# Physics of Top Quark at LHC

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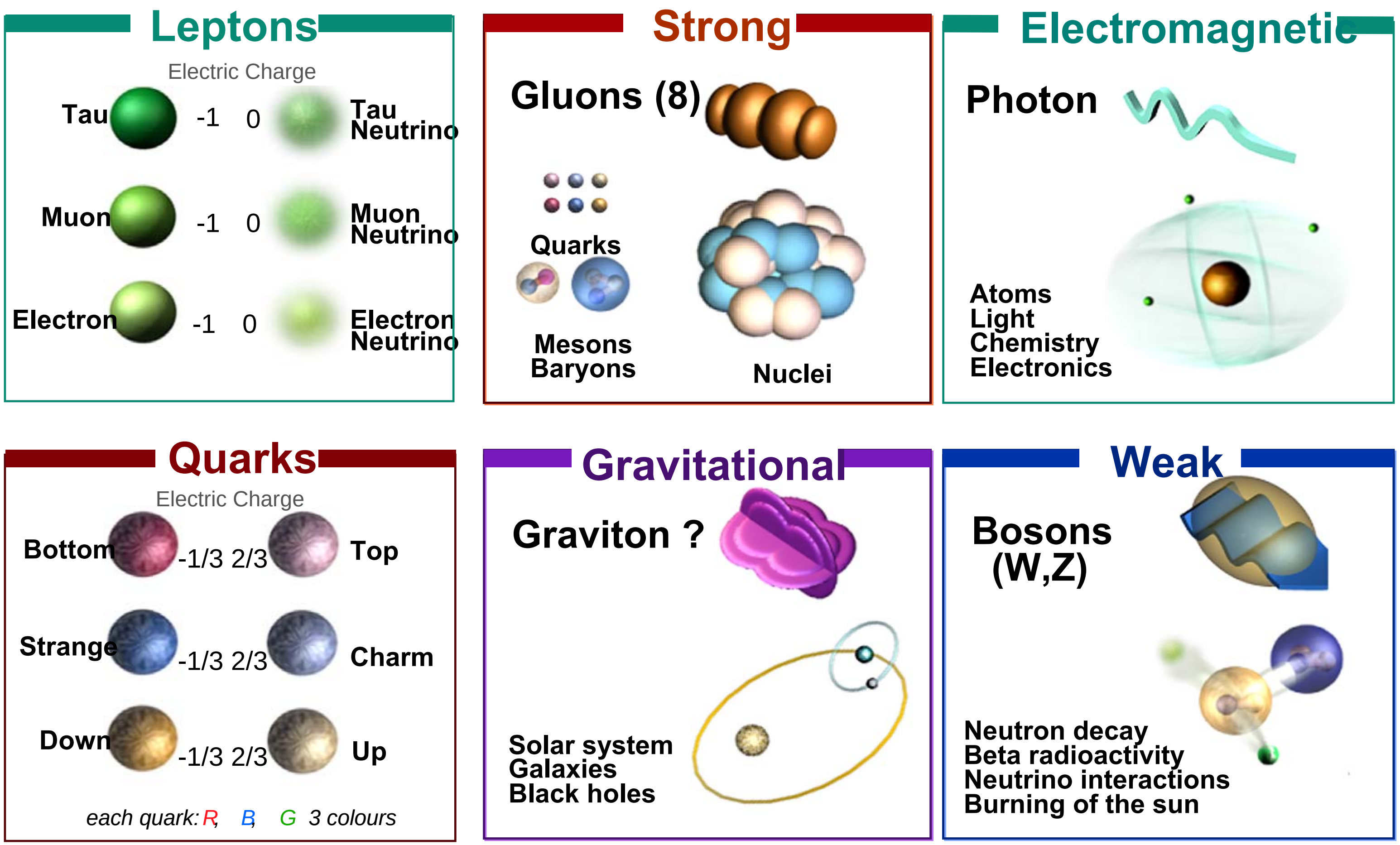
# Standard Model of Particle Physics




*The particle drawings are simple artistic representations*

# Introduction

- Properties of top quark:
  - Charge 2/3 e
  - Spin 1/2
  - Color triplet
  - Weak isospin partner of b quark $T_3 = 1/2$
- Why top quark should exist?
  - Theoretical consistency of SM
    - Anomaly Cancellation

# Introduction

- Consistency of b quark measurements with the SM.
- Consistency of precision measurements.

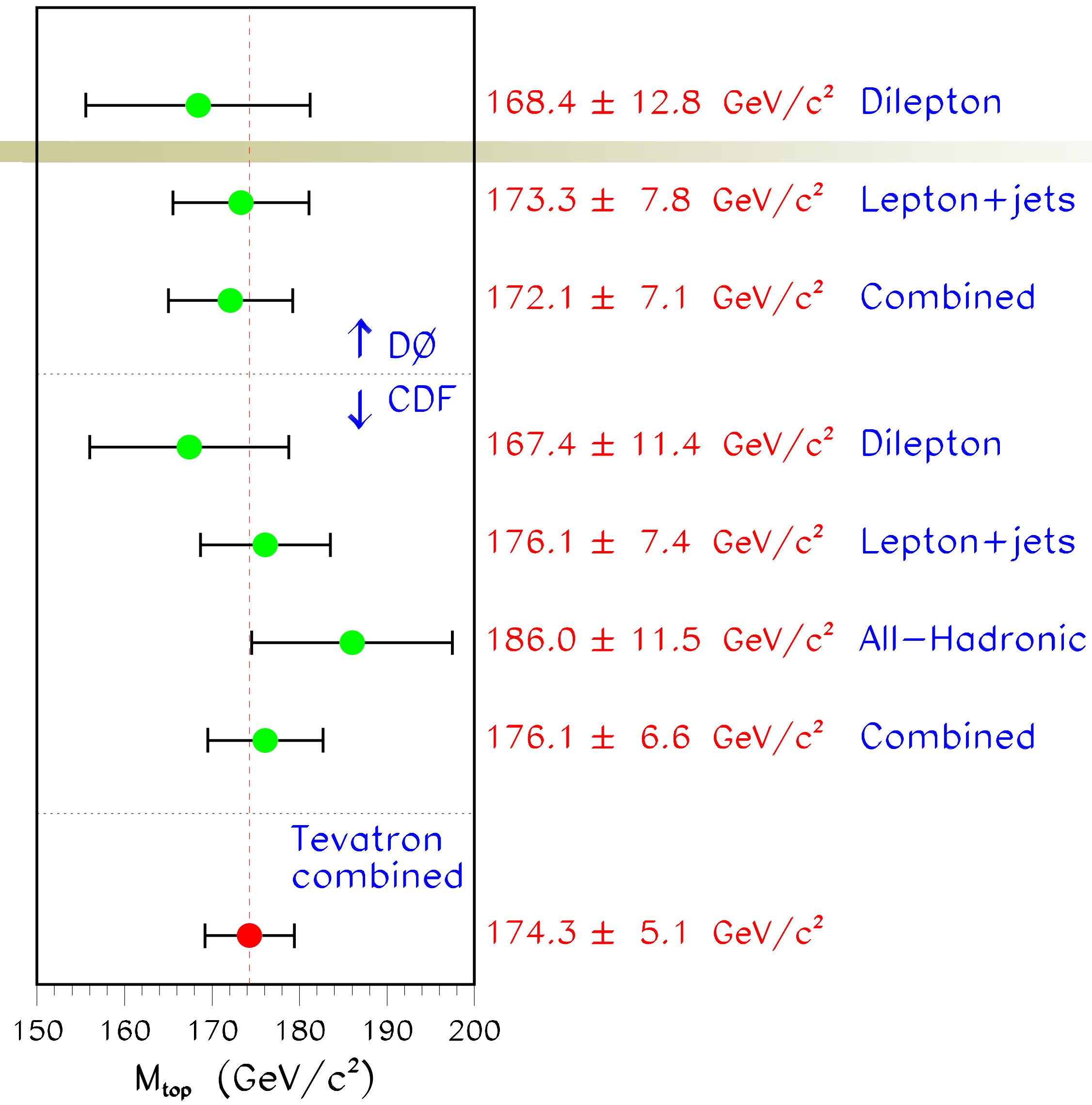
- Top quark was discovered in 1995 at Tevatron Run I with:

$$m_t = 174.3 \pm 5.1 \text{ GeV}$$

$$\sigma_{tt} = 5.9 \pm 1.7 \text{ pb}$$

**2004 (D0)**: $m_t = 178 \pm 4.3$ GeV

# Tevatron Top Quark Mass Measurements



# Top Quark Fact Sheet

- Interesting points about Top:
  - Heaviest known elementary particle.
  - $\tau_t = 4 \times 10^{-25}$ s
  - $\tau_{had} = 28 \times 10^{-25}$ s
  - Production & decay vertices $10^{-16}$ m
  - $m_t > \Lambda_{qcd} \approx 200$ MeV
  - Perturbative QCD can be applied.

# Fact Sheet

- $m_t$ is very closed to EWSB scale. ($v$ = 246.21 GeV)
- Yukawa coupling is close to 1. ($m_f = G_f\, v/\sqrt{2}$)
- Due to large mass of top, $\beta \leq 0.5$, little boost
  - Decay products
    - Good Angular Separation, High momenta
    - Central region of the detector with high $p_T$

# Top at Hadron Colliders

- **At Hadron Colliders:**
  - **Expected Rates:**
    - Tevatron (Run I, $\sqrt{s}$ = 1.8 TeV) $5 \times 10^{-5}$ Hz
    - Tevatron (Run II, $\sqrt{s}$ = 1.96 TeV) $7 \times 10^{-5}$ Hz
    - LHC (Low lumi., $\sqrt{s}$ = 14 TeV) 10 HZ
    - LHC will be a true top factory producing some 10 million top pairs every year.
  - At hadron colliders large QCD backgrounds.
  - Initial energy is unknown.

# Types of Particle Collider

## Electron-Positron Collider (e.g. LEP)


Electrons are elementary particles

$$E_{collision} = E_{e-} + E_{e+} = 2\ E_{beam}$$

LEP, $E_{collision} \sim 90$ GeV $= m_Z$

Can tune beam energy so that always produce a desired particle!

## Proton-Proton Collider (e.g. LHC)


$$E_{proton1} = E_{d1} + E_{u1} + E_{u2} + E_{gluons1}$$

$$E_{proton2} = E_{d2} + E_{u3} + E_{u4} + E_{gluons2}$$

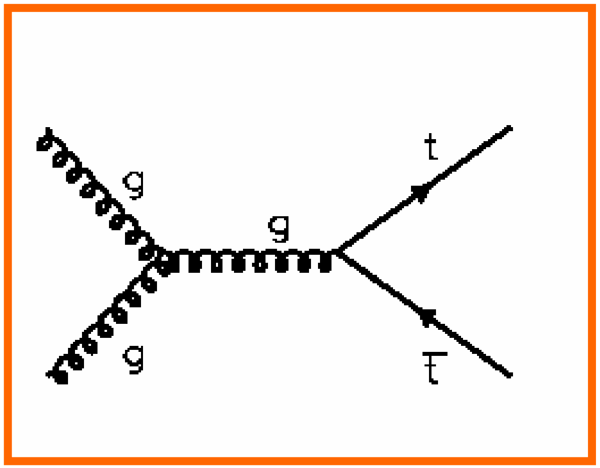
Collision could be between quarks or gluons, so

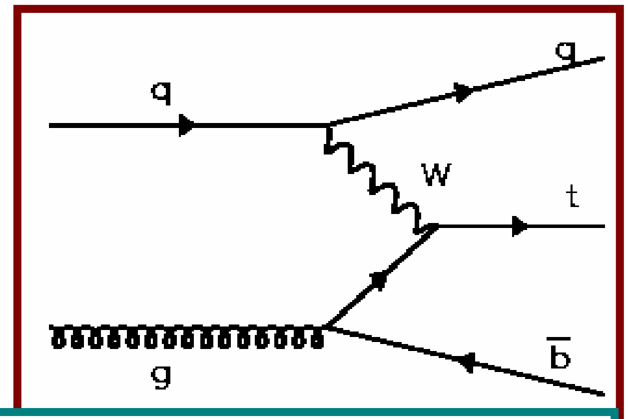
$$0 < E_{collision} < (E_{proton1} + E_{proton2})$$

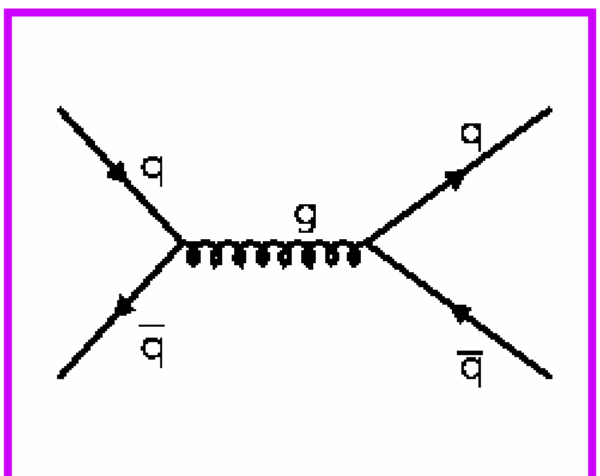
With a single beam energy "search" for particles of unknown mass!

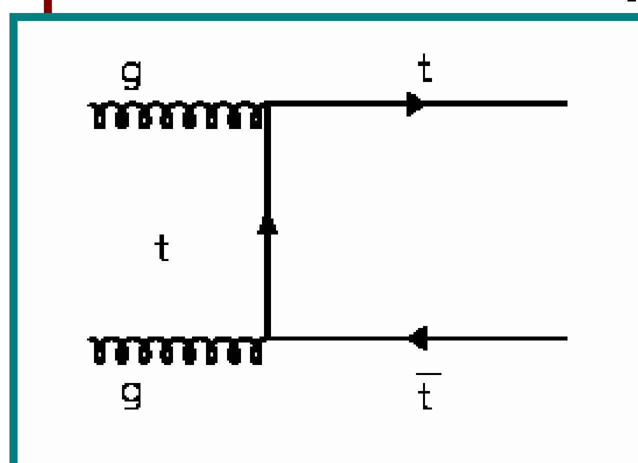
# Feynman Diagrams

- Top Pair Production:



# Feynman Diagrams

- **Contribution to top pair production:**
  - Gluon Fusion
  - qqbar annihilation
  - Relative contribution depends on CM energy.
- **At Tevatron:**
  - 90% (qqbar annihilation), 10% (gluon fusion)
- **At LHC:**
  - 13% (qqbar annihilation), 87% (gluon fusion)

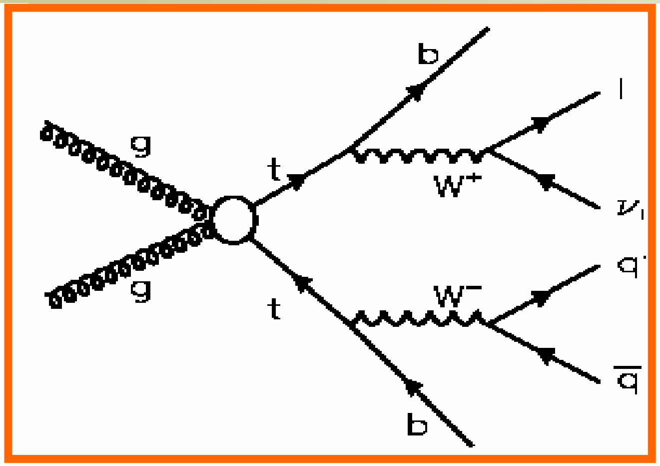
# Density Functions

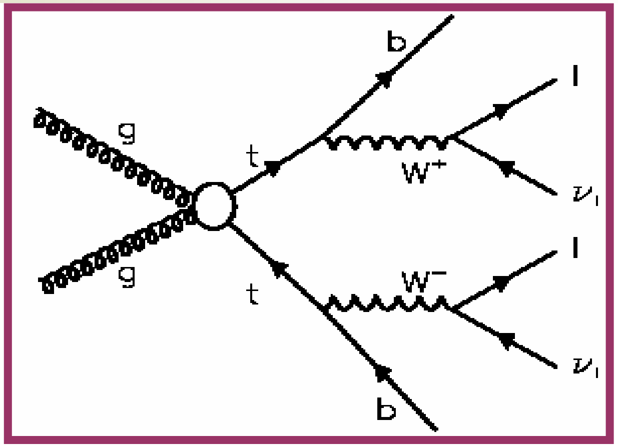
- **Simple to understand:**
  - at Tevatron
  - Threshold energy for ttbar ≈ 400 GeV
  - $\hat{s} = x_1 x_2 s$, where $x_1$ and $x_2$ is the energy of partons expressed as fraction of energy of beam protons.
  - $x = x_1 = x_2 = 0.2$ (Tevatron) $\sqrt{s} = 1.8$ TeV
  - $x = x_1 = x_2 = 0.025$ (LHC) $\sqrt{s} = 14$ TeV
  - At large values of x the quark distribution functions are larger than that of gluons and vice-versa.

# Measurements

- Properties of top which can be measured:
  - $m_t$ Mass of top (known with 3% accuracy)
  - Decay width $\Gamma_t$
  - Spin
  - Charge
  - Gauge Couplings
  - Yukawa Coupling
  - $V_{tb}$

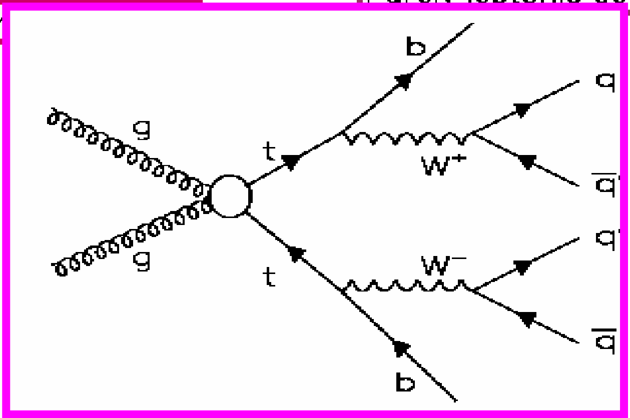
# Top Anti-Top Decay modes




Semi leptonic decay m

Purely leptonic decay mode of ttbar



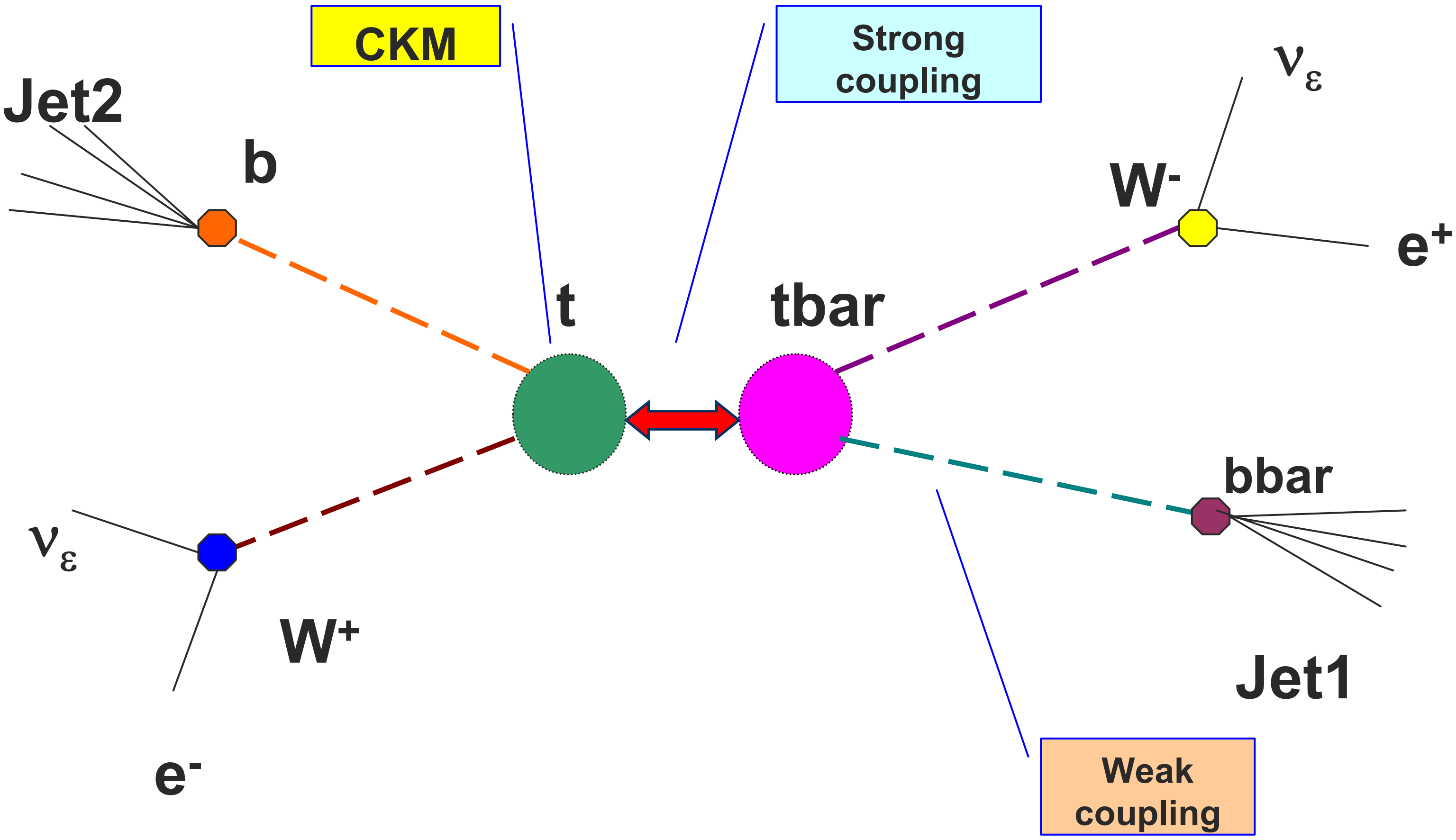

Purely hadronic decay mode of ttbar

# Decay of top quark

- Decay of top quark:
  - *Br* $(t \rightarrow bW) > 0.998$
  - *Br* $(t \rightarrow sW \text{ or } dW) \sim 10^{-13}$ (CC decays)
  - Br $(t \rightarrow cg \text{ or } c\gamma) \sim 4 \times 10^{-13}$ (NC decays)
  - $t \rightarrow bW$ is purely $V - A$ charge-current interaction.
  - In top decays W boson is real and has longitudinal helicity:

$$\Re = (m^2_t/M^2_W)/(1+m^2_t/M^2_W) = 0.701 \pm 0.016$$

# Top decay diagram



# Top Decay modes

## In Standard Model : $t \longrightarrow W^+b$

| Decay mode | Branching Ratio |
|---|---|
| $tt \to W^+W^-bb \to bbqq'qq'$ | 36/81 |
| $tt \to W^+Wbb \to bbqq'e\nu$ | 12/81 |
| $tt \to W^+Wbb \to bbqq'\mu\nu$ | 12/81 |
| $tt \to W^+Wbb \to bbqq'\tau\nu$ | 12/81 |
| $tt \to W^+Wbb \to e\nu\mu\nu bb$ | 2/81 |
| $tt \to W^+Wbb \to e\nu\tau\nu bb$ | 2/81 |
| $tt \to W^+Wbb \to \mu\nu\tau\nu bb$ | 2/81 |
| $tt \to W+Wbb \to e\nu e\nu bb$ | 1/81 |
| $tt \to W+Wbb \to \mu\nu\mu\nu bb$ | 1/81 |
| $tt \to W+Wbb \to \tau\nu\tau\nu bb$ | 1/81 |

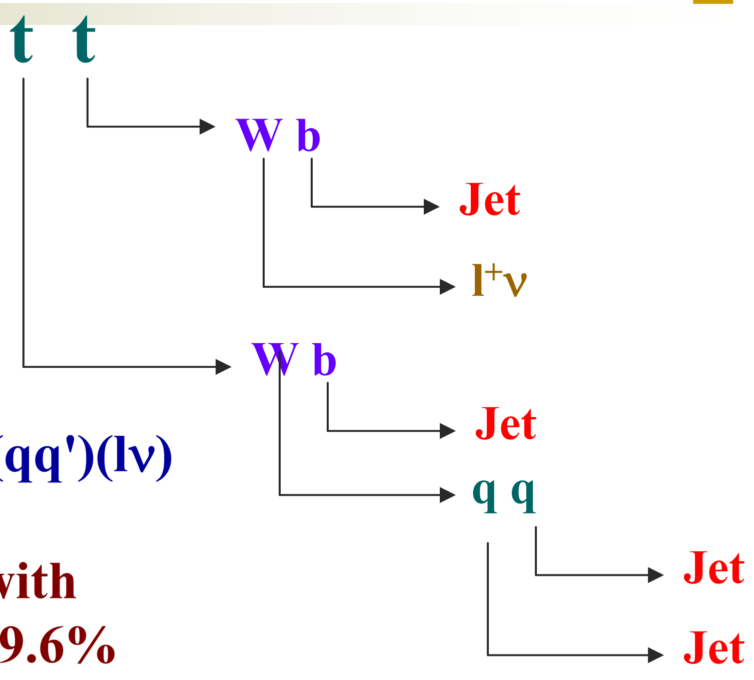
- ud, us, ub
- cd, cs, cb
- td, ts, tb
- $l\nu$ , $l = e,\mu,\tau$

$$N_{ttbar} = L \times \sigma_{ttbar}$$

# Branching ratio of W decays

| $W^+/W^-$ Decay modes | $W^+\to cs,ud$ (6/9) | $W^+\to e^-\nu_e$ (1/9) | $W^+\to \mu^-\nu_\mu$ (1/9) | $W^+\to \tau^-\nu_\tau$ (1/9) |
|---|---|---|---|---|
| $W^-\to cs,ud$ (6/9) | 36/81 | 6/81 | 6/81 | 6/81 |
| $W^-\to e^-\nu$ (1/9) | 6/81 | 1/81 | 1/81 | 1/81 |
| $W^-\to \mu^-\nu_\mu$ (1/9) | 6/81 | 1/81 | 1/81 | 1/81 |
| $W^-\to \tau^-\nu_\tau$ (1/9) | 6/81 | 1/81 | 1/81 | 1/81 |

# 1. Semi leptonic decay mode




**Main Reaction (tt→W+W-bb→bb(qq')(lν))**

- **Medium sized branching ratio with the managable background 29.6%**

1. **tt → bbqq'e$\nu_e$....... (4 jets + e +$E_{miss}$ )**
2. **tt → bbqq'$\mu\nu_\mu$....... (4 jets + $\mu$ +$E_{miss}$ )**

# Event Selection Criteria

Three methods to measure the mass of top quark

- Three jets invariant mass of the hadronic top decay
- The entire ttbar system is fully exploited to determine the top quark mass from a kinematics fit.
- Using kinematics fit, but jets are reconstructed using a continuous algorithms

# Event Selection Criteria

- **At least 1 lepton with $|\eta| < 2.4$**
- **Exactly 1 lepton with $P_t > 20$ GeV**
- **Lepton Isolation Criteria**
- **Missing $E_t > 20$ GeV**
- **At least 4 jets reconstructed with a cone size ($R_{cone} =$ 0.4)**
- **4 jets with $E_t > 40$ GeV**
- **At least two jets to be tagged as b jets**
- **Total $E_t > 450$ GeV**
- **Exactly 2 b jets with $E_t > 50$ GeV**
- **$60 < M^{rec}_W < 100$ GeV**
- **Rec. top mass difference $|m_t - m^{rec}_t| < 25$ GeV**
- **$P_t$ (jjb > 250 GeV**

# Background Processes

- **W+jets→lν+jets    Dominant Background**
  **Z+jets→$l^+l^-$+jets = 1.2x$10^3$ pb    (232/year)**
- **WW→lν+jets = 17.1 pb    (10/year)**
- **WZ→lν+jets = 3.41 pb    (8/year)**
- **ZZ→$l^+l^-$+jets = 9.21 pb    (14/year)**
- **……………………………………………………………………………**
- **Total BG events    (1922/year)**
- **At production level   S/B = $10^{-5}$**

# Systematic Uncertainties in Top Mass

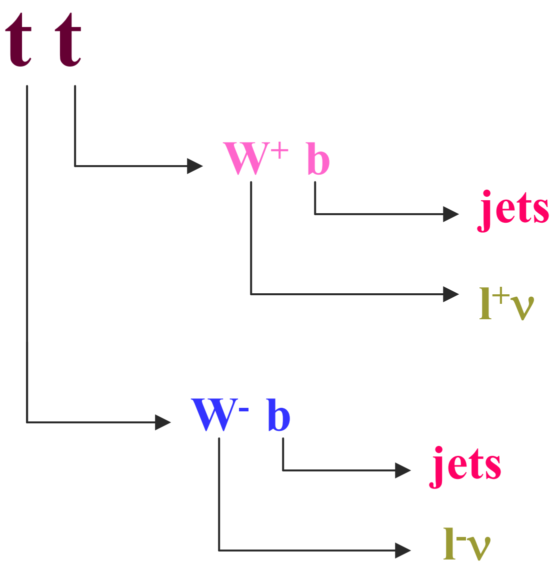
Main contributions

- Jet energy scale
- ISR and FSR
- MC generator
- Method for mass fitting
- Model for background

# 2. Purely Leptonic Decays

- **Main Reaction (tt--->$W^+W^-$bb--->bb(lν)(lν)**
- **pp--->tt--->bbe$\nu_e$e$\nu_e$.......(4jets+2e+$E_{miss}$ )**
- **Branching Ratio = 1/81 =1.23 %**
  **(100,000/year)**
- **pp--->tt--->bbμ$\nu_\mu$e$\nu_e$.......(4jets+2e+$E_{miss}$ )**
- **Branching Ratio = 2/81 = 2.46 %**
  **(200000/year)**
- **pp--->tt--->bbμ$\nu_\mu$μ$\nu_\mu$.......(4jets+2μ+$E_{miss}$ )**
- **Branching Ratio = 1/81 = 1.23 %**
  **(100,000/year)**
- **..........................................................................................................**
- **Total BR for Leptonic Decay = 4.9 %**
  **(400,000/year)**

# Detection of leptons and signatures




- Two opposite sign leptons with |h| < 2.5
- $P_t(l_1) > 35$ GeV
- $P_t(l_2) > 25$ GeV
- $E_{miss} > 40$ GeV
- $|M_{ll}-M_Z| > 10$ GeV
- $M^2_W = (l_1 + \nu_1)^2$ , $M^2_W = (l_2 + \nu_2)^2$
- $M^2_{top} = (l_1 + b_1 + \nu_1)^2$ , $M^2_{top} = (l_2 + b_2 + \nu_2)^2$
- Two b-jets with $P_t > 25$ GeV (S/B = 10) , $|\eta| < 2.4$, $\Delta R_{cons} = 0.4$
- For two neutrinos "neutrino weighting" technique is used
- Neutrino rapidities, top mass, charged lepton and b-quark momenta, system can be solved for transverse and longitudinal momentum components of neutrino
- After event selection 80000 signal events are left

# b-tagging

- **How to distinguish a b jet from a lighter quark jet:**
- **– can contain low-$p_\perp$ leptons from $b \to c\ l\ \nu$**
- **(BR=10% per lepton)**
- **B hadrons have lifetimes long enough so that**
- **they can travel several mm before decaying**
- **$\Rightarrow$ b-jet particles come from a displaced vertex**

# Background Processes

- **Dilepton decays have low statistics**
- **bbbar→lν+jets**
- **WW+jets→(2l)(2ν)+jets**
- **Background is small mainly dominated by Z decays to leptons**
- **Leptons misidentification increases**
- **Drell-Yan processes associated with jets**
- **$Z\rightarrow t^{+}t^{-}$ (associated with jets)**
- **WW + jets**
- Backgrounds easier to eliminate than in all-hadronic mode because of lepton tag.
- Most promising decay mode for search

# 3. Purly Hadronic Decays

Main Reaction (tt→$W^+W^-$bb→bb(jj)(jj)) (370 pb)

- pp→tt→bbudud............(2 bjets+4 quark jets)
- Branching Ratio = 9/81 (911,000/year)
- pp→tt→bbusus.............(2 bjets+4 quark jets)
- Branching Ratio = 9/81 (911,000/year)
- pp→tt→bbubub...........(2 bjets+4 quark jets)
- Branching Ratio = 9/81 (911,000/year)
- pp→tt→bbcdcd............(2 bjets+4 quark jets)
- Branching Ratio = 9/81 (911,000/year)
- pp→tt→bbcscs.............(2 bjets+4 quark jets)
- Branching Ratio = 9/81 (911,000/year)
- pp→tt→bbcbcb...........(2 bjets+4 quark jets)
- Branching Ratio =9/81 (911,000/year)
- ........................................................................................................................
- Total BR of purely Hadronic decays = 9/81*6 = 66 %

(5.41M/year)

# Event Selection Criteria

- **Multi jet trigger threshold ~ 4 jets**
- **Events are selected by requiring at least six or more jets with $P_t$ = 40 GeV, and at least two of them are tagged as b-jets**
- **Jets are required to satisfy $|\eta| < 3$ ($|\eta| < 2.5$ for b-jet candidates)**
- **Jets are reconstructed using a fixed cone algorithm with $\Delta R = 0.4$**
- **Sum of the transverse momenta of the jets is required to be greater than 200 GeV**
- **At least one b-tagging is required using secondary vertices**
- **Tagging required efficiency 60% with at least 100 rejection against prompt jets**
- **ttbar signal efficiency for these cuts should be 19.3 %**
- **Only 0.29 % of QCD multi-jets events should be survived**
- **For QCD multi-jet cross-section of $1.4 * 10^{-3}$ mb and $P_t > 100$ GeV, S/B ~ 1/57**

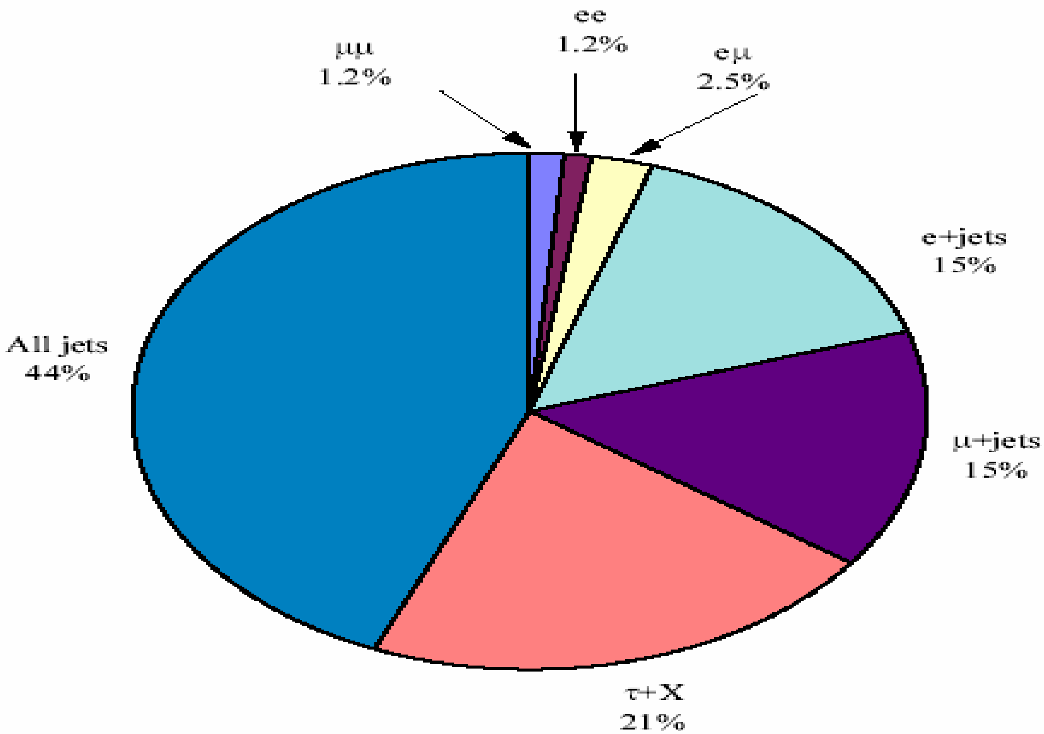
# Background Processes

- ($q_i q_j$ ---> $q_i q_j$, $q_i g$ ---> $q_i g$, gg ---> gg, qqbar---> gg, gg ---> qqbar,
- $q_i q_i$bar---> $q_j q_j$bar)
- $\sigma(pp \rightarrow 6 \text{ jets}) \approx 10^3 \, \sigma(pp \rightarrow t\,t \rightarrow b\,b + 4 \text{ light-quark jets})$
- **Difficult to distinguish between light jets and b jets**
- **Kinematics cut technique**
- **High statistics required**
- **Least interesting decay mode**
- **Large QCD multi-jet events**

# Comments

- **All jets in the final state create difficulty in triggering.**
- **QCD background is generated with a pt cut on the hard scattering process above 100 GeV, resulting cross-section 1.73 mb.**
- **The requirement of having at lest two b-tagged jets in the final stat helps in rejecting a large part of the physical background, but also reduces considerable the signal sample. The fraction of signal events with at least two b-tagged jets is three times smaller than the fraction with at least one b-tagged jet. Requiring only one b-tagged jet would decrease the S/B ratio from 78 to 28, which would be still acceptable.**

# Overview of Branching ratios



# Theoretical uncertainties in Top Mass

- **Renormalization scale < 10 MeV**

  **(30-150 GeV)**
- **Strong coupling constant < 75 MeV**
- **MS bar ~ ± 12 MeV**

**Which implies that at LHC accuracy in top mass will be of the order of 1 GeV**

# Spin Correlation in ttbar production

- **Top decay width = $\Gamma_t$ = 1.4 GeV**
- **QCD Hadronization scale = $\Lambda_{qcd}$ = 0.22 GeV.**
- **Time scale for depolarization of top spin**

  **$= m_t / \Lambda^2_{qcd} >> 1/\Gamma_t \sim 10^{-24}$ s**
- **Spin correlation in decay products of tt systems is interesting for several reasons.**
- **It provides probe of a quark that is at least free of confinement of effects.**
- **Since life time of top quark is proportional to CKM matrix element $|V_{tb}|^2$ , so observation of spin correlation would yield, information about lower limit of $|V_{tb}|$ with out assuming that there are three generation of quarks.**
- **Charged leptons +weak isospin quarks are sensitive to the initial polarization**
- **$1/\sigma * d^2\sigma/d(\cos\Theta_+)d(\cos\Theta_-) = [1+\kappa\cos\Theta_+ + \cos\Theta_-]/4$**