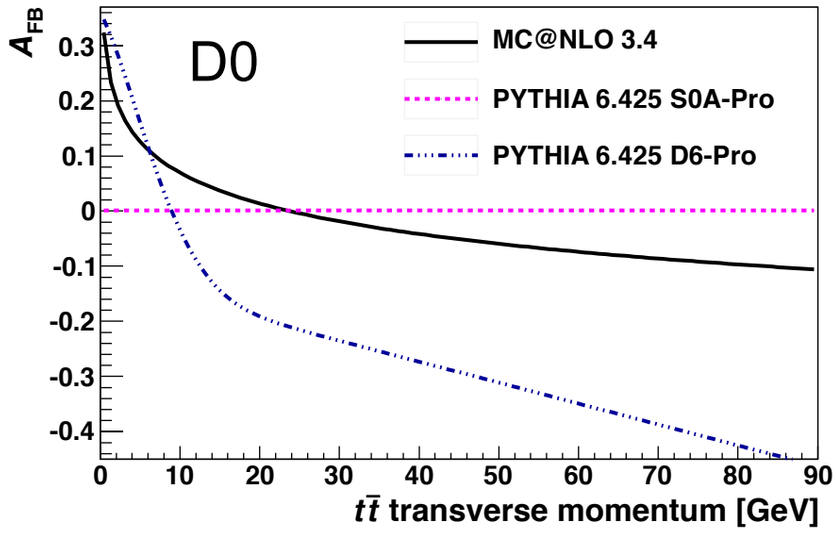
Top Quark Angular Distributions- Theory

Stephen Parke, Fermilab

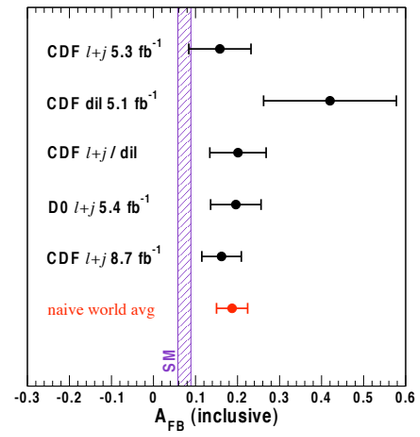
- Forward Backward Asymmetry in Production
- Angular Distributions inTop Decay
  - Unpolarized
  - Polarized
- Spin Correlations in Top Pair Production
  - unlike & like helicity partons: theory
  - Approximate Method and Observation
- Polarization in Single Top Production
- Summary & Conclusions

Forward Backward Asymmetry

- LO $A_{FB} = 0$
- NLO $A_{FB} \approx 7\%$
- LO + PS $A_{FB} \neq 0$!!!

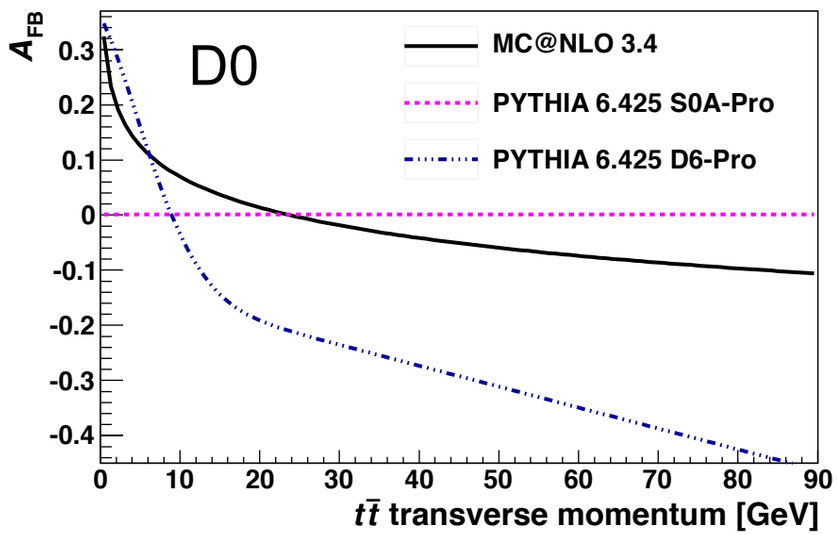


Inclusive FB asymmetry

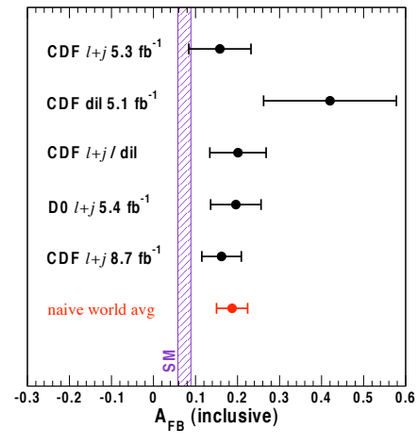


Forward Backward Asymmetry

- LO $A_{FB} = 0$
- NLO $A_{FB} \approx 7\%$
- LO + PS $A_{FB} \neq 0$!!!



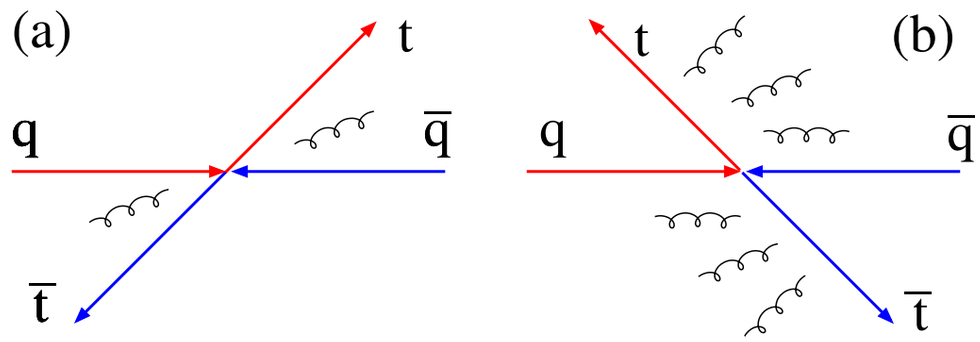
Inclusive FB asymmetry



arXiv:1205.1466v1

QCD Coherence and the Top Quark Asymmetry

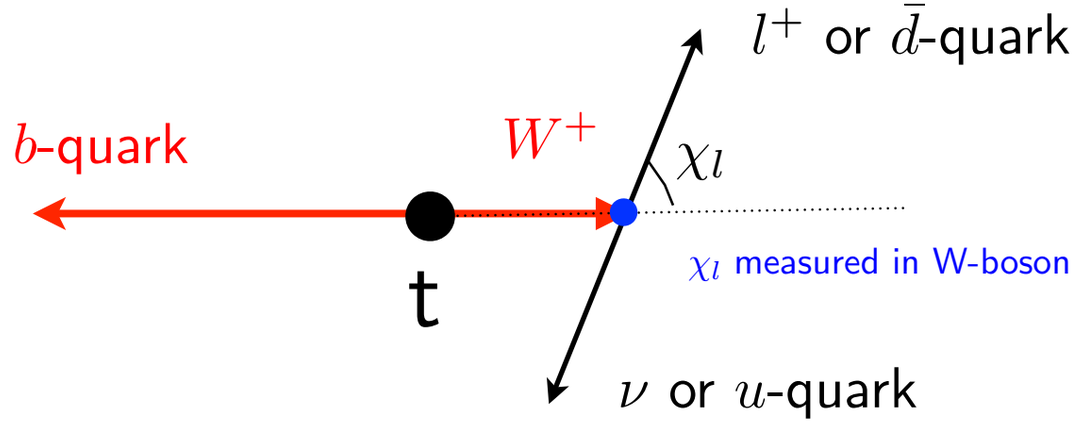
Peter Skands[1], Bryan Webber[2] and Jan Winter[1]



- Similar effects seen in Herwig and Sherpa but quantitatively different !

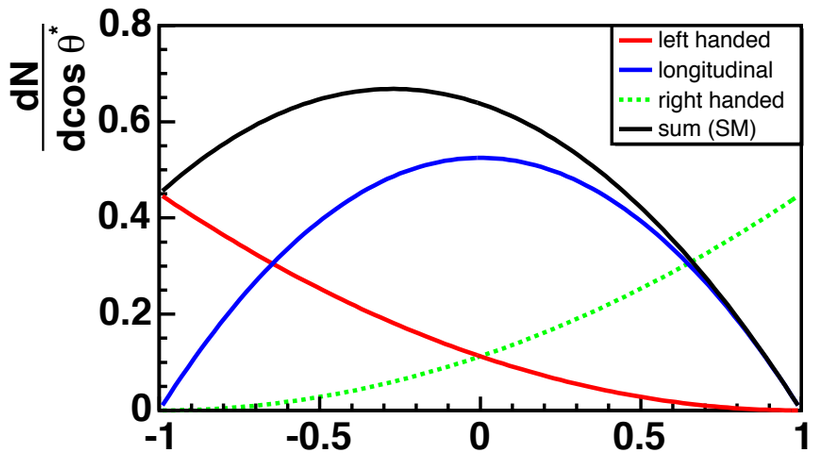
Is FB asymmetry fully under control in SM?

Unpolarized Top Decay:



χ_l measured in W-boson rest frame wrt to b-quark direction

$$\theta^* = \chi_l$$

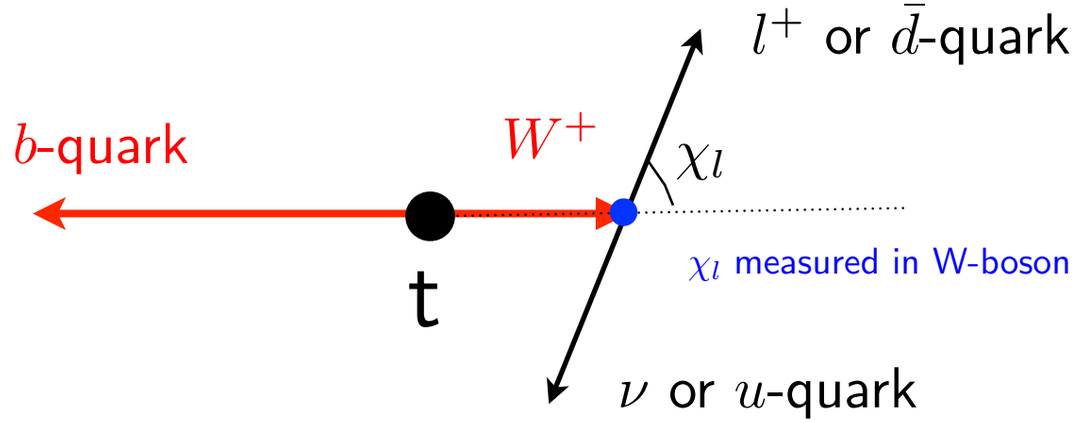


longitudinal transverse (L)

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\chi_l} = \frac{3}{4}\frac{(m_t^2\sin^2\chi_l + 2m_W^2(1-\cos\chi_l)^2/2)}{(m_t^2+2M_W^2)}$$

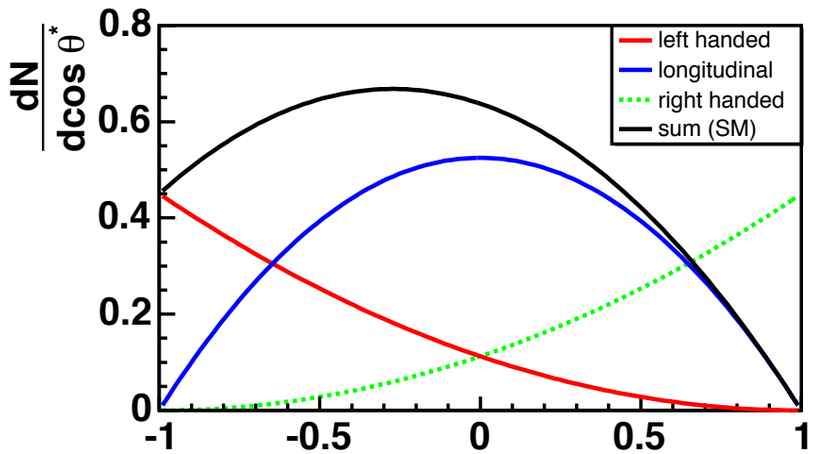
$$W\ Helicity\ Fractions = \begin{cases} longitudinal & \sim m_t^2 \approx 70\% \\ transverse(L) & \sim 2m_W^2 \approx 30\% \\ transverse(R) & \mathcal{O}(m_b^2) \ll 1\% \end{cases}$$

Unpolarized Top Decay:



χ_l measured in W-boson rest frame wrt to b-quark direction

$\theta^* = \chi_l$

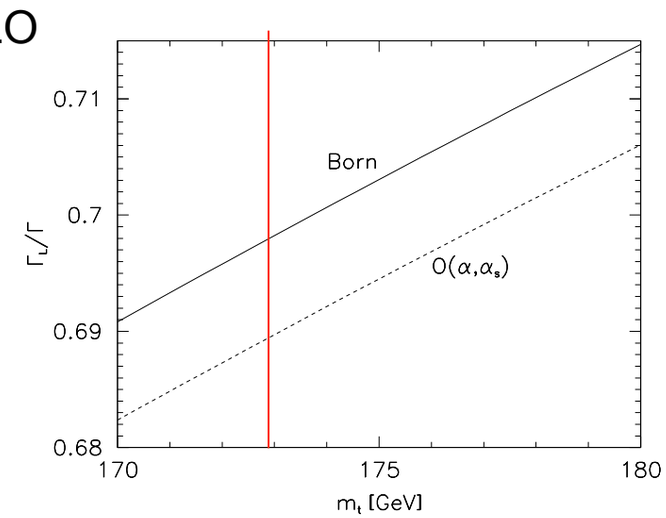


longitudinal transverse (L)

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\chi_l} = \frac{3}{4}\frac{(m_t^2\sin^2\chi_l + 2m_W^2(1-\cos\chi_l)^2/2)}{(m_t^2+2M_W^2)}$$

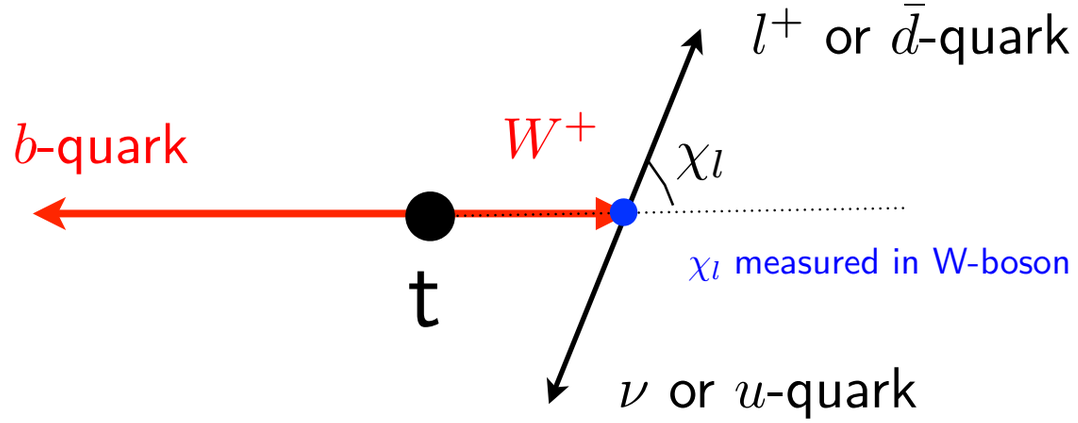
$$W\ Helicity\ Fractions = \begin{cases} longitudinal & \sim m_t^2 \approx 70\% \\ transverse(L) & \sim 2m_W^2 \approx 30\% \\ transverse(R) & \mathcal{O}(m_b^2) \ll 1\% \end{cases}$$

NLO



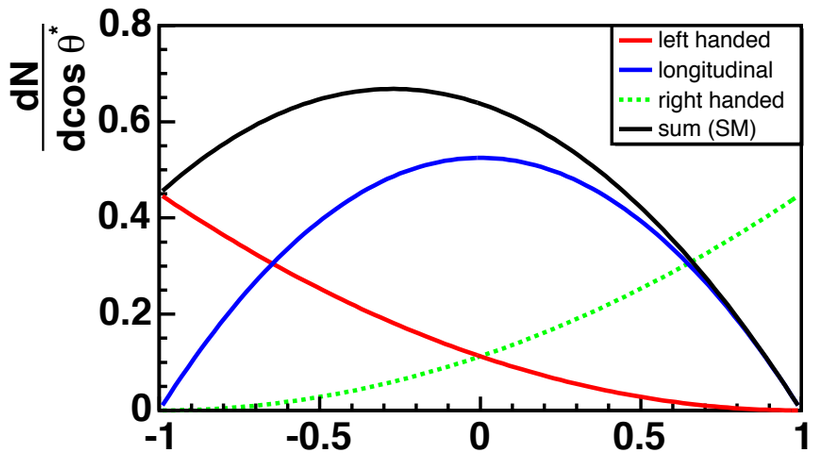
Jerabek and Kuhn hep-ph/0209185

Unpolarized Top Decay:



χ_l measured in W-boson rest frame wrt to b-quark direction

$\theta^* = \chi_l$

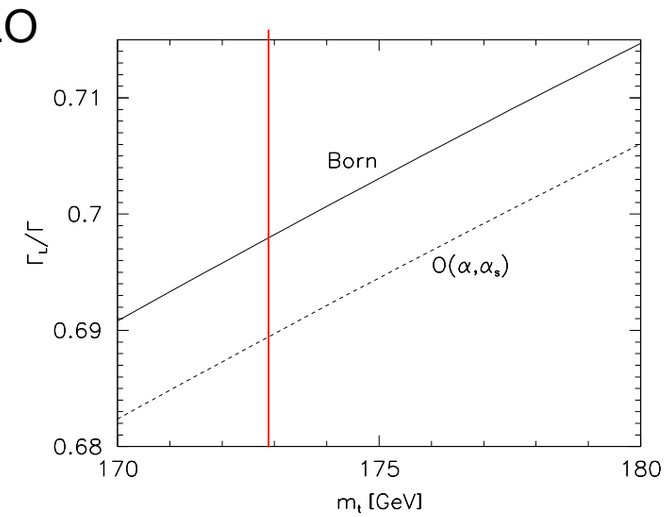


longitudinal transverse (L)

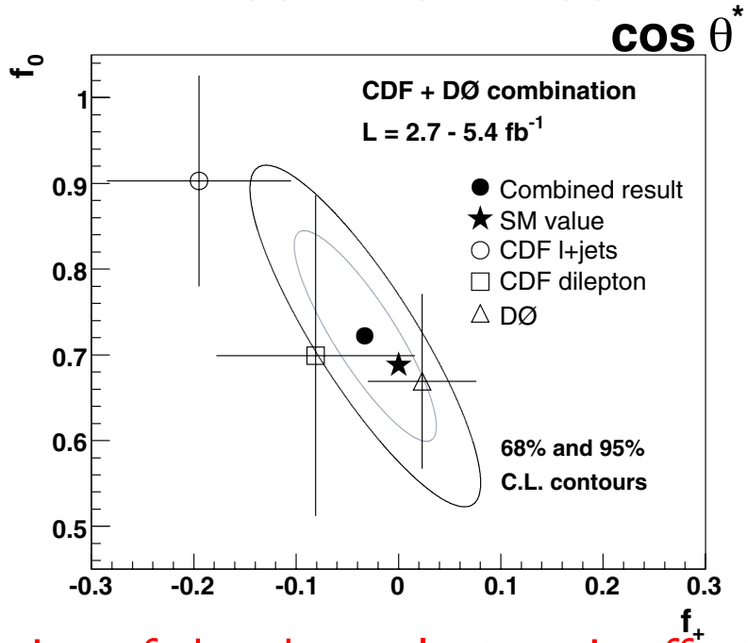
$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\chi_l} = \frac{3}{4}\frac{(m_t^2\sin^2\chi_l + 2m_W^2(1-\cos\chi_l)^2/2)}{(m_t^2+2M_W^2)}$$

$$W\ Helicity\ Fractions = \begin{cases} longitudinal & \sim m_t^2 \approx 70\% \\ transverse(L) & \sim 2m_W^2 \approx 30\% \\ transverse(R) & \mathcal{O}(m_b^2) \ll 1\% \end{cases}$$

NLO



Jerabek and Kuhn hep-ph/0209185



p_T distribution of the charge leptons is effected by these helicity fractions and can be used to measure the helicity fractions:

Top is a UNIQUE Quark:

Scales:

$$G_F m_t^3 \gg \Lambda_{QCD} \gg \frac{\Lambda_{QCD}^2}{m_t}$$

Top is a UNIQUE Quark:

Scales:

$$G_F m_t^3 \gg \Lambda_{QCD} \gg \frac{\Lambda_{QCD}^2}{m_t}$$

Top Width

~1 GeV

Top is a UNIQUE Quark:

Scales:

$$G_F m_t^3 \gg \Lambda_{QCD} \gg \frac{\Lambda_{QCD}^2}{m_t}$$

Top Width

~1 GeV

Hadronization

~0.1 GeV

Top is a UNIQUE Quark:

Scales:

$$G_F m_t^3 \gg \Lambda_{QCD} \gg \frac{\Lambda_{QCD}^2}{m_t}$$

Top Width	Hadronization	Spin Decorrelation
~1 GeV	~0.1 GeV	~0.0001 GeV

Top is a UNIQUE Quark:

Scales:

$$G_F m_t^3 \gg \Lambda_{QCD} \gg \frac{\Lambda_{QCD}^2}{m_t}$$

Top Width	Hadronization	Spin Decorrelation
~1 GeV	~0.1 GeV	~0.0001 GeV

Angular correlations of Top decay products contain information about Top spin at Production !!!

similar to W, Z's in this respect.

Polarized Top Decay:

Polarized Decay:

angle between decay product and spin axis in top quark rest frame

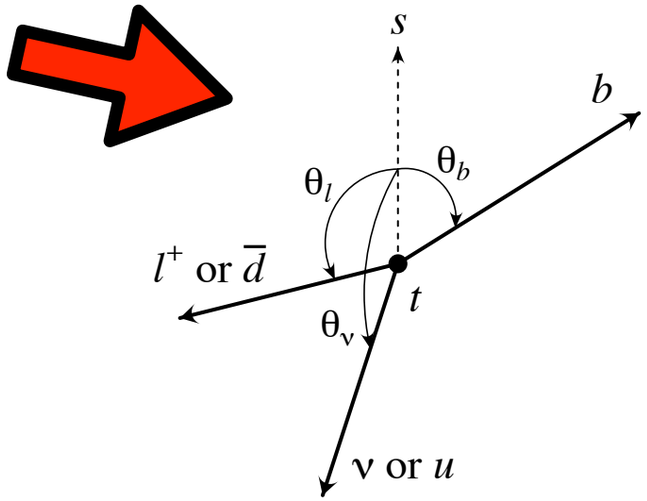
$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\chi_i} = (1+\alpha_i\cos\chi_i)/2, \quad \text{where} \quad \alpha_i = \begin{cases} +1.0 & (+0.998) & l^+ \\ +1.0 & (+0.966) & \bar{d}\text{-quark} \\ -0.31 & (-0.314) & \bar{\nu} \\ -0.31 & (-0.317) & u\text{-quark} \\ -0.41 & (-0.393) & b\text{-quark} \end{cases}$$

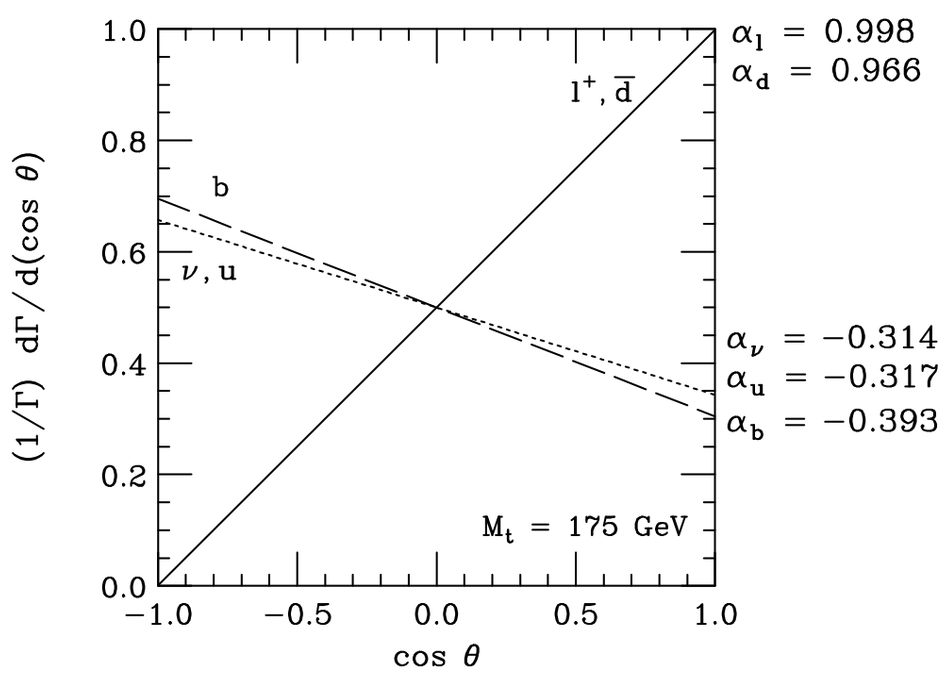
LO NLO

for $t \to b + e^+ + \nu$ then $|\mathcal{M}|^2 \sim (t_2 \cdot e)(b \cdot \nu)$: top spin couples directly to l^+ or d-quark

where $t_2 = \frac{t - m s_t}{2}$ is a massless momentum parallel to top spin axis, s_t

(χ, ϕ)





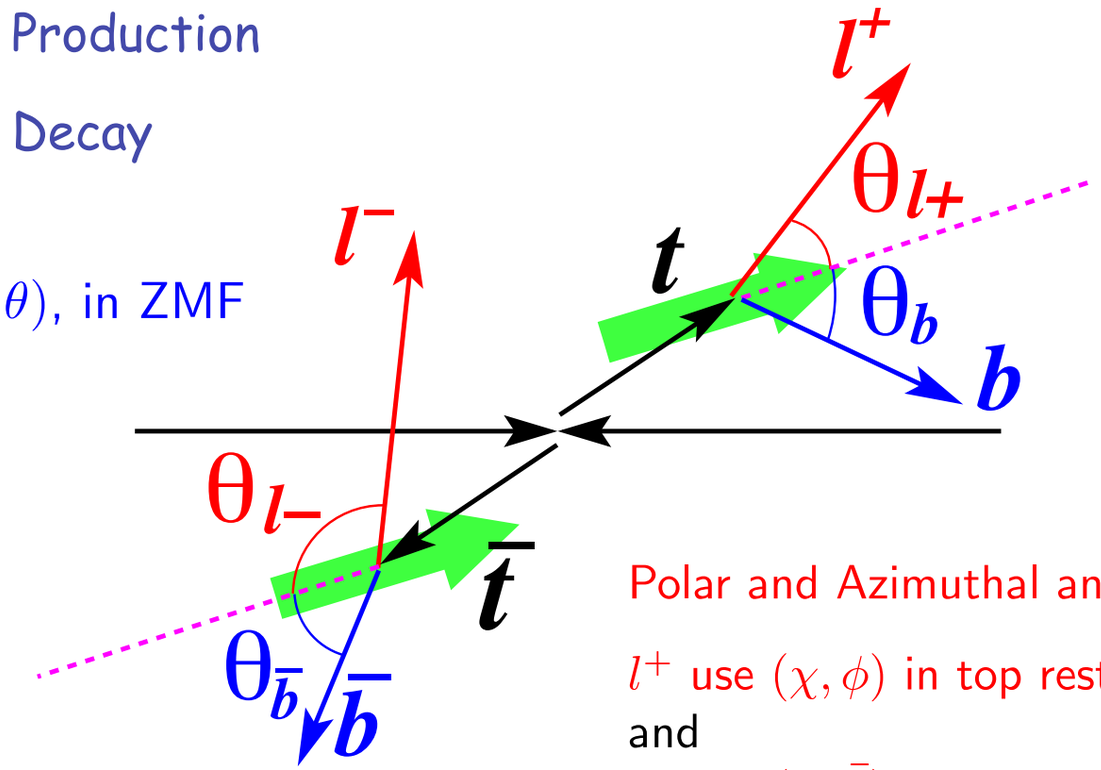
Note: Coefficients for b, u, and $\bar{d}$ are for partons; jets differ slightly at NLO.

(LO: Jeżabek and Kühn, *Phys. Lett.* **B329**, 317 (1994);
NLO: Brandenburg, Si, and Uwer, *Phys. Lett.* **B539**, 235 (2002).)

Spin Correlations:

- Sensitive to BOTH Production and Decay of the Top Quark Pair
  - sensitive to New Physics in Production
  - sensitive to New Physics in Decay

Top speed and scattering angle, (β, θ), in ZMF



Polar and Azimuthal angles of the decay products:

l^+ use (χ, ϕ) in top rest frame wrt to s_t
and
l^- use $(\bar{\chi}, \bar{\phi})$ in anti-top rest wrt $s_{\bar{t}}$

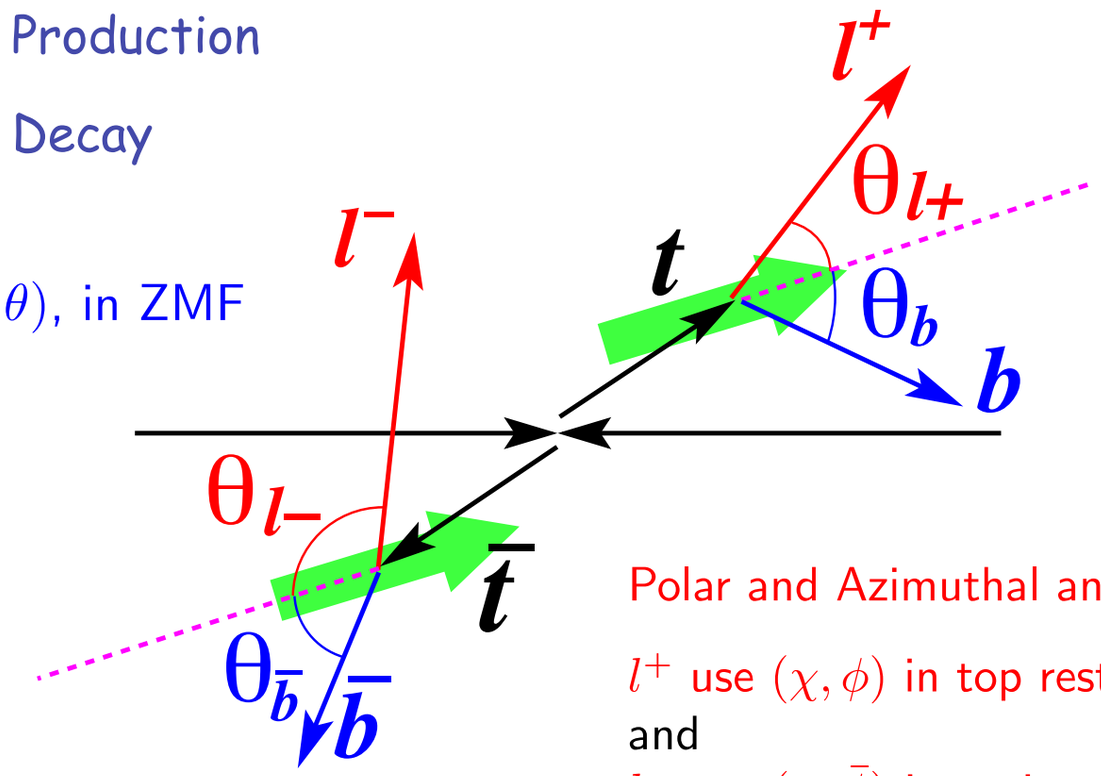
(ϕ and $\bar{\phi}$ measured relative to scattering plane!)

$\theta_+ = \chi$ and $\theta_- = \bar{\chi}$

Spin Correlations:

- Sensitive to BOTH Production and Decay of the Top Quark Pair
  - sensitive to New Physics in Production
  - sensitive to New Physics in Decay

Top speed and scattering angle, (β, θ), in ZMF



Polar and Azimuthal angles of the decay products:

l^+ use (χ, ϕ) in top rest frame wrt to s_t
and
l^- use $(\bar{\chi}, \bar{\phi})$ in anti-top rest wrt $s_{\bar{t}}$

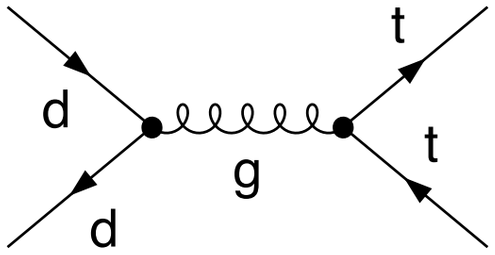
(ϕ and $\bar{\phi}$ measured relative to scattering plane!)

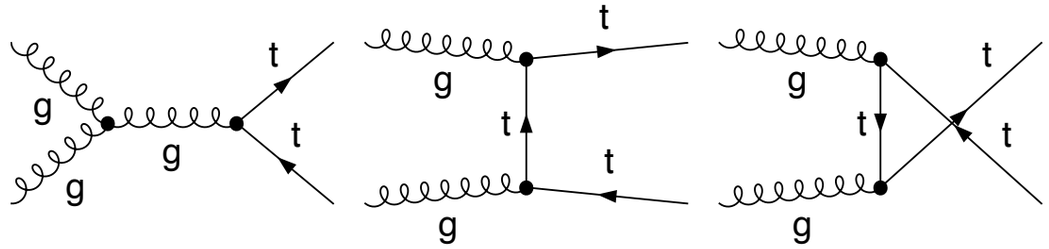
$\theta_+ = \chi$ and $\theta_- = \bar{\chi}$

- Choice of Spin Axis:

- in general UD+DU+UU+DD spins projections of Tops produced
- much SIMPLER description if only UD+DU or UU+DD spin projections produced for some spin axis
- SAME physics, just interference terms more important and less transparent for generic axis choice !

Pair Production at LO



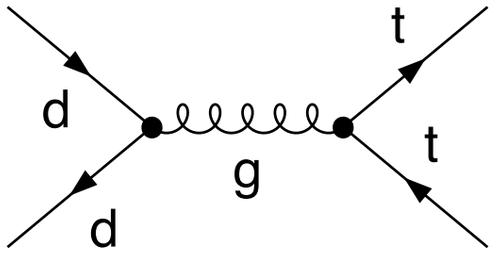


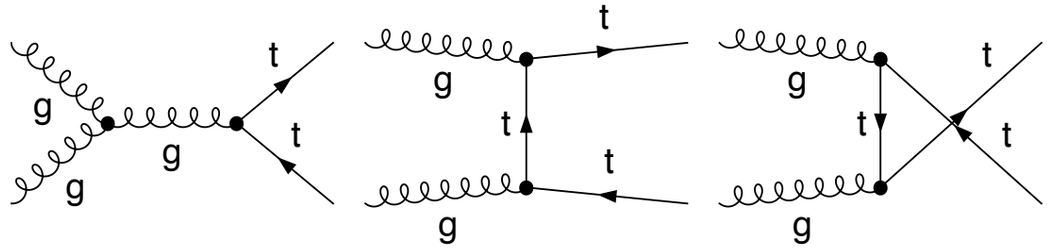
$$|\mathcal{M}|^2 \sim (2 - \beta^2 s_\theta^2)$$

$$|\mathcal{M}|^2 \sim \frac{(7+9\beta^2 c_\theta^2)}{(1-\beta^2 c_\theta^2)^2} [\beta^2 s_\theta^2 (2 - \beta^2 s_\theta^2) + (1 - \beta^4)]$$

$c_\theta^2 \rightarrow 1$ favoured as $\beta \rightarrow 1$!!!

Pair Production at LO





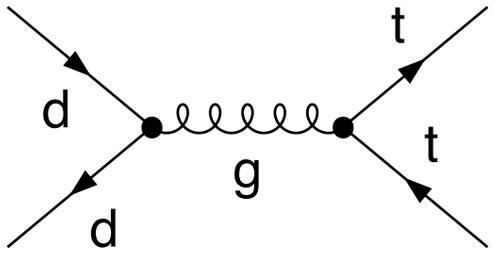
$$|\mathcal{M}|^2 \sim (2 - \beta^2 s_\theta^2)$$

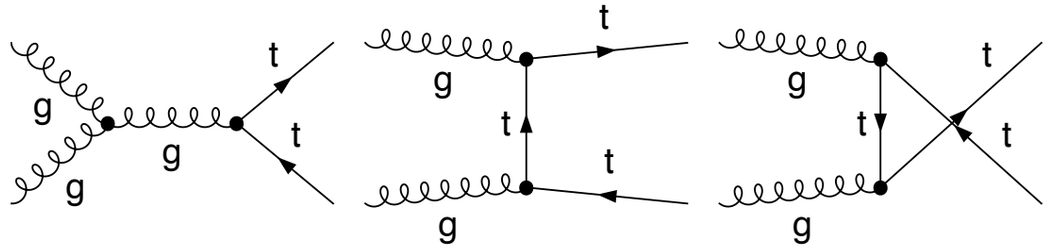
$$|\mathcal{M}|^2 \sim \frac{(7+9\beta^2 c_\theta^2)}{(1-\beta^2 c_\theta^2)^2} [\beta^2 s_\theta^2 (2 - \beta^2 s_\theta^2) + (1 - \beta^4)]$$

$c_\theta^2 \to 1$ favoured as $\beta \to 1$!!!

helicity quarks: unlike

Pair Production at LO





$$|\mathcal{M}|^2 \sim (2 - \beta^2 s_\theta^2)$$

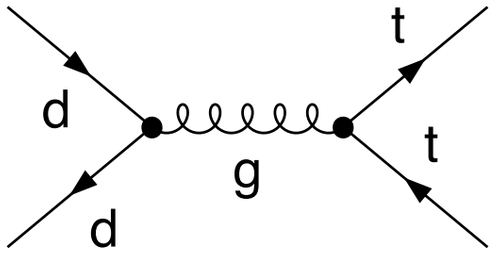
$$|\mathcal{M}|^2 \sim \frac{(7+9\beta^2 c_\theta^2)}{(1-\beta^2 c_\theta^2)^2} [\beta^2 s_\theta^2 (2 - \beta^2 s_\theta^2) + (1 - \beta^4)]$$

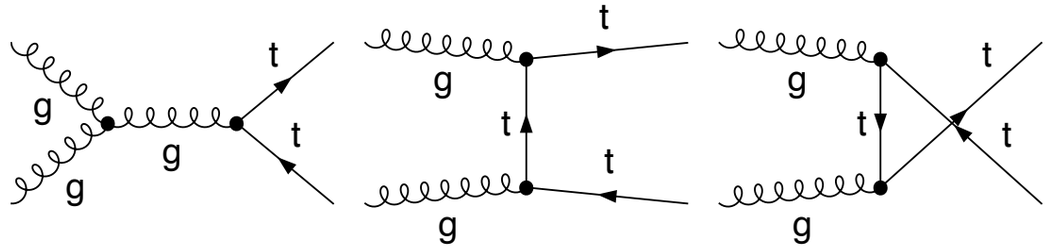
$c_\theta^2 \to 1$ favoured as $\beta \to 1$!!!

helicity quarks: unlike

helicity gluons: unlike + like

Pair Production at LO





$$|\mathcal{M}|^2 \sim (2 - \beta^2 s_\theta^2)$$

$$|\mathcal{M}|^2 \sim \frac{(7+9\beta^2 c_\theta^2)}{(1-\beta^2 c_\theta^2)^2} [\beta^2 s_\theta^2 (2 - \beta^2 s_\theta^2) + (1 - \beta^4)]$$

$c_\theta^2 \to 1$ favoured as $\beta \to 1$!!!

helicity quarks: unlike

helicity gluons: unlike + like

Identical Spin Correlations

TTbar Production:

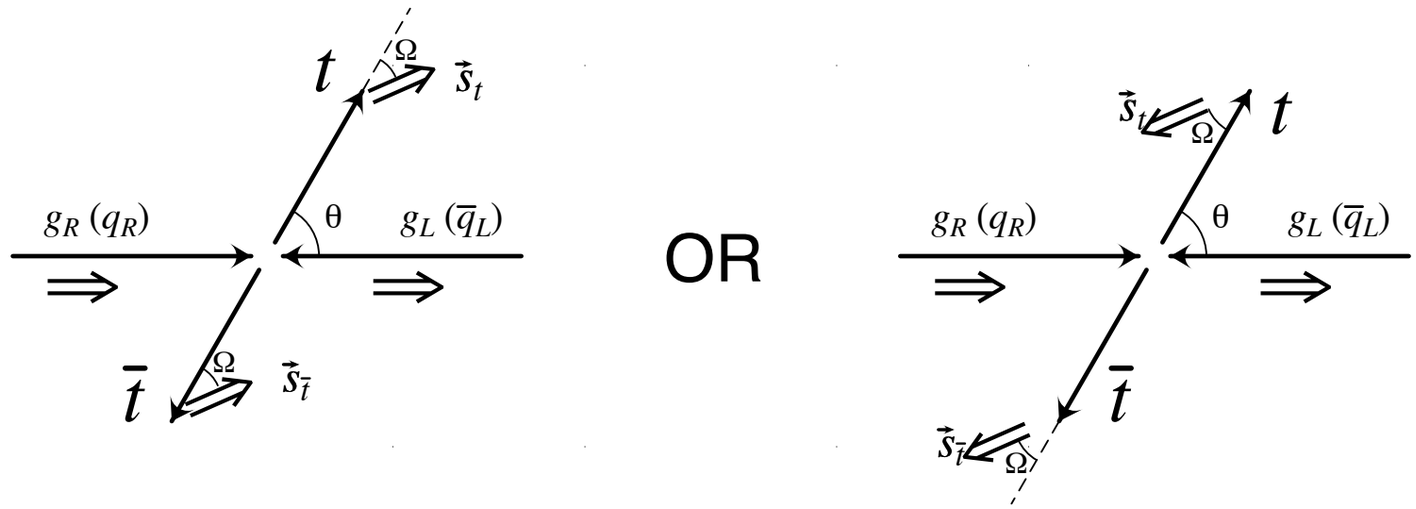
- Unlike helicity partons:
  - Tevatron: (qL qbarR or qR qbarL) LHC:(gL gR, gR gL)
    - Off-diagonal basis --- (interpolate btw beamline at threshold, helicity at Ultra High Energy)

Parke & Shadmi hep-ph/9606419 and Mahlon & Parke hep-ph/9706304

$$\tan\Omega = (1-\beta^2)\tan\theta$$

$$q_L\bar{q}_R,\ q_L\bar{q}_R,\ g_Lg_R,\ g_Rg_L$$

$$\rightarrow t_U\bar{t}_D + t_D\bar{t}_U$$



$$\left(1+\sqrt{1-\beta^2\sin^2\theta}\right)^2 :\ \left(1-\sqrt{1-\beta^2\sin^2\theta}\right)^2$$

TTbar Production:

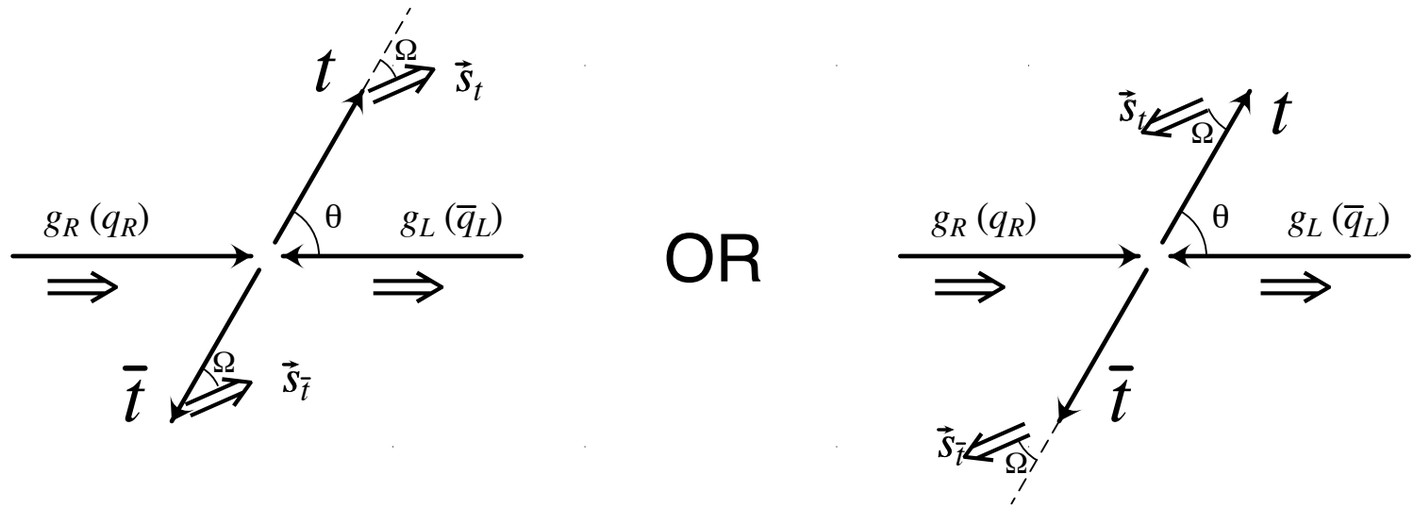
- Unlike helicity partons:
  - Tevatron: (qL qbarR or qR qbarL) LHC:(gL gR, gR gL)
    - Off-diagonal basis --- (interpolate btw beamline at threshold, helicity at Ultra High Energy)

Parke & Shadmi hep-ph/9606419 and Mahlon & Parke hep-ph/9706304

$$\tan\Omega = (1-\beta^2)\tan\theta$$

$$q_L\bar{q}_R,\ q_L\bar{q}_R,\ g_Lg_R,\ g_Rg_L$$

$$\rightarrow t_U\bar{t}_D + t_D\bar{t}_U$$



$$\left(1+\sqrt{1-\beta^2\sin^2\theta}\right)^2 : \left(1-\sqrt{1-\beta^2\sin^2\theta}\right)^2$$

Full matrix element squared, Production and Decay:
(χ, ϕ): $l^\pm$ or d-quark special role as they couple directly to spin
(other decay products only thru momentum conervation)

$$|\mathcal{A}|^2_{LR} + |\mathcal{A}|^2_{RL} \quad \sim \quad (1\ or\ \beta^2 s_\theta^2)[(2-\beta^2 s_\theta^2)(1+c_\chi c_{\bar{\chi}}) \quad +\beta^2 s_\theta^2 s_\chi s_{\bar{\chi}}\cos(\phi+\bar{\phi})]$$

|UD|^2 and |DU|^2 interf btw UD and DU tops!

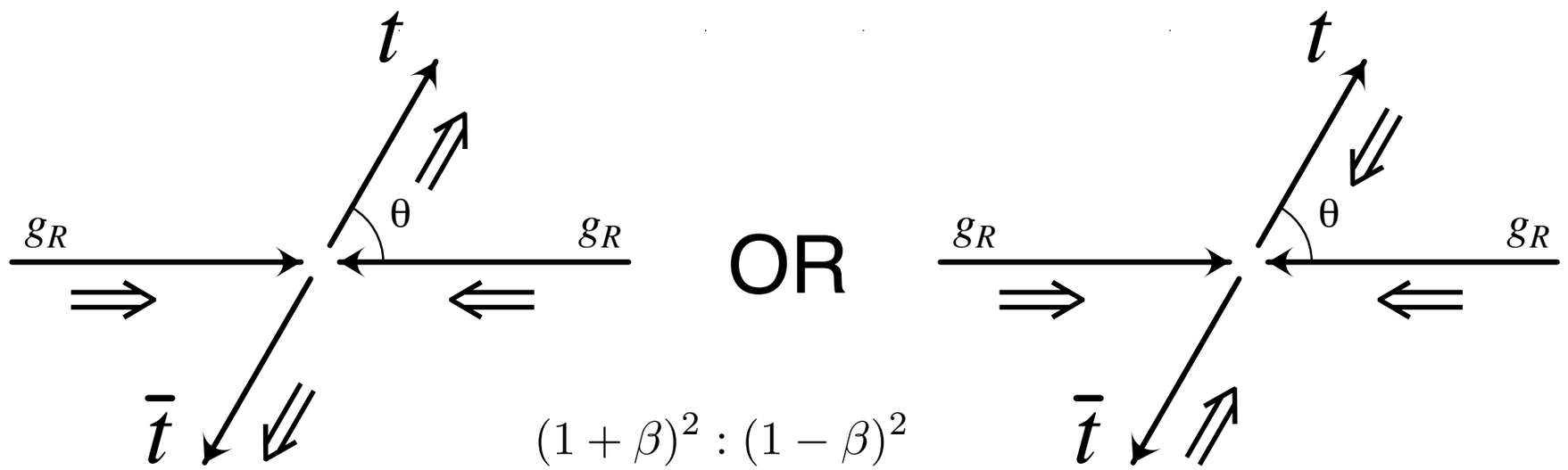
qqbar: over all factor $(b\cdot\nu)(\bar{b}\cdot\bar{\nu})$

gg: over all factor $(b\cdot\nu)(\bar{b}\cdot\bar{\nu})\,\dfrac{(7+9\beta^2c_\theta^2)}{(1-\beta^2c_\theta^2)^2}$

TTbar Production:

- Like helicity partons (gL g L or gR gR)
  - helicity in ZMF

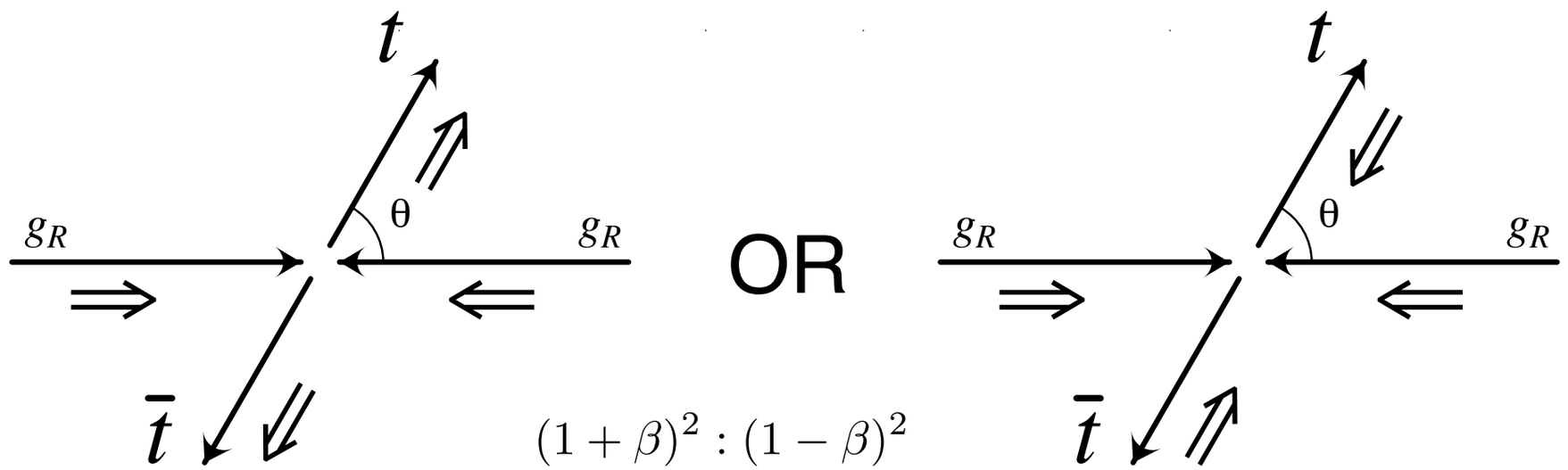
$$g_L g_L,\ g_R g_R \to t_L \bar{t}_L + t_R \bar{t}_R.$$



TTbar Production:

- Like helicity partons (gL g L or gR gR)
  - helicity in ZMF

$$g_L g_L,\ g_R g_R \to t_L \bar{t}_L + t_R \bar{t}_R.$$



Full matrix element squared, Production and Decay:
(χ, ϕ): $l^{\pm}$ or d-quark special role as they couple directly to spin
(other decay products only thru momentum conervation)

$$|\mathcal{A}|^2_{LL} + |\mathcal{A}|^2_{RR} \quad \sim \quad (1-\beta^2)\ [(1+\beta^2)(1 - c_\chi c_{\bar{\chi}}) \quad -(1-\beta^2) s_\chi s_{\bar{\chi}} \cos(\phi - \bar{\phi})]$$

|LL|^2 and |RR|^2

interf btw LL and RR tops!

$$\text{over all factor } (b{\cdot}\nu)(\bar{b}{\cdot}\bar{\nu}) \frac{(7+9\beta^2 c_\theta^2)}{(1-\beta^2 c_\theta^2)^2}$$

Considerations:

- Choice of Spin Axis:
  - Beamline: always know direction of incoming partons
  - ZMF Helicity: requires reconstruction
  - Off-Diagonal: requires reconstruction

- Spin Analyzing Particles:
  - $l^{\pm}$: strongest correlation with spin but are accompanied by ν's
  - d-quark: not easy to distinguish from u-quarks
  - b-quark less correlated than $l^{\pm}$
  - u-quark: d-quarks have higher correlation
  - ν: impossible

- Important Variables:
  - $c_{\chi}c_{\bar{\chi}}$: requires full reconstruction
  - $(\phi + \bar{\phi})$ about spin axis: need to known production plane
  - $(\phi - \bar{\phi})$ about spin axis: no need to known production plane

No ideal combination:

Reconstruction challenging with dilepton events
Correlations reduced with only one charged lepton.

Considerations:

- Choice of Spin Axis:
  - Beamline: always know direction of incoming partons
  - ZMF Helicity: requires reconstruction
  - Off-Diagonal: requires reconstruction
- Spin Analyzing Particles:
  - $l^{\pm}$: strongest correlation with spin but are accompanied by ν's
  - d-quark: not easy to distinguish from u-quarks
  - b-quark less correlated than $l^{\pm}$
  - u-quark: d-quarks have higher correlation
  - ν: impossible
- Important Variables:
  - $c_{\chi}c_{\bar{\chi}}$: requires full reconstruction
  - $(\phi + \bar{\phi})$ about spin axis: need to known production plane
  - $(\phi - \bar{\phi})$ about spin axis: no need to known production plane

No ideal combination:

Approximations to one of these criteria !!!

Reconstruction challenging with dilepton events
Correlations reduced with only one charged lepton.

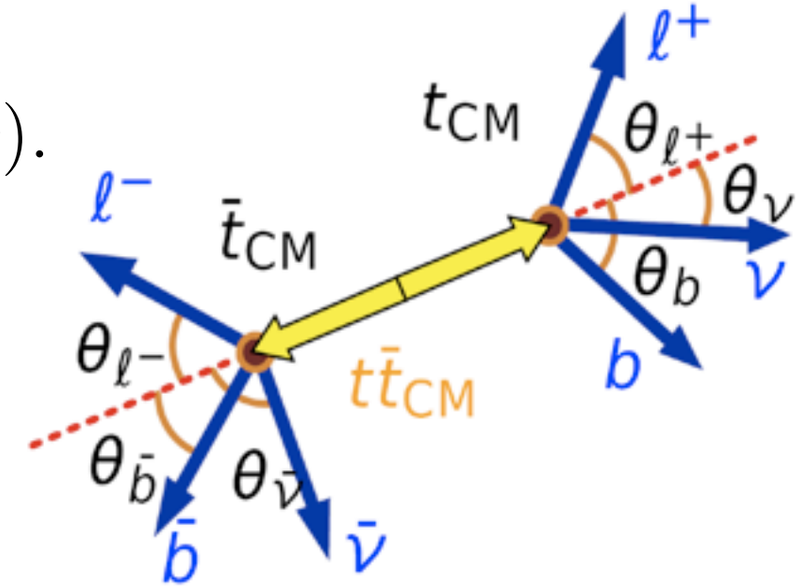
Cos Cos Correlations:

Spin Correlations depend on Spin Axis (size of C):

Mahlon & SP hep – ph/9512264
Stelzer & Willenbrock hep – ph/9512292

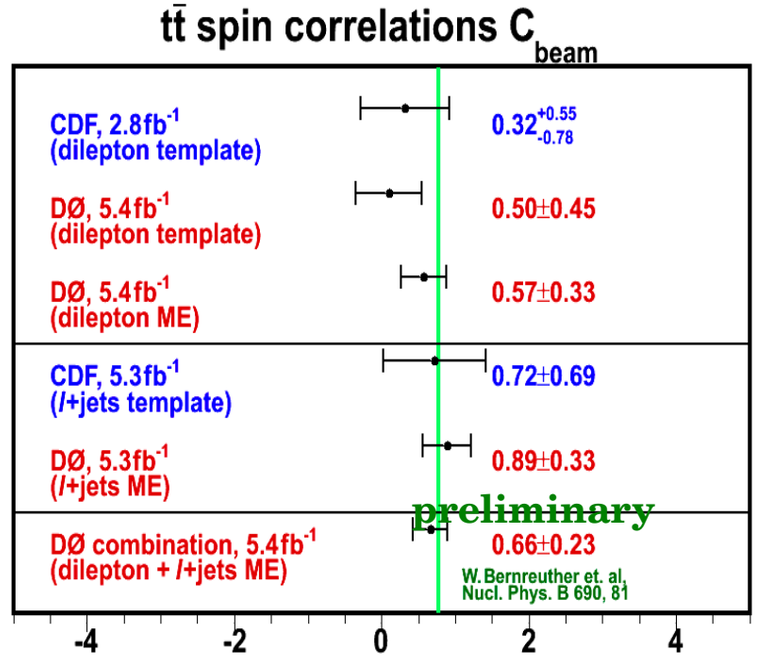
$$\frac{1}{\sigma_T}\frac{d^2\sigma}{d\cos\chi_i d\cos\bar{\chi}_{\bar{i}}} = \frac{1}{4}(1 + C_{t\bar{t}}\ \alpha_i\ \bar{\alpha}_{\bar{i}}\ \cos\chi_i \cos\bar{\chi}_{\bar{i}}).$$

$$C \neq 0 \quad C_{t\bar{t}} \equiv \frac{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow} - \sigma_{\uparrow\downarrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow} + \sigma_{\uparrow\downarrow} + \sigma_{\downarrow\uparrow}}.$$



Useful Spin Axis: ZMF Helicity / Beamline / Off-Diagonal

	$p\bar{p}$ at $\sqrt{s} = 2$ TeV		pp at $\sqrt{s} = 14$ TeV	
	LO	NLO	LO	NLO
$C_{hel.}$	−0.456	−0.389	0.305	0.311
C_{beam}	0.910	0.806	−0.005	−0.072
$C_{off.}$	0.918	0.813	−0.027	−0.089

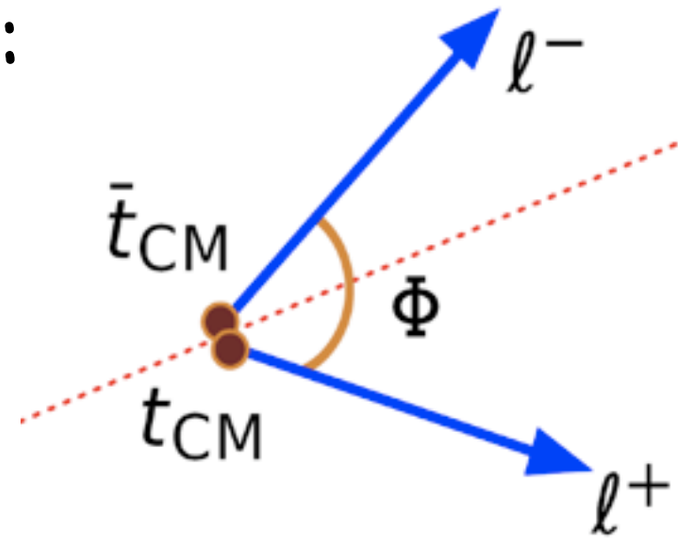


Bernreuther, Brandenburg, Si and Uwer arXiv:hep-ph/0107086 PRL

Azimuthal Correlations:

Azimuthal Correlations (interference terms):

$$\frac{1}{\sigma_T}\frac{d\sigma}{d\Delta\phi} = \frac{1}{2}(1 - D\cos\Delta\phi)$$



Φ → angle between the two spin analysers (in the corresponding *t* rest frame)

Production axis in ZMF (Helicity)

Bernreuther and Si arXiv:1003.3826 NPB

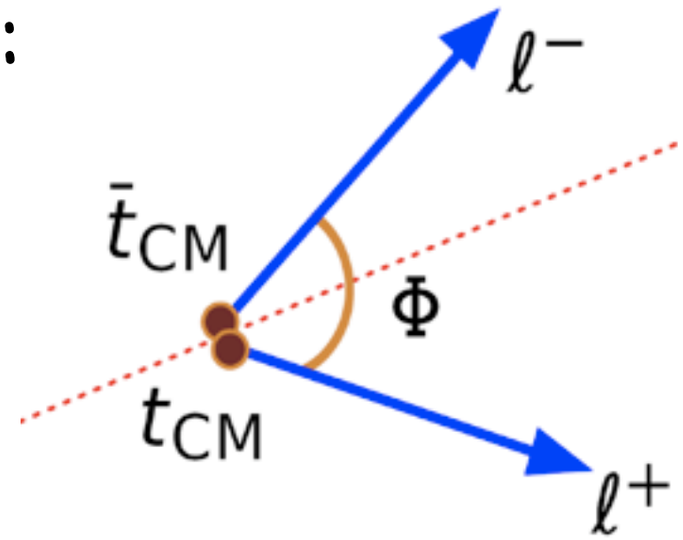
$M_{\max} = 550$ GeV

	Tevatron			LHC (10 TeV)			LHC (14 TeV)		
μ	$m_t/2$	m_t	$2m_t$	$m_t/2$	m_t	$2m_t$	$m_t/2$	m	$2m$
$\sigma_{\ell\ell}$ (pb)	0.043	0.042	0.038	2.31	2.03	1.76	5.00	4.38	3.82
D	0.139	0.145	0.151	-0.257	-0.252	-0.257	-0.240	-0.247	-0.230
$D(M_{\max})$	0.125	0.132	0.138	-0.344	-0.340	-0.347	-0.340	-0.353	-0.338

Azimuthal Correlations:

Azimuthal Correlations (interference terms):

$$\frac{1}{\sigma_T}\frac{d\sigma}{d\Delta\phi} = \frac{1}{2}(1 - D\cos\Delta\phi)$$



Φ → angle between the two spin analysers (in the corresponding t rest frame)

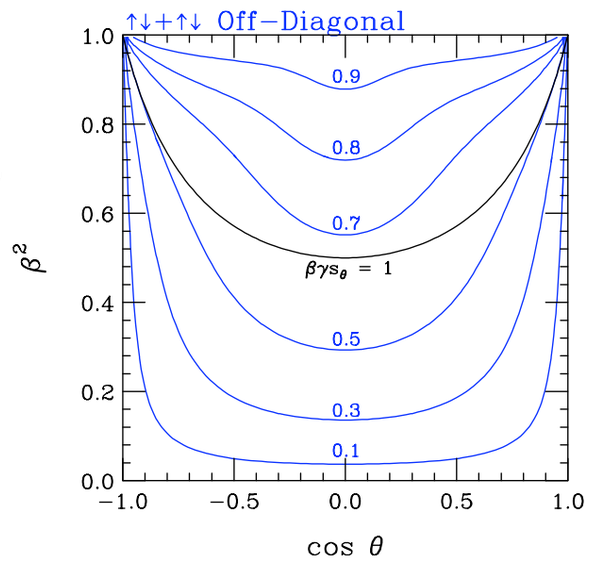
Production axis in ZMF (Helicity)

Bernreuther and Si arXiv:1003.3826 NPB

$M_{\max} = 550$ GeV

	Tevatron			LHC (10 TeV)			LHC (14 TeV)		
μ	$m_t/2$	m_t	$2m_t$	$m_t/2$	m_t	$2m_t$	$m_t/2$	m	$2m$
$\sigma_{\ell\ell}$ (pb)	0.043	0.042	0.038	2.31	2.03	1.76	5.00	4.38	3.82
D	0.139	0.145	0.151	-0.257	-0.252	-0.257	-0.240	-0.247	-0.230
$D(M_{\max})$	0.125	0.132	0.138	-0.344	-0.340	-0.347	-0.340	-0.353	-0.338

What about the distribution of $(\phi + \bar{\phi})$ about helicity or off-diagonal axis, in the region where the unlike helicity processes dominates?
when $\beta\gamma\sin\theta > 1$, e.g. $M_{t\bar{t}} > 500GeV$ and $|\cos\theta| < 0.7$

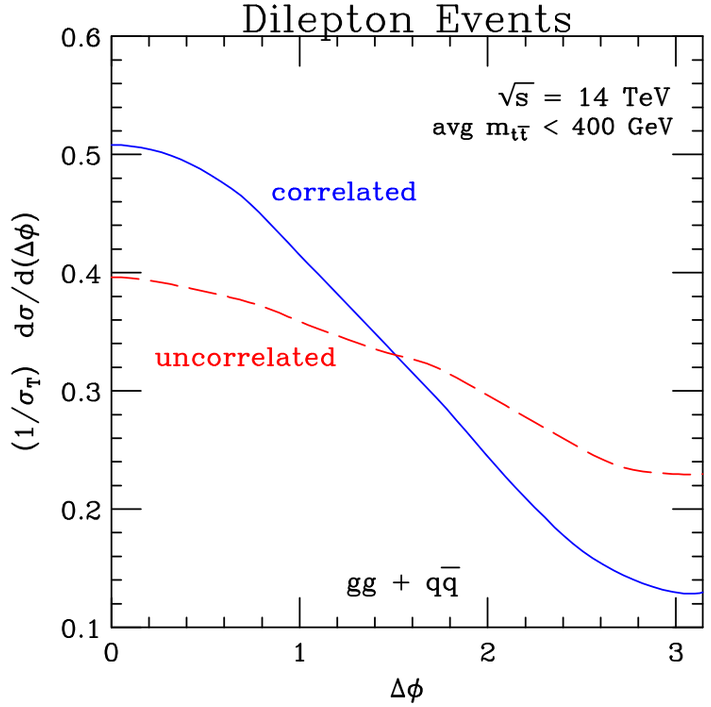


Approximate Method:

$\Delta\Phi$ about beamline for dilepton events:

- $|\cos\theta| \to 1$ for $t\bar{t}$ produced from gg fusion, along beamline:
- Suggests using beamline as the axis instead of production axis (helicity):
- Measure $\Delta\Phi$ about beam axis for di-Lepton events:
- Simple to measure and invariant under boosts along beamline:
- No top reconstruction necessary:
- But, Is this sensitive to Spin Correlations? Yes!

$t\bar{t}$: $\Delta\phi_{\ell\,\ell'}$ with $M_{t\bar{t}} < 400$ GeV



[Mahlon, Parke, arXiv:1001.3422]

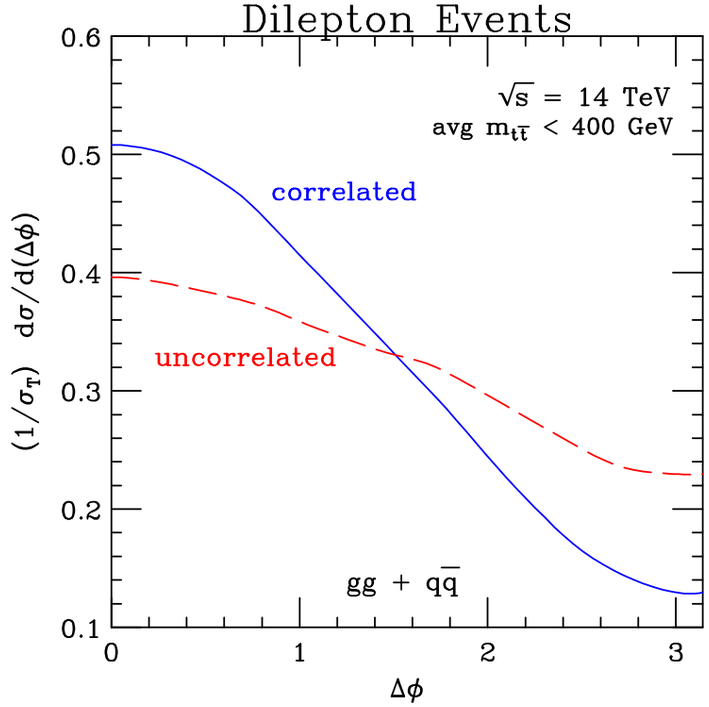
Approximate Method:

$\Delta\Phi$ about beamline for dilepton events:

- $|\cos\theta| \to 1$ for $t\bar{t}$ produced from gg fusion, along beamline:
- Suggests using beamline as the axis instead of production axis (helicity):
- Measure $\Delta\Phi$ about beam axis for di-Lepton events:
- Simple to measure and invariant under boosts along beamline:
- No top reconstruction necessary:

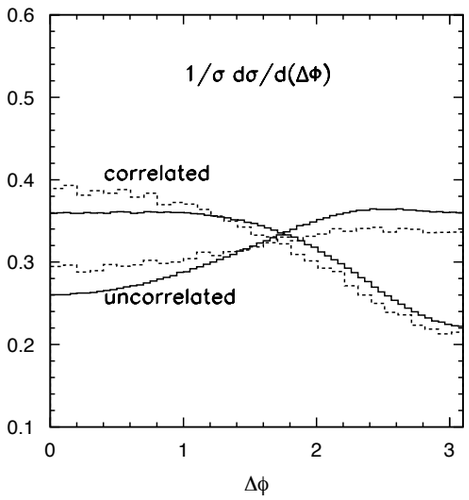
$t\bar{t}$: $\Delta\phi_{\ell\,\ell'}$ with $M_{t\bar{t}} < 400$ GeV

- But, Is this sensitive to Spin Correlations? Yes!



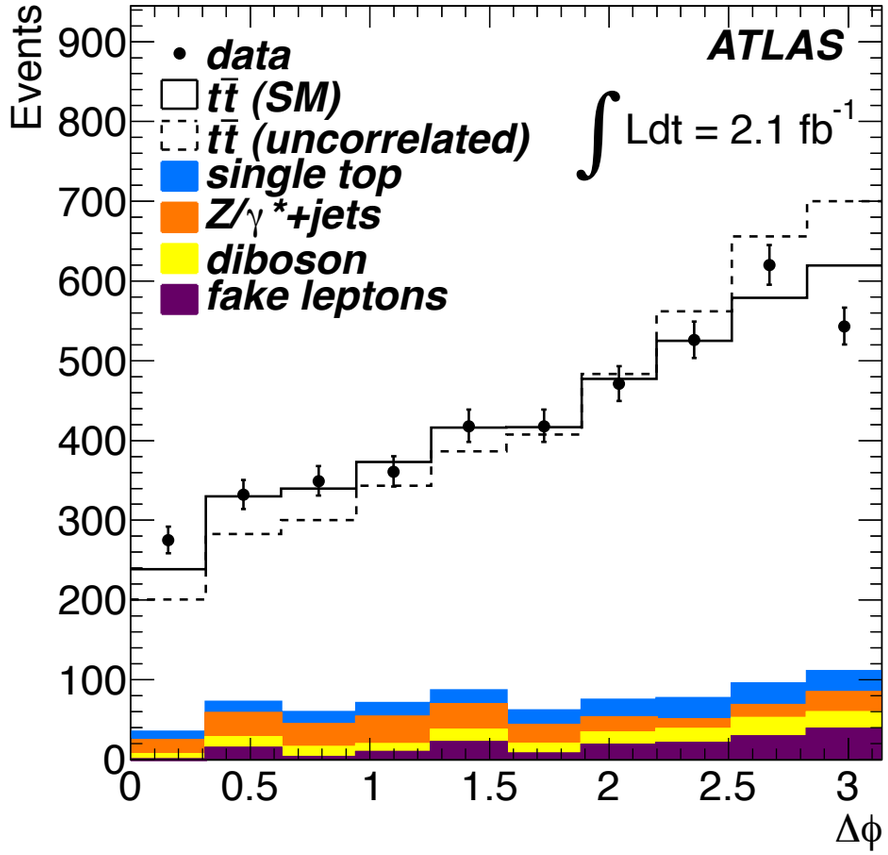
[Mahlon, Parke, arXiv:1001.3422]

NLO gives
similar difference



Bernreuther and Si arXiv:1003:3926

Atlas Observation:



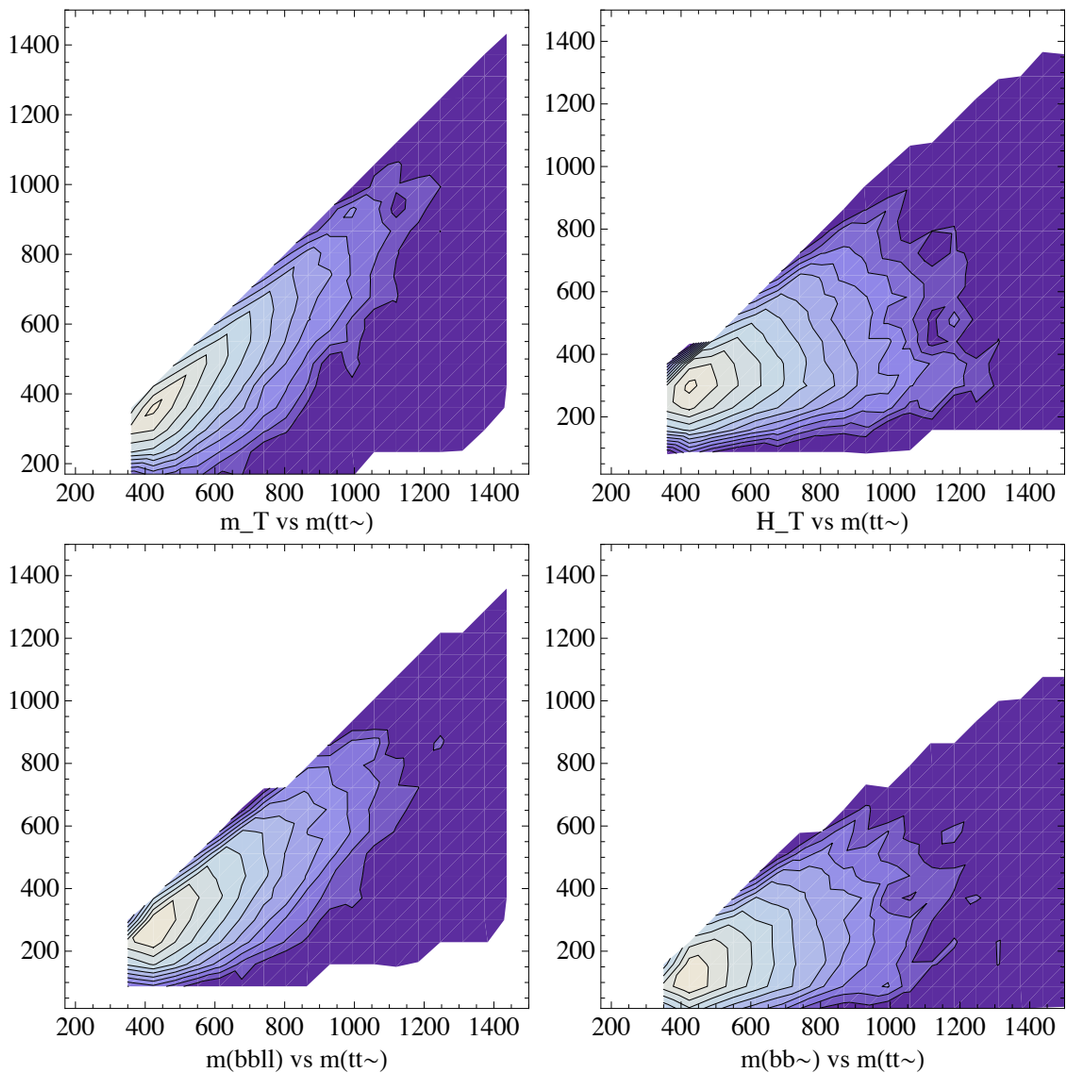
No Mtt cut:

- Sensitive to interference between LL and RR from $g_L g_L$ and $g_R g_R$ fusion:
- Insensitive to $g_L g_R$, $g_R g_L$ and $q\bar{q}$ production

Is there a variable sensitive to top spin correlations for production from unlike helicity partons which doesn't require reconstruction ???

Cuts without Full Reconstruction

with Rakhi Muhbubani and Jan Winter, CERN

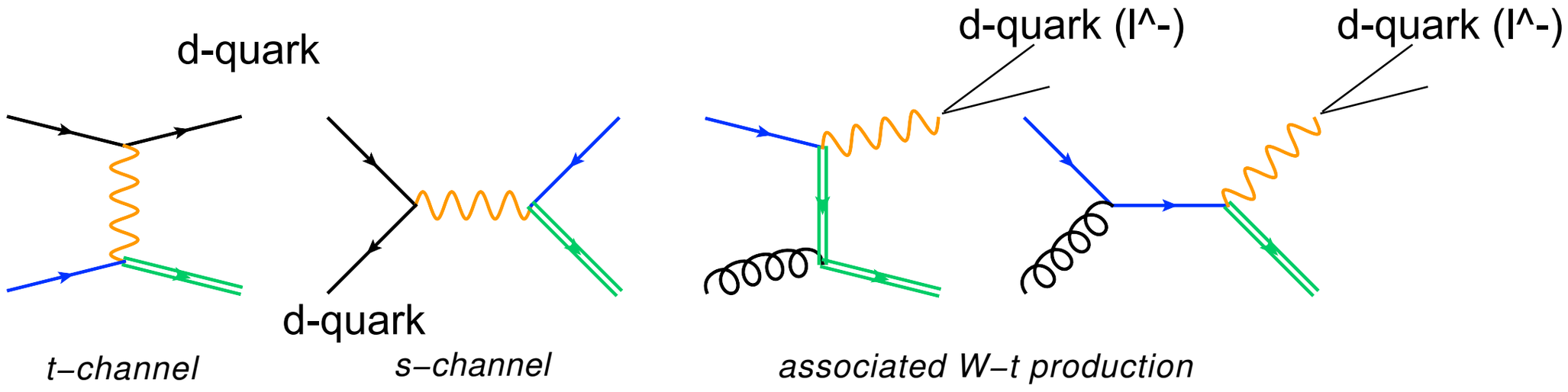


M_T is best variable!

$$m^2_{T,t\bar{t}}[m_{\nu\nu}] = m^2_{\ell\ell b\bar{b}} + m^2_{\nu\nu} + 2\left(\sqrt{p^2_{T,\ell\ell b\bar{b}} + m^2_{\ell\ell b\bar{b}}}\sqrt{p^2_{T,\ell\ell b\bar{b}} + m^2_{\nu\nu}} + p^2_{T,\ell\ell b\bar{b}}\right)$$

0 0

Single Top Production:



- In the Top rest frame the Spin of the Top is aligned with d-quark (or $l^{\pm}$)

- Correlates the charge lepton (or d-quark) in Top decay with this d-quark

In monte carlo (LO, NLO, ...), fit for

$$P_t \text{ with } \frac{1}{\sigma_T}\frac{d\sigma}{d\cos\chi_l} = \frac{1}{2}(1 - \ P_t\ \alpha_l\ \cos\chi_l)$$

in top rest frame.

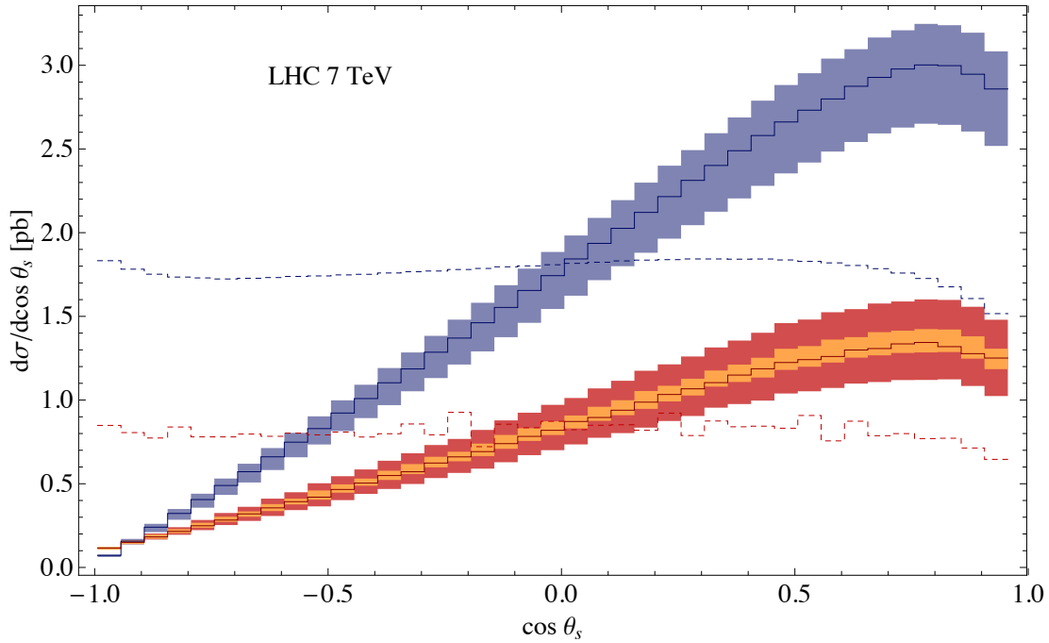
LO $$P_t(\ s-channel) > P_t(\ t-channel) > P_t(\ tW-channel)$$

- P_t is large, $\sim 90\%$, comes from V-A structure of couplings

- which also implies that at UHE, top is produced as a t_L

t-channel Single Top

single top: $\cos(\vec{p}^{\,*}_{\rm spec}, \vec{p}^{\,*}_{\ell})$



LO

NLO

[Falgari et.al: arXiv:1102.5267]

$\frac{1}{\sigma_T}\frac{d\sigma}{d\cos\theta_S}$: removes shift in total cross section

LO G. Mahlon and S. J. Parke, Phys. Lett. B **476** (2000) 323 [arXiv:hep-ph/9912458].

Summary & Conclusions

- Interplay between higher order and shower MC needs further study for FB asymmetry,...
- Angular correlations in Top Quark Decay
  - have significant effects on the momentum distribution of the top decay products (W_L, W_-)
  - are useful for separation of signal & background, polarization eg single top production
  - provide tests for anomalous couplings to top quarks
- Spin correlations in Top Pair Production
  - tests full production, decay chain for top quarks
  - has been observed (> 5 sigma Atlas) but only from gLgL and gRgR production thru interference of LL and RR tops, using Delta Phi variable
  - what about production from unlike helicity partons?
- Top quarks provide a rich Laboratory for precision tests of the SM and searches for New Physics