Physics and Experiments with Future Linear e^+e^- Colliders

Sitges, 28.4. - 5.5. '99

Top Quark Mass Definitions and the $t\bar{t}$ threshold cross section

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Content

- Outline of the problem: $\sigma(e^+e^- \to t\bar{t})$ @ threshold and the Pole Mass scheme

- The source of the problem: IR sensitivity and strong correlations

- The way out: Short Distance Mass definitions,

- ▸ Impact on the threshold cross section

- Conclusions

I. $\sigma(e^+e^- \to t\bar{t})$ @ threshold

→ talks of M. Peskin, Y. Sumino

- threshold scan best suited for a precise determination of the top quark mass m_t.
  ▷ very small exp. errors !
- But:
  How good is our theoretical prediction ? Are there large
  ▷ systematic uncertainties ?

  Recent NNLO corrections ⟹
  large

  - LO → NLO → NNLO :
    Peakshift
  - μ - dependence

DESY 97-100

Exp. analysis: Martinez, Miquel, ... Schmitz.

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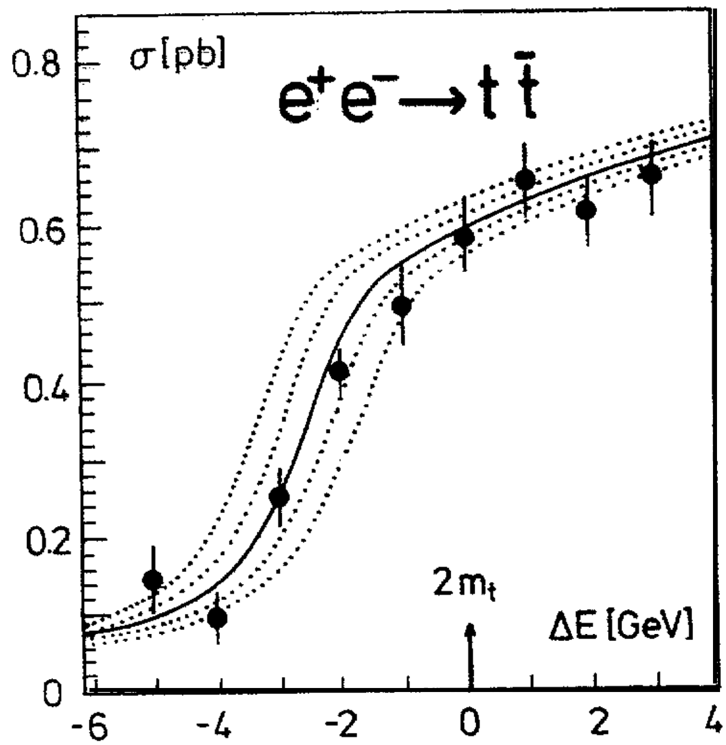


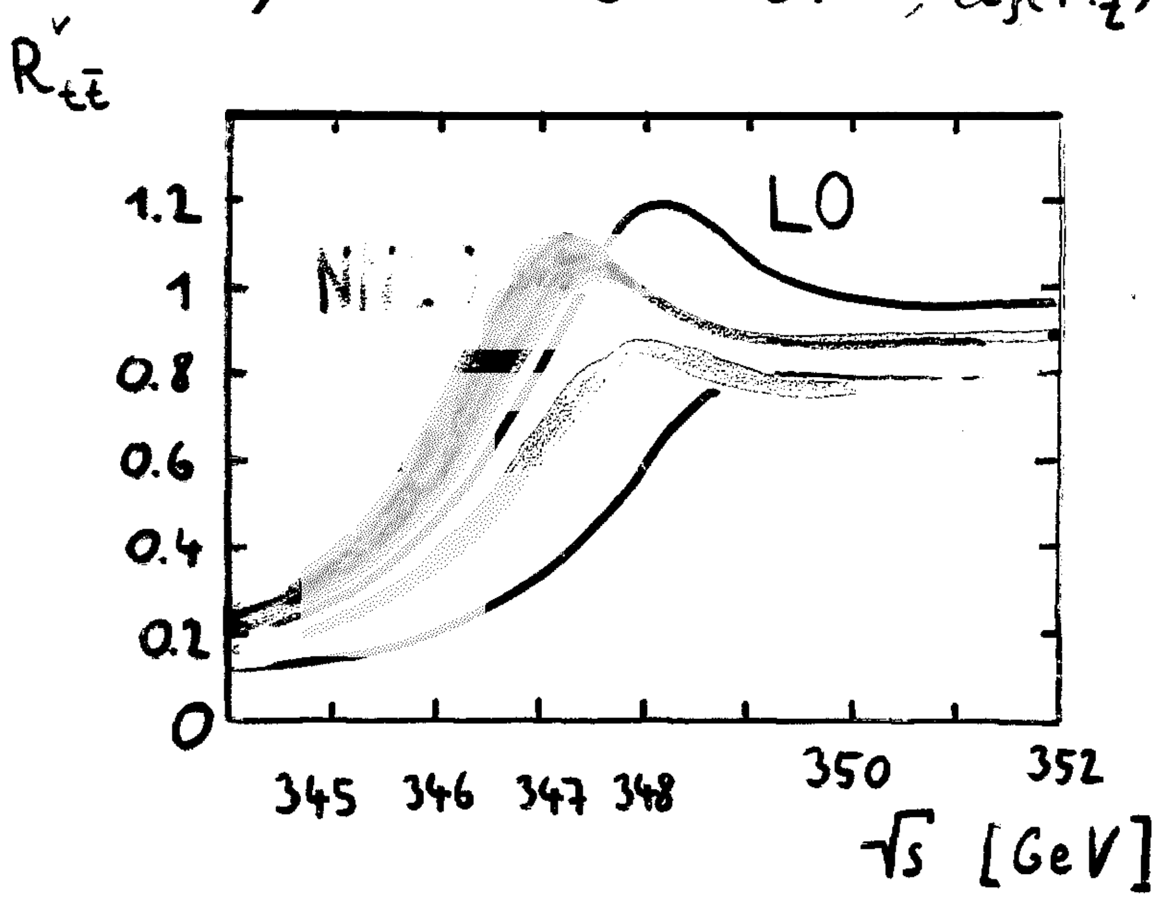
9 point scan; 5 or even 3 points might be the better strategy. Analyses under way...

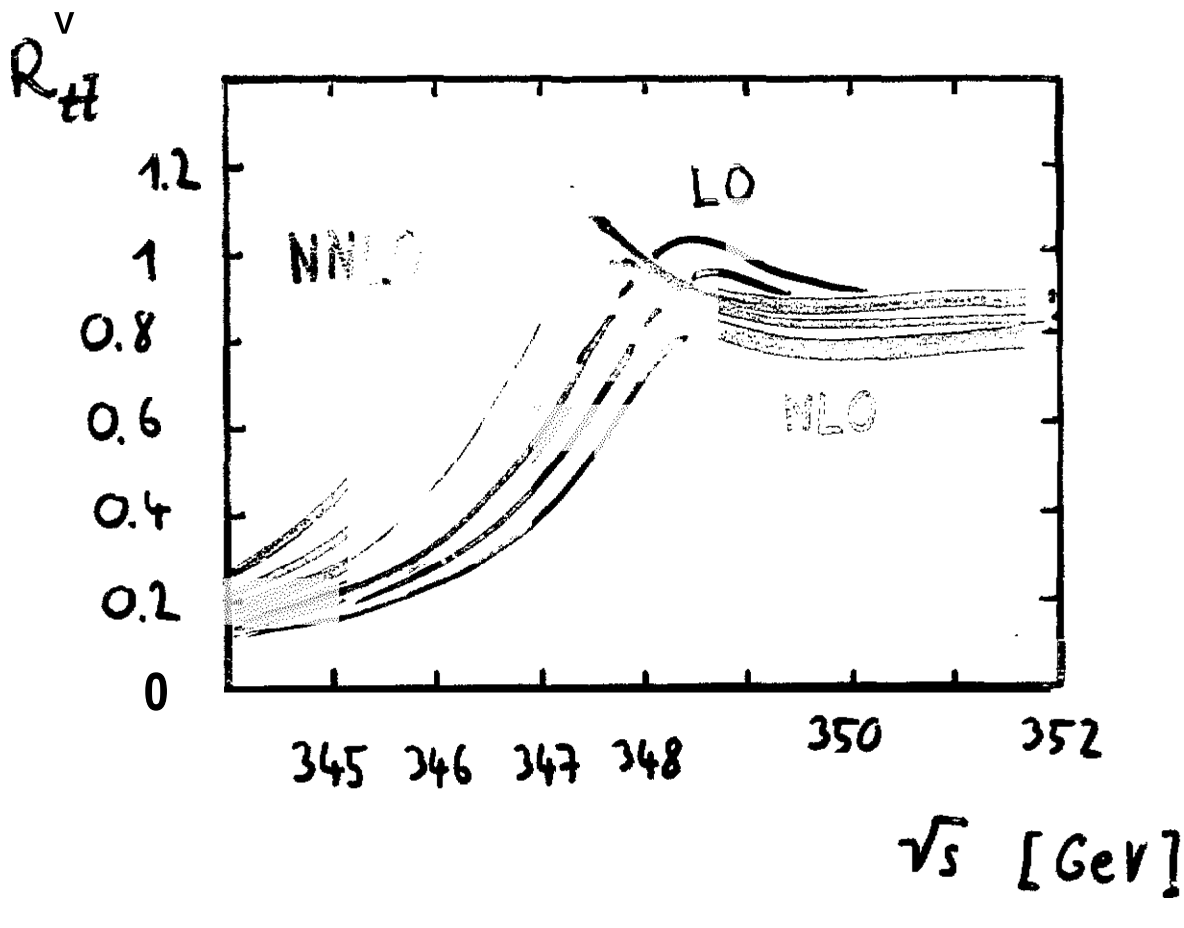
$E = \sqrt{s} - 2m_t^{pole}$

Figure 7: *Excitation curve of the top quarks including initial-state radiation and beamstrahlung. The errors of the data points correspond to an integrated luminosity of $\int \mathcal{L}$ = 50 fb^{-1} in toto. The dotted curves indicate shifts of the top mass by 200 and 400 MeV. Ref.[29, 40].*

Latest TESLA Design: ~ 21000 $t\bar{t}$ / 50 fb^{-1}

$\mu = 15 \ldots 60$ GeV , $\alpha_s(M_Z) = 0.118$





Pole Mass Scheme

(II.) The problem: IR sensitivity and strong $\alpha_s \leftrightarrow m_t$ correlations

which mass?

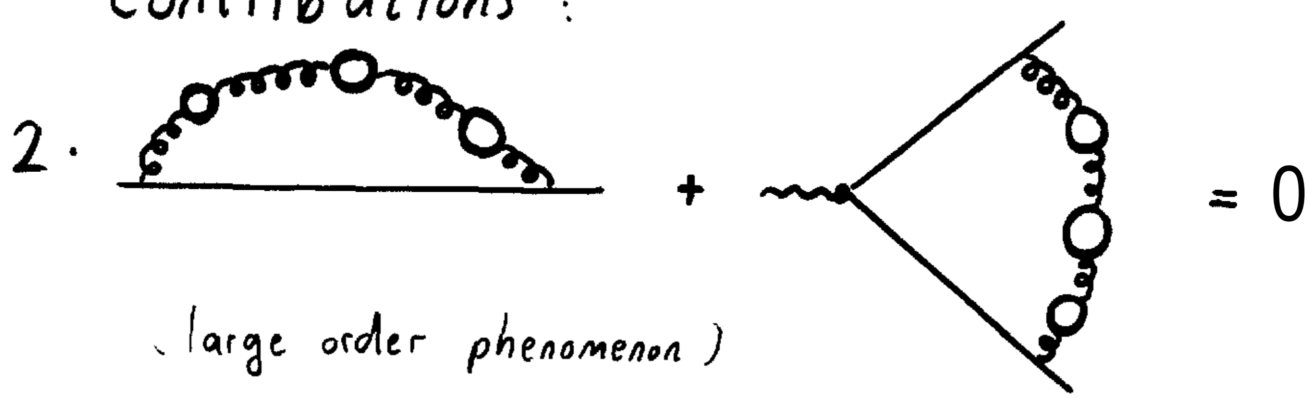
- On the one hand:
  - threshold regime, non-relativistic system, large mass, formulation of effective theories $\rightarrow$ m^{pole} is very useful
  - m^{pole} is IR finite and gauge-independent to all orders in pQCD. A. Kronfeld

- But on the other hand:
  - m^{pole} is NOT an observable !
  - defined only up to IR ambiguity of $\mathcal{O}(\Lambda_{QCD})$ ($\rightarrow$ confinement)
  - the large width $\Gamma_t \sim 1.5$ GeV does NOT protect m^{pole}

- Energy of the 1S resonance is (in principle) an observable and unambiguous.

$\rightarrow \quad E_{static}(r) = 2m + V(r)$

has no IR ambiguity:
cancellation of the leading IR Renormalon contributions:



(large order phenomenon)

$\Longrightarrow$ use a scheme, where also the single contributions m, V, are NOT IR-sensitive ("short distance")

$$E_{static}(r) = 2m_t^{pole} + V(r)$$

$$= 2m^{\text{short distance}} + V^{SD}(r)$$

- But: Cancellation of leading IR contributions is <u>not sufficient to cure the strong $\alpha_s \leftrightarrow m_t$ correlations</u> at "low" (NLO, NNLO) orders:

"IR"

$$M_{peak} = 2M_t - \delta M_{peak}^{LO} - \delta M_{peak}^{NLO} - \delta M_{peak}^{NNLO,\{\beta_0, rest\}}$$

μ [GeV]	δM_{peak}^{total}	δ^{LO}	δ^{NLO}	δ^{NNLO,β_0}	$\delta^{NNLO,rest}$
15	2.8	1.89	0.31	0.24	0.37
30	2.58	1.26	0.75	0.31	0.27
60	2.39	0.69	1.09	0.40	0.20

($\alpha_s = 0.118$, $m_t^{pole} = 175$ GeV)

→ leading IR contributions are only ~ half of the game.

Subtraction of non-IR contributions needed to "stabilize the peak".

III.) Short Distance Mass Definitions

- "Potential Subtracted" Mass $m^{PS}(\mu_f)$:

subtract universal IR-contributions from the potential:

$$m^{PS}(\mu_f) = m^{pole} - \delta m(\mu_f)$$

$$\boxed{\delta m(\mu_f) = -\frac{1}{2} \int\limits_{|\vec{q}|<\mu_f} \frac{d^3q}{(2\pi)^3} \, \tilde{V}(q)}$$

$$V(r, \mu_f) = V(r) + 2\,\delta m(\mu_f)$$

$$\Lambda_{QCD} \ll \mu_f \lesssim m_t C_F \alpha_s(\mu) \approx 30 \text{ GeV}$$

$\mu_f = 3$ GeV: Results presented in [illegible] talk.

[illegible]

[illegible]

Use of m^{PS} in numerics à la Hoang + Teubner:

→ good stabilization of the peak.

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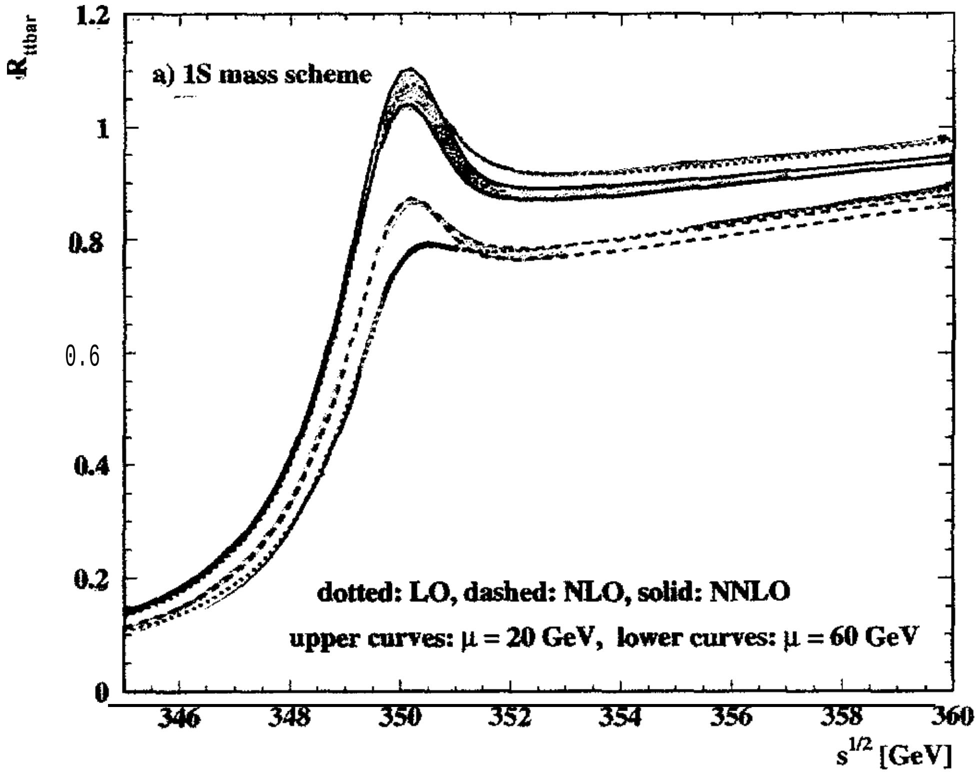
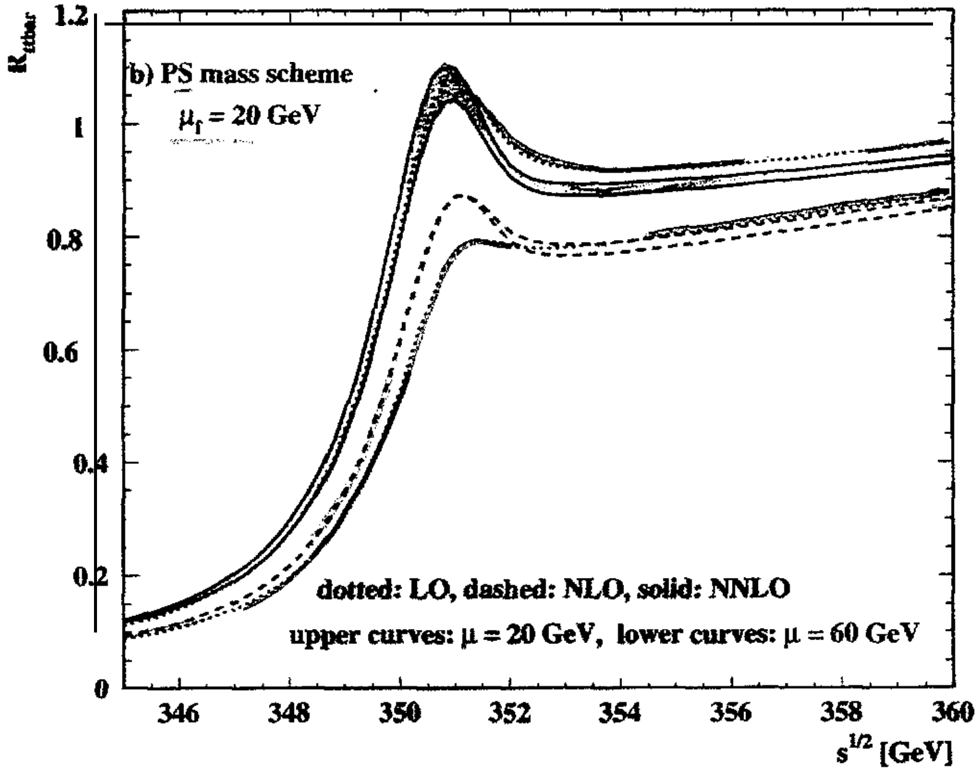


R_ttbar
a) 1S mass scheme
dotted: LO, dashed: NLO, solid: NNLO
upper curves: μ = 20 GeV, lower curves: μ = 60 GeV
s^1/2 [GeV]



R_ttbar
b) PS mass scheme
μ_f = 20 GeV
dotted: LO, dashed: NLO, solid: NNLO
upper curves: μ = 20 GeV, lower curves: μ = 60 GeV
s^1/2 [GeV]
LO

$\rightarrow$ m^{PS} can be extracted reliably from $\sigma_{tot}(e^+e^- \to t\bar{t})$ @ threshold.

$\rightarrow$ Relation to $m^{\overline{MS}}$ preferred at high energies and in EW precision observables:

assume $m_t^{\overline{MS}}(m_t^{\overline{MS}}) = 165.0$ GeV:

$$m_t^{pole} = [\,165.0 + 7.6 + 1.6 + 0.6\,(\text{est.})\,]\ \text{GeV}$$

$$m_t^{PS}(\mu_f = 20\ \text{GeV}) = [\,165.0 + 6.7 + 1.2 + 0.3\,(\text{est.})\,]\ \text{GeV}$$

("est." = large-β_0-limit)

- Similar to m^{PS}:

"low scale running mass" $m^{LS}(\mu_{LS})$:

$\rightarrow$ Subtract the IR contributions from the heavy quark self energy.

→ Universality of the leading IR sensitivity → similarity of m^{PS}, m^{L}

$$m^{LS}(\mu_{LS}) - m^{pole} = -\frac{16}{9}\frac{\alpha_s}{\pi}\mu_{LS}\left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}\left(\frac{\mu_L}{m^2}\right.\right.$$

$$m^{PS}(\mu_{PS}) - m^{pole} = -\frac{4}{3}\frac{\alpha_s}{\pi}\mu_{PS}\left[1 + \mathcal{O}(\alpha_s)\right]$$

→ μ_{LS} (or μ_{PS}) can be chosen to achieve subtraction of non-IR corrections to the peak position at NLO, NNLO.

- M^{1S} := half of the perturbative mass of the fictitious ($\Gamma_t \to 0$) toponium 1S ground state

→ close to the "quasi-observable" 1S-peak, but defined within PT.

→ subtraction of the same universal IR contribution as m^{PS}, m^{LS}.

→ no dependence on additional scale.

→ stabilization of the peak in σ_{tot} "by construction":

→ normalization-uncertainty still big.

Comparison $m^{pole} \leftrightarrow M^{1S}$:

$$M_{peak} = 2M_{1S} + \delta M_{peak,1S}^{LO} + \delta M_{peak,1S}^{NLO} + \delta M_{peak,1S}^{NNLO}$$

μ[GeV]	$\delta M_{peak,1S}^{total}$	δ^{LO}	δ^{NLO}	δ^{NNLO}
15	0.17	0.16	0.02	0.00
30	0.12	0.30	-0.09	-0.08
60	0.11	0.54	-0.32	-0.1

($\alpha_s = 0.118$, $M_{1S} = 175$ GeV)

→ assume $M_{1S} = 175 \pm 0.2$ GeV ,

$\alpha_s(M_Z) = 0.118 \pm x \cdot 0.001$:

$$m_t^{\overline{MS}}(m_t^{\overline{MS}}) = \Big[\, 175 - \underset{LO}{7.58} - \underset{NLO}{0.96} - \underset{NNLO\ (est.)}{0.23} \pm \underset{\delta M_{1S}}{0.2} \pm \underset{\delta\alpha_s}{x \cdot 0.07} \,\Big]\ \text{GeV}$$

.... more detailed analysis presented

IV. Conclusions

- NNLO corrections to $\sigma_{tot}(e^+e^- \to t\bar{t})$ @ threshold are uncomfortably large:
  - → 1S - peak position
  - → μ - dependence
  - → normalization

- This partly due to the use of the pole mass m_t^{pole} which is IR ambiguous.

- With suitable short distance mass definitions like m^{PS}, m^{LS}, M^{1S} the long distance sensitivity is cured and m_t can be extracted with a precision $\lesssim 200$ MeV from the total cross section.