Top quark mass and couplings

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Top quark physics

One of (at least) two particles to escape (direct) scrutiny at lepton colliders

It is **important** to know its properties: contributions through loops

It is a quark we **can** characterize well: top-anti-top tagging, polarization

Precise measurements of properties and interactions provide sensitivity to new physics

- top quark mass
- couplings to photon/Z-boson

Top quark mass today

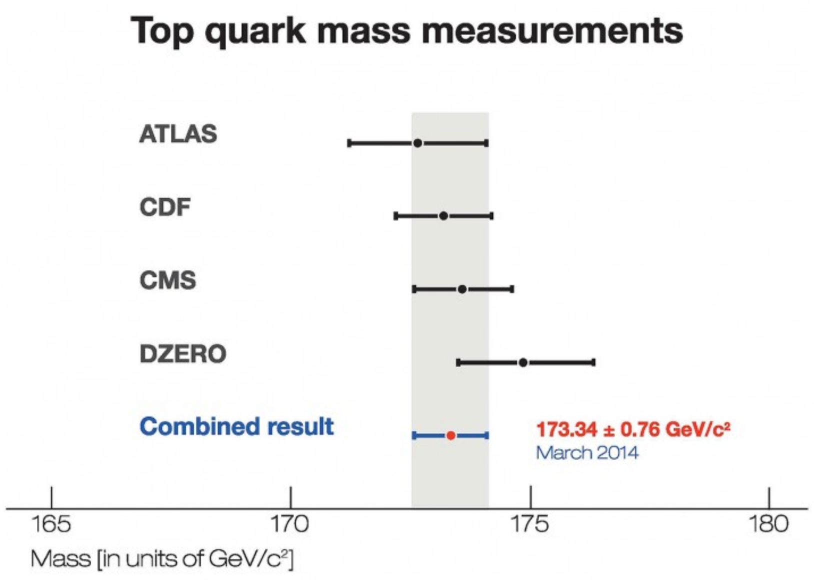
Measurements & prospects

Consistent set of measurements from 4 experiments

Combined precision well below 1 GeV

CMS: 200 MeV after 3/ab (conventional method, *CMS-FTR-13-017-PAS)*

based on "assumptions [that] are optimistic but not unrealistic."



Interpretation: cornering the top quark mass

Theory to relate MC mass to rigorously defined scheme

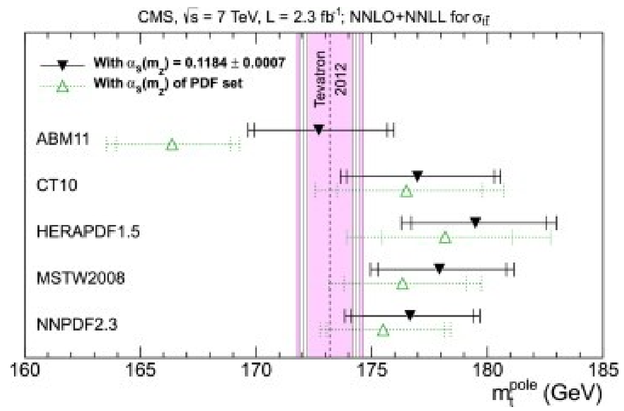
Experiments to compare increasingly precise results of a number of methods

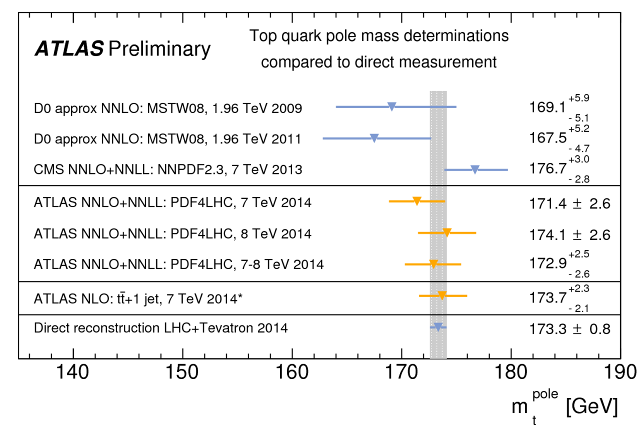
Experiments extract pole mass directly, from (differential) x-sec: 2.3-3.0 GeV

Snowmass, Determination of the top quark mass circa 2013: methods, subtleties, perspective, arXiv:1310.0799

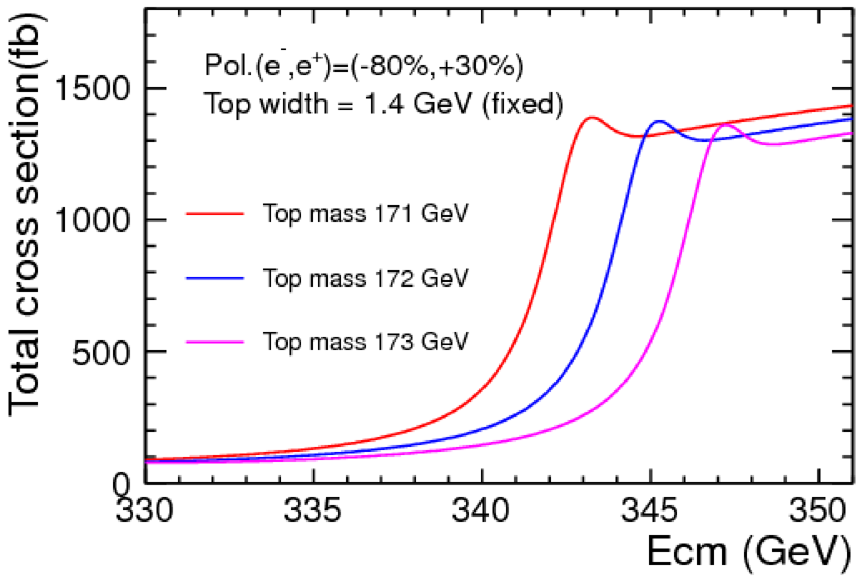
MITP, High precision fundamental constants at the TeV scale, arXiv:1405.4781

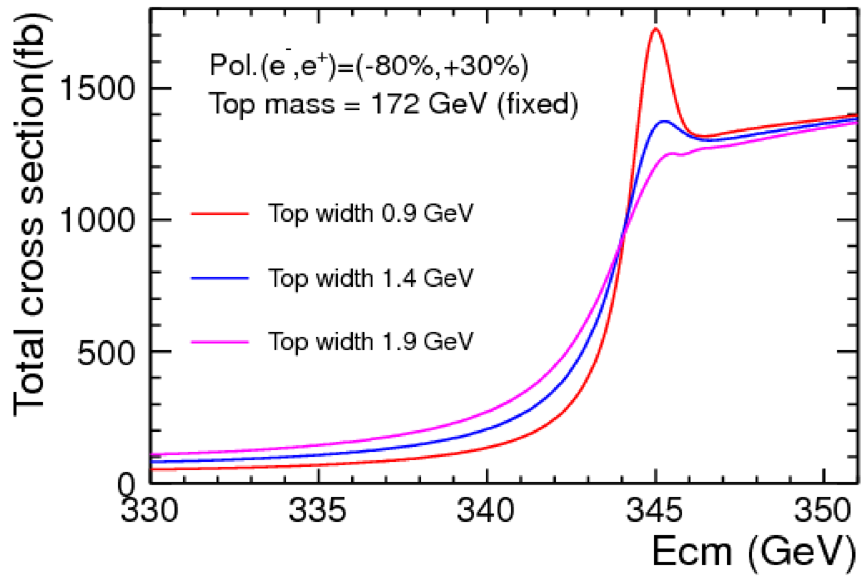
A. Hoang (TOP2014), The top mass: interpretation and theory uncertainties, arXiv:1412.3649





Top mass from an LC threshold scan





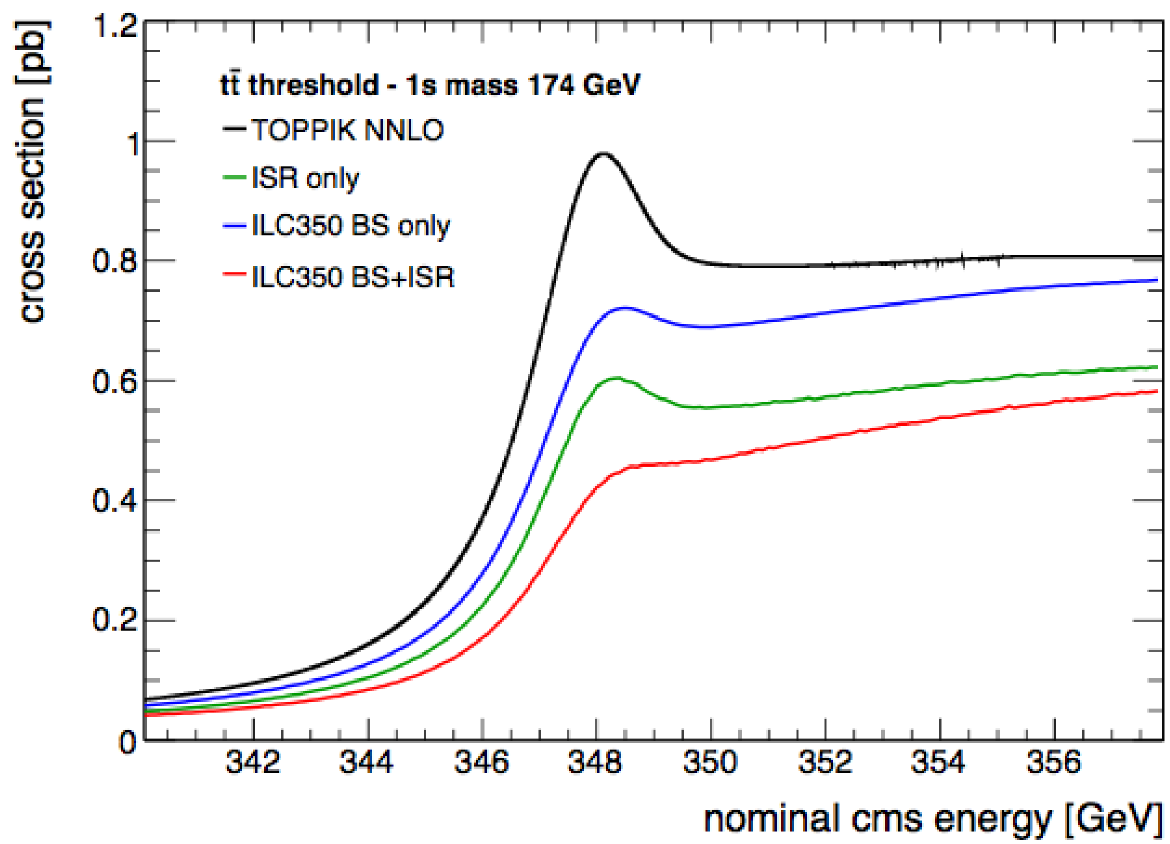
Threshold shape depends strongly on mass, width. Normalization sensitive to strong coupling constant and top Yukawa coupling.

Kuhn, Acta Phys.Polon. B12 (1981) 347

Beam energy spread and ISR smear the shape

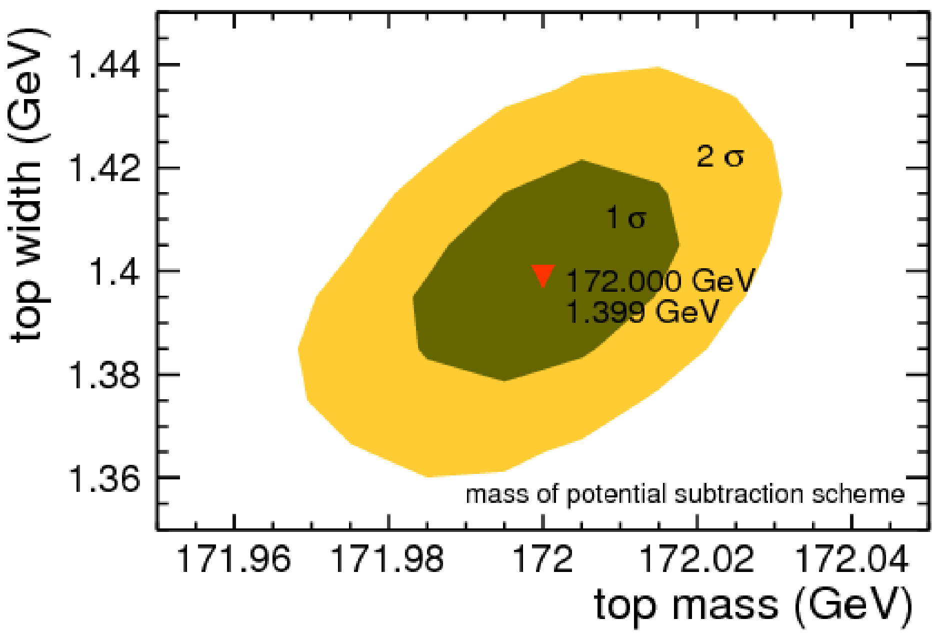
CLIC has slightly more pronounced tail in luminosity spectrum

FCC-ee luminosity spectrum is broader, but more symmetric

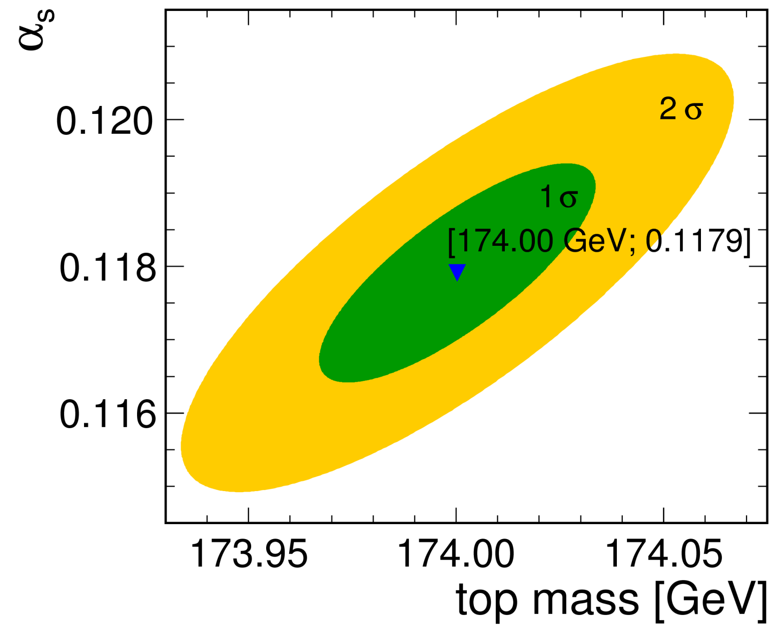


Fitting for the top mass

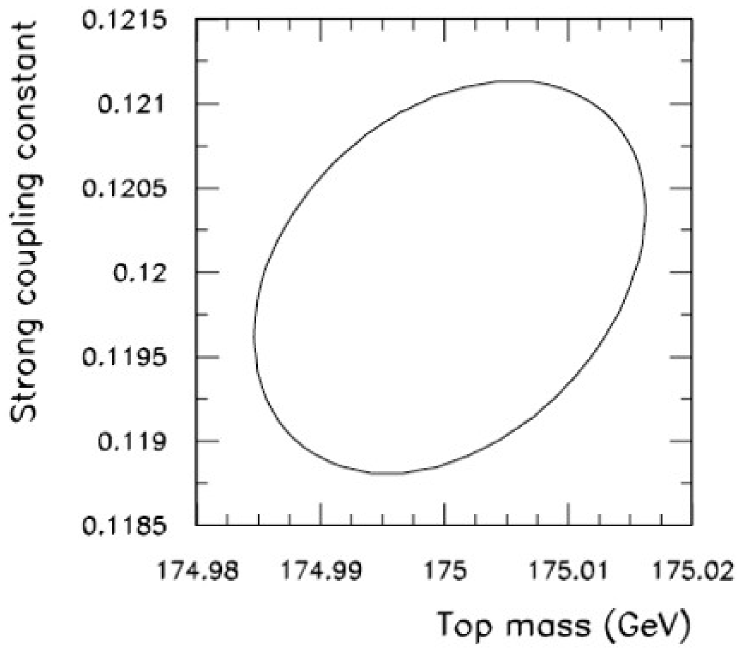
Horiguchi et al., arXiv:1310.0563



Seidel, Simon, Tesar, Poss, EPJ C73 (2013)



Martinez, Miquel, EPJ C27, 49 (2003)



Several authors have applied multi-parameter fits to cross-section obtained in scan (+ other distributions)

Minor differences between ILC, CLIC and FCC-ee

Statistical precision on 1S or PS mass for 10 x 10/fb:

16 – 30 MeV

(range of results can be understood from assumptions and fit details)

Top mass systematics

Experimental systematic uncertainties:

5% uncertainty non-$t\bar{t}$ bkg → 18 MeV (Seidel, Simon, Tesar, Poss)

Single top "contamination" → < 30 MeV (Boronat et al.,arXiv:1411.2355)

10^{-4} precision on $\sqrt{s}$ → 30 MeV (Seidel, Simon, Tesar, Poss)

Realistic uncertainty on lumi-spectrum → 10 MeV (Sailer & Poss, EPJC (2014) 74:2833, F. Simon, AWLC14, arXiv:1411.7517)

Theory uncertainty in 1S mass extraction:

Evaluation of NNLO+NNLL, NNNLO → 50 MeV? (F. Simon, private comm.)

Top mass systematics

Theory uncertainty in conversion to $\overline{\text{MS}}$ scheme:

3-loop calculation → ~100 MeV

4-loop calculation → <10 MeV

(P. Marquard et al., arXiv:1502.01030, PRL114 (2015))

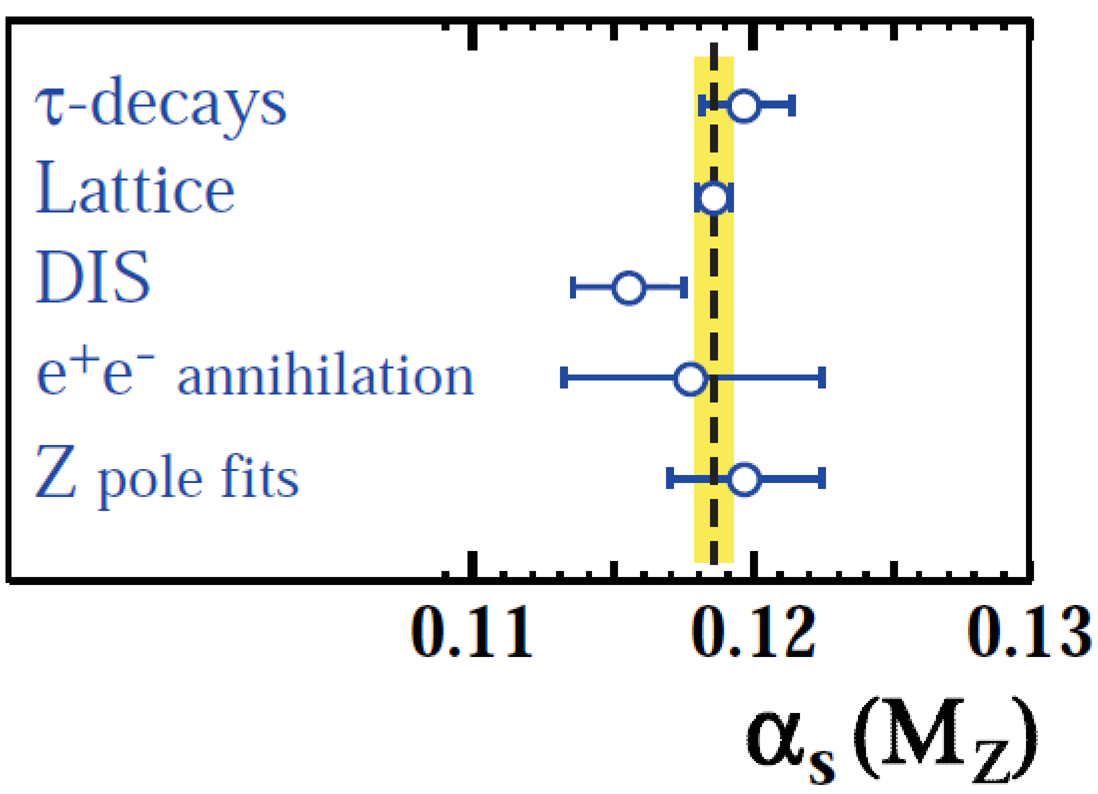
Parametric (α_s) → ~50 MeV

Current world average (PDG)
Uncertainty is 0.0006
→ 50 MeV on mass

$$\frac{m_t(m_t)}{GeV} = 163.643 \pm 0.007 + 0.069\,\delta_{\alpha_s} - 0.096\,\delta_{m_t}^{1S}$$

$$\delta_{\alpha_s} = [0.1185 - \alpha_s]/0.001$$

$$\delta_{m_t}^{1S} = [172.227\,GeV - m_t]/0.1$$

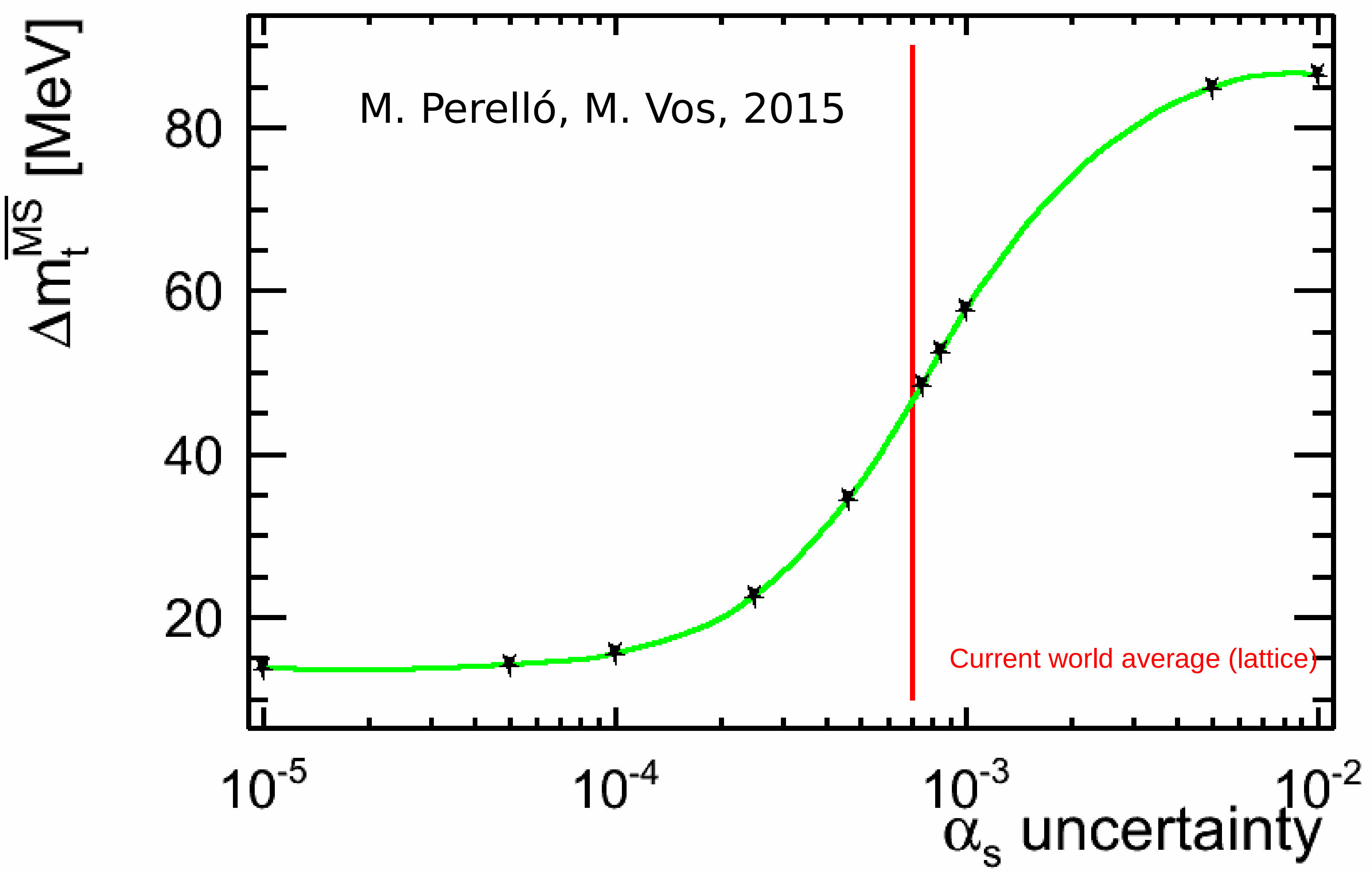


(LC) prospects for α_s? How can we reduce the error by a factor 2-3?

Top quark mass & α_s

Uncertainty on strong coupling constant strikes twice:

- as a degree of freedom in the fit to extract 1S mass (δM^{1S} goes from 12 MeV → 42 MeV)
- as a parametric error in the 1S → $\overline{MS}$ conversion



Top quark mass precision vs. prior knowledge of strong coupling strength

$t\bar{t}g$ x-section at $\sqrt{s}$ = 500 GeV has similar sensitivity to α_s as threshold production, but very small top mass dependence. With large luminosity a competitive α_s can be obtained, provided theory & exp. systematics can be controlled to ~0.5%.

Alternative techniques

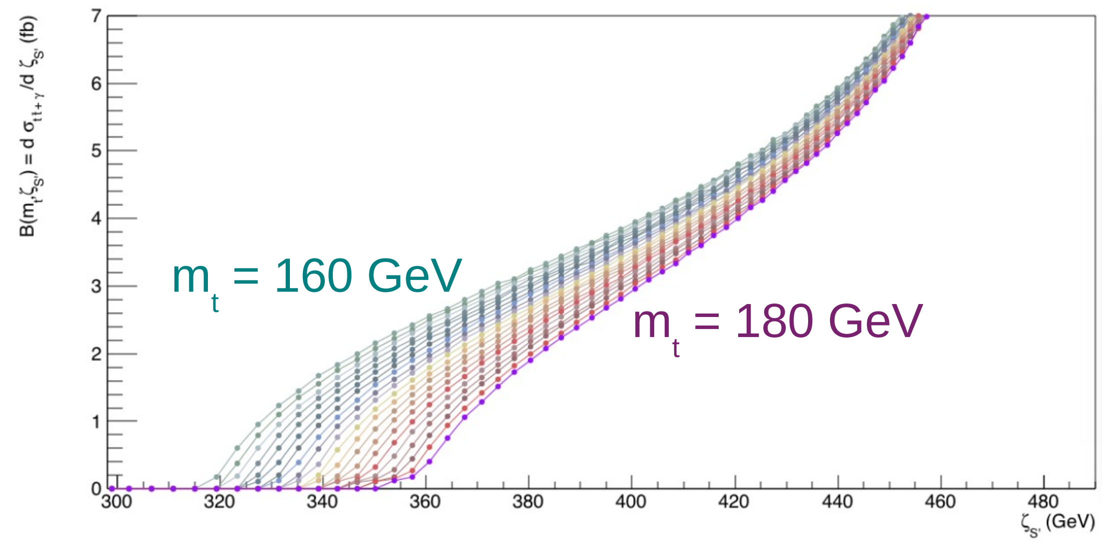
Scenarios start with 500 GeV. The first top quark mass measurement will be made there.
Special opportunities at 1 TeV? Below threshold? 250 GeV seems unlikely to add much after 500 GeV

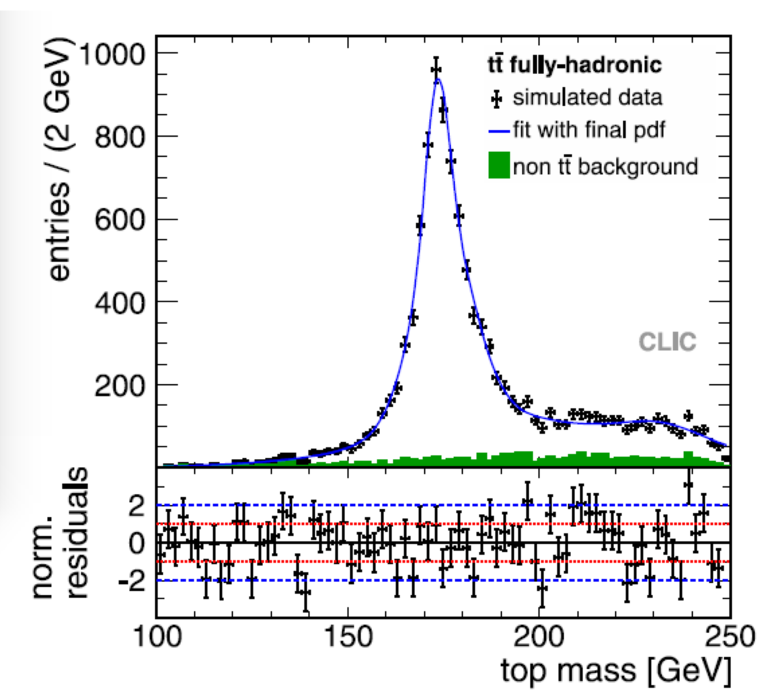
Extraction of the top quark mass from the differential ttγ and ttg cross-section versus s'

Precision seems competitive for √s ~ 400 GeV

Boronat, Fuster, Gomis, in preparation

(cf. m(b) at m(Z) at LEP, EPJC73 (2013) 2438, ATLAS-CONF-2014-053)





Conventional measurement on top decay products

80 MeV stat. precision at 500 GeV

→ input to clarify MC mass interpretation

Seidel, Simon, Tesar, Poss, EPJ C73 (2013)

Boosted top quark jets at a 1 TeV e^+e^- collider

- Extraction from top jets (Hoang, Mantry et al., PRD77 (2008) 074010 & 114003)
  (rigorous SCET interpretation, can “compete” with threshold scan)
- Experimental studies largely lacking so far

Top quark mass: summary

A very precise measurement of the top quark mass, $\Delta m_t \sim$ 50 MeV, can be extracted from a threshold scan

+ $\Delta\ \alpha s$ < 0.001 (not competitive with world average)

+ $\Delta\ \Gamma_t$ < 30 MeV (translate to constraint on V_{tb})

+ $\Delta\ y_t/y_t \sim$ 4.2% (if a precise value of α_s is inserted, otherwise 35%)

Note that one has to read several articles and contact a few people to assemble a correct and complete LC prospect

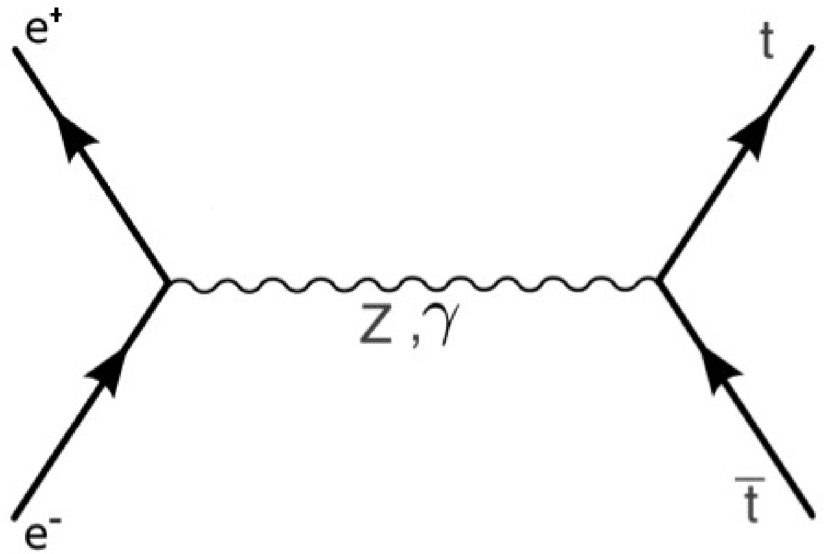
→ produce a single authorative source for this prospect...

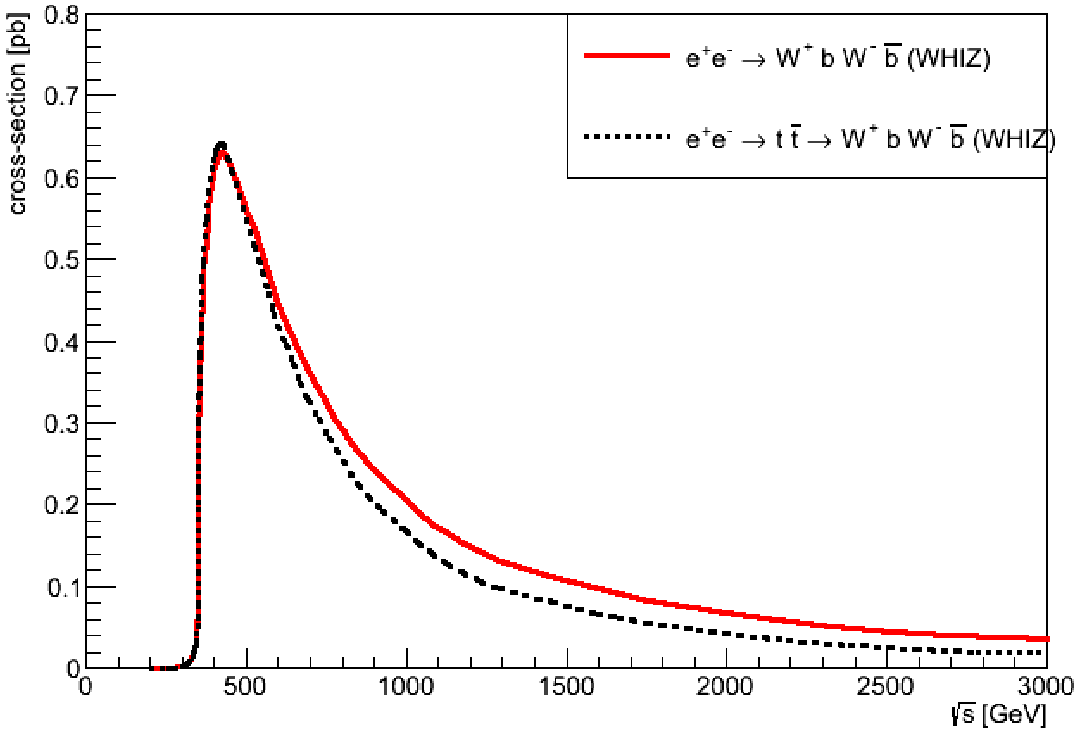
Top couplings to γ/Z

Electro-weak $e^+e^- \rightarrow Z/\gamma* \rightarrow t\bar{t}$ production is the dominant source of top quarks at the ILC

At the LHC the process $q\bar{q} \rightarrow Z/\gamma* \rightarrow t\bar{t}$ cannot be isolated, but associated $t\bar{t}\gamma$ and $t\bar{t}Z$ production have been observed

Some overlap with studies of tWb vertex at LHC (single top, top decay), and indirect sensitivity of LEP precision tests and B-factories





Top quark couplings: TDR times

measure

$\sigma(+)\quad A_{FB}(+)$

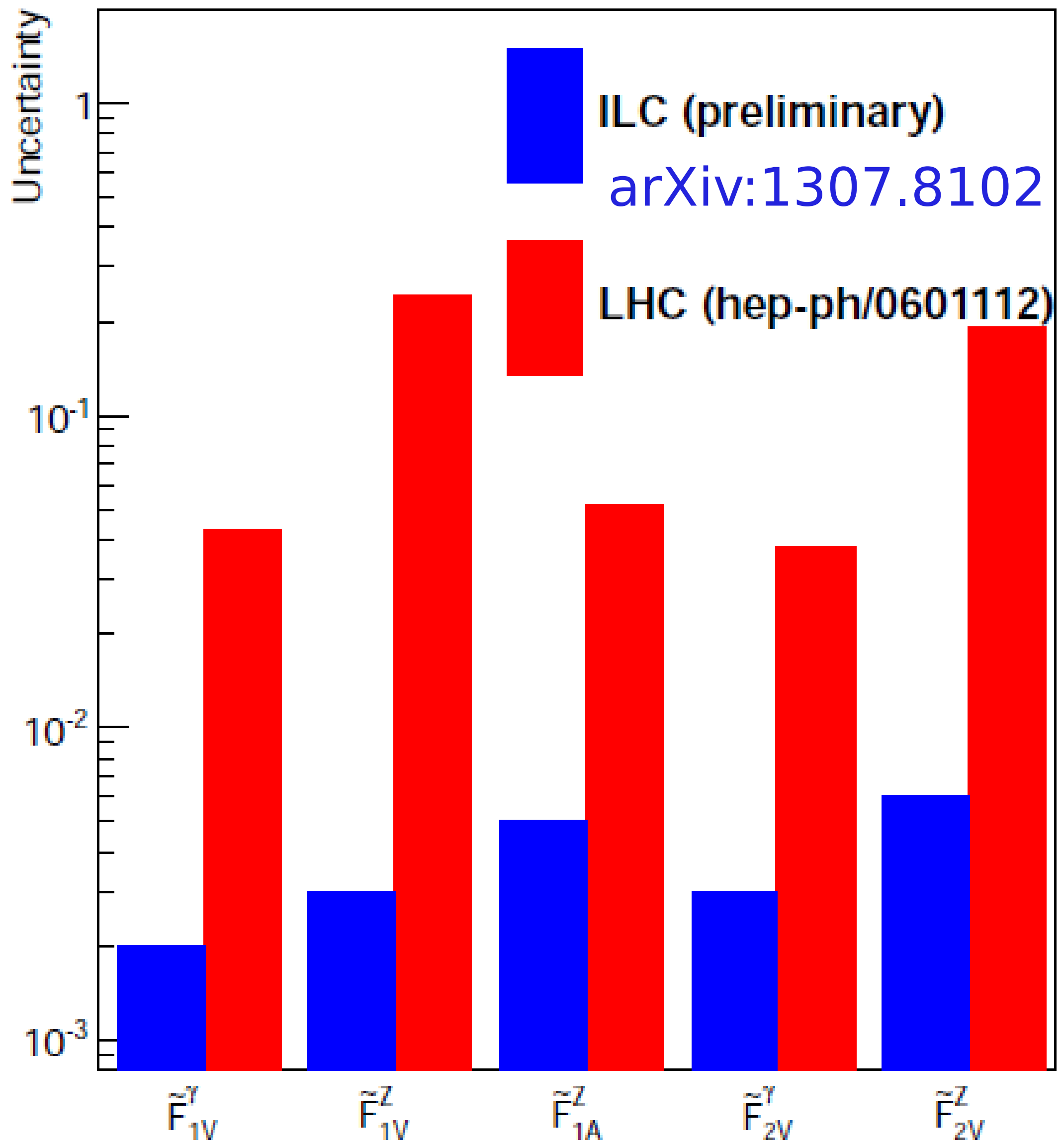
$\sigma(-)\quad A_{FB}(-)$

extract

$$\left.\begin{array}{l}(+=e^-_R)\\(-=e^-_L)\end{array}\right\}\Rightarrow\left\{\begin{array}{ccc}F^{\gamma}_{1V} & * & F^{\gamma}_{2V}\\ F^{Z}_{1V} & F^{Z}_{1A} & F^{Z}_{2V}\end{array}\right\}$$

Measure 2 observables
for 2 beam polarizations:
- x-section
- FB asymmetry

Extract form factors in groups
(assuming SM for remaining groups)



Assumptions:

LHC: 14 TeV, 300/fb

LC: √s = 500 GeV, L = 500/fb

$P(e^-)$ = +/- 80%, $P(e^+)$= -/+ 30%

$\delta\sigma$ ~ 0.5% (stat. + lumi)

δA_{FB} ~ 1.8% (stat., covers systematics?)

Polarization needed to disentangle photon and Z-boson form factors!

Especially for ttZ LC precision is better than existing (model-dependent) limits from top decay, LEP T-parameter, B-factories (full comparison in progress)

LHC potential

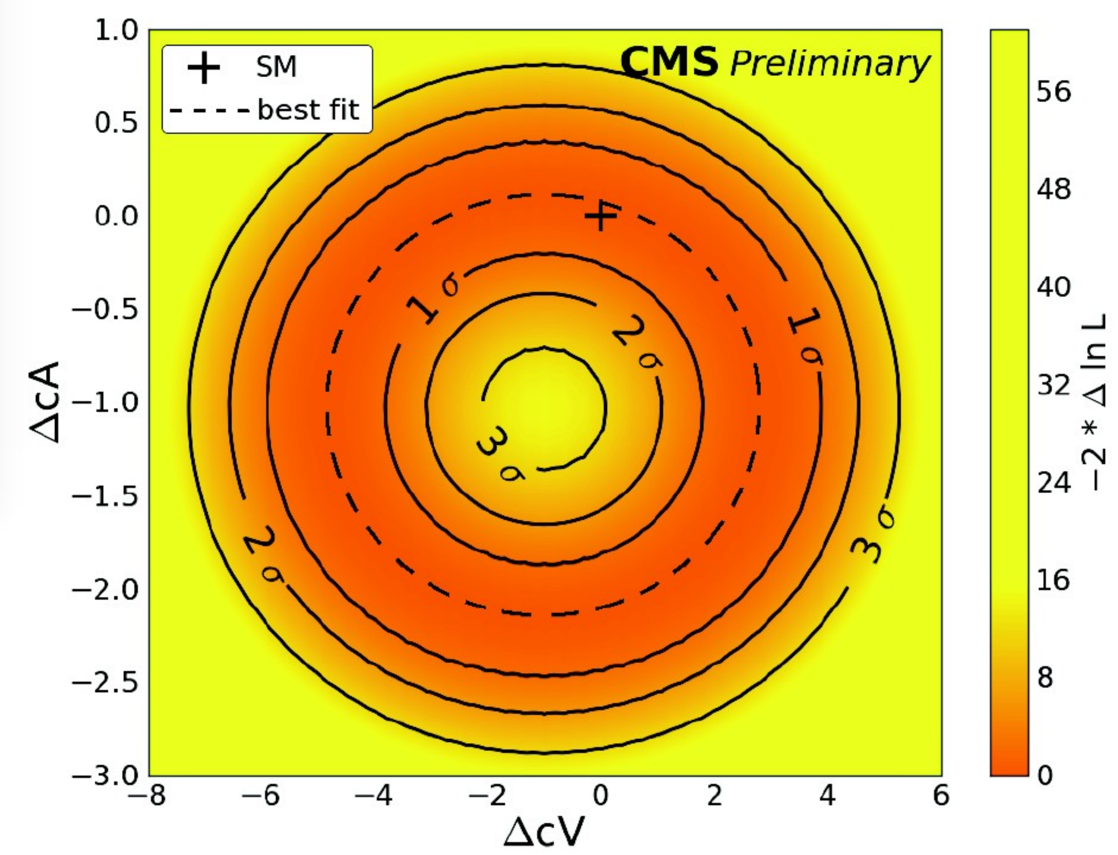
ATLAS/CMS, 8 TeV found 3σ each for $t\bar{t}Z$

(EPJ C74 (2014) 3060, ATLAS-CONF-2014-038)

CMS: preliminary claim for observation of ttZ at 6.4σ level

(A. Brinkerhoff, TOP LHC WG meeting, May 20, 2015, PhysicsResultsTOP14021)

No write-up, but first (weak) limits on D6 operators and t-Z vector and axial coupling



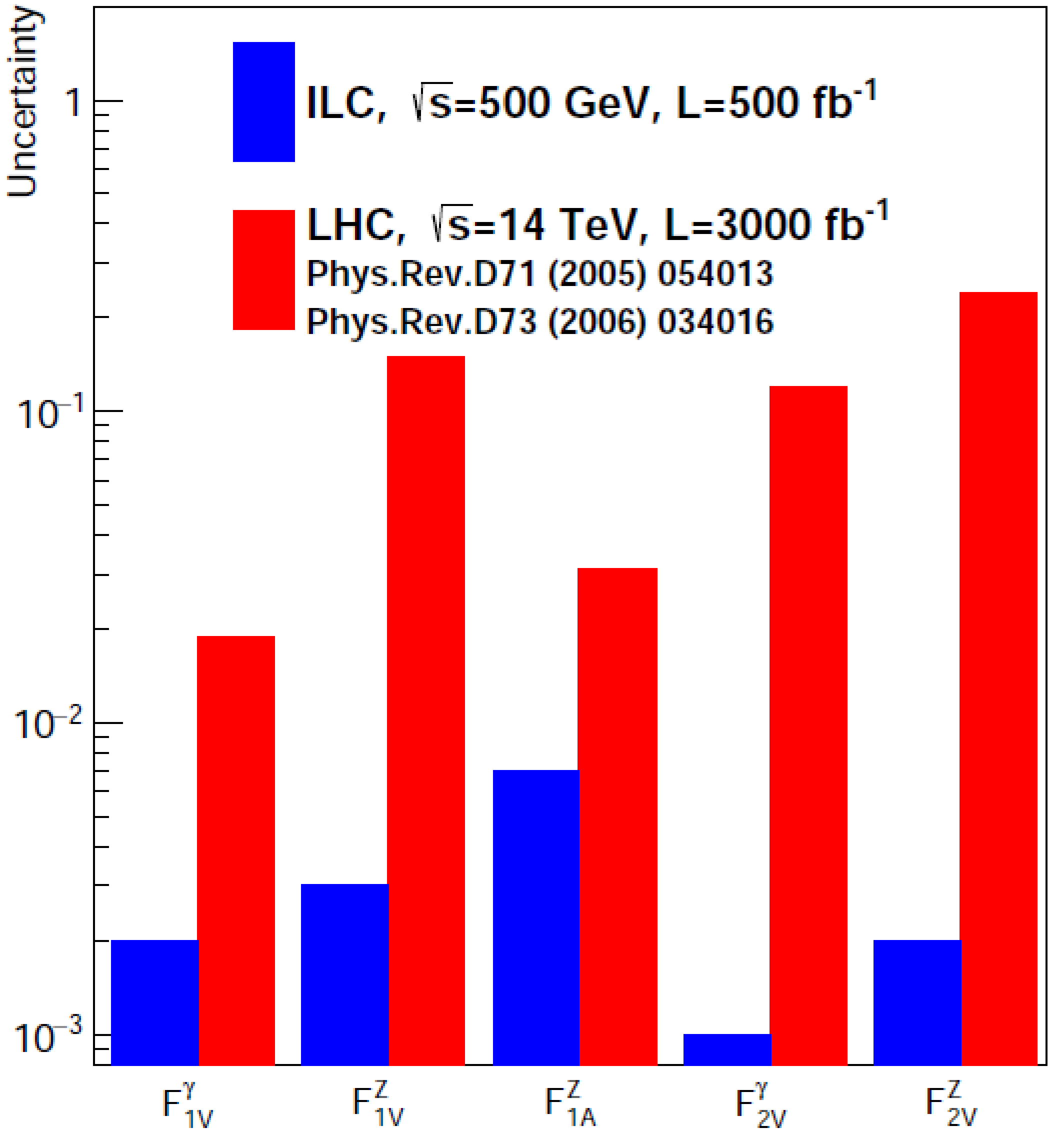
LHC prospects

Now that we have actually observed a few ttγ and ttZ candidate events, shouldn't we update the LHC prospects from 2006?

3 ab^{-1} prospects are better, of course

No formal prospects from ATLAS or CMS, but Röntsch and Schulze revisited the LHC prospects for several couplings.
Probing top-Z dipole moments at the LHC and ILC, arXiv:1501.05939 [hep-ph]
Constraining couplings of top quarks to the Z boson in $t\bar{t}$ + Z production at the LHC, JHEP 1407 (2014) 091

NLO calculation improves sensitivity wrt Snowmass study in 2006.



Top quark couplings: sensitivity vs. sqrt(s)

Impact of new physics on cross-section and asymmetries depends on sqrt(s).
Sensitivity increases strongly at large sqrt(s) for axial dipole moments and four-fermion operators;

→ factor 10 and more between 0.5 and 3 TeV

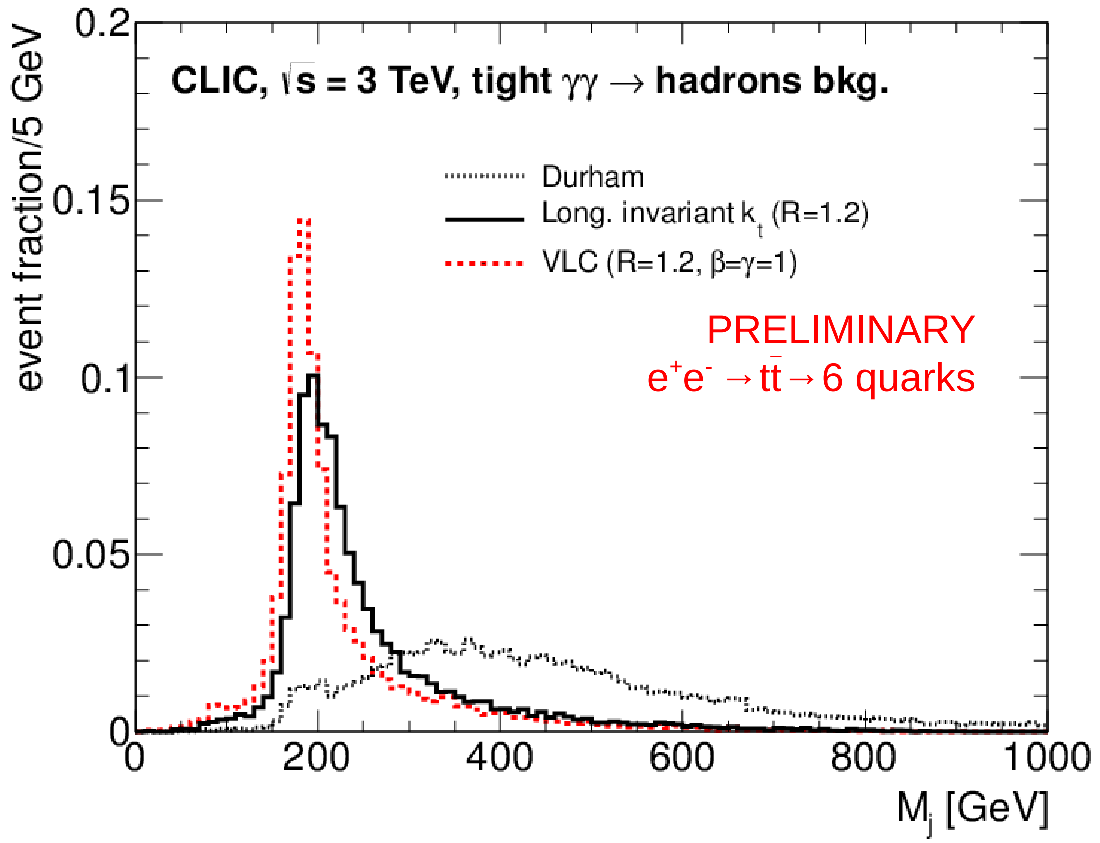
Much less pronounced increase for vector dipole moments, none for $F_{1V/A}^{\gamma,Z}$

$$\Gamma^{\mu}_{t\bar{t}(\gamma,Z)} = ie\left[\gamma^{\mu}\left[\widetilde{F}_{1V}^{\gamma,Z} + \widetilde{F}_{1A}^{\gamma,Z}\gamma^{5}\right] + \frac{\left(p_t - p_{\bar{t}}\right)^{\mu}}{2m_t}\left[\widetilde{F}_{2V}^{\gamma,Z} + \widetilde{F}_{2A}^{\gamma,Z}\gamma^{5}\right]\right]$$

Top quark couplings: sensitivity vs. sqrt(s)

Precision of the measurements of cross-section and asymmetries depends on:

- available statistics
  - s-channel process: drop in x-section not compensated by increase in luminosity
- top quark boost
  - A_{FB} drops rapidly towards sqrt(s) = 2 m_t
- reconstruction
  - less ambiguity for highly boosted tops (no systematic comparison so far)
- control of systematics
  - ????

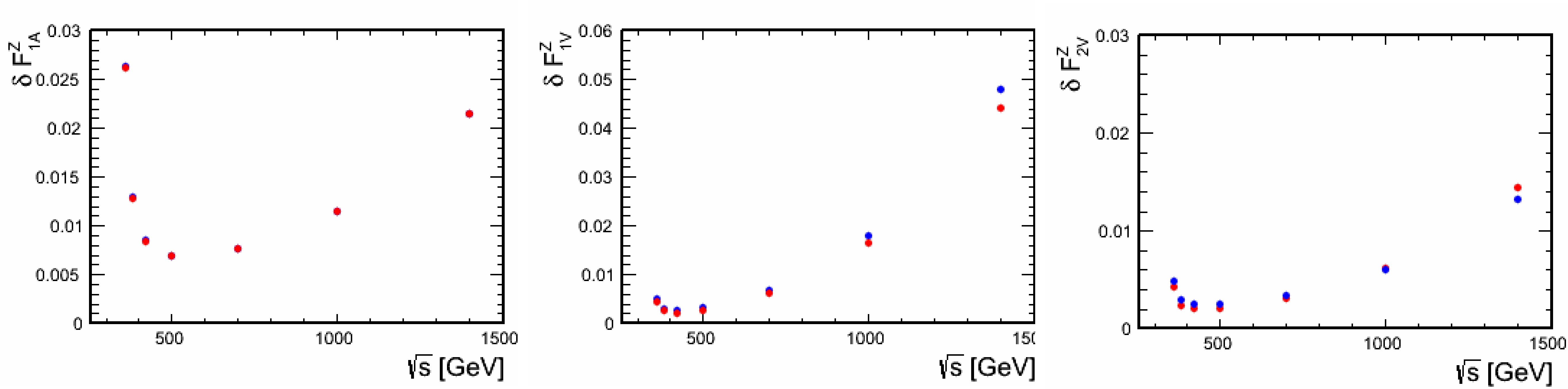


Top quark couplings: sensitivity vs. sqrt(s)

Simple evaluation of statistical uncertainty. A thorough full-simulation CLIC study started.

stat. dominated uncertainty:
$\delta\sigma/\sigma \sim 1/\sqrt{N}$ $\quad \delta A_{FB} = (1 - A^2_{FB}) \times \delta\sigma/\sigma$
Integrated luminosity: 2 x 250/fb

Nominal beam polarization (e^- 80%, e^+ 30%)
Electron polarization only



F_{1V}; shallow minimum → *optimal around 400 GeV*

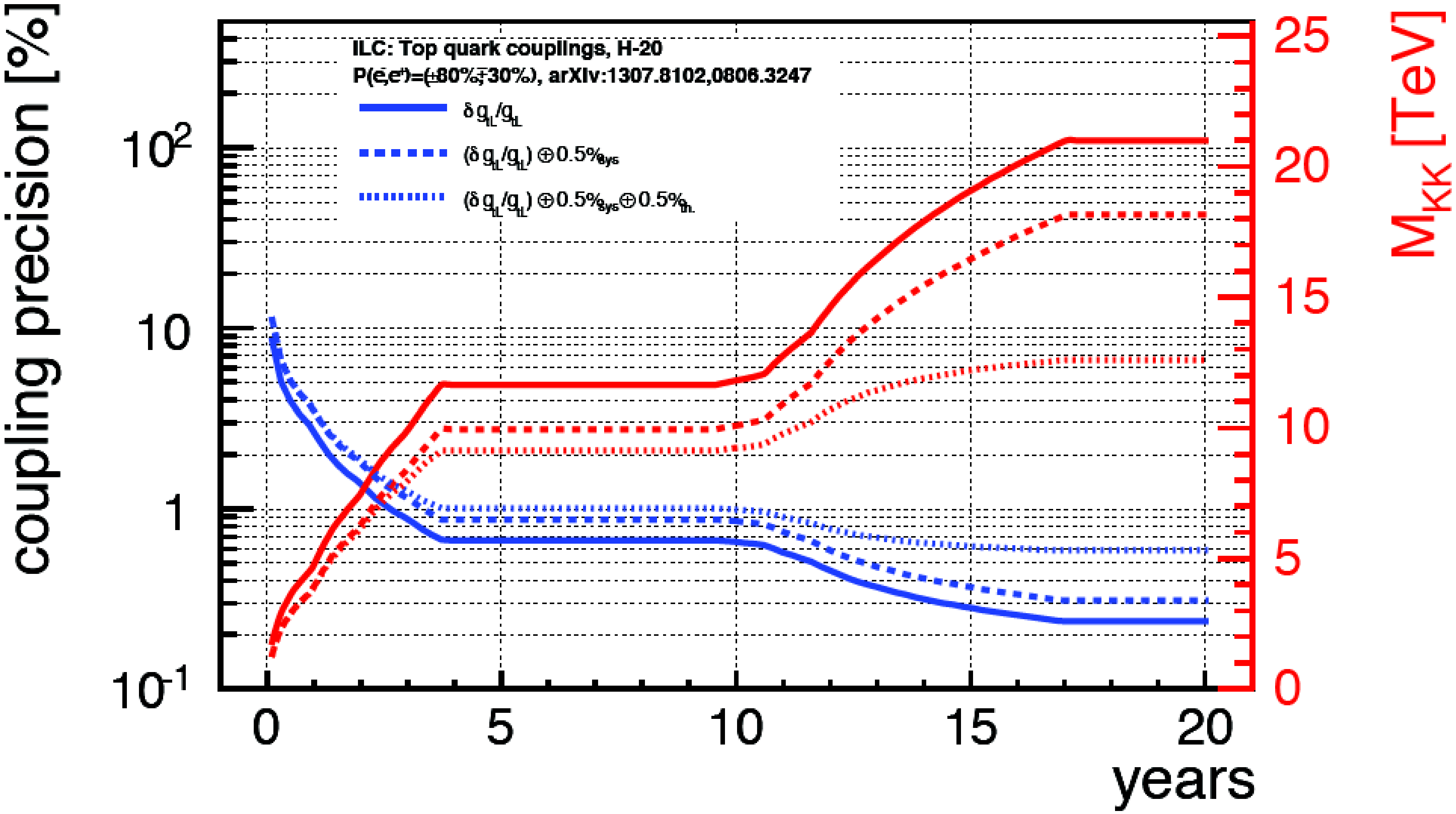
F_{1A}; A_{FB} degraded strongly close to threshold → *500 GeV*

F_{2V}; impact of new physics grows strongly with energy → 1-3 TeV

Truly optimal: comprehensive program at several energies

Complete 20-year ILC programme

H20: 500/fb @ 500 GeV, 200/fb @ 350 GeV, 500/fb @ 250 GeV, 3500/fb @ 500 GeV, 1500/fb @ 250 GeV



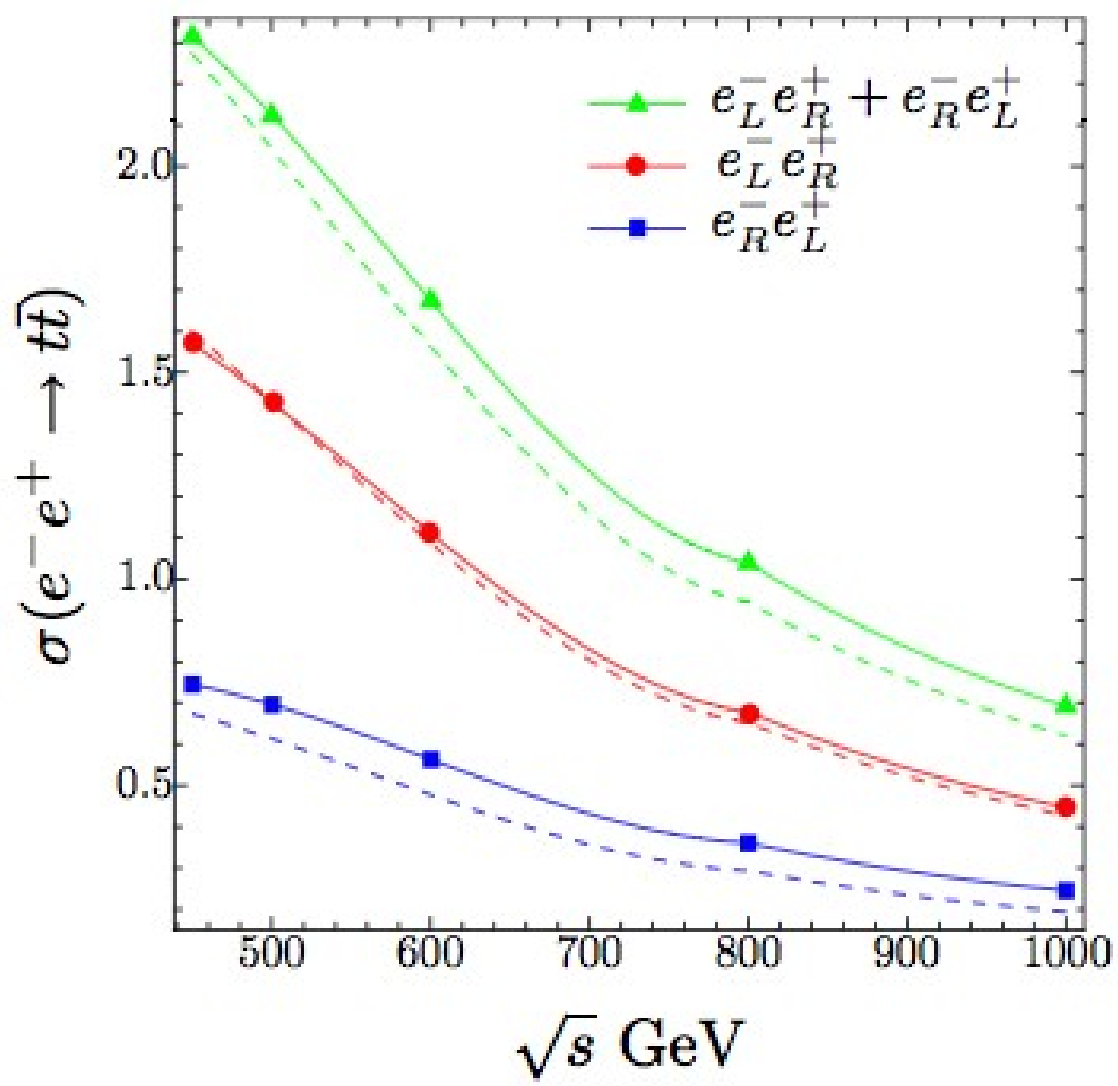
New: polarized EW corrections

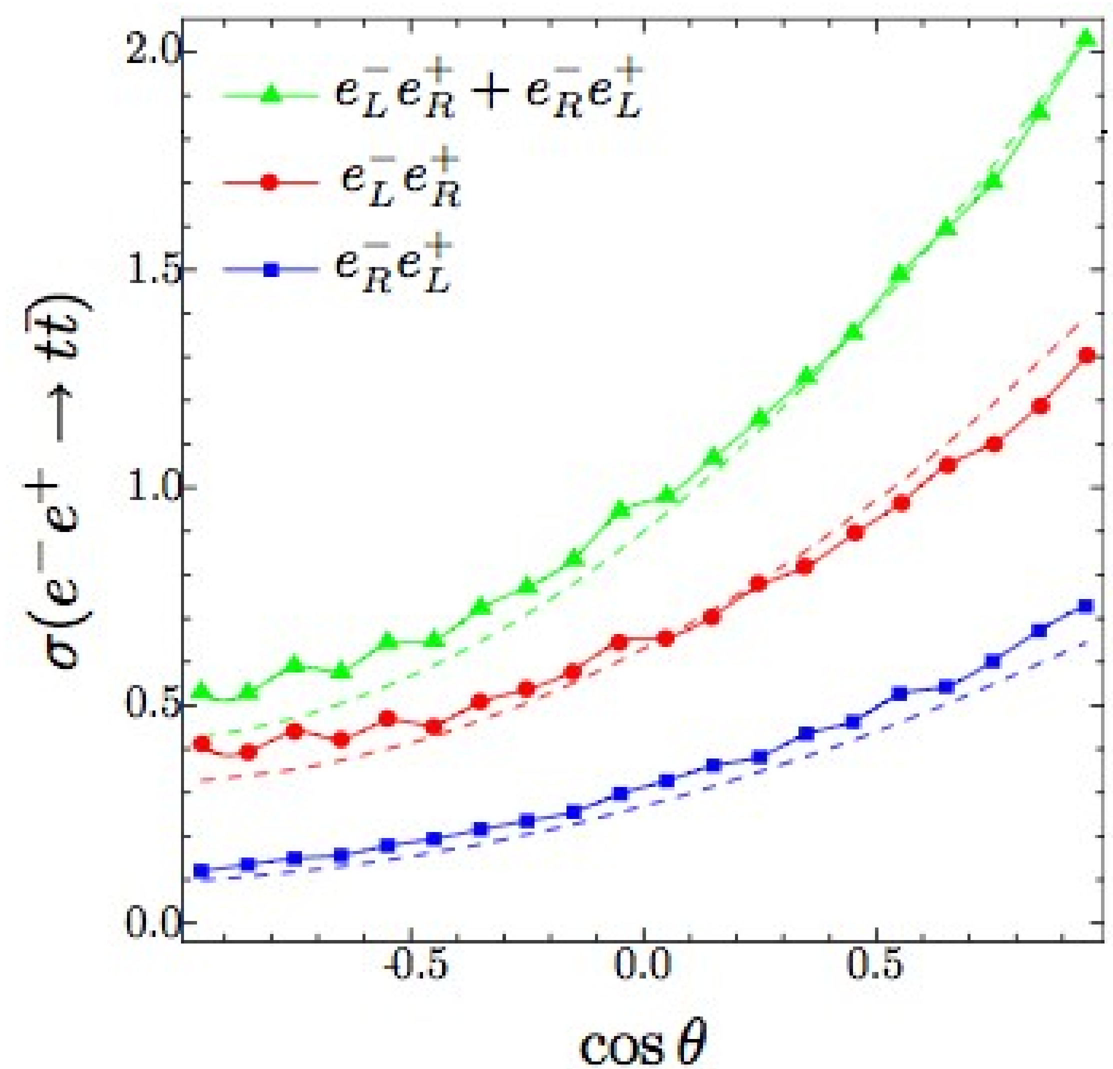
Khiem, Kou, Kurihara, le Diberder, Probing new phyiscs using top quark polarization in the e+e- → tt process at future Linear Colliders, arXiv:1503.04247 [hep-ph]

Tree-level + NLO EW corrections

Tree-level only

Impact of 1-loop electro-weak corrections:
- numerically large (5% for x-sec, 10% for AFB)
- ISR photons, trivial EW, but remaining still large





See also: Nhi M.U. Quach, Monday physics session

Matrix element on di-lepton final state

Khiem, Kou, Kurihara, le Diberder, Probing new phyiscs using top quark polarization in the e+e- → tt process at future Linear Colliders, arXiv:1503.04247 [hep-ph]

GRACE six-fermion process without narrow-width approximation
(no ISR, no single top, no hadronization, no detector)

Show feasibility of kinematic reconstruction of the di-lepton final state: $e^+e^- \rightarrow t\bar{t} \rightarrow l^+ \nu l^- \bar{\nu} b\bar{b}$

Optimal analysis extracts all ten form factors – simultaneously – from angular distribution using the (LO) matrix element

$\mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma}$	$\mathcal{R}e\ \delta\tilde{F}_{1V}^{Z}$	$\mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma}$	$\mathcal{R}e\ \delta\tilde{F}_{1A}^{Z}$	$\mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma}$	$\mathcal{R}e\ \delta\tilde{F}_{2V}^{Z}$	$\mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma}$	$\mathcal{R}e\ \delta\tilde{F}_{2A}^{Z}$	$\mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma}$	$\mathcal{I}m\ \delta\tilde{F}_{2A}^{Z}$
0.0037	−0.18	−0.09	+0.14	+0.62	−0.15	0	0	0	0
	0.0063	+.14	−0.06	−0.13	+0.61	0	0	0	0
		0.0053	−0.15	−0.05	+0.09	0	0	0	0
			0.0083	+0.06	−0.04	0	0	0	0
				0.0105	−0.19	0	0	0	0
					0.0169	0	0	0	0
						0.0068	−0.15	0	0
							0.0118	0	0
								0.0069	−0.17
									0.0100

Sub-% precision. Note 0 correlation F2A with CP-conserving form factors
Lepton+jets final state, with same optimal ME extraction, yields factor two better precision

Comparison to FCC-ee

Recent publication assesses potential of FCC-ee

P. Janot, arXiv:1503.01325

- run right above threshold; study assumes 2.4 ab^{-1} at $\sqrt{s}$ = 365 GeV

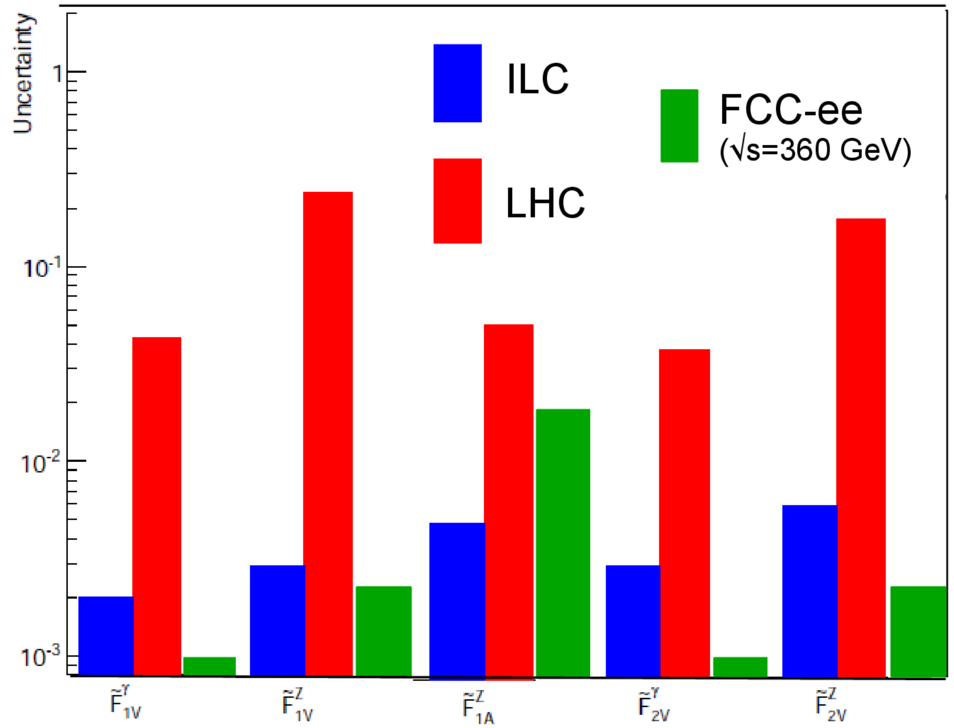
    (theory systematics close to threshold to be evaluated)

- no beam polarization, use final-state polarization instead

    (ILC beam polarization expected to be known to 10^{-3}, can one understand final state polarization to that level?)

Fast simulation analysis based on lepton energy and angle yields:

- similar precision to ILC for Z couplings, except F1AZ
- significantly better than ILC for photon couplings



Good to see interest in this measurement
Full study needed to understand systematics

Top quark couplings: summary

Linear Collider top quark physics programme has exquisite sensitivity to new physics through a precise characterization of $t\bar{t}\gamma$ and $t\bar{t}Z$ vertices, with sub-% to per mil level precision on all anomalous form factors/operators, an order of magnitude better than LHC prospects from associated production

Evaluation of sqrt(s) dependence

→ **best precision** between 400 GeV and 700 GeV

→ **best sensitivity** for some form factors/operators at very high energy

Sophisticated ME extraction of form factors

→ optimal use of information; simultaneous extraction of 10 form factors demonstrated

Polarized NLO EW corrections

→ large effect, quite different for both polarizations, important to include in ME analysis

Valencia LC top workshop

Third LC top workshop at IFIC Valencia

June 30th – July 2nd

Tentative programme on INDICO

http://ific.uv.es/~toplc15/index.html

Register ASAP.
Send us suggestions for topics and contributions!

Conclusions

Linear collider with $\sqrt{s}$ > 2 mt is an excellent chance to precisely measure crucial top quark properties and gain sensitivity to BSM physics

New developments:

- top quark mass: determine $\overline{MS}$ mass to ~50 MeV
  - *theory systematic in 1S → $\overline{MS}$ conversion much reduced (but, beware of α_s)*
  - *the ball is in the experimentalists' court: solid assessment of systematics required*
  - *develop early mass extraction method for first data at 500 GeV*
- top quark couplings to Z and photon
  - *First (weak) LHC limits on t-Z vertex*
  - *ME method (le Diberder et al.) allows simultaneous extraction of all form factors*
  - *first mapping of potential vs. center-of-mass energy*