Top & EW

(Theory Overview)

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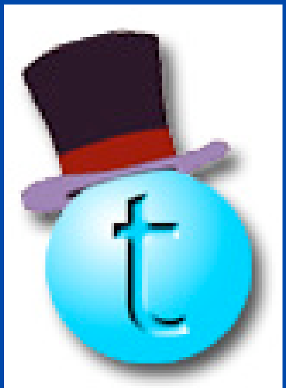

SLAC Summer Institute
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Outline

- Introduction: Why are top & EW measurements so important today?
- EW Bosons
- Top Production and Decay
- Outlook

Electroweak Symmetry Breaking

- The EW bosons (W, Z, and γ) require gauge symmetries to be theoretically consistent.
- However, the gauge invariance would forbid masses for the W and Z, (and also for the fermions); thus the symmetry must be broken.
- We still have not identified the agent of the EW symmetry breaking, and thus we still don't know what the responsible dynamics are.
- The SM has an ansatz based on a fundamental Higgs field. Until we see it, the SM is still incomplete and unproven. (A Sham!)

M Peskin

- We know the energy scale at which the symmetry breaking operates – it can't be too far above the W and Z masses! So whatever the theory is, it must be within grasp in the near future!
- Whatever the theory of EWSB, the most massive objects (which felt the breaking most strongly) are the place to learn about it.
- Thus, it is natural to explore precision measurements of top and the Electroweak bosons, particularly in high energy processes.
- We study top and EW physics to learn about physics beyond the SM!

EW Bosons

Precision Data

- The bulk of our information about the EW bosons comes from the precision data collected by programs at SLAC and CERN at the Z-pole.
- Basic properties such as the Z mass and width were determined, as well as the couplings to fermions.

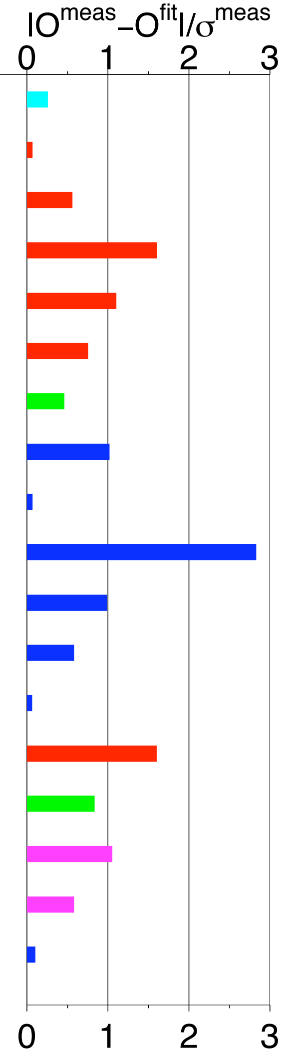
$$R_b = \frac{\left(g_L^b\right)^2 + \left(g_R^b\right)^2}{\sum_q \left[\left(g_L^q\right)^2 + \left(g_R^q\right)^2\right]}$$

$$A_b^{FB} = \frac{3}{4} A_e A_b$$

$$A_b = \frac{\left(g_L^b\right)^2 - \left(g_R^b\right)^2}{\left(g_L^b\right)^2 + \left(g_R^b\right)^2}$$

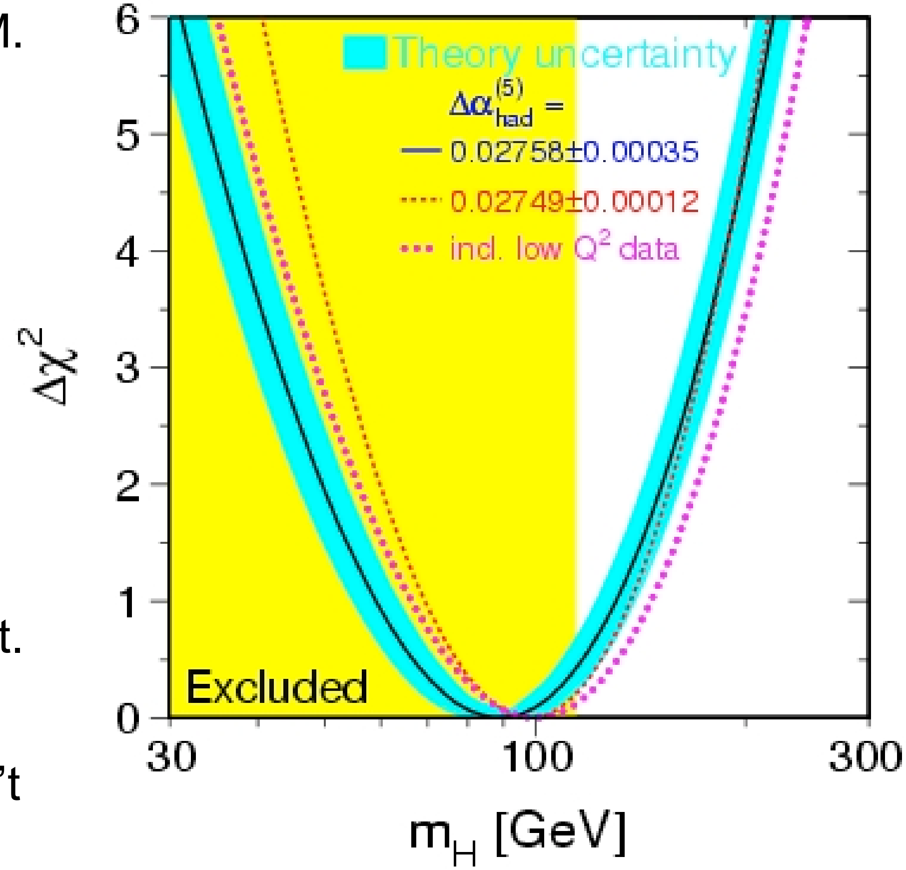
- The data is an amazing confirmation of the Standard Model at the per mil level.

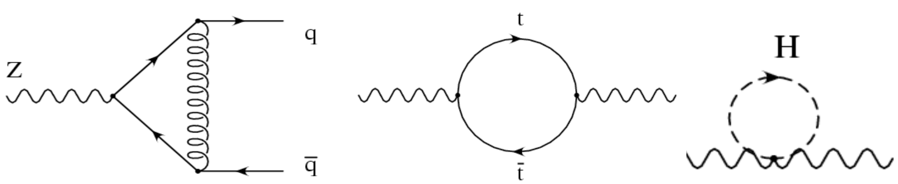
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



EW Fit

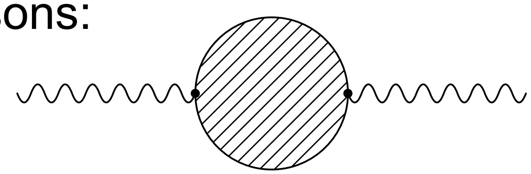
- We can use this information to fit the SM.
- Inputs
  - Tree Level:
    - α_{EM}, EM coupling constant.
    - G_μ, the Fermi decay constant (extracted from muon decay).
    - M_Z, the Z mass itself.
  - Loop Level:
    - m_t, the top mass.
    - α_S, the strong coupling constant.
    - M_H, the Higgs boson mass.
- In the SM, the only one of these we don't know is the Higgs boson mass.
- The fit to the SM is actually a fit to m_H (plus "jiggling" the known parameters around within their error bars).





Oblique Corrections

- Physics associated with mass generation seems most likely to most drastically affect the heavy objects: W, Z, and top.
- In that case, the effects to the light fermions are expected to be small, and we can parameterize the effects on the data as modifications to the propagation of the heavy gauge bosons:



- If the scale of new physics is sufficiently large compared to the Z mass, such effects can generally be described by the three Peskin - Takeuchi parameters:
  - **S** characterizes the wave-function (couplings) of the Z (on-shell)
  - **T** characterizes the relative W and Z masses at zero external momentum.
  - **U** characterizes the difference between the W and Z wave-functions.
- We can map these to dimension-6 (and higher) operators that result when heavy physics is integrated out. They are the generic leading residual of heavy physics which obeys our assumptions.
- Thus, in any theory satisfying these very reasonable assumptions, **S**, **T**, and **U** describe the leading corrections to SM prediction for precision EW data.

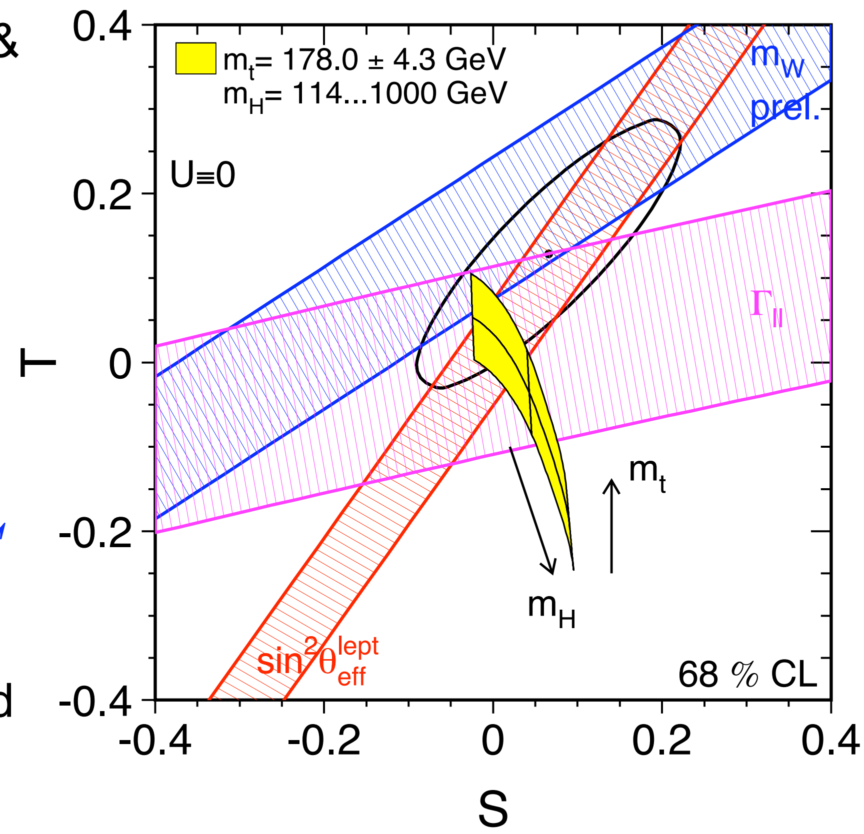
Fits to S & T

- In practice, because **U** corresponds to an even higher dimensional operator than **S** & **T,** and since we know the Z properties more precisely than those of W, **U** is not usually as important as **S** and **T** in constraining a specific model.

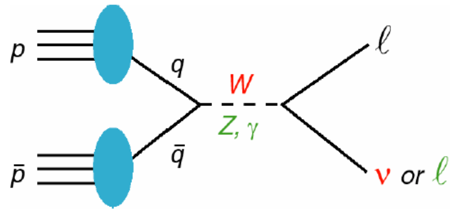
- Related variabls, often equivalent in practice, are the Altarelli parameters:

$$\epsilon_1 \leftrightarrow T \quad , \quad \epsilon_2 \leftrightarrow -U \quad , \quad \epsilon_3 \leftrightarrow S$$

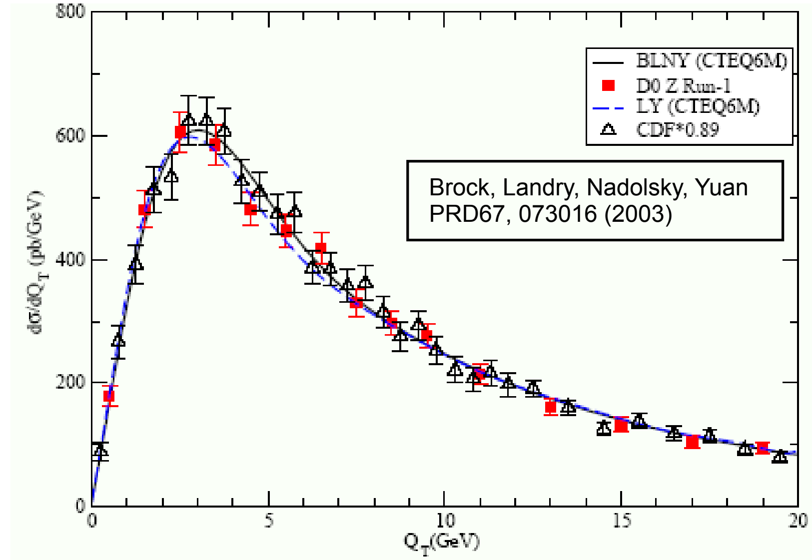
- The effects of top and Higgs can be captured by changes in **S** and **T** compared to some reference values.
- We can see how the SM's indirect preference for a light Higgs could be a red herring, if BSM physics modifies **S** and **T** appropriately.

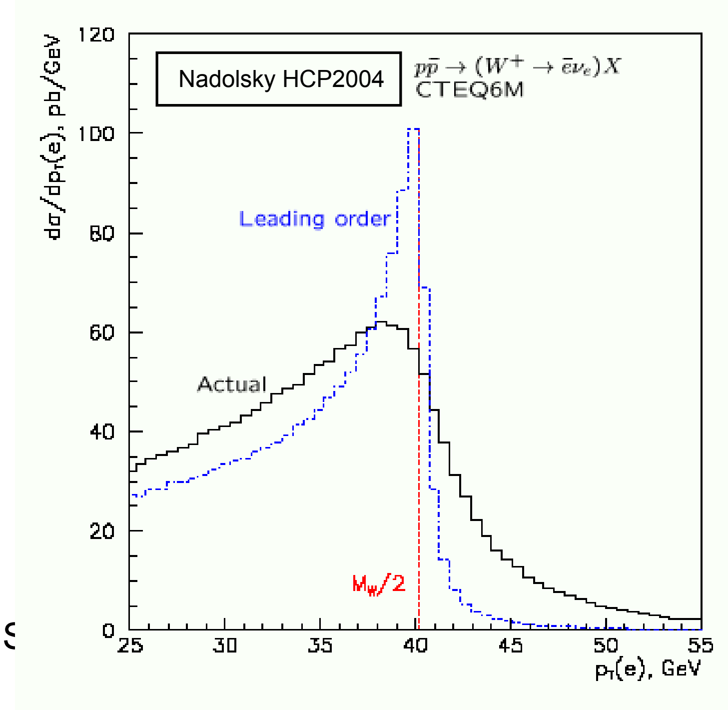


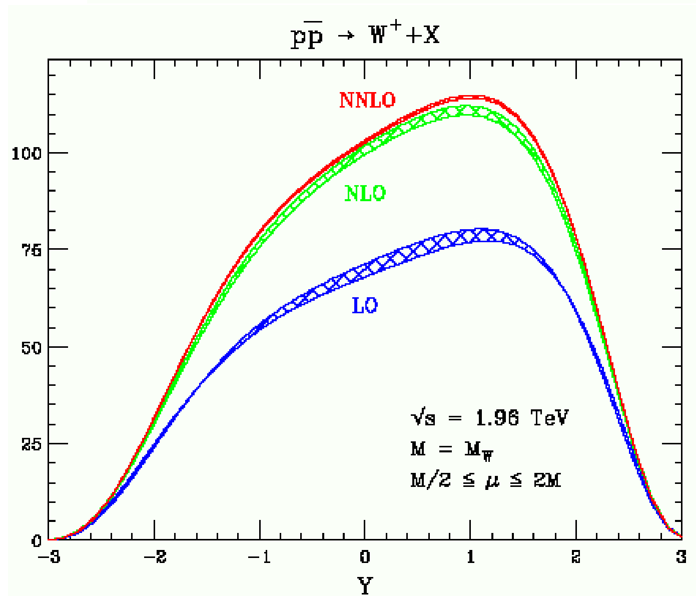
Hadro-production



- Production of EW bosons is a very important process at a hadron collider.
  - Measurement of M_W
    - W kinematics (QCD)
    - QED final state radiation
    - EW Corrections
  - PDFs
  - Luminosity Measurement?
  - **Test of QCD / Resummation / MC**







Anastasiou, Dixon, Melnikov, Petriello PRD69, 094008 (04)

Di-Boson Production

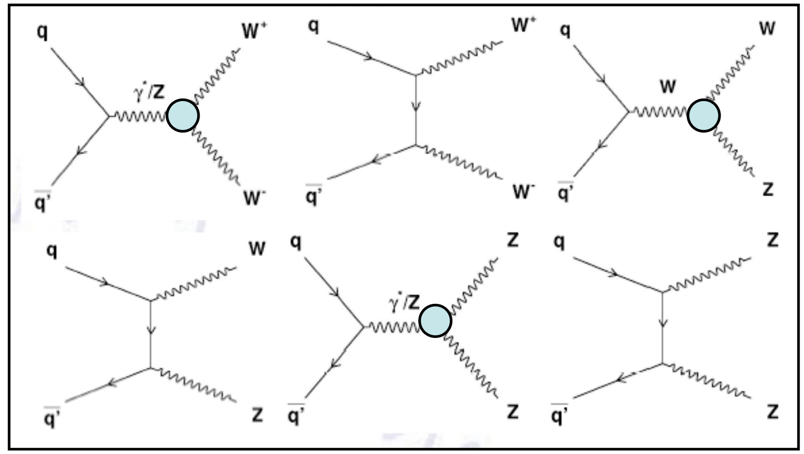
New Physics generically parameterized as:

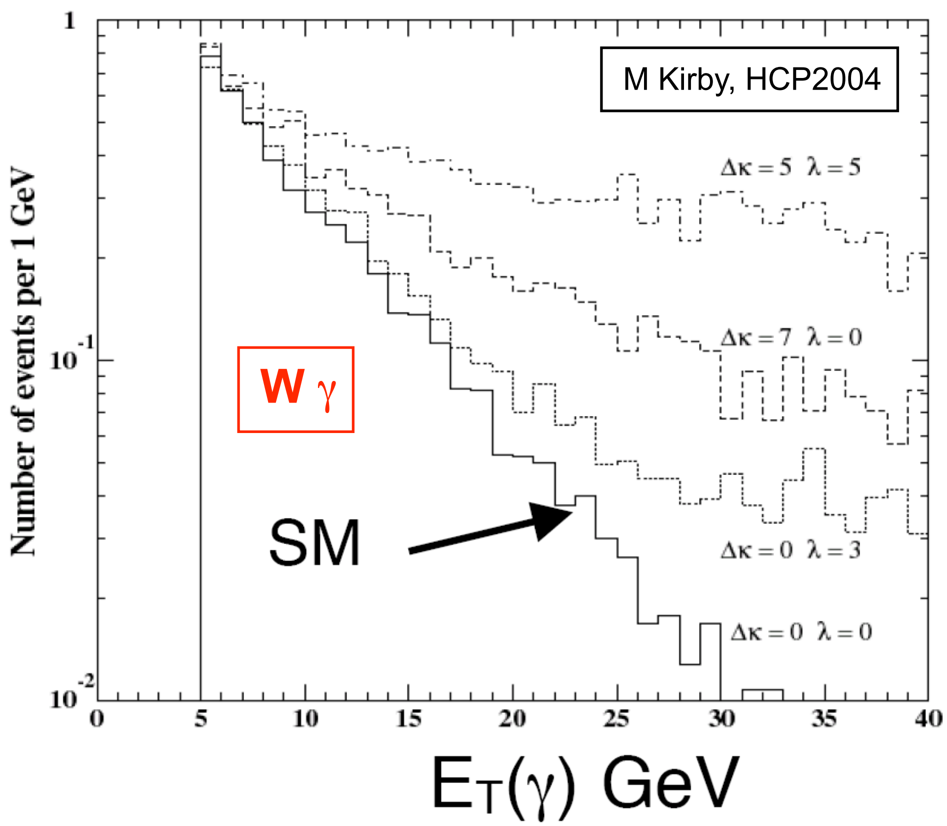
$$L = L_{SM} + \Delta\kappa_\gamma \left(W_\mu^+ W_\nu^- F^{\mu\nu}\right) + \frac{\lambda}{m_W^2}\left(W_\mu^{+\nu} W_\nu^{-\rho} F_\rho^\mu\right) + \ldots$$

$$F^{\mu\nu} \equiv \left(\partial^\mu A^\nu - \partial^\nu A^\mu\right)$$

$$W_+^{\mu\nu} \equiv \left(\partial^\mu W_+^\nu - \partial^\nu W_+^\mu\right)$$

$\Delta\kappa_\gamma, \lambda \to 0$: SM Limit





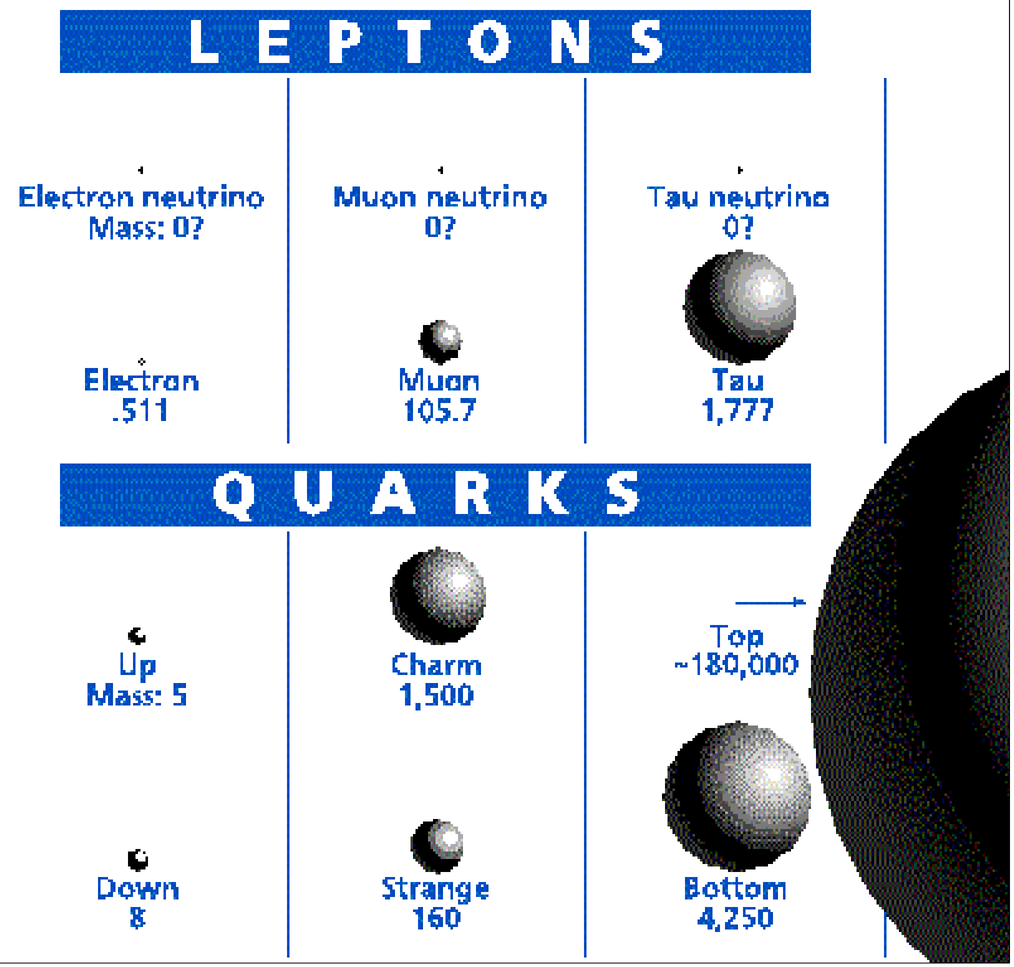
- Even in the SM, diboson production is an important process to understand because it shares many characteristics (and is a background to) Higgs.
- Triple gauge vertices are difficult to access with any other process, and are expected to be sensitive to physics beyond the Standard Model.
- The current luminosity is just enough to observe several of these processes; Tevatron will explore radically new territory in the near future!

Top

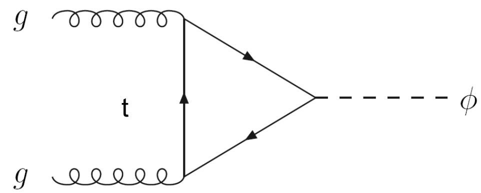
The King of Fermions!

- In the SM, top is superficially much like other fermions.
- What really distinguishes it is the huge mass, roughly 40x larger than the next lighter quark, bottom.
- This may be a strong clue that top is special in some way.
- It also implies a special role for top within the Standard model itself.
- Top is only fermion for which the coupling to the Higgs is important: it is a laboratory in which we can study EWSB.

SM Fermions



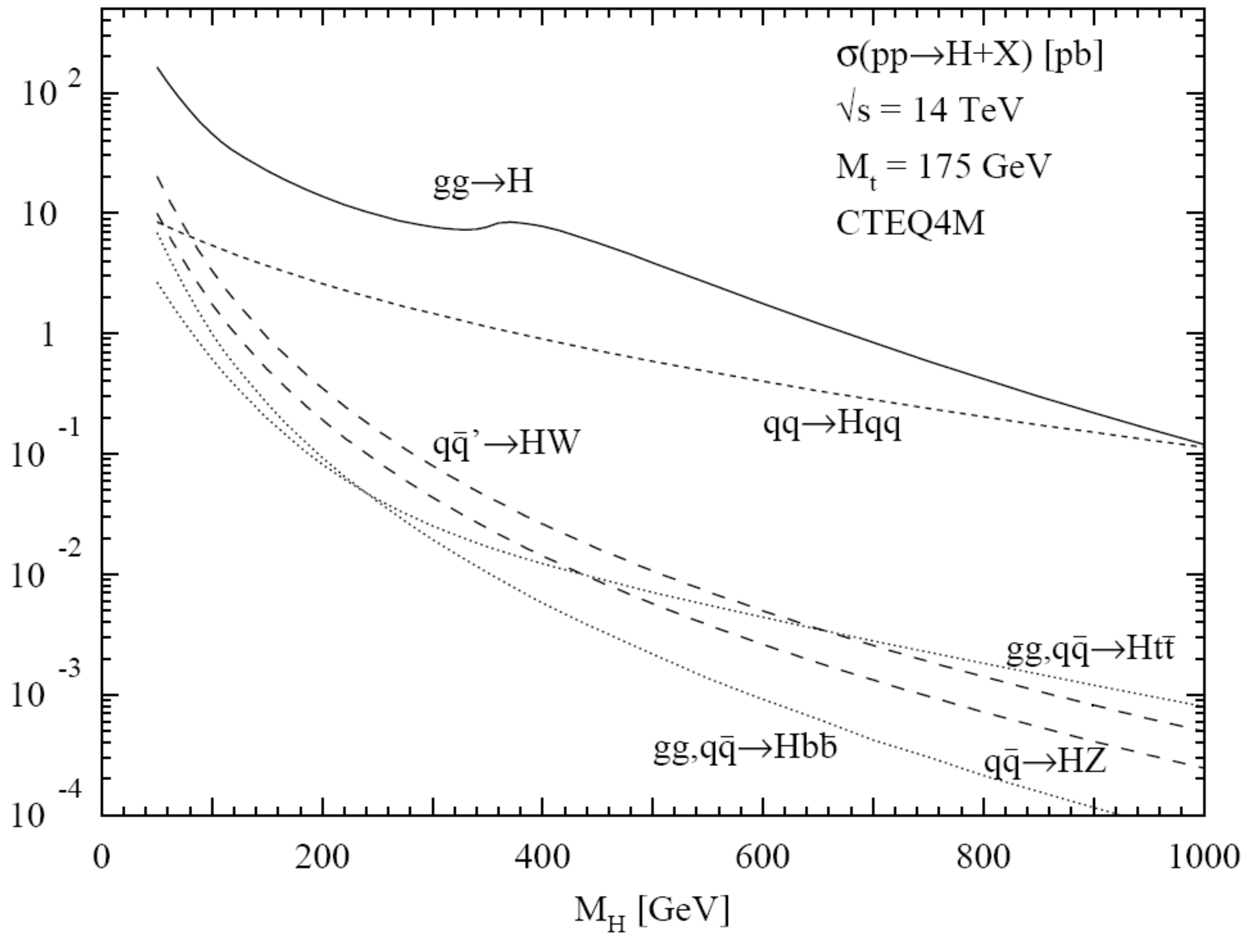
Higgs Physics



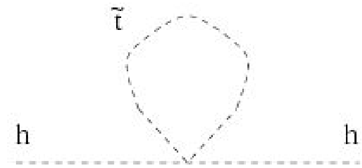
The large top mass means a strong coupling to the Higgs. Thus, several mechanisms of Higgs production rely on Top.

One in particular takes advantage of the fact that top is colored. Loops of top quarks mediate an interaction between Higgs and gluons. Despite being loop suppressed, this process *dominates* Higgs production at the LHC!

Top also contributes to the Higgs coupling to two photons, though the dominant piece is from W's.

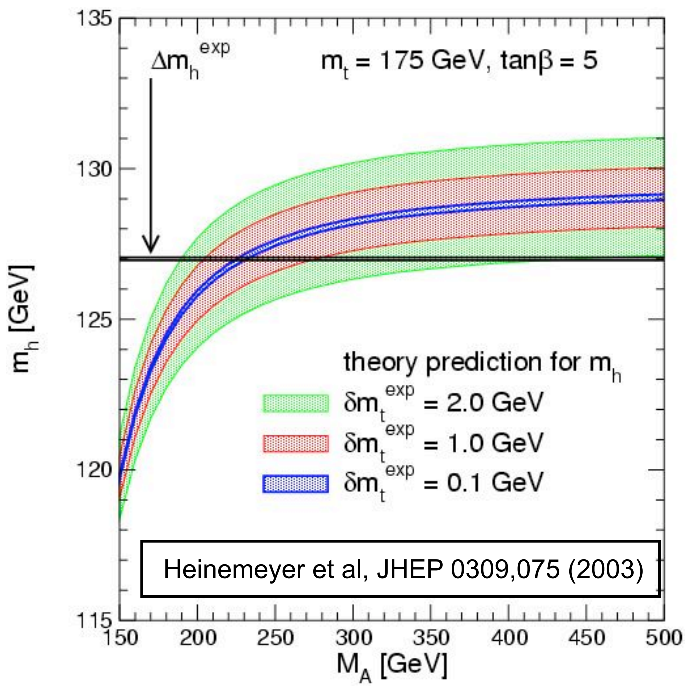


Top Sector and SUSY



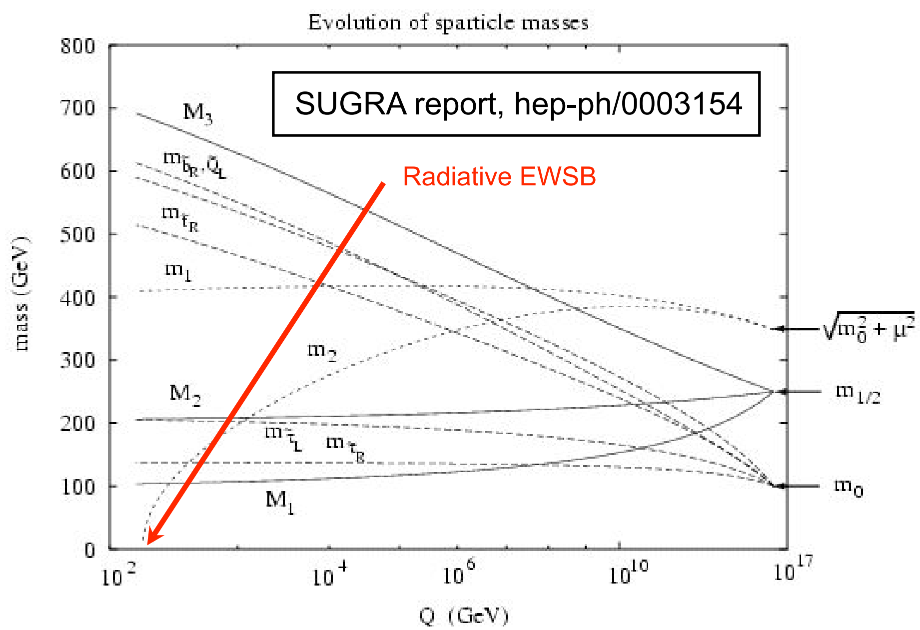
Top plays an important role in the minimal supersymmetric standard model.

- Most importantly, the MSSM only survives the LEP-II bound on m_h because of the large y_t:



- (m_t < 160 GeV rules out MSSM!)

- The large top Yukawa leads to the attractive scenario of radiative electroweak symmetry-breaking:



- This mechanism is also essential in many little Higgs theories.

Top in the Standard Model

- In the SM, top is the marriage between a left-handed quark doublet and a right-handed quark singlet.
- This marriage is consummated by EWSB, with the mass (m_t) determined by the coupling to the Higgs (y_t).
- This structure fixes all of the renormalizable interactions of top, and determines what is needed for a complete description of top in the SM.
- Mass: linked to the Yukawa coupling (at tree level) through: $m_t = y_t\, v$.
- Couplings: g_S and e are fixed by gauge invariance. The weak interaction has NC couplings, fixed in addition by s^2_W. CC couplings are described by V_{tb}, V_{ts}, and V_{td}.

Top in the SM

α=1: top

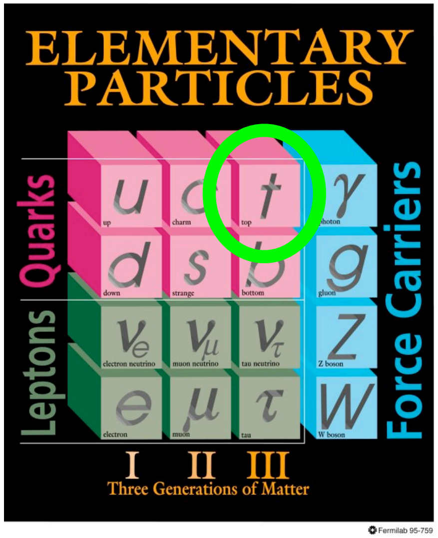
$$Q_{i\alpha} = \begin{bmatrix} t_L^i \\ b_L^i \end{bmatrix}$$

α=2: bottom

i: color index

$$t_R^i$$

Top is two separate objects:
A left-handed quark doublet.
A right-handed quark singlet.



In 4 component notation: $t_i = \begin{bmatrix} t_R^i \\ t_L^i \end{bmatrix}$

H: Higgs (doublet)
G: gluons
B,W^n: $W^\pm$, Z, γ

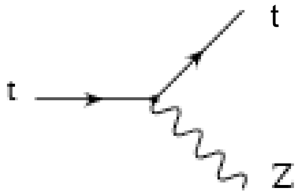
$$L = i\bar{Q}_{i\alpha}\gamma^\mu \left(D_\mu Q\right)_{i\alpha} + i\bar{t}_i\gamma^\mu \left(D_\mu t\right)_i + y_t \tilde{H}\bar{Q}t + H.c.$$

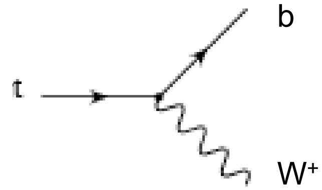
$$\left(D_\mu Q\right)_{i\alpha} \equiv \partial_\mu Q_{i\alpha} + i g_S T_{ij}^a G_\mu^a Q_{j\alpha} + i g_W \tau_{\alpha\beta}^n W_\mu^n Q_{i\beta} + i\frac{1}{6} g_Y B_\mu Q_{i\alpha}$$

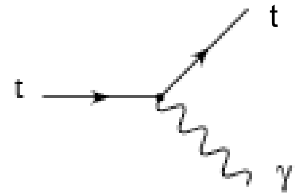
$$\left(D_\mu t\right)_i \equiv \partial_\mu t_i + i g_S T_{ij}^a G_\mu^a t_j + i\frac{2}{3} g_Y B_\mu t_i$$

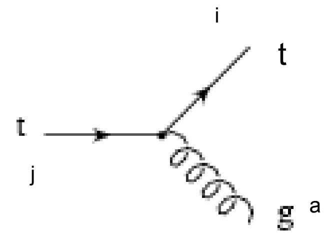
Feynman Rules

- From the Lagrangian we can read off the SM Feynman rules involving top.
  - Gauge bosons:









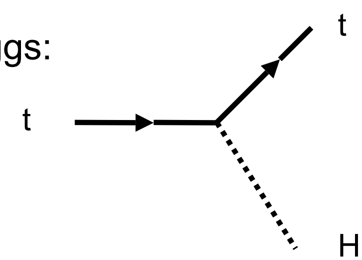
$$-i\frac{e}{\sin\theta_W\cos\theta_W}\gamma^\mu \times \left[\left(\frac{1}{2}-\frac{2}{3}\sin^2\theta_W\right)P_L+\left(-\frac{2}{3}\sin^2\theta_W\right)P_R\right]$$

$$-i\frac{e}{\sin\theta_W}\gamma^\mu P_L$$

$$+i\frac{2e}{3}\gamma^\mu$$

$$-ig_S T^a_{ij}\gamma^\mu$$

  - Higgs:



$$-i\frac{m_t}{v}$$

Measurements

- How well are these quantities known?
- g_S, e, and s^2_W are well known (g_S at per cent level, EW couplings at per mil level) from other sectors.
- m_t is reconstructed kinematically at the Tevatron:
  - Run I: m_t = **178 ± 4.3 GeV**
  - Run IIb: prospects to a precision of **± 2 GeV** (systematic).
- V_{td}, V_{ts}, and V_{tb} are (currently) determined indirectly:
  - V_{td}: **0.004 – 0.014** (< 0.09)
  - V_{ts}: **0.037 – 0.044** (< 0.12)
  - V_{tb}: **0.9990 – 0.9993** (0.08 – 0.9993)
  - These limits assume the 3 (4^+?) generation SM, reconstructing the values using the unitarity of the CKM matrix.
- V_{tb} can be measured directly from single top production.

PDG: http://pdg.lbl.gov/pdg.html

New Interactions

- A model independent way to study new physics is provided by effective Lagrangians, adding interactions beyond those in the SM.
- The SM already contains all renormalizable interactions (with couplings of mass dimension 4 or less); we must include non-renormalizable terms.
- Couplings for 'higher dimensional' operators have negative dimension so that the Lagrangian stays at dimension 4:

Counting Dimension

Ψ	: 3/2
H, V_μ	: 1
∂_μ	: 1

$$\underbrace{g}_{\text{dimension } 0} \times \overbrace{\underbrace{\bar{\Psi}}_{3/2}\gamma_\mu \underbrace{\Psi}_{3/2} \underbrace{V^\mu}_{1}}^{\text{dimension } 4} \qquad \overbrace{\frac{1}{\Lambda^2}}^{\text{dimension } -2} \times \overbrace{\underbrace{\bar{\Psi}}_{3/2}\gamma_\mu \underbrace{\Psi}_{3/2} \underbrace{\bar{\Psi}}_{3/2}\gamma^\mu \underbrace{\Psi}_{3/2}}^{\text{dimension } 6}$$

- This theory makes sense as an expansion in energy. Observables depend on $\mathbf{E^n / \Lambda^n}$, so provided $\mathbf{E \ll \Lambda}$, the expansion makes sense.
- Gauge symmetries of the Standard Model such as SU(3) invariance, etc. are still respected by the new interactions.
- They can be understood as residual effects from very heavy particles.

Nonstandard Top Interactions

- Top may couple in a funny way to strange, down, or bottom:

$$\frac{g}{\sqrt{2}} \sum_i \left(\kappa_R^{Wtd_i} \bar{t} \gamma_\mu P_R d_i + \kappa_L^{Wtd_i} \bar{t} \gamma_\mu P_L d_i \right) W_+^\mu + h.c.$$

  - All of these modify all three single top rates.
  - But aren't these operators dimension 4?
    - Yes, but their SU(2)xU(1) description was dimension 6!

$$\frac{1}{\Lambda_{Wts}^2} \left(H^\dagger H \right) \overline{Q_3} \gamma^\mu \left(D_\mu Q_2 \right) + h.c.$$

$$\rightarrow \frac{\left(v^2 \right)}{\Lambda_{Wts}^2} \bar{t} \gamma^\mu P_L \left(W_\mu^+ s \right) + \ldots$$

$\frac{\left(v^2 \right)}{\Lambda_{Wts}^2} \leftrightarrow \kappa_L^{Wts}$

- Top may have FCNC's with up or charm and Z/g/γ:

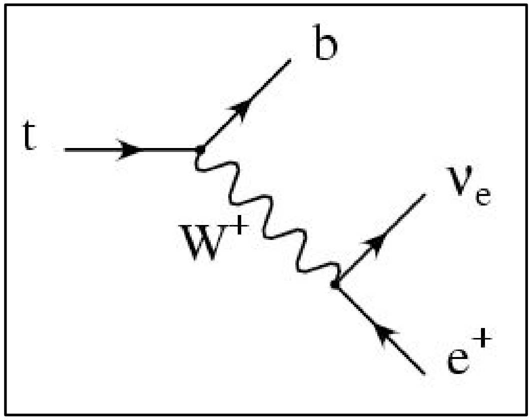
$$\frac{g}{\cos\theta_W} \sum_i \left(\kappa_R^{Ztu_i} \bar{t} \gamma_\mu P_R u_i + \kappa_L^{Ztu_i} \bar{t} \gamma_\mu P_L u_i \right) Z^\mu + h.c.$$

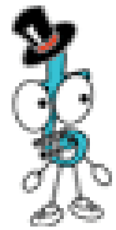
$$+ g_S \sum_i \left(\frac{1}{\Lambda_R^{gtu_i}} \bar{t} \sigma_{\mu\nu} P_R u_i + \frac{1}{\Lambda_L^{gtu_i}} \bar{t} \sigma_{\mu\nu} P_L u_i \right) G^{\mu\nu} + h.c.$$

$$+ \frac{2}{3} e \sum_i \left(\frac{1}{\Lambda_R^{\gamma tu_i}} \bar{t} \sigma_{\mu\nu} P_R u_i + \frac{1}{\Lambda_L^{\gamma tu_i}} \bar{t} \sigma_{\mu\nu} P_L u_i \right) F^{\mu\nu} + h.c$$

These new interactions can arise in many models. They lead to new single top modes, top decays, and more exotic processes …

Top Decay



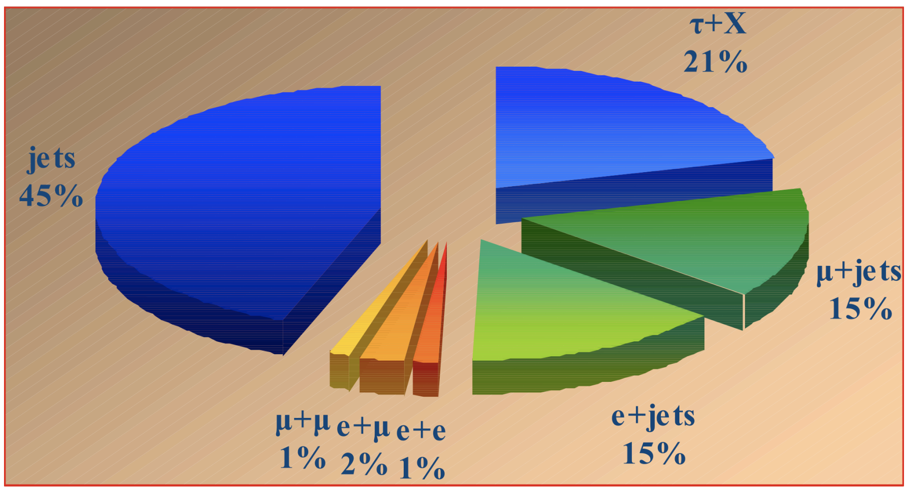


$$\frac{\mathrm{BR}(t \text{ ® } Wb)}{\mathrm{BR}(t \text{ ® } Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = \begin{matrix} 1.12^{+0.12+0.17}_{-0.19-0.13} \\ 1.03^{+0.19}_{-0.17} \end{matrix}$$

⇩

V_{tb} >> V_{ts}, V_{td}

CDF hep-ex/0505091
DØ note 4833-CONF

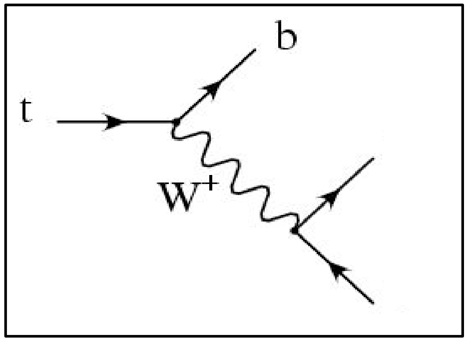


- SM: BR into W^+b ~ 100%.
- Top decay represents our first glimpse into top's weak interactions.
- In the SM, *W-t-b* is a left-handed interaction: γ^μ **(1 - γ_5)**.
- However, the decay does not offer a chance to measure the *magnitude* of the *W-t-b* coupling, but only its *structure*.
- This is because the top width is well below the experimental resolutions.
- Top is the only quark for which Γ_t >> Λ_{QCD}. This makes top the only quark which we see "bare" (in some sense).

➢ Top spin "survives" non-perturbative QCD (soft gluons).

Top Decay: Basics

- Top decays through the electroweak interaction into a W boson and (usually) a bottom quark. Decays into strange or down quarks are suppressed by the small CKM elements V_{ts} and V_{td}. It is extremely short-lived.
- Top is the only quark heavy enough to decay into a real (on-shell) W boson.

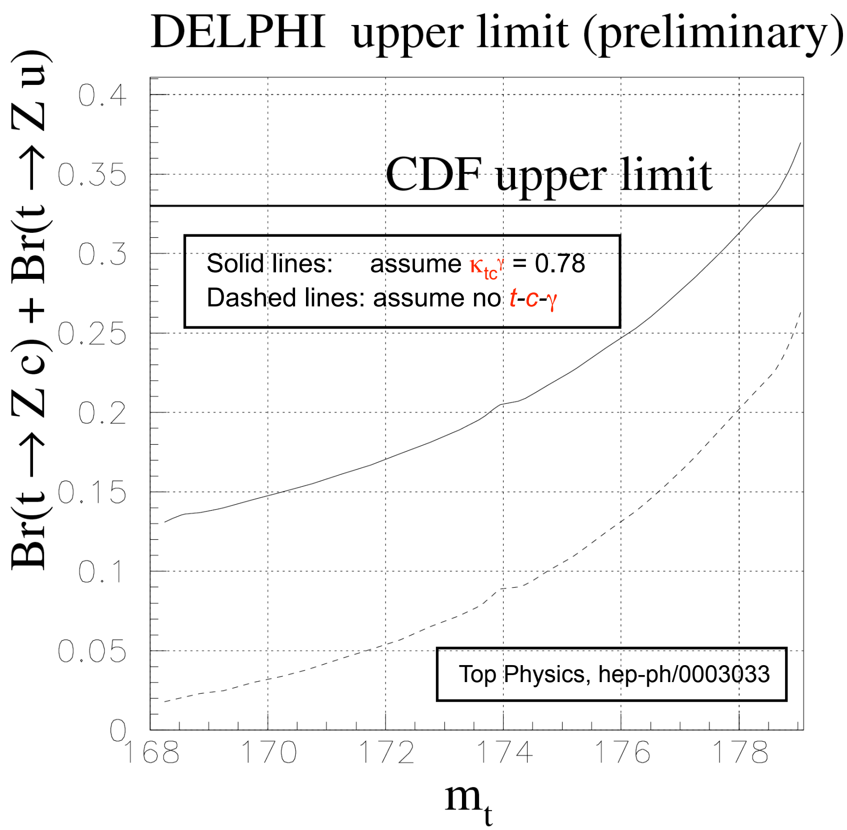


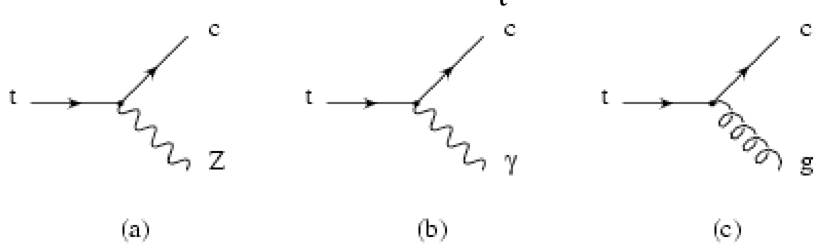
$$\Gamma_t = \frac{G_F\, M_{\rm top}^3}{8\,\pi\,\sqrt{2}}\ |V_{tb}|^2\ \left(1 - \frac{M_W^2}{M_{\rm top}^2}\right)^2\ \left(1 + 2\,\frac{M_W^2}{M_{\rm top}^2}\right)$$

- The experimental signature is a jet containing a bottom quark and the W decay products. The W boson decays into all of its possible final states (eν, μν, τν, or jets).
- So we classify top decays by how the W boson decays.
- The relative branching ratios are easy to predict just by knowing that the W couplings are universal, and that the light fermion masses are all so small compared to M_W that we can ignore them. Further, the CKM elements are nearly diagonal, so counting three colors each of ud and cs, we have:

$$BR(W \rightarrow e\nu) : BR(W \rightarrow \mu\nu) : BR(W \rightarrow \tau\nu) : BR(W \rightarrow \text{jets}) = 1 : 1 : 1 : 6$$

Rare Decays?





- Many rare decays of top are possible.
- These can be searched for in large $t\,\bar{t}$ samples, using one standard decay to ‘tag’ and verifying the second decay as a rare one.
- One example is a FCNC: *Z-t-c*

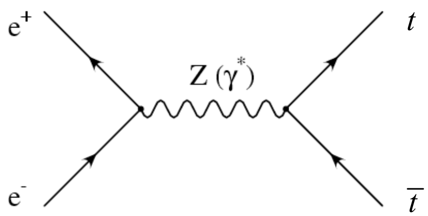
$$\frac{1}{\Lambda^2} W_{\mu\nu} (H\overline{Q}_3)\sigma^{\mu\nu} c_R \;\text{®}\; \frac{g}{2\cos\theta_W}\kappa_{tc}^{Z} Z_\mu \bar{t}\gamma^\mu c$$

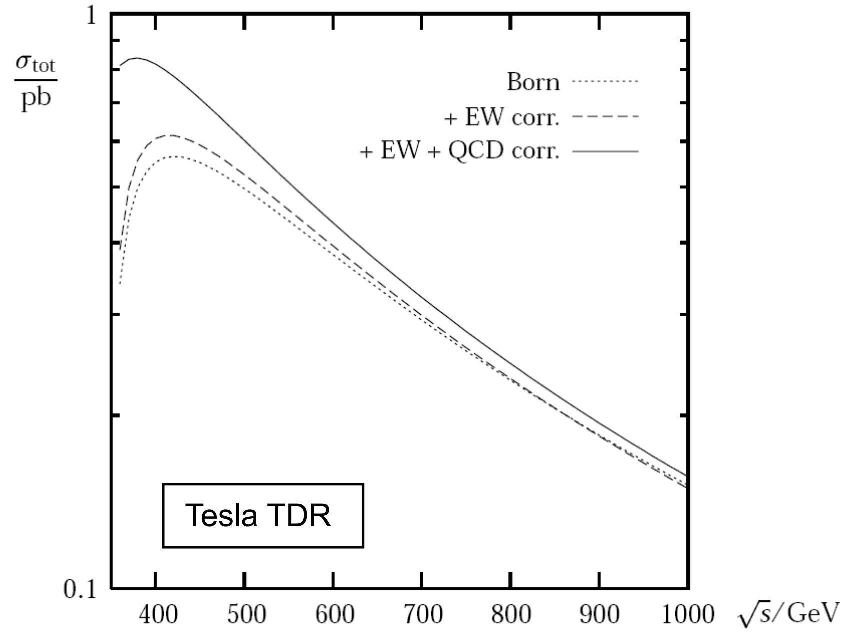
$$\kappa_{tc}^{Z} \leftrightarrow \frac{v\;\, m_t}{\Lambda^2}$$

- At LEP II, the same physics that results in $t \to Zq$ would lead to $e^+e^- \to Z^* \to tq$.
- More possibilities, such as $t \to c\gamma$, $t \to cg$, etc…

Top Production

- At energies greater than 2 mt, the dominant process for producing top is e+e- → t tbar through off-shell photon or Z boson.





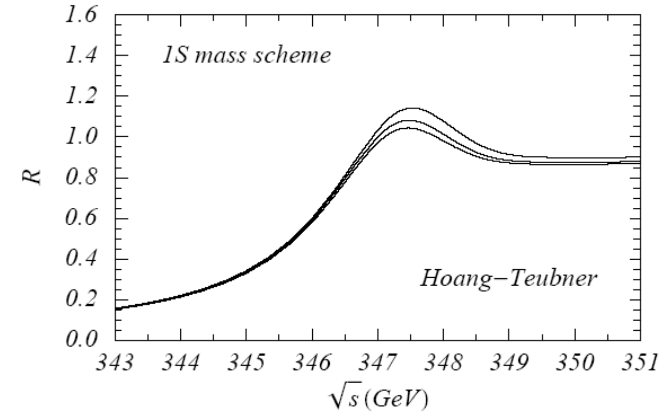
- The cross section near threshold is of order 1 pb, so for 100 fb-1, one expects roughly 100,000 top pairs.
- By determining the final spins of the top quarks, and by using polarized beams, the top couplings to the Z and γ can be extracted for individual chiral operators.
- These couplings can be measured to the level of a few per cent, and are difficult to measure at a hadron collider because of large QCD backgrounds.

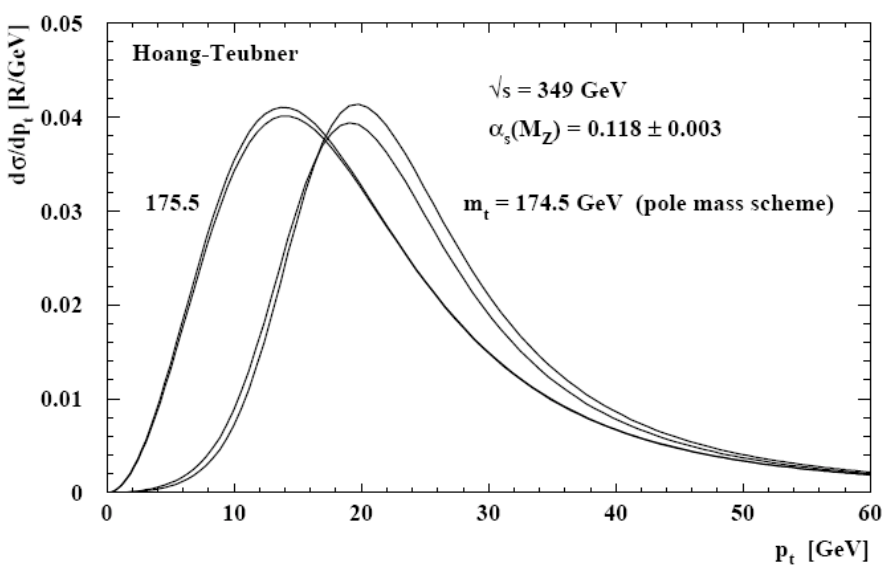
Form factor	SM value	$\sqrt{s} = 500$ GeV		$\sqrt{s} = 800$ GeV	
		$p = 0$	$p = -0.8$	$p = 0$	$p = -0.8$
F_{1V}^Z	1		0.019		
F_{1A}^Z	1		0.016		
$F_{2V}^{\gamma,Z} = (g-2)^{\gamma,Z}{}_t$	0	0.015	0.011	0.011	0.008
$\mathrm{Re}\, F_{2A}^{\gamma}$	0	0.035	0.007	0.015	0.004
$\mathrm{Re}\, d_t^{\gamma}$ $[10^{-19}$ e cm$]$	0	20	4	8	2
$\mathrm{Re}\, F_{2A}^{Z}$	0	0.012	0.008	0.008	0.007
$\mathrm{Re}\, d_t^{Z}$ $[10^{-19}$ e cm$]$	0	7	5	5	4
$\mathrm{Im}\, F_{2A}^{\gamma}$	0	0.010	0.008	0.006	0.005
$\mathrm{Im}\, F_{2A}^{Z}$	0	0.055	0.010	0.037	0.007
F_{1R}^{W}	0	0.030	0.012		
$\mathrm{Im} F_{2R}^{W}$	0	0.025	0.010		

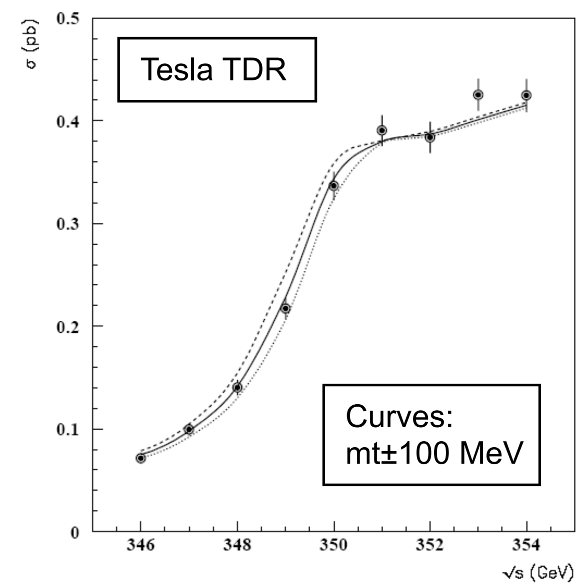
Threshold Scan

- By scanning in energy close to the production threshold, one can precisely measure the top mass.
- Though toponium states don't really have time to form before top decays, they affect the shape of the turn-on and thus offer an opportunity to measure $\alpha_S(m_t)$.
- The threshold turn-on is known to NLO in QCD.
- Combined with the top p_T distribution, the mass and α_S can be disentangled.

A Hoang, T Teubner PRD58, 114023 (1998)







Below Threshold?

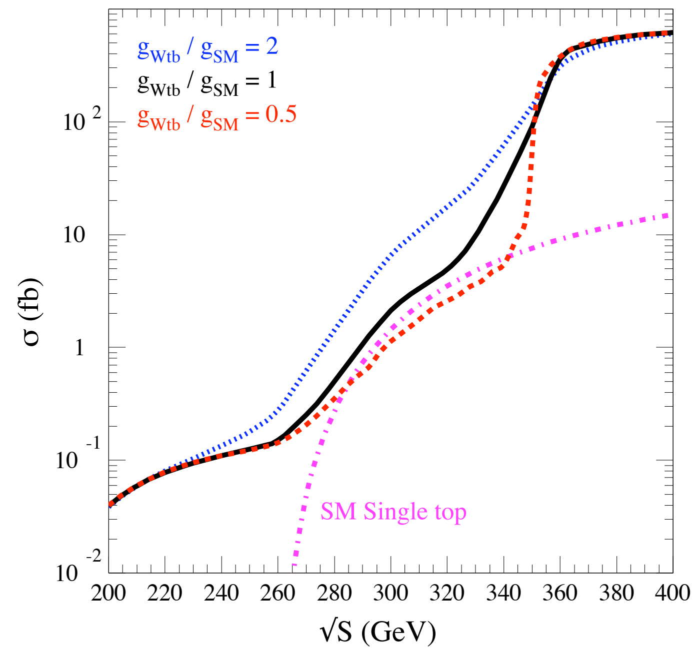
- The threshold scan is a powerful way to measure the top mass and width.
- Together, in the SM, the coupling and the width are closely related:

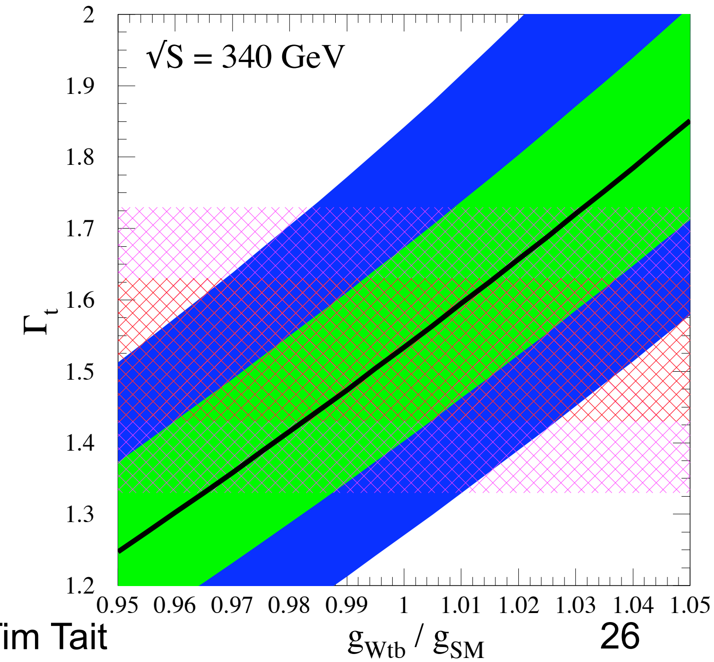
$$\Gamma_t = \left(\frac{g_{Wtb}}{g}\right)^2 \frac{G_F m_t^3}{\sqrt{2}8\pi}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right) + \Gamma_{new}$$

- There is also an advantage to running below the t t threshold, because it allows you to determine the coupling independently from the width.

$$\mathcal{M}_{total} : \mathcal{M}\left(e^+e^- \to t\bar{t}\right) \otimes \frac{1}{M_{Wb}^2 - m_t^2 + i m_t \Gamma_t} \otimes \mathcal{M}\left(t \to Wb\right)$$

- On-shell, the decay matrix element recreates the BR(t Wb) ~ 1.
- Off-shell, there is sensitivity to both width and coupling.





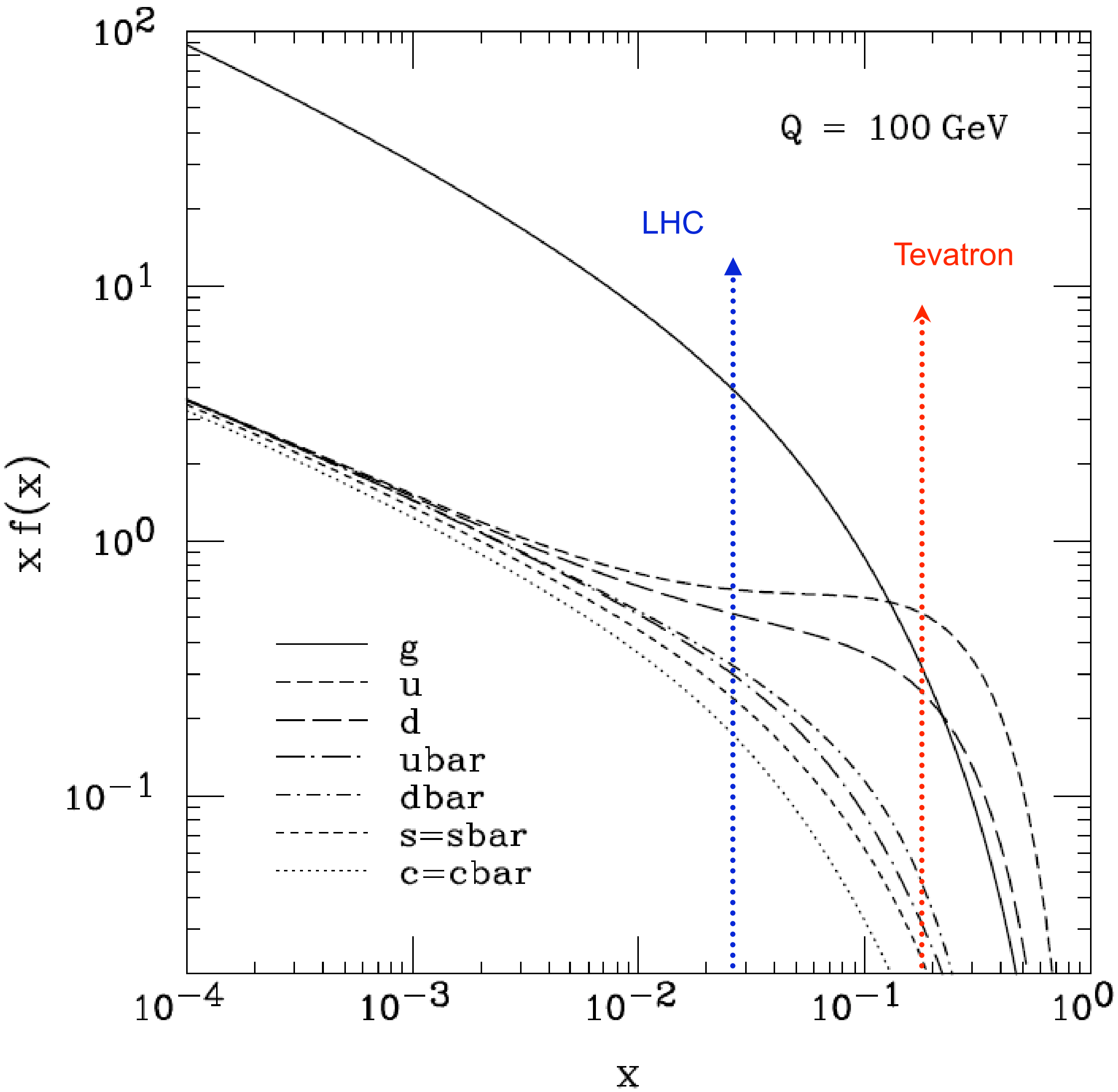
Hadro-production

- At a hadron collider, we must reconcile the fact that what we have control over theoretically are scatterings of quarks and gluons (partons), but what we collide experimentally are hadrons.
- The parton distribution functions (PDFs) are the bridge between hadronic initial states and partonic reactions.
- Consider production of some final state **F** from initial hadrons H_1 and H_2:

$$\sigma(H_1 H_2 \rightarrow F + X) = \int dx_1 dx_2 \sum_{a,b} f_{a/H_1}(x_1) f_{b/H_2}(x_2) \hat{\sigma}(ab \rightarrow F + X)$$

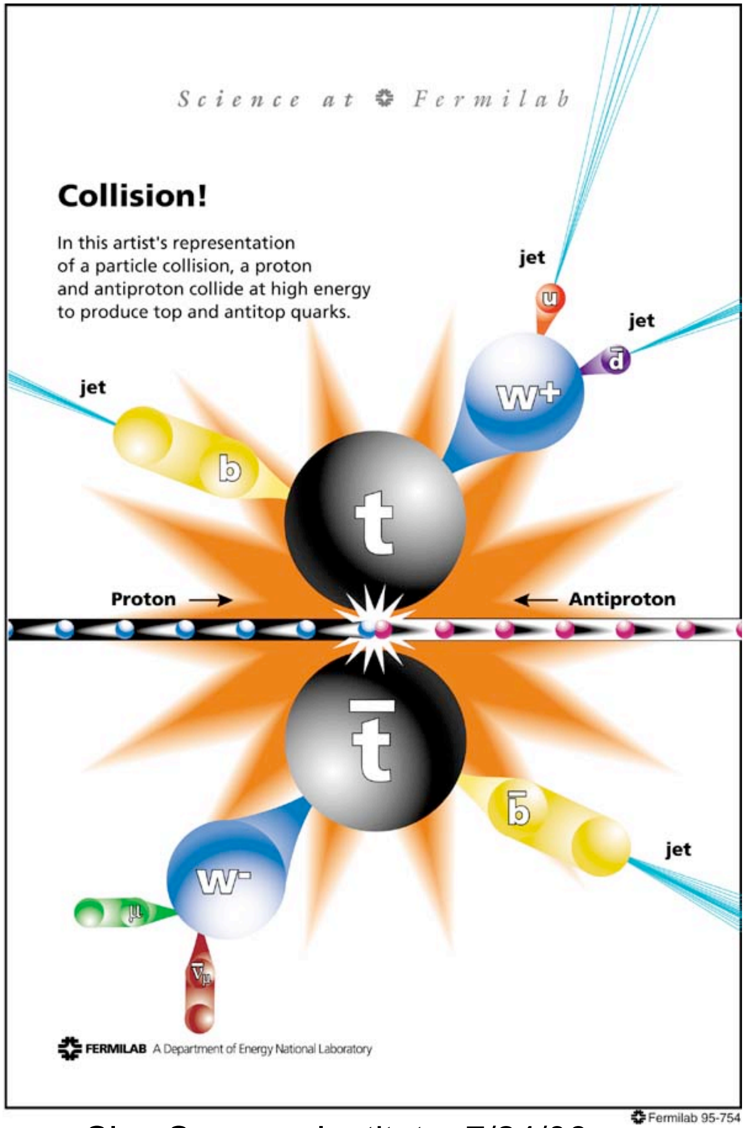
- The non-perturbative physics is contained in the functions f. These also contain all possible collinear emission of partons, resumming large logs to improve perturbation theory.
- The factorization theorem implies that these functions are universal. So once we measure them in some process, we can compute any other process. (Higher order corrections in Λ^2 / Q^2 are usually tiny for processes involving top which have $Q \sim m_t$).
- Because they have resummed an infinite number of soft or collinear emissions, the cross sections derived from them are necessarily *inclusive* quantities.

PDFs

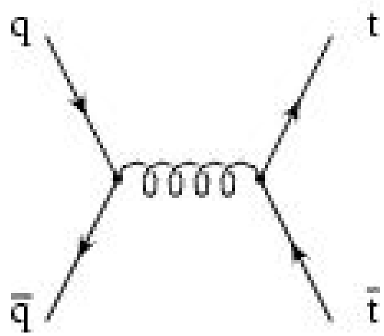


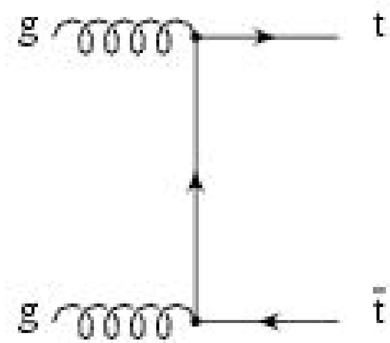
10^2
10^1
10^0
10^{-1}
x f(x)
Q = 100 GeV
LHC
Tevatron
g
u
d
ubar
dbar
s=sbar
c=cbar
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
x

$t\bar{t}$ Production



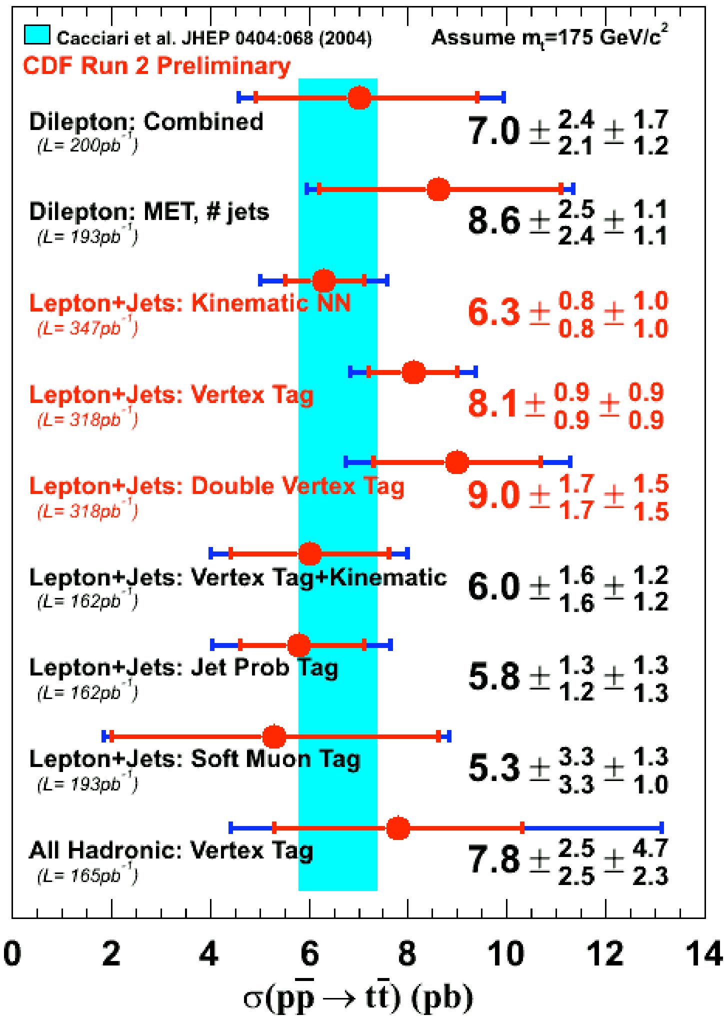
- At a hadron collider, the largest production mechanism is pairs of top quarks through the strong interaction.
- (Production through a virtual Z boson is much smaller).
- At leading order, there are gluon-gluon and quark-anti-quark initial states.



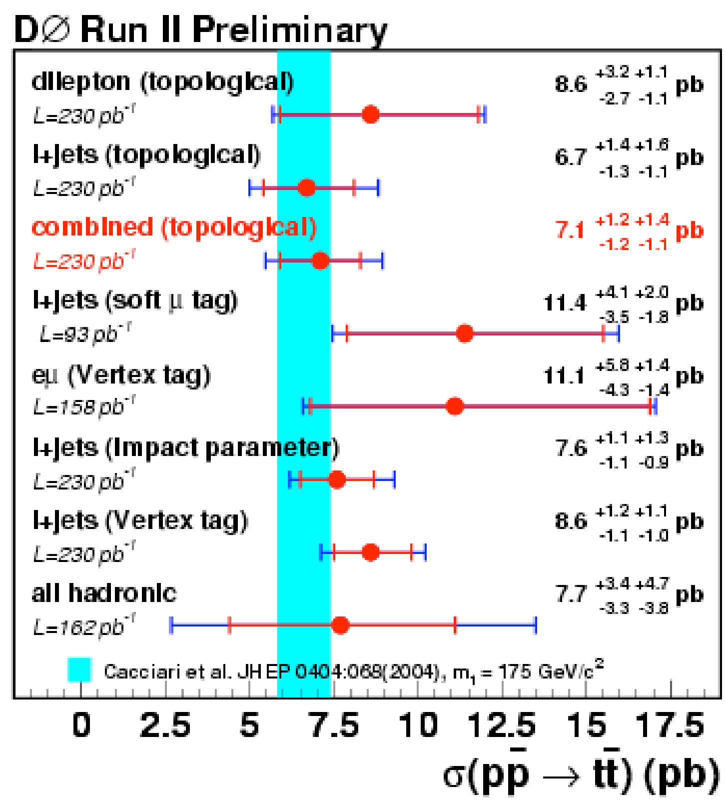


- At Tevatron, $q\bar{q}$ dominates (~85%).
- At LHC, gg is much more important.

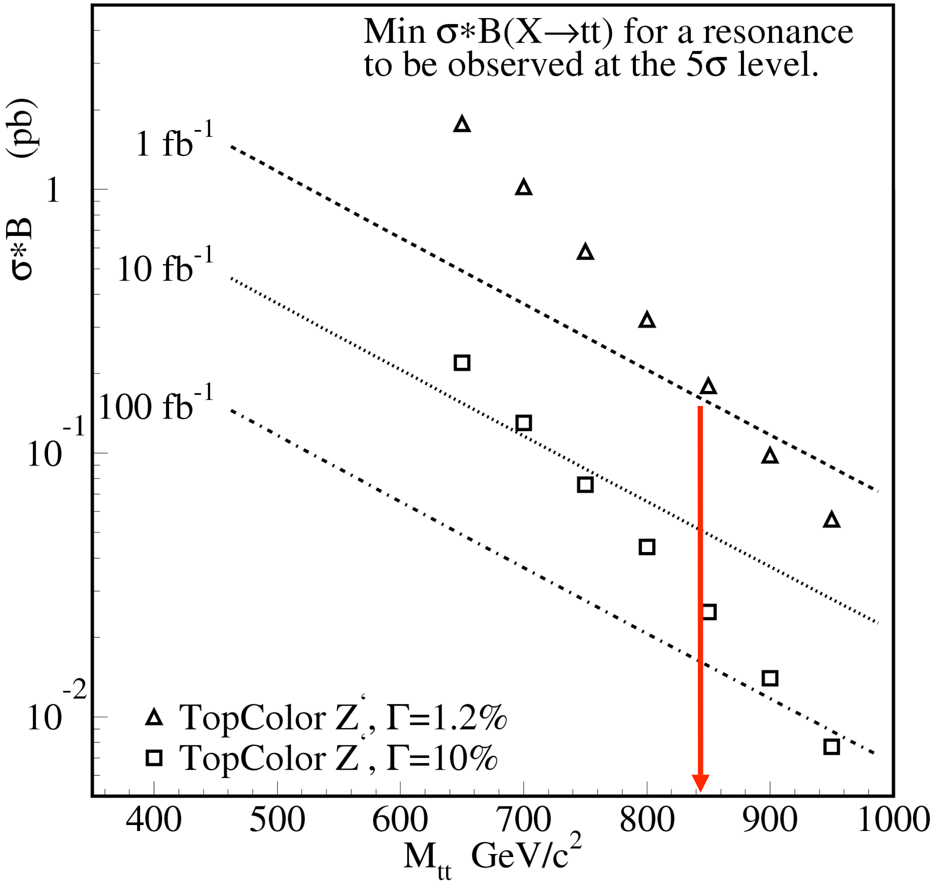
$t\bar{t}$ Production Rates



- An impressive array of cross section measurements are performed across many top decay channels.
- Measurements help to test & tune the variety of cutting edge QCD predictions on the market.



New $t\bar{t}$ Resonances?



Future EW Physics at the Tevatron, TeV-2000 Study Group

- A neutral boson can contribute to tt production in the s-channel.
- Many theories predict such exotic bosons with preferential coupling to top:
  - TC², Top Seesaw: top gluons

    Hill PLB345,483 (1995)
    Dobrescu, Hill PRL81, 2634 (1998)

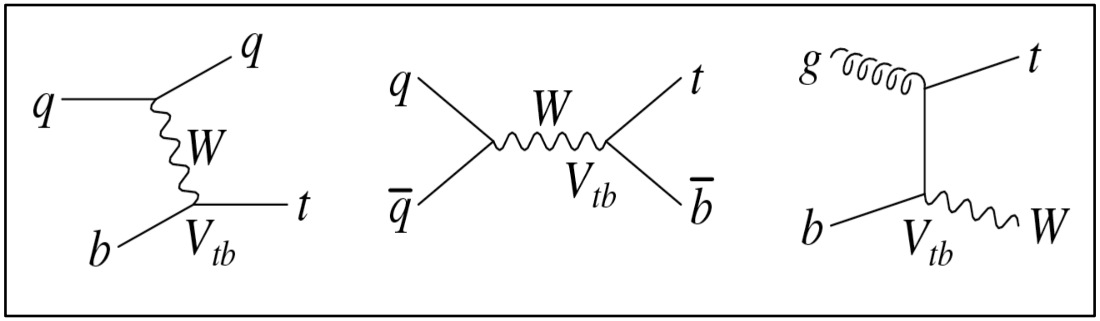
  - TC², Topflavor: Z'

    Hill PLB345,483 (1995)
    Chivukula, Simmons, Terning PRD53, 5258 (1996)
    Nandi, Muller PLB383, 345 (1996)
    Malkawi, Tait, Yuan PLB385, 304 (1996)

- Search strategy: resonance in tt.
- Tevatron: up to ~ **850 GeV**

Single Top Production

- Top's EW interaction.
  - Three modes:
    - T-channel: q b → q' t
    - S-channel: q $\bar{q}$' → t $\bar{b}$
    - Associated: g b → t W^-
- **Coming soon to Run II!**



Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD 66 (02) 054024
Tait, PRD 61 (00) 034001; Belyaev, Boos, PRD 63 (01) 034012

σ	Tevatron Run I	Tevatron Run II	LHC	Run II Limits
σ_t (NLO)	1.45±0.08 pb	1.98±0.13 pb	247±12 pb	< 5.0 pb
σ_s (NLO)	0.75±0.07 pb	0.88±0.09 pb	10.7±0.9 pb	< 6.4 pb
σ_{tW} (LL)	0.06±0.01 pb	0.09±0.02 pb	56±8 pb	
Total	**2.26±0.11 pb**	**2.95±0.16 pb**	**314±15 pb**	

DØ hep-ex/0505063
CDF PRD71, 012005 (2005)

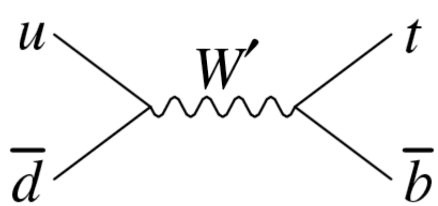
Now in MCFM!

s- Versus t-Channels

- s-channel Mode
  - Smaller rate
  - Extra b quark final state
  - $\sigma_s \, \alpha \, |V_{tb}|^2$
  - Polarized along beam axis at Tevatron.

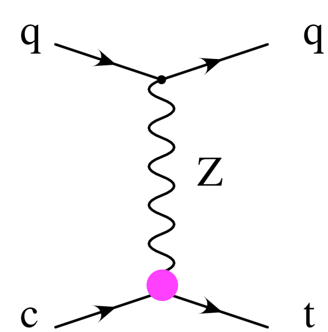
Mahlon, Parke PLB476 323 (2000); PRD55 7249 (1997)

- Sensitive to resonances
  - Possibility of on-shell production.
  - Need final state b tag to discriminate from background.

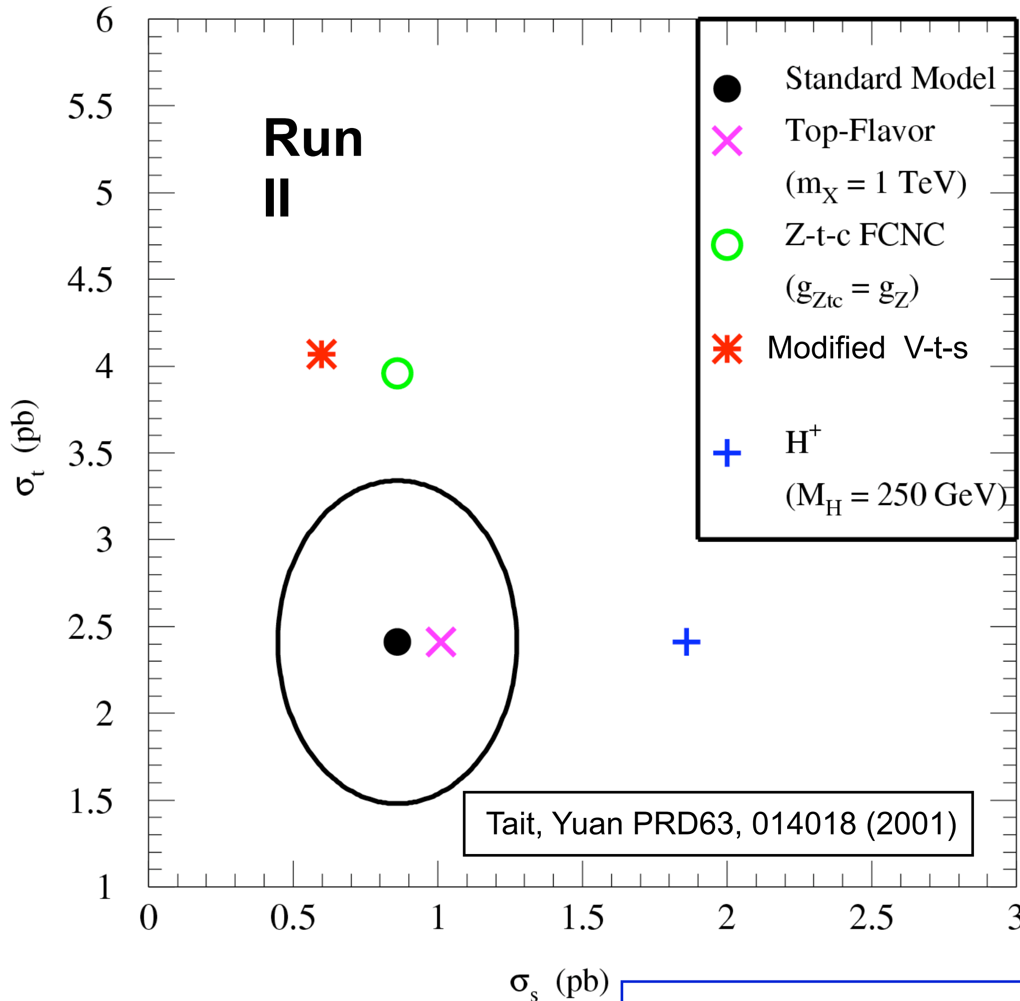


- t-channel Mode
  - Dominant rate
  - Forward jet in final state
  - $\sigma_t \, \alpha \, |V_{tb}|^2$
  - Polarized along spectator jet axis.

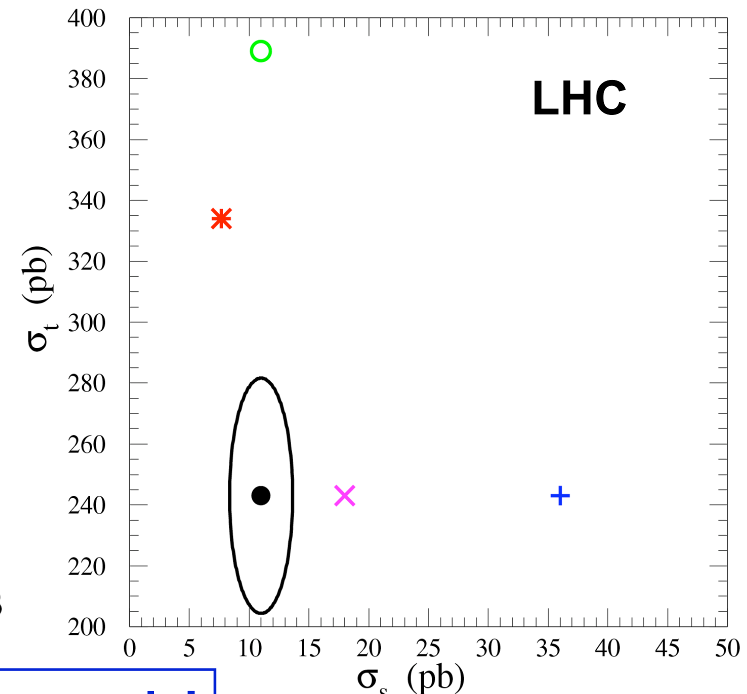
- Sensitive to FCNCs
  - New production modes.
  - t-channel exchange of heavy states always suppressed.



σ_s-σ_t Plane



Since they are sensitive to different physics and have different, final states, σ_s and σ_t should be measured independently!



Theory + Stat errors only!

Outlook

- Top and EW bosons are unique as a laboratory for EWSB and fermion masses. The Tevatron is currently the only place in the world which can study them at high energies, but LHC and ILC will soon provide information too.
- Measurements of m_t and m_W at Tevatron are essential for the EW fit, and our understanding of the SM.
- Ultimately, we would like to confirm the SM picture for EWSB, but most people believe that we are likely to find something more interesting and more profound.

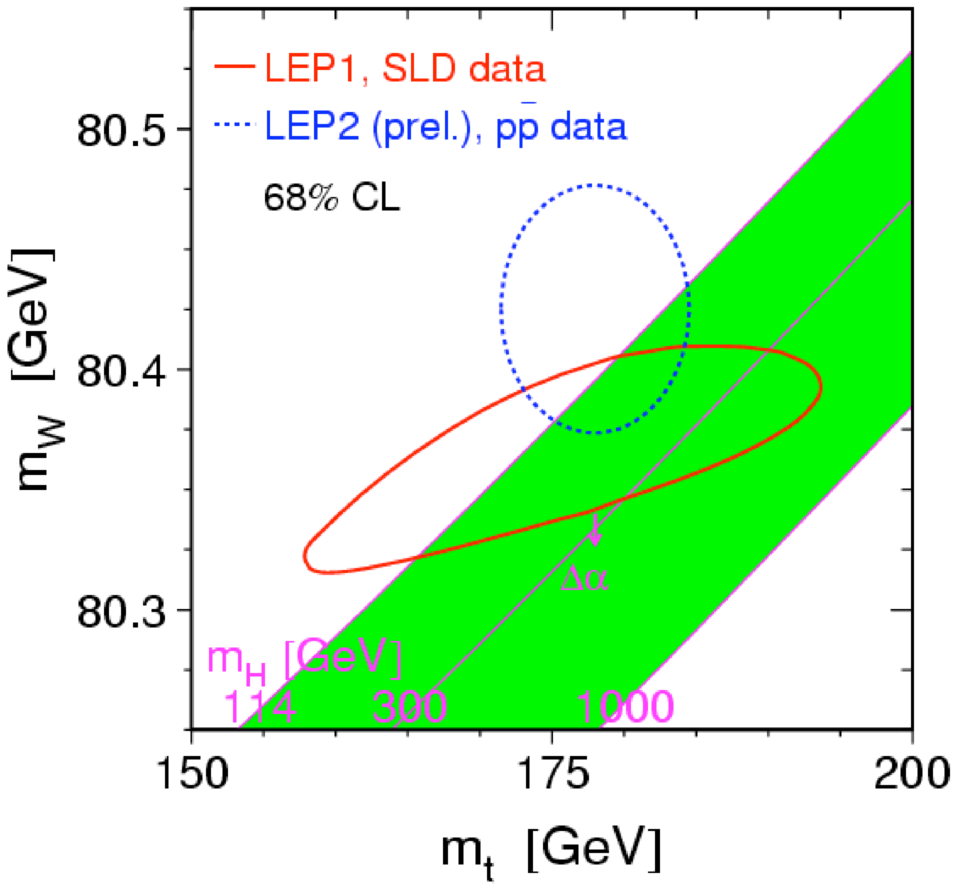
- Deviations in the SM expectations can be parameterized by higher dimension operators. Their form reflects the nature of the high energy physics which produced them.

- Many rare processes are being now probed for the first time, including di-boson production, high energy t tbar, and single top.
- There is a lot of exciting top and EW physics coming up, and I look forward to seeing it!

Supplementary Slides

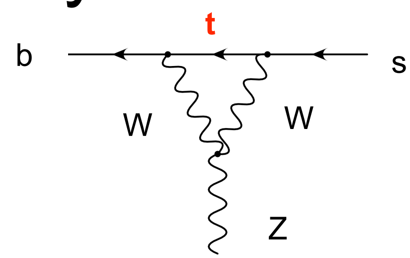
Top & EW in the SM

- EW Fit:



- Flavor Physics:

***i.e.*:**



Buchalla, Buras, Lautenbacher RMP68,1125 (1996)

– $B \rightarrow X_s \nu\bar{\nu}$

$$\mathrm{BR}(B \rightarrow X_s \nu\bar{\nu}) = 4.1\times10^{-5}\,\frac{|V_{ts}|^2}{|V_{cb}|^2}\left[\frac{m_t(m_t)}{170\ \mathrm{GeV}}\right]^{2.30}$$

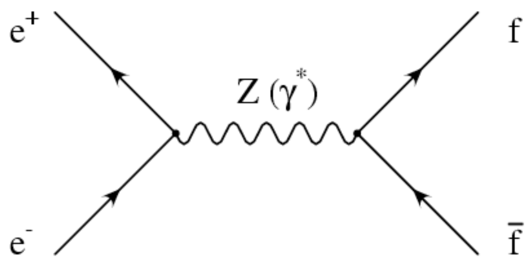
– $B_s \rightarrow \mu^+\mu^-$

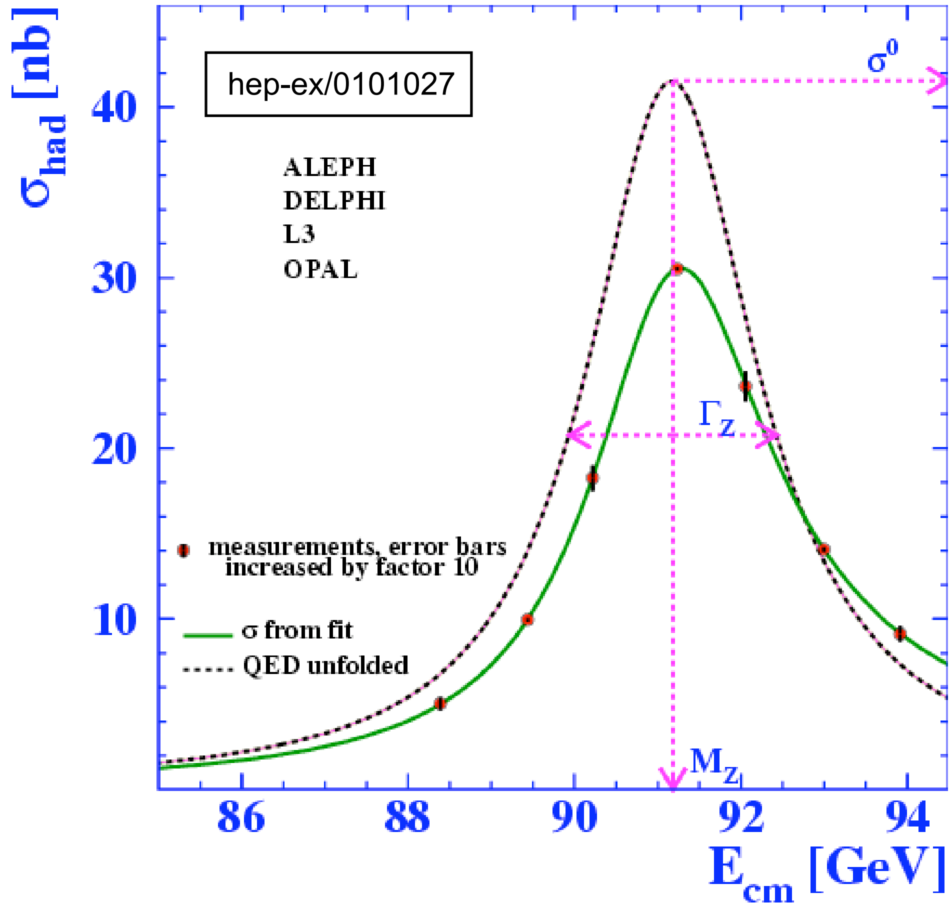
$$\mathrm{BR}(B_s \rightarrow \mu^+\mu^-) = 4.18\times10^{-9}\left[\frac{|V_{ts}|}{0.04}\right]^2\left[\frac{m_t(m_t)}{170\ \mathrm{GeV}}\right]^{3.12}$$

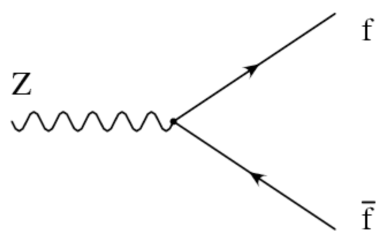
Precision inputs from the top & EW sectors for precise SM predictions.

The Basic Process

- Electrons and positrons are collided together to produce a Z boson (close to) on resonance.
- The rate of production (into visible decay modes), and its energy dependence, provide information:
  - M_Z, the Mass.
  - Γ_Z, the total decay width.
  - σ_0, the hadronic cross section.

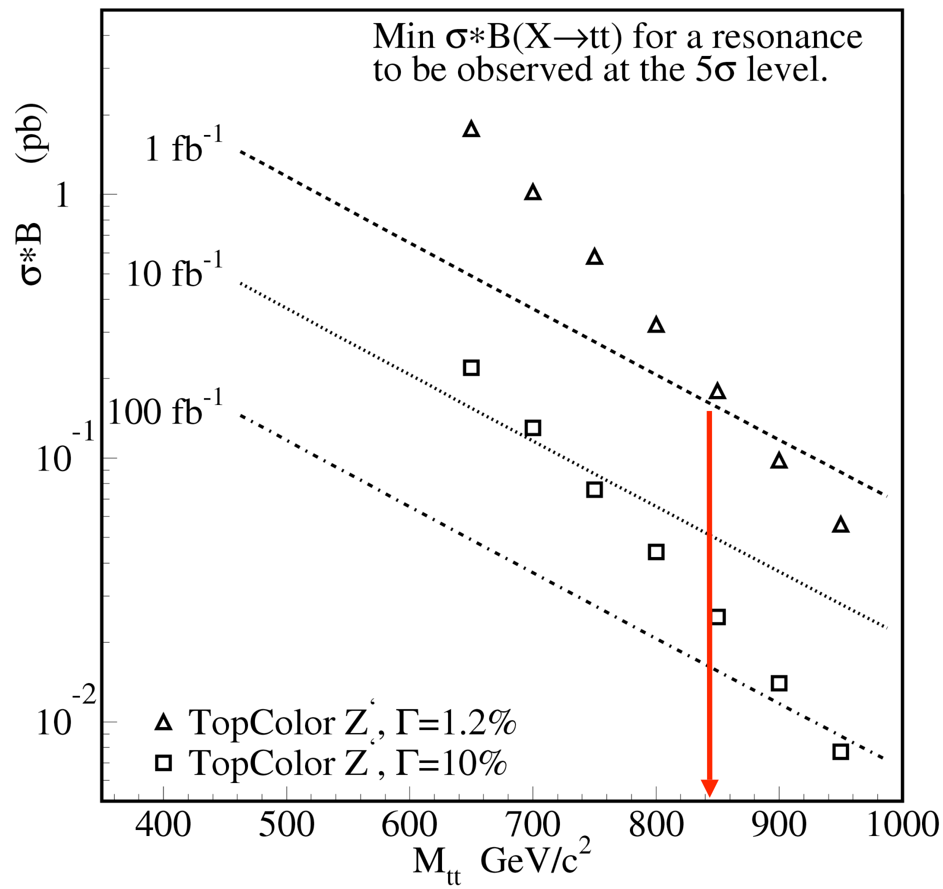






$$\gamma^\mu \left(g^f{}_R P_R + g^f{}_L P_L \right)$$

$t\bar{t}$ Resonances



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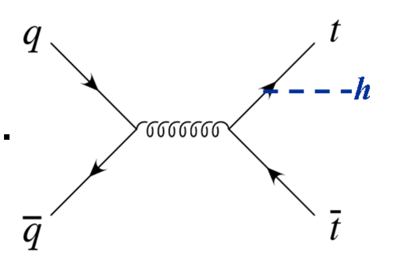
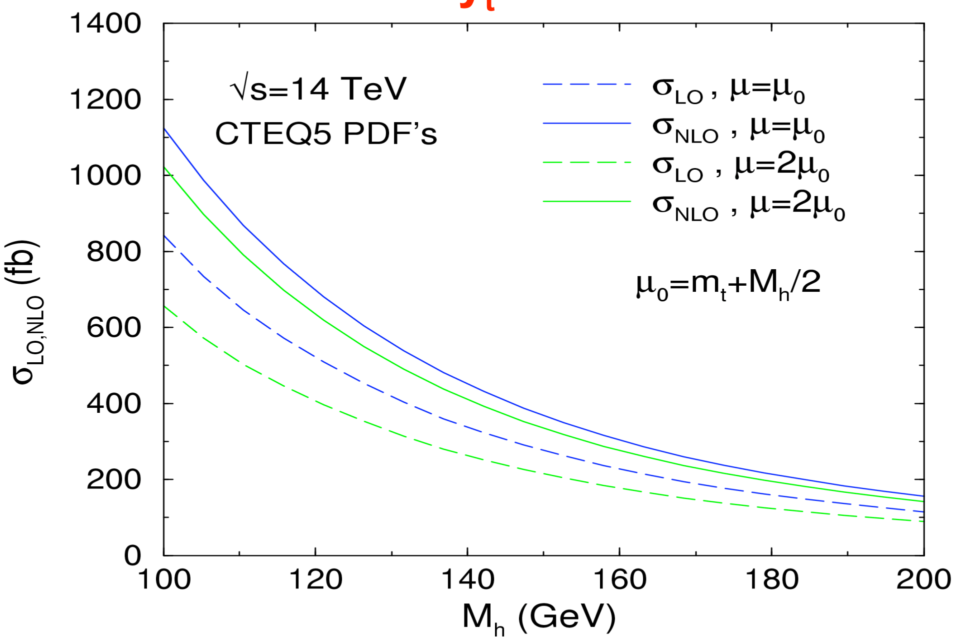
    Chivukula, Simmons, Terning PRD53, 5258 (1996)
    Nandi, Muller PLB383, 345 (1996)
    Malkawi, Tait, Yuan PLB385, 304 (1996)

- Search strategy: resonance in tt.
- Tevatron: up to ~ **850 GeV**.
- LHC: up to ~ **4.5 TeV**.

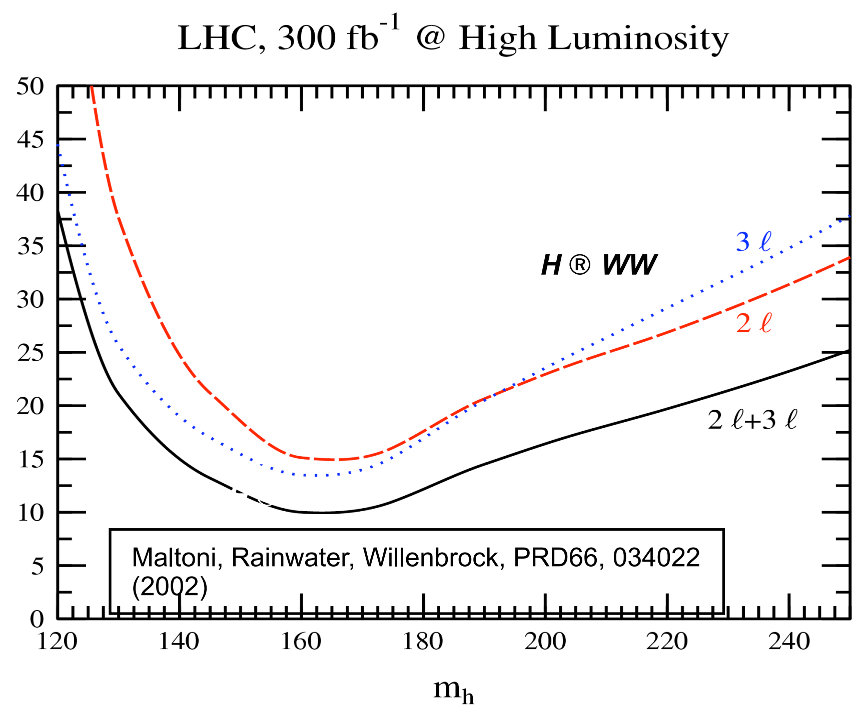
Top Yukawa Coupling

- SM prediction for the t coupling to the Higgs: $y_t^{\overline{MS}} = \frac{M_t^{\overline{MS}}}{v} \cong 1$
- We'd like to directly verify the relation to roughly the same precision as m_t itself: a few %.
  - Higgs radiated from $t\bar{t}$ pair is probably the best bet.
    - LHC: y_t to about **10-15%** for m_h **< 200 GeV**.

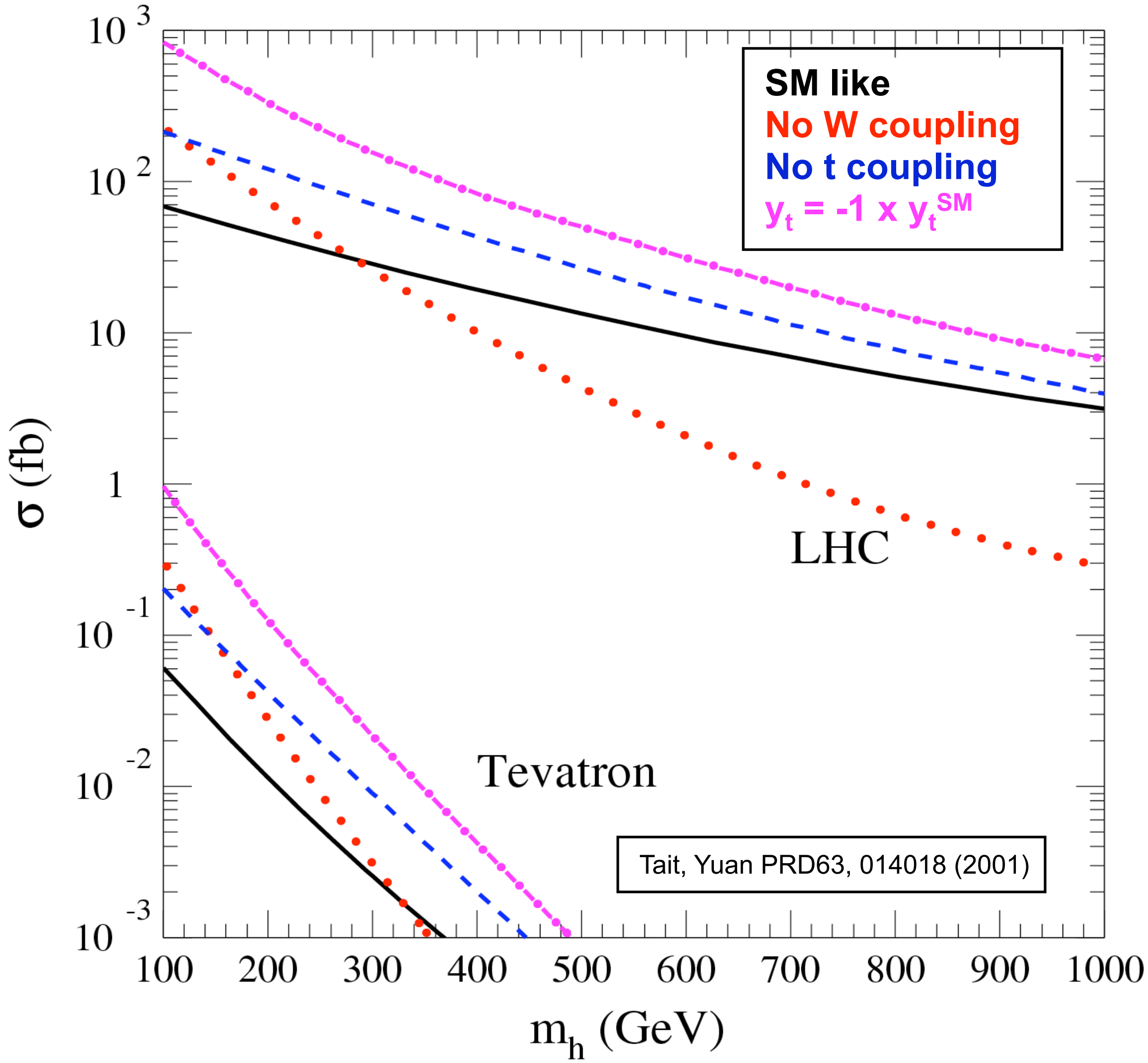




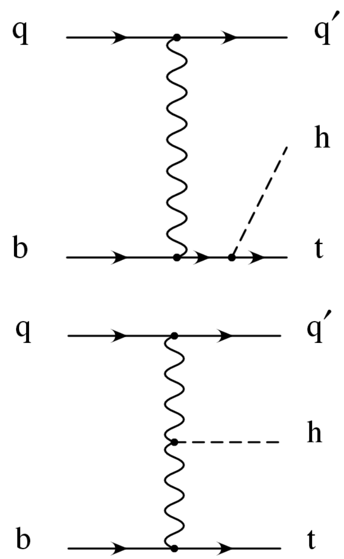
NLO: Dawson, Jackson, Orr, Reina, Wackeroth, PRD 68, 034022 (2003)



Single Top + Higgs



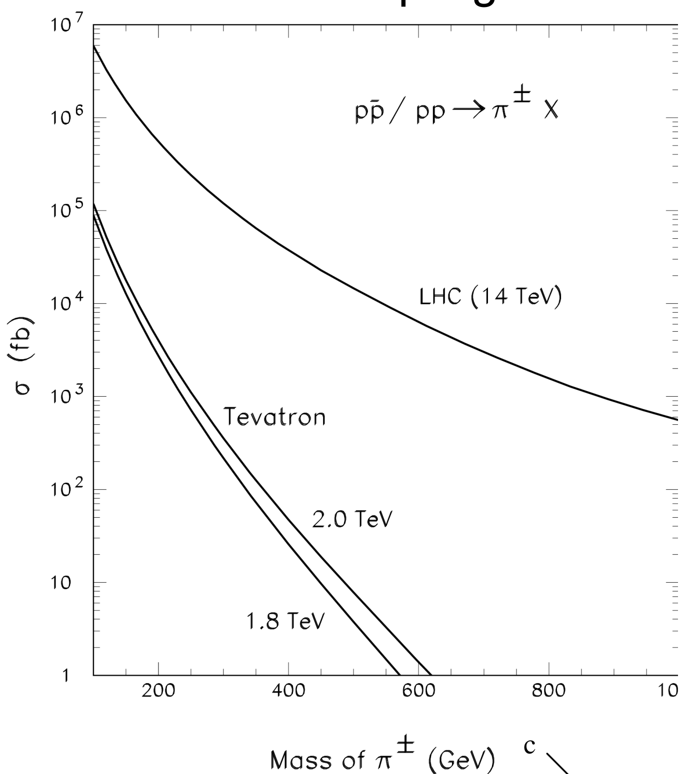
- Very small in the SM because of an efficient cancellation between two Feynman graphs.
- Thus, a sensitive probe of new physics.
- Observable at LHC?

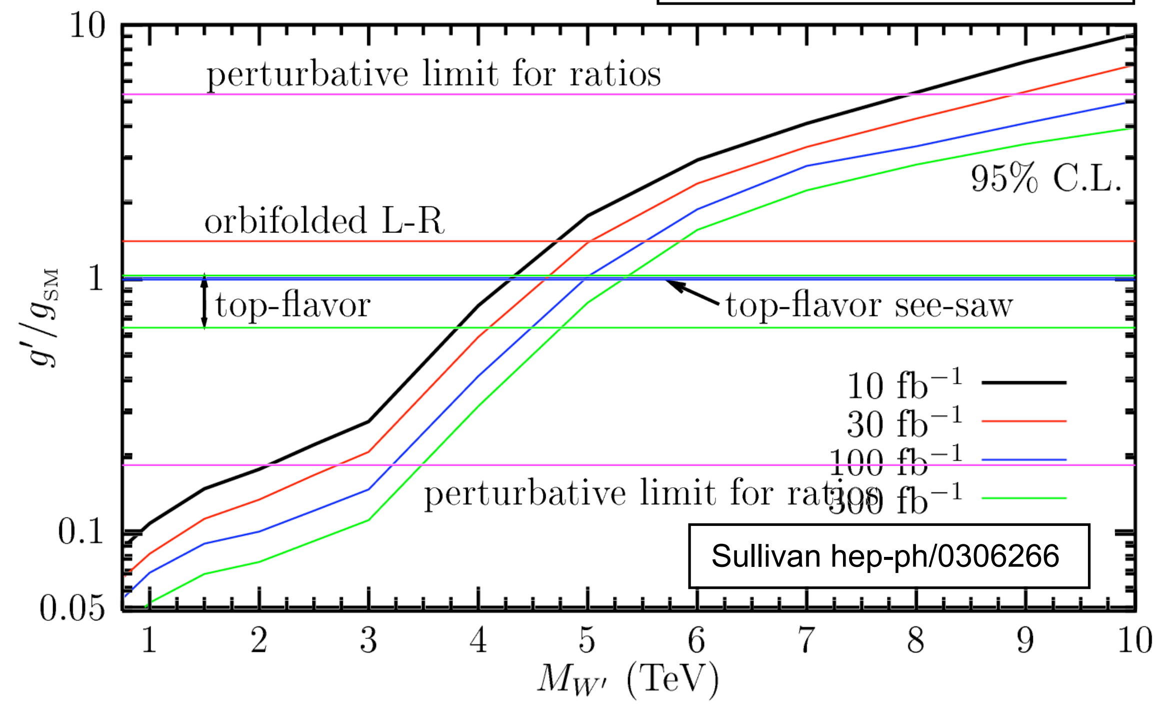


Charged Resonance

- Charged Higgs **H⁺**, Top-pion π^+
  - RH coupling!
- Topflavor: **W' → t $\bar{b}$**

Simmons, **PRD55, 5494 (1997)**





He, Yuan PRL83,28 (1999)