Precision top quark physics at a future linear e^+e^- collider

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F. Richard, R. Poeschl (LAL Orsay)
I Garcia, E. Ros, P. Ruiz Femenia (IFIC Valencia)

LC top physics

350 GeV:

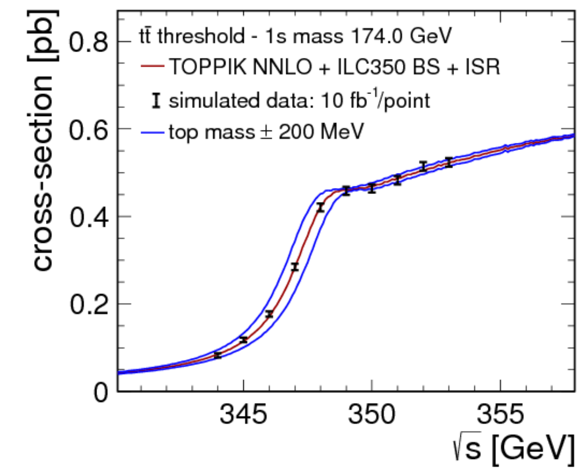
top quark mass to < 100 MeV from threshold scan (+width & Yukawa)

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

Martinez, Miquel, EPJ C27, 49 (2003)

Seidl, Simon, Tesar, Poss, EPJC73 (2013) 2530

A. Juste et al. ArXiv:1310.0799

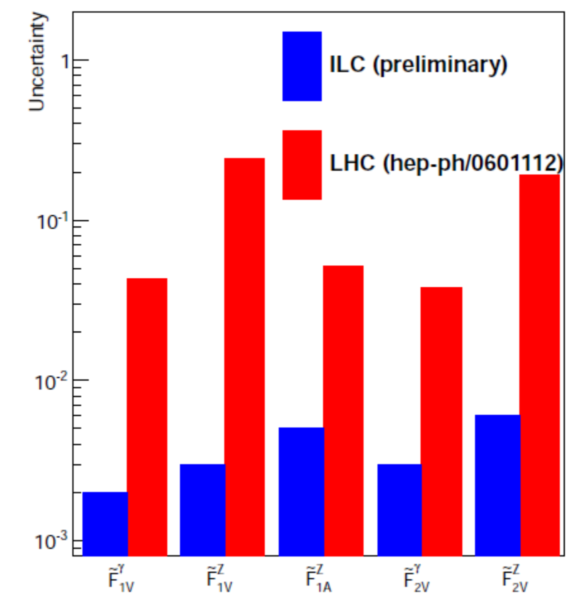


500 GeV:

New physics: precise characterization of tt̄Z and tt̄γ vertices

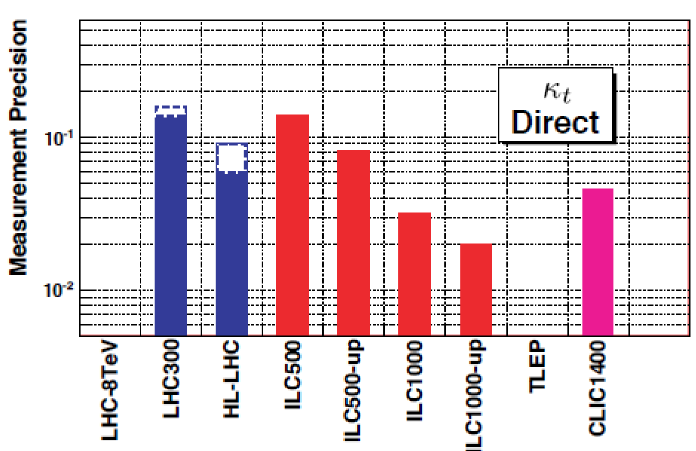
M.S. Amjad et al., arXiv:1307.8102

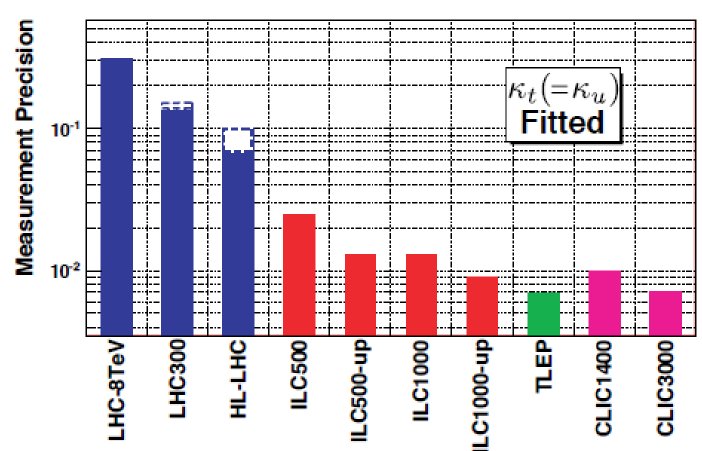
F. Richard, arXiv:1403.2893



500-1500 GeV:

tt̄H direct access to top Yukawa coupling





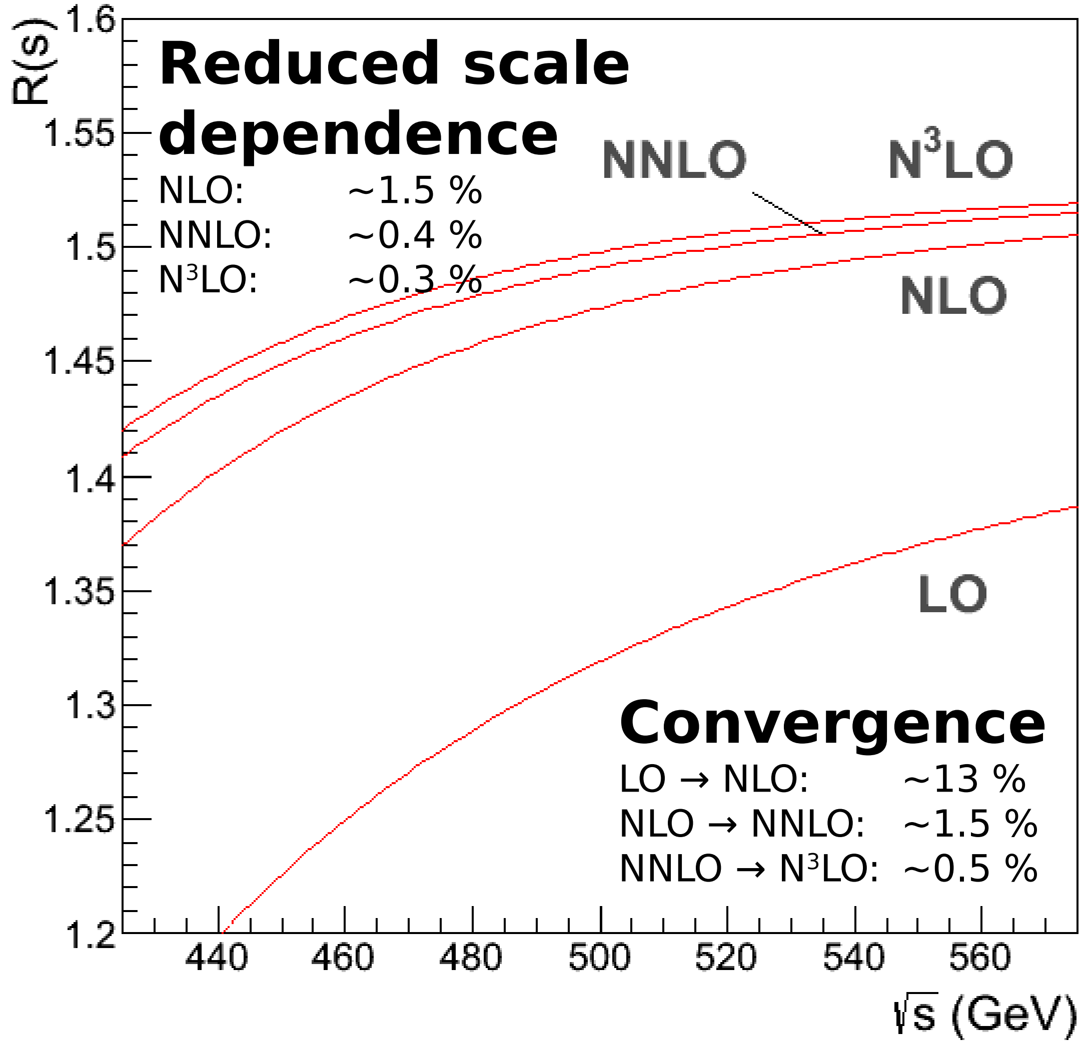
How tightly are these objectives tied to the center-of-mass energy assumed in the study?
Can we extract the top quark mass precisely and rigorously at √s > 360 GeV?
How does our new physics reach change with center-of-mass energy?
What's the sweet spot for the top Yukawa coupling measurement?

Theory status

State-of-the-art: $O(\alpha_s^3)$ QCD corrections of $e^+e^- \rightarrow tt$ x-sec with per mil precision

One-loop EW corrections have a large effect: 3% on σ, next order likely small

R(s) = cross-section normalized to x-sec for massless fermion



QCD corrections

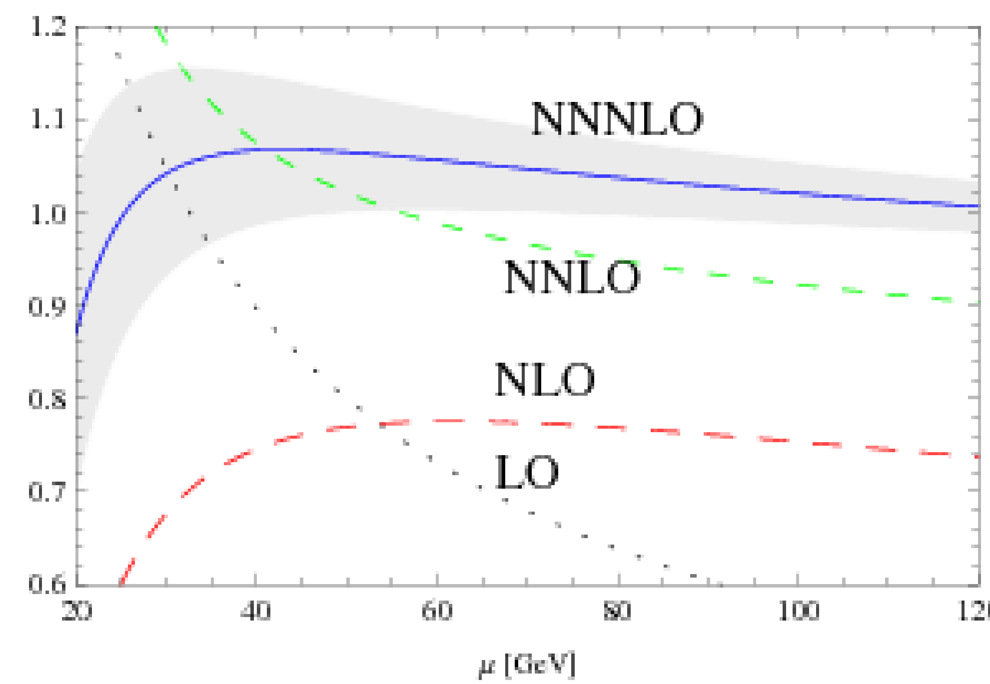
to $e^+e^- \rightarrow tt + X$

Kiyo, Maier, Maierhöfer, P. Marquard, arXiv:0907.2120
Hoang, Mateu, Zebarjad, Nucl. Phys. B 813 (2009) 349-369

Bernreuther, Bonciani et al., hep-ph/0604031

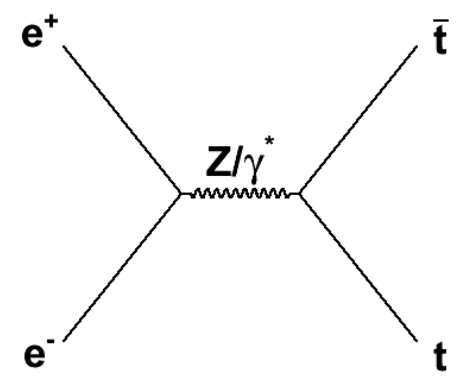
Electroweak corrections

Glover et al. hep/ph04010110
Fleischer et al. hep/ph0302259
Khiem et al., arXiv:1403.6556/6557

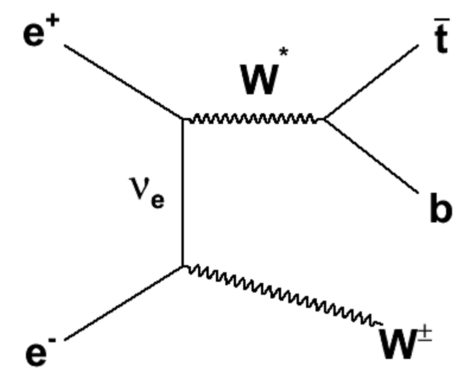


At threshold: NNNLO resummed calculations include quasi-bound-state effects (see Peter Marquard's talk in the top session)

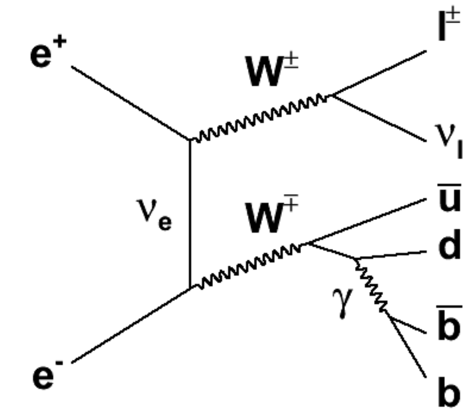
Top quark pairs vs. WbWb



Top quark pair production...



...Single top quark production...



...WWγ/Z/h...

$WbW\bar{b} \rightarrow$ 6 fermions has several non-negligible sources

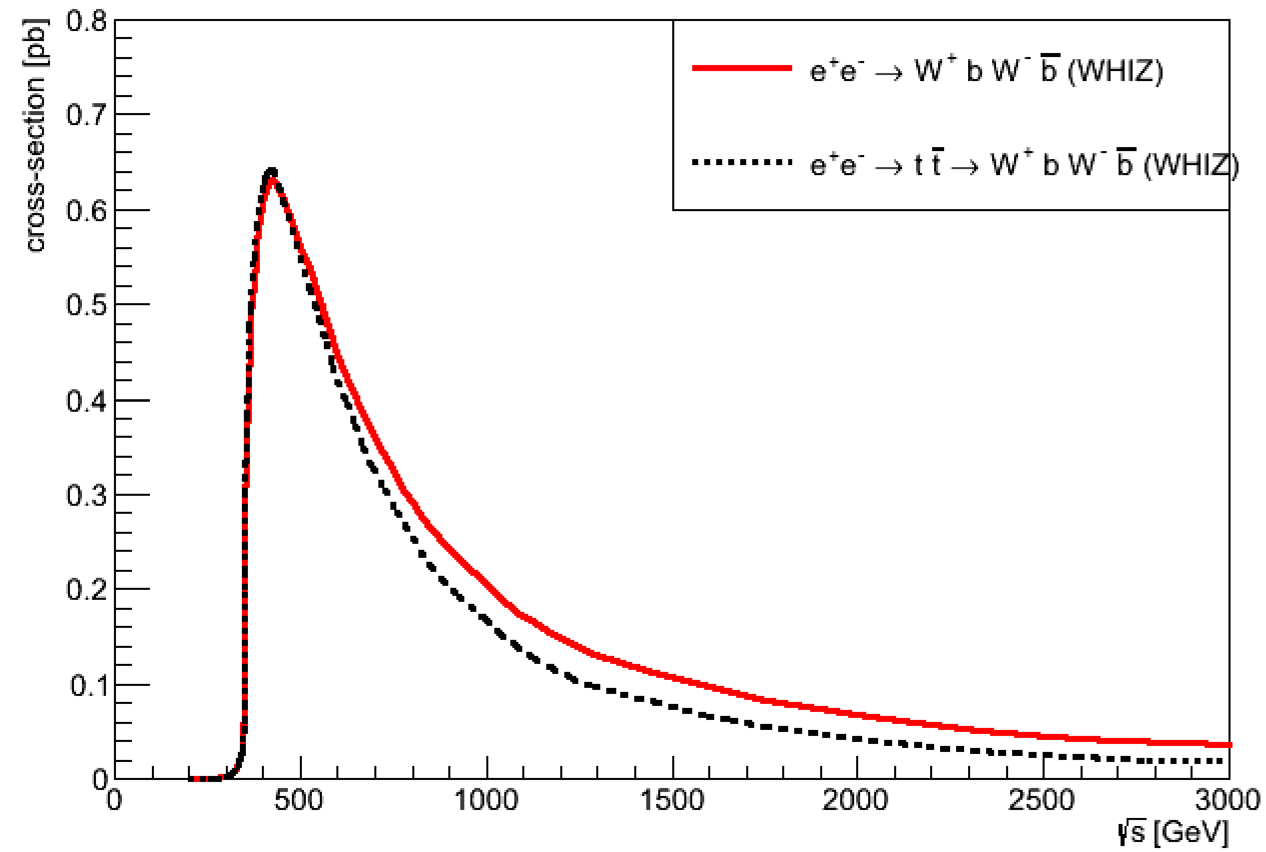
($t\bar{t}$ ~ 90%, single top ~9%, WWγ/Z/h ~ 1%)

Do we select $t\bar{t}$ or WbWb?

(at 500 GeV single top practically indistinguishable)

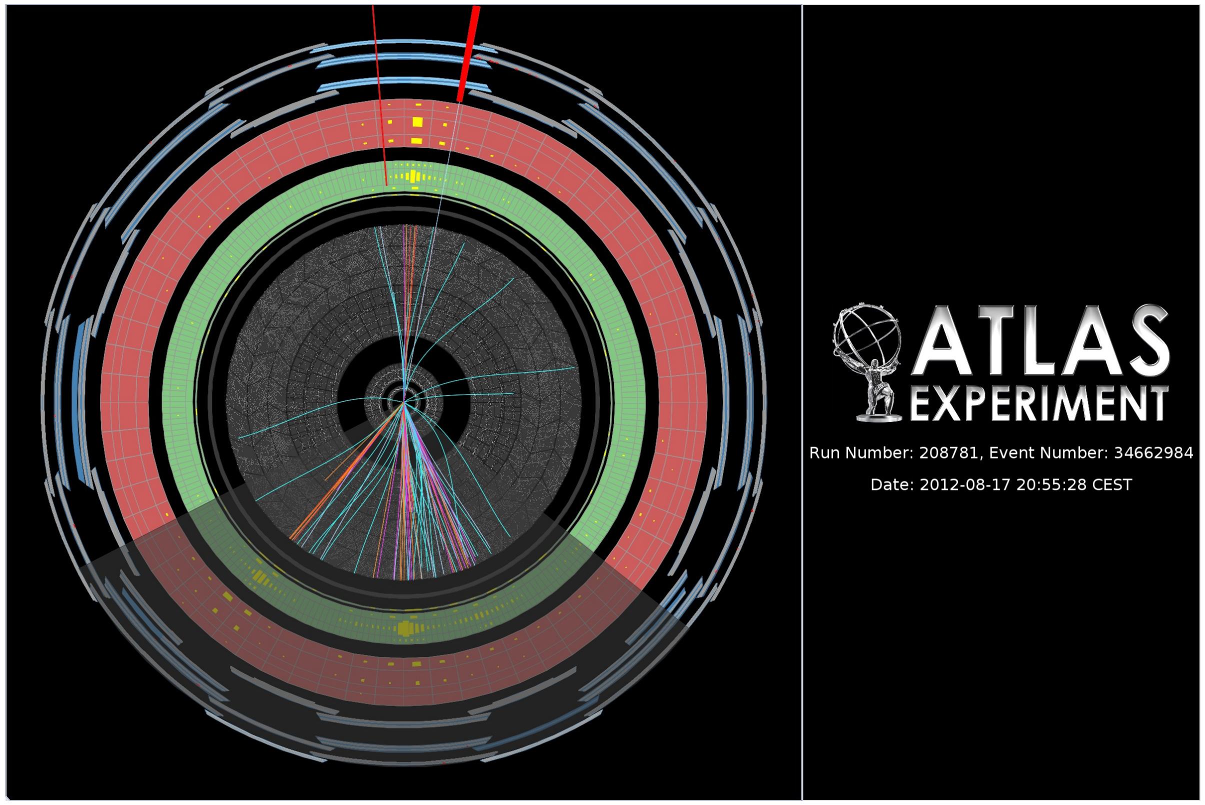
The WbWb cross section is 5 to 50% larger than the top quark pair cross-section

Difference increases with center-of-mass energy



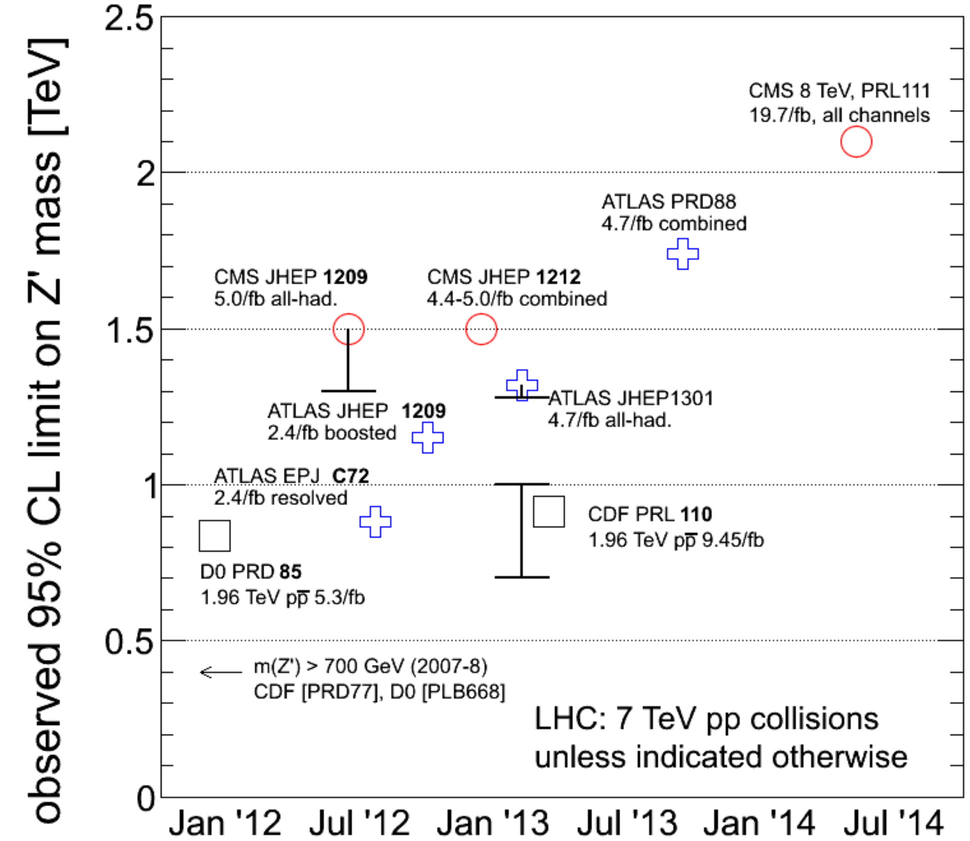
Must measure rate and properties of WbWb production. For a precise comparison of data and prediction more theory work is needed!

Who's afraid of boosted top quarks?



LHC data, likely $t\bar{t}$ (purity ~70%), m ~ 2.5 TeV

Searches: mZ' > 2.1 TeV (was 900 GeV)

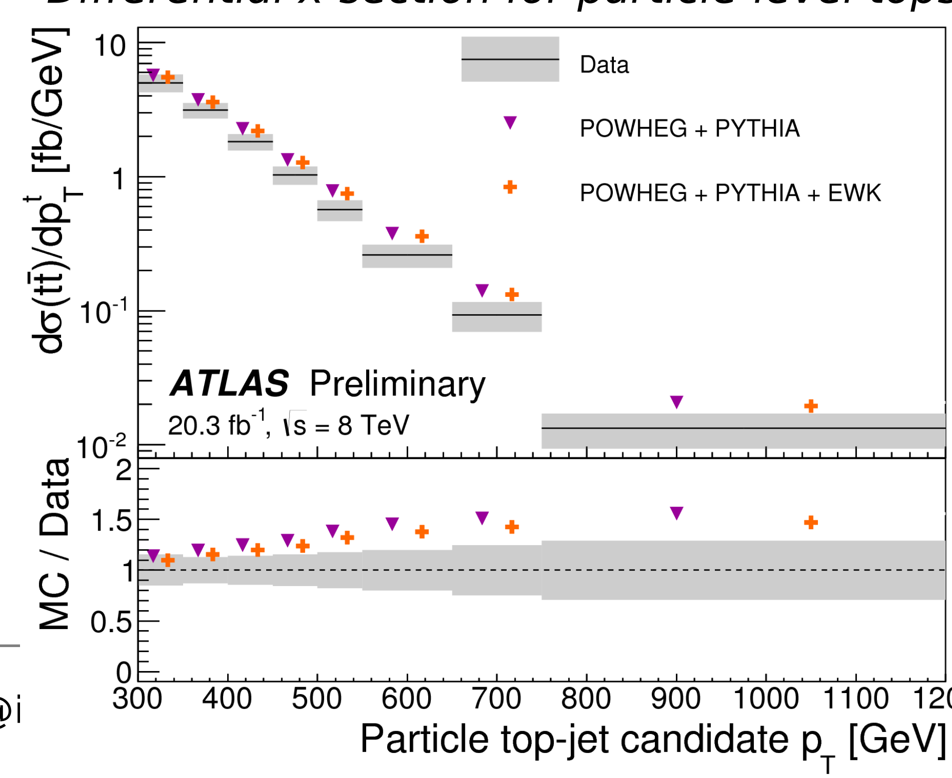


Boosted tops reconstructed as "fat jets" and tagged using jet substructure

Searches have attained a mass reach > 2 TeV
EPJC74 (2014) 2792

Fully corrected measurement up to p_T > 1 TeV
ATLAS-CONF-NOTE-2014-057

Differential x-section for particle-level tops



Boosted top at LC

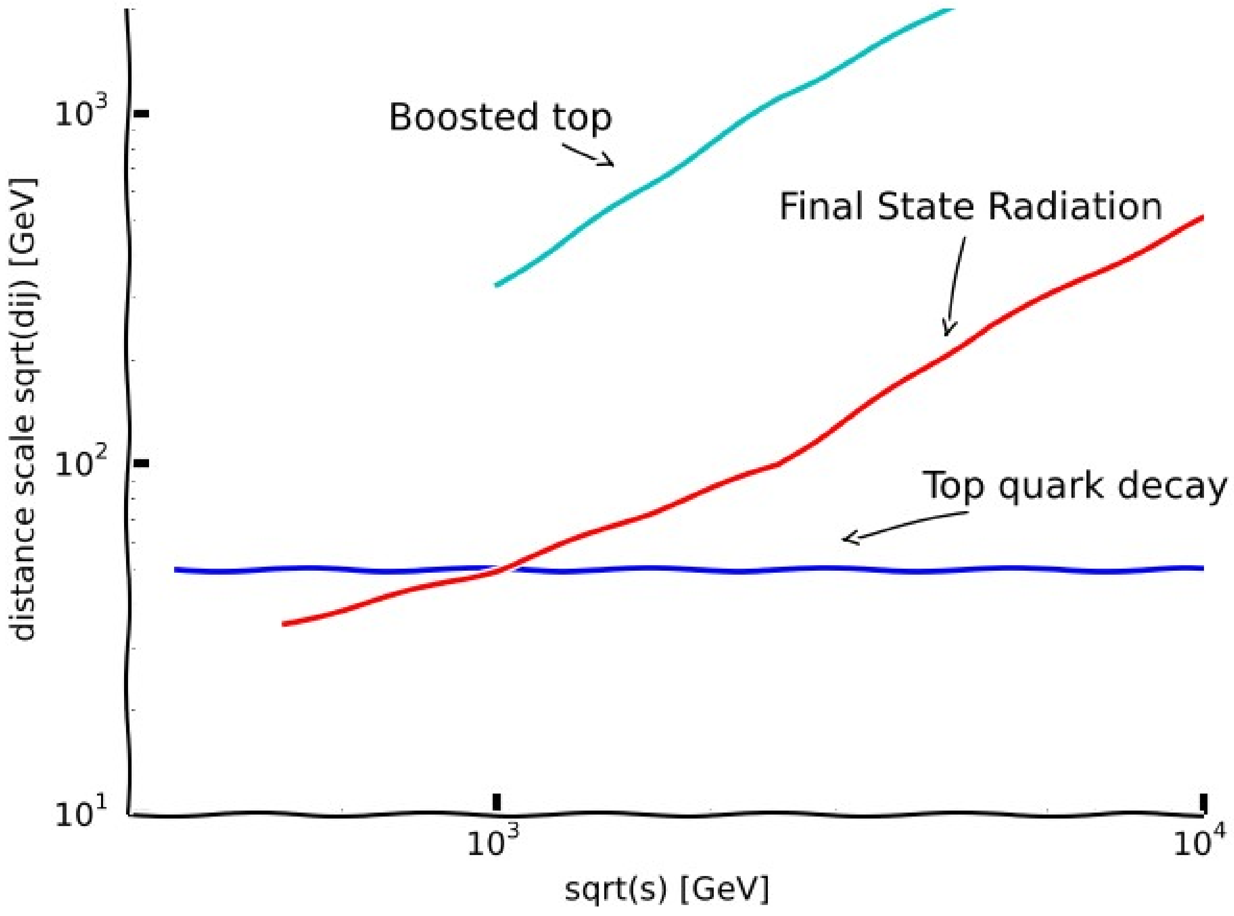
Increase in luminosity nearly compensates for drop in cross-section at large energy
500 GeV: 600 fb x 500/fb ~ 300.000 pairs
1 TeV: 200 fb x 1000/fb ~ 200.000 pairs

Selection: cross section is large compared to other 6-fermion processes:
$\sigma(tt) \approx 600$ fb at 500 GeV
W^+W^- and $q\bar{q}$ are easily reduced requiring jet multiplicity, b-jets...
(note: flavour tagging performance depends on b-jet energy)

N=6 exclusive clustering at low energy

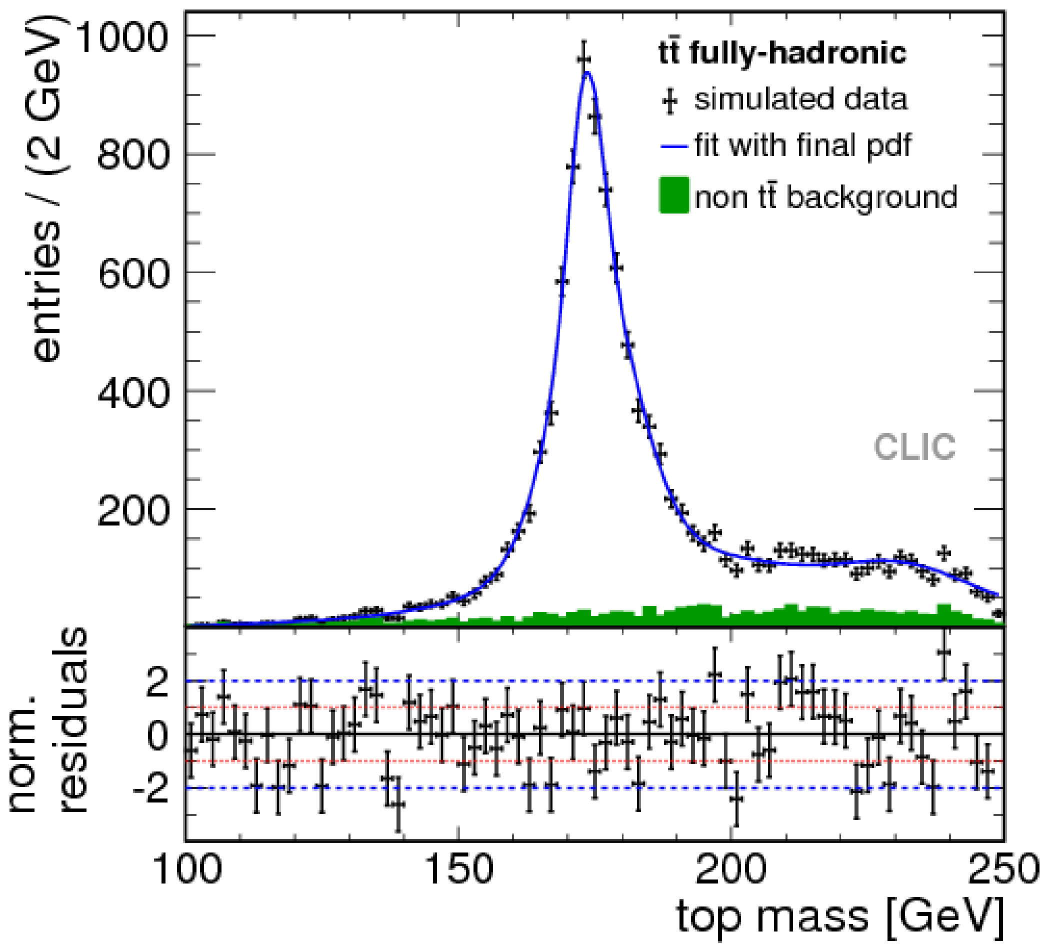
N=2 exclusive clustering at $\sqrt{s} > 1$ TeV

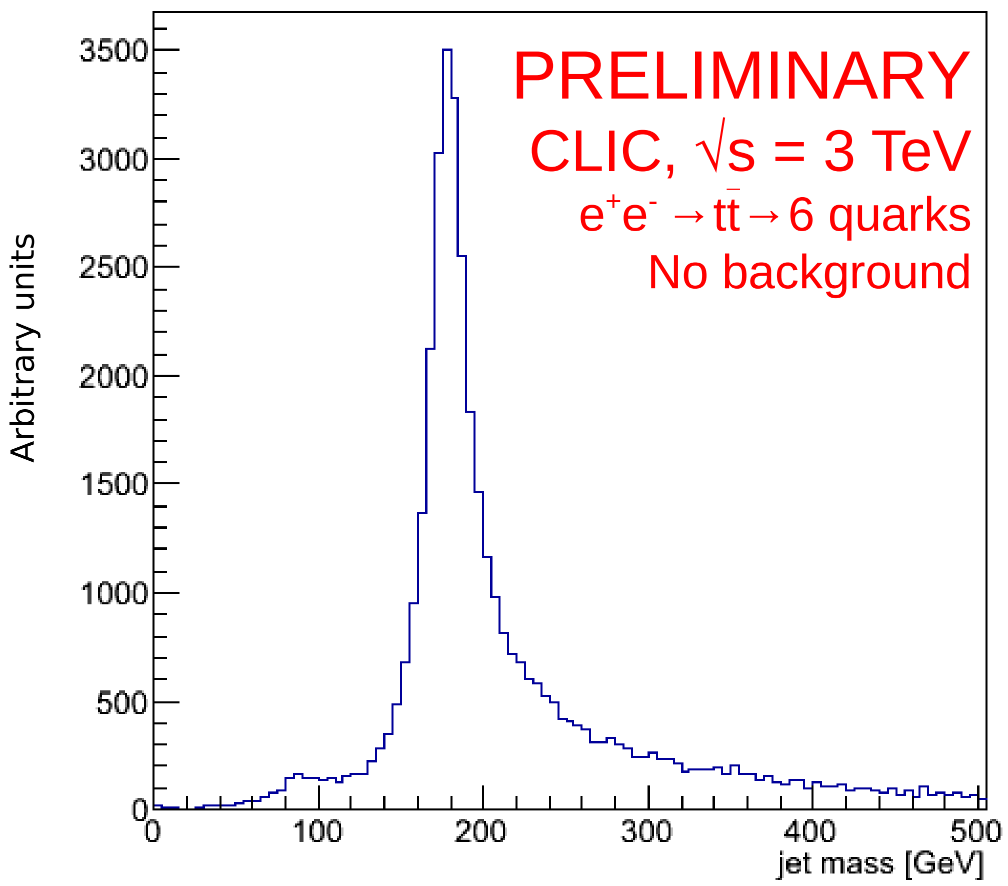
Radiation from top quarks threatens N=6 exclusive clustering at high energy, but N=2 clustering takes over right in time



"Evolution of average distance scales"

Top quark selection/reconstruction





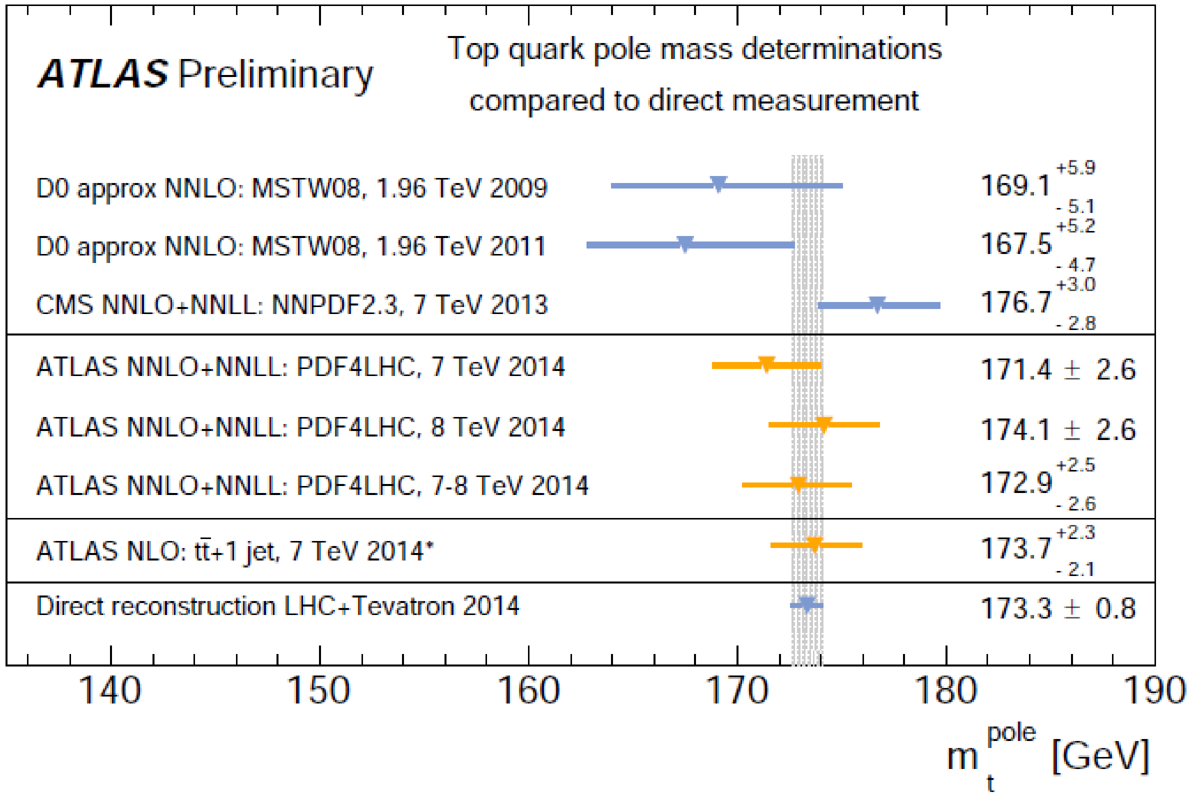
Top reconstruction is non-trivial at any center-of-mass energy

Low energy: challenging combinatorics
alleviated by kinematic fit

High energy: top jets → no combinatorics for s = 1 TeV and up!
must deal with background (jet grooming)

Top reconstruction at high energy may well be better than at low energy!

Top quark mass



LHC is taking top mass interpretation seriously!

LC mass extraction at threshold is considered the final verdict.

This measurement is tied to $\sqrt{s} = 2m_t$

Very hard to beat precision and rigour of interpretation in continuum.

Linear Collider alternatives to threshold scan:

- Direct measurement (Seidel et al.)

  (stat. precision ~80 MeV at $\sqrt{s}$ = 500 GeV)

- Extract pole/$\overline{MS}$ mass in continuum (Boronat, Fuster, in progress)

  (precision to be evaluated)

- Extraction from top jets (Mantry et al.)

  (rigorous SCET interpretation, precision unknown, $\sqrt{s}$ = 1 TeV)

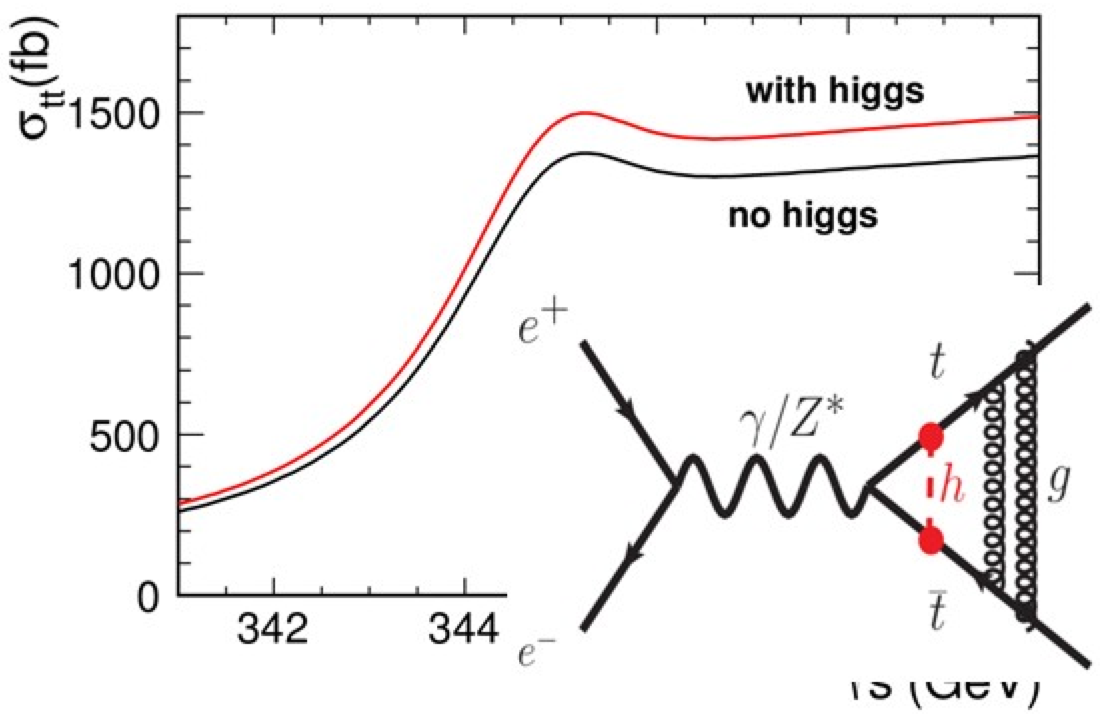
Explore alternatives, but don't give up on the threshold scan unless you have to

What else is there at √s ~ 350 GeV?

Electric dipole moment, from TESLA TDR:
If a light neutral Higgs boson (mh < 160 GeV) with undefined CP parity exits, its reduced scalar and pseudoscalar couplings to top quarks could be of order 1 which leads to CP-violating form factors that can be sizeable not too far away from the tt threshold. A few % at √s = 370 GeV,
W. Bernreuther, T. Schröder, T.N. Pham. Phys. Lett., B279:389, 1992.

h(125) can still have pseudo-scalar admixture, but the effect is expected to be smaller than the few % in TESLA times (W. Bernreuther, very preliminary)

Some studies claim top Yukawa coupling can be measured to a few % statistical Uncertainty...
(cf. 35% in Martinez & Miguel → significant theory error, precise extraction requires α_s to be known way better than current world average)

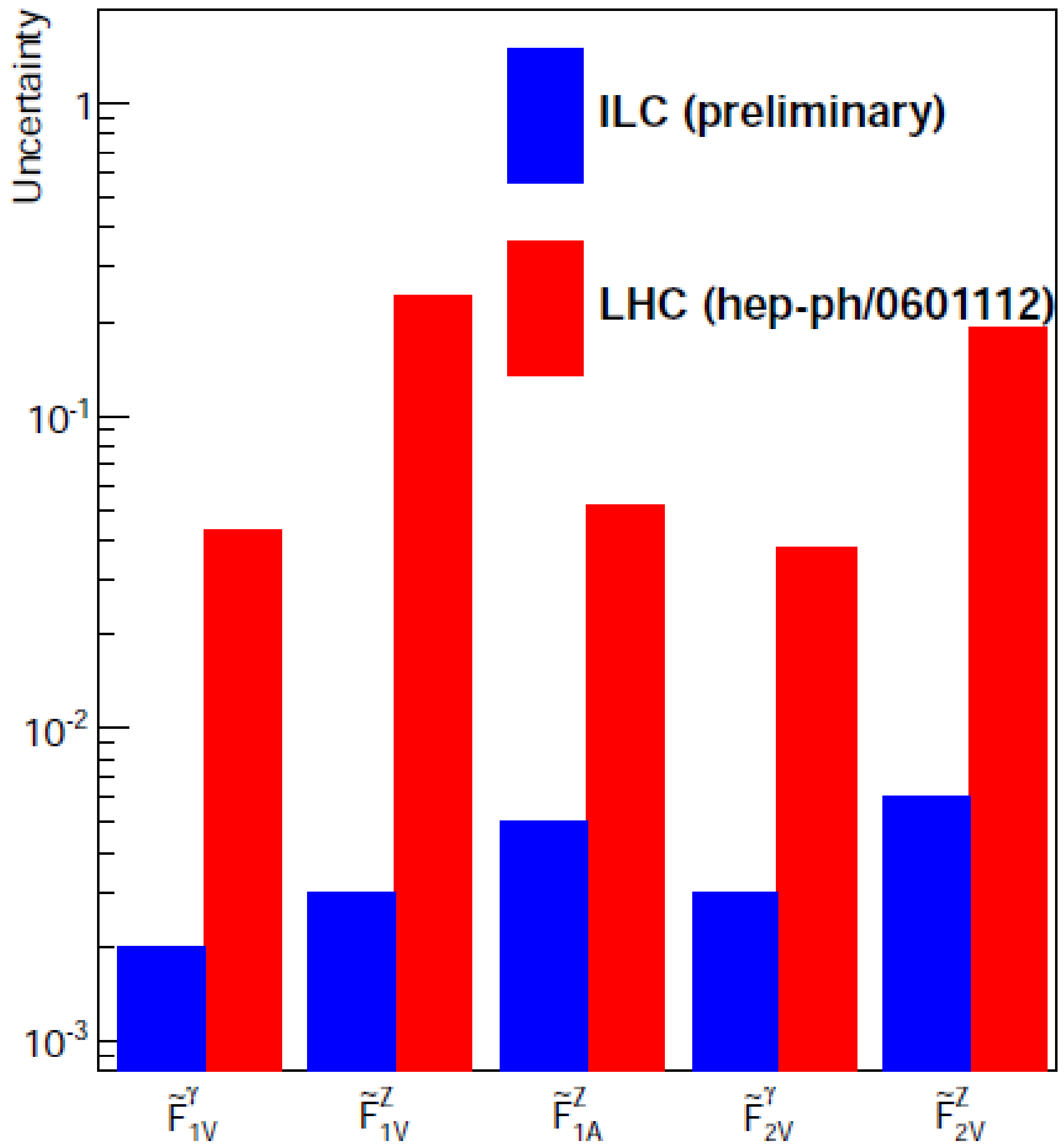


Top quark couplings

$$\left.\begin{matrix} \sigma(+) & A_{FB}(+) & \lambda_{hel}(+) & (+ = e_R^-) \\ \sigma(-) & A_{FB}(-) & \lambda_{hel}(-) & (- = e_L^-) \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F_{1V}^{\gamma} & * & F_{2V}^{\gamma} \\ F_{1V}^{Z} & F_{1A}^{Z} & F_{2V}^{Z} \end{matrix}\right\}$$

Measure 3 observables
for 2 beam polarizations:
- x-section
- FB asymmetry
- top polarization

Extract 5 form factors



Assumptions:

LHC: 14 TeV, 300/fb

LC: √s = 500 GeV, L = 500/fb

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

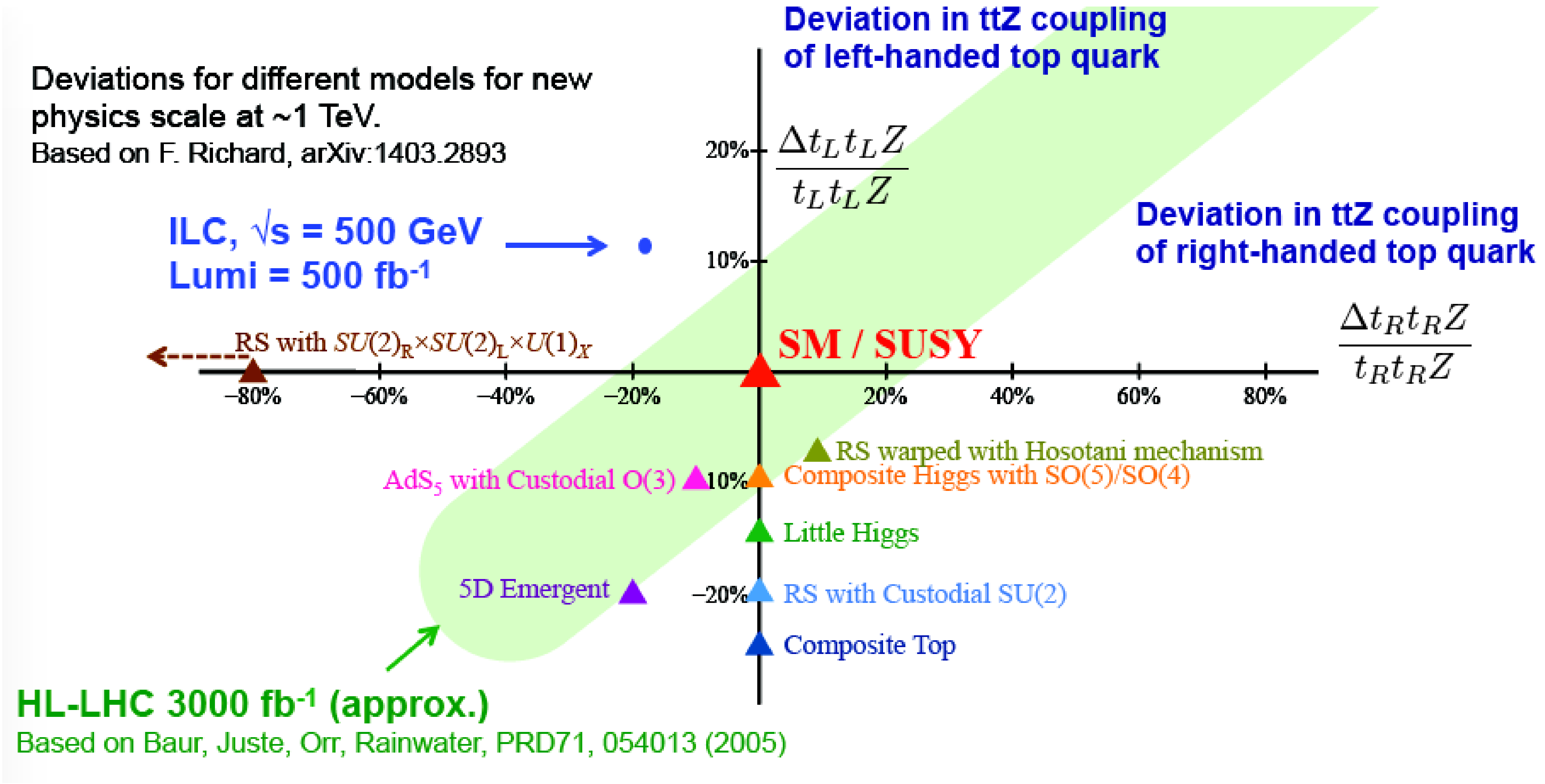
$\delta\sigma$ ~ 0.5% (stat. + lumi)

δA_{FB} ~ 2% (stat. + syst.)

$\Delta\lambda_{hel}$ ~ 4% (stat. + syst.)

Polarization needed to disentangle photon and Z-boson form factors! arXiv:1307.8102
Quantitative result for impact of positron polarization can be obtained quickly

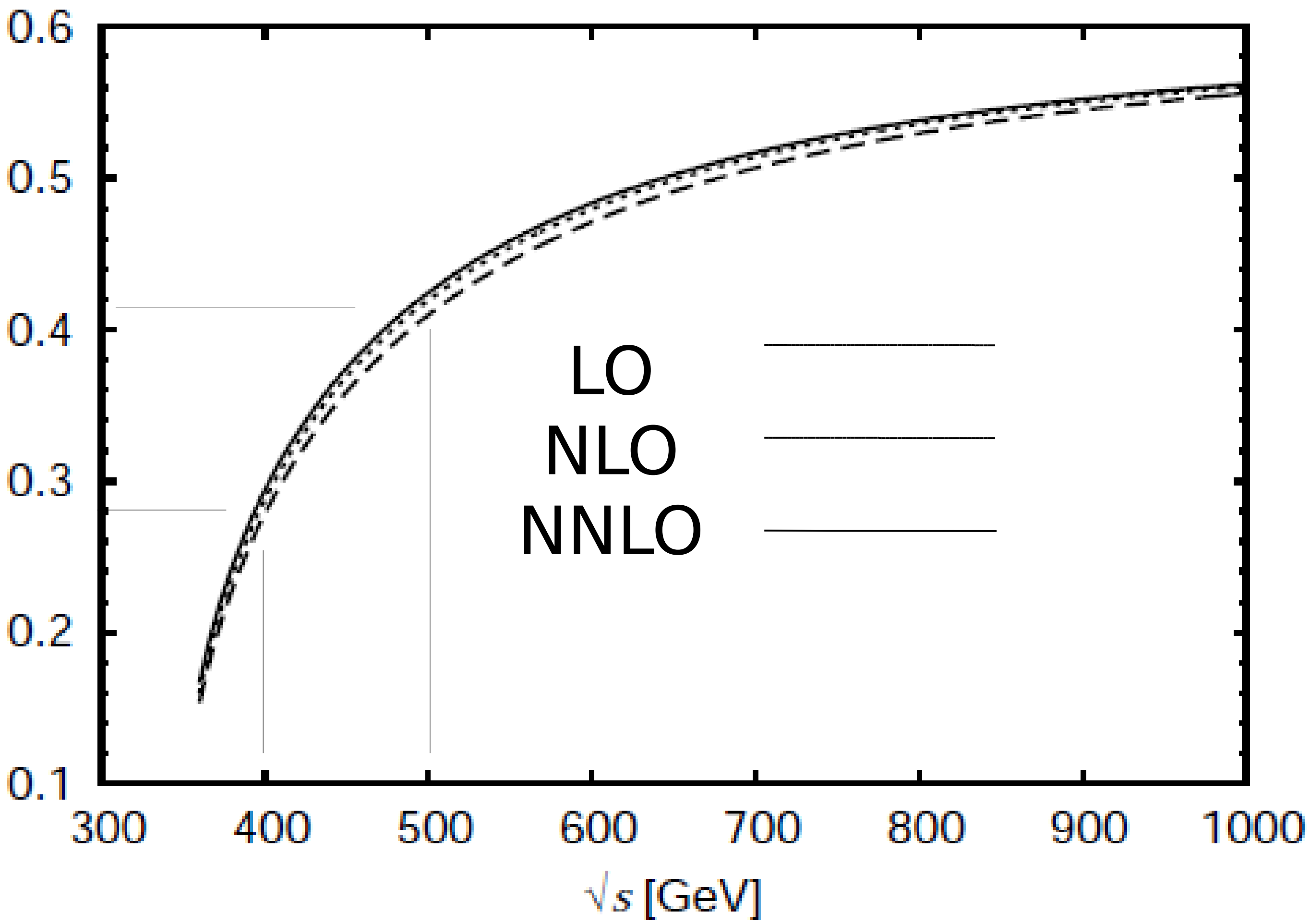
New physics sensitivity



Quantify new physics reach of a precise top couplings measurement

A_{FB} versus √s

What about A_{FB} ?



Order α_s^2 results in Bernreuther, Bonciani et al., hep-ph/0604031

"… we conclude that the 2-parton QCD corrections to the lowest order asymmetry are moderate to small for √s > 400 GeV"

Scale variations yield <1% error @ NNLO

One-loop EW corrections have a large effect: 20% on A_{FB}, at 500 GeV.

Two-loop contribution seems small

If we want to measure A_{FB} precisely we have to move away from threshold.

A 500 GeV LC has a twice higher asymmetry than at 400 GeV.
Precision vs. √s to be evaluated.

Sensitivity to BSM physics

Assuming 1.5 % deviations on A_{FB} measurement can be observed (J. Trenado, M.V.):

ILC500 GeV: sensitive for Z'_{SSM} mass up to ~3 TeV

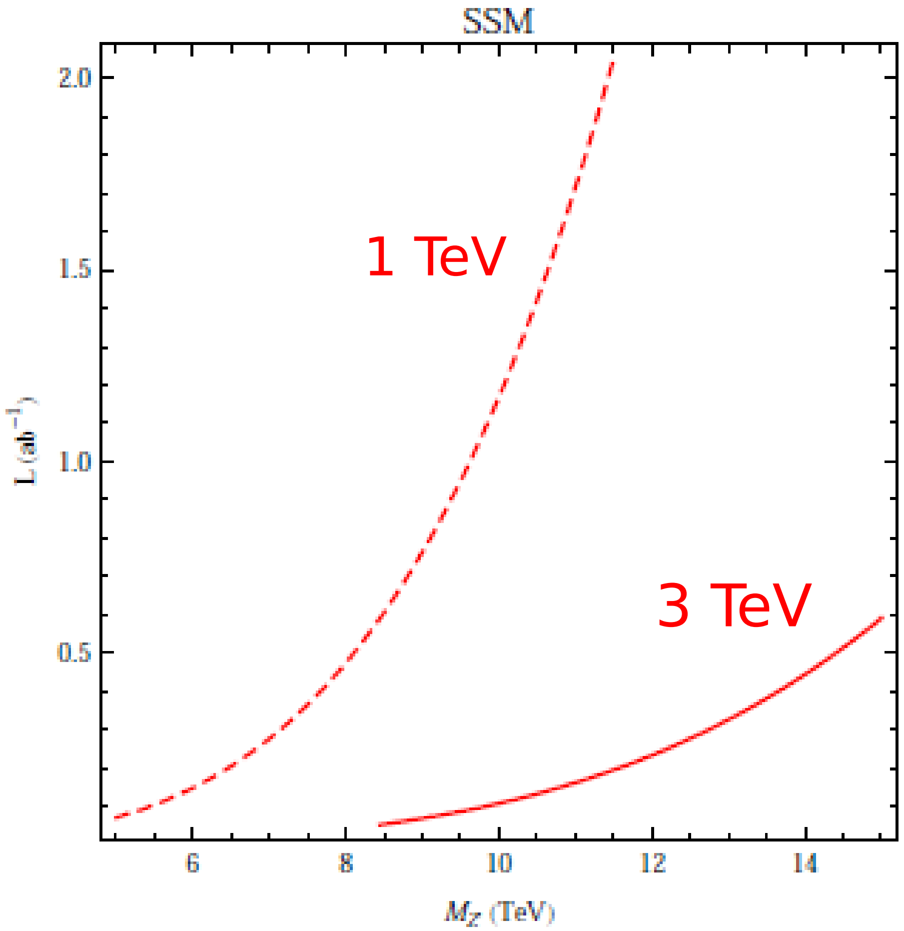
Z' mass	SM	1 TeV	2 TeV	3 TeV	4 TeV	5 TeV
A_{FB}^{tt}	0.41 ± 0.01	0.289	0.382	0.397	0.401	0.407

ILC1 TeV : mass reach for Z'_{SSM} > 5 TeV

Z' mass	SM	1 TeV	2 TeV	3 TeV	4 TeV	5 TeV
A_{FB}^{tt}	0.554	0.289	0.434	0.513	0.532	0.537

Luminosity required to see signals of massive Z' *Assumptions: $\delta\sigma/\sigma = 0.7\%$, $\delta A_{FB}/A_{FB} = 1.5\%$, $\delta A_{LR}/A_{LR} = 2\%$*

F. Corradeschi, LCWS10, arXiv:1202.0660 and M. Battaglia, LCWS11



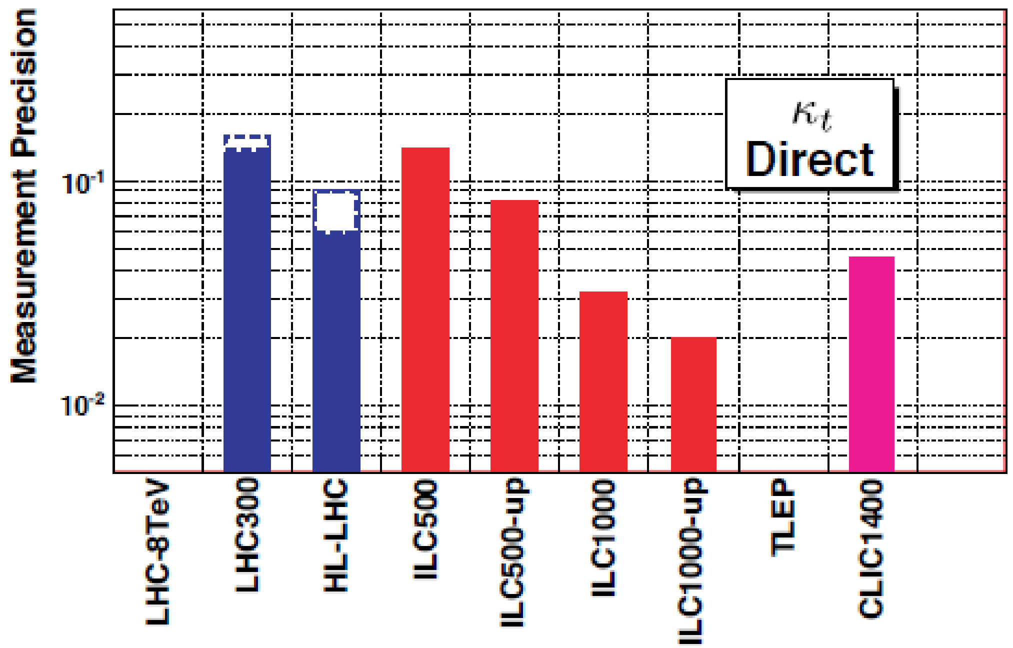
The closer we get [to the new physics scale], the more we feel [its indirect effects]

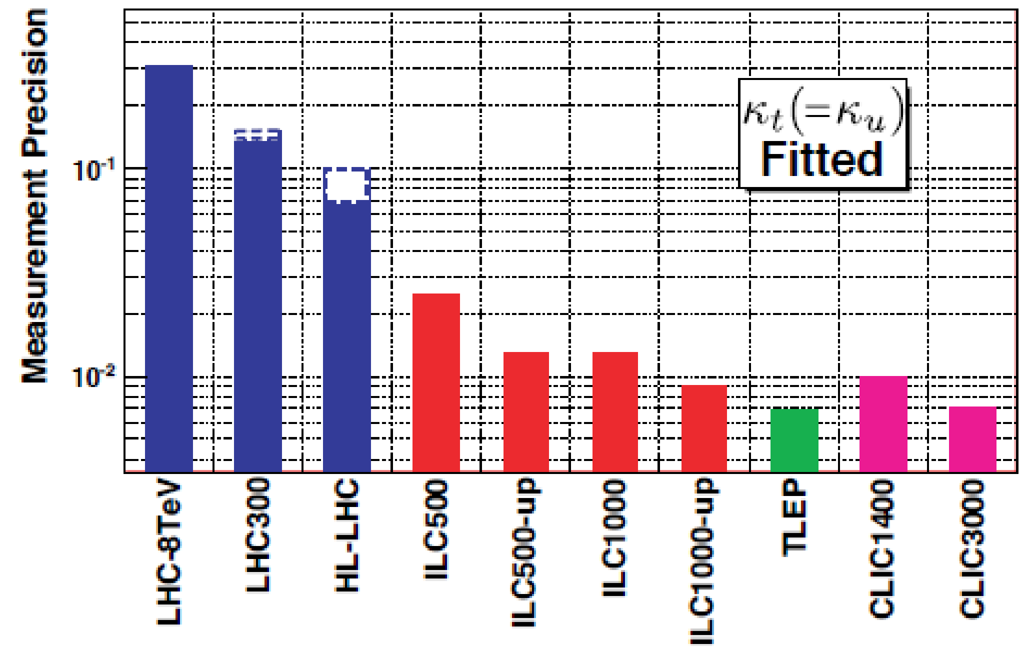
Made explicit in effective operator analysis → constant form factors replaced by c/Λ^2, where Λ is new physics scale

J.A. Aguilar argues for measurements at several energies, arXiv:1206.1033

$t\bar{t}H$

Snowmass Higgs report



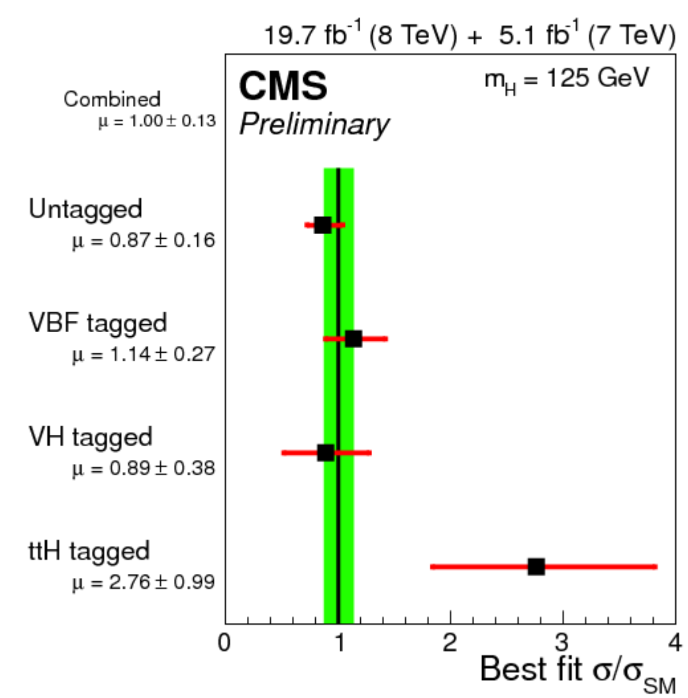


Associated production of a Higgs boson with a top quark pair is a direct probe of the top Yukawa coupling

Fit extracts more precise, but less direct, values from $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ (LHC) and $H \rightarrow c\bar{c}$ (LC)

LHC direct $t\bar{t}H$ prospects have large uncertainty.

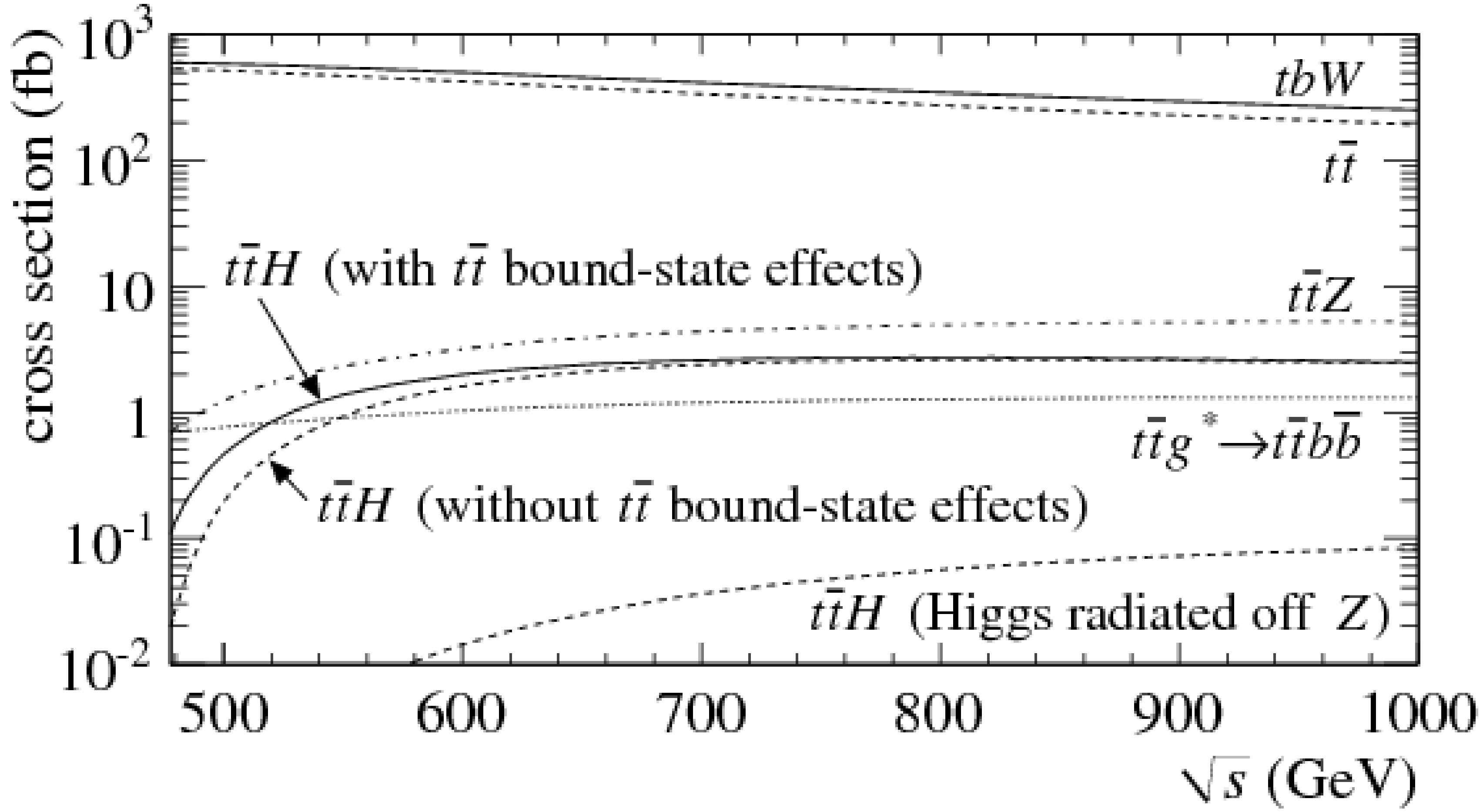
Be ready to react to the unexpected.



$t\bar{t}H$

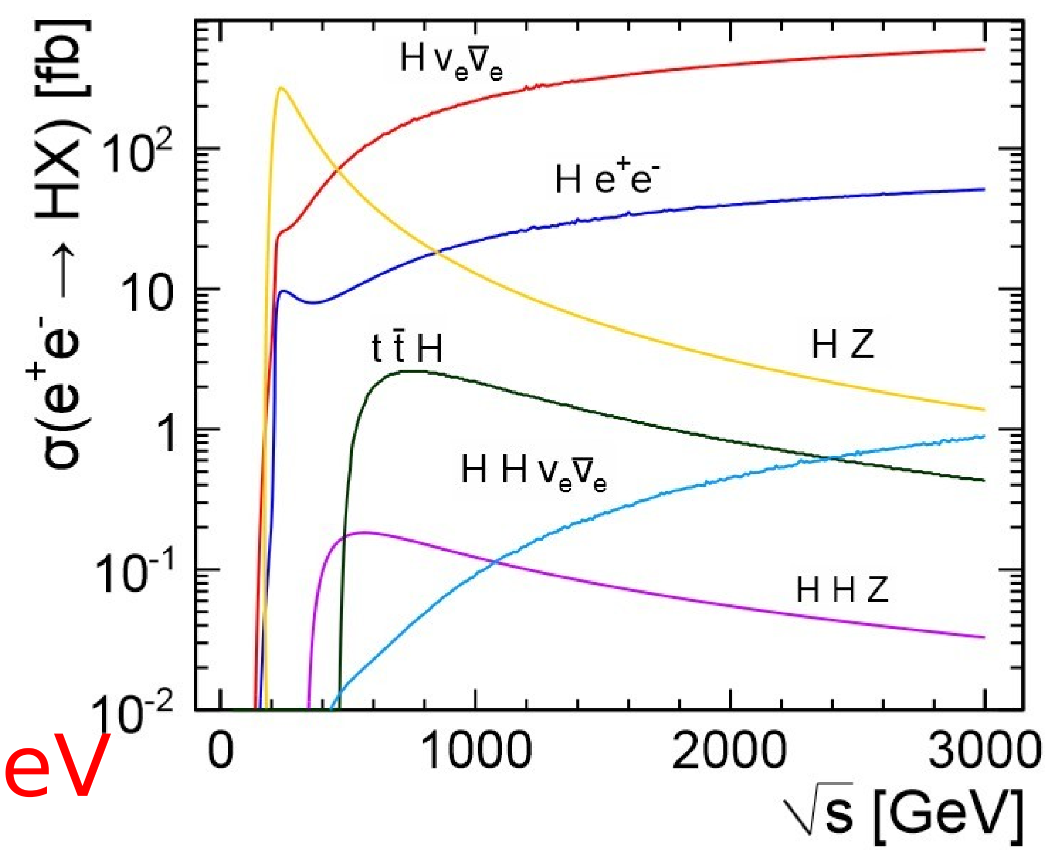
Cross-section:
550 is better than 500!

Gentle rise to 700 GeV



Beyond 750 GeV x-sec drops:
- factor 2 at √s = 1.6 TeV
- nearly one order at 3 TeV

loss with larger instantaneous luminosity



Consider range 550 < √s < 1600 GeV

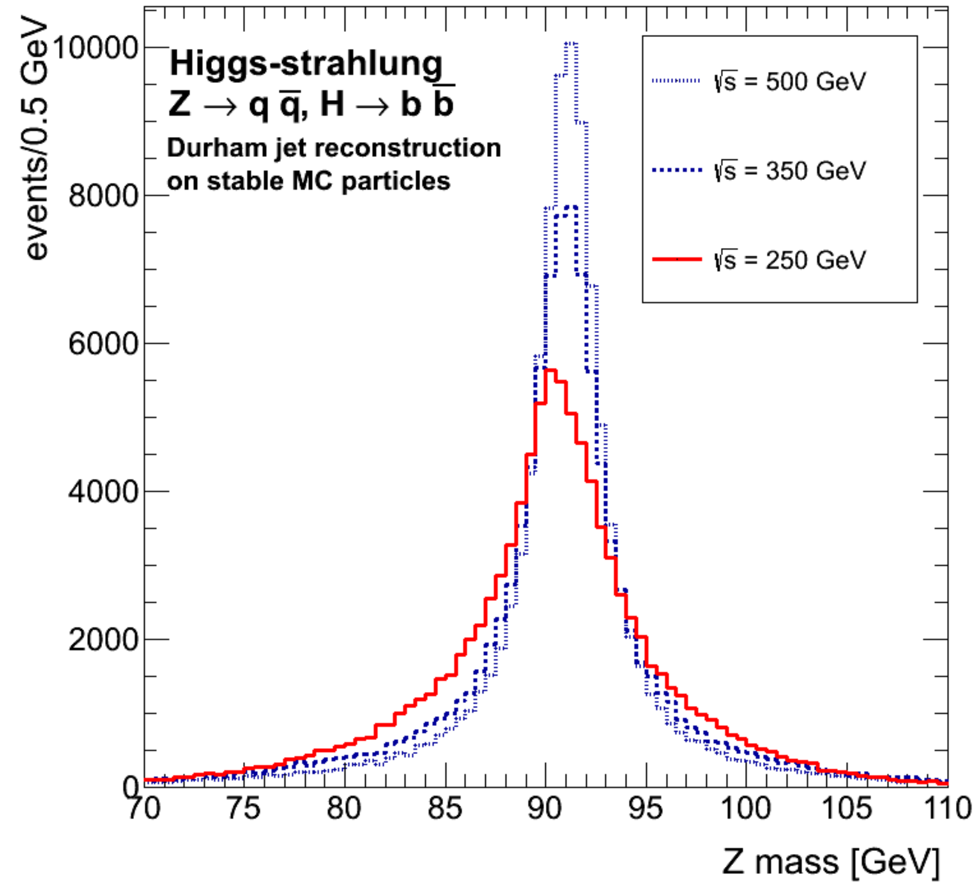
Jet reconstruction

Jets are better defined at higher energy (algorithmic confusion decreases)

Energy is measured best at low energy (dE/E ~ 3%)

ttH jet reconstruction strategies:
- fully resolved H → bb: 6 or 8 jets (l+jets, fully hadronic)
- half-boosted: 4 W-jets, two b-jets, one Higgs jet
  (H → WW, Junping Tian)
- fully boosted: 2 top jets, 1 Higgs jet

All of these work to some extent, none of them are perfect



From published studies:

Yonamine et al., Measuring the top Yukawa at the ILC at √s = 500 GeV, PRD84
  1 ab^{-1} → 6j+l, 8j → S/B~0.6+0.3, significance = 5.2σ → δy ~ 10%

Price et al., Full simulation of the top Yukawa coupling at the ILC at √s = 1 TeV, arXiv:1409.7157
  1 ab^{-1} → 6j+l, 8j → S/B~0.4 + 0.3, significance = 7.5+10 → δy ~ 4%

Study ongoing for 1.4 TeV, Ph. Roloff (opening plenary), S. Redford (Higgs session) δy ~ 4.5%

Summary

Top quark mass and $t\bar{t}Z$ and $t\bar{t}\gamma$ couplings measurement are pillars of the LC case

$$\delta m_t^{MS} < 100\ MeV\ ,\ \delta F_{1V}^{\gamma,Z}\ ,\delta F_{1A}^{\gamma,Z} < 1\,\%$$

One real “sweet spot” → top quark pair threshold at 350 GeV offers unique opportunities (mass, influence of the Higgs boson)

Coupling measurement can be performed nearly anywhere in the continuum; achieves best new physics reach at higher energy

Polarization is needed → exact impact of different scenarios to be evaluated

Some boost is needed for A_{FB} → evaluate precision at 380, 400, 420 GeV

Measurement of top Yukawa in ttH requires at least 550 GeV; sensitivity vs √s exhibits a broad maximum

exact position is uncertain, likely ~1 TeV, result not competitive with fit → wait for 1.4 TeV run?

To be taken into account more consistently across all energies:

theory uncertainties, single top strategy