Top physics with CMS

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on behalf of the CMS collaboration

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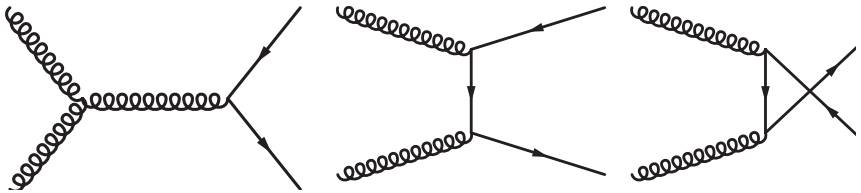
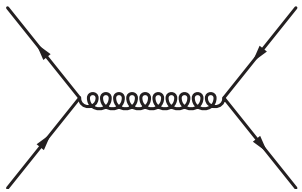
Outline

$t\bar{t}$ Physics at LHC

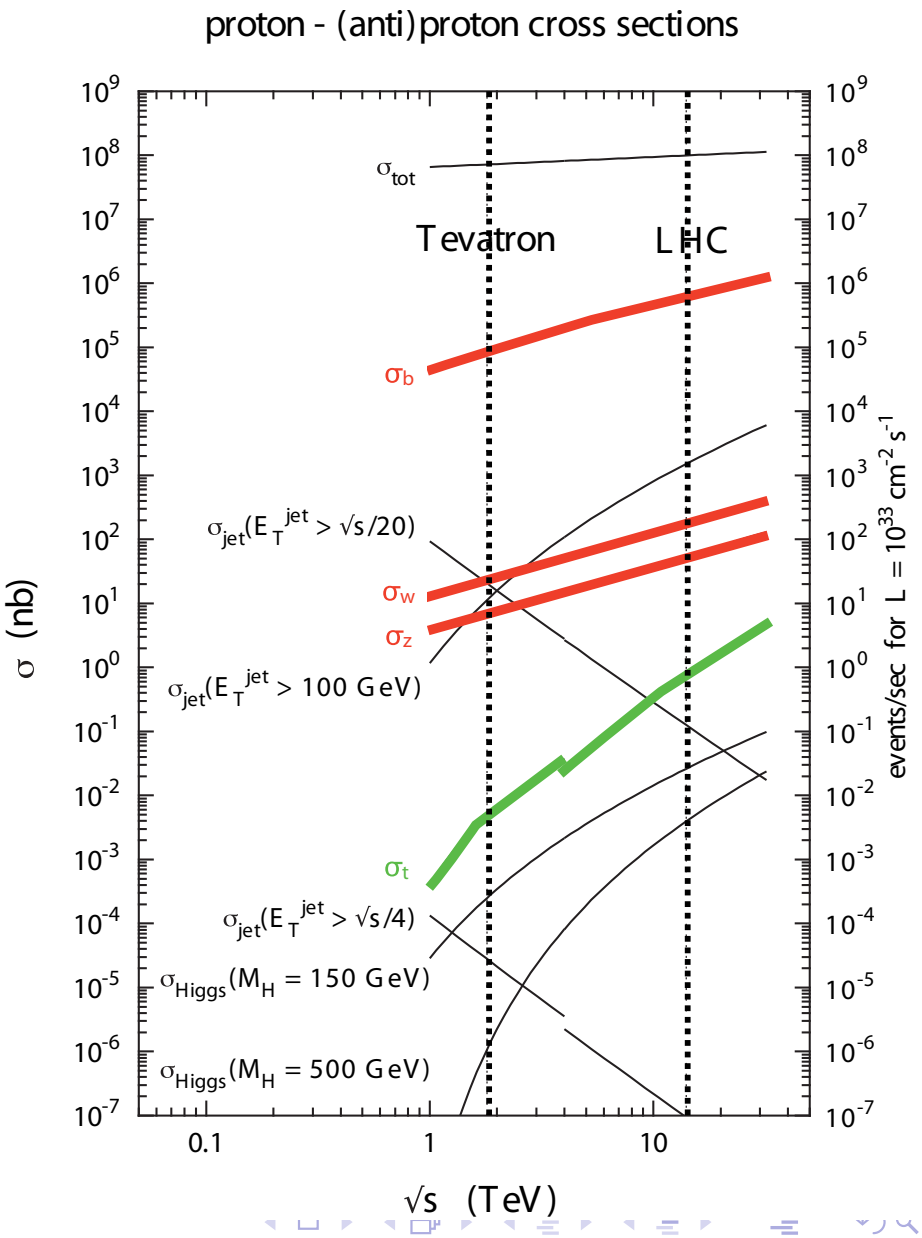
- $\sigma(pp \to t\bar{t}) \sim 830$ pb (NLO)
- $\sim 87\%$ gluon fusion



- $\sim 13\%$ quark annihilation



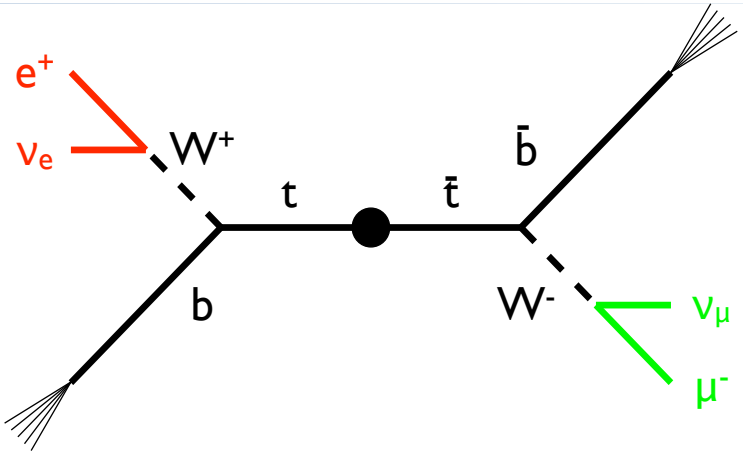
- approximately one $t\bar{t}$-pair per second at $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ $\Rightarrow$ LHC is a top factory!
- $\mathrm{BR}(t \to bW) \sim 100\%$
- other rare SM decays either CKM suppressed or via FCNC



Dilepton Channel

clean final state signature

- two isolated opposite-sign high momentum leptons
- two jets from b quark hadronisation

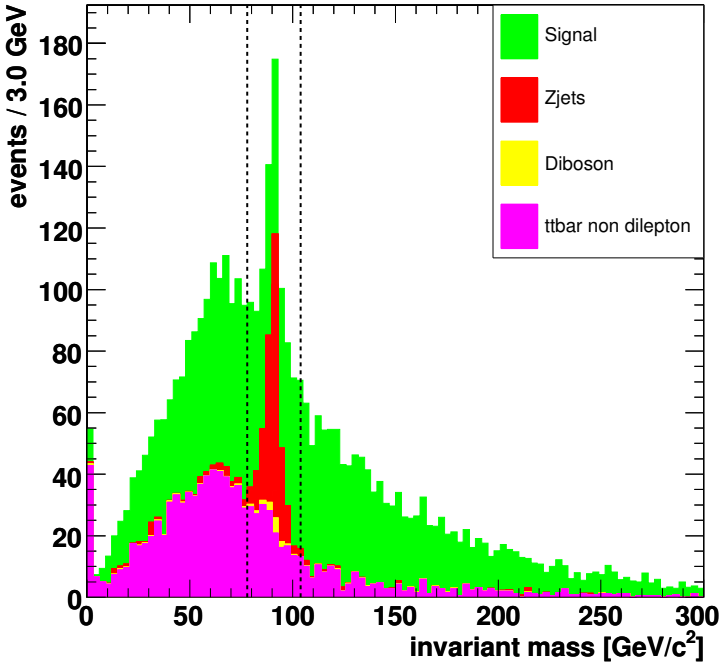


lowest BR (1/9)

- 54 pb (LO) at LHC
- 27 pb (LO) without $W^{\pm} \rightarrow \tau^{\pm}\nu$

⇒

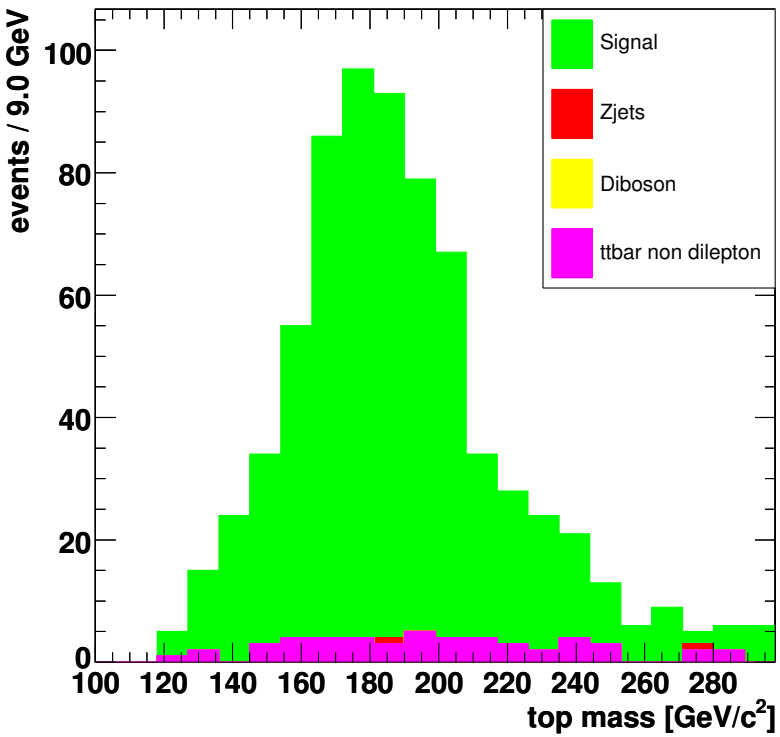
- high trigger probability
- signal can be seen with less than 1 fb^{-1}
- S/B = 12 achieved (e and μ)



Event Reconstruction in the Dilepton Channel

event kinematic has large sensitivity to m_t

$$\left.\begin{array}{lcl} 0 & = & \sum_{i\in\{\ell,\nu,b\}} p_T^i \\ m_{W^\pm}^2 & = & (p^{\ell^\pm} + p^{\nu|\overline{\nu}})^2 \\ m_t^2 & = & (p^{\ell^\pm} + p^{\nu|\overline{\nu}} + p^{b|\overline{b}})^2 \end{array}\right\} 0 = \sum_{i=0}^{4} c_i(m_t, p^{\ell^\pm}, p^b, p^{\overline{b}})(p_x^{\overline{\nu}})^i$$



kinematically underconstrained

- use m_W, assume m_t and try to solve kinematics
- weight solutions with SM neutrino spectrum
  $\longrightarrow$ distribution of most likely solutions / top mass

Measurements in the Dilepton Channel

mass measurement (1 and 10 fb^{-1})

main systematics: b-jet energy scale

$$1 \quad \mathrm{fb}^{-1} : \Delta m_t = \pm 1.5\,(\mathrm{stat.}) \pm 4.5\,(\mathrm{syst.})\ \mathrm{GeV/c}^2$$
$$10 \quad \mathrm{fb}^{-1} : \Delta m_t = \pm 0.5\,(\mathrm{stat.}) \pm 1.1\,(\mathrm{syst.})\ \mathrm{GeV/c}^2$$

cross section measurement (10 fb^{-1})

only $e - \mu$ dilepton events to remove Drell-Yan background

Effect	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$	Effect	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$
Jet Energy Scale	3.6%	Pile-Up	3.6%
b-tag efficiency	3.8%	Underlying Event	4.1%
Lepton reco.	1.6%	Heavy quark fragm.	5.1%
$E_{\mathrm{T}}^{\mathrm{miss}}$	1.1%	PDF uncertainties	5.2%
		ISR and FSR	2.5%

$$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} = \pm 0.9\%\,(\mathrm{stat.}) \pm 11\%\,(\mathrm{syst.}) \pm 3\%\,(\mathrm{lumi.})$$

Lepton+Jets Channel

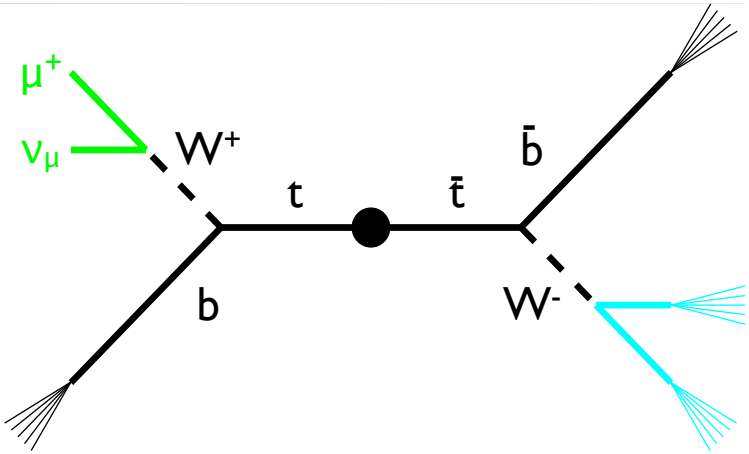
golden channel

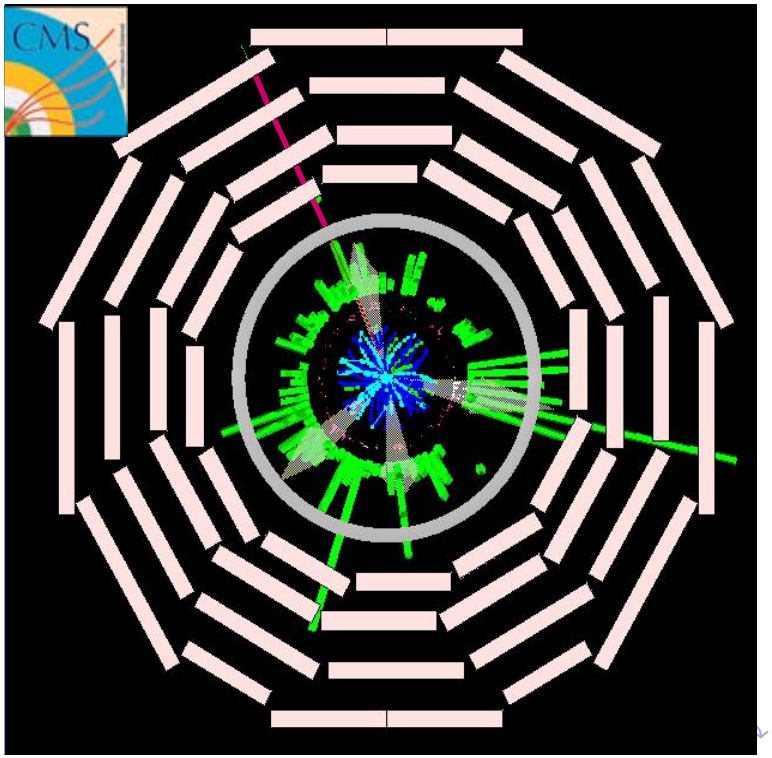
- clean signature
- large branching ratio

selection in μ channel

- single-muon trigger
- isolated muon
- four non-overlapping jets
  two b-tagged, two anti-b-tagged
- kinematic fit (m_W constraint)
- likelihood ratio

$< 4\%$ non-$t\bar{t}$ background
S/B > 8 achieved in μ channel



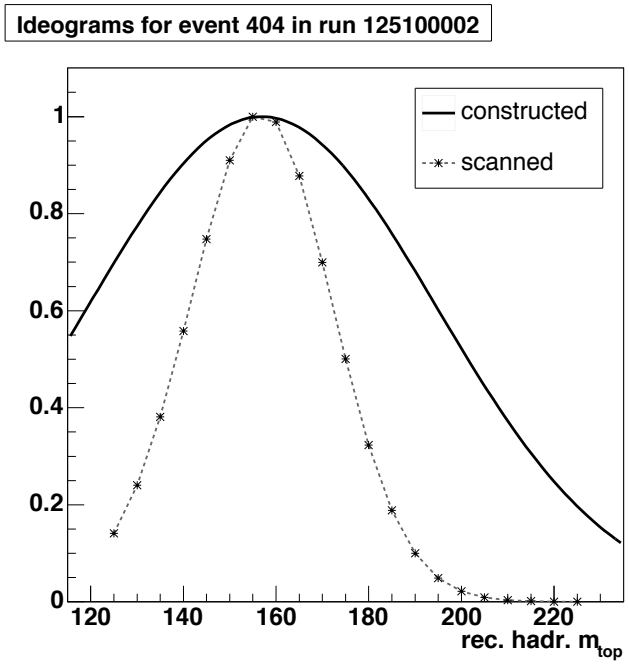


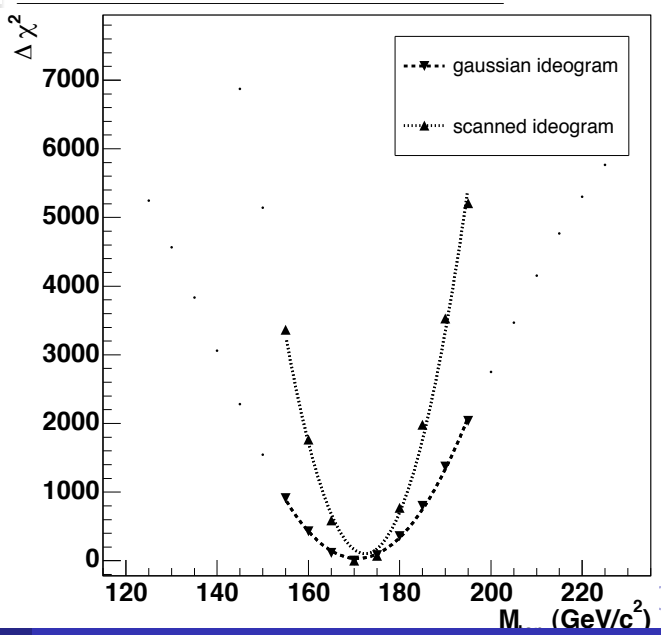
Top Quark Mass Estimator

event-by-event likelihood approach

- probability or ideogram of an event $P(y|m_t) \sim \exp\left(-\frac{1}{2} \cdot \chi^2(y|m_t)\right)$ with $\chi^2(y|m_t) = \left(\frac{m_t - m_t^{fit}}{\sigma_{m_t}^{fit}}\right)^2$
- convolution with th. expected probability density $P(m_t|M_t)$
  $\mathcal{L}_i(M_t) = \int P(y|m_t) \cdot P(m_t|M_t) dm_t$

  $P(m_t|M_t)$ includes Breit-Wigner shape of signal, combinatorial and process background; with M_t as the true value of the top mass
- maximum likelihood method on combination of all convoluted ideograms





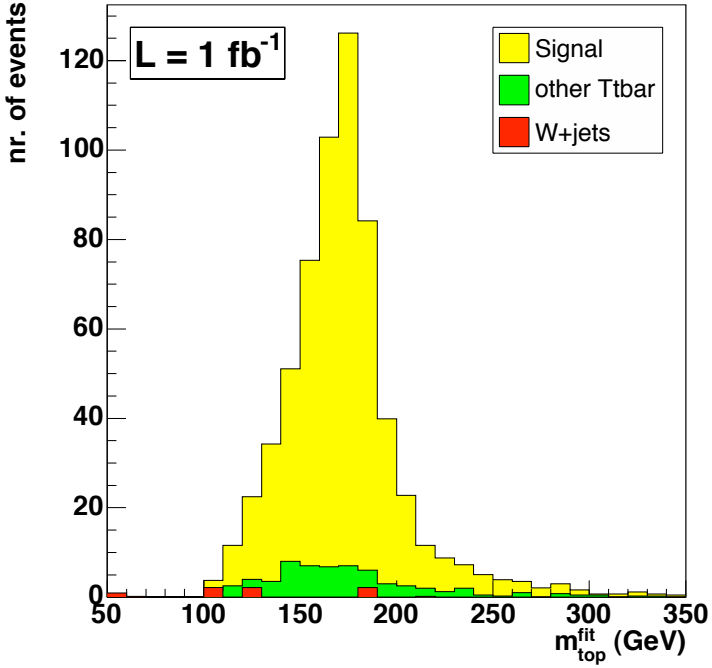
Mass Measurement in the Lepton+Jets Channel

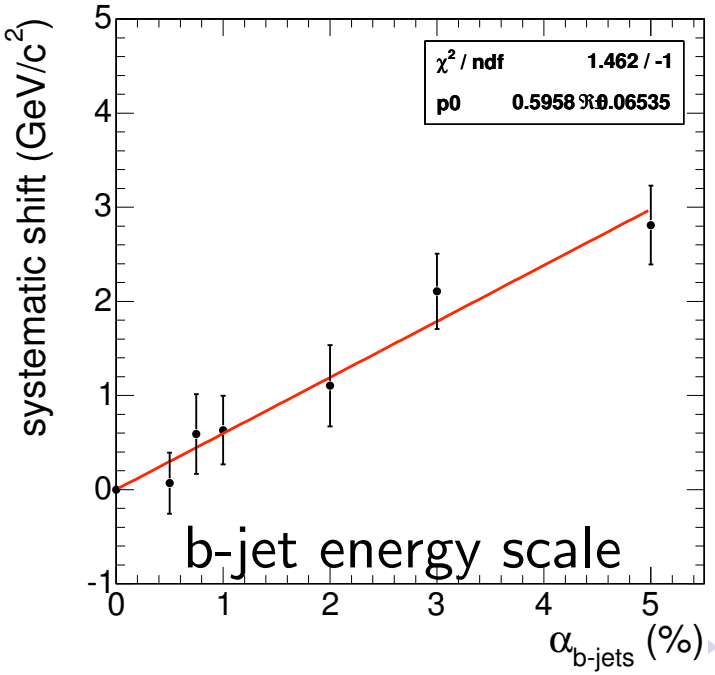
ideogram method

- self calibrating using m_W constraint
- reduced bias and systematic error

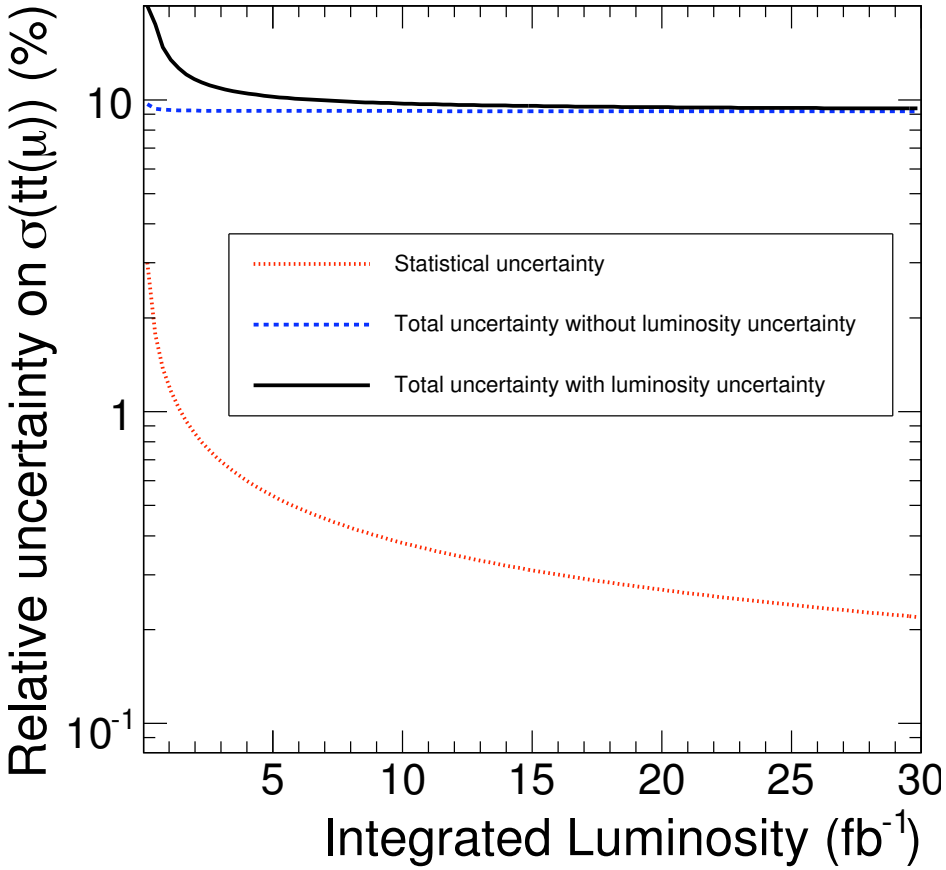
$\Delta m_t \approx 1\,\mathrm{GeV/c^2}$ possible

	Standard Selection		
	Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up	0.32	0.23	0.21
Underlying Event	0.50	0.35	0.25
Jet Energy Scale (light)	1.80	0.15	0.06
Jet Energy Scale (heavy)	1.05	0.98	0.90
Radiation (pQCD)	0.80	0.27	0.22
Fragmentation	0.40	0.40	0.30
b-tagging	0.80	0.20	0.18
Background	0.30	0.25	0.25
Parton Density Functions	0.12	0.10	0.08
Total Systematical uncertainty	3.21	1.27	1.13
Statistical Uncertainty (10fb^{-1})	0.32	0.36	0.21
Total Uncertainty	3.23	1.32	1.15





Cross Section in the Lepton(μ)+Jets Channel



	$\Delta\hat{\sigma}_{t\bar{t}(\mu)}/\hat{\sigma}_{t\bar{t}(\mu)}$		
	1 fb^{-1}	5 fb^{-1}	10 fb^{-1}
Simulation samples (ϵ_{sim})		0.6%	
Simulation samples (F_{sim})		0.2%	
Pile-Up (30% On-Off)		3.2%	
Underlying Event		0.8%	
Jet Energy Scale (light quarks) (2%)		1.6%	
Jet Energy Scale (heavy quarks) (2%)		1.6%	
Radiation (Λ_{QCD}, Q_0^2)		2.6%	
Fragmentation (Lund b, σ_q)		1.0%	
b-tagging (5%)		7.0%	
Parton Density Functions		3.4%	
Background level		0.9%	
Integrated luminosity	10%	5%	3%
Statistical Uncertainty	1.2%	0.6%	0.4%
Total Systematic Uncertainty	13.6%	10.5%	9.7%
Total Uncertainty	13.7%	10.5%	9.7%

cross section error $\approx$ 10%

Hadronic Channel

well defined multi-jet final state

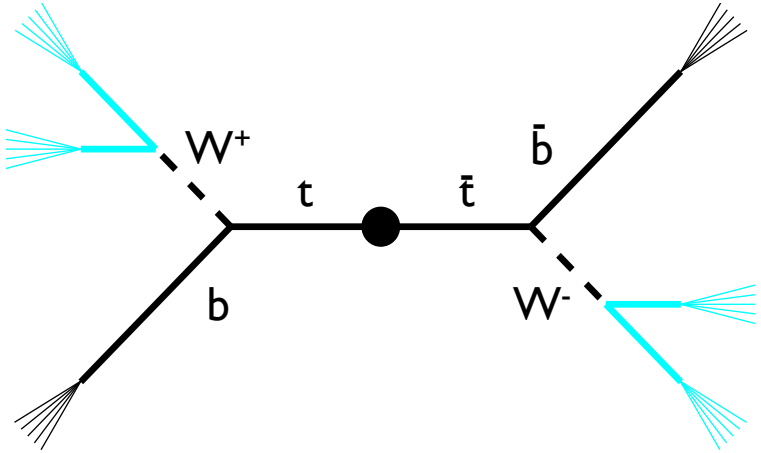
- six jets
- two b-jets, four light quark jets

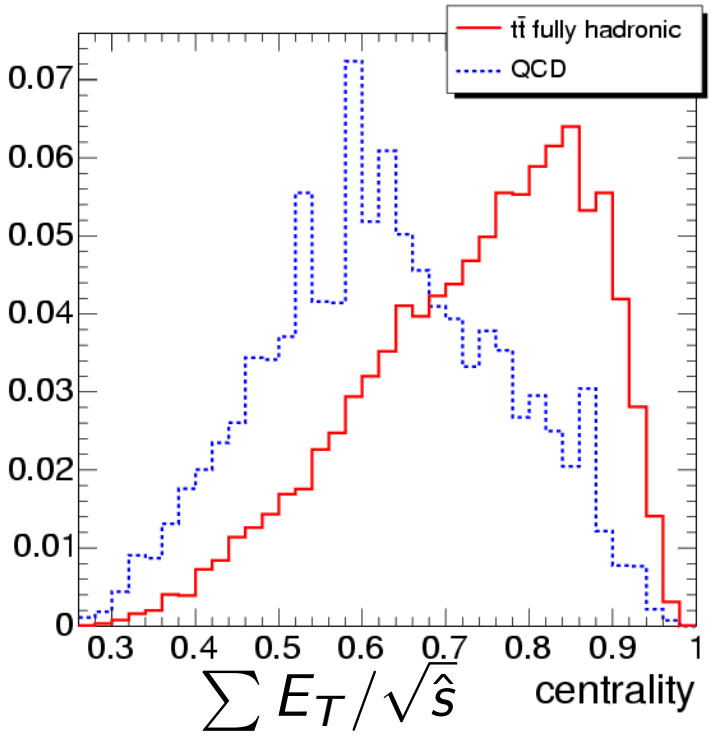
enormous QCD background

selection

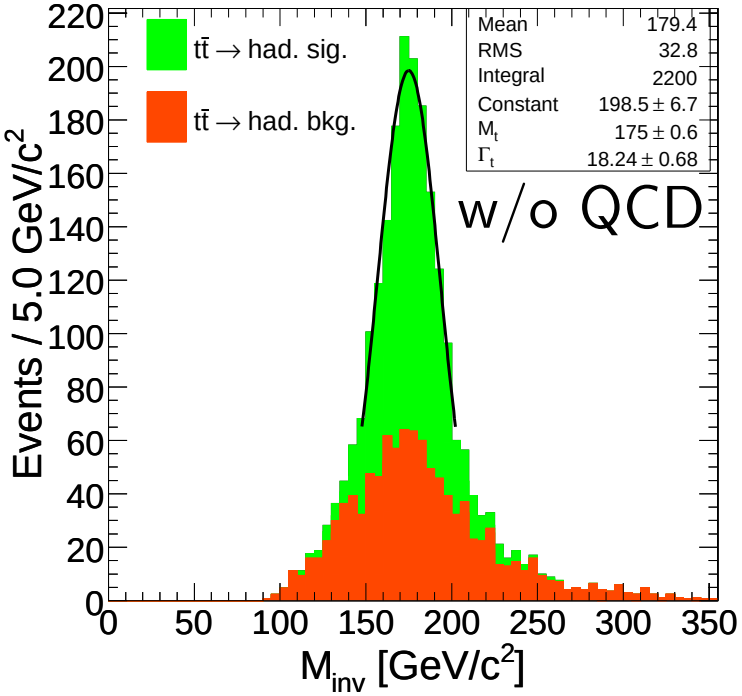
- specific multi-jet trigger with online b-tagging
  - 17% signal efficiency
  - S/B $\approx$ 1/300
- event shape variables, e.g. centrality
- simple cut based and neural network

S/B $\approx$ 2/3 (cut based)
cross section measurement to $\approx$ 20%





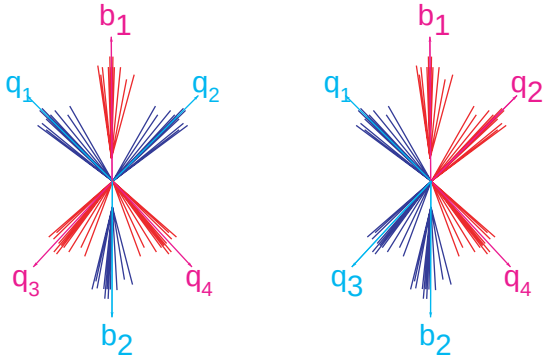
Mass Measurement in the Hadronic Channel



	Δm_t[GeV/c^2]
Pile Up	0.4
Underlying Event	0.6
PDF	1.4
IS/FS Radiation	2.3
Fragmentation	0.9
Jet Energy Scale	2.3
b-Tagging	0.3
Background	2.0

systematic uncertainties

combinatorial background, e.g.



1 fb^{-1}

already systematics dominated

$\Delta m_t = \pm 0.6\,(\text{stat.}) \pm 4.2\,(\text{syst.})\ \text{GeV/c}^2$

$t\bar{t}$ Events with J/ψ (Mass Measurement)

very clean experimental reconstruction

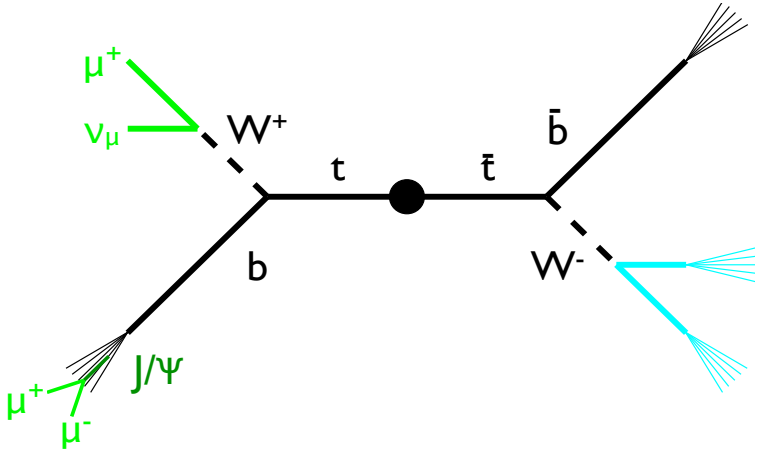
- only leptons, no jets
- no b-tagging, limited use of jet energy

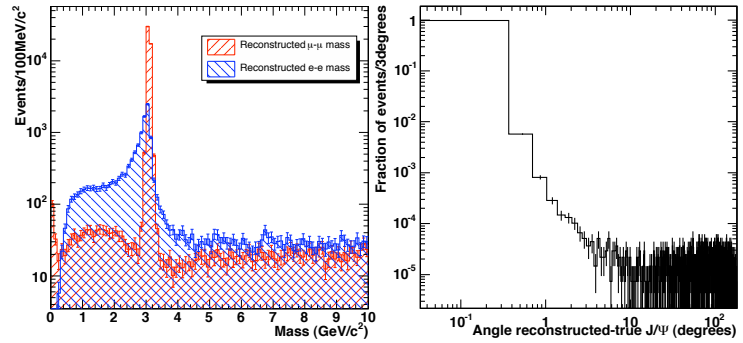
extremely low BR

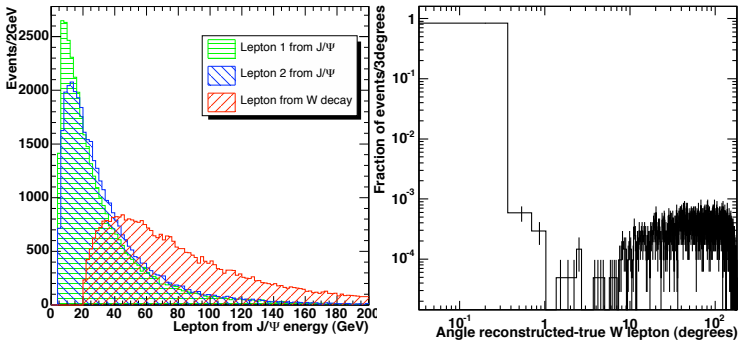
$5.5 \cdot 10^{-4} \rightarrow$ 4500 events per 10 fb^{-1}

selection of J/ψ and ℓ from W

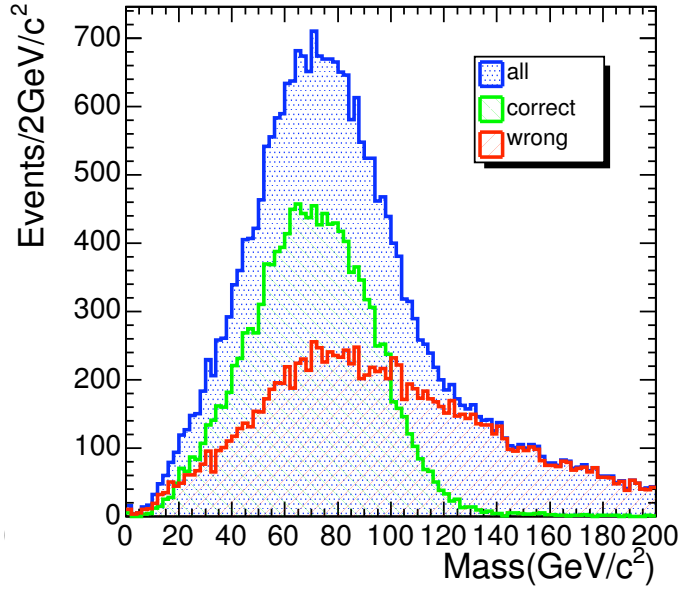
- inclusive lepton trigger
- J/ψ candidate using $m_{\ell\ell}$ and angle
- isolated high p_{T} lepton from W
- remove same flavour leptons near Z mass



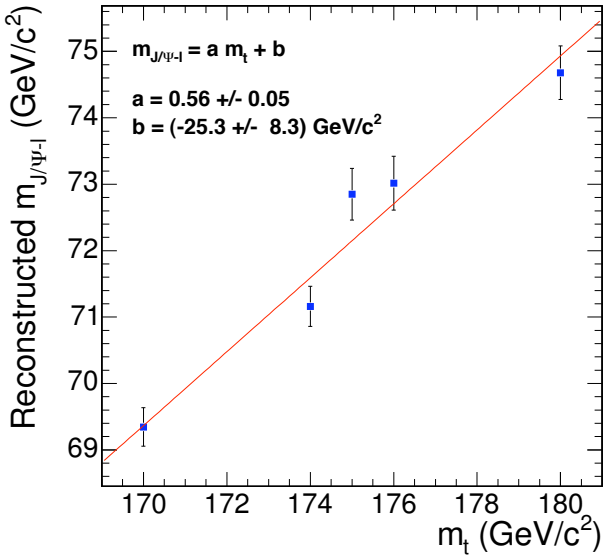




Mass Measurements in the J/ψ Channel



quartic polynomial fit to $m_{J/\psi\ell}$ most sensitive to m_t



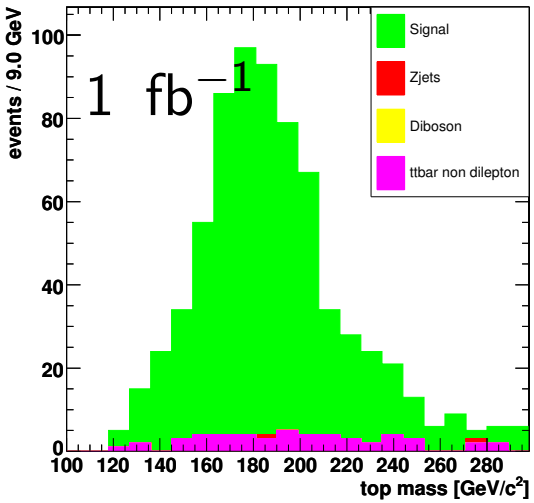
different contributions to systematics than in other $t\bar{t}$ studies (esp. theory)

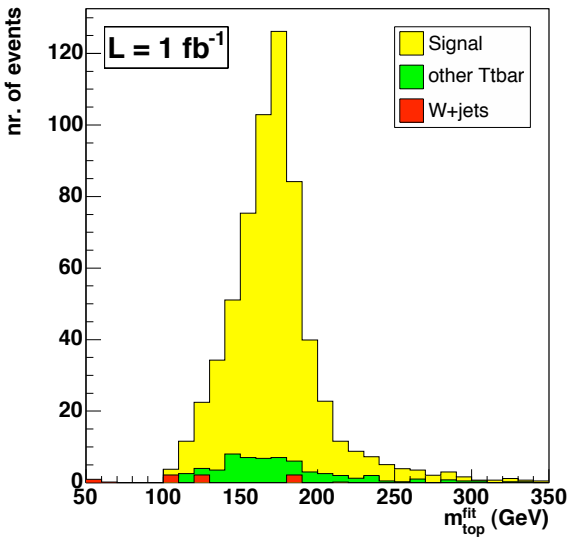
Source	δm_t(GeV/c^2)
Λ_{QCD}	0.31
Q^2	0.56
Scale definition	0.71
b-quark fragmentation	0.51
Light jet fragmentation	0.46
Minimum bias/Underlying event	0.64
Proton PDF	0.28
Total theoretical	1.37
Electron E scale	0.21
Muon p scale	0.38
Electron E resolution	0.19
Muon p resolution	0.12
Jet E scale	0.05
Jet E resolution	0.05
Background knowledge	0.21
Total experimental	0.54
Total systematic	1.47

for 20 fb^{-1} already systematics dominated
$\Delta m_t = \pm 1.2\,(\text{stat.}) \pm 1.5\,(\text{syst.})$ GeV/c^2

$t\bar{t}$ Top Mass Summary

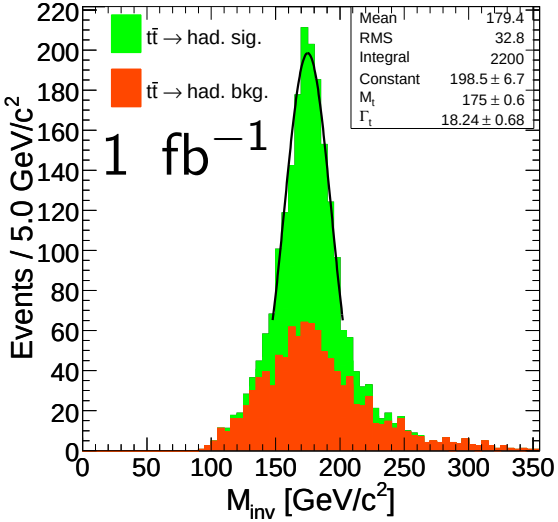
dilepton
$\pm 1.2\ \mathrm{GeV/c^2}$

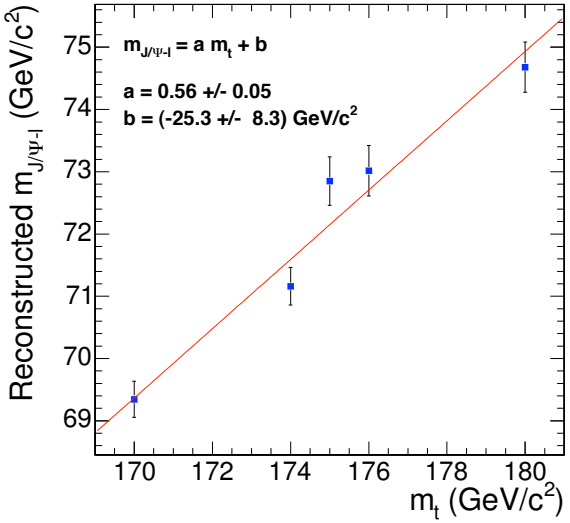




Lepton+Jets
$\pm 1.2\ \mathrm{GeV/c^2}$

hadronic
$\pm 4.2\ \mathrm{GeV/c^2}$





J/ψ
$\pm 1.5\ \mathrm{GeV/c^2}$

top mass accuracy of O(1 GeV/c^2) with well understood data (10 fb^{-1})

Spin Correlation in $t\bar{t}$ Events

large width of top quark

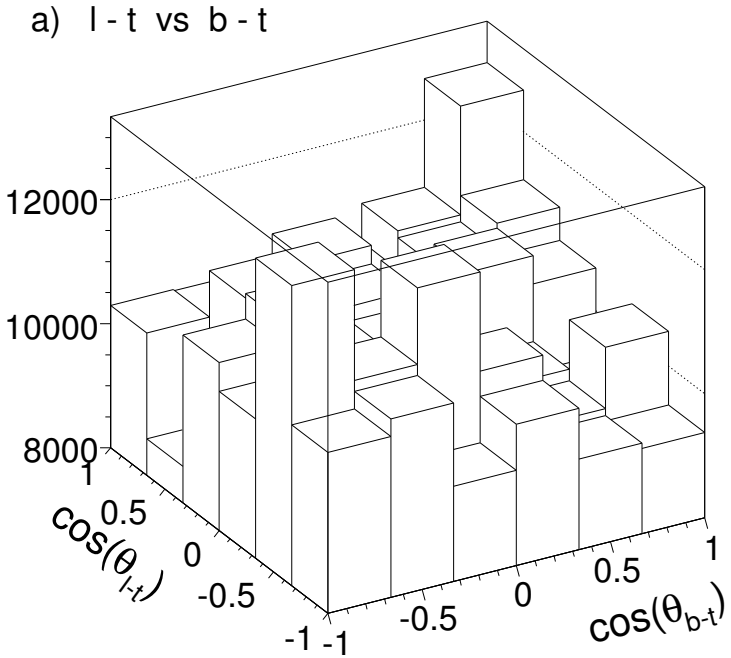
- decay before hadronisation
- angular distribution of decay products $\rightarrow$ spin information of $t\bar{t}$

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

- quark annih.: $\mathcal{A} = -0.469$
- gluon fusion: $\mathcal{A} = 0.431$

measured in double diff. distribution:

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_l\, d\cos\theta_q} = \frac{1}{4}(1 - \mathcal{A}\kappa_l\kappa_q \cos\theta_l \cos\theta_q)$$



- TopReX generator used
- weighted PYTHIA events simulated

$$\Delta\mathcal{A}_{b-t,l-t}/\mathcal{A}_{b-t,l-t} = 27\%$$
$$\Delta\mathcal{A}_{q-t,l-t}/\mathcal{A}_{q-t,l-t} = 17\%$$

$t\bar{t}$ FCNC Events

Decay	SM	two-Higgs	SUSY with $\not{R}$	Exotic Quarks	Exper. Limits(95% CL)
$t \to gq$	5×10^{-11}	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 5 \times 10^{-4}$	< 0.29 (CDF+TH)
$t \to \gamma q$	5×10^{-13}	$\sim 10^{-7}$	$\sim 10^{-5}$	$\sim 10^{-5}$	< 0.0059 (HERA)
$t \to Zq$	$\sim 10^{-13}$	$\sim 10^{-6}$	$\sim 10^{-4}$	$\sim 10^{-2}$	< 0.14 (LEP-2)

selection

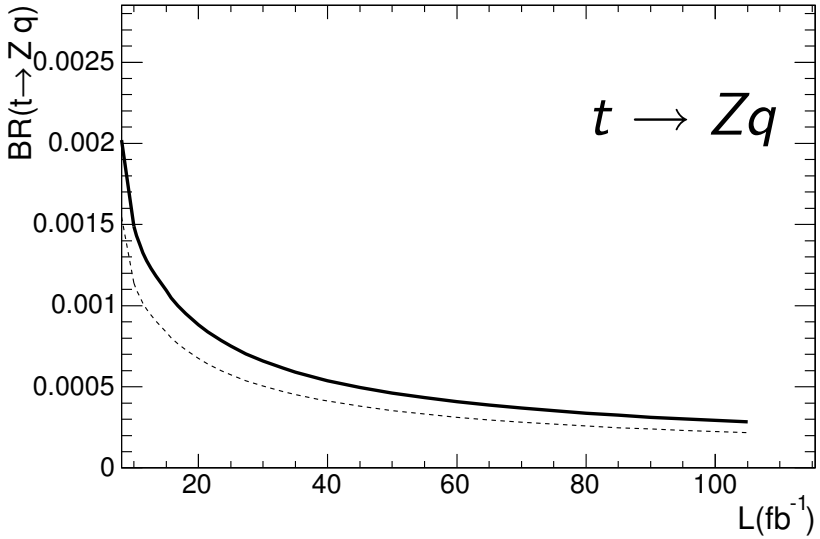
$t\bar{t}$ events generated with TopReX

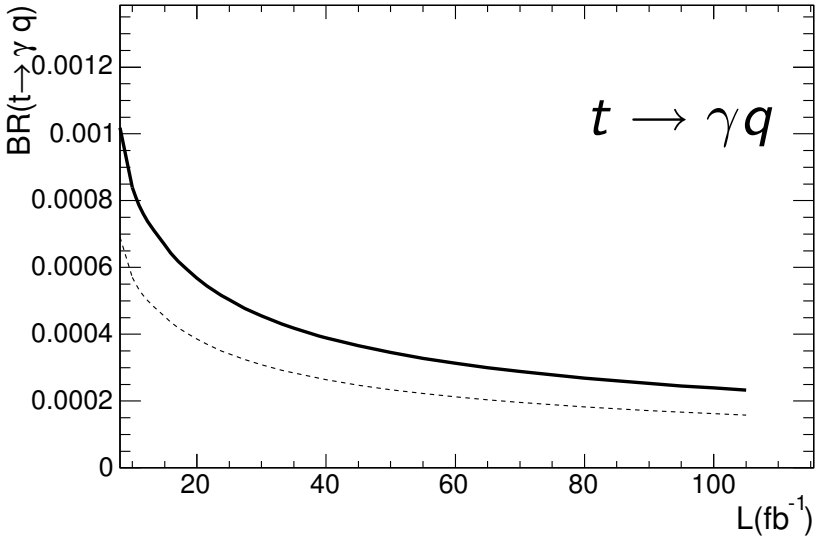
one SM decaying top + jet and Z or γ

main background $t\bar{t}$

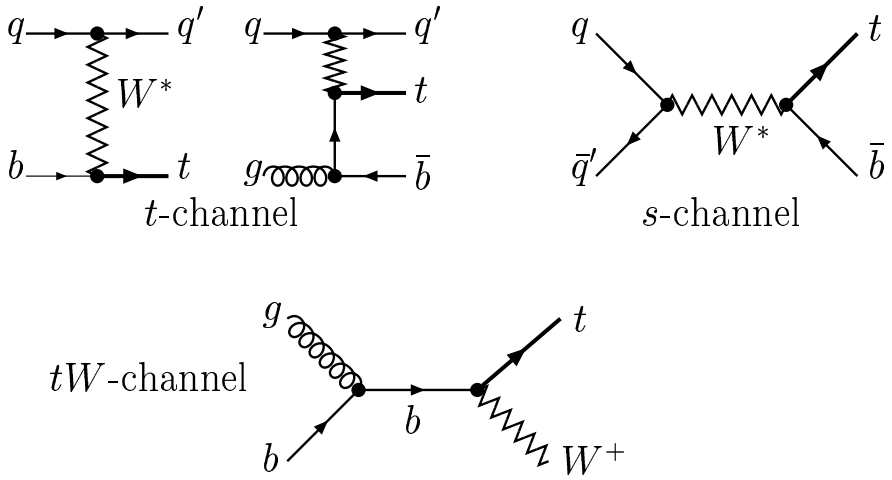
mass cut on jet and Z or γ

FCNC signals detectable at 5 σ:





Single Top Production at LHC



$\sigma \cdot \mathrm{BR}(W \to \ell\nu)$	
t-channel:	81.7 pb
s-channel:	3.3 pb
tW-channel:	40 pb

- direct measurement of the CKM matrix element V_{tb}
- investigation of the structure of tWb vertex
- generated with SingleTop and TopReX

background

- $t\bar{t}$ (830 pb) with similar final state
- multi-jet QCD and W+jets events
  $\rightarrow$ use only leptonic W decays from top quark & background determined from control samples

Single Top Cross Section

t-channel selection

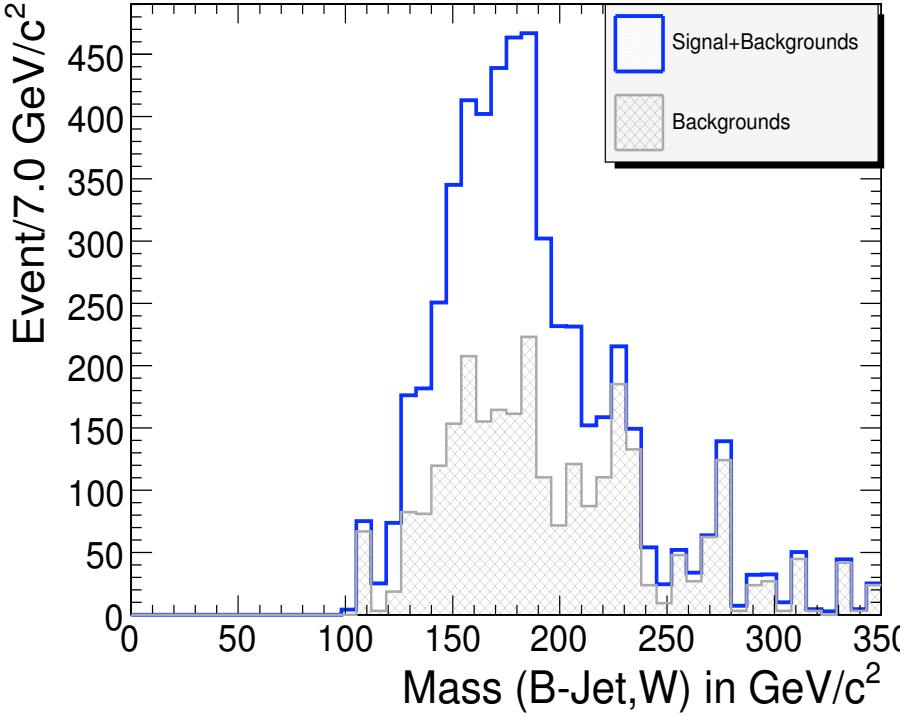
- muon, b-jet & light forward jet p_{T} and η cut
- $|\vec{\sum}_T|$ cut window
- top mass window

tW-channel selection

ratio method

- define $t\bar{t}$-rich control region
- use ratio of efficiencies in control and signal region
  $S = \frac{R_{t\bar{t}}(N_S - N_S^0) - (N_C - N_C^0)}{R_{t\bar{t}} - R_{tW}}$

$\rightarrow$ systematics (PDF, JES, b-tag, lumi.) cancel to large extent



$\sigma \cdot \mathrm{BR}(W \rightarrow \ell\nu)$ and est. error

t-channel:	81.7 pb	10%
s-channel:	3.3 pb	36%
tW-channel:	40 pb	17-24%

Summary

improvements

- $t\bar{t}$
  - $\Delta m_t \approx 1\,\mathrm{GeV/c^2}$ possible with O(10 fb^{-1})
  - $\Delta\sigma/\sigma \approx 10\%$ (di-, semileptonic) $-$ 20 (hadronic)%
- spin correlation
  correlation coefficient measurable to 17% $-$ 27% in Lepton+Jets channel
- FCNC decays
  BSM decays detectable at 5 σ (BR $\approx 10^{-4}$)
- single top
  cross section in the different channels to 10% $-$ 36% measurable

LHC will be a top factory

Large cross section and favourable S/B ratio will permit much improved measurements of top quark properties.