Probing top Higgs Yukawa coupling at the LHC via single top +h production

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In collaboration with Vernon Barger (U. Wisconsin) and Kaoru Hagiwara (KEK), PRD99(2019)031701 [arXiv:1807.00281] and work in progress.

Outline

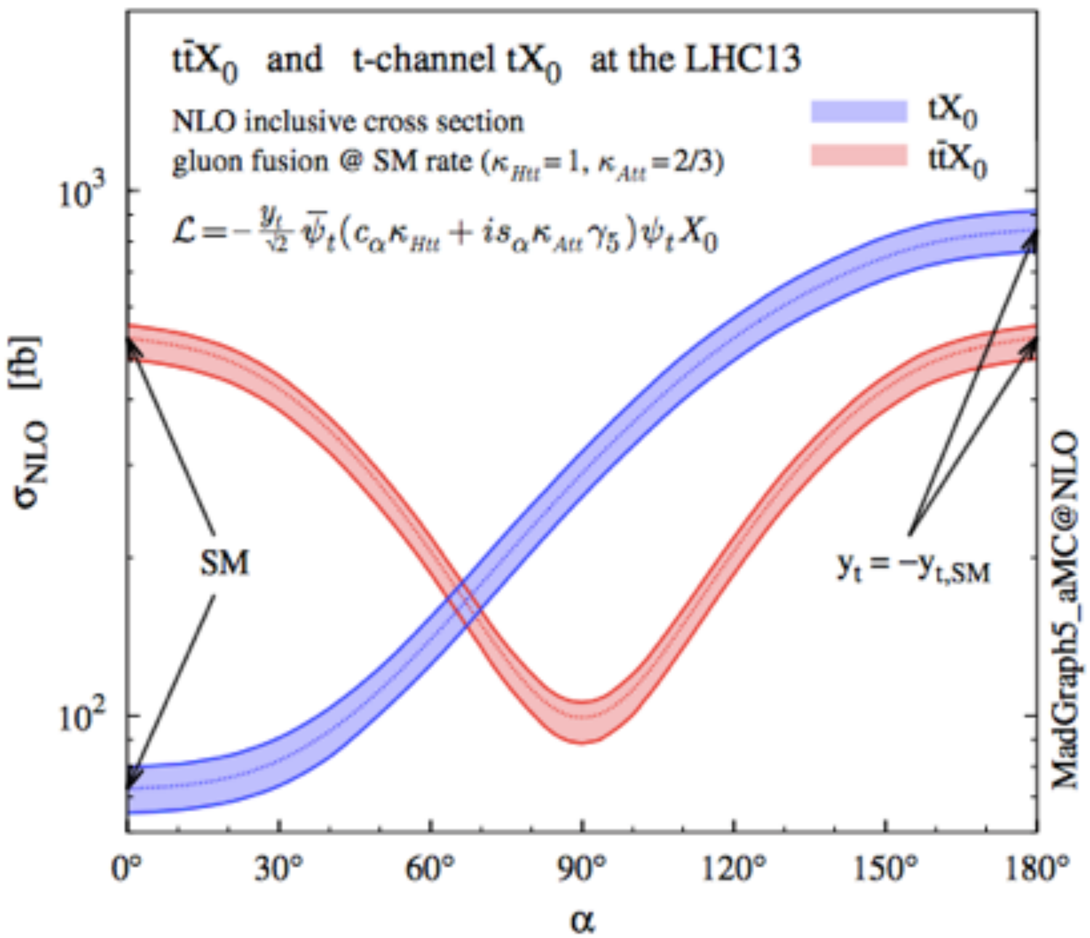
- Top Higgs Yukawa couplings with CP violation
- Helicity amplitudes: t+h: ub > dt h and $\bar{d}$b > $\bar{u}$t h

  $\bar{t}$+h: d$\bar{b}$ > $\bar{u}$t h and $\bar{u}\bar{b}$ > $\bar{d}\bar{t}$ h
- Single top + Higgs event distributions
- Azymuthal asymmetry of t/$\bar{t}$+h+jet distributions
- Top quark polarisation and its azimuthal asymmetry
- T-odd asymmetries and CPV test in pp collisions
- Summary

Top Yukawa coupling

$$
\begin{aligned}
\mathcal{L} &= -g_{htt} h \bar{t} \left(\cos\xi_{htt} + i \sin\xi_{htt} \gamma_5\right) t \\
&= -g_{htt} h (t_R^\dagger, t_L^\dagger) \begin{pmatrix} e^{-i\xi_{htt}} & 0 \\ 0 & e^{i\xi_{htt}} \end{pmatrix} \begin{pmatrix} t_L \\ t_R \end{pmatrix} \\
&= -g_{htt} h (e^{-i\xi_{htt}} t_R^\dagger t_L + e^{i\xi_{htt}} t_L^\dagger t_R)
\end{aligned}
$$

$$
g_{htt} = \frac{m_t}{v} \kappa_{htt}, \qquad \kappa_{htt} > 0, \quad -\pi < \xi_{htt} \le \pi
$$



F.Demartin, F.Maltoni, K.Mawatari & M. Zaro (2015)

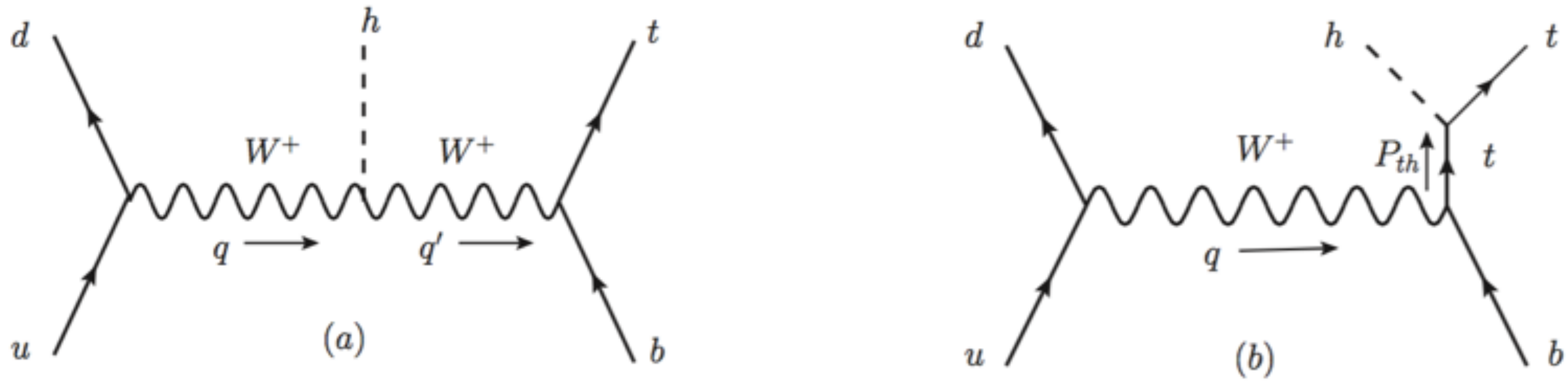
$$
pp \to t + h + \text{anything}
$$

$$
\sigma_{tot}(|\xi_{htt}| = \pi) \sim 10\ \sigma_{tot}^{SM}(\xi_{htt} = 0)
$$

change the sign of Yukawa coupling

In the SM, strong destructive interference between the htt and hWW amplitudes

ub>dth production



$$M_\sigma \sim u_L(p_d)^\dagger \sigma^\mu_- u_L(p_u) \frac{-g_{\mu\nu} + q_\mu q_\nu / m_W^2}{q^2 - m_W^2}$$

common to both diagrams

$$\left(u_R^\dagger(p_t,\sigma), u_L^\dagger(p_t,\sigma)\right) \left\{ g_{hWW} \frac{-g^\nu_\rho + q'^\nu q'_\rho / m_W^2}{q'^2 - m_W^2} + \frac{g_{htt}\delta^\nu_\rho}{P_{th}^2 - m_t^2} \begin{pmatrix} e^{-i\xi} & 0 \\ 0 & e^{i\xi} \end{pmatrix} \begin{pmatrix} m & P_{th}\cdot\sigma_+ \\ P_{th}\cdot\sigma_- & m \end{pmatrix} \right\} \begin{pmatrix} 0 & \sigma^\rho_+ \\ \sigma^\rho_- & 0 \end{pmatrix} \begin{pmatrix} u_L(p_b) \\ 0 \end{pmatrix}$$

$\bar{u}(p_t,\sigma)$

$\cos\xi + i \sin\xi\gamma_5$ | $P_{th}\cdot\gamma + m$ | γ^ρ | $\frac{1-\gamma_5}{2}u(p_b)$

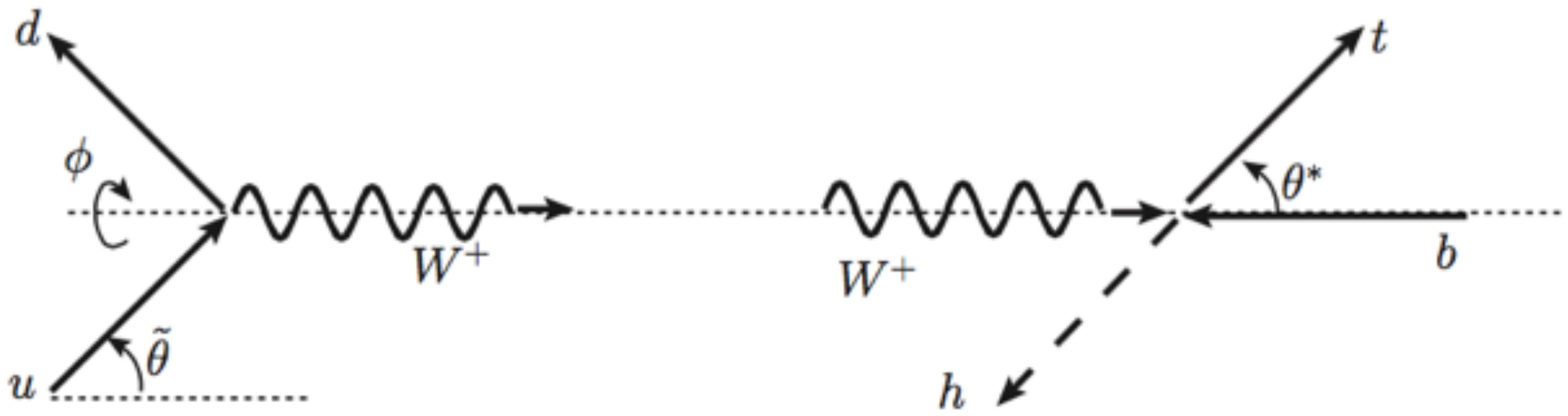
$$g_{hWW} = \frac{2m_W^2}{v}\kappa_{hWW} \quad (\kappa_{hWW} = 1)$$

Amplitudes

$$M_\sigma = \sum_{\lambda=\pm1,0} j(u \to dW_\lambda^+)\ \hat{M}(W_\lambda^+ b \to t_\sigma h)$$

Breit frame — W^+b=th rest frame

$\vec{q}$ direction is along the positive z-axis



Breit frame

$$p_u^\mu = \tilde{\omega}(1, \sin\tilde{\theta}\cos\phi, -\sin\tilde{\theta}\sin\phi, \cos\tilde{\theta}),$$

$$p_d^\mu = \tilde{\omega}(1, \sin\tilde{\theta}\cos\phi, -\sin\tilde{\theta}\sin\phi, -\cos\tilde{\theta}),$$

$$q^\mu = p_u^\mu - p_d^\mu = (0,0,0,2\tilde{\omega}\cos\tilde{\theta}) = (0,0,0,Q)$$

$$\cos\tilde{\theta} = \frac{1}{2\hat{s}/(W^2+Q^2)-1}$$

$$\tilde{\omega} = Q/2\,(2\hat{s}/(W^2+Q^2)-1)$$

$$\tilde{\omega}\cos\tilde{\theta} = Q/2$$

$$j_\lambda = (-1)^{(\lambda+1)} u_L^\dagger(p_d)\sigma_-^\mu u_L(p_u)\epsilon_\mu^*(q,\lambda) = \begin{cases} \pm\sqrt{2}\tilde{\omega}(1\pm\cos\tilde{\theta})e^{\pm i\phi}, & \text{if } \lambda=\pm1 \\ -2\tilde{\omega}\sin\tilde{\theta}, & \text{if } \lambda=0 \end{cases}$$

Amplitudes

$$M_\sigma = \sum_{\lambda=\pm1,0} j(u \to dW^+_\lambda)\ \hat{M}(W^+_\lambda b \to t_\sigma h)$$

$$M_+ = \frac{1-\tilde{c}}{2}e^{i\phi}\sin\frac{\theta^*}{2}A\frac{1+\cos\theta^*}{2}$$ ← λ=+1, J_Z=3/2

$$+\frac{1+\tilde{c}}{2}e^{-i\phi}\sin\frac{\theta^*}{2}\left[A\left(\frac{1+\cos\theta^*}{2}+\epsilon_1\right)-B\left(e^{-i\xi}+\delta\delta' e^{i\xi}\right)\right]$$ ← λ=-1, J_Z=-1/2

$$+\frac{\tilde{s}}{2}\cos\frac{\theta^*}{2}\frac{W}{Q}\left[A\left(\frac{q^*E_h^*+q^{0*}p^*\cos\theta^*}{Wp^*}+\epsilon_1\right)-B\left(e^{-i\xi}+\delta\delta' e^{i\xi}\right)\right]$$ ← λ=0, J_Z=1/2

$$M_- = -\frac{1-\tilde{c}}{2}e^{i\phi}\cos\frac{\theta^*}{2}A\delta\frac{1-\cos\theta^*}{2}$$ ← λ=+1, J_Z=3/2

$$-\frac{1+\tilde{c}}{2}e^{-i\phi}\cos\frac{\theta^*}{2}\left[A\left(\delta\frac{1-\cos\theta^*}{2}-\epsilon_2\right)+B\left(\delta e^{-i\xi}+\delta' e^{i\xi}\right)\right]$$ ← λ=-1, J_Z=-1/2

$$-\frac{\tilde{s}}{2}\sin\frac{\theta^*}{2}\frac{W}{Q}\left[A\left(\delta\frac{q^*E_h^*+q^{0*}p^*\cos\theta^*}{Wp^*}+\epsilon_2\right)-B\left(\delta e^{-i\xi}+\delta' e^{i\xi}\right)\right]$$ ← λ=0, J_Z=1/2

$$A = 2g^2 D_W(q)\tilde{\omega}\sqrt{2q^*(E^*+p^*)}\frac{mp^*}{m_W^2}g_{hWW}D_W(q'),$$ >0

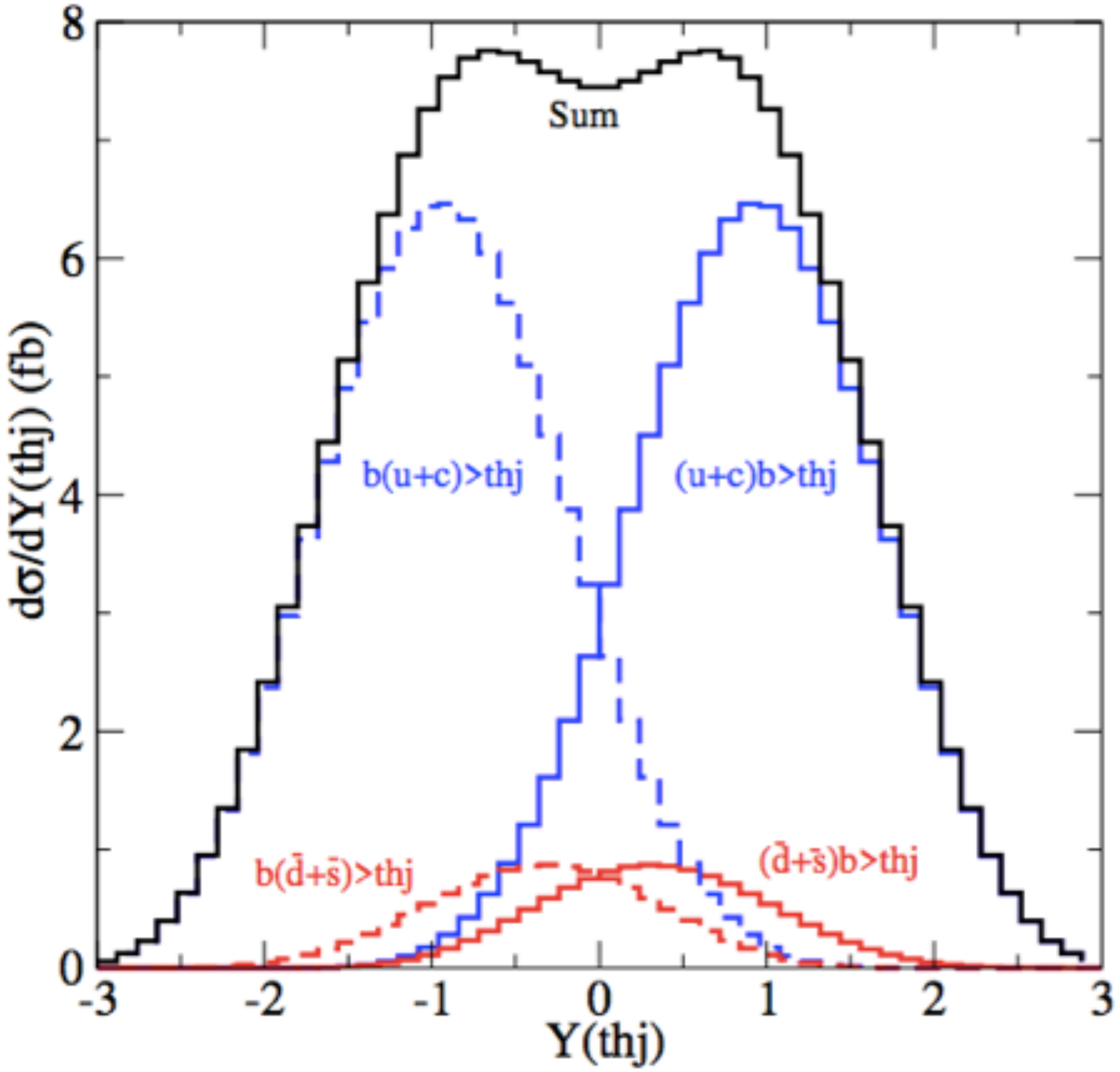
$$B = -2g^2 D_W(q)\tilde{\omega}\sqrt{2q^*(E^*+p^*)}W g_{htt}D_t(P_{th}),$$ >0

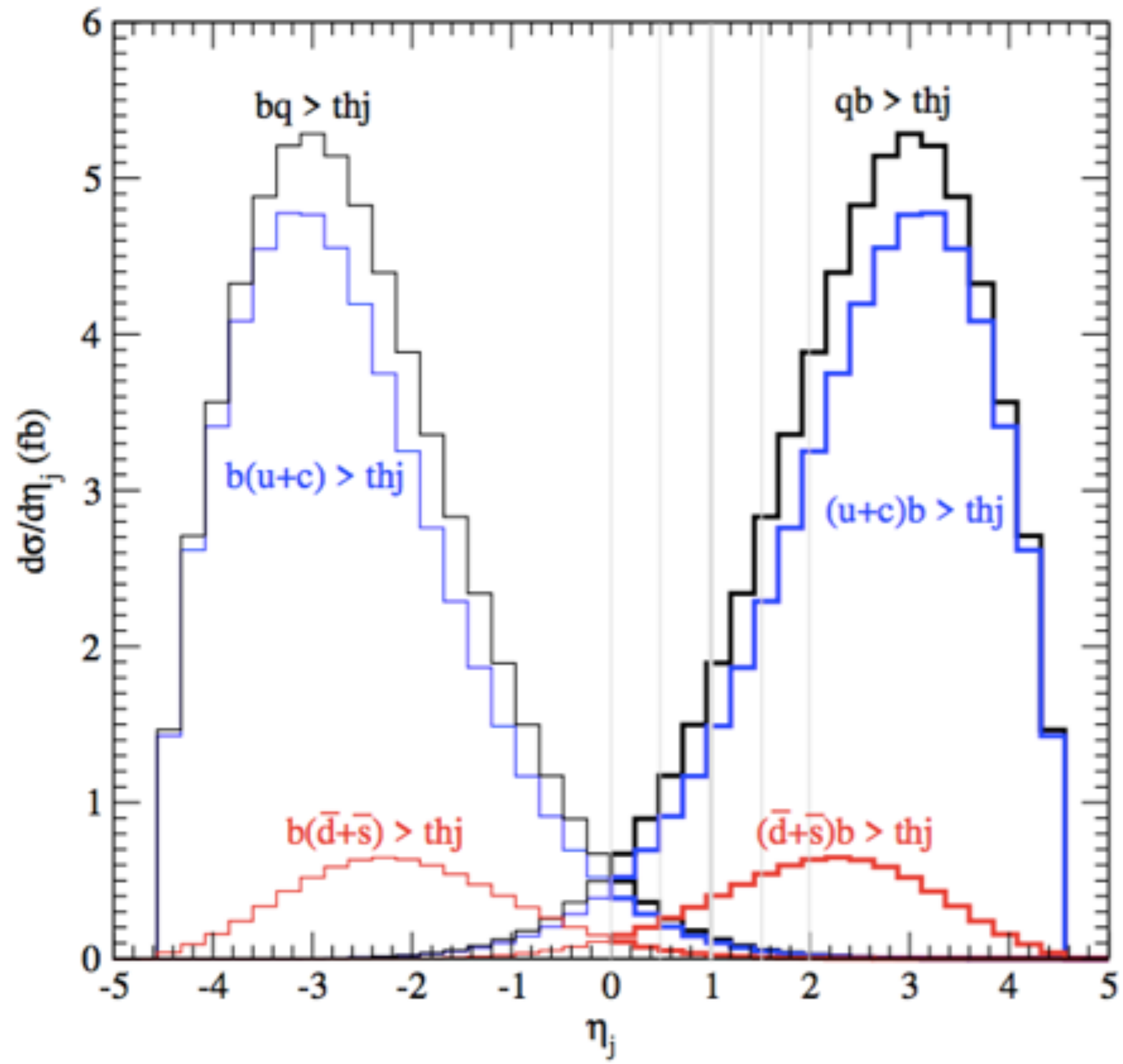
$$\delta = m_t/(E^*+p^*)$$

$$\delta' = m_t/W$$

→ $\delta \sim \delta'$ at high energy high W (W=m_{th})

distributions



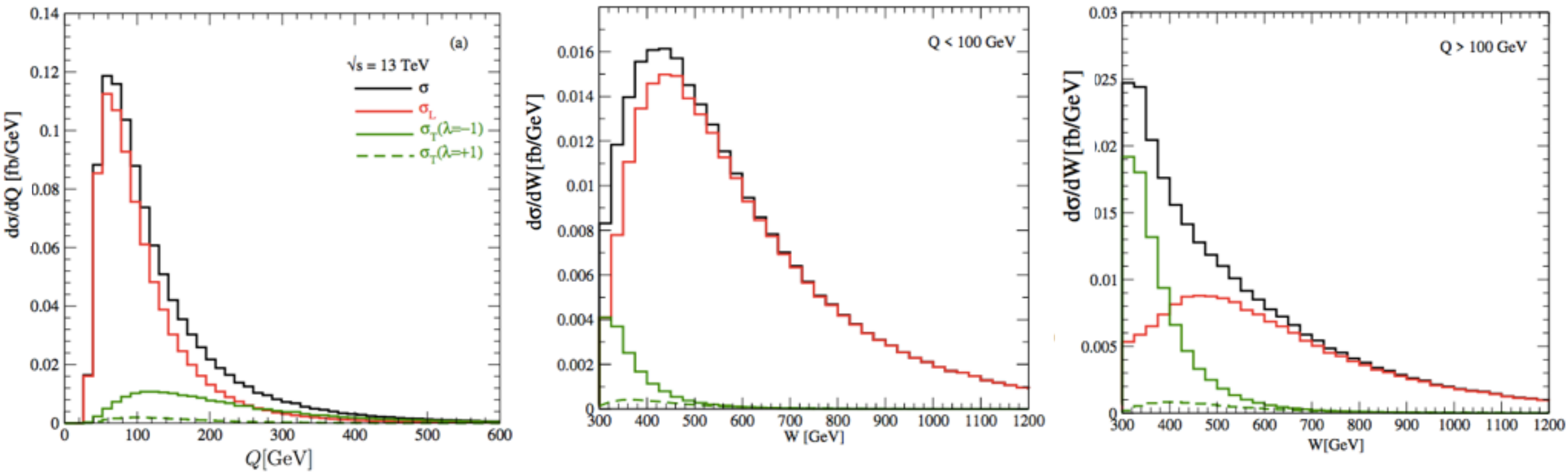


Cut	$\sigma(qb \to thj)$[fb]			$\sigma(bq \to thj)$[fb]			$\sigma(thj)$[fb]	Purity[%]	Fraction in qb[%]	
	$ub+cb$	$\bar{d}b+\bar{s}b$	Sum	$bu+bc$	$b\bar{d}+b\bar{s}$	Sum		qb	$ub+cb$	$\bar{d}b+\bar{s}b$
$\eta_j > 0$	12.74	1.75	14.49	0.32	0.076	0.40	14.89 (100%)	97.3	87.9	12.1
$\eta_j > 0.5$	12.43	1.66	14.09	0.15	0.031	0.18	14.27 (95.8%)	98.7	88.2	11.8
$\eta_j > 1$	11.90	1.50	13.40	0.065	0.011	0.076	13.48 (90.5%)	99.4	88.8	11.2
$\eta_j > 1.5$	11.02	1.28	12.30	0.026	0.0033	0.029	12.33 (82.8%)	99.8	89.6	10.4
$\eta_j > 2$	9.69	0.99	10.68	0.0093	0.00086	0.010	10.69 (71.8%)	99.9	90.7	9.3

Q and W distribution

$Q = \sqrt{-q^2}$ invariant momentum transfer of the virtual W^+

$W = \sqrt{P_{th}^2} = m(th)$ the invariant mass of the th system



W_L is dominant in low Q (Q<100 GeV) and large W (W>400 GeV)

W_T is significant in large Q (Q>100 GeV) and small W (W<400 GeV)

Azimuthal angle distribution

$$\frac{d\sigma}{dW\,d\phi} \sim |M_+|^2 + |M_-|^2$$

For instance, at high W

$$M_+ \sim \frac{1+\tilde{c}}{2} e^{-i\phi} \sin\frac{\theta^*}{2} \left[A\frac{1+\cos\theta^*}{2} - \underline{Be^{-i\xi}} \right] \qquad \lambda = -1$$

$$+ \frac{\tilde{s}}{2} \cos\frac{\theta^*}{2} \boxed{\frac{W}{Q}} \left[A\frac{1+\cos\theta^*}{2} - \underline{Be^{-i\xi}} \right] \qquad \lambda = 0$$

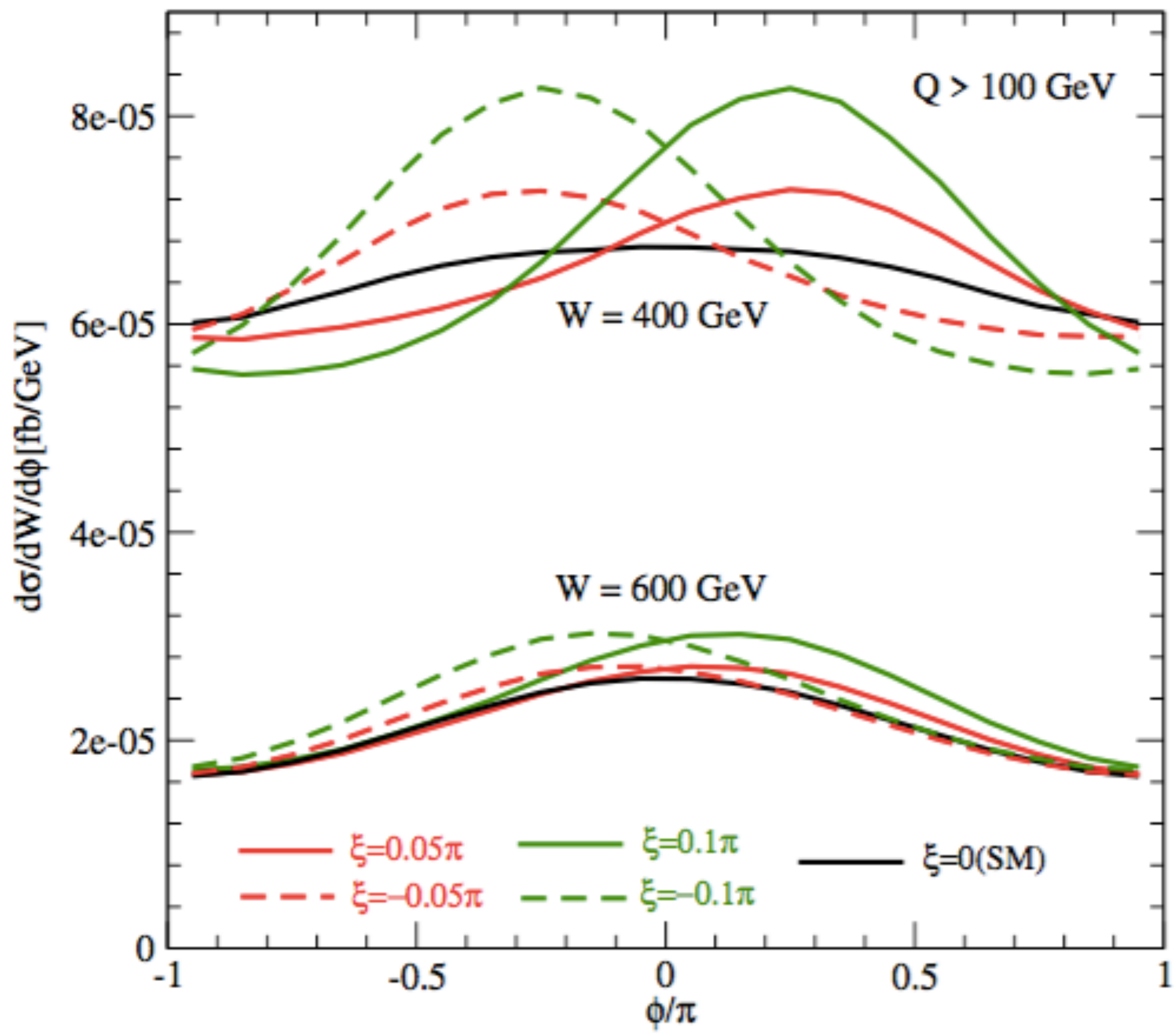
$|M_+|^2$ contains terms proportional to $\underline{\sin\phi\sin\xi}$

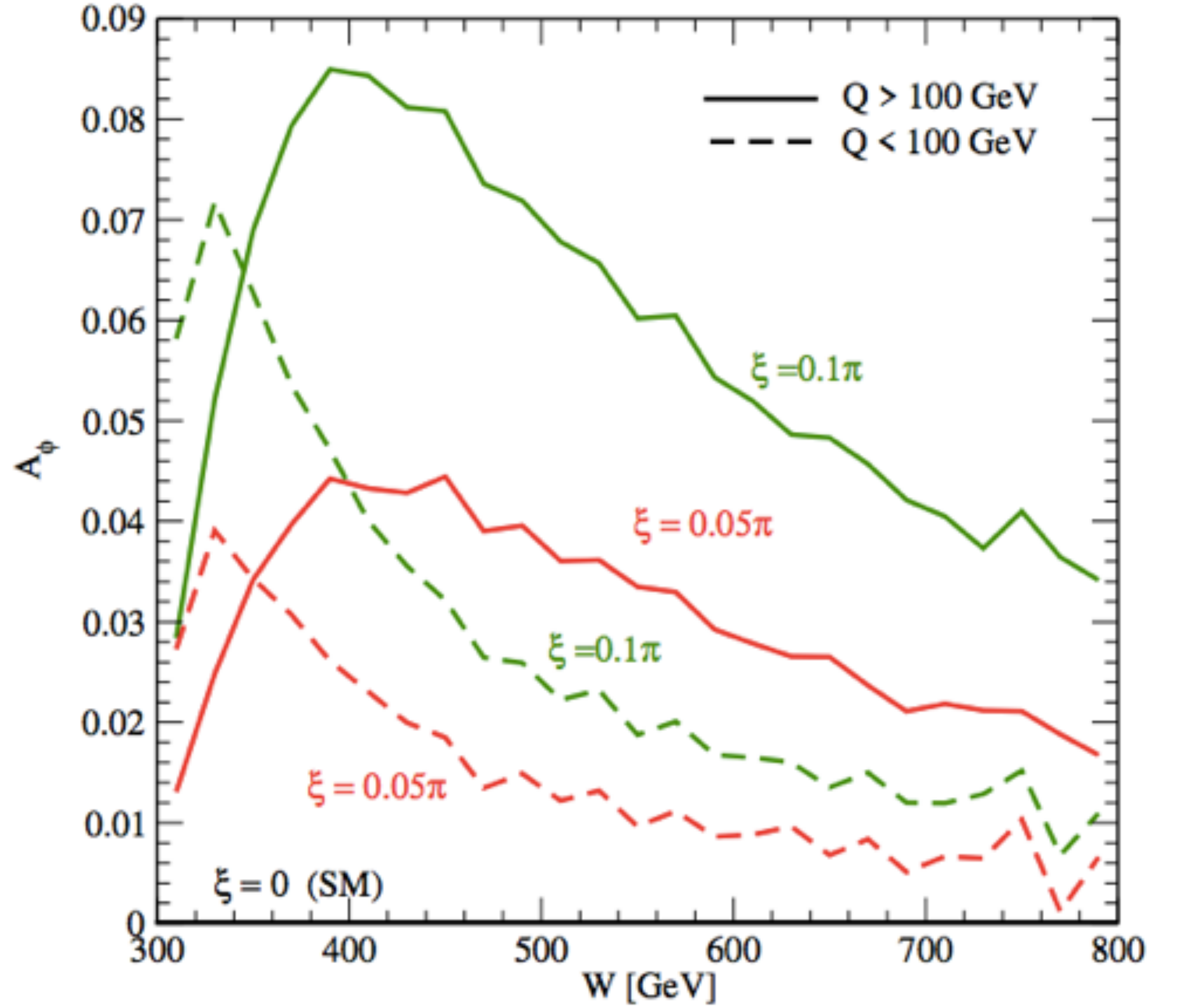
in the interference between λ=−1 and λ=0 terms. ⟶ A_φ

Asymmetry is large at small W & large Q (W_T is comparable to W_L)
small at large W & small Q (W_L dominates over W_T)

$|M_-|^2$ contains terms proportional to $2\cos\xi$ ⟶ not sensitive to CPV

Azimuthal angle distribution





asymmetry $$A_\phi(W) = \frac{\int_0^\pi d\sigma/dW/d\phi - \int_{-\pi}^0 d\sigma/dW/d\phi}{\int_0^\pi d\sigma/dW/d\phi + \int_{-\pi}^0 d\sigma/dW/d\phi} \quad \begin{array}{ll} = 0, & \text{if SM } (\xi = 0) \\ > 0, & \text{if } \xi > 0 \\ < 0, & \text{if } \xi < 0 \end{array}$$

Asymmetry is large at small W & large Q (W_T is comparable to W_L)
small at large W & small Q (W_L dominates over W_T)

Polarization

For general mixed state, we introduce differential cross section matrix

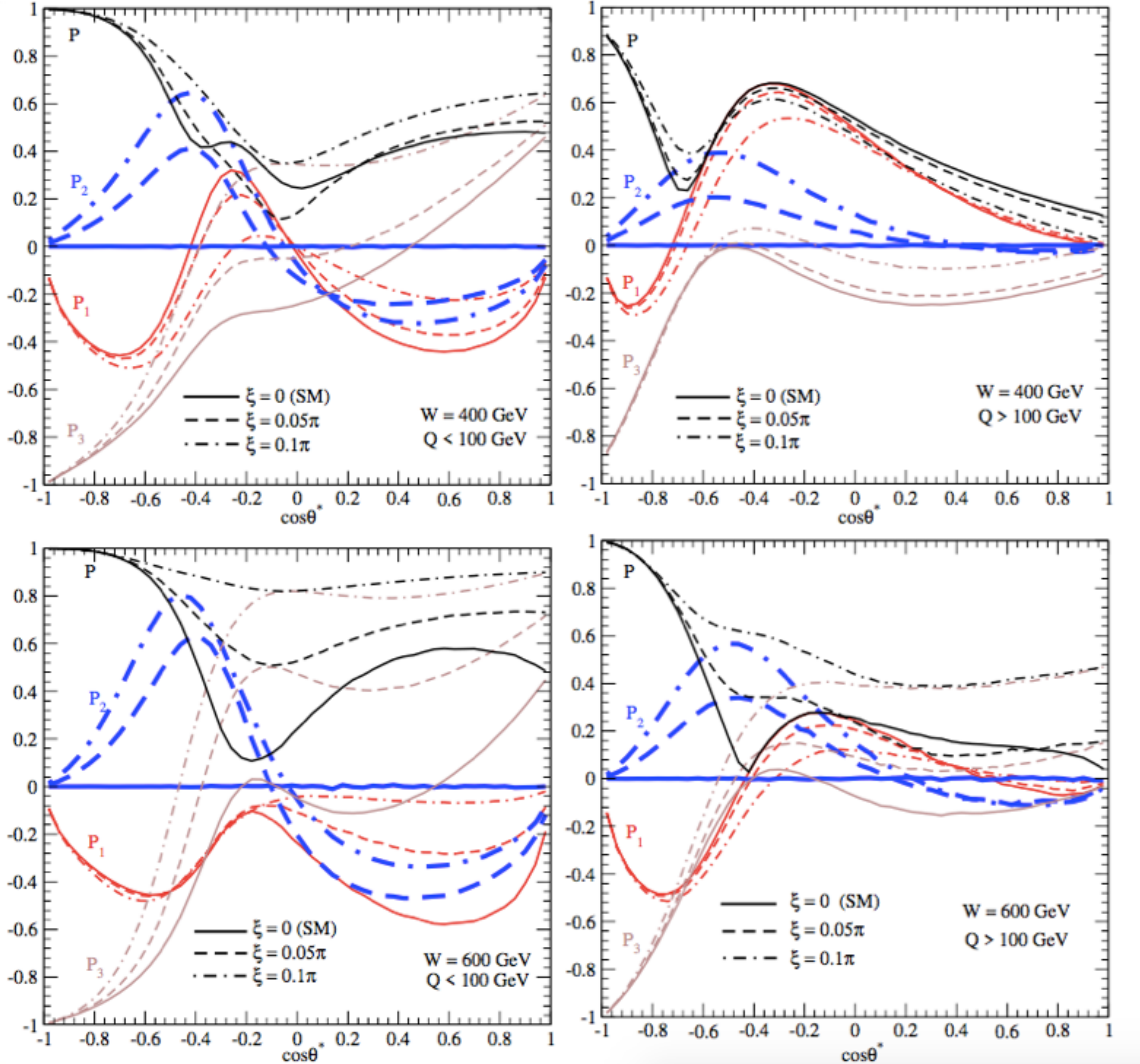
$$d\sigma_{\lambda\lambda'} = \int dx_1 \int dx_2 D_{u/p}(x_1) D_{b/p}(x_2) \frac{1}{2\hat{s}} \overline{\sum} M_\lambda M^*_{\lambda'} d\Phi_{dth}$$

where the phase space integration can be restricted. For an arbitrary kinematical distributions, $d\sigma = d\sigma_{++} + d\sigma_{--}$, the polarisation density matrix is defined as

$$\rho_{\lambda\lambda'} = \frac{d\sigma_{\lambda\lambda'}}{d\sigma_{++} + d\sigma_{--}} = \frac{1}{2}\left[\delta_{\lambda\lambda'} + \sum_{k=1}^{3} P_k \sigma^k_{\lambda\lambda'}\right]$$

The 3-vector **P** =(P_1,P_2,P_3) gives the general polarisation of the top quark. The magnitude P = |**P**| gives the degree of polarisation (P=1 for 100% polarization, P=0 for no polarisation). The orientation gives the direction of the top quark spin in the top rest frame.

We find **P** lies in the W+b>th scattering plane in the SM (xi=0). Polarisation component orthogonal to the production plane, P_2, appears when xi is nonzero. The sign of P_2 determines the sign of xi.


P
P2
P1
P3
ξ = 0 (SM)
ξ = 0.05π
ξ = 0.1π
W = 400 GeV
Q < 100 GeV
W = 400 GeV
Q > 100 GeV
W = 600 GeV
Q < 100 GeV
W = 600 GeV
Q > 100 GeV
cosθ*

naive T-odd asymmetries

$$T: \quad (t, \vec{x}) \to (-t, \vec{x}), \quad \vec{p} \to -\vec{p}, \quad \vec{s} \sim \vec{x} \times \vec{p} \to -\vec{s}$$

$$T\text{-}odd: \quad \vec{p_1} \times \vec{p_2} \cdot \vec{p_3} \to -\vec{p_1} \times \vec{p_2} \cdot \vec{p_3}$$

$$\vec{p_1} \times \vec{p_2} \cdot \vec{s} \to -\vec{p_1} \times \vec{p_2} \cdot \vec{s}$$

$$A_\phi \sim \langle \frac{\vec{p}_u \times \vec{p}_d \cdot \vec{p}_t}{|\vec{p}_u \times \vec{p}_d| \cdot |\vec{p}_t|} \rangle \qquad P_2 = \langle \frac{\vec{q} \times \vec{p}_t \cdot \vec{s}_t}{|\vec{q} \times \vec{p}_t| \cdot (1/2)} \rangle$$

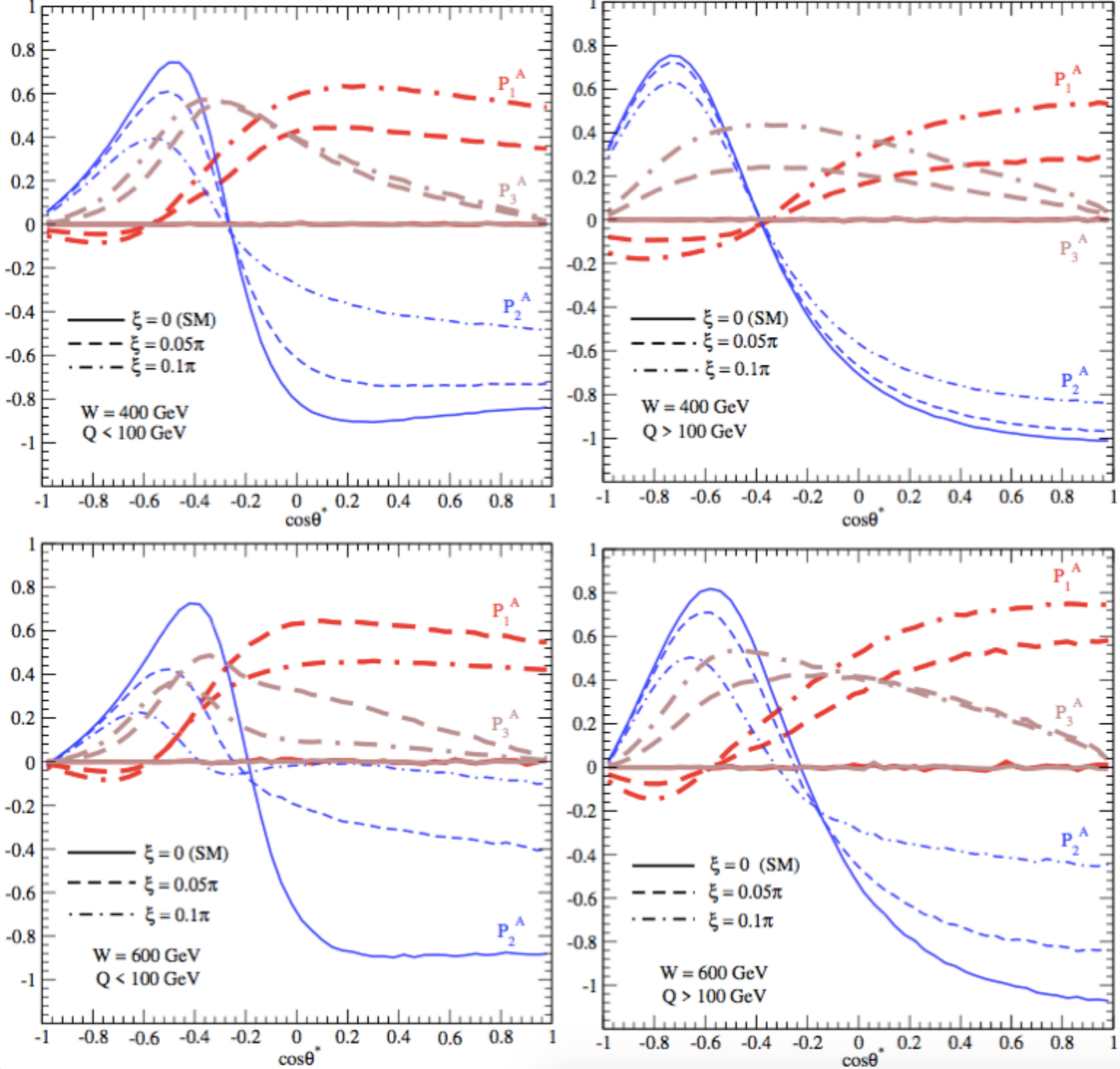
The top quark polarisation **P** =(P_1,P_2,P_3) are obtained after azimuthal angle integration of the jet about the virtual W momentum direction in the rest frame of Wb and th. Therefore, we are measuring the asymmetries in the 2>2 process

$$W^+(\lambda) + b \to th$$

We can define more complicated T-odd polarisation asymmetries in the 2 >3 process such as

$$\langle \frac{(\vec{q} \times \vec{p}_j) \times (\vec{q} \times \vec{p}_h) \cdot \vec{s}_t}{|(\vec{q} \times \vec{p}_j) \times (\vec{q} \times \vec{p}_h)| \cdot (1/2)} \rangle \qquad \langle \frac{(\vec{p}_b \times \vec{p}_j) \times (\vec{p}_b \times \vec{p}_h) \cdot \vec{s}_t}{|(\vec{p}_b \times \vec{p}_j) \times (\vec{p}_b \times \vec{p}_h)| \cdot (1/2)} \rangle$$

$$P_k^A = P_k(\phi > 0) - P_k(\phi < 0)$$ k=1 and 3 are T-odd, k=2 is not



P1 A
P3 A
P2 A
ξ = 0 (SM)
ξ = 0.05π
ξ = 0.1π
W = 400 GeV
Q < 100 GeV
W = 400 GeV
Q > 100 GeV
W = 600 GeV
Q < 100 GeV
W = 600 GeV
Q > 100 GeV
cosθ*

Expected number of events @ HL-LHC

	$\sqrt{s}$ 14 TeV	Number of events @$3ab^{-1}$	Decay channel	Branching Ratio	Number of events	
$\sigma(th)+\sigma(\bar{t}h)$	90 fb	270,000	$(b\ell\nu)(b\bar{b})$	0.13	34,000	✓✓
			$(b\ell\nu)(\gamma\gamma,\ell\ell jj,\mu\mu,4\ell)$	0.0011	300	✓✓
$\sigma(t\bar{t}h)$	613 fb	1,840,000	$(bl\nu)(bjj)(b\bar{b})$	0.17	310,000	✓✓✓
			$(bl\nu)^2(b\bar{b})$	0.028	52,000	✓✓✓
			$(bl\nu)(bjj)(\gamma\gamma,\ell\ell jj,\mu\mu,4\ell)$	0.0015	2,800	✓✓✓
			$(bl\nu)^2(\gamma\gamma,\ell\ell jj,\mu\mu,4\ell)$	0.00025	460	✓✓✓

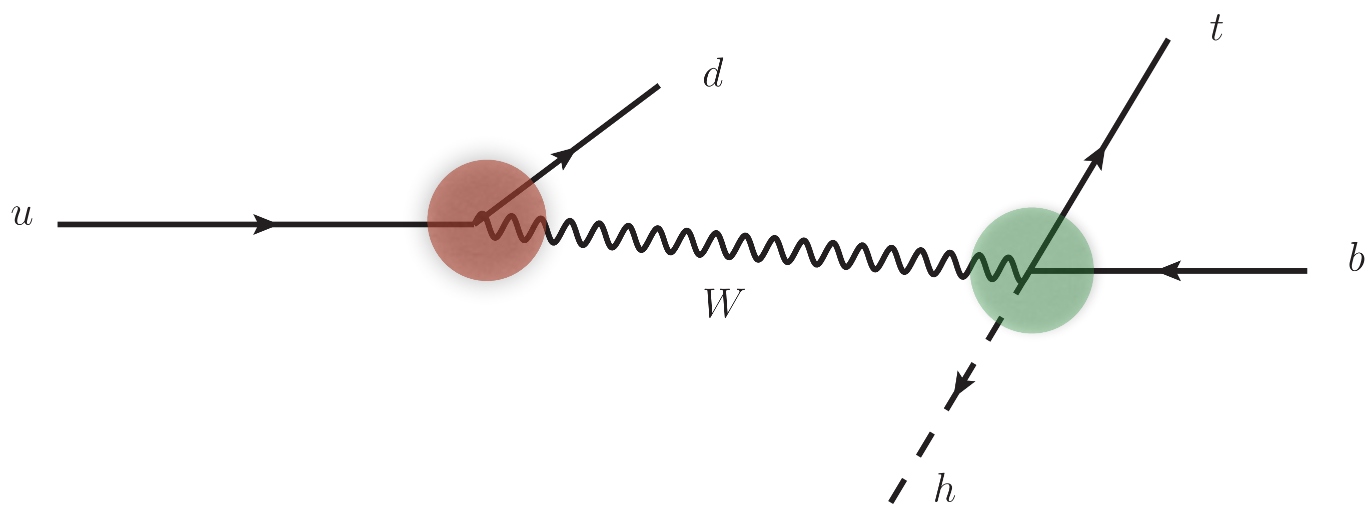
- t>blv mode for CP sensitivity (t vs. $\bar{t}$)
- h decay should not have neutrinos to determine t($\bar{t}$) frame.

	Decay channel	Branching ratio		Decay channel	Branching Ratio	
$t\rightarrow$	bjj	0.67	$h\rightarrow$	$b\bar{b}$	0.58	✓
	$b\ell\nu(\ell=e,\mu)$ ✓	0.22		$\ell\bar{\ell}jj$	0.0025	
	$b\tau\nu$ ✓	0.11		$\gamma\gamma$	0.0023	
				$\mu\bar{\mu}$	0.00022	
				4ℓ	0.00012	

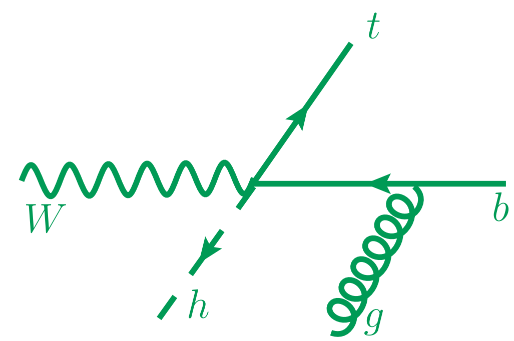
(0.0025 + 0.0023 + 0.00022 + 0.00012) → 0.0051 ✓

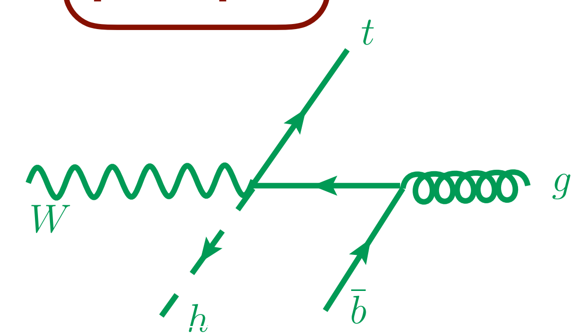
- For a few percent asymmetry measurement, h> bb is necessary

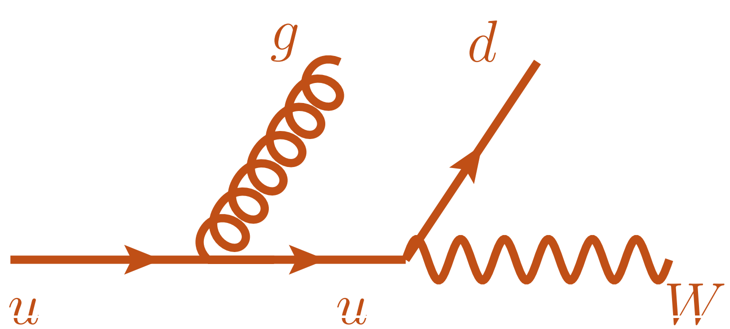
Radiative corrections



Color singlet (W) exchange factorizes QCD corrections into q> q'W emission and Wb>th production parts @NLO.







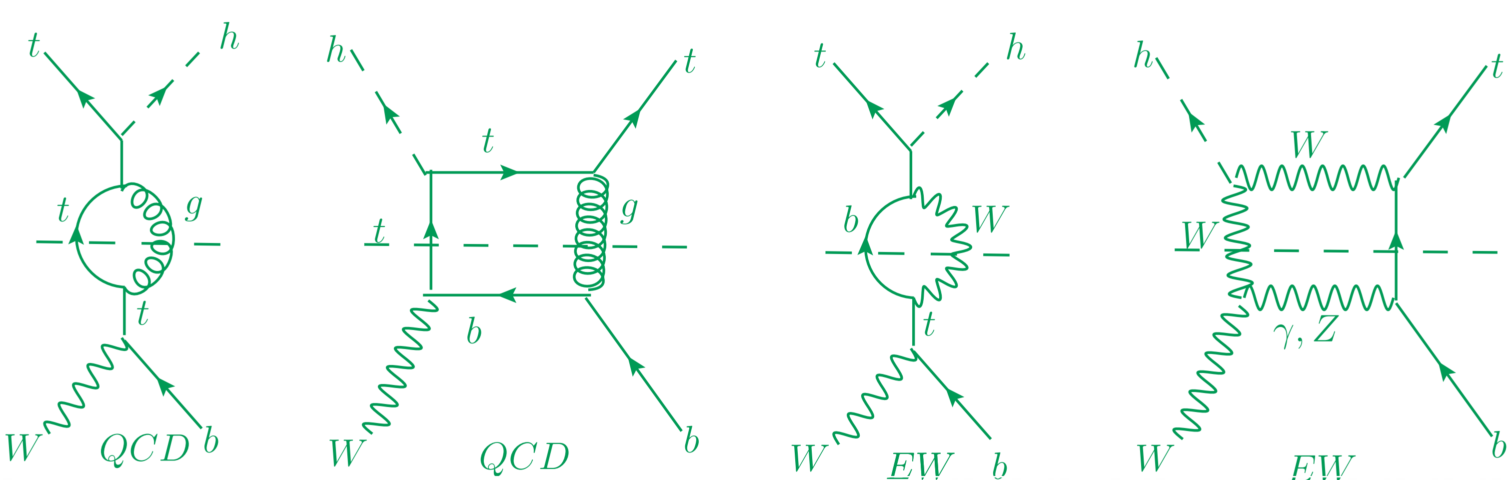
•b>bg makes W(m_{th}) softer.

•g>bb correction depends on b PDF.

•CP conserving T-odd asymmetry @1-loop.

•NLO corrections are the same as DIS and VBF process.

•g-jet miss-tag washes out A_φ and $P^A_{1,3}$ but P_2 is not affected.



Summary

- Single top+Higgs production is an ideal probe of the top Yukawa coupling because the htt and hWW amplitudes interfere strongly.

- Azimuthal asymmetry between the u>dW^+ emission and the W^+b>th production planes probes the sign of CP violating phase.

$$A_\phi \sim \int_0^{\pi} (|M_+|^2 + |M_-|^2) d\phi - \int_{-\pi}^{0} (|M_+|^2 + |M_-|^2) d\phi \ \propto \ \sin \xi_{htt}$$

- The azimuthal asymmetry A_φ arises from the interference between transverse and the longitudinal W contributions and is large at large Q (Q>100 GeV) and small W (W~400GeV).

- Top quarks produced in this process are strongly polarized because it is 100% polarised at each kinematical configuration of the subprocess ub>dth.

- Polarization can be measured by using the density matrix.

$$\rho_{\lambda\lambda'} = \frac{1}{\int (|M_+|^2 + |M_-|^2) d\Phi} \int \begin{pmatrix} |M_+|^2 & M_+ M_-^* \\ M_- M_+^* & |M_-|^2 \end{pmatrix} d\Phi = \frac{1}{2} \left[\delta_{\lambda\lambda'} + \sum_{k=1}^{3} P_k \sigma^k_{\lambda\lambda'} \right]$$

- We find large P = |**P**| when jet momentum is integrated over with Q<100GeV, at large W=m(th)>400GeV

$$P_2 \propto \sin \xi \ (P_2 = 0 \text{ for } \xi = 0)$$

$$P_2 > 0.5, \quad \text{at} \cos\theta^* \sim -0.4 \text{ for } \xi = 0.05\pi (W = 600 \text{ GeV}, \ Q < 100\text{GeV})$$

Summary (continued)

- The azimuthal asymmetry of the top polarisation inside the Wb to th scattering plane, $P_k^A = P_k(\phi > 0) - P_k(\phi < 0)$ k=1,3 are also sensitive to the sign of ʒ . The asymmetries are large for large Q (Q>100GeV) and small W (W ~ 400 GeV) because of W_L–W_T interference.

- All the asymmetries that determine the sign of ʒ are T-odd:

$$A_\phi \sim \langle \frac{\vec{p}_u \times \vec{p}_d \cdot \vec{p}_t}{|\vec{p}_u \times \vec{p}_d| \cdot |\vec{p}_t|} \rangle \qquad P_2 = \langle \frac{\vec{q} \times \vec{p}_t \cdot \vec{s}_t}{|\vec{q} \times \vec{p}_t| \cdot (1/2)} \rangle$$

$$P_1^A, P_3^A \sim \langle (\vec{q} \times \vec{p}_j) \times (\vec{q} \times \vec{p}_h) \cdot \vec{s}_t \rangle, \langle (\vec{p}_b \times \vec{p}_j) \times (\vec{p}_b \times \vec{p}_h) \cdot \vec{s}_t \rangle$$

- T-odd asymmetries arise from SM radiative contributions at 1-loop order of QCD and EW.

- NLO corrections, b-quark PDF uncertainty, b-quark mass effects, etc, should be studied.