Top kvark II

(S. Tokár, 16. 11. 2001|

Základné vlastnosti

Základné konštituenty látky

leptóny	Q	T_3	Kvarky	Q	T_3
ν_e ν_μ ν_τ	0	1/2	u c t	2/3	1/2
e μ τ	-1	-1/2	d s b	-1/3	-1/2

Tab.1: Fundamentálne fermióny, Q ≡elektrický náboj v [**e**], T_3 ≡ slabý izospin.

Hmotnosť t-kvarku: $m_{top} = 174.3 \pm 5.1$ GeV/c^2

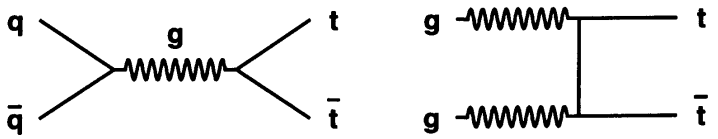
Objavený - kedy : 1995

Kde : Fermilab

1.1 Produkcia top kvarku

Základné mechanizmy produkcie t-kvark (v $p\bar{p}$ (pp)-zrážkach) sú (viď. Obr.1):

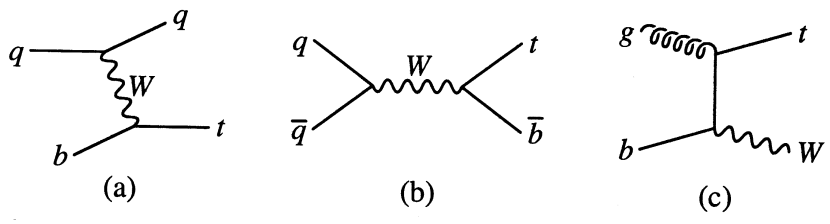
- Kvark-anitikvarková anihilácia
- Gluónová fúzia.



Obr. 1: Dominantné produkčné mechanizmy pre t-kvark.

Dominantné produkčné mechanizmy sú sprostredkované ***silnými interakciami*** a kvarky sú produkované v pároch ($t\bar{t}$).

Produkcia ***singletného t-kvarku*** sa uskutočňuje prostredníctvom ***slabých interakcií*** (Obr.2).



Obr. 2: Produkcia singletného *t*-kvarku via slabé interakcie: (a) *t*-kanálový proces ; (b) *s*-kanálový proces; (c) asociovaná produkcia *t*-kvarku.

Existujú 3 základé procesy single top produkcie:

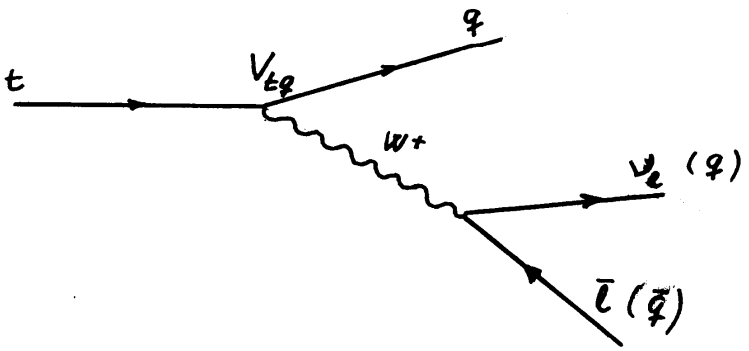
- *t*-kanálový proces: realizuje sa pomocou priestoru-podobného W bozónu ($q^2 < 0$). Virtuálny W bozón je pohltený *b*-kvarkom z protónového mora a mení ho na *t*-kvark.
- *s*-kanálový proces: času-podobný virtuálny W-bozón (s virtualitou $q^2 > (m_t + m_b)^2$) vzniká anihiláciou kvarkového páru ;
- asociovaná produkcia: single top kvark je produkovaný spolu s reálnym W-bozónom. Jednym z počiatočných partónov je b-kvark z protónového mora.

1.2 Rozpad *t*-kvarku

Top-kvark sa rýchlo rozpadá bez hadronizácie (m_{top}(≈175 GeV) >> M_W (≈ 80 GeV).

Pri slabých prechodoch môže ***t*** prechádzať na ***b***, ***s*** a ***d*** kvarky – intenzita prechodu je charakterizovaná elementom V_{tq} (q=b,c,s) matice *CKM* (Obr. 3).

Prakticky: rozpad *t*-kvarku ide výlučne cez kanál t →Wb (V_{tb}≈1).



Obr. 3 : Rozpad *t*-kvarku, amplitúda rozpadu t →Wq je úmerná elementu matice CKM (V_{tq}).

Rozpadová položírka procesu t →Wb :

$$\Gamma(t \to Wb) = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1 - 3\frac{M_W^4}{m_t^4} + 2\frac{M_W^6}{m_t^6}\right) \approx 1.56 GeV$$

$$\tau_{top} = \frac{\hbar}{\Gamma(t \to Wb)} = \frac{6.58 \cdot 10^{-25} GeV \cdot s}{1.58 GeV} \approx 4 \cdot 10^{-25} s$$

Keďže,
$\tau_{hadr} \approx 10^{-23} s$ platí: $\tau_{top} << \tau_{hadr}$, teda t-kvark sa rozpadne ešte pred sformovaním hadrónu.

On Measurement of the Top Quark Charge

Status of the Top charge

CDF and D0: The correlations of the ***b*** quarks and the ***W*** bosons in

$p\bar{p} \to t\bar{t} \to W^- W^+ b\bar{b}$ are not determined!

Consequence:

Besides the SM charge assignment ($Q_{top} = +2/3$), the „top quark“ could be an exotic quark with charge $Q_{top} = -4/3$.

$$SM: \quad t \to bW^+ \to b\, l^+ \bar{\nu}$$
$$Exot.: \quad \tilde{t} \to bW^- \to b\, l^- \nu$$

Moreover the present precision electroweak data are fully consistent with a –4/3 charge quark of mass ≈ 170 GeV.

How to determine top charge:

- By measuring the charge of its decay product (*W* boson, *b* jet)
- Via photon radiation in $t\bar{t}$ events: ($pp \to t\bar{t}\gamma$) and $pp \to t\bar{t}$, $t \to Wb\gamma$) – the $t\bar{t}\gamma$ cross section ~ Q_{top}^2.

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The top charge measurement via photon radiation $t\bar{t}$ events.

Top quark can radiate photons in:

- Top production $pp \to \bar{t}t\gamma$
- Top decay: $pp \to \bar{t}t, \quad t \to Wb\gamma$

For the top quark charge analysis are suitable:

- Dilepton events: $pp \to \gamma b\bar{b}(l\nu)(l\nu)$
- Lepton + jets events: $pp \to \gamma l^{\pm}\nu b\bar{b}jj$

Lepton + jets modes analysis (by *Bauer et al.)*

3 contributions to $pp \to \gamma l^{\pm}\nu b\bar{b}jj$:

- Radiation in top production: $pp \to t\bar{t}\gamma \to \gamma l^{\pm}\nu b\bar{b}jj$:
- Radiative top decay: $pp \to t\bar{t} \to \gamma W^{+}bW^{-}\bar{b} \to \gamma l^{\pm}\nu b\bar{b}jj$ (t or $\bar{t}$ quark decays radiatively $-t \to Wb\gamma$)
- Radiative W decay: $pp \to t\bar{t} \to W^{+}bW^{-}\bar{b} \to \gamma l^{\pm}\nu b\bar{b}jj$, W decays radiatively, $W \to l\nu\gamma \quad W \to jj\gamma$).

Suppression of radiative W decay:

$$m(jj\gamma) > 90\,GeV \quad \text{and} \quad m_T(l\gamma; \not{p}_T) > 90GeV$$

where $\not{p}_T$ is missing transverse momentum,

$m_T(l\gamma; \not{p}_T)$ is the $l\gamma\not{p}_T$ cluster transverse mass:

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

The matrix elements for $gg, \bar{q}q \rightarrow t\bar{t}\gamma \rightarrow \gamma l^{\pm}\nu b\bar{b}jj$

were calculated using MADGRAPH + HELAS library (the spin correlations for the top decay).

For the numeric simulations the set of SM input parameters were used:

m_{top}=175 GeV, m_b=5 GeV, M_W =80.3 GeV, $\sin^2\theta_W$ =0.23 and $\alpha(M_W)$=1/128.

MRSR2 parton distribution functions employed.

Applied cuts (for LHC):

$p_T(b) > 15\,GeV$ $\quad$ $|\eta(b)| < 2$

$p_T(l) > 20\,GeV$ $\quad$ $|\eta(l)| < 2.5$

$p_T(j_{1,2}) > 20\,GeV$ $\quad$ $|\eta(j_{1,2})| < 2.5$

$p_T(\gamma) > 30\,GeV$ $\quad$ $|\eta(\gamma)| < 2.5$

$p_T > 20\,GeV$ $\quad$ $\Delta R(i,j) > 0.4$ for i≠j

$m(jj\gamma) > 90\,GeV$ and $m_T(l\gamma; \not{p}_T) > 90\,GeV$

η ≡ pseudorapidita and $\Delta R(i,j) = \sqrt{\Delta\phi(i,j)^2 + \Delta\eta(i,j)^2}$ is the separation between 2 particles *i* and *j* in the pseudorapidity and azimuthal angle plane.

No background processes were considered.

The events passing the LHC cuts can be divided into 3 samples:

1. events satisfying $t\bar{t}\gamma$ cuts

   $m(bjj\gamma) > 190\,GeV$ and $m_T(bl\gamma; \not{p}_T) > 190\,GeV$ (radiative top quark decays suppressed – almost pure $t\bar{t}\gamma$ sample)

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

   process $pp \to t\bar{t},\ t \to Wb\gamma,\ W \to l\nu$ dominates ($t \to Wb\gamma,\ W \to l\nu$ cuts)

3. for

   $m_T(b_{1,2}l\gamma; \not{p}_T) > 190\,GeV$ and $150\,GeV < m_T(b_{1,2}jj\gamma) < 190\,GeV$

   process $pp \to t\bar{t},\ t \to Wb\gamma,\ W \to jj$ dominates ($t \to Wb\gamma,\ W \to jj$ cuts)

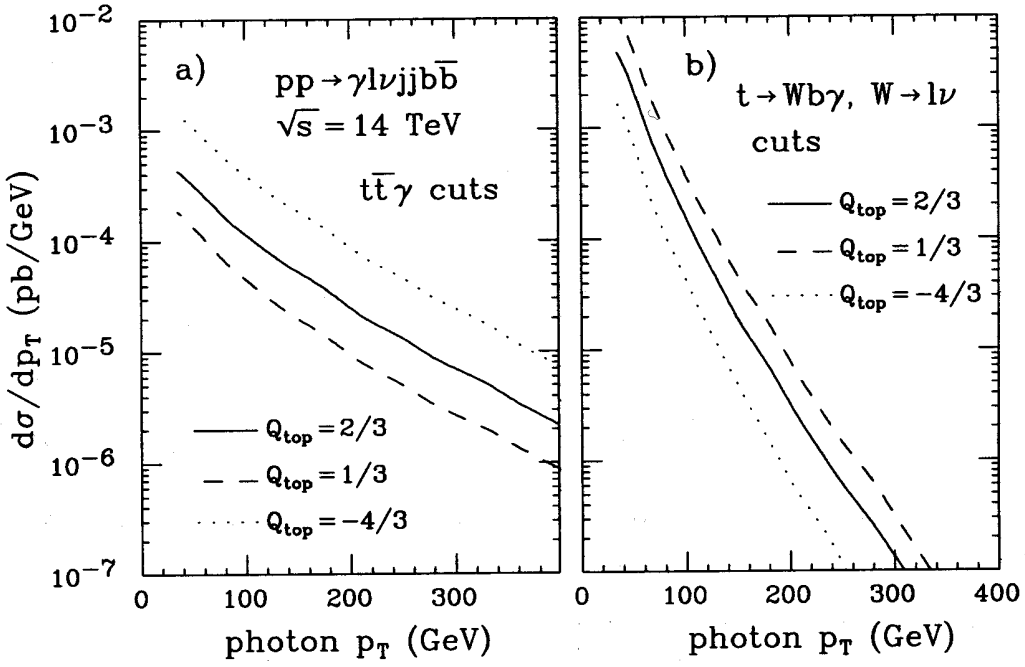


Fig. 1: The differential cross section for the photon p_T in the reaction $pp \to \gamma l\nu jjb\bar{b}$ at the LHC for 3 different "top" quark charges.

The top charge determined via its decay products.

The event samples suitable for the analysis:

- ***Dilepton decays*** ($t\bar{t} \to (l\nu)(l\nu)b\bar{b}$)
- ***Semilepton decays*** ($t\bar{t} \to (l\nu)(jj)b\bar{b}$) can be used.

Remark. All jet decay modes are not suitable due to the high QCD background.

The *b*-jet charge can be determined via the charges of the tracks belonging to the jet (DELPHI collab.):

$$q_{bjet} = \frac{\sum_i q_i \left| \vec{j} \cdot \vec{p}_i \right|^{\kappa}}{\sum_i \left| \vec{j} \cdot \vec{p}_i \right|^{\kappa}} \qquad (1)$$

Where:

q_i ($\vec{p}_i$) is the charge (momentum) of a b-jet track,

$\vec{j}$ is the b-jet direction and κ an exponent.

Production of the $t\bar{t}$ pairs in LHC

Typ eventu	Branching (%)	# events / 10 fb^{-1}
$t\bar{t} \to WWb\bar{b} \to (jj)(jj)b\bar{b}$	65.5	5 500 000
$t\bar{t} \to WWb\bar{b} \to (l\nu)(jj)b\bar{b}$	29.6	2 500 000
$t\bar{t} \to WWb\bar{b} \to (l\nu)(l\nu)b\bar{b}$	4.9	400 000

Choice criteria for the di-lepton sample

Applied cuts to $t\bar{t} \to WWb\bar{b} \to (l\nu)(l\nu)b\bar{b}$
1. Two isolated high- p_T leptons (e, μ) $p_T^{(1)} > 35\,GeV$, $p_T^{(2)} > 25\,GeV$ and $\lvert\eta\rvert < 2.5$ 2. Big missing transverse energy $E_T^{miss} > 40\,GeV$ 3. At least ***two*** *b*-jets with $p_T > 25\,GeV$ (one or two tagged as *b*-jets) 4. ***Z***-boson cut: $\lvert M^{ll} - M^{Z} \rvert > 10\,GeV$ (if leptons of the same type – *ee*, $\mu\mu$)

PYTHIA 6.125 simulations: the charge distribution in $b(\bar{b})$ jets.

- The $b(\bar{b})$ jet charge found by the weighting (1) using $\kappa = 1.0$
- Criterion for the choice of jet tracks: $R(part,b) < 0.2$

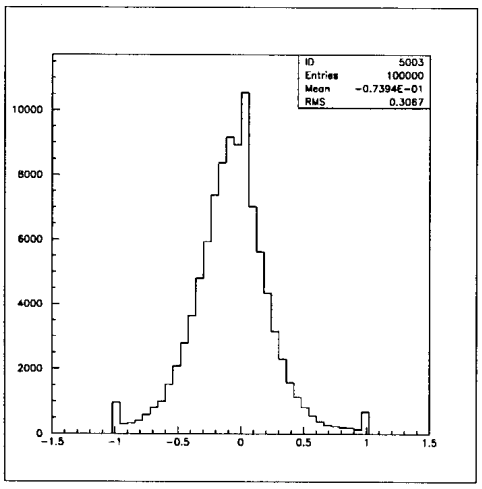


Fig. 2: The b-jet charge distribution (PYTHIA 6.1)

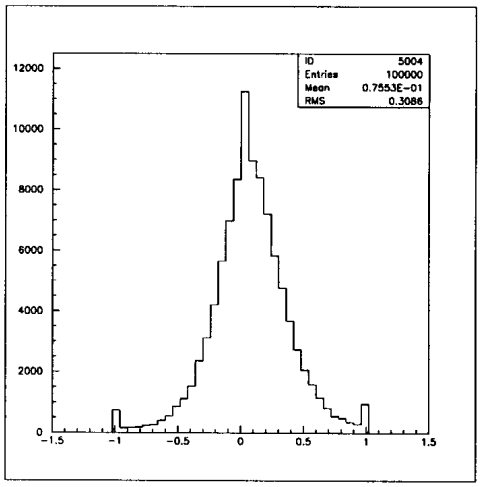


Fig. 3: The $\bar{b}$ -jet charge distribution (PYTHIA 6.1)

$$R = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$$

Where φ is azimuth angle and η is pseudorapidity

Reconstruction the *b*-jet charge by ATLAFAST.

Choice of events: di-lepton events from $t\bar{t}$ decays.

Applied cuts:

- Two b-jets with p_t(*b*-jet) > 25 GeV/c
- Two opposite charge leptons with $p_t(l^{\pm}) > 35$ GeV/c (25 GeV/c)

Assignment of leptons and *b*-jets: (l^+, *b*-jet) and (l^-, *b* – jet): via restrictions on the lepton-jet invariant mass ($\mathbf{M_{inv}}$**-cut**).

$$m(l^+, b_{jet}) < m_{top} \quad \text{and} \quad m(l^-, b_{jet}) > m_{top}$$

$$m(l^-, \bar{b}_{jet}) < m_{top} \quad \text{and} \quad m(l^+, \bar{b}_{jet}) > m_{top}$$

Track choice for *b*-jet's requirement: $R(b_{jet}, track) < 0.4$

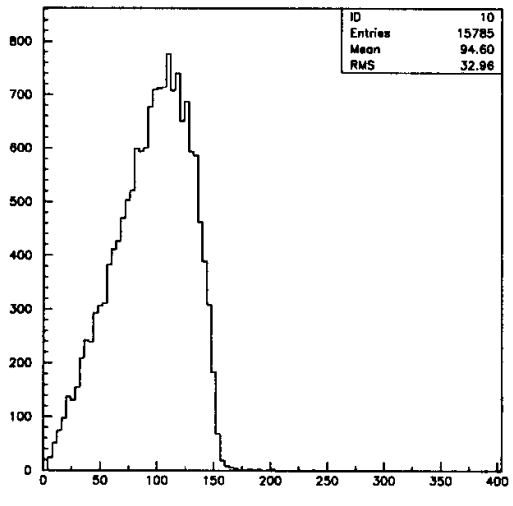


Fig. 4: Invariant mass ***m(l,bjet)*** for ***l*** and ***b***-jet from the same top quark

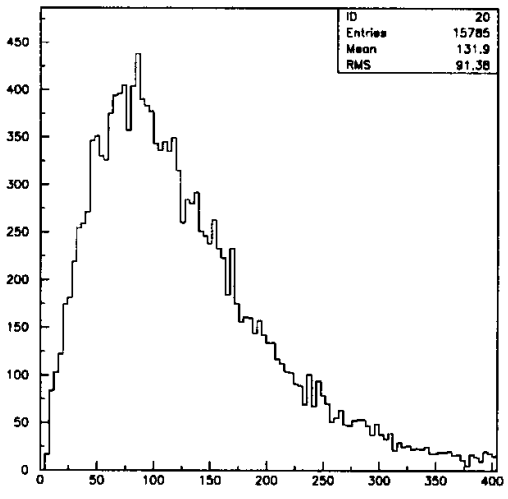


Fig. 5: Invariant mass ***m(l,bjet)*** for ***l*** and ***b***-jet from the different top quarks

Efficiency of M_{inv}-cut

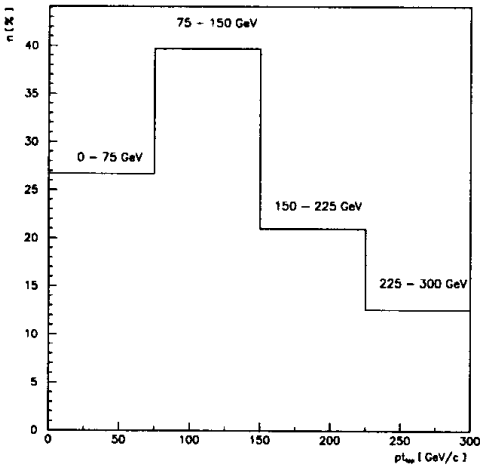


Fig. 6: The top quark p_t distribution

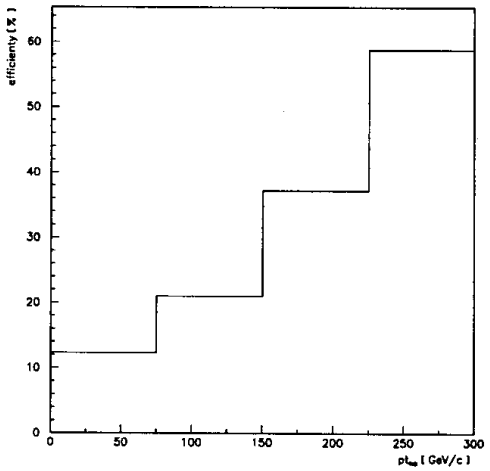


Fig. 7:The relative efficiency of M_{inv}-cut

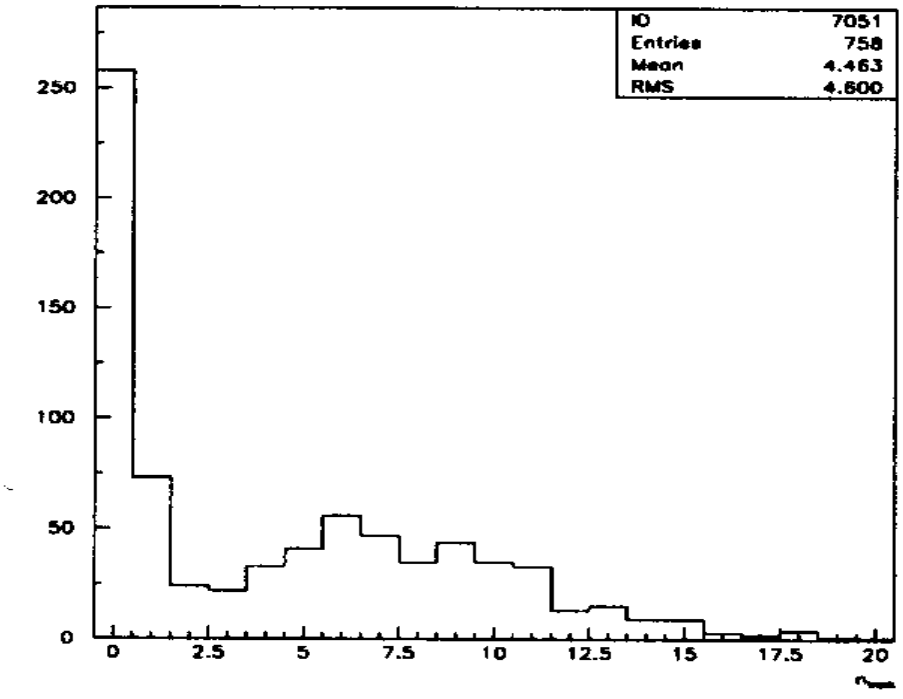


Fig. 8: Tracking efficiency for the b-jet tracks (R<0.4 used).

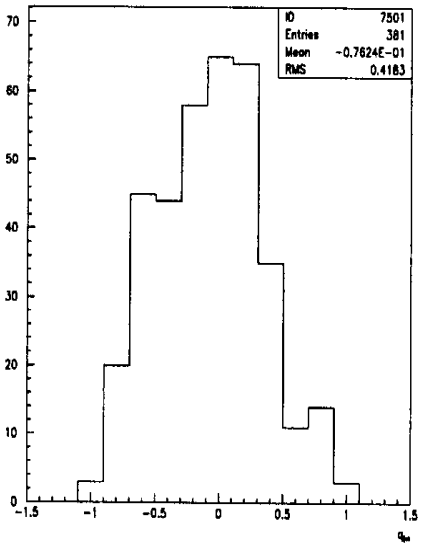


Fig. 9: The $\boldsymbol{b}$-jet charge distribution (2 b-jets)

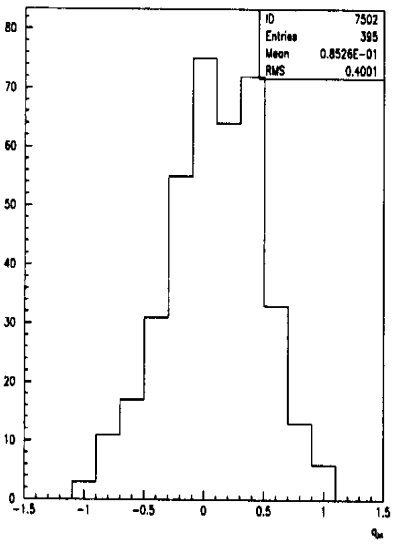


Fig. 10: The $\bar{\boldsymbol{b}}$ -jet charge distribution (2 b-jets)

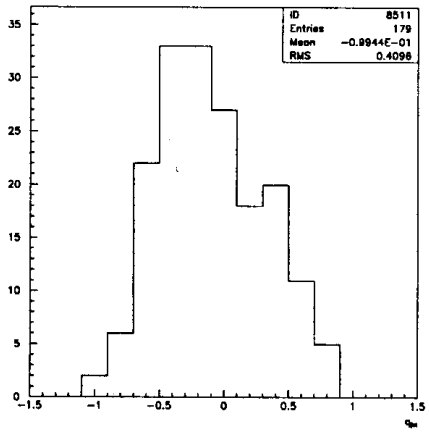


Fig. 11: The $\boldsymbol{b}$-jet charge distribution (1 b-jets)

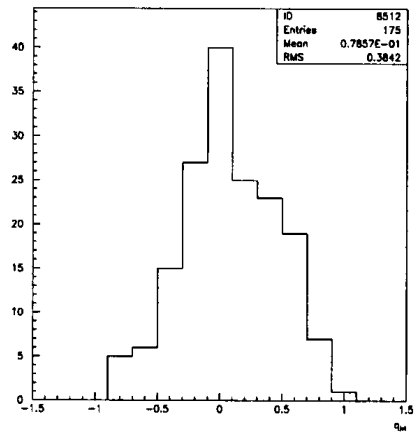


Fig. 12: The $\bar{\boldsymbol{b}}$ -jet charge distribution (1 b-jets)

The reconstructed $b(\bar{b})$-jet charge distributions

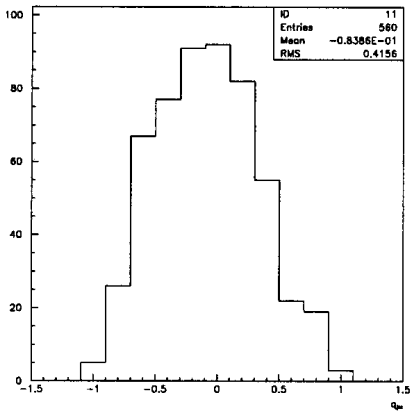


Fig. 13: Distribution of the *b*-jet charge

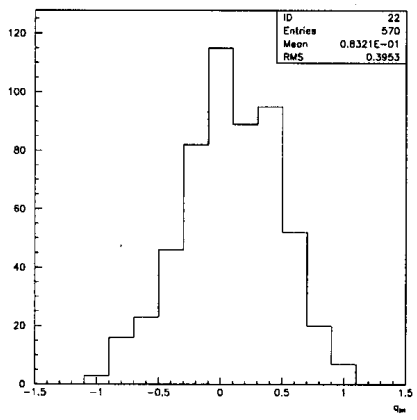


Fig. 14: Distribution of the $\bar{b}$-jet charge

The obtained mean charges (after rescaling):

$$q(b_{jet}) = -0.0839 \pm 0.018 \quad \text{and} \quad q(\bar{b}_{jet}) = 0.0832 \pm 0.017$$

Statistics:

# of *tt* events	480 000
# of dilepton events	22 183
# of dilepton events after cuts, $1b_{jet}$ ($2\ b_{jet}$)	1 951 (1 747)
# of dilepton events after M_{inv}-cut	744 (758)
# of dilepton .. after tracks recon.	b_{jet} 179 (381) $\bar{b}_{jet}$ 175 (381)

The Charge distribution in $b(\bar{b})$ strings – PYTHIA 6.125 simulations.

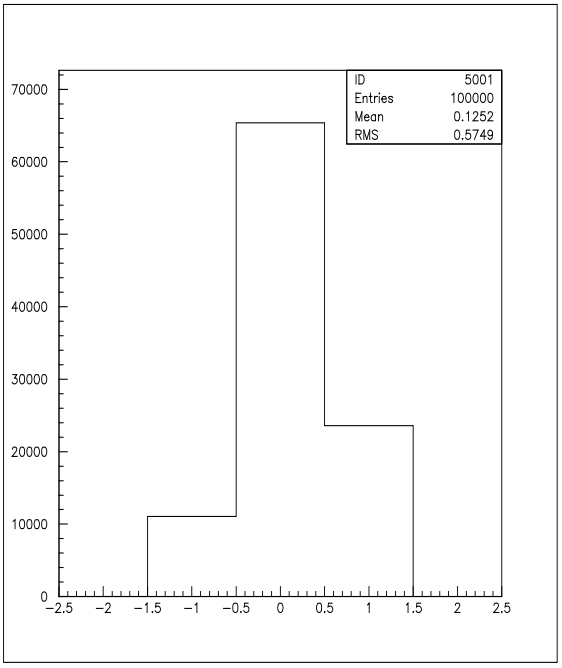


Fig. 15: The b-string charge (PYTHIA 6.1)

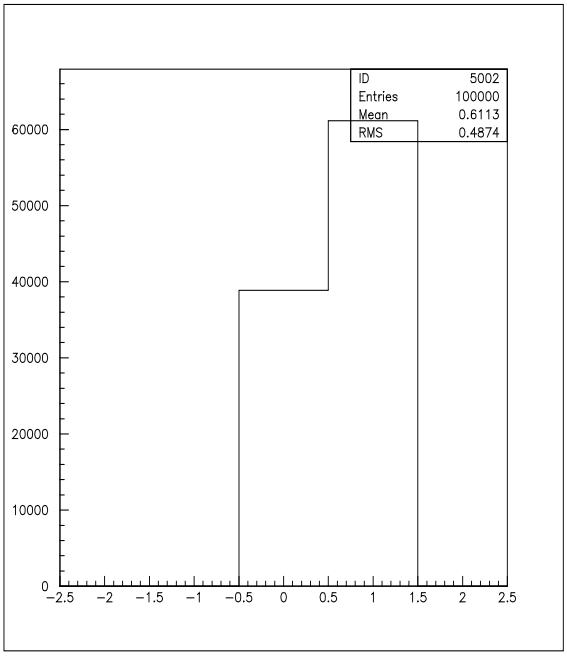


Fig. 16: The $\bar{b}$ -string charge (PYTHIA 6.1)

The b-jet charge for the different κ values

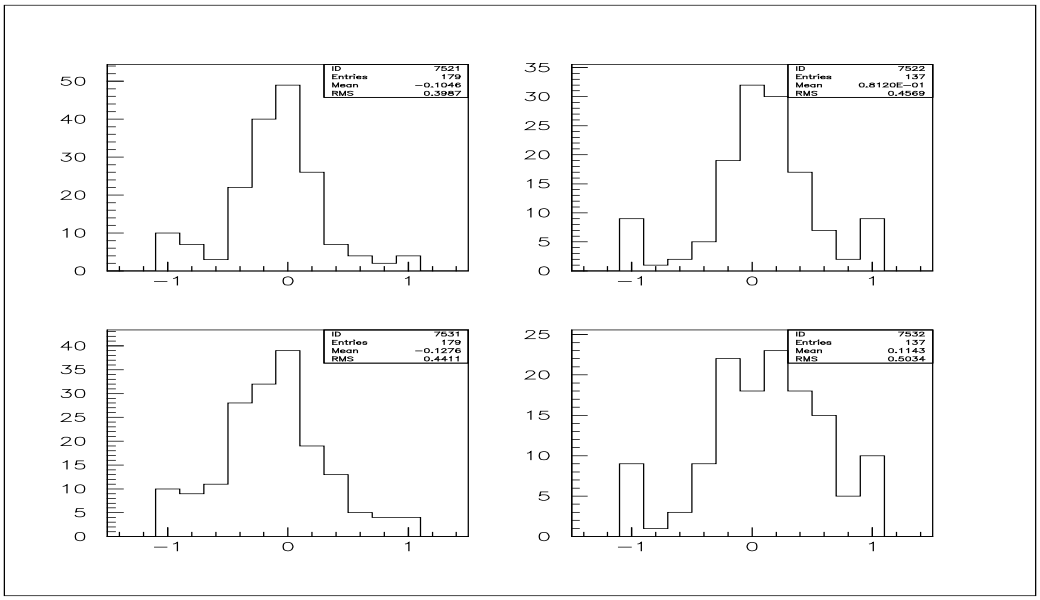
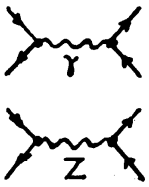


Fig. 17:The b-jet charge distribution for $\kappa = 0.8$ and 1.0.

3. Nepriame svedectvá existencie t-kvarku

3.1 Predo-zadná asymetria (FB-asymmetry)

Ak uvažujeme proces $e^+e^- \to f\bar{f}$, tak tento proces (viď. diagramy na obr. 1) v dôsledku interferencie medzi vektorovou a axiálne-vektorovou časťou amplitúdy Z-výmeny a interferencie amplitúd s Z-bozónom a fotónom vedie k asymetrii dopredu (F) a nazad (B) produkovaných fermiónov ($f(\bar{f})$):



$$e_0^2 \frac{Q_e Q_f}{s} \gamma_\mu \otimes \gamma^\mu$$

$$\frac{e_0^2}{4 s_W^{02} c_W^{02}} \frac{[\gamma_\mu (I_3^e - 2Q_e s_W^{02}) - I_3^f \gamma_\mu \gamma_5] \otimes [\gamma^\mu (I_3^f - 2Q_f s_W^{02}) - I_3^f \gamma^\mu \gamma_5]}{s - M_Z^{02}}$$

$$A_{FB}^{(f)} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \qquad (3.1)$$

kde σ_F (σ_B) je účinný prierez produkcie fermiónu f dopredu (dozadu).

Pre asymetriu A_{FB} pri hmotnosti Z-bozónu ($s = M_Z^2$), za predpokladu nepolarizovaných zväzkov, zanedbanie γ-výmeny a γZ-interferencie, platí:

$$A_{FB}^{(f)} = \frac{3}{4} A_e A_f + \cdots, \qquad A_f = \frac{2 g_V^f g_A^f}{\left(g_V^f\right)^2 + (g_A^f)^2} \qquad (3.2)$$

kde

$$g_V^f = \sqrt{\rho_f}\left(I_3^f - 2Q_f s_W^2\right) \qquad g_A^f = \sqrt{\rho_f} I_3^f , \quad f = e, \mu, \tau, s, c, b$$

$s_W = \sin\theta_W$ je uhol elektroslabého zmiešavania , $\rho_f \equiv$ elektroslabé korekcie

Porovnanie experimentálne zmeranej asymetria pre produkciu $b\bar{b}$ s predpoveďou SM:

$A_{FB}^{(b)}\left(s = M_Z^2\right)$	Experiment (MeV)	Štandardný model	
		$I_3^b = -\frac{1}{2}$	$I_3^b = 0$
	0.0984 ± 0.0024	0.1030 ± 0.0009	0.

3.2 Položírka rozpadu $Z \to b\bar{b}$

SM pre položírku rozpadu $Z \to b\bar{b}$ dáva:

$$\Gamma\left(Z \to b\bar{b}\right) = \frac{G_F M_Z^3}{6\sqrt{2}\pi}\left(g_V^2 + g_A^2\right)\cdot C_{QCD} = \frac{G_F M_Z^3}{3\sqrt{2}\pi}\left(\left(I_3^b - Q_b s_W^2\right)^2 + Q_b^2 s_w^4\right)\cdot C_{QCD} \qquad (3.3)$$

kde

$$C_{QCD} = 3\left(1 + \frac{\alpha_S}{\pi} + 1.409\frac{\alpha_S^2}{\pi^2} - 12.77\frac{\alpha_S^3}{\pi^3}\right) \qquad (3.4)$$

predstavuje QCD-korekcie (faktor 3 je farebný faktor).

Porovnanie experimentu s predpoveďami SM:

	Experiment (MeV)	Štandardný model	
		$I_3^b = -\frac{1}{2}$	$I_3^b = 0$
$\Gamma\left(Z \to b\bar{b}\right)$	377.4 ± 2.1	376.0 ± 0.1	24.2 ± 0.1

3.3 Neprítomnosť FCNC (flavor meniace neutrálne prúdy).

Kvarkové stavy uvedené v Tab.1 sú vlastnými stavmi slabého izospinu, no nie sú vlastnými stavmi slabých interakcií. Flavorovými čistými stavmi sú kvarky ***d', s'*** a ***b'***:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad (3.5)$$

Kde

V je unitárna matica ($V^+V = 1$) nazývaná CKM matica (Cabibbo, Kobayashi, Maskawa). Nediagonálnosť CKM-matica znamená prítomnosť nabitých slabých prúdov meniacich flavor. Napr. slabé prechody $b \xrightarrow{W} c, u$ a $s \xrightarrow{W} u$ sa uskutočňujú via nabité prúdy s väzbovými konštantami úmernými V_{cb}, V_{ub} a V_{us}.

V prípade, že *b*-kvark má izospinového partnera (slabý izospin), tj., že existuje *t*-kvark, potom v dôsledku unitarity $\boldsymbol{V}$ a univerzality väzby $\boldsymbol{Z}$ k 3 generáciám sa väzbové konštanty slabých neutrálnych prúdov meniacich flavor vyrušia:

$$Z_\mu\left(\bar{d}'\Gamma^\mu d' + \bar{s}'\Gamma^\mu s' + \bar{b}'\Gamma^\mu b'\right) = Z_\mu\left(\bar{d}\Gamma^\mu d + \bar{s}\Gamma^\mu s + \bar{b}\Gamma^\mu b\right) \qquad (3.6)$$

Kde

$$\Gamma_\mu^f = i\frac{g}{2c_W}\gamma_\mu\left(v_f - a_f\gamma_5\right) = i\frac{g}{2c_W}\gamma_\mu\left((1-\gamma_5)I_3^f - 2Q_f\, s_w^2\right) = \Gamma_\mu^{(f)I} + \Gamma_\mu^{(f)Q} \qquad 3.7$$

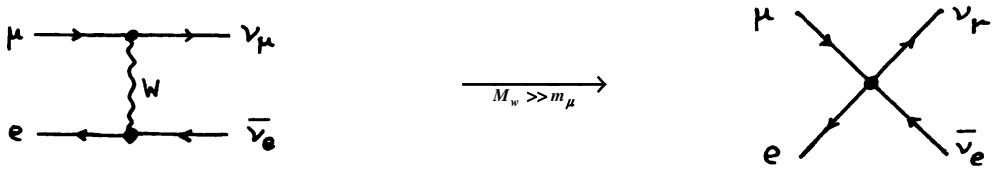
Vzťah 3.6 platí len v prípade, že $\Gamma_\mu^f = \Gamma_\mu$ pre $f = d, s, b$. Ak však b je izotopický singlet, teda $\Gamma_\mu^{(b)I} = 0$, zatiaľ čo $\Gamma_\mu^{(d)I} = \Gamma_\mu^{(d)I} \neq 0$. To vedie k tomu, že väzbové konštanty slabých neutrálnych prúdov meniacich flavor pre procesy $Z\bar{b}s, Z\bar{b}d$ sú úmerné $V_{tb}^* V_{ts}, V_{tb}^* V_{td}$, čo znamená, že rýchlosť rozpadov via slabé neutrálne prúdy meniace flavor ako $b \xrightarrow{Z} s, d$, je rovnaká ako v prípade rozpadov $b \xrightarrow{W} c, u$.

Prakticky by to znamenalo, že rozpad $b \to \mu^+ \mu^- X$ by mal branching ratio ≥ 1%, čo sa nepozoruje ($B_{exp} < 6.8 \cdot 10^{-7}$, CL 90%).

4. Top kvark a precízna elektroslabá fyzika

4.1 Fermiho konštanta a parametre SM

Uvažujme rozpad miónu $\mu^- \to e^- \tilde{\nu}_e \nu_\mu$.



$$i\left(\frac{e}{2\sqrt{2}\,s_W}\right)^2 \frac{J_{CC}^{(\mu)} \cdot J_{CC}^{(e)}}{q^2 - M_W^2} \longrightarrow i\frac{G_\mu}{\sqrt{2}} J_{CC}^{(\mu)} \cdot J_{CC}^{(e)}$$

Kde $J_{CC}^{(l)} = \bar{u}_{\nu_i} \gamma_\mu (1-\gamma_5) u_l$ je nabitý slabý prúd (l=e,μ).

Dôležitý moment:

charakteristická škála slabých interakcií ($1/M_W$) << charakteristická škála μ/rozpadu ($1/m_\mu$).

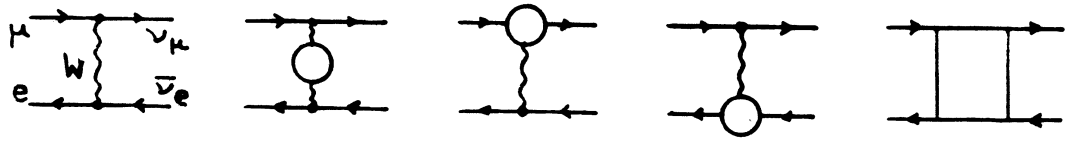
Vzťah medzi Fermiho konštantou a parametrami SM:

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2} \qquad (4.1)$$

Keď zo vzťahu (1) vypočítame M_W – dostaneme: $M_W = 77.6$ **GeV,** zatiaľ čo experimentálna hodnota je $M_W = 80.419 \pm 0.056$ **GeV.**

Dôvod rozdielu: nebrali sme do úvahy korekcie vyšších rádov!

4.2 Korekcie vyšších rádov, Δr a t-kvark



$$\frac{G_F}{\sqrt{2}} = \frac{e_0^{\,2}}{8 s_W^{02} M_W^{02}} \left[1 + \frac{\Sigma^W(0)}{M_W^2} + (vertex, box) \right] \qquad (4.2)$$

Kde

e_0, s_W^0, M_W^0 sú holé parametre (náboj, $\sin\theta_W$, hmotnosť Z)

$\Sigma^W(0)$ je vlastná energia W-bozónu.

Po renormalizácii, ktorá spočíva v tom, že vypočítame príspevky vyšších rádov a predefinujeme základné parametre, tj. prejdeme od holých parametrov e_0, s_W^0, M_W^0 k fyzikálne pozorovaným e, s_W, M_W, dostaneme:

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2}\left(1 + \Delta r\right) \tag{4.3}$$

Kde Δr je konečná veličina závislá na e, M_W, M_Z, M_H, m_t predstavujúca výsledok zahrnutia vyšších rádov a dá sa vyjadriť ako

$$\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + (\Delta r)_{rem} \tag{4.4}$$

kde $\Delta\alpha$ predstavuje korekcie 2. rádu k propagátoru fotónu od ľahkých fermiónov:

$$\Delta\alpha = -\operatorname{Re}\hat{\Pi}^{\gamma}\left(M_Z^2\right) = \sum_f Q_f^2 \frac{\alpha}{3\pi}\left(\frac{5}{3} - \log\frac{M_Z^2}{m_f^2}\right) \tag{4.5}$$

$\Delta\rho$ predstavuje korekcie 2. rádu k propagátoru W bozónu :

$$\Delta\rho = N_C \frac{\alpha}{16\pi s_W^2 c_W^2}\frac{m_t^2}{M_Z^2} \tag{4.6}$$

(N_C=*3* je počet farieb).

$(\Delta r)_{rem}$ predstavuje všetky ostatné korekcie včítane logaritmickej závislosti od hmotnosti *t*-kvarku a Higgsovho bozónu:

$$(\Delta r)_{rem}^{top} = \frac{\alpha}{4\pi s_W^2}\left(\frac{c_W^2}{s_W^2} - \frac{1}{3}\right)\log\frac{m_t}{M_Z} + \cdots \qquad (\Delta r)_{rem}^{Higgs} = \frac{\alpha}{16\pi s_W^2}\frac{11}{3}\left(\log\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) \tag{4.7}$$

Vzľah 4.4 je možné použiľ na určenie hmotnosti t-kvarku - $\Delta\alpha = 0.0602 \pm 0.0009$, typická hodnota $(\Delta r)_{rem} \approx 0.01$. Výpočty dávajú:

$$m_t = 168.2^{+9.6}_{-7.4}\, GeV$$

Poznámka 1. Vzťahy 4.7 umožňujú urobiť aj ohraničenie na hmotnosť Higgsovho bozónu.

Poznámka 2. Efekty vyšších (všetkých) rádov poruchovej teórie je možné získať zámenou:

$$1 + \Delta r \to \frac{1}{1 - \Delta r}$$