Top Spin Effects at Colliders

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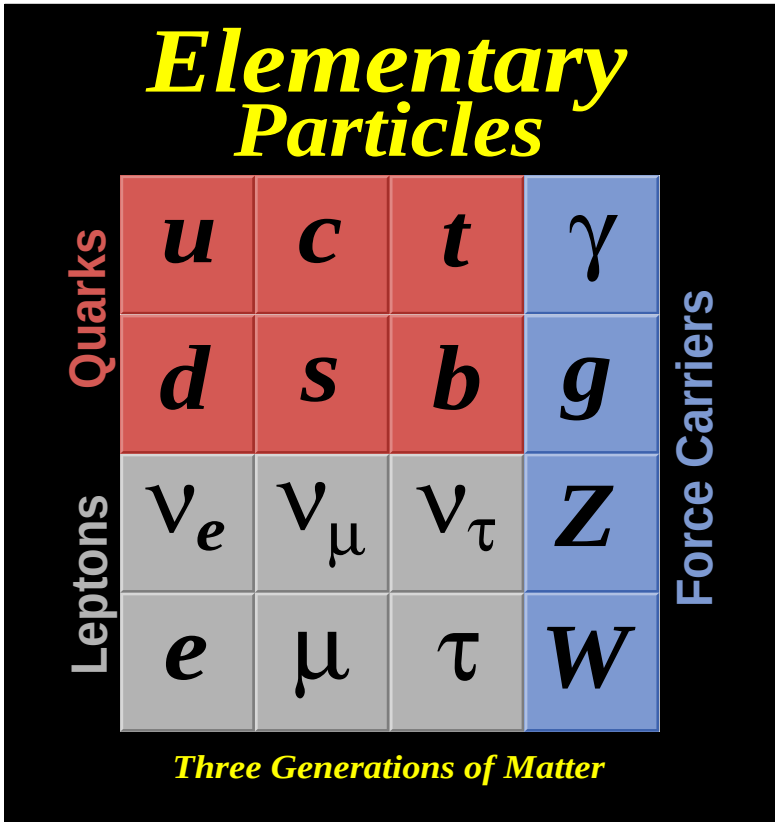
1. **Physics Issues**

2. **Theoretical Research at SDU**

Physics Issues:

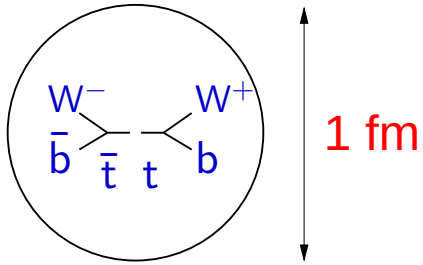


Top Quark is the heavist fundamental particle!!

Physics Issues:

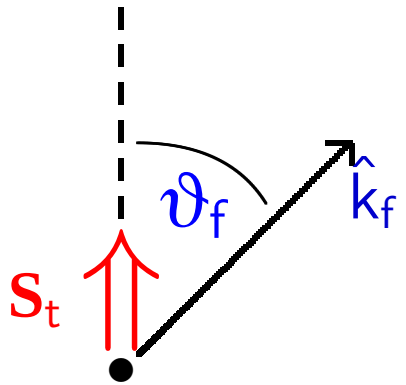
Special Characters of Top-Quarks

- **Top quark as heavy as gold atom $\leftrightarrow$ yet pointlike particle!?**
- **Strong interactions of top quarks can be reliably predicted. (asset!)**
- **Extremely instable**: Lifetime $\sim 4 \times 10^{-25}$s $\ll$ characteristic
  Hadronization time $\sim 28 \times 10^{-25}$s
  $\Rightarrow$ Top-Quark decays before hadronization!



$\Rightarrow$ **Unique opportunity to investigate interactions of a bare quark!**
$\Rightarrow$ **Top-Polarization is not 'polluted' by the hadronization process!**

- Within SM, $t \to Wb$ **parity-violating** ($V-A$ Structure as well as μ-Decay)
  $\Rightarrow$ **Top-Polarization** is transfered to its decay-products



Top-Quark Spin-Density-matrix $\rho = [\mathbb{1} + \mathbf{P}_t \cdot \sigma]/2$

Decay-product f "analyze"

Top-Quark Polarization $\mathbf{P}_t$

Within SM, $t \to W^+ b \to f + X$: $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\vartheta_f} = \frac{1}{2}(1 + \kappa_f |\mathbf{P}_t| \cos\vartheta_f)$

$-1 \le \kappa_f \le 1$ **Important Top-Spin-Analyser** (incl. QCD Corrections)

Czarnecki, Jezabek, Kühn '91

Brandenburg, Si, Uwer '02

$\Rightarrow$ **Top Quark Spin Effects can be measured**

Useful observables:

$t, \bar{t}$ polarisation and $t\bar{t}$ spin correlations

Physics Issues:

Top Quark Spin Effects are important:

- **Dynamics of top production and decay is not known very precisely so far:**

  Is $t \to b$ decay vertex really (V-A) ? New decay modes $t \to bH^+, t \to \tilde{t} + ...$, ... ?

  Exp. analyses require precise SM predictions.

- **Excellent probe of mechanism of EWSB**

  if (light) Higgs boson H will be found

  measure its Yukawa coupling(s) $y_t \bar{t} t H$

  definite prediction within SM:

  $y_t = m_t/(246 GeV) \simeq 0.7$

  Search for heavy resonances, e.g. heavy non-standard Higgs bosons, that couple strongly to $t\bar{t}$

- **Good probe for non-SM parity and/or non-SM CP violation**:

  effects could be induced, e.g., by non-standard Higgs bosons

Physics Issues:

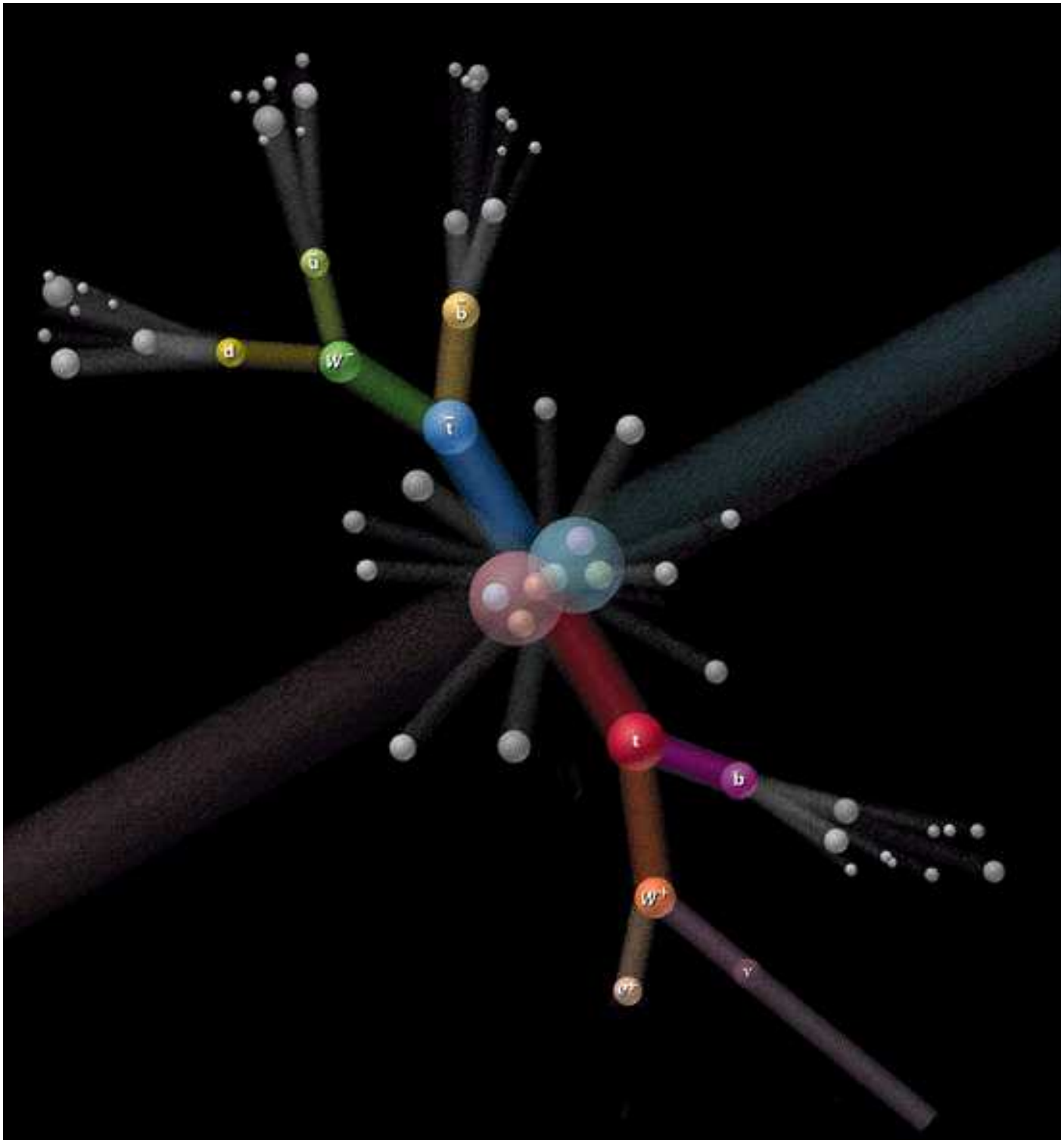
Collider	Tevatron Run 1	Tevatron Run 2	LHC	LC
Type	$p\bar{p}$	$p\bar{p}$	pp	e^+e^-
Run-time	1992-1996	2001-2008(?)	2007-?	2015(?)-?
E_{CM} (TeV)	1.80	1.96	14.0	$< 2m_t - \sim 1.0$
$\sigma(t\bar{t})$ (pb)	~ 5	~ 7	~ 800	~ 0.8
σ(single t) (pb)	~ 1	~ 1.5	~ 300	~ 0

Tevatron (Run II): $\sim 10^4/\mathrm{y}$ $t\bar{t}$ Pairs

Large Hadron Collider: $10^{7-8}/\mathrm{y}$ $t\bar{t}$ Pairs

Linear Collider: $10^5/\mathrm{y}$ $t\bar{t}$ Pairs

$t, \bar{t}$ polarization and $t\bar{t}$ spin correlations will be usefull tools to test SM and search for 'new physics' beyond SM!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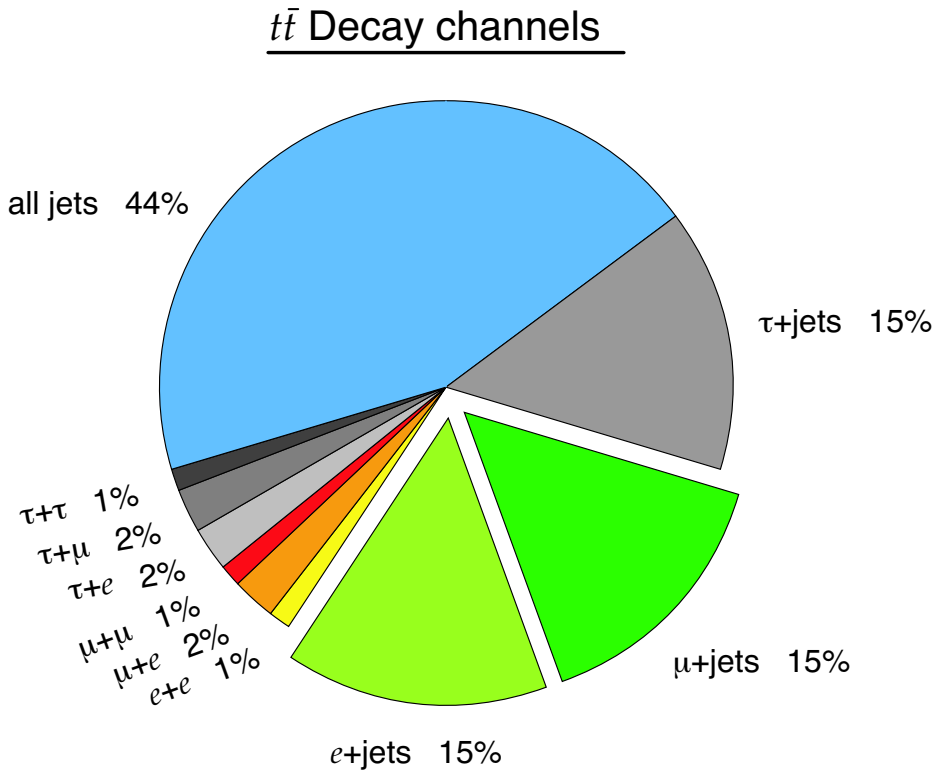
Top-Quark Production and Decay: eg.

$$p\bar{p}/(pp) \to t\bar{t}X \to bW^+\bar{b}W^- + X \to b\ell^+\nu\bar{b}\ell^-\bar{\nu} + X \to B_1\ell^+B_2\ell^- + p_T^{miss} + X$$

The distance between Top Quark Production- and Decay-verrtex is only $\sim 10^{-16}$m
$\Rightarrow$ Reconstruct Top Quark from its Decay Product!

Dilepton Channel:
$W^+ \to \ell^+\nu$, $W^- \to \ell^-\bar{\nu}$
Single Lepton Channel:
$W^+ \to \ell^+\nu$, $W^- \to d_i\bar{u}_j$
$W^+ \to u_i\bar{d}_j$, $W^- \to \ell^-\bar{\nu}$
Hadronic Channel:
$W^+ \to u_i\bar{d}_j$, $W^- \to d_i\bar{u}_j$



Investigation of Top Quark Spin-Effects

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\ \cos\theta_2} = \frac{1}{4}\Big\{1 + B_1\ \cos\theta_1 + B_2\ \cos\theta_2 - C\ \ \cos\theta_1\ \cos\theta_2\Big\}$$

$\theta_1 = \sphericalangle(\hat{\mathbf{a}}_1, \hat{\mathbf{a}})$, $\theta_2 = \sphericalangle(\hat{\mathbf{a}}_2, \hat{\mathbf{b}})$, $\hat{\mathbf{a}}, \hat{\mathbf{b}}$: interpreted as **Spin-Quantum Axis**

- B_1 and B_2 reflects top quark spin polarization
  - for pure QCD effects, only component normal to scattering plane
  - Weak int. leads to the component parrallel to scattering plane

- $\mathbf{C} = \kappa_+\kappa_- \frac{\mathbf{N}(\uparrow\uparrow)+\mathbf{N}(\downarrow\downarrow)-\mathbf{N}(\uparrow\downarrow)-\mathbf{N}(\downarrow\uparrow)}{\mathbf{N}(\uparrow\uparrow)+\mathbf{N}(\downarrow\downarrow)+\mathbf{N}(\uparrow\downarrow)+\mathbf{N}(\downarrow\uparrow)}$: $\quad -1 \le \mathbf{C} \le +1$

  Spin-Correlation Strength for Chosen Quantum Axis

- C reflects spin-spin correlations between t and $\bar{t}$
  - contr. from initial $q\bar{q}$ and gg induced by pure QCD effects have different sign $\Longrightarrow$ C can be used as a tool to determine PDF

Selected Publications

- Next-to-Leading Order QCD Corrections to Top Quark Spin Correlations at Hadron Colliders: The Reactions $q\bar{q} \to t\bar{t}(g)$, Phys.Lett.B483:99-104,2000.
- Next-to-Leading Order QCD Corrections to Top Quark Spin Correlations at Hadron Colliders: The Reactions $gg \to t\bar{t}(g)$ and $gq(\bar{q}) \to t\bar{t}q(\bar{q}$, Phys.Lett.B509:53-58,2001.
- Top Quark Spin Correlations at Hadron Colliders: Predictions at Next-to-Leading Order QCD, Phys.Rev.Lett.87:242002,2001.
- QCD Corrected Spin Analyzing Power of Jets in Decays of Polarized Top Quarks, Phys.Lett.B539:235-241,2002.
- Top Quark Pair Production and Decay at Hadron Colliders, Nucl.Phys.B690:81-137,2004.
- Top Quark Pair Production and Decay at Polarized Photon Collider, Phys. Lett. B615:68-78,2005.
- Mixed QCD and Weak Corrections to $t\bar{t}$ Production by $q\bar{q}$ Annihilation, Phys. Lett. B???,???-???,2006.

Results for Spin-Correlation at NLO QCD

$$C = \kappa_f \kappa_{\bar{f}} \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

1. $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV (Tevatron), CTEQ6, $\mu_F = \mu_R = m_t = 175$ GeV

Decay-Channel: $t\bar{t} \to$		$\ell^+ + \ell^- + X$	$\ell + \text{Jet} + X$	$\text{Jet} + \text{Jet} + X$
C_{hel}	LO	-0.471	-0.240	-0.123
	NLO	-0.352	-0.168	-0.080
C_{beam}	LO	**0.928**	0.474	0.242
	NLO	**0.777**	0.370	0.176

2. pp at $\sqrt{s} = 14$ TeV (LHC), CTEQ6, $\mu_F = \mu_R = m_t = 175$ GeV

Decay-Channel: $t\bar{t} \to$		$\ell^+ + \ell^- + X$	$\ell + \text{Jet} + X$	$\text{Jet} + \text{Jet} + X$
C_{hel}	LO	**0.319**	0.163	0.083
	NLO	**0.326**	0.158	0.076

Spin-Correlations

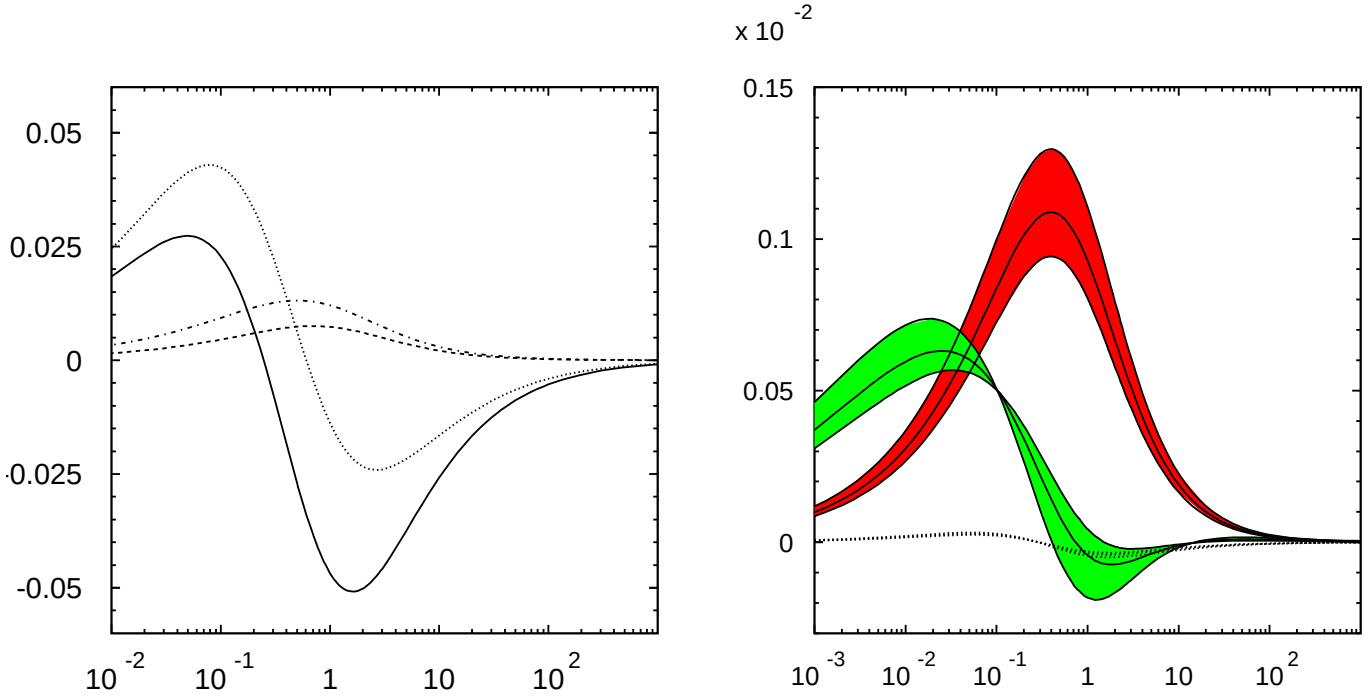
Theory:

- **Tevatron**: **Large** Spin-Correlation in **Beam basis**
  QCD Correction $\sim -$**(10-30)%**
- **LHC**: Beambasis small; **Helicity basis** good, QCD Correction **small**
- **Definite Prediction** of perturbative QCD!
- **Theoretical Uncertainty**
  Variation of Renormalization- and Factorization-scale $m_t/2 \leq \mu \leq 2m_t$:
  Tevatron: $\Delta C_{beam} \sim \pm 5\%$ LHC: $\Delta C_{hel} \lesssim 1\%$

Experiment:

- Tevatron (Run II):
  SM-Spin-Correlationen as 2σ Effect
- LHC: $\Delta_{exper.} C \sim 0.03$
  $\Rightarrow$ **Test Spin-correlationen within SM**
  $\Rightarrow$ **Top-Quark $\sim$ "bare" Quark**

Results for Top quark polarization



Left:*Scaling functions* $f^{(0)}(\rho)_{q\bar{q}}$ *(dashed for* $q = d$*-type, dash-dotted for* $q = u$*-type);* $f^{(1)}(\rho)_{q\bar{q}}$ *(solid for* $q = d$*-type, dotted for* $q = u$*-type),* **Right**:*Contributions of the LO (solid) and NLO QCD (dashed) contributions and of the mixed* $\alpha_s^2\alpha$ *contributions (dotted and dash-dotted line refers to initial d-type and u-type quarks, respectively) to the cross section in units of* $1/m_t^2$*, and* m_H *= 114 GeV.*

Results for Top quark polarization

Results for $\sigma_{q\bar{q}}$ at NLO

Tevatron		$\mu = \frac{m_t}{2}$(pb)	$\mu = m_t$(pb)	$\mu = 2m_t$(pb)
CTEQ6L	LO QCD	4.808	3.622	2.836
CTEQ6.1M	NLO QCD	4.148	3.976	3.681
	LO QCD	4.568	3.396	2.629
	Mixed	0.0434	0.0401	0.0367
LHC CTEQ6L	LO QCD	53.733	45.913	40.168
CTEQ6.1M	NLO QCD	51.589	55.738	57.559
	LO QCD	59.078	50.296	43.858
	Mixed	-0.641	-0.444	-0.305

Results for $2\sigma_{q\bar{q}} < \mathbf{s}_t \cdot \mathbf{p} >$ at Tevatron($\sqrt{s} = 1.96$TeV) and $2\sigma_{q\bar{q}} < \mathbf{s}_t \cdot \mathbf{k} >$ LHC($\sqrt{s} =$ 14TeV).

Tevatron		$\mu = \frac{m_t}{2}$(pb)	$\mu = m_t$(pb)	$\mu = 2m_t$(pb)
CTEQ6.1M	Mixed	-0.00291	-0.00374	-0.00406
LHC CTEQ6.1M	Mixed	-0.0687	-0.0758	-0.0804

Works in Progress

- Mixed QCD and Weak Corrections to $t\bar{t}$ Production by $gg \longrightarrow t\bar{t}$
- The influence of invariant mass cuts
- Threshold Resummation

works in plan

Window to search for 'new' Physics

- **Search for Resonance in $t\bar{t}$ invariant mass spectrum**
- **Search for new particle in Top-Decay**
- **Search for Effects with small contributions from SM**

Top-Quark Physics will play an important role in particle physics!

Thanks a lot for your attention!