❸ Top-quark-physics

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- Measurement of the top-mass
- Top-quark couplings
- Top-Higgs Yukawa coupling → Higgs section
- Conclusions

Introduction

- The top quark is the heaviest fermion ($m_{\mathrm{t}} \approx 175\,\mathrm{GeV} \sim v$)
- In the SM it is just the isospin partner of the b-quark
- however in some models it plays a special role in electroweak symmetry breaking

➧ it is very important to study the top properties

- since $m_{\mathrm{t}}^2 \gg m_{\mathrm{W}}^2$ the top width is very large

$$\Gamma_t \approx \frac{G_{\mathrm{F}} m_{\mathrm{t}}^3}{8\sqrt{2}\pi} \approx 1.7\,\mathrm{GeV} \gg \lambda_{QCD} \;\Rightarrow$$

  – there exist no toponium resonances at threshold
  – the top decays before it fragments
    $\Rightarrow$ the top-polarization gets preserved to the decay, like the τ at LEP

LHC:

- $\sigma(t\bar{t}) \sim 1\,\mathrm{nb}$ $\Rightarrow$ huge data samples should allow very precise studies of top decays, especially rare decays
- $t\bar{t}$ production by strong interaction $\Rightarrow$ no interesting information on $t\bar{t}Z$ coupling
- $t\bar{t}$ production in continuum $\Rightarrow$ no threshold scan possible

LC:

- $\sigma(t\bar{t}) \sim 1\,\mathrm{pb}$ $\Rightarrow$ $\sim 10^5$ $t\bar{t}$ events allow for precise studies
- $t\bar{t}$ production via γ, Z exchange $\Rightarrow$ $t\bar{t}Z$ couplings can be measured
- $\sqrt{s}$ can be adjusted at will $\Rightarrow$ threshold scan possible

Measurement of the top-mass

Why do we want to know the top-mass as accurate as possible?

- a future theory of flavor hopefully predicts fermion masses or mass/ratios
  $\rightarrow$ The mass of the heaviest quark should be known as close as possible to the precision of the τ-mass
- in precision tests of the SM m_{t} enters quadratically:
  - $\Delta m_{\mathrm{W}}/\Delta m_{\mathrm{t}} = 0.006$
    ultimately: $\Delta m_{\mathrm{W}} = 6\,\mathrm{MeV}$
  - $\Delta \sin^2\theta^{\ell}_{\mathrm{eff}}/\Delta m_{\mathrm{t}} = 0.00003/\,\mathrm{GeV}$
    ultimately: $\Delta \sin^2\theta^{\ell}_{\mathrm{eff}} = 0.00002$

  $\Rightarrow$ need $\Delta m_{\mathrm{t}} < 1\,\mathrm{GeV}$
- In SUSY models radiative corrections to light Higgs (h) mass: $\Delta m_h/\Delta m_{\mathrm{t}} \approx 1$
  $\Rightarrow$ aim for $\Delta m_{\mathrm{t}} \approx \Delta m_h \approx 50\,\mathrm{MeV}$

What is the top mass?

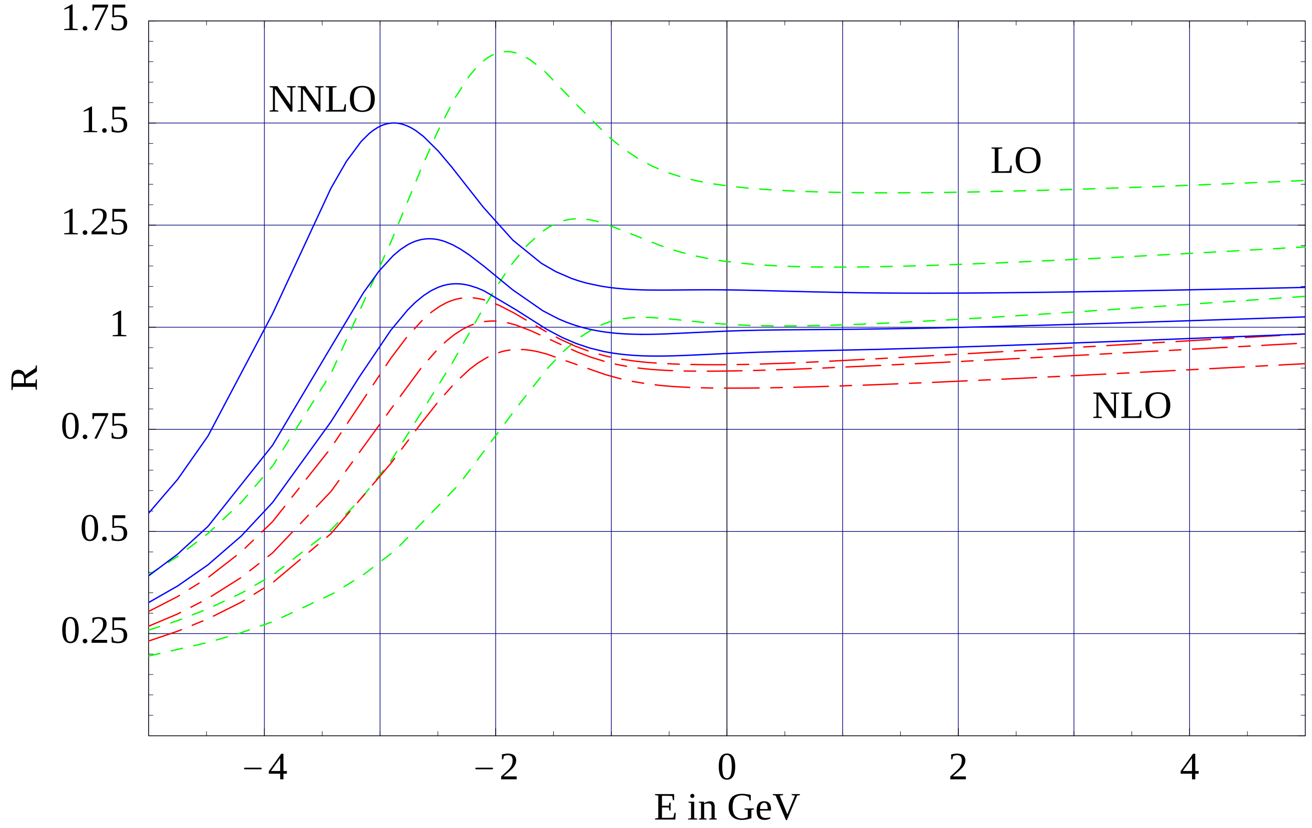
- Quarks are not free particles $\Rightarrow$ their mass is not unambiguously defined
- pole mass: pole of propagator, natural definition if top-decays are reconstructed
- $\overline{\text{MS}}$-mass: running mass in QCD (like coupling constant), needed in radiative corrections
- conversion pole mass $\longrightarrow$ $\overline{\text{MS}}$-mass has theoretical uncertainties of $\mathcal{O}(1\,\text{GeV})$
- limit of all top-reconstruction methods
- additional ambiguity of same order for reconstruction methods since only color neutral objects can be reconstructed
- threshold scans: no natural mass definition, can do calculations in several ones

Most promising method: threshold scan

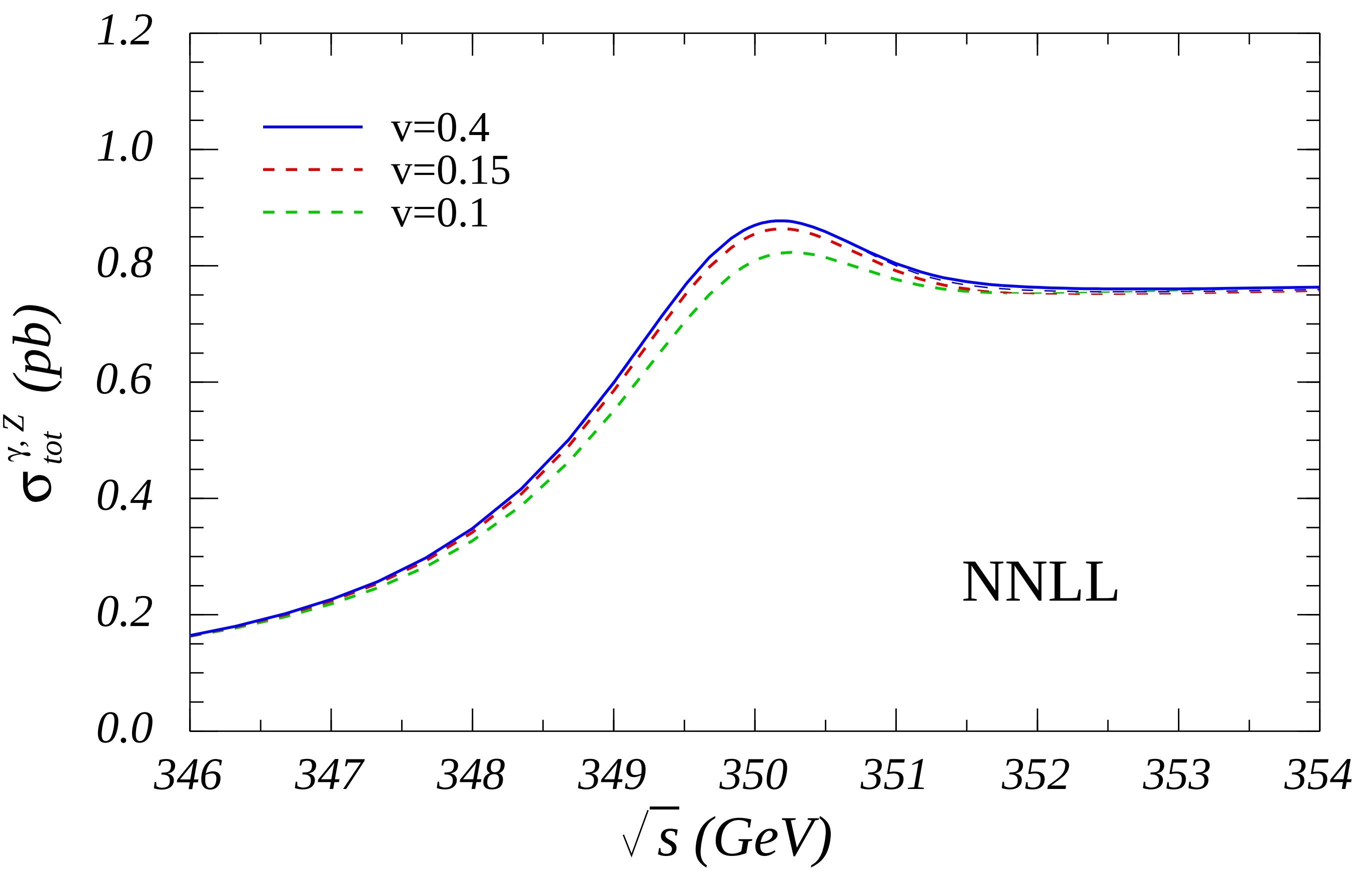
- Due to large top mass and the corresponding short lifetime no toponium resonances are existing any more
- However still large corrections due to Coulomb-like QCD potential:

$$E_{\mathrm{tot}}(r) = 2m_{\mathrm{t}} + V(r)$$
$$V(r) \propto \frac{\alpha_s(1/r)}{r}$$

- QCD corrections known to 3rd order (pole mass)



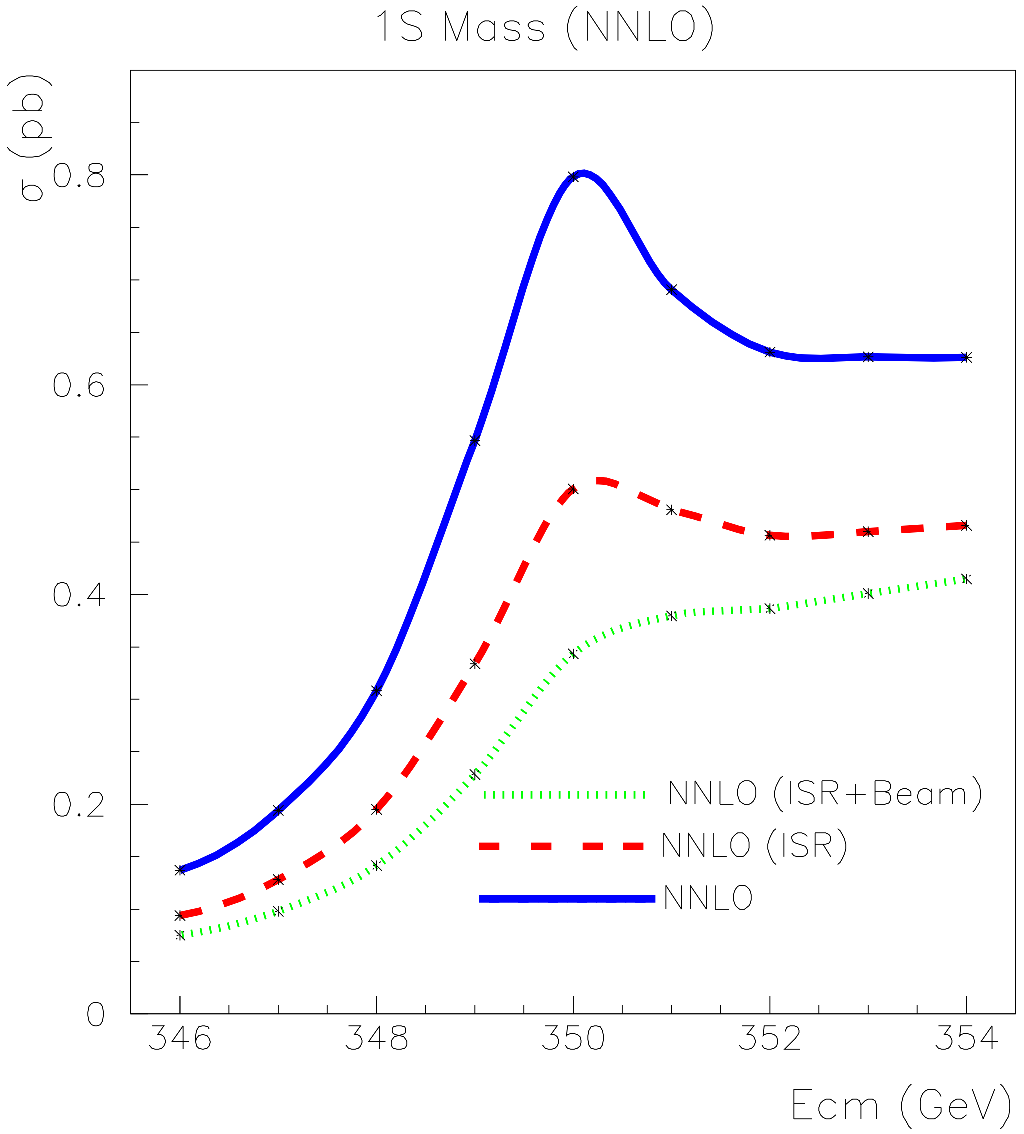
- large scale dependence and huge shift of the peak from order to order using pole mass
- theoretical error on m_t unclear
- in addition the same uncertainty appears going from m_pole to $m_{\overline{\mathrm{MS}}}$
- both problems can be solved by redefining the mass, shifting part of the potential to the mass definition



(v=top velocity parameter, should be > 0.15)

Threshold cross section now very well under control

- In the QCD-corrected cross section some remnant of the 1S peak remains visible



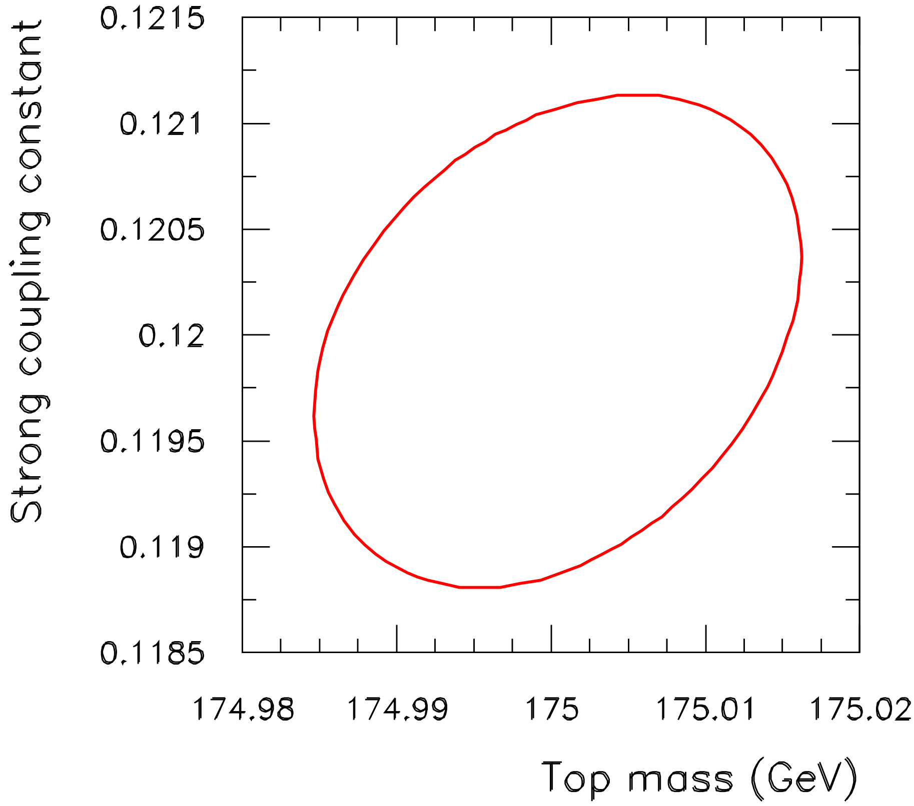
- This peak is completely washed out by ISR, beamstrahlung and beamenergy-spread
- However uncertainties in beam parameters do not effect precision of m_t measurement

Additional information:

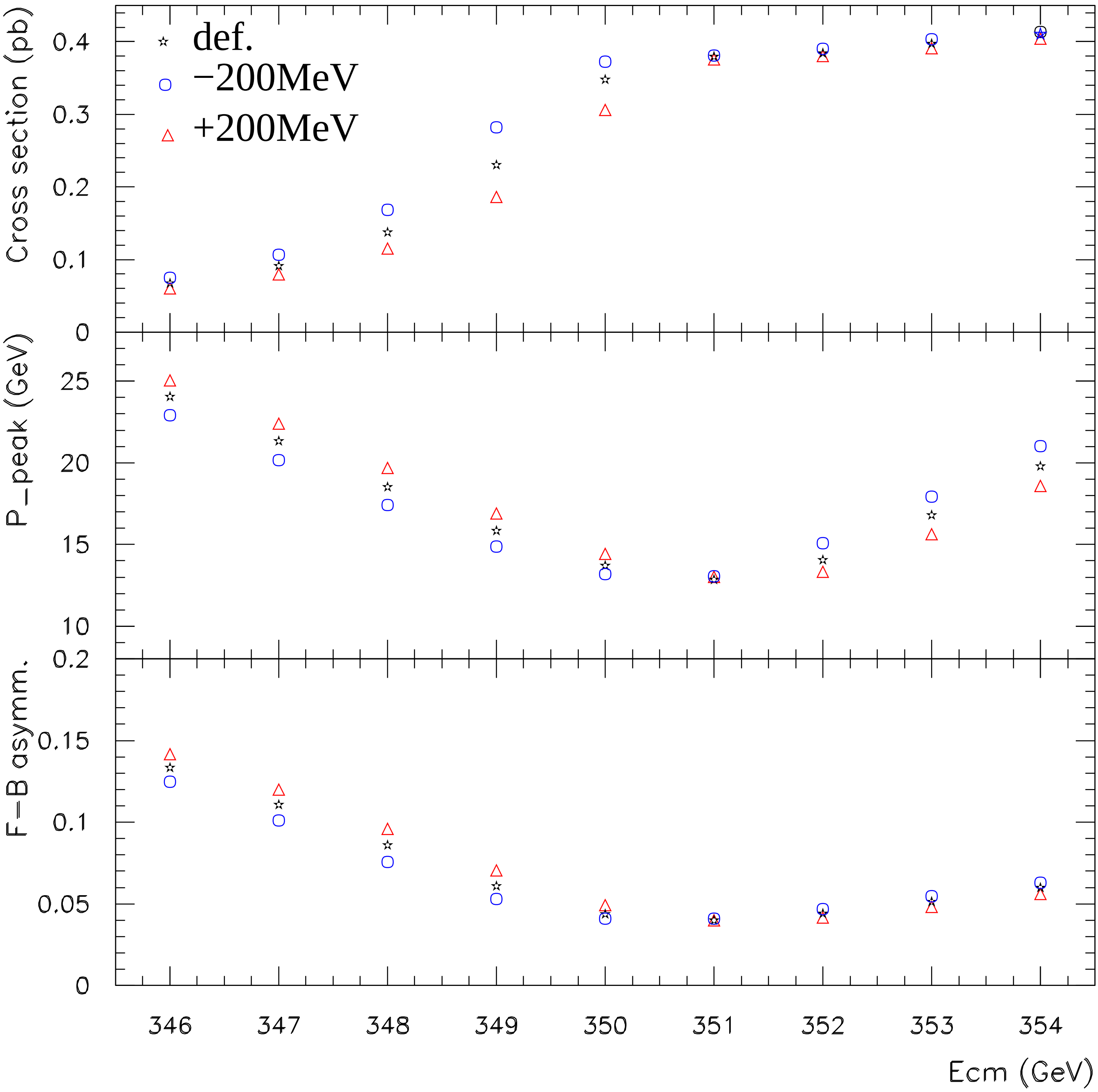
- absolute value of the $t\bar{t}$ cross section: sensitive to α_s, Γ_t
- Momentum distribution of top quarks near threshold sensitive to $m_{\rm t}$
- Forward backward asymmetry: sensitive to Γ_t
- Can try multi-parameter fits

Results (10 scan points with $\mathcal{L} = 30\,\mathrm{fb}^{-1}$ each):

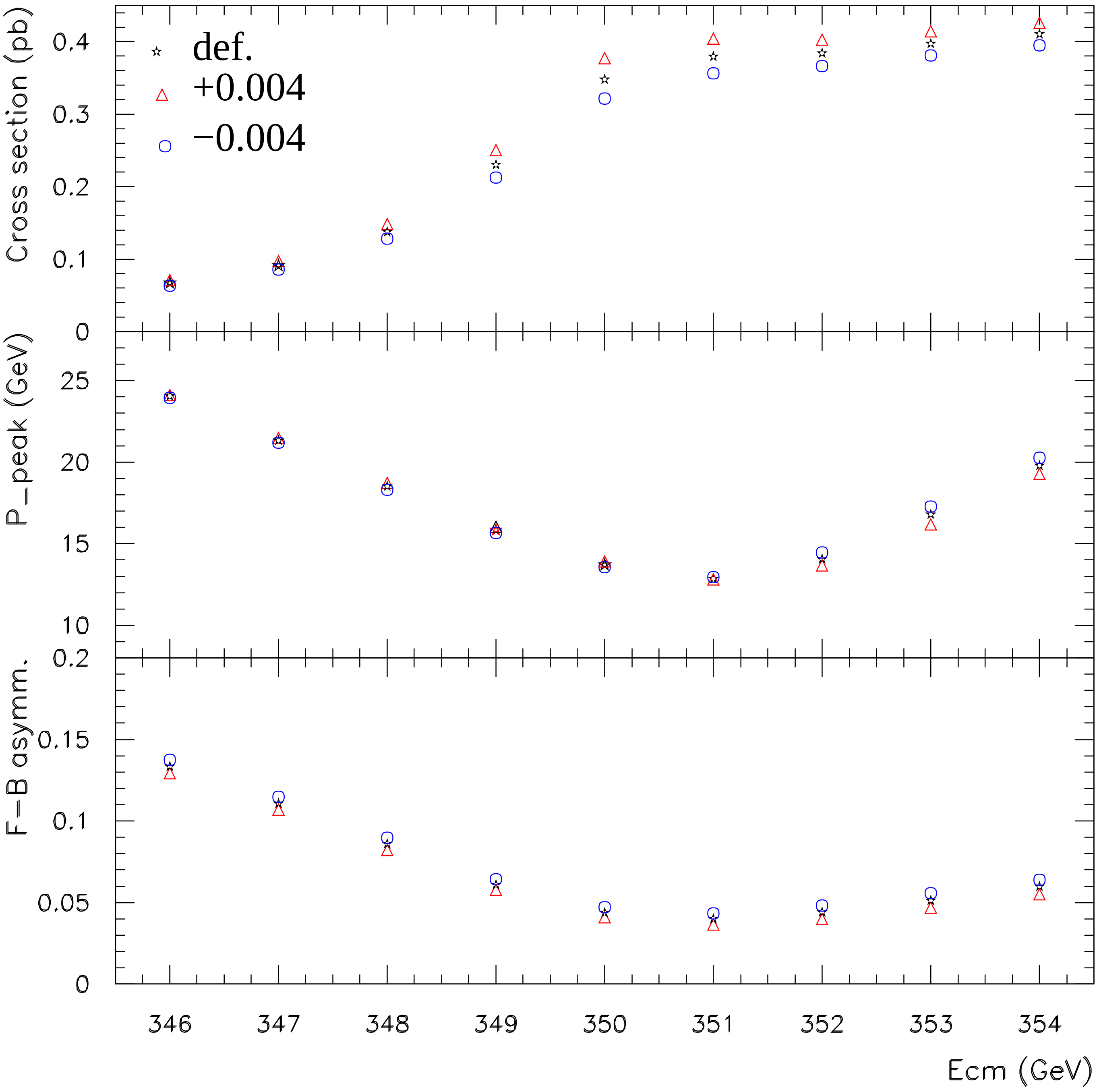
$$\begin{aligned} \Delta m_{\rm t} &= 34\,\mathrm{MeV} \\ \Delta\Gamma_{\rm t} &= 42\,\mathrm{MeV} \\ \Delta\alpha_s &= 0.0023 \end{aligned}$$



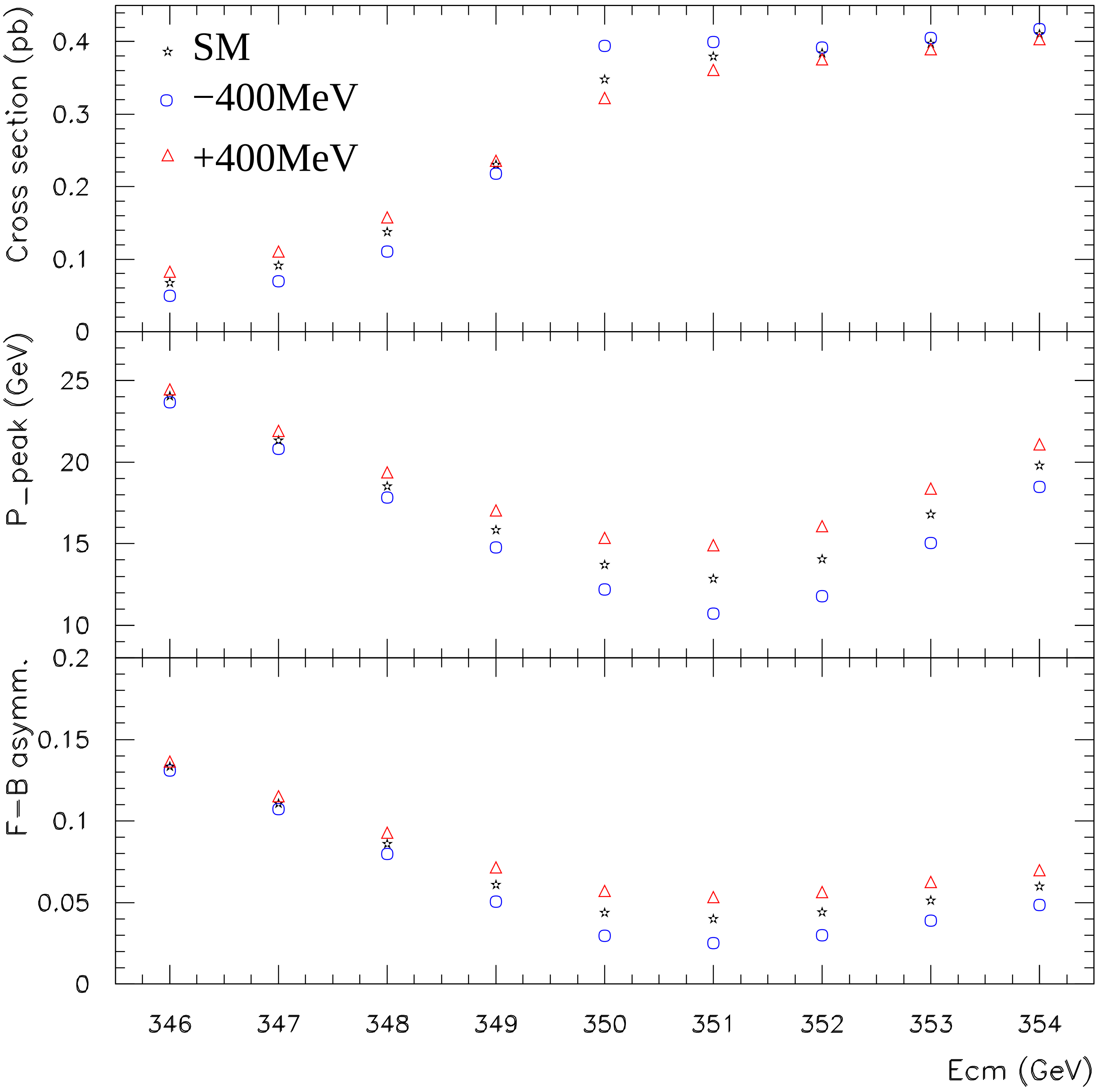
Sensitivity to m_t



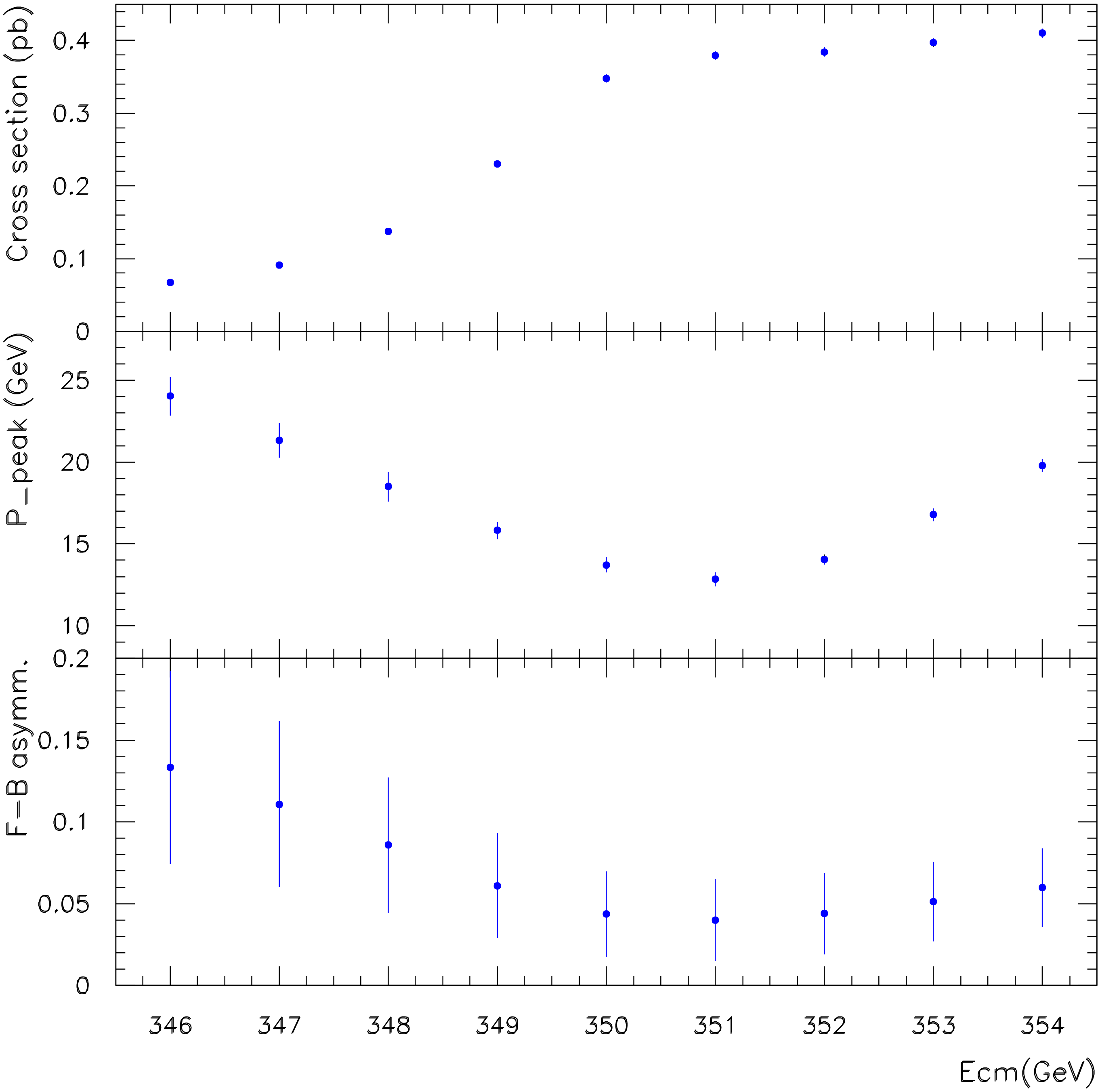
Sensitivity to α_s



Sensitivity to Γ_t



Expected experimental scan results



One step further:

The absolute value of the cross section is also sensitive to the Ht Yukawa coupling (y_t)

$\Rightarrow$ can take α_s from other measurements and fit y_t instead

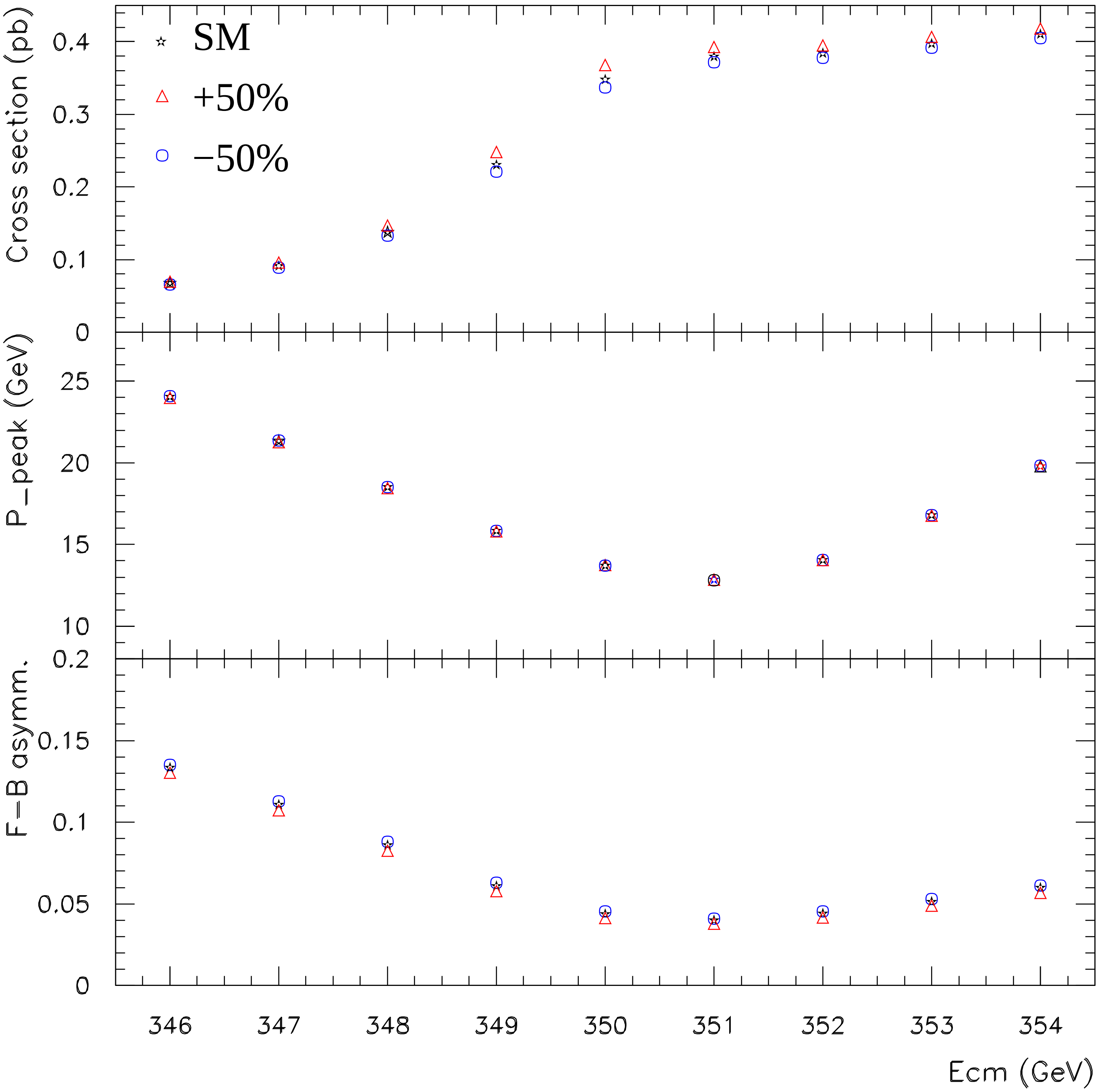
Result:

$$\frac{\Delta y_t}{y_t} = {}^{+0.35}_{-0.65}$$

for a 3-parameter fit

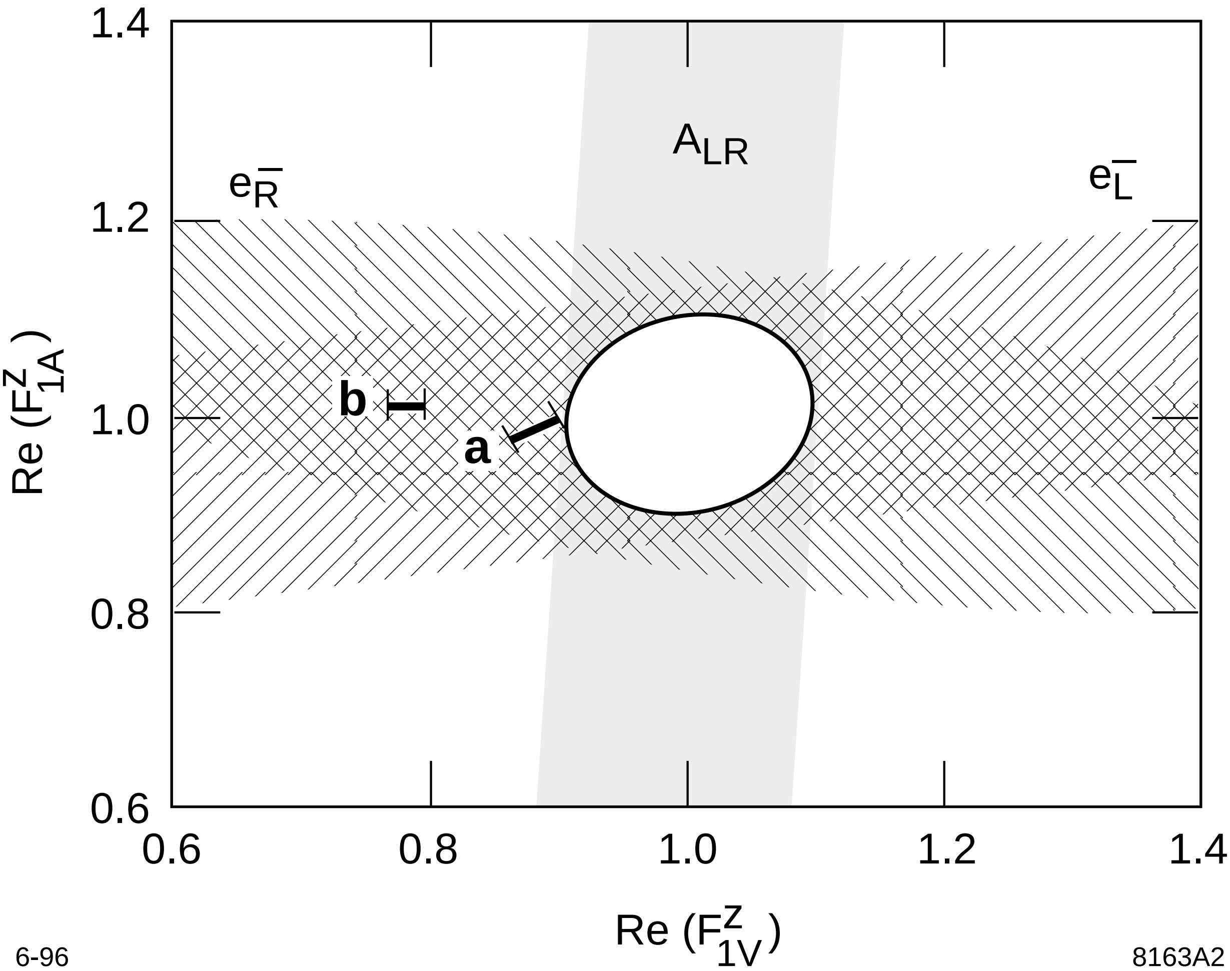
(LHC: $\Delta m_{\mathrm{t}} \approx \pm 1.5\,\mathrm{GeV}$)

Sensitivity to y_t



$t\bar{t}Z$ couplings

- the top-couplings to the Z can be obtained from $t\bar{t}$-production in the continuum
- due to the interference between Z and γ exchange the total cross section and the left-right asymmetry are sensitive to the Z-couplings
- a very conservative analysis at $\sqrt{s} = 400\,\text{GeV}$ gives 90% c.l. limits on the 10% level for anomalous couplings



- this precision is sensitive to some ETC-models

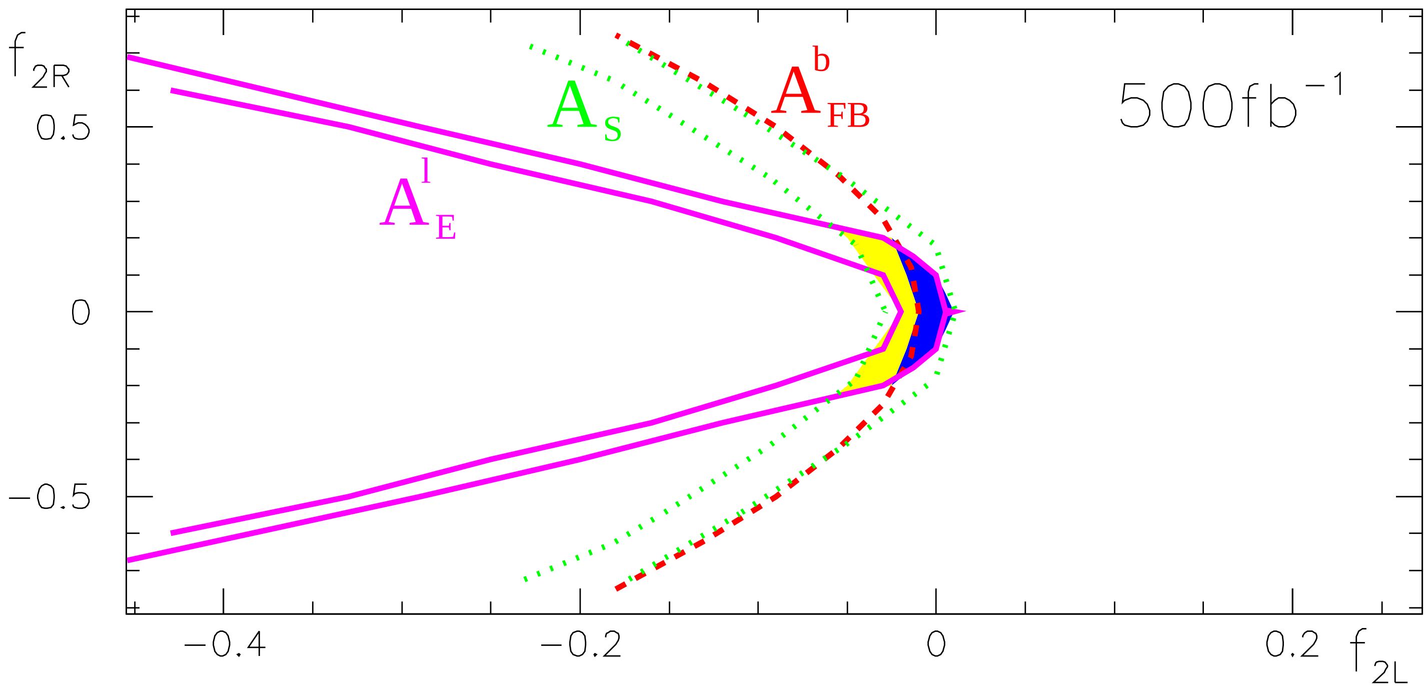
Wtb couplings

- effective Lagrangian:

$$\mathcal{L} = \frac{g}{\sqrt{2}}\Big[W^-_\mu \bar{b}(\gamma_\mu f_{1L} P_- + \gamma_\mu f_{1R} P_+)t - \frac{1}{2M_W} W_{\mu\nu}\bar{b}\sigma^{\mu\nu}(f_{2R}P_- + f_{2L}P_+)t\Big] + \text{h.c.}$$

($P_\pm = 1/2(1 \pm \gamma_5)$ SM: $f_{1L} = 1$, rest=0

- Present data put tight constraints on f_{1L}, f_{1R}, so try to measure f_{2L}, f_{2R}
- use $e^+e^- \rightarrow t\bar{t} \rightarrow X\ell\nu$ at $\sqrt{s} = 500\,\text{GeV}$ and assume $t\bar{t}Z$-vertex to be standard
- analyze A^{b}_{FB}, A^{ℓ}_{FB} and lepton energy in top rest frame
- results: $\Delta f_{2L} \approx 0.02$, $\Delta f_{2R} \approx 0.2$



Conclusions on top-quark physics

- The $t\bar{t}$ threshold seems theoretically well under control
- The top quark mass can be measured to $\sim 50\,\mathrm{MeV}$ which is more than one order of magnitude better than what LHC can do
- the top width can be measured on the 3% level in the threshold scan
- the LC is the unique place to test $t\bar{t}Z$-couplings and can do that with a precision to better than 10%
- for t-decay physics probably the LHC is better due to much higher statistics