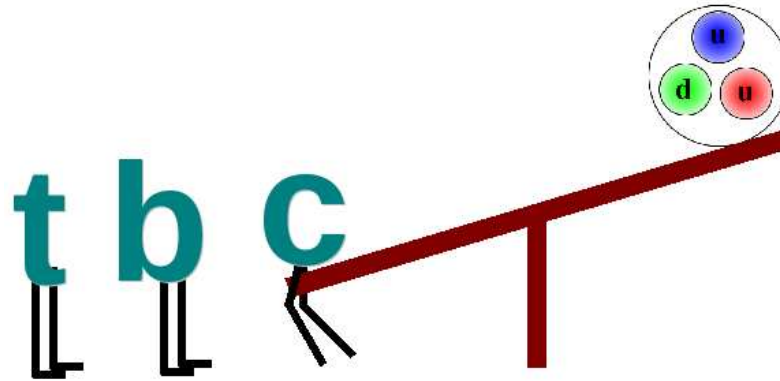




Heavy quarks



Zack Sullivan

Illinois Institute of Technology

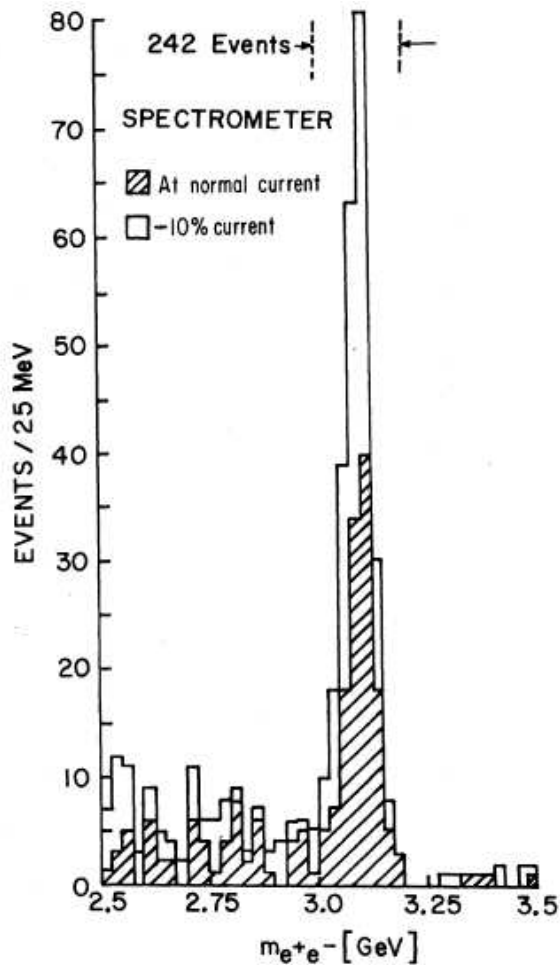


Outline

1. Heavy quark discovery and meaning
2. Heavy quark mass
 - What is it?
 - Why do we care about the top-quark mass in particular?
3. Heavy quark cross sections
 - Top cross section
 - Bottom cross section anomaly
 - (Single-)top cross section (Lecture 2)



A charming discovery



The first heavy quark, **charm** was discovered in 1974 in $p\bar{p}$ collisions at BNL and e^+e^- at SLAC

The observations were published together:
PRL 33, 1404 (1974); PRL 33, 1406 (1974)

The J/ψ was recognized as a $c\bar{c}$ bound state
 $\Rightarrow m_c \sim 1.5 \text{ GeV}$

The existence of a 4th quark confirmed the Glashow-Iliopoulos-Maiani explanation for why FCNC decays ($s \rightarrow d\nu\bar{\nu}$) did not occur.

— And it loosened the shackles of $SU(3)_{\text{flavor}}$, **Gell-Mann's "Eightfold way"**



A charming crisis

While the J/ψ was clearly a quark bound state, it had an extremely narrow width of 88 keV.

This caused a minor crisis in the fledgling QCD...

After all how could a strongly interacting state be narrow?

$\Gamma_\rho \sim 150$ MeV, $\Gamma_\omega \sim 8.5$ MeV, $\Gamma_\phi \sim 4.3$ MeV, $\Gamma_{J/\psi} \sim 88$ keV

An explanation was found by Appelquist and Politzer, PRL 34, 43 (75).

Write the width as

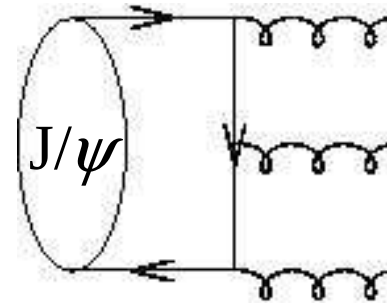
$$\Gamma(^3S_1 \rightarrow 3 \text{ gluons}) = |R(0)|^2 |M(q\bar{q} \rightarrow ggg)|^2$$

Following the model of positronium, solve the Schroedinger Eqn. for $R(r) = \frac{2}{a_0^{3/2}} e^{-r/a_0}$,

where $a_0 = \frac{1}{\alpha_s m_c / 2}$.

$|M(q\bar{q} \rightarrow ggg)|^2 \sim \alpha_s^3$ — one power for each gluon

$\Rightarrow \Gamma(^3S_1 \rightarrow 3 \text{ gluons}) \sim 0.2 \alpha_s^6 m_c \sim 90$ keV; $\alpha_s \approx 0.26$





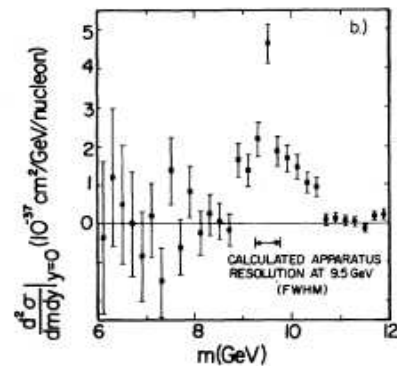
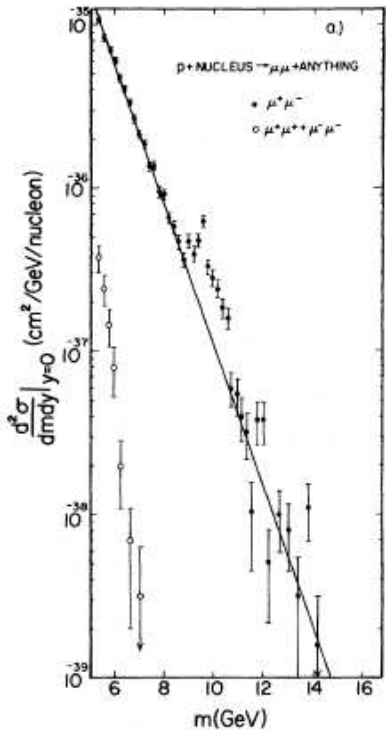
A beautiful discovery

In 1975 the τ was discovered and led to the search for other 3rd-generation particles.

In 1977 the Upsilon (a $b\bar{b}$ bound state) was observed at the Fermilab Tevatron. [PRL 39, 252 \(1977\)](#)

(The Upsilon is also very narrow.)

Once the bottom quark was found it was clear that a sixth quark was needed to complete the family structure.

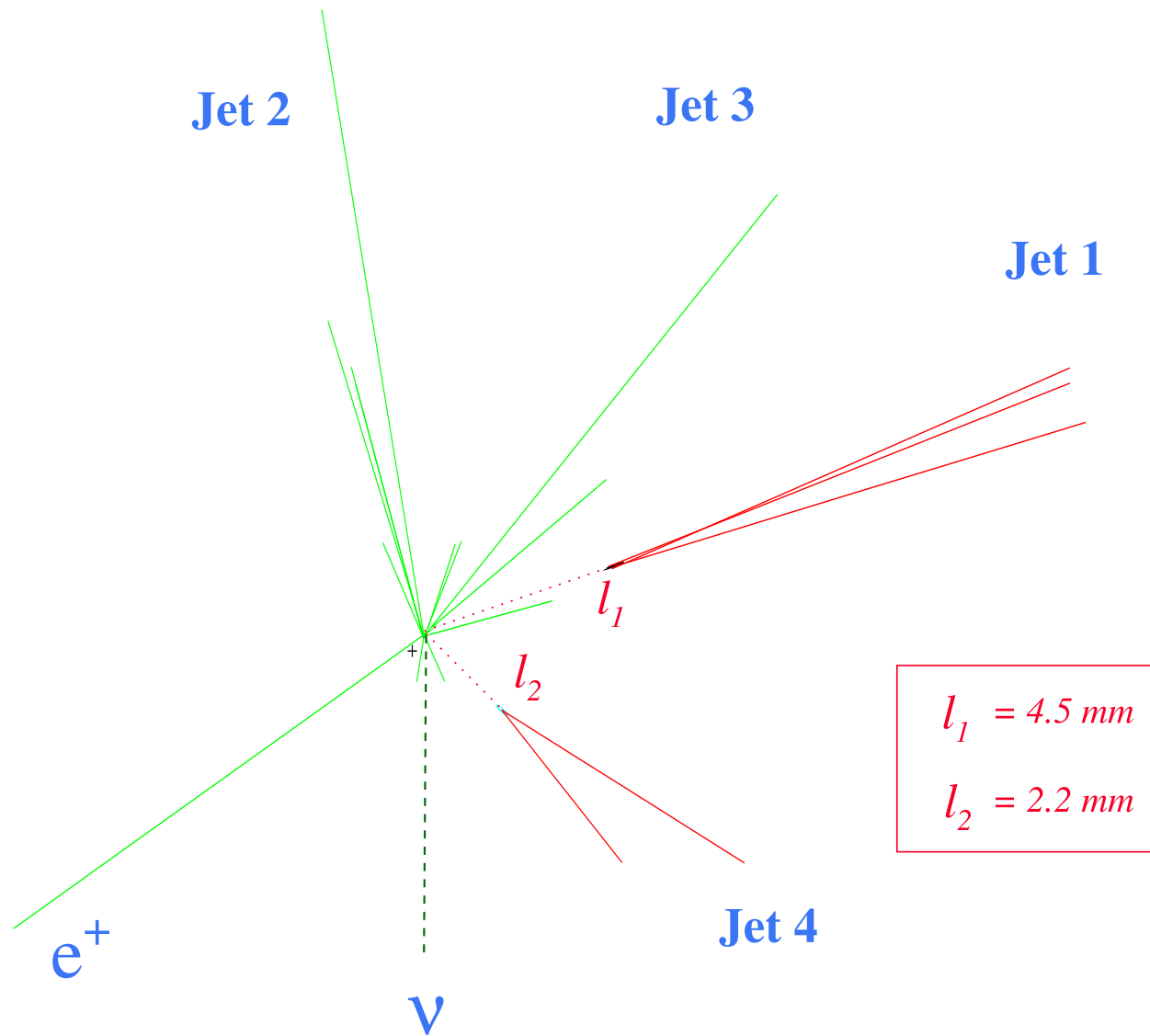


matter: fermions

quarks	u	c	t	+2/3
	d	s	b	-1/3
leptons	e	μ	τ	-1
	ν_e	ν_μ	ν_τ	0



"This is the top quark."



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

24 September, 1992
run #40758, event #44414



Of course the top had been found before...

IT IS LIKELY THAT $m_t < m_W$

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.

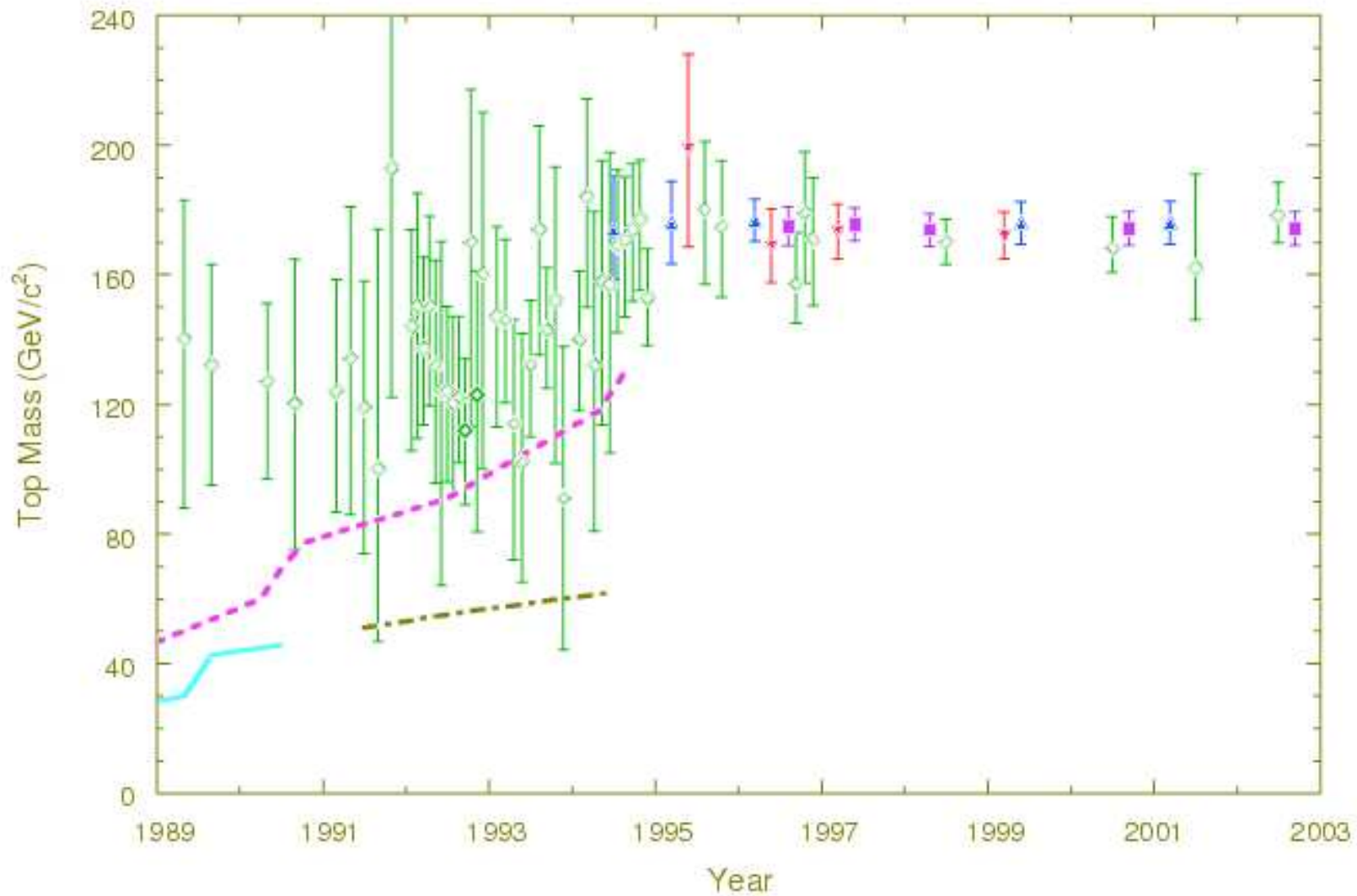
ABSTRACT

A clear signal is observed for the production of an isolated large-transverse-momentum lepton in association with two or three centrally produced jets. The two-jet events cluster around the W^2 mass, indicating a novel decay of the Intermediate Vector Boson. The rate and features of these events are not consistent with expectations of known quark decays (charm, bottom). They are, however, in agreement with the process $W \rightarrow t\bar{b}$ followed by $t \rightarrow b\bar{c}$, where t is the sixth quark (top) of the weak Cabibbo current. If this is indeed so, the bounds on the mass of the top quark are $30 \text{ GeV}/c^2 < m_t < 50 \text{ GeV}/c^2$.

UA1, Phys. Lett. B 147, 493 (1984)



Was the top-quark mass predicted?



Look at the predictions in Sept. 1992...



The real evidence... (1995)

Elusive Particle Found By Scientists in Illinois

Continued From Page A1

1977. Since the infancy of the universe shortly after the Big Bang — estimated at 10 billion to 20 billion years ago — only the up and down quarks have survived in nature, and the protons and neutrons that make up the nuclei of all atoms are built from combinations of these two quarks. The other quarks disappeared from the observed universe, but have been recreated by modern particle accelerators.

Dr. Leon M. Lederman, a winner of the Nobel Prize in Physics and a former director of Fermilab, said at today's meeting that he doubted there could be any more quark types but that "we know there's a lot of dark matter out in the universe that we can't identify."

"We're still in for a lot of surprises," he added.

But more important than merely completing the table of quarks predicted by theory, the top quark may now begin to shed light on a deep philosophical question: everything in the universe, from the most distant galaxy to a rose petal, is made of quarks. Were the masses and other properties of these particles determined by random chance, or by some fundamental unifying plan? If so, what is that plan, and how might gravity, the least understood of the four forces of nature, be related to it?

"This monster, compared with all the other quarks, is like a big cow."

Trying to understand the fundamentals of the universe.

It's an egg in a nest of little sparrow eggs," said Dr. Paul D. Grimm, a leader of the D0 group, "it's so peculiar it must hold clues to some important new physics."

"The top quark has turned out to be so heavy," added Dr. John Pho-

ph, "there are one or more than one Higgs bosons."

"We're so stumped by the discovery of the top quark that we haven't yet begun to fill all the data," said Dr. Ross Klima of Fermilab, one of the leaders of the experiment search. "But this particle is so astonishingly heavy that its decay may give us hints of a lot of other things, perhaps even of supersymmetric particles."

The quest for supersymmetric particles by the world's most powerful accelerators during the last decade has failed to turn up any evidence that they exist, but according to some theories, they may be so heavy they are beyond reach of present-day accelerators. If supersymmetric particles could be shown to exist, they might offer scientists a tool for learning how gravity is related to the other forces of nature: the electromagnetic force and the strong and weak nuclear forces.

Even when trillions of protons and antiprotons are made to collide in Fermilab's huge accelerator at combined energies of two trillion electron-volts, the creation of top quarks by the miniature fireballs remains a rare event.

Dr. Graham of the D0 collaboration said today that his group, which has been running its detector on and off since 1992, has found 17 collisions resulting in evidence of the creation of a top quark. The team was able to calculate the mass of the particle as 176 billion electron-volts, give or take about 10 billion electron-volts. (Particle physicists measure mass in terms of its energy equivalent, because the units are more practical. Einstein's famous equation E=mc² defines the equivalence of mass and energy.)

For their part, according to Dr. William Corbett Jr., a leader of the rival CDF Collaboration, two separate counting techniques using the CDF detector have turned up a total of about 11 top quark events. The group calculates the mass of the top quark as about 178 billion electron-volts, give or take about 13 billion.

These results, the competing teams say, are in reasonably close agreement. At any rate, they agree that they have found the quark, and that there is only one chance in about one million that the results could have been caused by anything but the decay of pairs of top and

THE NEW YORK TIMES NATIONAL FRIDAY, MARCH 3, 1995

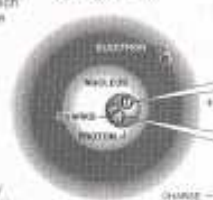
The Top Quark: What Is It?

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.

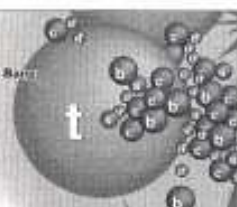
THE STUFF OF ATOMS. The nuclei of ordinary matter, like the hydrogen atom below, contain protons and neutrons made up of two kinds of quarks, up and down.

THE BIG BANG. The other kinds of quarks, which existed just after the Big Bang, 30 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.

Hydrogen Atom



The Big Bang



The 6 Quarks

Mass in millions of electron-volts		
UP	CHARM	TOP
MASS 2	MASS 1,500	MASS 176-180
DOWN	STRANGE	BOTTOM
MASS 5	MASS 150	MASS 4,500

Source: Fermilab, Department of Energy



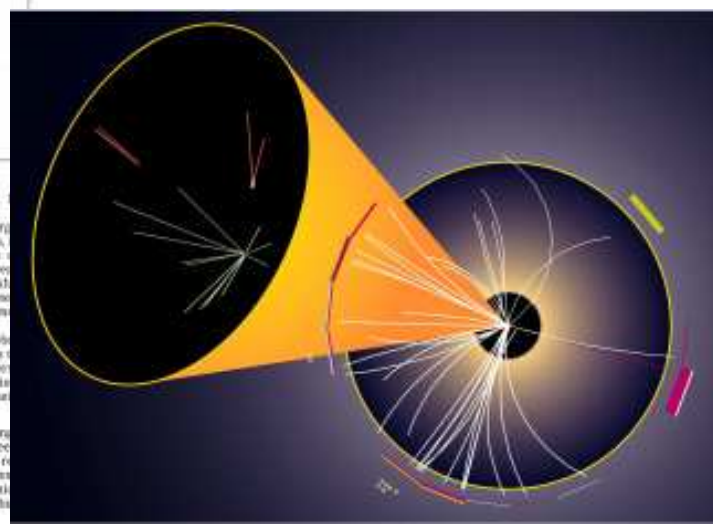
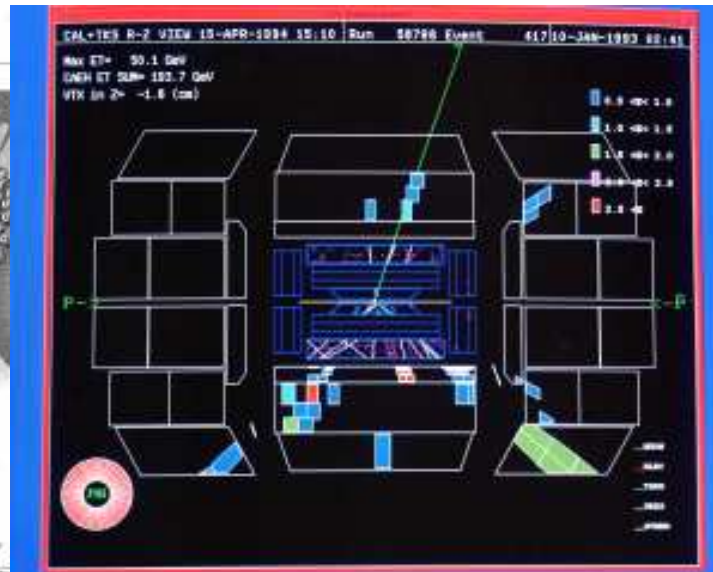
Forging a link between the physical and the metaphysical.

that the machine has at least more years of useful life.

The stakes for the high-energy physics community are enormous, terms of job security, the risks failure and the promise of groundbreaking for leaders of successful experiments. Competition between physicists is often vicious and sometimes bitter.

The CDF and D0 detector collaborations have gone to great lengths (and even looking at each other's experiments — a policy that persisted even today minutes before the joint seminar began.

"We know that some of the young physicists on both sides have been exchanging pirated copies of our reports, but we've tried to suppress such exchanges," one physicist said. "I don't think there is trickery, but





What is a heavy-quark?

A heavy quark is a quark with $m_q \gg \Lambda_{\text{QCD}}$.

	Pole mass M	$\overline{\text{MS}}$ mass $\overline{m}(\overline{m})$
Charm	$\sim 1.3\text{--}1.7 \text{ GeV}$	$1.27_{-0.11}^{+0.07} \text{ GeV}$
Bottom	$\sim 4.5\text{--}5 \text{ GeV}$	$4.20_{-0.07}^{+0.17} \text{ GeV}$
Top	$173.1 \pm 0.6 \pm 1.1 \text{ GeV (?)}$	$\sim 163 \text{ GeV}$

PDG; TevEWG

Pole Mass: $\sim \frac{1}{\not{p} - M}$

$\overline{\text{MS}}$ Mass: Related to pole mass by

$$\frac{M}{\overline{m}(\overline{m})} = 1 + \frac{4}{3} \left(\frac{\alpha_s}{\pi} \right) + \left(\frac{\alpha_s}{\pi} \right)^2 (-1.0414 \ln(M^2/\overline{m}^2) + 13.4434) + \dots$$

It seems kind of funny to list 2 different masses...



What is the top-quark mass?

Answer 1: A parameter of the Lagrangian $L \sim m_t \bar{t}t$

Answer 2: An effective coupling between t - t - h

$m_t = Y_t / (2\sqrt{2}G_F)^{1/2} \approx 1$ in the SM

Answer 3: The kinematic mass seen by the experiments

Right after the discovery of the top quark, Martin Smith and Scott Willenbrock asked this question about the “pole mass” of the top quark. They showed that a renormalon (the closest pole of the Borrel transform) induced an ambiguity of $\mathcal{O}(\Lambda_{QCD})$ in the definition of the pole mass.

This led to the recommendation to use the $\overline{\text{MS}}$ mass for top quarks as a standard.

We theorists are good at setting standards that make our life easier ... most perturbative calculations use the $\overline{\text{MS}}$ mass for simplicity.

Of course mass is NOT measured directly. Instead, it affects the distribution of events that are measured, and that distribution is used to INFER the mass.

At the ILC, we hope to measure m_t to about 100 MeV by scanning over the $t\bar{t}$ threshold.



$t\bar{t}$ 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 Λ_{QCD} .

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

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

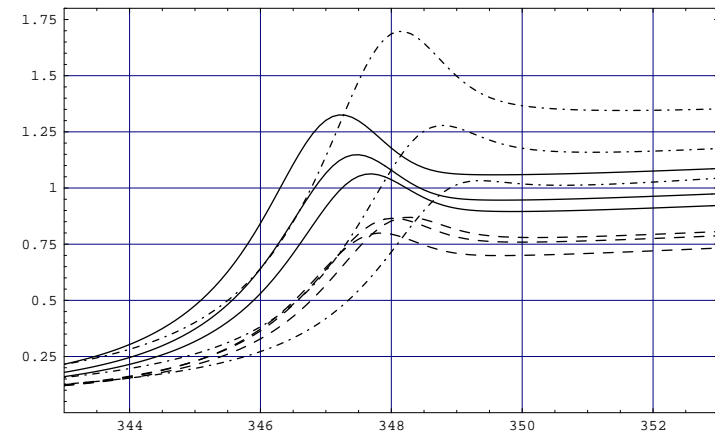
There are large non-relativistic corrections

$$\sigma_{t\bar{t}} \propto v \sum \left(\frac{\alpha_s}{v} \right) \times \left\{ \frac{1}{\sum(\alpha_s \ln v)} \right\} \\ \times \left\{ \begin{array}{l} \text{LO}(1) + \text{NLO}(\alpha_s, v) + \text{NNLO}(\alpha_s^2, \alpha_s v, v^2) \\ \text{LL} + \text{NLL} + \text{NNLL} \end{array} \right\}$$

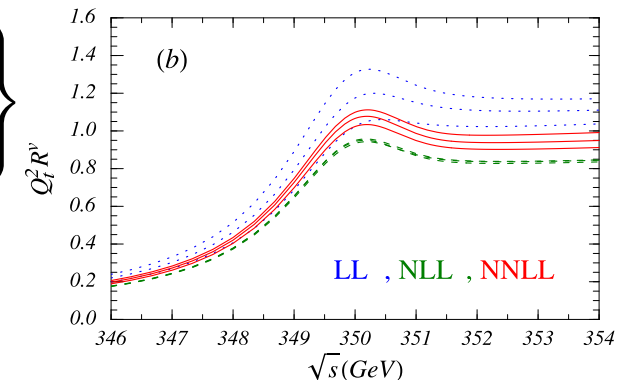
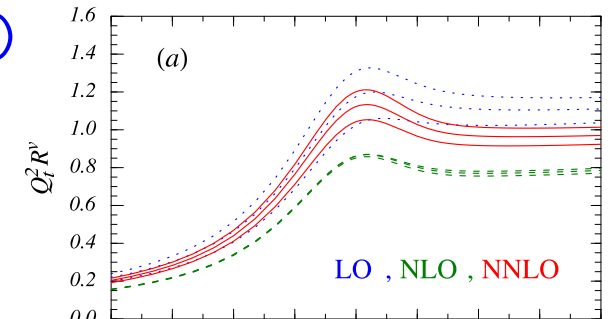
Normalization changes, but peak stable.

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

$\delta m_t \sim 100 \text{ MeV}$ is attainable



Yakovlev, Groote PRD63, 074012(01)

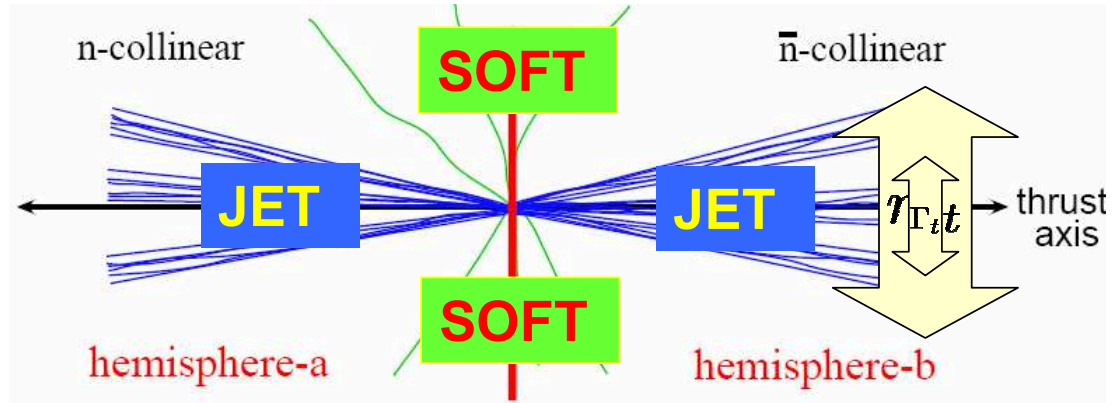


Hoang, Manohar, Stewart, Teubner



$t\bar{t}$ continuum mass

A recent idea based on Soft Collinear Effective field Theory (SCET) recommends just summing all of the QCD radiation into a top-quark jet mass.



$$Q \gg m_t \gg \Gamma_t > \Lambda_{\text{QCD}}$$

Fleming, Hoang, Mantry, Stewart, PRD 77, 114003 (08)

Factorization of the effective field theories into hard, jet, and ultra-soft pieces was shown.

$$\frac{d^2\sigma}{dM_t^2 dM_{\bar{t}}^2} = \sigma_0 H_Q(Q, \mu) \int_{-\infty}^{\infty} dl^+ dl^- J_n(s_t - Ql^+, \mu) J_{\bar{n}}(s_{\bar{t}} - Ql^-, \mu) S_{\text{hemi}}(l^+, l^-, \mu)$$

If correct you could have another stable and accurate mass definition.

Personal Opinion: Even if this case does not work, these EFT techniques will be central to theoretical physics in the future.



What mass do we measure?

The statement has been made that you measure a 1S mass at threshold, and a top-jet mass in the continuum (using the new calculations).

Other masses have been mentioned: \overline{MS} mass, pole mass, (could have mentioned peak mass, Breit-Wigner mass, ...)

Which mass do we measure? None of them.

We measure line-shapes or particle flow or invariant masses with cuts and ISR/FSR effects.

To the extent experimentalists use LO Monte Carlo programs, the mass is dominated by kinematics, and hence is close to the pole mass.

What we really care about is a mass we can use in many calculations. The most convenient mass is the \overline{MS} mass.

— So whatever you extract, translate to that!

The challenge going forward will be to ensure that, whatever you use, the experimental and theoretical definitions agree.



Is this focus on masses just better
bookkeeping?

The top-quark mass offers us more

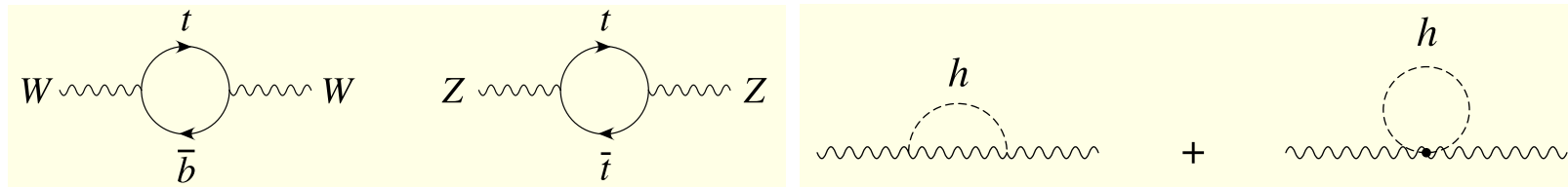


Why study the top-quark mass?

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 propagators.



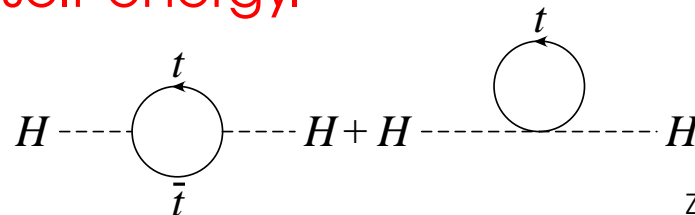
Assuming α , G_F , and M_Z as inputs, M_W^2 at 1-loop is:

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

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

Inverting the formula provides a logarithmic constraint on M_H .

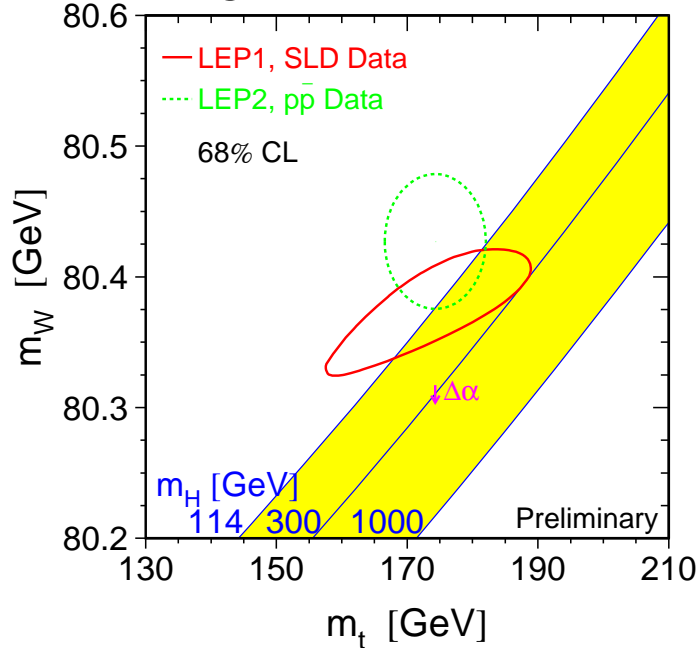
Higgs searchers put it differently: the top quark provides a large correction to the Higgs self-energy.





Constraints on Higgs mass from W and t

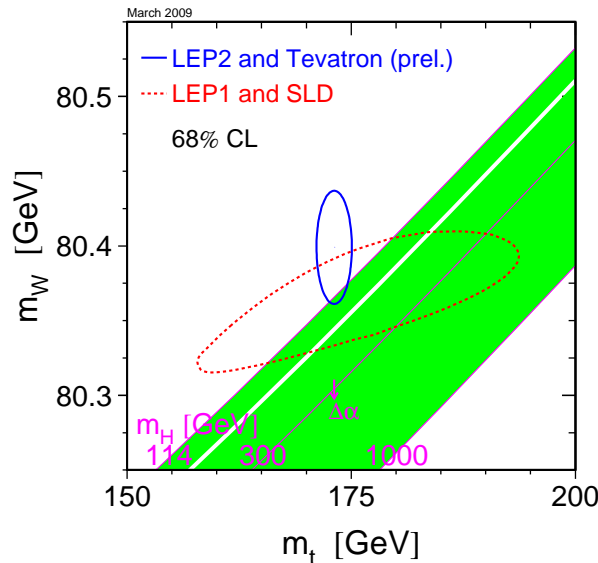
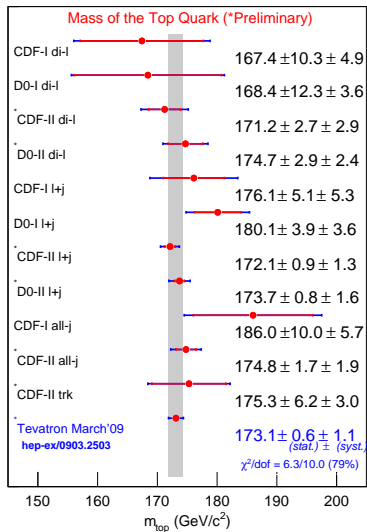
M_H is logarithmically sensitive to variations of M_W and m_t .



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



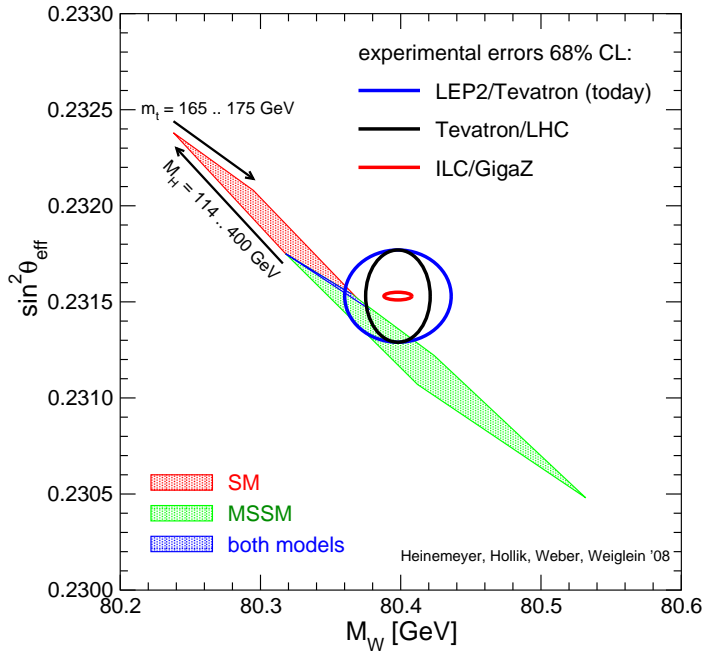
Winter 2009
 $m_t = 173.1 \pm 0.6 \pm 1.1$ GeV
 (Close to the first $t\bar{t}$ event...)

Tevatron EWWG



How well do we need to know m_t ?

There is a better way than “blue band plots” to look at this in the SM.



Heinemeyer *et al.*

- Assume M_H is known.
- M_W will be measured to ~ 20 MeV
 \Rightarrow Need m_t to ~ 3 GeV at LHC.
 (We already know it to 1.3 GeV.)

- A linear collider can measure M_W to ~ 6 MeV.

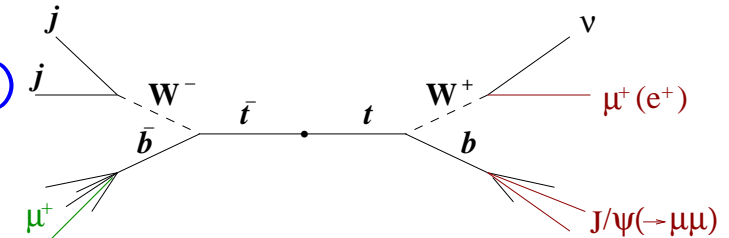
Giga-Z can measure $\sin^2 \theta_W \sim 10^{-5}$

\Rightarrow Need m_t to ~ 1 GeV.

At the LHC:

- Several channels can reach < 1 GeV (stat.)
- To reach systematics < 1 GeV use:

$M_{J/\psi \ell \nu}$ w/ template for m_t . ($\sim 300 \text{ fb}^{-1}$)



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).



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

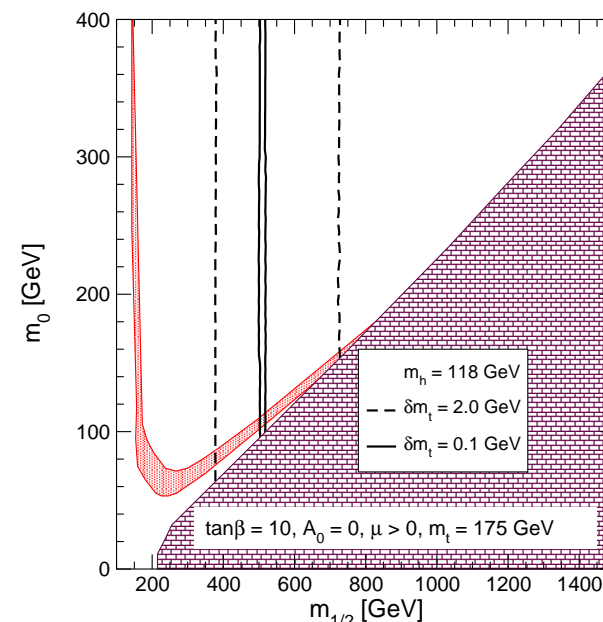
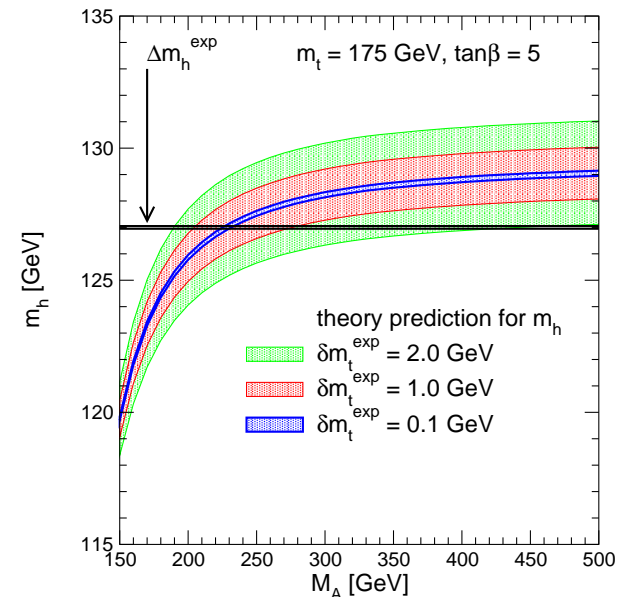
$$\Delta M_H^2 \approx \frac{3G_F m_t^4}{\sqrt{2}\pi^2 \sin^2 \beta} \ln \left(\frac{\overline{m}_t^2}{m_t^2} \right)$$

- 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.

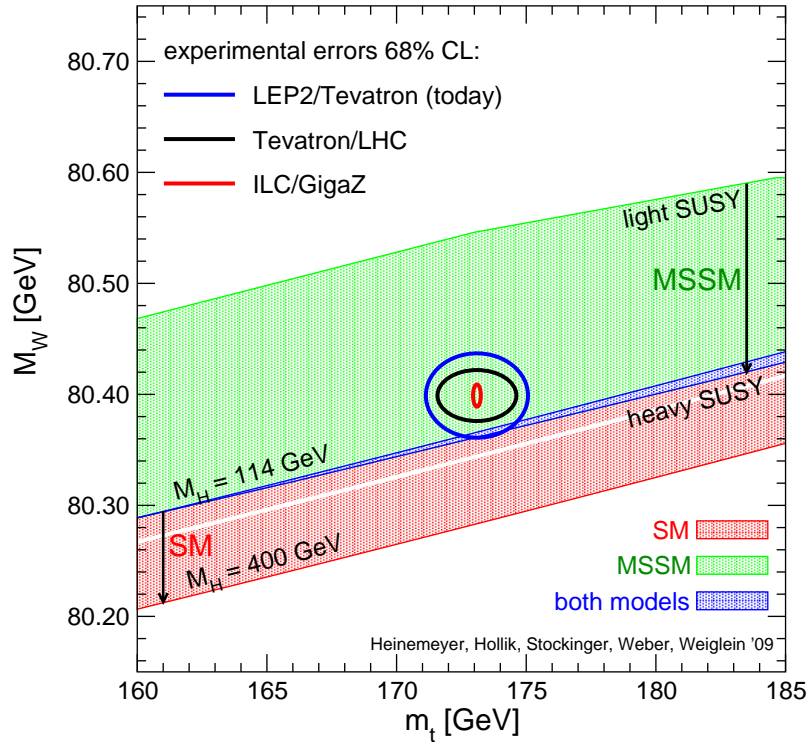
This needs major effort

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

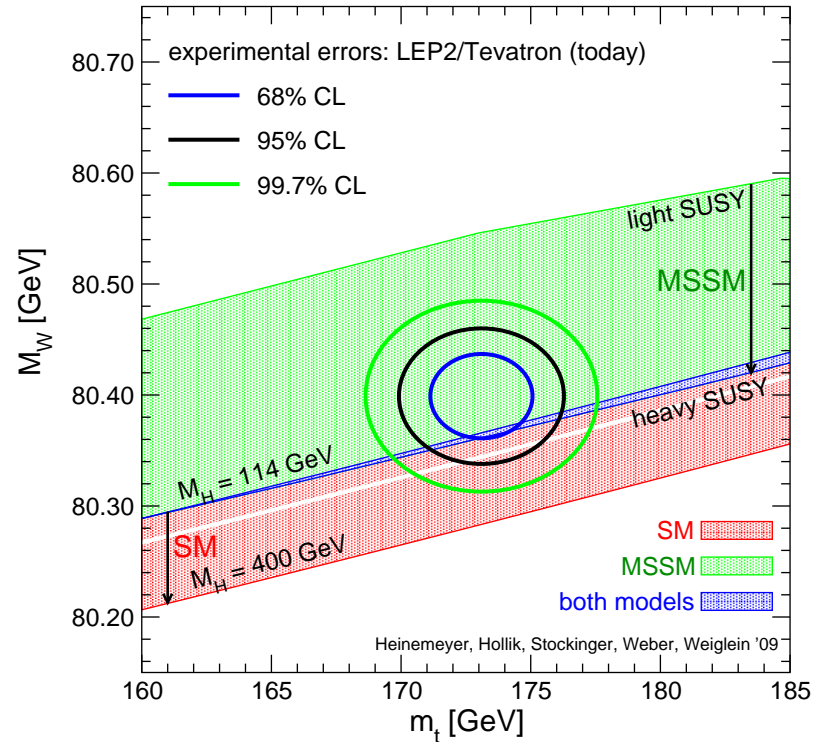




M_W vs. m_t for MSSM Higgs



“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.



To extract masses we depend on well-defined predictions of observables

Let's look at the total top-quark cross section

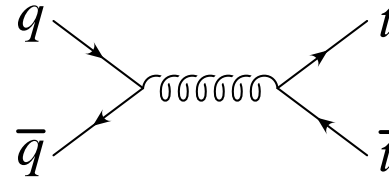


Top-quark pair ($t\bar{t}$) production

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

Leading contribution at
Tevatron

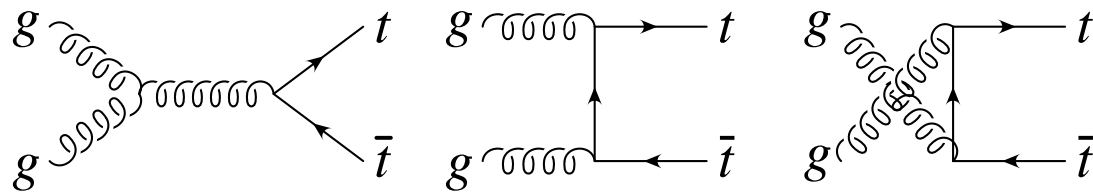
Tev (RunII)	85%
LHC	10%



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

Leading contribution at LHC

Tev (RunII)	15%
LHC	90%



At the Tevatron, $t\bar{t}$ is produced close to 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.

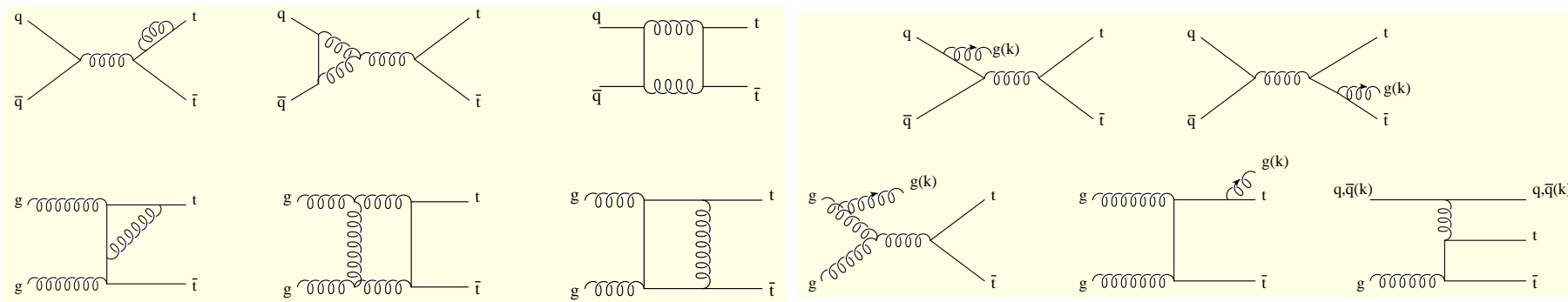
At Run II there are already hundreds.

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.
⇒ 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

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

Near threshold, the LO cross section vanishes:

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

At NLO there are soft and collinear singularities:

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

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

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

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



Threshold resummation

Threshold logarithms can be resummed via exponentiation, similar to the case of Drell-Yan (DY) or $e^+e^- \rightarrow \text{jets}$.

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 $\lim N \rightarrow \infty$, which leads to threshold corrections of the form:

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

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

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



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:

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

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)

Bonciani, Catani, Mangano, Nason, NPB 529, 424 (98)

Implementation: 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, Contopaganos, PRD 54, 2085 (96)

Catani, Mangano, Nason, Trentadue, NPB 478, 273 (96)



Nomenclature and uncertainties

Bad nomenclature

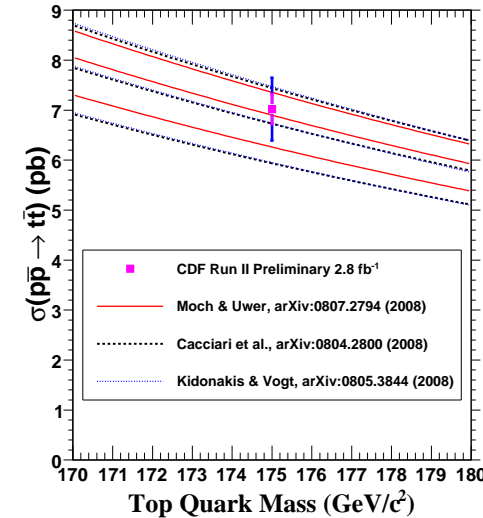
“NNLO-NNLL”

This is really NLO+the Sudakov-like resummation we saw above, where the exponent is re-expanded to the 3rd LL.

There is nothing NNLO about it.

Moch and Uwer do “NNLO_{approx}”

This is NLO+real NNLL resummed.



Unusual uncertainties

NLO scale uncertainty of $\pm 10\%$ \rightarrow $\pm 5\%$ w/ NLL correction

Including PDF uncertainty, \rightarrow $\pm 15\%$ 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): $s = M_{t\bar{t}}^2 = (p_t + p_{\bar{t}})^2$

$\sigma \pm 1\text{PI/PIM} \pm \text{scale} \pm \text{PDF}$

Run I $5.24 \pm 0.31 \pm 0.2 \pm 0.6$ pb

Run II $6.77 \pm 0.42 \pm 0.1 \pm 0.7$ pb

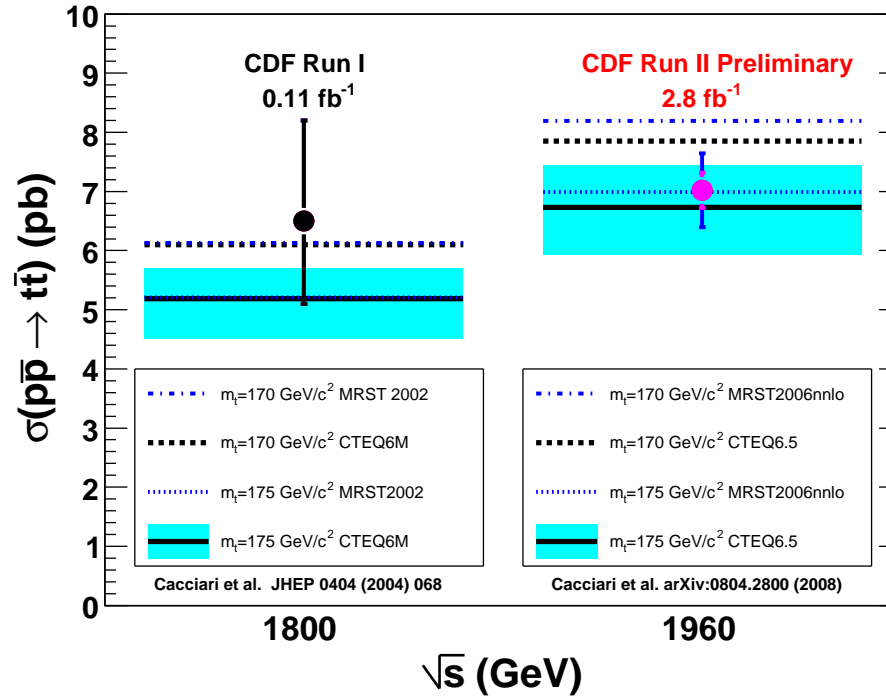
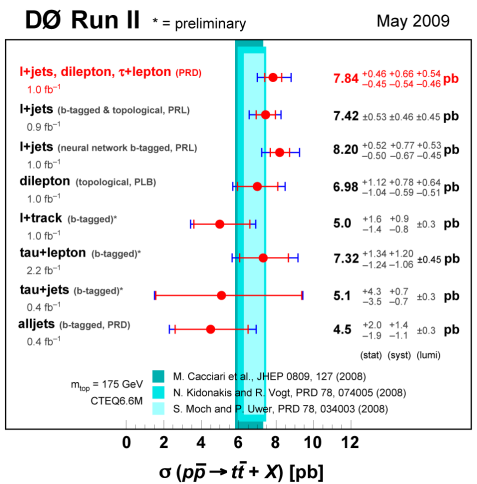
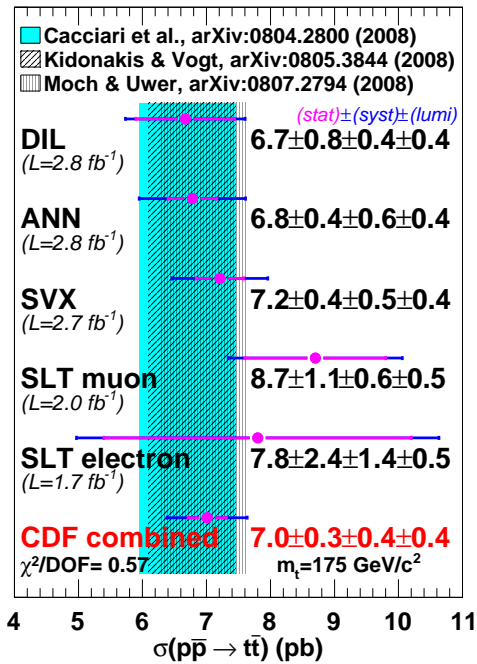
LHC is not dominated by threshold kinematics:

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

Full NNLO is needed!



Tevatron data



Great agreement so far!
 Lighter top-quark mass preferred.
 Experiment will be better than theory soon.



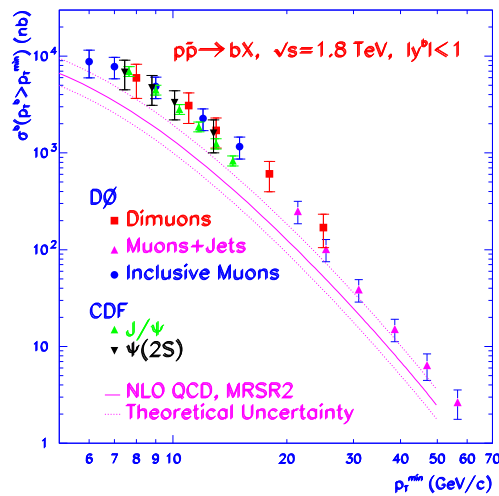
QCD is flavor blind

Let's apply the same calculations to the
bottom-quark cross section



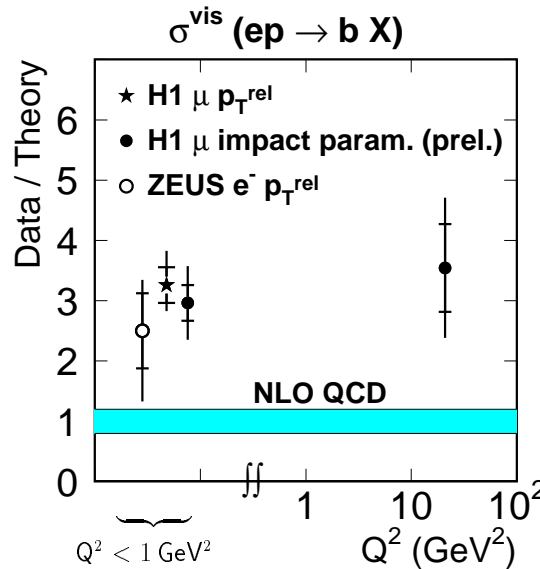
How about the b -quark cross section?

There was a long-standing (20 year) problem that the b -quark cross section was consistently underestimated by factors of 2–3.



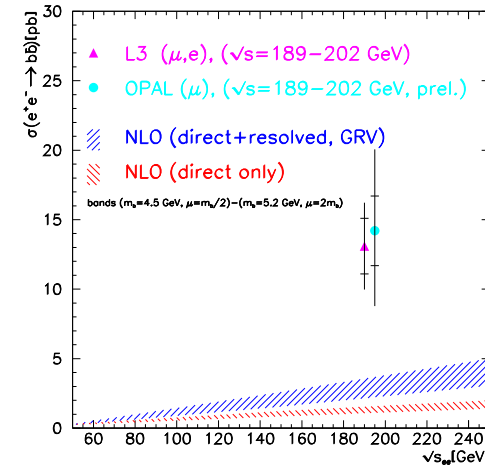
Tevatron

Several modes;
 $b \rightarrow J/\psi$ most precise
 CDF and DØ



HERA

Excess in both DIS
 & photoproduction
 Sefkow, hep-ex/0109038



LEP

$$\sigma(e^+e^- \rightarrow e^+e^-b\bar{b}) \approx \gamma\gamma \rightarrow b\bar{b}$$



We do not see b -quarks

Unlike t quarks, b quarks hadronize to long-lived B hadrons

What we actually have is:

$$\frac{d\sigma(b \rightarrow B \rightarrow J/\psi)}{dp_T} = \int \frac{dz}{z} \frac{d\sigma(b)}{d\hat{p}_T} \otimes D(b \rightarrow B; z) \otimes D(B \rightarrow J/\psi)$$

Fragmentation functions D are non-perturbative!

Nevertheless, a modified perturbative approximation called “Peterson fragmentation” was historically used.

Peterson, Schlatter, Schmitt, Zerwas, PRD 27, 105 (83)

$$D(b \rightarrow B; z) \sim \frac{1}{z[1 - 1/z - \epsilon_Q/(1 - x)]^2} \text{ with } \epsilon_Q \sim \frac{\Lambda^2}{m_Q^2} \text{ and } \langle 1 - z \rangle \sim \sqrt{\epsilon_Q}$$

NOTE: $\epsilon_b = \frac{m_b^2}{m_B^2}$, however it is floated in practice to approximate unknown non-perturbative physics...

Perhaps it is not surprising this did not work too well

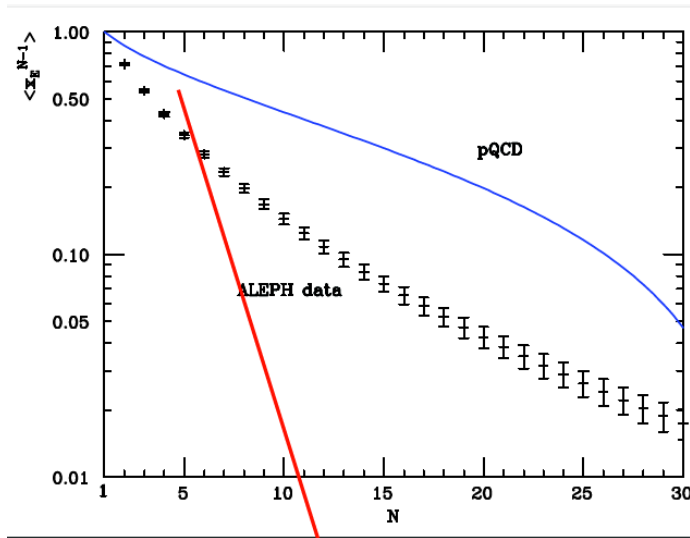


Better idea: Extract non-perturbative fragmentation from data

Cacciari and Nason fit LEP $Z \rightarrow b\bar{b}$ data to directly extract D_{np} .

Cacciari, Nason, PRL 89, 122003 (02)

Translating the LEP data to Mellin space:



This gap:
non-perturbative QCD

$$D_N \equiv \int_0^1 x^{N-1} D(x) dx = \langle x^{N-1} \rangle$$

In this space:

$$\langle x \rangle_{\text{expt}} = \langle x \rangle_{\text{pQCD}} \langle x \rangle_{\text{np}}$$

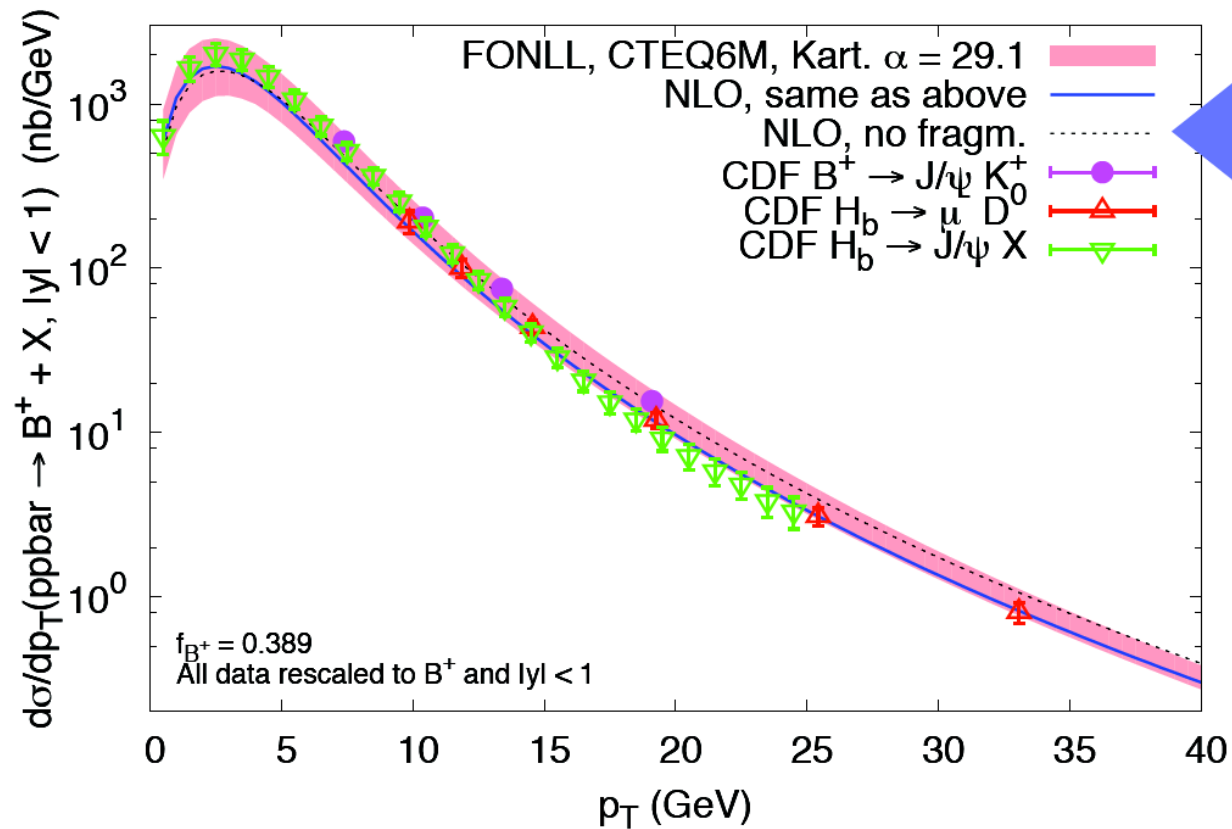
LEP is sensitive to $N = 2$.

Tevatron is sensitive to $N \sim 4$.

This is a HUGE extrapolation



B-meson cross sections at Tevatron



Conclusion: NLO with corrected fragmentation has “excellent agreement with the data”

Do you agree? — Look at $B \rightarrow j/\psi$. Data and theory are independently correlated at each bin.

Perhaps one of you will check this “solution”



Conclusions

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

$$m_t = 173.1 \pm 1.3 \text{ GeV}$$

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

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

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/NNNLL
- To utilize this information we need higher-order (3-loop, soon 4-loop) calculations of EW processes.



Conclusions

2. The b -quark production saga has taught us we have to think carefully about the final state as well as the matrix element.

We broke the cross section up:

$$\frac{d\sigma(B)}{dp_T} \Rightarrow \frac{d\sigma(b)}{dp_T} \otimes D(b \rightarrow B)$$

Heavy quarks forced us to learn more about fragmentation, D .

3. We are in an age of precision QCD!

Whether we are looking at masses, or cross sections, the big lesson is we need to be certain theorists and experimentalists are discussing the same physics!

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