Single Top Quark. First Evidence

Edward Boos and Lev Dudko

Skobeltsyn Institute of Nuclear Physics, Moscow State University

Outline

- Part 1
  - Introduction
  - Basic single top processes and rates
  - Decays and spin correlations
  - "New Physics" via single top quark
  - NLO event generator SINGLETOP
- Part 2
  - First Evidence by D0
  - Conclusions

M. Beneke *et al.*, "Top quark physics," arXiv:hep-ph/0003033

LHC/LC Study Group, "Physics interplay of the LHC and the ILC," Phys.Rept.426:47-358,2006, arXiv:hep-ph/0410364

E.E. Boos, V.E. Bunichev, L.V. Dudko, V.I. Savrin, A.V. Sherstnev, "Method for simulating electroweak top-quark production events in the NLO approximation: SingleTop event generator," Phys. Atom. Nucl. **69**, 1317 (2006)

E. Boos, V. Bunichev, L. Dudko and M. Perfilov, "Interference between W' and W in single-top quark production processes," arXiv:hep-ph/0610080

V. M. Abazov *et al.* [D0 Collaboration], "Search for W' boson production in the top quark decay channel," Phys. Lett. B **641** (2006) 423

V. M. Abazov [D0 Collaboration], "Evidence for production of single top quarks and first direct measurement of —Vtb—," arXiv:hep-ex/0612052

Top quark

- $Q^t_{em} = +\frac{2}{3} \mid e \mid$
- Weak isospin partner of b quark: $T^t_3 = \frac{1}{2}$
- Color triplet
- spin-$\frac{1}{2}$

$$\begin{array}{lcccccc} & & & & \underline{SU(3)} & \underline{SU(2)} & \underline{U(1)_Y} \\ Q^i_L = & \begin{pmatrix} u_L \\ d_L \end{pmatrix} & \begin{pmatrix} c_L \\ s_L \end{pmatrix} & \begin{pmatrix} t_L \\ b_L \end{pmatrix} & 3 & 2 & \frac{1}{6} \\ u^i_R = & u_R & c_R & t_R & 3 & 1 & \frac{2}{3} \\ d^i_R = & d_R & s_R & b_R & 3 & 1 & -\frac{1}{3} \end{array}$$

In the Standard Model top quark couplings are uniquely fixed by the principle of gauge invariance, the structure of the quark generations, and a requirement of including the lowest dimension interaction Lagrangian.

Top quark has been found by the Fermilab CDF and D0 collaborations.

RUN1 results:

- $M_t = 174.3 \pm 3.2(stat) \pm 4.0(syst)$
- $\lambda_t(M_t) = 1.00 \pm 0.03$
- $\sigma_{t\bar{t}}(CDF\ M_t = 175GeV) = 6.5^{+1.7}_{-1.4} pb$
  $\sigma_{t\bar{t}}(D0\ M_t = 172GeV) = 5.9 \pm 1.7 pb$
- The 95% Confidence Level Limit on single top production cross section :

  13.5 pb by CDF

  39 pb (17 pb Neural Network) (s-channel) and
  58 pb (22pb Neural Network) (W-gluon fusion) by D0

  SM prediction: $\sigma_{SM} = 2.43 \pm 0.32$ pb
- FCNC coupling limits
  $Br(t \to Zq) < 33\%(95\%CL)$ $Br(t \to \gamma q) < 3.2\%(95\%CL)$

Top quark is the heaviest elementary particle found so far with a mass slightly less than the mass of the gold nucleus.

- Top decays ($\tau_t \sim 5 \times 10^{-25}\ sec$) much faster than a typical time-scale for a formation of the strong bound states ($\tau_{QCD} \sim 3 \times 10^{-24}\ sec$). So, top provides, in principle, a very clean source for a fundamental information.
- Top is so heavy and point like at the same time. So, one might expect a possible deviations from the SM predictions more likely in the top sector.
- Top Yukawa coupling $\lambda_t = 2^{3/4} G_F^{1/2} m_t$ is very close to unit. Studies of top may shed a light on an origin of the mechanism of the EW symmetry breaking.

Top quark physics will be a very important part of research programs for all future hadron and lepton colliders. Processes with Single Top Quark production play a special role.

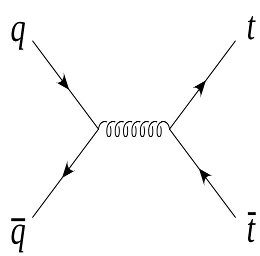
Maximal value of the CP even light Higgs in MSSM is about 135-140 GeV (not M_Z) due to large top quark mass

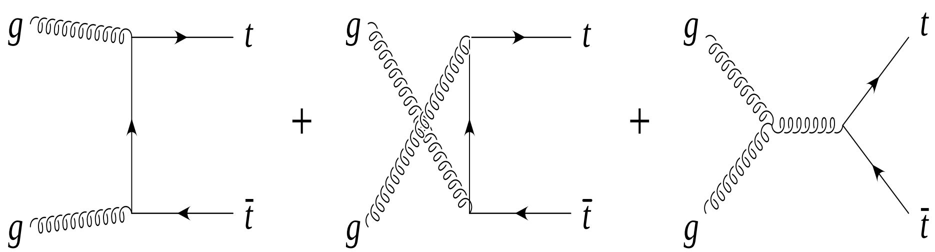
$$M_h^{\max} = \sqrt{M_Z^2 + \epsilon}$$

$$\epsilon = \frac{3G_F \overline{m}_t^4}{\sqrt{2}\pi^2 \sin^2\beta}\left[f(t)\right], \qquad where \qquad t = \log\left(\frac{M_S^2}{m_t^2}\right)$$

At hadron and lepton colliders, top quarks may be produced either in pairs or singly.

Top pair:





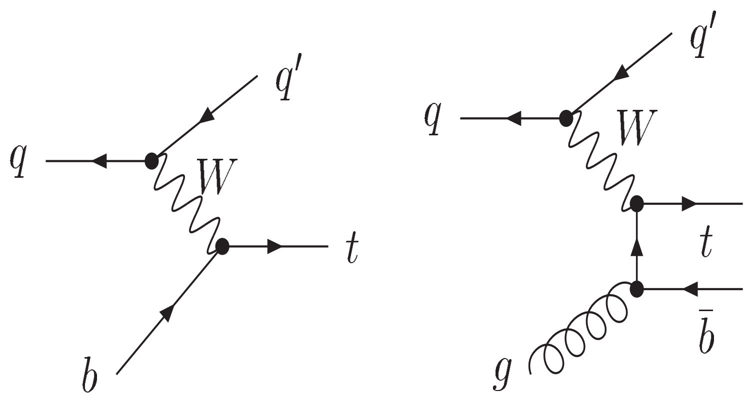
Three mechanisms of the single top production:

t-channel ($Q_W^2 < 0$)

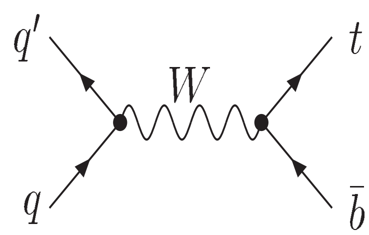
s-channel ($Q_W^2 > 0$)

associated tW ($Q_W^2 = M_W^2$)

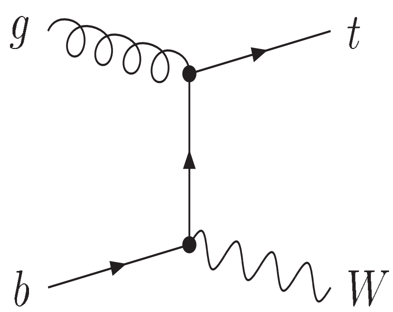
Q_W^2 - W-boson virtuality



t-channel



s-channel



Wt associated production

Same classification for LO, NLO ... QCD corrections

Consistent way to make computation and generate events

However different channels may lead to the same final states in some kinematical regions:

tb - s-channel + t-channel if light jet has small p_t

tbj - t-channel + s-channel with extra hard jet

The main goals to search for single top:

- Independent electroweak channel of the top quark production
- Direct $|V_{tb}|$ CKM matrix element measurement
- Significant background to Higgs and many "new physics" (MSSM) processes
- Unique spin correlations properties
- Process of interest for "New physics"
  - W_{tb} anomalous couplings
  - FCNC
  - Searches for W' (Kaluza-Klein excitation of W-boson)
  - Searches for new strong dynamics (π_T, ρ_T)
- New delicate analysis techniques to extract small signals

Basic production processes cross sections

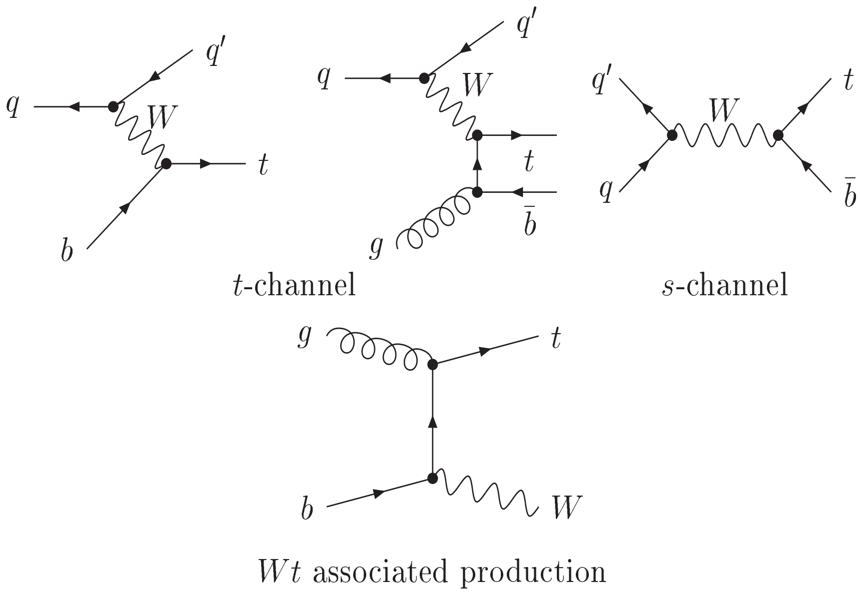
	σ_{NLO} (pb)	$q\bar{q} \to t\bar{t}$	$gg \to t\bar{t}$
Tevatron ($\sqrt{s} = 1.8$ TeV $p\bar{p}$)	$4.87 \pm 10\%$	90%	10%
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$6.70 \pm 10\%$	85%	15%
LHC ($\sqrt{s} = 14$ TeV pp)	$833 \pm 15\%$	10%	90%

	s channel	t channel	Wt
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$0.90 \pm 5\%$	$2.0 \pm 5\%$	$0.1 \pm 10\%$
LHC ($\sqrt{s} = 14$ TeV pp)	$10.6 \pm 5\%$	$250 \pm 5\%$	$75 \pm 10\%$

The single top rate is about 0.4 of the top pair rate

$|V_{tb}|$ measurements

At LHC and Tevatron Run2 via single top



V_{tb}^2 could be measured with an accuracy of 10% dominated by systematics

At ILC (1 TeV, 500 fb^{-1}) in $e\gamma$ collisions -

2-3 % accuracy dominated by statistics

$|V_{tb}|$ measurements

If CKM unitarity and 3 generations are assumed

$|V_{tb}| = 0.9991^{+0.000034}_{-0.00004}$

Without the 3-generation unitarity constrain $|Vtb|$ is left practically unconstrained

$|Vtb| = 0.07 - 0.9993$

From top quark loop contributions to $\Gamma(Z \to b\bar{b})$

$|V_{tb}| = 0.77^{+0.18}_{-0.24}$

From measurements of $R = \frac{|V_{tb}|^2}{|V_{tb}|^2+|V_{ts}|^2+|V_{td}|^2}$ by D0 and CDF analysing top pair production

$R = 1.03^{+0.19}-0.17 => |V_{tb}| > 0.78$

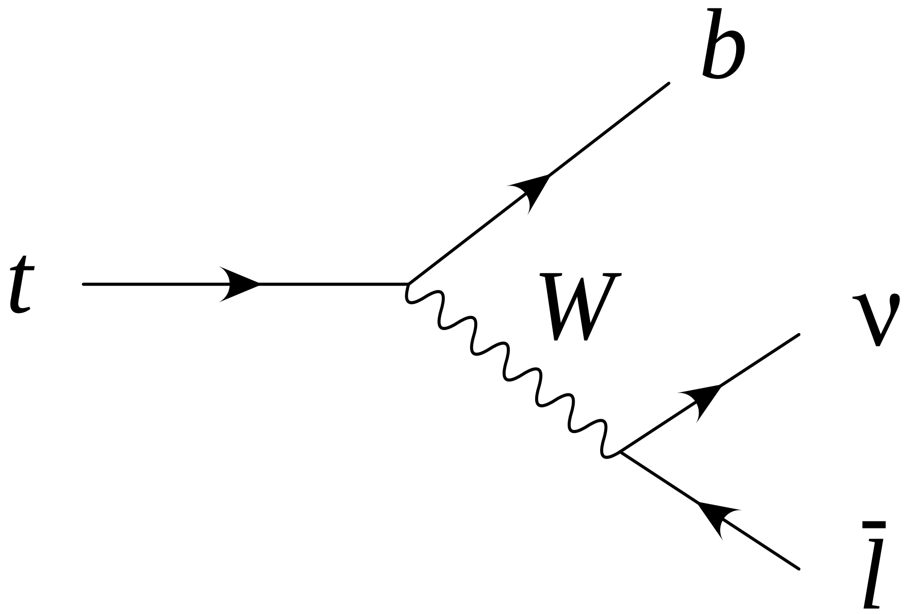
Measurements from the single top: Production*Decays $=> |V_{tb}|^2 \frac{|V_{tb}|^2}{|V_{tb}|^2+|V_{ts}|^2+|V_{td}|^2+(Exotics)}$

Assumptions (no 3-generation unitarity constrain):

* V-A interaction

* $|V_{tb}|^2 >> |V_{ts}|^2 + |V_{td}|^2 + (Exotics)$

In SM top decays to W-boson and b-quark practically with 100% probability



$d\Gamma \sim |\mathcal{M}|^2 \sim (t + ms) \cdot \ell b \cdot \nu$, where in the top-quark rest frame, the spin four-vector is $s = (0, \hat{s})$, and $\hat{s}$ is a unit vector that defines the spin quantization axis of the top quark

In the top quark rest frame:
$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \cos\theta_\ell)$
Hence the charged lepton tends to point along the direction of top spin.

Mahlon,Parke; E.B.,Sherstnev

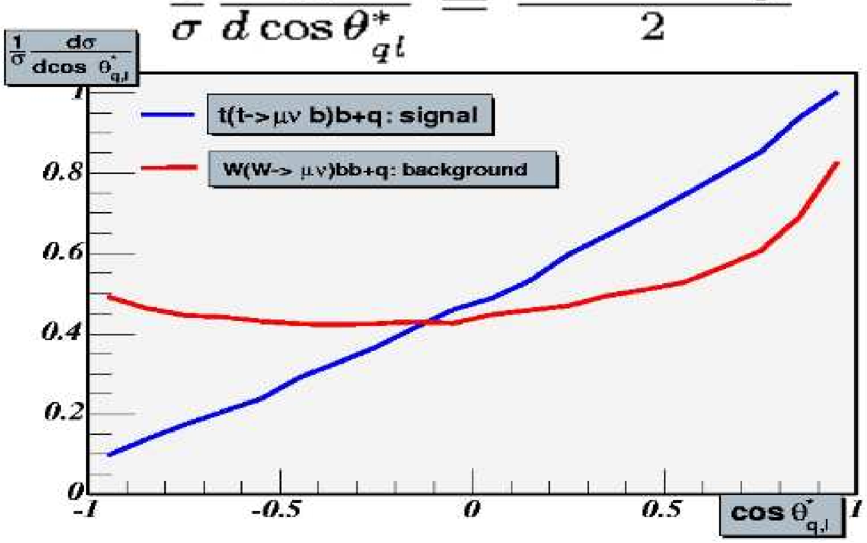
Spin_correlations:_theoretical_view

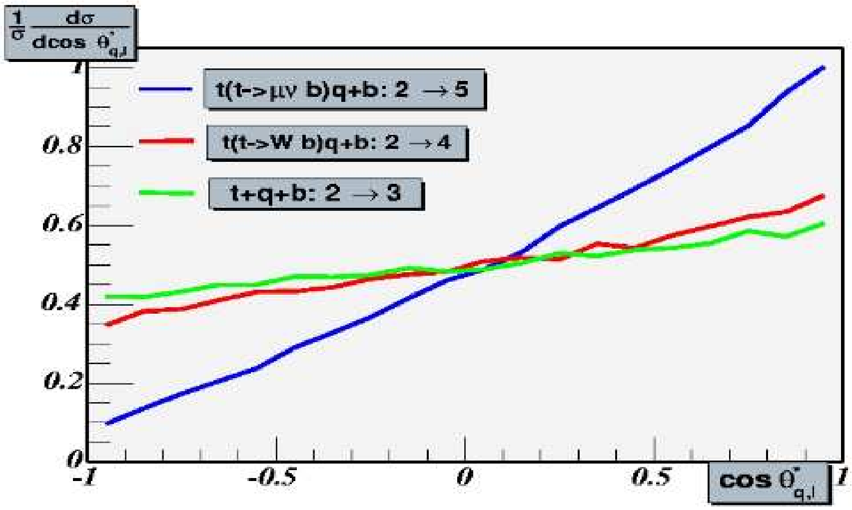
Single top quark is produced highly polarized via the Wtb vertex. Since top quarks do not have a time to form strong bound state, we can investigate a top polarization. There is a unique top spin decomposition axis in the top rest frame: momentum of lepton in top the rest frame from top decay: $t \to b\, l\, \nu_l$

For t-channel the best variable θ^*_{ql} - angle between lepton and quark momenta in the top rest frame

The top polarization can be defined as parameter P in a distribution

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{ql}} = \frac{1+P\cos\theta^*_{ql}}{2}$$





In ideal theoretical situation we have for t-channel:

$$P_{top} \approx 90\%$$

New Physics via Single Top (examples):

- W_{tb} anomalous couplings
- FCNC
- W'
- ...

Anomalous Top Couplings

The top quark interactions of dimension 4:

$$\mathcal{L}_4 = -g_s \bar{t}\gamma^\mu T^a t G^a_\mu - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \bar{t}\gamma^\mu (v^W_{tq} - a^W_{tq}\gamma_5) q W^+_\mu$$
$$-\frac{2}{3} e \bar{t}\gamma^\mu t A_\mu - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \bar{t}\gamma^\mu (v^Z_{tq} - a^Z_{tq}\gamma_5) q Z_\mu$$

The dimension 5 couplings have the generic form:

$$\mathcal{L}_5 = -g_s \sum_{q=u,c,t} \frac{\kappa^g_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f^g_{tq} + i h^g_{tq}\gamma_5) q G^a_{\mu\nu} - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \frac{\kappa^W_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^W_{tq} + i h^W_{tq}\gamma_5) q W^+_{\mu\nu}$$
$$-e \sum_{q=u,c,t} \frac{\kappa^\gamma_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^\gamma_{tq} + i h^\gamma_{tq}\gamma_5) q A_{\mu\nu} - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \frac{\kappa^Z_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^Z_{tq} + i h^Z_{tq}\gamma_5) q Z_{\mu\nu}$$

where $|f|^2 + |h|^2 = 1$.

Present constrains come from

- Low energy data via loop contributions
  $K_L \to \mu^+\mu^-$, $K_L - K_S$ mass difference, $b \to l^+l^-X$, $b \to s\gamma$
- LEP2
- Tevatron Run1
- HERA
- Unitarity violation bounds

Anomalous Wtb Couplings

- Lagrangian

$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{tb} \left[W_\nu^- \bar{b} \gamma_\mu P_- t - \frac{1}{2M_W} W_{\mu\nu}^- \bar{b} \sigma^{\mu\nu} (F_2^L P_- + F_2^R P_+) t \right] + h.c.$$

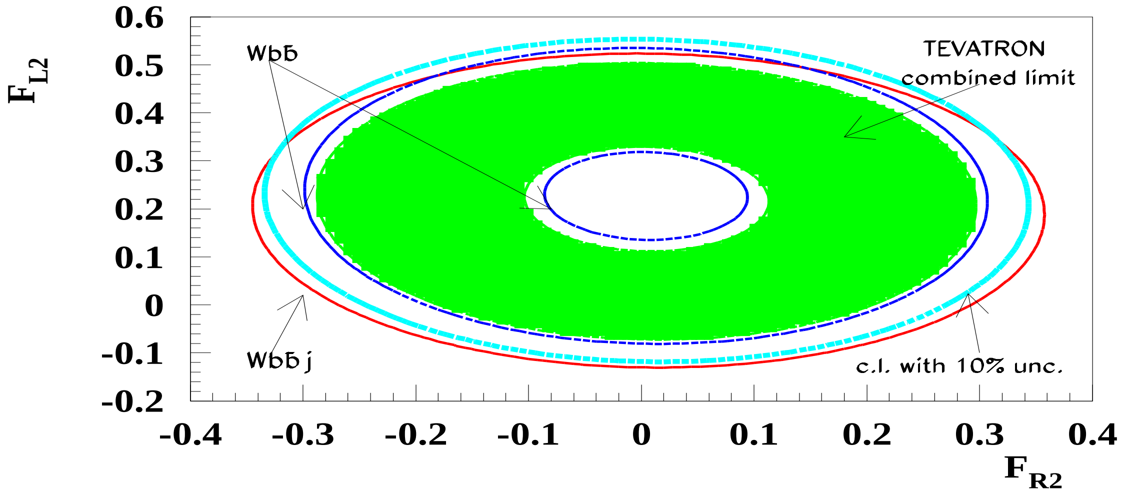
with $W_{\mu\nu}^\pm = D_\mu W_\nu^\pm - D_\nu W_\mu^\pm$, $D_\mu = \partial_\mu - ieA_\mu$, $\sigma^{\mu\nu} = i/2[\gamma_\mu, \gamma_\nu]$ and $P_\pm = (1 \pm \gamma_5)/2$. The couplings F_2^L and F_2^R are proportional to the coefficients of the effective Lagrangian
$F_{L2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W - ih_{tb}^W)$,
$F_{R2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W + ih_{tb}^W)$, $|F_{L2,R2}| < 0.6$ from unitary bounds

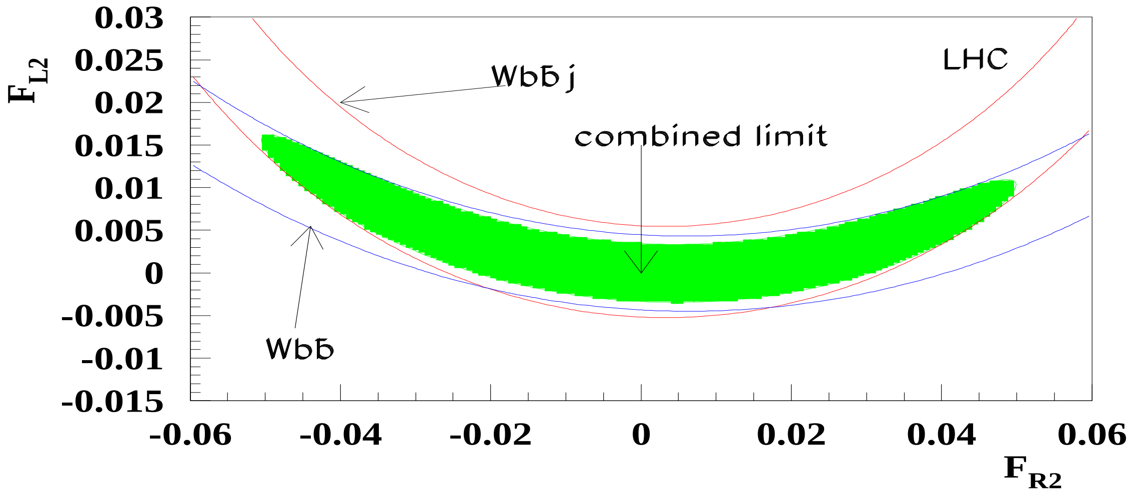
- $|V_{tb}|$ is very close to 1 in SM with 3 generations. ($|V_{tb}|$ is very weakly constrained in case of 4 generations, e.g.)

- A possible $V + A$ form factor is severely constrained by the CLEO $b \to s\gamma$ data to 3×10^{-3} level

Wtb anomalous couplings limit on TEVATRON and LHC:

(E.Boos,L.Dudko,T.Ohl,EPJ99)





Uncorrelated limits on anomalous couplings from measurements at different machines.

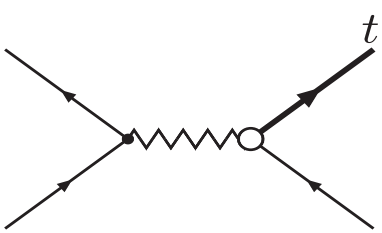
	F_2^L	F_2^R
Tevatron ($\Delta_{sys.} \approx 10\%$)	$-0.18 \div +0.55$	$-0.24 \div +0.25$
LHC ($\Delta_{sys.} \approx 5\%$)	$-0.052 \div +0.097$	$-0.12 \div +0.13$
γe ($\sqrt{s_{e^+e^-}} = 0.5$ TeV)	$-0.1 \div +0.1$	$-0.1 \div +0.1$
γe ($\sqrt{s_{e^+e^-}} = 2.0$ TeV)	$-0.008 \div +0.035$	$-0.016 \div +0.016$

FCNC couplings

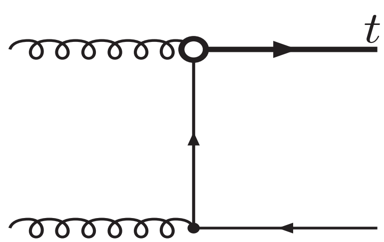
- Couplings: $tqg,\ tq\gamma,\ tqZ$, where $q = u, c$

$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\left[\kappa_{tq}^{\gamma,Z} e\bar{t}\sigma_{\mu\nu} q F^{\mu\nu}_{\gamma,Z} + \kappa^{g}_{tq} g_s \bar{t}\sigma_{\mu\nu}\frac{\lambda^i}{2} q G^{i\mu\nu}\right] + h.c.$$

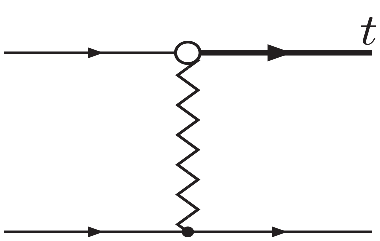
Information on FCNC couplings come from either top pair production with subsequent decays to rear modes $t \to q\,V$, where $V = \gamma, Z, g$
or from additional contributions to the single top production



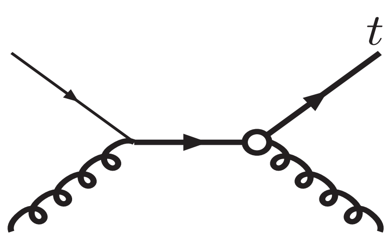
$q\bar{q} \to t\bar{c}$



$cg \to tg$



$c\bar{q} \to t\bar{q}$



$gg \to t\bar{c}$

All present and expected limits are presented in terms of Br fractions:

$$\Gamma(t \to qg) = \left(\frac{\kappa_{tq}^{g}}{\Lambda}\right)^2 \frac{8}{3}\alpha_s m_t^3 \quad , \quad \Gamma(t \to q\gamma) = \left(\frac{\kappa_{tq}^{\gamma}}{\Lambda}\right)^2 2\alpha m_t^3,$$

$$\Gamma(t \to qZ)_\gamma = \left(|v_{tq}^Z|^2 + |a_{tq}^Z|^2\right) \alpha\, m_t^3 \frac{1}{4M_Z^2 \sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_Z^2}{m_t^2}\right),$$

$$\Gamma(t \to qZ)_\sigma = \left(\frac{\kappa_{tq}^{Z}}{\Lambda}\right)^2 \alpha\, m_t^3 \frac{1}{\sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(2 + \frac{M_Z^2}{m_t^2}\right)$$

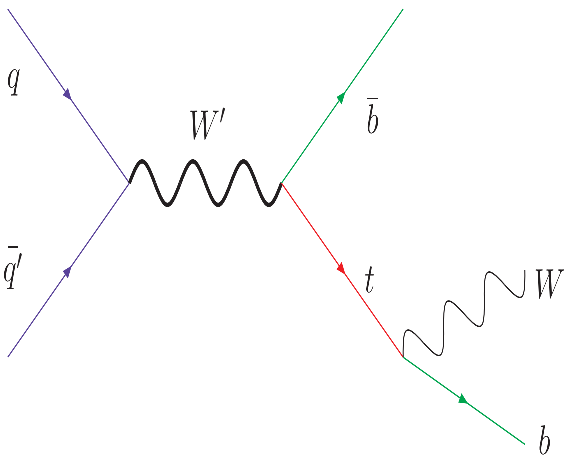
Current constraints

	CDF	LEP-2	HERA
BR($t \to gq$)	$\leq 29\%$	–	–
BR($t \to \gamma q$)	$\leq 3.2\%$	–	$\leq 0.7\%$
BR($t \to Zq$)	$\leq 32\%$	$\leq 7.0\%$	–

Future expectations

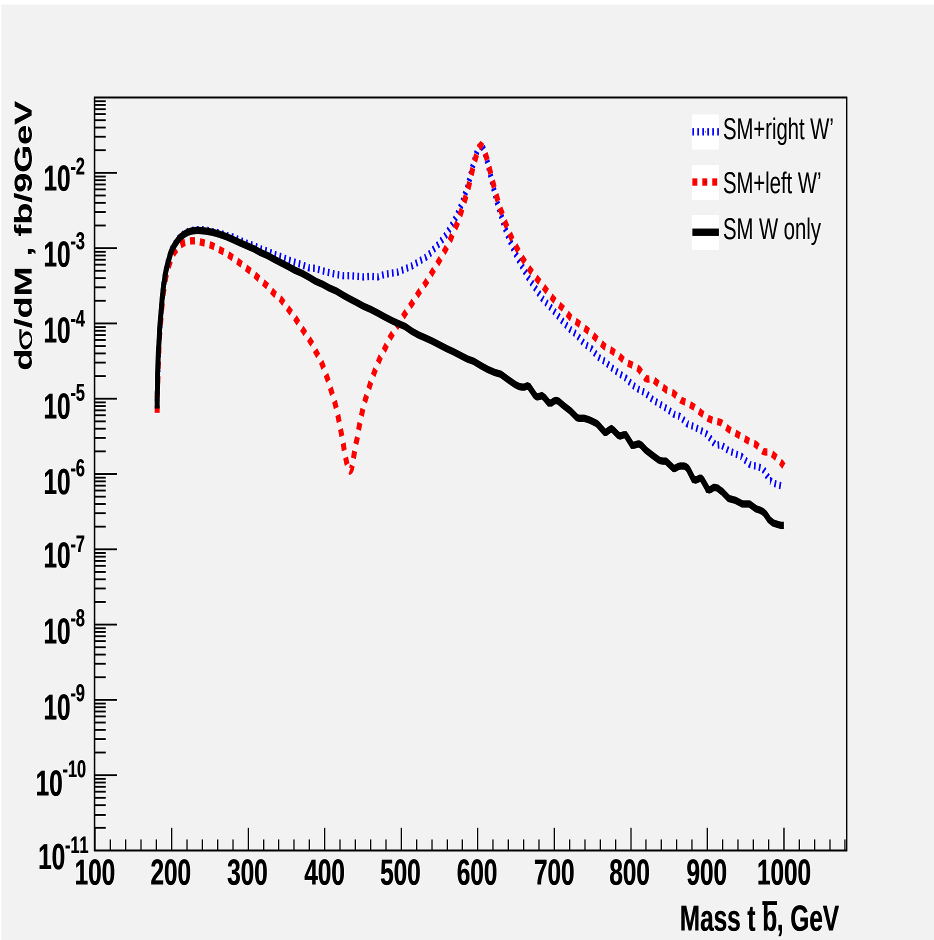
	Tevatron	LHC		e^+e^-
$t \longrightarrow$	Run II	decay	production	$\sqrt{s} > 500$ GeV
$g\,q$	0.06%	1.6×10^{-3}	1×10^{-5}	–
$\gamma\,q$	0.28%	2.5×10^{-5}	3×10^{-6}	4×10^{-6}
$Z\,q$	1.3%	1.6×10^{-4}	1×10^{-4}	2×10^{-4}

Searches for W'

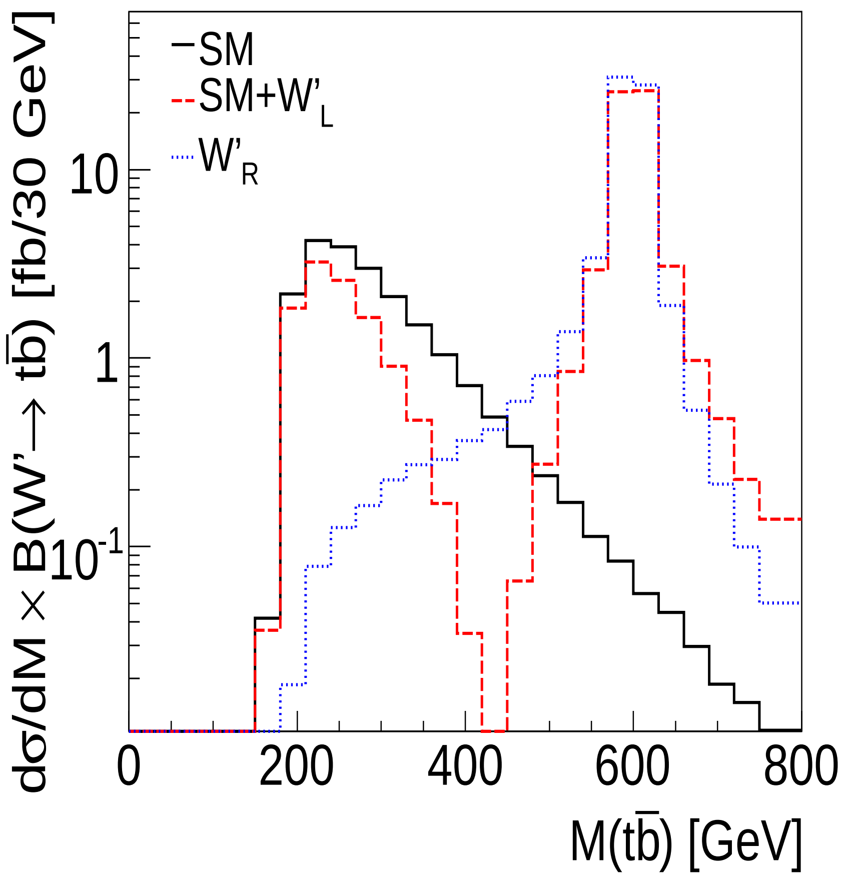


$$\mathcal{L} = \frac{V_{q_i q_j}}{2\sqrt{2}} g_w \overline{q}_i \gamma_\mu \left(a^R_{q_i q_j} (1 + \gamma^5) + a^L_{q_i q_j} (1 - \gamma^5) \right) W' q_j + \text{H.c.}\,, \qquad (1)$$

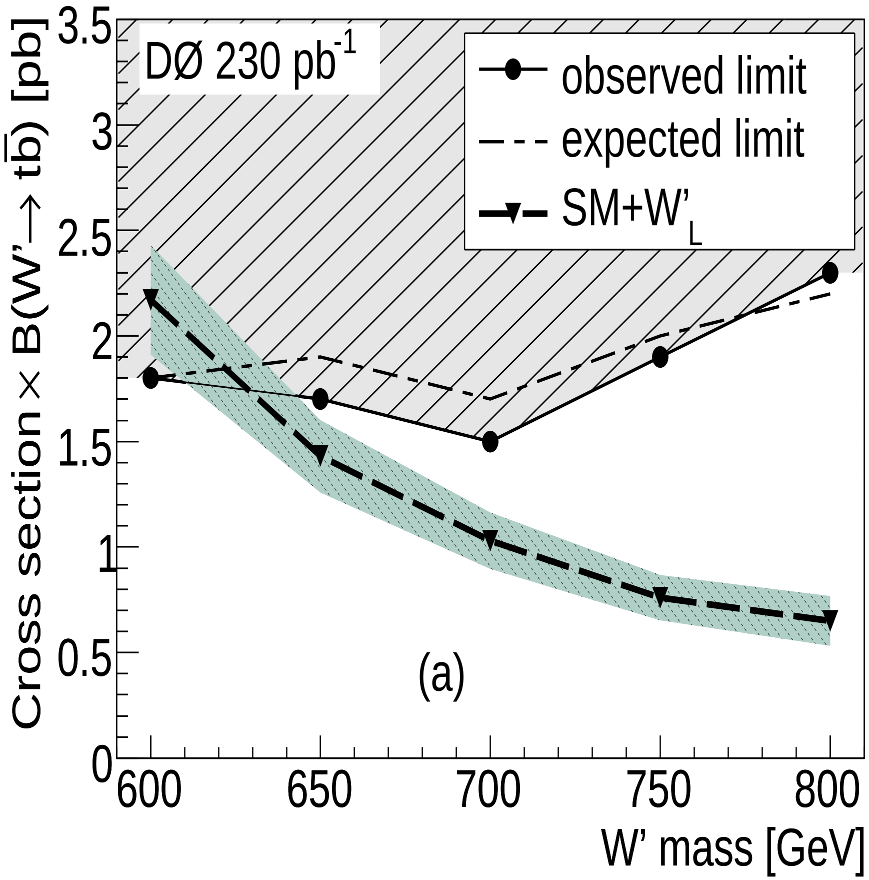
The notations are taken such that for so-called SM-like W' $a^L_{q_i q_j} = 1$ and $a^R_{q_i q_j} = 0$.

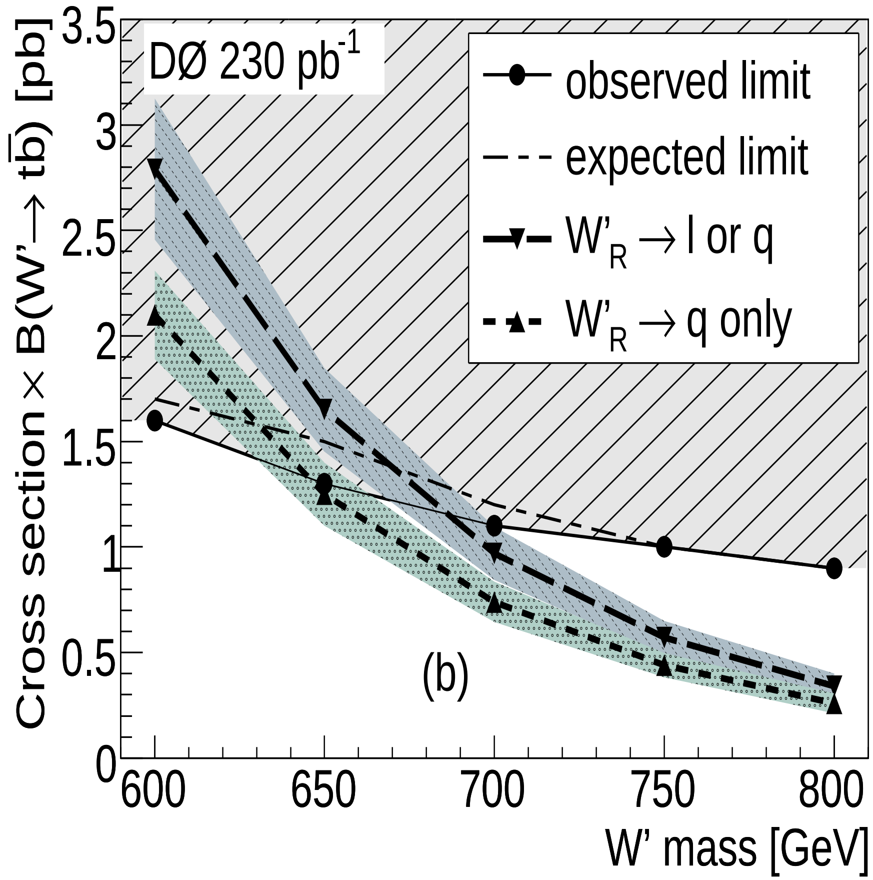


SM+right W'
SM+left W'
SM W only
dσ/dM , fb/9GeV
Mass t b̄, GeV



SM
SM+W'_L
W'_R
dσ/dM × B(W'→ tb̄) [fb/30 GeV]
M(tb̄) [GeV]





Mass range upto 610-670 GeV depending on the interaction variant is excluded

Signatures for both t- and s- single top production channels: $p\bar{p} \to l\nu_l b\bar{b}(q)$
isolated charged lepton + missing energy + one or two b-jet(s)
+ zero or one “forward” hadronic light jet

The problem of background reduction is significantly more serious in single top searches comparing to the top pair

- smaller invariant mass ($\hat{s}$) threshold and therefore larger backgrounds
- less number of final high P_t jets and therefore stronger $W^{\pm}$+multi-jet background
- rather soft second b-jet which makes its tagging less efficient
- top pair production itself gives a significant background contribution

One needs to generate signal and background events as accurate as possible

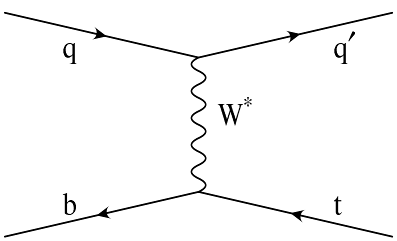
Problems and requirements for a generator for the single top signal:

- Double counting and negative weights
- Matching of various NLO contributions at the generator level. One should have the correct NLO rate and correct shapes of the NLO distributions
- Matching to showering programs
- Correct spin correlations
- Finite top and W widths
- Separation Top and antiTop since the rates are different (for the LHC)
- Anomalous Wtb and FCNC couplings

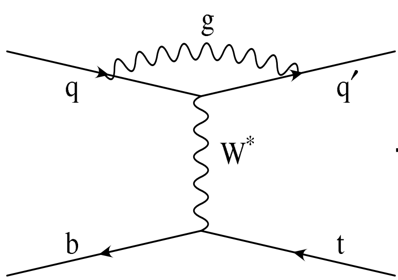
Generators used for the single top signal:

SingleTop - generator based on CompHEP (PYTHIA and NLO computations)

LO order and representative loop and tree NLO diagrams to the t- and s- channel single top production

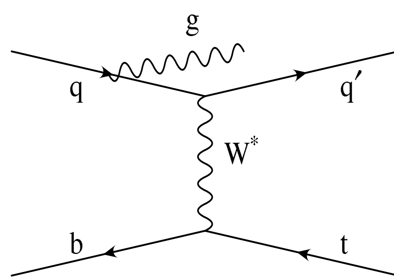


1.1



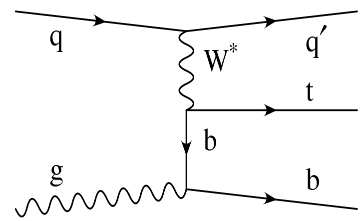
+ ... ,

1.2



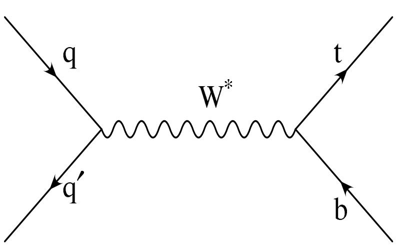
+ ... ,

1.3

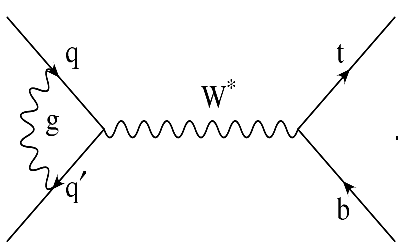


+ ...

1.4

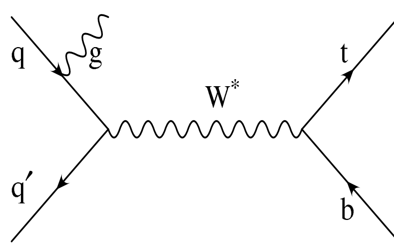


2.1



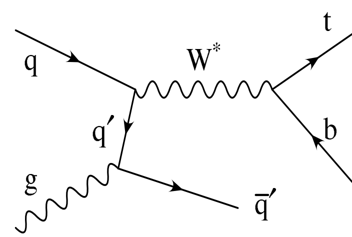
+ ... ,

2.2



+ ... ,

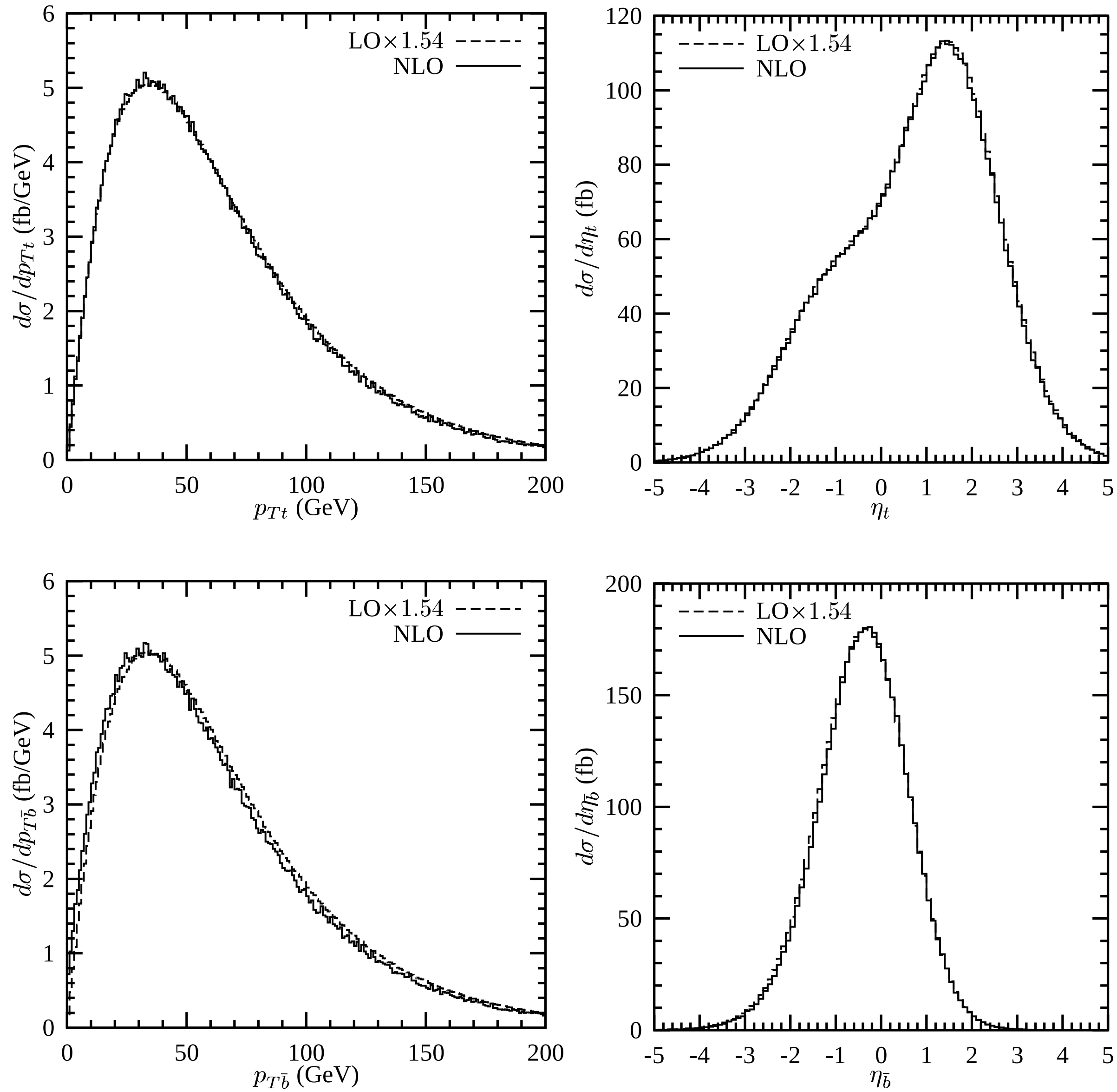
2.3



+ ...

2.4

s-channel at NLO and LO times a K-factor of 1.54 (Zack Sullivan)



Transverse momentum and pseudorapidity of the top quark and $\bar{b}$-jet

t-channel

Splitting on p_t of the b-jet (b-jet not from top decay)

$2 \longrightarrow 2$ with ISR at "small" p_t region
(CompHEP + ISR from PYTHIA)

$2 \longrightarrow 3$ at "large" p_t region
(CompHEP)

(for both cases with spin correlated $1 \longrightarrow 3$ top subsequent decay)

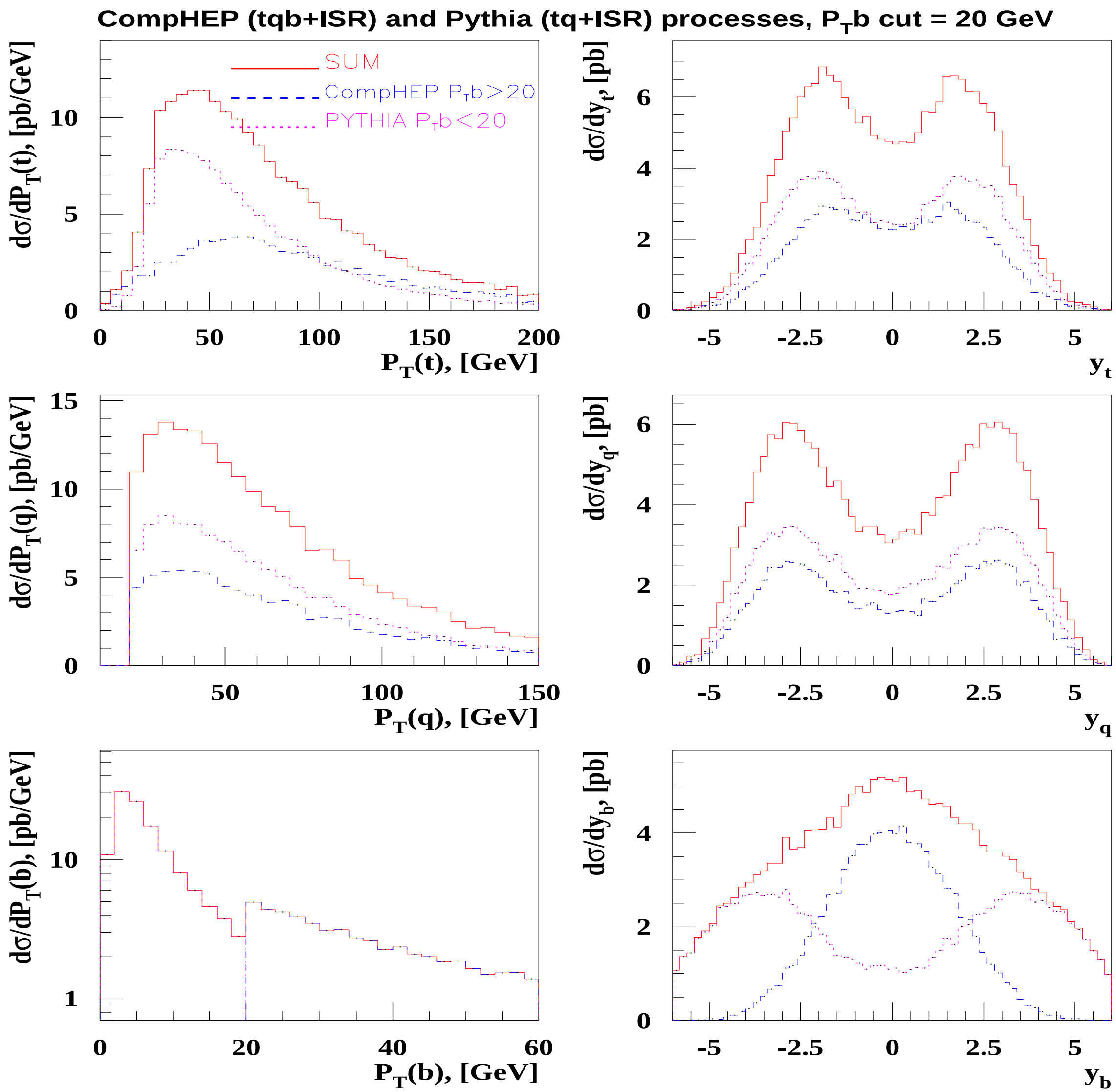
The separation parameter $(P_0)_t^b$ of "small" and "large" p_t regions is turned such that:

1. The total rate is normalized to the NLO rate

$$\sigma_{2\to 2}\,|_{P_t^b<(P_0)_t^b} + \sigma_{(2\to 3)}\,|_{P_t^b>(P_0)_t^b}$$
$$= \sigma_{\rm NLO}$$

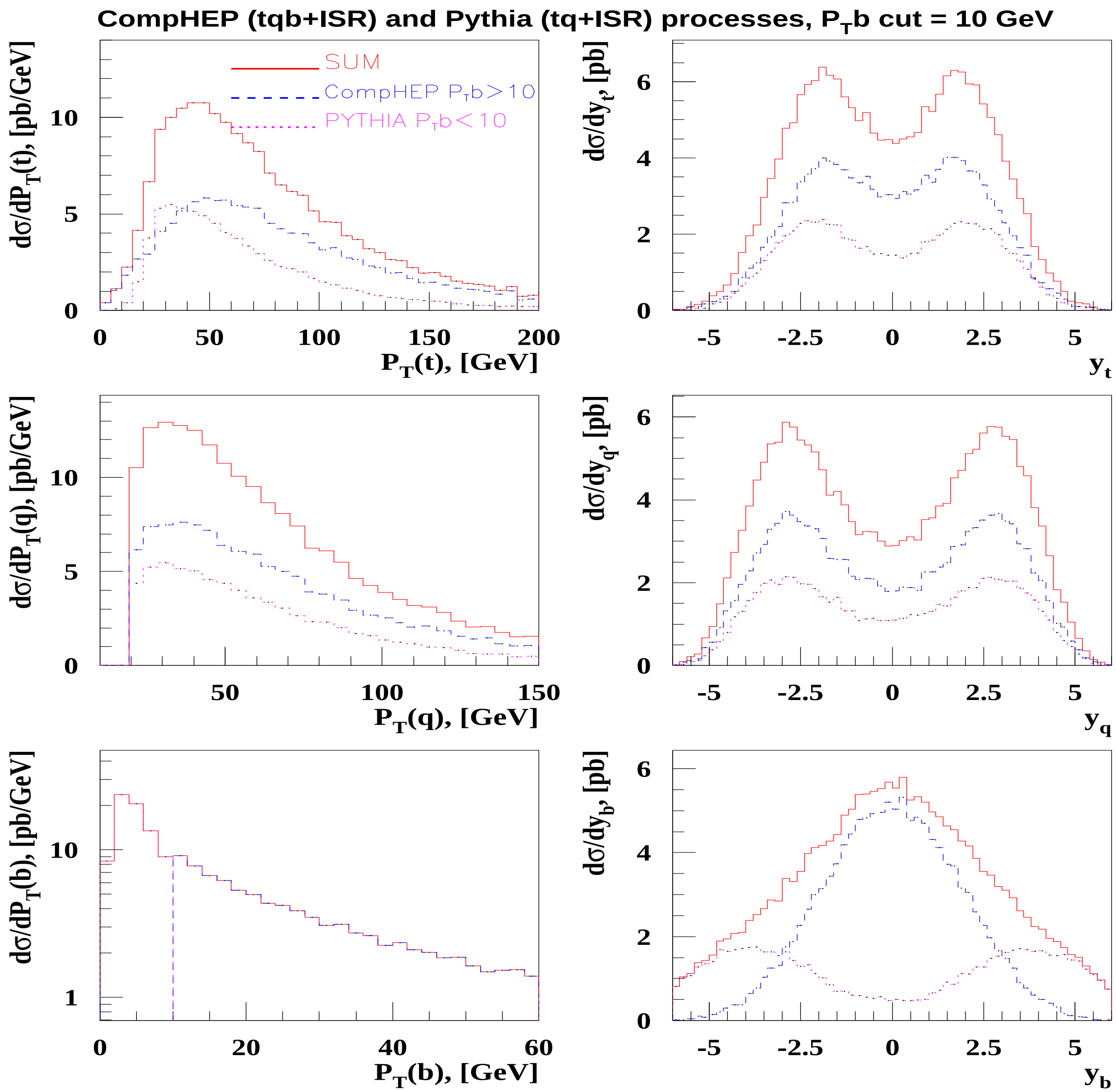
2. The distributions are smooth

Matching CompHEP&PYTHIA($2 \to 2$) and CompHEP ($2 \to 3$) distributions ($P_T^q > 20$ GeV)



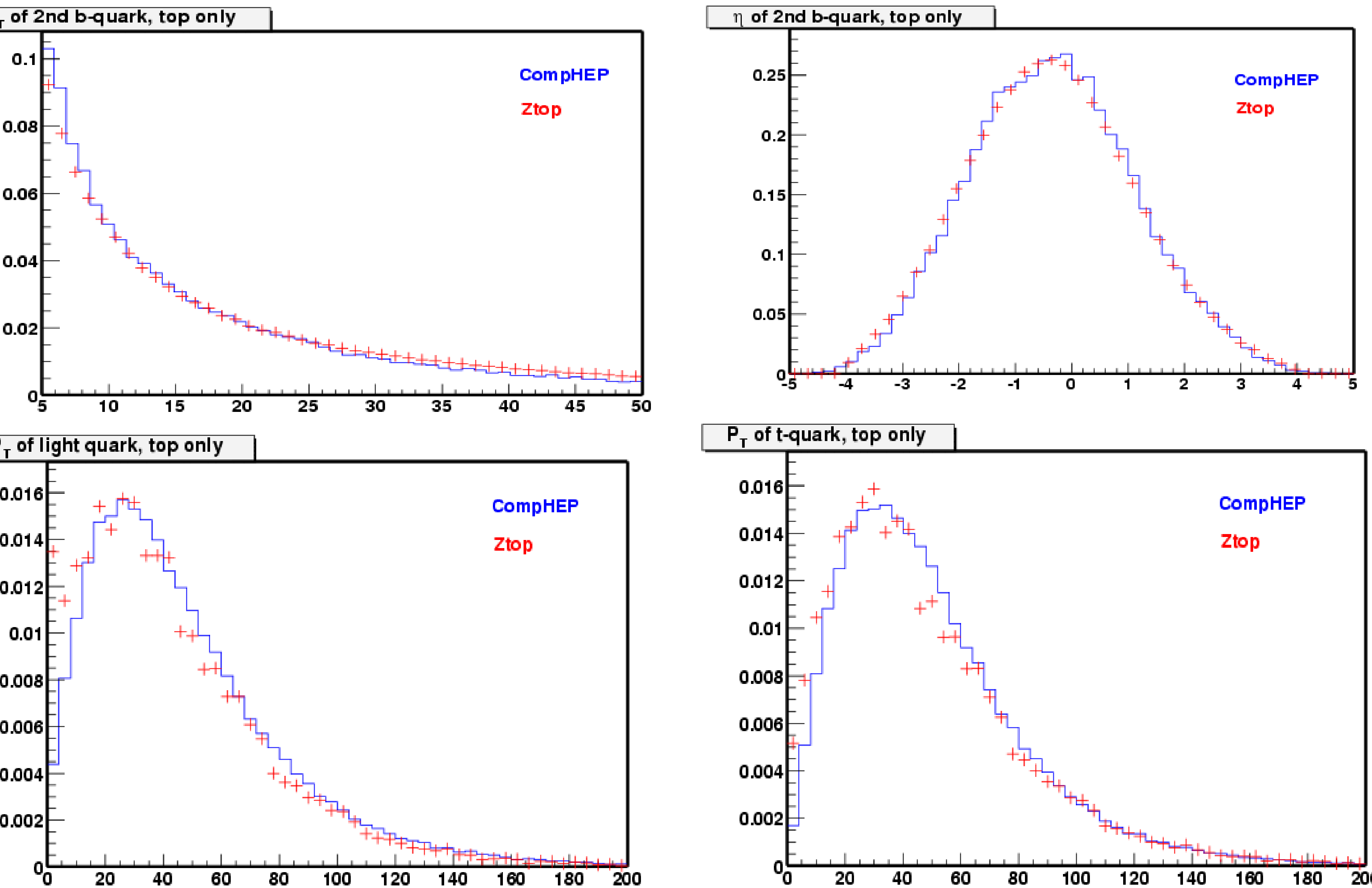
including deays $2 \to 4$ and $2 \to 5$ (LHC)

Matching CompHEP&PYTHIA($2 \to 2$) and CompHEP ($2 \to 3$) distributions ($P_T^q > 10$ GeV)



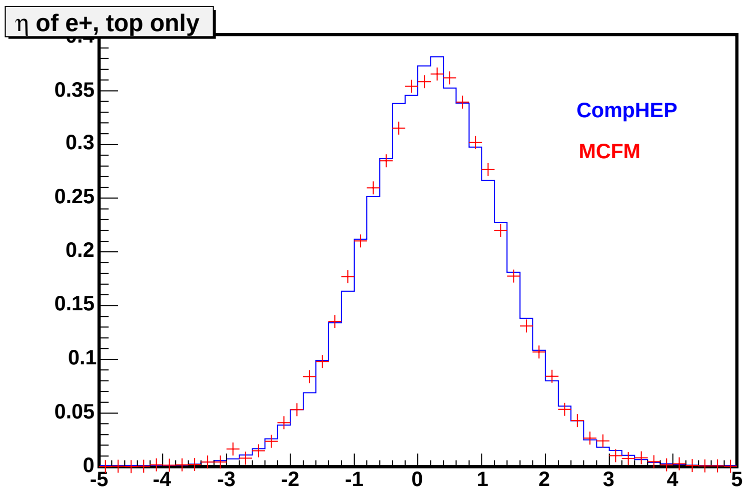
including deays $2 \to 4$ and $2 \to 5$ (LHC)

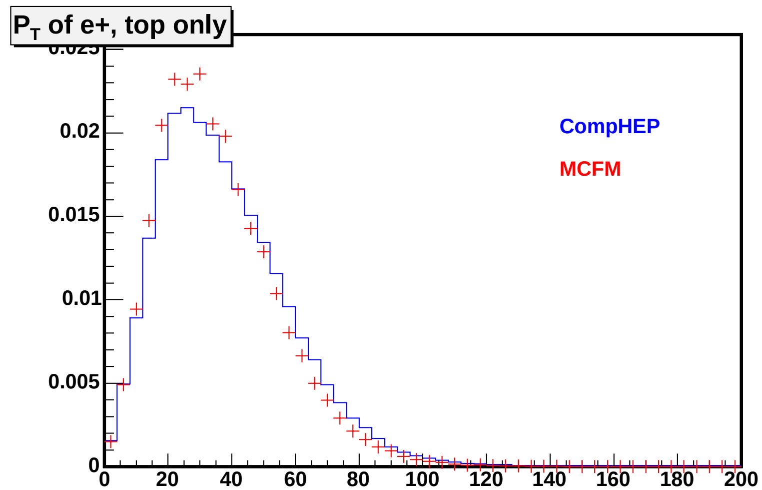
ignal Model by SingleTop generator («effectively» NLO, based on CompHEP).
omparison with exact NLO distributions «ZTOP» hep-ph/0408049

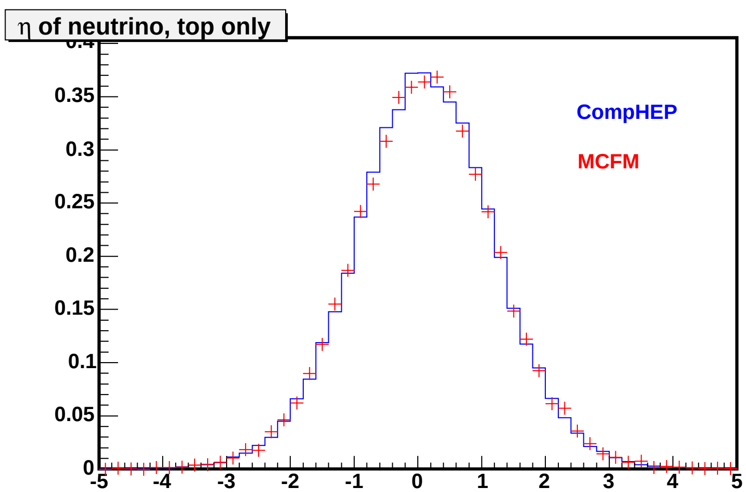


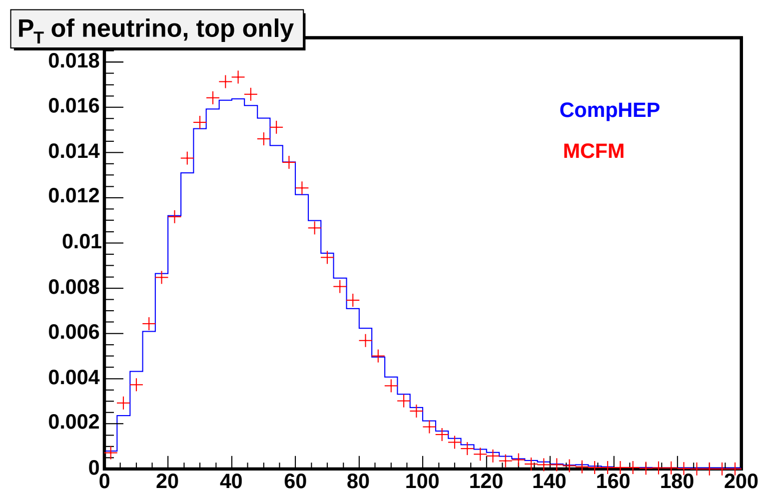
Comparisons with MCFM for top decay products (t-channel):

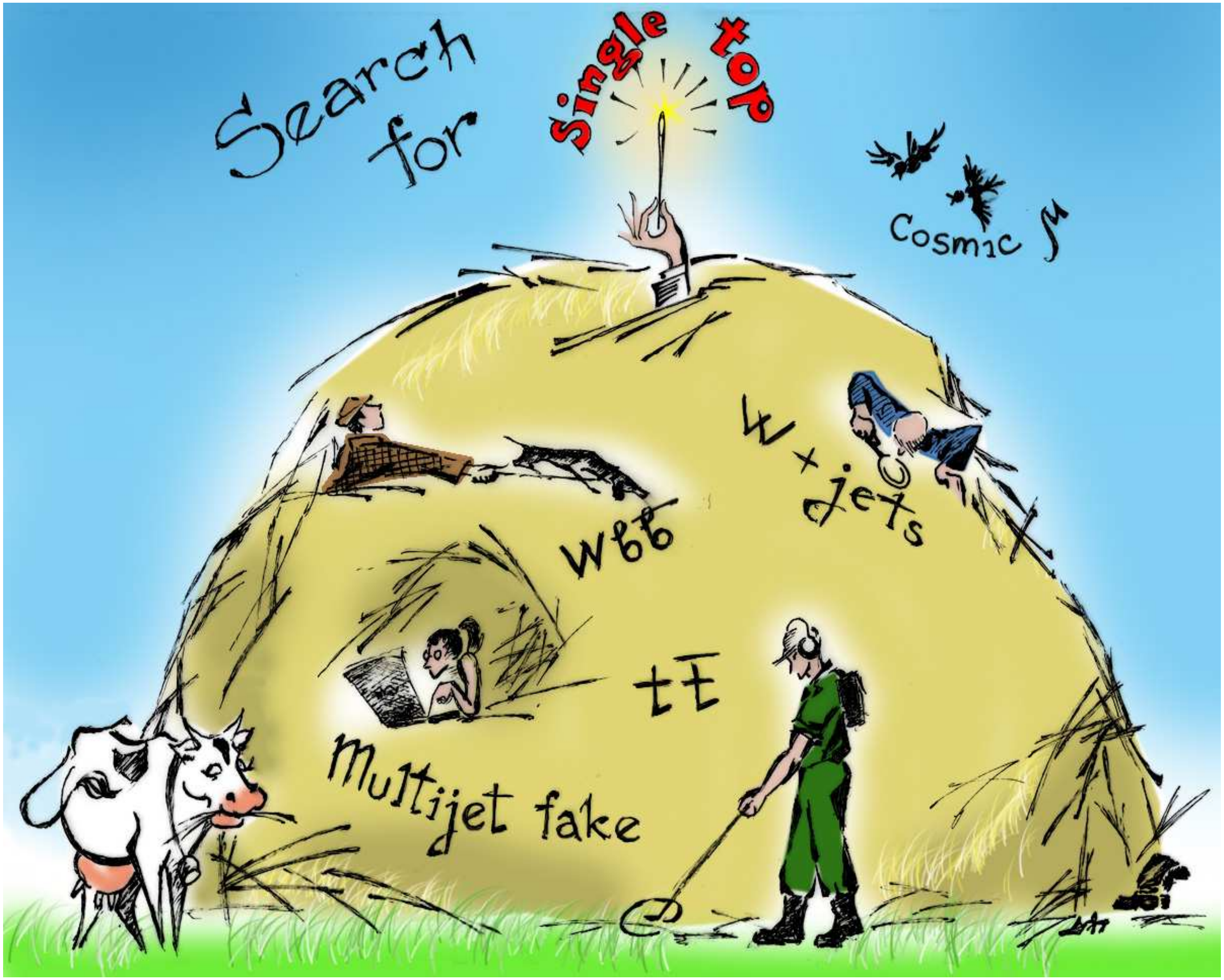
Transverse momentum and pseudorapidity of l and ν_l from top decay



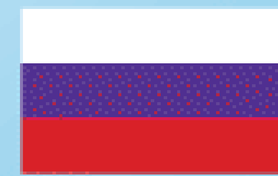







Search for
single top
Cosmic μ
W + jets
$Wb\bar{b}$
$t\bar{t}$
Multijet fake

Часть II: Экспериментальное наблюдение одиночного рождения топ кварка на детекторе D0



JINR, Dubna
ITEP, Moscow
Moscow State U.
IHEP, Protvino
PNPI, St. Petersburg

Коллаборация DZero: 600 человек, 90 институтов, 19 стран

Группа DZero Single Top:

E. Aguilo, P. Baringer, A. Bean, C. Belanger-Champagne, J.A. Benitez, E.E. Boos, R. Brock, V. Bunichev, K. Chan, L. Christofek, Y. Coadou, L.V. Dudko, M. Erdmann, T. Gadfort, A. Garcia-Bellido, C. Gerber, D. Gillberg, G. Gutierrez, P. Gutierrez, A.P. Heinson, U. Heintz, S. Herrin, S. Jabeen, S. Jain, A. Juste, S. Kappler, D. Kau, G. Kertzscher, M. Kirsch, L. Li, J. Mitrevski, R. Moore, M. Narain, D. O'Neil, M. Pangilinan, J. Parsons, M. Perflov, C. Potter, H.B. Prosper, R. Schwienhorst, E. Shabalina, J. Steggemann, T. Tim, C. Tully, M. Vetterli, B. Vachon, G. Watts, M. Weber

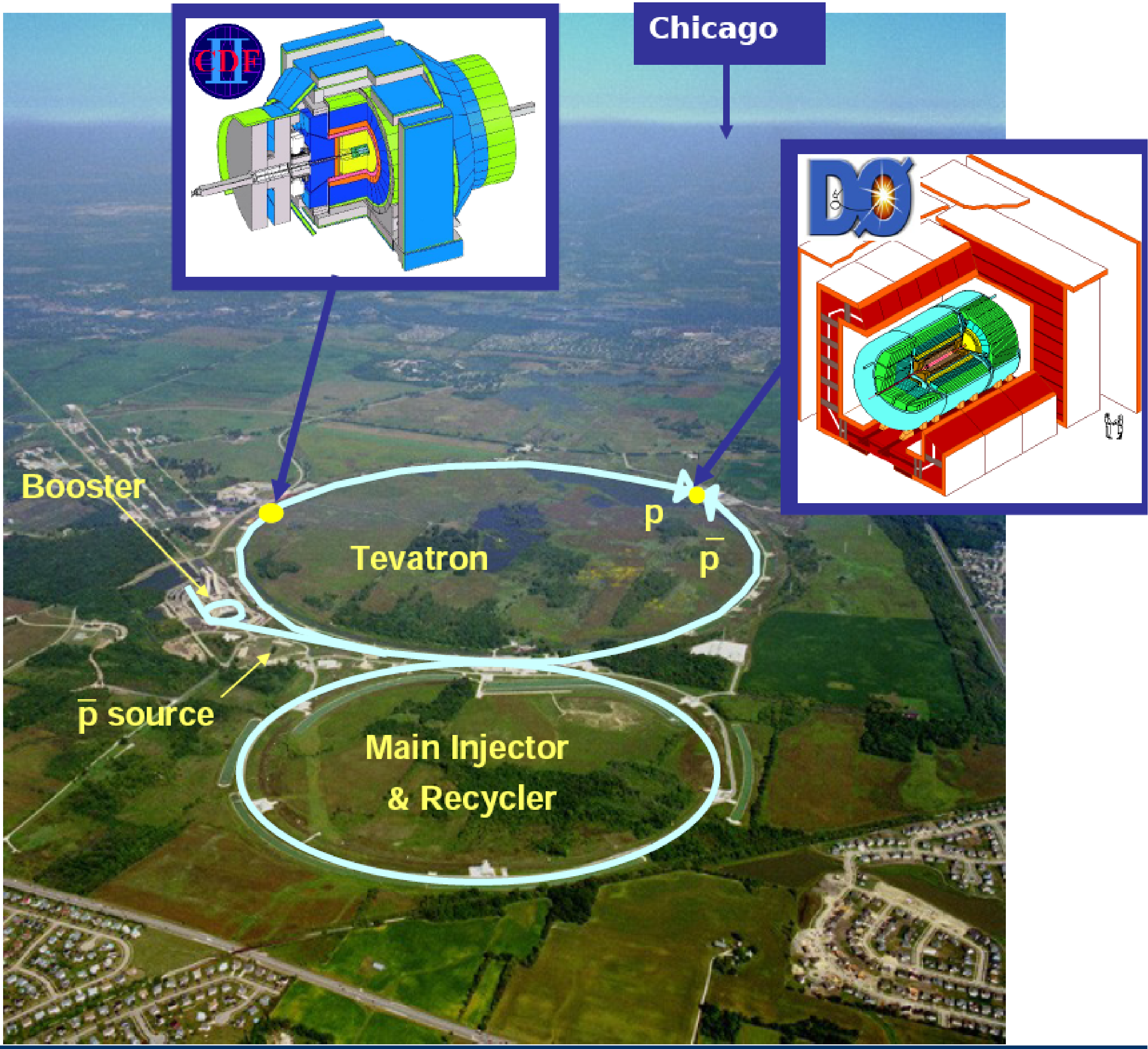
The Tevatron

The highest energy particle accelerator in the world!

Proton-antiproton collider

Run I 1992-1995
Top quark discovered!

Run II 2001-09(?)
$\sqrt{s}$ = 1.96 TeV
Δt = 396ns
>$1 fb^{-1}$ delivered
Peak Lumi: $10^{32} cm^{-2} s^{-1}$



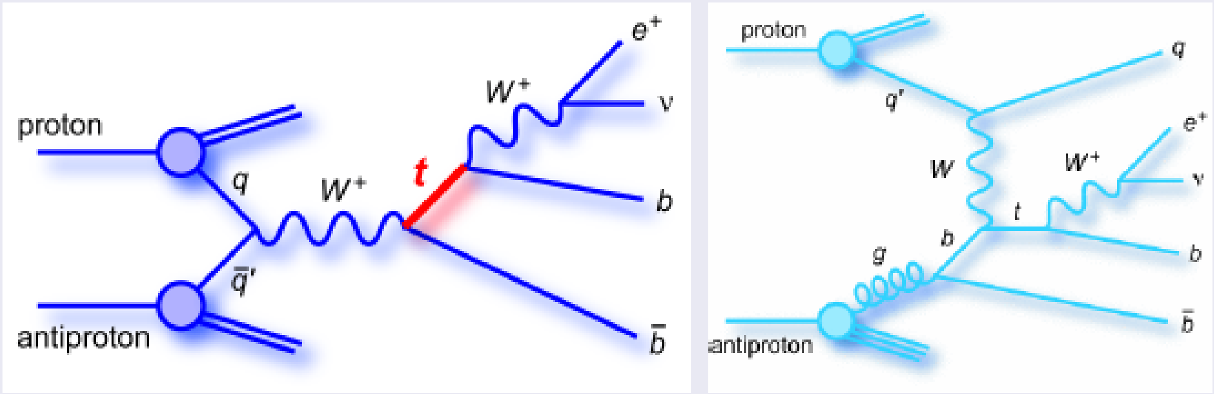
Историческое введение

	s-channel	t-channel
Theory NLO cross section:	0.88 pb	1.98 pb

95% CL upper cross section limits [pb]:

	s-channel	t-channel
Run I (100 pb^{-1})		
D0 (Phys.Rev.D63:031101,2001; Phys.Lett.B517:282-294,2001)	17	22
CDF (Phys.Rev.D65:091102,2002)	18	13
Run II		
CDF (160 pb^{-1}; Phys.Rev.D71:012005,2005)	13.6	10
D0 (230 pb-1; Phys.Lett.B622:265-276,2005)	6.4	5
D0 230 pb^{-1}, Comparison of the analysis methods:		
Cut based analysis	10.6	11.3
Decision Tree	8.3	8.1
Neural Net	6.4	5

Предварительный отбор событий



Signature

- isolated lepton
- $\not{E}_{\mathrm{T}}$
- 2-4 jets
- at least 1 b-jet

- Only one tight and no other loose lepton
  - electron: $p_T > 15$ GeV and $|\eta_{det}| < 1.1$
  - muon: $p_T > 18$ GeV and $|\eta_{det}| < 2$
- $15 < \not{E}_{\mathrm{T}} < 200$ GeV
- 2-4 jets with $p_T > 15$ GeV and $|\eta_{det}| < 3.4$
  - Leading jet with $p_T > 25$ GeV and $|\eta_{det}| < 2.5$
  - Second leading jet $p_T > 20$ GeV

Моделирование и Данные

- Сигнал: NLO генератор SingleTop
- Фон:
  - ttbar (l+jets, ll+jets), ALPGEN, MLM matching, NLO нормировка
  - W+jets (Wjj, Wbb, Wcc, ...), ALPGEN, MLM matching, нормировка на данные
  - Multijets Fake (jbb, jjbb, ...) одна из струй (j) идентифицируется как лептон, фон оценивается из данных
- Данные (предварительный отбор, без b-tagging)
  - e-channel 913 pb^{-1}, 39762 события
  - mu-channel 871 pb^{-1}, 27738 событий

Определение фракции W+jets и QCD Multijets Fake событий в Данных

- Matrix Method определяет фракции событий с реальным и ложным лептоном до b-tagginga, вероятности ложной идентификации определяются из анализа событий Z->ll

$$N^{loose} = N^{loose}_{fake} + N^{loose}_{real}$$

$$N^{tight} = \varepsilon_{fake} N^{loose}_{fake} + \varepsilon_{real} N^{loose}_{real}$$

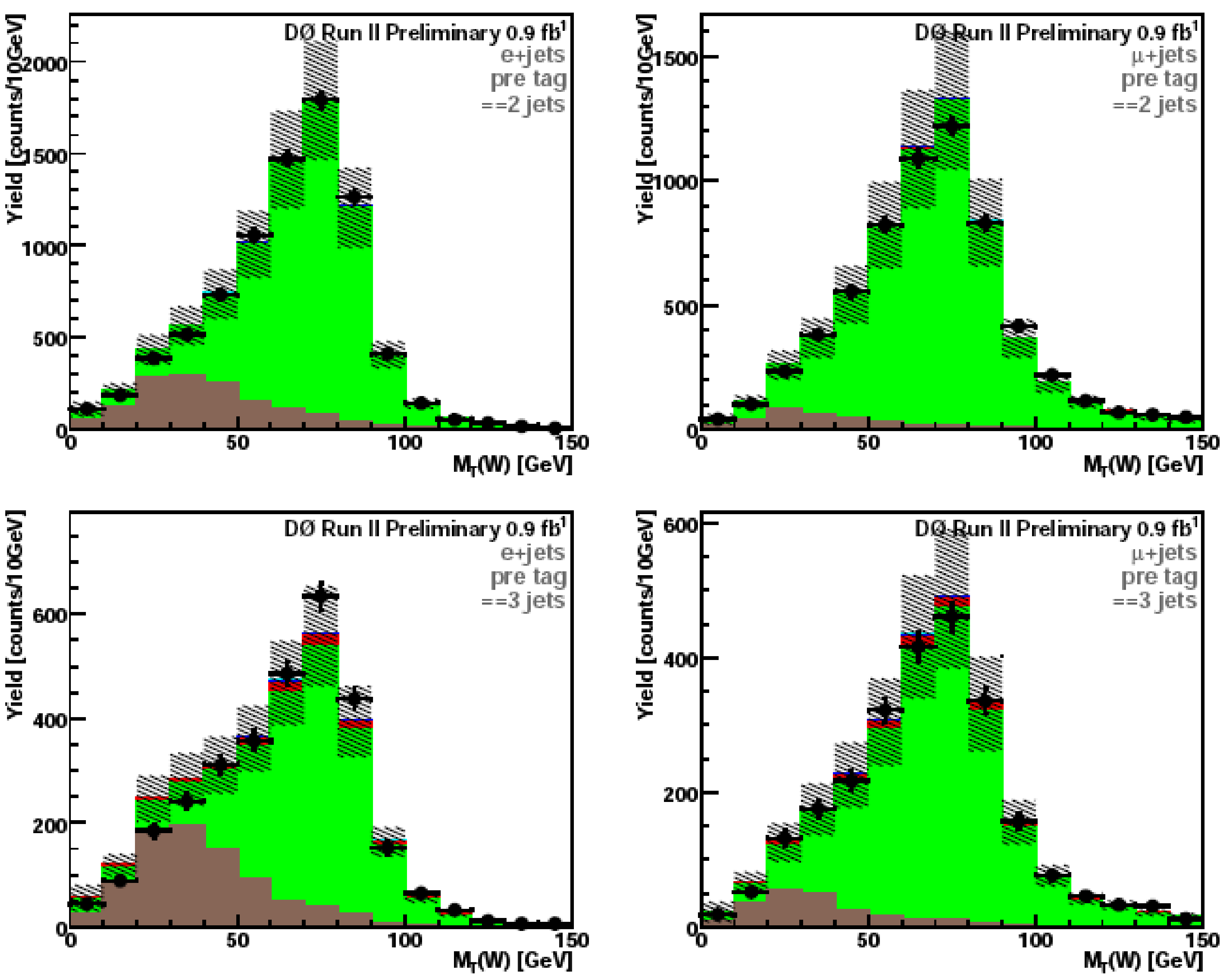
$$N^{final}_{WQCD} = N^{final}_{W+jets} + N^{final}_{fake-l}$$

Loose, tight - критерии идентификации лептона

Normalization of W+Jets and Multijets to Data

	Electron Channel					Muon Channel				
	1 jet	2 jets	3 jets	4 jets	5+ jets	1 jet	2 jets	3 jets	4 jets	5 jets
N_{loose}	38,935	15,213	7,118	2,191	654	18,714	7,092	3,054	878	221
N_{tight}	27,370	8,220	3,075	874	223	17,816	6,432	2,590	727	173
N^{fake-e}_{tight}	1,691	1,433	860	256	86	498	329	223	56	10
N^{real-e}_{tight}	25,679	6,787	2,215	618	137	17,319	6,105	2,369	669	162
ε_{real-e}	0.873	0.874	0.874	0.875	0.875	0.991	0.989	0.987	0.961	0.878
ε_{fake-e}	0.177	0.193	0.188	0.173	0.173	0.408	0.358	0.342	0.309	0.253

W+jets (зеленый), Multijet fake (коричневый), ttbar (красный), Данные



Результаты первичного отбора

Source	Event Yields in 0.9 fb^{-1} Data Electron+muon, 1tag+2tags combined 2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \rightarrow ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \rightarrow l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 131	460 ± 75	253 ± 42
Data	697	455	246

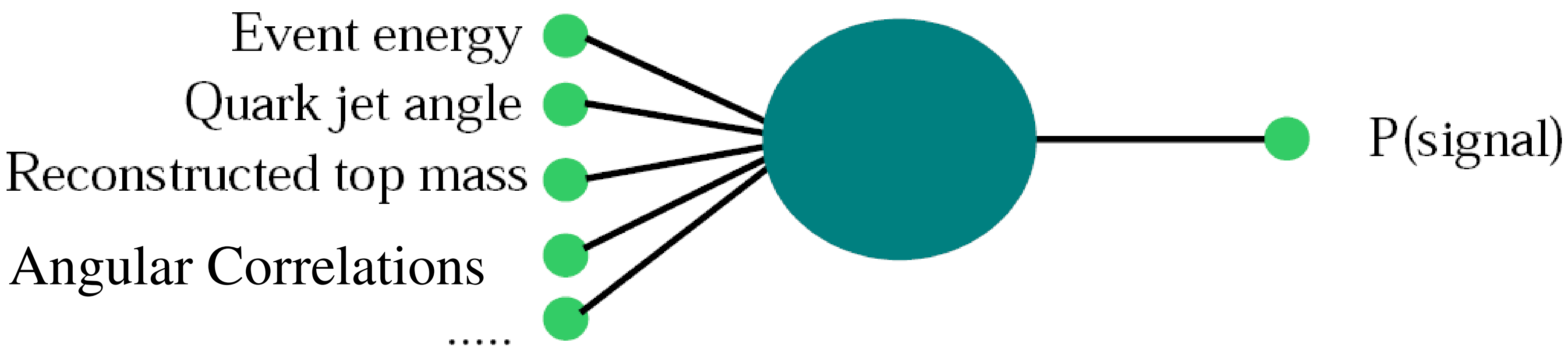
Оптимизация регистрации сигнала

Optimized Event Analysis

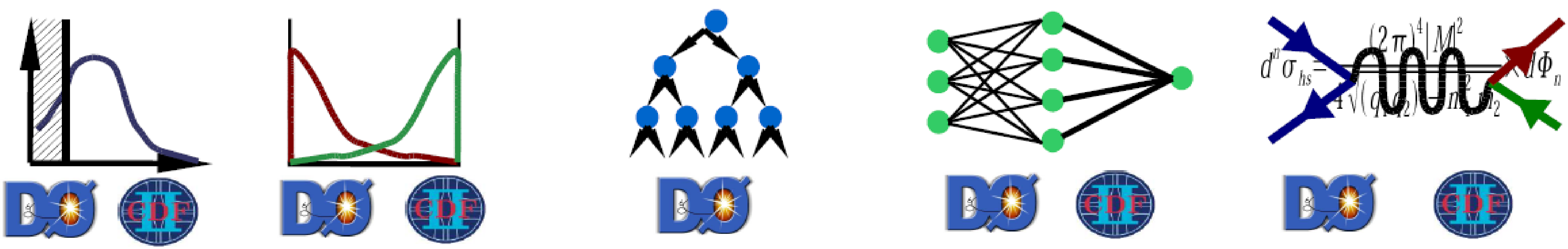
Input: discriminating variables

Method: multivariate analysis

Output: signal probability



Cut-Based | Likelihoods | Decision Trees | Neural Networks | Matrix Elements



Method of Optimal Observables

- Provides general receipt how to choose most effective variables to separate Signal/Background
- Based on the analysis of Feynman diagrams which contribute to signal and Background
- Described in different examples:
  - Higgs search hep-ph/0406152 p.69-71 (E.Boos and L.Dudko)
  - Single Top search AIHENP'99 (E.B. and L.D.), hep-ph/9903215 and D0 publications on Single Top Search
  - Proceedings of TEV4LHC workshop

Three Classes of Variables

- "Singular" Sensitive Variables (denominator of Feynman diagrams)

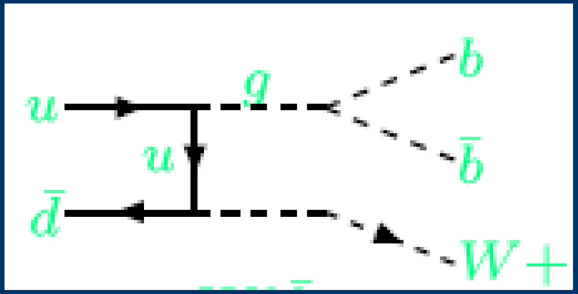
Most of the rates of signal and background processes come from the integration over the phase space region close to the singularities. If some of the singular variables are different or the positions of the singularities are different the corresponding distributions will differ most strongly

s-channel singularities

$$M^2_{f1,f2} = (p_{f1} + p_{f2})^2$$

t-channel singularities

$$\hat{t}_{i,f} = (p_f - p_i)^2 = -\sqrt{\hat{s}}e^{Y} p^f_T e^{-|y_f|}$$



Three Classes of Variables

- "Angular" variables, Spin effects
  (numerator of Feynman diagrams)

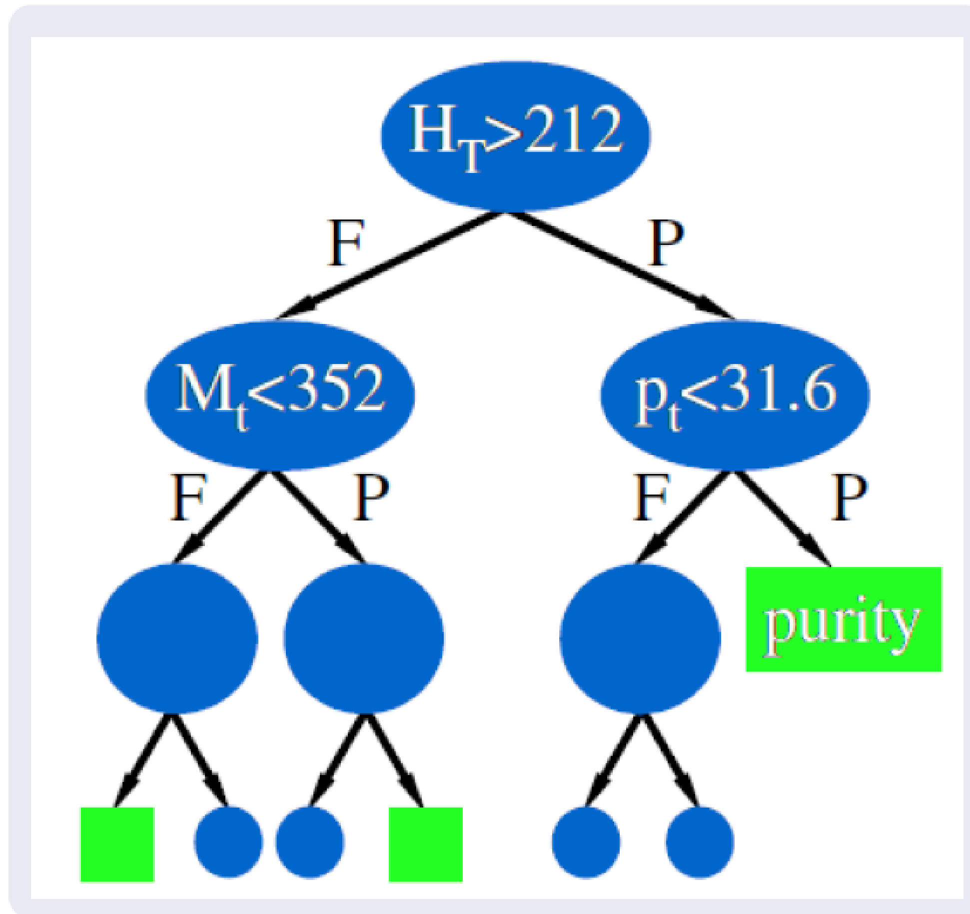
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{ql}} = \frac{1+P\cos\theta^*_{ql}}{2}$$

- "Threshold" variables
  s_hat and Ht variables relate to the fact that various signal and background processes may have very different energy thresholds

Decision Trees

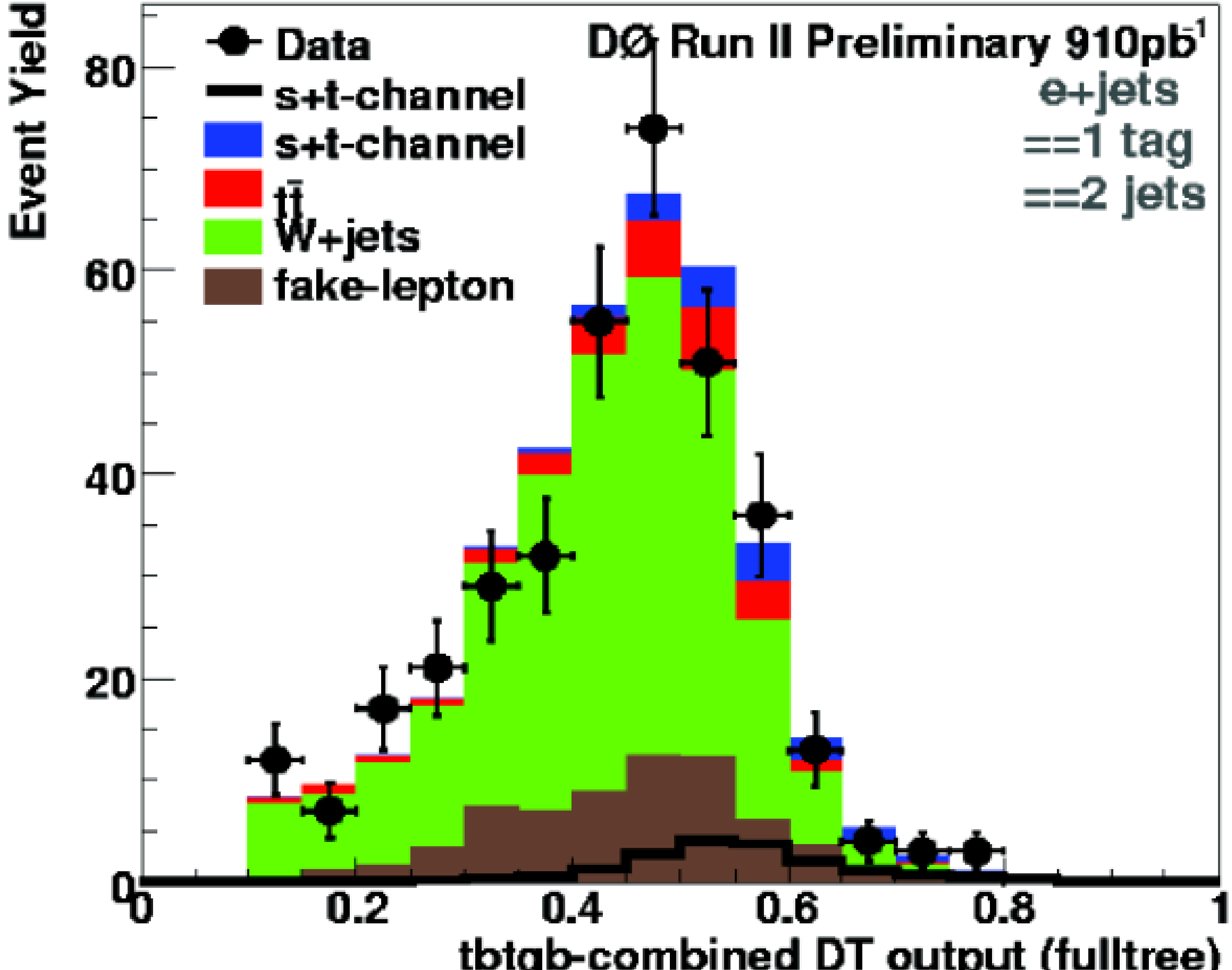
Train

- Start with all events (first node)
- For each variable, find the splitting value with best separation between children (best cut).
- select best variable and cut and produce Failed and Passed branches
- Repeat recursively on each node
- Stop when improvement stops or when too few events left. Terminal node = leaf.



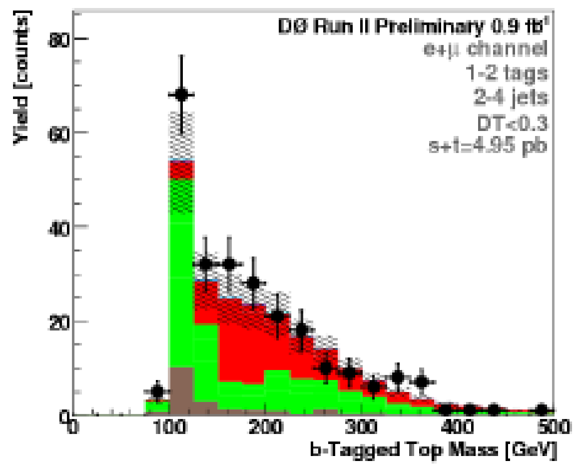
Decision Trees on Data

Of course, we have 36 different Decision Trees, let's look at electron, 2 jet, 1 tag:

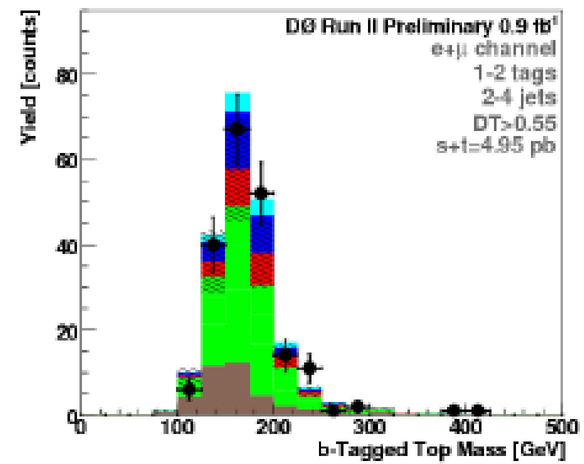


Decision Trees - Event Characteristics $M(W, b)$

$DT < 0.3$



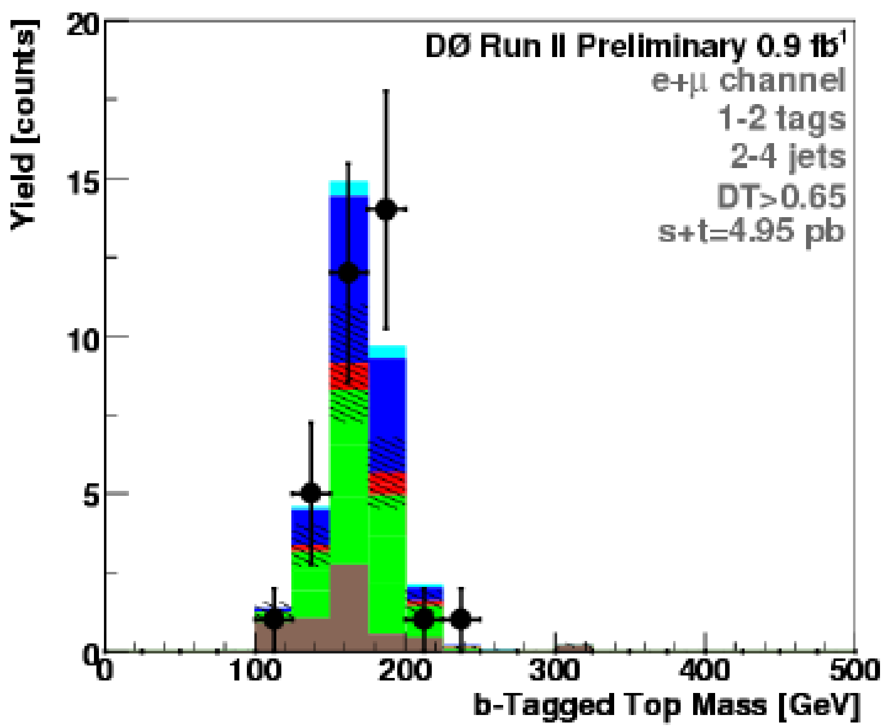
$DT > 0.55$



Key for Plots

- Data
- tb
- tqb
- $t\bar{t}$
- W + jets
- Multijets
- ±1σ uncertainty on background

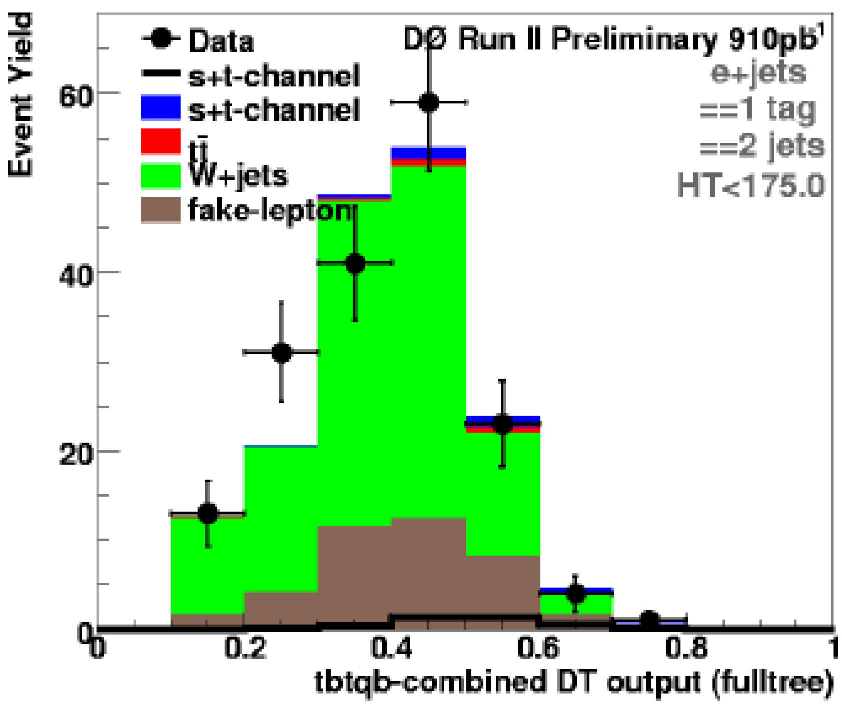
$DT > 0.65$

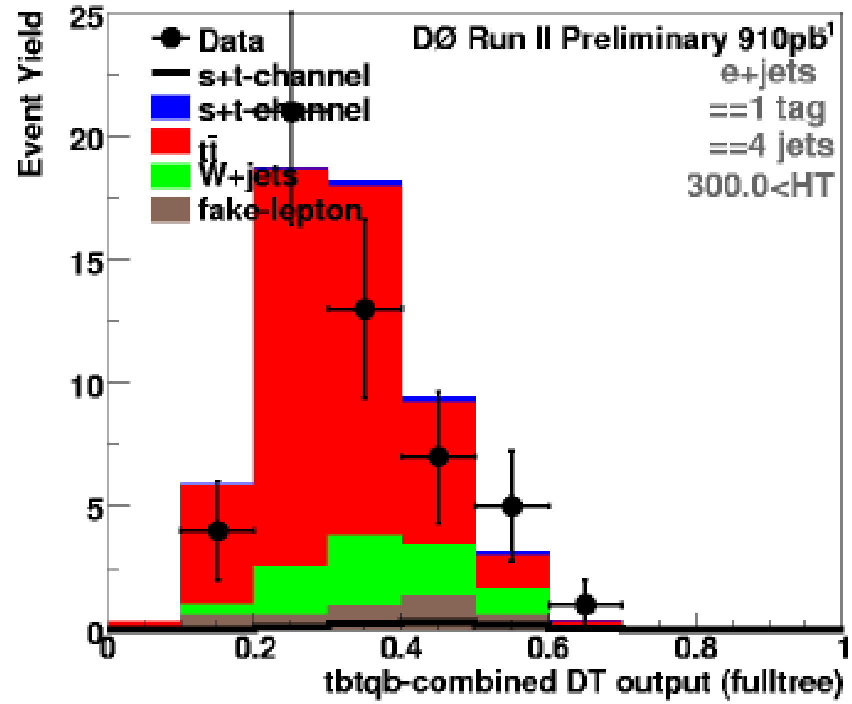


- Excess in high DT output region.

Cross-check samples

- "W+jets": =2jets, H_T(lepton,$\not\!\!E_T$,alljets) $<$ 175 GeV
- "ttbar": =4jets, H_T(lepton,$\not\!\!E_T$,alljets) $>$ 300 GeV
- Shown: tb+tqb DT output for e+jets



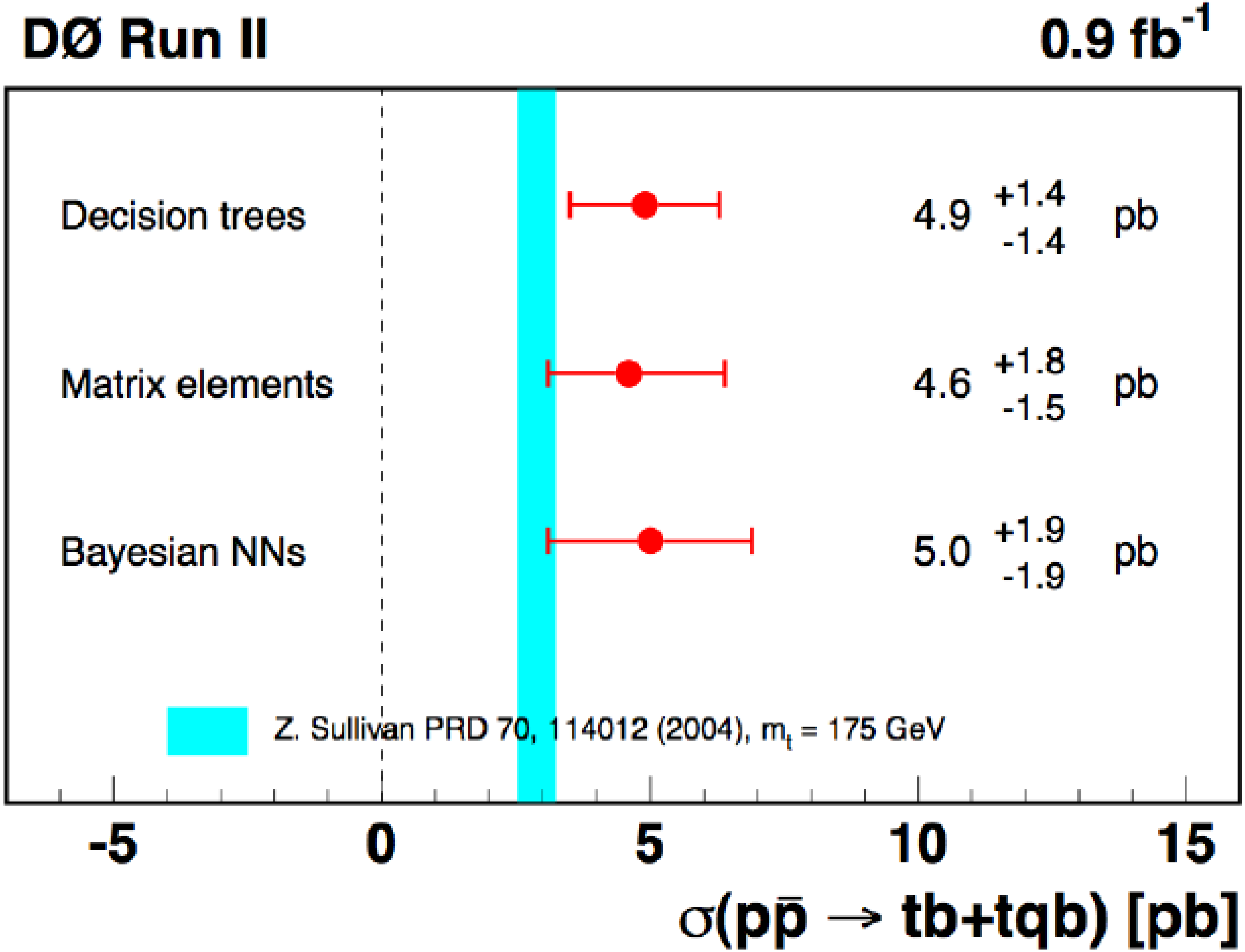


- Good agreement of model with data

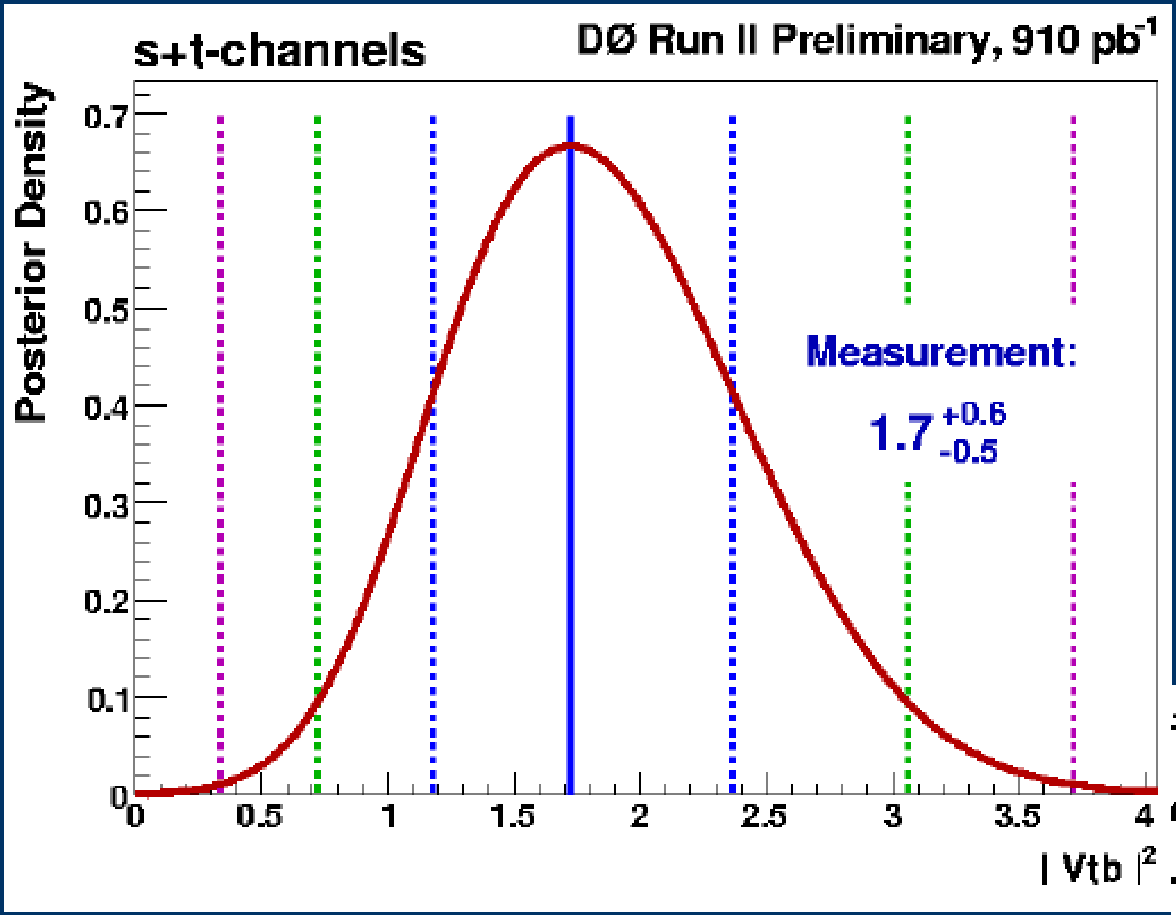
Ensemble Testing

- To verify that all of this machinery is working properly we test with many sets of **pseudo-data**.
- Wonderful tool to test analysis methods! Run DØ experiment 1000s of times!
- Generated ensembles include:
  1. 0-signal ensemble ($s + t\ \sigma = 0pb$)
  2. SM ensemble ($s + t\ \sigma = 2.9pb$)
  3. "Mystery" ensembles to test analyzers ($s + t\ \sigma = ??pb$)
  4. Ensembles at measured cross section ($s + t\ \sigma =$measured)
  5. A high luminosity ensemble
- Each analysis tests linearity of "response" to single top.

$s + t$ Summary - All methods



Measuring $|V_{tb}|^2$

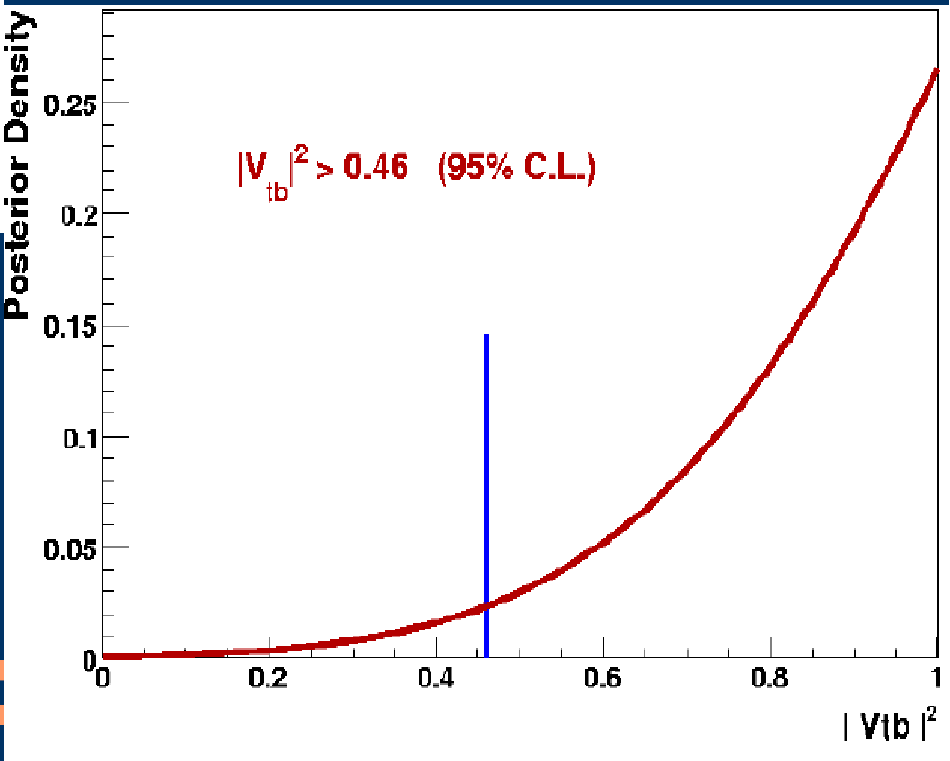


First direct measurement:
|Vtb| = 1.3 +/- 0.2

Constrain |Vtb| to physical region and integrate:

$|V_{tb}| > 0.68$

$|V_{tb}| = 1.00^{-0.12}_{+0}$



Conclusions

Preliminary First Evidence for Single Top Quark Production!!

- $s + t$ cross section: 4.9 ± 1.4pb
- 3.4σ significance!

- Three techniques in good agreement.
- First direct measurement of $|\mathrm{V_{tb}}|$!!

$$|\mathrm{V_{tb}}| = 1.00^{-0.12}_{+0}$$