Helicity dependencies in jet substructures for boosted top quarks

Y. Kitadono, H.n. Li,
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– Theory and Experiment in Bari
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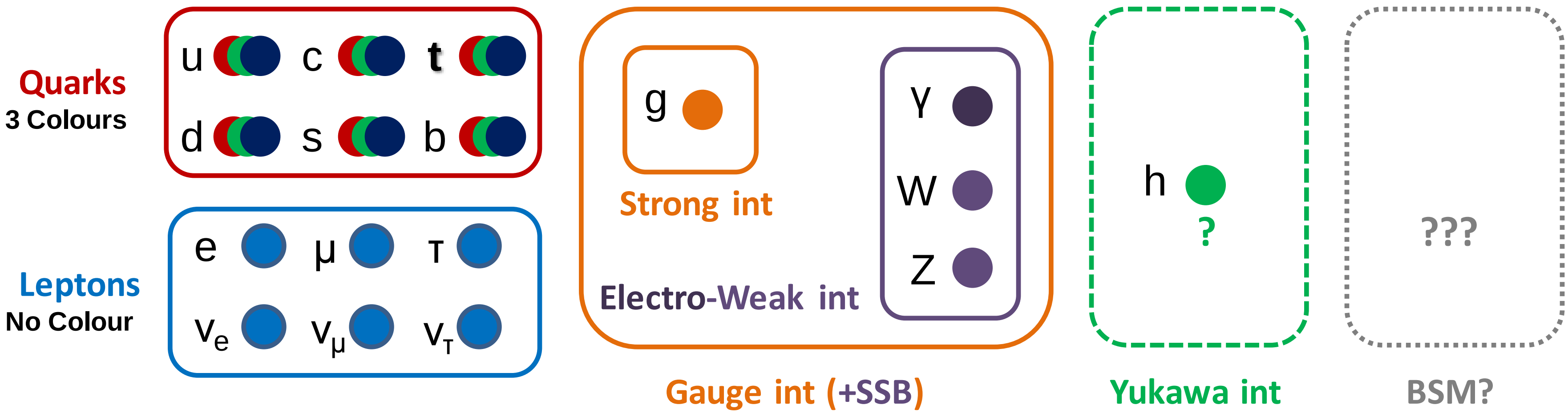
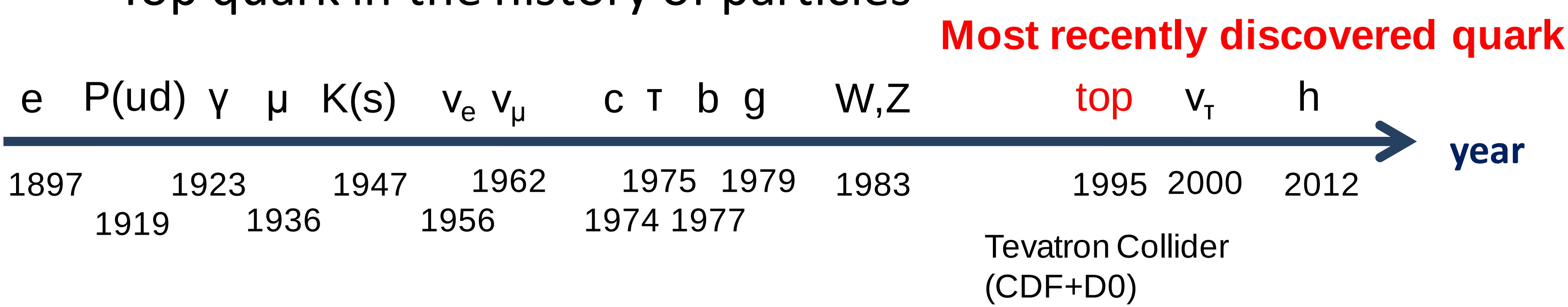
1. Introduction

- Top quark in the Standard Model(SM)



- Top quark in the history of particles



Unique Nature of Top Spin

- Top decay (100% t → bW)

$$\Gamma(t \to bW)_{\rm SM} = \frac{G_F m_t^3 |V_{tb}|^2}{8\pi\sqrt{2}} \simeq 1.5\ \text{GeV} > \Lambda_{\rm QCD} \simeq 0.2\ \text{GeV}$$

life time vs. Hadronisation time

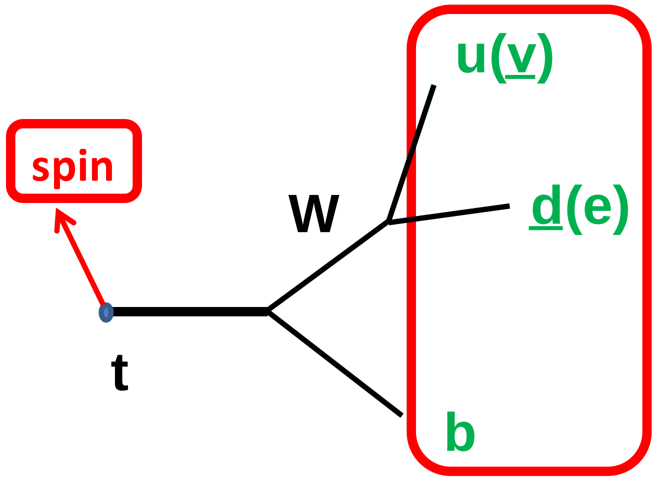
$$\tau_{\rm top} = 1/\Gamma < \tau_{\rm had} = 1/\Lambda_{\rm QCD}$$

- Top decays before the hadronisation:

angles, energy distribution reflects the information of the “bare top quark”.

Measurement of bare quark indirectly

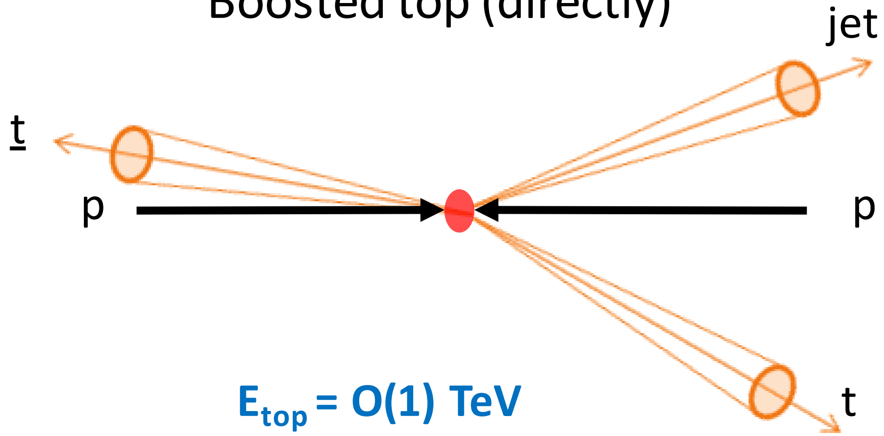
(different from other quarks !)

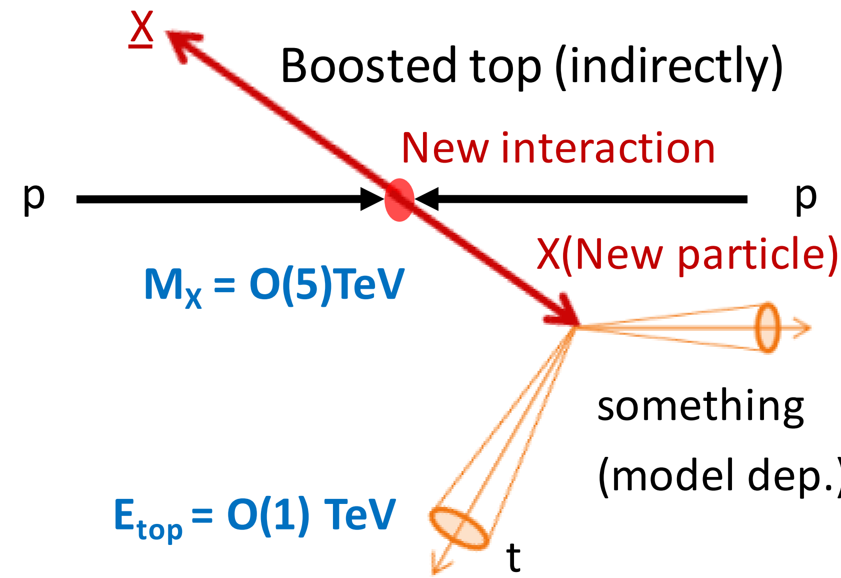


Boosted top and jet substructure

- At LHC(7-14 TeV), even heavy particles (W,Z,h,top...) can be produced with a large velocity = boosted W,Z,h,top...

Boosted top (directly)

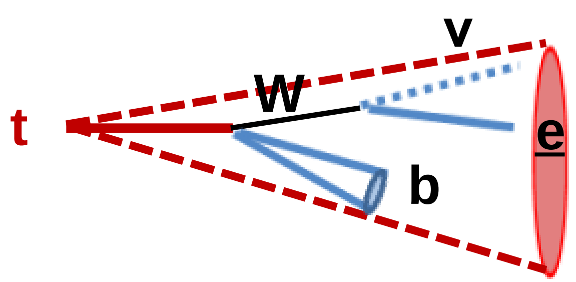




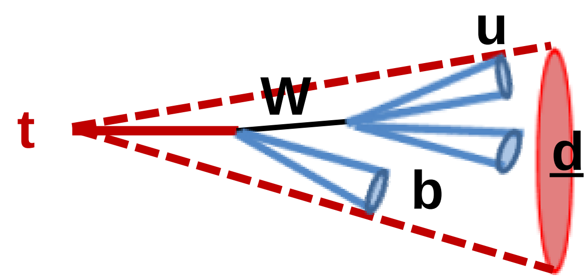
- Boosted top search is important both for SM and BSM

(our result is within SM, but possible to extend it to BSM)

- Decay particles from boosted top collimated in a cone.
  In such case, difficult to distinguish them from background



leptonc top decay (1-jet)
No isolated lepton !



hadronic top decay (3-jets)
Collimated jet structure !

- We need more information about jets, especially inside of jets.

Take a look at detail in the jet

= Study of the Jet Substructure !

Motivation of this work

- Highly boosted particles:

→ 1) **Helicity** is better than spin

2) **Helicity** coincides with **Chirality**

We can expect something about the relation between helicity and its jet substructures.

- Can we distinguish the helicity of top quark with jet substructures ?

Is there difference between (h=+) and (h=-) in top jet substructure ?

→ If there is, useful for distinguishing the helicity.

*) We may study the general Chiral structure of top quark

$$\mathcal{M}_{tbw} \;=\; \frac{g}{\sqrt{2}}\epsilon^{*\mu}\bar{b}\left[(V_{tb}^{*}+f_L)\gamma_\mu P_L + f_R\gamma_\mu P_R + i\sigma_{\mu\nu}q^{\nu}(g_L P_L + g_R P_R)t\right]$$

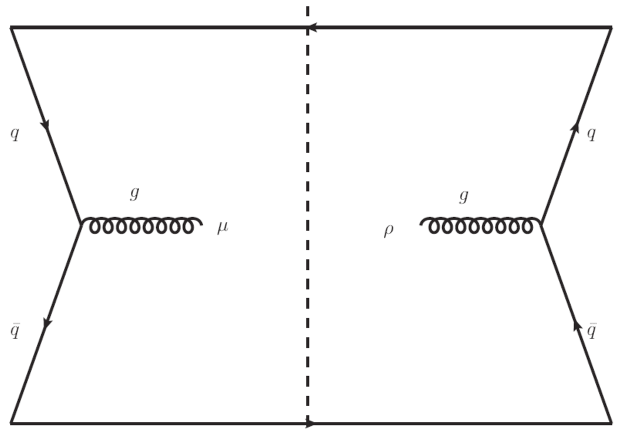
with the jet substructures.

2. Factorisation and spin decomposition

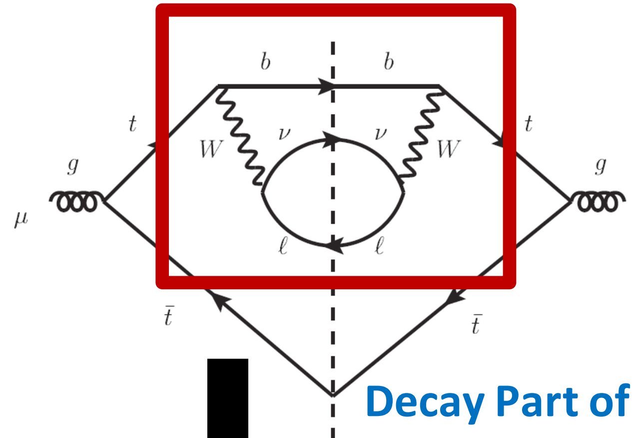
- Consider $q\bar{q} \to t\bar{t}$ as am example for our case:

$$\left|\overline{\mathcal{M}}\right|^2 =$$

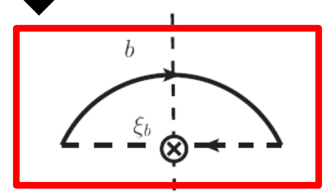
Total

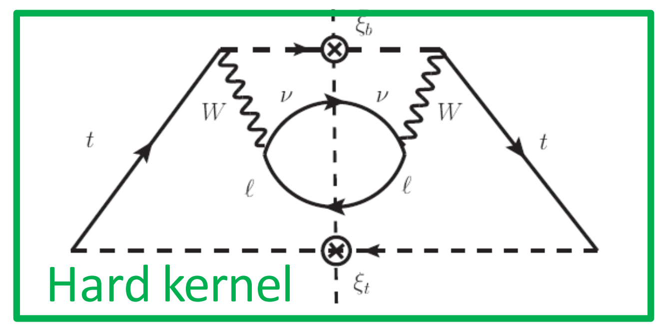


Production Part



Decay Part of Top (semi-leptonic)





- Factorisation of t,b jets and spin decomposition

Anti-top → a part of production

top → a part of decay

bottom → b-jet function (replaced with resummed one)

Unpol. top → $\frac{1}{2}(\mathbf{1} + \gamma^5 \not{s}_t) + \frac{1}{2}(\mathbf{1} - \gamma^5 \not{s}_t)$

- Factorised cross section (t-jet mass distribution)

$$\sigma(q\bar{q} \to t\bar{t}) = \sigma^{s_t} + \sigma^{\bar{s}_t} \qquad J_t = J_t^{s_t} + J_t^{\bar{s}_t}$$

Decomposition of two spin states

$$\frac{d\sigma^{s_t}}{dm^2_{J_t}} = \sigma_{pro}(E_{J_t}, \cos\theta_{J_t}) J_t^{s_t}(m^2_{J_t}, E_{J_t}) \mathrm{dPS}_{t\bar{t}},$$

Hard part — top-jet function — Phase space

- Normalised mass distribution

depends on only top-jet function

$$\frac{1}{\sigma}\frac{d\sigma^{s_t}}{dm^2_{J_t}} = \frac{J_t^{s_t}(m^2_{J_t})}{\int dm^2_{J_t} J_t(m^2_{J_t})}, \qquad \frac{1}{\sigma}\frac{d\sigma^{\bar{s}_t}}{dm^2_{J_t}} = \frac{J_t^{\bar{s}_t}(m^2_{J_t})}{\int dm^2_{J_t} J_t(m^2_{J_t})},$$

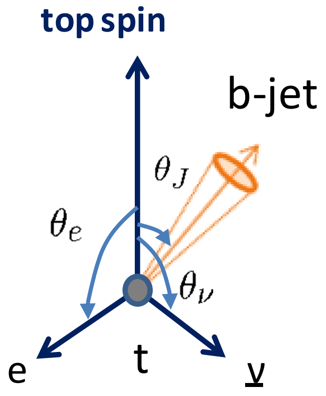
- Polarised top-jet function (at rest frame of top)

$$J_t^{s_t}(m^2_{J_t}) = \bar{f}_t(\xi_t) \int dz_b dx_{J_b} d\cos\theta_{J_b} \times [F_a(\xi_t, x_{J_b}, z_{J_b}) + |\vec{s}_t| F_b(\xi_t, x_{J_b}, z_{J_b}) \cos\theta_{J_b}] J_b(m^2_{J_b}, x_{J_b}, z_{J_b})$$

$$F_a(\xi_t, x_{J_b}, z_{J_b}) = \sqrt{\xi_t} x_{J_b} \beta_{J_b} f_W(\xi_t, x_{J_b}, z_{J_b}) \left[-\frac{1}{3}x^2_{J_b} + \frac{1+z_b}{2}x_{J_b} - \frac{2}{3}z_{J_b}\right],$$

$$F_b(\xi_t, x_{J_b}, z_{J_b}) = f_W(\xi_t, x_{J_b}, z_{J_b}) \left[-\frac{1}{3}x^3_{J_b} + \frac{1+3z_b}{6}x_{J_b} + \frac{4}{3}z_{J_b}x_{J_b} - \frac{2}{3}z_{J_b}(1+3z_{J_b})\right]$$

$$\xi_t = \frac{m^2_{J_t}}{m^2_t}, \quad x_{J_b} = \frac{2E_{J_b}}{m_{J_t}}, \quad z_{J_b} = \frac{m^2_{J_b}}{m^2_{J_t}}, \quad \eta_t = \frac{\Gamma_t}{m_t}, \quad \xi = \frac{m^2_W}{m^2_{J_t}}, \quad \eta = \frac{\Gamma_W}{m_W}$$

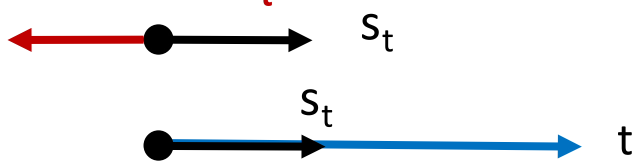


- **Helicity** (h = plus or minus) and **Boost** from Lorentz transformation

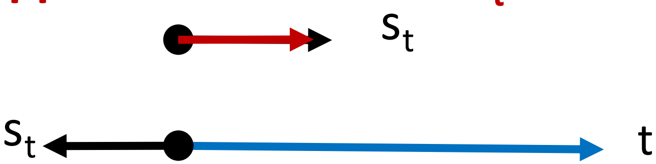
$$s_t^\mu = (0,0,0,1)$$ **Z axis = top spin direction**

J. Shelton,
PRD 79, 014032 (2009)

Boost frame v_t



Opposite Boost frame v_t



t-jet axis = t spin: **h = plus**

t-jet axis = - t spin: **h = minus**

For top

$$\begin{pmatrix} \bar{E}_t \\ \bar{k}_t^z \end{pmatrix} = \gamma_t \begin{pmatrix} 1 & v_t \\ v_t & 1 \end{pmatrix} \begin{pmatrix} m_{J_t} \\ 0 \end{pmatrix} = \gamma_t m_{J_t} \begin{pmatrix} 1 \\ v_t \end{pmatrix}$$

For bottom

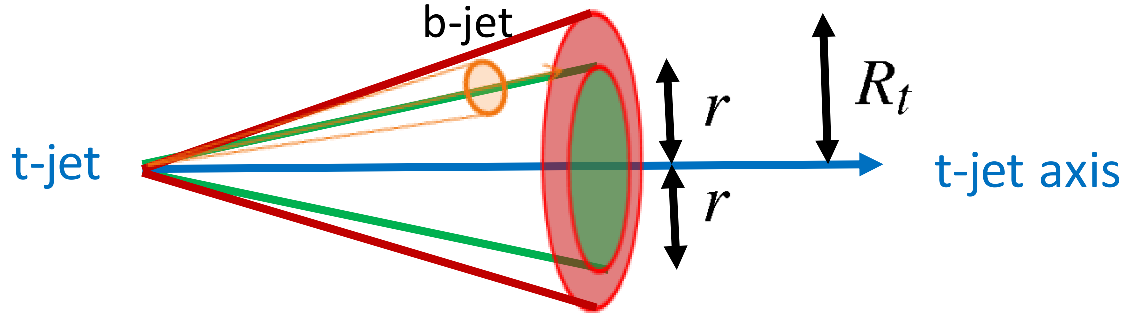
$$x_{J_b} = 2\gamma_t^2 \bar{x}_{J_b}(1 - v_t \cos\bar{\theta}_{J_b}),$$

$$\cos\theta_{J_b} = \frac{-v_t + \cos\bar{\theta}_{J_b}}{1 - v_t \cos\bar{\theta}_{J_b}}.$$

We know the relation between rest frame and boost frame.

Jet energy profile (jet substructure)

- Consider a small cone (angle r: $0 < r < R_t$) in top-jet.
  Accumulate the sub-jet energy in the small cone.



$$\text{Ratio}(E_{J_t}, R_t, r) \equiv \frac{\text{Jet (transeverse) energy in cone } r}{\text{Jet (transverse) energy in cone } R_t}$$

(Jet energy profile)

- This ratio describe a "spread" of the accumulation of the sub-jet energy in the small cone r.

3. Results (energy profile of top jets)

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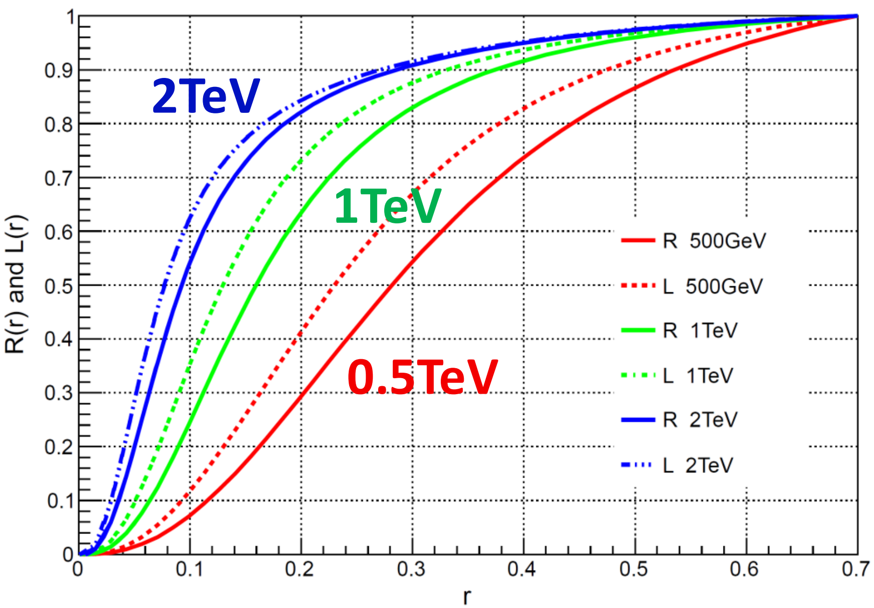
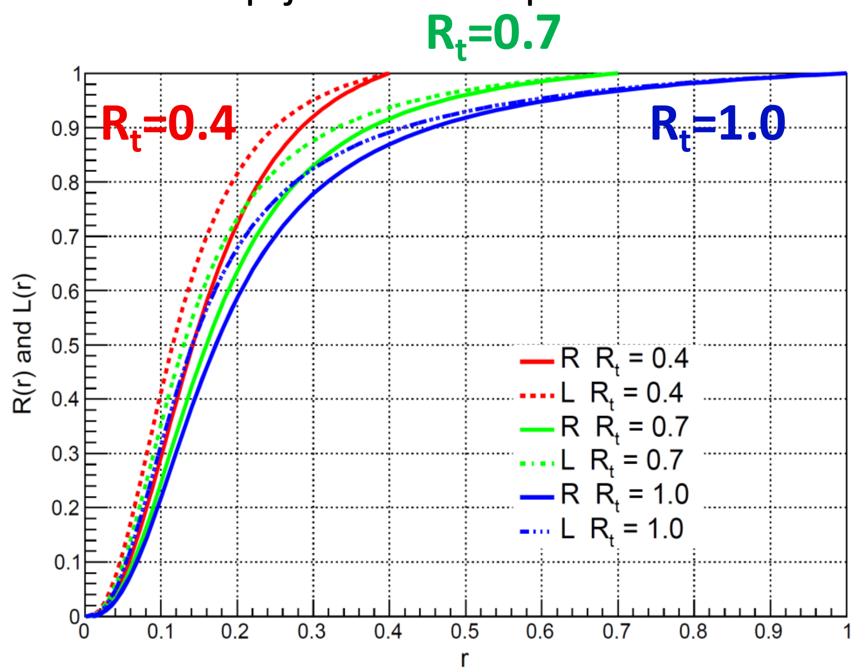
Top-jet energy dependence



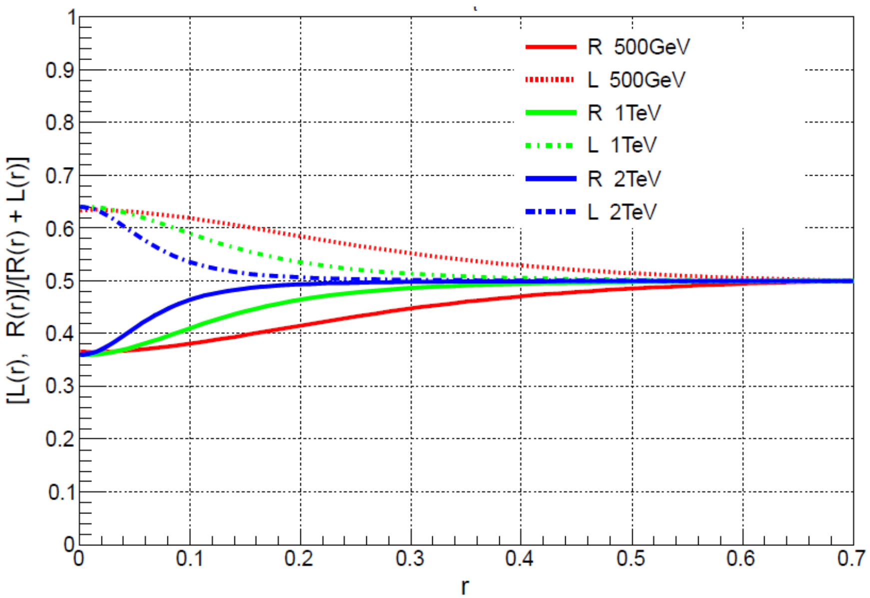
Top-jet radius dependence



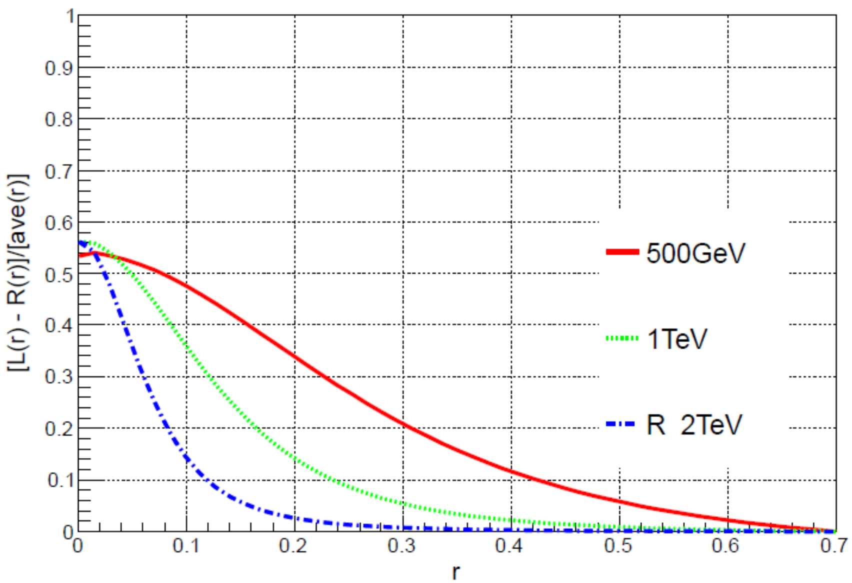
- b-jet energy profile = LO*Sudakov factor
- Left > Right tendency (L is faster than R) again.
- |L-R| deference decrease as E_{jt} increase.
- Top-jet radius dependence is not so large.

Left-Right difference (Ratio)

Ratio of R(L) in total (R+L)



Ratio of (L-R)/average, average=(R+L)/2



- L-R difference is large at small r region (r < 0.2)
- (L-R)/average is about 30(10)% at r=0.1 for 1(2)TeV top jet.
- |L-R| deference decrease as E_{jt} increase again.
- This difference comes from V-A structure of weak interaction.

Discussion

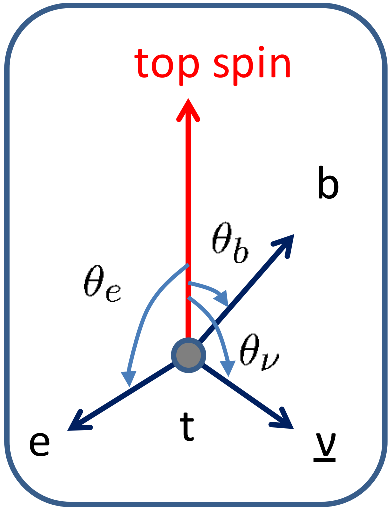
- Why **Left (h=minus)** is larger than **Right (h=plus)** ?

→ Angular distribution obeys **V-A interaction**

- Let's start with top spin (spin analysing power κ_i) at the rest frame of top.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 + \underline{\kappa_i}\cos\theta_i) \qquad \langle\cos\theta_i\rangle = \frac{\kappa_i}{3}$$

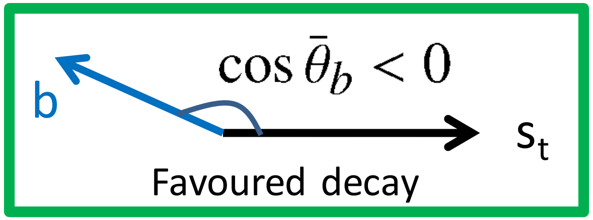
Spin analyzing power

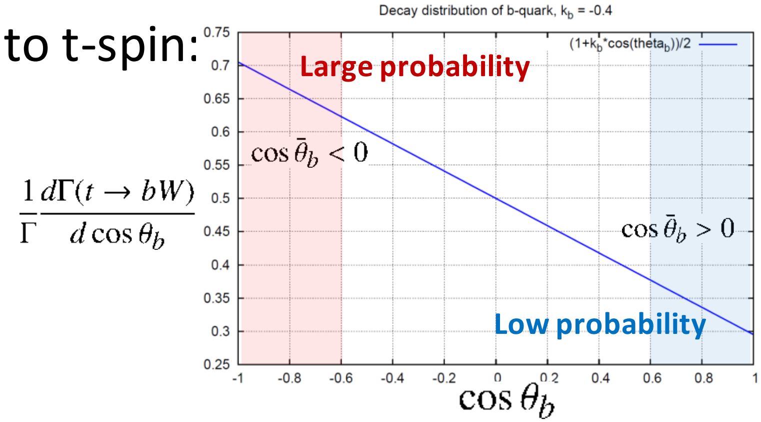


	lep	d	u	b	J_{least}	J_{thrust}
κ_i	0.999	0.97	-0.31	**-0.37**	0.47	-0.31

Brandenburg,Si,Uwer (2002),
Fisher,Groote,Koerner,Mauser,Lampe (1999).

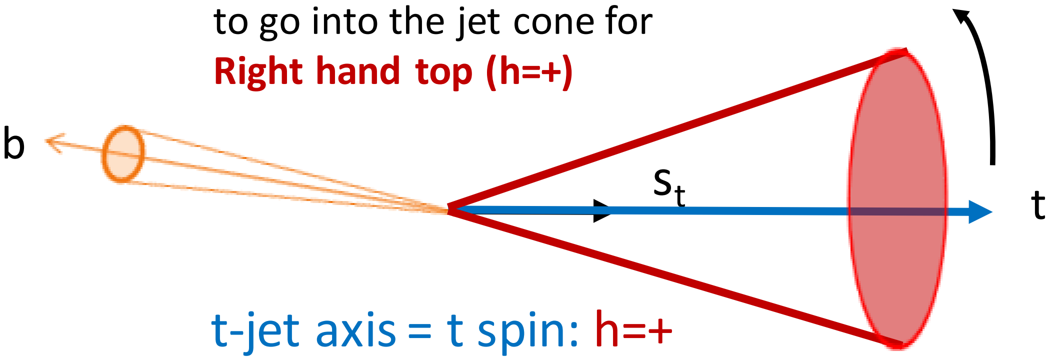
- So b-quark tends to go to opposite direction to t-spin:





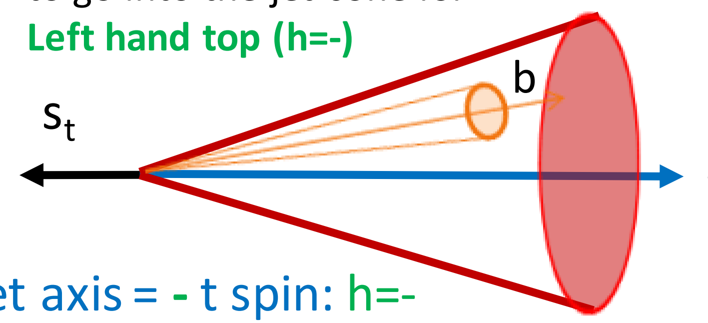
- Small (or middle) boost for top quark:

b-quark has a smaller chance to go into the jet cone for **Right hand top (h=+)**



t-jet axis = t spin: h=+

b-quark has a larger chance to go into the jet cone for **Left hand top (h=-)**

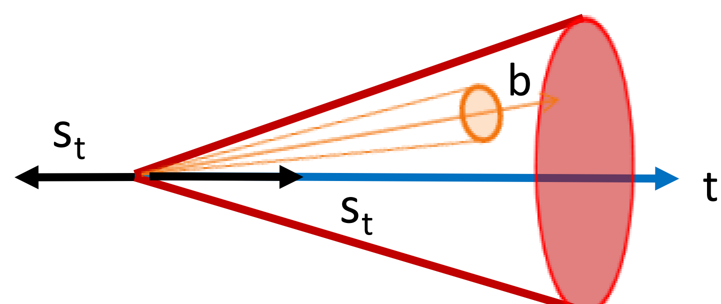


t-jet axis = - t spin: h=-

- Large boost for top quark:

Both R and L go into the jet cone

→ **No difference between R and L for favoured angle of b-quark**



Summary

- Helicity/Chirality dependence of jet substructure for polarised t-jet.
- pQCD factorisation and (partially) resummation effects.
- R(h= +),L(h= -) dependence on energy profile of top jet.
- Energy profile of L(helicity -) top jet is larger than R(helicity +) top jet.
- Top jet substructure is useful to study of helicity (Chirality) of top.

Future work:

- Application of our formalism to hadronic decay process.
- R, L dependence in other jet observables.
- Generalised top vertex or BSM (charged Higgs, W', …) can be taken into account in our formalism.