Phenomenology of Single-Top Physics at the Tevatron

C.-P. Yuan
Michigan State University

Tsinghua University, Beijing, China
July 2005

In collaboration with:
Qing-Hong Cao, R. Schwienhorst, J. Benitez, R. Brock

Outline

1. Introduction
   - Top quark production at hadron colliders
   - Theoretical tools for NLO calculation
2. Phenomenology of s-channel single top process
   - Acceptance
   - Kinematics of the final state objects
   - Kinematical and spin correlation
3. Phenomenology of t-channel single top process
   - Acceptance
   - Kinematics of the final state objects
   - Kinematical and spin correlation
4. General analysis of top quark polarization and W helicity
   - General Formulation of t-b-W couplings
   - What have we known from indirect measurements?
   - How to perform direct measurements at Tevatron & LHC?
   - Distinguish different models of EWSB
5. Summary and outlook

Part I

Introduction

1. Top quark pair production at hadron colliders
2. Single top quark production at hadron colliders
3. Theoretical tools for NLO calculation
   - ☞ Narrow width Approximation (NWA)
   - ☞ Phase Space Slicing Method (PSS)

Top quark:

- Huge mass, almost 40x heavier than the next lighter quark bottom

☞ Top is only fermion whose coupling to the Higgs boson is important in SM

$\Longrightarrow$ It is a laboratory in which we could study EWSB.

- Short lifetime

☞ Top quark decays before it feels non-perturbative strong interaction

$$\tau_{decay} = \frac{1}{\Gamma_t} \sim 4.4 \times 10^{-25} \left(\frac{m_t}{180}\right)^3 \text{sec},$$

$$\frac{1}{\Lambda_{QCD}} \sim \frac{1}{0.2\,\text{GeV}} \sim 3.3 \times 10^{-24}\text{sec}$$

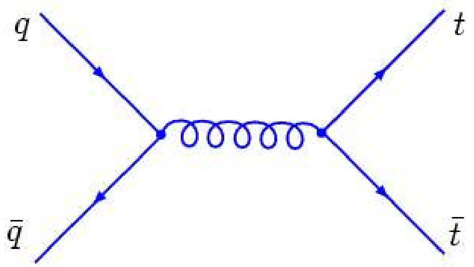
$\Longrightarrow$ studying the bare quark

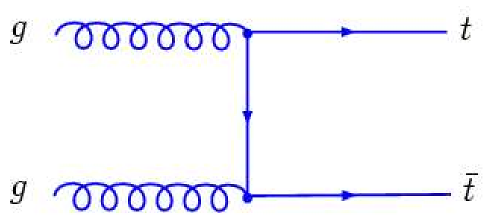
☞ Top quark decays through the weak interaction, $Br(t \to Wb) \simeq 1$

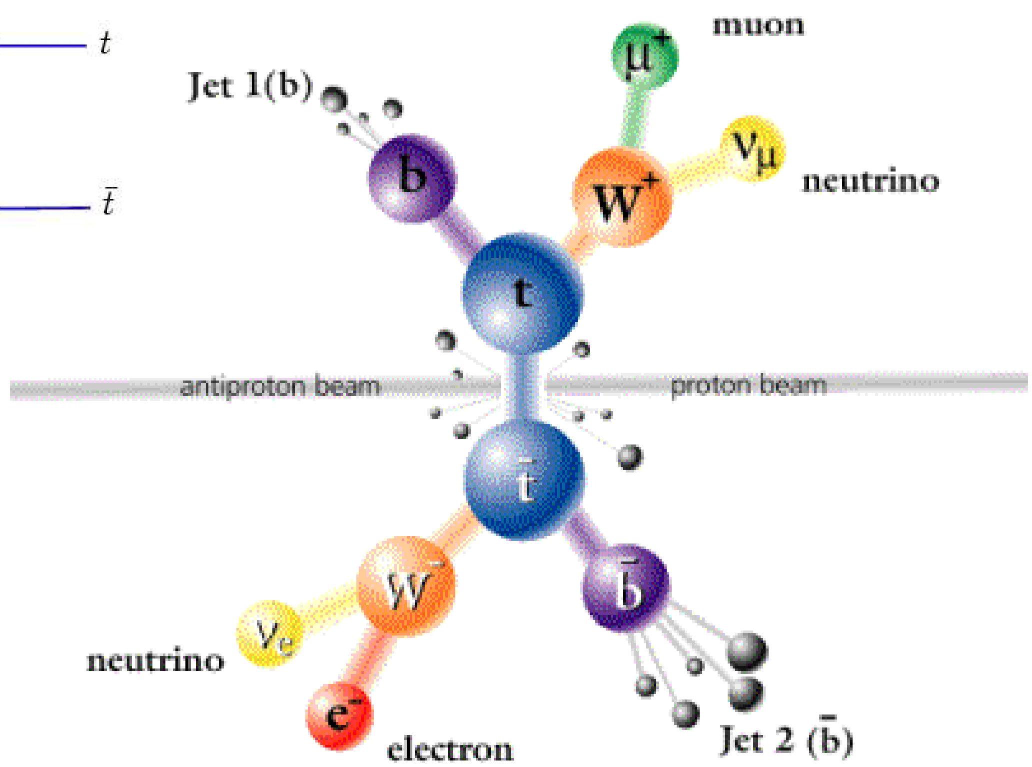
$\Longrightarrow$ Spin information are well kept among its decay products.

Top quark production at the Tevatron

- At a hadron collider, the largest production mechanism of top quarks is through the strong interaction.







☞ At the Tevatron

$q\bar{q}$ dominates (~85%)

☞ At the LHC

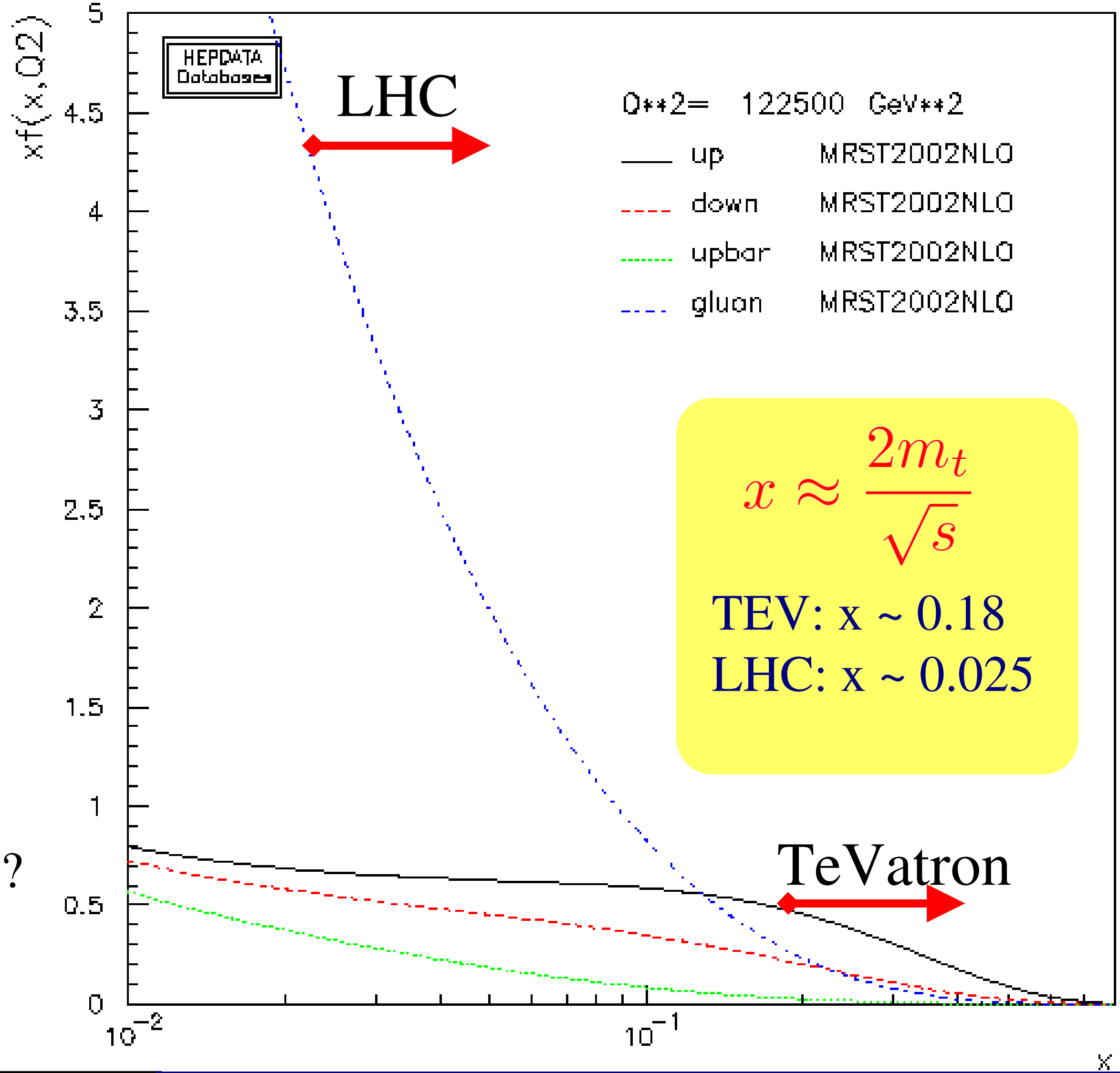
gg dominates (~90%)

Top quark pair production cross section

TEV (1.96 TeV) ~ 7 pb
0.8 events per hour at recent Tevatron

LHC (14 TeV) ~ 900 pb
0.8 events per second at initial/low lumi LHC

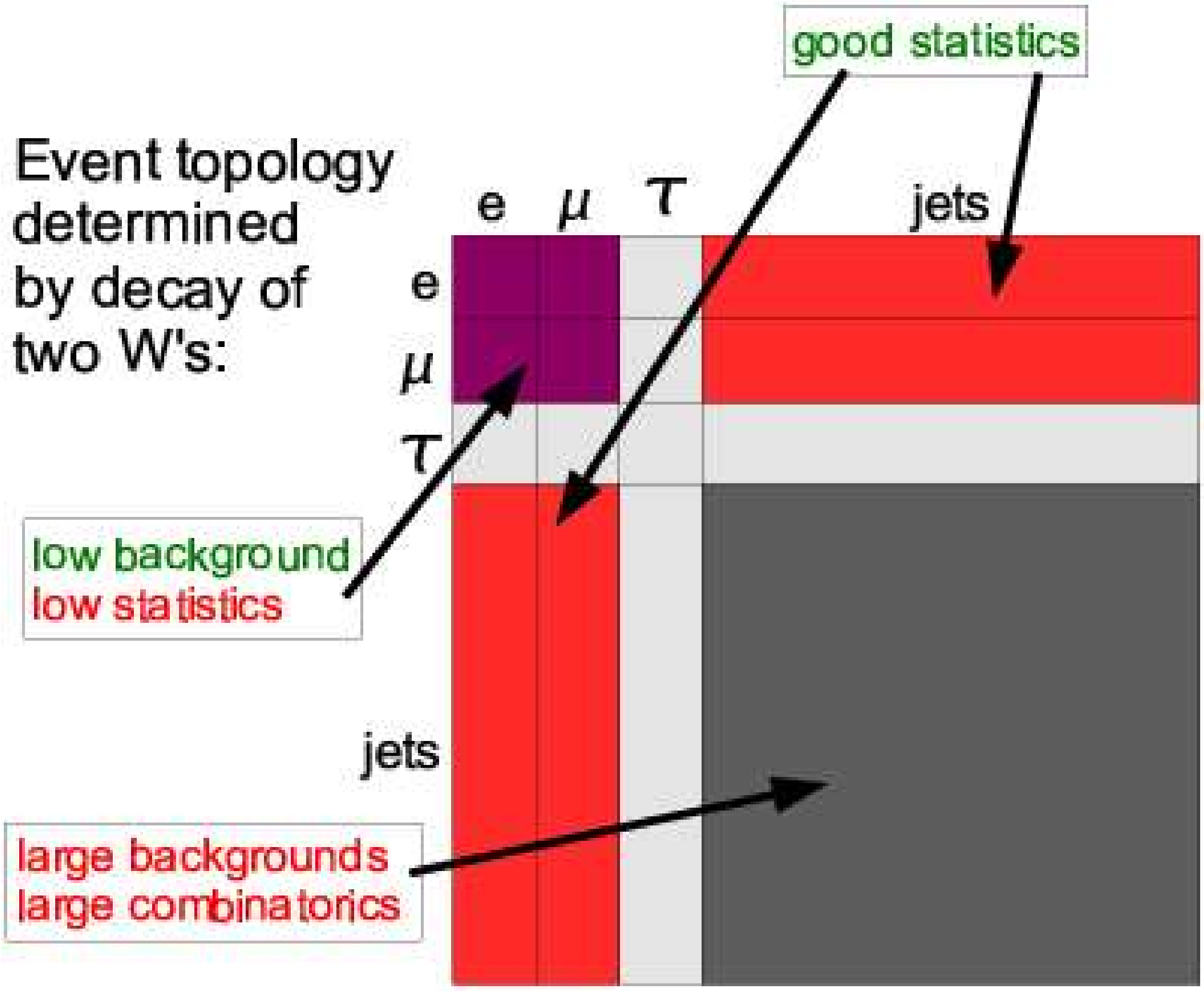
- Why is qq annihilation dominant at the TeVatron but gg fusion at LHC?
- Why does cross section increase by 100x for only 7x increase in √s?



$$x \approx \frac{2m_t}{\sqrt{s}}$$

TEV: x ~ 0.18
LHC: x ~ 0.025

Top quark decay

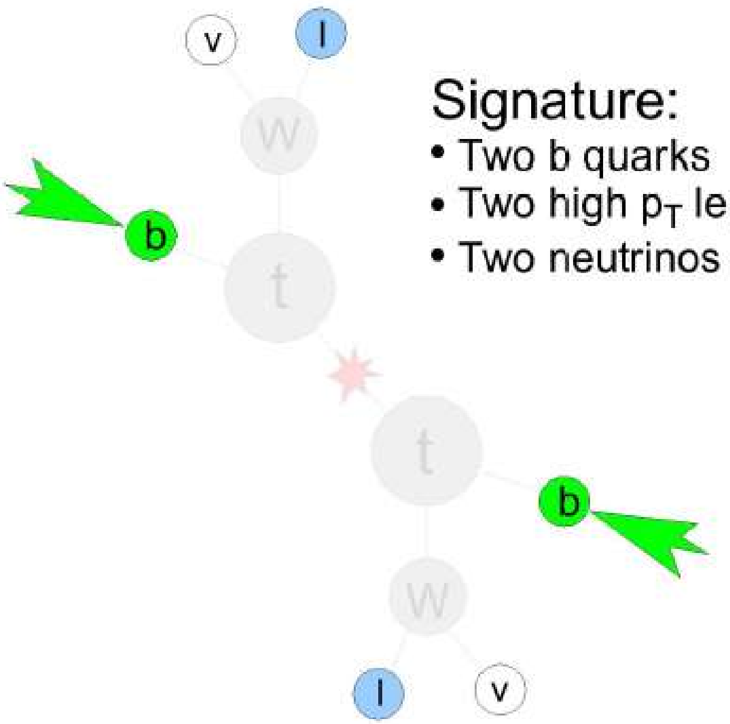


Top quark is unique among fermions: $m_t > M_W$

$$Br(W \to \text{leptons}) = \frac{1}{3}$$

$$Br(W \to \text{quarks}) = \frac{2}{3}$$

Dilepton channel



Signature:
- Two b quarks
- Two high p_T leptons
- Two neutrinos

Typical Event Selection:
- One high p_T lepton (>15 GeV)
- Oppositely charged high p_T lepton or isolated track (>15 GeV)
- Two or more high p_T jets (>20 GeV)
- Missing E_T (>25 GeV)

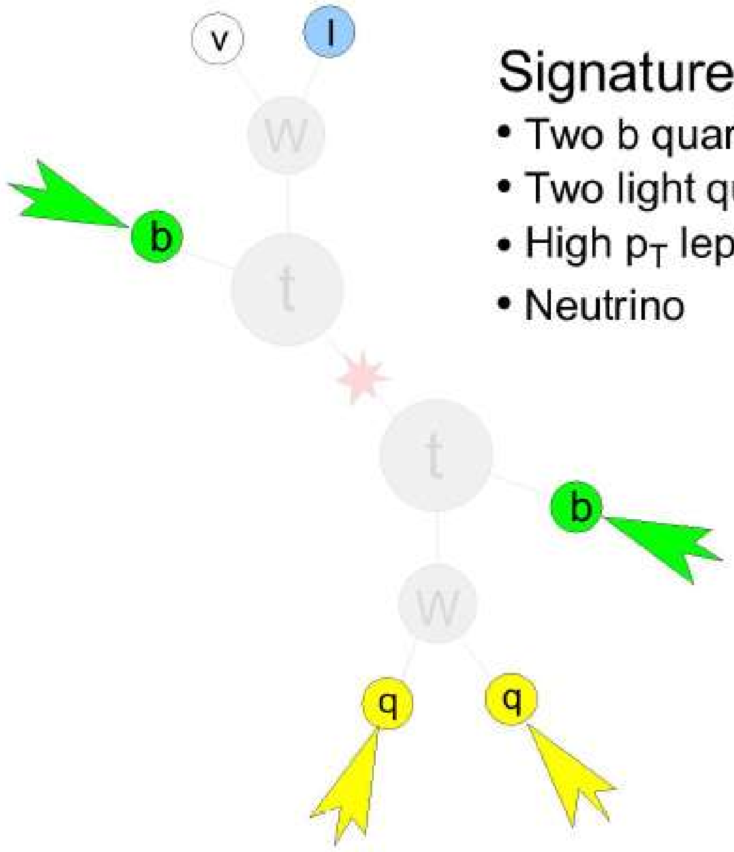
Backgrounds:
- Diboson (WW, WZ, ZZ)
- Drell-Yan
- $Z \rightarrow \tau\tau$
- W+jets with fake lepton

Small branching ratio → low statistics

Large S/B

Two neutrinos → underconstrained kinematics
Need to assume knowledge of some quantity

Lepton + Jets channel



Signature:
- Two b quarks
- Two light quarks
- High p_T lepton
- Neutrino

Typical Event Selection:
- One high p_T lepton (>20 GeV)
- Four or more high p_T jets (>15/20 GeV)
- Missing E_T (>20 GeV)
- b-tagging (optional)

Larger branching ratio → better statistics

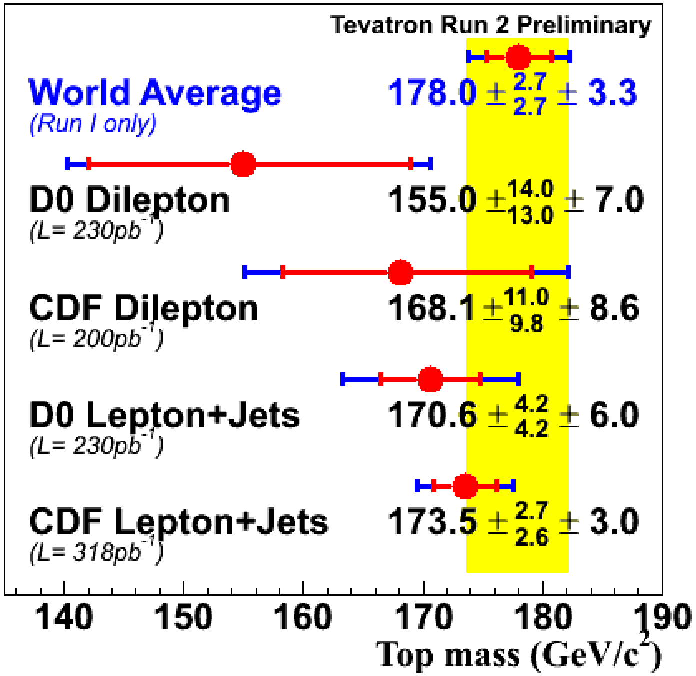
More background

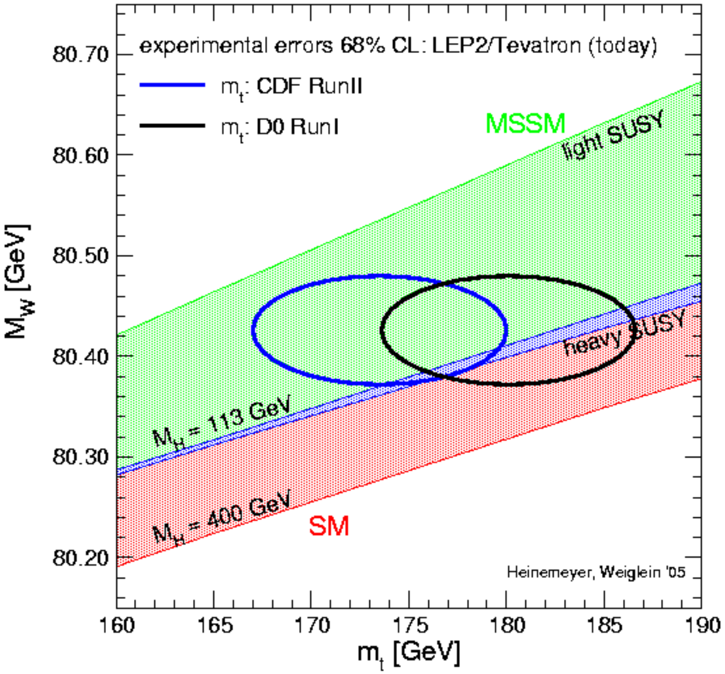
One neutrino → overconstrained kinematics

Backgrounds:
- W+jets
- Multi-jet with fake lepton

Top quark mass: measured from top quark pair production

- Top quark mass: one of the most important parameter in SM
  - receive large quantum correction from the Yukawa interaction with Higgs boson
  - together with M_W, can constrain the unknown Higgs boson mass

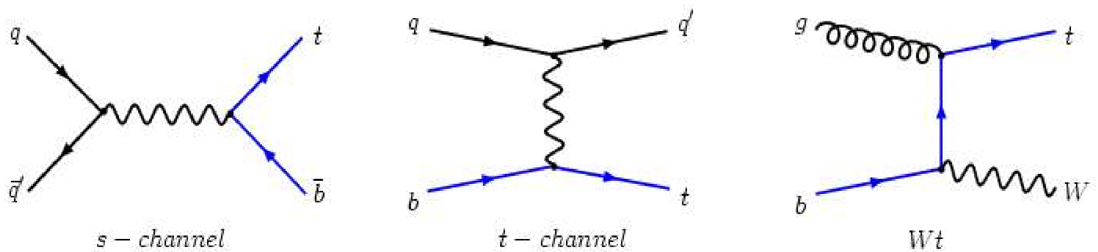




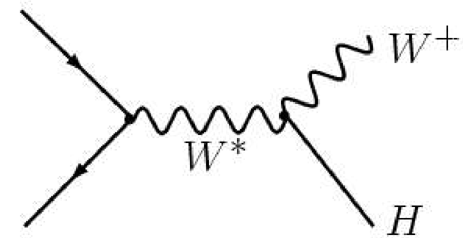
$$m_H = 114^{+69}_{-45}\ \text{GeV}$$ $m_H < 208$ GeV @ 95% C.L

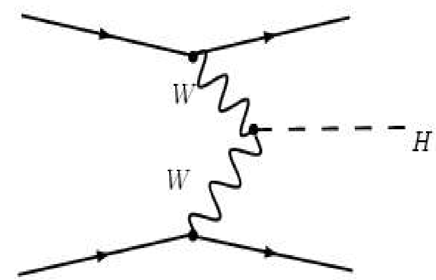
Single top production in SM

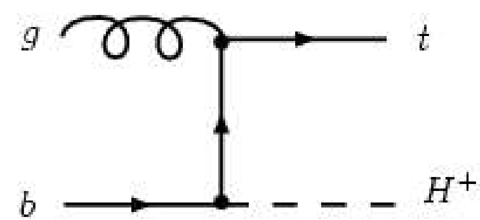
- Single top quarks are produced at hadron colliders through interactions involving a W boson and b quark $\Longrightarrow \sigma \propto |V_{tb}|^2$



- At tree level there are three modes:
  - ☞ s-channel W exchange ($Q^2 = p_W^2 > 0$)
    Large rate at Tevatron Run II, small rate at LHC
    major background for SM Higgs seaches
  - ☞ t-channel W exchange ($Q^2 = p_W^2 < 0$)
    Dominant rate at Tevatron Run II and LHC
    helping out with W-fusion Higgs searches
  - ☞ Wt associated production ($Q^2 = p_W^2 = m_W^2$)
    Very tiny rate at Tevatron Run II, large rate at LHC
    background to $gb \to H^+ t$ at LHC

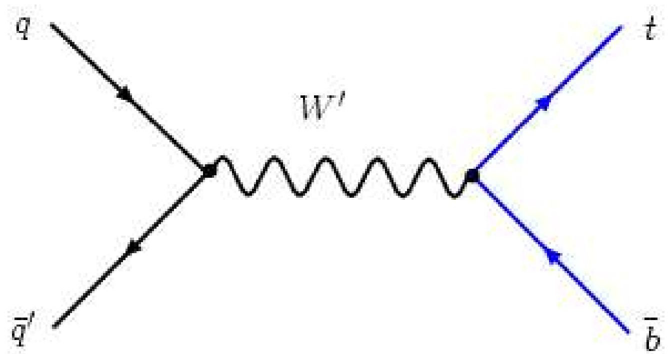




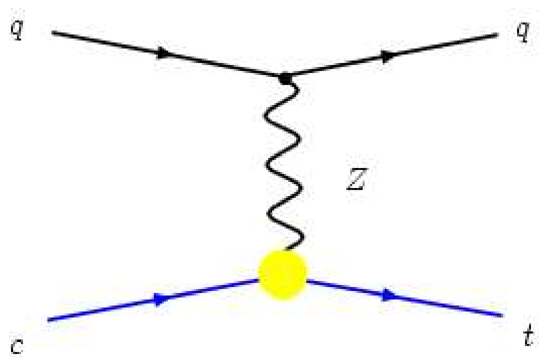


s-channel vs. t-channel

- s-channel
  - Smaller rate
  - Extra b quark in final state
- sensitive to charged resonances
  - Possibility of on-shell production
  - Need final state b tag to discriminate from background



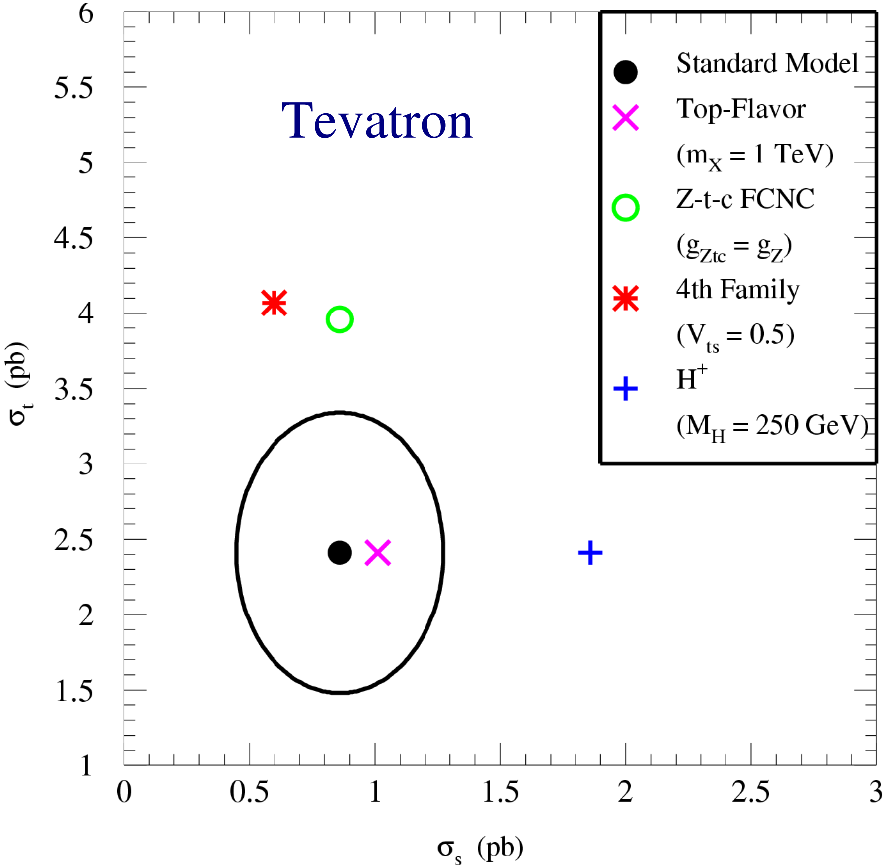
- t-channel
  - Dominant rate
  - Forward jet in final state
- sensitive to FCNCs
  - New production modes
  - t-channel exchanged of heavy states always suppressed

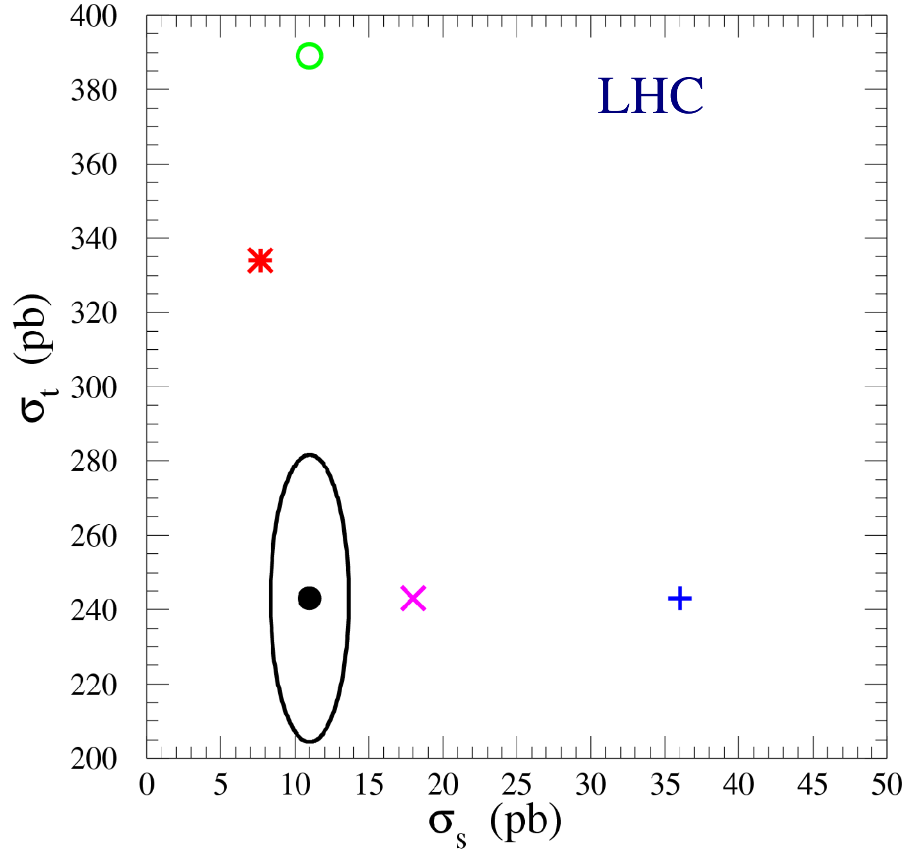


s-channel vs. t-channel

Since they are sensitive to different physics and have different final states, σ_s and σ_t should be measured separately.

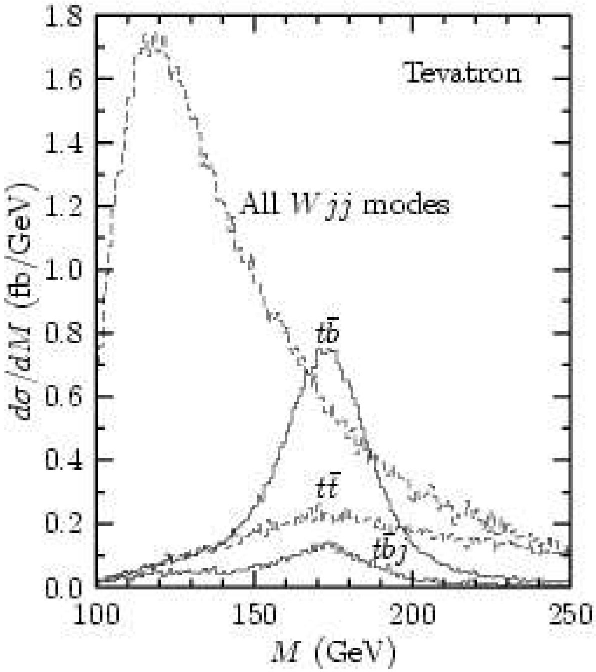
Tait, Yuan PRD63, 014018 (2001)



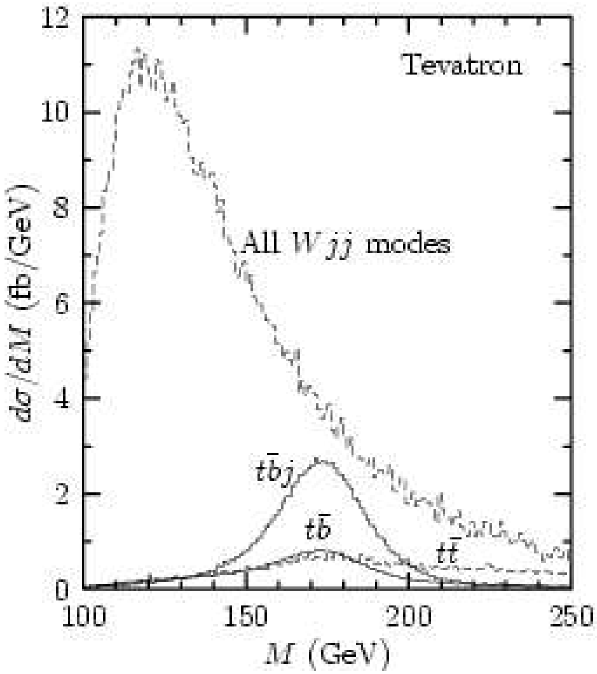


Discovery potential (LO study)

- s-channel (double b-tagging)
  signal: 2 b-tags, 1 charged lepton and $\not{E}_T$
- t-channel (single b-tagging)
  signal: 1 b-tag, 1 forward jet, 1 charged lepton and $\not{E}_T$



$t\bar{b}$: s-channel
$t\bar{b}j$: t-channel



☞ T. Stelzer, Z. Sullivan, S. Willenbrock, PRD 58, 094021 (1998)
☞ Complete signal and background study,
A. S. Belyaev, E. E. Boos, L.V. Dudko, PRD 59, 075001 (1999)

D0 Run-II single top analysis with 230pb^{-1}

Reinhard Schwienhorst, pheno 2005

	s-channel	t-channel
NLO x-sec	0.88 pb	1.98 pb
D0 Run-I	<17 pb	< 22 pb
CDF Run-II(160 pb^{-1})	<13.6 pb	<10.1 pb
D0 Run-II	<6.4 pb	<5.0 pb

* D0 Run-II use Neural Network and binned likelihood method

- This is just the beginning
  - ☞ Expect 3X dataset by end of year
  - ☞ Improve all aspects of the analysis

Precision measurement of V_{tb} at the LHC

John Parsons, Top Quark Symposium, Michigan, April 2005

- Able to separate single top signal from the large backgrounds ($t\bar{b}$, Wjj, $Wb\bar{b}$), as well as from each other

- ATLAS has shown that it is possible to separately isolate each of the three processes :

30fb^{-1}

Process	S	B	S/B	$S/\sqrt{B}$	δV_{tb}
t-channel	27k	8.5k	3.1	286	0.40%
Wt	6.8k	30k	0.22	39	1.40%
s-channel	1.1k	2.4k	0.46	23	2.70%

precison measurement

only simple kinematics cuts being imposed

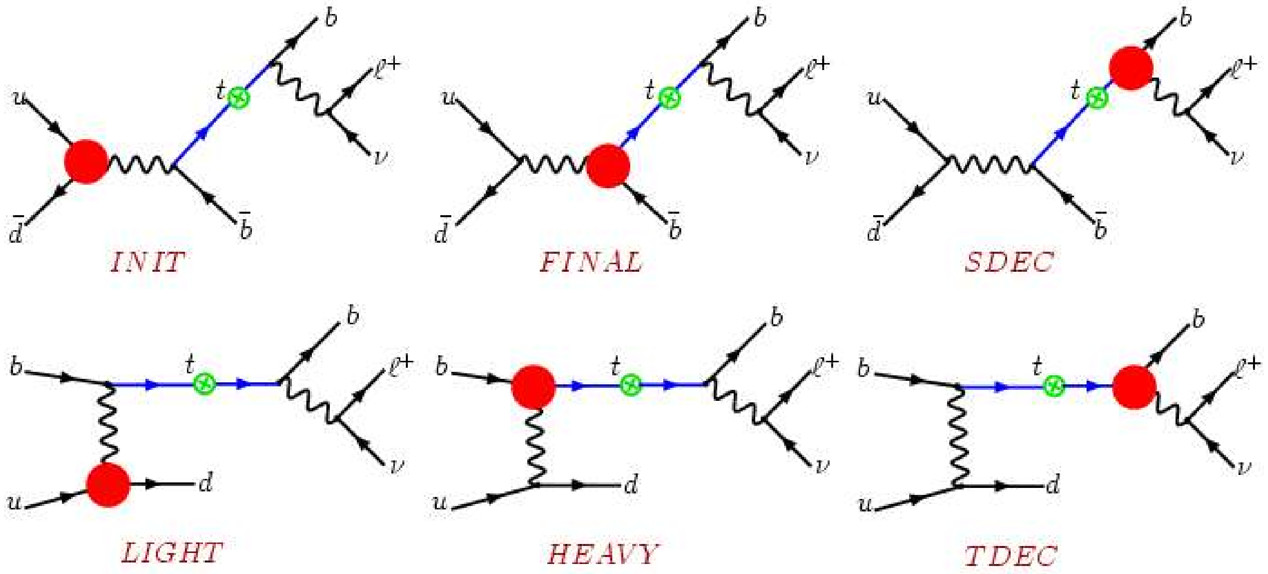
- Statistical error on V_{tb} will be smaller than systematic errors from luminosity determination and from theory prediction

Why NLO?

- It is very important to understand the acceptances at NLO, including the QCD corrections to both single top quark production and decay.
  - reduce the dependence on the unphysical scale
  - improve the matching between theoretical and experimental jets
- Recent progresses
  - Z. Sullivan, hep-ph/0408049
  - J. Campbell, R.K. Ellis, hep-ph/0408158
  - Q.-H. Cao and C.-P. Yuan, hep-ph/0408180
  - Q.-H. Cao, R. Schwienhorst, and C.-P. Yuan, hep-ph/0409040
  - Q.-H. Cao, R. Schwienhorst, J. Benitez, R. Brock, and C.-P. Yuan, hep-ph/0504230

Categorizing single top processes

- We separate the single-top processes into smaller gauge invariant sets to organize our calculations.

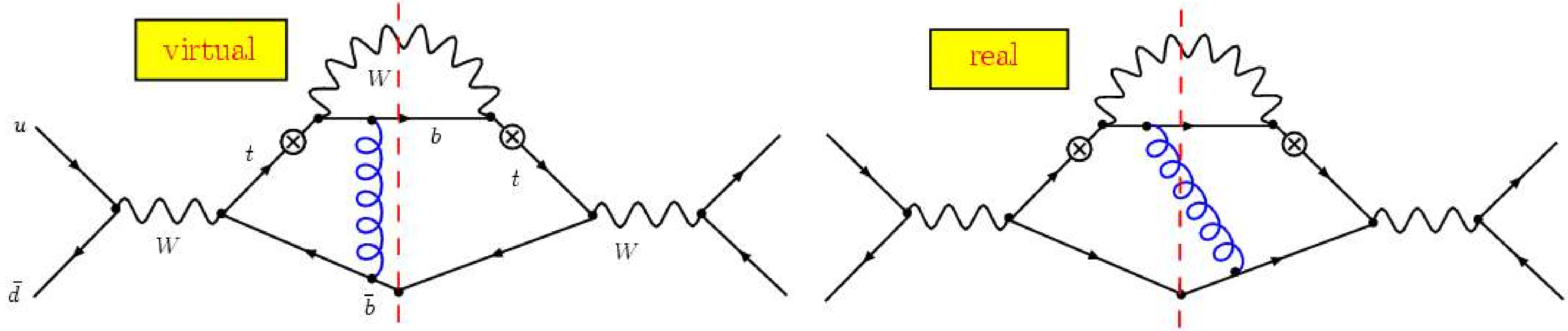


● includes soft + virtual and real emission corrections.

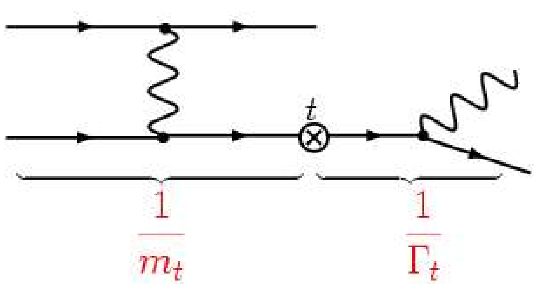
- Keeping track on each individual contribution is useful to compare event generators with exact NLO predictions.

Categorizing single top processes

- We ignore the interference effects (IEs) between the top production and decay,



- Characteristic time scale for top quark production and its decay:



In general, production and decay are separated by a large time.

$\Longrightarrow$ IEs ~ zero.

Soft gluon ($E_g \sim \Gamma_t$) radiation, near the top threshold, leads to nonfactorizable corrections.

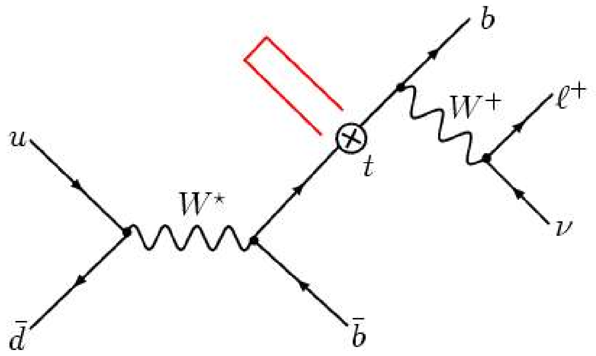
$\Longrightarrow$ IEs . $\sim \alpha_s \Gamma_t / m_t$

R. Pittau, PLB 386,397 (1996)

Methods used in our NLO calculation: NWA

- To link the top quark production with its decay and also preserve the spin correlation between the final state particles, narrow width approximation (NWA) is usually adopted.
  - ☞ keep only diagrams with a resonant top propagator
  - ☞ In the limit of $\Gamma_t \to 0$, using

$$\int \mathrm{d}p^2 \frac{1}{(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2} = \frac{\pi}{m_t\Gamma_t},$$



  - ☞ the matrix element squre becomes

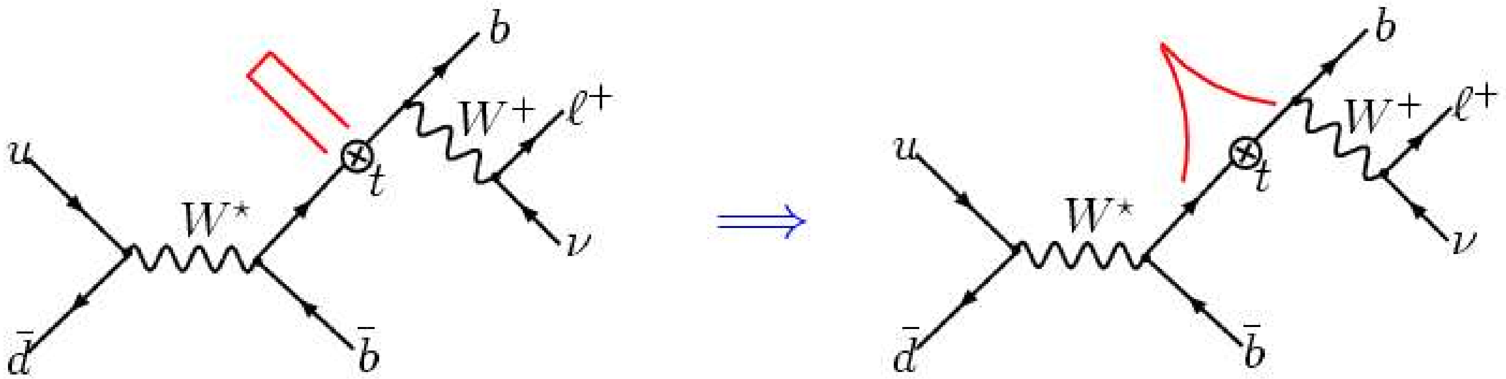
$$|\mathcal{M}|^2 = \left|\mathcal{M}_{dec}(\cdots, p_t^{\lambda_t})\right|^2 \frac{\pi}{m_t\Gamma_t}\delta(p_t^2 - m_t^2)\left|\mathcal{M}_{prd}(\cdots, p_t^{\lambda_t})\right|^2$$

  - ☞ and the phase space is

$$\mathrm{d}\Phi = \mathrm{d}\Phi_{prd}\,\frac{1}{2\pi}\,\mathrm{d}p_t^2\,\mathrm{d}\Phi_{dec}.$$

Methods used in our NLO calculation: NWA

- NWA (fixed top quark mass)
  - works well in both s-channel and t-channel single-top processes for the total event rate and distributions of various kinematics variables.
  - cannot reproduce the distribution of the reconstructed top quark invairant mass.



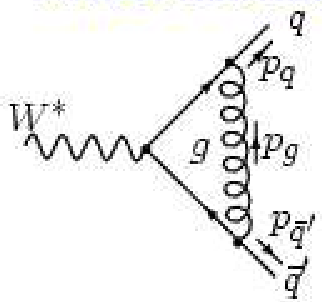
- The “modified” narrow width approximation (MNWA) is adopted in our calculation.
  - Generate Breit-Wigner distribution of the intermediate state top quark mass in phase space.
  - Use the generated top quark mass to calculate the matrix elements.

Methods used in our NLO calculation: PSS

Divergencies: Ultraviolet, infrared (soft and collinear) singularities.

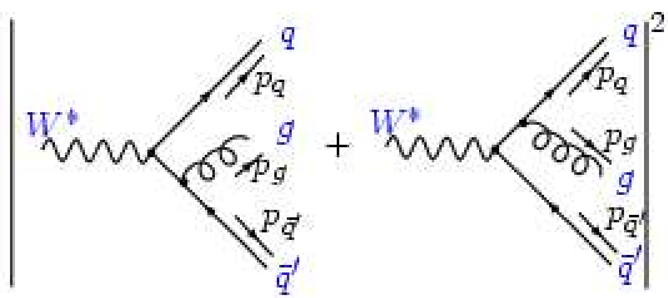
Example: $w \longrightarrow q\bar{q}'(g)$, q, $\bar{q}'$ are massless quarks.

- Virtual corrections:



$$\int^{\infty} d^4 p_g \frac{\not{p}_g \; \not{p}_g}{(p_g^2)(p_g^2)(p_g^2)} \longrightarrow \infty \quad \text{UV, soft and collinear}$$

- Real corrections:



$\longrightarrow \infty$ when $p_g \longrightarrow 0$ (soft)
or $p_g \parallel p_q$ (collinear)
or $p_g \parallel p_{\bar{q}'}$ (collinear)

- UV: removed by renormalization. Soft: cancelled (KLN)
- Collinear: absorbed into PDFs or FFs.

Methods used in our NLO calculation: PSS

There are a few modern techniques that allow us to calculate the differential QCD corrections. These techniques combine analytic calculations with numerical integration.

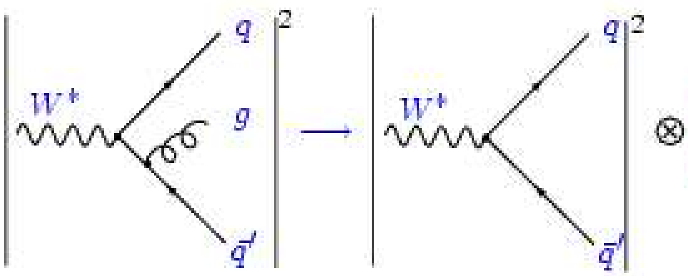
- Phase space slicing method with two cutoffs
  H. Baer, J. Ohnemus, J. F. Owens, PRD 40, 2844 (89)
  B. W. Harris, J. F. Owens, PRD 65:094032 (02)
- Phase space slicing method with one cutoff
  e^+e^-: W.T. Giele, E.W.N. Glover, PRD 46, 1980 (92)
  initial hadrons: W.T. Giele, E.W.N. Glover, D.A. Kosower, NPB403, 633 (93)
  massive partons, fragmentation: E. Laenen, S. Keller, PRD 59, 114004 (99)
- Dipole subtraction method
  dipole formalism: S. Cantani, M. Seymour, NPB 485, 291 (97)
  massive partons: L. Phaf, S. Weinzierl, JHEP 0104, 006 (01),
  S. Catani, S. Dittmaier, M. H. Seymour, Z. Trocsanyi, NPB 627, 189 (02).

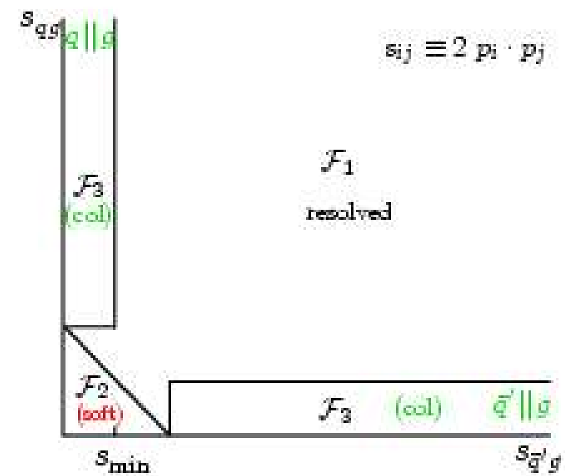
Trick: how to handle the real emission corrections?

Methods used in our NLO calculation: PSS

Phase space slicing method with one cutoff (s_{min})

- Introduce a theoretical cutoff (s_{min}) to split the phase space of real emission corrections into three region: soft, collinear and resolved (Hard).
- Make approximation to the matrix element in soft and collinear regions.



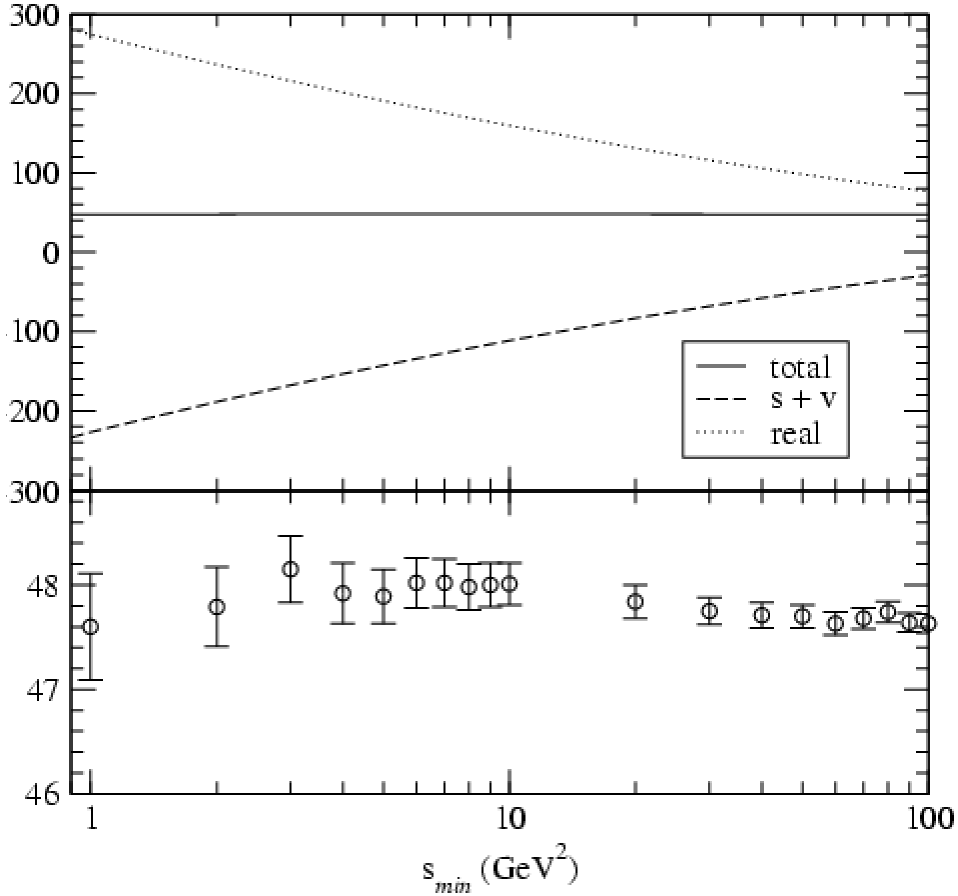


- Add in virtual corrections and mass factorization terms, IR divergencies disappear, but the result depends on cutoff s_{min}.
- Resolved region corrections are integrated out numerically, which also depends on s_{min}.

Summing them up gives a theoretical cutoff independent prediction.

Theoretical cutoff dependence (s-channel)

- Summing over the soft, collinear, virtual and resolved corrections will give us a cutoff independent result.



Inclusive s-channel single top quark cross section at Tevatron with $_R$= $_F$=m_t for m_t=178 GeV.
The decay branching ratio $t \to bW^+(\to e^+\nu)$ is included.

Our calculation does not depend on the theoretical cutoff s_{min}.

In the following calculation, we take s_{min}=5 GeV^2.

Inclusive s-channel single top cross section

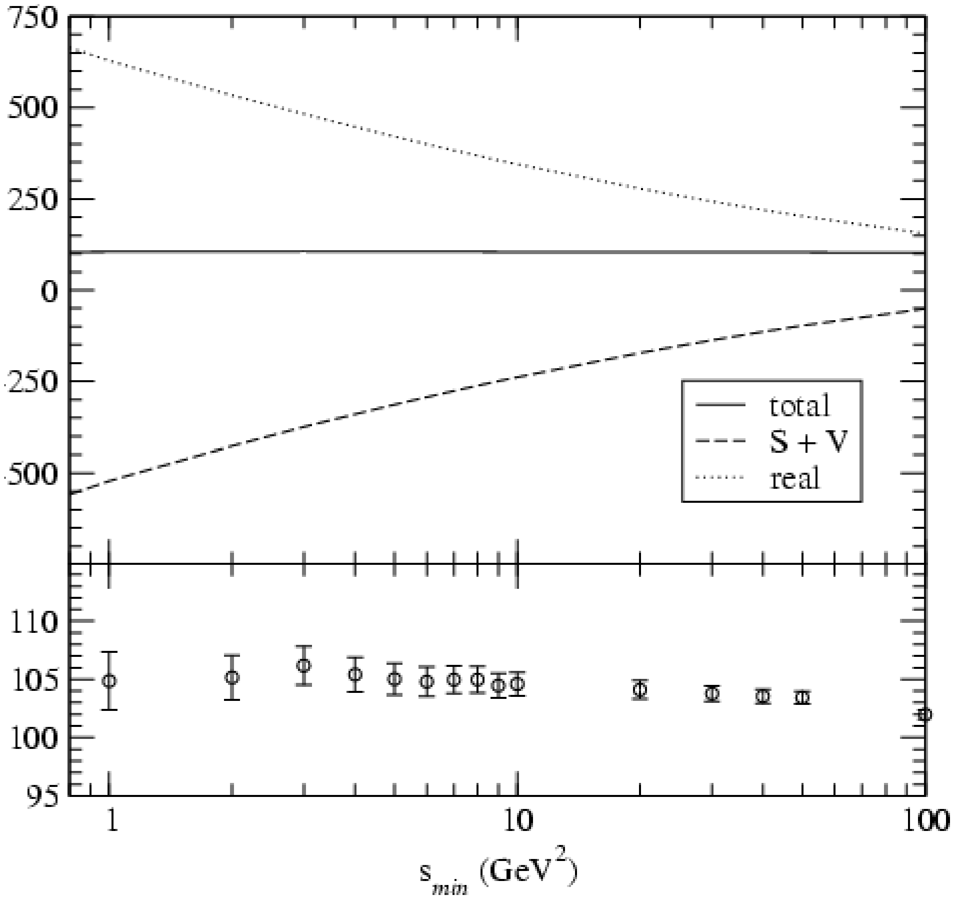
The branching ratio of $t \to bW^+(\to e^+\nu)$ *is included (CTEQ6M1 PDF)*

	σ (fb)	Fraction of NLO (%)
Born Level	31.2	65.0
$O(\alpha_s)$ INIT	10.7	22.3
$O(\alpha_s)$ FINAL	5.5	11.5
$O(\alpha_s)$ SDEC	0.57	1.19
$O(\alpha_s)$ sum	16.8	35.0
NLO	47.9	100

The INIT contribution dominates in the $O(\alpha_s)$ contributions.

Theoretical cutoff dependence (t-channel)

- Summing over the soft, collinear, virtual and resolved corrections will give us a cutoff independent result.



Inclusive t-channel single top quark cross section at Tevatron with $\mu_R=\mu_F=m_t$ for m_t=178 GeV.
The decay branching ratio $t \to bW^+(\to e^+\nu)$ is included.

Our calculation does not depend on the theoretical cutoff s_{min}.

For t-channel single top process, we take s_{min}=1 GeV^2 .

Inclusive t-channel single top cross section

The branching ratio of $t \to bW^+(\to e^+\nu)$ *is included (CTEQ6M1 PDF)*

	σ (fb)	Fraction of NLO (%)
Born Level	99.2	94.6
$O(\alpha_s)$ HEAVY	5.56	5.31
$O(\alpha_s)$ LIGHT	1.03	0.98
$O(\alpha_s)$ TDEC	-0.81	-0.77
$O(\alpha_s)$ sum	5.54	5.28
NLO	104.8	100

The HEAVY contribution dominates in the $O(\alpha_s)$ contributions because the bulk part of the radiative corrections originating from the light quark line have been absorbed into the definition of the light quark PDFs.

Part II

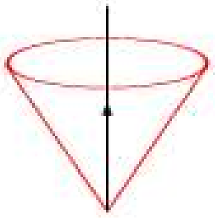
Phenomenology of the s-channel single top process

1. Jet finding algorithm and kinematics cuts
2. Acceptance
3. Kinematics of the final state objects
   - ☞ Top quark reconstruction
   - ☞ Kinematical and spin correlation
   - ☞ background to Higgs boson searches

Jet finding algorithm

Born level s-channel single-top signal:

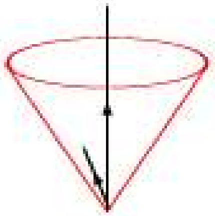
2 b-jets, 1 charged lepton and $\not{E}_T$ (1 parton = 1 jet)



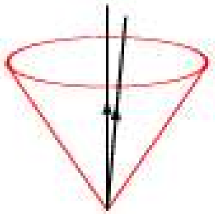
NLO s-channel single-top signal:

2 b-jets, 1 charged lepton and $\not{E}_T$ (+ 1 non-b-jet)

Jet algorithm is used to define the infrared safe observables.



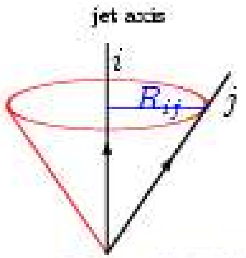
1. Soft problem: adding an infinitely soft parton should not changed # of jets
2. Collinear problem: replacing any massless parton with an exactly collinear pair of massless partons should not change # of jets.
3. insensitive to hadronization and longitudinal boosts



Cone algorithm is used in our analysis:

Lorentz-invariant open angle $R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$

where η: pseudo-rapidity, ϕ: azimuthal angle



Kinematical cuts

- Smaller $|p_Z(\nu)|$ of two-fold solutions is used to reconstruct the W boson. ($\sim$ 70% efficiency)
- Basic kinematical cuts:

$$
\begin{aligned}
P_T^\ell &\geq 15\,\mathrm{GeV} \quad , \quad |\eta_\ell| \leq \eta_\ell^{max}, \\
\not{E}_T &\geq 15\,\mathrm{GeV} \quad , \\
E_T^j &\geq 15\,\mathrm{GeV} \quad , \quad |\eta_j| \leq \eta_j^{max}, \\
\Delta R_{\ell j} &\geq R_{cut} \quad , \quad \Delta R_{jj} \geq R_{cut}\,.
\end{aligned}
$$

- To understand the impact of kinematical cuts on the acceptances, two sets of cuts are considered:

loose cuts:

$$
\eta_\ell^{max} = 2.5, \quad \eta_j^{max} = 3.0, \quad R_{cut} = 0.5
$$

tight cuts:

$$
\eta_\ell^{max} = 1.0, \quad \eta_j^{max} = 2.0, \quad R_{cut} = 1.0
$$

Acceptance of inclusive two-jet events (s-channel)

$t\bar{b}+t\bar{b}j$	σ [fb]		Acceptances (%)	
	LO	NLO	LO	NLO
(a)	22.7	32.3	73	64
(b)	19.0	21.7	61	46
(c)	14.7	21.4	47	45

(a): loose cuts $\eta_\ell^{max}=2.5$, $\eta_j^{max}=3.0$ and $R_{cut}=0.5$

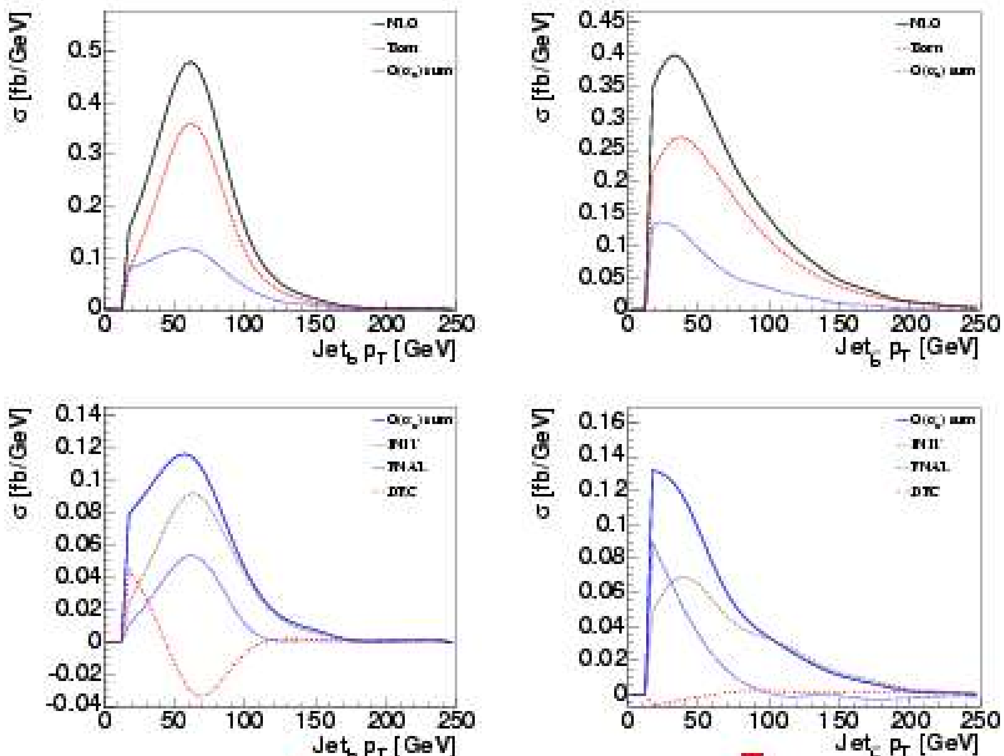
(b): loose cuts $\eta_\ell^{max}=2.5$, $\eta_j^{max}=3.0$ and $R_{cut}=1.0$

(c): tight cuts $\eta_\ell^{max}=1.0$, $\eta_j^{max}=2.0$ and $R_{cut}=0.5$

- The acceptances are sensitive to the kinematical cuts.
  - A large R_{cut} reduces the acceptance significantly because more events fail the lepton-jet separation cut.
  - With tight cuts, LO and NLO acceptances are almost the same.
  - With loose cuts, LO and NLO acceptances are quite different.
    - $\Longrightarrow$ cannot use k-factor with LO kinematics
    - $\Longrightarrow$ $\Delta\sigma \sim 10\%$, $\Delta|V_{tb}| \sim 5\%$
    - $\Longrightarrow$ Important to have full NLO kinematics
- To maximize the acceptance, the loose cuts (a) are used in the following study.

Final object distributions

- Lepton and $\not{E}_T$: not sensitive to NLO QCD corrections.
- b and $\bar{b}$ distributions



b $\quad\quad$ $\bar{b}$

NLO corrections broaden the LO distributions and shift the peak position to lower valule.

b and $\bar{b}$ are sensitive to DEC and FINAL contributions, respectively.

INIT contribution dominates over FINAL and DEC.
$\Longrightarrow$ soft gluon resummation
$\Longrightarrow$ improve the prediction on kinematical acceptance

To quark reconstruction

- The two b-jets in the final state cannot be distinguished experimentally (by detectors).
- To study the kinematics and spin correlations, top quark event needs to be reconstructed.
  Task: b-jet needs to be separeted from $\bar{b}$-jet.
- Thus, a prescription is needed to identify the correct b in order to reconstruct top quark event.

Best-jet algorithm

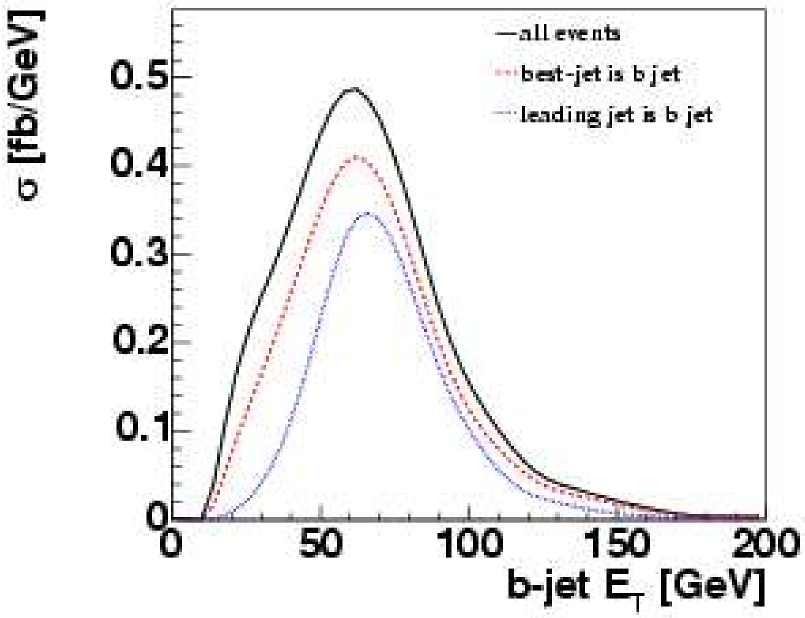
Jet (or 2-jet system) which gives an invariant mass closest to 178 GeV, when combined with W boson.

Leading-jet algorithm

highest p_T jet in the event as "b-jet".

b identification efficiency

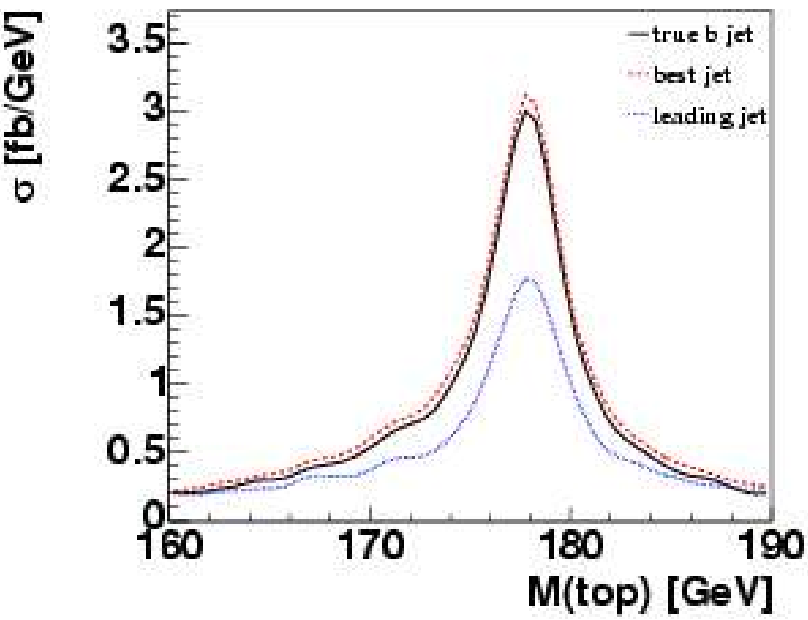
- fraction of picking up correct b



best-jet algorithm: 80%

Leading-jet algorithm: 55%

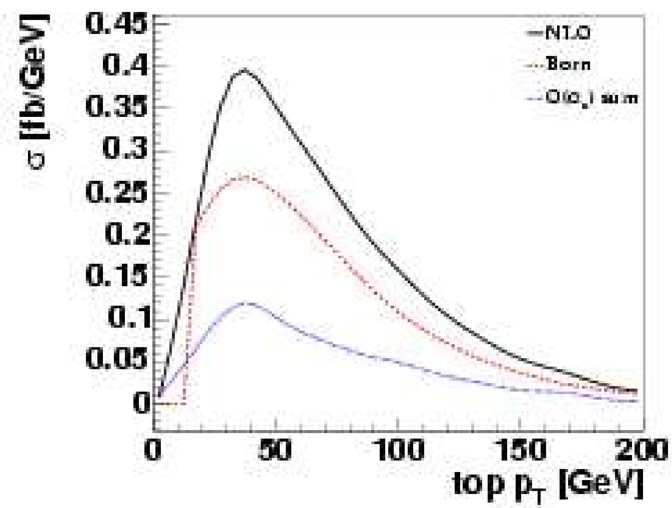
- reconstructed top quark mass

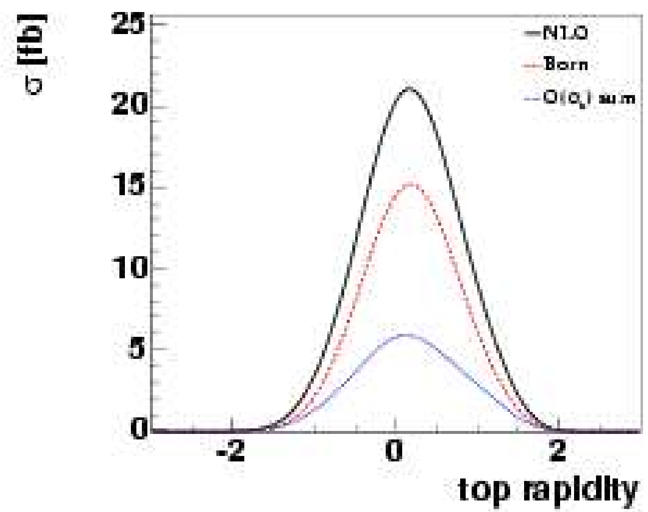


more evident

The best-jet algorithm shows higher efficiency than the leading-jet algorithm.

Reconstructed top quark (W + best-jet) distribution

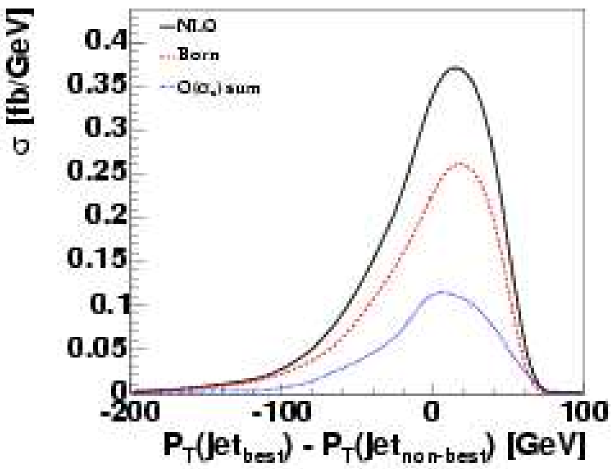


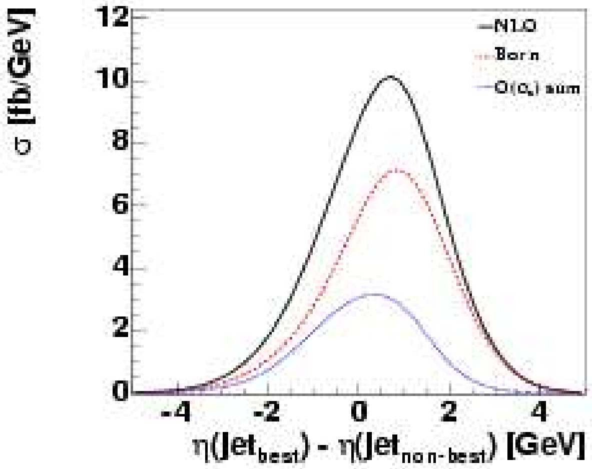


- NLO corrections change p_T of top quark event in the small p_T region largely.
- NLO corrections shift the top quark event to more central region.
- Best-jet algorithm results in distributions that are very similar to those obtained using the true b (or $b + g$) from the top quark decay.

Kinematical correlation between b and $\bar{b}$

- At Born level, b (best-jet) and $\bar{b}$ (non-best-jet) are highly correlated.





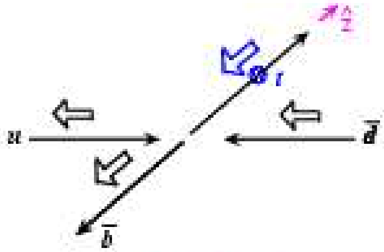
- At NLO
  - Transverse momentum difference is not largely affected.
  - The $O(\alpha_s)$ corrections have a larger effect on the pseudo-rapidity difference.
  - The addtional gluon radiated from FINAL and DEC corrections tends to weaken the correlation between b and $\bar{b}$.

Top quark polarization

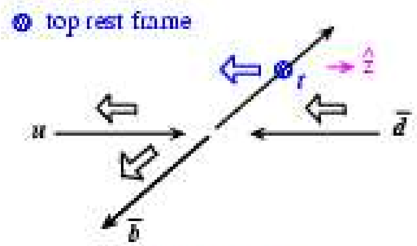
In SM, top quark produced in single-top event is highly polarized. Polarization of top is defined in its rest frame.

Degree of polarization depends on the direction of z-axis in top rest frame.

1. Helicity basis: $t\bar{b}(j)$
   $\hat{z}$: along the top quark direction of motion in the c.m. frame of system.
2. Helicity basis $(t\bar{b})$
   $\hat{z}$: along the top quark direction of motion in the c.m. frame of $t\bar{b}$.
3. Optimal basis (maximal spin correlation)
   $\hat{z}$: along the direction of d-type quark (predominantly, from anti-proton).



Helicity basis



Optimal basis

P	$\bar{P}$	Fraction
u	$\bar{d}$	98%
$\bar{d}$	u	2%

Top quark polarization

- Among the top quark decay products, the charged lepton is maximally correlated with top quark spin.

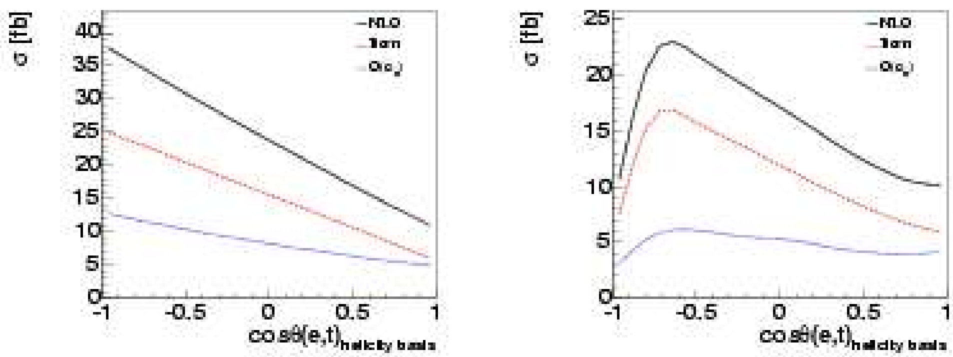
$$\frac{1}{\Gamma(t \to b\ell\nu)} \frac{d\Gamma(t \to b\ell\nu)}{d\cos\theta} = \frac{1}{2}\left(1 + \frac{N_- - N_+}{N_- + N_+}\cos\theta\right)$$

- θ is the angle, in the top-quark rest frame, between the direction of the charged lepton and the spin of the top quark.
  - Helicity basis: top spin along its moving direction
  - Optimal basis: top spin along the anti-proton moving direction
- The degree of polarization $\mathcal{D}$ and the fraction of polarization $\mathcal{F}$,

$$\mathcal{D} = \frac{N_- - N_+}{N_- + N_+}, \qquad \mathcal{F}_{\mp} = \frac{1 \pm \mathcal{D}}{2}.$$

Top quark polarization

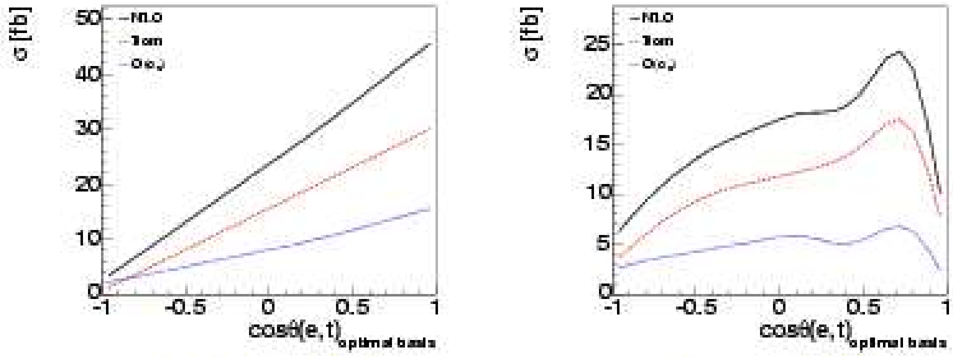
- Helicity basis ($t\bar{b}$)



$$\cos\theta_{hel} = \frac{\vec{p_t} \cdot \vec{p_\ell}^{\,\star}}{|\vec{p_t}| \cdot |\vec{p_\ell}^{\,\star}|}$$

$\vec{p_t}$: three-momentum defined in c.m. frame of the two incoming partons
$\vec{p_\ell}^{\,\star}$: charged lepton three-momentum defined in rest frame of top quark.

- Optimal basis



without cuts parton level

with cuts and reconstruction

$$\cos\theta_{opt} = \frac{\vec{p}_{\bar{p}}^{\,\star} \cdot \vec{p_\ell}^{\,\star}}{|\vec{p}_{\bar{p}}^{\,\star}| \cdot |\vec{p_\ell}^{\,\star}|}$$

$\vec{p}_{\bar{p}}^{\,\star}$: anti-proton three-momentum in the rest frame of top quark
$\vec{p}_{\ell}^{\,\star}$: charged lepton three-momentum in the top quark rest frame.

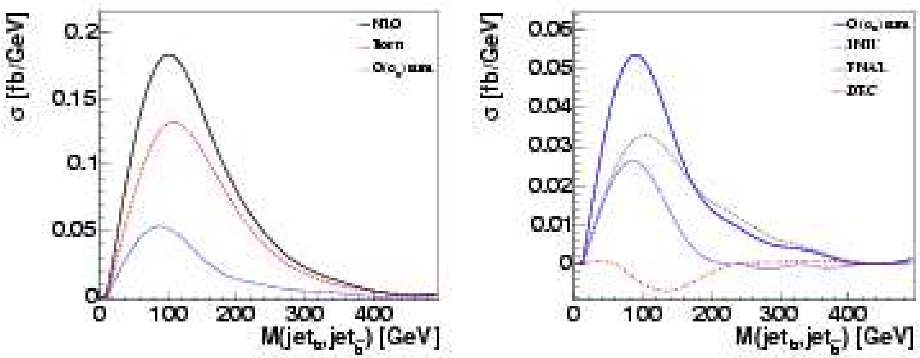
Degree and fraction of top quark polarization

		$\mathcal{D}$		$\mathcal{F}$	
		LO	NLO	LO	NLO
Helicity	Parton level	0.63	0.58	0.82	0.79
$(t\bar{b})$	Reconstructed events	0.46	0.37	0.73	0.68
Helicity	Parton level	0.63	0.54	0.82	0.77
$(t\bar{b}j)$	Reconstructed events	0.46	0.37	0.73	0.68
Optimal	Parton level	-0.96	-0.92	0.98	0.96
	Reconstructed events	-0.48	-0.42	0.74	0.71

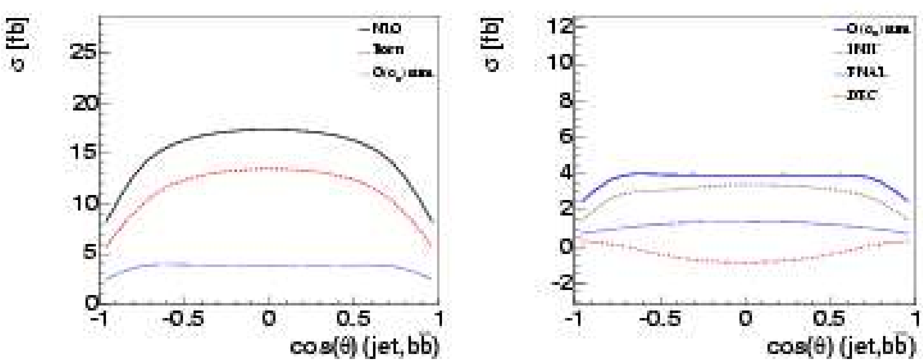
1. The strong spin correlation at parton level is smeared out after event reconstruction due to the imperfect W-reconstruction.
2. NLO QCD corrections also smear out the spin correlation.
3. With t-reconstruction, both bases give about the same fraction of polarization.

Intrinsic background to SM Higgs searching

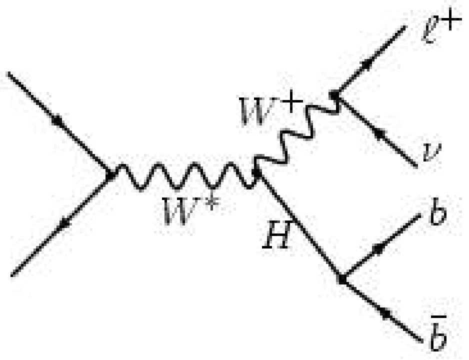
- Invariant mass of (b jet and $\bar{b}$ jet)



- Angular distribution of $\cos\theta_b$ in $b\bar{b}$



- SM Higgs searching channel



$115 < m_H < 130$ GeV

- The DEC contribution flattens out the $O(\alpha_s)$ corrections compared to Born level
  $\Longrightarrow$ closer to Higgs signal distribution
  $\Longrightarrow$ This becomes more important as shape is concerned.

Part III

Phenomenology of the t-channel single top process

1. Acceptance
2. Event topology
3. Kinematics of the final state objects
   - ☞ Spectator jet and b-jet
   - ☞ Top quark reconstruction
   - ☞ Spin correlation

Acceptance of inclusive two-jet events (t-channel)

$t\bar{q}+t\bar{q}j$	σ [fb]		Acceptances (%)	
	LO	NLO	LO	NLO
(a)	65.6	64.0	66	61
(b)	56.8	48.1	57.3	46
(c)	31.1	34.0	31.2	32.4

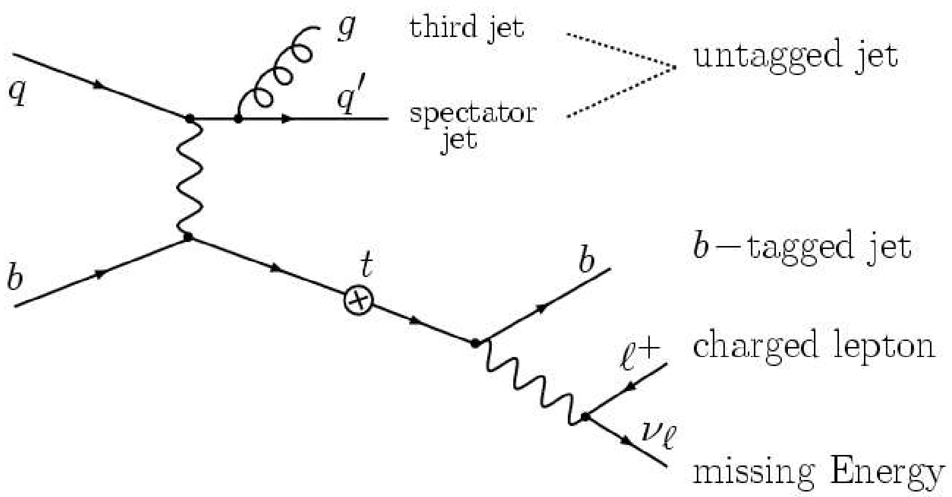
(a): loose cuts $\eta_\ell^{max}=2.5$, $\eta_j^{max}=3.0$ and $R_{cut}=0.5$

(b): loose cuts $\eta_\ell^{max}=2.5$, $\eta_j^{max}=3.0$ and $R_{cut}=1.0$

(c): tight cuts $\eta_\ell^{max}=1.0$, $\eta_j^{max}=2.0$ and $R_{cut}=0.5$

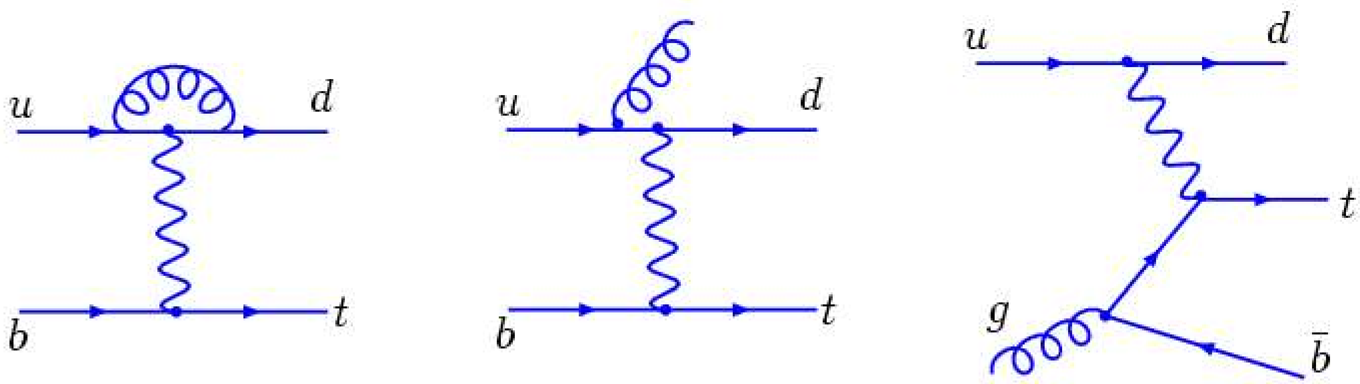
- The acceptances are sensitive to the kinematical cuts.
  - A large R_{cut} reduces the acceptance significantly because more events fail the lepton-jet separation cut.
  - With tight cuts, LO and NLO acceptances are almost the same. In contrast to the case of loose cuts, NLO accpetance is larger than LO.
  - With loose cuts, LO and NLO acceptances are quite different. $\Longrightarrow$ cannot use k-factor with LO kinematics
- To maximize the acceptance, the loose cuts (a) are used in the following study.

Event Topology



Collider signature: (besides of ℓ^+ and $\not{E}_T$)

- Born level type inclusive 2-jet events:
  1 b-jet, 1 untagged jet (spectator jet)
- Exclusive 3-jet events:
  1 b-jet, 2 untagged jets
- Exclusive 3-jet events (Wg-fusion):
  2 b-jets, 1 untagged jets



Unique signature of the t-channel process

New method to detect a heavy top quark at the Fermilab Tevatron

C.-P. Yuan
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 15 May 1989)

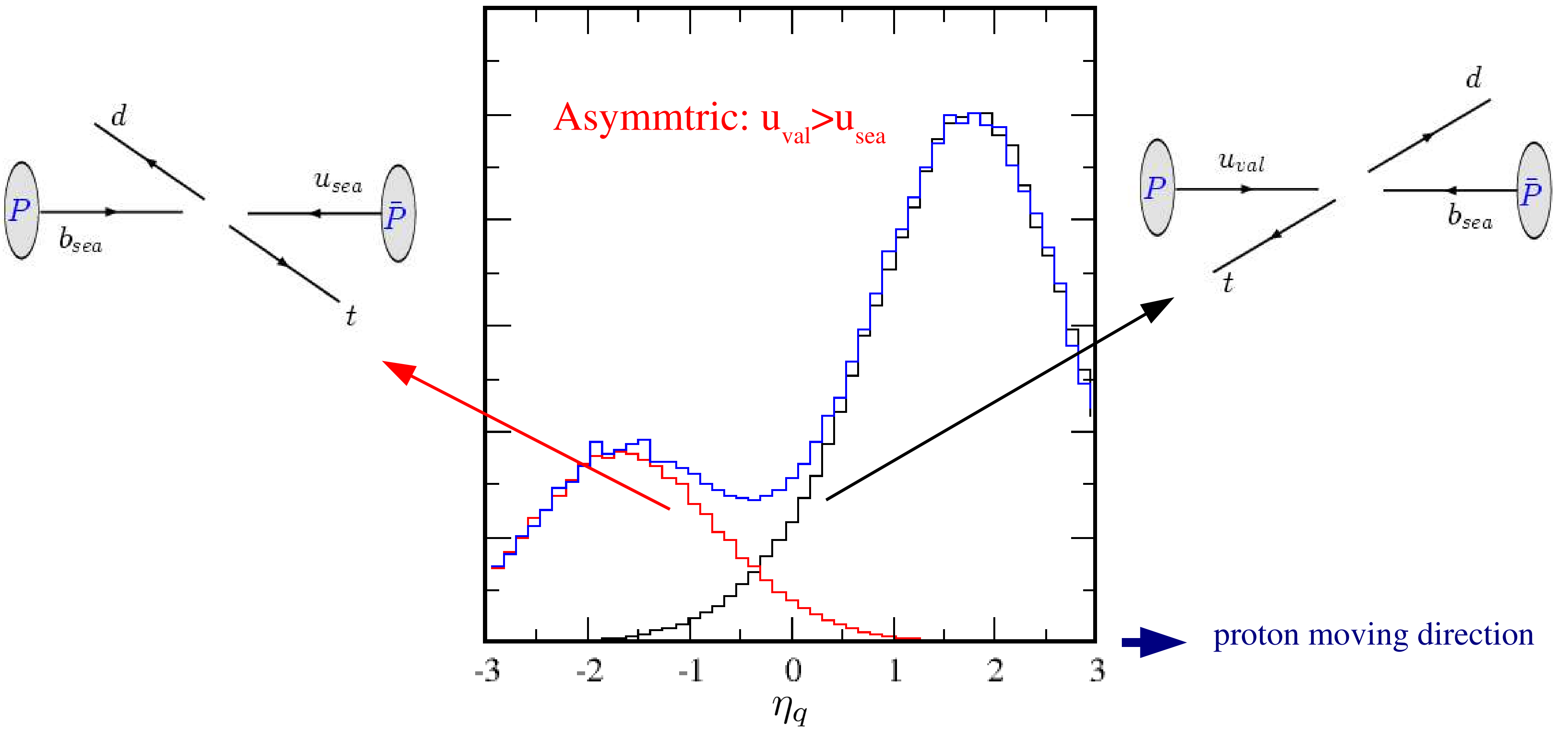
We present a new method to detect a heavy top quark with mass $\boxed{\sim 180\ \text{GeV}}$ at the upgraded Fermilab Tevatron ($\sqrt{S} = 2$ TeV and integrated luminosity 100 pb^{-1}) and the Superconducting Super Collider (SSC) via the W-gluon fusion process. We show that an almost perfect efficiency for the "kinematic b tagging" can be achieved due to the characteristic features of the transverse momentum P_T and rapidity Y distributions of the spectator quark which emitted the virtual W. Hence, we can reconstruct the invariant mass $M^{e\nu b}$ and see a sharp peak within a 5-GeV-wide bin of the $M^{e\nu b}$ distribution. We conclude that more than one year of running is needed to detect a 180-GeV top quark at the upgraded Tevatron via the W-gluon fusion process. Its detection becomes easier at the SSC due to a larger event rate.

The first paper in the literature to discuss the unique kinematics of the forward jet in the t-channel single-top event.

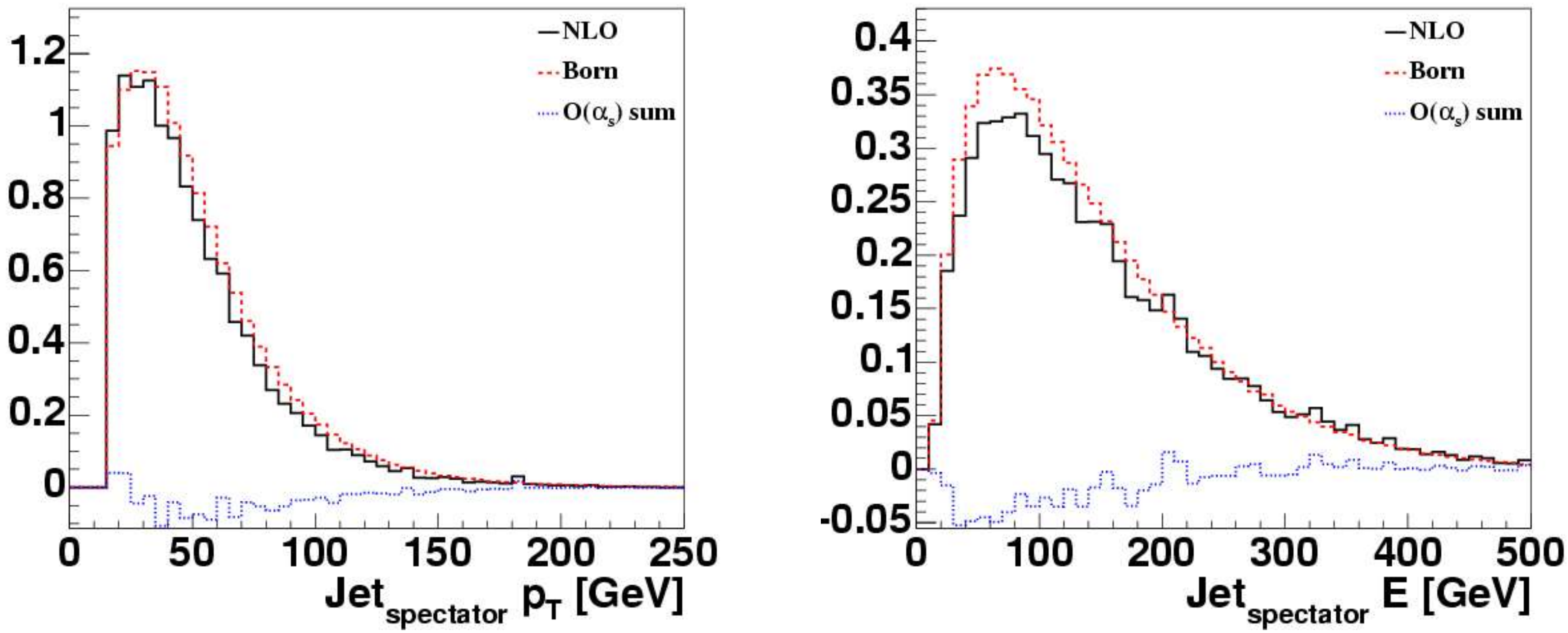
Unique signature of the t-channel process

Asymmetric rapidity distribution of the spectator jet

helps to suppress backgrounds $\Longrightarrow$ Its kinematics needs to be well studied.



Transverse momentum and energy distributions of the spectator jet

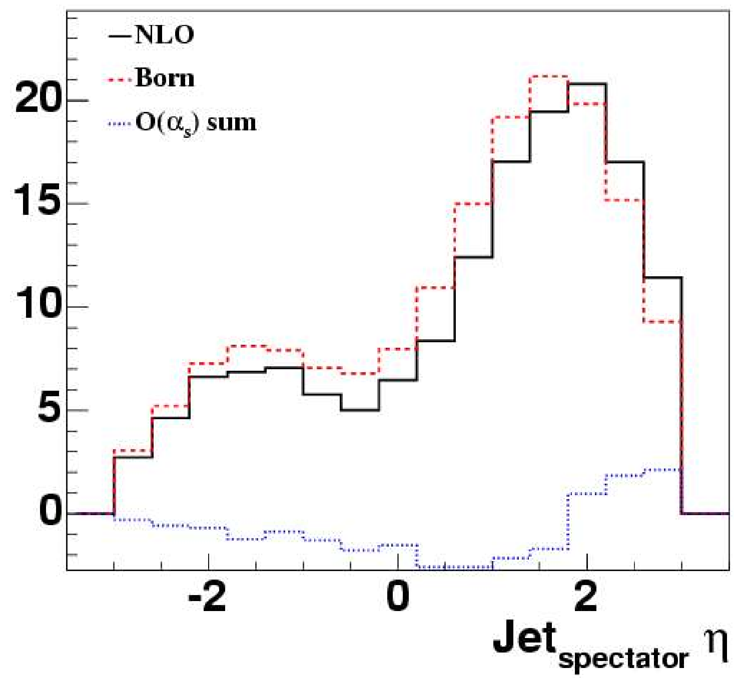


- The p_T distribution of spectator jet peaks around ~ $M_W/2$.
- The energy distribution peaks around ~ M_W.

Large pT and E can be used to distinguish the spectator jet from the soft gluon jet.

- The O($_S$) corrections shift its p_T to low value due to gluon radiation from th light quark line.

Rapidity distribution of the spectator jet at NLO

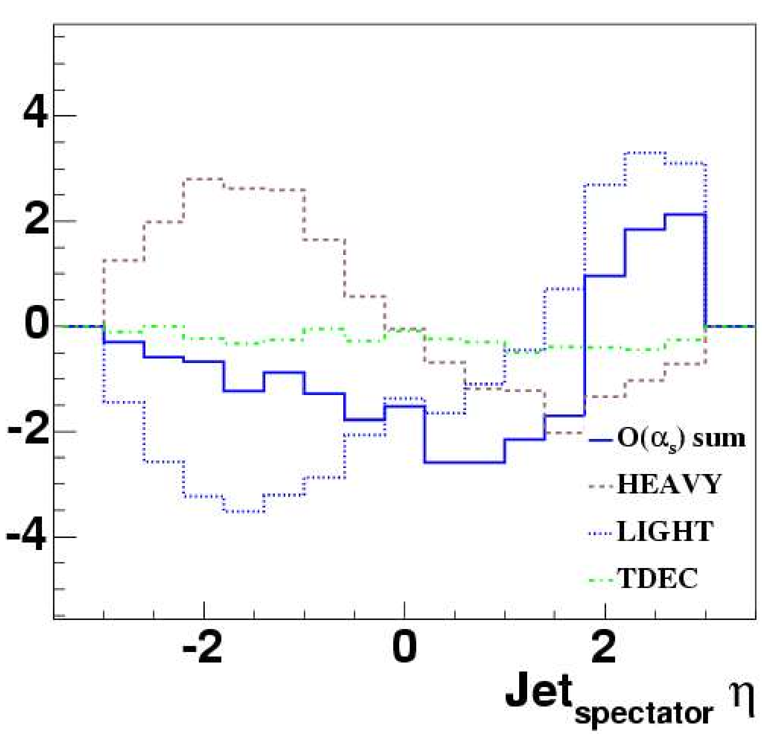


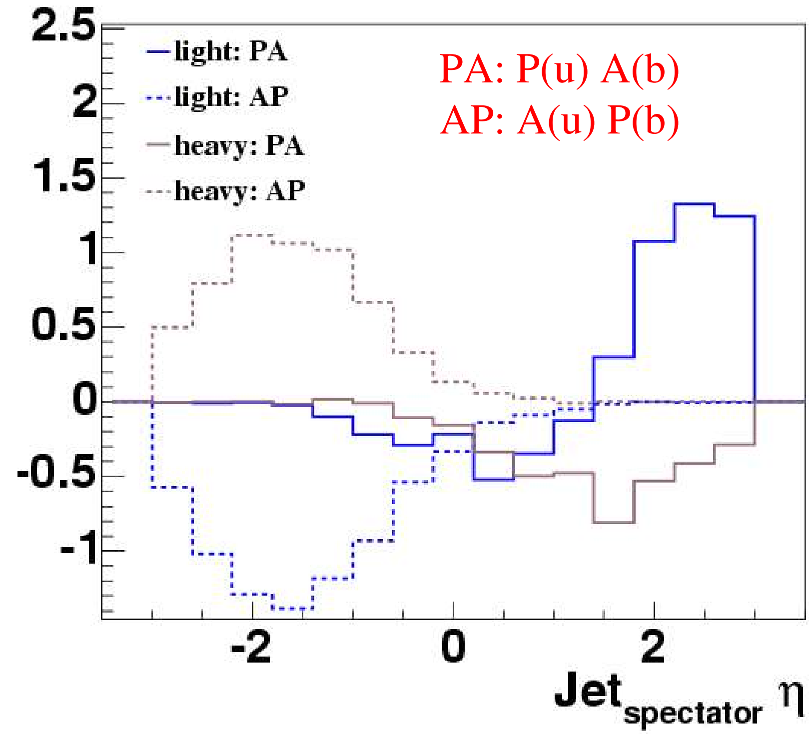
- The $O(\alpha_s)$ corrections even shift the spectator jet to more forward direction due to additional gluon radiation.

  impose harder cut on the spectator jet rapidity to suppress backgrounds

- The shift is small because the $O(\alpha_s)$ corrections are small.

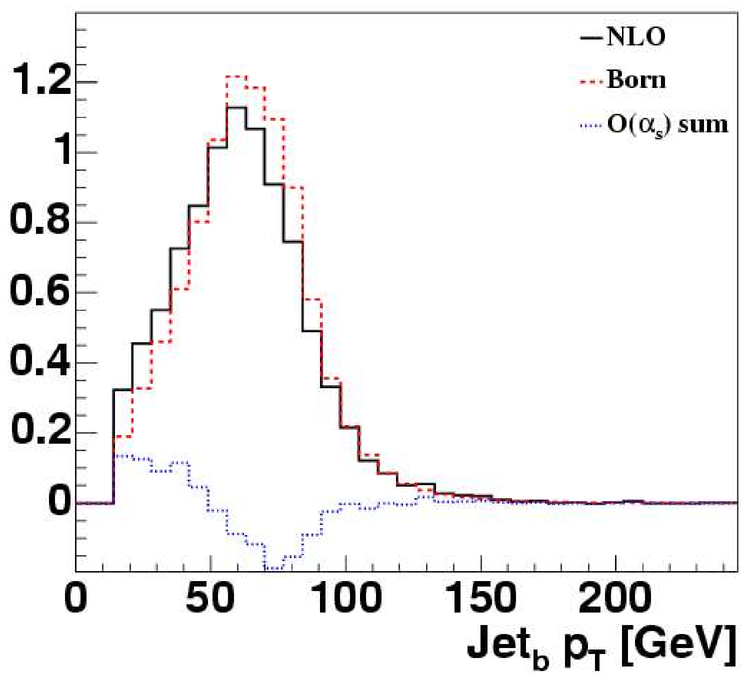
Why so?

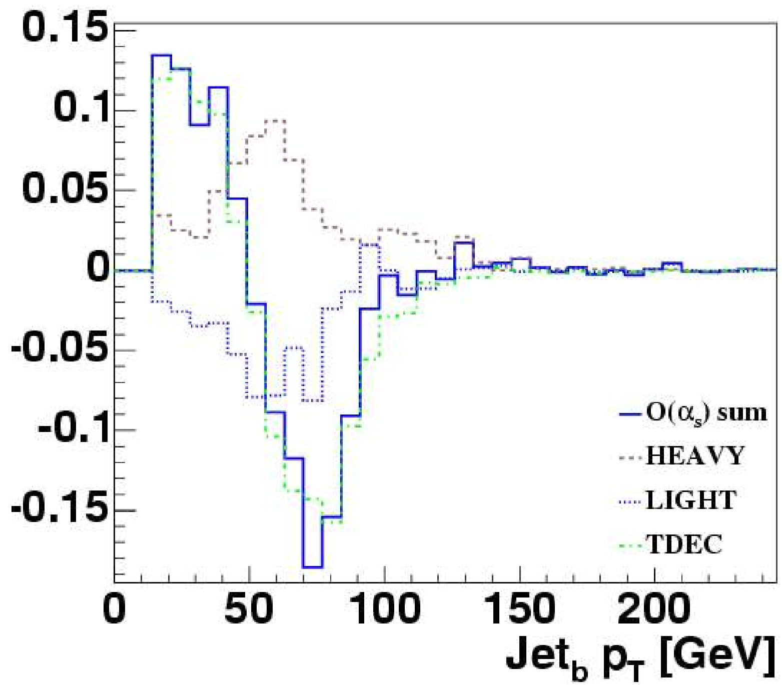




- LIGHT and HEAVY corrections have almost opposite contributions.
- LIGHT shifts the spectator jet to the forward direction while HEAVY shifts it to the central region
- TDEC contribution does NOT change the distribution.

Transverse momentum of the b-jet

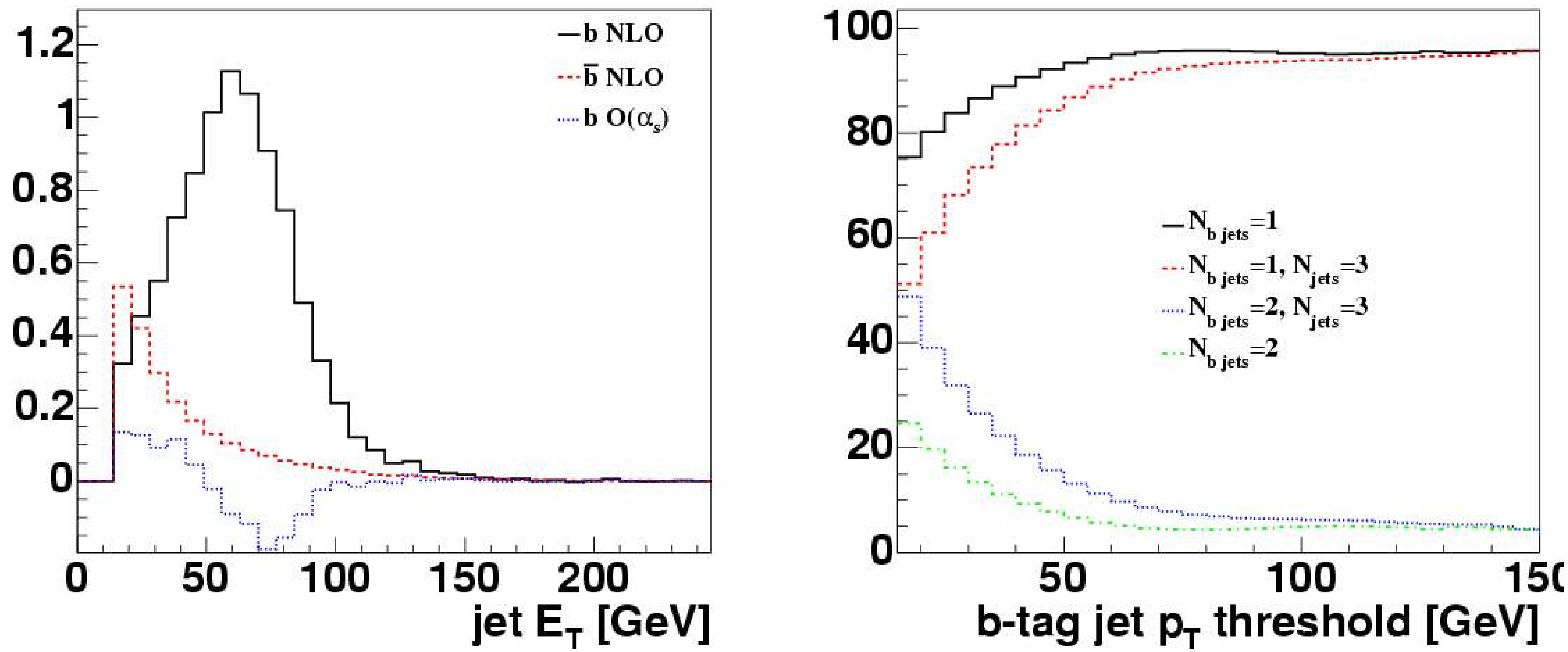




- p_T^b distribution is predominantly determined by top quark mass therefore peaks at $\sim m_t/3$
- The *O*($_s$) contributions shift p_T^b to lower value.
- TDEC contributions dominate over the LIGHT and HEAVY contribution.

collinear enhancement

Two b-jets in the Wg-fusion process

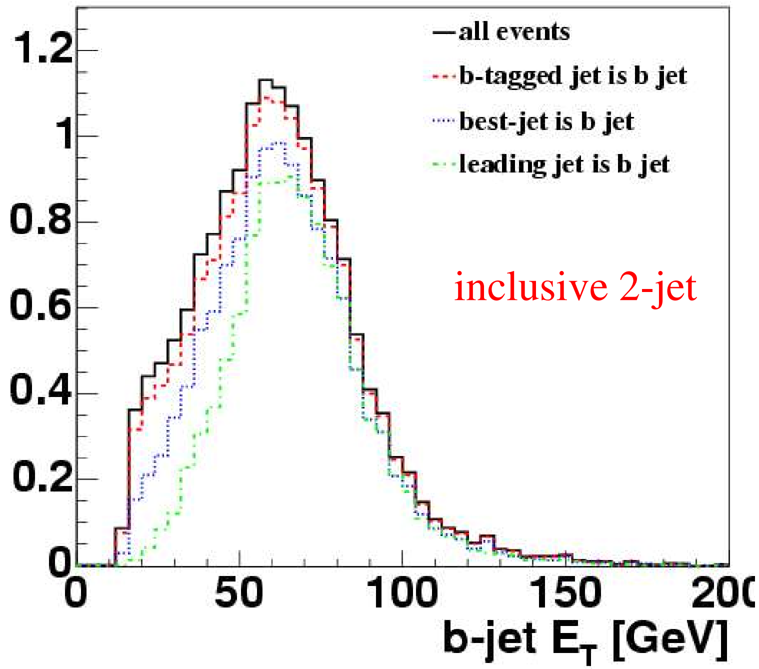


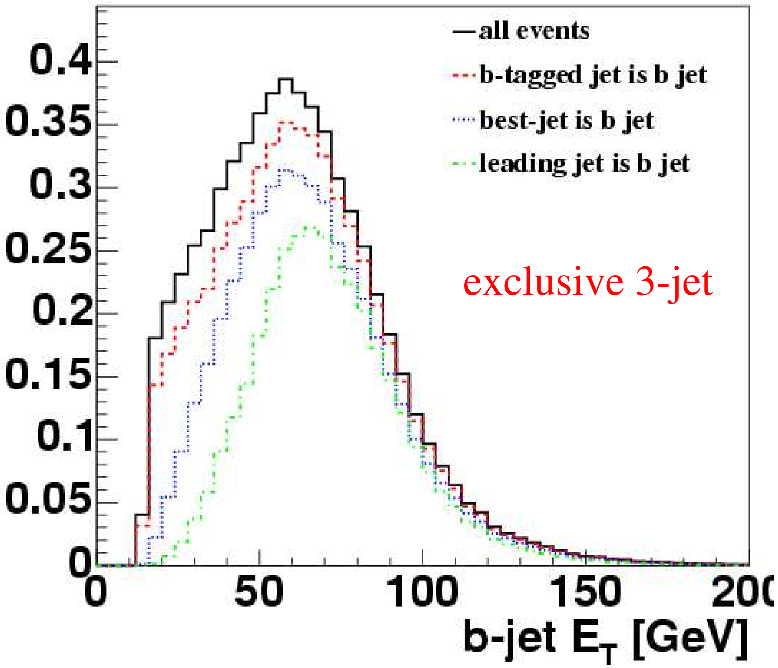
- Easy to separate two b-jets

  $p_T(\bar{b})$ distribution peaks around zero due to collinear physics.

- The fraction of events with two b-tagged jets is high for low jet p_T, but drops quickly.
- For exclusive three-jet events, the fraction of events with two b-tagged jets is much higher.

b-identification efficiency





- Leading b-tagged jet corresponds to the b quark from top decay most of the time

Leading b-tagged jet	Best-jet
inclusive 2-jet event: 95%	inclusive 2-jet event: 80%
exclusive 3-jet event: 90%	exclusive 3-jet event: 72%

works well due to the kinematical difference between b and $\bar{b}$

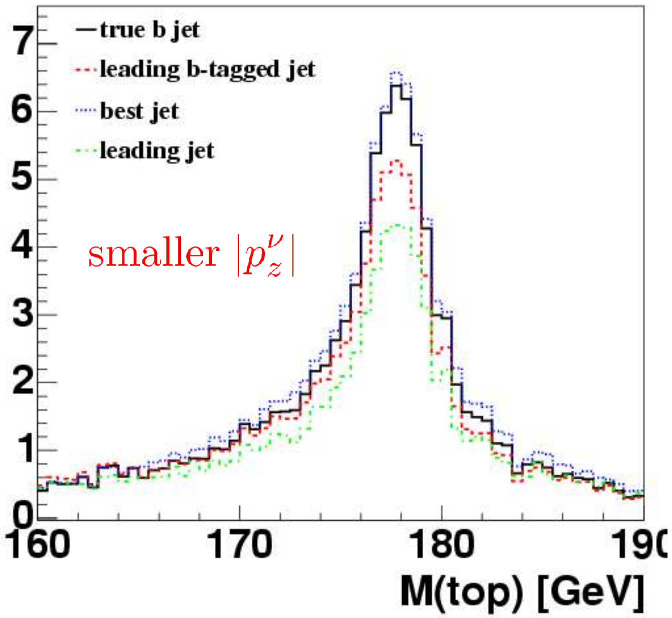
p_z^ν determination and efficiency

- Two ways to determine p_z^ν based on the scenario of b identification

	best-jet algorithm	leading b-tagged jet algorithm
M_W	using W-boson mass constrain to get two-fold solution of p_z^ν $M_W = \sqrt{(p_e + p_\nu)^2} \Longrightarrow p_{z1}^\nu, p_{z2}^\nu$	
b	using top mass constrain to pick up correct b-jet from top quark decay	using leading b-tagged jet to pick up correct b-jet from top quark decay
p_z^ν	smaller $\lvert p_z^\nu \rvert$	using top mass constrain to pick up correct p_z^ν
Eff.	~70%	LO: 92% NLO: 84%

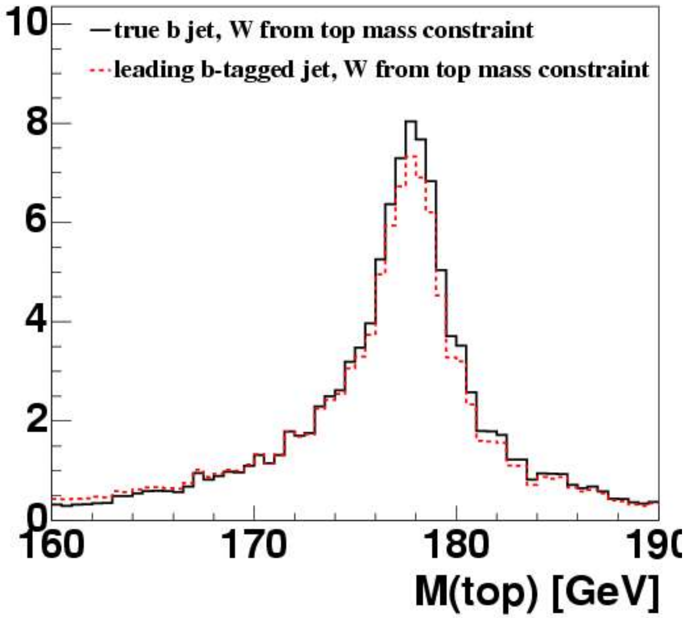
mainly due to Γ_W and Γ_t

Smaller p_z^ν vs. Top quark mass constrained p_z^ν



Leading jet : worst
Leading b-tagged jet: good
Best jet: best

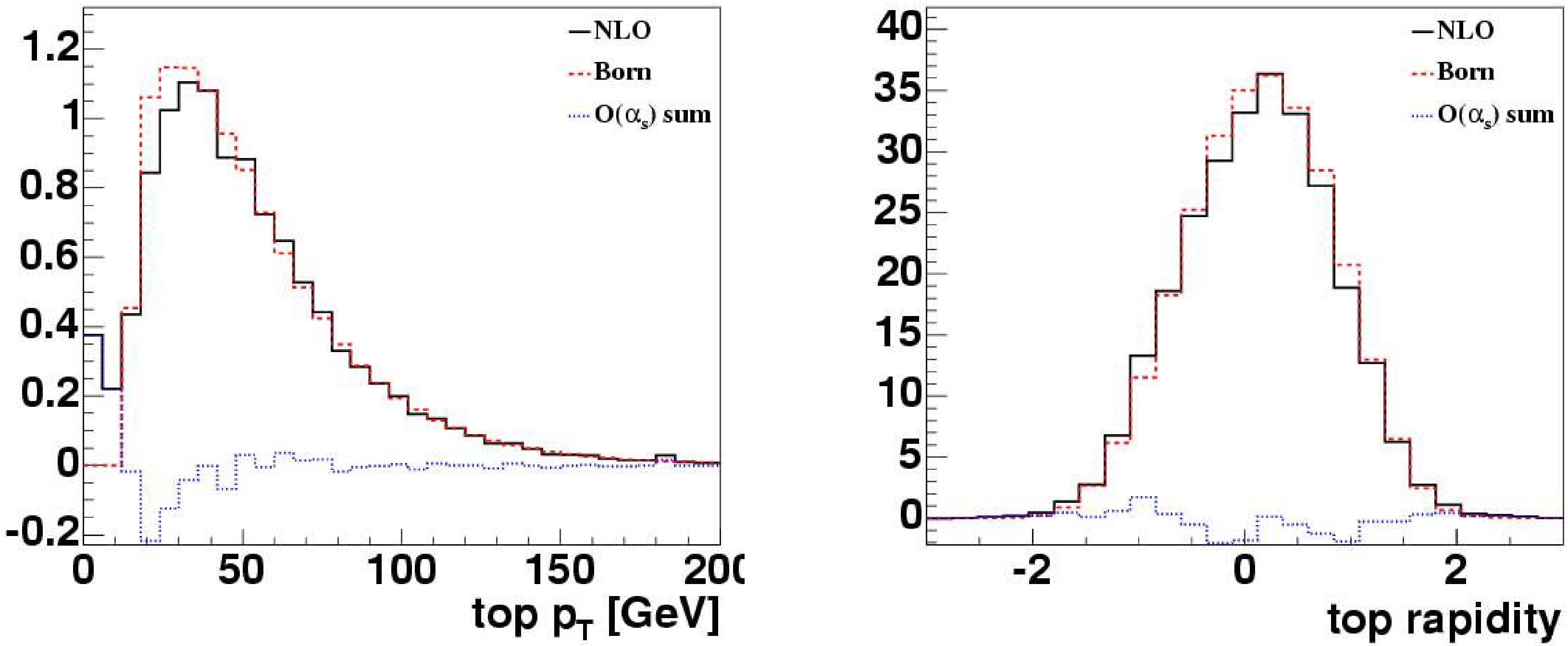
Best jet algorithm can pick up wrong jets to get correct top quark mass.



The overall height of the mass peak is higher than in the left figure indicating this method reconstruct W boson and b jet correctly more often.

We can also properly reconstruct the true top quark width with very high efficiency.

Kinematics distribution of the reconstructed top quark

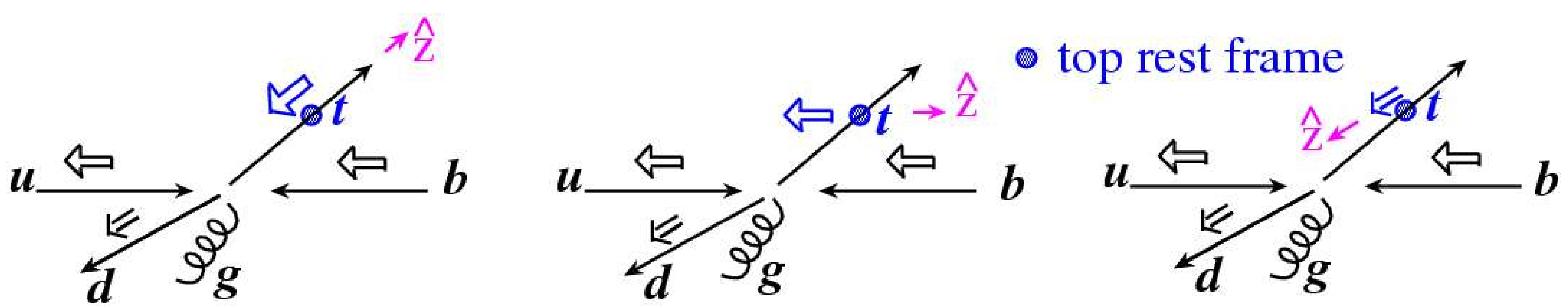


- The $O(\alpha_s)$ corrections tend to shift top quark p_T to large value.
- The $O(\alpha_s)$ corrections only have a small effect on top quark rapdity.

  LIGHT and HEAVY corrections cancel with each other and leave top quark rapidity almost unchanged.

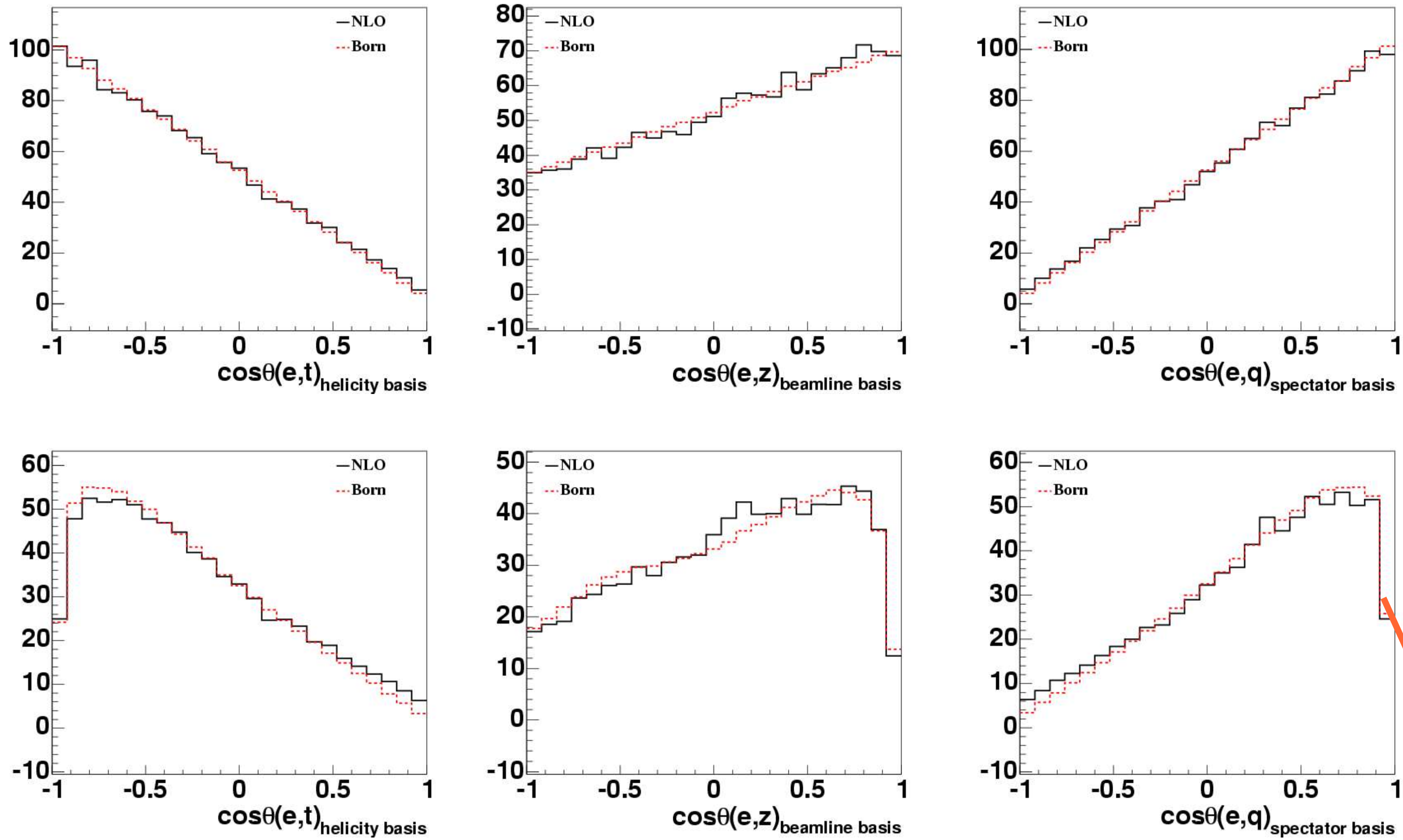
Top quark polarization: spin bases

- Helicity basis:
  tq(j)-frame
  z: along the top quark moving direction in the c.m. frame of incoming partons
  tq-frame
  z: along the top quark moving direction in the c.m. frame of top quark and the spectator quark
- Beamline basis:
  z: along the incoming proton beam direction
- Spectator basis:
  z: along the moving direction of the spectator quark



Helicity basis   Beamline basis   Spectator basis

Top quark polarization



without cuts
parton level

with cuts and
reconstruction

drop off
ΔR_{ej}

Helicity (tq-frame) Beamline Spectator

Degree and fraction of top quark polarization

		$\mathcal{D}$		$\mathcal{F}$	
		LO	NLO	LO	NLO
Helicity $tq(j)$	Parton level	0.96	0.74	0.98	0.87
	Recon. event	0.84	0.73	0.92	0.86
Helicity tq	Parton level	0.96	0.94	0.98	0.97
	Recon. event	0.84	0.75	0.92	0.88
Spectator	Parton level	-0.96	-0.94	0.98	0.98
	Recon. event	-0.85	-0.77	0.93	0.89
Beamline	Parton level	-0.34	-0.38	0.67	0.69
	Recon. event	-0.3	-0.32	0.65	0.66

At the parton level, tq-frame have larger d.o.p. than tq(j)-frame

After event reconstruction, tq-frame and tq(j)-frame have almost the same d.o.p.

Degree and fraction of top quark polarization

		$\mathcal{D}$		$\mathcal{F}$	
		LO	NLO	LO	NLO
Helicity $tq(j)$	Parton level	0.96	0.74	0.98	0.87
	Recon. event	0.84	0.73	0.92	0.86
Helicity tq	Parton level	0.96	0.94	0.98	0.97
	Recon. event	0.84	0.75	0.92	0.88
Spectator	Parton level	-0.96	-0.94	0.98	0.98
	Recon. event	-0.85	-0.77	0.93	0.89
Beamline	Parton level	-0.34	-0.38	0.67	0.69
	Recon. event	-0.3	-0.32	0.65	0.66

At the parton level, tq-frame have larger d.o.p. than tq(j)-frame

After event reconstruction, tq-frame and tq(j)-frame have almost the same d.o.p.

Helicity basis (tq-frame) give almost the same d.o.p. as the spectator basis.

Degree and fraction of top quark polarization

		$\mathcal{D}$		$\mathcal{F}$	
		LO	NLO	LO	NLO
Helicity $tq(j)$	Parton level	0.96	0.74	0.98	0.87
	Recon. event	0.84	0.73	0.92	0.86
Helicity tq	Parton level	0.96	0.94	0.98	0.97
	Recon. event	0.84	0.75	0.92	0.88
Spectator	Parton level	-0.96	-0.94	0.98	0.98
	Recon. event	-0.85	-0.77	0.93	0.89
Beamline	Parton level	-0.34	-0.38	0.67	0.69
	Recon. event	-0.3	-0.32	0.65	0.66

At the parton level, tq-frame have larger d.o.p. than tq(j)-frame

After event reconstruction, tq-frame and tq(j)-frame have almost the same d.o.p.

Helicity basis (tq-frame) give almost the same d.o.p. as the spectator basis.

- Beamline basis gives the worst degree of polarization (d.o.p.) of top quark.
- At the LO, there is no difference between the Helicity basis (tq-frame and tq(j)-frame) and the spectator basis
- High order QCD corrections blur the spin correlation effect, except for the beamline basis.

Part IV

Top polarization and W helicity

1. General Formulation of t-b-W couplings
2. What have we known from indirect measurements?
3. How to perform direct measurements at Tevatron & LHC?
4. Distinguish different models of EWSB

In collaboration with:

C.-R. Chen and F. Larios, hep-ph/0503040.

General Formulation of t-b-W couplings

- Top quark couplings to gauge bosons in the non-linear chiral Lagrangian framework ($SU(2)\times U(1)$ invariant)

$$\boxed{\begin{aligned}\mathcal{L} = &\bar{b}\gamma^{\mu}(\kappa_{1L}^{\dagger}P_L + \kappa_{2R}^{\dagger}P_R)t\Sigma_{\mu}^{-} + \partial_{\nu}\Sigma_{\mu}^{-}\bar{b}\sigma^{\mu\nu}(\kappa_{3L}^{\dagger}P_L + \kappa_{4R}^{\dagger}P_R)t \\ &+\bar{b}(\kappa_{5L}^{\dagger}P_L + \kappa_{6R}^{\dagger}P_R)\partial_{\mu}t\Sigma^{-\mu} + \bar{b}(\kappa_{7L}^{\dagger}P_L + \kappa_{8R}^{\dagger}P_R)t\partial_{\mu}\Sigma^{-\mu} + h.c.\end{aligned}}$$

Here, κ_L, and κ_R are two arbitrary complex parameters,

$$\Sigma_{\mu}^{\pm} = \frac{1}{\sqrt{2}}(\Sigma_{\mu}^{1} \mp i\Sigma_{\mu}^{2}), \qquad \Sigma_{\mu}^{a} = -\frac{i}{2}Tr(\tau^{a}\Sigma^{\dagger}D_{\mu}\Sigma),$$

$$\begin{pmatrix} t \\ b \end{pmatrix}_L \equiv \Sigma F_L = \Sigma \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}_L, \qquad \begin{array}{l} t_R = f_{1R} \\ b_R = f_{2R} \end{array}.$$

- In the unitary gauge,

$$\Sigma_{\mu}^{\pm} \to -\frac{1}{2}gW_{\mu}^{\pm},\ t_L \to f_{1L},\ t_R \to f_{2R},\ \text{etc.}$$

General Formulation of t-b-W couplings (not necessary to be on-shell)

- New physics effects can be summarized in effective Lagrangian:

$$\begin{aligned}\mathcal{L} = & \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t \\ & - \frac{g}{\sqrt{2} m_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t \\ & + \frac{g}{\sqrt{2} m_W} \bar{b} (f_3^L P_L + f_3^R P_R) \partial_\mu t W^{-\mu} \\ & + \frac{g}{\sqrt{2} m_W} \bar{b} (f_4^L P_L + f_4^R P_R) t \partial_\mu W^{-\mu} + h.c.\end{aligned}$$

$\Longrightarrow$ 8 different form factors

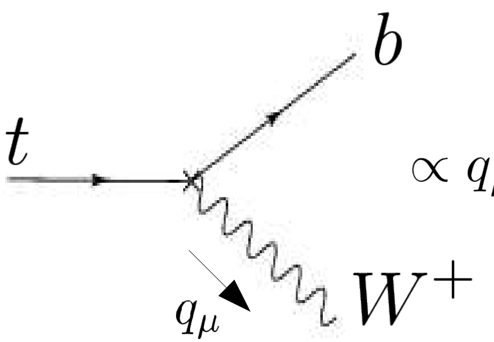
General Formulation of t-b-W couplings (for on-shell t and b)

- Gordon Identity ⟹ reduce from 8 to 6 form factors

$$\mathcal{L} \supset \gamma_\mu, \sigma_{\mu\nu} q^\nu, q_\mu$$

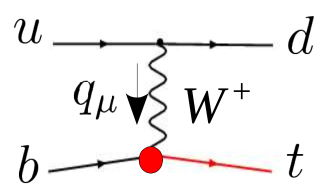
q_μ term: not contribute for either on-shell or off-shell W boson.

☞ on-shell W boson in top decay

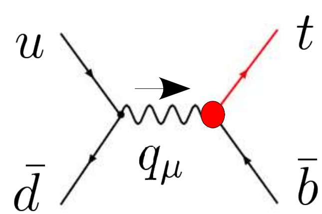


$$\propto q_\mu \epsilon^\mu = 0$$

☞ off-shell W boson in single top production



$$q_\mu \propto (p_u - p_d)_\mu \sim 0$$



$$q_\mu \propto (p_u + p_d)_\mu \sim 0$$

⟹ reduce from 6 to 4 form factors

General Formulation of t-b-W couplings

- The general t-b-W effective Lagrangian (dim-4 and dim-5 couplings)

$$\mathcal{L}_{tbW} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b}\gamma^\mu (f_1^L P_L + f_1^R P_R) t$$

$$- \frac{g}{\sqrt{2} m_W} \partial_\nu W_\mu^- \bar{b}\sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + h.c.$$

☞ In the SM,

$$f_1^L = 1, \; f_1^R = f_2^L = f_2^R = 0.$$

☞ The couplings may be sensitive to new physics.

Propose a most general analysis

Choose independent experimental observables to study the constraints of effective w-t-b couplings.

☞ Four independent variables in the effective Lagrangian

$$\left.\begin{array}{l} f_1^L \\ f_1^R \\ f_2^L \\ f_2^R \end{array}\right\} \text{four form factors}$$

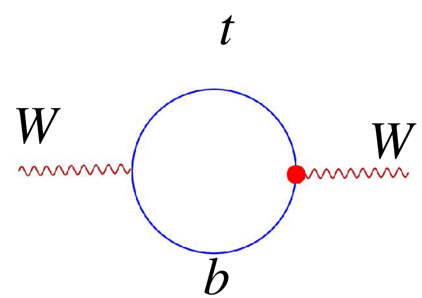
☞ Four experimental observables

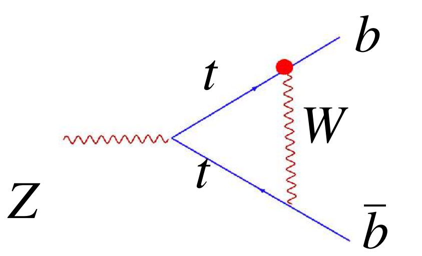
$$\left.\begin{array}{l} f_0 \\ f_- \end{array}\right\} \text{top decay} \qquad (f_0 + f_- + f_+ = 1)$$

$$\left.\begin{array}{l} \sigma_t \\ \sigma_s \end{array}\right\} \text{Single top production}$$

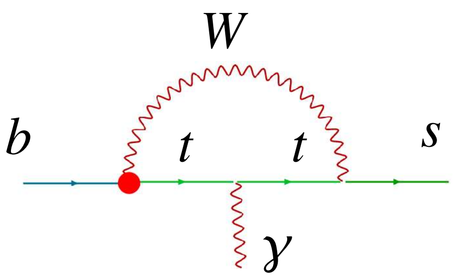
What do we know from indirect measurements?

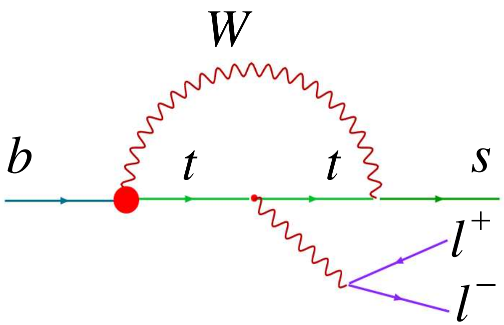
Indirect limits on dim-4 and dim-5 couplings





coupling	LEP	$b \to s\gamma$	$b \to s l^+ l^-$
$\epsilon_L \equiv f_1^L - 1$	0.02	0.3	0.5
f_2^R	0.1	-	0.4
f_1^R	-	0.002	-
f_2^L	-	0.005	-



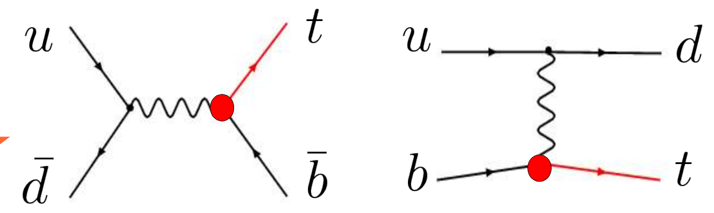


one coupling at a time.

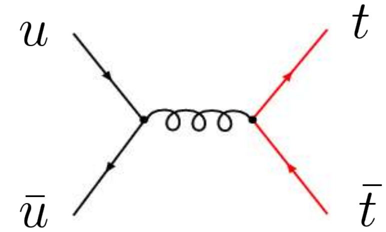
- May cancel with other contributions (originated from other light fields)
- Assume no other new physics effect

What do we know from direct measurements?

coupling	Tevatron	LHC
ϵ_L	10^{-1}	10^{-2}
f_2^R	0.3	0.003
f_1^R	0.7	0.08
f_2^L	0.3	0.05



$$A_{FB} = \frac{\Gamma_F - \Gamma_B}{\Gamma_F + \Gamma_B}$$



one coupling at a time.

Tevatron: $(2\ fb^{-1}) \times (6\ pb) \sim 10^4\ \ \bar{t}\,t\ events$

LHC: $(100\ fb^{-1}) \times (8\times 10^2\ pb) \sim 10^8\ \ \bar{t}\,t\ events$

How to perform direct measurements at Tevatron and LHC?

- Measurement of W helicity fractions in top decay

$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\cos\theta} = f_0\frac{3}{4}\sin^2\theta + f_-\frac{3}{8}(1-\cos\theta)^2 + f_+\frac{3}{8}(1+\cos\theta)^2$$

- Theoretical prediction:

LO:

$$f_0 = \frac{\Gamma_0}{\Gamma_t} = \frac{a_t^2}{a_t^2+2} = 0.71$$

$$f_- = \frac{\Gamma_-}{\Gamma_t} = \frac{2}{a_t^2+2} = 0.29$$

$$f_+ = \frac{\Gamma_+}{\Gamma_t} = 0$$

$$a_t = \frac{m_t}{m_W} = \frac{178.0}{80.4}$$

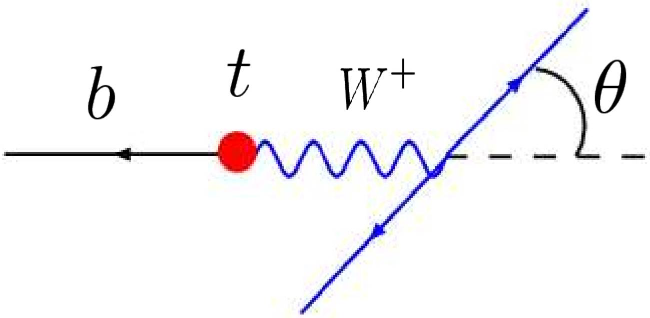
Beyond LO:

$$f_0 = 0.701$$

$$f_- = 0.297$$

$$f_+ = 0.002$$

$$O(\alpha_s^2), EW, m_b, \Gamma_W$$



hep-ph/0209185

How to perform direct measurements at Tevatron and LHC?

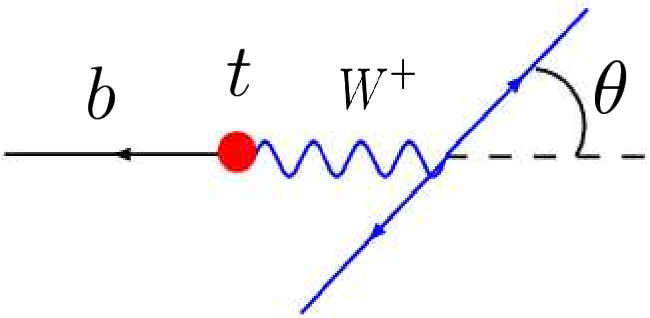
- Measurement of W helicity fractions in top decay

$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\cos\theta} = f_0\frac{3}{4}\sin^2\theta + f_-\frac{3}{8}(1-\cos\theta)^2 + f_+\frac{3}{8}(1+\cos\theta)^2$$

- Experimental measurements: (from $t\bar{t}$ pairs @ Tevatron)

D0: $f_0 = 0.56 \pm 0.32 \quad f_+ < 0.24$

hep-ex/0404040



CDF: $f_0 = 0.91 \pm 0.38 \quad f_+ < 0.18$

hep-ex/0411070

$\Longrightarrow$ Expected @ $2\ \mathrm{fb}^{-1}$: $\dfrac{\Delta f_0}{f_0} \sim 10\%,\ f_+ < 0.05$

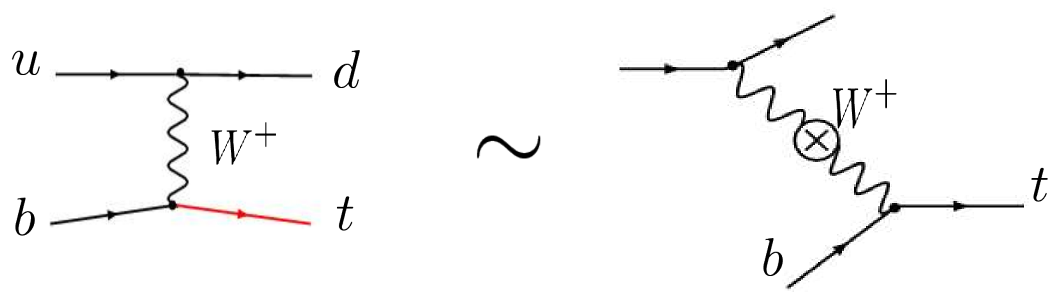
General analysis

How to combine f_0 and f_-(or f_+) measurements with the single top cross section measurements?

- Can σ_t be expressed as

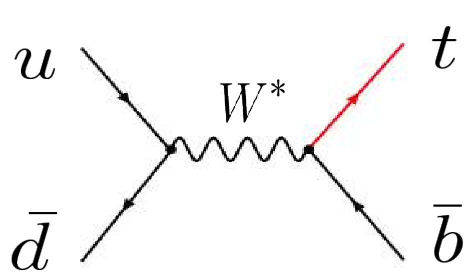
small

$$\sigma_t \sim (\cdots) f_0 + (\cdots) f_- + (\cdots) f_+ + (\cdots)$$



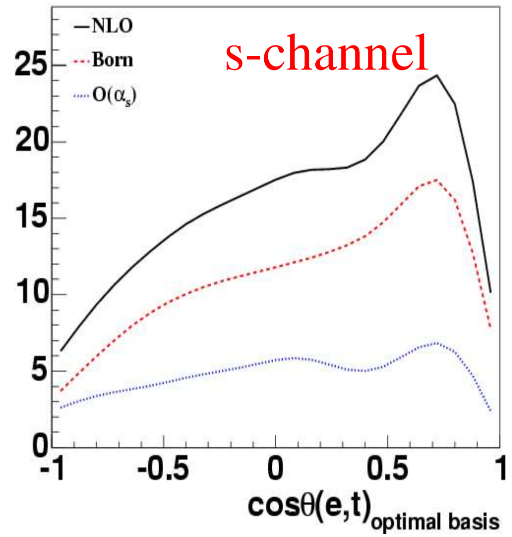
- Can σ_s be expressed as

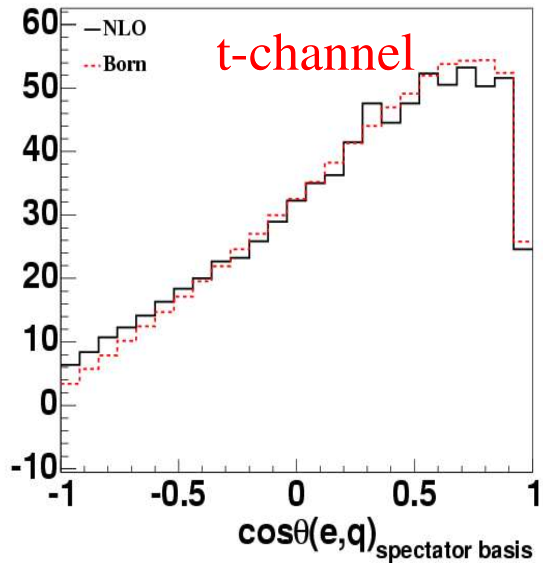
$$\sigma_s \sim (\cdots) f_0 + (\cdots) f_- + (\cdots) f_+ + (\cdots)$$



Single top cross sections and distributions

- NLO QCD correction to differential cross section have been calculated. NWA is adopted in order to keep top quark spin information.
- Spin correlation effects have been examined in different spin bases.





LO : CTEQ6L1, NLO : CTEQ6M, for $m_t = 178\text{GeV}$

Channel	Tevatron (t LO)	Tevatron (t NLO)	LHC (t LO)	LHC (t NLO)	LHC ($\bar{t}$ LO)	LHC ($\bar{t}$ NLO)
t-channel	0.827	0.924	146.0	150.0	84.9	88.5
s-channel	0.27	0.405	4.26	6.06	2.59	3.76

Four observables in terms of four independent variables

$$f_0 = \frac{a_t(1+x_0)}{a_t(1+x_0)+2(1+x_m+x_p)}$$

$$f_- = \frac{2(1+x_m)}{a_t(1+x_0)+2(1+x_m+x_p)}$$

$$f_+ = \frac{2\,x_p}{a_t(1+x_0)+2(1+x_m+x_p)}$$

$$x_0 = (f_1^L + f_2^R/a_t^2)^2 + (f_1^R + f_2^L/a_t^2)^2 - 1$$

$$x_m = (f_1^L + f_2^R\,a_t^2)^2 - 1$$

$$x_p = (f_1^R + f_2^L\,a_t^2)^2$$

$$x_5 = a_t^2\left((f_2^R)^2 + (f_2^L)^2\right)$$

$$a_t = m_t/m_W$$

only depend on $f_2^{L,R}$, not $f_1^{L,R}$.

$$f_0 + f_- + f_+ = 1$$

$$\Delta\sigma \equiv \sigma - \sigma^{SM}$$

$$\Delta\sigma_t = a_0\,x_0 + a_m\,x_m + a_p\,x_p + a_5\,x_5$$
$$\sim(\cdots)\,f_0 + (\cdots)\,f_- + (\cdots)\,f_+ + a_5\,x_5$$

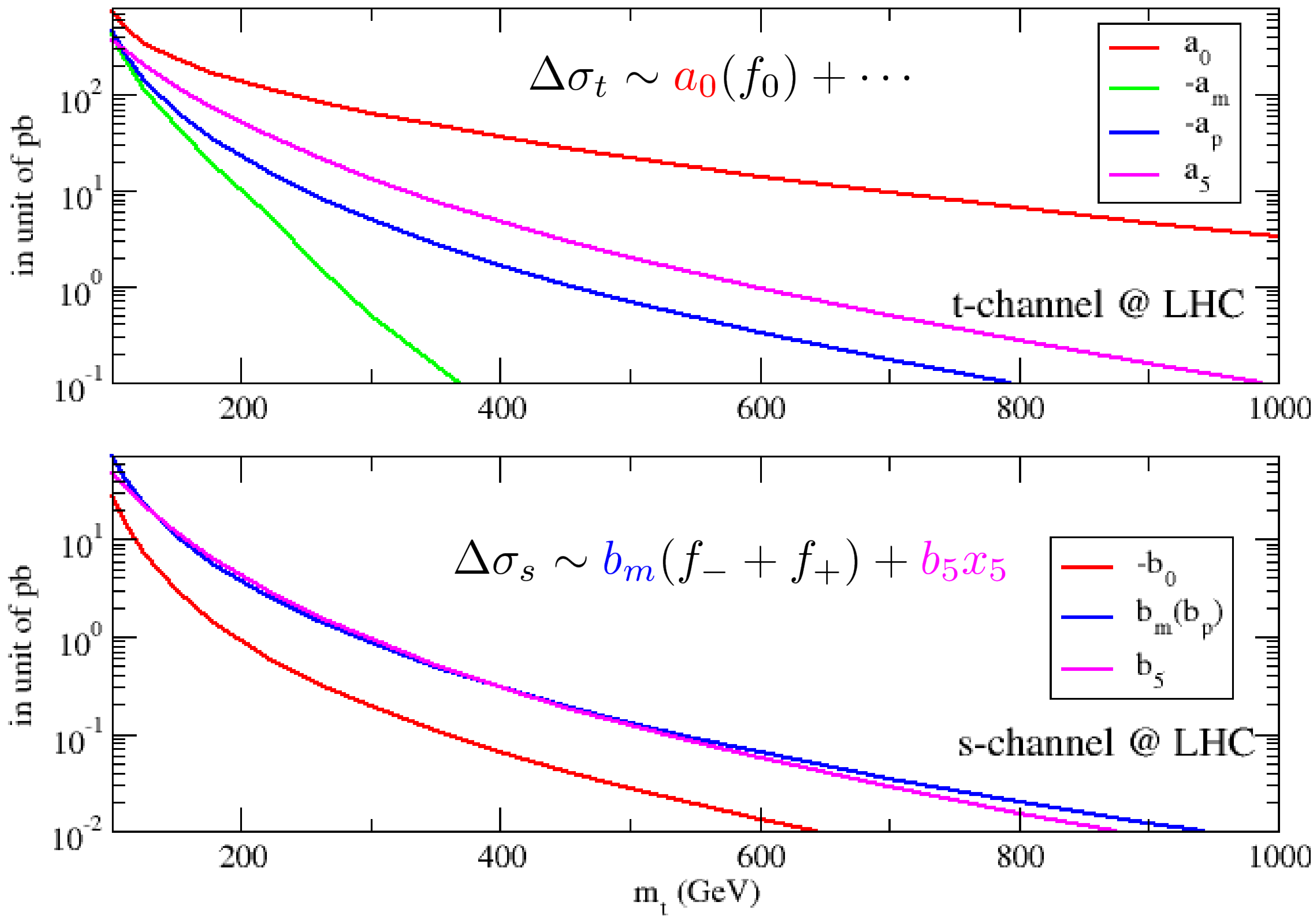
t-channel	a_0	a_m	a_p	a_5
Tevatron	0.896	-0.069	-0.153	0.247
LHC (t)	165.2	-19.1	-34.2	62.5

$$\Delta\sigma_s = b_0\,x_0 + b_m\,x_m + b_p\,x_p + b_5\,x_5$$
$$\sim(\cdots)\,f_0 + (\cdots)\,f_- + (\cdots)\,f_+ + b_5\,x_5$$

s-channel	b_0	b_m	b_p	b_5
Tevatron	-0.081	0.352	0.352	0.230
LHC (t)	-1.41	5.67	5.67	6.34

CTEQ6L1

Coefficients v.s. top quark mass (or t' in new physics models)



Distinguish different model of EWSB

An illustration with two couplings (to simplify discussion)

- Assume b_R couplings are small (for $m_b \sim 0$) $\Longrightarrow f_1^R = f_2^L \sim 0 \Longrightarrow f_+ \sim 0$

$$f_- = \frac{2\,(1+\epsilon_L + a_t\, f_2^R)^2}{a_t^2\,(1+\epsilon_L + f_2^R/a_t)^2 + 2\,(1+\epsilon_L + a_t\, f_2^R)^2}$$

If $f_2^R \to 0$, then

$$f_- = \frac{2}{a_t^2+2} = f_-^{SM}$$

- The sign of Δf_- depends on models $\quad f_2^R \lesssim 0 \;\Leftrightarrow\; \Delta f_- \lesssim 0$

  - ☞ MSSM $\quad \epsilon_L = 0.01\,,\quad f_2^R = 0.005 \quad f_0 \searrow \quad f_- \nearrow$

    (ϵ_L can be either positive or negative. SUSY-QCD and SUSY-EW corrections have opposite contributions.) hep-ph/0306278

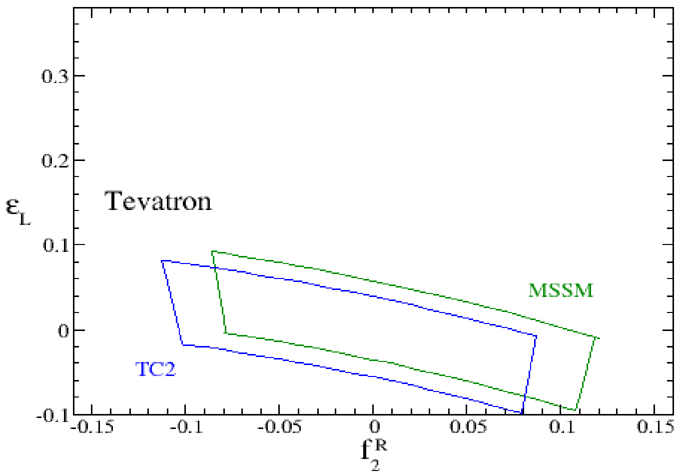
  - ☞ TC2 $\quad \epsilon_L = -0.01\,,\quad f_2^R = -0.005 \quad f_0 \nearrow \quad f_- \searrow$

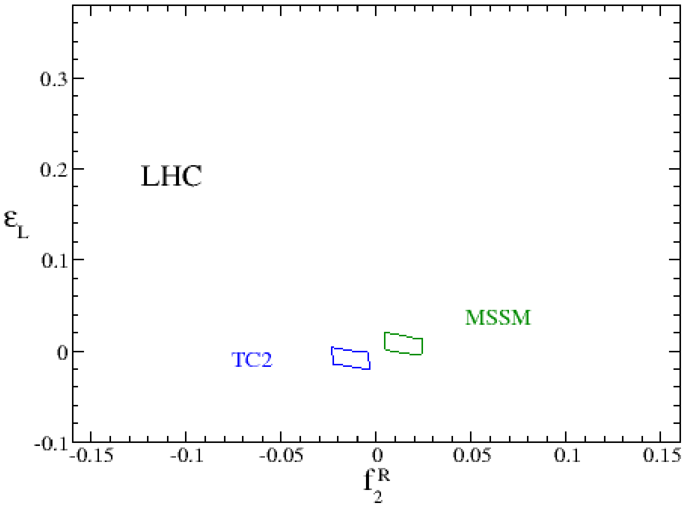
    (typically, $\epsilon_L < 0$) hep-ph/0501145

Distinguish different model of EWSB

(assume $f_1^R \sim f_2^L \sim 0$ for small b_R contribution)

	MSSM	TC2
ϵ_L	0.01	-0.01
f_2^R	0.005	-0.005
$\Delta f_0 / f_0^{SM}$	-0.5%	0.5%
$\Delta f_- / f_-^{SM}$	1.2%	-1.2%
Tevatron $\Delta\sigma_t / \sigma_t^{SM}$	2.1%	-2.0%
Tevatron $\Delta\sigma_s / \sigma_s^{SM}$	3.2%	-3.1%
LHC $\Delta\sigma_t / \sigma_t^{SM}$	2.2%	-2.1%
LHC $\Delta\sigma_s / \sigma_s^{SM}$	3.4%	-3.3%
$\Delta\Gamma_t / \Gamma_t^{SM}$	3.5%	-3.4%





Summary and outlook

❶ The s-channel single particle inclusive rate (with acceptance) is dominated by the initial state contribution, while the t-channel single particle inclusive rate is dominated by the heavy quark line contribution.

❷ With loose kinematical cuts to maximize the acceptances, the full NLO kinematics needs to be studied. (A constant K-factor with LO kinematics won't work)

❸ In order to reconstruct top quark event, the best-jet algorithm is better in the s-channel process, while the leading b-tagged jet algorithm is best in the t-channel process.

❹ Higher order corrections change the kinematical and spin correlations largely. After event reconstruction, in the sense of d.o.p. of top quark,

Optimal basis	$\simeq$	Helicity basis (tb-frame)	in s-channel
Spectator basis	$\simeq$	Helicity basis (tq-frame)	in t-channel

Summary and outlook

❺ NLO QCD corrections to s-channel single top process is important to SM Higgs boson search via WH production. In particular, NLO top quark decay contribution has to be included to make more reliable background prediction

❻ LHC is a precision measurement machine for single top quark physics.

V_{tb} can be measured accurately to percentage level at initial low lumi LHC

❼ The precision measurement of W-t-b coupling can probe the new physics effects.

Use top quark polarization and W Helicity to test different models

In five years, single top physics will go from discovery to precision.

Backup slides