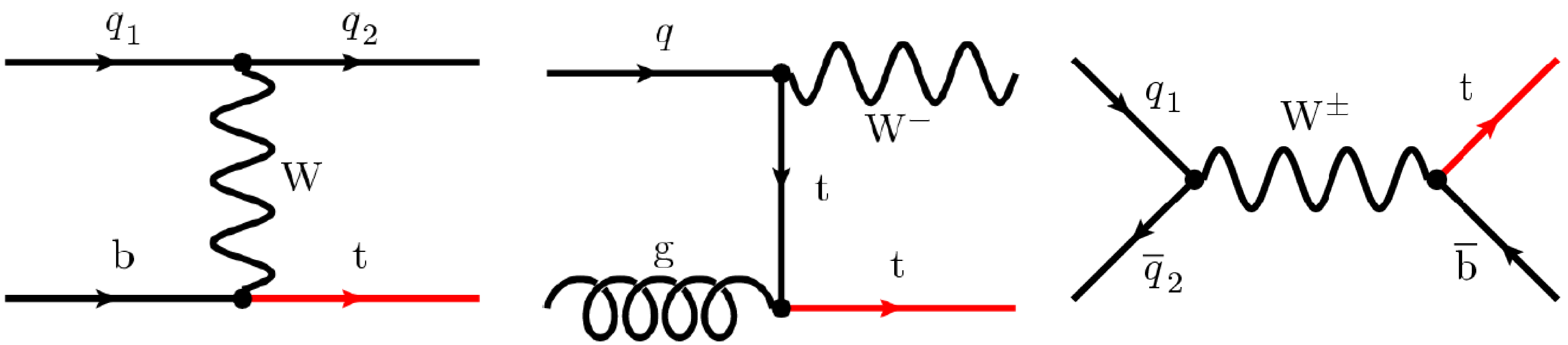



Relation between gluon gluon-initiated and quark anti-quark initiated processes is inverted between LHC and Tevatron

| Collider | $q\bar{q}$ | gg |
|---|---|---|
| Tevatron $p\bar{p}$ (1.96 TeV) | ~85% | ~15% |
| LHC pp (7 TeV) | ~20% | ~80% |

**5 million top quark pairs produced at the LHC**

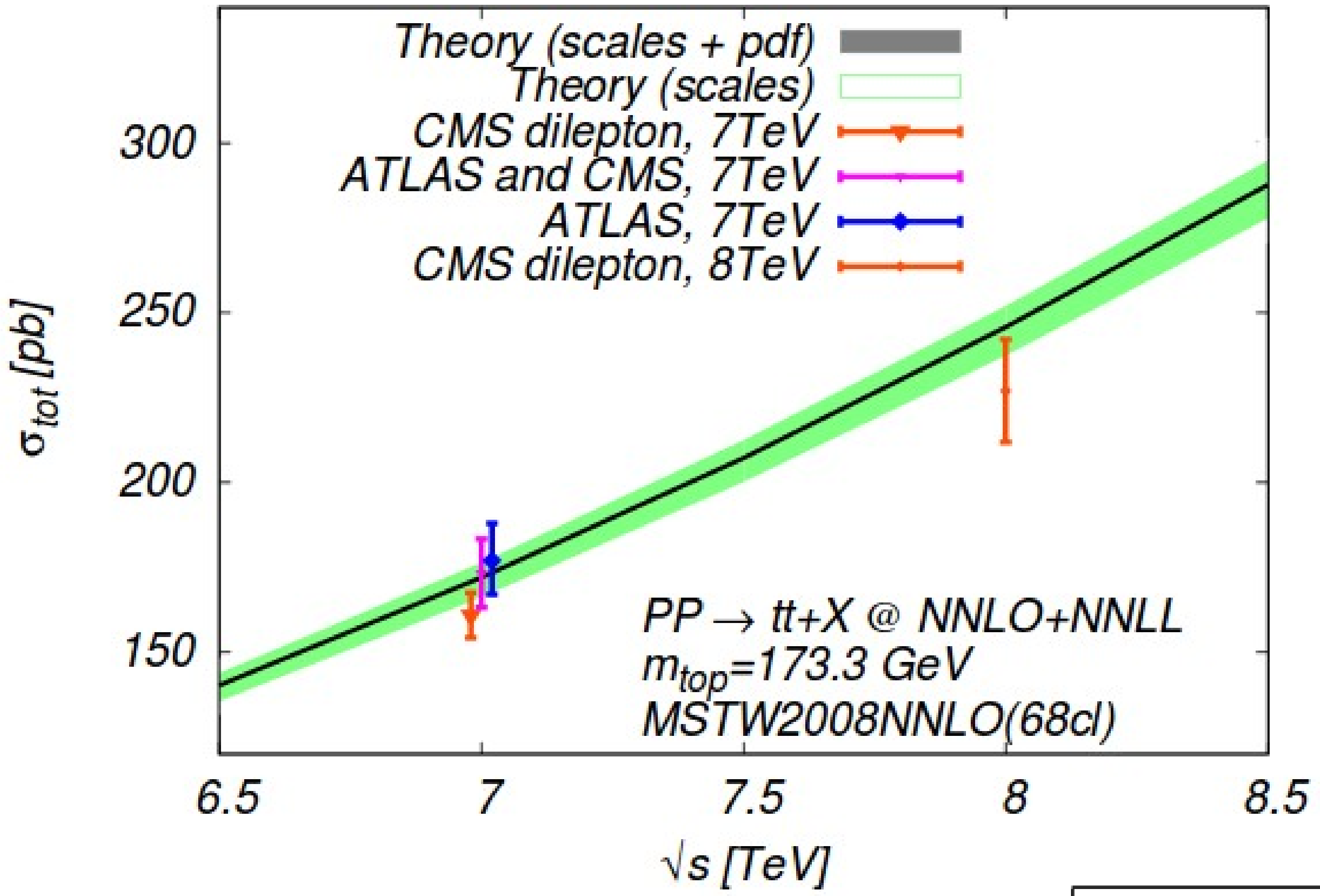
## single t: weak interaction




| Collider | s-channel $\sigma_{tb}$ | t-channel $\sigma_{tqb}$ | tW-channel $\sigma_{tW}$ |
|---|---|---|---|
| Tevatron $p\bar{p}$ (1.96 TeV) | 1.05 pb | 2.08 pb | 0.22 pb |
| LHC pp (7 TeV) | 4.63 pb | 64.6 pb | 15.7 pb |
| LHC pp (8 TeV) | 5.55 pb | 87.1 pb | 22.2 pb |

**1 million top quarks from single-top production**

## Status of top physics – hadron colliders




**Theory milestone:**
full NNLO and NNLL result for top quark pair production at hadron colliders

K-factor (NLO → NNLO) ~ 10%
Scale stability ~ 5 %

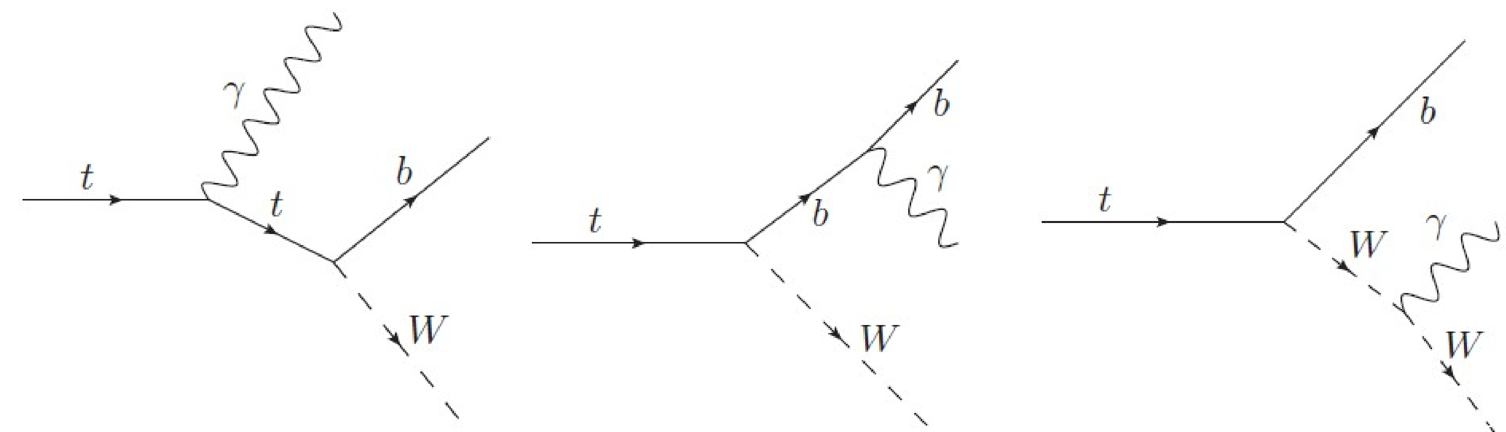
| Collider | $\sigma_{\rm tot}$ [pb] | scales [pb] | pdf [pb] |
|---|---|---|---|
| Tevatron | 7.009 | $+0.259(3.7\%)$ $-0.374(5.3\%)$ | $+0.169(2.4\%)$ $-0.121(1.7\%)$ |
| LHC 7 TeV | 167.0 | $+6.7(4.0\%)$ $-10.7(6.4\%)$ | $+4.6(2.8\%)$ $-4.7(2.8\%)$ |
| LHC 8 TeV | 239.1 | $+9.2(3.9\%)$ $-14.8(6.2\%)$ | $+6.1(2.5\%)$ $-6.2(2.6\%)$ |
| LHC 14 TeV | 933.0 | $+31.8(3.4\%)$ $-51.0(5.5\%)$ | $+16.1(1.7\%)$ $-17.6(1.9\%)$ |

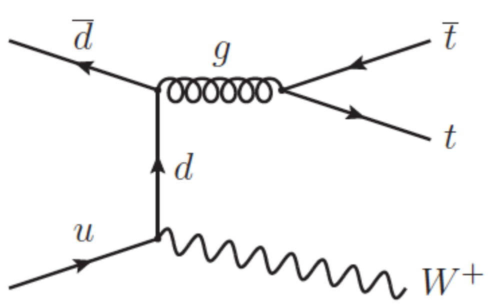
## Associated production: Top quark pair + EW gauge bosons

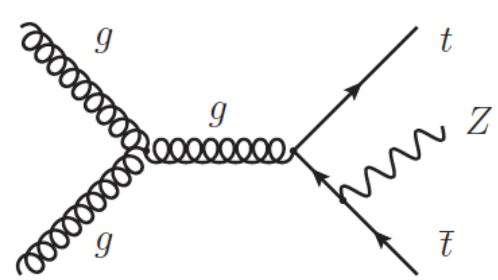
Measure production rate of top quark pairs with Z (W) and photon

BR x σ(ttγ) =
2.0 ± 0.5 (stat.)
± 0.7 (syst.)
± 0.1 (lumi.) pb

Significance 2.7σ
Expected 3.0σ




same-sign dilepton ($t\bar{t}V$) or trilepton events ($t\bar{t}Z$)

$$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}\,(\text{stat.})\;^{+0.06}_{-0.03}\,(\text{syst.})\,\text{pb} \quad 3.3\sigma$$

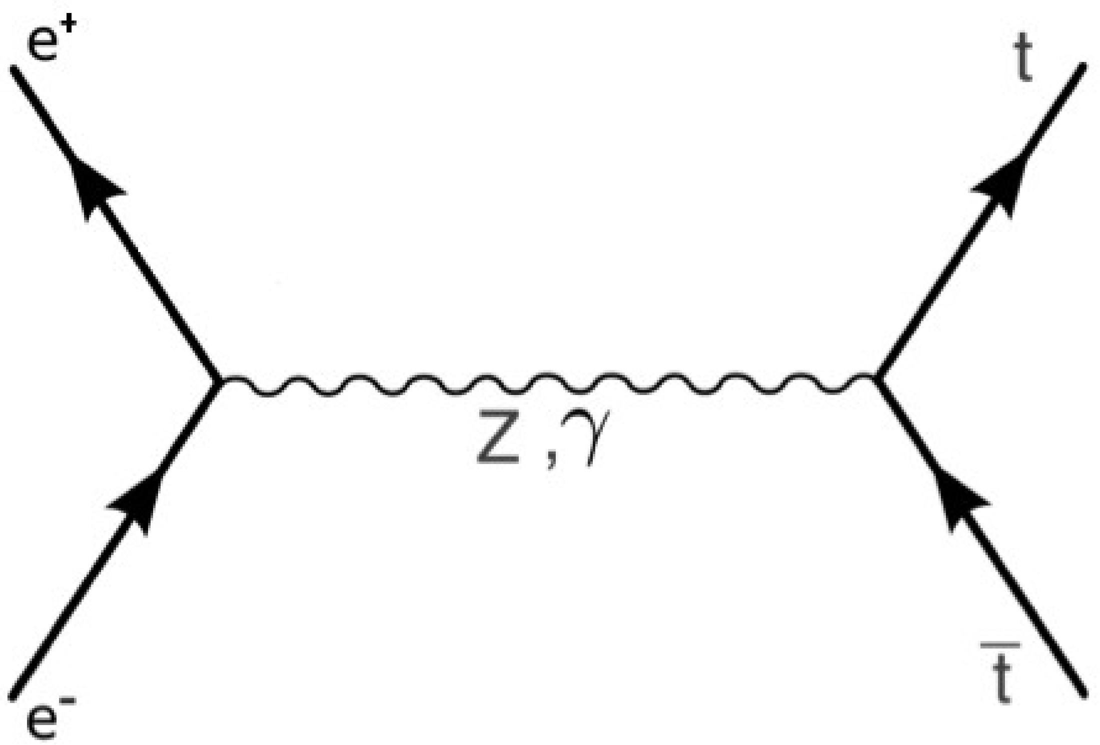
$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}\,(\text{stat.})\;^{+0.09}_{-0.07}\,(\text{syst.})\,\text{pb} \quad 3.0\sigma$$

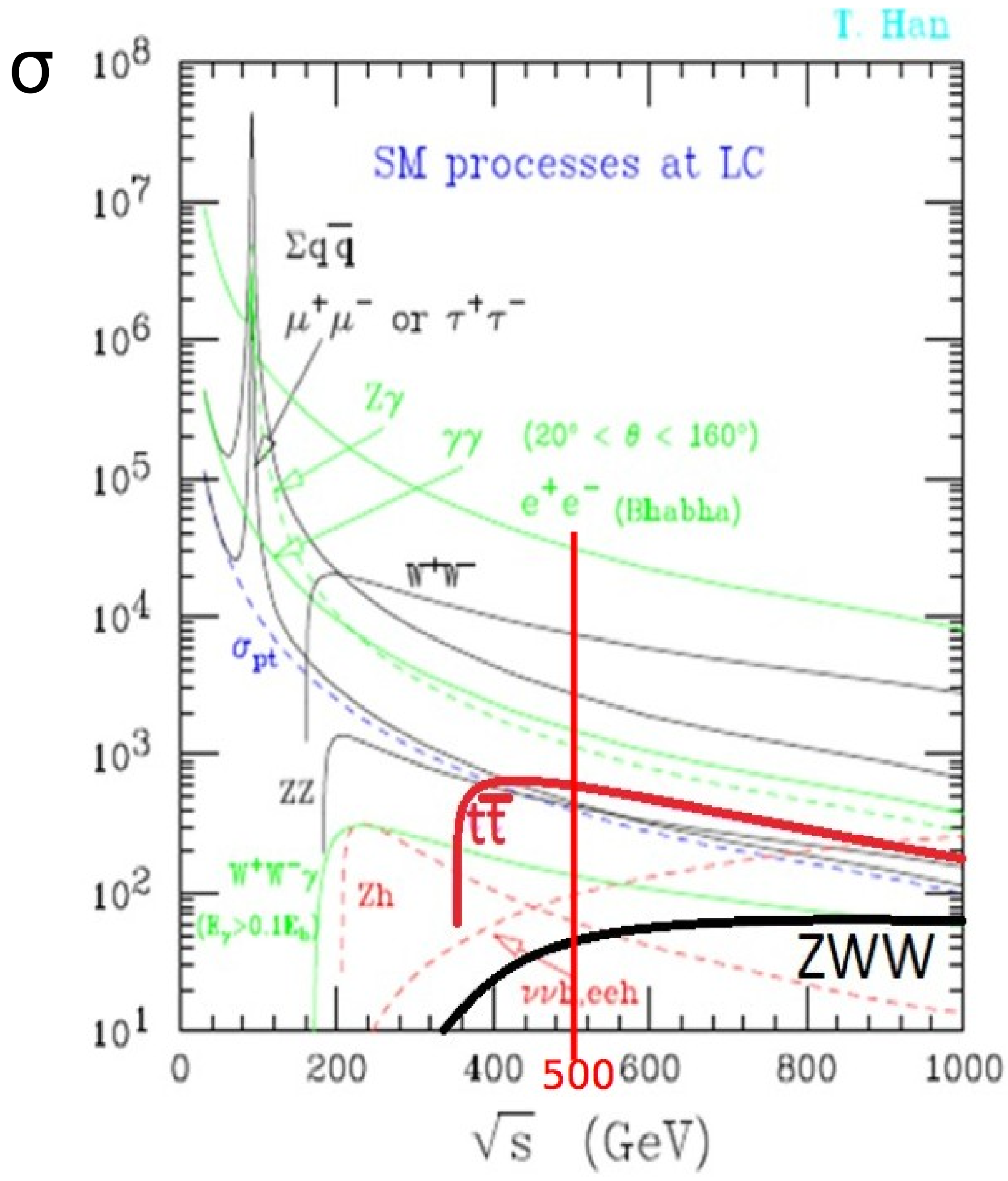
CMS establishes $t\bar{t}V$ signal at 4.7 σ
(V=W,Z), PRL 110 (2013) 172002

A probe of new physics, see F. Richard, arXiv:1304.3594

# Top at LC

# Top production at the (I)LC



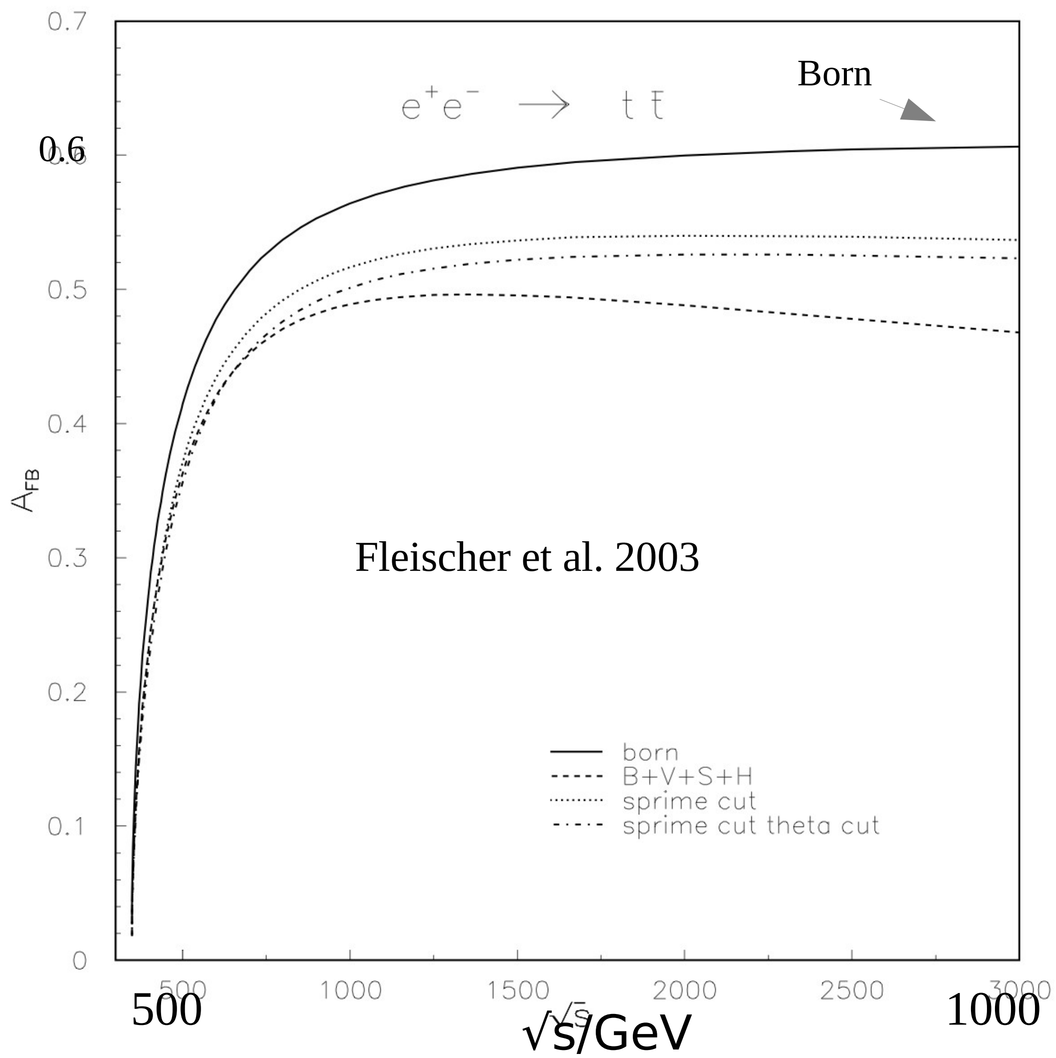

- Top quark production is one of the dominant processes
  → Clean and efficienct selection

- Top quark production through **electroweak** processes
  → no competing QCD production

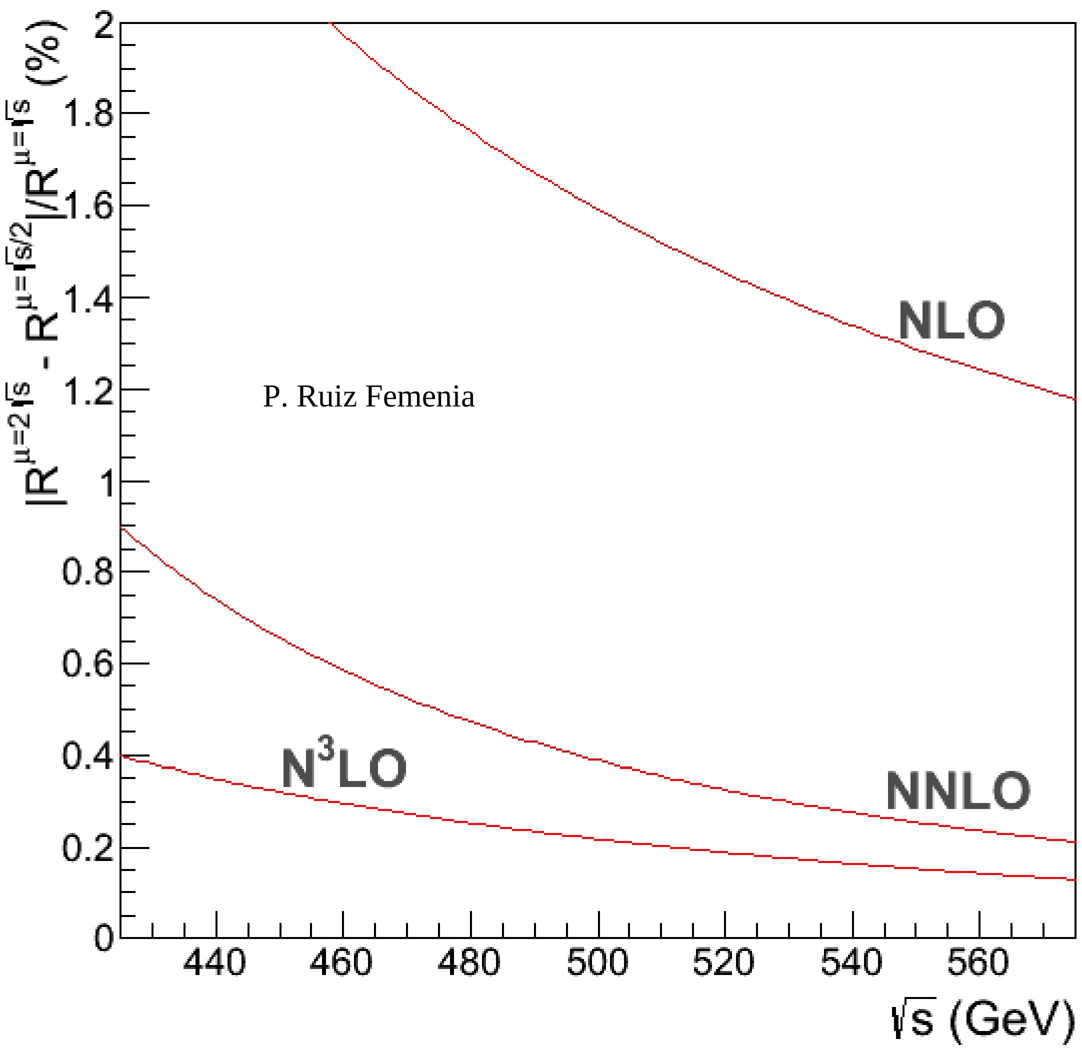
-ILC is promising for high precision top quark 'tomography'

## Top quark pair production in the continuum

*Electroweak corrections – impact on $A_{FB}$*




*Variation in predicted x-section due to scale variations*

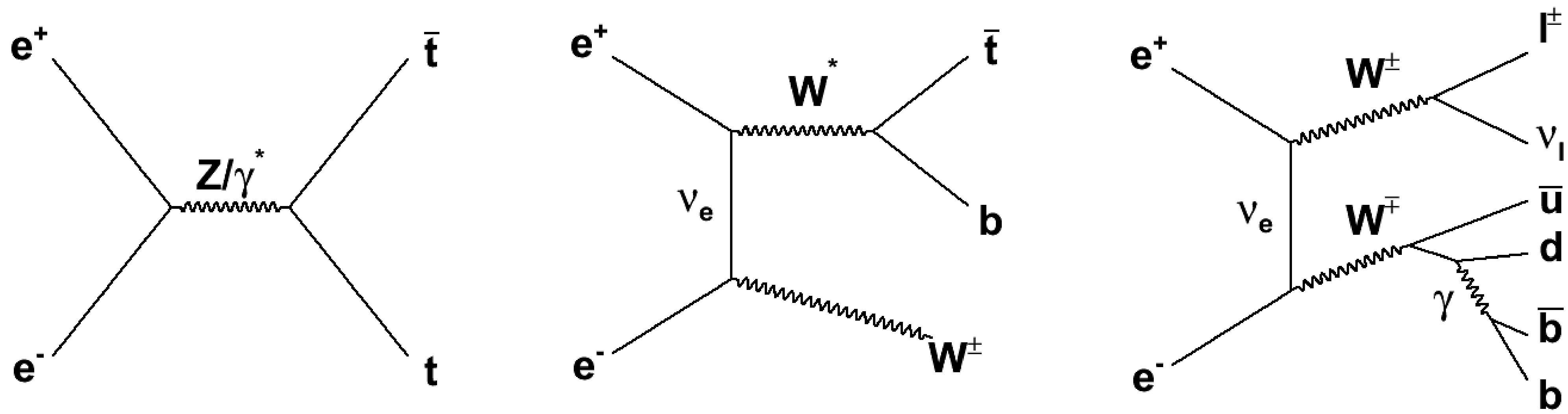


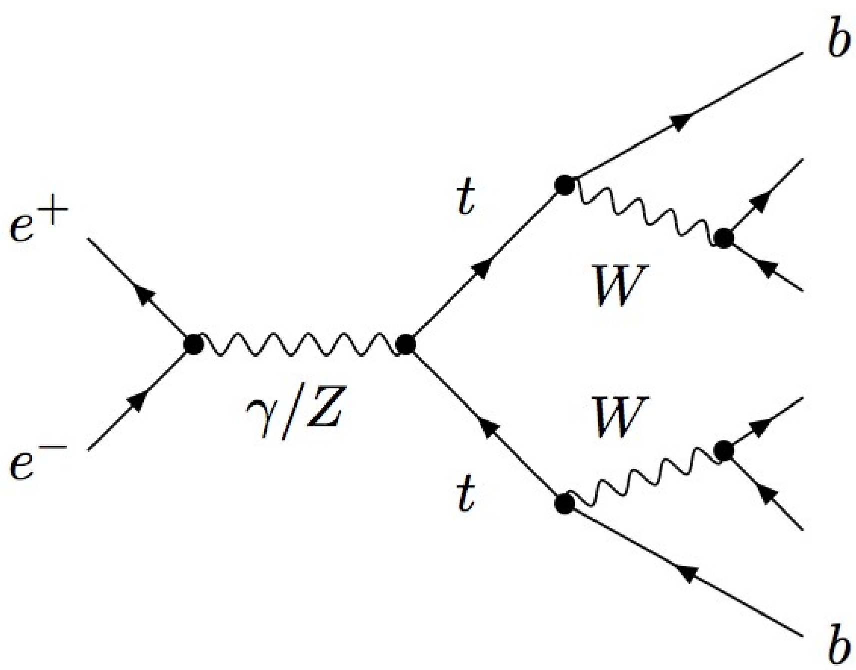

**For true precision there is nothing like $e^+e^-$**

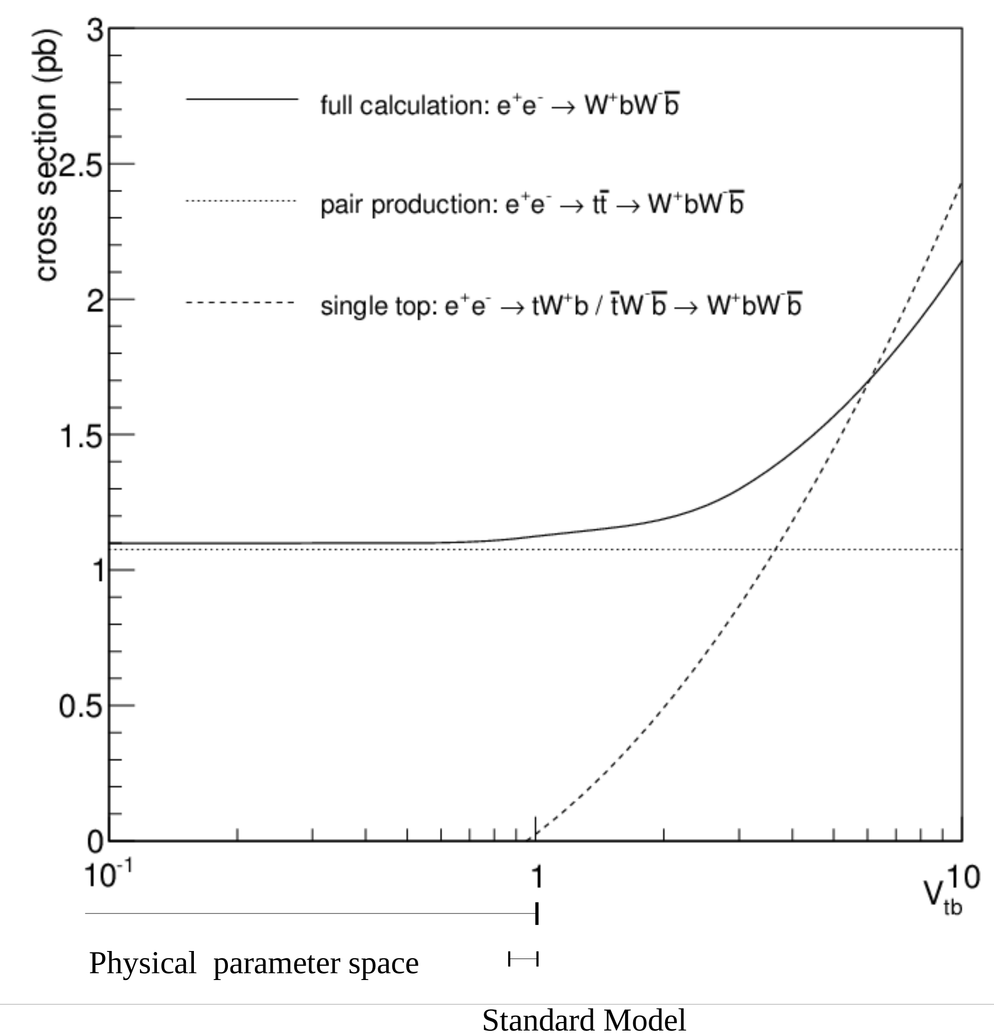
QCD corrections calculated to N$^3$LO, scale variations ~ 0.3%

Electroweak corrections are sizable (estimation of size of two-loop corrections ongoing, useful inputs have been received from Hollik, Khiem, Ruiz → hopefully settled soon)

# Closer look: can we study $e^+e^- \rightarrow t\bar{t}$ in isolation?



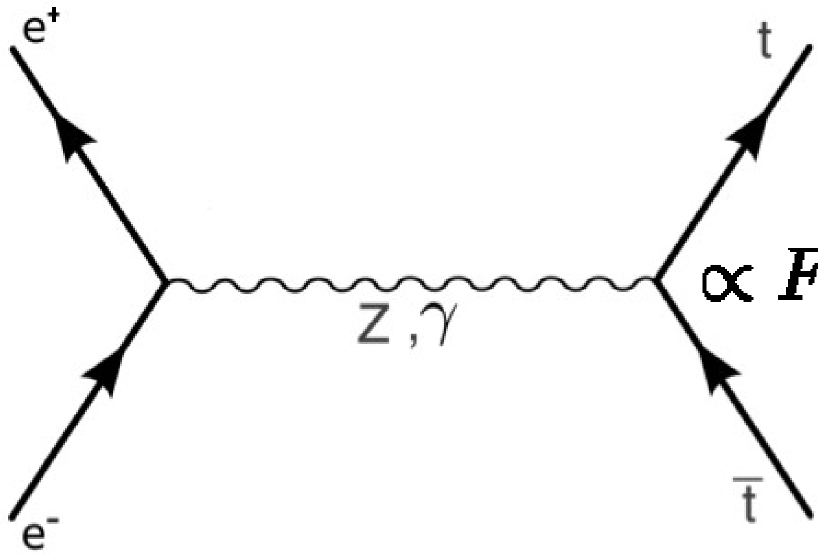




No, can only define observables in a meaningful way if we consider the full six-fermion ($e+e- \rightarrow b\bar{b}l\nu jj$) process

See also talk by P. Ruiz Femenia

## The ttZ and ttγ vertices




$\propto F^{X}_{i,V}$

$$\Gamma^{ttX}_{\mu}(k^2,q,\bar{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2)+\gamma_5 F^X_{1A}(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\mu\left(iF^X_{2V}(k^2)+\gamma_5 F^X_{2A}(k^2)\right)\right\}, \quad (2)$$

$$\mathcal{F}^L_{ij} = -F^\gamma_{ij} + \left(\frac{-\frac{1}{2}+s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F^Z_{ij}$$

$$\mathcal{F}^R_{ij} = -F^\gamma_{ij} + \left(\frac{s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F^Z_{ij},$$

Pure $\gamma$ or pure $Z^0$ : $\sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

$Z^0/\gamma$ interference : $\sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

## Event generation

- Event generator WHIZARD interfaced to PYTHIA

$e^+e^-$ -> 6f: 250 $fb^{-1}$ for two beam polarisations: $e^-_L e^+_R$ and $e^-_R e^+_L$

Events were generated with full simulation and results were scaled for realistic beam polarisation

$$P, P' = \mp 0.8, \pm 0.3$$

$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

Full Standard Model background
Common samples for ILD and SiD studies

- GEANT4 and ILCSoft for detector simulation and reconstruction

- ILD features a full software suite

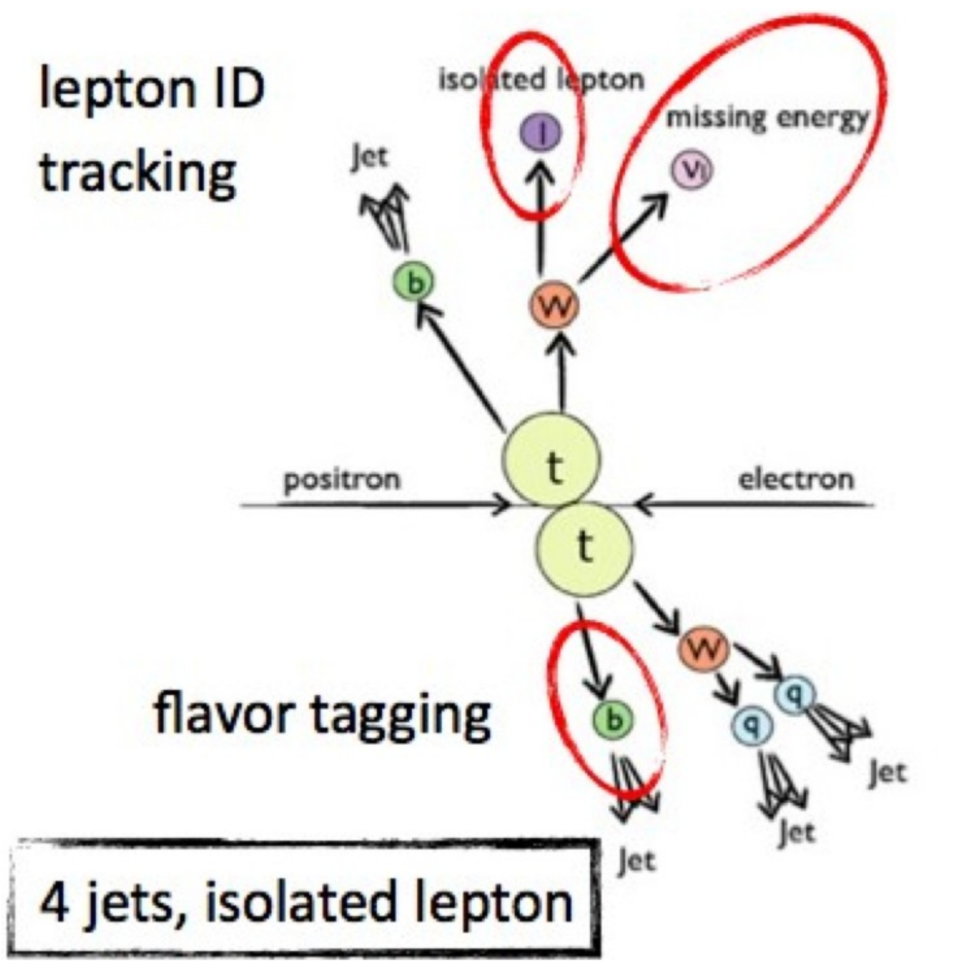
  - Mokka as geometry interface to GEANT4
  - MARLIN as analysis framework for event reconstruction
  - Interface to toolkits such as PandoraPFA or LCFIVertex

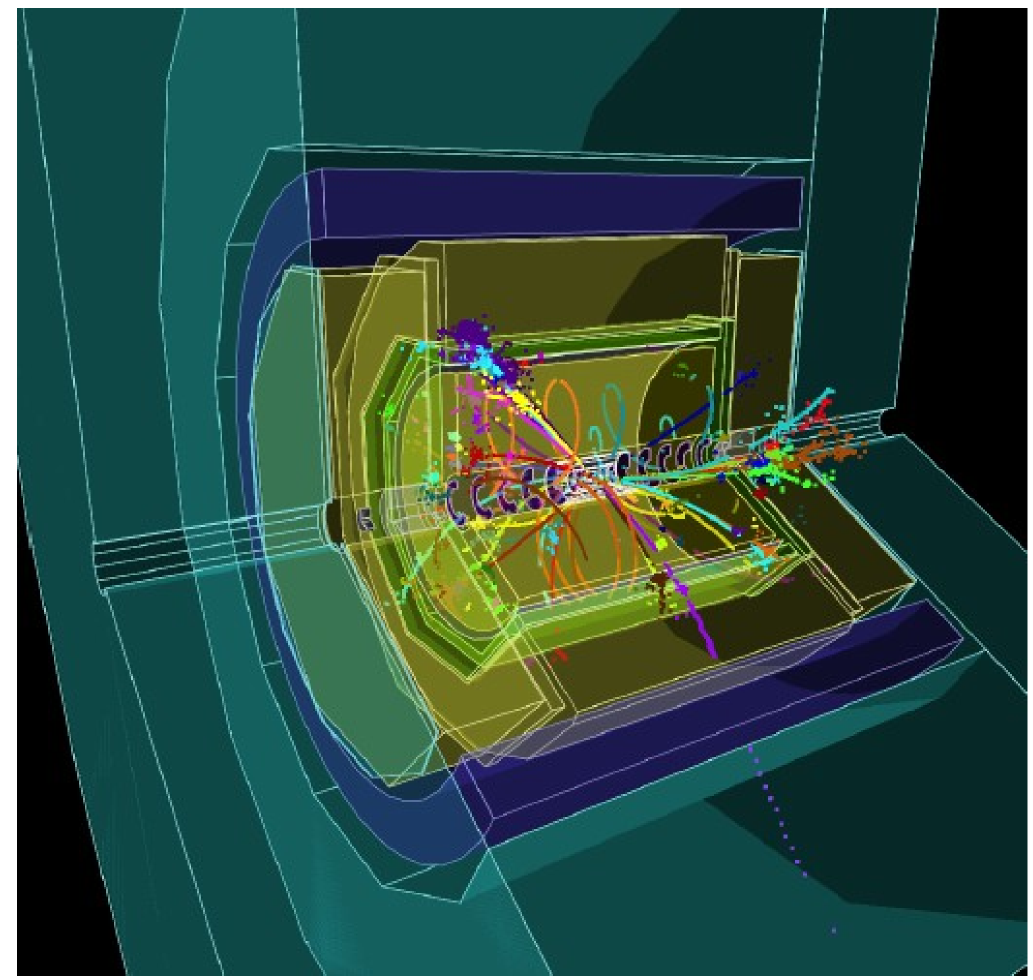
- Detector simulation is based on input from worldwide detector R&D

# Top quark reconstruction

Three different final states:
1) Fully hadronic (46.2%) → 6 jets
**2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino**
3) Fully leptonic (10.3%) → 2 jets + 4 leptons

$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bqq')(b\ell\nu)$$

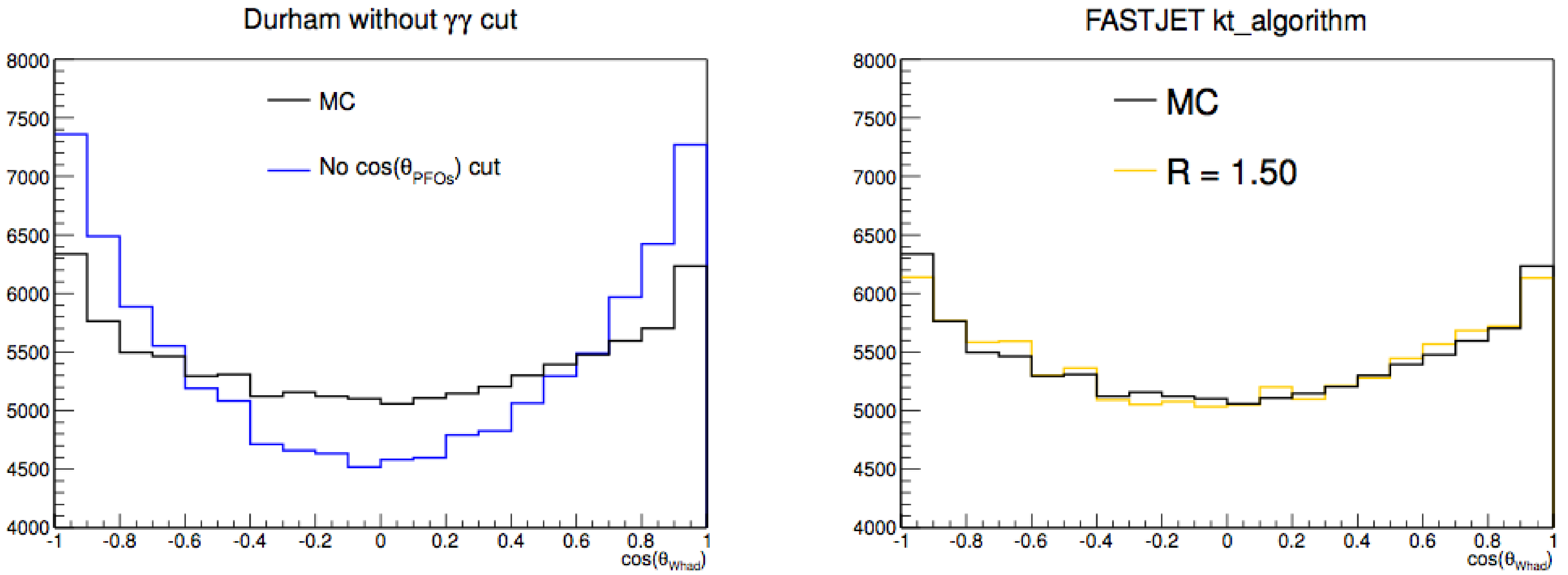


Final state reconstruction uses all detector aspects

## Background

Main source of pile up: γγ → hadrons
ILC about 1.7 evts. / bunchXing (including muons)




(a) Durham (b) $k_t$, $R = 1.5$

**Study of different jet algorithms (following CLIC CDR studies)**

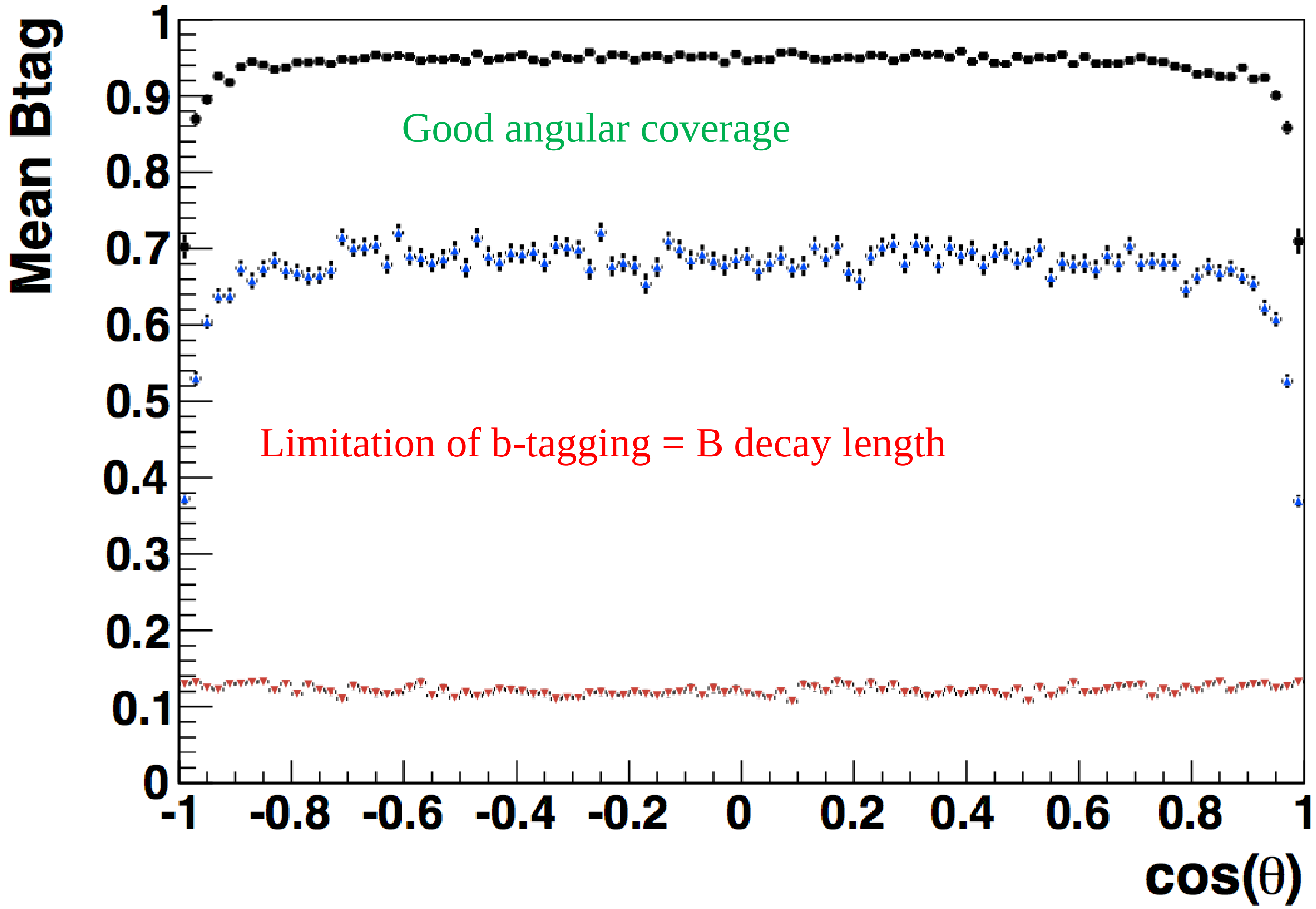
- Durham (and other $e^+e^-$ jet algorithms) fail to remove hadron background
- Successful removal using longitudinally invariant $k_T$ algorithm (exclusive 4-jet, R=1.5)

→ all results based on this solution

- Not our final answer: alternatives under investigation

# B tagging

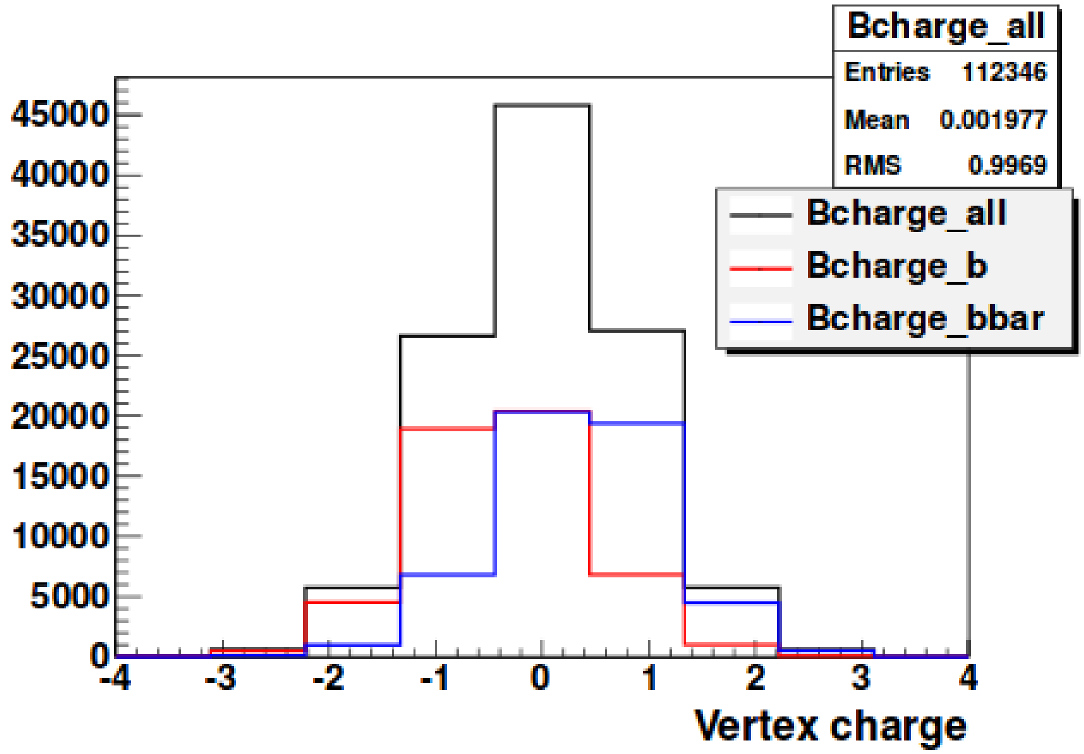
- Reconstruct 4 jets, select two with the highest b-tagging score
- 2 “light” jets assigned to hadronic W-boson candidate
- Hadronic top candidate formed by:
  - hadronic W and b-jet
  - keep combination that minimizes $\chi^2$ (based on mass, energy, etc.)

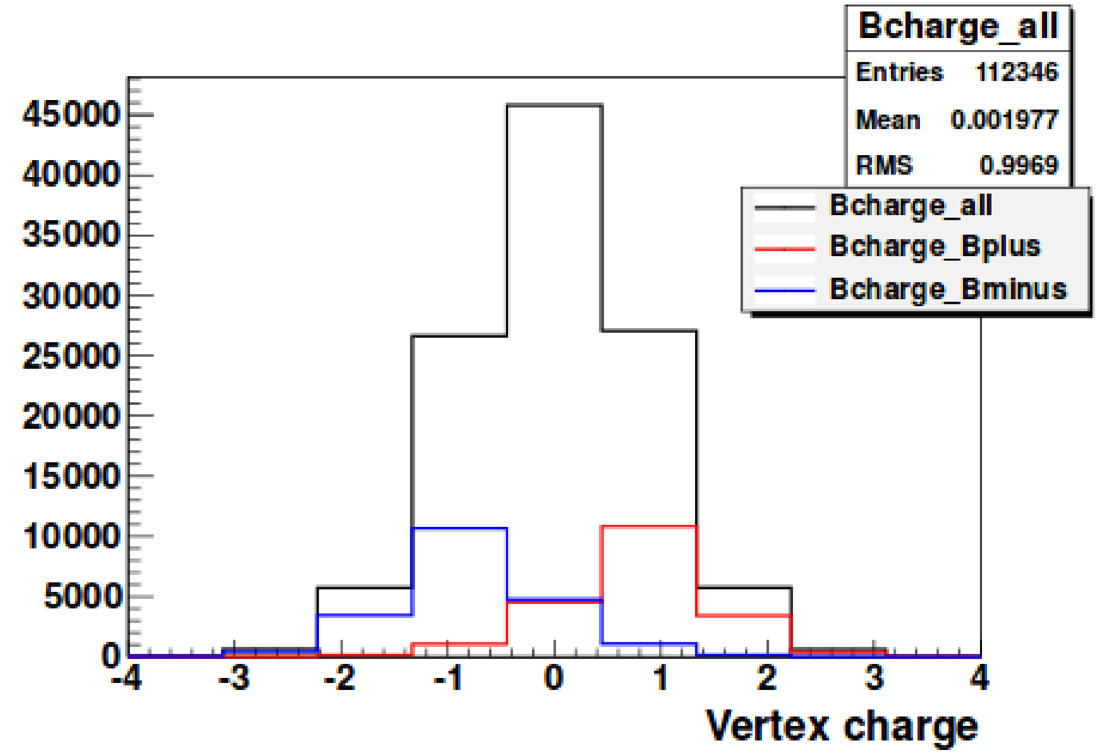



Polar angle of b-jet

Efficient and nearly uniform b-tagging

# Jet/vertex charge



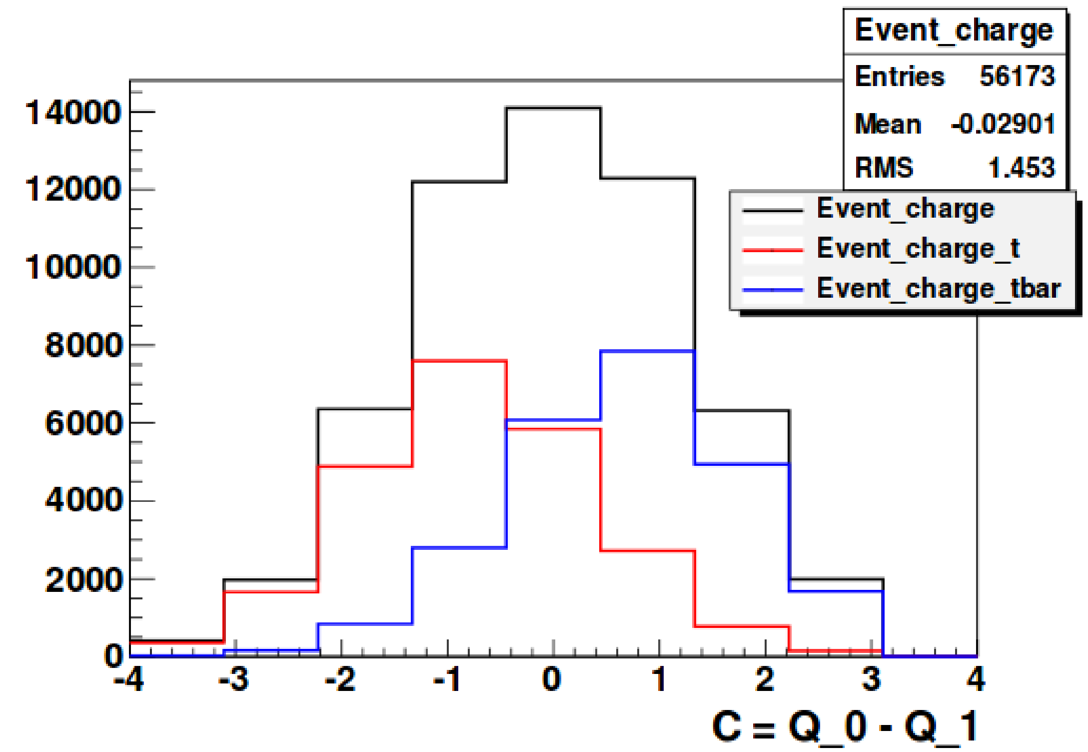

**Needed for fully hadronic study**

→ LC-REP-2013-008

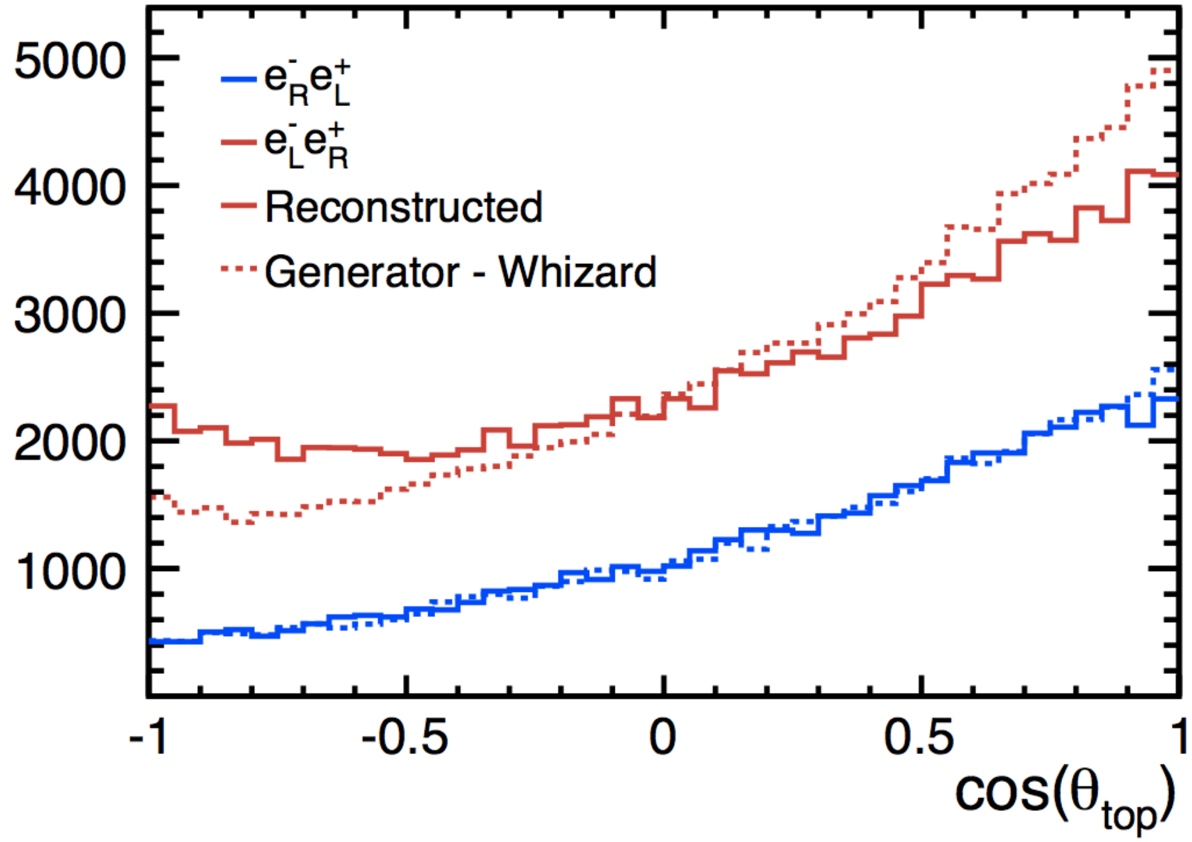
**Useful also in lepton+jets channel**

→ help in events with ambiguous W-b combinatio

Combine with $\chi^2$... under study



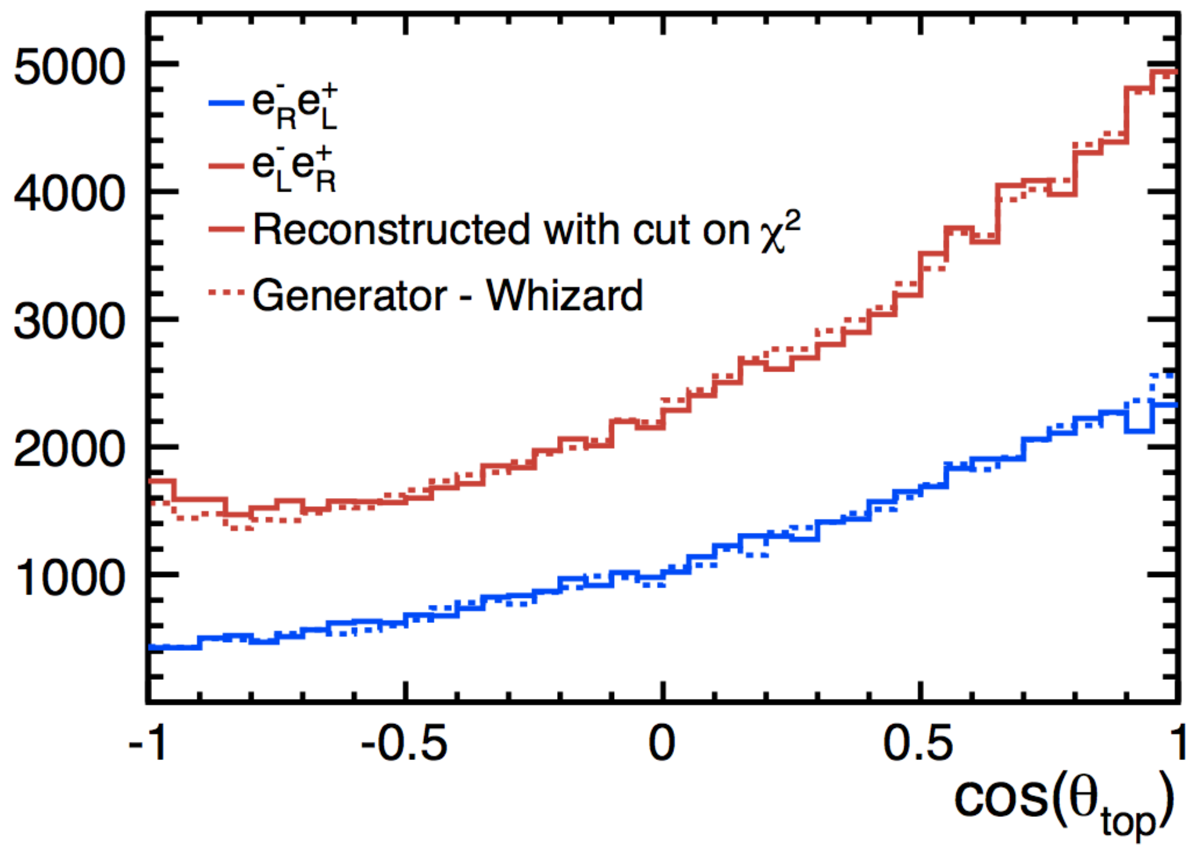
# Reconstruction of top quark polar angle




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

Precise reconstruction of $\theta_{top}$
in case of right handed electron beams

**(Current) remedy to address ambiguities:**
**Select cleanly reconstructed events by kinematic fit or $\chi^2$ analysis**




Precise reconstruction for both beam polarisations

- Efficiency Penalty for $e_L$
- $\varepsilon_{tot}$: $e_R$ ~ 50%, $e_L$ ~ 30%

Precision on $A_{FB}$ ~ 2%

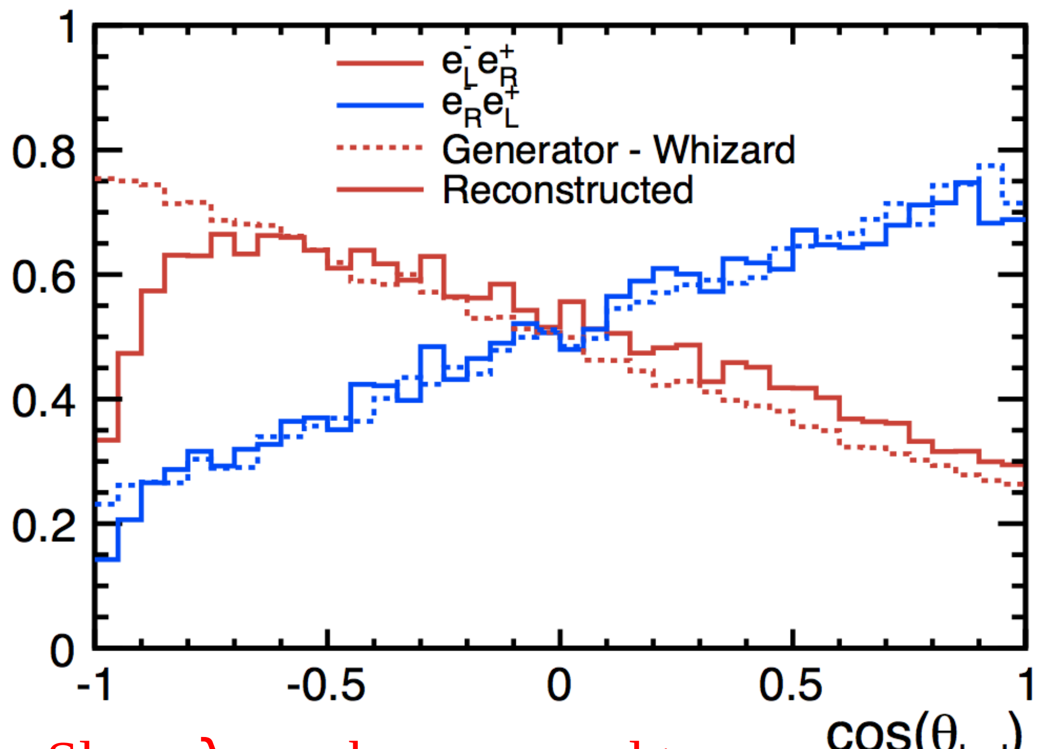
# Top quark polarization

Measure angle of decay lepton in top quark rest frame
Lorentz transformation benefits from well known initial state

Differential decay rate :

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta_\ell} = \frac{1+\lambda_t cos\theta_\ell}{2} \quad \text{with } \lambda_t = 1 \text{ for } t_R \text{ and } \lambda_t = 1 \text{ for } t_L$$

Slope measures fraction of $t_{R,L}$ in sample




- Measurement of decay lepton almost 'trivial' at LC
  High reconstruction efficiency for leptons
- Reconstructed slope coincides with generated slope

Slope $\lambda_t$ can be measured to an accuracy of about 3-4%

**Measure 6 observables, extract 5 form factors**

$$\left.\begin{matrix} \sigma(+) & A_{FB}(+) & \lambda_{hel}(+) & (+=e^-_R) \\ \sigma(-) & A_{FB}(-) & \lambda_{hel}(-) & (-=e^-_L) \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F^{\gamma}_{1V} & * & F^{\gamma}_{2V} \\ F^{Z}_{1V} & F^{Z}_{1A} & F^{Z}_{2V} \end{matrix}\right\}$$

The cross section can be measured to 0.5% (stat. + lumi)

The forward-backward asymmetry to 2% (stat. + syst.)

The slope of helicity distribution to ~4% (stat. + syst.)

**Similar results to TESLA TDR, but:**

- simultaneous extraction of photon and Z form factors
- full simulation & reconstruction
- inclusion of systematic effects
  (knowledge of polarization, energy, ...)

# Systematic uncertainties

- Beam energy: $10^{-4}$ at 500 GeV

- 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

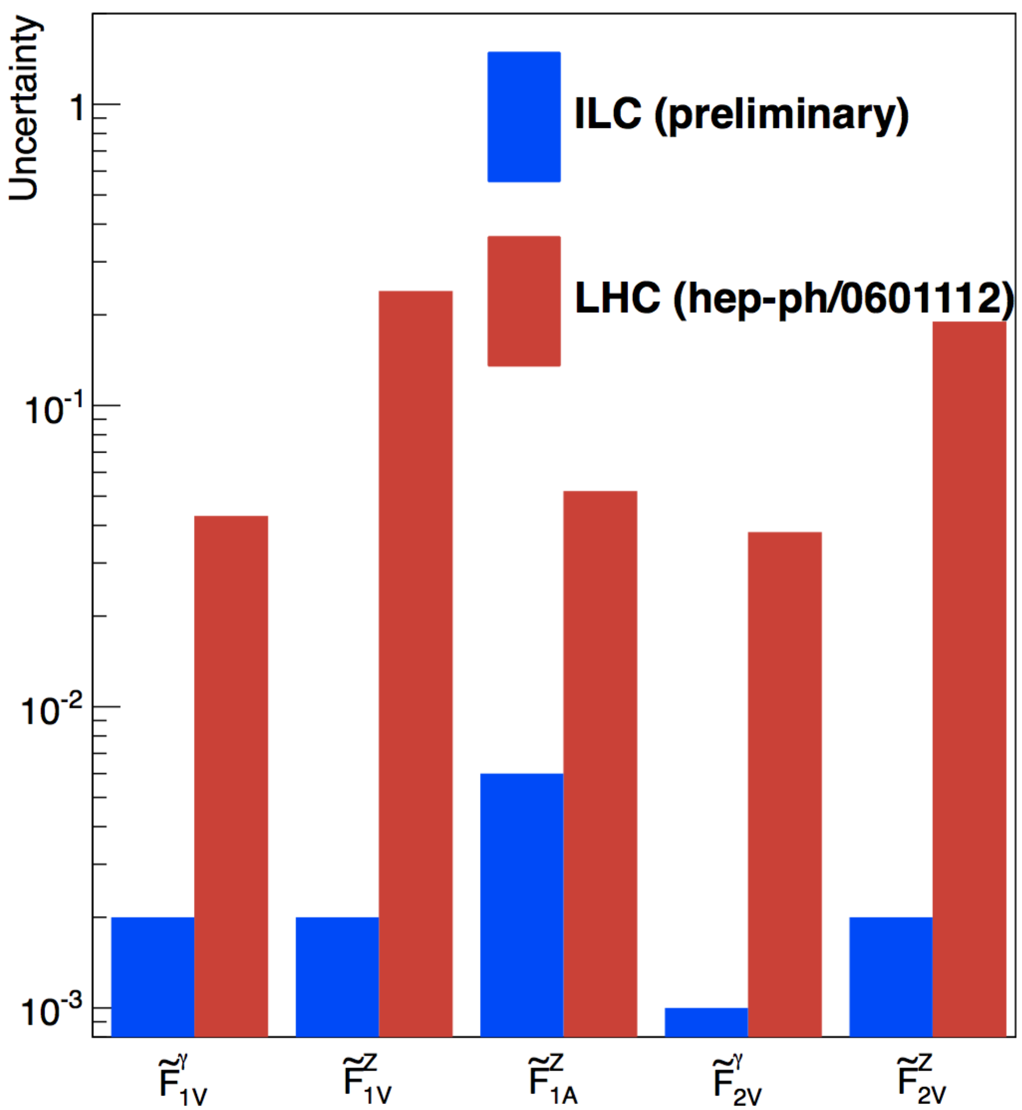
- Migrations/Ambiguities: Critical for $A_{FB}$:
  Need further studies but expect to control them better than the theoretical error
  Remedy may come from b charge measurement

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

Under discussion with theory groups:
- Role of single top production
- Electroweak NLO predictions (Correction LO → NLO ~ 15%)

## Prospects for LC precision

Accuracy on CP conserving couplings




Nominal LHC ($\sqrt{s}$ = 14 TeV, 300 $fb^{-1}$) can characterize top EW couplings with precision between 4 and 20%. Estimate based on:

*Baur, Juste, Orr, Probing electroweak top couplings at hadron colliders, Phys. Rev. D71 (2005)*

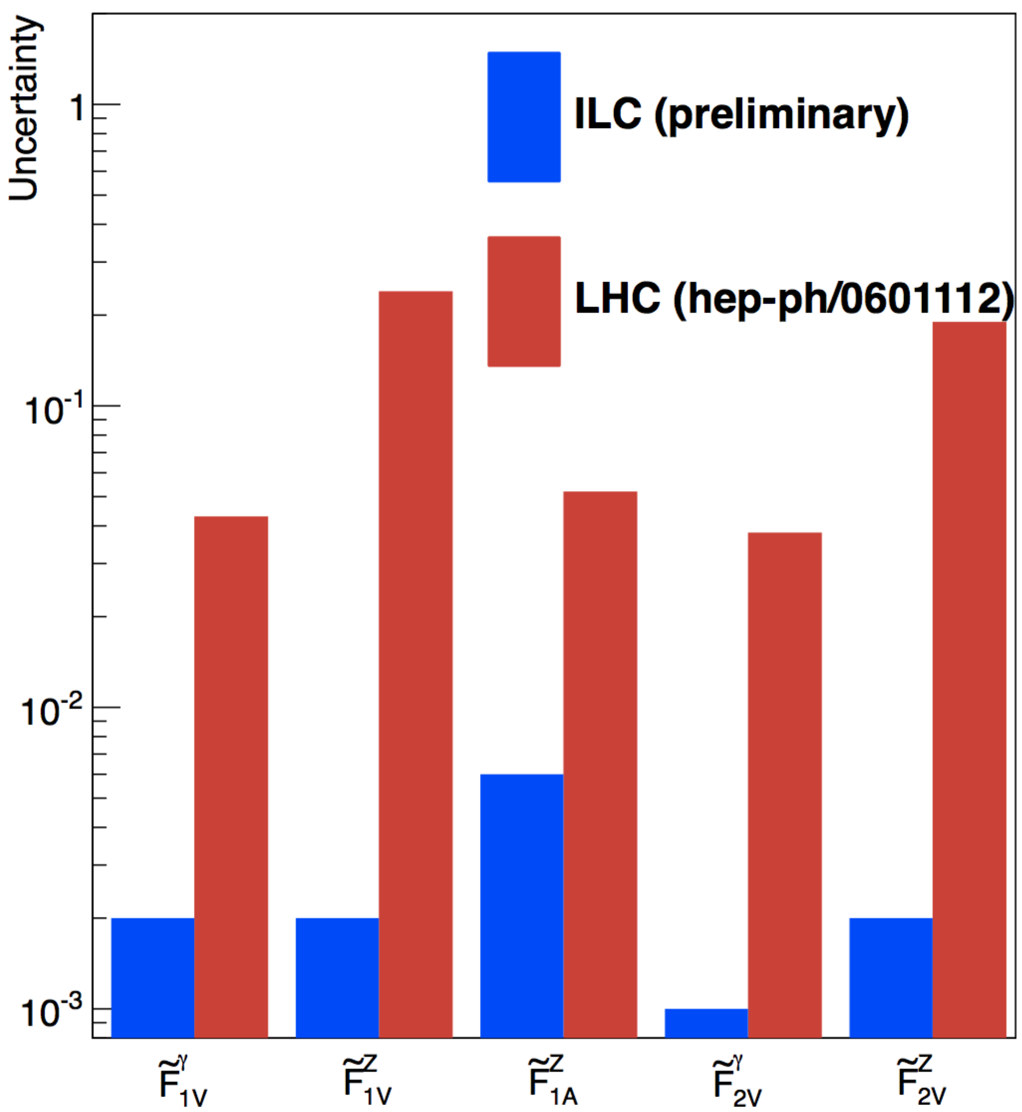
Echoed in Snowmass 2005 and Snowmass 2013

*Top Couplings: pre-Snowmass Energy Frontier 2013 Overview, arXiv:1309.1947*

## Prospects for LC precision

Precision: cross section ~ 0.5%, Precision $A_{FB}$ ~ 2%, Precision $\lambda_t$ ~ 3-4%

Accuracy on CP conserving couplings




Nominal ILC ($\sqrt{s}$ = 500 GeV, 500 $fb^{-1}$) can characterize top EW couplings with precision of several per mil. Estimate based on:
*M.S Amjad et al., A precise determination of top quark electro-weak couplings at the ILC operating at √s=500 GeV, LC-REP-2013-007, arXiv:1307.8102*

*LEP (Z → bb), Tevatron (cross-section, $A_{FB}$), LHC (resonance searches, ttV, polarization) and (ultimatley) ILC provide tight set of constraints on BSM physics*

*Measuring $F_{2V}$ (and thus (g-2)t) to ~1% yields a test of top compositeness scale up to 100 TeV*

ILC indeed is a high precision machine for electroweak top couplings

## CP violating form factors

Next steps: measure also the CP violating form factors

$$\Gamma_{\mu}^{ttX}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\mu \left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\},$$

Observables constructed with lepton from top decay (q+) , from Bernreuther et al.:

$$O_+^{Re} = (\hat{q}_+^* \times \hat{q}_{\bar{X}}) \cdot \hat{e}_+$$

$$O_+^{Im} = -[1 + (\frac{\sqrt{s}}{2m_t} - 1)(\hat{q}_{\bar{X}} \cdot \hat{e}_+)^2]\hat{q}_+^* \cdot \hat{q}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{q}_{\bar{X}} \cdot \hat{e}_+ \hat{q}_+^* \cdot \hat{e}_+$$

*Bernreuther, Brandenburg, Overmann, "CP Nonconservation in Top Quark Production by (Un) Polarized e+e- and Collisions", hep-ph/9602273*
*Explored at parton level in TESLA TDR, hep-ph/0106315*

Asymmetries ($O_+$ - $O_-$) form optimized observables to extract Re[$F_{2A}$ ] and Im[$F_{2A}$ ] with the best posible analyzing accuracy.

# CP violating observables – first preliminary results

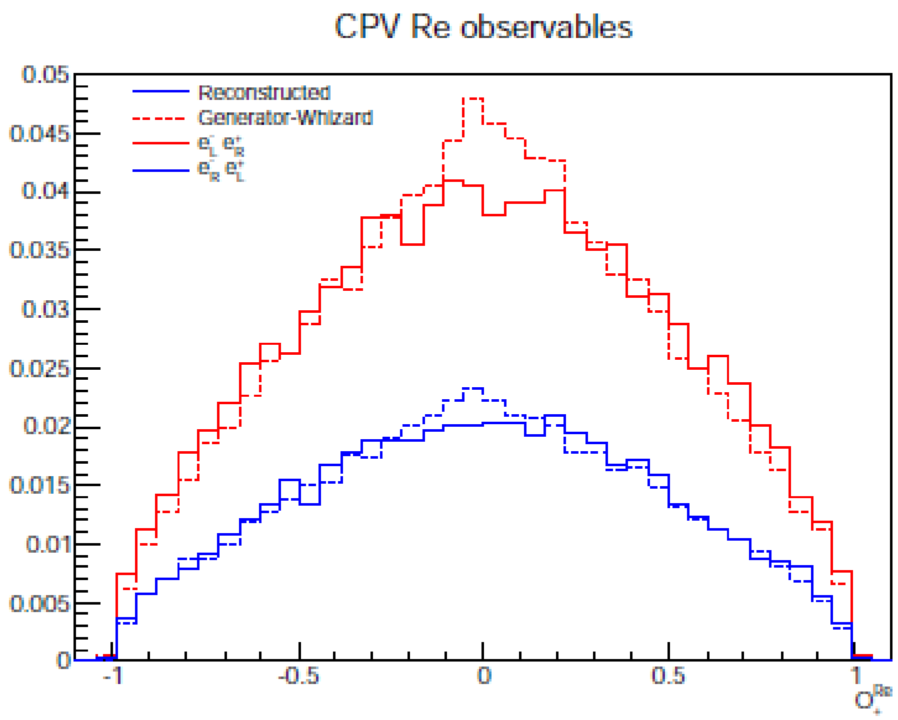
**Experimental study: full simulation**

- DBD samples
- generated with WHIZARD
- full simulation (ILD) including background
- same reconstruction/selection
- results pass sanity checks

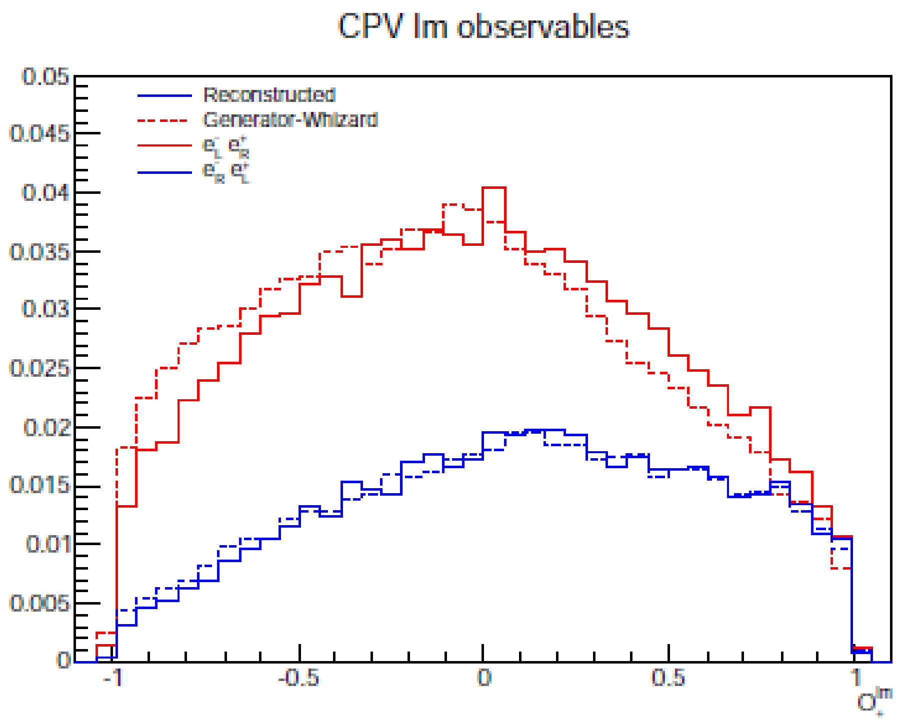
**Introducing non-zero form-factors**

- MadGraph set-up by Sudhir Gupta (Monash) and German Valencia (Iowa)
  - tested and working
  - cross-check of analytical results
- WHIZARD effective operators? (see J.A. Aguilar et al., arXiv:1206.1033)

Migrations are observed, but not fatal
Expect results in one of the next LCWS




(a) $O_+^{Re}$




(c) $O_+^{Im}$

# ILC500 measures top quark electroweak couplings to

$\delta F_{1V}^{\gamma,Z}, \delta F_{1A}^{\gamma,Z}$ ~1%     An order of magnitude better than LHC prospects!

## All LC strong points conspire to achieve this:

- calculability, theory errors at few per mil level
- controlled initial state; center-of-mass energy and polarization
- excellent detectors to reduce exp. systematics

## These prospects now rest on even more solid ground:

– full simulation & sophisticated reconstruction

– Evaluation of dominant systematic uncertainties