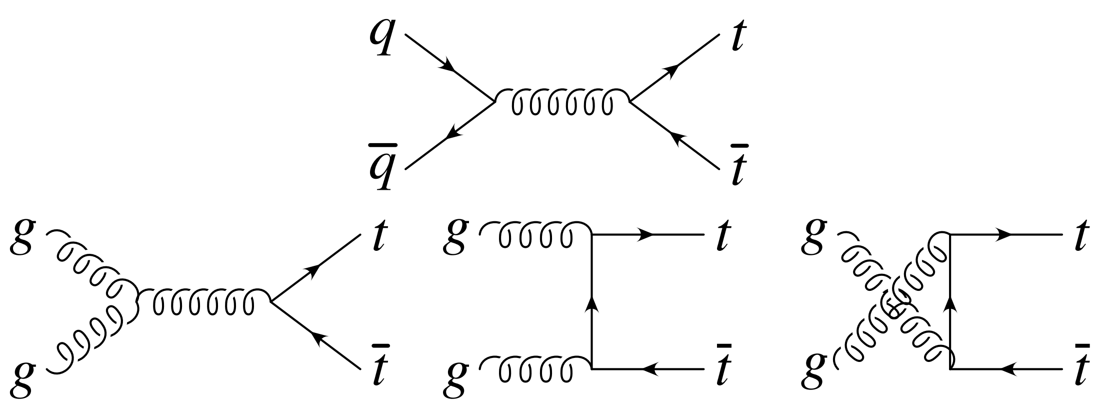
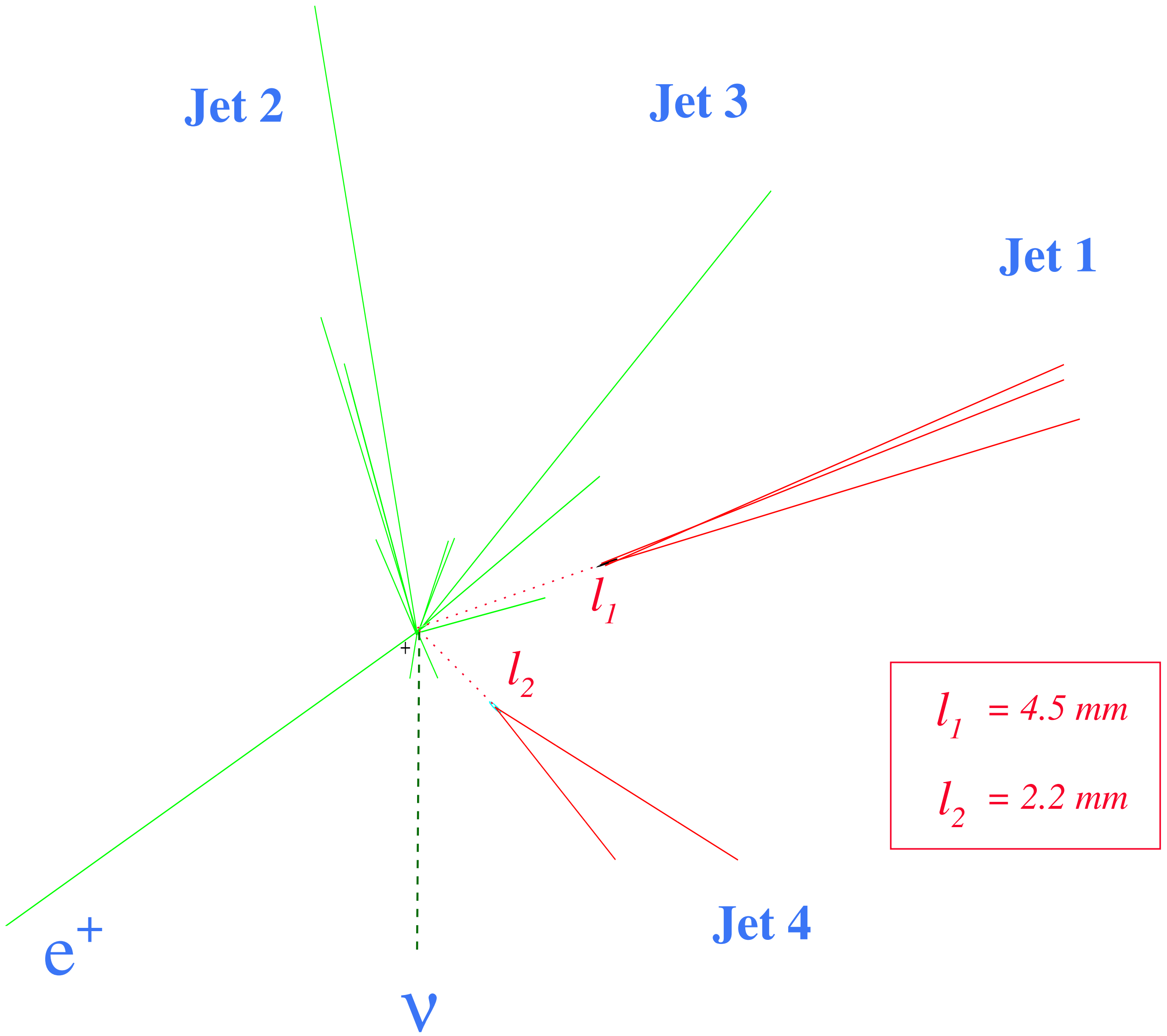
THE TRUTH ABOUT $t\bar{t}$ PRODUCTION



Zack Sullivan
Southern Methodist University

“This is the top quark.”



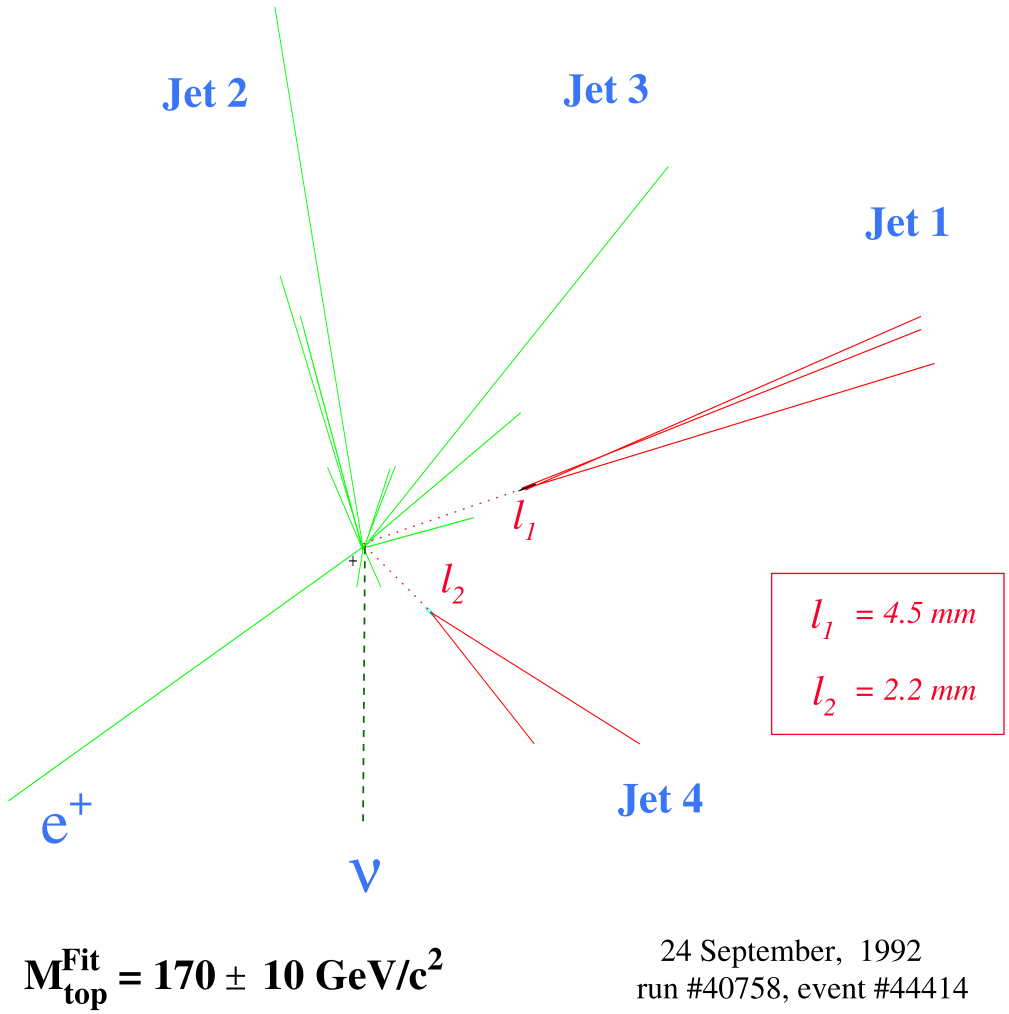
$$M_{top}^{Fit} = 170 \pm 10\ \mathrm{GeV}/c^2$$

24 September, 1992
run #40758, event #44414

Contents

What we want to know

1. m_t: Top-quark mass
   — and EW physics
2. $\sigma_{t\bar{t}}$: Top-quark cross section
   — threshold region
   — new physics
3. y_t: Top-quark Yukawa
   — $t\bar{t}H$ and tH^-
4. $\vec{s}_t$: Top decay and spin
   — longitudinal W-bosons



Of course the top had been found before. . .

IT IS LIKELY THAT $m_t \leq m_W$

F. Halzen*)

CERN - Geneva

Phys. Lett. B 182, 388 (1986)

A B S T R A C T

Within the standard model with three generations, the experimental data on the rate of W versus Z events in $p\bar{p}$ collisions favour $m_t < m_W$. The bound is sharpened for $N_\nu > 3$. We discuss the virtues as well as the shortcomings in the procedure to determine the t-quark mass from such data. Neutrino experiments sensitive to u(x)/d(x) structure function ratios can help.

The real evidence. . . (1995)

THE NEW YORK TIMES NATIONAL FRIDAY, MARCH 3, 1995

Elusive Particle Found By Scientists in Illinois

Continued From Page A1

The Top Quark: What Is It?

FILLING IN THE LAST BLANK The top quark is the last of the six types of quarks predicted to exist by the Standard Model, the physics theory describing the particles that make up all matter. Along with leptons (like electrons) and force-carrying particles called bosons, quarks are the building blocks of the universe.

THE STUFF OF ATOMS The nuclei of ordinary matter, like the hydrogen atom below, contain protons and neutrons made up of two kinds of quarks, up and down.

THE BIG BANG The other kinds of quarks, which existed just after the Big Bang, 10 to 20 billion years ago, can now be produced only with particle accelerators. The top quark, the most massive quark by far, was also the most elusive. Two teams now say they have found it; they give overlapping estimates of its mass.

The Big Bang

Hydrogen Atom

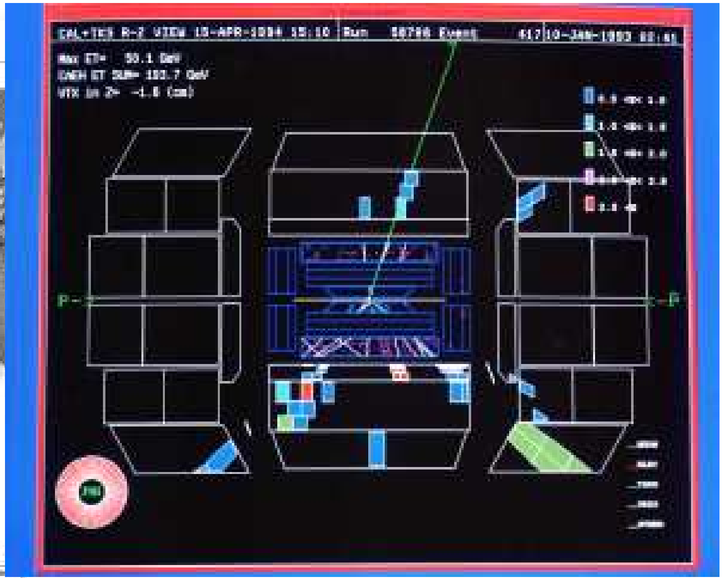
The 6 Quarks
Mass in millions of electron-volts

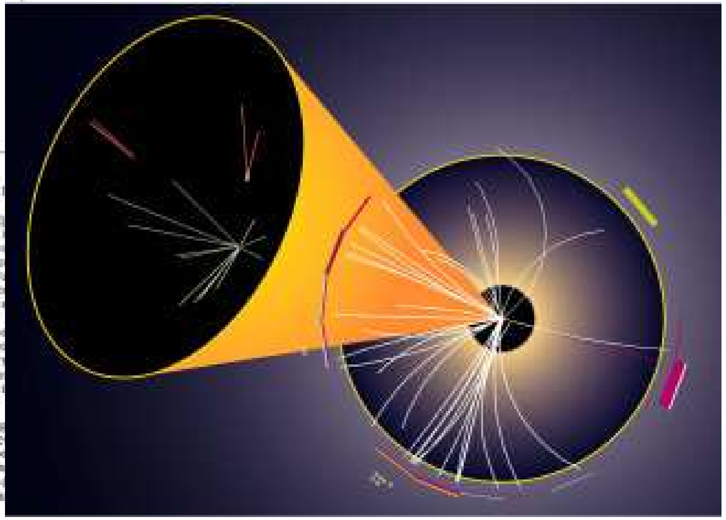
UP MASS: 8	CHARM MASS: 1,500	TOP MASS: 176,000–199,000
DOWN MASS: 8	STRANGE MASS: 160	BOTTOM MASS: 4,250

Source: Fermilab, Department of Energy

Forging a link between the physical and the metaphysical.

Trying to understand the fundamentals of the universe.



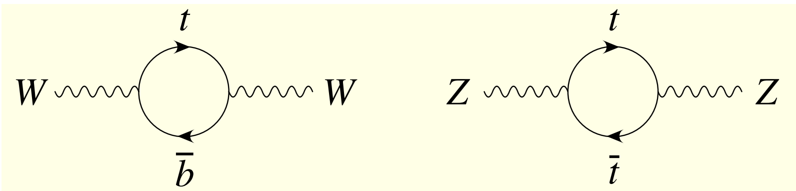


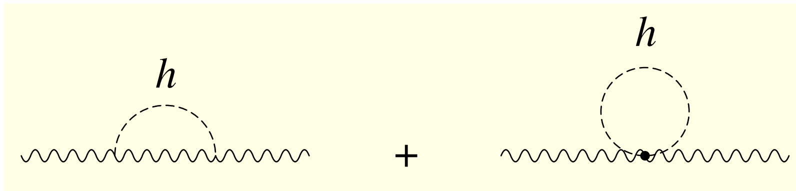
Why study the top-quark mass?

Answer: Electroweak (EW) precision physics

EW radiative corrections depend on the top-quark mass (m_t).
Using the value measured at the Fermilab Tevatron, EW precision fits constrain the Higgs boson mass M_H.

Both the top quark and Higgs contribute at 1-loop to the W/Z propagtors.





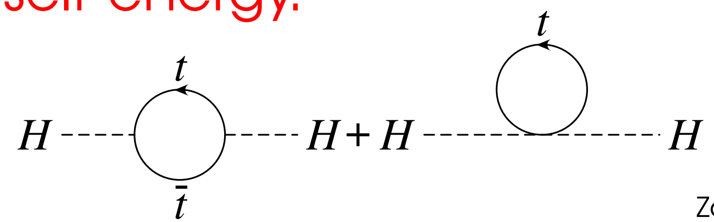
Assuming α, G_F, and M_Z as inputs, M_W^2 at 1-loop is:

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W} \frac{1}{1-\Delta r(m_t, m_H)}$$

where $\Delta r(m_t, m_H) \approx c_t m_t^2 = c_H \ln(M_H^2/M_Z^2) + \cdots$

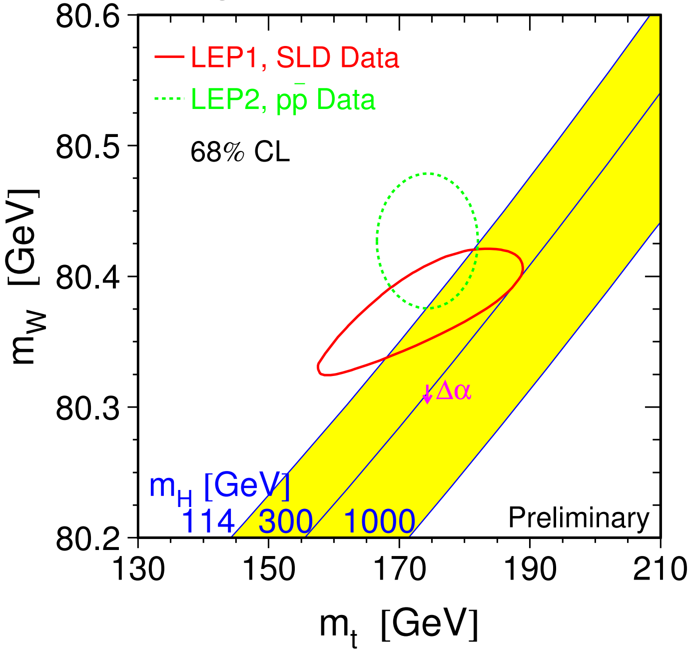
Inverting the formula provides a logarithmic contraint on M_H.

Higgs searchers put it differently: the top quark provides a large correction to the Higgs self-energy.



Constraints on Higgs mass from W and t

M_H is logarithmically sensitive to variations of M_W and m_t.



End of Run I

$m_t = 174.3 \pm 5.1$ GeV (3%)

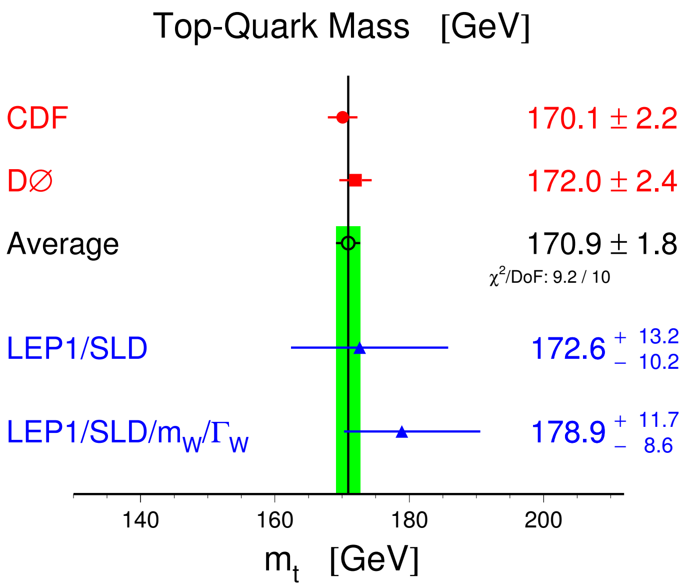
(Better than EW precision)

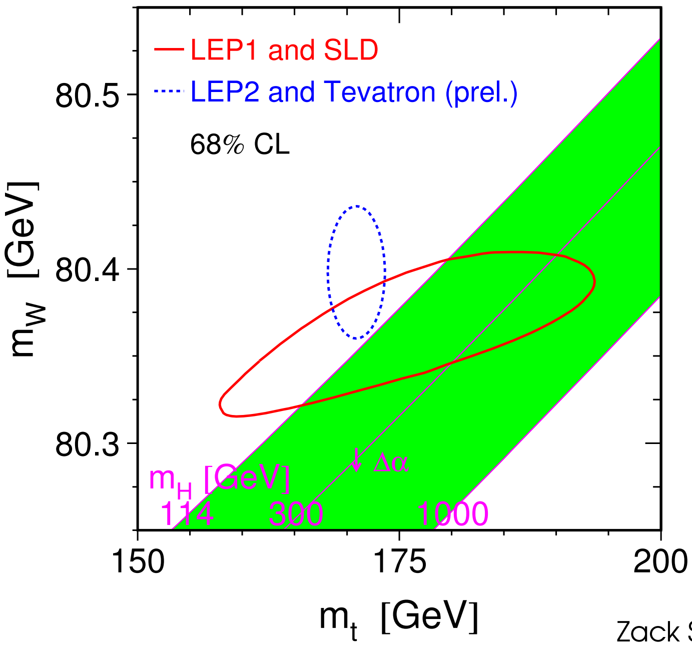
Early Summer 2005

$m_t = 178.0 \pm 4.3$ GeV (fishy)

Late Summer 2005

$m_t = 172.7 \pm 2.9$ GeV





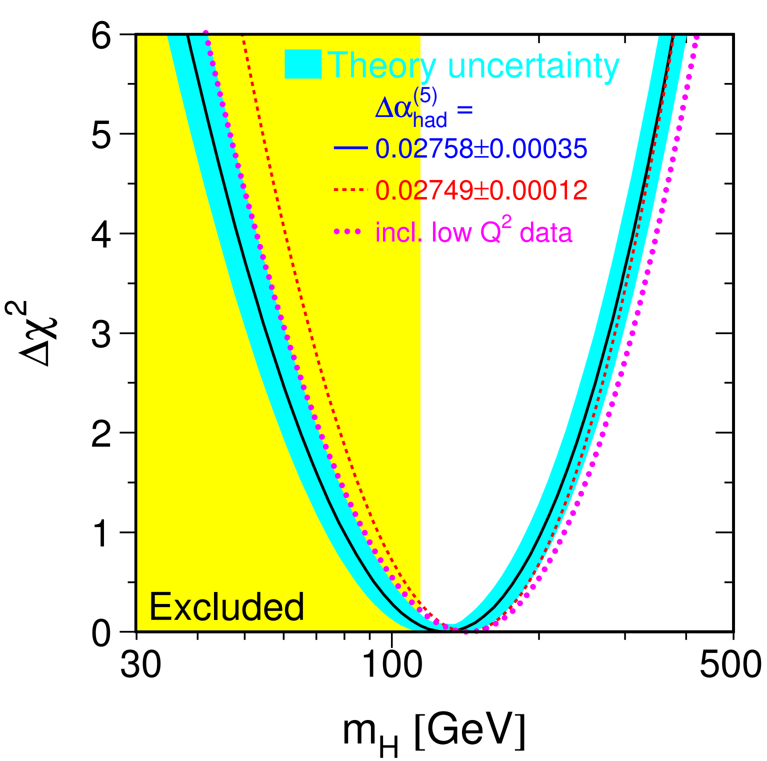
Winter 2007

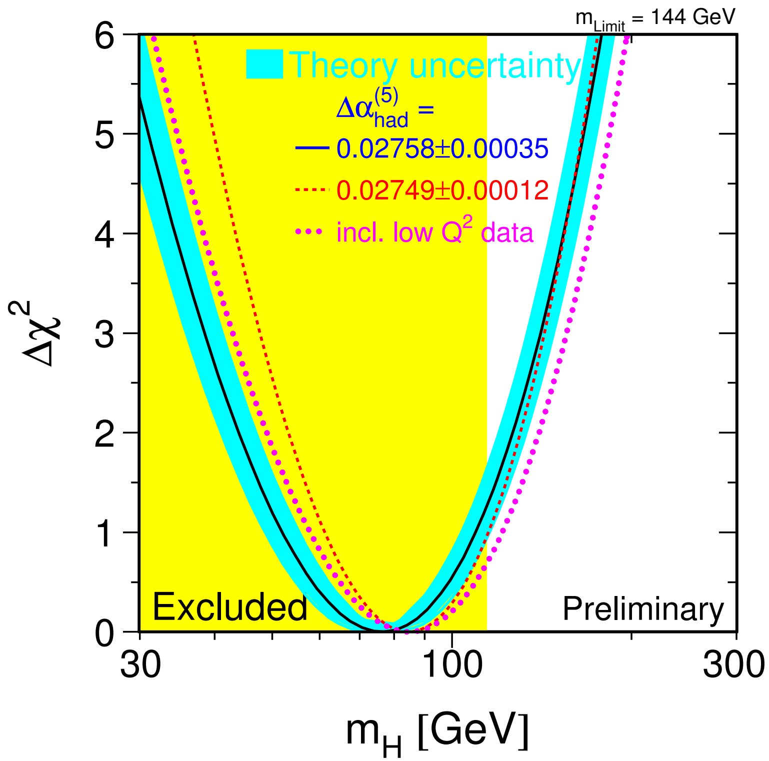
$m_t = 170.9 \pm 1.8$ GeV

(Same as the first $t\bar{t}$ event...)

Tevatron EWWG

Famous “blue-band” plots
Much ado about nothing





Early summer 2005,
Higgs searchers euphoric:
“Higgs on the verge of discovery”

$$M_H = 117^{+67}_{-45}\ \text{GeV}$$
$$M_H < 251\ \text{GeV}(95\%)$$

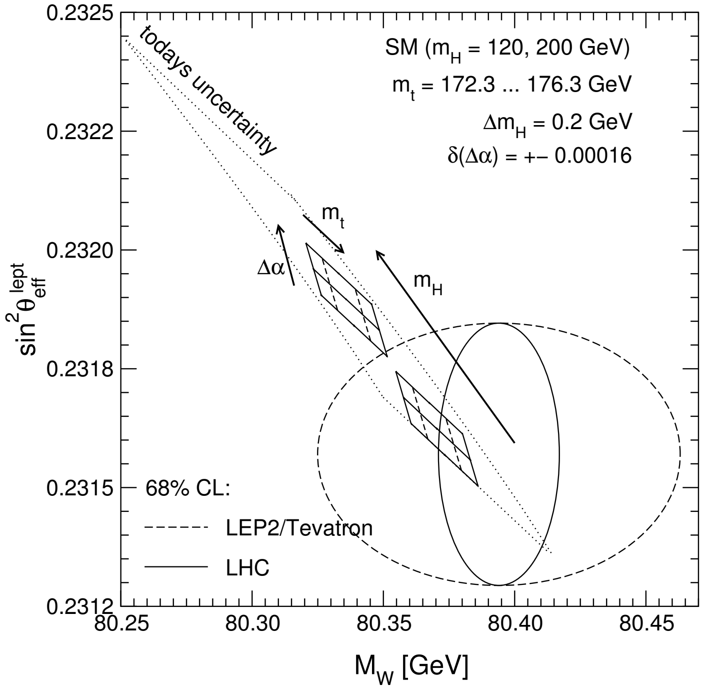
Winter 2007,
Higgs searchers euphoric:
“Higgs on the verge of exclusion”

$$M_H = 78^{+33}_{-24}\ \text{GeV}$$
$$M_H < 144 - 187\ \text{GeV}(95\%)$$

1. These plots are only valid in the SM.
2. Shift was less than 1σ.

How well do we need to know m_t?

There is a better way to look at this in the SM.



Beneke et al., hep-ph/0003033

- Assume M_H is known.
- M_W will be measured to ~ 20 MeV
  $\Rightarrow$ Need m_t to ~ 3 GeV.
  (We already know it to 1.8 GeV.)
- A linear collider can measure M_W to ~ 6 MeV.
  Giga-Z can measure $\sin^2\theta_W \sim 10^{-5}$
  $\Rightarrow$ Need m_t to ~ 1 GeV.

The bottom line: We have already saturated the information we can extract about a SM Higgs from top-quark measurements given any near-term collider (i.e., LHC).

My personal opinion: These indirect constraints are fun, but cannot be taken too seriously. Direct measurements will be made soon that will show us what Nature does.

How well do we *want* to know m_t?

Most excitement about Higgs production has nothing to do with the SM.

Models of new physics predict different sensitivity to the top-quark mass.

SUSY Higgs masses are VERY sensitive to the top-quark mass

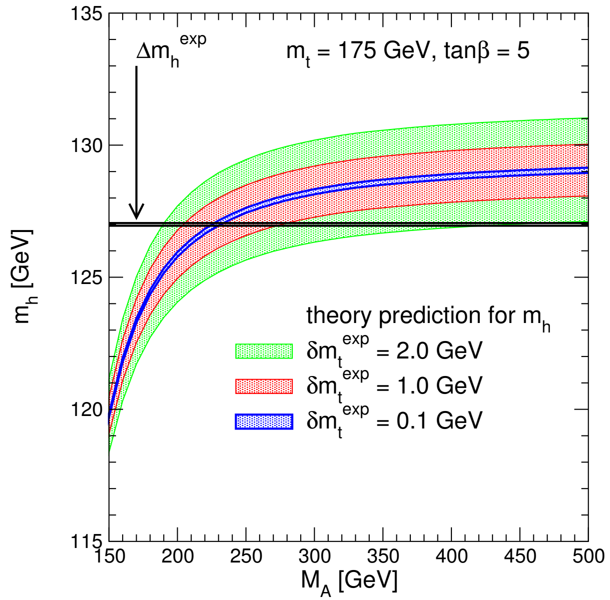
$$\Delta M_H^2 \approx \frac{3 G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta} \ln\left(\frac{\overline{m}_{\tilde{t}}^2}{m_t^2}\right)$$

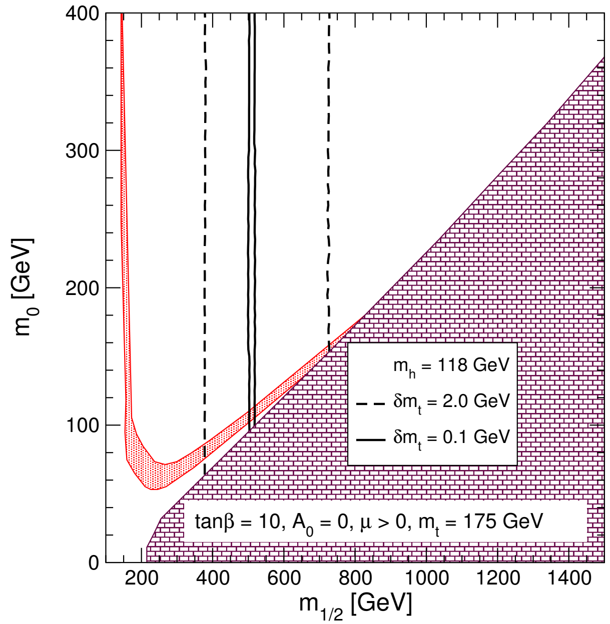
- Experimental error from LHC *may* reach ~ 200 MeV (using rare decays)
- $\delta M_H \sim \delta m_t$, so we will want $\delta m_t \sim 100$ MeV.

  Warning: 4-loop corrections are comparable in size.

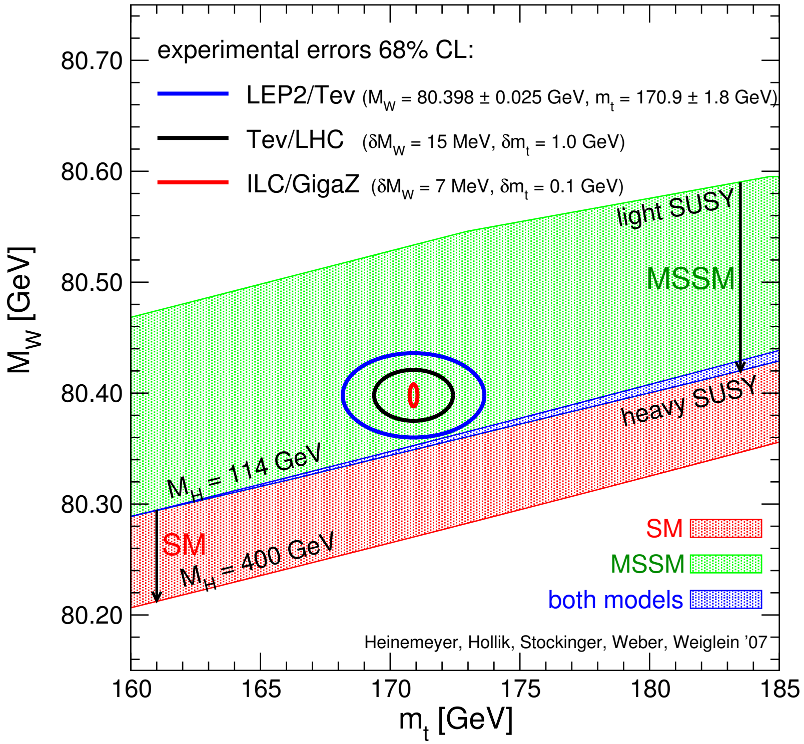
  This needs major effort

If a smaller error in m_t is achieved, we gain indirect access to M_A, A_t, $m_{1/2}$, etc.

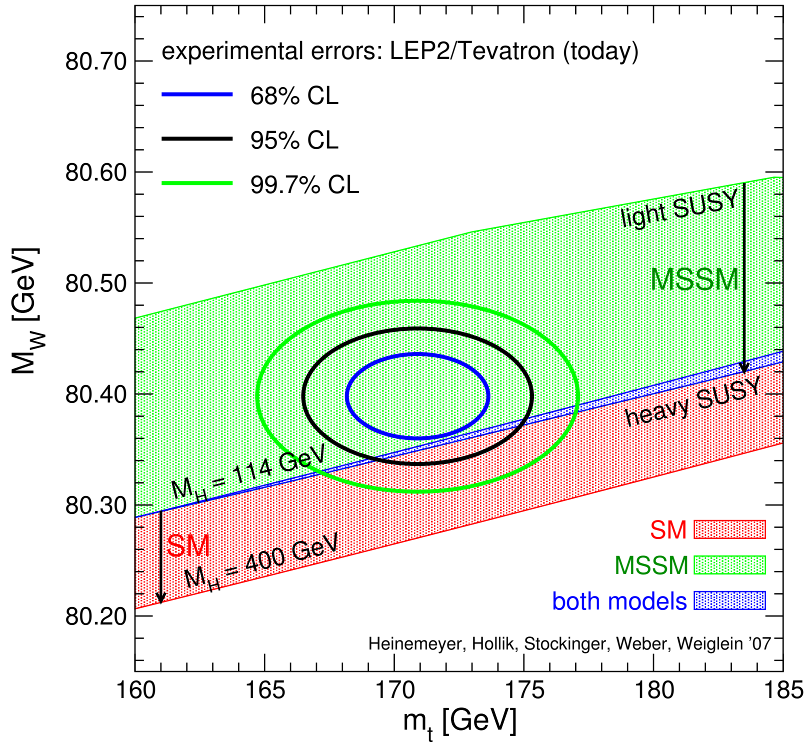




M_W vs. m_t for MSSM Higgs



"SUSY Higgs is favored"



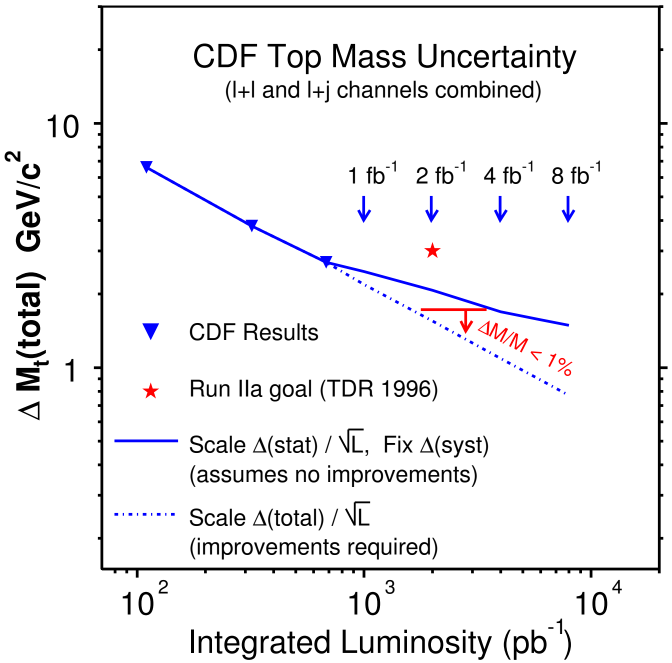
No one tends to show this plot.

It is clear that whatever physics explains electroweak symmetry breaking, there is at least an effective interaction whose mass scale is low.

How do we get to accurate top-quark mass?

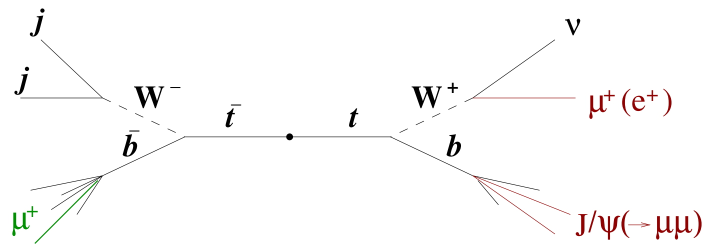
Tevatron

- Run IIa (2fb^{-1}) predicted reach of ± 3 GeV
  Already at ± 1.8 GeV (comb.) with 1 fb^{-1}.
- Expected a systematic brick wall at ± 2 GeV.
  So far, things are scaling like luminosity.
- One major improvement:
  Kinematic fits to M_{Wb} were used
  A better choice assigns each event a probability that is a function of m_t.



LHC

- Several channels can reach < 1 GeV (stat.)
- To reach systematics < 1 GeV use:
  $M_{J/\Psi \ell \nu}$ w/ template for m_t. (~ 300 fb^{-1})



Linear collider

- Strive for $\delta m_t \sim 100 - 200$ MeV.
  Requires a scan of $t\bar{t}$ threshold (understanding threshold is key)

To reach any of these accuracies requires better understanding of $t\bar{t}$ production & kinematics, and backgrounds.

Residual errors in the top-quark mass

The dominant errors at the Tevatron are now entirely due to modelling.

Systematic uncertainties	(GeV/c2)
JES residual	0.42
Initial state radiation	0.72
Final state radiation	0.76
Generator	0.19
Background composition and modeling	0.21
Parton distribution functions	0.12
b-JES	0.60
b-tagging	0.31
Monte Carlo statistics	0.04
Lepton pT	0.22
Multiple Interactions	0.05
Total	1.36

One reducible uncertainty comes from modelling of the b jet, and its energy scale. This will improve with additional data.

A recent study of QCD color-reconnection in showering may indicate larger than expected showering ambiguities ~ 1.5 GeV. Significant comparisons with data are required before this will be resolved.

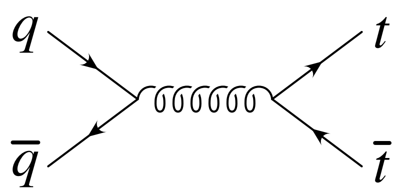
Skands, Wicke, hep-ph/0703081

Top-quark pair ($t\bar{t}$) production

$$q\bar{q} \rightarrow t\bar{t}$$

Leading contribution at Tevatron

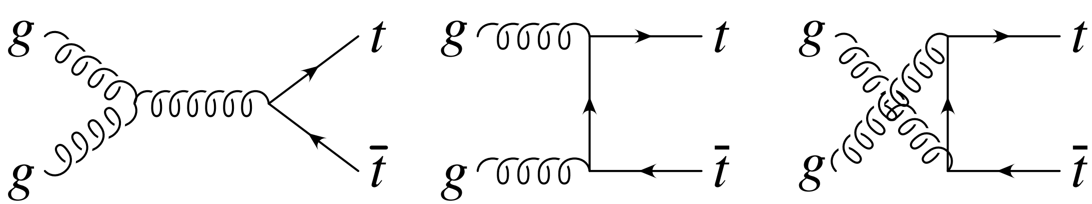
Tev (RunII)	85%
LHC	10%



$$g\bar{g} \rightarrow t\bar{t}$$

Leading contribution at LHC

Tev (RunII)	15%
LHC	90%



At the Tevatron, $t\bar{t}$ is produced close the the kinematic threshold $\hat{s} \approx 4m_t^2$, so $x \sim 0.2$. At LHC $x \sim 0.02$.

A few dozen reconstructed $t\bar{t}$ pairs in Run I of the Tevatron was enough for discovery.

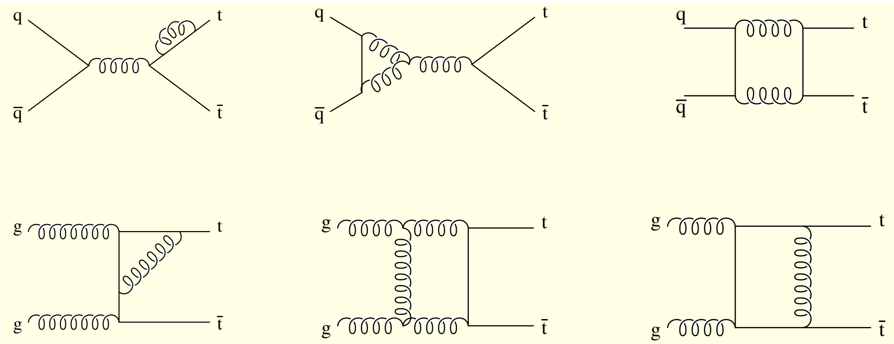
At Run II there are already hundreds.

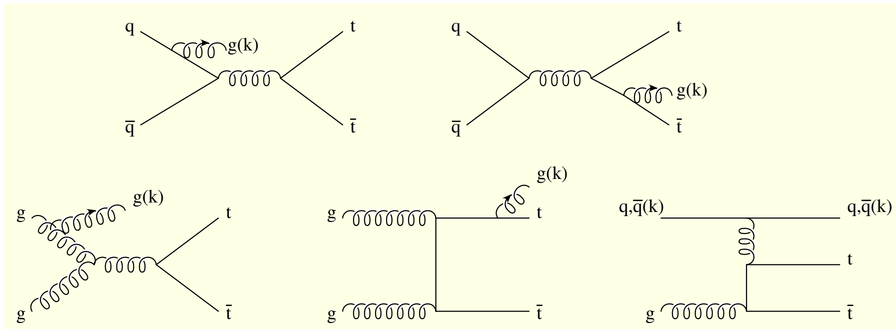
At LHC there will be about 1 pair/second produced!

NLO calculations

- The production rate of $t\bar{t}$ is a sensitive probe of strong interactions.
- $t\bar{t}$ production is already becoming a precision measurement.

  $\Rightarrow$ Very precise theory is required to understand the dynamics and match the experimental precision that will be available.





Complete NLO calculations exist for total and differential cross sections.

Nason, Dawson, Ellis, NPB 303, 607 (88), NPB 327, 49 (89);
Beenakker, Kuijf, van Neerven, Smith, PRD 40, 54 (89);

plus Meng, Schuler, NPB 351, 507 (91)

But this is not enough at the Tevatron. . .

Large threshold corrections in $t\bar{t}$

The top-quark decays before the bound state forms. However, pseudo-bound states of $t\bar{t}$ near threshold ($\hat{s} = 4m_t^2$) cause large logarithmic enhancements to the cross section.

Schematically, the $t\bar{t}$ NLO cross section is

$$\sigma_{ij}^{\rm NLO}(m_t^2,\mu) = \frac{\alpha_s^2(\mu)}{m_t^2}\left\{c_{ij}^0 + 4\pi\alpha_s(\mu)\left[c_{ij}^1(\rho) + \bar{c}_{ij}^1(\rho)\ln\left(\frac{\mu^2}{m_t^2}\right)\right]\right\};\ \rho = \frac{4m_t^2}{\hat{s}}$$

Near threshold, the LO cross section vanishes:

$$c_{q\bar{q}}^0(\rho) \approx \frac{T_R C_F}{2N_c}\pi\beta \stackrel{\beta\to 0}{\longrightarrow} 0;\quad c_{gg}^0(\rho) \approx \frac{T_R}{N_c^2-1}(C_F - C_A/2)\pi\beta \stackrel{\beta\to 0}{\longrightarrow} 0$$

At NLO there are soft and collinear singularities:

$$c_{q\bar{q}}^1(\rho) \stackrel{\beta\to 0}{\longrightarrow} \frac{1}{4\pi^2}c_{q\bar{q}}^0(\rho)\left[(C_F - C_A/2)\frac{\pi^2}{2\beta} + 2C_F\ln^2(8\beta^2) - (8C_F + C_A)\ln(8\beta^2)\right]$$

$$c_{gg}^1(\rho) \stackrel{\beta\to 0}{\longrightarrow} \frac{1}{4\pi^2}c_{gg}^0(\rho)\left[\frac{N_c^2+2}{N_c(N_c^2-2)}\frac{\pi^2}{4\beta} + 2C_A\ln^2(8\beta^2) - \frac{(9N_c^2-20)C_A}{N_c^2-2}\ln(8\beta^2)\right]$$

$$\bar{c}_{q\bar{q}}^1(\rho) \stackrel{\beta\to 0}{\longrightarrow} \frac{1}{4\pi^2}c_{q\bar{q}}^0(\rho)\left[-2C_F\ln(4\beta^2) + \overline{C}_2(\mu^2/m_t^2)\right]$$

$$\bar{c}_{gg}^1(\rho) \stackrel{\beta\to 0}{\longrightarrow} \frac{1}{4\pi^2}c_{gg}^0(\rho)\left[-2C_A\ln(4\beta^2) + \overline{C}_3(\mu^2/m_t^2)\right]$$

Threshold resummation

Threshold logarithms can be resummed via exponentiation, similar to the case of Drell-Yan (DY) or $e^+e^- \to$jets.
Challenges are IS/FS interference, scale difference between m_t and v_t.

Historically, logs are resummed in moment space (Mellin-transform space)
The cross section for the N-th moment under a Mellin-transform is:

$$\sigma_N(m_t^2) = \int_0^1 d\rho\, \rho^{N-1} \sigma(\rho, m_t^2)$$

The threshold region corresponds to the $\lim N \to \infty$, which leads to threshold corrections of the form:

$$\sigma_N^{\rm LO} \left[1 + \sum_{n=1}^{\infty} \alpha_s^n \sum_{m=1}^{2n} c_{n,m} \ln^m N \right]$$

In Drell-Yan, this structure exponentiates to a radiative form factor $\Delta_{DY,N}$:

$$\begin{aligned} \Delta_{DY,N}(\alpha_s) &= \exp\left[\sum_{n=1}^{\infty} \alpha_s^n \sum_{m=1}^{n+1} G_{n,m} \ln^m N \right] \\ &= \exp\Big[\underbrace{g_{DY}^{(1)} \alpha_s \ln^2 N}_{\rm LL} + \underbrace{g_{DY}^{(2)} \alpha_s \ln N}_{\rm NLL} + \underbrace{g_{DY}^{(3)} \alpha_s^2 \ln N}_{\rm NNLL} + \cdots \Big] \end{aligned}$$

Realization of threshold resummation in $t\bar{t}$

Generalizing Drell-Yan-like resummation to $t\bar{t}$ requires:

— Dealing with soft-gluons from IS, FS, and IS/FS interference.

— Dealing with gg color octet states.

The solution is to recast the cross section for moment N in the form:

$$\sigma_{ij} = \sum_{I,J} M^{\dagger}_{ij,I,N} [\Delta_{ij,N}]_{I,J} M_{ij,J,N}$$

where the sum on I, J is over all color states, $[\Delta_{ij,N}]_{I,J}$ is the radiation form factor, and M are matrices in color space.

The advantage is that it describes a formal expansion of the logarithms that can be improved to NNLL, NNNLL, NNNNLL, (and then you collapse)

Formalism: Kidonakis, Sterman, PLB 387, 867 (96)

Implementation:
Bonciani, Catani, Mangano, Nason, NPB 529, 424 (98)
Kidonakis, Vogt, PRD 68, 114014 (03)
Cacciari, Frixione, Mangano, Nason, JHEP 04, 68 (04)

Prior to this formalism there were 2 competing calculations that performed the integrations by truncating the moments. This was mathematically inconsistent, but gave reasonable numerical results. May we never go back. . .

Berger, Contapaganos, PRD 54, 2085 (96)
Catani, Mangano, Nason, Trentadue, NPB 478, 273 (96)

Nomenclature and uncertainties

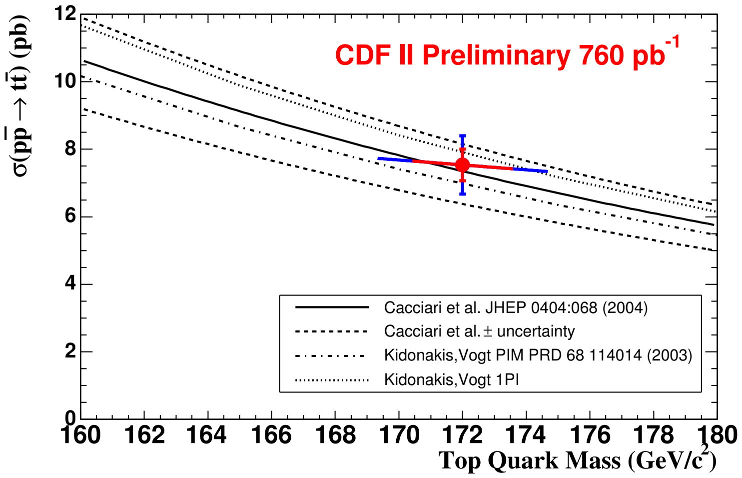
Bad nomenclature

"NNLO-NNNLL"

This is horrible nomenclature.

This is really NLO+the Sudakov-like re-summation we saw above, where the exponent is re-expanded to NNNLL.

There is nothing NNLO about it.



Unusual uncertainties

NLO scale uncertainty of $\pm 10\% \longrightarrow \pm 5\%$ w/ NLL correction
Including PDF uncertainty, $\longrightarrow \pm 15\%$ at Tevatron

There is an additional uncertainty due to expansion kinematics:

- 1 particle inclusive (1PI): $s = (p_q + p_{\bar{q}})^2$
- Pair invariant mass (PIM): $s = M_{t\bar{t}}^2 = (p_t + p_{\bar{t}})^2$

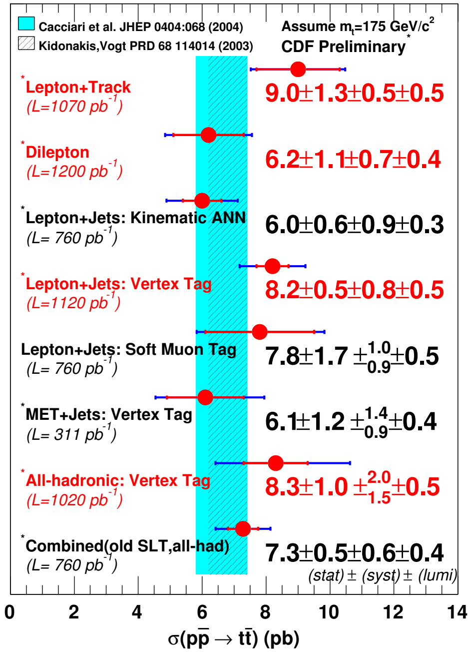
	σ	±1PI/PIM	±scale	± PDF
Run I	5.24±	0.31	± 0.2	±0.6 pb
Run II	6.77±	0.42	± 0.1	±0.7 pb

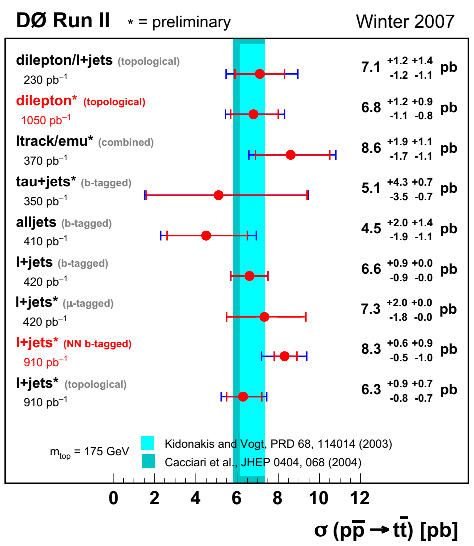
LHC is not dominated by threshold kinematics:

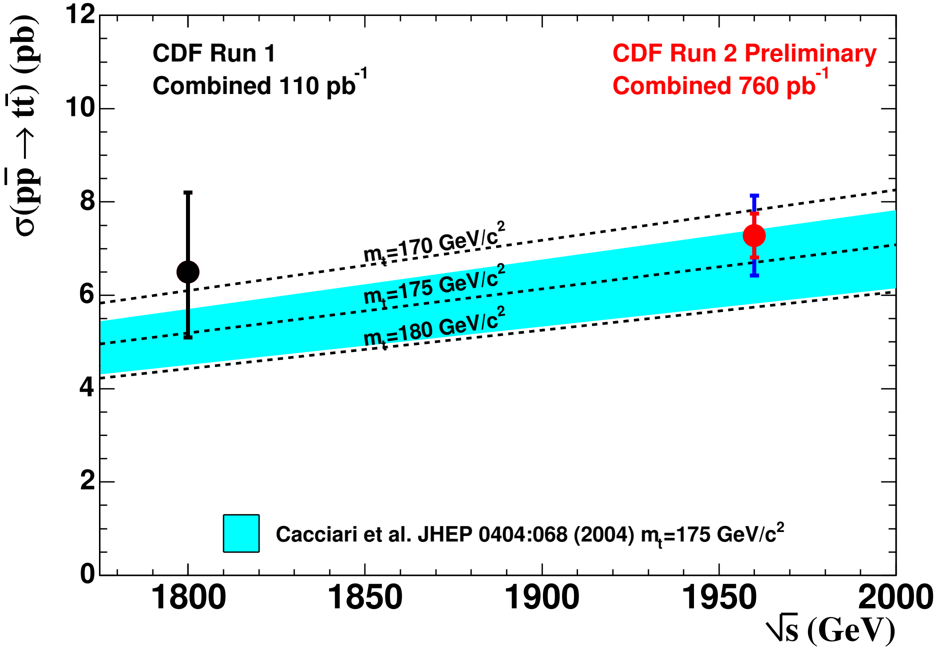
$\sigma = 825 \pm 50 \pm 100 \pm 90$ pb.

Full NNLO is needed!

Tevatron data







Great agreement so far!

Lighter top-quark mass preferred.

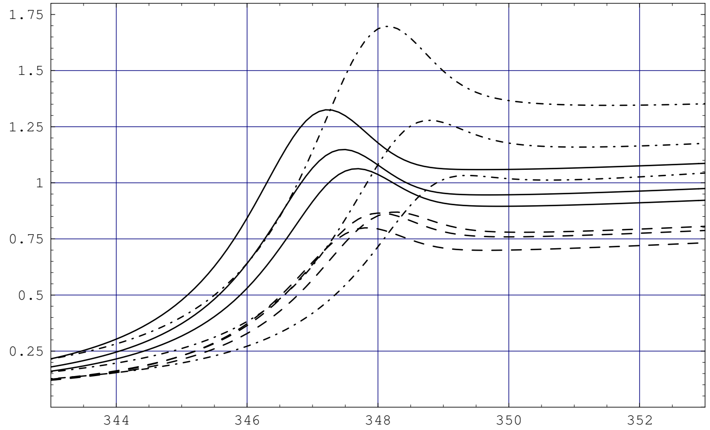
Experiment will be better than theory soon.

$t\bar{t}$ threshold at a linear collider (LC)

There is a subtle question when you try to make a precision measurement of QCD: What mass do you use?

The pole mass is not defined beyond $\Lambda_{\rm QCD}$.

In fact it is not well-defined at all, since there are no free quarks.



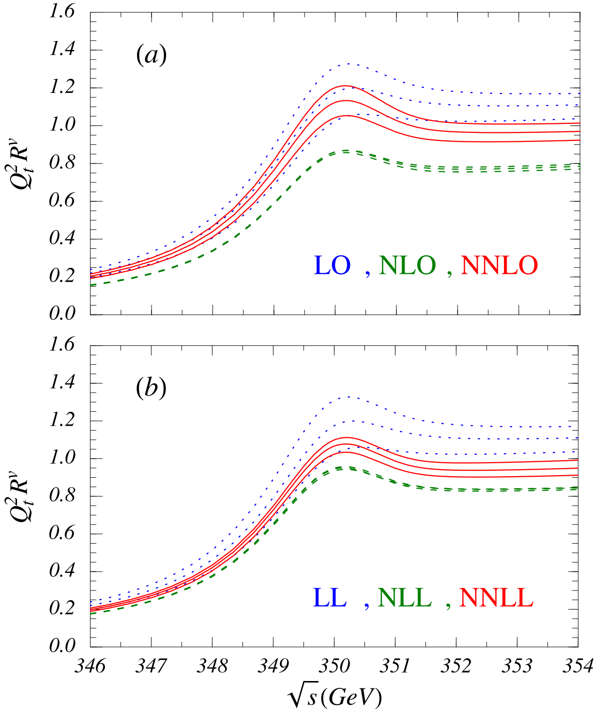
Yakovlev,Groote PRD63, 074012(01)

Solution: Use the 1S mass (pseudo bound state)

There are large non-relativisitic corrections

$$\sigma_{t\bar{t}} \propto v \sum \left(\frac{\alpha_s}{v}\right) \times \left\{ \begin{array}{c} 1 \\ \sum(\alpha_s \ln v) \end{array} \right\}$$

$$\times \left\{ \begin{array}{l} \mathrm{LO}(1) + \mathrm{NLO}(\alpha_s, v) + \mathrm{NNLO}(\alpha_s^2, \alpha_s v, v^2) \\ \mathrm{LL} + \mathrm{NLL} + \mathrm{NNLL} \end{array} \right\}$$



Normalization changes, but peak stable.

$\delta\sigma_{t\bar{t}}$ is $\pm 6\%$ before ISR/beamstrahlung

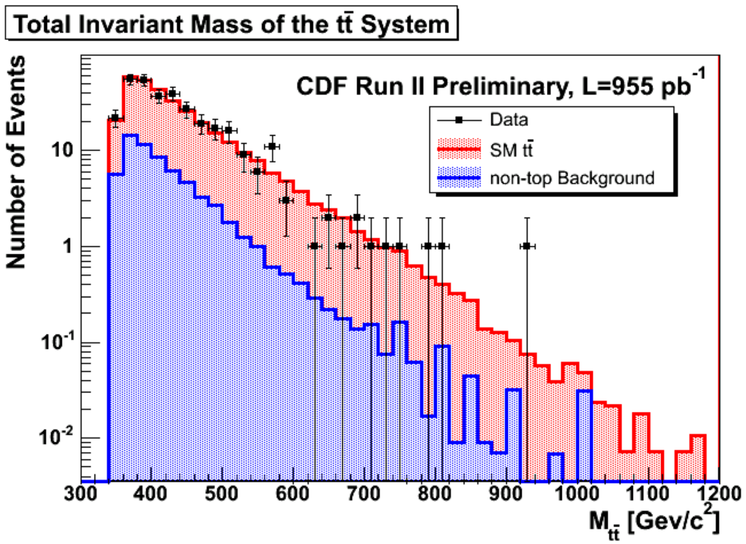
$\delta m_t \sim 100$ MeV is attainable

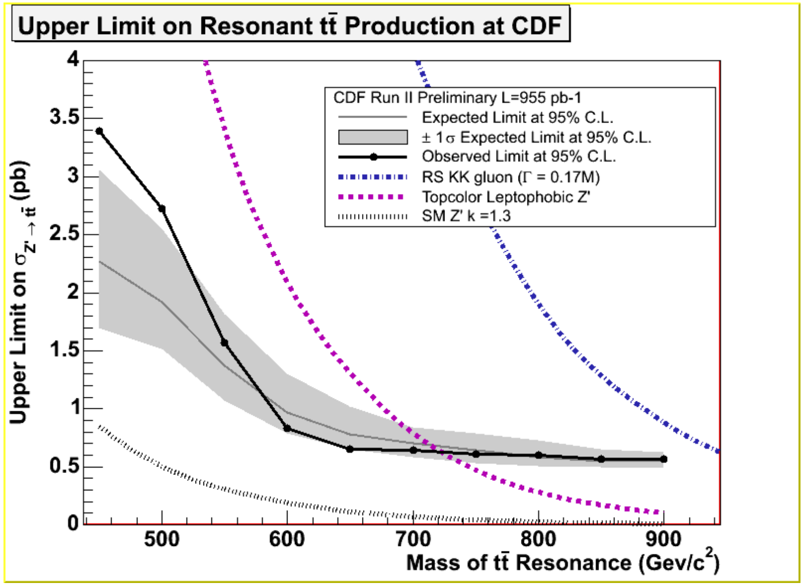
Hoang, hep-ph/0310301

Looking for Z' resonances

Nearly any model you write down that has an extended gauge structure (U(1), SU(2), etc.), KK modes of the Z or gluon, axigluons, top color, etc. will produce a new neutral current, generically called a Z'.

If you couple to quarks, you have the possibility of resonant production and decay to top pairs at a hadron collider.





- All of limits are for models with enhanced coupling and narrow width.
- There is no direct reach for a SM-like Z' right now.
- $M_{Z'} < 720$ GeV leptophobic, KK limit not strictly applicable.

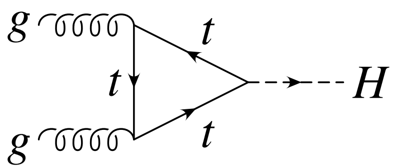
Top-quark Yukawa coupling y_t

The top quark mass is generated as the coupling strength between the top quark and Higgs $\mathcal{L}_{\text{Yukawa}} = -y_t \bar{t} t H$.

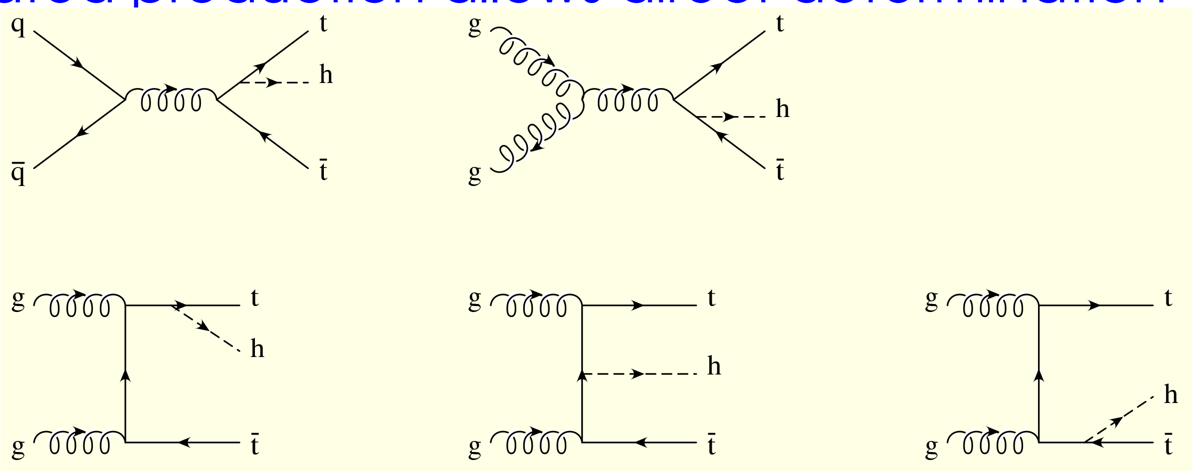
$$\Rightarrow y_t \approx \frac{\sqrt{2} m_t}{246\ \text{GeV}} = 0.98 \pm 0.01$$

We want to measure y_t directly to 1% to confirm its relationship with the top-quark mass.

- Higgs exchange at threshold is too weak.
- Gluon-gluon fusion is indirect
  (and may be subject to interference effects)



- $t\bar{t}H$ associated production allows direct determination



We will see the reach is limited at LHC or a LC.

$t\bar{t}H$ at LHC

Extracting y_t from $t\bar{t}H$ requires an accurate prediction for the measured cross section.

Fortunately, there are 2 fully differential NLO calculations performed in different ways — they agree

Beenakker et al, NPB 653, 151 (03)

Dawson et al, PRD 68, 034022 (03)

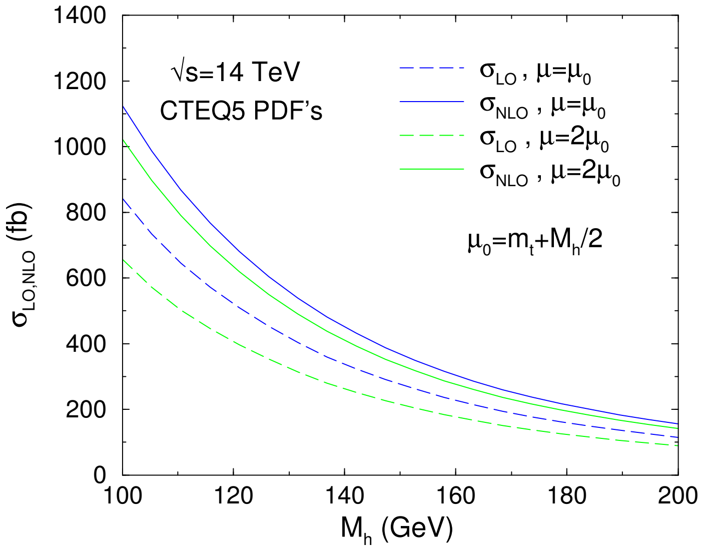
Unfortunately, uncertainties are large (∼20%):

$\mu : \pm 15\%$, PDF: $\pm 6\%$, $m_t : \pm 7\%$

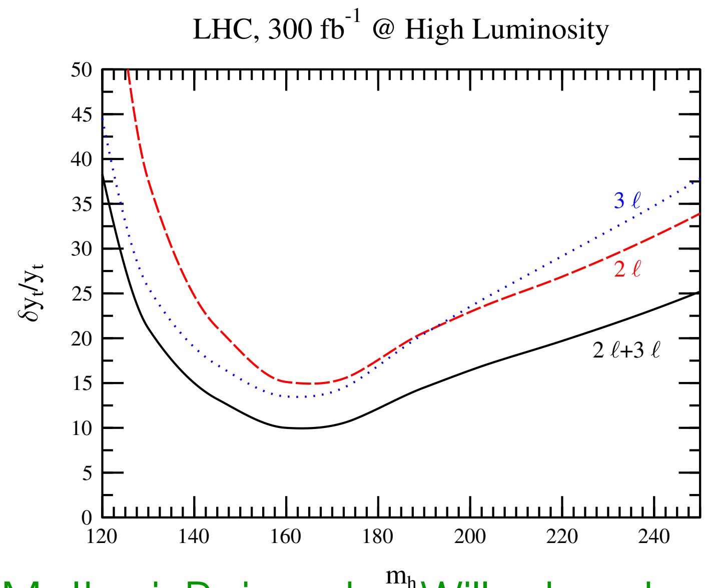
Combining $H \to b\bar{b}$ and $H \to WW$ at LHC

$\Rightarrow \delta y_t \sim \pm 10\%$ at best

Let's look at this more closely. . .



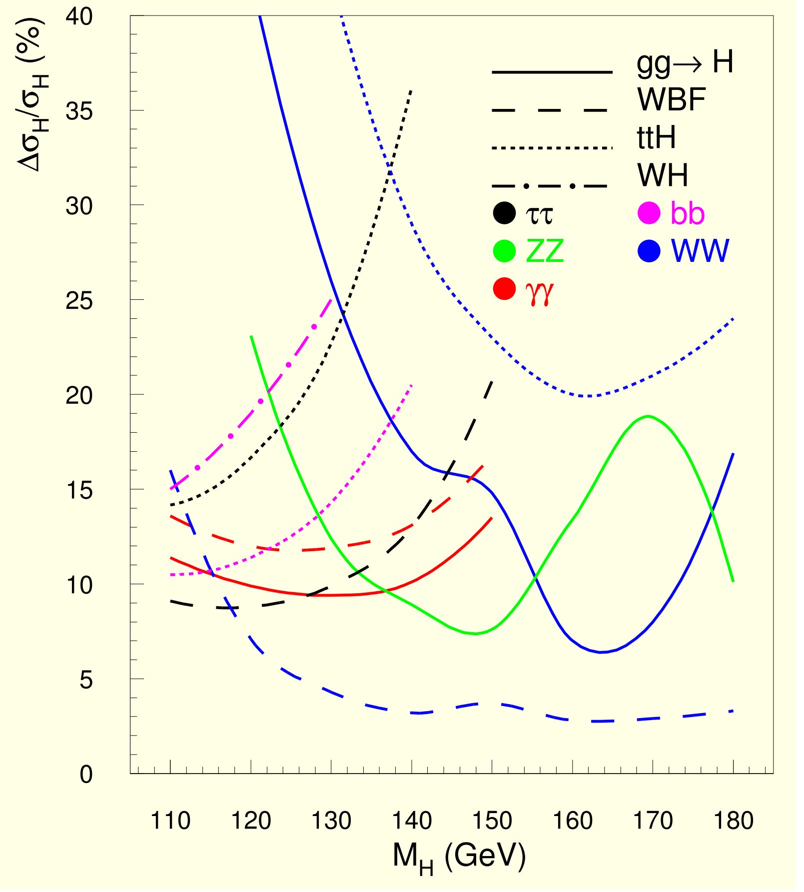
Dawson et al, PRD 68, 034022 (03)



Maltoni, Rainwater, Willenbrock, PRD 66, 034022 (02)

Production modes at LHC

Extraction of y_t is part of a larger plan to extract several couplings at once at the LHC.



Maltoni, Rainwater, Willenbrock; Belyaev, Reina

- Below 130-140 GeV

$$gg \to H \to \gamma\gamma, WW, ZZ$$
$$qq \to qqH \to$$
$$qq + (\gamma\gamma, WW, ZZ, \tau\tau)$$
$$\boxed{q\bar{q}/gg \to t\bar{t}H \to t\bar{t} + (b\bar{b}, \tau\tau)}$$

- Above 130-140 GeV

$$gg \to H \to WW, ZZ$$
$$qq \to qqH \to qq + (\gamma\gamma, WW, ZZ)$$
$$\boxed{q\bar{q}/gg \to t\bar{t}H \to t\bar{t}WW}$$

Using ratios to get y_t

Given a particular production and decay channel, we find in the narrow width approximation:

$$\sigma_i(H) \times BR(H \to jj)_{\text{exp}} = \frac{\sigma_i^{\text{th}}(H)}{\Gamma_i^{\text{th}}} \frac{\Gamma_j \Gamma_i}{\Gamma_{\text{tot}}}$$

Define the combination

$$Z_{ij} = \frac{\Gamma_j \Gamma_i}{\Gamma_{\text{tot}}}$$

Each width is proportional to the (Yukawa)^2.

Current LHC estimates are:

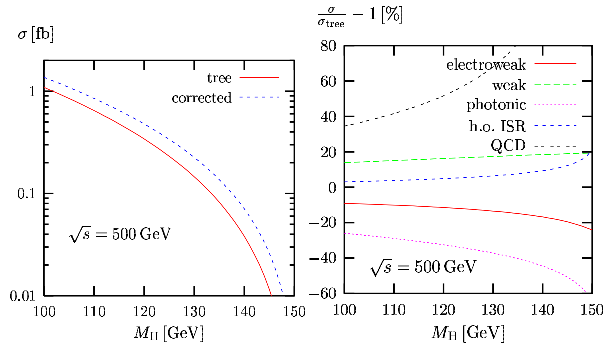
Ratios of couplings can be determined in a model-independent manner at the 10–20% level. E.g.,

$$\frac{y_t^2}{y_g^2} \propto \frac{\Gamma_t}{\Gamma_g} = \frac{Z_{t\tau} Z_{W\gamma}}{Z_{W\tau} Z_{g\gamma}}$$

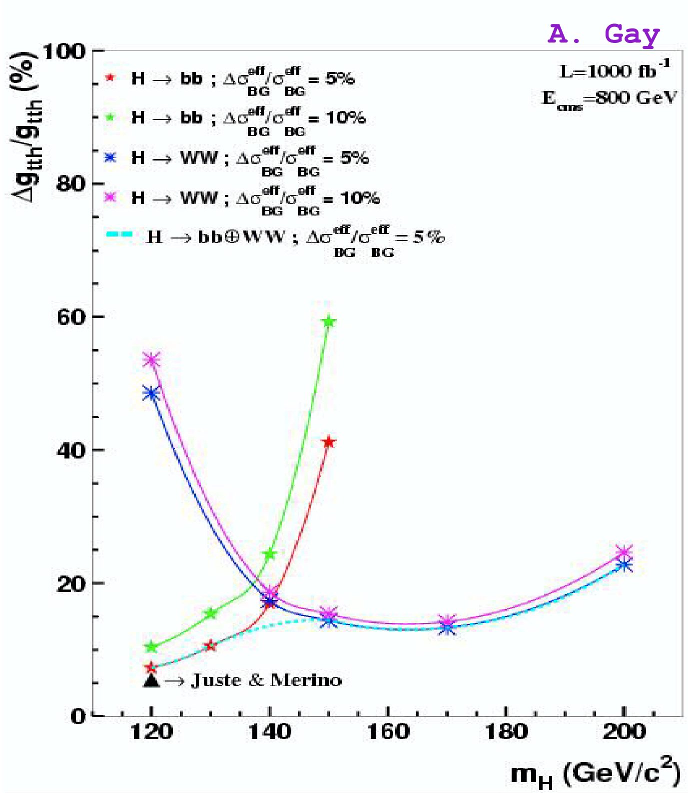
Assuming $\Gamma_{\text{tot}} = \Gamma_b + \Gamma_\tau + \Gamma_W + \Gamma_Z + \Gamma_g + \Gamma_\gamma$, individual couplings can be determined to 10–30%.

$t\bar{t}H$ at a linear collider and y_t

Calculating $t\bar{t}H$ at an e^+e^- collider is very challenging.



- There are many 10% corrections near threshold.
- There are now a few NLO calculations:
  You, *et al.*, PLB 571, 85 (03)
  Belanger, *et al.*, PLB 571, 163 (03)
  Denner, *et al.*, PLB 575, 290 (03)
- SUSY corrections tend to reduce $\sigma_{t\bar{t}H}$ another 20–30%
  J.J. Liu, *et al.*, PRD 72, 033010 (05)



This measurement is only tenable with a high energy linear collider ≥ 800 GeV and lots of luminosity.

At best you get $\pm 10\%$ if $M_H < 180$ GeV

Bottom line: There is no known way to get δy_t below 10%, and certainly not to 1%. Maybe you can figure this out. . .

tH^- at the Tevatron and LHC

In any 2HDM there is a charged Higgs.

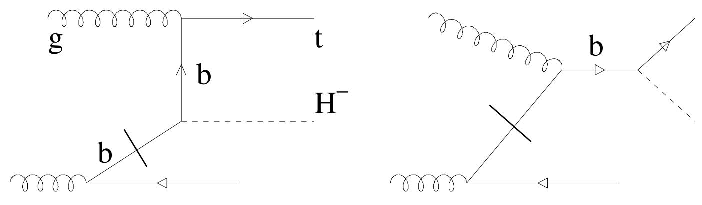
- If the neutral Higgs(es) are SM-like they may be unobservable.
  $H^{\pm}$ may be the only one we see.

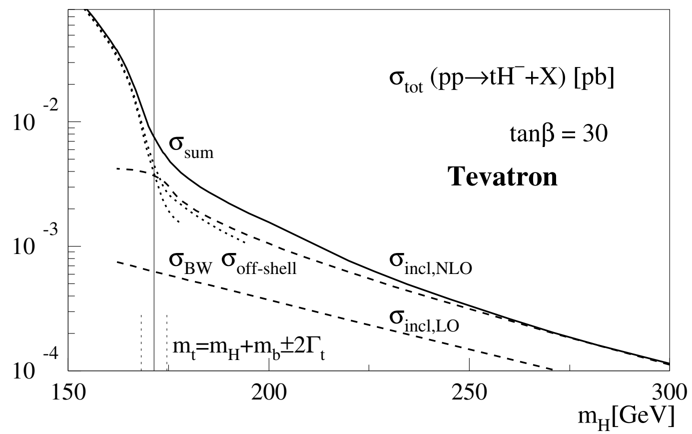
- If $m_t > M_H$, then we can look for $t \to bH^+$ in $t\bar{t}$ production.
  Both $t \to bH^+$ and $H^+ \to t\bar{b}$ rates are known at NLO
  Carena *et al.*, NPB 577, 88 (00)

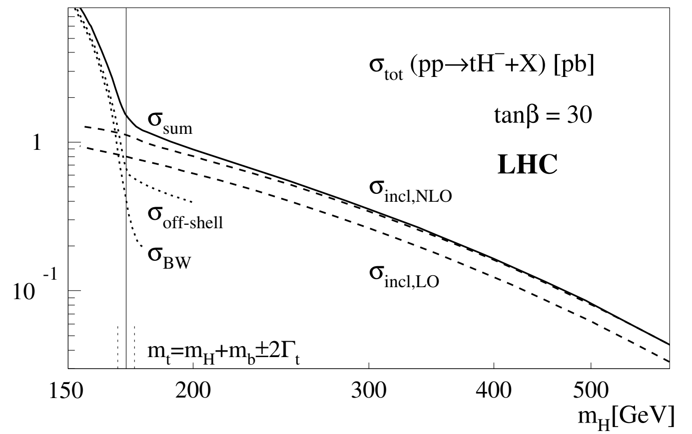
  Current limits are poor:
  BR$(t \to bH^+) < 0.2$–0.8 CDF, DØ

- Fully differential $tH^-/\bar{t}H^+$ NLO rates also known Berger *et al.*, hep-ph/0312286
  Needed to utilize correlations in decays

- In SUSY, corrections can be 50% if the μ-parameter or $\tan\beta$ are large.



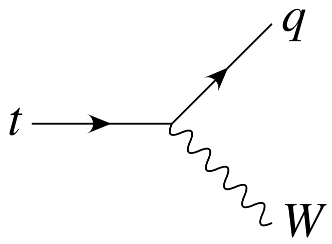




Top quark decays

The large width of the top quark (~ 1.5 GeV) allows it to decay before it depolarizes ($\sim \lambda_{QCD}^2/m_t = 1$ MeV), or hadronizes ($\sim \lambda_{QCD} = 300$ MeV).

A. Falk, M. Peskin, PRD 49, 3320 (1994)

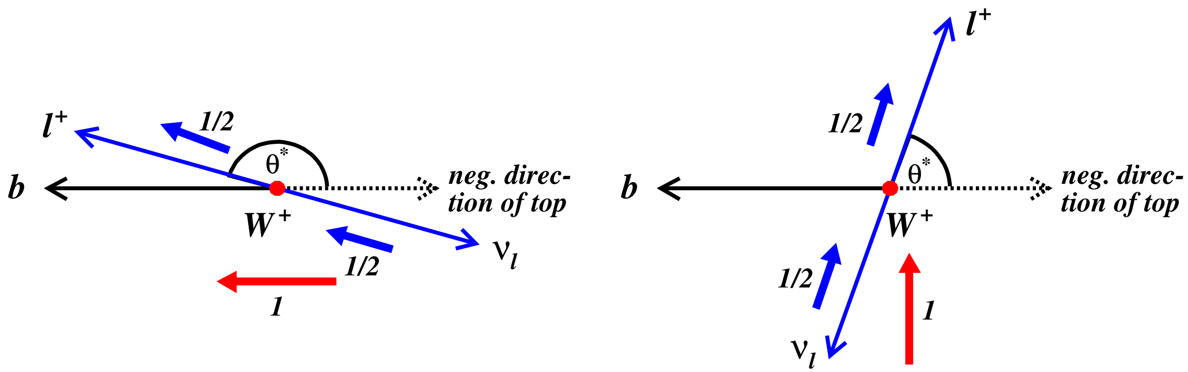


$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^\mu \frac{1}{2}(1-\gamma_5)$$

In single-top we looked at the polarization of the top-quark.
In $t\bar{t}$ we use the event rate to look at the polarization of the W.

The $V-A$ interaction means the W only couples to the left-handed piece of the top-quark. If $m_b = 0$, the spin-1 W boson comes out left-handed $s_z = -1$ or longitudinal $s_z = 0$, never right-handed $s_z = +1$.

W polarization is embedded in the angular distribution of its decay products in the W rest frame.



Deriving the width to polarized W bosons

The amplitude for ($t(p_t) \to b(p_b)W^+(p_W)$) follows from the Feynman rule:

$$\mathcal{A}(t \to bW^+) = -i\frac{g}{2\sqrt{2}}V_{tb}\overline{u}(p_b)\gamma^\mu(1-\gamma_5)u(p_t)\epsilon_\mu^{\lambda\star}(p_W)$$

The width to a given W-boson polarization is:

$$\frac{1}{2m_t}\int d\text{PS}\overline{\sum}|\mathcal{A}(t \to bW^+)|^2$$

Assume the top-quark in unpolarized (the gluon produces right/left equally in $t\bar{t}$, though we are ignoring spin correlation between tops).

In the rest frame of the top quark we have:

$$\begin{aligned}
p_t &= (m_t, 0, 0, 0) \\
p_W &= (E_W, 0, p\sin\theta_W^t, p\cos\theta_W^t) \\
p_b &= (E_b, 0, -p\sin\theta_W^t, -p\cos\theta_W^t) \\
\epsilon_0 &= \frac{1}{M_W}(p, 0, E_W\sin\theta_W^t, E_W\cos\theta_W^t) \\
\epsilon_\pm &= \frac{1}{\sqrt{2}}(0, 1, \pm i\cos\theta_W^t, \mp\sin\theta_W^t)
\end{aligned}$$

where $E_W = \frac{m_t^2+m_W^2}{2m_t}$ and $p = \frac{m_t^2-m_W^2}{2m_t}$.

$t\bar{t}$ The fraction of longitudinal W bosons

The amplitude squared is:

$$\overline{\sum}|\mathcal{A}(t\to bW^+)|^2 = \frac{g^2}{8}|V_{tb}|^2\mathrm{Tr}[(\not{p}_t+m_t)\not{\epsilon}^\star_\lambda(1-\gamma_5)(\not{p}_b+m_b)\not{\epsilon}_\lambda]$$

If we ignore the b mass for the moment we get: $(r = M_W/m_t)$

$$\overline{\sum}|\mathcal{A}_-|^2 = \frac{2G_F m_t^4}{\sqrt{2}}|V_{tb}|^2 2r^2(1-r^2)$$

$$\overline{\sum}|\mathcal{A}_0|^2 = \frac{2G_F m_t^4}{\sqrt{2}}|V_{tb}|^2(1-r^2)$$

The fraction of longitudinal W-bosons is:

$$F_0 \equiv \frac{\Gamma_0}{\Gamma_{\mathrm{tot}}} = \frac{1}{1+2r^2} = \frac{m_t^2}{m_t^2+2M_W^2} \simeq 0.69$$

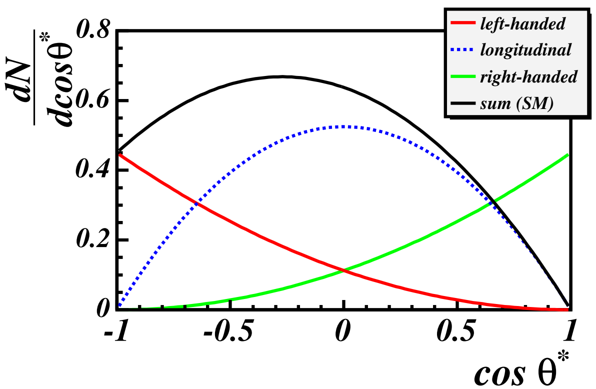
If you turn back on the b mass, $F_+ = 3\times 10^{-4}$.

Current experimental results are:

$F_0 = 0.59 \pm 0.14$ (CDF)

$F_+ = -0.03 \pm 0.07$ or < 0.10 at 95% C.L. (CDF)

$F_+ = 0.056 \pm 0.10$ or < 0.23 at 95% C.L. (DØ)



Conclusions

1. The study of $t\bar{t}$ has become a game precision measurements.
   - The top-quark now has the best measured mass (1%) of any quark.

     $$m_t = 170.9 \pm 1.8 \text{ GeV}$$

   - The measured top-quark cross section has uncertainties comparable in size to the theoretical calculations.

     $\sigma_{\text{exp}} = 7.3 \pm 0.8$ pb, $\sigma_{\text{th}} = 6.8 \pm 0.8$ pb at Run II (175 GeV)

We are theory and physics modeling constrained!

- We need a better handle on W+heavy-quark final states — dominates mass uncertainty.
- We need even higher order calculations valid near threshold — NNLO/NNNNLL
- To utilize this information we need higher-order (3-loop, soon 4-loop) calculations of EW processes.

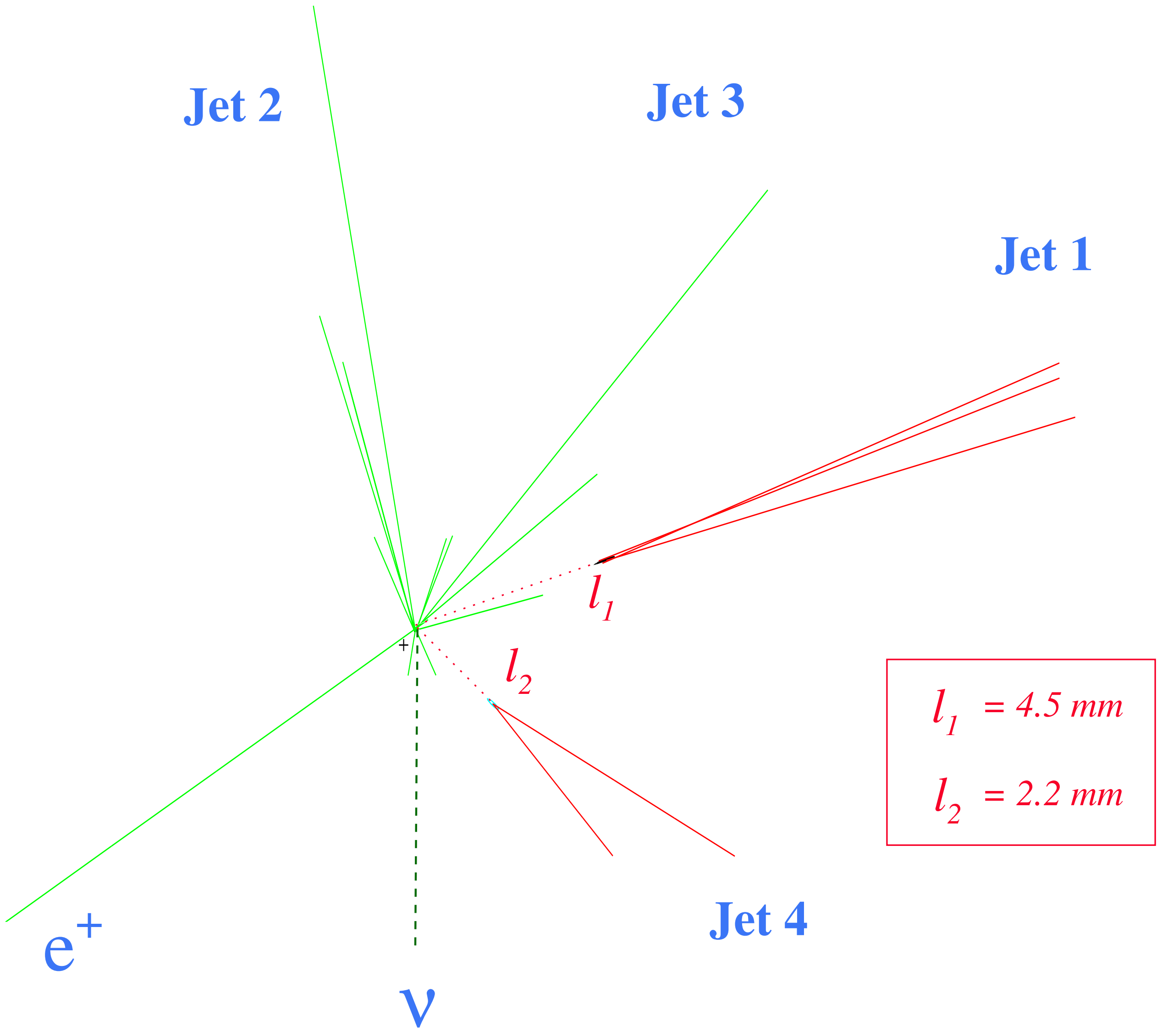
Conclusions

2. We have a prediction for the top-quark Yukawa $y_t = 0.98 \pm 0.01$.
   - It will be very difficult to test this to better than 10%. The experimental backgrounds are tough.
3. The study of spin correlations and W polarization are a nice complement to single-top-quark studies.
   - In principle there is information about y_t embedded in F_0, but it is difficult to extract.
   - These correlations will be more important when you look for new physics at LHC that is hiding under the 1 top-pair/second background.
4. I did not cover evidence that the top-quark really is charge $2/3$, and not $-4/3$.
5. I did not cover new ttj calculation, or color-flow issues.

We are in an age of precision QCD!

Your help will be needed in maximizing our understanding of the fantastic data we now have from the Tevatron and will have from LHC.

I end where I began. . .



$$M_{top}^{Fit} = 170 \pm 10 \text{ GeV}/c^2$$

24 September, 1992
run #40758, event #44414