Topping at the ILC

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A Top$_{\mathrm{QCD}}$ Review

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What we (don't) know . . .

Tevatron (Run I) (& LEP):

$$m_{\rm top}^{?} = 178 \pm 4.3 \text{ GeV}$$

$$B(t \to W_0 b) = 0.91 \pm 0.39$$

$$B(t \to W_+ b) = 0.11 \pm 0.15$$

$$B(t \to \gamma q) < 0.032$$

$$B(t \to Zq) < 0.33$$

$$\frac{B(t \to Wb)}{\Sigma_{d,s,b} B(t \to Wq)} = 0.94^{+0.31}_{-0.24}$$

$$\sigma_{p\bar{p} \to t\bar{t}} = 6.2 \pm 1.7 \text{ pb}$$

Tevatron (Run II): . . .

What we (don't) know . . .

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Tevatron (Run II): . . .

$\Rightarrow$ Top roughly SM-like

$\nearrow$ room for "fancy" New Physics ideas

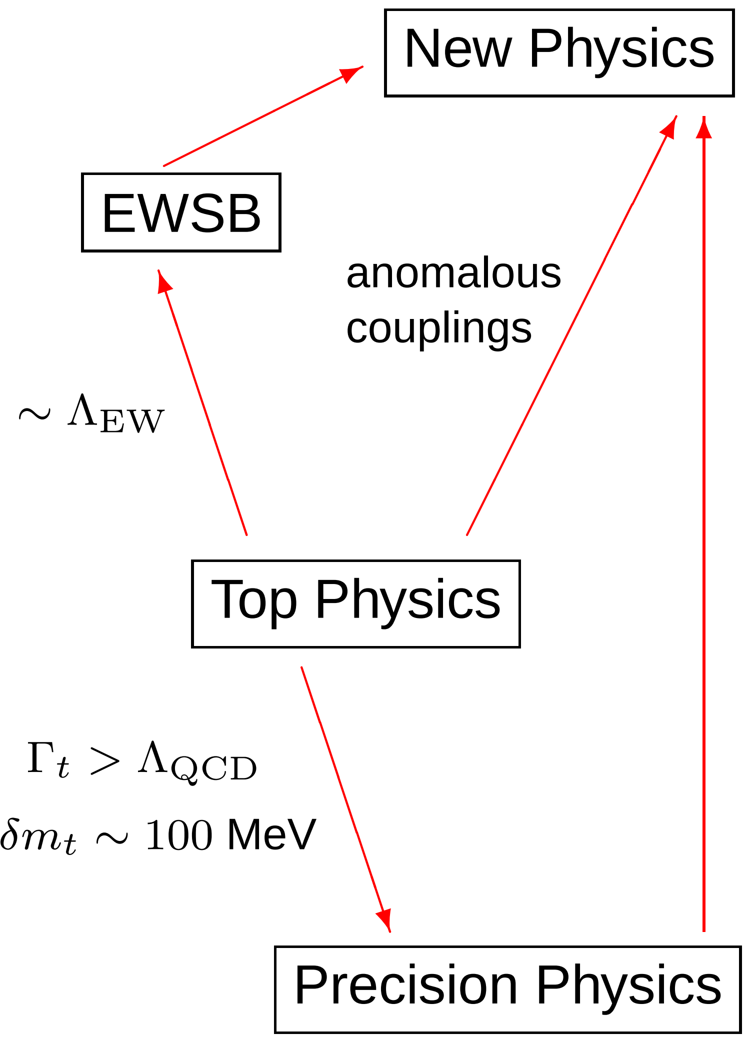
$\Updownarrow$

ILC

$\Updownarrow$

$\searrow$ room for lots of "hard work"

Topping at the ILC



EWSB:

$\longrightarrow$ just a heavy quark ?
$\longrightarrow$ special role for the top in EWSB ?
$\longrightarrow$ strong constraint on any model

- Higgs mechanism

SM: $m_t = g_{\rm ttH} V$

$e^+e^- \to t\bar{t}H$, $\sqrt{s} = 800$ GeV $\qquad \mathcal{L} = 10^3\,\text{fb}^{-1}$

$\delta g_{\rm tth}/g_{\rm tth} = 5 - 6\,\%$ $\quad$ ($m_h = 120$ GeV)

$\delta g_{\rm tth}/g_{\rm tth} = 10\,\%$ $\quad$ ($m_h = 190$ GeV)

Gay, Besson, Winter

$\sqrt{s} \approx 350$ GeV $\qquad \mathcal{L} = 300\,\text{fb}^{-1}$

$\delta g_{\rm tth}/g_{\rm tth} = 20 - 50\,\%$ ($m_h = 120$ GeV)

Martinez, Miquel

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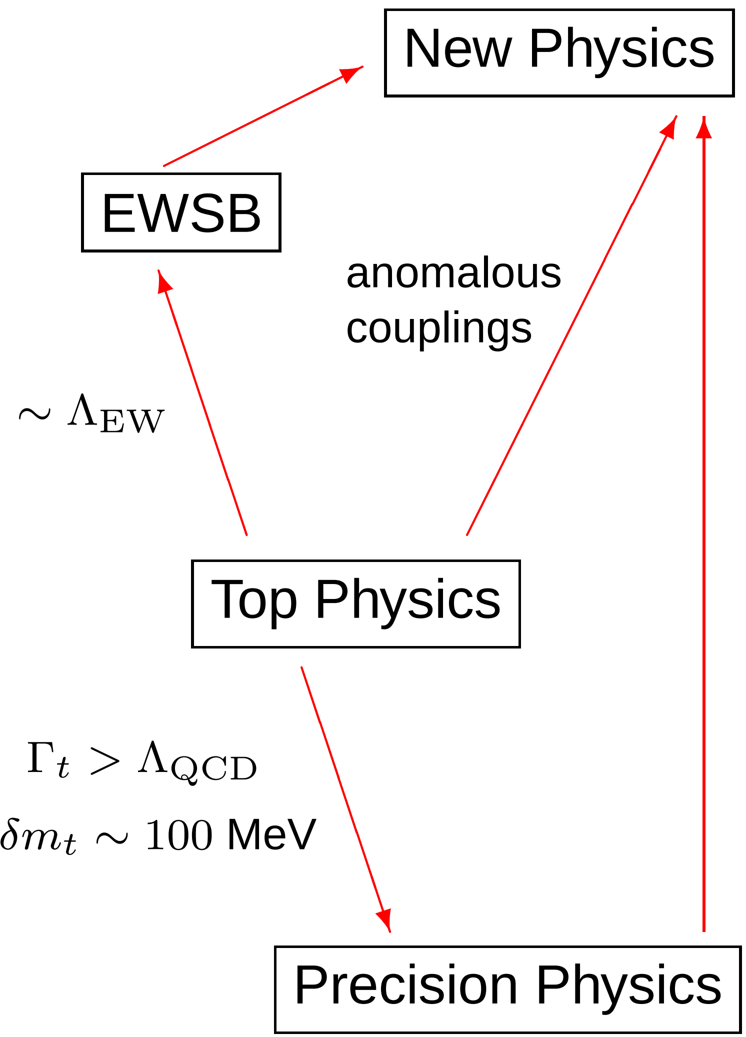

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- Higgs mechanism

SUSY: $\longrightarrow H_1, H_2 \; \tan\beta = v_2/v_1$
$\longrightarrow t \longrightarrow H^+ b\,,\ \tilde{t}\tilde{\chi}$
$\longrightarrow$ squark mixing
$\longrightarrow$ unification (RGE's)
$\longrightarrow$ Higgs masses
$\longrightarrow$ drives SSB (mSUGRA)
$\longrightarrow$ split SUSY

Little Higgs: $\longrightarrow$ H = pseudo Goldstone
$\longrightarrow$ heavier Top
$\longrightarrow e^+e^- \longrightarrow t\bar{t}H$
$\longrightarrow$ drives SSB

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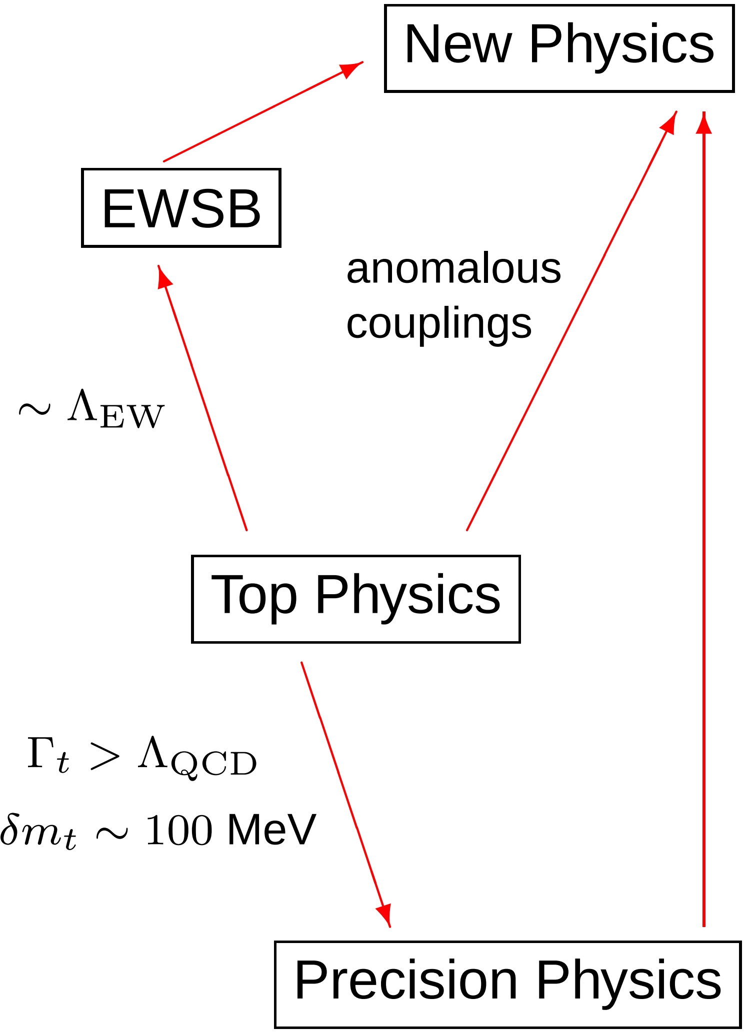

<u>EWSB:</u>

$\longrightarrow$ just a heavy quark ?

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- DSB

topcolor (+ technicolor):

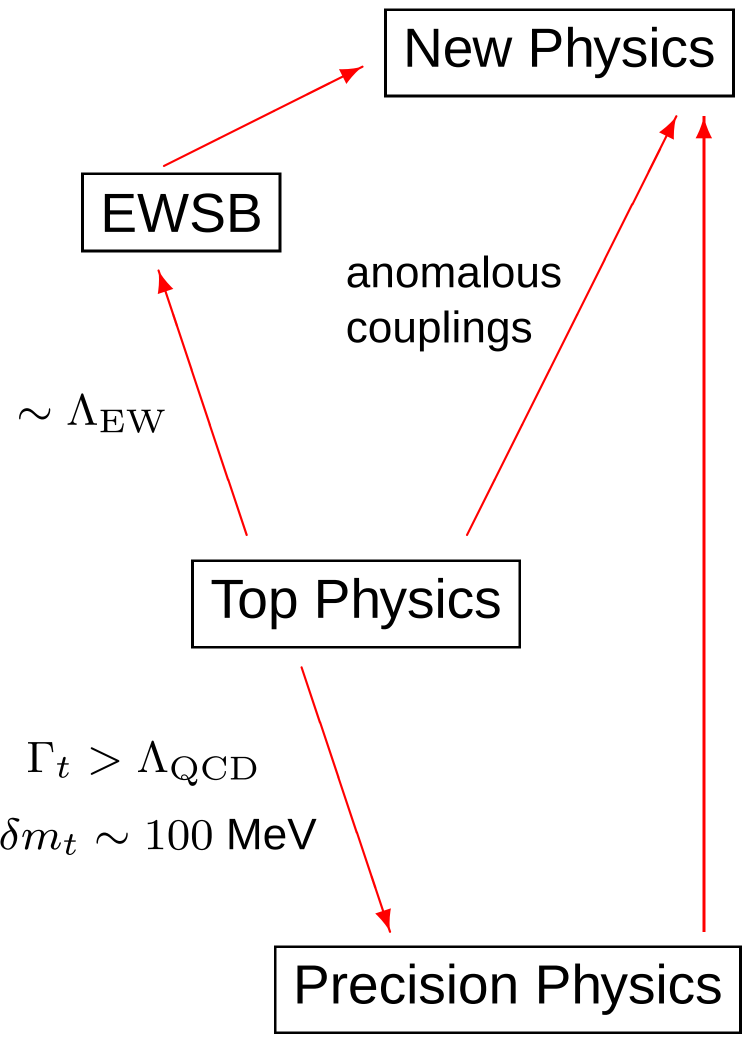
$\longrightarrow SU(3)_{\rm 3rd} \neq SU(3)_{\rm 1st+2nd}$

$\longrightarrow$ broken to $SU(3)_c$

$\longrightarrow$ top condensation

$\longrightarrow t \longrightarrow \pi^+ b$

Topping at the ILC



Anomalous Couplings:

$\longrightarrow$ rare/anomalous/exotic decays

$\longrightarrow$ rare/anomalous/exotic production

$\longrightarrow$ top spin: $\Gamma_t > \Lambda_{\rm QCD}$

$\longrightarrow$ CP-violation

$\Updownarrow$ $\Longleftarrow$ B-physics e.g. $B \to s\gamma$

- TC2: FCNC's, $t \to \pi^+ b$
- SUSY: exotic decays, FCNC's, CP-violation
- Multi-Higgs: exotic decay, CP-violation
- extra dimension: spin observables
- 4th generation: V_{tb} modified

$\Longrightarrow$ . . . lots of possibilities

vast literature

Example: FCNC's

$\sqrt{s} = 500$ GeV	SM	2HDM-III	MSSM	TC2
$\sigma(\gamma\gamma \to t\bar{c})[\mathrm{fb}]$	$\mathcal{O}(10^{-8})$	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10)$
$\sigma(e\gamma \to et\bar{c})[\mathrm{fb}]$	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(1)$
$\sigma(e^+e^- \to t\bar{c})[\mathrm{fb}]$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-1})$
$Br(t \to cg)$	$\mathcal{O}(10^{-11})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-4})$
$Br(t \to cZ)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-4})$
$Br(t \to c\gamma)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-6})$
$Br(t \to cH)$	$< 10^{-13}$	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-1})$

Yang, hep-ph/0409351

$1\ \mathrm{fb} \Leftrightarrow 10^2 - 10^3$ events $\qquad$ ($\mathcal{L} = 100 - 1000$ fb^{-1})

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Yang, hep-ph/0409351
Aguilar-Saavedra, hep-ph/0409342

Experimental capabilities:

- top decay: $\sigma(gg \to t\bar{t})_{\mathrm{LHC}} \sim 10^3$ pb $\longrightarrow$ LHC
  $\sigma(e^+e^- \to t\bar{t})_{\mathrm{ILC}} \sim 1$ pb
  competitive & complementary
- single top production (incl. $e^\pm$ polarization) $\longrightarrow$ ILC

3σ discovery limits: $t \to qZ$ $\mathcal{O}(10^{-5})$–$\mathcal{O}(10^{-6})$
$t \to q\gamma$ $\mathcal{O}(10^{-6})$

Example: tt-Z, tt-Photon

Comparison: lepton + jets, p_T-distribution (1σ limits)

talk by U. Baur

coupling	LHC (300 fb^{-1})	e^+e^- (snowmass)
$\Delta\widetilde{F}^{\gamma}_{1V}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{1A}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2V}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2A}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}
$\Delta\widetilde{F}^{Z}_{1V}$	$^{+0.34}_{-0.72}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\widetilde{F}^{Z}_{1A}$	$^{+0.079}_{-0.091}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\widetilde{F}^{Z}_{2V}$	$^{+0.26}_{-0.34}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\widetilde{F}^{Z}_{2A}$	$^{+0.35}_{-0.35}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}

$$\Gamma^V_\mu = ie\left\{\gamma_\mu\left(\tilde{F}^V_{1V}+\gamma_5\tilde{F}^V_{1A}\right) + \frac{(q-q')_\mu}{2m_t}\left(\tilde{F}^V_{2V}+\gamma_5\tilde{F}^V_{2A}\right)\right\}$$

- $\mathcal{O}(\%)$ precision at ILC
- polarization crucial: $P(e^-)=0.8$

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- $\mathcal{O}(\%)$ precision at ILC
- polarization crucial: $P(e^-) = 0.8$

General needs:

$\longrightarrow$ coherent conventions
$\longrightarrow$ fully exploit of polarization
$\longrightarrow$ vary more than 1 coupling
$\longrightarrow$ optimized observables
$\longrightarrow$ QCD corrections

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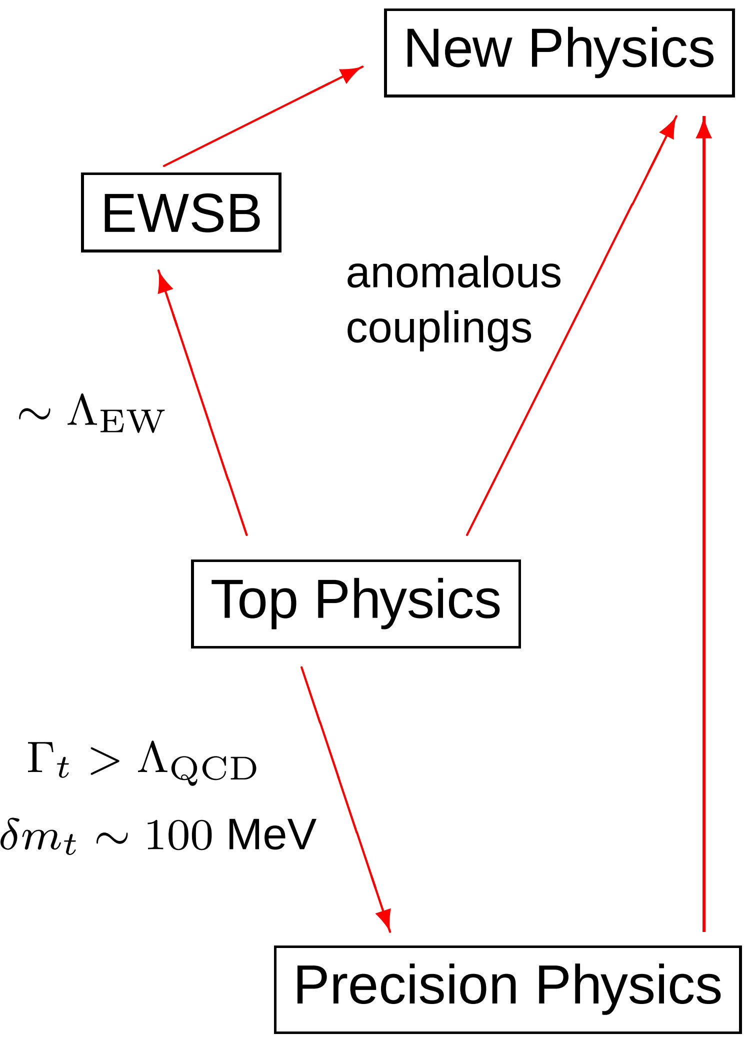

Top = pQCD laboratory:

Total Cross Sections (e^+e^-):

$\sigma(t\bar{t})$, continuum: $\mathcal{O}(\alpha_s^2)$ ✓, 1-loop ew. ✓
2-loop Sudakovs ✓

$\sigma(t\bar{t})$, threshold: NNLL QCD (✓), (N)LL ew. ✓

$\sigma(t\bar{t}H)$: $\mathcal{O}(\alpha_s)$ ✓, 1-loop ew. ✓
$t\bar{t}$ threshold effects ✓ talk by Hoang

Spin Correlations & Distributions (e^+e^-):

$\sigma(t\bar{t})$: $\mathcal{O}(\alpha_s)$ ✓

Need: ($\sim 10^6$ $t\bar{t}$ events)

- ⋆ $e^+e^- \rightarrow 6f$ (`Lusifer`) $\rightarrow \mathcal{O}(\alpha_s)$
- ⋆ $e^+e^- \rightarrow 8f$ $\rightarrow \mathcal{O}(\alpha_s)$
- ⋆ unstable particles
- ⋆ non-factorizable corrections

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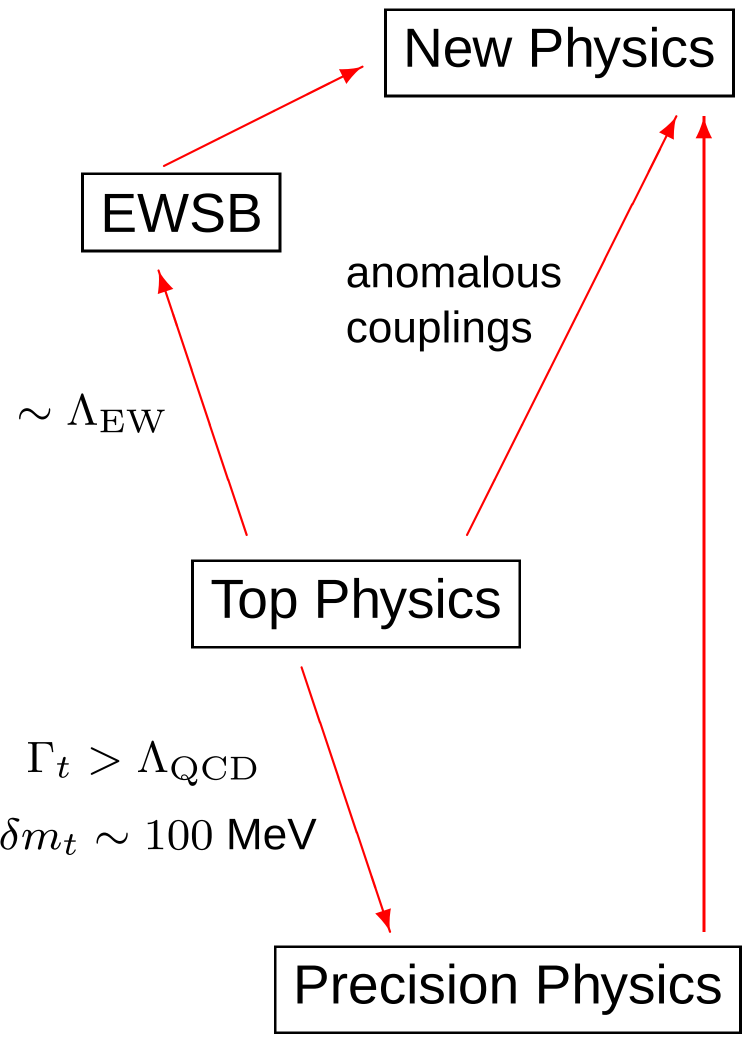


Top Mass Measurement

Why $\delta m_t \sim 100$ MeV is useful:

$\longrightarrow$ S.Heinemeyer

⋆ ew. precision observables

$$\delta m_t \lesssim 0.2 \text{ GeV} \leftrightarrow (\delta M_w)^{\rm GIGA-Z}$$

$$\delta m_t \lesssim 0.5 \text{ GeV} \leftrightarrow (\sin^2 \theta_{\rm eff})^{\rm GIGA-Z}$$

⋆ lightest MSSM Higgs mass

$$m_h^2 \simeq M_z^2 + G_F m_t^4 \ln\left(\frac{M_{\rm susy}}{m_t}\right)$$

$$\Rightarrow \delta m_h \sim \delta m_t$$

⋆ mSUGRA:

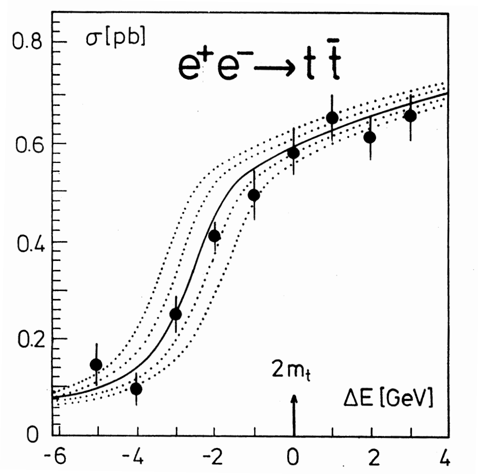
$\longrightarrow$ constrains high scale parameters

$\longrightarrow$ constrains cold dark matter candidates

High Precision Top Mass

Threshold Scan: $\sqrt{s} \simeq 350$ GeV (Phase I)

- ▷ count number of $t\bar{t}$ events
- ▷ color singlet state
- ▷ background is non-resonant
- ▷ physics quite well understood (renormalons, summations)



$\rightarrow \delta m_t^{\rm exp} \simeq 50$ MeV

$\mathcal{L} = 300\,\mathrm{fb}^{-1}$
$9+1$ scan points
[Peralta, Martinez]

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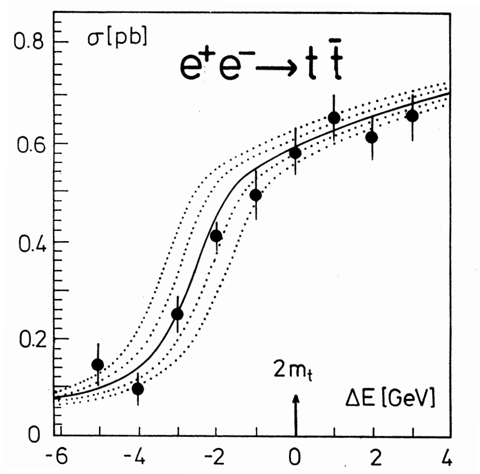

$\longrightarrow \delta m_t^{\rm exp} \simeq 50$ MeV

$\longrightarrow \delta m_t^{\rm th} \simeq 100$ MeV

(param. est. $\longrightarrow$ many authors)

What mass?

$\sqrt{s}_{\rm rise} \sim 2m_t^{\rm thr}$ + pert.series

(short distance mass: 1S $\leftrightarrow$ $\overline{\rm MS}$)

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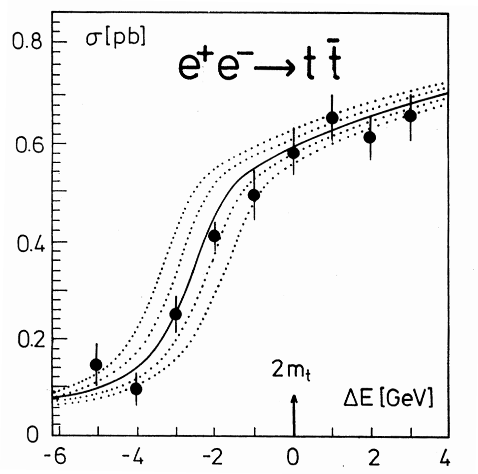

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ongoing work:

- effects from lumi spectrum measurements: $\Delta m_t \sim -50$ MeV $\longrightarrow$ S. Boogert
- higher order corrections
  - ▷ NNLL finite lifetime corrections: $\Delta m_t = +(30-50)$ MeV $\longrightarrow$ A. Hoang
  - ▷ $\mathcal{O}(\alpha_s^3)$ fixed-order Coulomb corrections $\longrightarrow$ M. Steinhauser

needed:
- ▷ full NNLL order $\leftrightarrow$ full NNNLO fixed order
- ▷ full NNLL electroweak corrections
- ▷ fully differential (unstable top quark)

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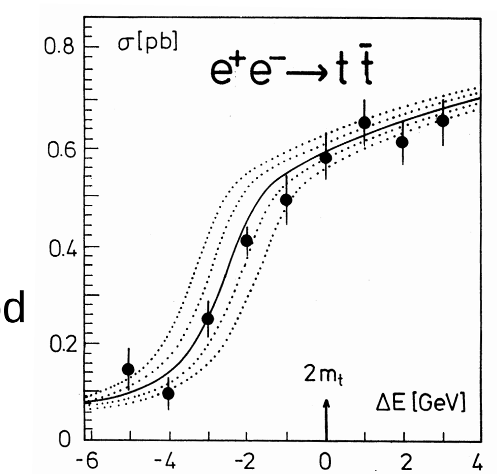

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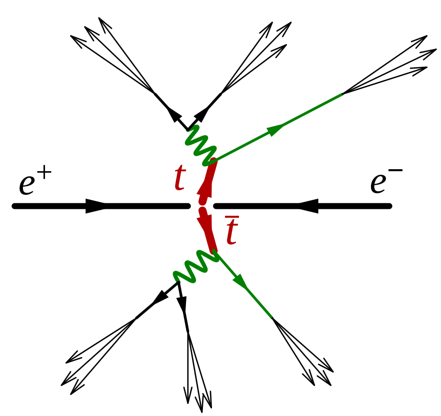
(short distance mass: 1S $\leftrightarrow \overline{\rm MS}$)

Reconstruction: any $\sqrt{s}$ (Phase I + II)

Chekanov,Morgunov:

- ▷ $e^+e^- \rightarrow 6$ jets ($y_{\rm cut}^6$)
- ▷ b-tagging
- ▷ $\vec{P}_1 + \vec{P}_2 < \Delta_p$
- ▷ $M_1 + M_2 < \Delta_M$



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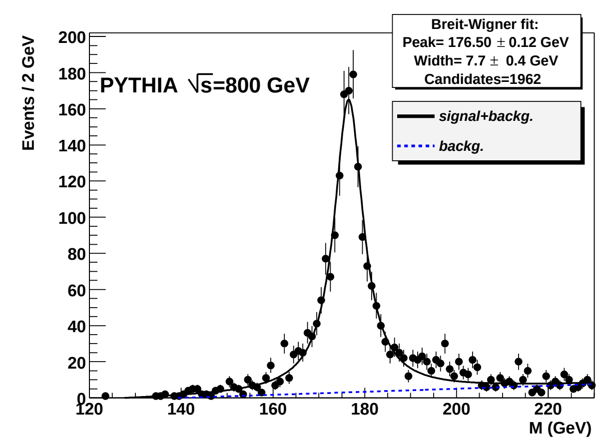
$(\mathcal{L} = 300\,{\rm fb}^{-1})$



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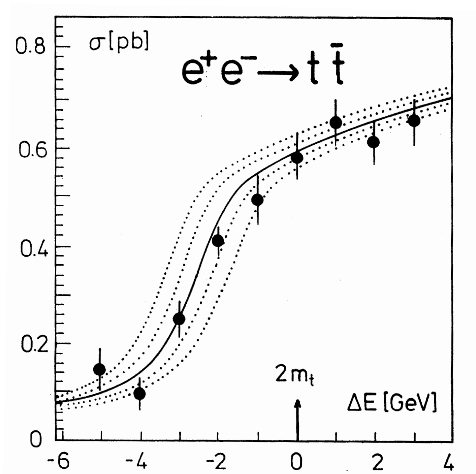

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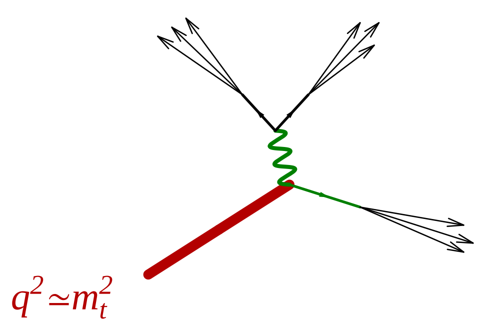

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Pole Mass ?

ambiguity: $\Delta m_t \sim \Lambda_{\rm QCD}$

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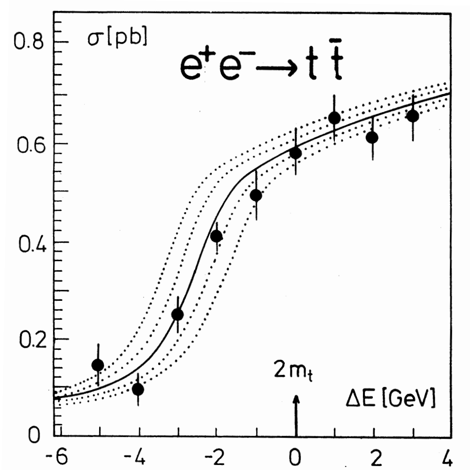

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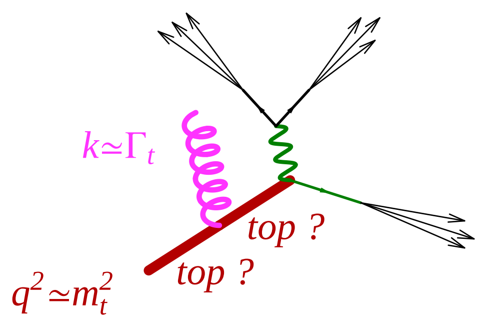

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ambiguity: $\Delta m_t \sim \Lambda_{\rm QCD}$
$\Delta m_t \sim \alpha_s(\Gamma_t)\,\Gamma_t$

There is s.th. to understand here !

Final Words

. . . there is plenty of interesting top physics to work on !

There are no free lunches here !

. . . let’s get started !