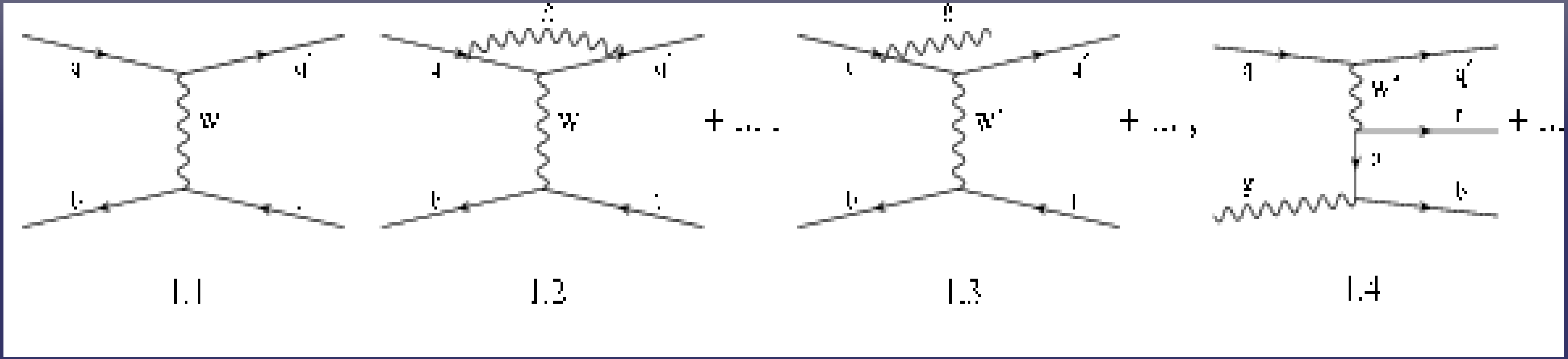
Overview of Single Top Theory and MC Model

L. Dudko

Introduction to Single Top
Problems of MC Model
SingleTop generator

t-channel Single Top Process



σ_NLO = 155.9 +7.5/-7.7 pb (t) [1]
90.3 +4.3/-4.5 pb (tbar)

uncertainty: PDF, Scale, Mtop, alpha_s, Mb

[1] Z. Sullivan hep-ph/0408049 (ZTOP)

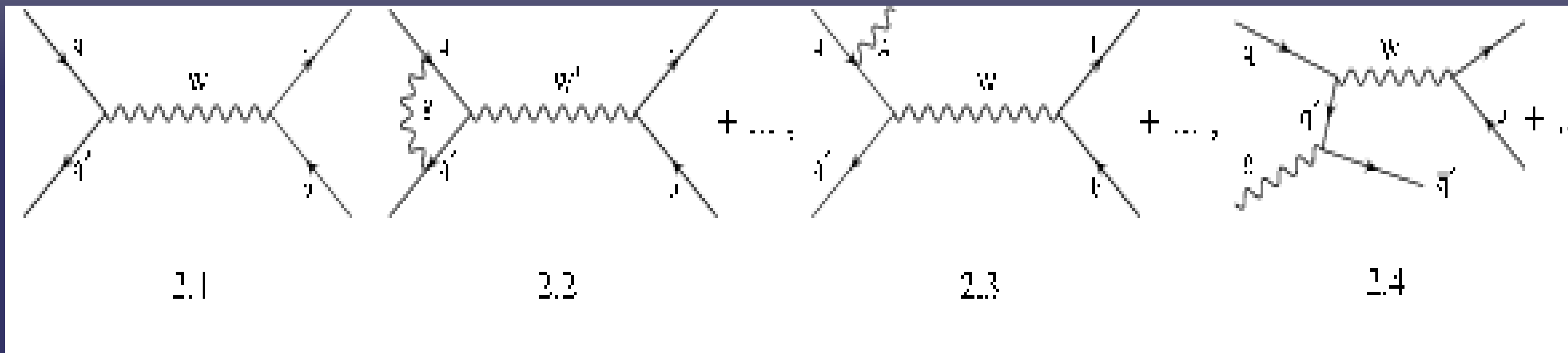
[2] J. Campbell, R.K. Ellis, F. Tramontano, hep-ph/0408158 (MCFM)

[3] Q.-H.Cao and C.-P.Yuan, hep-ph/0408180; Q.-H.Cao, R.Schwienhorst C.-P.Yuan, hep-ph/0409040

Qing-Hong Cao, Reinhard Schwienhorst, Jorge A. Benitez, Raymond Brock, C.-P. Yuan hep-ph/0504230

[2],[3] include NLO corrections to production&decay and final top width

s-channel Single Top Process



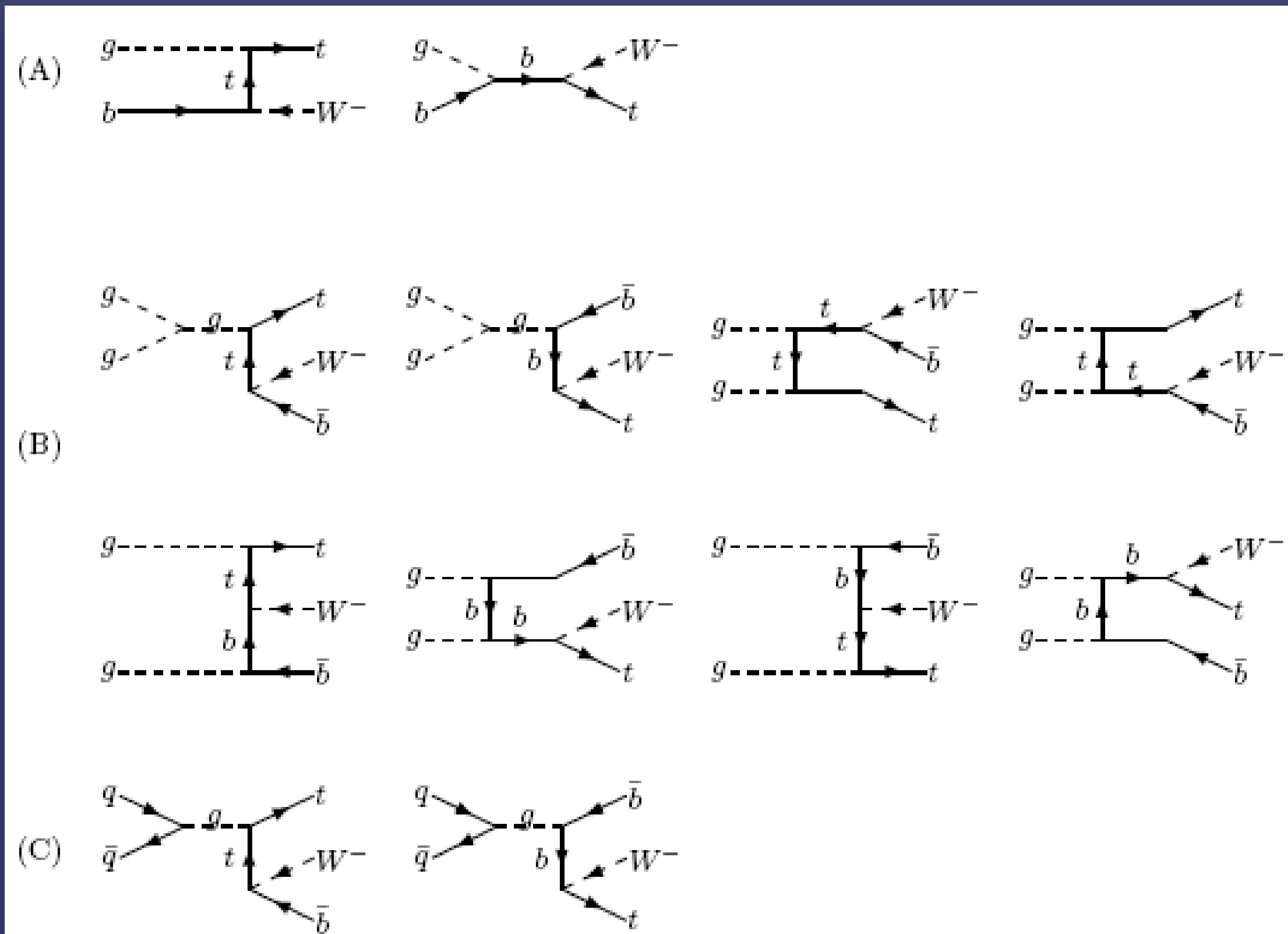
σ_NLO = 6.56 +0.69/-0.63 pb (t)   [1]
4.09 +0.43/-0.39 pb (tbar)

uncertainty: PDF, Scale, Mtop, alpha_s, Mb

[1] Z. Sullivan hep-ph/0408049 (ZTOP)
[2] J. Campbell, R.K. Ellis, F. Tramontano,
hep-ph/0408158 (MCFM)
[3] Q.-H.Cao and C.-P.Yuan, hep-ph/0408180;
Q.-H.Cao, R.Schwienhorst C.-P.Yuan, hep-ph/0409040, hep-ph/0504230

[2],[3] include NLO corrections to production&decay and final top width

tW process



σ_LO = 62 +/-17 pb

A.Belyaev, E.Boos,
Phys.Rev.D63, 034012

What is Interesting in Single Top

- Independent electroweak channel of the top quark production
- Direct Vtb CKM matrix element measurement
- Significant background for Higgs and many “new physics” processes
- Unique spin correlations properties
- Processes of interest for “New Physics”
  - Wtb anomalous couplings
  - FCNC
  - New strong dynamics
  - R-parity violating SUSY effects
  - Kaluza-Klein excitation of W-boson or W'

hep-ph/0003033, hep-ph/0410364

Anomalous Wtb Couplings

- Lagrangian

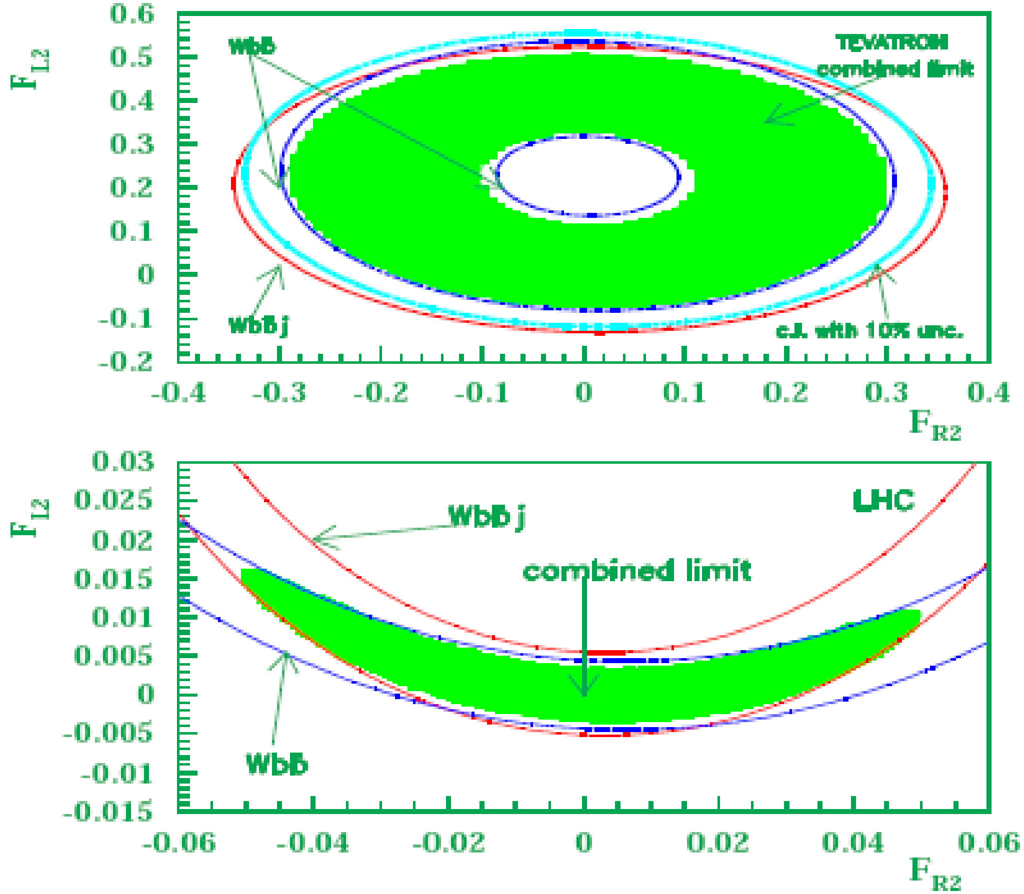
$$\mathcal{L} = \frac{g}{\sqrt{2}} \left[W_\nu^- \bar{b} \gamma_\mu P_- t - \frac{1}{2M_W} W_{\mu\nu}^- \bar{b} \sigma^{\mu\nu} (F_2^L P_- + F_2^R P_+) t \right] + h.c.$$

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 $C_{tW\Phi}$ and $C_{bW\Phi}$ of the effective Lagrangian $F_2^{L(R)} = \frac{C_{t(b)W\Phi}}{\Lambda^2} \frac{\sqrt{2} v M_W}{g}$

- A possible $V + A$ form factor is severely constrained by the CLEO $b \to s\gamma$ data

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 and Single top quark production

- Couplings: tcg, tug, $tc\gamma$, $tu\gamma$

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

tcg, tug coupling and Single top production at Tevatron and LHC

Malkawi,Tait(95); Tait,Yuan(96); Han,Hosch,Whisnant,Young,Zhang(98)

Discovery limits

	Run 1	Run 2	Run 3	LHC
E_{cm} (TeV)	1.8	2.0	2.0	14.0
$\mathcal{L}$ (fb^{-1})	.1	2	30	10
κ_c^g/Λ (TeV^{-1})	.31	.092	.046	.013
κ_u^g/Λ (TeV^{-1})	.082	.026	.013	.0061

Mahlon,Parke; E.B.,Sherstnev

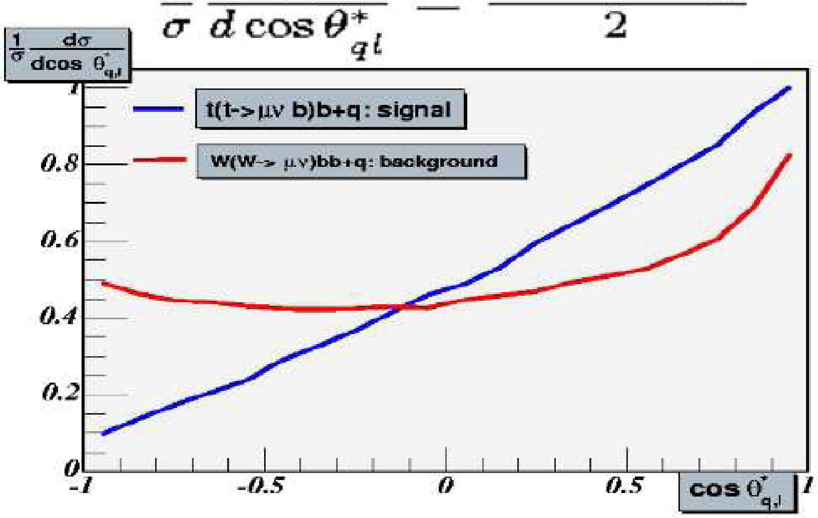
Spin_correlations:_theoretical_view

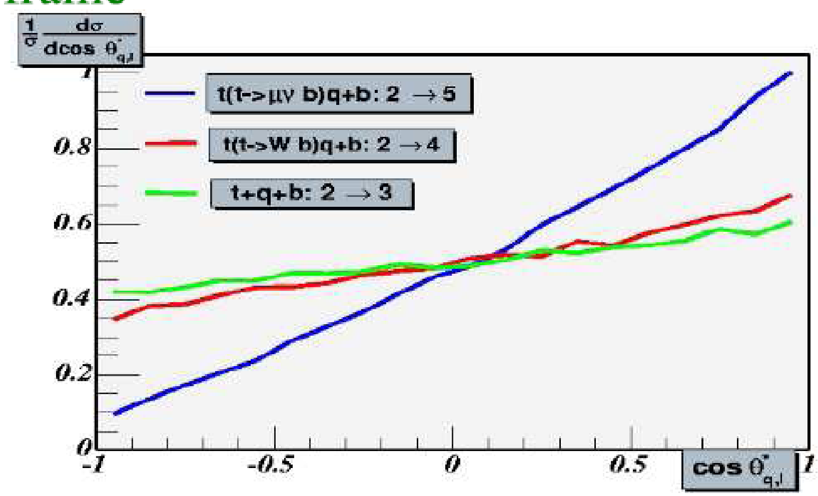
Single top quark is produced highly polarized via the Wtb vertex. Since top quarks do not have a time to form strong bound state, we can investigate a top polarization. There is a unique top spin decomposition axis in the top rest frame: momentum of lepton in top the rest frame from top decay: $t \to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

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

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



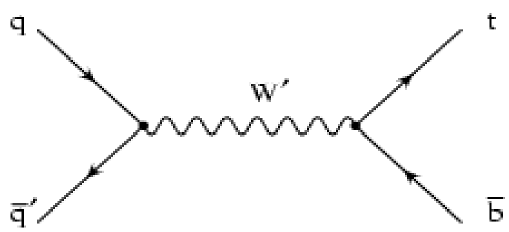


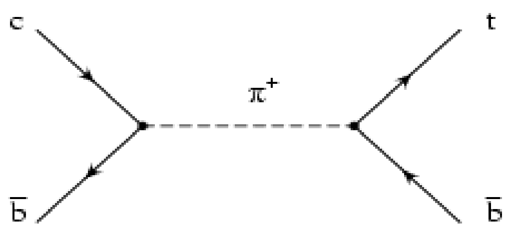
In ideal theoretical situation we have for t-channel:

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

Extra Vector and Scalar Bosons

[T.Tait, C.-P.Yuan CERN-TH/2000-224]





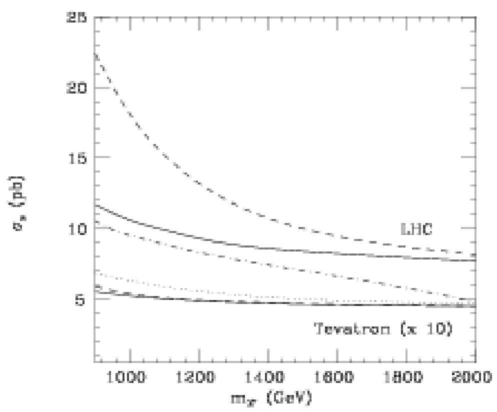


Figure 1: The NLO rate of $q\,\bar{q}' \to W, W' \to t\,\bar{b}$ (σ_S) in pb at the Tevatron (lower curves) and LHC (upper curves).

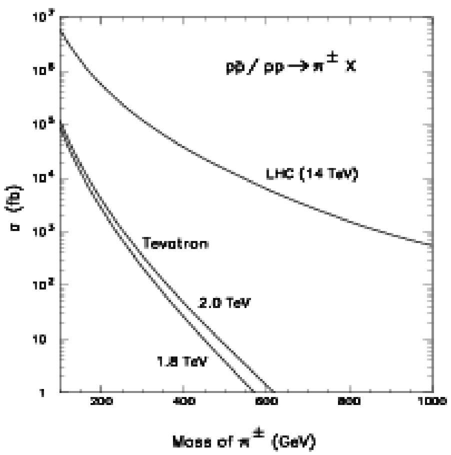


Figure 2: The LO rate of single top production through the reaction $c\,\bar{b} \to \pi^+ \to t\,\bar{b}$ as a function of $M_{\pi^\pm}$, assuming a t_R-c_R mixing of 20%.

MC Generators of Single Top Signal

- ONETOP
- TopRex
- Generators based on MadGraph & MadEvent
- Generators based on Pythia
- Generators based on CompHEP

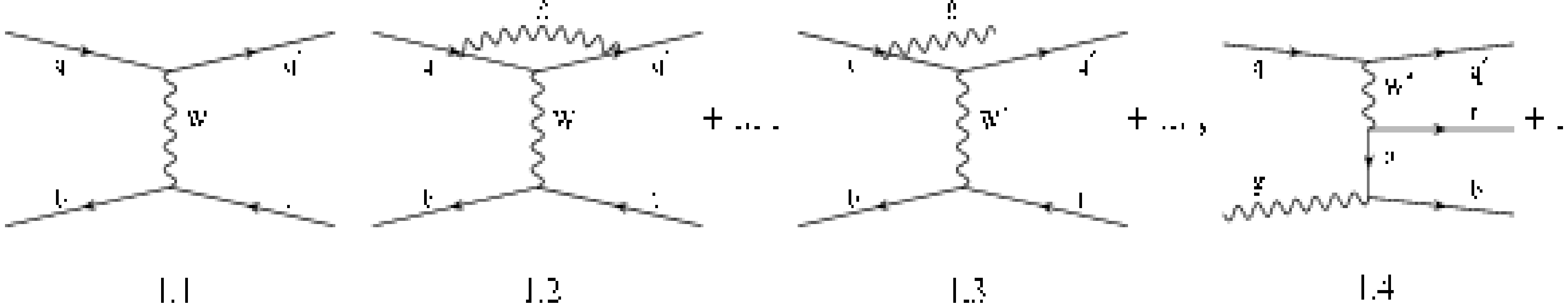
Problems and requirements for a generator for the single top signal:

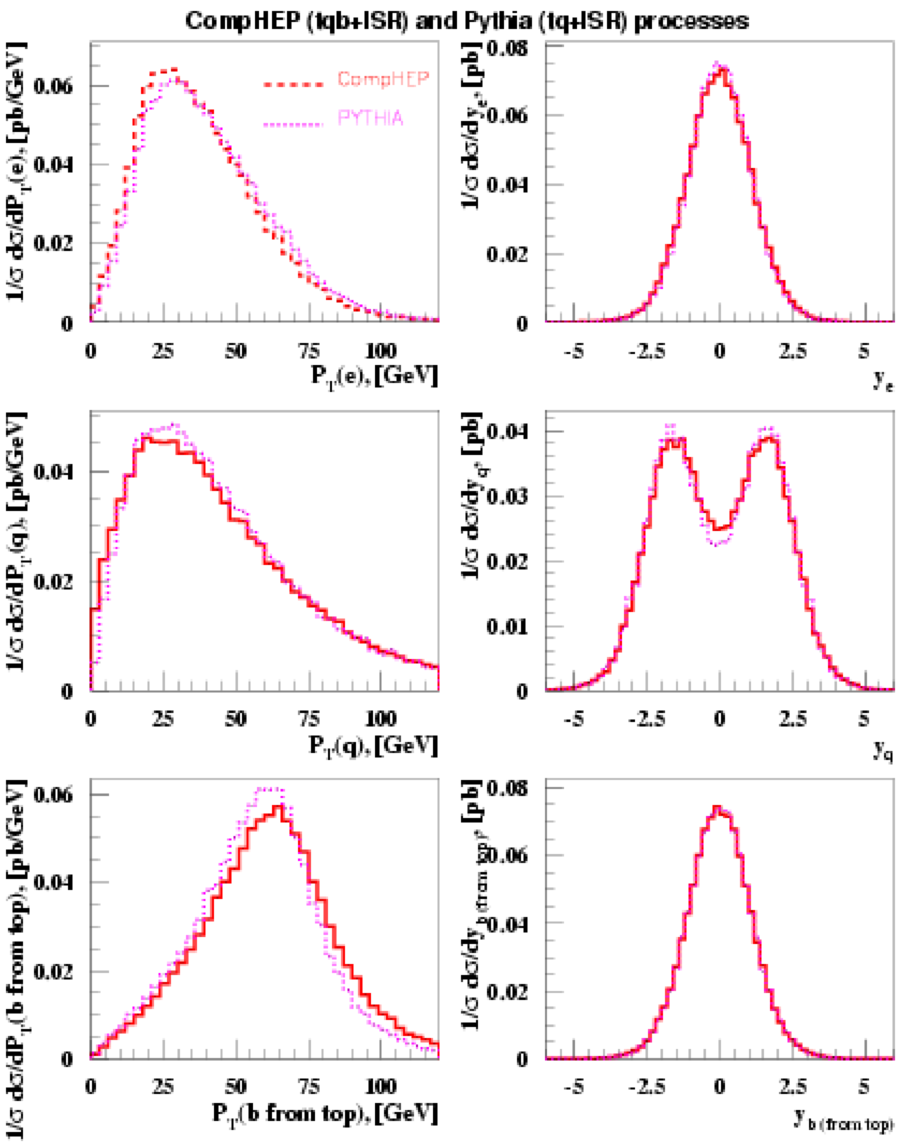
- Double counting and negative weights
- Matching of various NLO contributions at the generator level. One should have the correct NLO rate and correct shapes of the NLO distributions
- Matching to showering programs
- Correct spin correlations
- Finite top and W widths
- Separation Top and antiTop since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

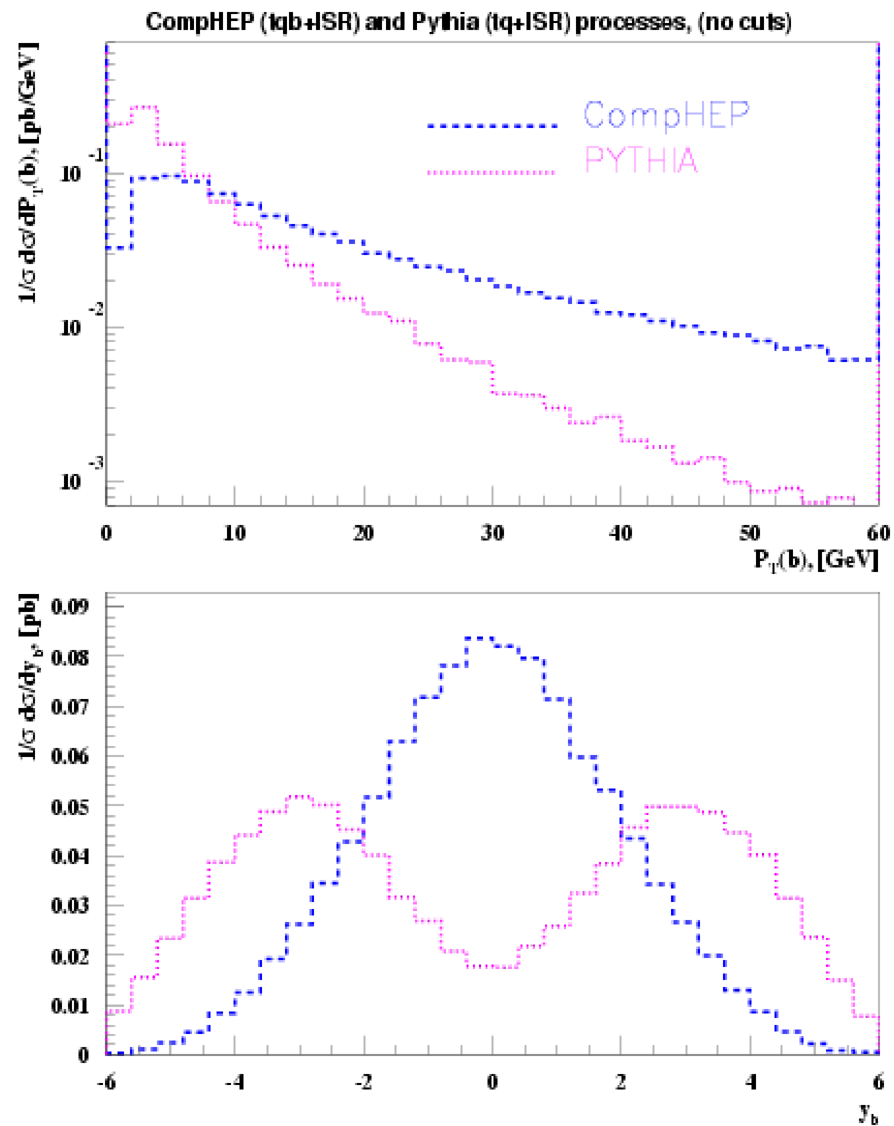
Generator SingleTop

E.Boos, V.Bunichev, L.Dudko,V.Savrin, A.Sherstnev

- Based on CompHEP, PYTHIA and CompHEP-PYTHIA interface (Les Houches Accord)
- Provides MC events at NLO level (distributions and rates of events)
- First described in CMS Note 2000/065 (hep-ph/0403113)
- Used and tested in D0 (Tevatron) analysis in Run I and Run II


1.1
1.2
1.3
1.4

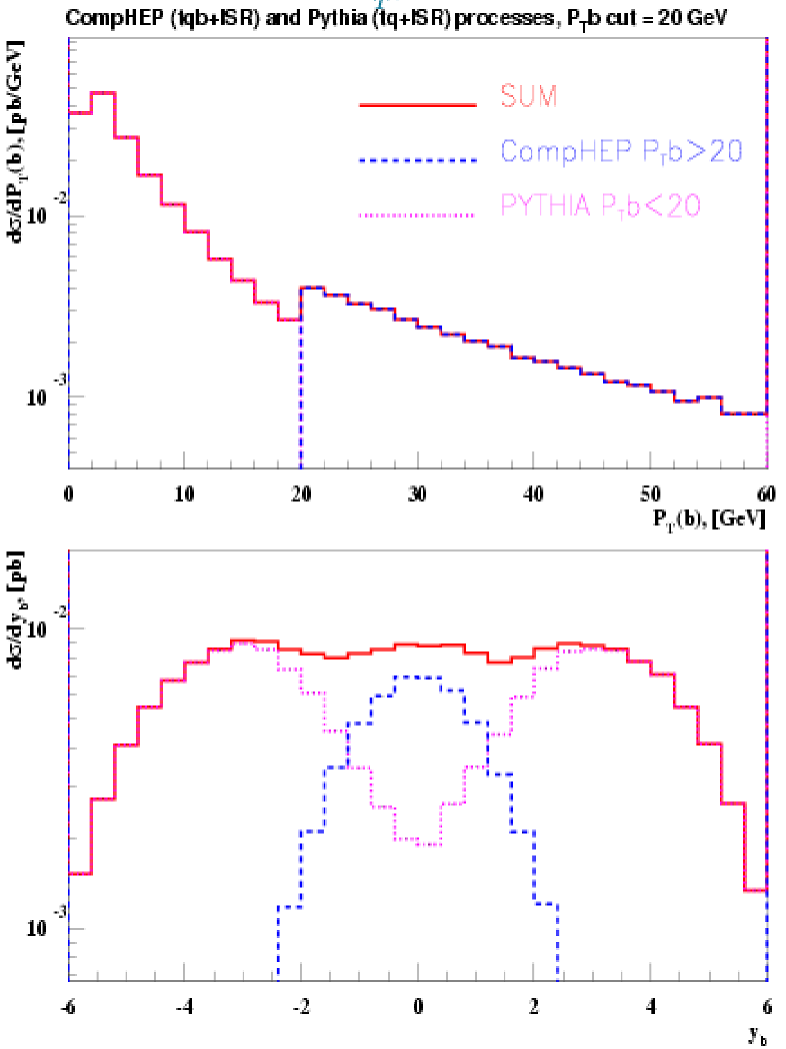

CompHEP (tqb+ISR) and Pythia (tq+ISR) processes
CompHEP
PYTHIA
1/σ dσ/dP_T(e), [pb/GeV]
P_T(e), [GeV]
1/σ dσ/dy_e, [pb]
y_e
1/σ dσ/dP_T(q), [pb/GeV]
P_T(q), [GeV]
1/σ dσ/dy_q, [pb]
y_q
1/σ dσ/dP_T(b from top), [pb/GeV]
P_T(b from top), [GeV]
1/σ dσ/dy_b (from top), [pb]
y_b (from top)


CompHEP (tqb+ISR) and Pythia (tq+ISR) processes, (no cuts)
CompHEP
PYTHIA
1/σ dσ/dP_T(b), [pb/GeV]
P_T(b), [GeV]
1/σ dσ/dy_b, [pb]
y_b

Matching of Pythia ($2 \to 2$) and CompHEP ($2 \to 3$) distributions:

$\sigma_{\mathrm{PYTHIA}}(2 \to 2) = \sigma_{\mathrm{NLO}} - \sigma_{\mathrm{CompHEP}}(2 \to 3)\,|_{P_T^b > cut(P_T^b)}$,

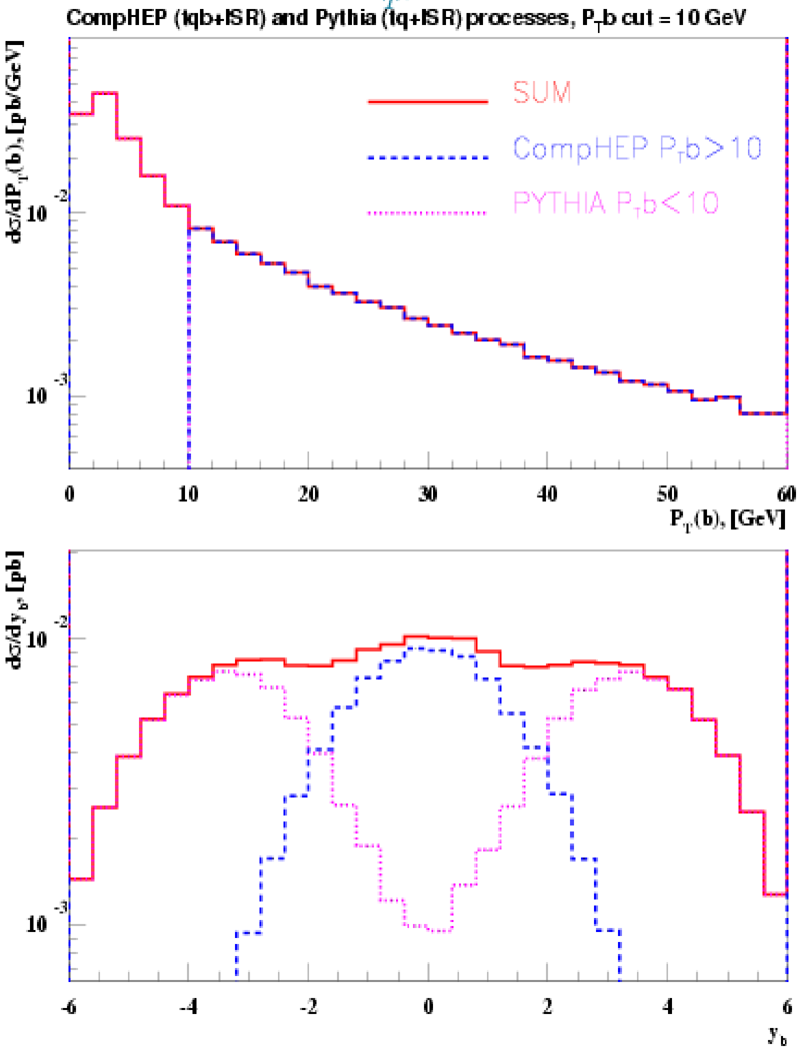
where, $\sigma_{\mathrm{CompHEP}}(2 \to 3)\,|_{P_T^b > 20\mathrm{GeV}} \approx 0.051$ pb



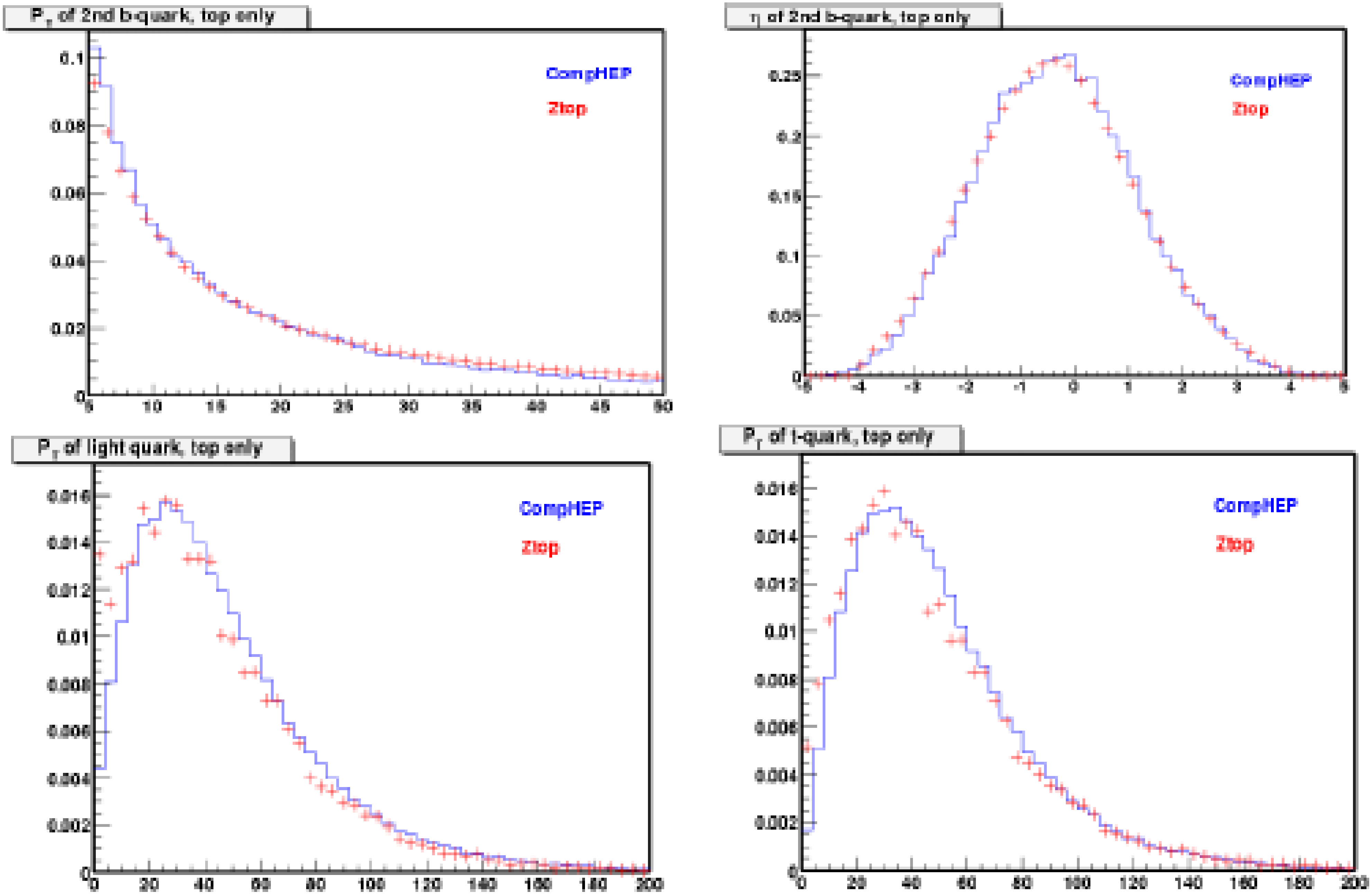
Final matching of Pythia ($2 \to 2$) and CompHEP ($2 \to 3$) distributions:

$\sigma_{\mathrm{PYTHIA}}(2 \to 2) = \sigma_{\mathrm{NLO}} - \sigma_{\mathrm{CompHEP}}(2 \to 3)\,|_{P_T^b > cut(P_T^b)}$,

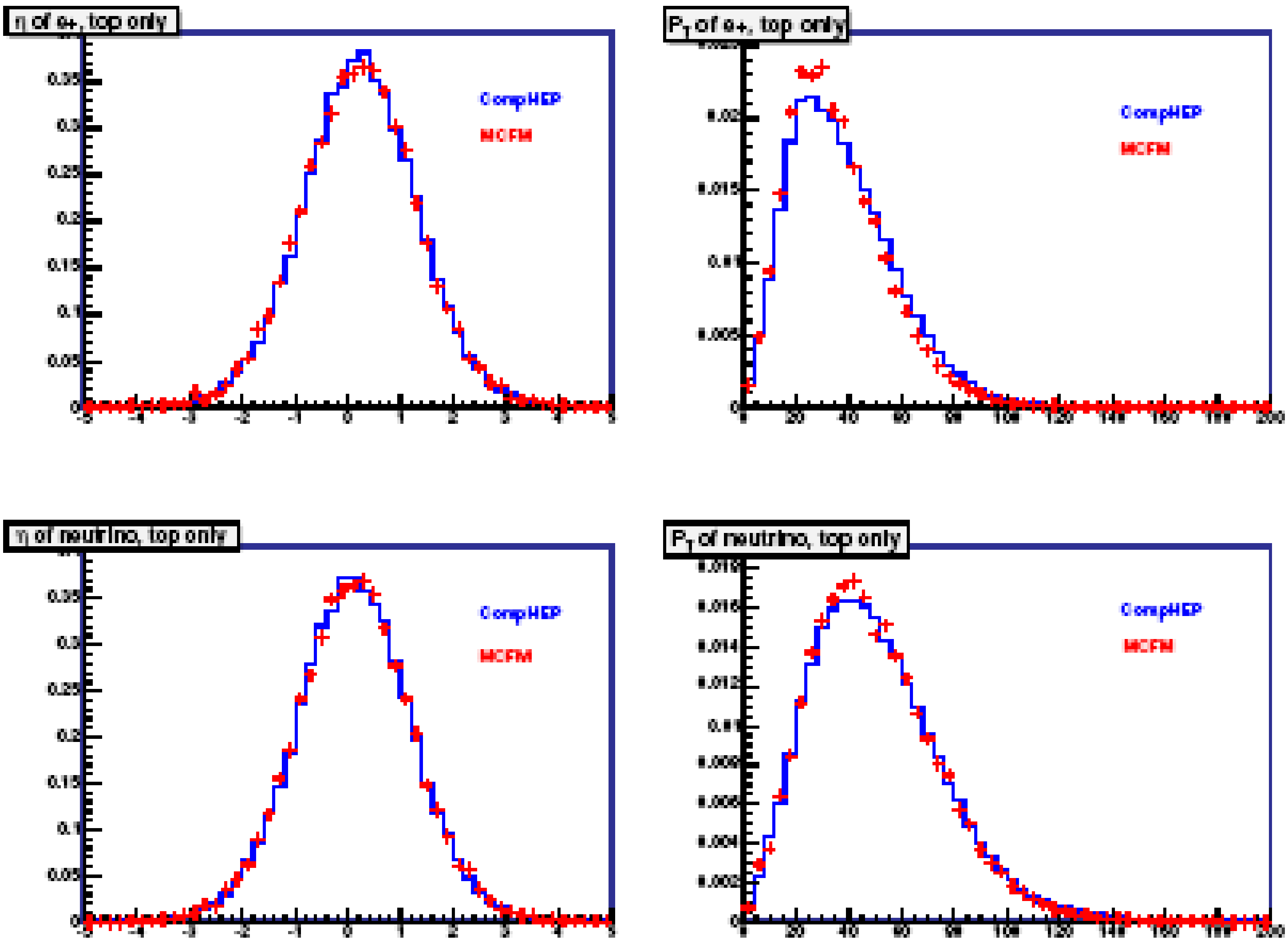
where, $\sigma_{\mathrm{CompHEP}}(2 \to 3)\,|_{P_T^b > 10\mathrm{GeV}} \approx 0.08$ pb



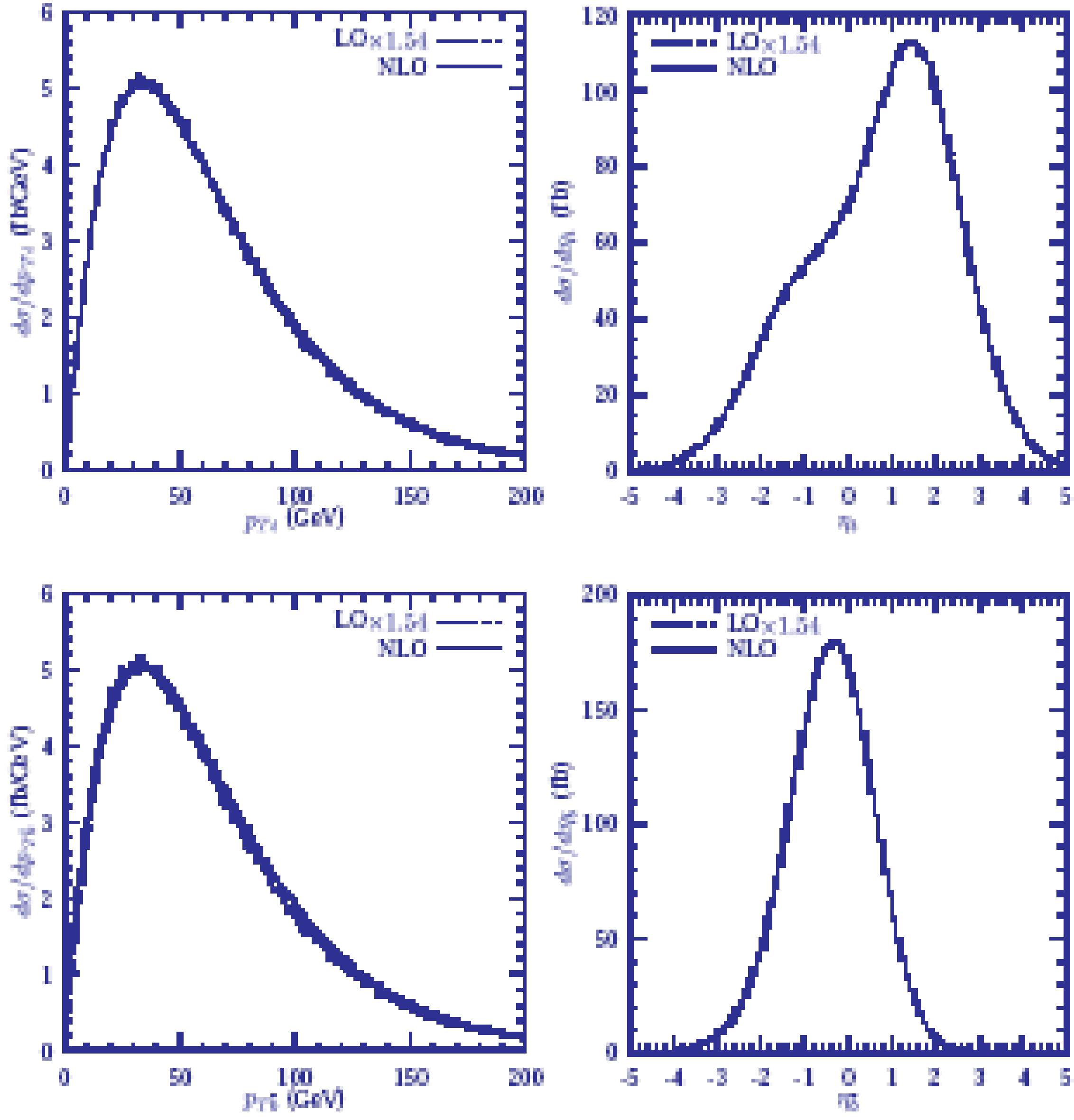
Signal Model by SingleTop generator («effectively» NLO, based on CompHEP).
Comparison with exact NLO distributions «ZTOP» hep-ph/0408049



Comparisons with MCFM for top decay products (t-channel):
Transverse momentum and pseudorapidity of l and ν_l from top decay



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

Concluding Remarks on Generator SingleTop

- "effective" NLO generator without double counting and negative weights
- all single top production modes including top decays with correct spin correlations and finite top and W-boson widths
- smooth matching of hard and soft emissions in the interface with Pythia. Rate is normalized to the NLO rate and distributions reproduce the result of fully differential NLO computations.
- partonic level events for final particles in a Les Houches format. Direct implementation to the latest PYTHIA version for showering and hadronization
- more comparisons with various NLO computations and other generators are on the way (specially, need to be done for the LHC)
- our matching procedure has been implemented recently to the TopRex

Overview of Single Top TEVATRON Experience

L. Dudko

CDF and D0 Analysis
Optimal Observables
High Level Analysis Methods

The Latest Tevatron Results

	s-channel	t-channel
NLO cross section	0.88 pb	1.98 pb
	95% CL upper cross section limits [pb]	
DØ Run I	17	22
CDF Run II (160pb^{-1})	13.6	10.1
This analysis (230pb^{-1})		
cut-based	10.6	11.3
DTs & binned likelihood	8.3	8.1
NNs & binned likelihood	6.4	5

Tevatron Systematic Uncertainties

DO (W&C talk R.S.)

Monte Carlo Systematic Uncertainties	
Components affecting normalization	
$\sigma_{t\bar{t}}$ theory and mass	18 %
$\sigma_{s(t)}$ theory	15 %(16 %)
Jet Fragmentation	6.0 %
ℓ ID	4.1 %
Branching Fraction	2.0 %
Components affecting shape and normalization	
SVT modeling, single (double) tag	10 %(20 %)
Jet Energy Scale	10 %
Trigger Modeling	6 %
Jet ID	5 %
Jet Energy Resolution	4 %

CDF (PRD 71 012005 (2005)

i	Source	t-channel	s-channel	Combined
1	JES	$^{+2.4}_{-6.7}$	$^{+0.4}_{-3.1}$	$^{+0.1}_{-4.3}$
2	ISR	± 1.0	± 0.6	± 1.0
3	FSR	± 2.2	± 5.3	± 2.6
4	PDF	± 4.4	± 2.5	± 3.8
5	Generator	± 5	± 2	± 3
6	Top quark mass	$^{+0.7}_{-6.9}$	-2.3	-4.4
7	ϵ_{trig}, ϵ_{ID}, luminosity	± 9.8	± 9.8	± 9.8

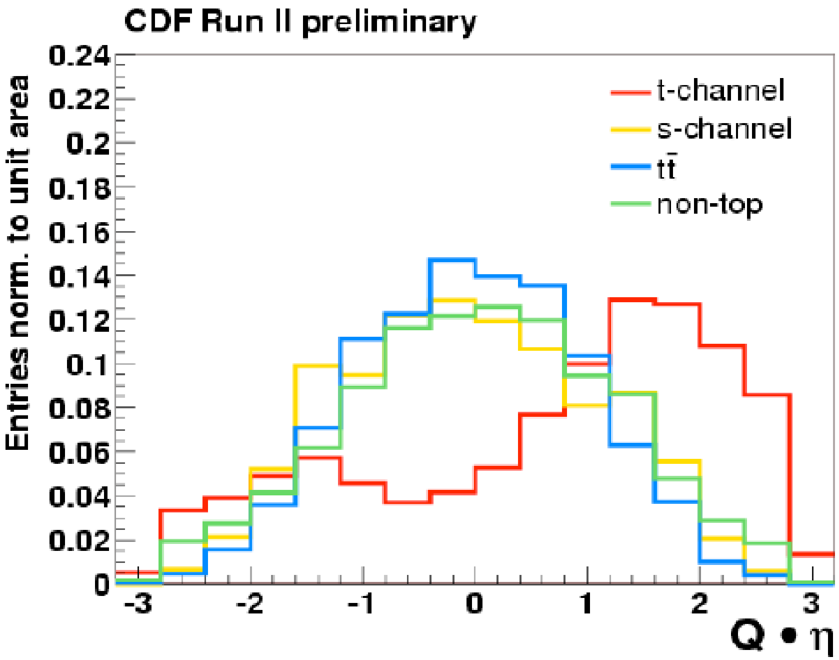
σ_NLO_t_channel_LHC = 155.9 +7.5/-7.7 pb (t) [1]
90.3 +4.3/-4.5 pb (tbar)

uncertainty: PDF, Q_Scale, Mtop, alpha_s, Mb

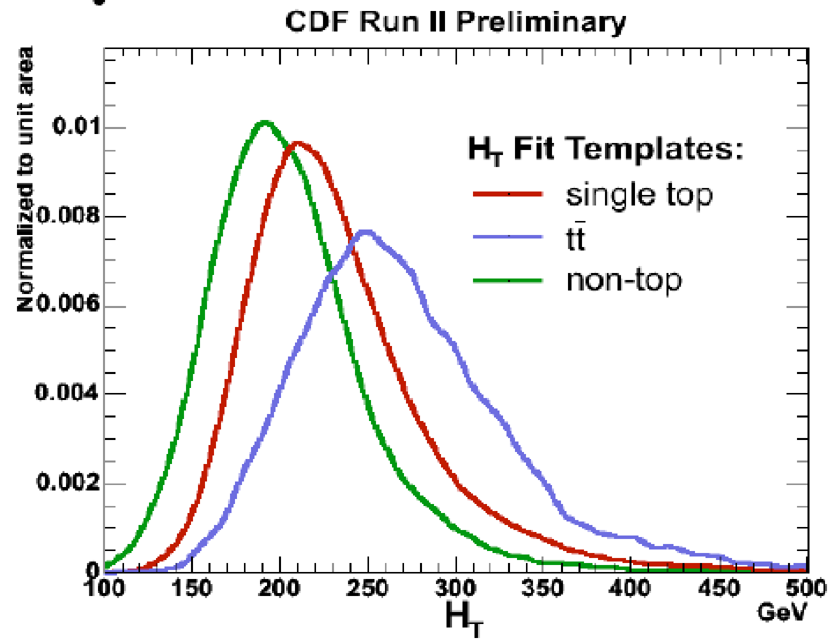
Generic Structure of Analysis

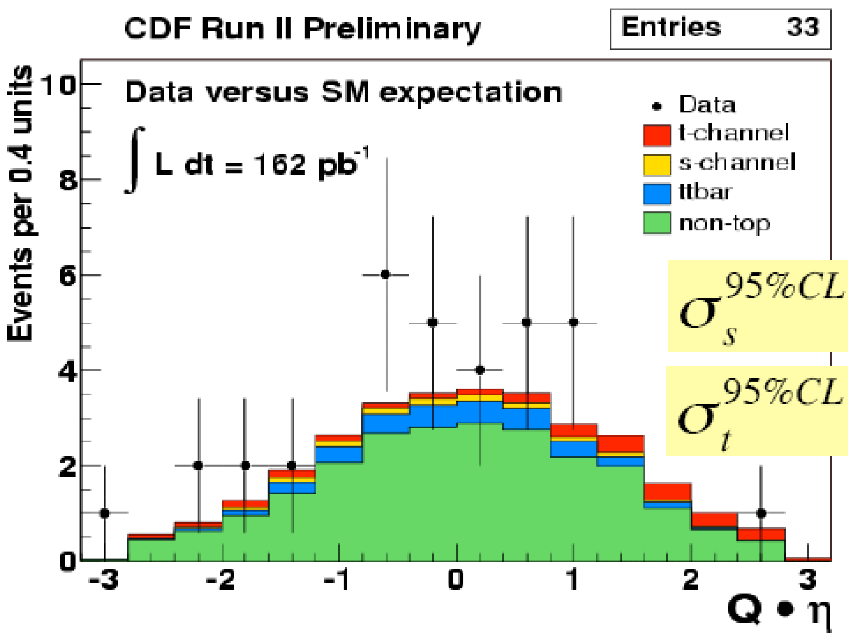
- Apply some preselection cuts
- Find some observables which help to sepa-rate signal from background
- Apply some method of High Level Analysis to get final numbers of the predicted Signal/Background and Data

CDF Analysis



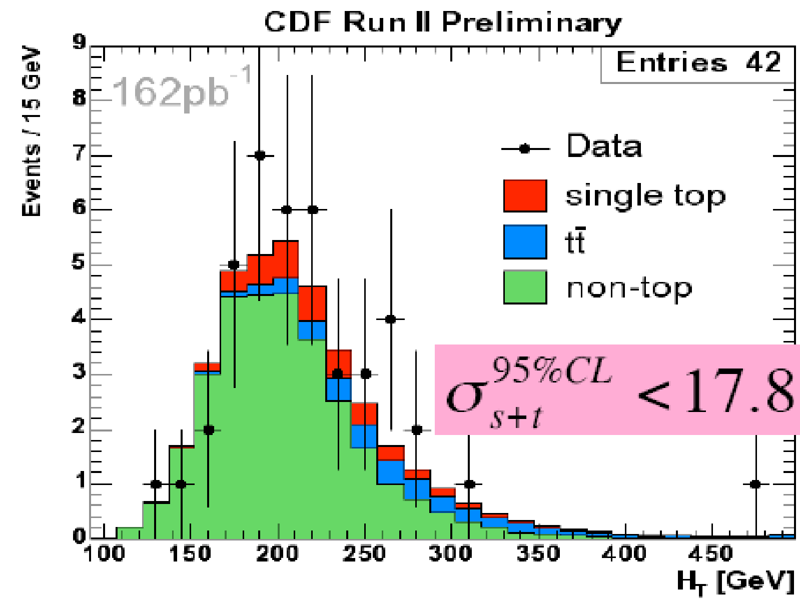
MC Templates





$$\sigma_s^{95\%CL} < 13.6 \text{ pb}$$

$$\sigma_t^{95\%CL} < 10.1 \text{ pb}$$



$$\sigma_{s+t}^{95\%CL} < 17.8 \text{ pb}$$

CDF Analysis

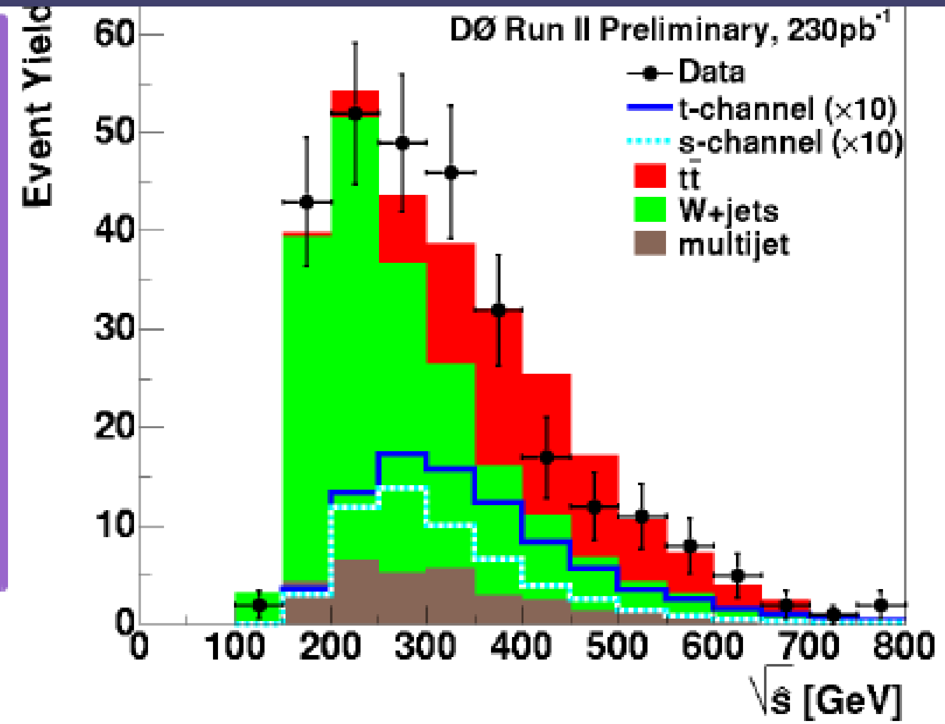
- Use Q(l) X Eta(q) to separate t, s -channel and backgrounds; Ht for the combined search
- Use Binned Likelihood of variables above
- Depends on number of b-tags

Process	N events in combined search	N events in separate search	
		1-b-tag-bin	double-tag-bin
$t\bar{t}$ ($\sigma = 6.70^{+0.71}_{-0.88}$ pb)	3.8 ± 0.9	3.2 ± 0.7	0.60 ± 0.14
non-top	30.0 ± 5.8	23.3 ± 4.6	2.59 ± 0.71
Sum Background	33.8 ± 5.9	26.5 ± 4.7	3.19 ± 0.72
t-channel ($\sigma = 1.98 \pm 0.26$ pb)	2.8 ± 0.5	2.7 ± 0.4	0.02 ± 0.01
s-channel ($\sigma = 0.88 \pm 0.11$ pb)	1.5 ± 0.2	1.1 ± 0.2	0.32 ± 0.05
Sum Single-Top	4.3 ± 0.5	3.8 ± 0.5	0.34 ± 0.05
Sum Expected	38.1 ± 5.9	30.3 ± 4.7	3.53 ± 0.72
Observed	42	33	6

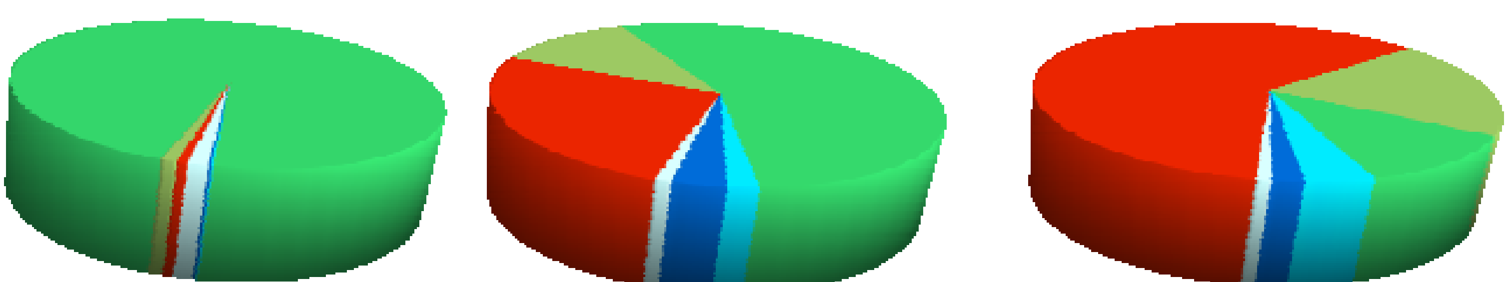
D0 Analysis

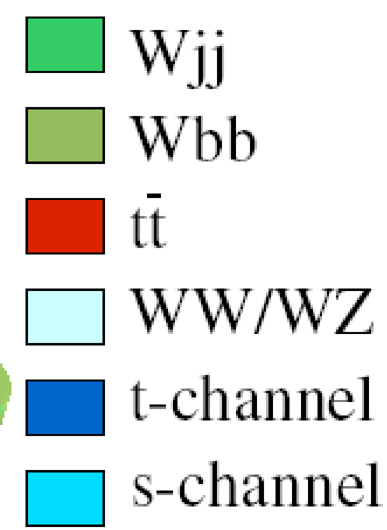
PHENO 03/05/05 talk by R. Schwienhorst

	s-channel	t-channel
Cut acceptance	23%	22%
b-tag efficiency	54%	38%
Signal yield	5.5	8.5
BKgnd yield	287	276
Signal/bkgnd	1:52	1:32



Pre-tagged	=1 b-tag	≥2 b-tags
7100 events	252 events	31 events





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.D.)
  - Single Top search AIHENP'99 (E.B. and L.D.),

    hep-ph/9903215 and D0 publications on Single Top Search
  - Ttbar in progress (E.B., L.D., H. Frisch, S. Levy)

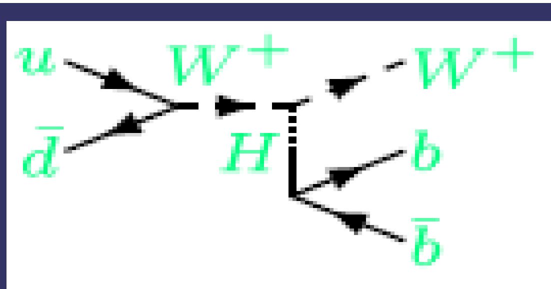
Three Classes of Variables

- “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

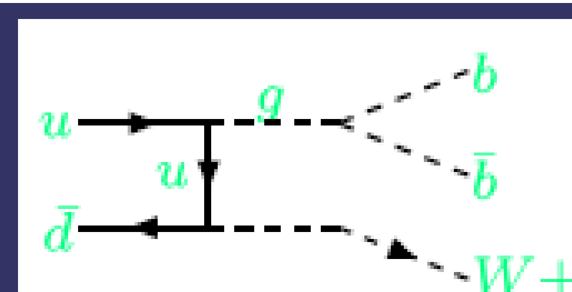
s-channel singularities

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



t-channel singularities

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



Three Classes of Variables

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

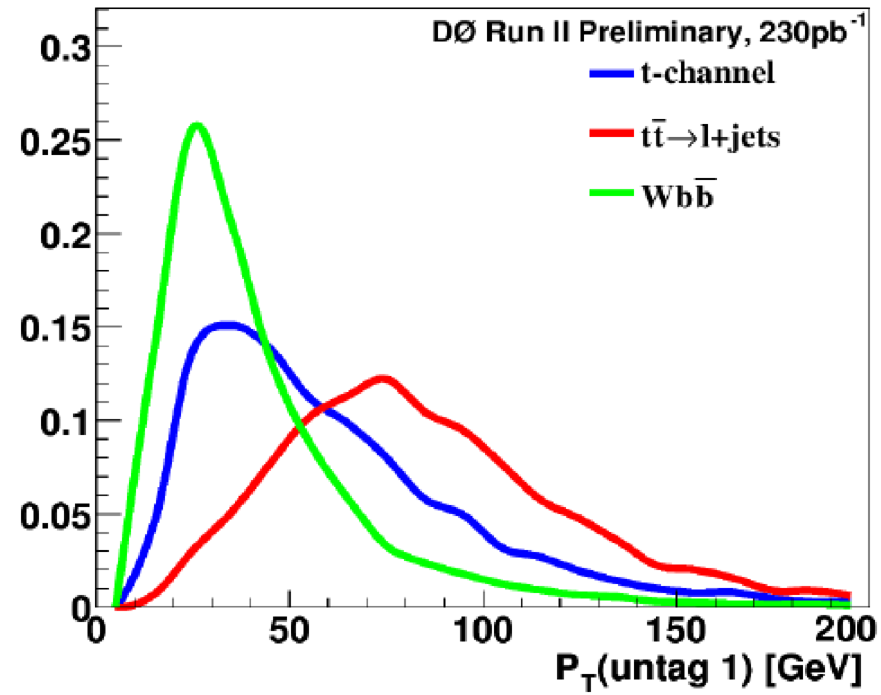
$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d(\cos\chi_\ell^W)} = \frac{3}{4}\,\frac{m_t^2\sin^2\chi_\ell^W + 2m_W^2\,\frac{1}{2}(1-\cos\chi_\ell^W)^2}{m_t^2+2m_W^2}$$

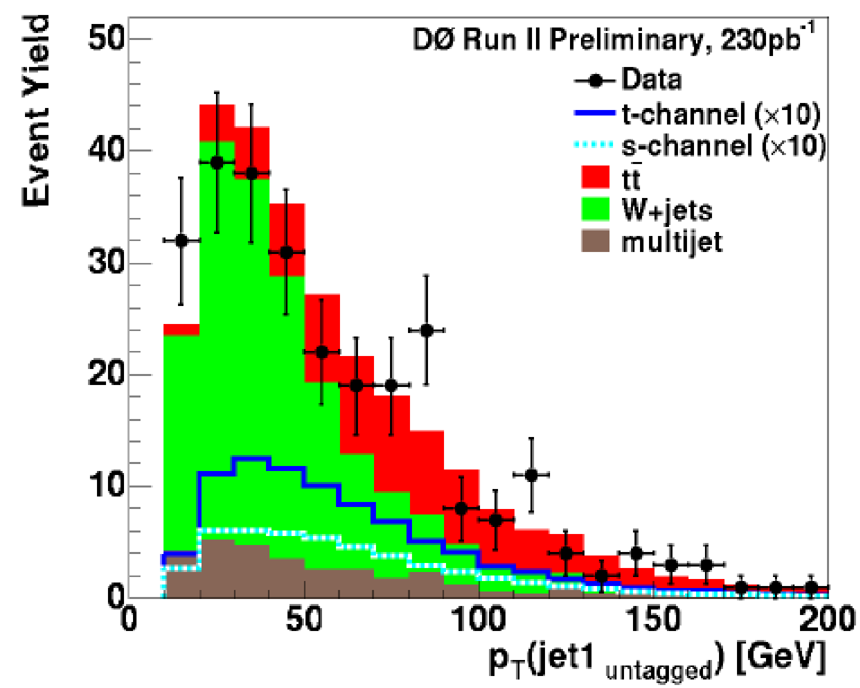
G. Mahlon, S. Parke Phys.Rev. D55 (1997) 7249-7254

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

Object p_T

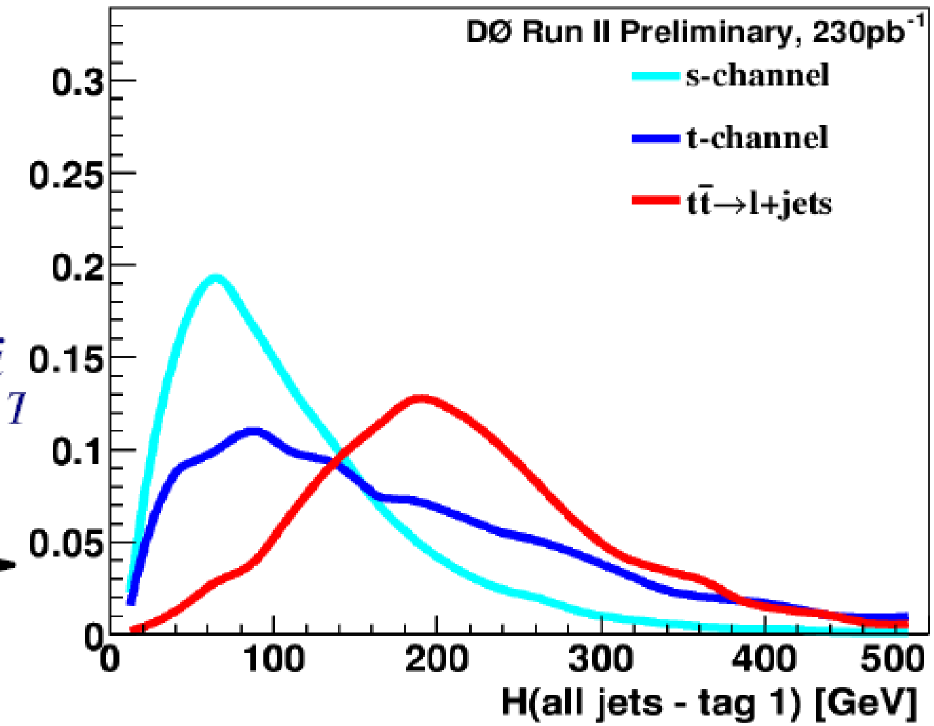
- p_T of jets:
  - Both s-channel and t-channel:
    - $\text{Jet1}_{\text{tagged}}$
  - Only t-channel:
    - $\text{Jet 1}_{\text{untagged}}$
    - $\text{Jet 2}_{\text{untagged}}$
  - Only s-channel:
    - $\text{Jet 1}_{\text{non-best}}$
    - $\text{Jet 2}_{\text{non-best}}$

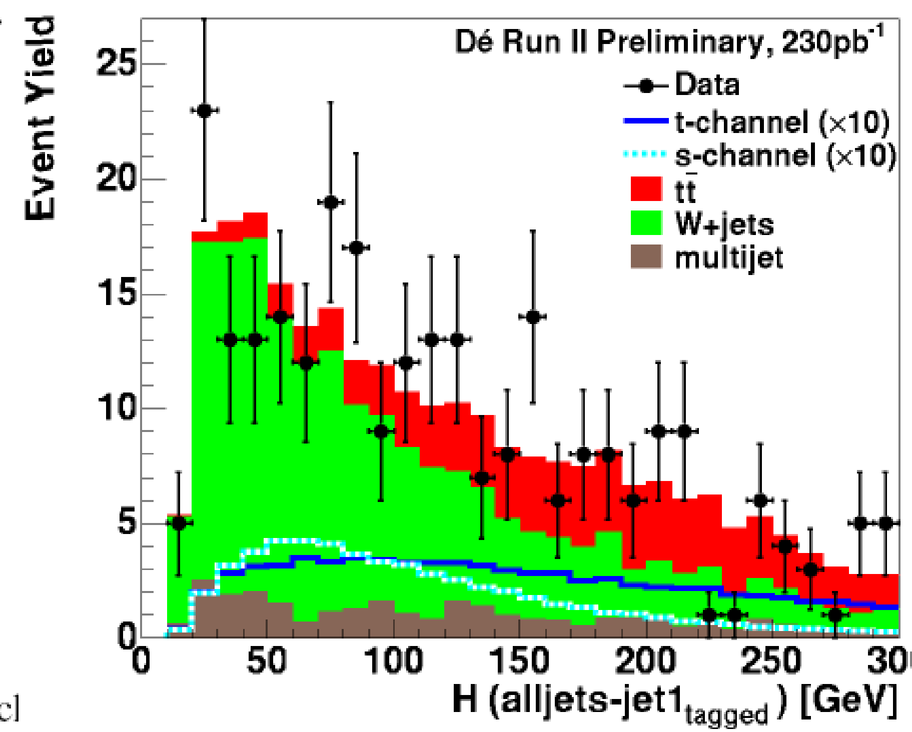




Event Energy

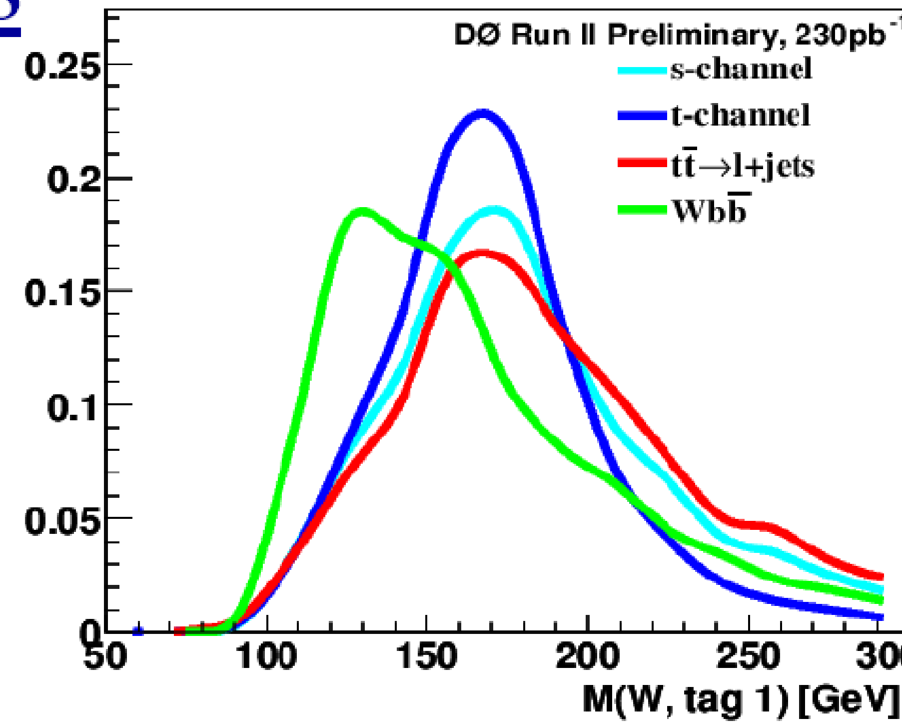
- Total energy $H = \Sigma_i E^i$
  transverse energy $H_T = \Sigma_i E^i_T$
  - Both s-channel and t-channel:
    - H(all jets – Jet1$_{tagged}$)
  - Only t-channel:
    - H_T(all jets)
    - H_T(all jets – Jet1$_{tagged}$)
  - Only s-channel:
    - H(all jets – Jet$_{best}$)
    - H_T(all jets – Jet$_{best}$)

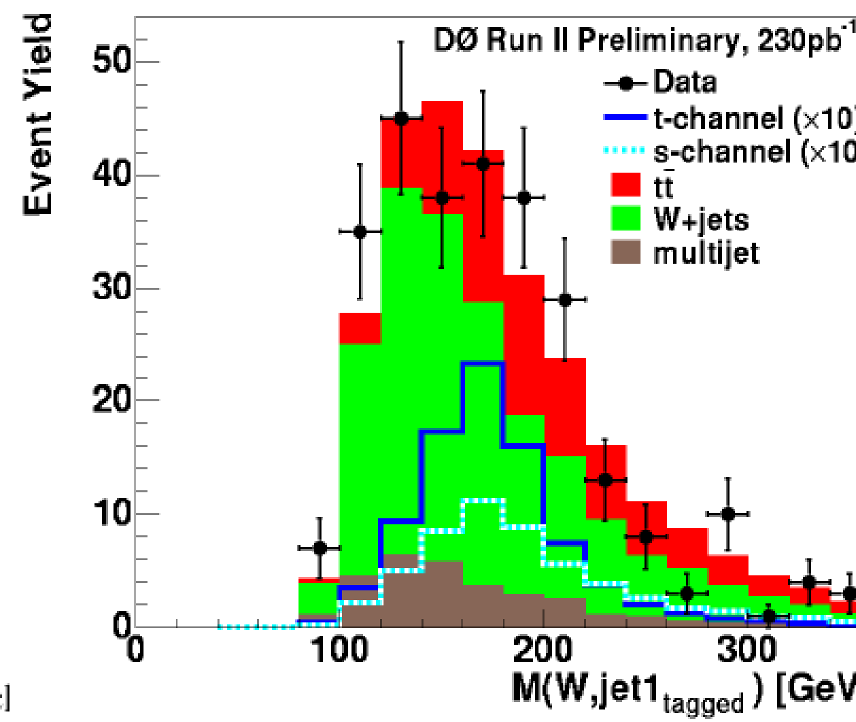




Reconstructed Objects

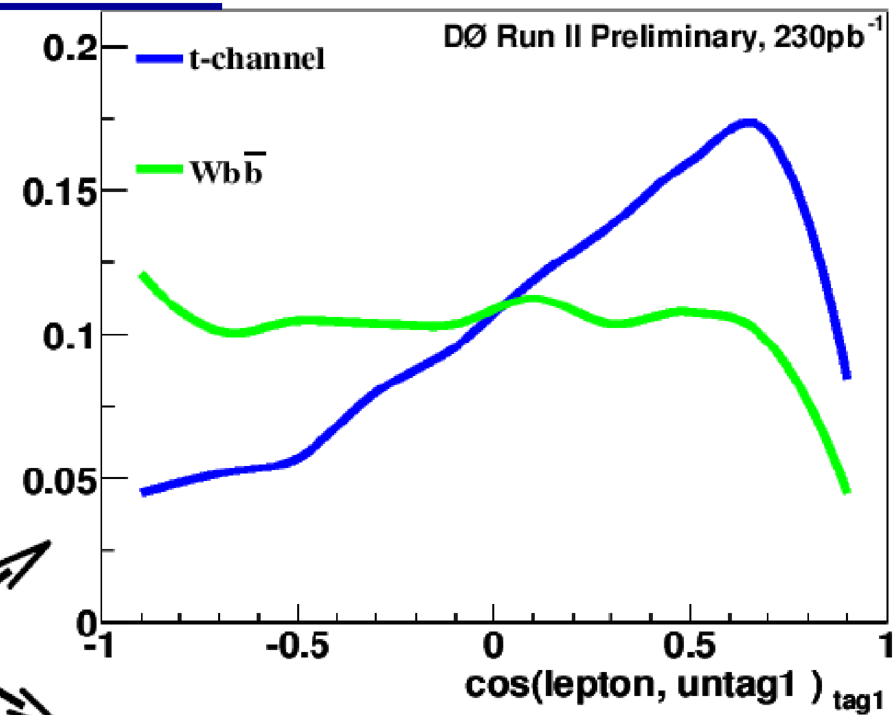
- Both s-channel and t-channel:
  - M(all jets)
  - p_T(all jets – Jet1_{tagged})
  - $M(\text{top}_{tagged})$
  - $\sqrt{\hat{s}}$
- Only t-channel:
  - M(all jets – Jet1_{tagged})
- Only s-channel:
  - M_T(Jet1, Jet2)
  - p_T(Jet1, Jet2)
  - M(all jets – Jet1_{best})
  - $M(\text{top}_{best})$

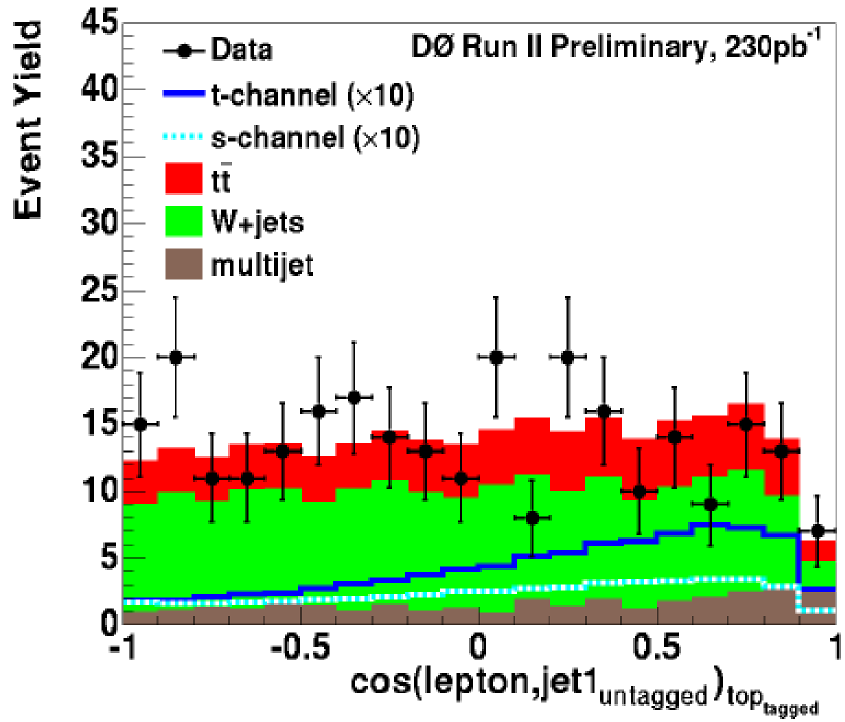




Angular Correlations

- Both s-channel and t-channel:
  - ΔR(Jet1, Jet2)
- Only t-channel:
  - $\eta(\text{Jet1}_{\text{untagged}}) \times Q(\text{lepton})$
  - $\cos(\text{lepton}, \text{Jet1}_{\text{untagged}})_{\text{top}_{\text{tagged}}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets}, \text{Jet1}_{\text{tagged}})_{\text{all jets}}$
- Only s-channel:
  - $\cos(\text{lepton}, Q(\text{lepton}) \times z)_{\text{top}_{\text{best}}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets}, \text{Jet1}_{\text{non-best}})_{\text{all jets}}$

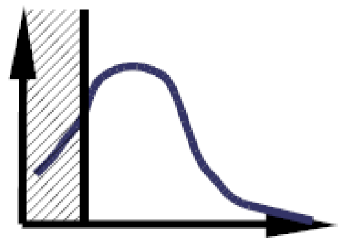




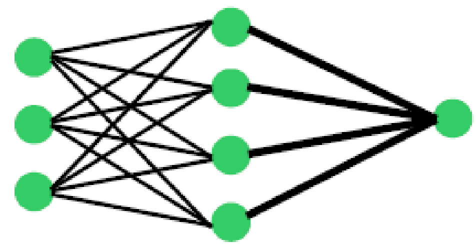
Separating Signal from Backgrounds

- Three analysis methods

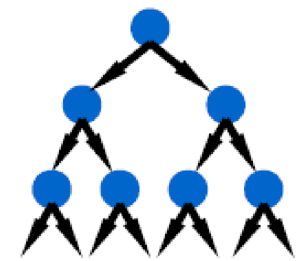
Cut-Based



Neural Networks



Decision Trees



- Each using the same structure:
  - Optimize separately for s-channel and t-channel
    - Optimize separately for electron and muon channel (same variables)
  - Focus on dominant backgrounds: W+jets, tt
    - W+jets – train on tb-Wbb and tqb-Wbb
    - tt – train on tb – $tt \to l + \text{jets}$ and tqb – $tt \to l + \text{jets}$
  - Based on same set of discriminating variables

➔ 8 separate sets of cuts/networks/trees

The Latest Tevatron Results

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

95% CL upper cross section limits [pb]

	s-channel	t-channel
DØ Run I	17	22
CDF Run II (160pb^{-1})	13.6	10.1
This analysis (230pb^{-1})		
cut-based	10.6	11.3
DTs & binned likelihood	8.3	8.1
NNs & binned likelihood	6.4	5

Neural Network Strategy

- Distinguish kinematically different backgrounds (ttbar, Wbb, Wjets, QCD fake, diboson)
- Construct set of “optimal observables” for each pair of Signal/Background (e.g. t-channel/Wbb)
- Train different networks for each pair of Signal/Background processes
- Combine NN outputs