Single Top Polarization at LHC

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Outline:

- Processes of single t-quark production at LHC
- Best spin decompose axis of t-quark in W^*-process and W-g fusion
- Improve of top spin measurement in tW-process
- Conclusion

Single top quark processes at LHC

There are three SM processes of single t-quark production at LHC:

▼ W^*-process (s-channel, $Q_W^2 > 0$) :

- $pp \to t, \bar{b}$
- $\sigma_{full}(t\ and\ \bar{t}) = 10.2 \pm 0.7$ pb at NLO.

▼ W-g fusion (t-channel, $Q_W^2 < 0$):

- $pp \to j, t, \bar{b}$
- $\sigma_{full}(t\ and\ \bar{t}) = 245 \pm 27$ pb at NLO.

▼ Wt-process (associated production, $Q_W^2 = m_W^2$):

- $pp \to t, W^-$
- $\sigma_{full}(t\ and\ \bar{t}) = 62.0^{+16.6}_{-3.6}$ pb at LO.

Main production vertex in the processes is Wtb-vertex with (V-A) structure. So one could wait top quark has high degree of polarization. $\Rightarrow$ How can we to measure top polarization?

Theory of spin in top quark production

Ordinary formalism of helicity amplitudes is not best for description of top quark spin, because of chiral and helicity states don't coincide.

Spin vectors formalism is based on operator $O_{MW} = -\gamma^5\gamma^\mu s_\mu$, where spin vector s_μ

$$s_\mu = \left(\frac{(\bar{\xi}\bar{p})}{m}, \bar{\xi} + \frac{(\bar{\xi}\bar{p})\bar{p}}{m(E+m)}\right)$$

Calculation technique: one can to decompose spin matrix of nonpolarized fermion to sum of two polarized states along and opposite a spin decompose axis $\bar{\xi}$

$$P_{full} = p^\mu\gamma_\mu + m \quad \rightarrow \quad S_- + S_+, \quad S_\pm = \frac{1}{2}(p_t^\mu\gamma_\mu + m_t)(1 \pm \gamma^5 s_t^\mu\gamma_\mu)$$

Squared matrix element, where $P_{full} \rightarrow S_\pm$, describes production of top quarks with spin polarization $\pm 1/2$.

Spin axis $\vec{n}_d^*$ in W^*-process[a]

One can decompose matrix element to sum

$$M(u\bar{d} \to t\bar{b}) = M(+,\vec{\xi}) + M(-,\vec{\xi})$$

▼ $\vec{\xi}$ – spin decompose axis (in the top rest frame!)

▼ $M(\pm,\vec{\xi})$ – matrix element with polarization $\pm 1/2$.

If $\vec{\xi} = \vec{n}_{\bar{d}}^*$ – direction of $\bar{d}$-quark momentum in top rest frame

$$M(-,\vec{\xi} = \vec{n}_{\bar{d}}^*) \equiv 0$$

Interpretation: t-quarks produced in $u\bar{d} \to t\bar{b}$ process are polarized along $\vec{n}_d^*$ direction

Connection: $M(u\bar{d} \to t\bar{b}) = M(t \to b + e^+\nu)$ and $\bar{d}$-quark is analogue of e^+ from top decay.

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[a]On base of articles of G. Mahlon and S. Parke:
Phys. Rev. **D55** (1997) 7249., Phys. Lett. **B476**, (2000) 323

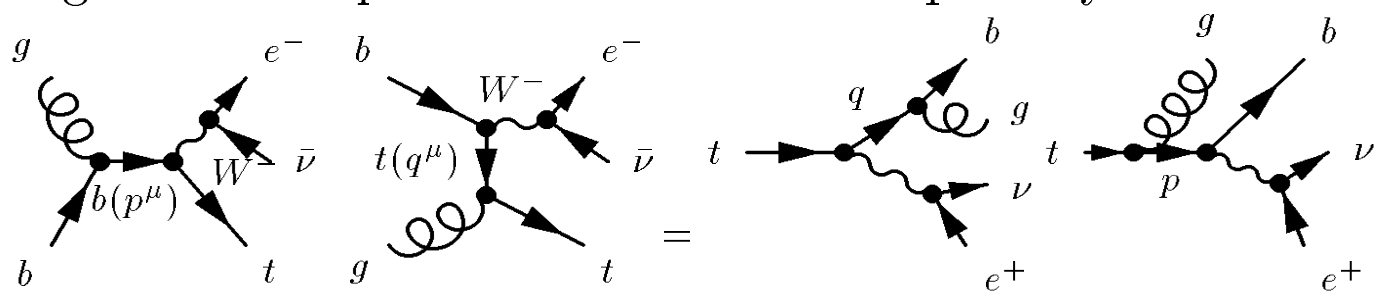
Spin axis $\vec{n}_d^*$ in W-g fusion

The process has 2 diagrams (in $2 \to 3$ approach):

▼ 1st diagram with Wtb-vertex of top production $\to \vec{s}_t \uparrow\uparrow \vec{n}_d^*$.

▼ 2nd diagram with gtt-vertex of top production $\to$ top is nonpolarized.

Two diagrams are equivalent to radiative top decay $t \to be^+\nu + g$



♦ $|M_{Wtb}|^2 \gg |M_{gtt}|^2$ in production kinematical region.

♦ $M_{Wtb} \otimes M_{gtt}$ interference behaves as $|M_{Wtb}|^2$.

Thus top quark possesses high polarization.

Spin asymmetry R_{spin} in W-g fusion

Definition of spin asymmetry in single top processes

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{\bar{\xi},e^+}} = \frac{1 + R_{spin} cos\theta_{\bar{\xi},e^+}}{2}$$

♦ R_{spin} is function of top quark spin decompose axis $\bar{\xi}$.

♦ There is connection between R_{spin} and $N_+(N_-)$ – number of events with top quark polarized along (opposite) spin decompose axis.

$$R_{spin} = (N_+ - N_-)/(N_+ + N_-)$$

For instance, in W-g fusion

$$R_{spin}(\bar{\xi} = \vec{n}^*_d) = 0.89\ (89\%)^{\mathrm{a}}$$

It means 94,5%(5,5%) of t-quarks in W-g fusion are polarized along (opposite) $\vec{n}^*_d$.

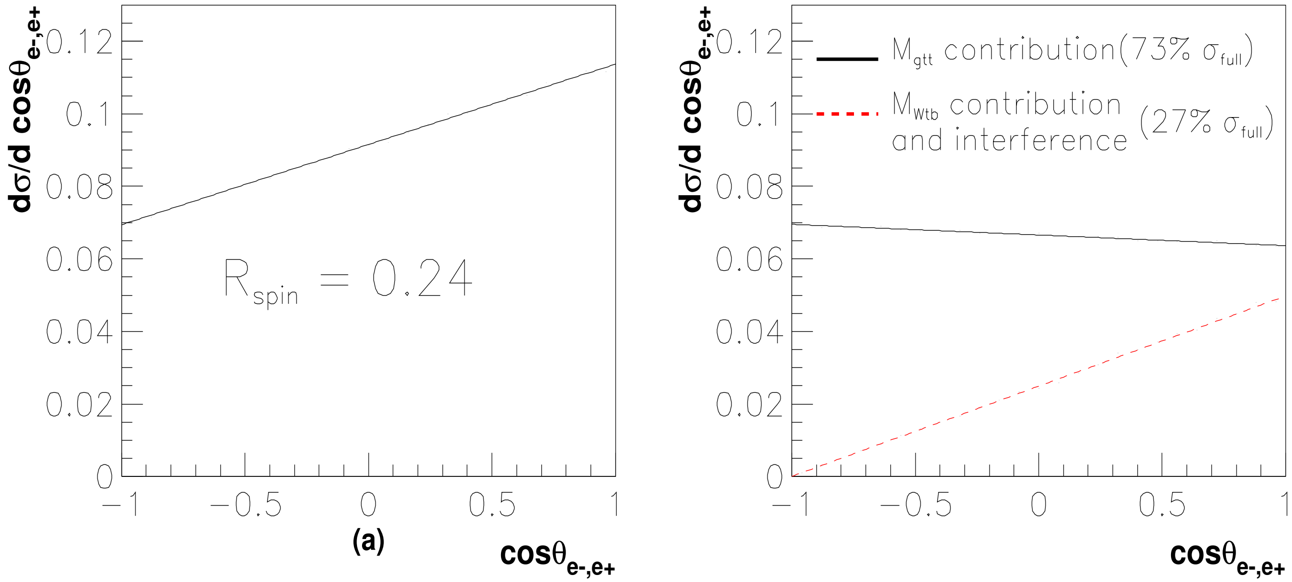
[a] G. Mahlon and S. Parke, Phys. Lett. **B476**, (2000) 323

tW-process atLHC

▼ 1st diagram with Wtb-vertex of top production $\rightarrow \vec{s}_t \uparrow\uparrow \vec{n}^*_{e^-}$

▼ 2nd diagram with gtt-vertex $\rightarrow$ top is nonpolarized

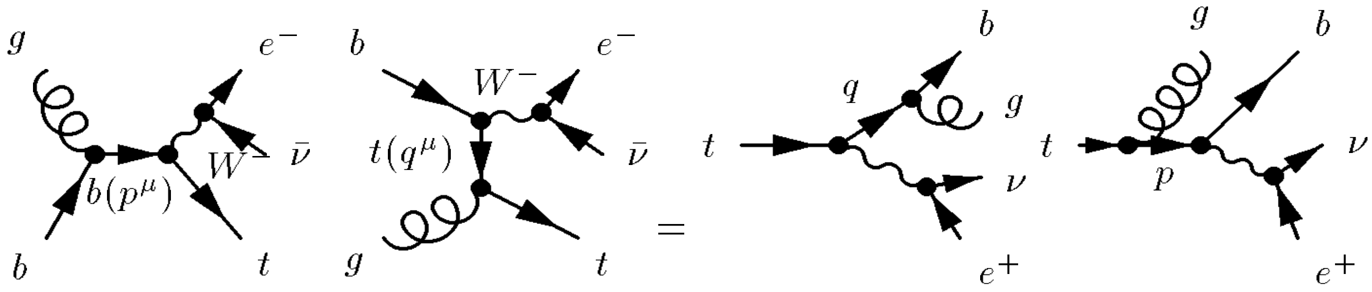
But$|M_{Wtb}|^2 \sim |M_{gtt}|^2$ in a production kinematical region $\Rightarrow$ top quark spin polarization is less visible...



Distribution $d\sigma/\cos\theta^*_{e^+,e^-}$ for process $pp \rightarrow t, W^- \rightarrow (e^+, \nu, b) + (e^-, \bar{\nu})$

So one needs to find some methods to increase R_{spin} (or degree of top polarization) for spin axis $\vec{n}^*_{e^-}$

Increase of R_{spin} of t-quark, 1st method



Using equivalence between tW-process and top decay $t \to e_+ \nu b$, one can to calculate $|M(-, t \to b e^+ \nu + g)|^2$ for the diagram with gtt-vertex in top quark rest frame:

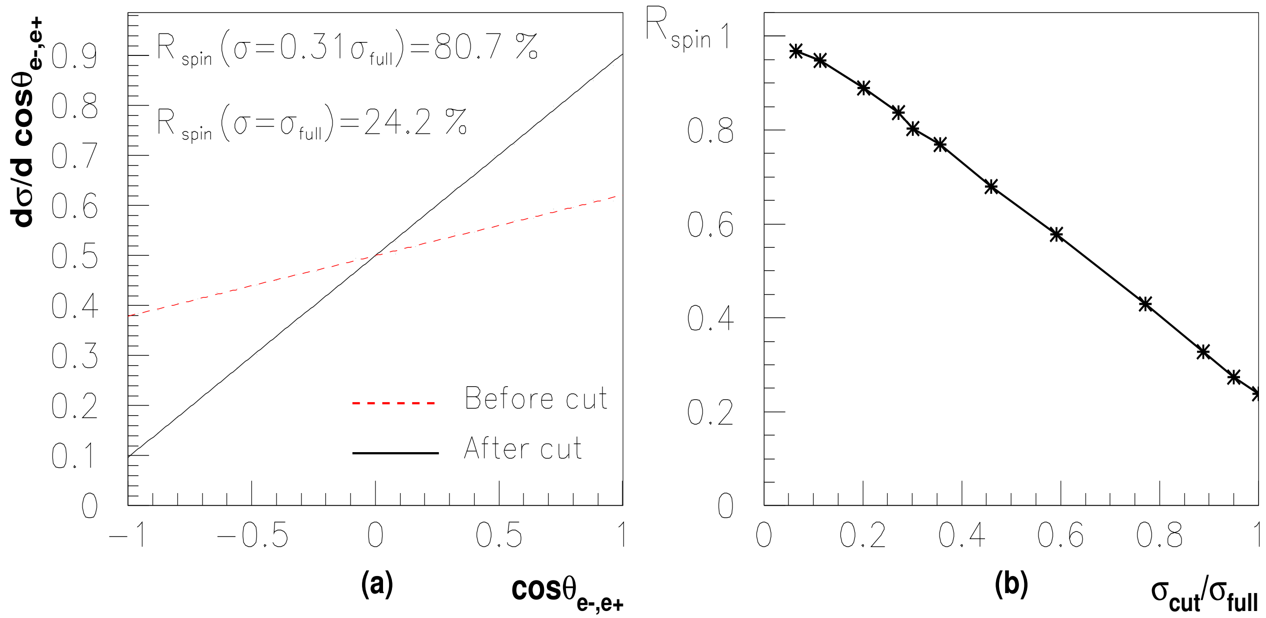
$$|M|^2 = \frac{2\, g_s^2\, g^2 |V_{tb}|^2}{(w^2 - m_W^2)^2 + (m_W \Gamma_W)^2} \, \frac{1}{(t \cdot g)^2} \, (b{\cdot}\nu) \Big[m_t E_e^* E_g^{*2} (1 - \vec{n}_e^* \vec{n}_g^*)^2 \Big]$$

So E_e^*, E_g and $\vec{n}_e^* \vec{n}_g^*$ are convenient variables for cutting of the events, containing top quark with the polarization $\vec{s}_t \uparrow\downarrow \vec{n}_{e^-}^*$.

We have found the best combination of them for the cut

$$X_{g,e^-} = E_g^* \cdot (1 - \vec{n}_e^* \vec{n}_g^*)$$

Increase of R_{spin} of t-quark, 1st method



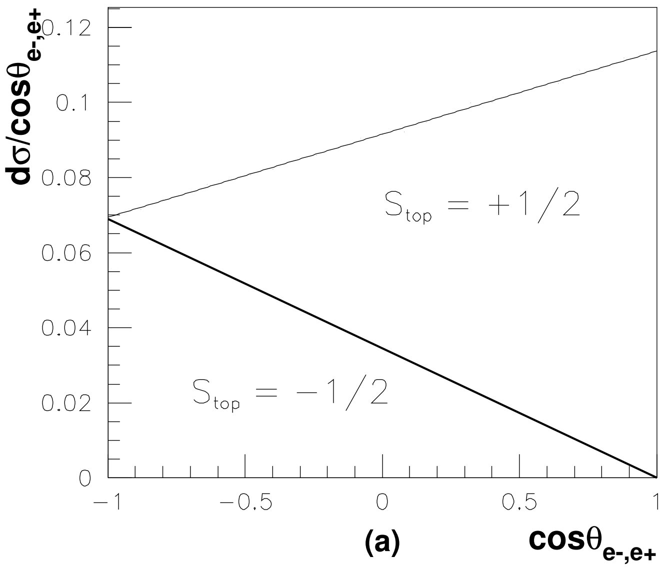
- plot (a): normalized distributions $\frac{1}{\sigma}\frac{d\sigma}{\cos\theta^*_{e^+,e^-}}$ for event without cuts (dash line) and with cut $X_{g,e^-} < 110\ GeV$.
- plot (b): Spin asymmetry R_{spin} vs. the fall of the cross section of tW-process for the cut X_{g,e^-}.

Increase of R_{spin} of t-quark, 2nd method

Distribution $d\sigma/\cos\theta^*_{e+,e-}$ is sum two ones for events with top polarized along $\vec{n}^*_{e-}$ (N_+) and opposite $\vec{n}^*_{e-}$ (N_-). They have a peak near different value of $\cos\theta^*_{e+,e-}$.

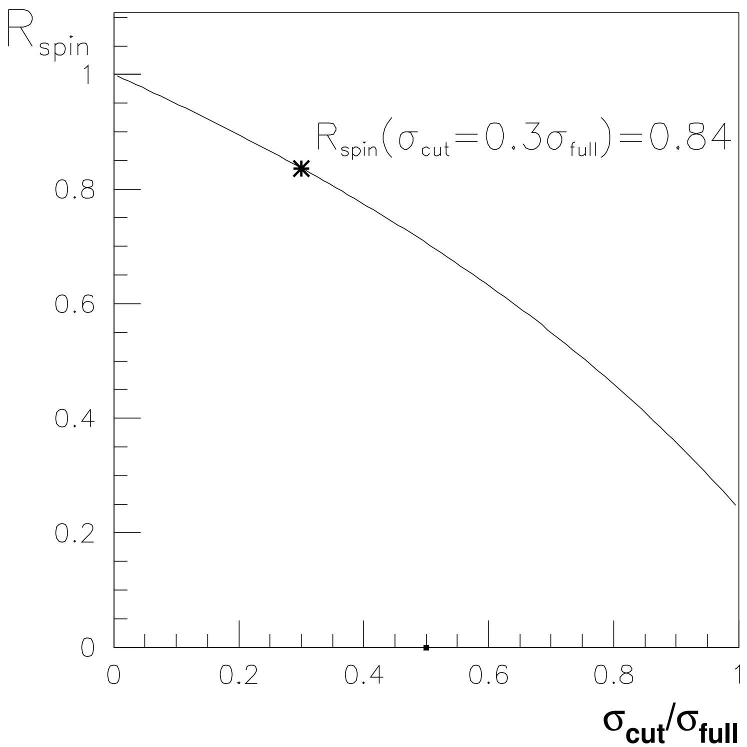
▼ events with $\vec{s}_t \uparrow\uparrow \vec{n}^*_{e-}$ $\rightarrow$ peak near $\cos\theta^*_{e+,e-} = 1$

▼ events with $\vec{s}_t \uparrow\downarrow \vec{n}^*_{e-}$ $\rightarrow$ peak near $\cos\theta^*_{e+,e-} = -1$



So appropriate variable for the cut is $\cos\theta^*_{e+,e-}$ itself.

Increase of R_{spin} of t-quark, 2nd method



- R_{spin} vs. the fall of the tW-process cross-section of tW-process for the cut $\cos\theta^*_{e-,e+}$
- Point, where $\sigma_{cut} = 0.3\sigma_{full}$, corresponds to the cut $\cos\theta^*_{e-,e+} > 0.86 \quad \Rightarrow \quad R_{spin} = 84\%$

Conclusions

▼ Application of generalized description of top spin allows to measure top polarization more effectively then in the helicity ideology. Especially in W^*-process and W-g fusion.

▼ Theoretical analysis also shows the possibility of the top polarization extraction in tW-process. But one requires special methods for its measurement. Our cut methods allow to increase R_{spin} to ~ 3.5 times at $\sigma_{cut} \simeq 0.3\sigma_{full}$ level.

▼ We have done theoretical analysis without consideration problem concerning phenomenological problem (quest of top rest frame, reconstruction neutrino momentum and so on). Next step is full phenomenological analysis, probably, with full simulation chain:

$$\text{CompHEP} \to \text{PYTHIA} \to \text{CMSIM} \to \text{ORCA}$$