Physics of Top Quark at LHC

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Standard Model of Particle Physics

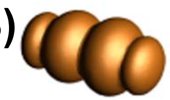
Leptons

Electric Charge

Tau	-1	0	Tau Neutrino
Muon	-1	0	Muon Neutrino
Electron	-1	0	Electron Neutrino

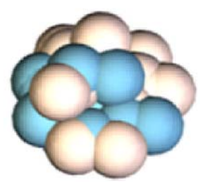
Strong

Gluons (8)



Quarks

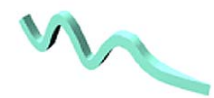
Mesons
Baryons



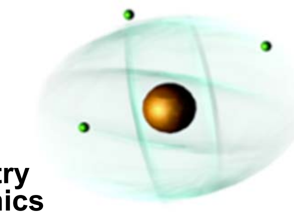
Nuclei

Electromagnetic

Photon



Atoms
Light
Chemistry
Electronics



Quarks

Electric Charge

Bottom	-1/3	2/3	Top
Strange	-1/3	2/3	Charm
Down	-1/3	2/3	Up

each quark: R, B, G 3 colours

Gravitational

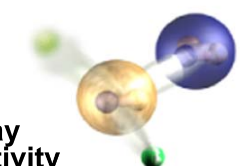
Graviton ?

Solar system
Galaxies
Black holes

Weak

Bosons
(W,Z)

Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun



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

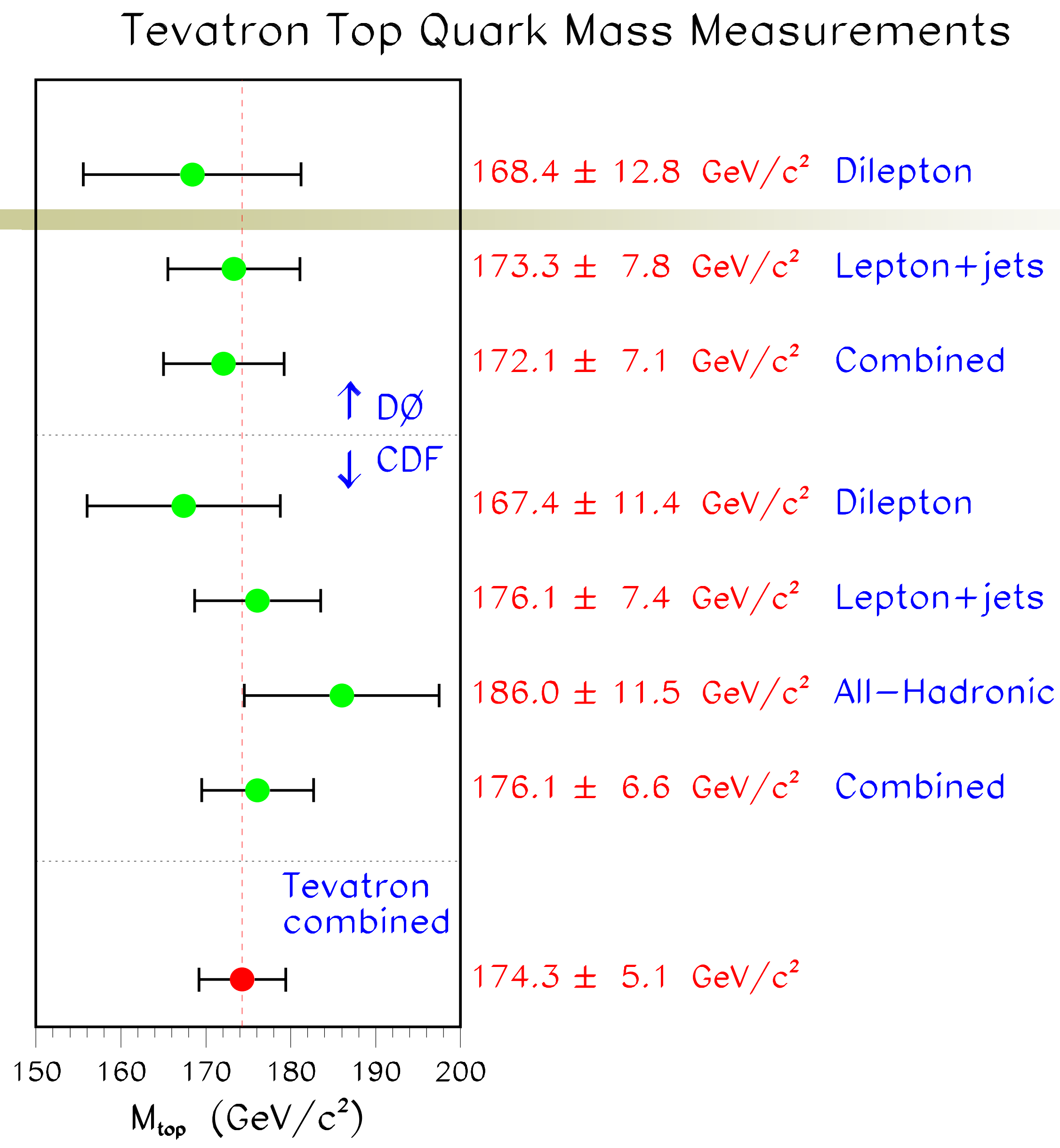
- Consistency of b quark measurements with the SM.
- Consistency of precision measurements.

- 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
168.4 ± 12.8 GeV/c² Dilepton
173.3 ± 7.8 GeV/c² Lepton+jets
172.1 ± 7.1 GeV/c² Combined
↑ DØ
↓ CDF
167.4 ± 11.4 GeV/c² Dilepton
176.1 ± 7.4 GeV/c² Lepton+jets
186.0 ± 11.5 GeV/c² All−Hadronic
176.1 ± 6.6 GeV/c² Combined
Tevatron combined
174.3 ± 5.1 GeV/c²
150 160 170 180 190 200
M_top (GeV/c²)

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, √s = 1.8 TeV) 5 x 10^{-5} Hz
    - Tevatron (Run II, √s = 1.96 TeV) 7 x 10^{-5} Hz
    - LHC (Low lumi., √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

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

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

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

Proton-Proton Collider (e.g. LHC)

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

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

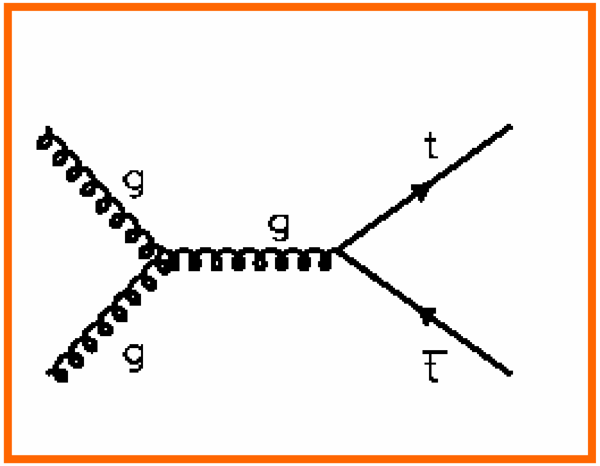
Collision could be between quarks or gluons, so

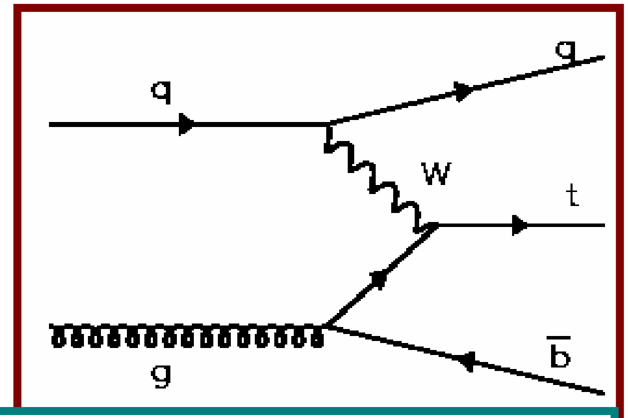
$$0 < E_{collision} < (E_{proton1} + E_{proton2})$$

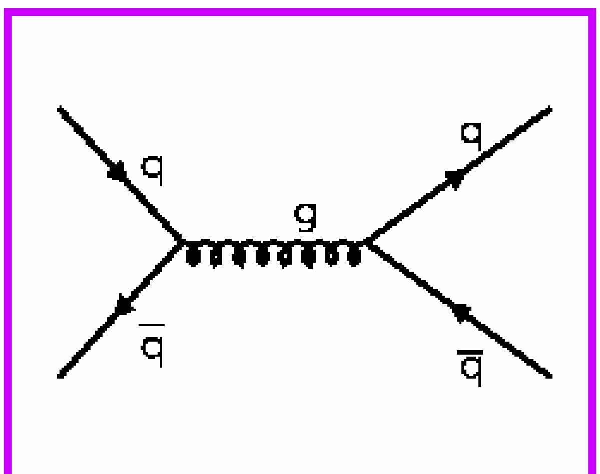
With a single beam energy "search" for particles of unknown mass!

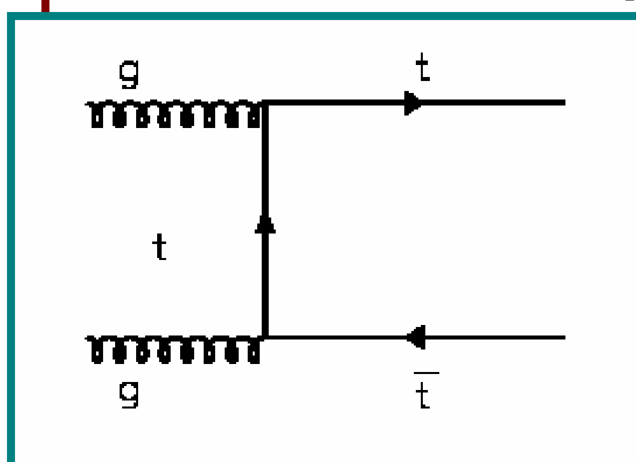
Feynman Diagrams

- 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)

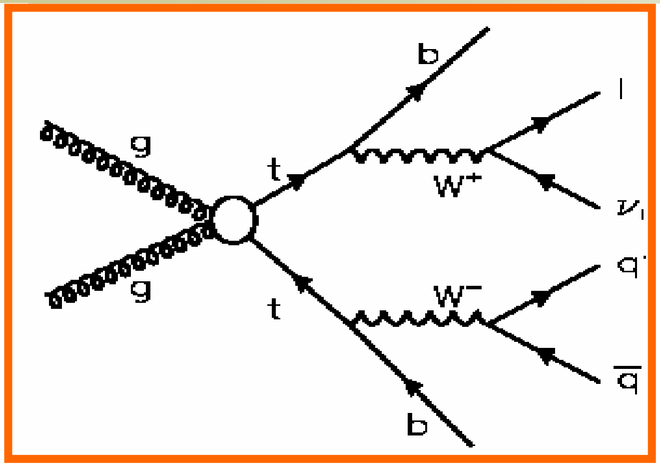
Density Functions

- **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.

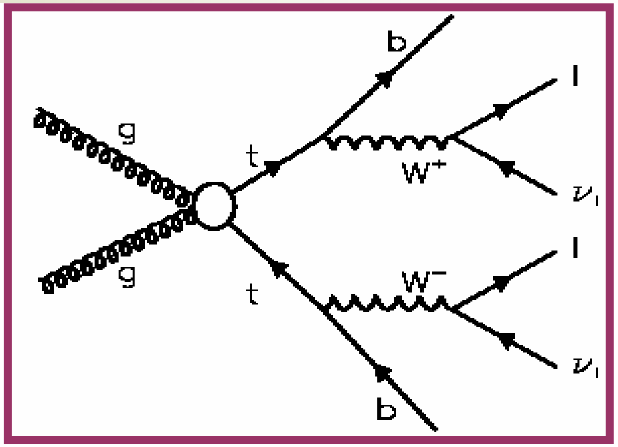
Measurements

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

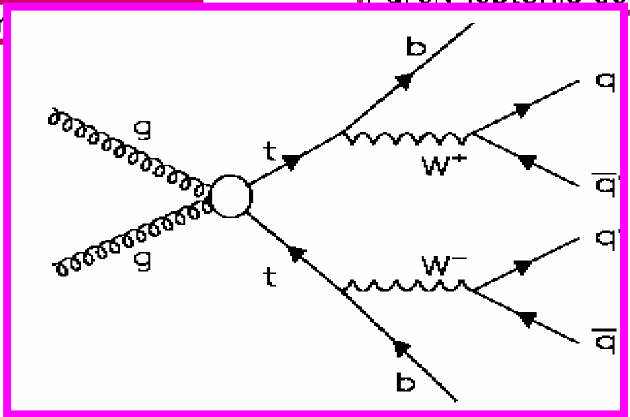
Top Anti-Top Decay modes



Semi leptonic decay m



Purely leptonic decay mode of ttbar



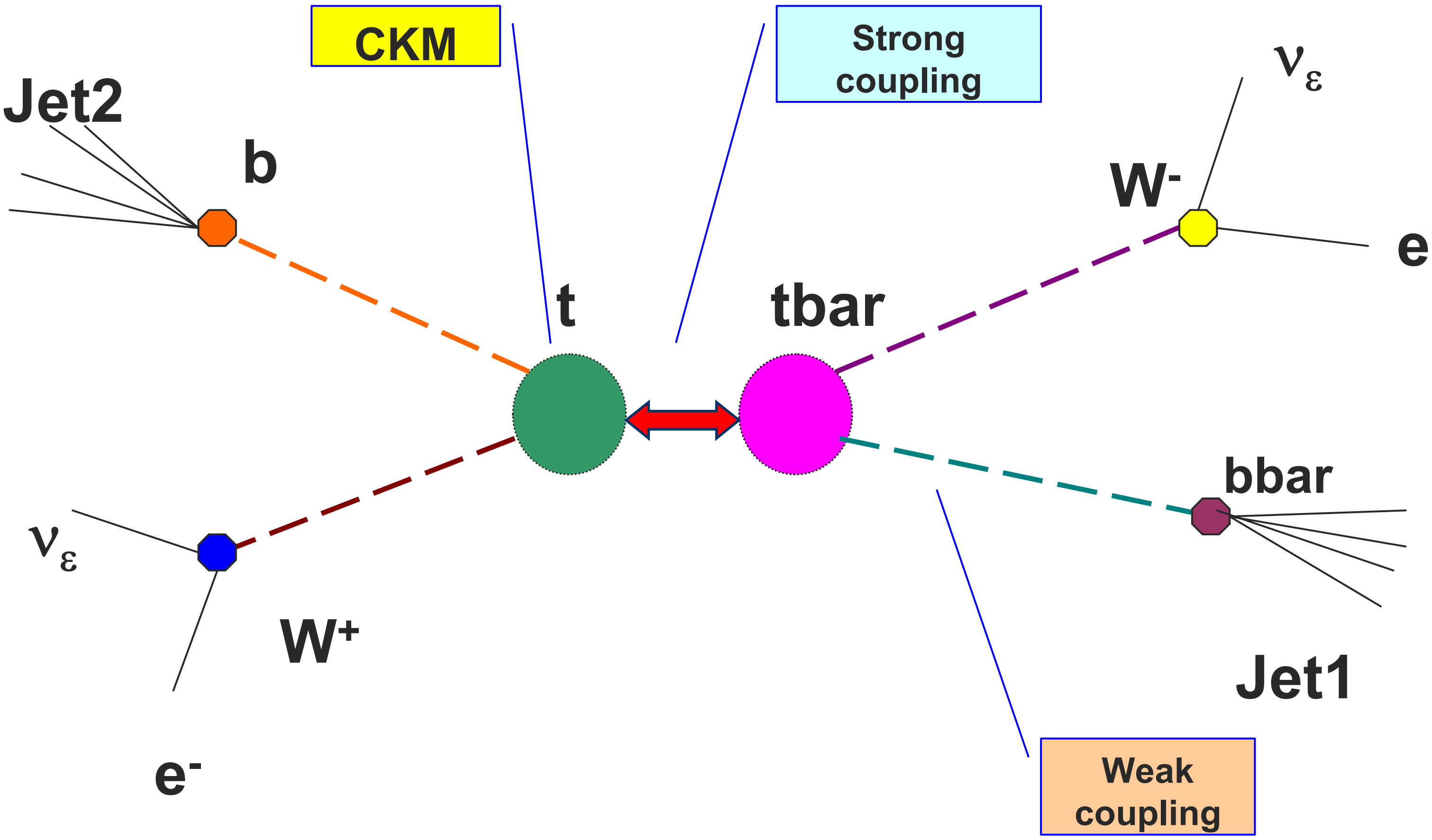
Purely hadronic decay mode of ttbar

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 : $t \rightarrow W^+b$

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

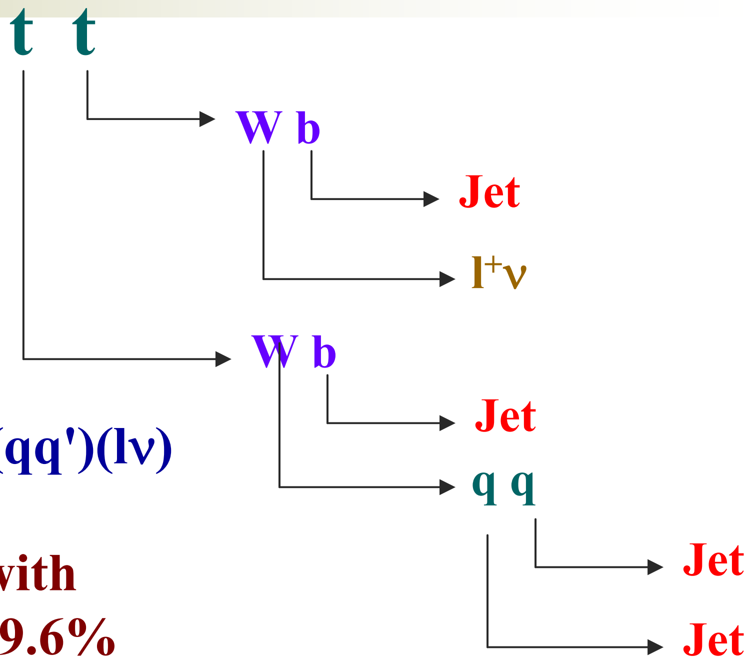
- ud, us, ub
- cd, cs, cb
- td, ts, tb
- $l\nu$, $l = e,\mu,\tau$

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

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'eν_e....... (4 jets + e +E_{miss})**
2. **tt → bbqq'$\mu\nu_\mu$....... (4 jets + μ +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 = 1.2×10^3 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

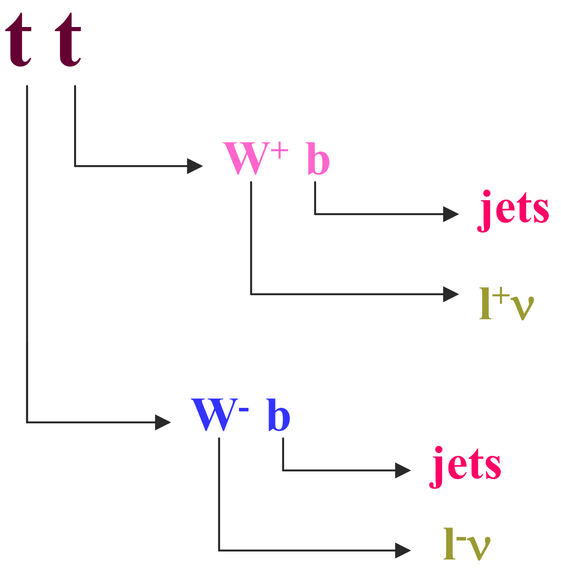
Main contributions

- 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--->bbeν_eeν_e.......(4jets+2e+E_{miss})**
- **Branching Ratio = 1/81 =1.23 %**
  (100,000/year)
- **pp--->tt--->bbμν_μeν_e.......(4jets+2e+E_{miss})**
- **Branching Ratio = 2/81 = 2.46 %**
  (200000/year)
- **pp--->tt--->bbμν_μμν_μ.......(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 $b \rightarrow c\ l\ \nu$**
- **(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→ 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**

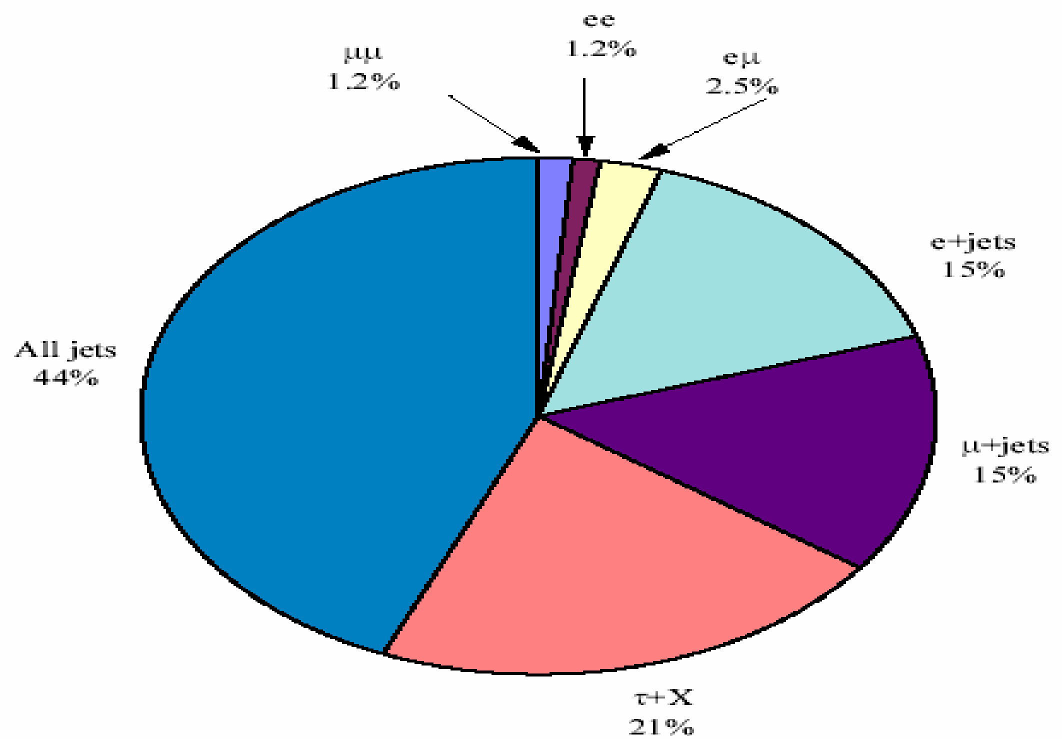
Background Processes

- $(q_i q_j \text{ ---> } q_i q_j,\ q_i g \text{ ---> } q_i g,\ gg \text{ ---> } gg,\ q\bar{q}\text{---> } gg,\ gg$ $\text{---> } q\bar{q},$
- $q_i q_i\text{bar---> } q_j q_j\text{bar})$
- $\sigma(pp \rightarrow 6 \text{ jets}) \approx 10^3\ \sigma(pp \rightarrow t\ t \rightarrow b\ b + 4 \text{ light-quark jets})$
- 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 = Γ_t = 1.4 GeV**
- **QCD Hadronization scale = Λ_{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**
- **$1/\sigma * d^2\sigma/d(\cos\Theta_+)d(\cos\Theta\_) = [1+\kappa\cos\Theta_+ + \cos\Theta\_]/4$**