The Top Quark: present and future

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NIU/NICADD

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from DØ to ATLAS

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1. Introduction

In the SM, the top quark is defined as the $SU(2)_L$ (weak isospin) partner of the bottom quark.

- $S = \frac{1}{2}$
- $Q = \frac{2}{3}$
- Transforms as a color triplet under the SU(3) gauge group of strong interactions.

None of these quantum numbers has been directly measured, but a large amount of indirect evidence support these assignments. These include precision measurements of $\Gamma(Z \to b\bar{b})$, A_{FB}, B^0-$\bar{B}^0$ mixing, and FCNC decays of B mesons.

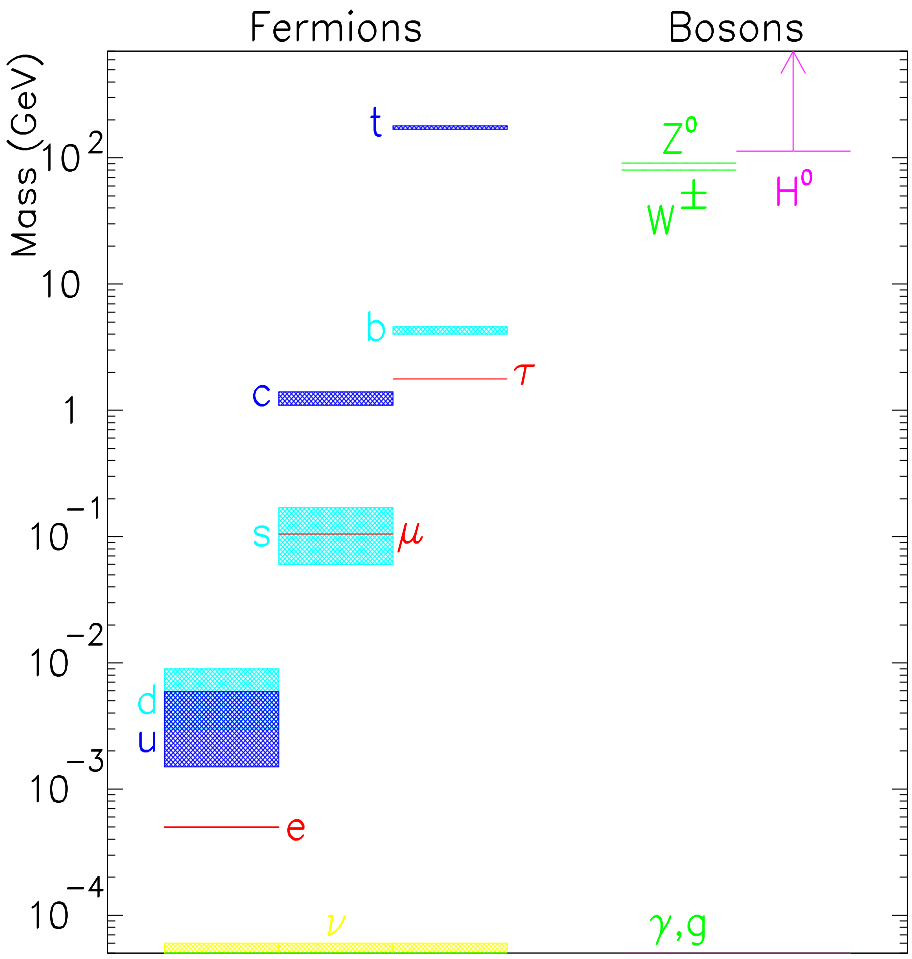
- Measurement of $\sigma(p\bar{p} \to t\bar{t})$ at the Tevatron is consistent with theoretical calculations for a color-triplet quark.
- Run 2 of the Tevatron (2001-2008) will firmly establish the identity of the top quark.
- The LHC (2007-) and the ILC (2015? -) will be needed for precise determination of top quark properties and to look for subtle hints of new physics.

1.1. Theoretical Perspective

The most pressing challenge in particle theory is to explain the dynamics behind mass generation:

1. EWSB $\Rightarrow$ W and Z acquire mass,
2. FSB $\Rightarrow$ fermion families & mass hierarchy.

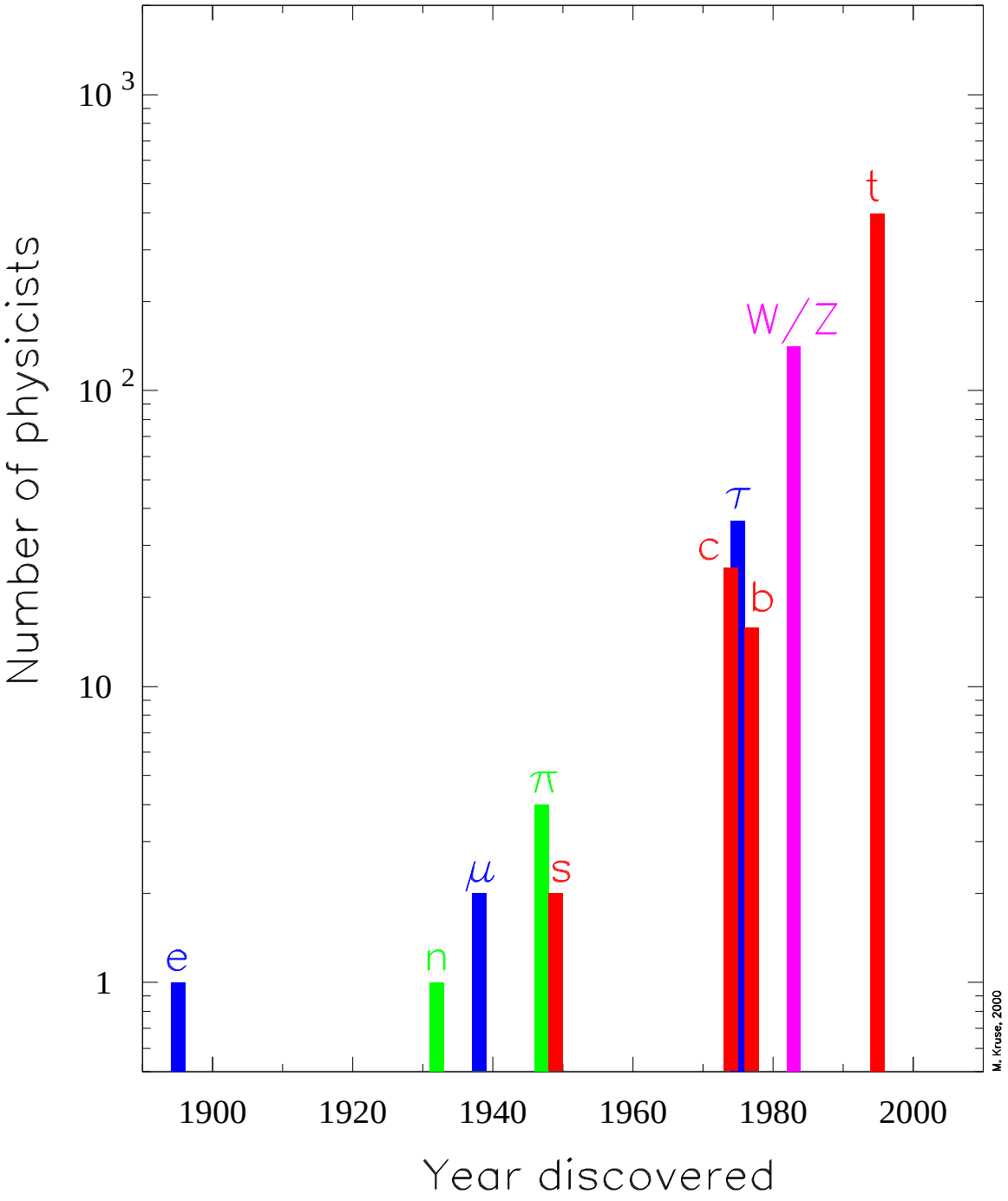
Its large mass sets the top quark apart.



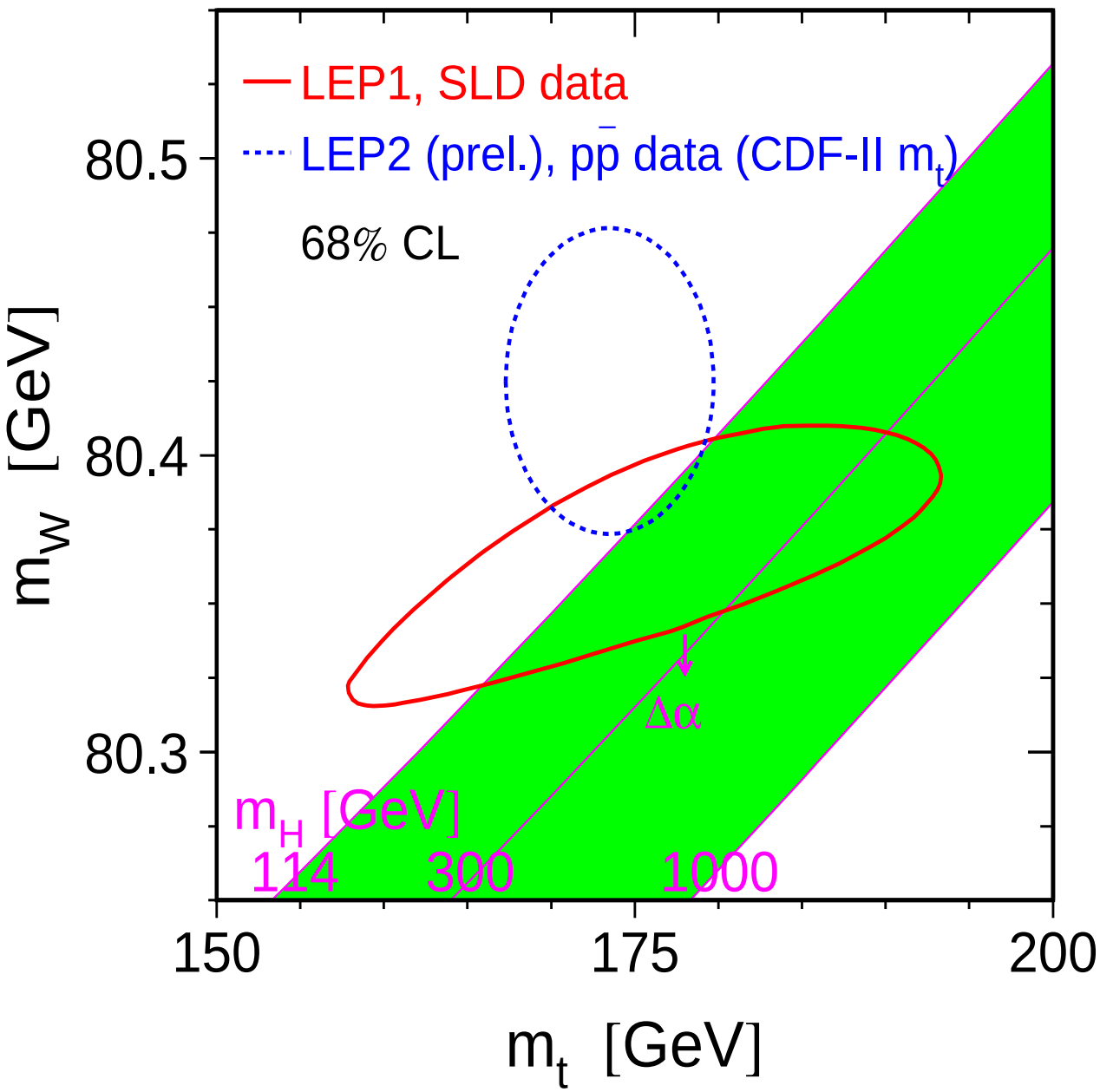
Some interesting consequences of large m_t

- Top and Higgs contribute to the radiative (loop) corrections to M_W $\Rightarrow$precise measurements of M_W and m_t together constrain M_{H^0}.
- The only fermion heavier than $W^\pm$ $\Rightarrow$
  - Extremely short life ($\tau_t \sim 4 \times 10^{-25}$ s). The top quark decays before hadronization ($\tau_{\rm had} \approx 28 \times 10^{-25}$ s). $\Rightarrow$opportunity to study the properties of a bare quark, free from long-range effects of the strong interaction, e.g. confinement.
  - On-shell W production in fermion decay $\Rightarrow$longitudinal component of W exposed $\Rightarrow$test of Higgs mechanism in EWSB.
- An excellent place to look for on-shell production of particles beyond the SM that must be heavier than other fermions ($\tilde{t}$, $H^\pm$).
- Most likely to shed light on the mechanism of generation of fermion masses. Interesting to the study of any mass-dependent coupling. Top Yukawa coupling is curiously close to 1.

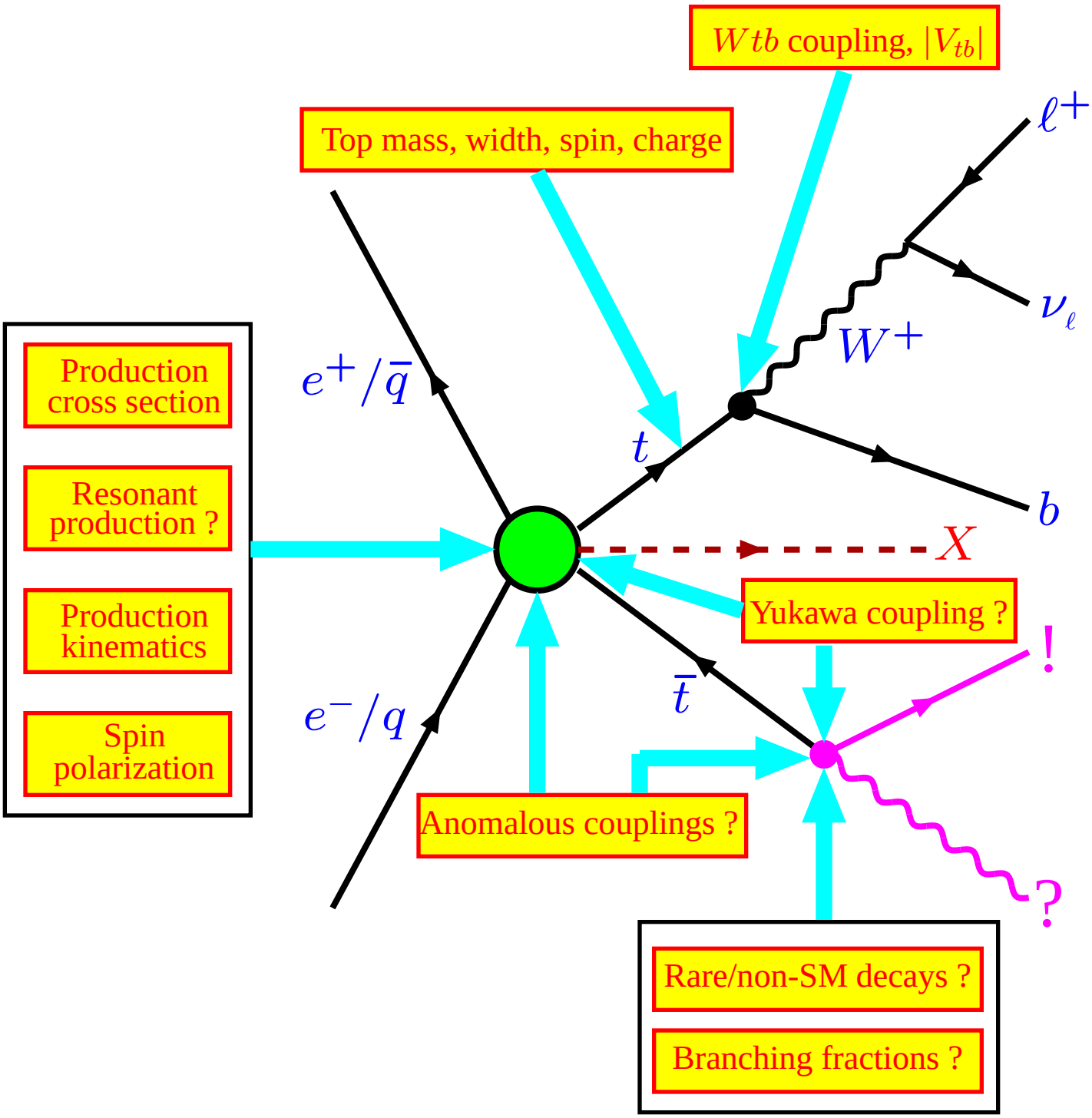
Discovery of elementary particles



Constraint on M_H from m_t and M_W



Top Physics Potential

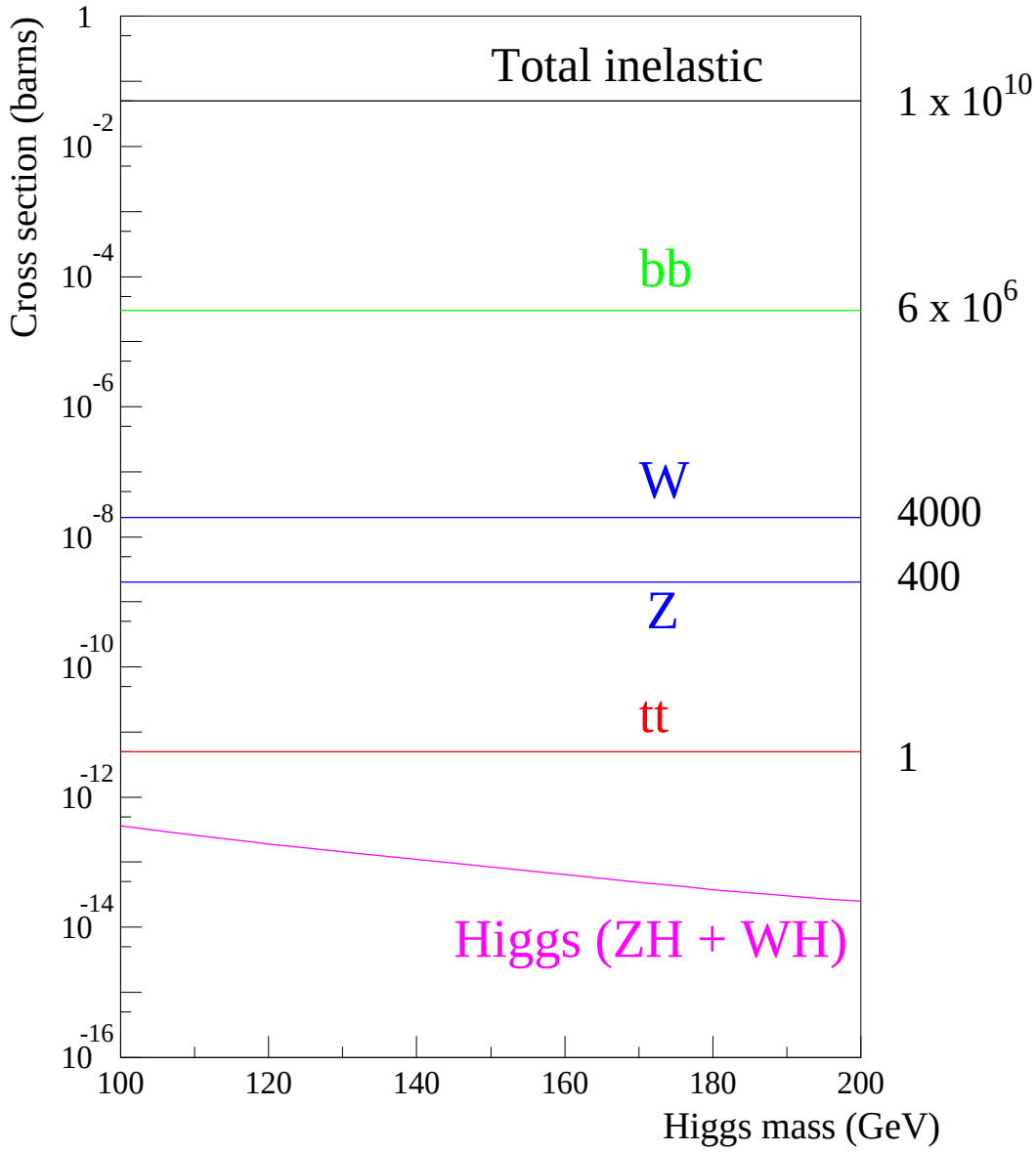


1.2. Experimental Arena

Top production at Tev2, LHC, and ILC

Collider	Tevatron	LHC	ILC
type	$p\bar{p}$	pp	e^+e^-
Operation time	2001-2008	2007-	2015(?)-
E_{CM} (TeV)	1.96	14.0	$\sim$1.0
$\langle\mathcal{L}\rangle$ (cm^{-2}s^{-1})	$\mathcal{O}(10^{32})$	$\mathcal{O}(10^{34})$	$\mathcal{O}(10^{34})$
$\int \mathcal{L}dt$ (fb^{-1})	~ 2	$\sim$300	$\sim$1000
σ_{total} (pb)	$\sim 10^{11}$	$\sim 10^{11}$	$\mathcal{O}(10)$
$\sigma(b\bar{b})$ (pb)	$\sim 3\cdot 10^7$	$\sim 3\cdot 10^8$	$\mathcal{O}(1)$
$\sigma(WX)$ (pb)	$\sim 4\cdot 10^4$	$\sim 2\cdot 10^5$	$\mathcal{O}(1)$
$\sigma(t\bar{t})(a)$ (pb)	$6.70^{+0.71}_{-0.88}$	825^{+58}_{-43}	~ 0.8
σ(single t) (pb)	2.91 ± 0.02	315^{+8}_{-2}	~ 0

Cross sections at Tevatron ($\sqrt{s} = 1.8$ TeV)

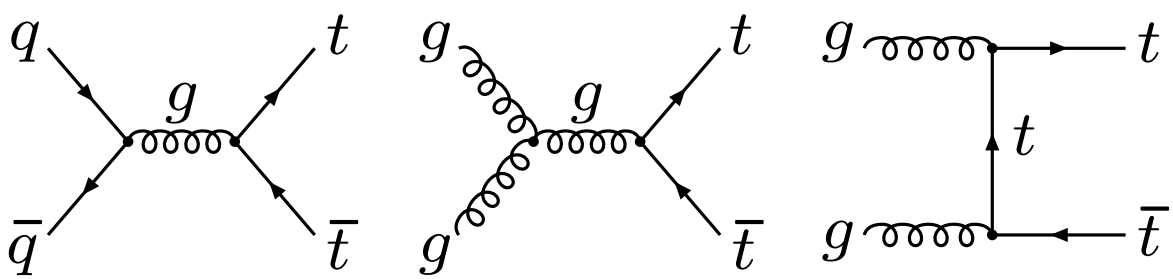


- Of over 10^{14} total collisions in Run 1, roughly one in every 10^{10} producing a $t\bar{t}$ event.
- When running at maximum luminosity, about 5 $t\bar{t}$ events are produced every hour in Run 2.

2. Production of Top Quarks

2.1. Top-antitop pair production

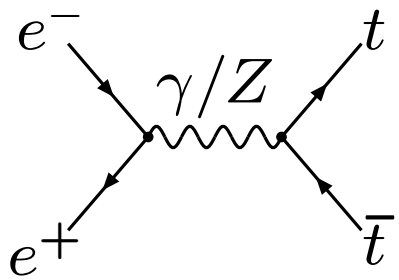
- At hadron colliders, top quarks are produced most often in pairs via strong interactions.



- Such events have been used in measuring the rate of production ($\sigma(p\bar{p} \rightarrow t\bar{t})$) and the mass of the top quark (m_t) at the Tevatron.

- Strong interaction $\Rightarrow$
  - More signal, but also extremely large background. Triggering is a major challenge.
  - Signal smudged by initial-state radiation, spectator interaction, multiple collisions.
  - Energy and polarization of colliding partons cannot be precisely controlled or determined.

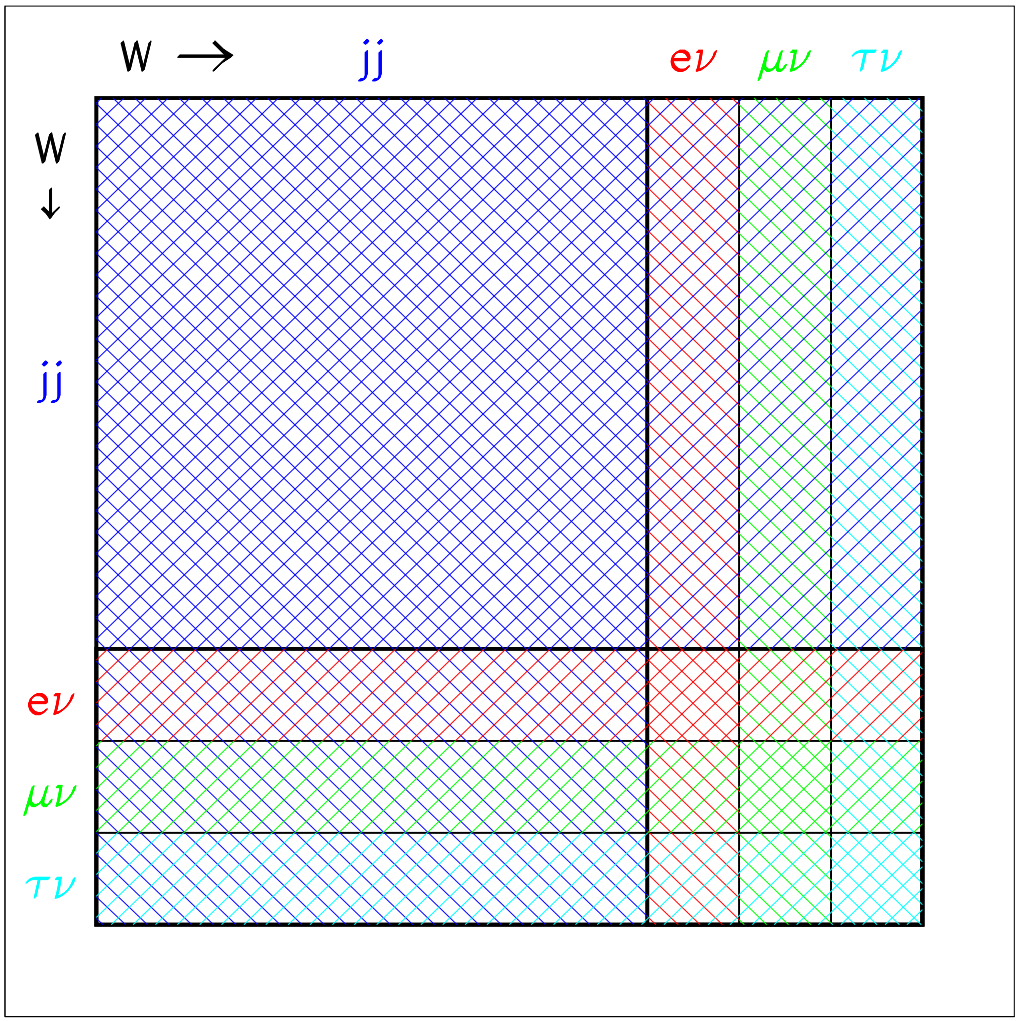
- At a lepton collider, top quarks are produced in pairs via electroweak interactions



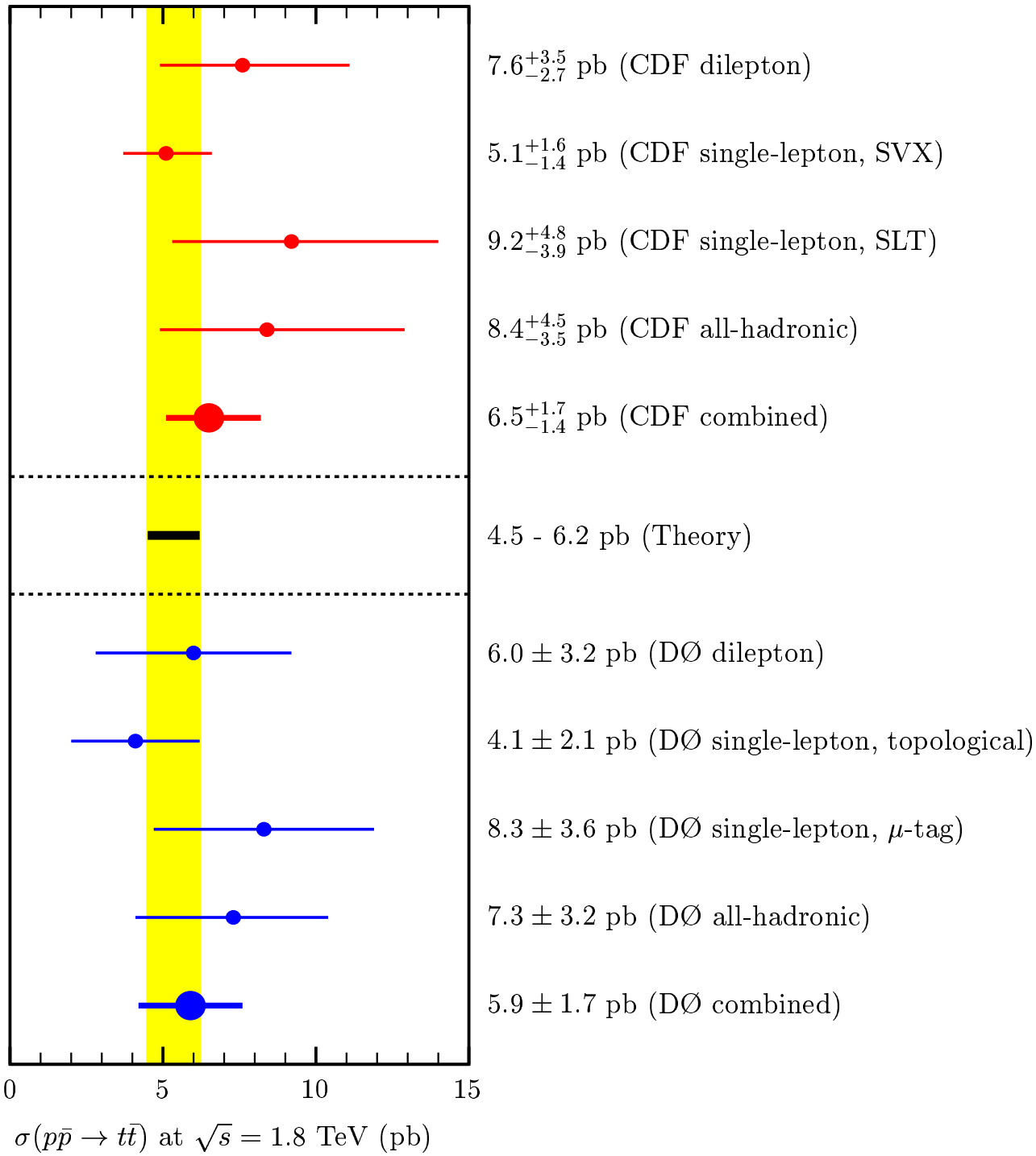
- Although the cross section for this process is much smaller, it has many desirable features. Electroweak interaction $\Rightarrow$
  - Fewer events, but background-free. No triggering necessary, all events are recorded.
  - No initial-state radiation, spectator interaction, multiple collisions. One clean event can be better than a hundred dirty ones.
  - Energy and polarization of colliding partons can be precisely controlled: extremely useful for precision measurements of mass, width, coupling parameters.
  - Events can be fully reconstructed.
  - Unique sensitivity to some new physics scenarios through production cross section, kinematics, and decays.

The final state signature of $t\bar{t}$ events

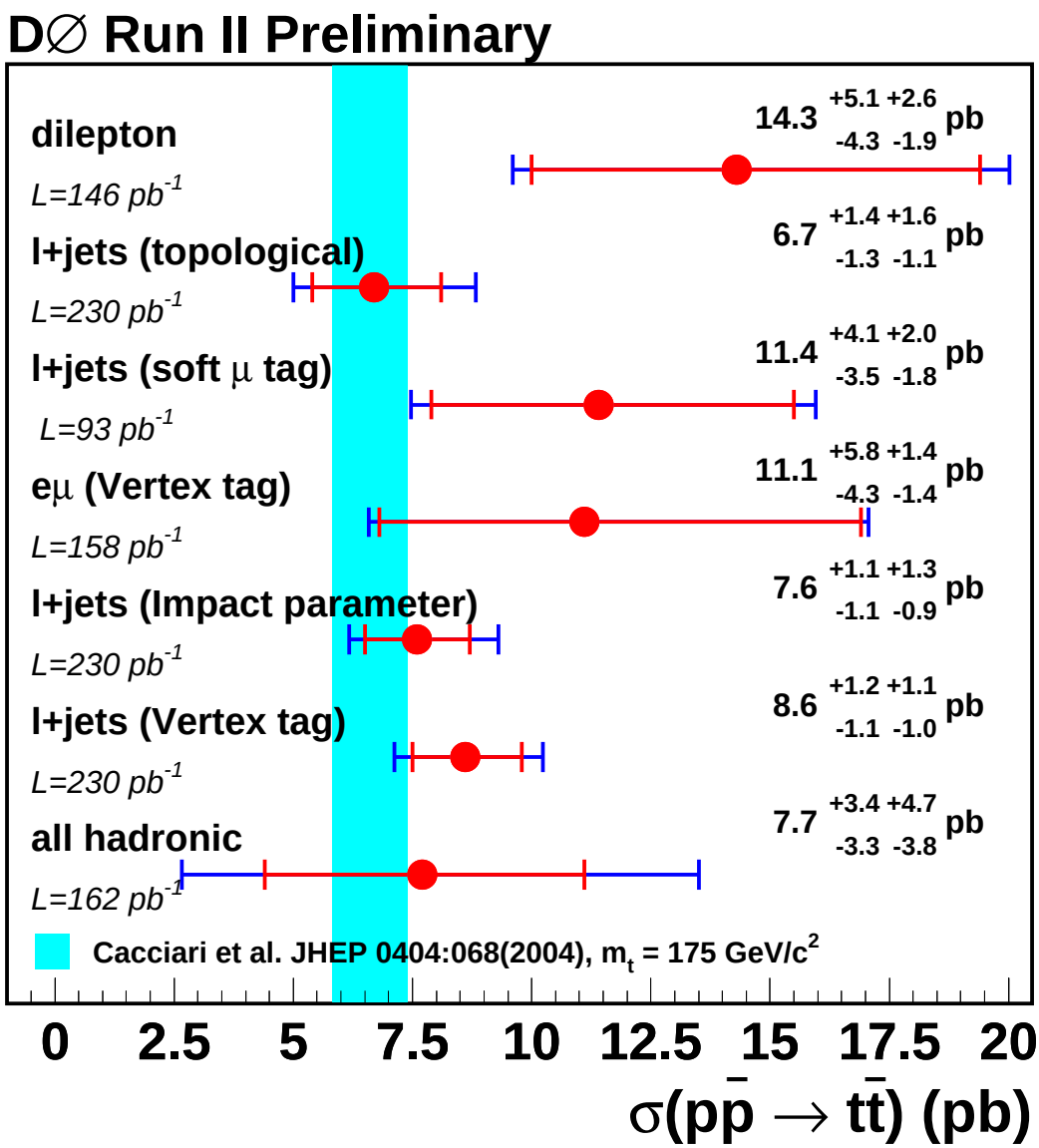
- In the SM, each top quark decays into a W boson and a b quark.
- The final state of a $t\bar{t}$ system is primarily classified by the decay modes of the two W bosons:



$\sigma(p\bar{p} \to t\bar{t})$ from Tevatron Run 1

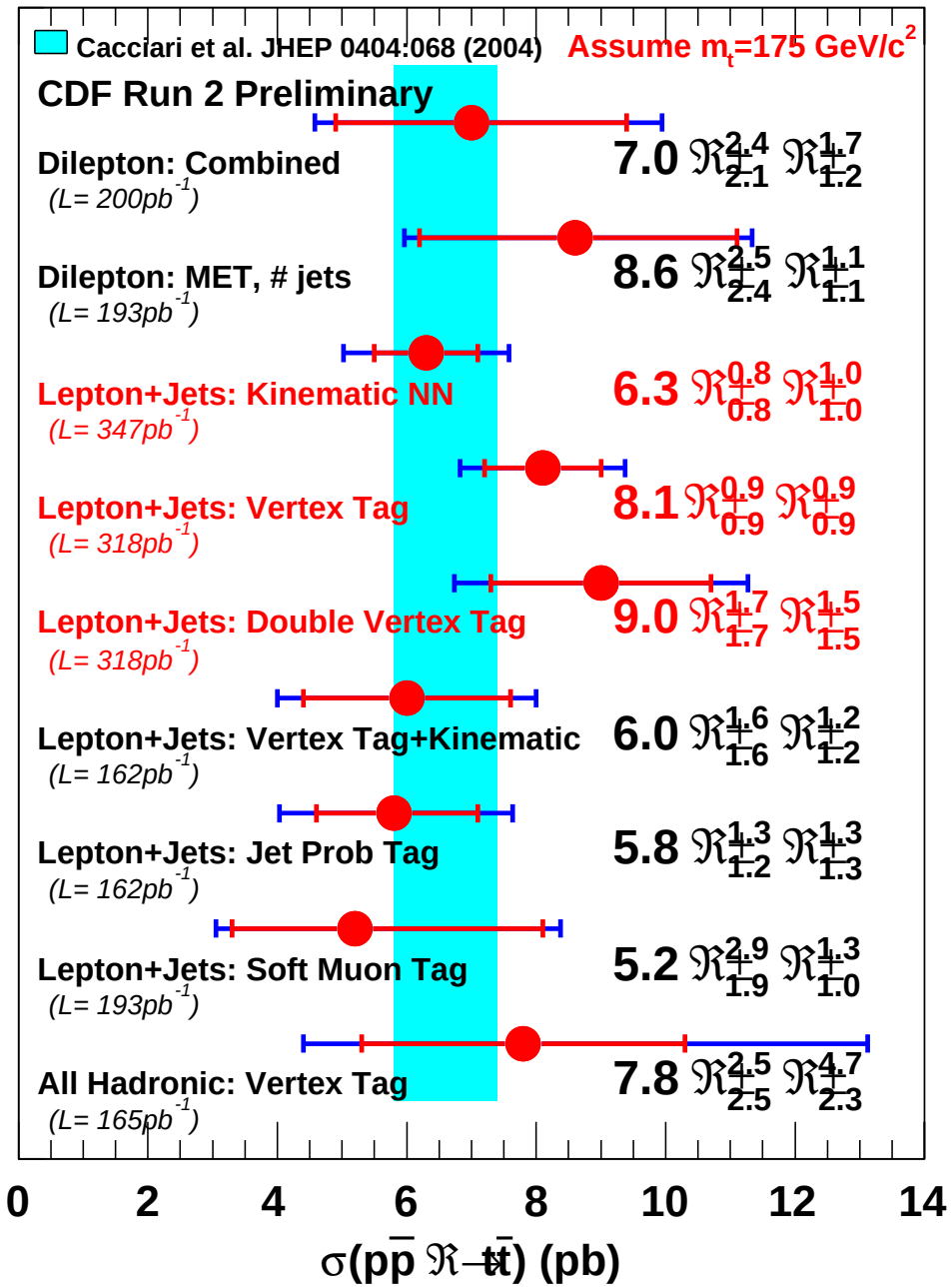


$\sigma(p\bar{p} \to t\bar{t})$ from DØ Run 2



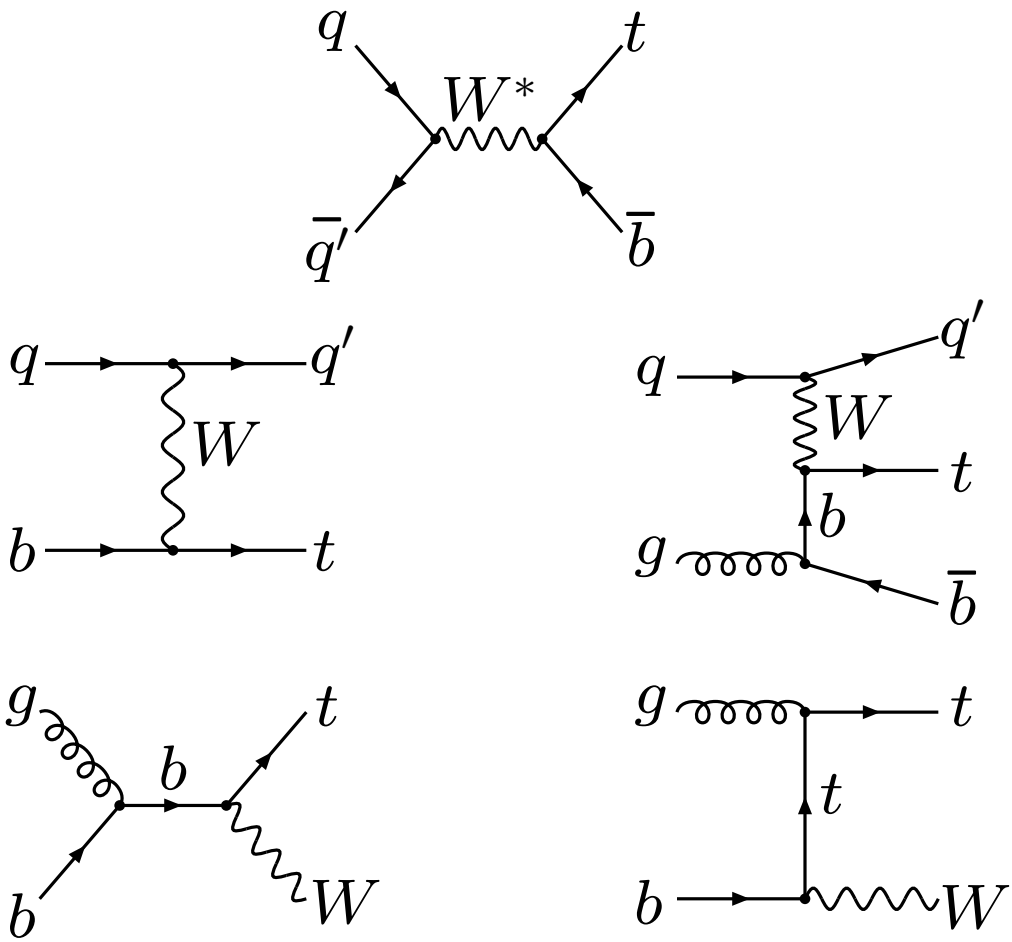
The uncertainty in theoretical calculations (full NLO+NLL or partial NNLO+NNLL) is due primarily to the renormalization scale (through $\alpha_s(\mu_r^2)$), the factorization scale (through $f_i(x_i, \mu_f^2)$), and $t\bar{t}$ kinematics.

$\sigma(p\bar{p} \to t\bar{t})$ from CDF Run 2



2.2. Single Top Production

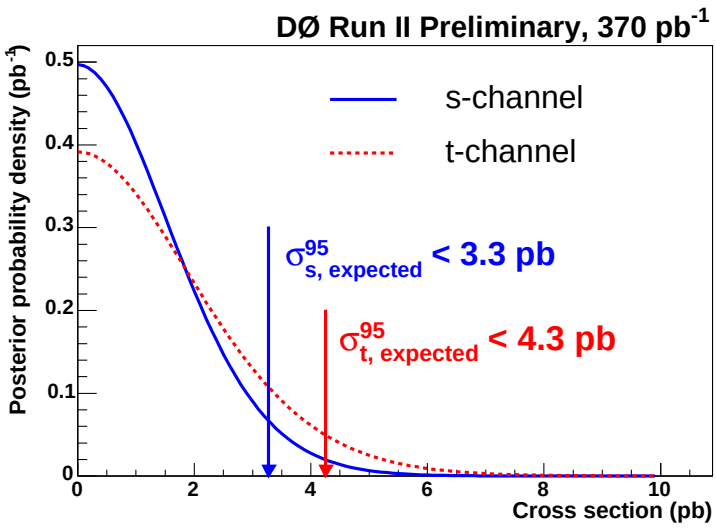
- At hadron colliders, top quarks can be produced singly via weak interactions.

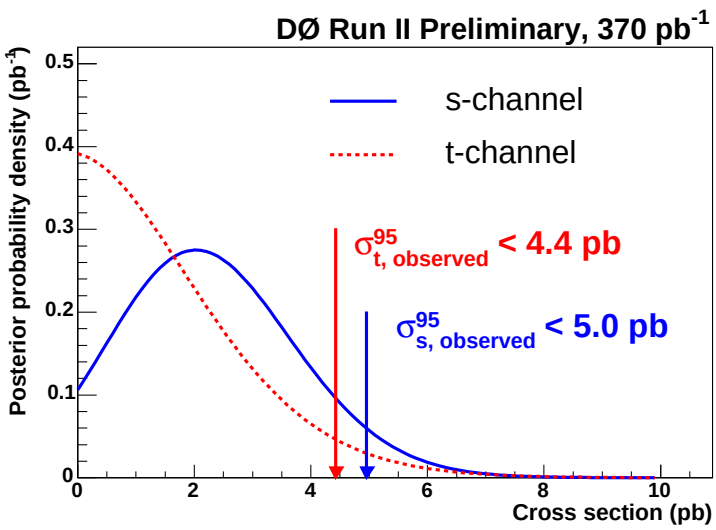


- Such events occur less than half as frequently as $t\bar{t}$ and the signal is more difficult to extricate from background.

- Rate and kinematics are direct probe of Wtb vertex in general and $|V_{tb}|$ in particular
  - All cross sections are proportional to $|V_{tb}|^2$.
  - $V - A$ structure of SU(2)$_L$ weak interaction $\Rightarrow$polarized production of top.
- Important background to WH production followed by $H \longrightarrow b\bar{b}$.
- Theoretical predictions:

Process	Tevatron Run 2	LHC (t)	LHC ($\bar{t}$)
$\sigma^{NLO}_{s-\text{chan}}$ (pb)	0.447 ± 0.002	6.55 ± 0.03	4.07 ± 0.02
$\sigma^{NLO}_{t-\text{chan}}$ (pb)	0.959 ± 0.002	152.6 ± 0.6	90.0 ± 0.5
$\sigma^{LL}_{\text{assoc.}}$ (pb)	0.093 ± 0.024	31^{+8}_{-2}	31^{+8}_{-2}





Upper limits from Tevatron (pb, 95% CL)

	CDF	DØ
$\sigma(tb)_{s-\text{channel}}$	3.2	5.0
$\sigma(tqb)_{t-\text{channel}}$	3.1	4.4
$\sigma(tb)_{s+t}$	3.4	

2.3. Sensitivity to New Physics

- Heavy scalar or vector bosons, both charged and neutral, fundamental and composite, appear in all extensions of the SM. ⇒new ways for both pair- and single-top production.
  - Neutral bosons (Z', ϕ^0, η_T) alter $\sigma(t\bar{t}X)$.
  - Charged bosons (W', $\phi^\pm$, $\pi_t^\pm$) alter $\sigma(tX)$.
- Since these models seek to explain why the top quark is so heavy, implications are usually stronger for top than for other fermions.
- Precision measurement of the cross sections and comparison with SM predictions allows us to constrain or discover such processes.
- We have found no significant deviation from the SM so far, but large uncertainties in both theoretical calculations and experimental measurements lead to rather weak constraints on parameters of new physics models.
- Some of these processes can hide behind the large background at hadron colliders (Tevatron, LHC), but will be easily detected at a lepton collider (ILC).

3. Decays of Top Quarks

3.1. SM decays

- The SM predicts $B(t \to Wb) > 0.998$.
- The rest goes to off-diagonal CKM modes, $t \to Wq$, where $q = s, d$. (more later).
- Flavor-changing neutral current (FCNC) decays, $t \to X^0 q$, where $X^0 = g, \gamma, Z, H$, are highly suppressed by the GIM mechanism. Branching fractions are $\mathcal{O}(10^{-13})$ - not accessible in the foreseeable future.
- Current direct limits on FCNC decays of top from Tevatron (CDF, Run 1):
  - $B(t \to c\gamma) + B(t \to u\gamma) < 0.032$,
  - $B(t \to cZ) + B(t \to uZ) < 0.33$,
- Expected from LHC: $\sim 2 \times 10^{-4}$ for both.
- Few extensions of the SM predict FCNC t decays at such high levels. Still, we need to stay alert...

W helicity in top decays

- In SM, $t \to Wb$ decays are described purely by the universal $V - A$ charged current interaction.
- The W is "real" in a top decay $\Rightarrow$distinctive helicities. Decay to a positive-helicity W boson is suppressed by a chiral factor m_b^2/M_W^2. So, the W helicity is essentially a superposition of only the zero- and negative-helicity states.
- At tree level in the SM, ignoring m_b, the fraction of longitudinal (zero-helicity) W bosons in the top rest frame is:

$$\mathcal{F}_0 = \frac{m_t^2/M_W^2}{1 + m_t^2/M_W^2} = 0.701 \pm 0.016 \tag{1}$$

- Finite m_b and NLO effects $\Rightarrow\sim$2% change.
- The large top mass exposes the longitudinal mode of the W $\Rightarrow$precise measurement of $\mathcal{F}_0$ serves as a stringent test of the SM.
- Indirect limit from $b \to s\gamma$ data (CLEO) constraints $\mathcal{F}_+$ to a few %.

- Angular distributions of decay products are sensitive functions of the $\mathcal{F}$'s.
- DØand CDF have measured the $\mathcal{F}$'s in dilepton and single-lepton channels using several strategies ($\mathcal{F}_+ = 0$ assumed for measurements of $\mathcal{F}_0$):

Expt(Run)	Method	Result
CDF(1)	$p_T(\ell)$	$\mathcal{F}_0 = 0.91 \pm 0.37 \pm 0.13$, $\mathcal{F}_+ < 0.28$ (98% CL)
CDF(1)	$M^2(\ell b)$	$\mathcal{F}_+ < 0.24$ (95% CL)
DØ(1)	ME	$\mathcal{F}_0 = 0.56 \pm 0.31$
CDF(2)	$\cos\theta^*$	$\mathcal{F}_0 = 0.61 \pm 0.12 \pm 0.04$, $\mathcal{F}_+ < 0.11$ (95% CL)
CDF(2)	$M^2(\ell b)$	$\mathcal{F}_+ < 0.09$
DØ(2)	$\cos\theta^*$	$\mathcal{F}_+ = 0.056 \pm 0.080 \pm 0.057$ $\mathcal{F}_+ < 0.23$ (95% CL)

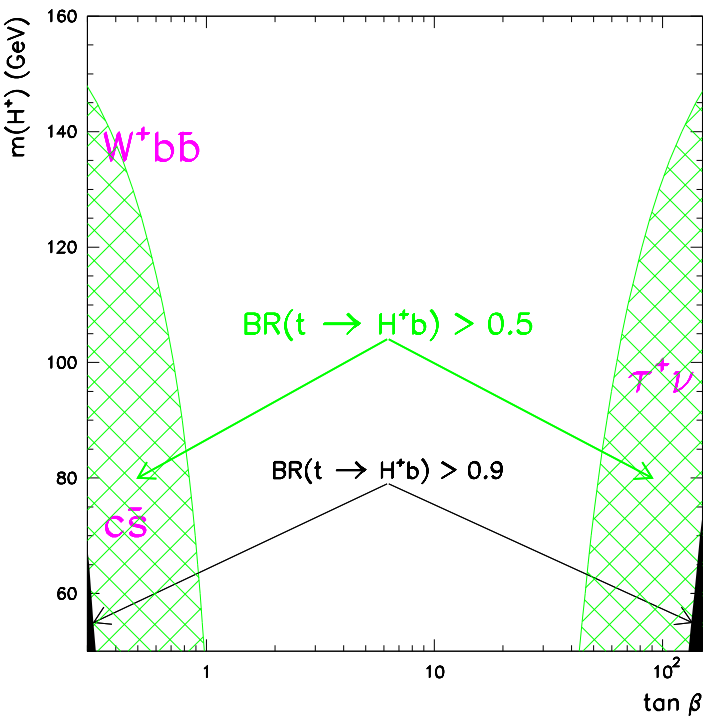
- The statistical uncertainty will be reduced by an order of magnitude by the end of Run 2, and to negligible levels at the LHC and the ILC.

3.2. Top Quark Decays Beyond the SM

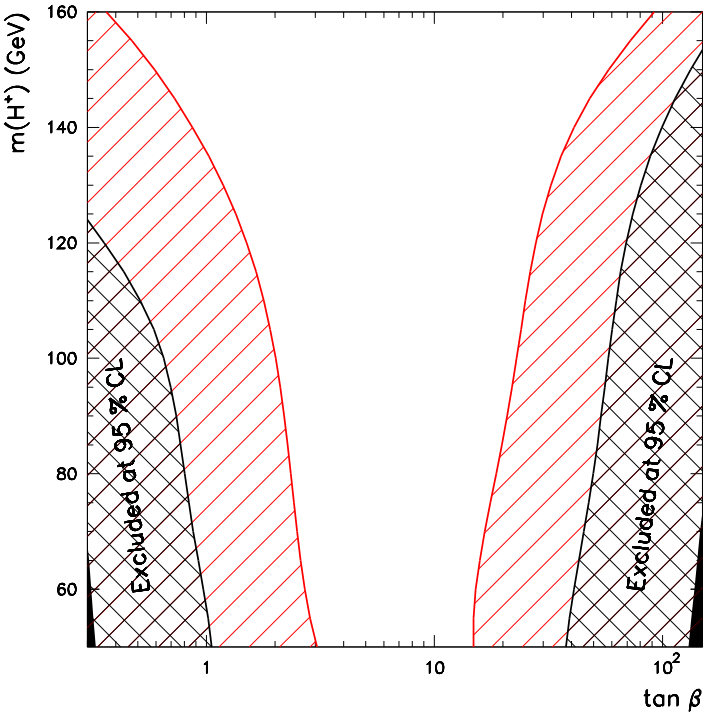
- In virtually every extension to the SM, alternative possibilities arise to compete with the SM modes:
  - Extended Higgs sector $\Rightarrow t \to H^+ b$,
  - SUSY $\Rightarrow t \to \tilde{t}\tilde{\chi}_1^0$,
  - TC2 $\Rightarrow t \to \pi_t^+ b$.
- In all cases, the coupling depends on fermion mass, or flavor, or both $\Rightarrow$look in data for deviations in the production rates and branching fractions from those predicted by the SM.
- Both appearance of new modes or enhancement over SM-predicted values, and disappearance of SM modes (to make way for new ones that may be hidden in excessive background) have been searched for by DØand CDF for some of the more popular scenarios.
- Often, there are too many free parameters, and one is forced to make "reasonable" assumptions about some of them in order to pin down the rest ...

Search for $t \to H^+ b$

- The Standard Model postulates one complex scalar (Higgs) doublet. After 3 of its 4 degrees of freedom are expended in giving mass to the $W^\pm$ and Z^0 bosons, one manifests itself as a physical particle: H^0.
- The simplest extension to the SM $\Rightarrow$a two-Higgs-doublet models (2HDM), resulting in five physical Higgs bosons: $H^0, h^0, A^0, H^\pm$.
- The electroweak sector in a 2HDM has 2 additional parameters: $\tan\beta$, M_{H^+} (or M_A), where $\tan\beta \equiv$ ratio of V.E.V.'s of the two doublets.
- If $M_{H^+} < m_t - m_b$, and $\tan\beta$ is not too close to $\sqrt{\frac{m_t}{m_b}}$, then $t \to H^+ b$ can compete with $t \to W^+ b$.
- Such a $H^\pm$ is not expected to noticeably alter the top production cross sections at any collider, but decays will be affected since Higgs coupling is proportional to mass.

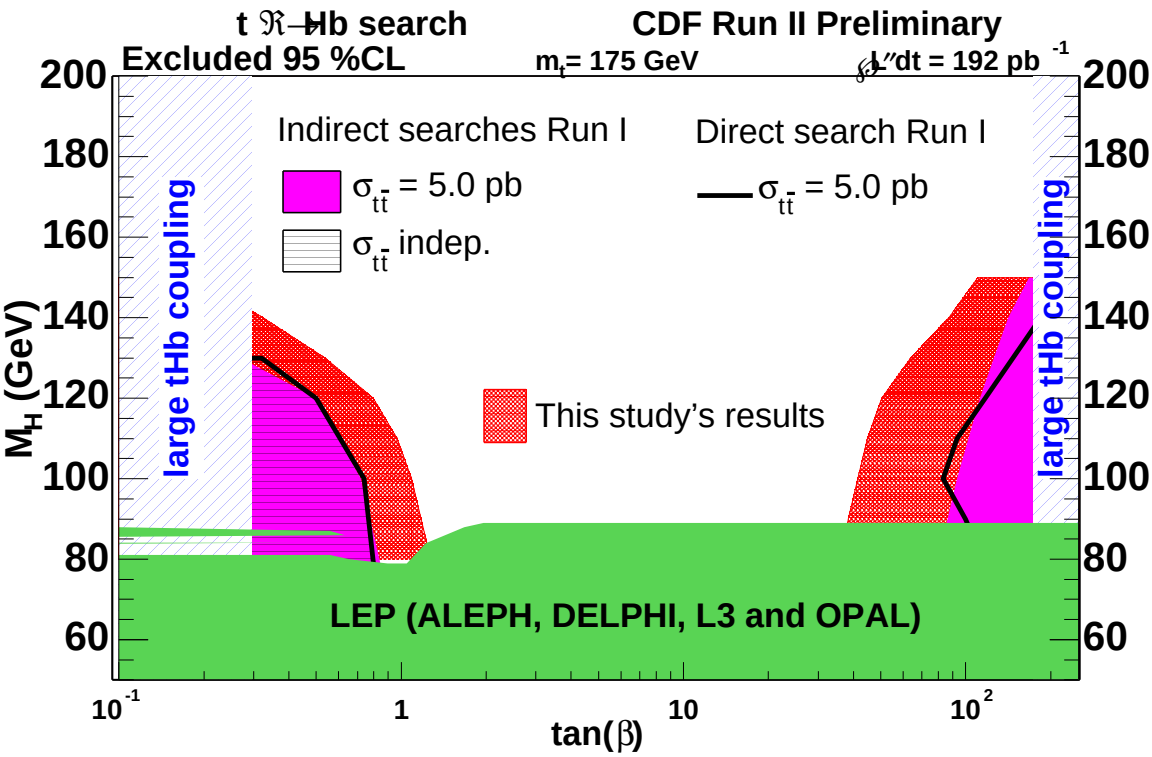


Disappearance search results from DØRun1:



The Run 1 (Run 2 expected) limit corresponds roughly to $B(t \to H^+b) < 0.45(0.11)$ at 95% CL, except where $Wb\bar{b}$ dominates.

Run 1 and preliminary Run 2 results from CDF:



- No sign of a light charged Higgs as yet.
- Some assumptions that went into in these analyses need closer scrutiny …
- …work in progress on several analyses.
- If $M_{H^+} > m_t$, $\sigma(p\bar{p} \to H^+X)$ is too small at the Tevatron, but not at the LHC.
- $pp \to H^+H^- \to t\bar{b}\tau\bar{\nu}_\tau$ is probably the most promising channel to search for a heavy charged Higgs at the LHC.

Supersymmetric Decays of the Top Quark

- The lightest stop, $\tilde{t}_1$ is thought likely to be the lightest squark, possibly lighter than top.
- This opens the possibility of $t \to \tilde{t}\tilde{\chi}_1^0$, which can end in either $bq_1\bar{q}_2\tilde{\chi}_1^0\tilde{\chi}_1^0$, or $c\tilde{\chi}_1^0\tilde{\chi}_1^0$, depending on the superparticle masses and couplings.
- Since the branching fraction cannot be too large, it is best to look for events where precisely one of the top decays in the new way.
- The final state objects are the same, but angular and momentum spectra are different.
- Unfortunately, often the new signatures face worse background than SM.
- Early results show nothing unusual, but they're pretty weak. Our main goal at this time is to understand the issues and set up the procedure. Stringent results will have to await high-volume (LHC) and/or ultra-clean (ILC) data.

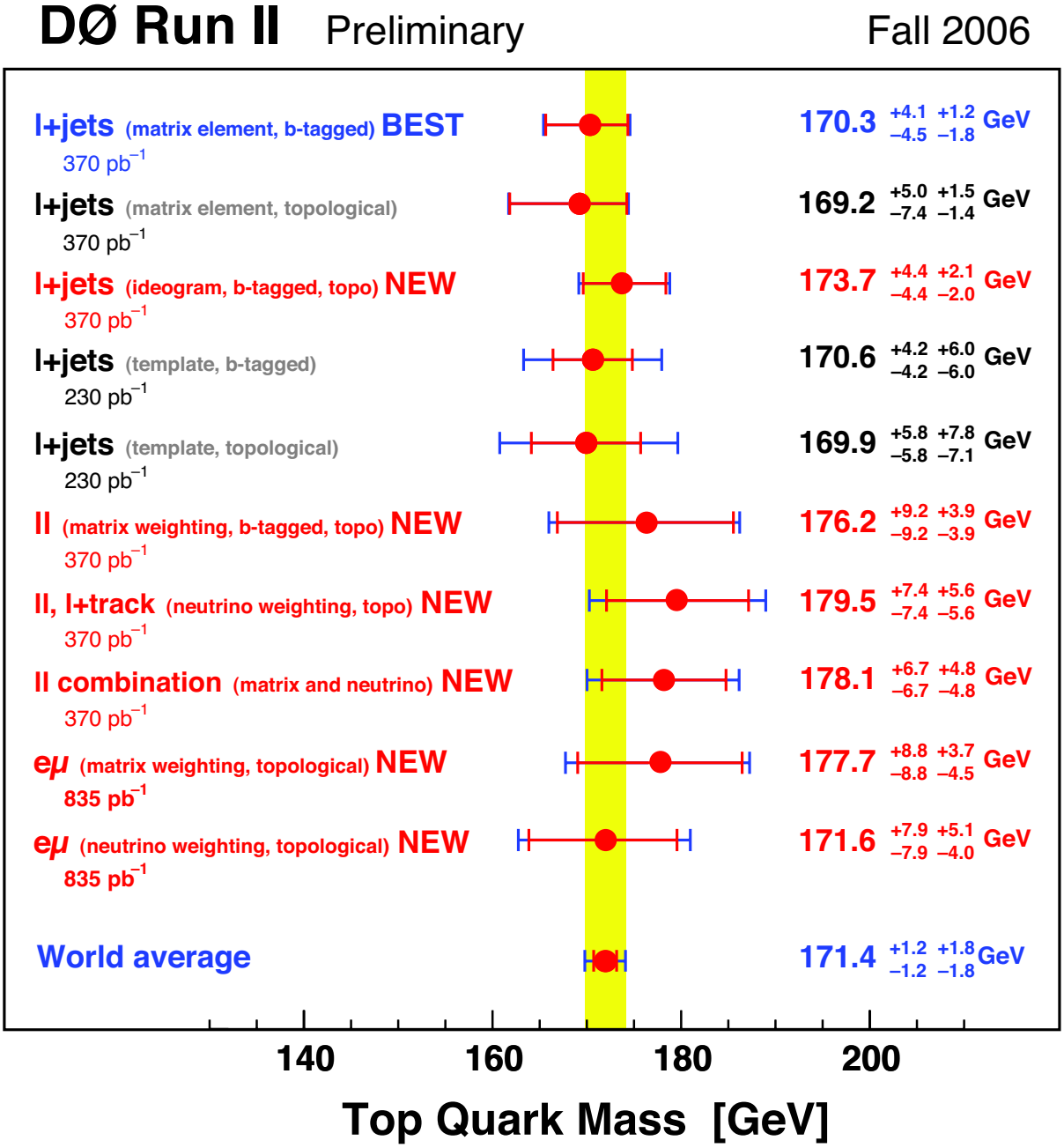
4. Top quark properties

4.1. Mass

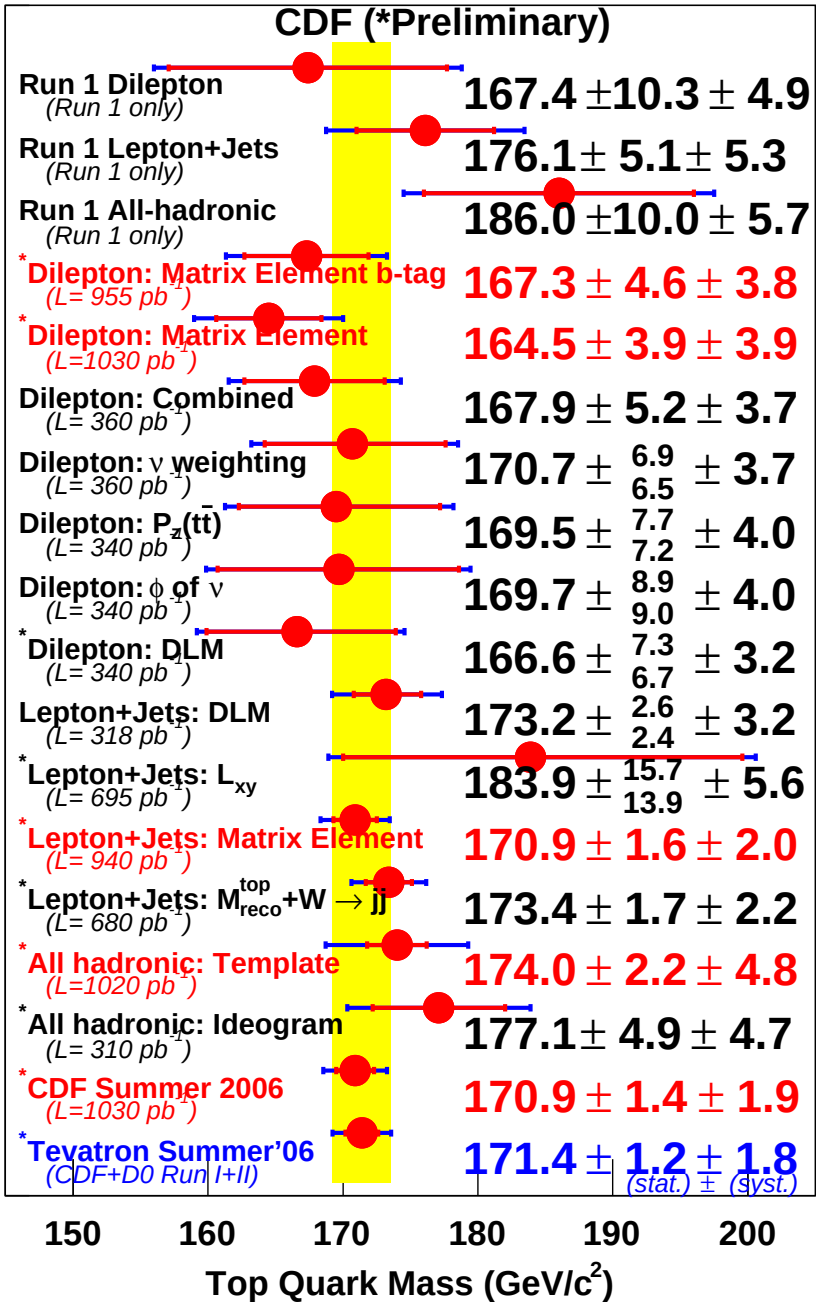
General procedure

- Event selection and background estimation is similar to those for $\sigma(t\bar{t})$ measurement, but any associated bias on m_t must be carefully accounted for.
- Examine strongly m_t-dependent variables (reconstructed m_t, if available, is a natural choice).
- Using simulated signal templates for different values of m_t, determine which one best fits the excess of data over background.
- Combinatorial ambiguities, compounded by extra jets from initial- and final state radiation, or occassional loss of a jet, pose difficulties.
- Weighing each candidate and each interpretation of it differently, depending on how well it fits signal and background hypotheses, affords the best measurement, but the procedure is quite complex.

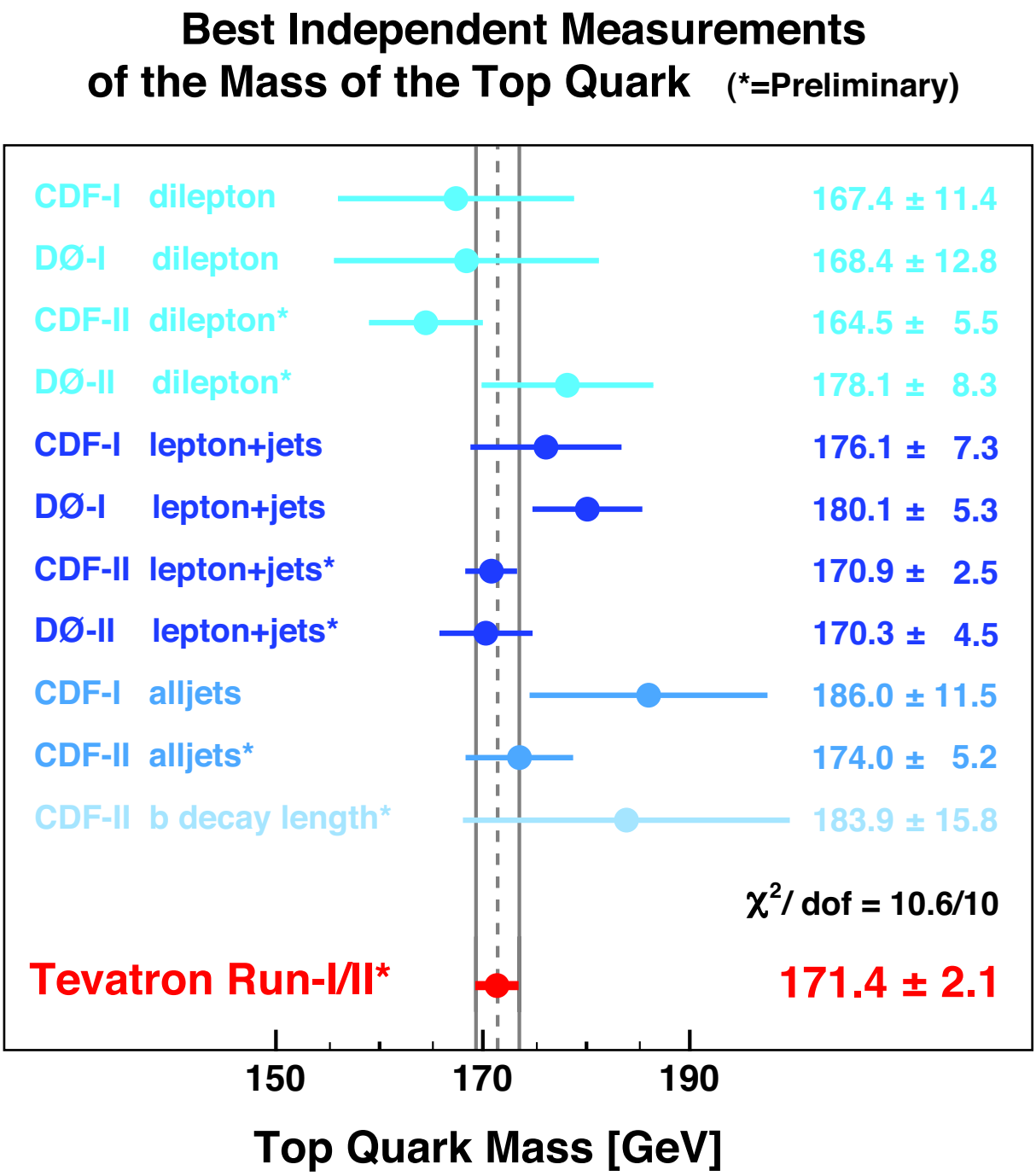
Latest m_t results from DØ



Latest m_t results from CDF



Combined m_t results from Tevatron



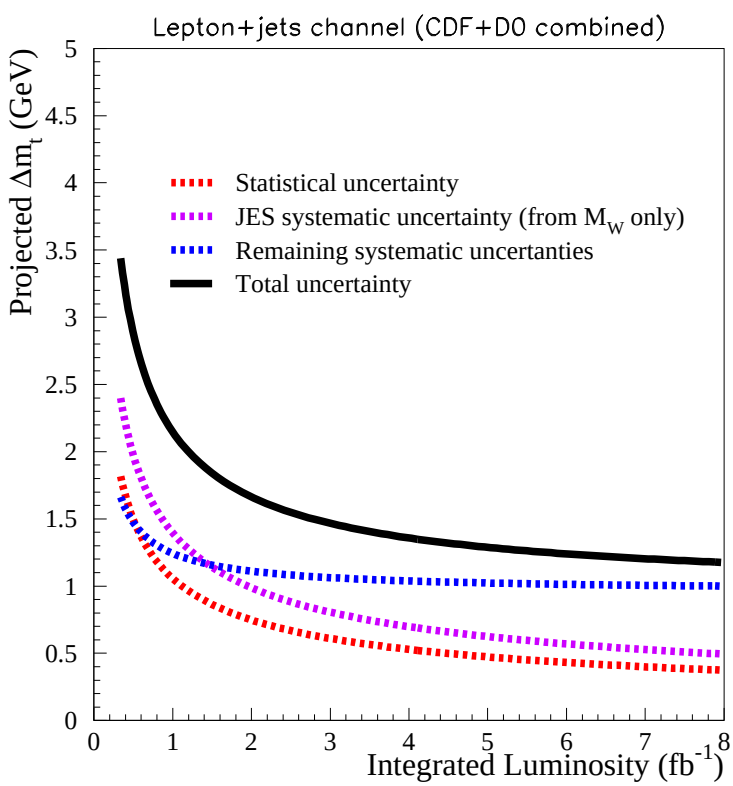
Present and future of top mass measurement

- Measuring m_t, together with M_W, is vitally important in order to constrain M_H.
- Top mass has now been determined to 1.2%.
- It is still limited by statistics. Some of the systematics will improve with statistics.
- Matrix-element method will further reduce the statistical uncertainty.
- Combining different channels and results from DØand CDF will help too.
- By the end of Run 2, we hope to bring the total uncertainty to less than 1.5 GeV.
- More precise but rarer final states ($b \to \psi \to \ell^+\ell^-$) will be accessible to the LHC experiments. These combined with end-point fits (another luxury afforded by huge statistics) could allow for $\sim$1 GeV precision in m_t from experiment. Note: $\frac{\delta\sigma(t\bar{t})}{\sigma(t\bar{t})} \approx 5\frac{\delta m_t}{m_t}$ at LHC.
- Theoretical uncertainties, owing to incompleteness of radiative corrections, are $\sim$1.5 GeV. These are very difficult to reduce.

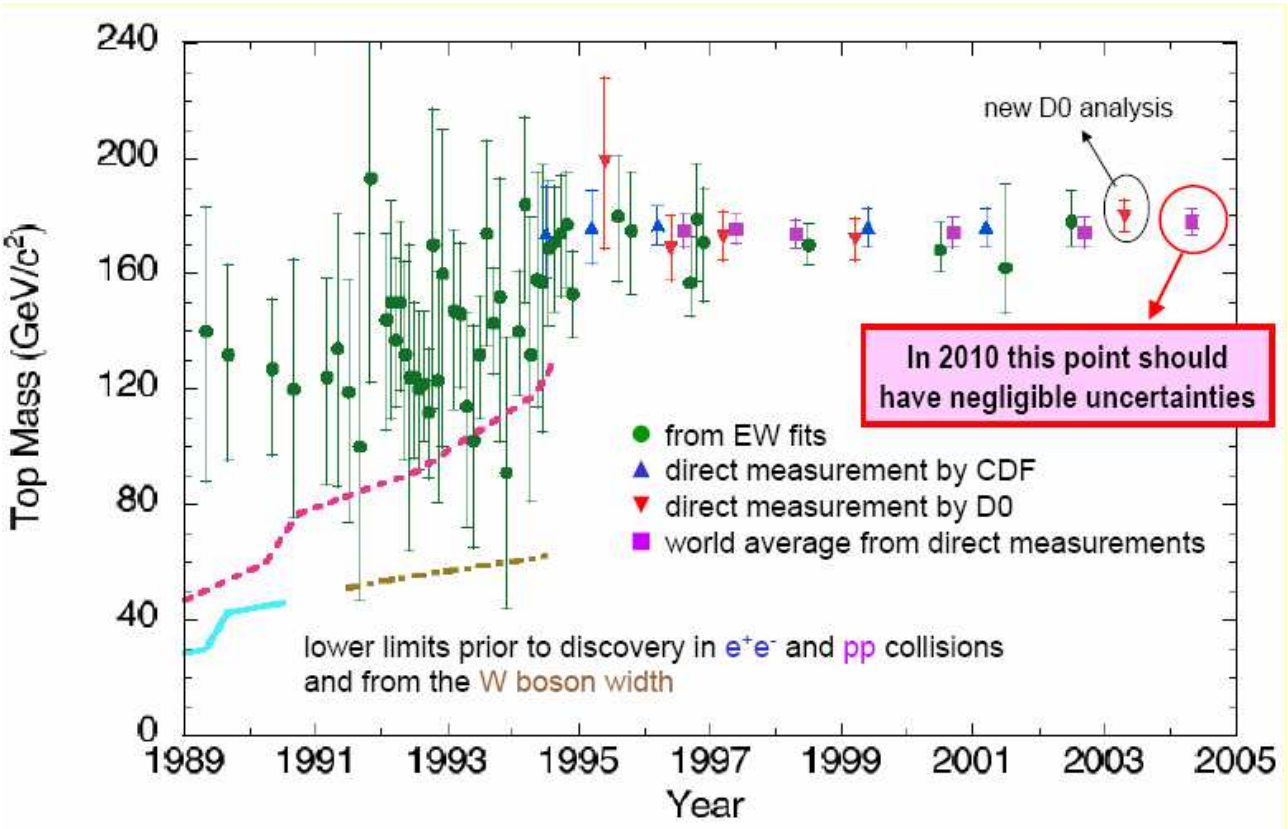
- At the ILC, threshold scans, full event reconstruction, and cleaner events, precise theoretical calculation of many sensitive variables $\Rightarrow$measurement of m_t within $\mathcal{O}(100)$ MeV.

Expected precision of m_t, M_W measurements:

Collider	Tevatron	LHC	ILC
type	$p\bar{p}$	pp	e^+e^-
δm_t (GeV)	< 1.5	< 1	0.1
δM_W (MeV)	26	9	1

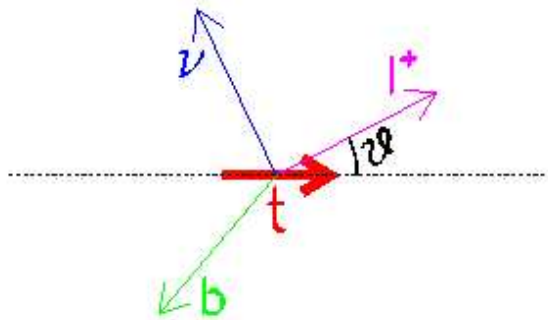


History of top mass measurements



4.2. Spin

- Decay before hadronization ⇒spin at production reflected on angular distribution of decay products.
  - No other quark decays quickly enough.
- At Tevatron and LHC, the colliding particles are unpolarized, so the spin of each top considered separately is random, but the spins of the top and the antitop in a given event are correlated.
- At the ILC, with polarized beams, the spin of each top quark, as well as the correlation, can be studied.
- The charged lepton and down-type quarks are most sensitive, but it is difficult to uniquely identify the latter ⇒only the dilepton and single-lepton channels are useful.
- A good test for Wtb coupling. A significant departure from the SM prediction could point to new physics.



Differential decay rate of top quark:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_i)} = \frac{1+\alpha_i\cos\theta_i}{2} \qquad (2)$$

particle (i)	α_i for m_t = 175 GeV
e^+ or d	1
ν or u	-0.31
W^+	0.41
b	-0.41

- For $t\bar{t} \to l^+l^-X$ events at the Tevatron, one studies the double-differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}. \qquad (3)$$

- All spin-correlation information is in κ.

- Within large statistical uncertainties, current measurements (from Run 1) are consistent with the SM predictions. The method has been established, vastly improved results are expected soon.

4.3. Charge

- Some theorists contend that the observed "top" could be an exotic quark with $Q = -\frac{4}{3}$.
- The only way to check this at hadron colliders is to compare the observed rate and kinematics of $t\bar{t}\gamma$ events with SM predictions.
- Either way, the rate is too low for a definitive test at the Tevatron.
- At the LHC, the issue can be resolved with 4-6 months of data ($\sim$10 fb^{-1}).
- At the ILC, $\sigma(t\bar{t})$ is extremely sensitive to Q_t. The debate can be settled with less than 1 hour of data.

4.4. Gauge couplings

- It is important to measure the top quark's coupling to the SM gauge bosons: g, $W^{\pm}$, Z, and γ, lest anomalous couplings, which may or may not involve new particles, go undetected. Search for CP violation in the top sector is normally addressed in this language.
- Couplings to g and $W^{\pm}$ are fairly well tested already at the Tevatron, and will continue to be refined through studies of pair- and single-top production, kinematics, spin correlations, W helicity, etc.
- Couplings to Z and γ are harder to study at hadron colliders, but will be possible with sufficient statistics at the LHC.
- The ILC will offer high-precision tests of all of top quark's gauge couplings, especially the electroweak.

4.5. Lifetime and V_{tb}

- The CKM matrix element V_{tb} is intimately related to the top quark lifetime. At LO,

$$\Gamma\left(t \to Wb\right) = \frac{G_F}{8\pi\sqrt{2}} m_t^3 \left|V_{tb}\right|^2 \left(1 - 3\,\frac{M_W^4}{m_t^4} + 2\,\frac{M_W^6}{m_t^6}\right) = 1.56\,\mathrm{GeV} \tag{4}$$

  where $\Gamma = \frac{\hbar}{\tau}$ is the width, and τ the lifetime, of the top quark.

- At NLO, $\Gamma_t = 1.42$ GeV.

- Indirect measurements assuming 3 generations of quarks lead to $0.9990 < |V_{tb}| < 0.9993$.

- Direct tests without the 3-generation assumption has been carried out at the Tevatron, by measuring

$$R \equiv \frac{B(t \to bW)}{B(t \to qW)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} \tag{5}$$

- Run 2 results

	CDF	DØ
R	$0.94^{+0.21+0.17}_{-0.19-0.13}$	$1.03^{+0.19}_{-0.17}$
R_{min} (95% CL)	0.61	0.61
$\lvert V_{tb}\rvert_{\text{min}}$ (95% CL)		0.78

- We expect R to be measured within 5% at the Tevatron, and within 3% at the LHC, which translates, assuming SM gauge couplings, to 12% and 5%, respectively, on $|V_{tb}|$.

- At the ILC, direct measurement of $\Gamma(t)$ from threshold scans should have a precision of $\mathcal{O}(1\%)$.

4.6. Yukawa couplings

- Yukawa couplings relate the matter content of the SM to the source of mass generation, the Higgs sector.

- When the Higgs field acquires a vacuum expectation value v, the top quark is endowed with a mass $m_t = \frac{Y_t v}{\sqrt{2}}$. Since $v = 246$ GeV and $m_t \approx 174$ GeV, $Y_t = 1$, a theoretically interesting value, leading to speculation that new physics studies of the top quark may open a door to new physics.

- The ttH coupling can be accessed through
  - $gg \to H$ (through a top-quark loop),
  - $gg \to tH$,
  - $gg \to ttH$.

- Unfortunately, the first suffers from overwhelming background, and the cross sections are too low for the other two at the Tevatron.

- Even at LHC, strong cancellations will limit the reach to light Higgs only (which, however, is strongly favored by the current measurements of m_t and M_W).

- Measurements of Higgs branching fractions based on large samples may prove more fruitful.

- Strong constraints can be put on models where $Y_t \gg 1$.

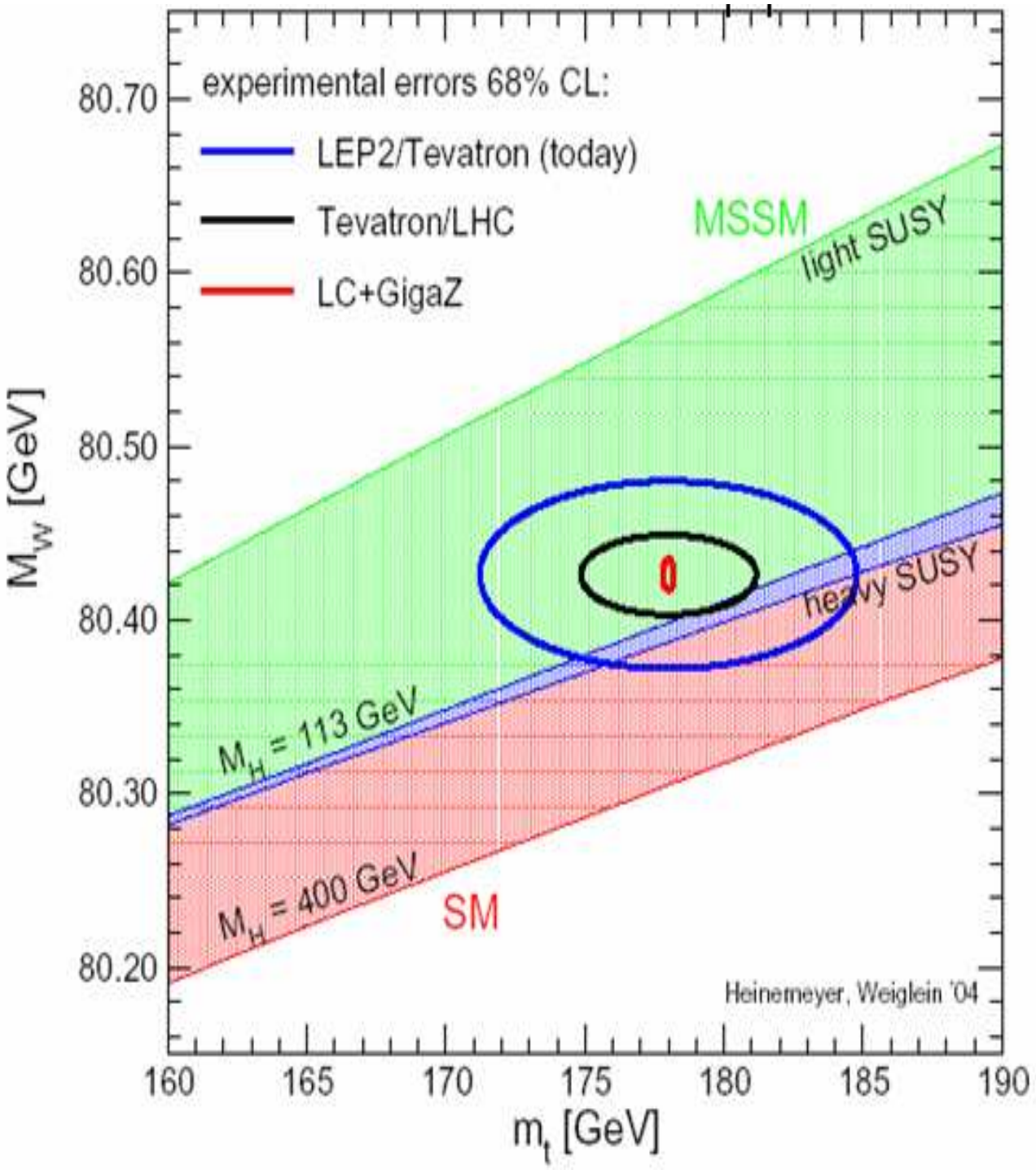
- Unless M_H is too large, precision measurements at the ILC of Higgs production and decay properties will yield the best results on Y_t.

Summary and Outlook

- Using 0.5 - 1 fb^{-1} of data collected at the Fermilab Tevatron, both DØand CDF have studied several aspects of top physics including measurements of its pair-production cross section and mass, several tests of the SM Wtb coupling, and some searches for physics beyond the SM.
- The mass of top quark has been determined within 1.2%, the most precise of all quarks.
- Within large statistical uncertainties, single top production, top-antitop spin correlation, and W helicity measurements agree well with the SM predictions.
- A search for charged Higgs bosons reveals no signal, and rules out a large part of previously unexplored parameter space.
- Results from searches for flavor-changing neutral currents in decays of the top quark are consistent with the SM.
- $M_{Z' \to t\bar{t}} < 680$ GeV excluded at 95 % CL.

We look forward with great expectations to the completion of Run 2 of the Tevatron, the LHC (2007-), and eventually the ILC (2015?-). Together, these enterprises will help us gain a better understanding of the workings of Nature.

"In physics, one discovery often leads to others. Top opens a new world – the domain of a very heavy fermion – in which the strange and wonderful may greet us."


experimental errors 68% CL:
LEP2/Tevatron (today)
Tevatron/LHC
LC+GigaZ
MSSM
light SUSY
heavy SUSY
M_H = 113 GeV
M_H = 400 GeV
SM
Heinemeyer, Weiglein '04
M_W [GeV]
m_t [GeV]
80.70
80.60
80.50
80.40
80.30
80.20
160
165
170
175
180
185
190