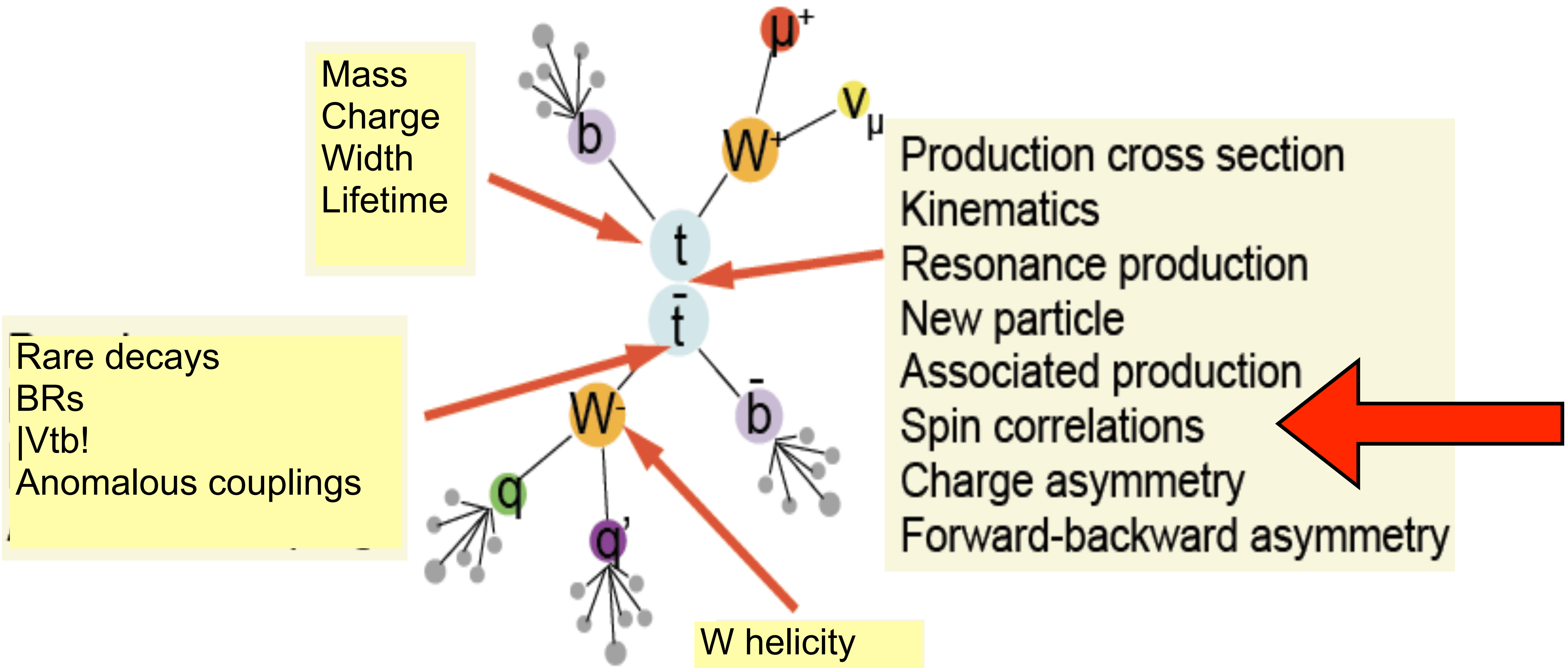
Spin Correlation Effects in T Tbar Production at LHC

Stephen Parke, Fermilab, 25 May 2009

with Greg Mahlon (arXiv/0906.wxyz)



Top spin polarization

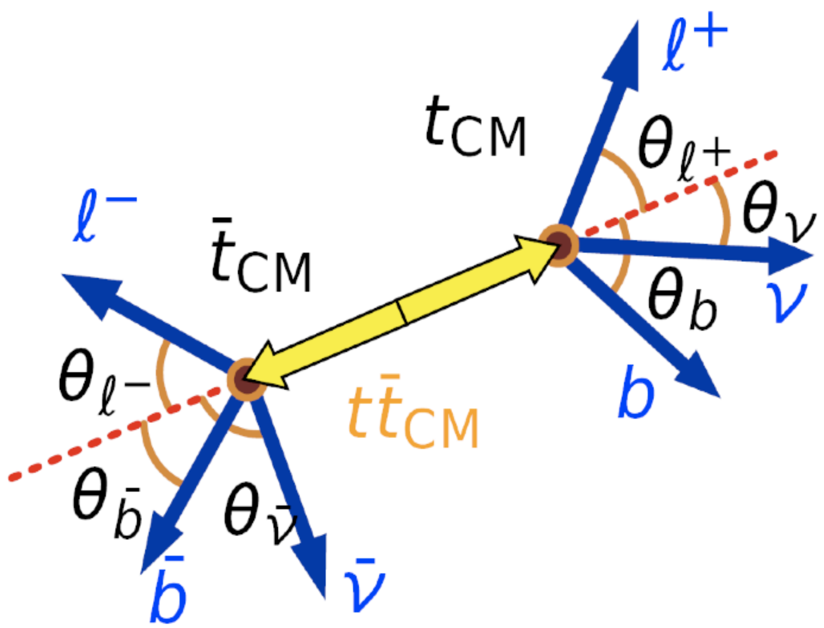
M. Cobal

- t quark decays before hadronization → spin info conserved
- In SM: top unpolarised, but tt spins correlated
- In new production models: modified correlations

$$\frac{1}{N}\frac{\delta^2 N}{\delta\cos\theta_1\,\delta\cos\theta_2} = \frac{1}{4}(1 - A|\alpha_1\alpha_2|\cos\theta_1\cos\theta_2)$$

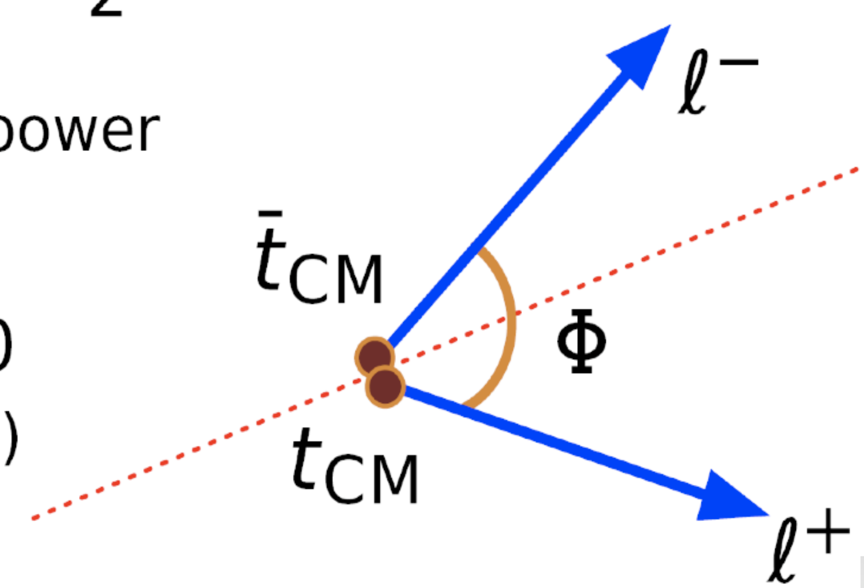
$$A = \frac{N_{same} - N_{opp}}{N_{same} + N_{opp}}$$

$$\frac{1}{N}\frac{dN}{d\cos\Phi} = \frac{1}{2}(1 - A_D|\alpha_1\alpha_2|\cos\Phi)$$



α → spin analysing power

$A^{SM} = 0.422$
$A_D^{SM} = -0.290$
$(m_{t\bar{t}} < 550$ GeV$)$



$\cos\theta$ → angle between the t (in $t\bar{t}$ rest frame) and the t decay product (in t rest frame)

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

Outline:

- Review $q\ \bar{q} \rightarrow t\ \bar{t}$ $\left\{ \begin{array}{l} \text{Mahlon \& SP hep}-\text{ph}/9512264 \\ \text{Stelzer \& Willenbrock hep}-\text{ph}/9512292 \end{array} \right.$
- $gg \rightarrow t\ \bar{t}$
- Where are the events at LHC
- di-Lepton events at low $m_{t\bar{t}}$
- NLO and Anomalous couplings
- Summary

Review: $q\,\bar{q} \to t\,\bar{t}$

One can chose a spin axis such that

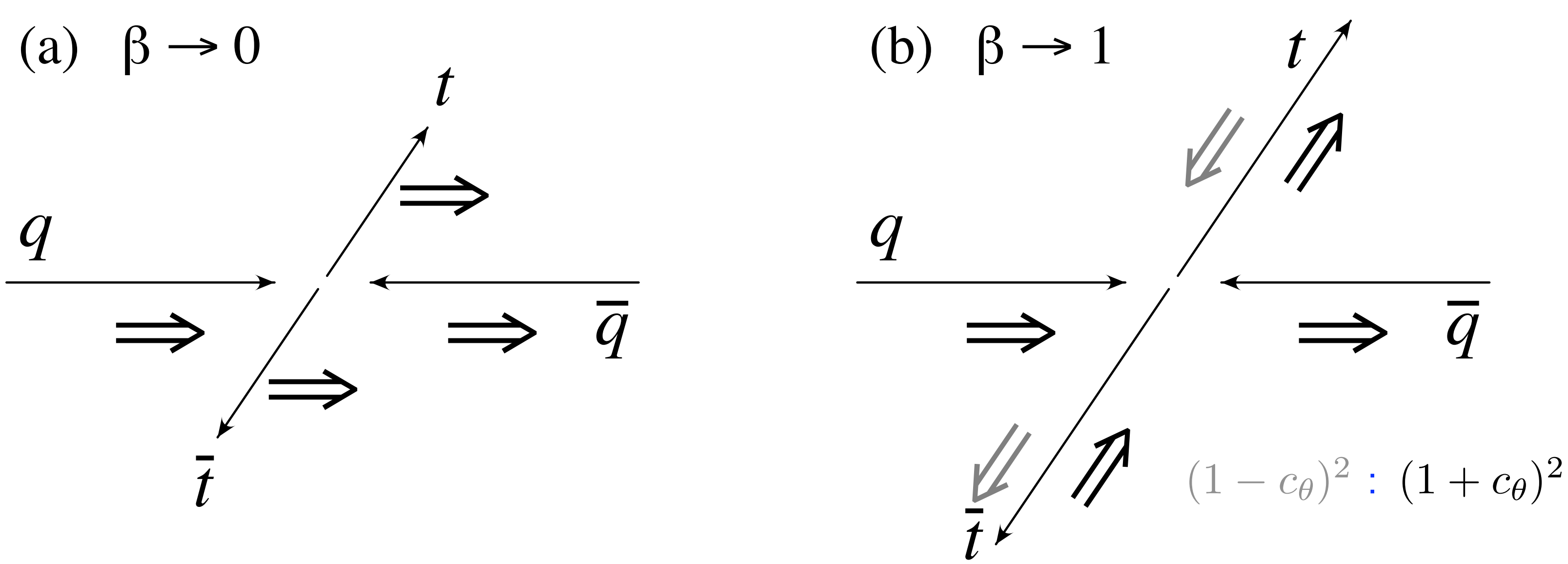
$q_L\bar{q}_R$ *or* $q_R\bar{q}_L \quad \to \quad t_U\bar{t}_D + t_D\bar{t}_U$ i.e. no $t_U\bar{t}_U$ *or* $t_D\bar{t}_D$

(the opposite — only UU+DD and no UD+DU — is not possible)

this spin axis is aligned with

- $q\bar{q}$ at threshold (beamline)
- $t\bar{t}$ at ultra-high energies (helicity)

and smoothly interpolates between these two.

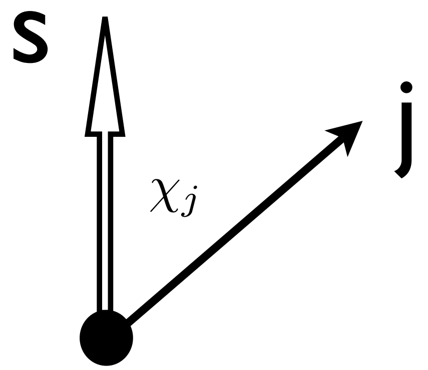


Off-Diagonal basis: UD or DU $= \left(1 \pm \sqrt{1-\beta^2 s_\theta^2}\right)^2$

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

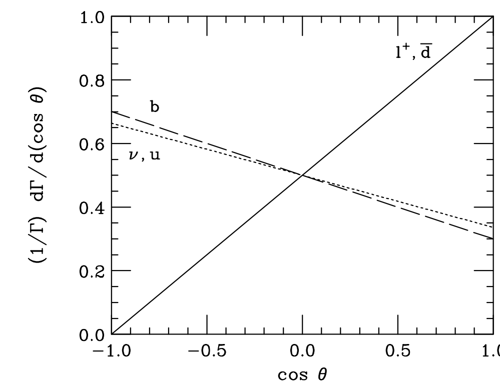
Polarized Top Deacay:

Top Rest Frame:



$$\frac{1}{\Gamma_t}\frac{d\,\Gamma}{d\cos\chi_j} = \frac{1}{2}(1+\alpha_j\cos\chi_j)$$

$$\alpha_j = \begin{cases} +1 & \bar{l}, d \\ -0.31 & \nu, \bar{u} \\ -0.41 & b \end{cases}$$

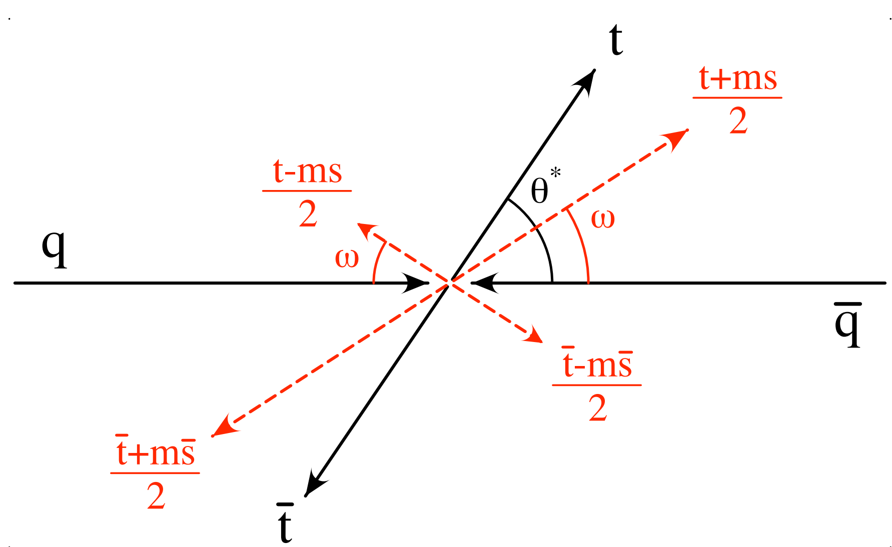


for anti-top $\bar{\alpha}_j = -\alpha_j$

in all frames the useful directions are given by

$$t_{1,2} = (t \pm ms)/2$$

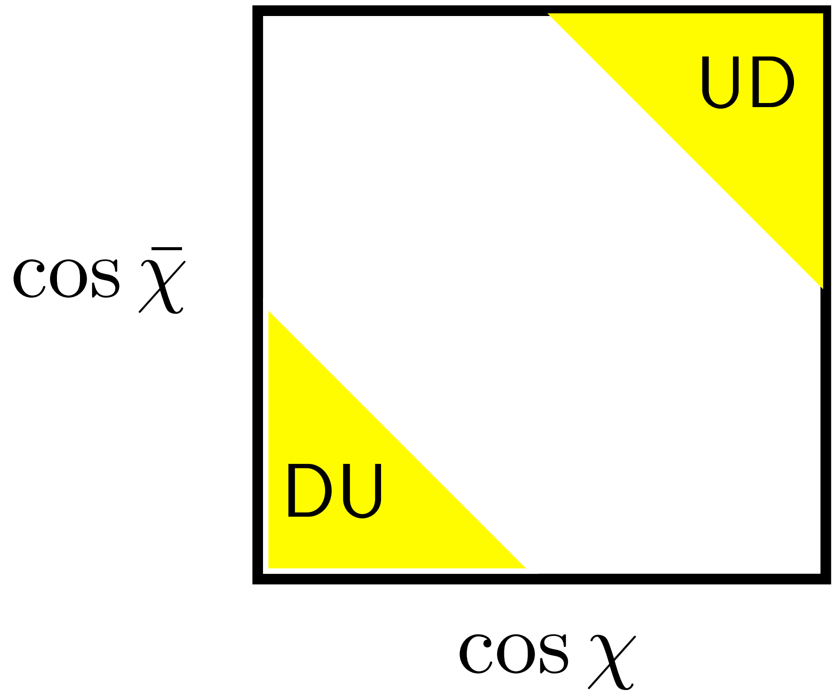
Note: $t_1^2 = t_2^2 = 0$ and $t_1 + t_2 = t$



Off Diagonal: $\sin\omega = \beta\sin\theta$

Combining Production and Decay:

- charged lepton decay mode



For this figure one has to construct

the top AND the anti-top rest frames !!!

- In other frames the charged leptons tend to be more back to back than if the tops decayed spherically (i.e. no correlations)

- In the ZMF (LAB) the correlations are (much) less obvious

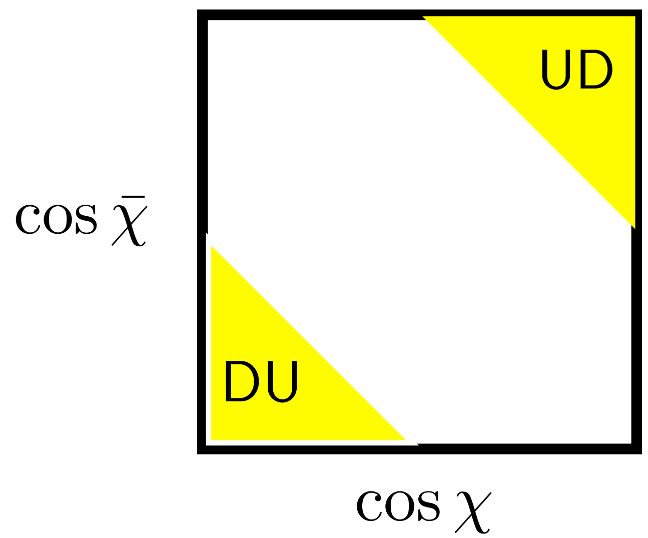
- What would be GREAT: a variable in the LAB that carries the signature of the spin correlation!

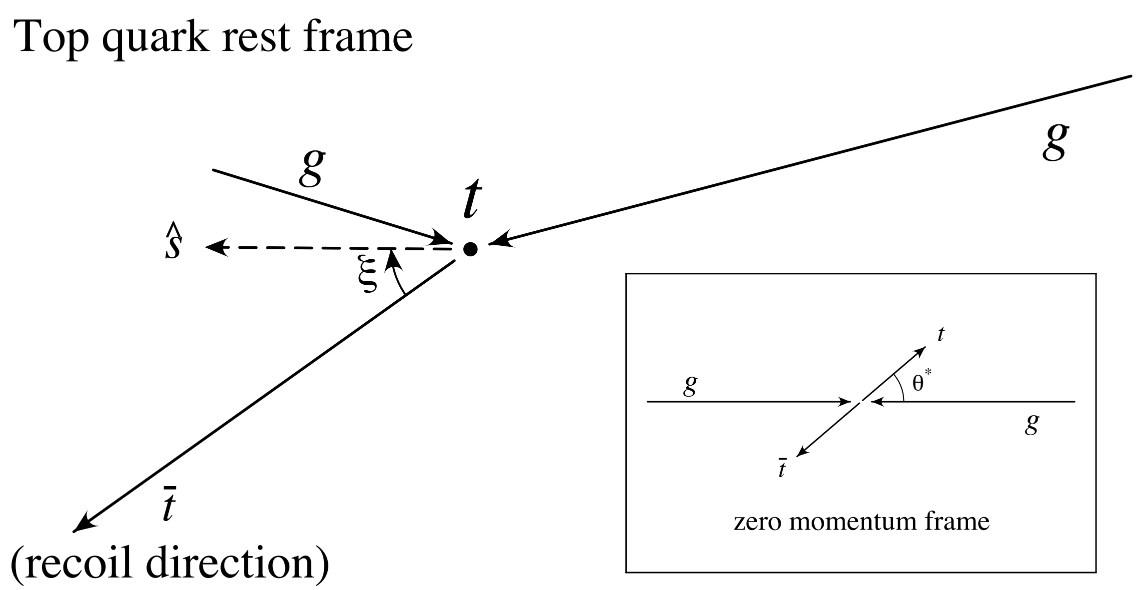
$gg \longrightarrow t\,\bar{t}$

UNLIKE helicity gluons:

$g_L g_R$ *or* $g_R g_L \longrightarrow t_U \bar{t}_D + t_D \bar{t}_U$ i.e. no $t_U \bar{t}_U$ *or* $t_D \bar{t}_D$

apart from a pre-factor identical to $q\bar{q} \rightarrow t\bar{t} \Rightarrow$ Off-Diagonal basis





$$\mathcal{M}(g_L g_R \rightarrow t_U \bar{t}_U \quad and \quad t_D \bar{t}_D) \sim \left(\frac{9+7\beta^2 c_\theta^2}{(1-\beta^2 c_\theta^2)^2}\right) \beta^2 s_\theta^2 \, (\gamma^{-1} s_\theta c_\xi - c_\theta s_\xi)^2$$

$$\rightarrow 0 \quad when \quad \tan\xi = \gamma^{-1}\tan\theta$$

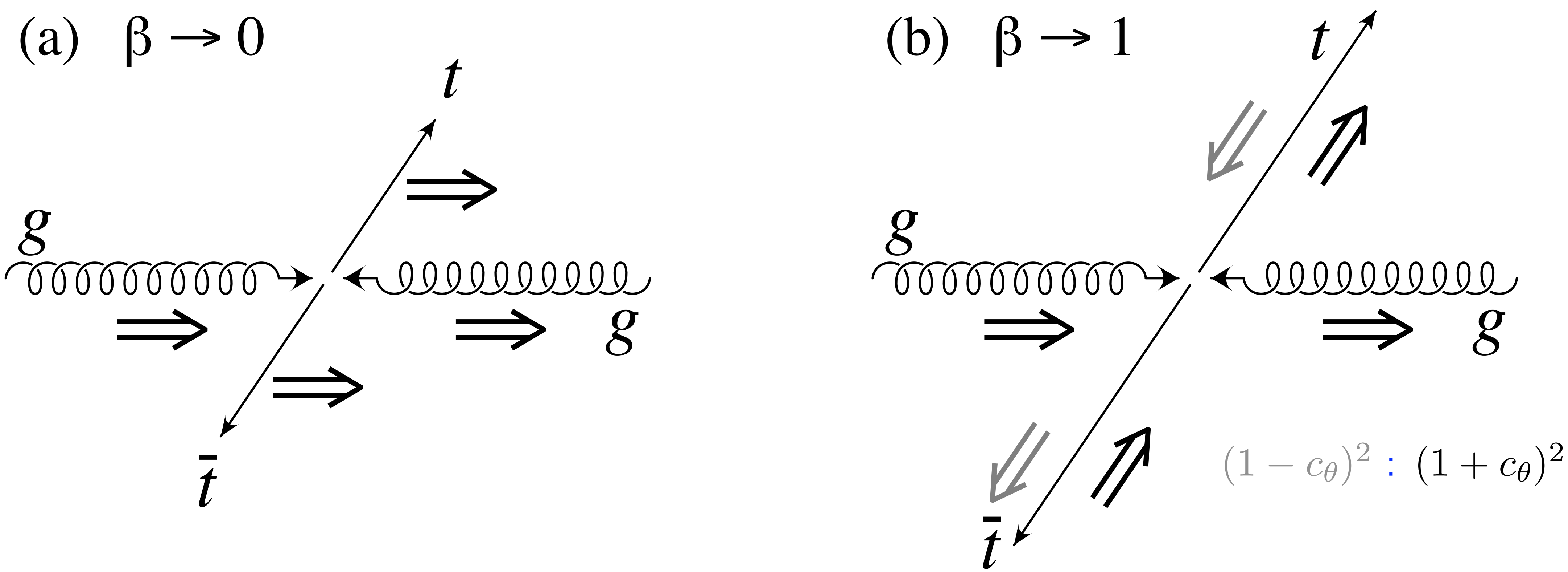
$$\frac{\partial}{\partial\xi} \sim J_+ - J_-$$

$$\mathcal{M}(g_L g_R \rightarrow t_U \bar{t}_D \quad or \quad t_D \bar{t}_U) \sim \left(\frac{9+7\beta^2 c_\theta^2}{(1-\beta^2 c_\theta^2)^2}\right) \beta^2 s_\theta^2 \, (\gamma^{-1} s_\theta s_\xi + c_\theta c_\xi \pm 1)^2$$

$$\rightarrow (\cdots)\,\beta^2 s_\theta^2 \left[1 \pm \sqrt{1-\beta^2\sin^2\theta}\right]^2$$

$\gamma\gamma \rightarrow t\bar{t}$ Hori, Kiyo and Nasuno hep-ph9712379

$g_L g_R$ *or* $g_R g_L \rightarrow t_U \bar{t}_D + t_D \bar{t}_U$ i.e. no $t_U \bar{t}_U$ *or* $t_D \bar{t}_D$



$gg \to t\,\bar{t}$

LIKE helicity gluons:

$g_L g_L \quad or \quad g_R g_R \quad \to \quad t_L \bar{t}_L \; + \; t_R \bar{t}_R$ i.e. no $t_L \bar{t}_R \; or \; t_R \bar{t}_L$

independent of energy.

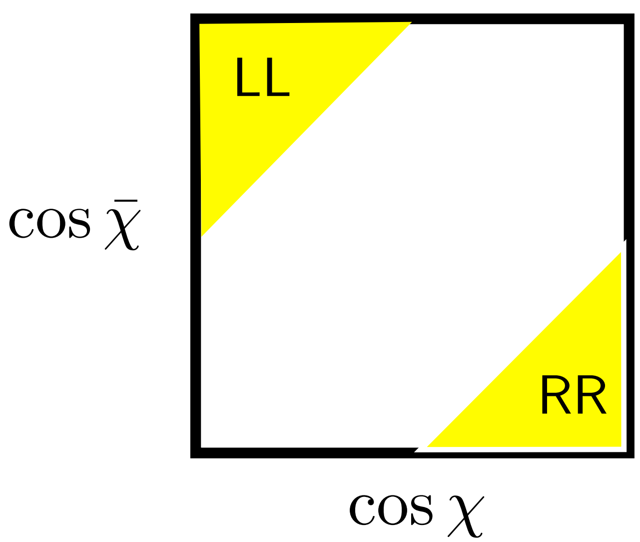
(the opposite — only UD+DU and no UU+DD — is not possible)

$$|\mathcal{M}(g_R g_R \to t_L \bar{t}_R \quad and \quad t_R \bar{t}_L)|^2 \sim \left(\frac{9 + 7\beta^2 c_\theta^2}{(1-\beta^2 c_\theta^2)^2}\right)\beta^2 s_\xi^2$$

$$\to \; 0 \quad when \quad \sin\xi = 0 \quad helicity$$

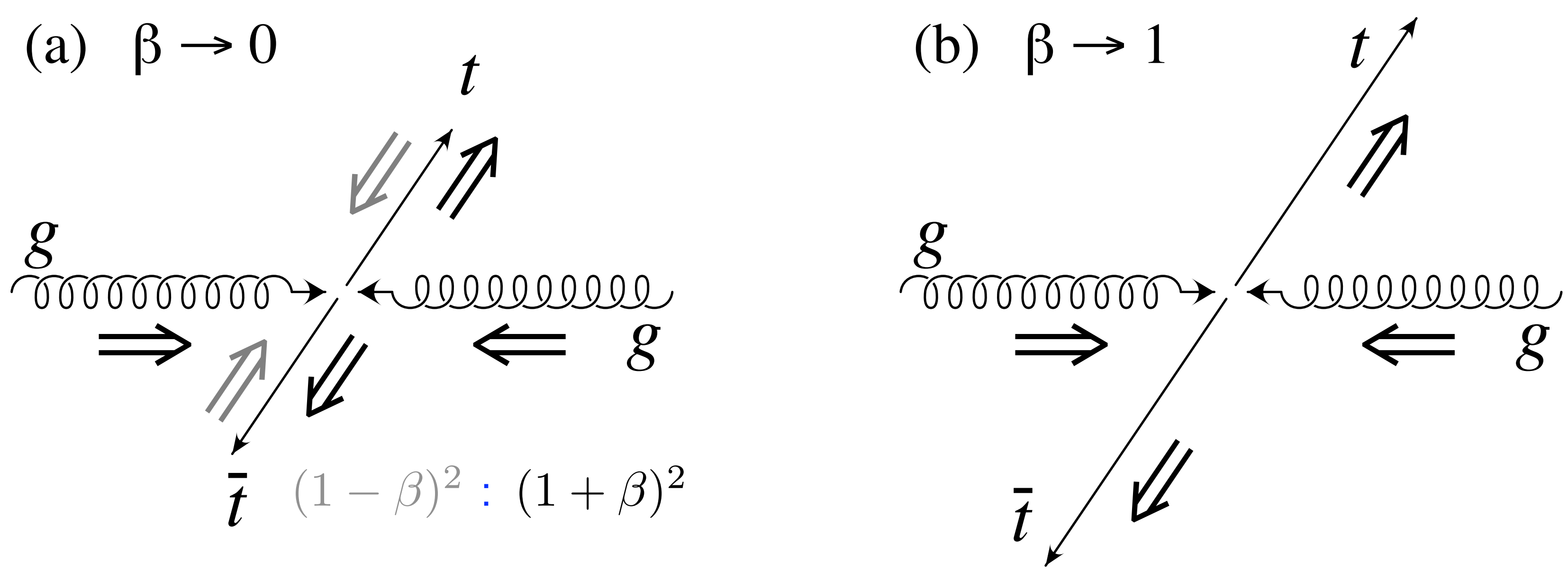
$$|\mathcal{M}(g_R g_R \to t_R \bar{t}_R \quad or \quad t_L \bar{t}_L)|^2 \sim \left(\frac{9 + 7\beta^2 c_\theta^2}{(1-\beta^2 c_\theta^2)^2}\right)(1 \pm \beta c_\xi)^2$$

$$\to \; (\cdots) \; [1 \pm \beta]^2$$

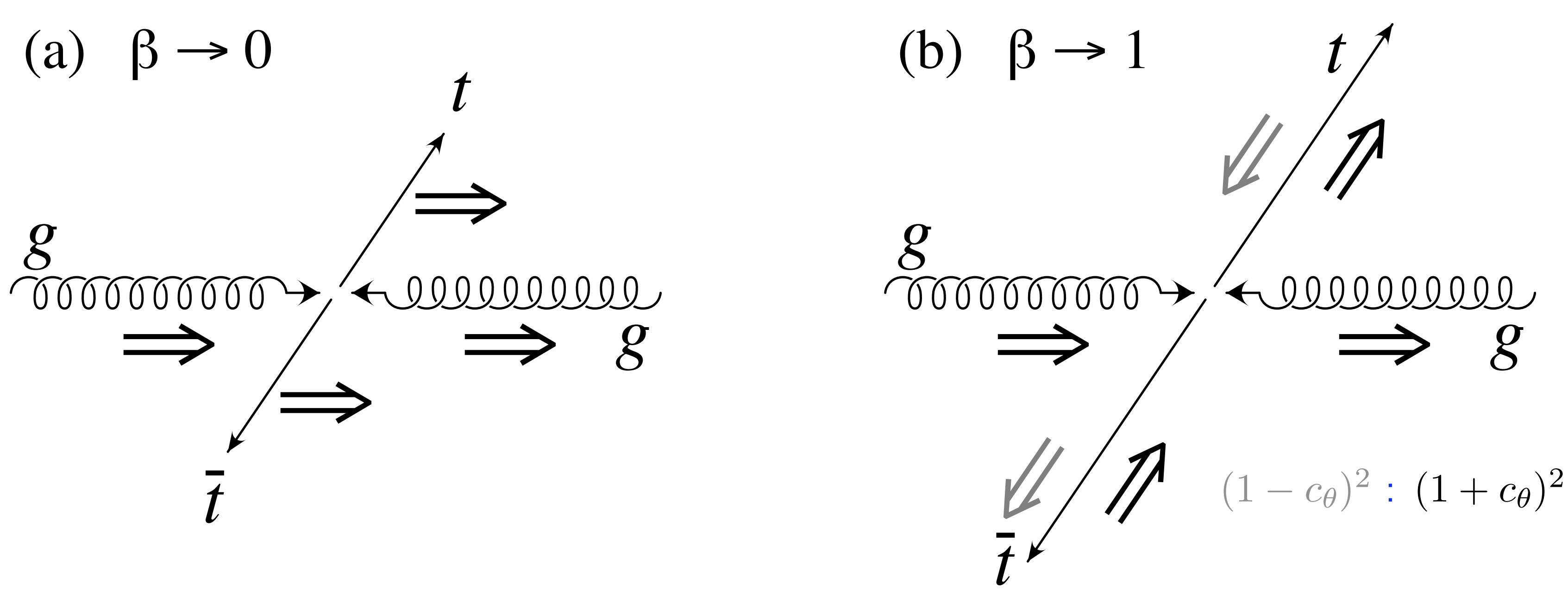


- In other frames, the charged leptons are less back to back than if there was no spin correlations.

$g_L g_L$ *or* $g_R g_R \;\rightarrow\; t_L \bar{t}_L \;+\; t_R \bar{t}_R$ i.e. no $t_L \bar{t}_R$ *or* $t_R \bar{t}_L$



$g_L g_R$ *or* $g_R g_L \;\rightarrow\; t_U \bar{t}_D \;+\; t_D \bar{t}_U$ i.e. no $t_U \bar{t}_U$ *or* $t_D \bar{t}_D$



- Because of the contributions from BOTH UNLIKE and LIKE helicity-gluons $gg \rightarrow t\,\bar{t}$ is much RICHER than $q\,\bar{q} \rightarrow t\,\bar{t}$.

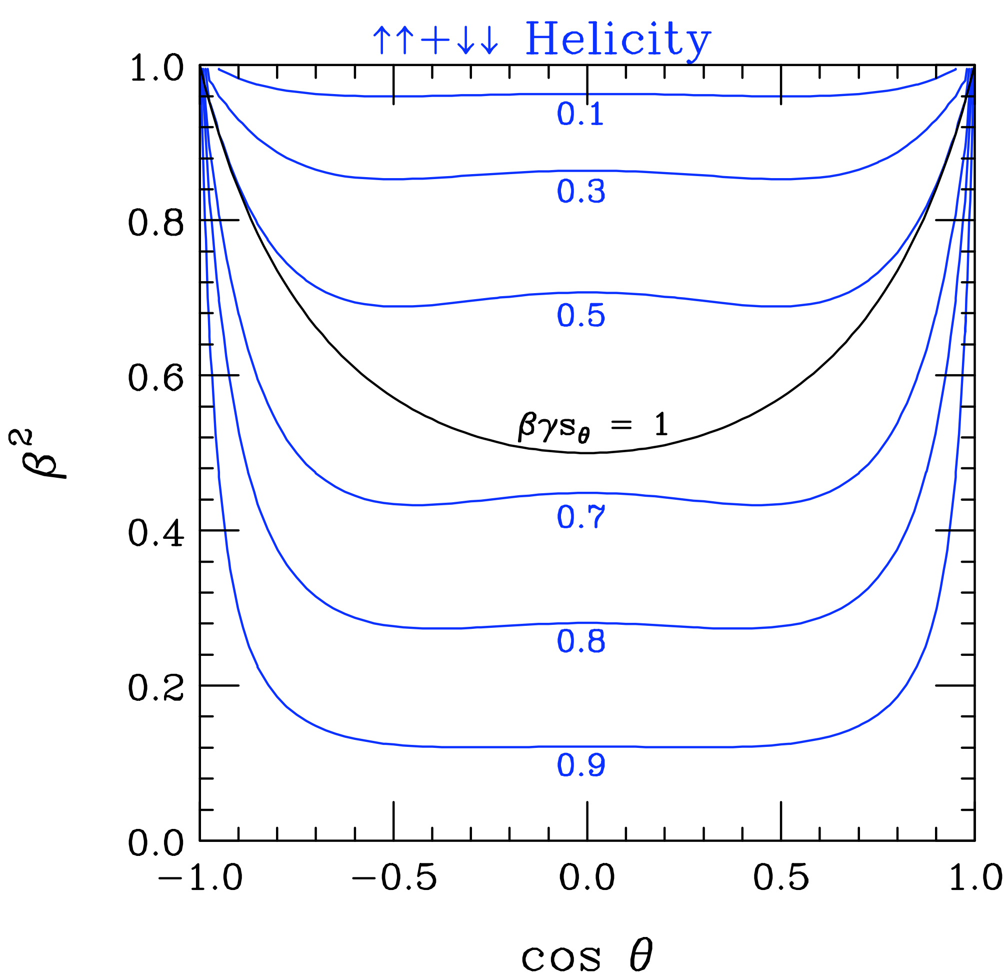
TOTAL:

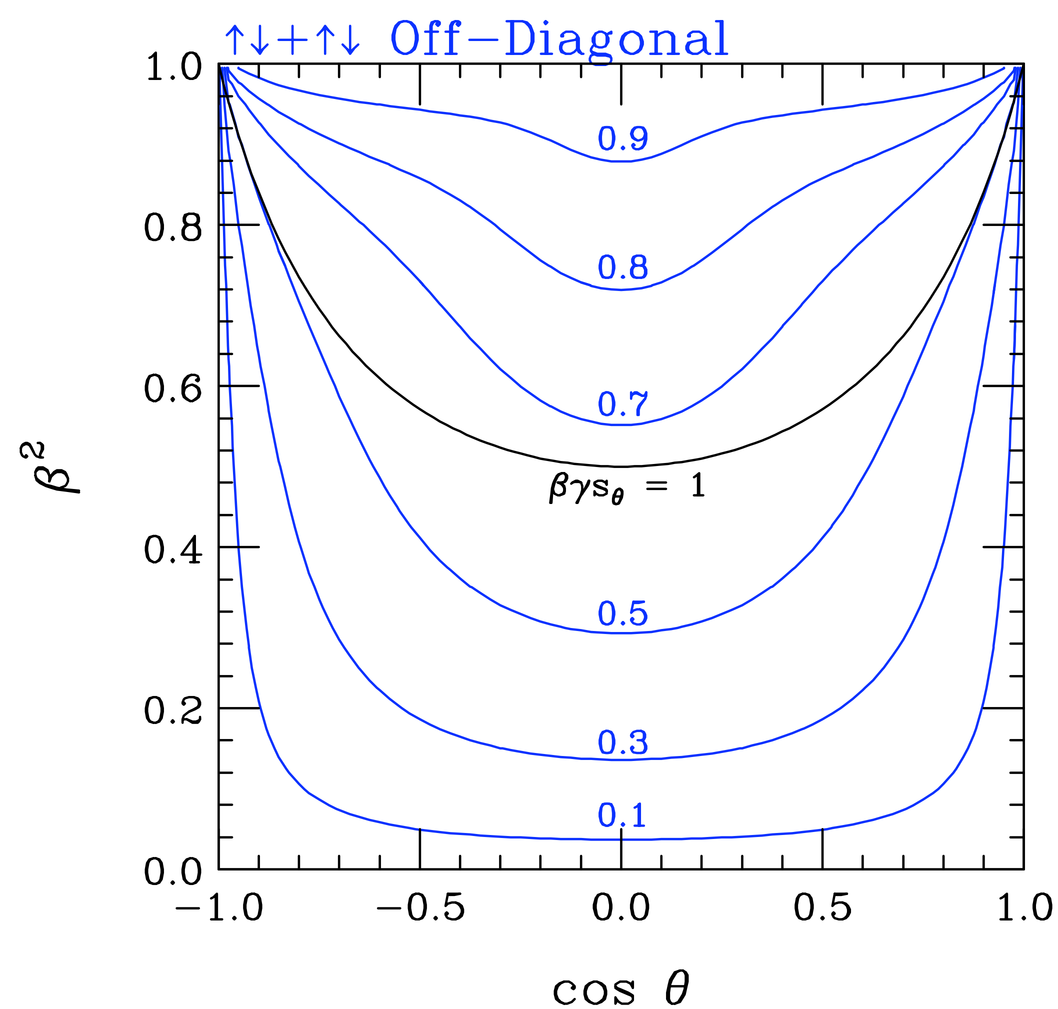
$$|\mathcal{M}(gg \to t\bar{t})|^2 \sim \left(\frac{9+7\beta^2 c_\theta^2}{(1-\beta^2 c_\theta^2)^2}\right)\left[(1-\beta^4) + \beta^2 s_\theta^2(2-\beta^2 s_\theta^2)\right]$$

LIKE *UNLIKE* (*equal when* $\beta\gamma s_\theta = 1$)

$$\beta^2 < \frac{1}{2-c_\theta^2}$$ *LIKE dominates*

$$\beta^2 > \frac{1}{2-c_\theta^2}$$ *UNLIKE dominates*





- Use Helicity for $\beta\gamma s_\theta < 1$ and Off-Diagonal for $\beta\gamma s_\theta > 1$

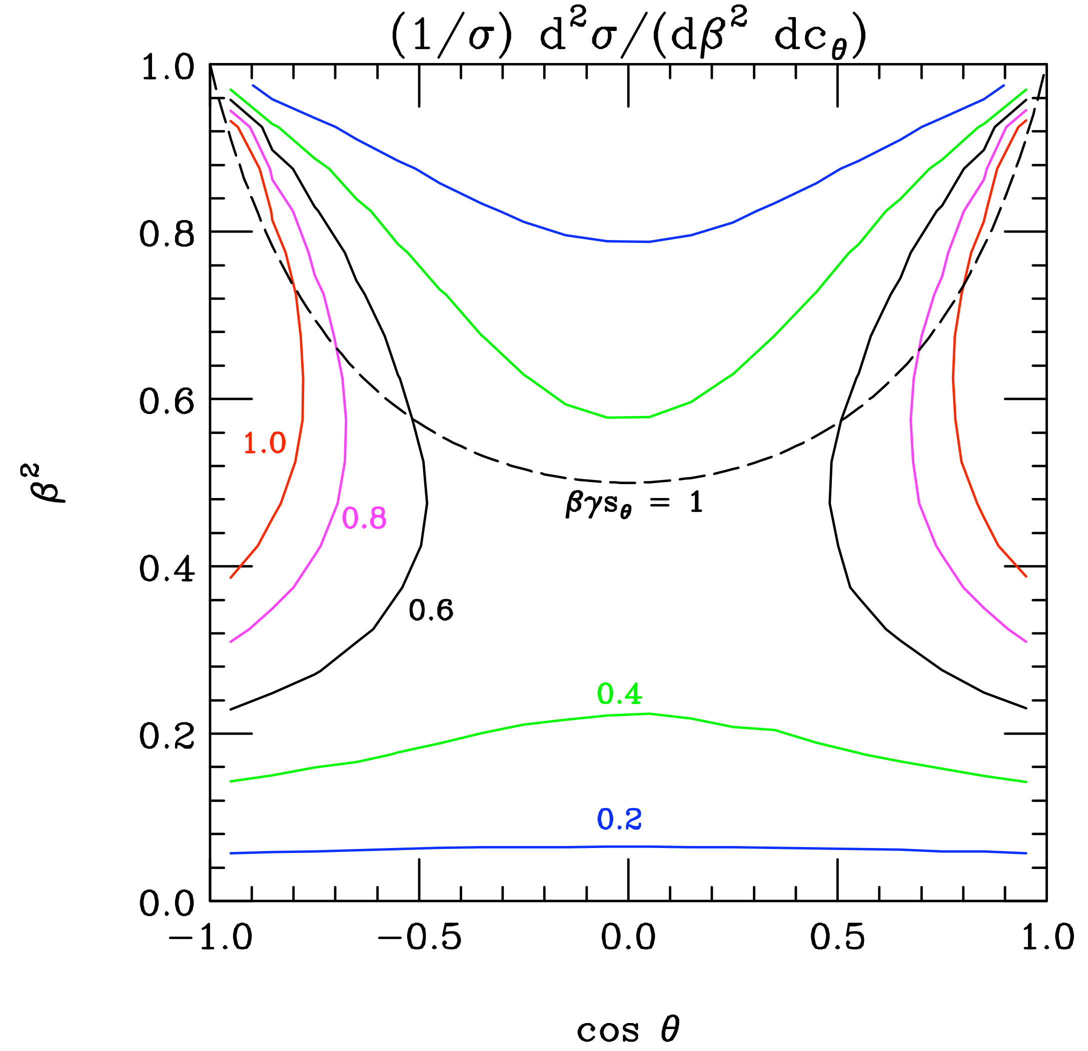
a good approx. to the best possible

Where are the Events?

$$\frac{1}{\sigma_T}\ \frac{d^2\sigma}{d\beta^2\, dc_\theta}$$

LHC @ 14 TeV
where $\sigma_T \approx 1\ nb$

$\beta\gamma s_\theta$	any	<1	>1
Total	100%	75	25
Like	65	55	10
Unlike	35	20	15



- Concentrate the low β region where the boost doesn't disguise the correlations.

$\Rightarrow$ LIKE Helicity Gluons

LIKE HELICITY GLUONS

- For on-mass shell tops and using spinor helicity gluon polarizations

$$\mathcal{M}(g_R g_R \to t\bar{t}) \sim \left(\frac{T^{a_1}T^{a_2}}{p_1 \cdot t} + \frac{T^{a_2}T^{a_1}}{p_2 \cdot t}\right)_{\bar{i}i} \quad m\ \bar{U}_t\ \gamma_{\mathbf{L}}\ V_{\bar{t}}$$

including decays ($t \to b + \bar{l} + \nu$ and $\bar{t} \to \bar{b} + l + \bar{\nu}$) is then simple (after Fierz), replace $\bar{U}_t \to \langle b - |\nu\rangle\langle\bar{l} + |(t+m)$ and $V_{\bar{t}} \to (-\bar{t} + m)|l+\rangle\langle\bar{\nu} + |\bar{b}-\rangle$.

- Sum RR + LL

$$|\mathcal{M}|^2_{corr} \sim m^2 \left[(t \cdot l)(t \cdot \bar{l}) + (\bar{t} \cdot l)(\bar{t} \cdot \bar{l}) - m^2 (l \cdot \bar{l})\right]$$

whereas the uncorrelated $|\mathcal{M}|^2 \sim (t \cdot \bar{l})(\bar{t} \cdot l)(t \cdot \bar{t})$.

- In the ZMF

$$\mathcal{S} \equiv \frac{|\mathcal{M}|^2_{corr}}{|\mathcal{M}|^2{}_{uncorr}} = \frac{(1-\beta^2)}{(1+\beta^2)} \frac{[(1+\beta^2)+(1-\beta^2)\,c_{\bar{t}\bar{l}} - 2\beta^2 c_{t\bar{l}}\, c_{\bar{t}l}]}{(1-\beta c_{t\bar{l}})(1-\beta c_{\bar{t}l})}$$

$$2 \geq \mathcal{S} \geq 0$$

- Maximum Value, $\mathcal{S} = 2$, when $c_{t\bar{l}} = -c_{\bar{t}l} = \pm 1$ and $c_{\bar{l}l} = +1$

Enhancement when charged leptons are parallel and correlated with $t\bar{t}$ axis.

Minimum Value, $\mathcal{S} = 0$, when $c_{t\bar{l}} = c_{\bar{t}l} = \pm 1$ and $c_{\bar{l}l} = -1$

Suppression when charged leptons are anti-parallel and correlated with $t\bar{t}$ axis.

However, the strength of the correlation with the $t\bar{t}$ axis is β dependent. None at threshold and strengthens as β increases.

- Look at angular distributions associated with the two charged leptons.

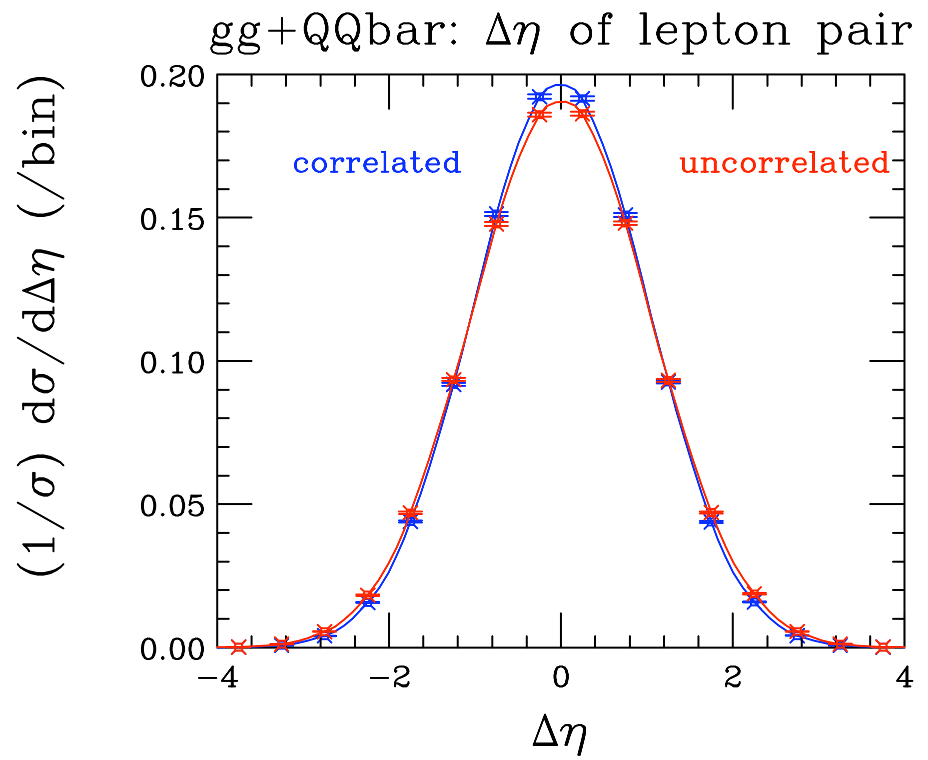
$$\Delta R,\ \Delta\eta \text{ and } \Delta\phi$$

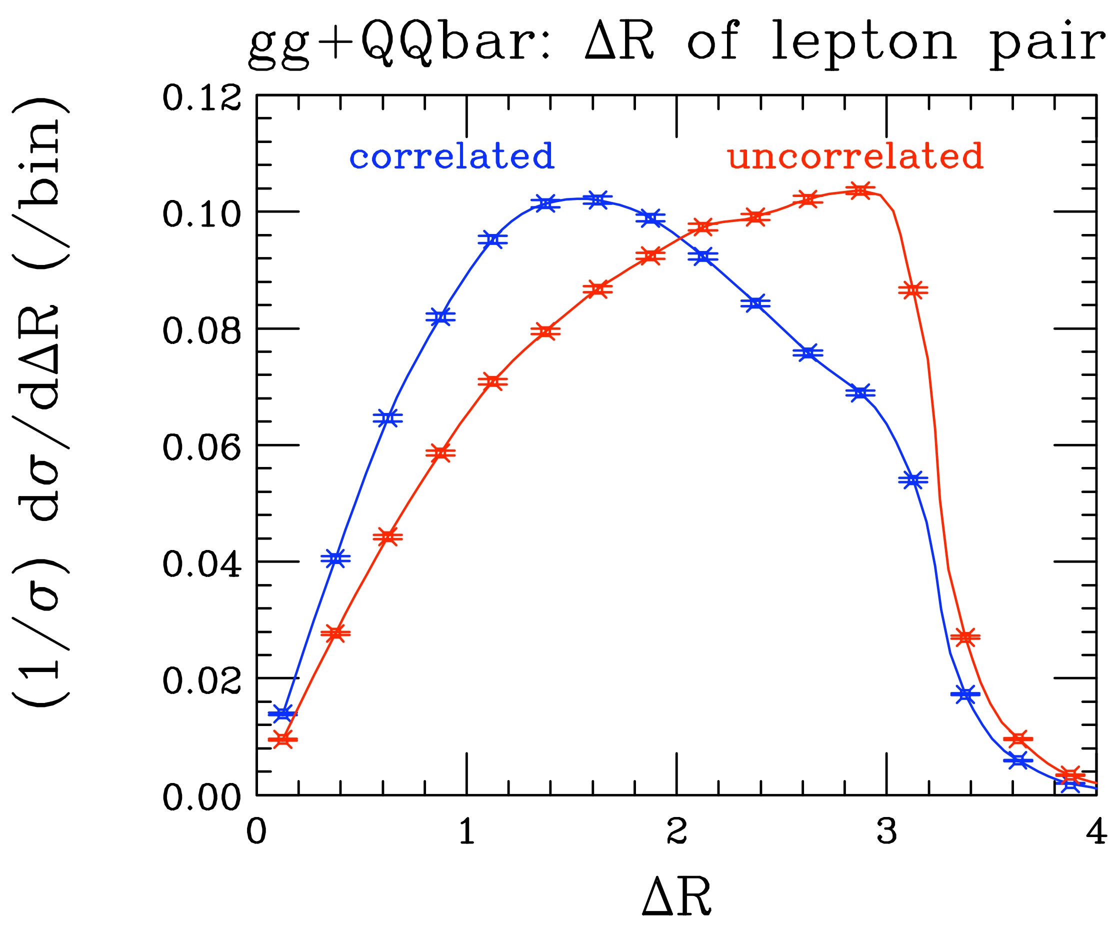
at low β.

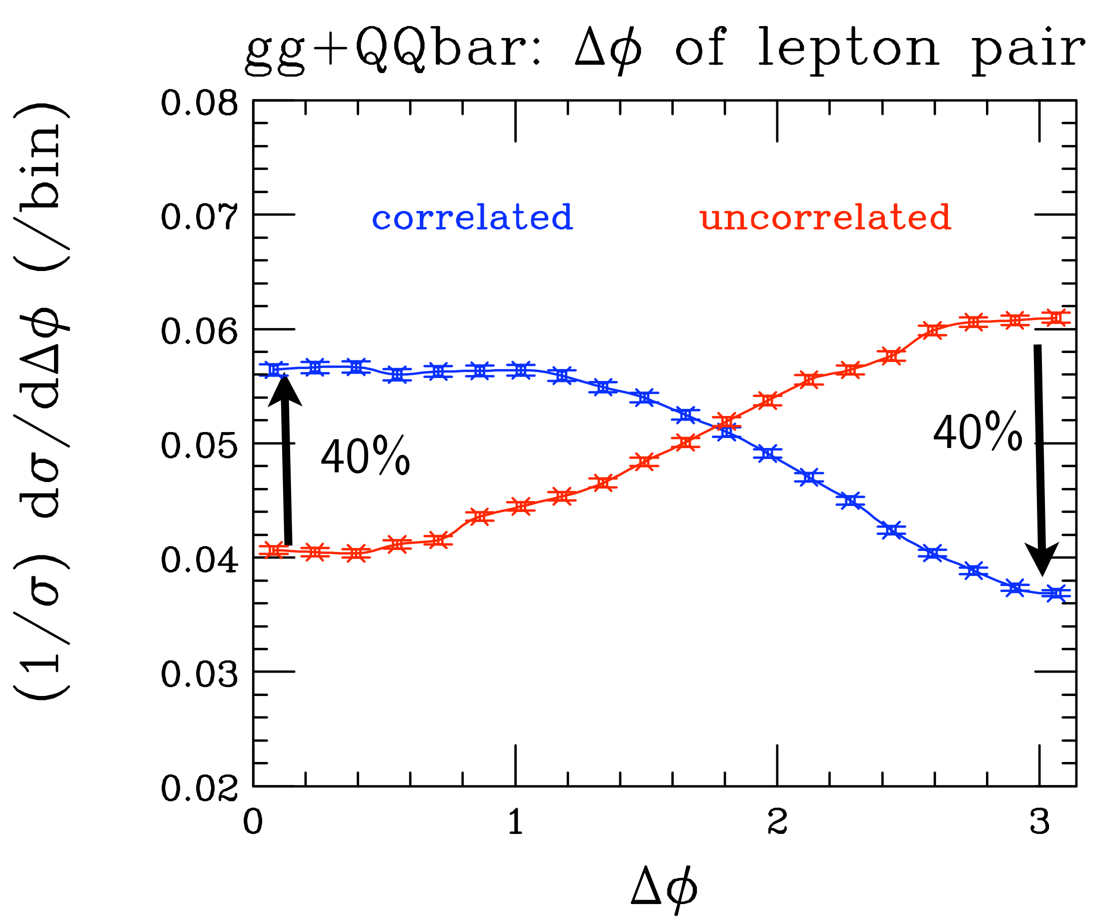
ΔR and $\Delta\phi$ for di-lepton Events

Cuts:

- $\beta \leq 0.5$ or $m_{t\bar{t}} \leq 400$ GeV
- $p_T^l > 20$ GeV and $|\eta_l| < 3$







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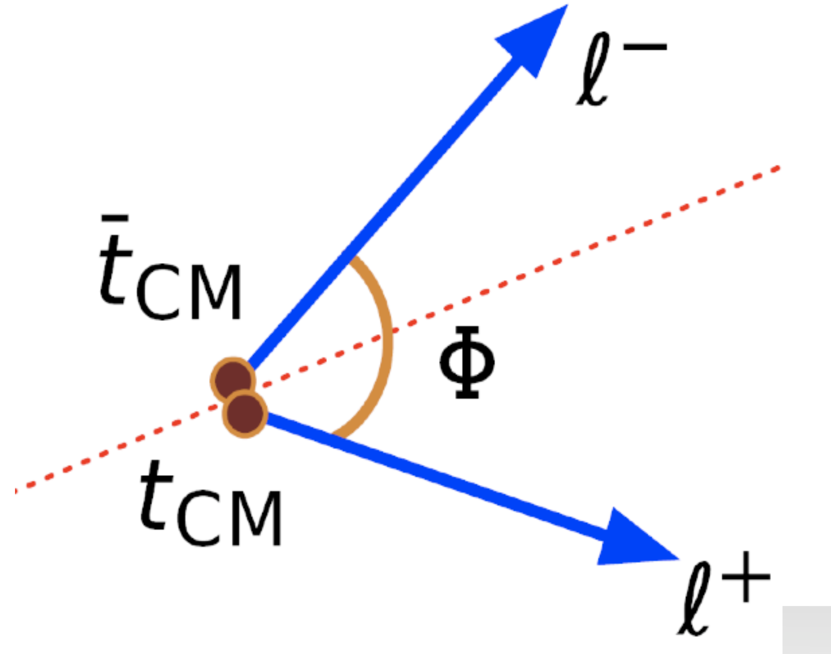
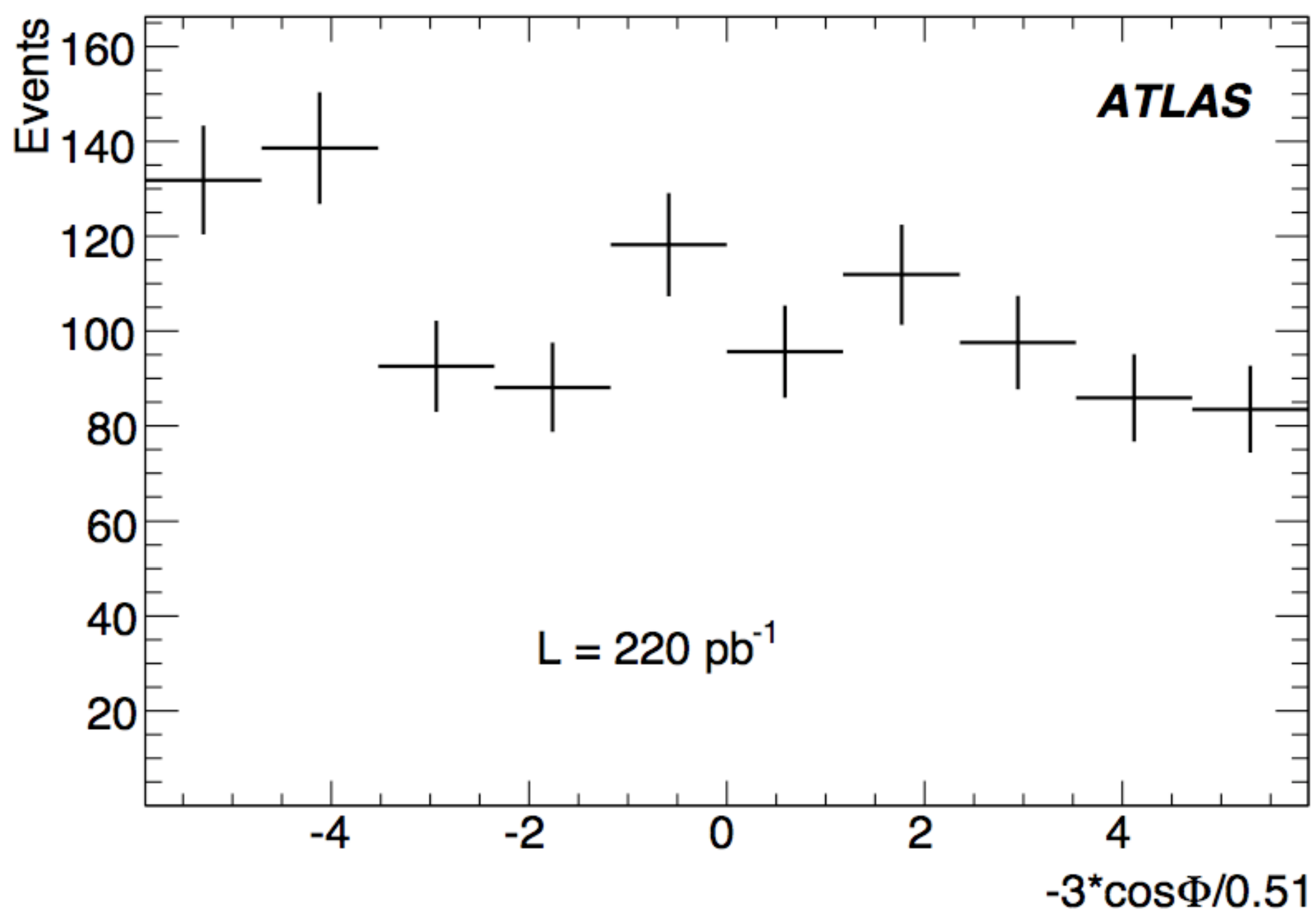


Φ → angle between the two spin analysers (in the corresponding t rest frame)

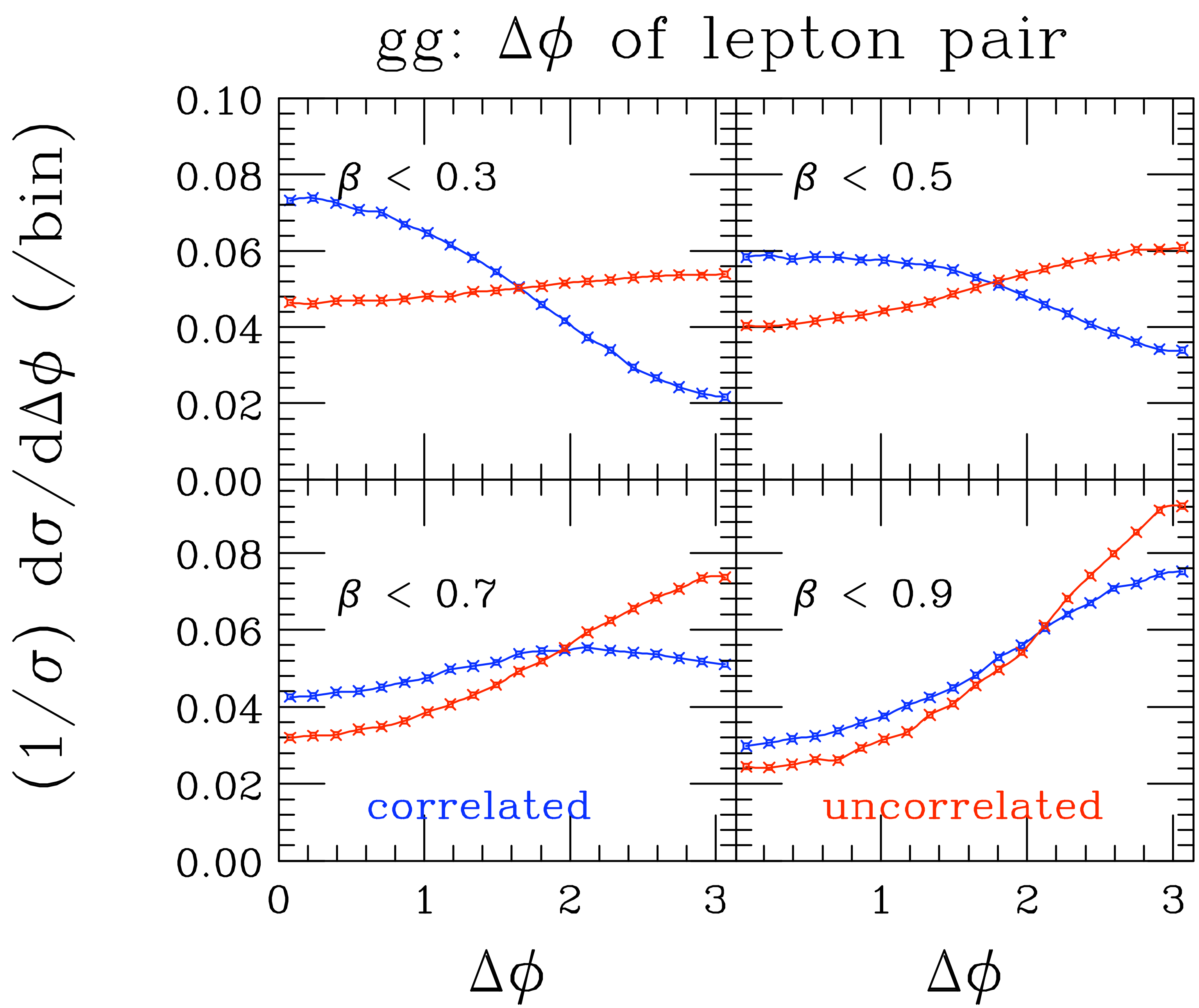
($m_{t\bar{t}} < 550$ GeV)



Questions:

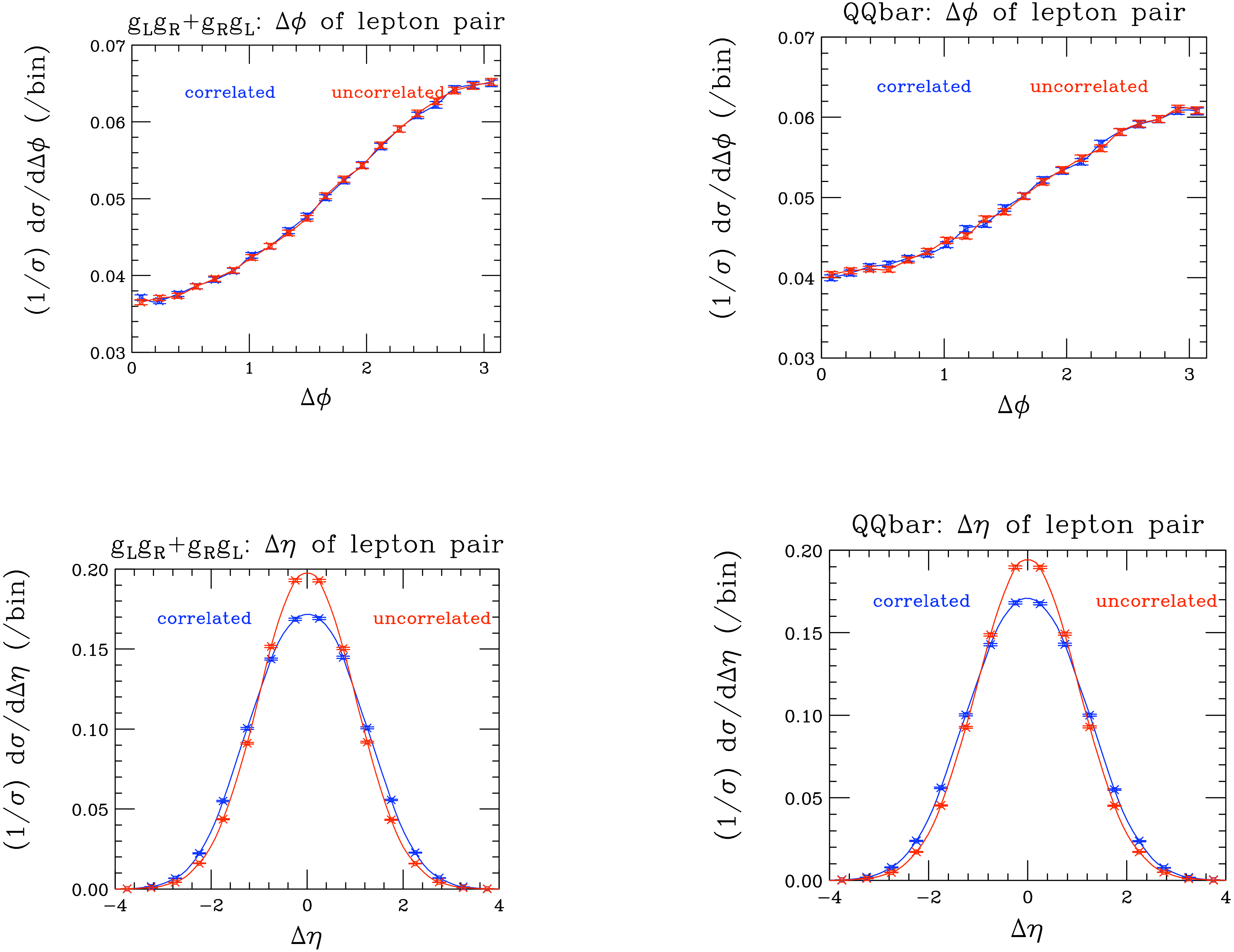
- What about varying the β or $m_{t\bar{t}}$ cut?
- What about contribution from $g_L g_R + g_R g_L$ and $q\bar{q}$?
- What about NLO effects?

Varying $m_{t\bar{t}}$ cut



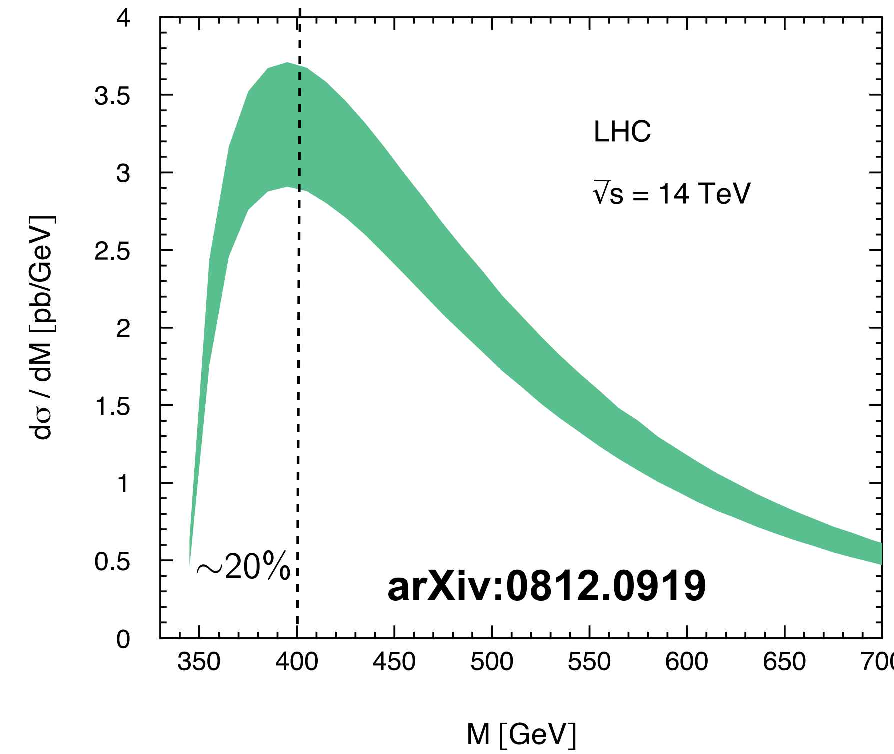
β	$m_{t\bar{t}}$ (GeV)
0.0	350
0.3	366
0.5	404
0.7	490
0.9	803

Contributions from $g_L g_R + g_R g_L$ and $q\bar{q}$



NLO

- Used MCFM special edition: Has NLO top production $\otimes$ decays !



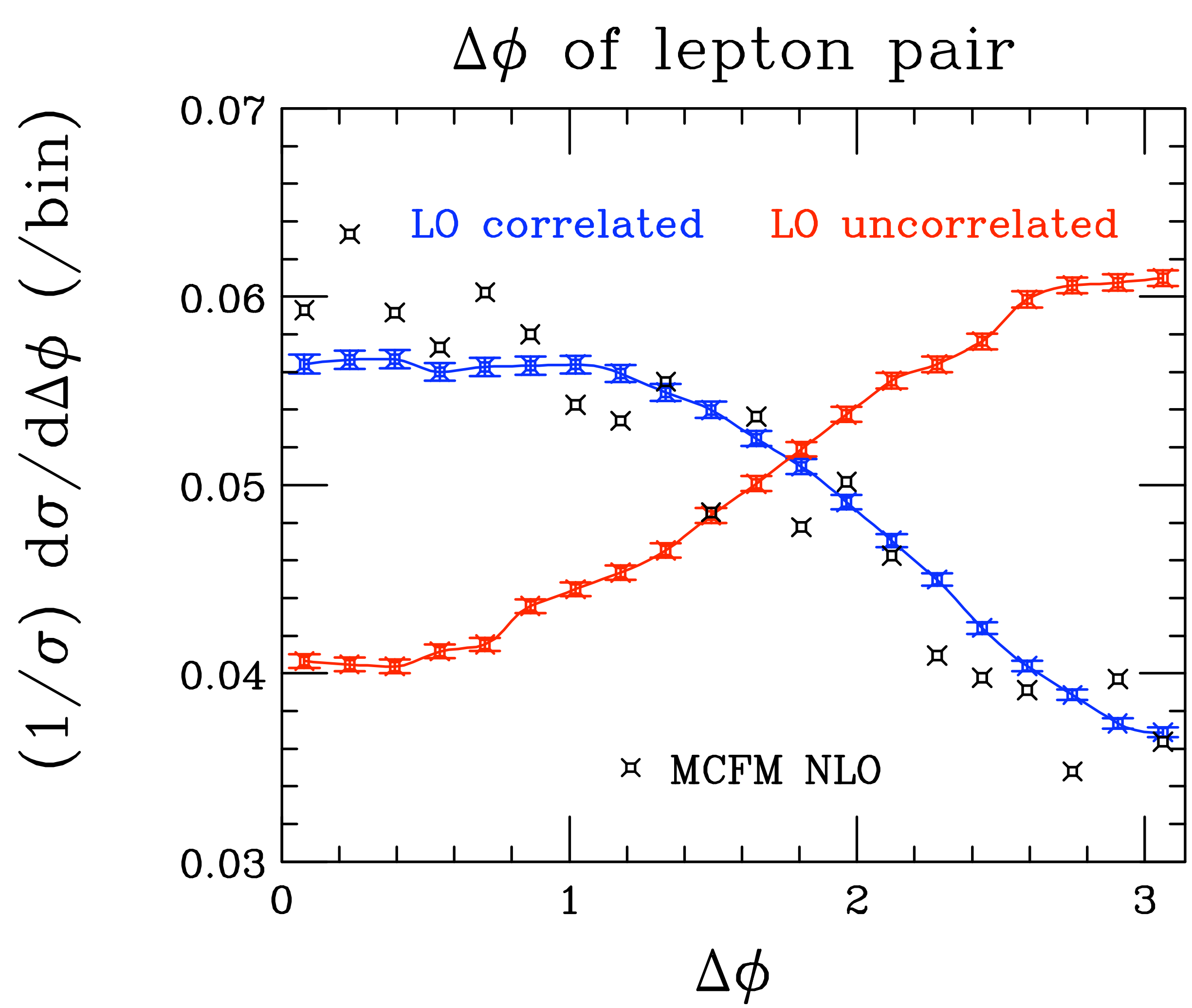
Cuts:

- $p_T^l > 20$ GeV and $|\eta_l| < 3$
- $\sqrt{\hat{s}} \leq 400$ GeV

- 20% of cross section passes these cuts or about 200 pb

- Events Produced per fb^{-1}:
  200pb $\times$ 1000 pb^{-1} $=$ 2 $\times$ 10^5
- di-lepton (e, μ) Branching Fractions $=$ 4/81
- Efficiency $\sim$ 10%

- 1000 di-lepton (e, μ) events per fb^{-1}



Anomalous Couplings:

- Chromo-magnetic moment of the top quark $\sim G_{\mu\nu}\bar{\Psi}_t\sigma^{\mu\nu}\gamma_5\Psi_t$

- Will affect the spin correlations of the top quark pair and hence the azimuthal distributions of the charged leptons from top.

- Previous studies, see hep-ph/0006021, have been for ILC, need to be repeated for LHC.

Summary

- Spin correlations in $gg \to t\ \bar{t}$ have a RICH structure, but simply understood when separated into the LIKE and UNLIKE gluon-helicity components.

- TTbar events at low invariant mass is a promising region of phase space

- In this region, LIKE helicity gluons dominate the production which give particularly strong correlations of the decay products

- ΔR and $\Delta\phi$ for the di-leptons are especially easy to measure and carry a characteristic signature of the correlations at low values of $m_{t\bar{t}}$

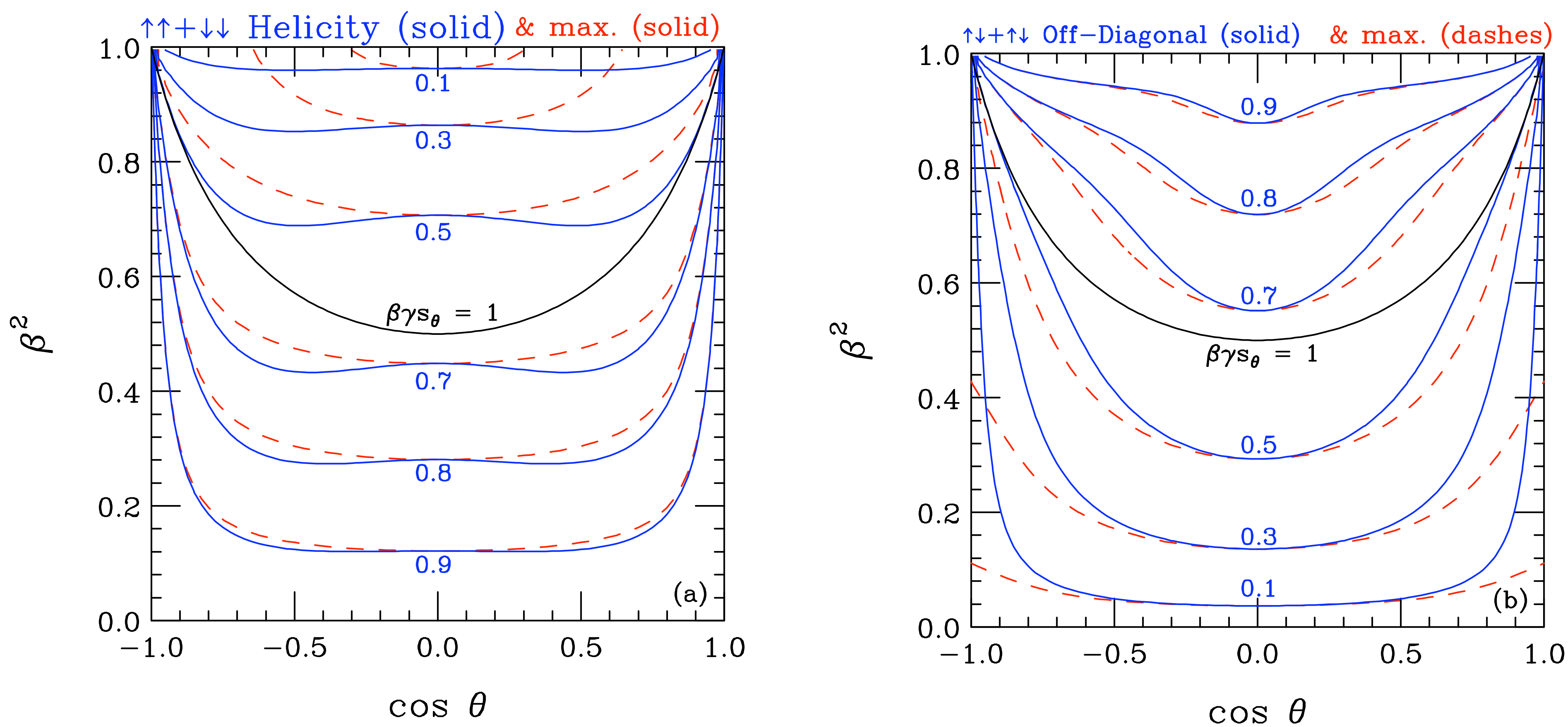
- Next: effects of anomalous couplings – e.g. chromo-magnetic moment of top quark extras:

Maximizing UU+DD or UD+DU for gg to TTbar

$$\tan 2\xi_{\{\text{same, oppo}\}} = \frac{2\gamma^{-1}\sin^3\theta\cos\theta}{(\sin^2\theta\cos^2\theta - \gamma^{-2}\sin^4\theta - \gamma^{-2})} \qquad \xi_{\text{oppo}} = \xi_{\text{same}} + \pi/2.$$

$$f_{\{\text{same, oppo}\}}(\theta,\beta) \equiv$$

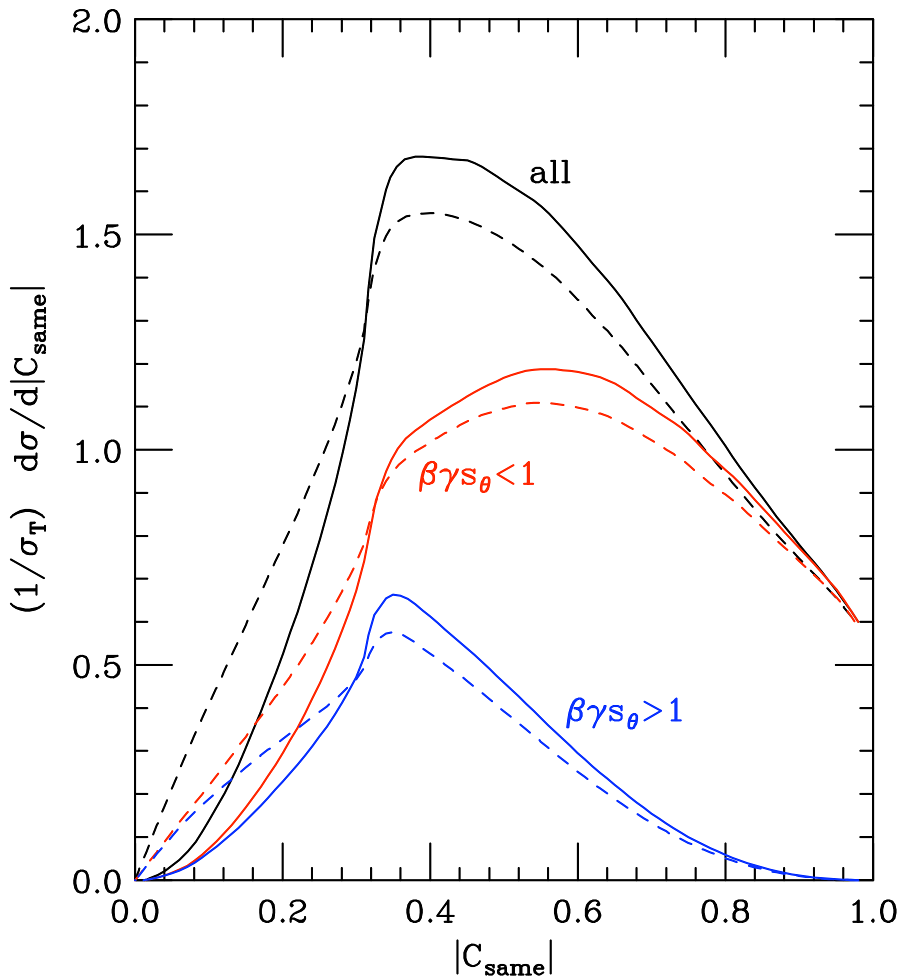
$$\frac{\gamma^{-2} + \frac{1}{2}\beta^2(\sin^2\theta\cos^2\theta + \gamma^{-2}\sin^4\theta + \gamma^{-2})\left\{1 \pm \sqrt{1 - \frac{(2\gamma^{-1}\cos\theta\sin\theta)^2}{(\sin^2\theta\cos^2\theta + \gamma^{-2}\sin^4\theta + \gamma^{-2})^2}}\right\}}{((1-\beta^4) + \beta^2\sin^2\theta(2 - \beta^2\sin^2\theta))}.$$



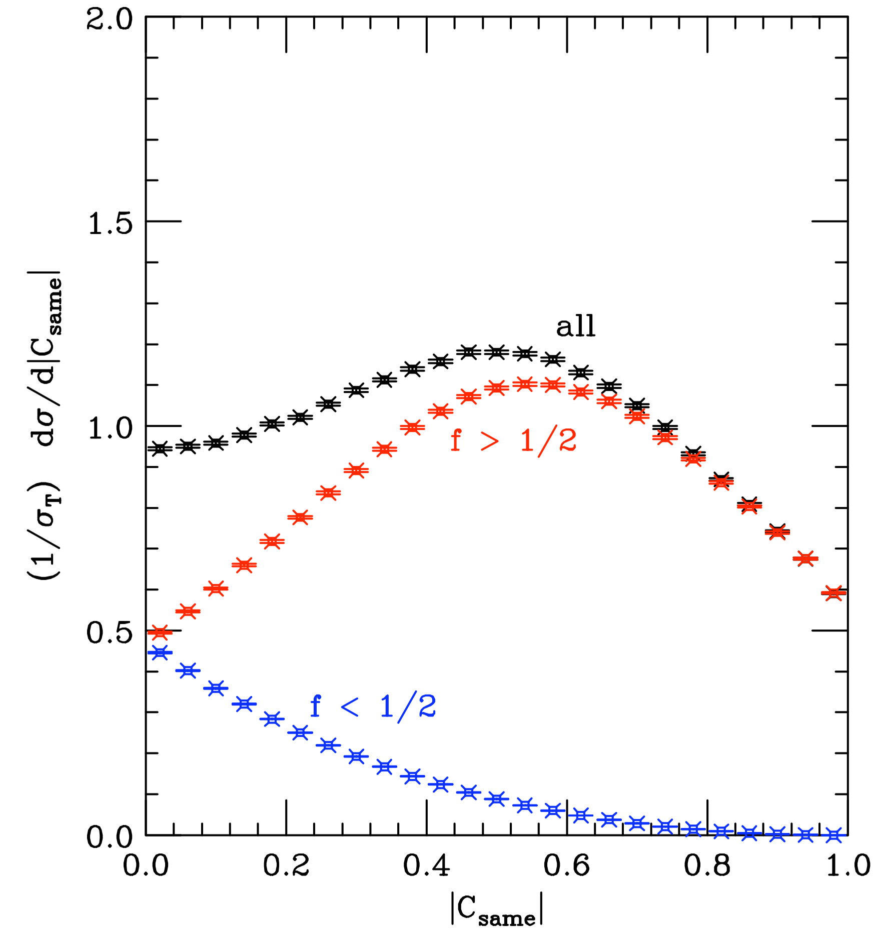
related to numerical work by P. Uwer in **hep-ph/0412097**

$$C_{same} \equiv 2f_{\uparrow\uparrow+\downarrow\downarrow} - 1 = 1 - 2f_{\uparrow\downarrow+\downarrow\uparrow} \equiv -C_{oppo}$$

Optimal and Hel./OD



Helicity



$\vert\langle C_{same}\rangle\vert$	all+flip	all+noflip	lower	upper
Optimal	0.55	0.35	0.60 (76%)	0.43
Hel./OD	0.53	0.34	0.57 (76%)	0.39
Hel.	0.48	0.41	0.52 (86%)	0.23

Angular reconstruction and results

- Light jet pairs which give the mass closest to Mw.
- Pair with b-jet which gives Mjjb closest to Mtop
  - 1D distributions of $\cos\theta_1\cos\theta_2$ and $\cos\Phi$ distributions corrected bin-by-bin back to generator level to extract spin correlation
- Statistical/systematic uncertainties

Measurement	Int L	stat	syst
$A(q\text{-}l) \approx 0.67$	1 fb^{-1}	0.17	0.18
$A_D(q\text{-}l) \approx -0.40$	1 fb^{-1}	0.11	0.09

- Require $O(10\ fb^{-1})$ to observe 5σ
  - Good control of systematics essential
    - B-tagging efficiency, jet energy scale, ISR/FSR …

Reconstructed, corrected to generator level