# *The Third Generation Quarks*

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Lecture 2

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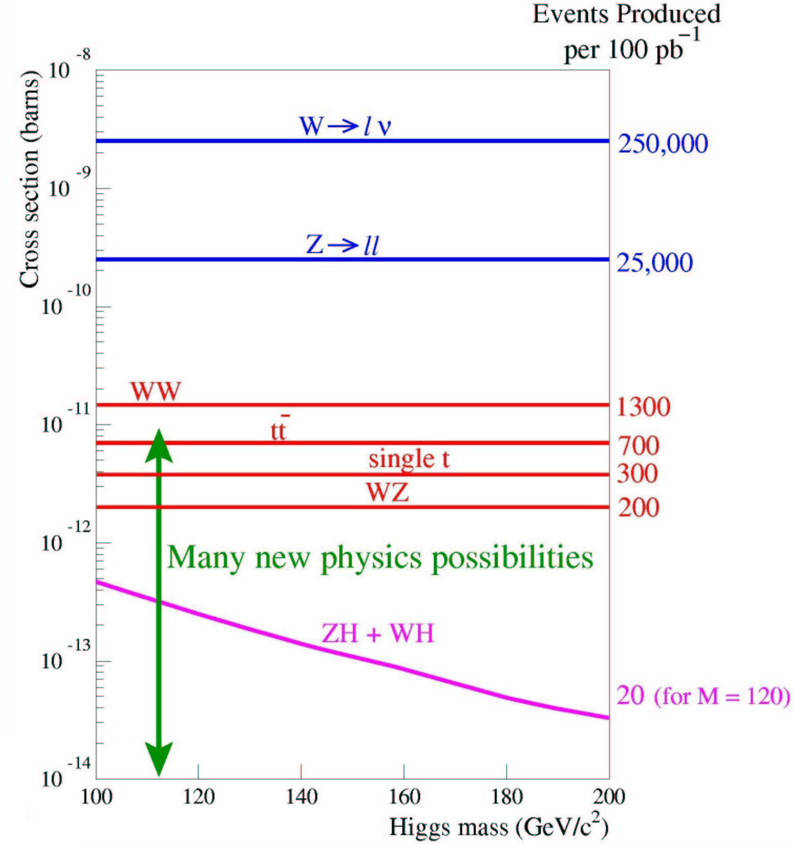
# Tevatron Run II

- Electroweak physics : W, Z's have large cross sections → high statistics, precision measurements
  - W, Z masses, widths, σ, W helicity
  - Gauge boson pair production

    New physics effects ≈ $s/\Lambda^2$
- Many new results appearing
  - Higgs searches
  - More top, Single top soon
  - New physics searches
  - B physics
  - QCD

Tevatron Rates




M. Kruse, 2004 FNAL User's Mrg

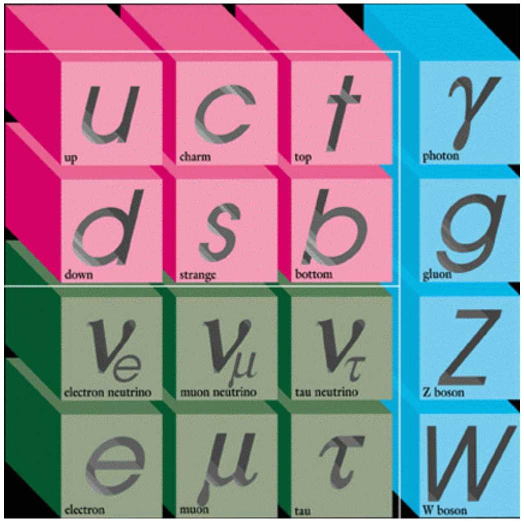
# *Physics landscape changes in 2007*

**Event Rates:**

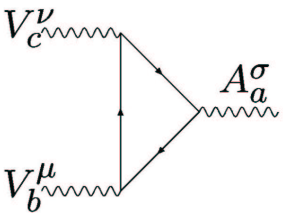
| Process | 10 $fb^{-1}$ at LHC | Previous experiments |
|---|---|---|
| $W \rightarrow e\nu$ | $10^8$ | $10^7$ Tevatron |
| $Z \rightarrow e^+e^-$ | $10^7$ | $10^7$ LEP |
| $t\bar{t}$ | $10^7$ | $10^4$ Tevatron |
| $b\bar{b}$ | $10^{12}$-$10^{13}$ | $10^9$ B factories |
| Higgs, $M_h$=130 GeV | $10^5$ | ? |
| $\tilde{g}\tilde{g}$, m=1 TeV | $10^4$ | -- |

# *Top and Bottom Quarks*

- The Third Generation and the Standard Model
- Top Quarks
  - Top Quark Decay
  - Pair Production
  - Single Top production
- Bottom Quarks
  - Pair Production



# *Who Needs a Top Quark?*




- Top needed for ***anomaly cancellation***
- Triangle diverges; grows with energy

$$T^{\mu\nu\sigma} \approx \int \frac{d^n k}{(2\pi)^n} \frac{1}{k^3}$$

- Anomaly independent of mass; depends only on gauge properties

$$T^{\mu\nu\sigma} \approx Tr\left[\eta_i t^a, \{t^b, t^c\}\right]$$

$$\eta_i = \pm 1 \;\; for \;\; \psi_{L,R}$$

Sensible theories can't have anomalies

# *Anomalies, continued*

- Standard Model Particles:

| Particle | SU(3) | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|
| $(u_R,d_R)$ | 3 | 2 | 1/6 |
| $\overline{u}_R$ | 3 | 1 | -2/3 |
| $\overline{d}_R$ | 3 | 1 | 1/3 |
| $(\nu_L,e_L)$ | 1 | 2 | -1/2 |
| $\overline{e}_R$ | 1 | 1 | 1 |

- $V=\gamma$, $A=W_a$ (SU(2) gauge bosons)

$$\sum T_3 Q_{em}{}^2 = N_c N_g \left(\frac{1}{2}\right)\left(\frac{2}{3}\right)^2 + N_c N_g \left(-\frac{1}{2}\right)\left(-\frac{1}{3}\right)^2 + N_g \left(-\frac{1}{2}\right)(1)^2 = 0$$

- $N_c$=3 is number of colors; $N_g$ is number of generations
- Anomaly cancellation requires complete generation

# *Top Quark Properties*

- Top is weak isospin partner of b quark
  - b quark properties well measured at LEP/SLD
  - Example: $Z \to b\bar{b}$:

$$\frac{\Gamma(Z \to b\bar{b})^{T_3^b=-\frac{1}{2}}}{\Gamma(Z \to b\bar{b})^{T_3^b=0}} = \frac{1+2Q_b\sin^2\theta_W + 4Q_b^2\sin^4\theta_W}{8Q_b^2\sin^4\theta_W}$$
$$\approx 13$$

  - b quark is $T_3$= -1/2 particle, so it must have $T_3$=1/2 partner
    - ***DEFINE this to be the top***

- SM: $Q_{em}=(T_3+Y)/2 \quad \Rightarrow Q_{em}^t=2/3|e|$
- Color triplet
- Spin-1/2

# *Top Couplings*

λ^a are 8 SU(3) color matrices

- Top-gluon coupling

$$g_s \lambda^a_{ij} \bar{t}_i \gamma^\mu t_j G^a_\mu$$

- Top -W coupling
  - Flavor changing with CKM matrix V, and left-handed

$$\frac{g}{2\sqrt{2}} \bar{t} \gamma^\mu (1-\gamma_5) V_{tq} q W_\mu{}^+$$

- Top -Z coupling
  - Violates parity symmetry

$$\frac{g}{4\cos\theta_W} \bar{t} \left( (1 - \frac{8}{3}\sin^2\theta_W)\gamma^\mu - \gamma^\mu \gamma_5 \right) t Z_\mu$$

- Top Higgs coupling
  - Of O(1)

$$\frac{M_t}{v} \bar{t} t h$$

# *Top Quark Decay Formula*

- Dominant decay of top quark is $t \to W^+ b$
- Theoretical error is ~1%

$$\Gamma_0 = \frac{G_F M_t^2}{8\pi\sqrt{2}} |V_{tb}|^2 \left(1 - \frac{M_W^2}{M_t^2}\right)\left(1 + \frac{2M_W^2}{M_t^2}\right)$$
$$= |V_{tb}|^2 1.42 GeV$$

Corrections to $\Gamma_0$:

| | |
|---|---|
| $M_W \neq 0$ | $-11.5\%$ |
| $\alpha_s, M_W = 0$ | $-9.5\%$ |
| $\alpha_s, M_W \neq 0$ | $+1.8\%$ |
| $\alpha_s^2, M_W = 0$ | $-2.0\%$ |
| $\alpha_s^2, M_W \neq 0$ | $+0.1\%$ |
| EW | $+1.7\%$ |

Theory well understood

# *No Free Quarks*

- QCD color confinement

⇨ Observe mesons and baryons

Charmed mesons: $D^+ = c\bar{d},\ D^0 = c\bar{u},\ \bar{D}^0 = \bar{c}u,\ D^- = \bar{c}d,\ \ldots$

Charmed, strange mesons: $D_s^+ = c\bar{s},\ D_s^- = \bar{c}s,\ \ldots$

$c\bar{c}$ mesons: $J/\psi,\ \chi_c,\ \psi',\ \ldots$

Bottom mesons: $B^+ = u\bar{b},\ B^0 = d\bar{b},\ \bar{B}^0 = \bar{d}b,\ B^- = \bar{u}b,\ \ldots$

Bottom, charmed mesons: $B_c^+ = c\bar{b},\ B_c^- = \bar{c}b,\ \ldots$

$b\bar{b}$ mesons: $\Upsilon,\ \chi_b,\ \ldots$

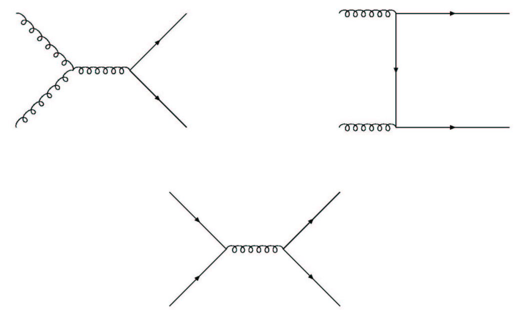
Non-perturbative binding

# *Top Quark is Different*

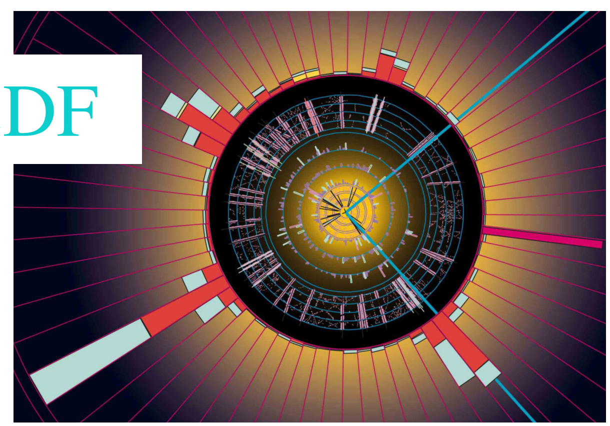
- Top quark decays before it can form bound states
  - Top quark lifetime: $\tau_t \approx 5 \times 10^{-25}$ sec
  - $\tau_{QCD} \approx 3 \times 10^{-24}$ sec
- Very different from b system: $\tau_b \approx 1.55 \pm 0.06$ ps
- Top quark interactions may be first indication of new physics beyond the SM
  - Top quark mass critical for precision measurements
  - Top quark couples strongly to Higgs, so it is window to electroweak symmetry breaking

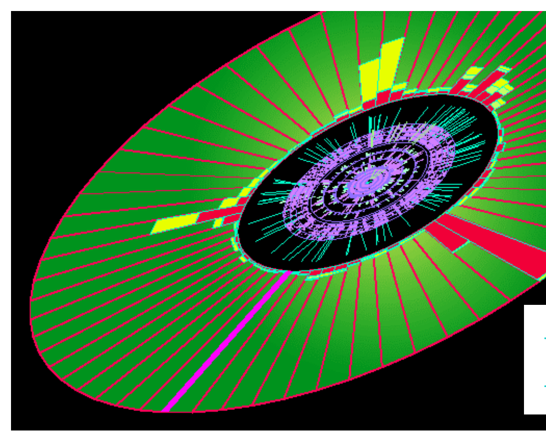
# *Top Quark Discovery at Fermilab in 1995*

- Run I, $p\bar{p}$ at $\sqrt{s}$=1.8 TeV, L~125 $pb^{-1}$
- Run II, $p\bar{p}$ at $\sqrt{s}$=1.96 TeV, eventually L~4-6 $fb^{-1}$
- Top quark produced by $gg \to t\bar{t}$
  $q\bar{q} \to t\bar{t}$



- Strongly produced; sensitive to $\alpha_s(\mu_R)$
- $M_t$=178±4.3 GeV >> $M_b$

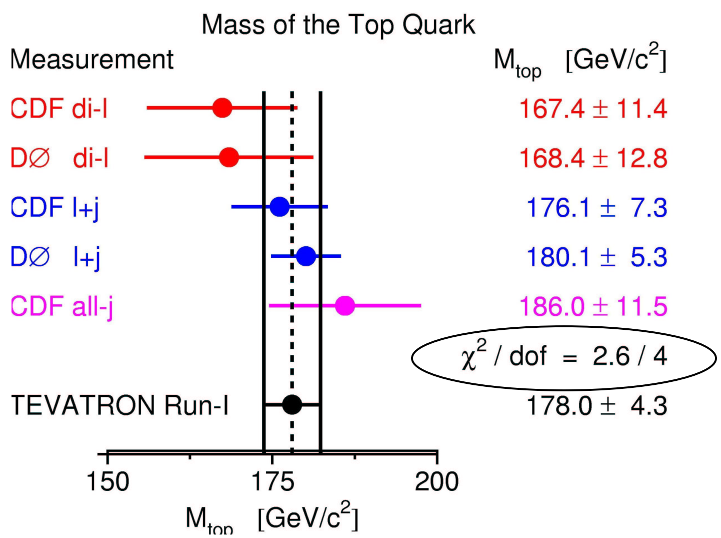


# *New CDF/D0 Combined Top Quark Mass*

Combination of Run I results:

**$M_t$=178.0±4.3 GeV**




Run II top masses arriving daily!

Good fit:

63% probability

Combination dominated by D0 lepton + jets result

CDF/D0 hep-ex/0404010

# *Why is the top quark mass so important?*

- In QED, running of α at scale M not affected by heavy quarks with $M_q$>> M

$$\alpha(q^2) = \alpha(M^2)\left[1 + \frac{\alpha(M^2)}{12\pi}\ln\left(\frac{q^2}{M^2}\right)\right]$$

Running of α from electron loop

- Decoupling theorem: diagrams with heavy virtual particles don't contribute at scales M << $M_q$ if
  - *Couplings don't grow with $M_q$*
  - *Gauge theory with heavy quark removed is still renormalizable*

# *Why is the top quark mass so important?*

- Spontaneously broken SU(2) x U(1) theory violates both conditions
  - *Longitudinal modes of gauge bosons grow with mass ($\varepsilon_L \approx p_V/M_V$)*

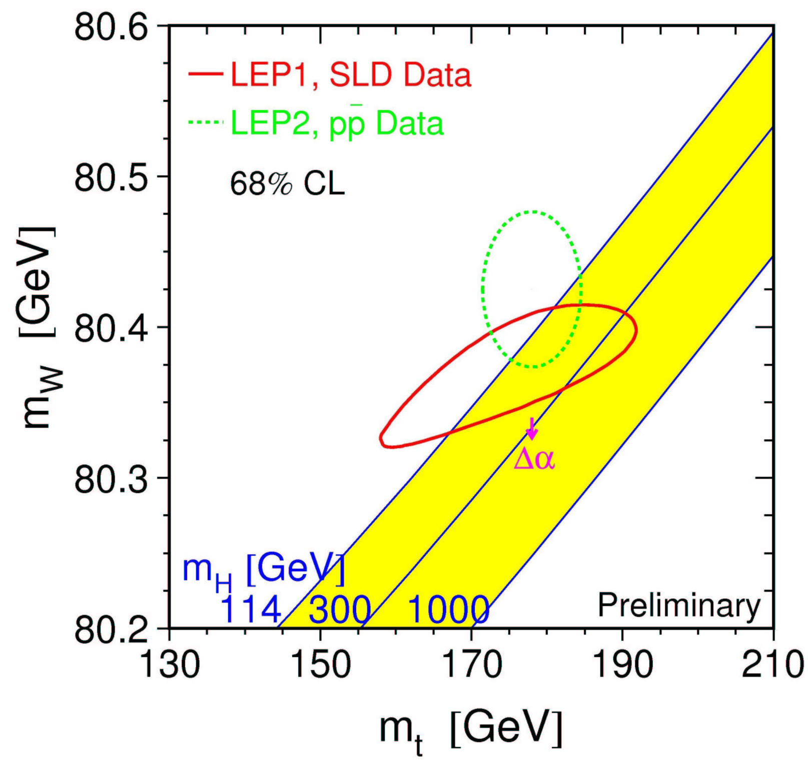
$$\frac{g}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma_5)V_{tq}qW_{\mu}^{+} \Rightarrow \frac{gM_t}{2\sqrt{2}M_W}\bar{t}(1-\gamma_5)V_{tq}qW_L^{+}$$

  - *Theory without top quark is not renormalizable*
- Effects from top quark grow with $M_t^2$

***Expect $M_t$ to have large effect on precision observables***

# *Why do we care so much about $M_t$?*

- $M_t$ is fundamental parameter
- $M_t$ measurement gives limit on $M_h$
- $\delta M_t$ must match $\delta M_W$:
  - Tevatron Run II with 2 $fb^{-1}$
  - $\delta M_W$~27 MeV
  - $\delta M_t$~3 GeV




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

# *Simple Example*

- ρ parameter

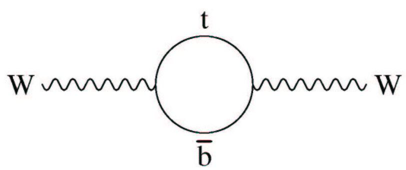
$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 + \ldots = \frac{A_{WW}(0)}{M_W^2} - \frac{A_{ZZ}(0)}{M_Z^2}$$

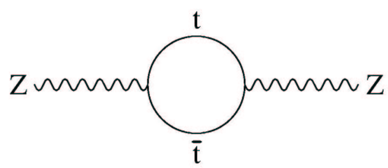
$$i\Pi^{\mu\nu}_{VV}(p) = A_{VV}(p^2)g^{\mu\nu} + B_{VV}p^\mu p^\nu$$

- Calculate in N=4-2ε dimensions

$$A_{ZZ}(0) = \frac{G_F M_W^2}{\sqrt{2}}\frac{N_c}{4\pi^2\cos\theta_W^2}\left(\frac{4\pi}{M_t^2}\right)^\varepsilon \frac{M_t^2}{\varepsilon}$$

$$A_{WW}(0) = \frac{G_F M_W^2}{\sqrt{2}}\frac{N_c}{4\pi^2}\left(\frac{4\pi}{M_t^2}\right)^\varepsilon M_t^2\left(\frac{1}{\varepsilon}+\frac{1}{2}\right)$$




$$\delta\rho = \frac{G_F}{\sqrt{2}}\frac{N_c}{8\pi^2}M_t^2$$

***Quadratic dependence on $M_t$***

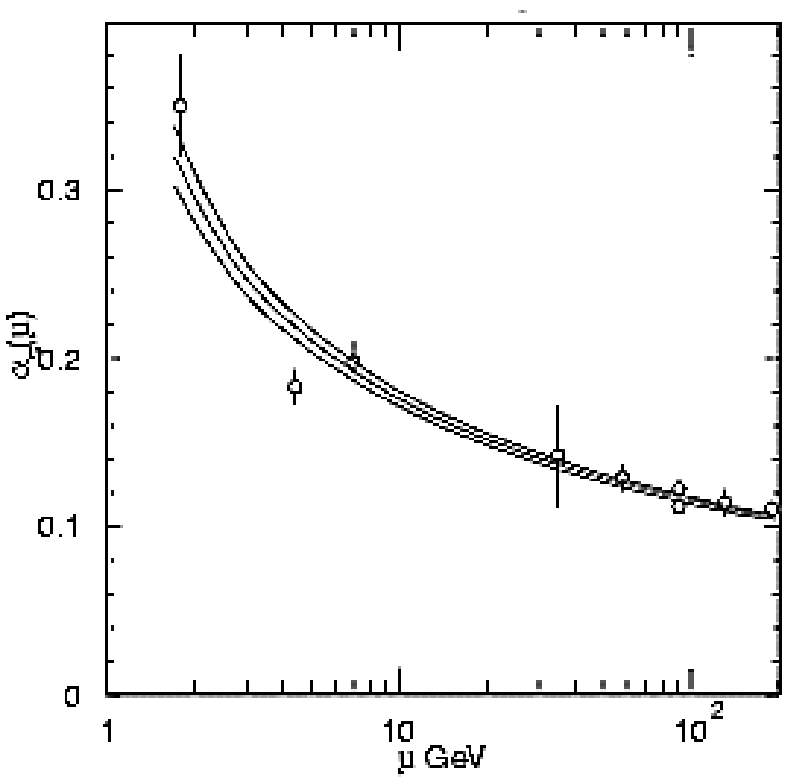
Same calculation gives logarithmic dependence on $M_h$

# *How heavy is a heavy quark?*

- A simple criterion:

Production and decay of heavy quarks can be calculated perturbatively

- QCD running coupling constant:




Reliable perturbative calculation in QCD requires $\alpha_s(\mu) << 1$

Renormalization scale $\mu$ ~ order of the hard scale

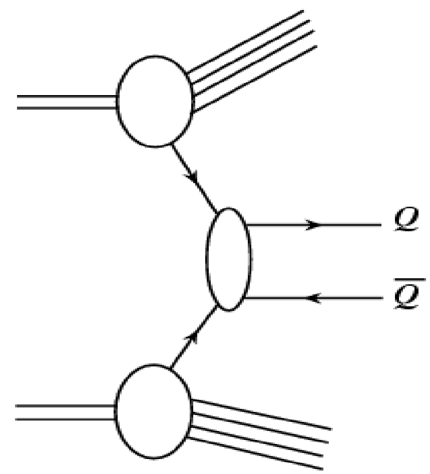
$\alpha_s(M_Z)$=.118

# *Top Quark Cross Section*

QCD factorization:

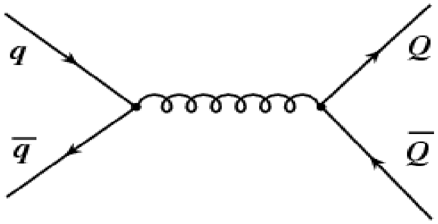
$$\sigma_H(S) = \sum_{i,j} \int dx_1 dx_2 F_i(x_1, \mu_F) F_j(x_2, \mu_F) \hat{\sigma}_{ij}(x_1, x_2)$$

- Hadronic energy, S
- Partonic sub-energy, $s = x_1 x_2 S$
- Parton distribution functions, $F_i(x, \mu_F)$




- To any given order in $\alpha_s$, $\sigma_H$ independent of $\mu$
- $\mu$ dependence of $\sigma_H$ often used to estimate theoretical uncertainty
- Typically see reduced scale dependence at higher orders

# *Heavy flavor pair production*




Dominates at Tevatron for top production (90% of cross section)

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d\hat{t}} = \frac{1}{16\pi\hat{s}^2} |\bar{M}_{q\bar{q}\to Q\bar{Q}}|^2$$

- Use to generate differential cross sections

$$\sum \left|\bar{M}_{q\bar{q}\to Q\bar{Q}}\right|^2 = \frac{(4\pi\alpha_s)^2 C_F}{N_c}\left(\frac{u_1^2+t_1^2}{s^2}+\frac{2M_Q^2}{s}\right)$$

$$s = 2k_1 \bullet k_2, \quad t_1 = -2k_1 \bullet p_1, \quad u_1 = -2k_1 \bullet p_2 = -s - t_1$$

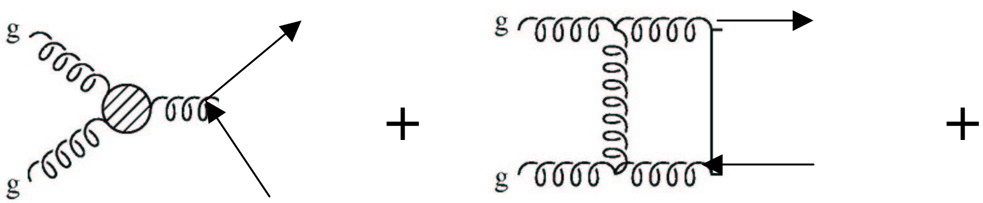
$$\hat{\sigma}_{q\bar{q}\to Q\bar{Q}} = \left(\frac{2}{9}\right)\frac{4\pi\alpha_s^2}{3\hat{s}}\left[1+\frac{2m_Q^2}{\hat{s}}\right]\sqrt{1-\frac{4m_Q^2}{\hat{s}}}$$

Threshold suppression, ~β

Same calculation valid for b production

# *Hadronic Cross Sections at NLO in QCD*

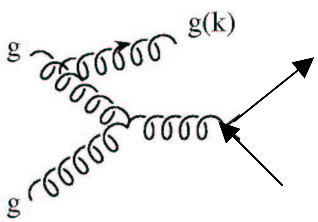
- NLO corrections from $\hat{\sigma}_{ij}^{NLO} = \hat{\sigma}_{ij}^{LO} + \delta\hat{\sigma}_{ij}^{NLO}$
- NLO corrections contain one loop virtual diagrams and real gluon emission
- Sample virtual diagrams:




- In N=4-2ε dimensions, virtual diagrams have $1/\varepsilon^2$ and $1/\varepsilon$ poles
- Add wavefunction, mass, coupling renormalization

# *Hadronic Cross Sections at NLO in QCD, 2*

- Sample real gluon emission diagram:




Gluon propagator:

$$\frac{1}{(p-k)^2}=\frac{-1}{\sqrt{s}E_g(1-\cos\theta)}$$

➢Soft singularity: $E_g \rightarrow 0$

➢Collinear singularity: $\cos\theta \rightarrow 0$

➢At NLO, also small contribution from qg initial state

- Need to
  - Renormalize UV divergences in $\sigma_{virt}$
  - Cancel IR divergences in $\sigma_{virt+}\sigma_{real}$
  - NLO result has form:

$$\hat{\sigma}_{ij}=\alpha_s^{\ 2}(\mu_R)\left(h_{ij}^{\ 0}+\frac{\alpha_s(\mu_R)}{4\pi}h_{ij}^{\ 1}+\frac{\alpha_s(\mu_R)}{4\pi}h_{ij}^{\ 2}\log\left(\frac{\mu_R^{\ 2}}{M_t^2}\right)\right)$$

  - $\alpha_s(M_t)$~0.1 so perturbation theory converges well

# *Hadronic Cross Sections at NLO in QCD, 3*

- Need to
  - Check $\mu$ dependence of $\sigma^{NLO}$:
    - To any given order in $\alpha_s$, $d\sigma_H/d\mu=0$
    - Using

$$\mu^2 \frac{\partial}{\partial \mu^2} F_i(x,\mu_F) = \frac{\alpha_s(\mu_F)}{2\pi} \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z) F_j\left(\frac{x}{z},\mu_F\right)$$

$$\frac{d\alpha_s(\mu_R)}{d\ln(\mu^2)} = -b_0 \alpha_s^2 + O(\alpha_s^3), \qquad b_0 = \frac{1}{4\pi}\left(\frac{11}{3}N_c - \frac{2}{3}n_{lf}\right)$$

    - $\mu$ dependence predicted

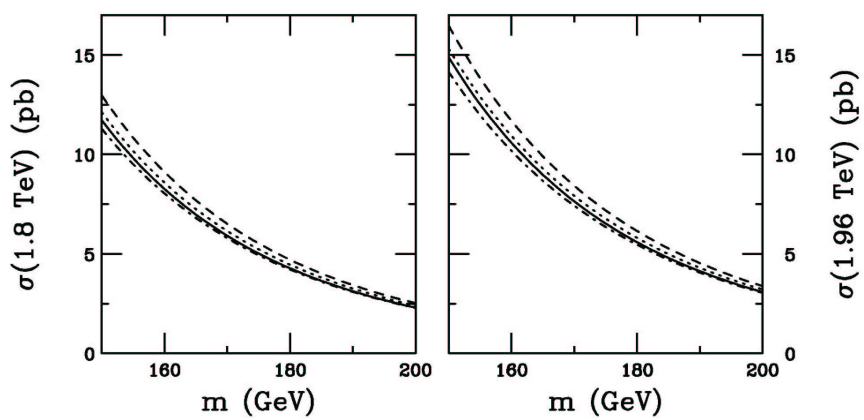
$$h_{ij}^{\ 2}(x_1,x_2) = 2\left\{4\pi b_0 h_{ij}^{\ 0}(x_1,x_2) - \sum_k \left[\int_{4M_t^2/s}^1 P_{ik}(z_1) h_{kj}^{\ 0}(x_1 z_1, x_2) + (1 \leftrightarrow 2, i \leftrightarrow j)\right]\right\}$$

  - Near threshold, corrections take form: $\sigma \approx \alpha_s \left(c_1^2 \ln^2 \beta^2 + c_1^1 \ln \beta^2\right)$
  - Large logarithms can be summed to improve convergence of perturbation theory

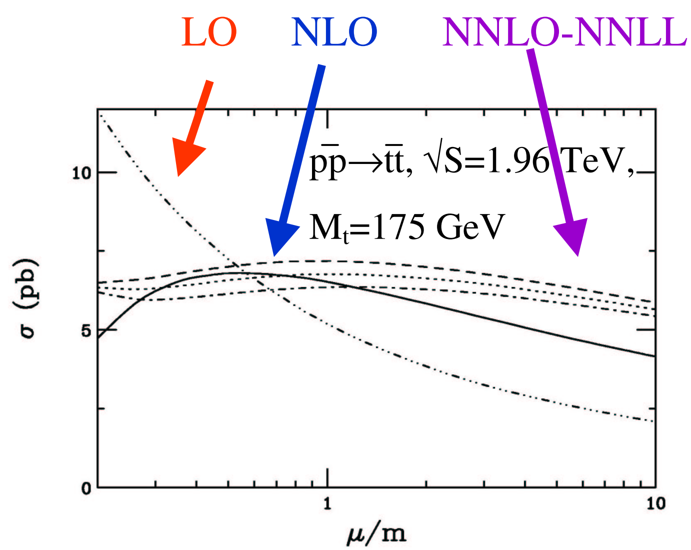
Scale dependence formally $O(\alpha_s^4)$

# *Theoretical predictions for top pair production*

- Ingredients
  - **Parton level cross section** with NLO matrix elements plus resummation to all orders of soft logarithms
    - Resummation improves stability with respect to scale variations
    - Very sensitive to $M_t$
  - **PDFs**




Note increase in rate at Run II




Scale variation

Kidonakis & Vogt, hep-ph/0308222

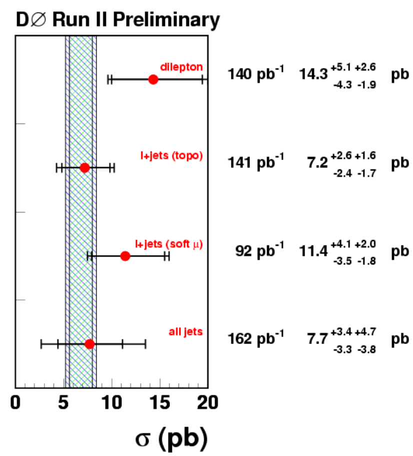
# *Top Pair Production, continued*

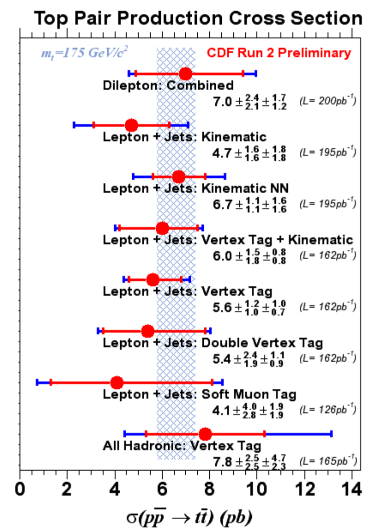
- PDF uncertainties (fix $\mu=M_t$, $\sqrt{S}=1.96$ TeV)
  - CTEQ6 family of PDFs
  - $M_t$=175 GeV:  $\sigma=6.70\pm0.45$ pb
  - $M_t$=180 GeV:  $\sigma=5.75\pm0.38$ pb
- Full range of uncertainties
  - $M_t/2<\mu<2M_t$, CTEQ6, MRST PDFs, $\sqrt{S}=1.96$ TeV
  - $M_t$=175 GeV:  $5.82<\sigma<7.41$ pb
  - $M_t$=180 GeV:  $5.0<\sigma<6.34$ pb

$\sigma(1.96)/\sigma(1.8)=1.295\pm0.15$ stable to scale choices, PDFs, $M_t$

➢Updated σ's from summer conferences (see Quadt talk)

➢Good agreement between theory/experiment



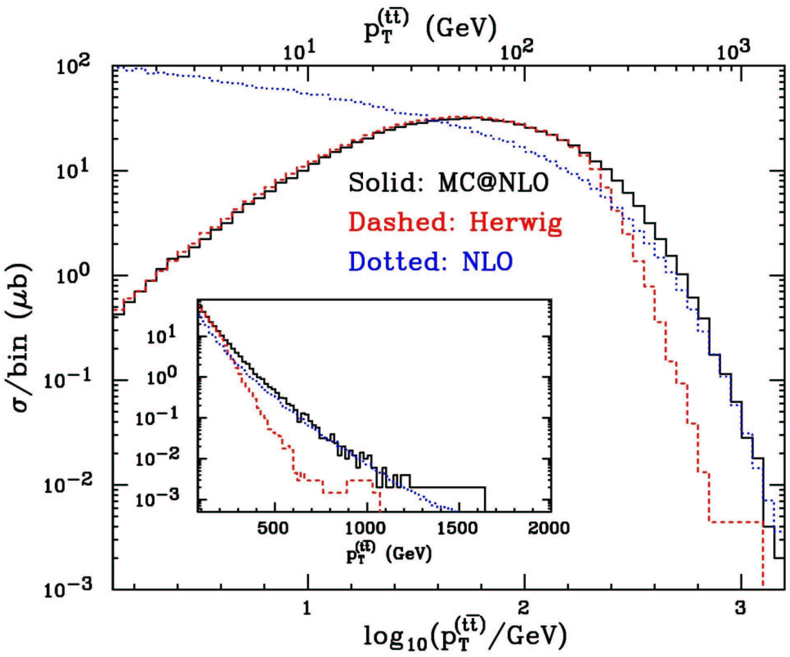

Cacciari, Frixione, Mangano, Nason, Ridolfi, hep-ph/0303085

# *Need Monte Carlos which include NLO*

- Match NLO with parton shower
- Subtract terms which are included in parton shower from NLO result
  - At high $p_T$, NLO
  - At low $p_T$, MC

MC@NLO

$pp \to t\bar{t}$ at LHC




Frixione, Nason & Webber, hep-ph/0305252

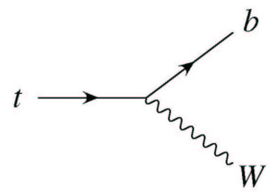
# *Top Quark Mixing*

- Weak interaction eigenstates are not mass eigenstates

$$L = -\frac{g}{2\sqrt{2}} \sum_{q=d,s,b} \bar{t} \gamma^{\mu} (1-\gamma_5) V_{tq} q W_{\mu}^{+} \; + h.c.$$

- Interactions mix down-type quarks with Cabbibo-Kobayashi-Maskawa Matrix V:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



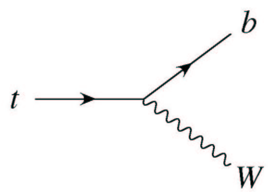

- Top quark emits W boson and become a b quark ($V_{tb}$), an s quark ($V_{ts}$) or a d quark ($V_{td}$)

$$V = \begin{pmatrix} 0.9741-0.9756 & 0.219-0.226 & 0.002-0.005 \\ 0.219-0.226 & 0.9732-0.9748 & 0.038-0.044 \\ 0.004-0.014 & 0.037-0.044 & V_{tb} \end{pmatrix}$$

# *Top Quark Decays*

- Unitarity of CKM matrix ($VV^+=1$) and assuming 3 generations:

$$1 = |V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2$$
$$V_{tb} \approx .9990 - .9993$$




- Dominant decay of top quark is $t \to Wb$
- More than 3 generations, almost no limit on $V_{tb}$

$$V_{CKM} = \begin{bmatrix} 0.9730-0.9746 & 0.2174-0.2241 & 0.003-0.0044 & \ldots \\ 0.213-0.226 & 0.968-0.975 & 0.039-0.044 & \ldots \\ <0.08 & <0.11 & 0.07-0.9993 & \ldots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

# *Top and CKM*

- Predict from unitarity: $|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2 = 1$
- $V_{ts}$ and $V_{td}$ measured indirectly from b physics

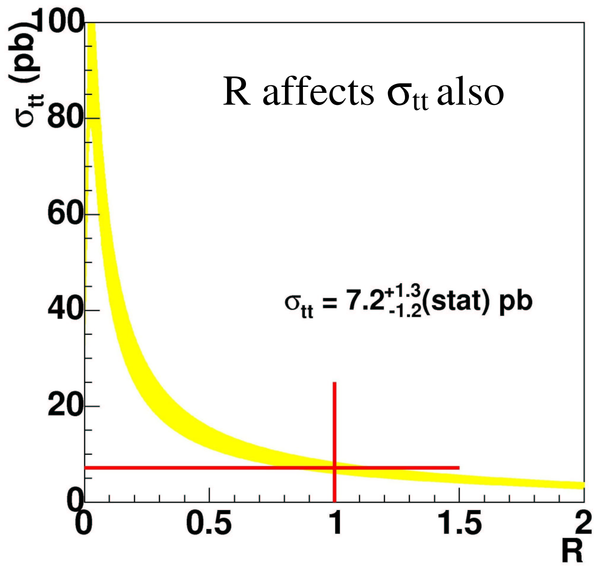
  - If 3 generations: $R = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2$
  - Measure $R = \frac{BR(t \to Wb)}{BR(t \to Wq)}$

D0 Run II (158-169 $pb^{-1}$) in e-jets and μ-jets channels (2 different lifetime triggers):

SVT: $R=0.70^{+0.27}_{-0.24}$ (stat)$^{+0.11}_{-0.10}$(syst)

CSIP: $R=0.65^{+0.34}_{-0.30}$(stat)$^{+0.17}_{-0.12}$(syst)

Reasonable agreement with 3 generation Standard Model




D0 note 4586-CONF

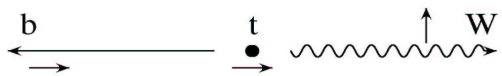
# *Top Quark Decay*

- Decay amplitude for t→Wb

$$A = -\frac{g}{2\sqrt{2}} V_{tb} \bar{u}_b \varepsilon_W (1-\gamma_5) u_t$$

- Substitute expressions for momenta & polarization vectors

Longitudinal $W$ (helicity 0):

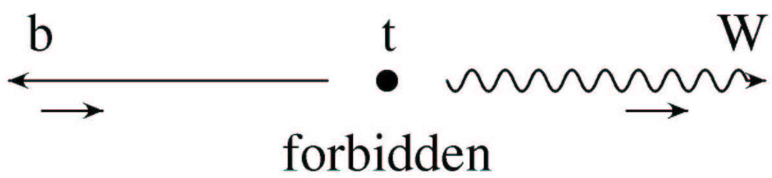



$$\begin{aligned}
p_W &= (E_W, 0, 0, |\vec{p_W}|) \\
\epsilon_L^W &= \frac{1}{M_W}(|\vec{p_W}|, 0, 0, E_W) \\
&= \frac{\vec{p_W}}{M_W} + \mathcal{O}\left(\frac{M_W}{M_t}\right) \\
\mathcal{A}(t \to bW_L) &= -\frac{g}{2\sqrt{2}} \bar{b} \frac{p_W}{M_W}(1-\gamma_5)t \\
&= -\frac{m_t}{\sqrt{2}v} \bar{b}(1+\gamma_5)t
\end{aligned}$$

$$\Gamma(t \to bW_L) \sim \frac{m_t^3}{v^2}$$

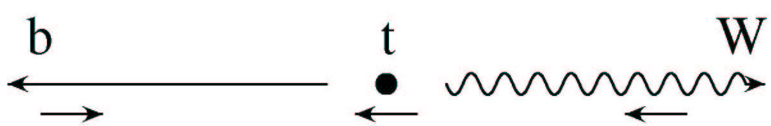
Left-handed fermion: spin is opposite from direction of motion

# *Top Quark Decay, 2*




•$h^W$=+ forbidden by angular momentum conservation

•Massless b quark always left-handed; heavy top can be either left- or right-handed




$$M = -\frac{ig}{2\sqrt{2}} V_{tb} \bar{u}_b \varepsilon_W (1-\gamma_5) u_t$$

- Decay amplitude for $t \to Wb$
- Transverse W: $\varepsilon^{\pm} = (1/\sqrt{2})(0,1,\pm i,0)$
  - $\Gamma(t \to W_T b) \sim g^2 M_t$
  - No enhancement

# *Top Quark Decay, 3*

$$F_0 = \frac{\Gamma(t \to W_L b)}{\Gamma(t \to Wb)_{tot}} = \frac{m_t^2/2M_w^2}{1 + m_t^2/2M_w^2} = 69.5\%\ (NLO)$$

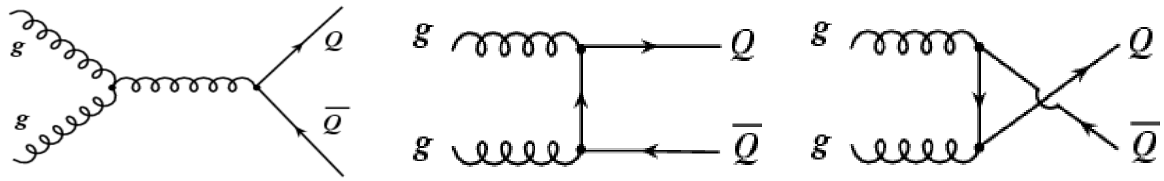
CDF Run I: $F_0$=91±37±13%

D0 Run I: $F_0$=56±31%

- W helicity correlated with momentum of decay leptons
  - $h^W$= + gives harder charged leptons than $h^{W=}$ -
  - 2 $fb^{-1}$ give 5% measurement

*Tests V-A structure of tbW vertex*

# LHC is Top Factory




$\hat{s} \approx x_1 x_2 S \approx (350\ GeV)^2$

$x_1 x_2 \sim 10^{-3}$ for $\sqrt{S}$=14 TeV

Production dominated by gluon fusion (~90% from gg )

- $\sigma \sim 800$ pb $\Rightarrow$ $10^7$ events/year
- Large statistics $\Rightarrow$ Precision measurements of:
  - Production cross section
  - Mass
- Probe rare decays of top and BSM top decays
- Top is background for new physics

# *Top at LHC*

- Precision measurement of top mass from leptons plus jet:

$$t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow (l\nu)(jj)(b\bar{b})$$

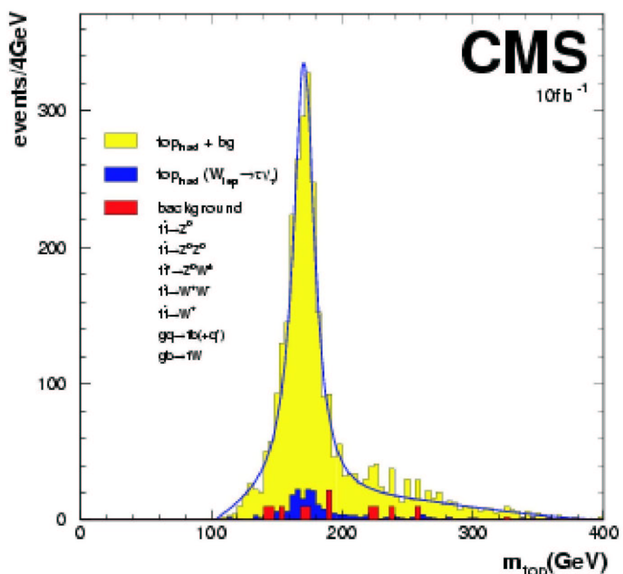
- Including e, μ, BR~30%

•Signal from MC@NLO

•Most important bkgd: W + jets (tree)

•Largest systematic uncertainties: jet energy scale, b fragmentation, initial and final state radiation

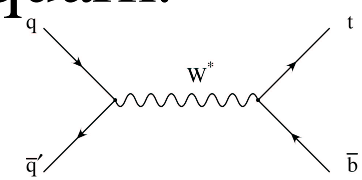
***δMt~2 GeV***

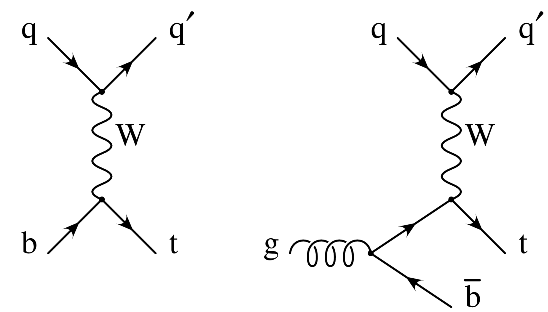


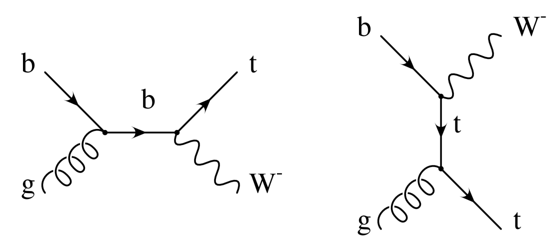

***S/B~6.5!***

# *Single Top in the SM*

- Single top produced at hadron colliders through interactions involving a W boson and b quark.
- Rates directly proportional to $|V_{tb}|^2$
- At tree level there are three modes:
  - s-channel W exchange
    - Large rates at Tevatron, small at LHC.
  - t-channel W exchange
    - Dominant mode at Tevatron and LHC.
  - t-W associated production
    - Small at Tevatron, large rate at LHC.



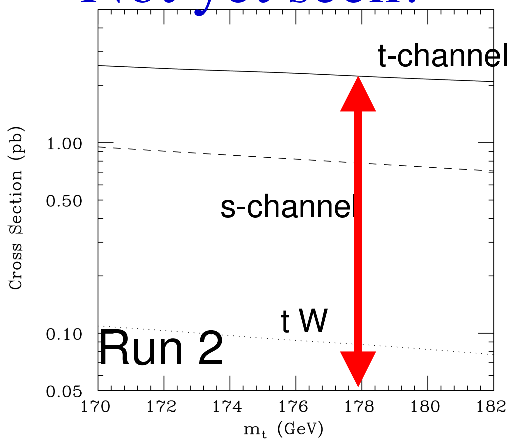



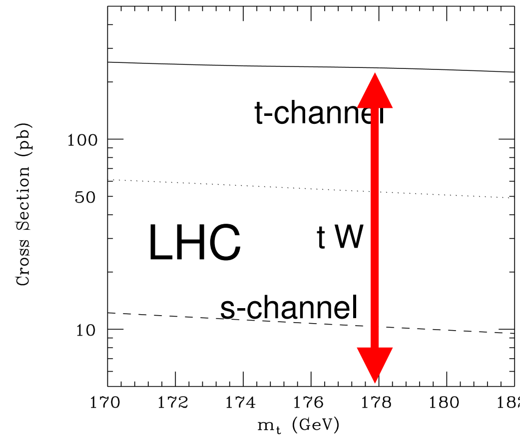

Sensitive to b quark PDFs

# *Single Top*

Not yet seen!




2-4 $fb^{-1}$ at Tevatron gives $V_{tb}$~±7-9%




| σ | Run I Limits | Tevatron Run 2 | LHC |
|---|---|---|---|
| $\sigma_t$ (NLO) | < 13.5 pb | 1.98±0.28 pb | 247±12 pb |
| $\sigma_s$ (NLO) | < 12.9 pb | 0.88±0.12 pb | 10.7±1.1 pb |
| $\sigma_{tW}$ (LL) | | 0.09±0.02 pb | 56±8 pb |
| **Total** | | **2.95±0.33 pb** | **314±15 pb** |

Uncertainties from PDFs, $\delta M_t$

Single top rate ~1/2 $t\bar{t}$ rate at Tevatron

Z. Sullivan, hep-ph/0408049

# *Single top at the LHC*

- Large background from σ(tt)=830 pb, σ(Wbb)>300 pb
- Large QCD multi-jet background
- Largest uncertainty is PDF uncertainty in theory
  - Assume 6% theory uncertainty

•$V_{tb}$ can be constrained using unitarity

•This assumes the SM, with 3 generations

•Physics beyond the SM can modify these results

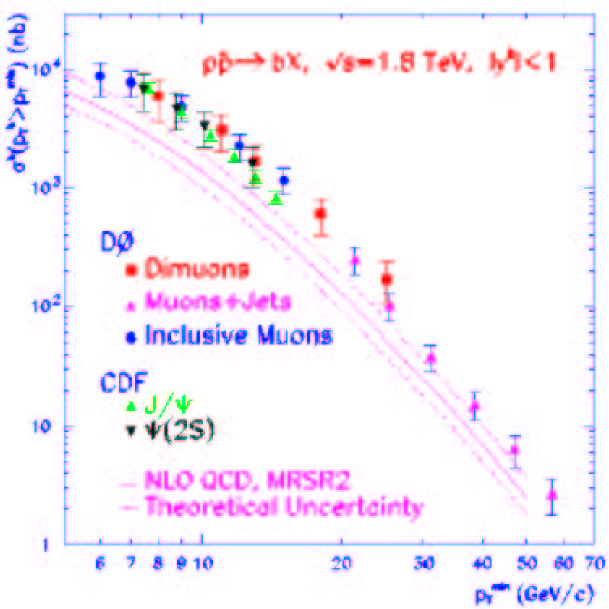
$\delta|V_{tb}|$ to:

.4% from Wg

1.4% from Wt

2.7% from W*

# *b-quarks at Tevatron*




- ➢We cannot really measure b-quark momentum
- ➢Long-standing puzzle

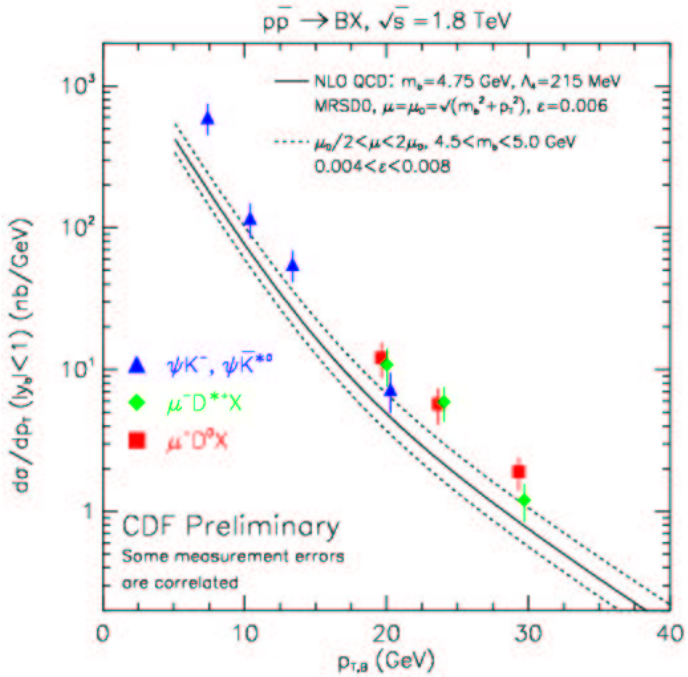
Usually model fragmentation by writing hadronic B meson σ as:

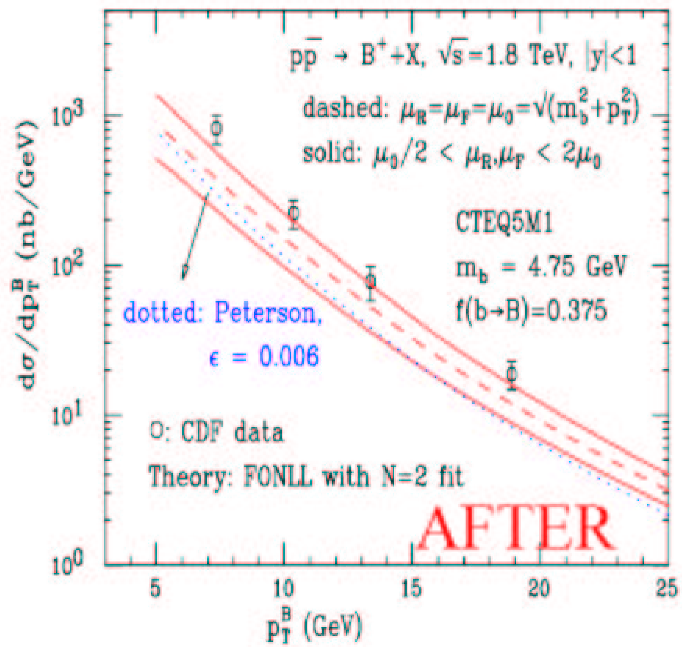
$$\frac{d\sigma}{dp_T} = \int d\hat{p}_T dz \frac{d\sigma}{d\hat{p}_T} D(z)\delta(1 - z\hat{p}_T)$$

Often use Peterson form:

$$D(z) \approx \frac{z(1-z)^2}{\left[(1-z)^2 + \varepsilon z\right]^2}$$

# b-mesons at Tevatron




Improved theory and
fragmentation functions

Cacciari, Nason, PRL 89 (2002)

# Conclusion

- Exploration of t- and b- quark properties sheds light on structure of SM
- So far, everything looks like the SM

Still hoping for something new