Top Quark Charge Determination

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Motivation:

CDF and D0 analyses + precision EW data do not exclude:

top quark seen in Fermilab is an exotic quark with Q_{top}=-4/3.

(D. Chang et al., Phys. Rev. D59, 091503)

How to determine the top charge?

- via radiative tt_bar events (sensitive to Q_{top})
- by measuring the charges of top decay products

  $\Rightarrow$ weighting b-jet tracks charges

  $\Rightarrow$ semileptonic b-decay

Top charge via photon radiation in $t\bar{t}$ events

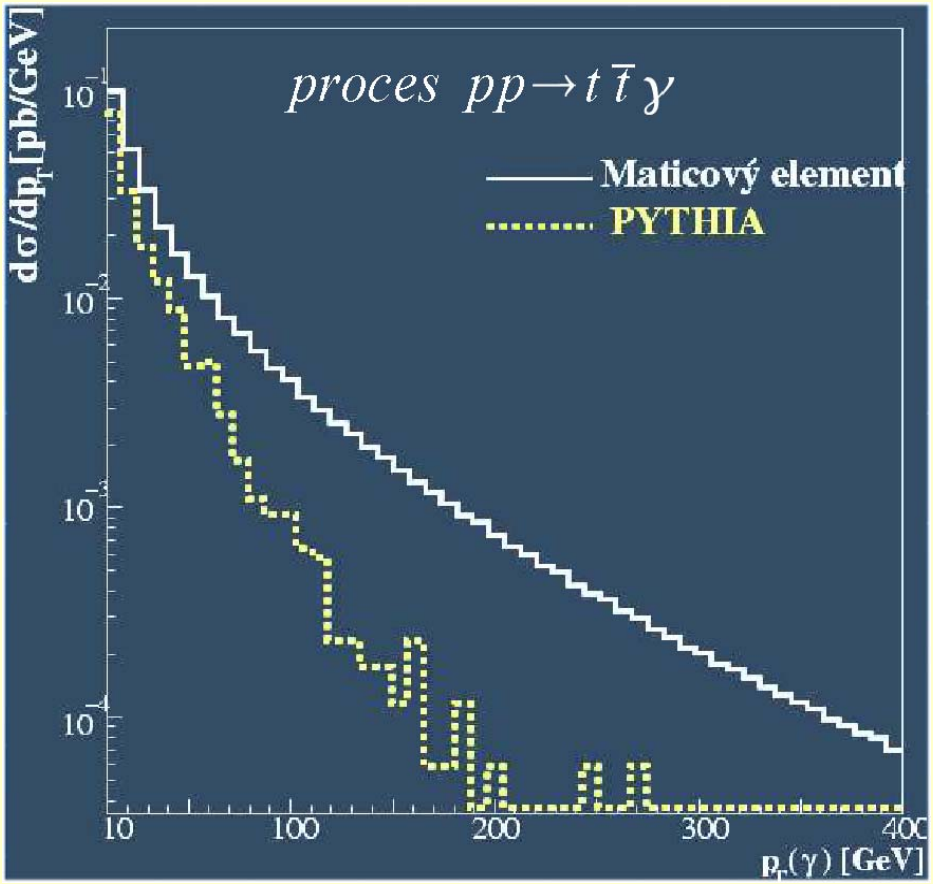
Signal Processes

- Radiative $t\bar{t}$ production $pp \to t\bar{t}\gamma$ (matrix el., PYTHIA)
- Radiative top decay $t\bar{t}, t \to Wb\gamma$ (matrix el., PYTHIA)

Background processes (non sensitive to Q_{top})

- Radiative W decay in $t\bar{t}, W \to jj\gamma\left(l\nu_l\gamma\right)$ (matrix el., PYTHIA)
- Other $t\bar{t}$ processes leading to high p_T photon (PYTHIA)
- Non $t\bar{t}$ radiative bkgd (W,Z+jets+γ) (matrix el., PYTHIA)

Why matrix elements?



Pythia vs matrix elements

$p_T(\gamma) > 10$ GeV, $|\eta|<3.5$

$t\bar{t}\gamma$ → σ_{PY} =0.66 pb

σ_{ME} = 2.33 pb

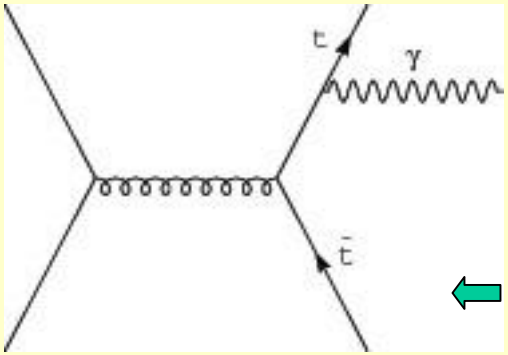
$Wb\gamma$ → σ_{PY} =0.66 pb

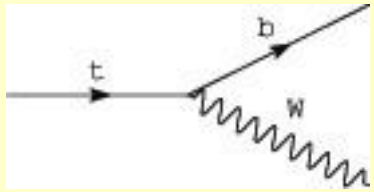
σ_{ME} = 2.33 pb

→ Using ISR, FSR for m_t systematics is questionable !

Soft photon (gluon) approximation used in Pythia is insufficient

Radiative Top Production



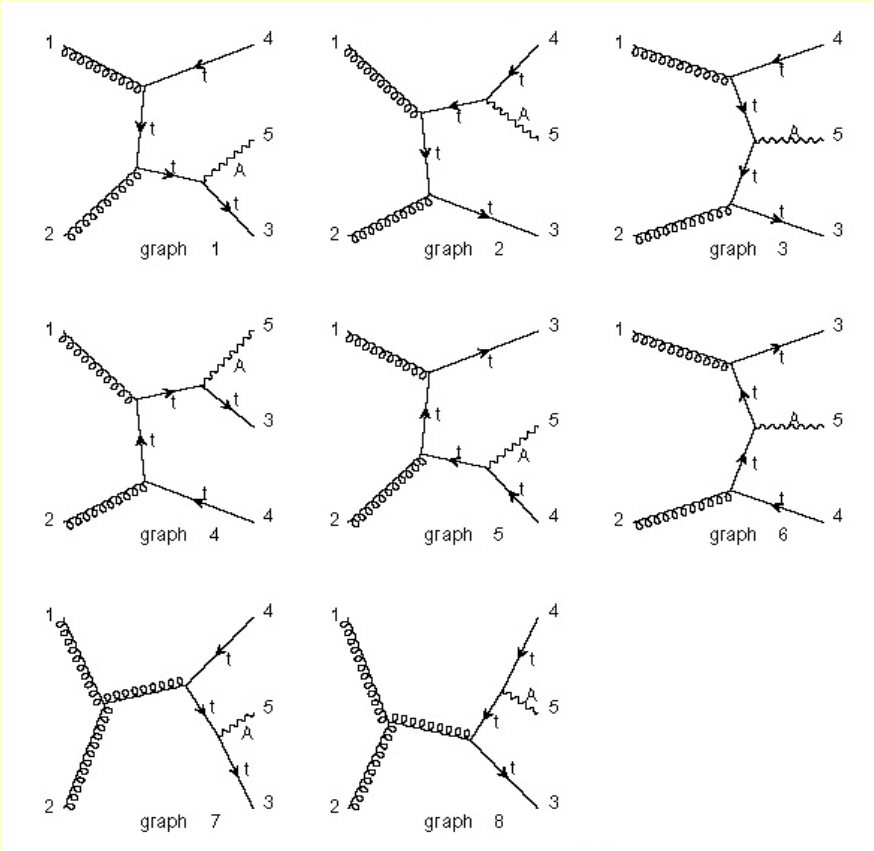


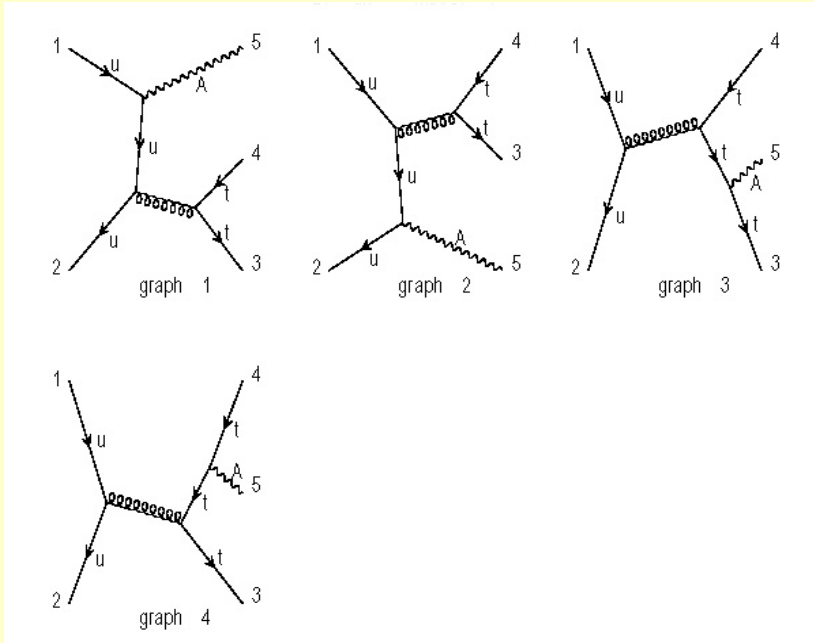
Radiative top production followed by top decay

- Production phase: matrix elements implemented into PYTHIA
- In initial state : gg and/or $q\bar{q}$
- $t\bar{t}\gamma$ production cross section $\sigma \sim Q^2_{top}$
- Important: virtuality of radiating top is required
- Decay of top : $t \rightarrow Wb \rightarrow b l\nu(jj)$

Top and W decay treated in narrow width approximation

Radiative top production diagrams





+ diagrams with d, s, c and b

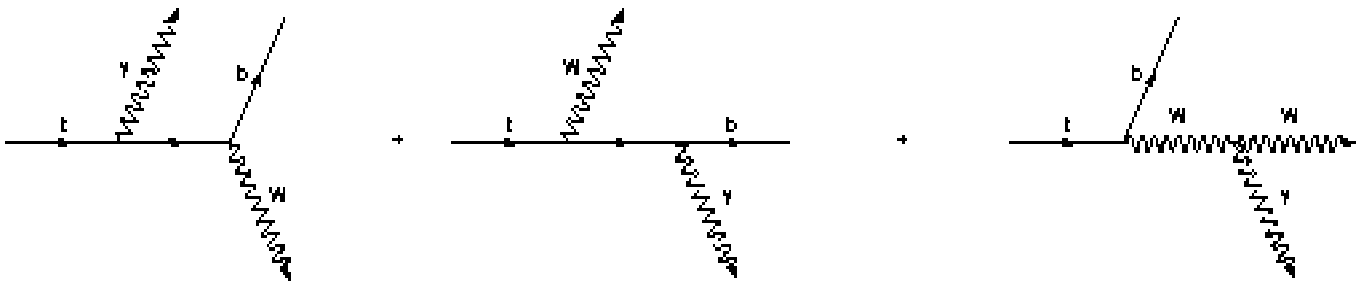
$t\bar{t}\gamma$ production by gluon fusion

LHC:90%, Tevatron:15%

$t\bar{t}\gamma$ production by quark annihilation

LHC:10%, Tevatron:85%

Radiative top decay



Radiative top decay: $pp \to t\bar{t}$ (production), $t \to Wb\gamma$ ...

- Decaying top quark is on-mass-shell
- Photons from W and b do not feel the top charge
- Destructive interference of the diagrams is expected: $\sigma(-4/3) < \sigma(2/3)$

Selection criteria

Selected sample: $t\bar{t} \to l\nu\, jjb\bar{b}\,\gamma$ (radiative lepton + jets ev.)

general top quark cuts (C1)

njets ≤ 4, $p_T > 20$ GeV, $\eta < 2.5$

nbjets = 2, $p_T > 20$ GeV, $\eta < 2.0$

nlept = 1, $p_T > 20$ GeV, $\eta < 2.5$

nphot = 1, $p_T > 30$ GeV, $\eta < 2.5$

missing $p_T > 20$ GeV

W reconstruction criteria

$|m(jj)-M_W| < 20$ GeV

$m(jj)=\min\{|m(j_i,j_k)-M_W|\}$

$m_T(l; \not{p}_T) < M_W + 20$ GeV

Radiative top production cuts

$m(b_{1,2}jj\,\gamma) > 190$ GeV

&

$m_T(b_{2,1}\, l\gamma; \not{p}_T) > 190$ GeV

$$m_T(bl\gamma; \not{p}_T) = \left(\sqrt{p_T^2(bl\gamma) + m^2(bl\gamma)} + \not{p}_T\right)^2 - \left(\vec{p}_T(bl\gamma) + \vec{\not{p}}\right)^2$$

Radiative top production

SM top radiative production

$t\bar{t}\gamma$ statistics

Sample: 10 fb^{-1}

(1 LHC L.L. year)

$Q = 2/3$	$\sigma[pb]$ $p_T > 10\,GeV\ \|y\| < 3.5$	ϵ [%] ATLFAST	events $(10\ fb^{-1})$
$pp \to t\bar{t}\gamma$	2.31	0.338	$78. \pm 8.8$
$pp \to t\bar{t};\ t \to Wb\gamma$	2.96	0.021	6.2 ± 2.5
$pp \to t\bar{t};\ W \to l\nu(jj)\gamma$	8.25	0.013	10.7 ± 3.4
$pp \to t\bar{t};\ (\pi^\circ, \eta, ..)_{pythia}$	550	$3.8 \cdot 10^{-4}$	20.7 ± 4.5
$pp \to W\gamma\ jets$	812	$4.3 \cdot 10^{-4}$	35.0 ± 6.0
total background			73 ± 8.6

Exotic q radiative production

$t\bar{t}\gamma$ statistics

$Q = -4/3$	$\sigma[pb]$ $p_T > 10\,GeV\ \|y\| < 3.5$	ϵ [%] ATLFAST	events $(10\ fb^{-1})$
$pp \to t\bar{t}\gamma$	7.34	0.338	248 ± 16
$pp \to t\bar{t};\ t \to Wb\gamma$	1.16	0.021	2.4 ± 1.5
$pp \to t\bar{t};\ W \to l\nu(jj)\gamma$	8.25	0.013	10.7 ± 3.4
$pp \to t\bar{t};\ (\pi^\circ, \eta, ..)_{pythia}$	550	$3.8 \cdot 10^{-4}$	20.7 ± 4.5
$pp \to W\gamma\ jets$	812	$4.3 \cdot 10^{-4}$	35.0 ± 6.0
total background			69 ± 8.4

30% uncertainty from scale $(m_t/2, 2m_t)$

→ CDF possibilities to measure photon-top coupling: None !

Top charge via top decay products

Suitable event samples:

- Dilepton sample $t\bar{t} \to (l\nu)(l\nu)b\bar{b}$ (400 kEvnt/10fb^{-1})
- Lepton +jets sample $t\bar{t} \to (l\nu)(jj)b\bar{b}$ (2500 kEvnt/10fb^{-1})
- All jets mode not suitable $\Rightarrow$ huge QCD bkgd

Cornerstone of the top charge determination:

- association of l^+ and/or l^- with correct b-jets
- determine the charge of the associated b-jet
- in SM the mean value of b-jet charge spectrum associated with l^+ (l^-) should be negative (positive)

b-jet charge determination

$$Q_{b-jet} = \frac{\sum_i^N q_i \left|\vec{j}\cdot\vec{p}_i\right|^\kappa}{\sum_i^N \left|\vec{j}\cdot\vec{p}_i\right|^\kappa}$$

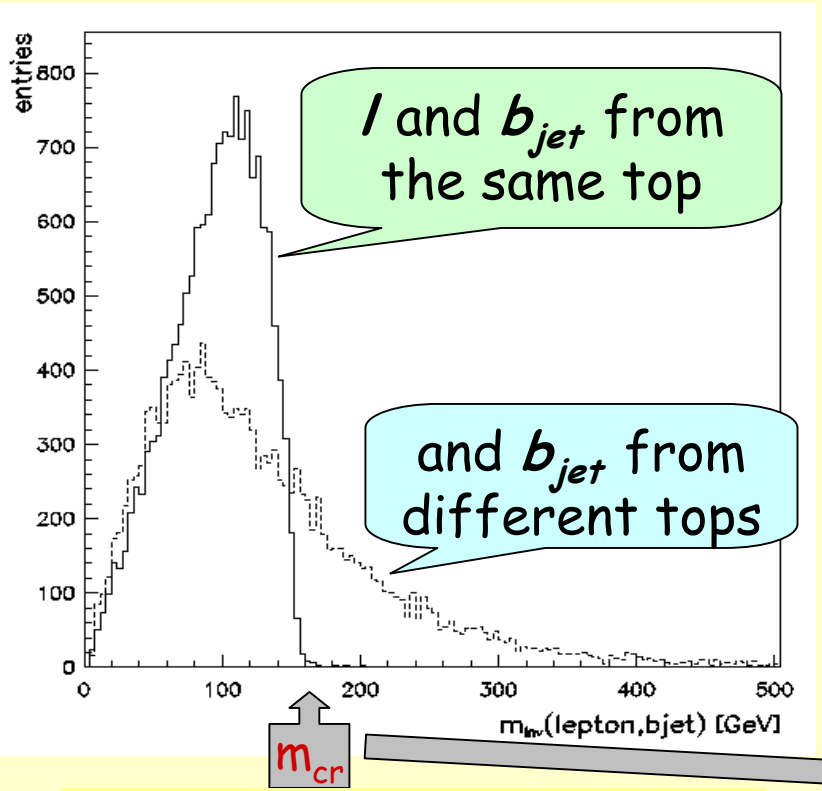
$q_i \equiv$ ith part. Charge
$\vec{p}_i \equiv$ ith part. momentum
$\vec{j}$ $\equiv$b-jet direction
κ $\equiv$ an exponent

Selection criteria

Di-lepton	Lepton + jets
2 isol. high p_T leptons (e, μ) $p_T^{(1)} < 35\,GeV$ and $p_T^{(2)} < 25\,GeV$	1 isol. high p_T leptons (e, μ)
$\not{E}_T > 40\,GeV$	$\not{E}_T > 20\,GeV$
At least 2 jets, p_T > 25 GeV 1 or 2 b-tagged, $\|\eta\|$< 2.5	At least 2 b-jets, p_T > 40 GeV
	In total 4 jets p_T > 40 GeV, $\|\eta\|$< 2.5
S/B ≈ 10 (Yellow Rep. 2000)	S/B ≈ 65 (P. Grenier, phys-note)

ATLAS experiment cuts

Association of lepton and b-jet



lepton-b_{jet} invariant mass

Di-lepton case

$$m\left(l^{+}, b_{jet}^{(1,2)}\right) < m_{cr} \quad \& \quad m\left(l^{+}, b_{jet}^{(2,1)}\right) > m_{cr}$$

$$m\left(l^{-}, b_{jet}^{(1,2)}\right) < m_{cr} \quad \& \quad m\left(l^{-}, b_{jet}^{(2,1)}\right) > m_{cr}$$

Lepton+jets case

$$m\left(l, b_{jet}^{(1,2)}\right) < m_{cr} \quad \& \quad m\left(l, b_{jet}^{(2,1)}\right) > m_{cr}$$

120 GeV < m(jjb) < 220 GeV

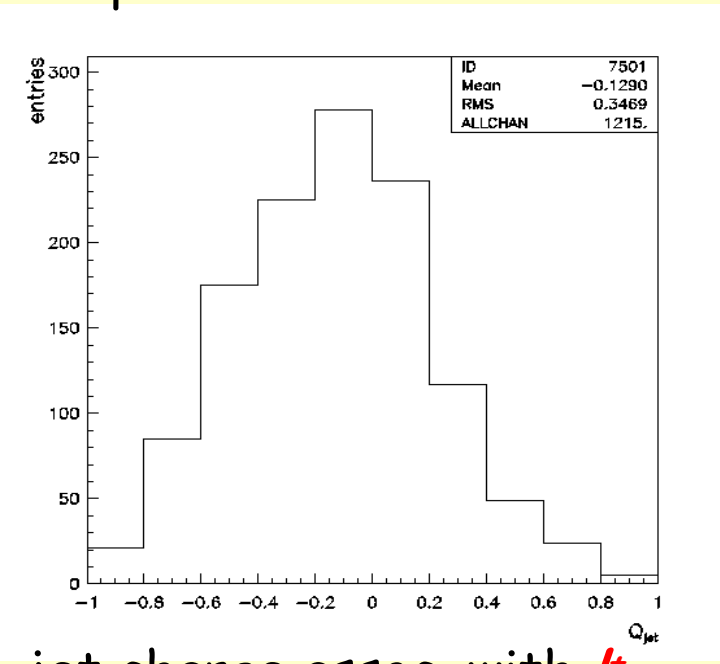
$m_{cr} \approx 160$ GeV

ATLAS: Particle generation $\Rightarrow$ PYTHIA

detector resolutions and efficiencies $\Rightarrow$ ATLFAST

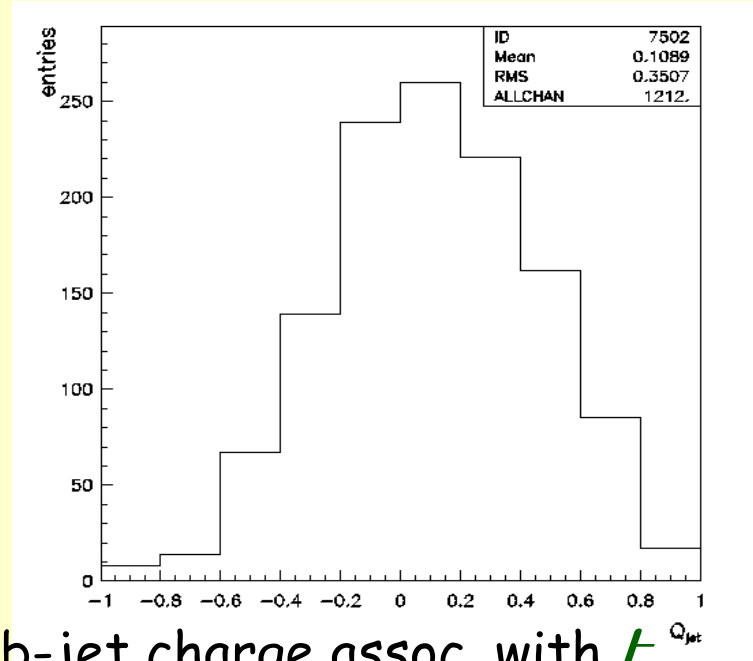
Reconstructed *b*-jet charge

Sample: 0.87fb^{-1} $\Rightarrow \approx$ 160 kEvn's (lepton+jets), $\approx$ 22 kEvn's (dilepton)



b-jet charge assoc. with l^+

$$\bar{Q}^{(l+)}_{b-jet} = -0.109 \pm 0.007$$



b-jet charge assoc. with l^-

$$\bar{Q}^{(l-)}_{b-jet} = 0.112 \pm 0.007$$

Independent fragmentation in PYTHIA (R_{cone} = 0.4)

$$\bar{Q}^{(l+)}_{b-jet} = -0.113 \pm 0.007 \qquad \bar{Q}^{(l-)}_{b-jet} = 0.117 \pm 0.008$$

For 5σ separation we need 63 inputs for each distribution

Top charge in CDF

✓ ~~radiative tt_bar events (sensitive to Q_{top})~~

✓ measuring the charges of top decay products

⇒ weighting b-jet tracks charges $Q_{b-jet} = \frac{\sum_i^N q_i \left|\vec{j}\cdot\vec{p}_i\right|^\kappa}{\sum_i^N \left|\vec{j}\cdot\vec{p}_i\right|^\kappa}$

Problems: association of W boson and b-jet (invariant mass criterion needs high statistics)

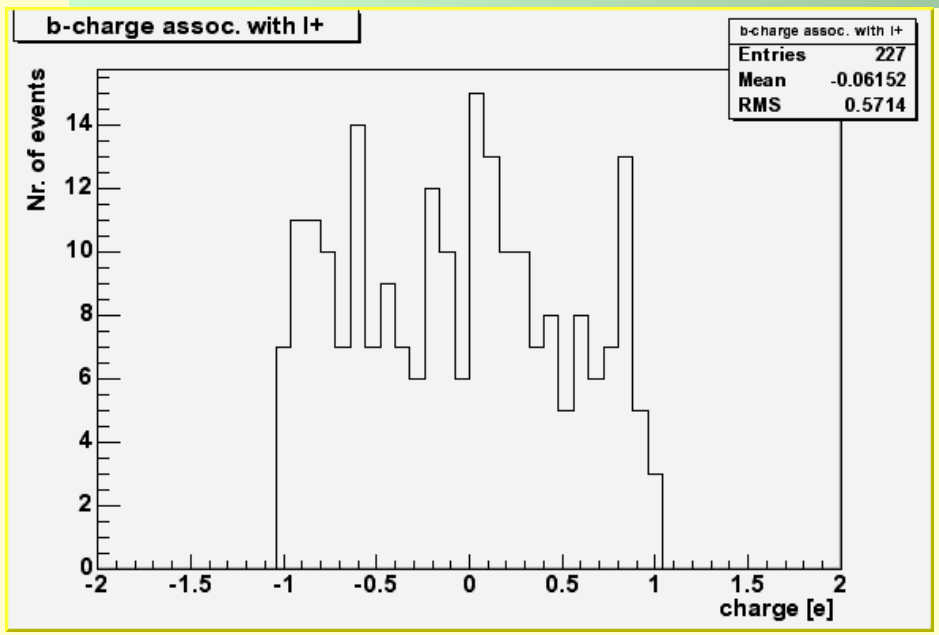
⇒ semileptonic b-decay: b →c,u +lν

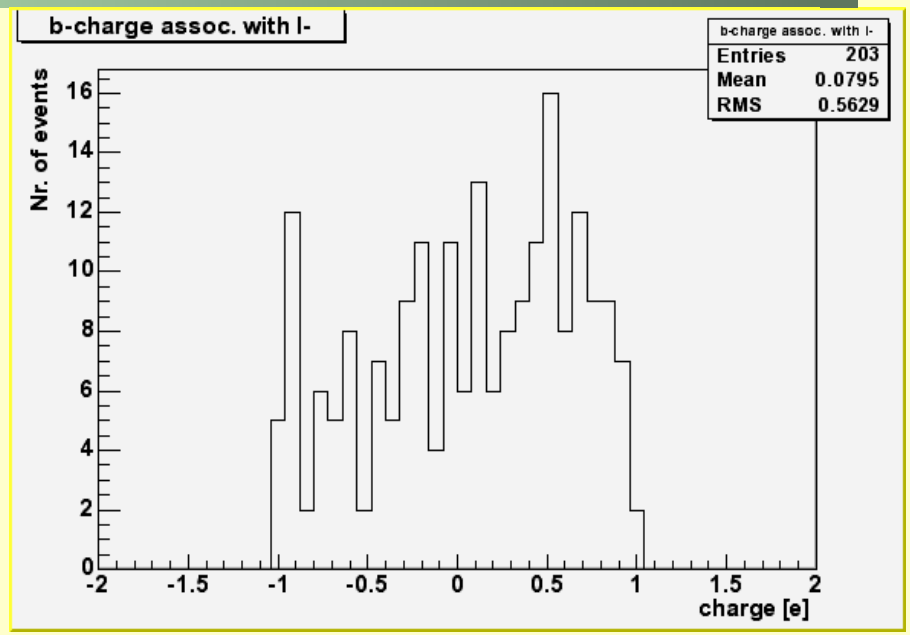
charge of lepton defines charge of b-jet

Problems:

- Low branching (2/9 of b-decay are taken)
- B_0 oscillation (change of lepton charge)

CDF: invariant mass criterion only





Sample lepton +jets: 6248 selected MC events (CDF cuts)

Invariant mass criterion applied: $m\left(l, b_{jet}^{(1,2)}\right) < m_{cr} \quad \& \quad m\left(l, b_{jet}^{(2,1)}\right) > m_{cr}$

$\langle Q_b \rangle$	σ	N_{evnt}		$\langle Q_b \rangle$	σ	N_{evnt}	
-0.0615	0.0379	227	l+	0.0795	0.0395	203	l-
-0.0738	0.0470	136	e+	0.0800	0.0527	111	e-
-0.0432	0.0633	91	μ+	0.0789	0.0596	92	μ-

W and b-jet association via kinematic fit

Kinematic fit (event by event) for lepton+jets sample:

Lepton and jets energy, jets direction (φ,η),

neutrino p_x, p_y, p_z vary freely (in errors inter.)

χ^2 uses constraints $M_{jjb}=m_t$, $M_{l\nu b}=m_t$, $M_{jj}=M_W \Rightarrow m_t$

Results: m_t, χ^2 found for each of 24 combinations

Association:

- topology with the lowest χ^2 taken as the correct one
- lepton sign defines sign of W and associated b-jet: (blν) giving m_t
- Tracks pointing to the b-jet are weighted → the found charge is accumulated to the distribution associated with (+) or (-) sign accordingly to the lepton sign.
- "charge" of b-jet - part of 2nd top branch (bjj) - is accumulated in the distribution with opposite (to previous case) sign.

Dilepton sample: a similar association procedure can be applied

Thank you !

Some additional slides follow

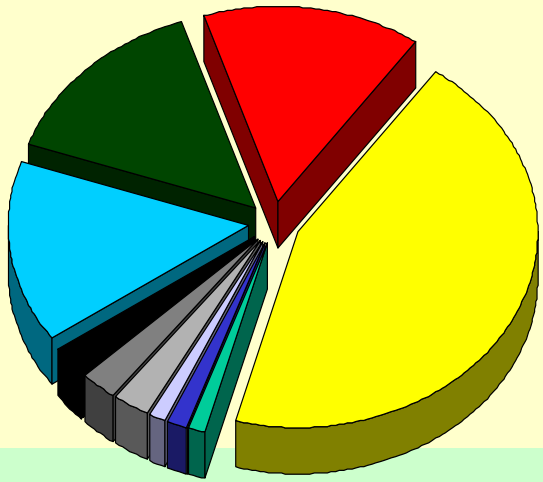
Top Quark Decay

SM: by far dominant $t \to bW$

$$\frac{\Gamma(t \to bW)}{|V_{tb}|^2} \approx 0.807 \times \frac{G_F m_t^3}{8\pi\sqrt{2}} = 1.42\,GeV$$

$\tau_{top} \approx 5\times10^{-25}$sec $<<$ τ_{hadr} (10^{-23}sec)

(m_t=175 GeV, M_W=80.4 GeV, α_S=0.03475)



Top decays before hadronization !!!

- No tt-bar bound states (gluon exchange)
- t,W helicity from SM V-A(no depolarization via hadronization)

tt-bar samples
defined via W decays

- Dilepton channels (ee, eμ, μμ)
  topological variables and b-tagging
- Lepton + jets ch. (e+jets, μ+jets)
  topological analysis and b-tagging
- All hadronic channel

$t\ \bar{t}$ Production Cross Section

Big $m_t \Rightarrow \alpha_s(m_t) \sim 0.1 \Rightarrow$ pExpansion coverges rapidly :

- $t\ \bar{t}$ cross section is a test of QCD predictions
  (Inclusive and differential cross sections)
- Acurate Xsection $\Rightarrow$ indirect determination of m_t
  (in SM is expected: $\Delta m/m \approx \Delta\ \sigma(tt)/\sigma(tt)$)
- Rapidity distr. assymetries of t and $\bar{t}$ are sensitive to light-quark PDF

- A discrepancy may indicate a new physics
  - Production via a high mass intermediate state
  - Non Wb decay model

ATLAS: Statistical uncertainties < 1%
$\rightarrow$ Systematics (Exp.& Theo.) will be dominant

$t\ \bar{t}$ Production Cross Section

Theory for top X-section (Inclusive and differential): NNLO-NNNLL (Kidonakis et al., PRD68,114014 (2003))

- Factorization

$$\sigma = \sum_f \int dx_1 dx_2\, F_i^{(1)}(x_1,\mu_F) F_j^{(2)}(x_2,\mu_F)\, \hat{\sigma}_{ij}(s;\mu_F,\mu_R)$$

Usual choice: $\mu_F = \mu_R = \mu \in (m_t/2, 2m_t)$

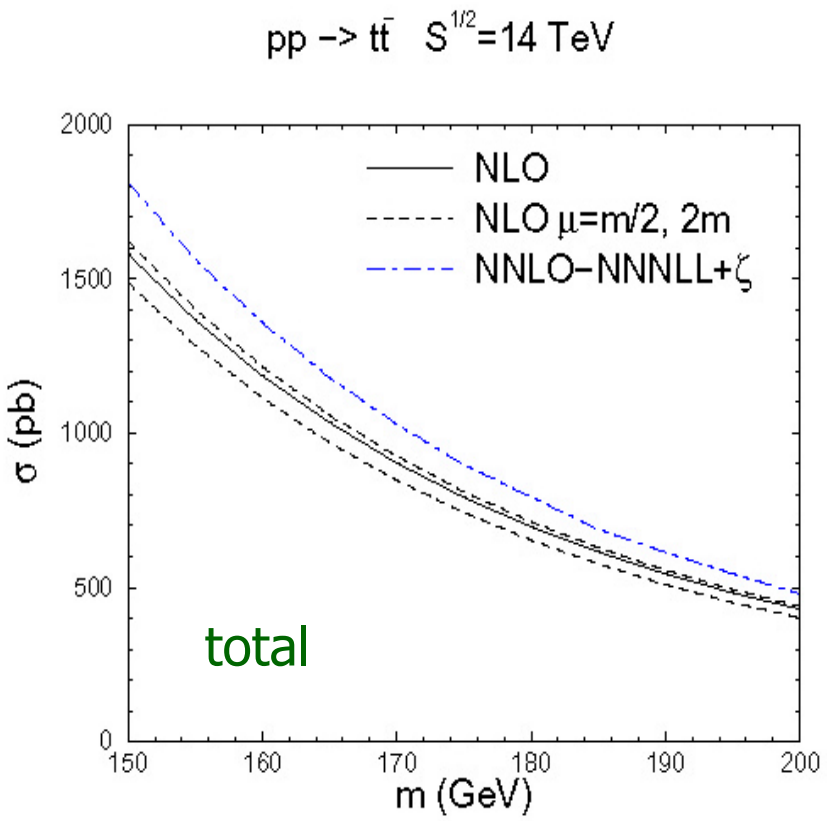
- Total Partonic Xsection:

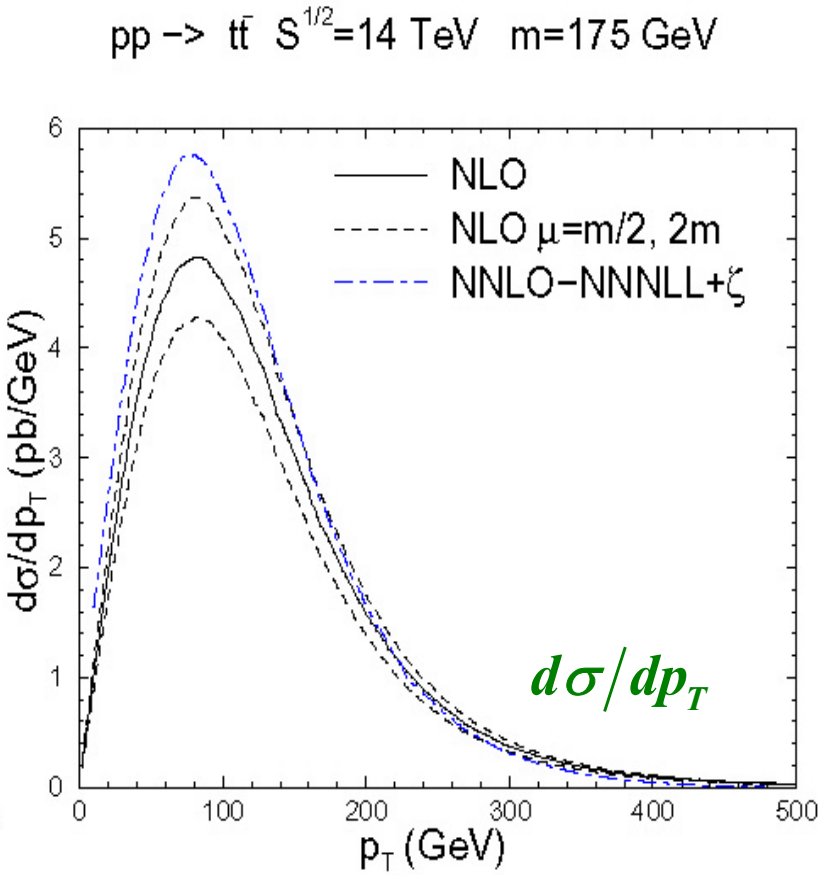
$$\hat{\sigma}_{ij} = \frac{\alpha_S^2(\mu)}{m^2} \sum_{n=0}^{\infty} \left(4\pi\alpha_S(\mu)\right)^n \sum_{k=0}^{n} f_{ij}^{(n,k)}(\eta) \ln^k\left(\frac{\mu^2}{m^2}\right)$$

$$\eta = \frac{s}{4m^2} - 1 \qquad s = (p_i + p_j)^2$$

Progress at MC: radiative gluon corrections included: MCatNLO (Frixione et al, hep-ph/0311223)

$t\ \bar{t}$ Cross Section at 14TeV



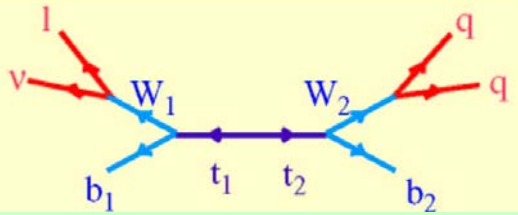


NNLO: uncertainty from scale ($m_t/2$, $2m_t$) < 3% !!!

(N.Kidonakis, hep-ph/0401147)

Top Mass measurement at ATLAS/LHC

Lepton +jets channel



Borjanovic et al.,
SN-ATLAS-2004-040

Process	Cross section (pb)	Efficienty (%)
tt signal	250	3.5
bb→ $l\nu + jets$	2.2×10^{6}	3×10^{-8}
W+jets→ $l\nu + jets$	7.8×10^{3}	2×10^{-4}
Z+jets→ $l^-l^+ + jets$	1.2×10^{3}	6×10^{-5}
WW→ $l\nu + jets$	17.1	7×10^{-3}
WZ→ $l\nu + jets$	3.4	1×10^{-3}
ZZ→ $l^-l^+ + jets$	9.2	3×10^{-3}

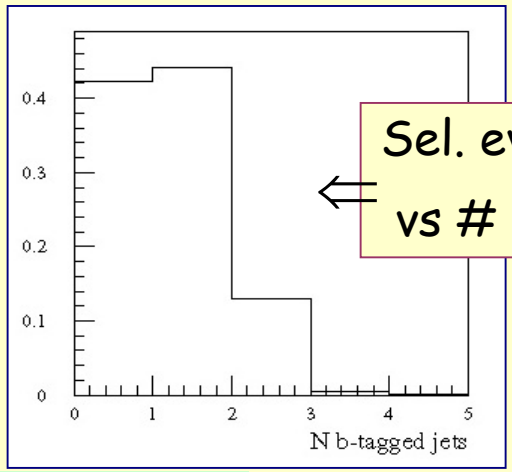
Signal vs Bkgd: x-section and sel. efficiency

At prod. level: S/B=10^{-5}
⇒ cuts applied:

$$p_T(l) \geq 20\,GeV,\ E_T^{miss} \geq 20\,GeV$$
$$\geq 4\ jets\ \left(p_T > 40\,GeV, |\eta| \leq 2.5,\ \Delta R = 0.4\right)$$

⇒ S/B~78, 8700 tt events /10fb^{-1},2b-tag

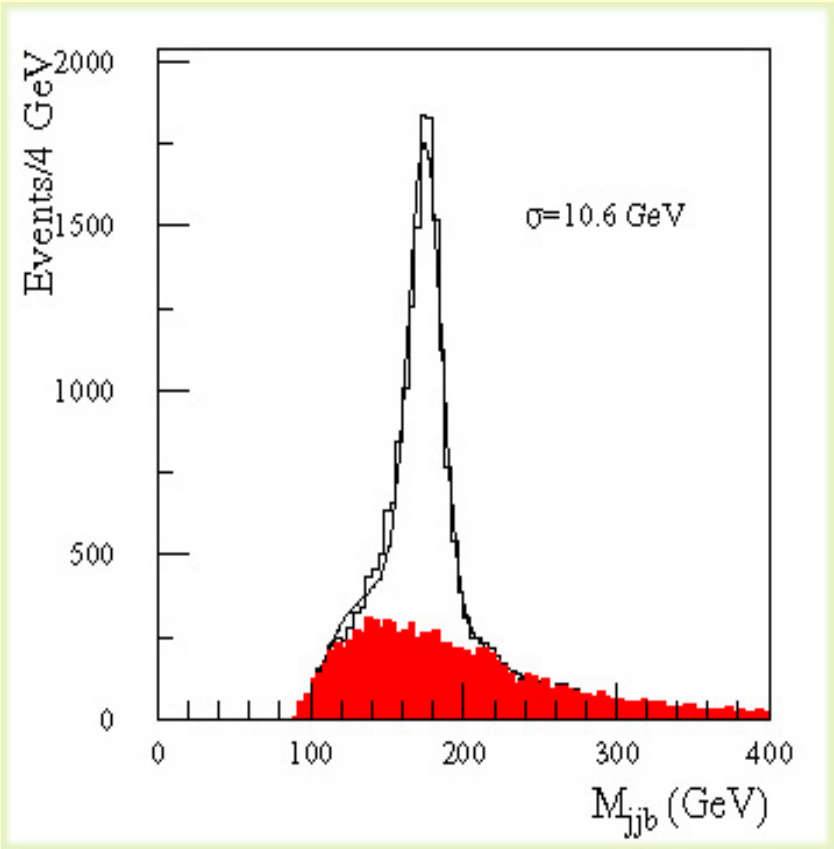
Purity 55% for 1 b-tagged, eff=2.5 %
66% for 2 b-tagged, eff=1.2 %
Top mass window : ±35 GeV

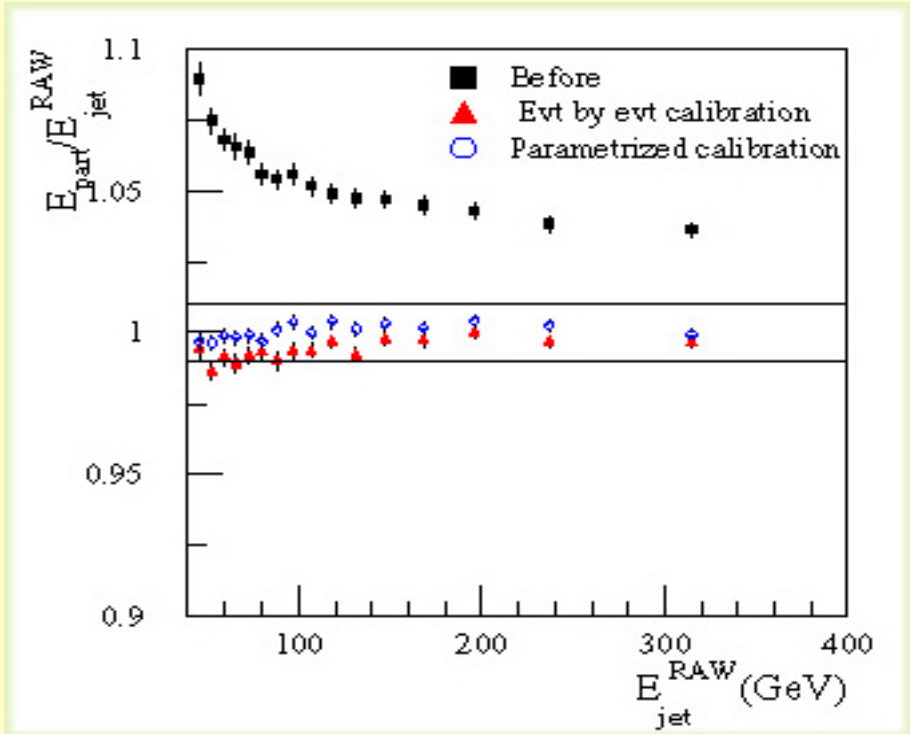


⇐ Sel. events vs # b-tags

Top mass in lepton + jets channel

Jet energy correction
$K=1.029+3.20/E_{raw}$
Needed to minimize Δm_t





⇐ **Invariant mass of jjb**
(b-jets calibtrated using Z+b events,
M_W window: ±20 GeV)

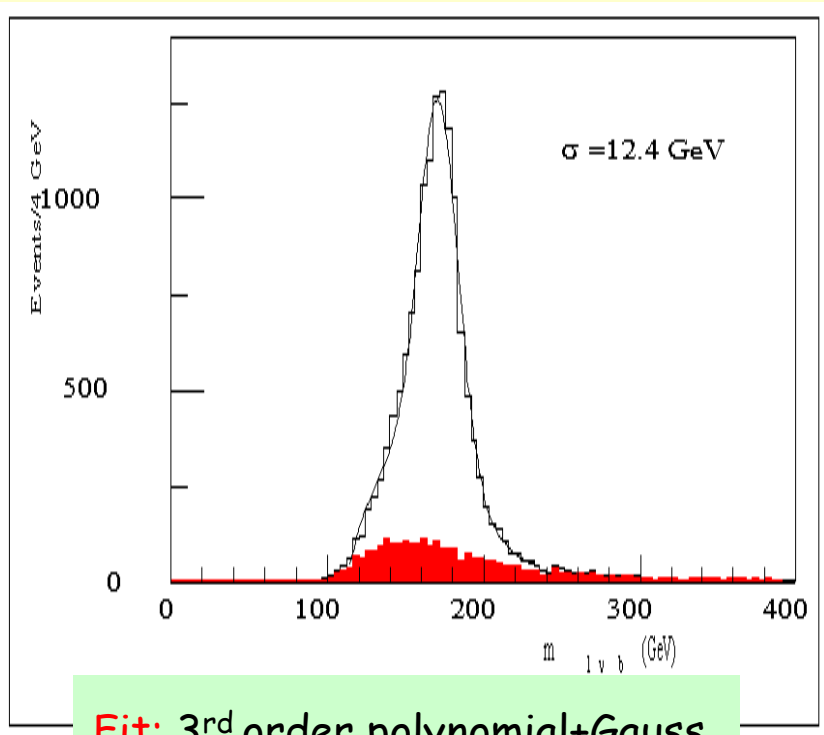
For **10 fb^{-1}** sample: Δm_t
- statistical error 100 MeV
- systematics ~ 1.3 GeV (FSR,..)

Top mass in lepton + jets channel

Leptonic part - mass reconstructed via :
- missing transverse energy ($E_T^{\nu} = E_T^{miss}$)
- constraint m(lν)=M_W for neutrino p_z

Result: two leptonic top masses due to twofold ambiguity in neutrino p_z

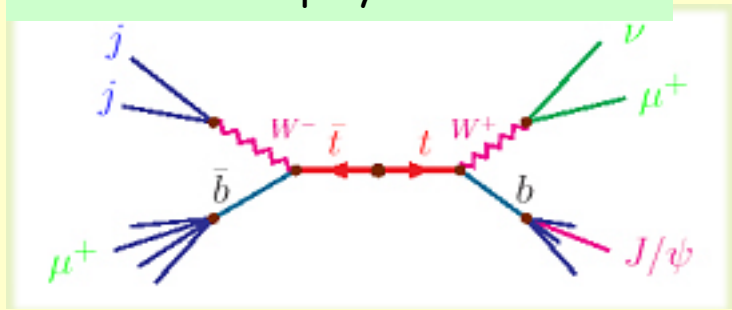
Kinematic fit (event by event):
Lepton and jets energy, jets direction (φ,η), neutrino p_x,p_y,p_z vary freely (in errors inter.)
χ^2 uses constraints $M_{jjb}=m_t$, $M_{l\nu b}=m_t$, $M_{jj}=M_W$
$\Rightarrow$ m_t find by fit , χ^2 < 4 $\rightarrow$ purity > 80%



Fit: 3rd order polynomial+Gauss

Promising: *l +J/ψ channel*

- Strong correlation between m_t & m(l,J/ψ)
- BR=3.2×10^{-5} (2700 ev/100fb^{-1}, sel. ε≈16%)
- non-sensitive to jet energy, S/B≈55



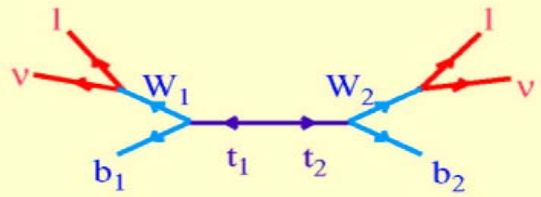
$t \rightarrow W^+b$, $W^+ \rightarrow l\nu$, $b \rightarrow J/\psi X$

Top mass in di-lepton channel

Selection: 2 isolated leptons (p_T>35,25 GeV)

High missing E_T (> 40 GeV)

2 b-jets with p_T > 25 GeV



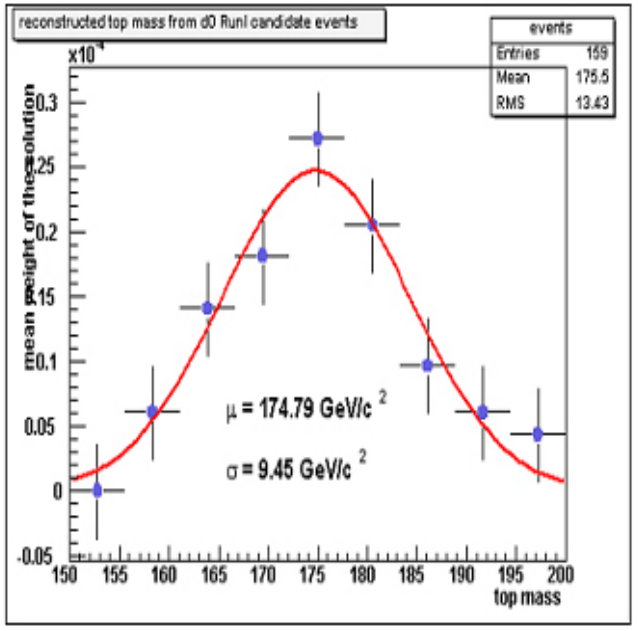
For each event: full reconstruction is done for different input top masses and mean weight is calculated for each input m_t

Neutrino momenta found from:

$$\sum p_x = \sum p_y = 0,\ m_{l^+\nu} = M_W,\ m_{l^-\tilde{\nu}} = M_W,$$

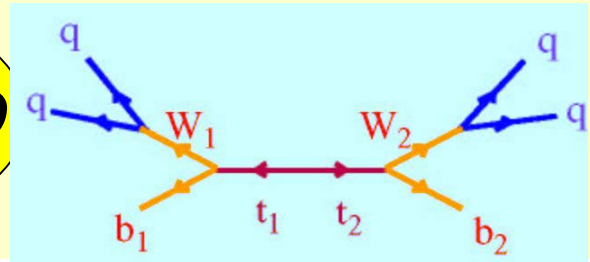
$$m(l^+\nu b) = m_t,\quad m(l^-\tilde{\nu} b) = m_t \quad m_t \text{ is known}$$

Source of uncertainty	δM_{Top} *(GeV)*	*Comments*
Statistic & reconstruction method	0.3	
b–jet energy scale	0.6	1% error
b–quark frag.	0.7	$(\varepsilon_b$=–0.006)–(ε_b=–0.035)
ISR	0.1	20%(ON–OFF)
FSR	0.6	20%(ON–OFF)
Parton distribution function	1.2	Mass shift from 2 different sets
Total	1.7	



Top mass in all jet channel

Selection:
≥6jets with p_T>40 GeV , ≥2 b-jets ⇒ **S/B =1/19**



Kinematic fit (two steps)

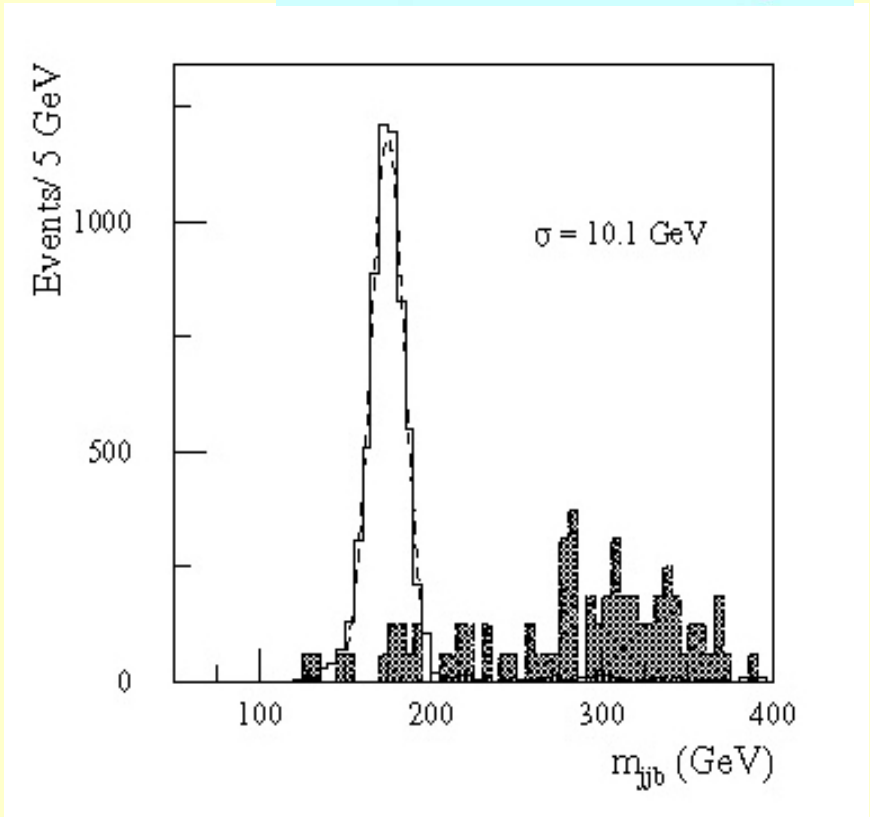
- **W's selection and reconstruction with W mass constraints**
- **Both W candidates are combined with the b-jets.**

Combination chosen using top mass constraint: m(t1) = m(t2)

Top mass window (130-200 GeV) ⇒ S/B = 6/1

High PT subsample ⇒ Selection

- **pT (t) > 200 GeV**
- **3300 evts/10 fb^{-1} ⇒S/B = 18/1**
- **$\Delta m^{stat}(t)$ = 0.2 GeV/c^2**
- **$\Delta m^{sys}(t)$ = 3 GeV/c^2**



Top mass and EW precision physics

Atlas top mass systematics (L=10fb^{-1}) : jet energy scale, b-jet frag., ISR, FSR, comb. Bckgd. All mass method combined ⇒

$$\Delta m_t(stat) = \pm 0.1\,GeV \qquad \Delta m_t(syst) = \begin{cases} +0.6 \\ -0.8 \end{cases} GeV$$

ISR, FSR via Pythia ⇒ Realistic: $\Delta m_t \approx 1$ GeV

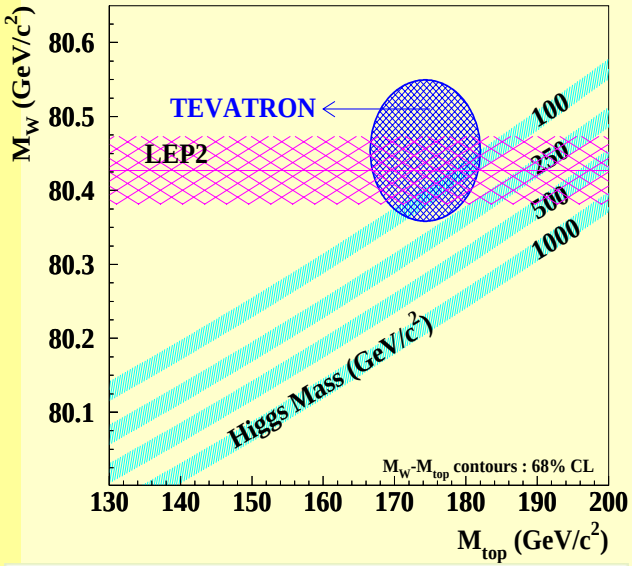
Masses of top, W and Higgs are bounded by

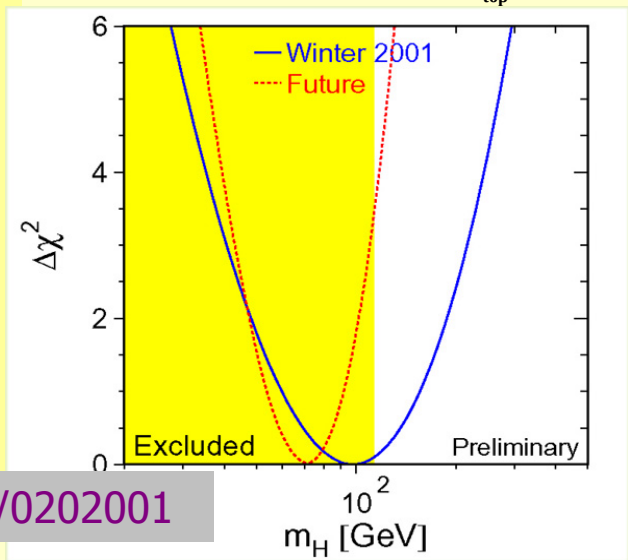
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}\left(1+\Delta r\right), \quad \Delta r = \Delta\alpha + \frac{s_W}{c_W}\Delta\rho + (\Delta r)_{nl}$$

Δr≡ rad. corrections ($\Delta\rho \sim m_t^2$, $(\Delta r)_{nl} \propto \ln M_H$)

Precise M_W and m_t ⇒ constraint on M_H!

present→LHC: Δm_t: 5→1 GeV, ΔM_W: 33→15 MeV



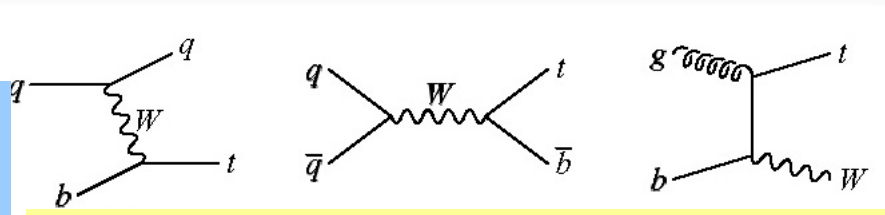


Grunwald et al, hep-ph/0202001

Single top production

Production via weak forces

- Xsection~$|V_{tb}|^2$
  (direct measurement of V_{tb})
- Significant bckgd to Higgs signal
- Single top ~100% polarization
  (test of V-A structure of EW)
- Possible new physics

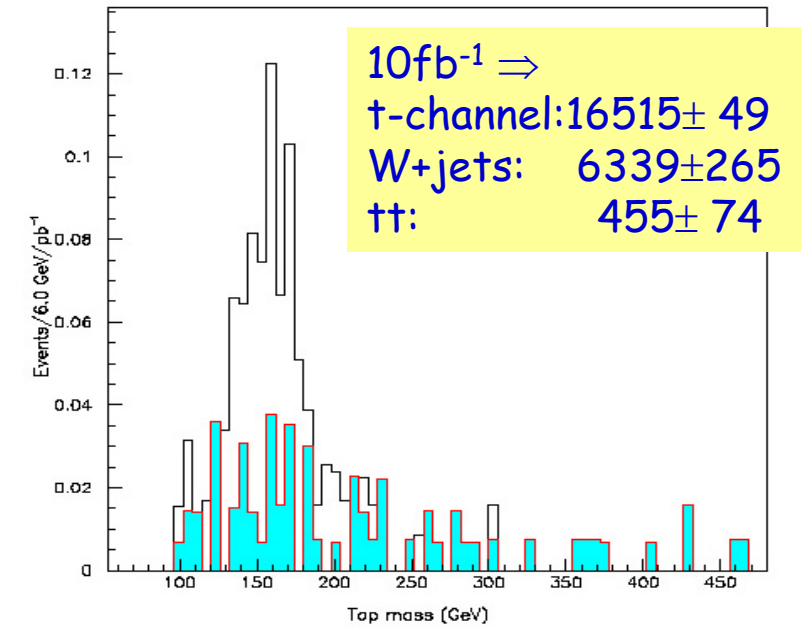


t-channel	s-channel	association production
245±27 pb	10.7±0.7 pb	51±9 pb

(at LHC 14 TeV, NLO)

Selection criteria

- Only 1 isolated lepton (p_T>20 GeV, $|\eta|$<2.5)
- miss-p_T > 20 GeV, 50 < m_T(l+ν) < 100 GeV
- exactly 2 jets: (p_T>20 GeV, $|\eta|$< 4)
  1 jet with p_T>20 GeV, $|\eta|$< 2.5
  1 jet with 50<p_T<100 GeV, 2.5 <$|\eta|$< 4
- Exactly one b-tagged jet(reduces tt-bkgd)
- Two jet invariant mass ∈(80,100) GeV
  (rejects WZ events)



Top quark charge

CDF, D0+precission EW data do not exclude :"top" quark is an exotic quark with charge –4/3 (Chang et al. PRD59, 091503)

Exotics: $t \to W^- b$ (in SM: $t \to W^+ b$)

Top charge determination:

- by measuring charges of top decay products
  $t \to W^+ b$ (W charge: $W^+ \to l^+ \nu$, $Q_{bjet} = \sum_i Q_i \left|\vec{j} \cdot \vec{p}_i\right| \Big/ \sum_i \left|\vec{j} \cdot \vec{p}_i\right|$)
- Via radiative $t\,\bar{t}$ events (sensitive to Q_t)

Analysis for ATLAS (10fb^{-1}) (Ciljak et al, Atl-Phys-2003-35):

- $l^+(l^-)$-bjet association criteria can be found to distinguish between mean $Q(b_{jet}l+)$ and Q(b-jet(l-)).
- Radiative top production ($pp \to tt\gamma$) can be used to measure foton-top coupling $\left(\sigma \sim Q_t^2\right) \Rightarrow$

Integrated Xsection: $\sigma^{seen}(Q=2/3) = 7.8 fb^{-1}$, $\sigma^{seen}(Q=2/3) = 24.8 fb^{-1}$
Background: $\sigma^{seen} = 6.5 fb^{-1}$

Conclusions

- Top quark physics is rich even at low luminosity LHC (10fb^{-1}/year)
  - SM: EW and QCD tests
  - Behind SM: probe SUSY
  - Determination of top characteristics (X-section, mass, width,charge..)
- Important background
  - Top quark production (pair and single) is main background to processes with multi lepton + jets in final state e.g. Higgs physics, SuSy
- High statistics studies at LHC (100fb^{-1}/year)
  - $\Delta m_t \leq 1$ GeV
  - BR for FCNC tVq $\approx 10^{-3}$ - 10^{-6}
  - Measurenent of CKM V_{tq}
  - ❖ We are looking forward to 2007…(LHC starts)