PHYSICS AT LHC 2004
Vienna, Austria, 13-17 July 2004

TOP QUARK PHYSICS AT CMS

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Motivation

• t-quark production and decays are evaluated within the SM with high accuracy without any phenomenological parameters

• X-section production and differential distributions are calculated with $\mathcal{O}(10\%)$ accuracy

• t-quark decays through ONE decay channel, $t \to bW^+$. Other decay channels have very small branching ratios (less then $\mathcal{O}(10^{-3})$)

• due to very small life-time of t-quark ($\sim 10^{-24}$ sec, $\tau_t \ll 1/\Lambda_{\rm QCD}$) we expect no formation of top-hadrons, $T(t\bar{t})$- or $M(t\bar{q})$-mesons and $\Lambda(tqq)$-baryons

any experimental observation of unusual process with top quark would be an indication of a New Physics beyond the Standard Model

current experimental status

- $t\bar{t}$ production cross-section
  Run-I, $\sqrt{s} = 1.8$ TeV CDF+ D∅: $\sigma_{t\bar{t}} = 6.2 \pm 1.7$ pb, $\sigma^{th}_{t\bar{t}} = 4.8 - 5.2$ pb
  Run-II, $\sqrt{s} = 1.96$ TeV,

CDF	$\sigma(t\bar{t}) = 7.0^{+2.4}_{-2.1}(stat)^{+1.6}_{-1.4}(syst) \pm 0.4(lumi)$ pb
$D\emptyset$	$\sigma(t\bar{t}) = 8.1^{+2.2}_{-2.0}(stat)^{+1.6}_{-1.4}(syst) \pm 0.8(lumi)$ pb
theory	$\diamond\ \sigma(t\bar{t}) = 6.70^{+0.71}_{-0.88}$ pb, $m_t = 175$ GeV

- t–quark mass: RPP-2002 (CDF + $D\emptyset$) $M_t = 174.3 \pm 5.1$ GeV

Run-I (2004)	$M_t = 179.0 \pm 3.5(stat) \pm 3.8(syst)$ GeV
CDF: new Run-II data	$M_t = 171.2^{+14.4}_{-12.5}(stat) \pm 9.9(syst)$ GeV
$D\emptyset$ reanalysis of Run-I data	$M_t = 180.1 \pm 5.6(stat) \pm 5.5(syst)$ GeV

- electroweak (single) top production

  two channels were investigated:

$$\begin{array}{lccc} t \text{ channel}: & qb & \longrightarrow & tq' \\ s \text{ channel}: & q\bar{q} & \longrightarrow & t\bar{b} \end{array} \Rightarrow \sigma(t) : \sigma(s) \approx 2 : 1$$

	Run I, $\sqrt{s} = 1.8$ TeV		
	theory	CDF	$D\emptyset$
t	1.47 ± 0.22 pb	< 13 pb	< 22 pb
s	0.75 ± 0.12 pb	< 18 pb	< 17 pb
	Run II, $\sqrt{s} = 1.96$ TeV		
	theory	CDF	$D\emptyset$
t	$1.98^{+023}_{-0.18}$ pb	< 8.5 pb	< 19.8 pb
s	$0.88^{+07}_{-0.06}$ pb		< 13.8 pb
$s + t$		< 13.7 pb	< 15.8 pb

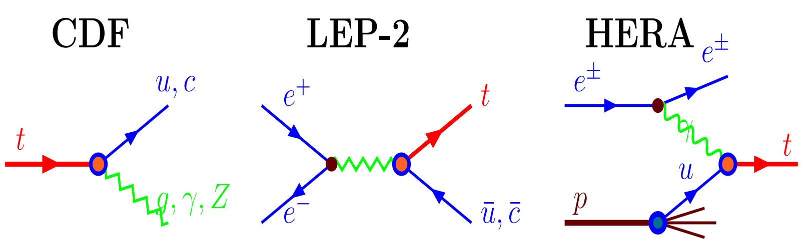
- t–quark properties

$$
\begin{array}{lcl}
R_b & = & \frac{\Gamma(t\to Wb)}{\Gamma(t\to Wq)} = 0.99^{+0.31}_{-0.24} \\
|V_{tb}| & > & 0.75 \ \text{ at } \ 95\% \text{ CL } \ (3 \ \text{ generations}) \\
\Gamma_{W_{long}} & = & 55 \ {}^{+48}_{-53} \ \% \ \ (70\% \ \text{ theory})
\end{array}
$$

- Run-I, $D\emptyset$: $t\bar{t} \to \ell^+\ell^- X$ correlations:

$$
\frac{d^2N}{d\,\cos\theta_+\, d\,\cos\theta_-} \propto (1 + A\cos\theta_+\ \cos\theta_-) \quad \Rightarrow \begin{cases} A_{\rm SM} = 0.88 \\ A_{exp} > -0.2 \ \ (\text{at } 68\% CL) \end{cases}
$$

- FCNC decays: CDF + LEP-2 + HERA, upper limits on BR$(t \to qV)$, $V = g, \gamma, Z$



$t \to$	CDF	LEP-2	HERA
$g\,q$	$\leq 29\%$		
$\gamma\,u$	$\leq 3.2\%$	$\leq 2.3\%$	$\leq 0.29\%$
$\gamma\,c$	$\leq 3.2\%$	$\leq 2.3\%$	
$Z\,q$	$\leq 32\%$	$\leq 8.1\%$	

- no narrow $R(t\bar{t})$ resonance was found with $M_R < 560$ GeV at $\Gamma_R = 0.012 M_R$

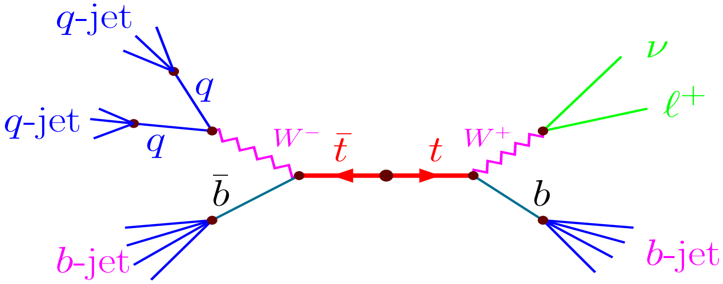
- top-quark production ($t\bar{t}$ and single top) leads to final states with:
  - ◇ one or two isolated charged lepton (electron or muon)
  - ◇ missing transverse energy ($\not{E}_{\top}$)
  - ◇ at least two hadronic jets
  - ◇ at least one b-jet

$\Longrightarrow$ all CMS sub-detectors, tracker, ECAL, HCAL, muon chambers will be explored for reconstruction of these objects

- ◇ $p_{\top}(\ell) > 20$ GeV and $|\eta(\ell)| < 2.4$
- ◇ $\not{E}_{\top} > 20$ GeV
- ◇ $E_{\top}(j) > 20$ GeV and $|\eta(j)| < 4.5$
- ◇ b-jets, $|\eta(B)| < 2.4$ with $\varepsilon(b) \sim 50-60\%$, $\varepsilon(c) \sim 10\%$, $\varepsilon(q,g) \sim 1-2\%$,

Top mass measurements

- semileptonic channel (L. Sonnenschein, CMS NOTE 2001/001)



$$t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow \ell^\pm \nu b\bar{b}q\bar{q}'$$

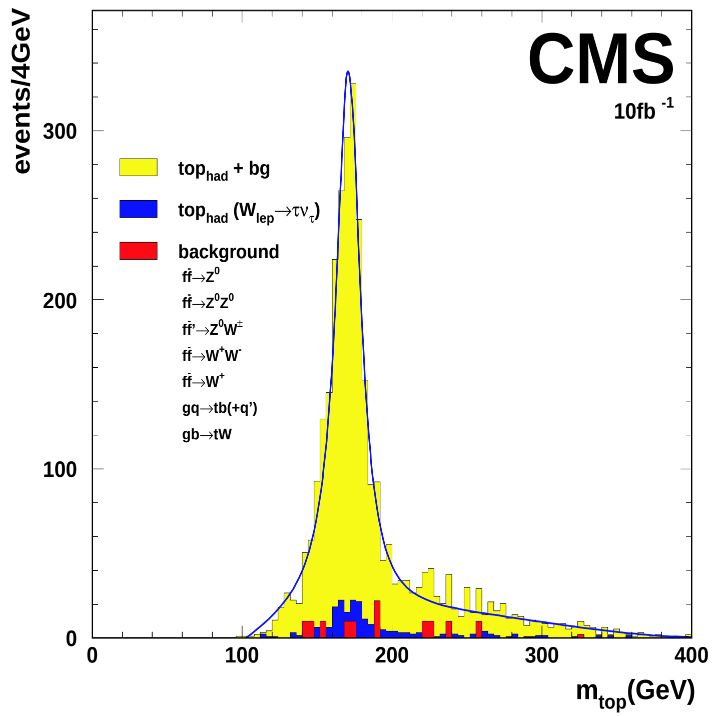
main of background comes from W+jets production
PYTHIA was used for signal and background generation
the fast MC package CMSJET was used for CMS detector simulation
selection criteria:

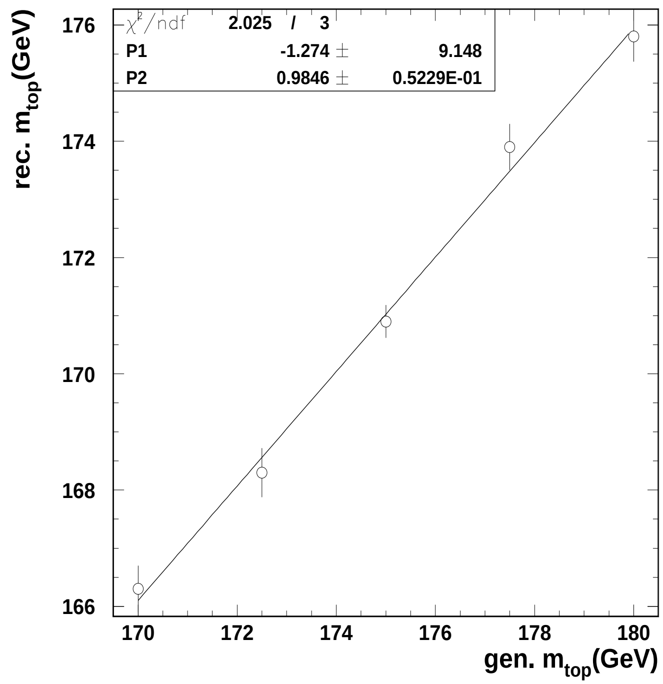
◇ only one isolated $e^\pm$ or $\mu^\pm$ with $p_\top > 20$ GeV, $|\eta| < 2.4$, $\Delta R > 0.3$ (isolation)
◇ $\not{E}_\top > 20$ GeV
◇ at least 4 jets with $E_\top > 40$ GeV, exactly 2 b-jets with $E_\top > 50$ GeV, $\epsilon_b \approx 52\%$
◇ $W \rightarrow q\bar{q}'$: $60 < M(j_1 j_2) < 100$ GeV
◇ $W \rightarrow \ell\nu$: transverse mass of $(\ell\nu)$-system, $m_\top(\ell\nu) < 100$ GeV
◇ $\cos(\phi_t - \phi_{\bar{t}}) < -0.8$
◇ reconstructed top masses difference $|m_t - m_{\bar{t}}| < 25$ GeV

- analysis details:

◇ 2.4×10^6 semileptonic events simulated with PYTHIA and reconstructed (10 fb^{-1})

◇ after all cuts: $N_S = 2960 \pm 53$ (efficiency $\approx 0.2\%$), $N_B = 120 \pm 55$, $S/B \sim 25$





◇ the estimated total error on top mass

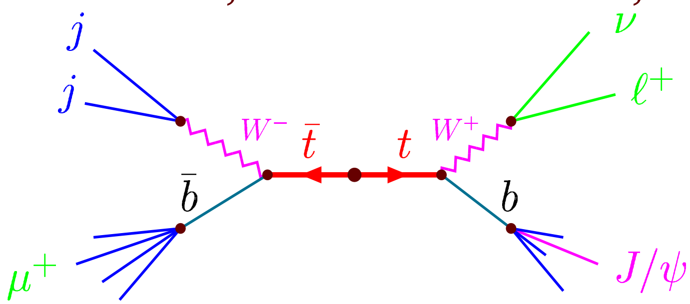
$\Delta m_t = (0.9 - 1.3)$ GeV + absolute energy scale $\Longrightarrow \delta m_t \leq 0.7\,\%$

- various sources of the errors were investigated

  statistical error: ~ 0.25 GeV, uncertainty of top-quark p_T spectrum ~ 0.4 GeV

- m_t from $t \to \ell J/\psi\, X$ decays

(I. Iashvili et al., CMS TN 1992/034; A. Kharchilava, CMS NOTE 1999/065)



$$t \to bW^+$$
$$W^+ \to \ell\nu + b \to J/\psi X$$
$$\Longrightarrow t \to \ell\, J/\psi\, X$$

◇ the invariant mass of $(\mu\ J/\psi)$ system is correlated to m_t
◇ no dependency of uncertainties on the jet energy scale
◇ only $\mathcal{O}(10^3)$ events are expected per year at high luminosity (100 pb^{-1})

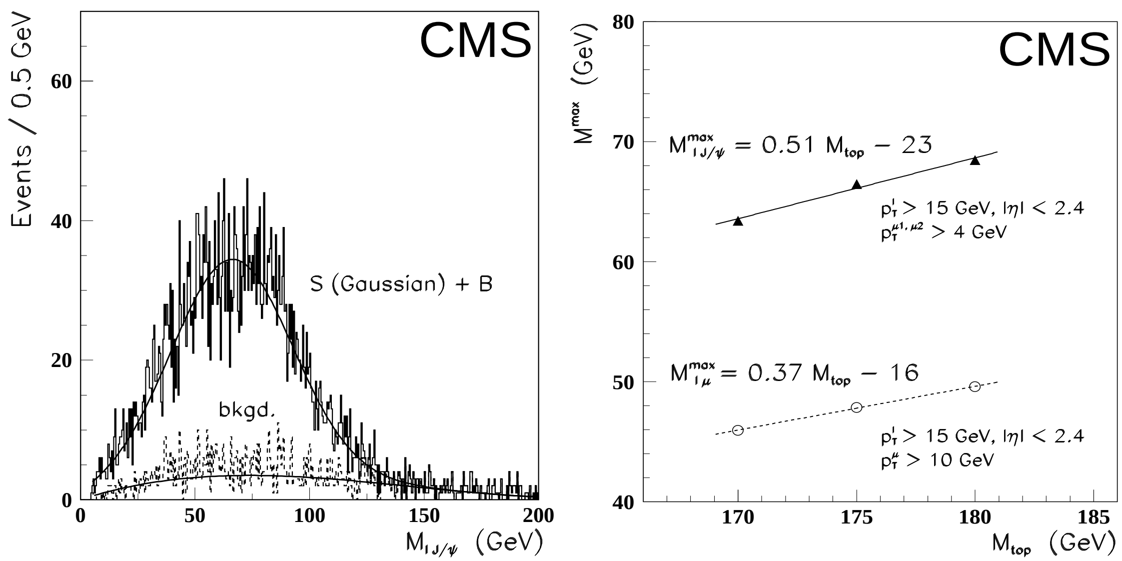
selection criteria:

◇ only one isolated $e^\pm$ or $\mu^\pm$ with $p_\top > 15$ GeV, and $|\eta| < 2.4$
◇ three non-isolated muons with $p_\top > 4$ GeV, and $|\eta| < 2.4$
◇ the invariant mass of two of these muons being consistent with J/ψ mass

◇ PYTHIA + Gaussian smearing of CMS detector resolution

◇ 4000 signal events could be expected for 4 years at high luminosity (100 fb^{-1})

◇ kinematic acceptance = 0.3 (due to soft muons), trigger reconstruction efficiency = 0.8



$$M^{max}_{\ell\, J/\psi} = 0.51 M_t - 23 \text{ (GeV)}$$

• total error (stat.+syst.) is $\delta m_t \leq 1$ GeV

precision is limited by theory (b-quark fragmentation)

the systematics are completely different from m_t measurement from the semileptonic events

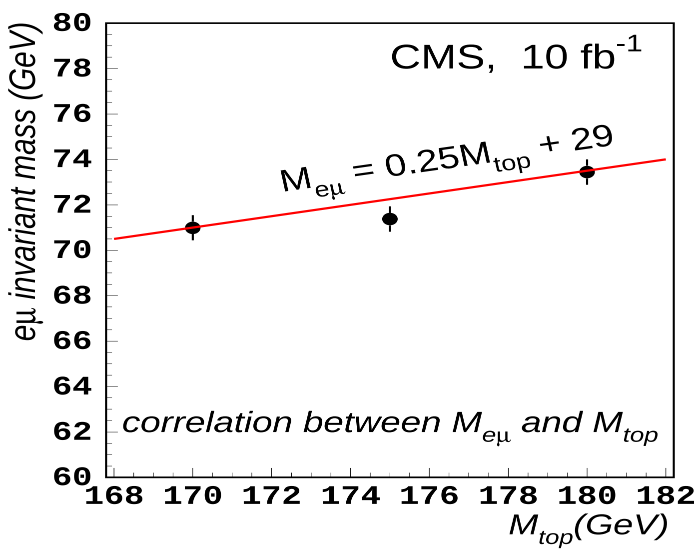
• dileptonic $t\bar{t}$ decays (R. Kaur, S.B. Beri, J.M. Kohli, CMS IN 2001/018)

$$t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow e^{\pm}\mu^{\mp}\nu\nu b\bar{b}$$

the invariant mass of $(e^{\pm}\mu^{\mp})$ system is correlated to m_t

selection criteria:

- ◇ two isolated $e^{\pm}$ and $\mu^{\pm}$ with $E_{\top} > 15$ GeV, and $|\eta| < 2.5$
- ◇ at least two jets with $E_{\top} > 15$ GeV, and $|\eta| < 2.5$
- ◇ isolation criterion: $\Delta R(\mu j) > 0.5$



$$\langle M(e^{\pm}\mu^{\mp})\rangle = 0.25M_t + 29 \text{ GeV}$$

$$\delta\langle M(e^{\pm}\mu^{\mp})\rangle \Longrightarrow \delta m_t \leq 2 \text{ GeV}$$

measurement of the W polarization in top decays

L. Sonnenschein, CMS NOTE 2001/001

SM predicts three different helicity states ($h_W = \pm 1, 0$) of W-boson in top decays. The right circular polarization ($h_W = +1$) is highly suppressed due to helicity conservation in the limit of vanishing b-quark mass. The fraction of the $h_W = 0$ state is large because of the large top mass:

$$\frac{\Gamma(h_W = -1)}{\Gamma_{tot}} = 0.297, \quad \frac{\Gamma(h_W = 0)}{\Gamma_{tot}} = 0.703, \quad \frac{\Gamma(h_W = +1)}{\Gamma_{tot}} = 0$$

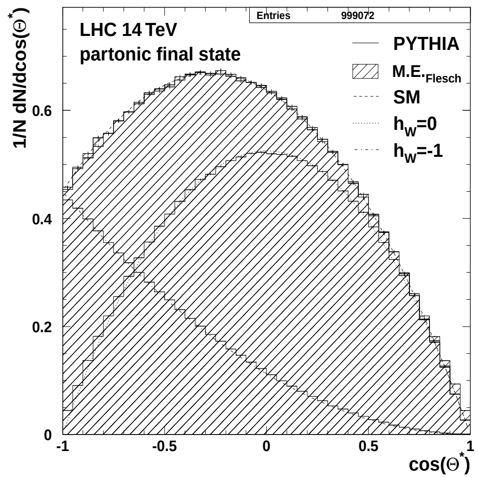
the sensitive variable for the W polarization is the angle θ^*_ℓ between the lepton in the W rest frame and the W in the top rest frame:

$$\frac{1}{N}\frac{dN}{d\cos\theta^*} = \frac{3}{8}\frac{1}{1-f}(1-\cos\theta^*)^2 - \frac{3}{4}\frac{1}{1-f}\sin^2\theta^*$$

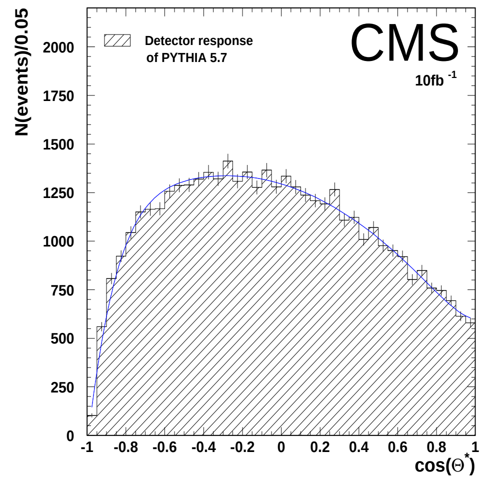
where $f = m_t^2/2m_W^2$ neglecting the b quark mass.

resulting distribution of $\cos\theta^*_\ell$

generator level



after detector simulation and event selection



analysis details:

◇ 2.4×10^6 semileptonic events simulated with PYTHIA and reconstructed (10 fb^{-1})

◇ selected signal events: $W^\pm \to e^\pm(\mu^\pm)\nu$

◇ expected accuracy on the measurements of $\frac{h_{W=0}}{h_{W\ tot}}$ is

$$\delta\left(\frac{h_{W=0}}{h_{W\ tot}}\right) = \pm 0.023(stat) \pm 0.022(syst)$$

measurement of spin correlation in $t\bar{t}$ production

spin correlations are parametrized by the asymmetry

$$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$

$$\mathcal{A}(gg) = +0.431 \pm 0.002, \quad \mathcal{A}(q\bar{q}) = -0.469 \pm 0.003,$$

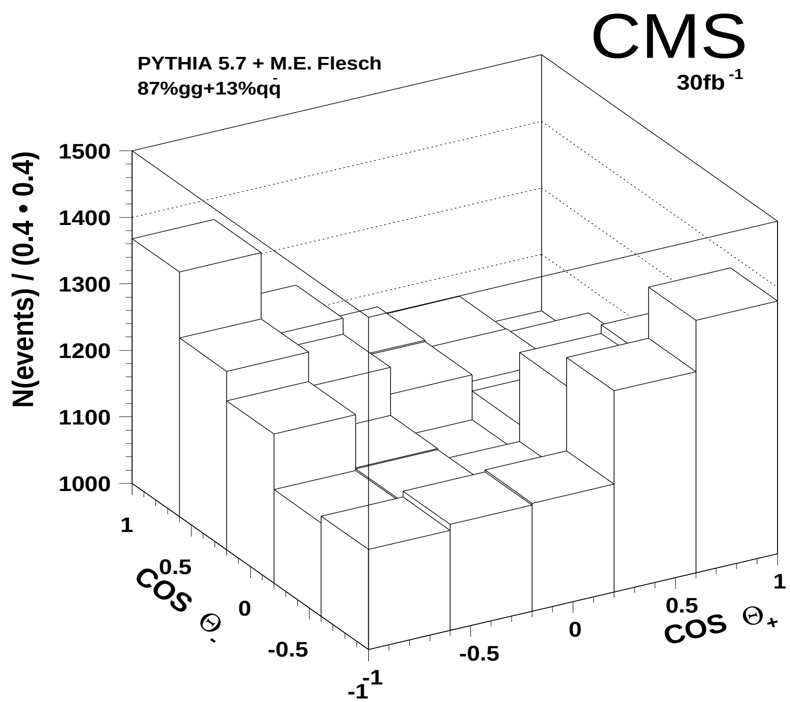
$$\mathcal{A}[t\bar{t} = gg(87\%) + q\bar{q}(13\%)] = 0.311 \pm 0.003$$

◇ top and topbar momenta could reconstructed from set of six kinematic equations

$$\frac{1}{N}\frac{d^2N}{d\cos\theta^*_{\ell+}\, d\cos\theta^*_{\ell-}} = \frac{1}{4}\left(1 - \mathcal{A}\cos\theta^*_{\ell+}\cos\theta^*_{\ell-}\right)$$

θ^*_ℓ is the angle between the ℓ in the top rest frame and the top in the $t\bar{t}$ pair rest frame

$\diamond$ 10^6 fully leptonic events $t\bar{t} \to bW^+\bar{b}W^- \to b\bar{b}\ell^+\ell^-\nu\bar{\nu}$ (corresponds to 30 fb^{-1})

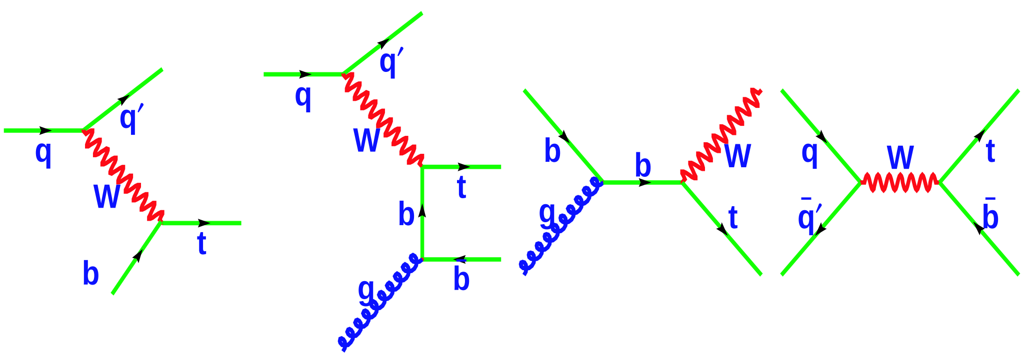


$$\mathcal{A} = +0.311^{+0.034}_{-0.035}(stat) \pm 0.028(syst)$$

Electro-Weak top production

- investigations of the electroweak (single) t-quark production will allow to:
  - ◇ direct measurement of V_{tb} CKM element (and check the unitarity of CKM)
  - ◇ examine the structure of $Wt\bar{b}$ vertex
  - ◇ search for possible New Physics effects (like FCNC, $H^{\pm}$, W', ...)

- three subprocesses contribute to single top production, $\sigma_{\rm EW}(t) \propto |V_{tb}|^2$



t-channel tW s-channel

$\sigma(t\text{-channel})$ = 245 ± 27 pb
S. Willenbrock *et al*, PR D56, 5919
$\sigma(tW)$ = 60 ± 10 pb
A. Belyaev, E.E. Boos, PR D63, 034012
$\sigma(s\text{-channel})$ = 10.2 ± 0.7 pb
M. Smith *et al*, PR D54, 6696

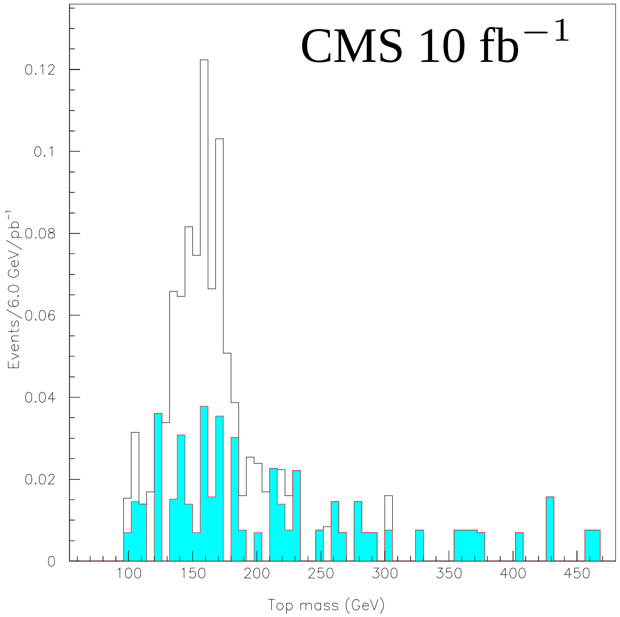
• search strategy for t-channel D. Green *et al*, CMS NOTE-1999/048 (1999)

$$qb \rightarrow q' t \Rightarrow q'_{\rm forw}\ b\ \ell^{\pm}\ \nu$$

background events: $t\bar{t}$, $W + $2jets, $W + $3jets, and WZ
PYTHIA 5.72 was used for generation of the signal and background ($t\bar{t}$ and WZ) events
VECBOS was used for W+jets production

• selection at generation level (PYTHIA)
◇ only one charged lepton ($e^{\pm}$ or $\mu^{\pm}$, $p_{\rm T} > 20$ GeV, $|\eta| < 2.5$ (is used in the analysis)
◇ at least one cluster with $E_{\rm T} > 15$ GeV and $|\eta| < 2.5$ and two or less clusters with
$E_{\rm T} > 25$ GeV and $|\eta| < 2.5$
◇ B-tagging parameterization (from full simulation): $|\eta| < 2.4$,
$\epsilon(b)$ is typically 50%, mis-tagging is low, 1-2%

• full simulation of CMS calorimeters (ECAL and HCAL), CMSIM (version 111, GEANT3)
jets: E(cell)> 5 GeV, clustering algorithm ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$)
• minimal value of $|P_z(\nu)|$ is used for W-boson momentum reconstruction



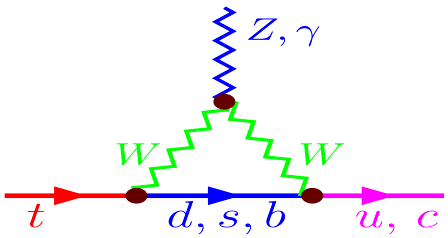
search strategy

◇ one isolated $e^{\pm}$ or $\mu^{\pm}$ with $p_T > 20$ GeV and $|\eta| \leq 2.5$
◇ $\not{E}_T \geq 20$ GeV and $50 < m_T(\ell\nu) < 100$ GeV
◇ one b-tagged jet with $p_T \geq 20$ GeV and $|\eta| \leq 2.5$
◇ one forward jet with $p_T \geq 50$ GeV and $2.5 < |\eta| \leq 4.0$
◇ leading jet with $p_T < 100$ GeV
◇ $M(jj) < 80$ GeV or $M(jj) > 100$ GeV
◇ mass window: $M_{rec}(W + B) = 160 \pm 20$ GeV

- after cuts: N(signal) = 6600, N(bkg) =1900 , S/B = 3.5:1 for 10 fb^{-1}
- selection efficiency $= 1.2\%$ (including BR$(W \rightarrow \ell\nu)$)
- dominant background comes from W+charm
- forward jet tag is very effective in enhancing of S/B ratio

Search for rare FCNC top decays

◇ theoretical predictions for BR($t \to qV$), $V = g,\ \gamma,\ Z$



$t \to$	SM	two-Higgs	SUSY
$g\,q$	5×10^{-11}	10^{-6}	10^{-3}
$\gamma\,q$	5×10^{-13}	10^{-6}	10^{-5}
$Z\,q$	$\sim 10^{-13}$	10^{-9}	10^{-4}

• search strategy: F. Gianotti *et al*, CERN-TH/2002-078, hep-ph/0204087 (2002).
$t\bar{t}$ pair production

$$pp \to t\bar{t}X, \quad \text{with} \;\; t \to qg, \quad t \to q\gamma, \quad t \to qZ$$

the other top decays in the SM mode: $t \to bW(\to \ell\nu)$:

- ◇ $t\bar{t}$ (800 pb) $\quad + \quad$ single top (240 pb)
- ◇ $W(\to e, \mu) + jets$ ($\sim$ 7500 pb for $\hat{k}_\top > 20$ GeV)
- ◇ $WW + WZ + ZZ$ (110 pb)
- ◇ $W\,\gamma$ (17.3 pb)

• TopReX 3.25 event generator is used for signal and background simulation
PYTHIA 6.158 is used for fragmentation
all events passed through CMSJET 4.703 for detector simulation
selection criteria:

◇ an isolated photon with $E_{\top} > 75$ GeV, and $|\eta| < 2.5$
◇ 1(3) isolated leptons with $E_{\top} > 20$ GeV, and $|\eta| < 2.5$
◇ $N(J) \geq 2$ with $E_{\top} > 30(50)$ GeV, and $|\eta| < 4.5$
◇ one b-tagged jets
◇ $|M(B+W) - m_t| \leq 25$ GeV and $|M(jet + \gamma(Z,g)) - m_t| \leq 25$ GeV

after application of all cuts separately for each channel one could expect (for 100 pb^{-1})

	$t \to q\gamma$	$t \to qZ$	$t \to qg$
$N(S)$	628	31	233
$N(B)$	38	3.9	15000
BR	2.5×10^{-5}	1.6×10^{-4}	1.6×10^{-3}

future promises and expectations

	present	Run-II	CMS
$\sigma(t\bar{t})$	6.2 ± 1.7pb	6–8 pb	830 pb
$\delta(\sigma(t\bar{t}))$	25%	10%	10%
$\delta(\sigma(t)_{EW})$		20%	10%
$\Delta(m_t)$ GeV	4.3	2 (?)	$\mathcal{O}(1)$ GeV
$\delta(m_t)$	2.4 %	1.1 %	$\mathcal{O}(0.5\%)$
spin correlations	$A > -0.2$ (0.88)	?	0.3 ± 0.05
$\delta\|V_{tb}\|$(BR)	15%	3%	?
$\delta\|V_{tb}\|$(EW)	–	12%	$\mathcal{O}(5)$%
BR$(t \to \gamma q)$	0.29%	0.20%	2.5×10^{-5}
BR$(t \to Zq)$	8.1%	1.3%	1.6×10^{-4}
BR$(t \to gq)$	29%	0.06%	0.16%

Conclusions

- CMS detector will be able to study different aspects of the top quark physics
- three methods of the t-quark mass measurements were investigated
- CMS could be achieved the accuracy of m_t up to 1 GeV (the systematic uncertainty)
- spin-spin correlations in $t\bar{t}$ production could be measured with $\sim 15\%$ accuracy
- CMS will be able isolate the single top events with S/B=3.5:1 and a clear peak visible in $M(Wb)$ distribution
- forward jet tag is a crucial point in the study of t-channel single top production
- CMS could reach a high sensitivity to rare FCNC top-quark decays, $\mathrm{BR}(t \to q\gamma) \sim 10^{-5}$, $\mathrm{BR}(t \to qZ) \sim 10^{-4}$, $\mathrm{BR}(t \to qg) \sim 10^{-3}$