Probing top Yukawa coupling at the LHC via associated production of single top and Higgs

Ya-Juan Zheng
(Iwate University)
岩手大学

Higgs 2023

December 1, 2023

Based on

[1] Vernon Barger, Kaoru Hagiwara, and YJZ,PRD99(2019)031701 [arXiv:1807.00281]
[2] Vernon Barger, Kaoru Hagiwara, and YJZ, JHEP09(2020)101 [arXiv:1912.11795].
[3] YJZ, work in progress

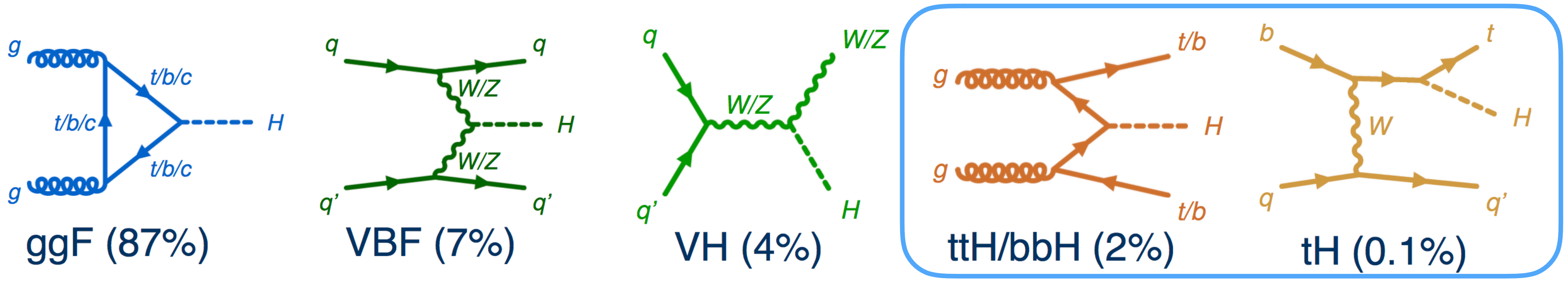
Outline

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

  $d\bar{b} > u\bar{t}h$ and $\bar{u}\bar{b} > \bar{d}\bar{t}\,h$ for pp>$\bar{t}$+h+j
- Single top/anti-top + Higgs event distributions
- Azymuthal asymmetry $A\varphi$ ($\bar{A}\varphi$) in pp > t+h+j ($\bar{t}$+h+j) events
- Top (anti-top) polarisation P_2 ($\bar{P}_2$) in pp > t+h+j ($\bar{t}$+h+j) events
- Summary

LHC searches and Constraints

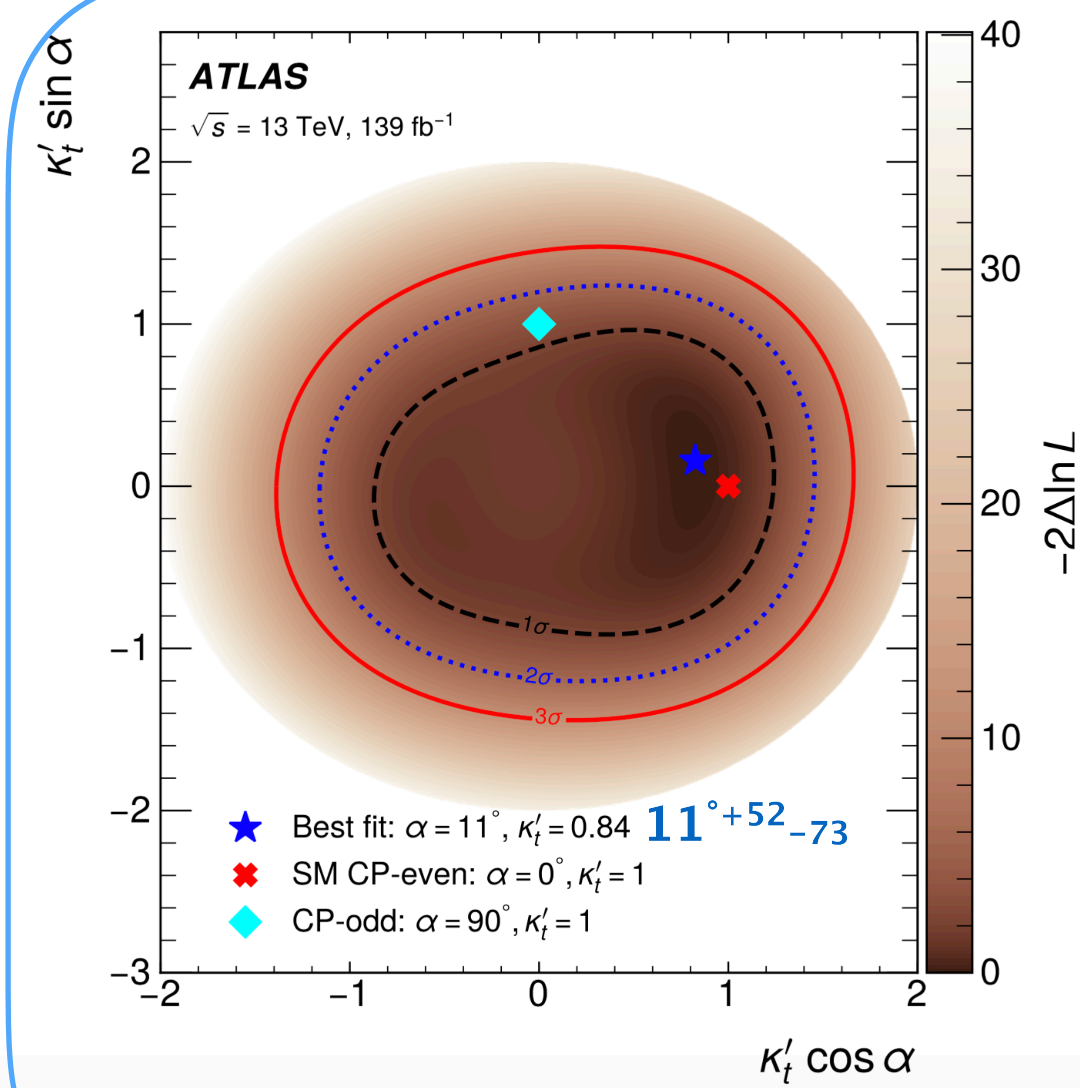
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

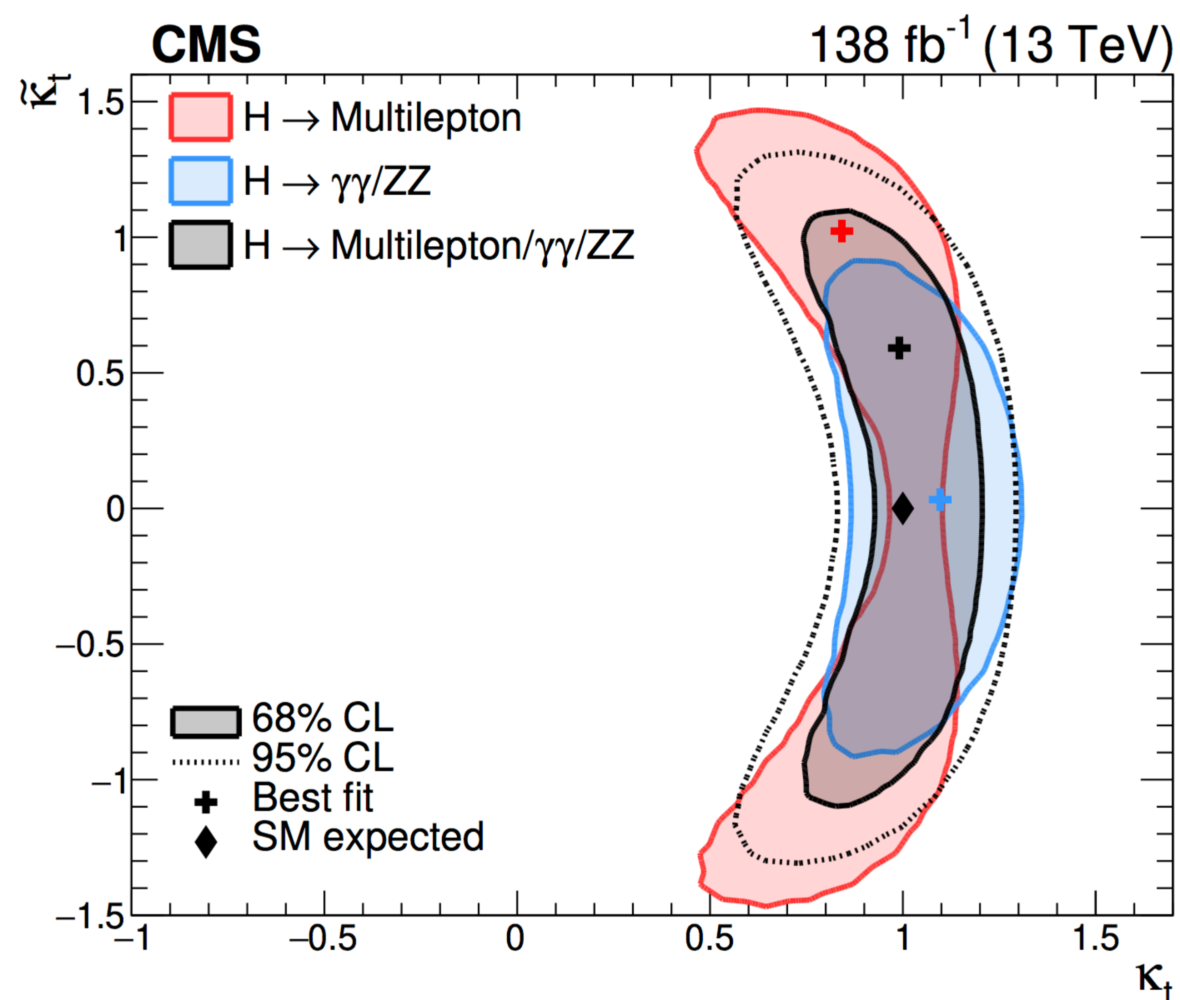


Hongtao Yang (USTC)

Process	Cross section [fb]
$t\bar{t}H$	507 [53]
tHq	74.3 [53]
tHW	15.2 [87]
ggH	4.86×10^4 [53]
qqH	3.78×10^3 [53]
WH	1.37×10^3 [53]
ZH	884 [53]

CMS:JHEP07(2023)092





ATLAS:ttH+tH, H>bb
arXiv:2303.05974

CMS:ttH+tH, H>ls/rr/ZZ
JHEP07(2023)092

Top Yukawa coupling

kappa framework

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

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

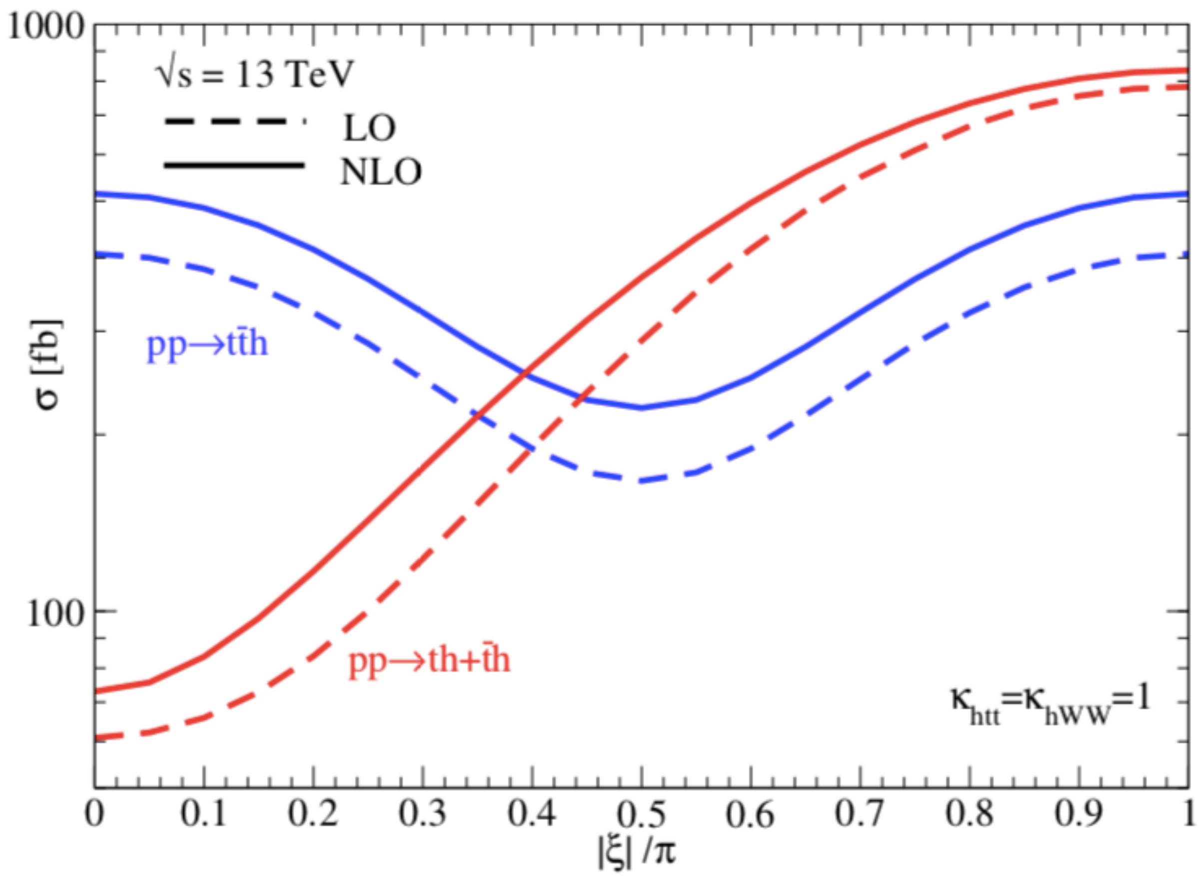
Gauge invariant Lagrangian with dimension six operator in SMEFT:

$$\mathcal{L} = -y_{\rm SM} Q^\dagger \phi t_R + \frac{\lambda}{\Lambda^2} Q^\dagger \phi t_R \left(\phi^\dagger\phi - \frac{v^2}{2}\right) + \text{h.c.}$$

$$Q = (t_L, b_L)^T$$

$$\phi = ((v + H + i\pi^0)/\sqrt{2}, i\pi^-)^T$$

$$g_{\rm SM} = \frac{y_{\rm SM}}{\sqrt{2}} = \frac{m_t}{v} \qquad g_{\rm SM} - g e^{i\xi} = \frac{\lambda v^2}{\sqrt{2}\Lambda^2}$$



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

$$\sigma_{tot}(|\xi_{htt}| = \pi) \sim 13\ \sigma_{tot}^{SM}(\xi_{htt} = 0)$$

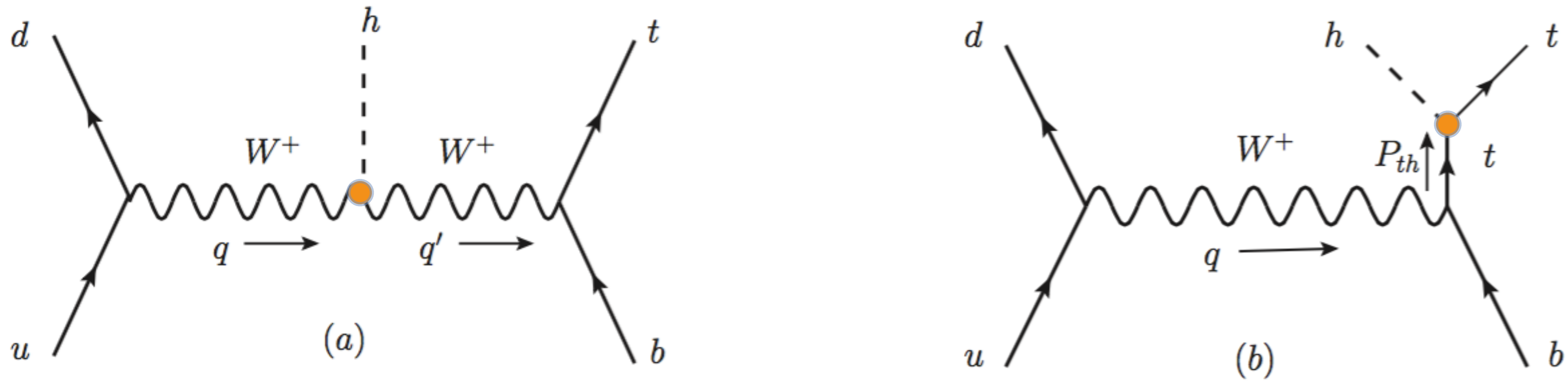
change the sign of Yukawa couplin

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

Preserving unitarity

W.Stirling, D.Summers, Phys.Lett.B283(1992)411-415
G.Bordes,B.van Eijk, Phys.Lett.B299(1993)315-320

ub > dth amplitudes



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

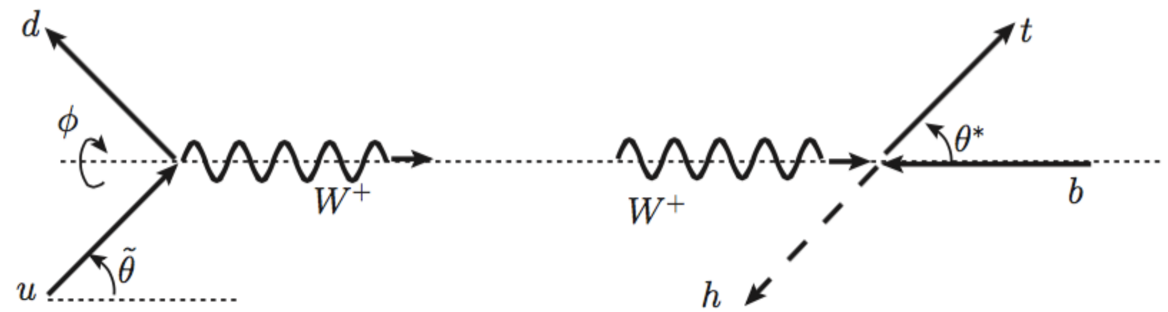
common to both diagrams

$$\underbrace{\left(u_R^\dagger(p_t,\sigma), u_L^\dagger(p_t,\sigma)\right)}_{\bar{u}(p_t,\sigma)} \left\{ g_{hWW}\frac{-g^\nu_\rho + q'^\nu q'_\rho/m_W^2}{q'^2-m_W^2} + \frac{g_{htt}\delta^\nu_\rho}{P_{th}^2-m_t^2} \underbrace{\begin{pmatrix} e^{-i\xi} & 0\\ 0 & e^{i\xi}\end{pmatrix}}_{\cos\xi + i\sin\xi\gamma_5} \underbrace{\begin{pmatrix} m & P_{th}\cdot\sigma_+\\ P_{th}\cdot\sigma_- & m\end{pmatrix}}_{P_{th}\cdot\gamma+m}\right\} \underbrace{\begin{pmatrix} 0 & \sigma_+^\rho\\ \sigma_-^\rho & 0\end{pmatrix}}_{\gamma^\rho} \underbrace{\begin{pmatrix} u_L(p_b)\\ 0\end{pmatrix}}_{\frac{1-\gamma_5}{2}u(p_b)}$$

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

Amplitudes (full process u b > d t h)

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



$$M_+ = \boxed{\frac{1-\tilde{c}}{2}e^{i\phi}}\sin\frac{\theta^*}{2}A\frac{1+\cos\theta^*}{2}$$

λ=+1 Jz=3/2

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

λ=-1 Jz=-1/2

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

λ=0 Jz=1/2

$$M_- = -\boxed{\frac{1-\tilde{c}}{2}e^{i\phi}}\cos\frac{\theta^*}{2}A\delta\frac{1-\cos\theta^*}{2}$$

λ=+1 Jz=3/2

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

λ=-1 Jz=-1/2

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

λ=0 Jz=1/2

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

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

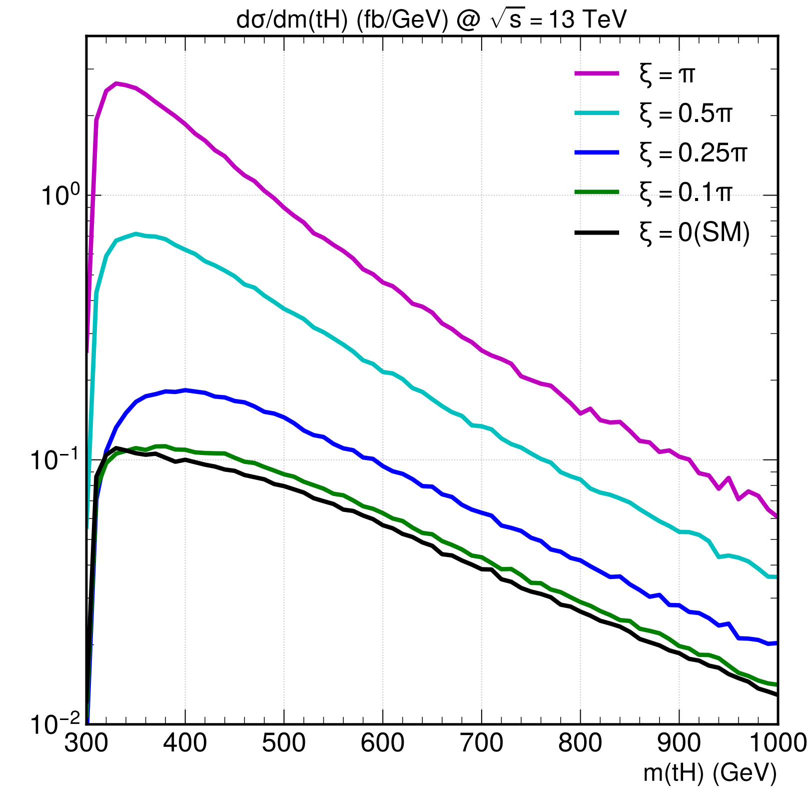
$$\delta = m_t/(E^*+p^*)$$
$$\delta' = m_t/W$$

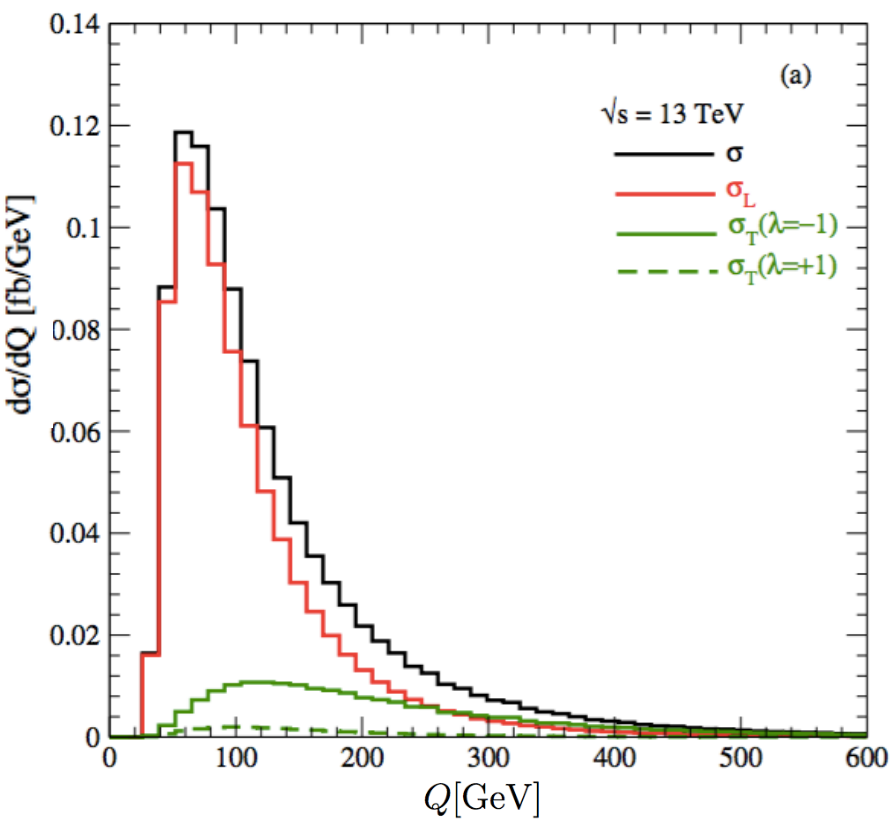
δ ~ δ' at high energy high W ($W=m_{th}$)

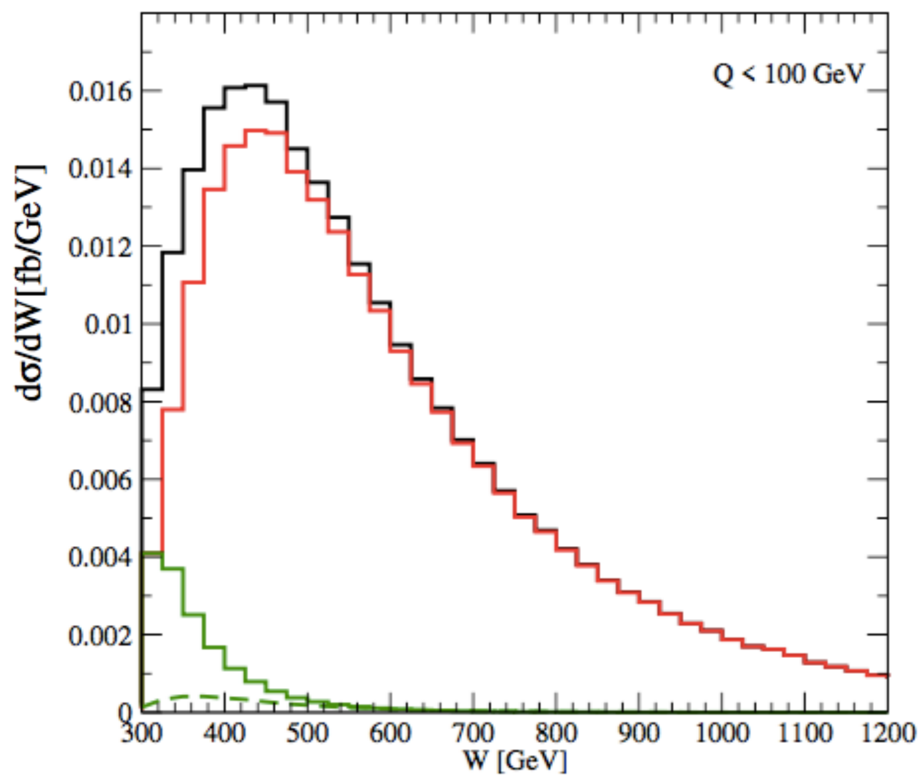
Q and W distribution

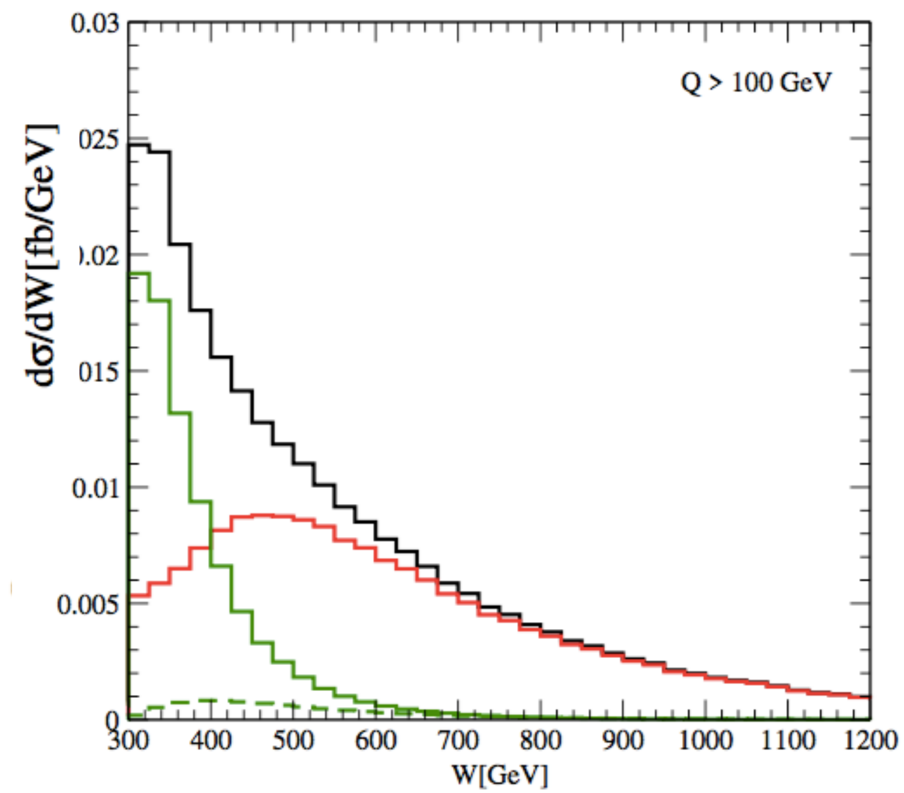
$Q = \sqrt{-q^2}$ invariant momentum transfer of the virtual W^+

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





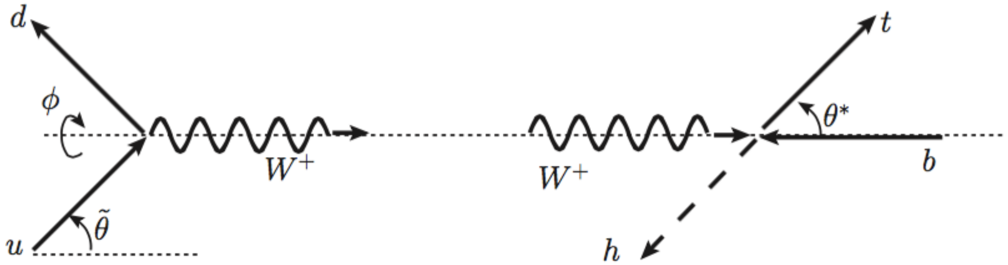




W_L is dominant in low Q (Q<100 GeV) and large W (W>400 GeV)

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

Azimuthal angle distribution



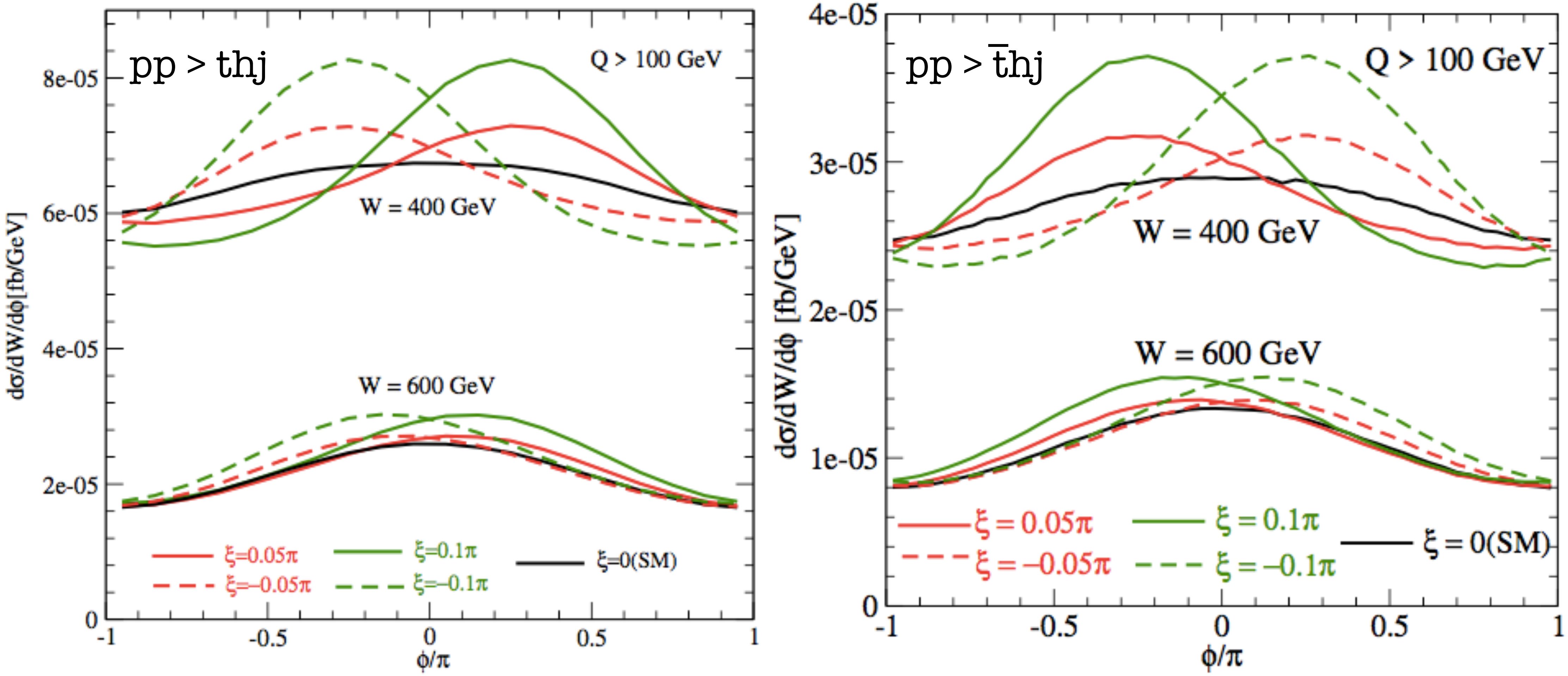


FIG. 8: Left panel: t. Right panel: $\bar{t}$. $d\sigma/d\mathtt{W}/d\phi$ v.s. ϕ at $\mathtt{W} = 400$ and 600 GeV for $Q > 100$ GeV. Black, red and green curves are for the SM ($\xi = 0$), $\xi = \pm 0.1\pi$, and $\pm 0.2\pi$. The solid curve are for $\xi \geq 0$, while the dashed curves are for $\xi < 0$.

asymmetry

$$A_\phi(\mathtt{W}) = \frac{\int_{-\pi}^{\pi} d\phi \ \mathrm{sgn}(\phi) d\sigma/d\mathtt{W}/d\phi}{d\sigma/d\mathtt{W}}$$

$> 0 \ (th)$ and $< 0 \ (\bar{t}h)$ for $\xi > 0$

$< 0 \ (th)$ and $> 0 \ (\bar{t}h)$ for $\xi < 0$

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$_T$)

Azimuthal asymmetry A_φ

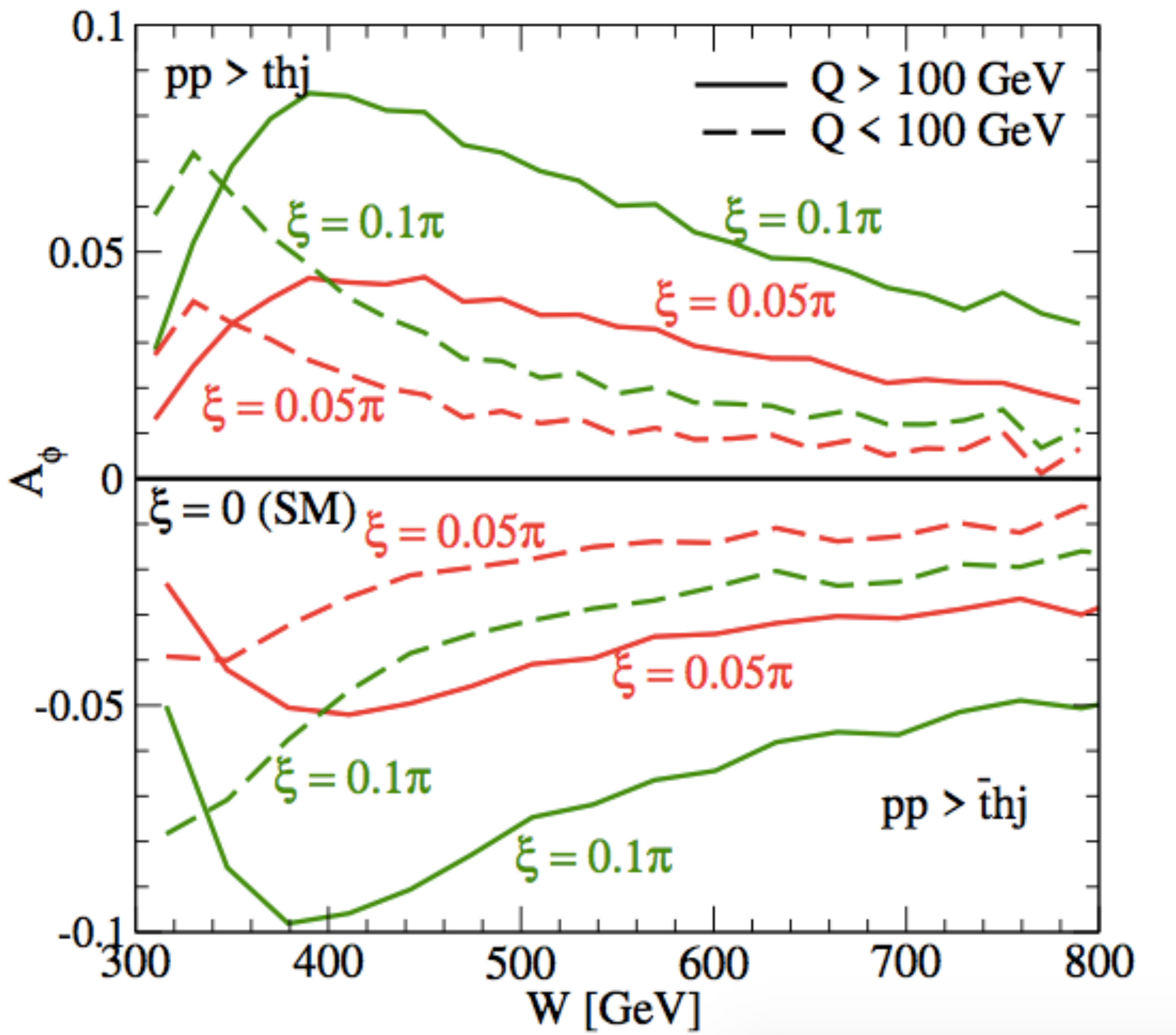


FIG. 11: Asymmetry $A_\phi(\mathtt{W})$ for $pp \to thj$ and $pp \to \bar{t}hj$ as functions of W, the invariant mass of th or $\bar{t}h$ system. Large Q ($Q > 100$ GeV) events are shown by solid lines, while small Q ($Q < 100$)GeV, events are shown by dashed curves. Results are shown for $\xi = 0$ (SM), $\xi = 0.05\pi$ (red) and 0.1π (green). $A_\phi > 0$ for th and A_ϕ <0 for $\bar{t}h$, when $\xi > 0$.

$|\mathcal{M}_+(ub > dth)|^2$ v.s. $|\overline{\mathcal{M}}_-(d\bar{b} > u\bar{t}h)|^2$

$$\mathcal{M}_+ = \frac{1-\tilde{c}}{2} e^{i\phi} \sin\frac{\theta^*}{2}\left[\frac{1+\cos\theta^*}{4}\bar{\beta} A\right] \qquad J_Z=3/2,\ \lambda=+1$$

$$+\frac{1+\tilde{c}}{2}\boxed{e^{-i\phi}}\sin\frac{\theta^*}{2}\left[\left(\frac{1+\cos\theta^*}{4}\bar{\beta}+\epsilon\delta\delta'\right)A-\left(e^{-i\xi}+\delta\delta' e^{i\xi}\right)B\right] \qquad J_Z=-1/2,\ \lambda=-1$$

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

$$\overline{\mathcal{M}}_- = \frac{1-\tilde{c}}{2} e^{i\phi} \sin\frac{\theta^*}{2}\left[\left(\frac{1+\cos\theta^*}{4}\bar{\beta}+\epsilon\delta\delta'\right)A-\left(e^{i\xi}+\delta\delta' e^{-i\xi}\right)B\right] \qquad J_Z=1/2,\ \lambda=+1$$

$$+\frac{1+\tilde{c}}{2}\boxed{e^{-i\phi}}\sin\frac{\theta^*}{2}\frac{1+\cos\theta^*}{4}\bar{\beta} A \qquad J_Z=-3/2,\ \lambda=-1$$

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

Top Polarization (mixed state)

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

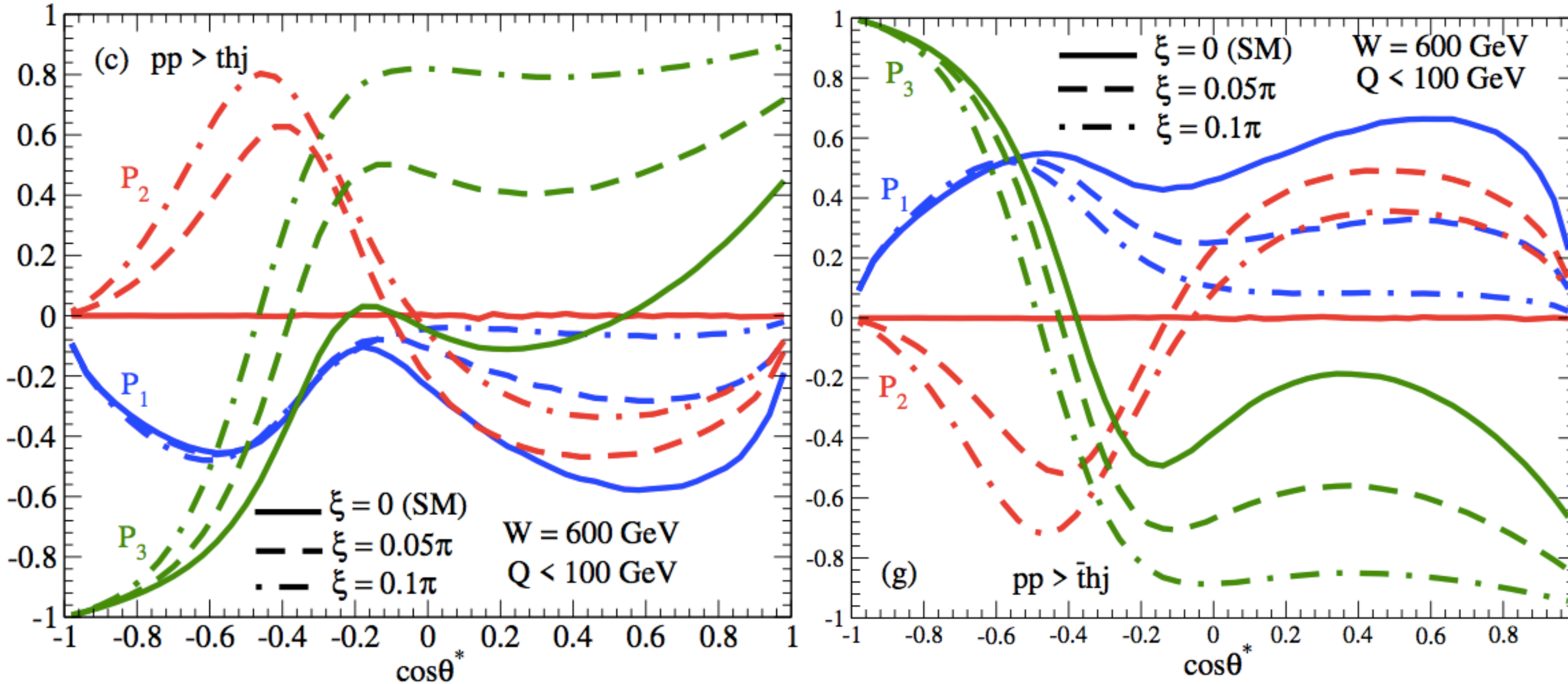
$$\rho_{\lambda\lambda'} = \frac{d\sigma_{\lambda\lambda'}}{d\sigma_{++} + d\sigma_{--}} = \frac{1}{2}\left[\delta_{\lambda\lambda'} + \sum_{k=1}^{3} P_k \sigma^k_{\lambda\lambda'}\right]$$

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.

$$P_2 = -2\mathrm{Im}(M_+ M_-^*)/(|M_+|^2 + |M_-|^2)$$

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

Top Polarization and anti-top polarisation P = (P1,P2,P3)



We find large |P2| when cosθ*<0, positive for t and negative for tbar. We therefore examine P2 for events with cosθ*<0 in the next slides.

Polarization P_2 of top and anti-top

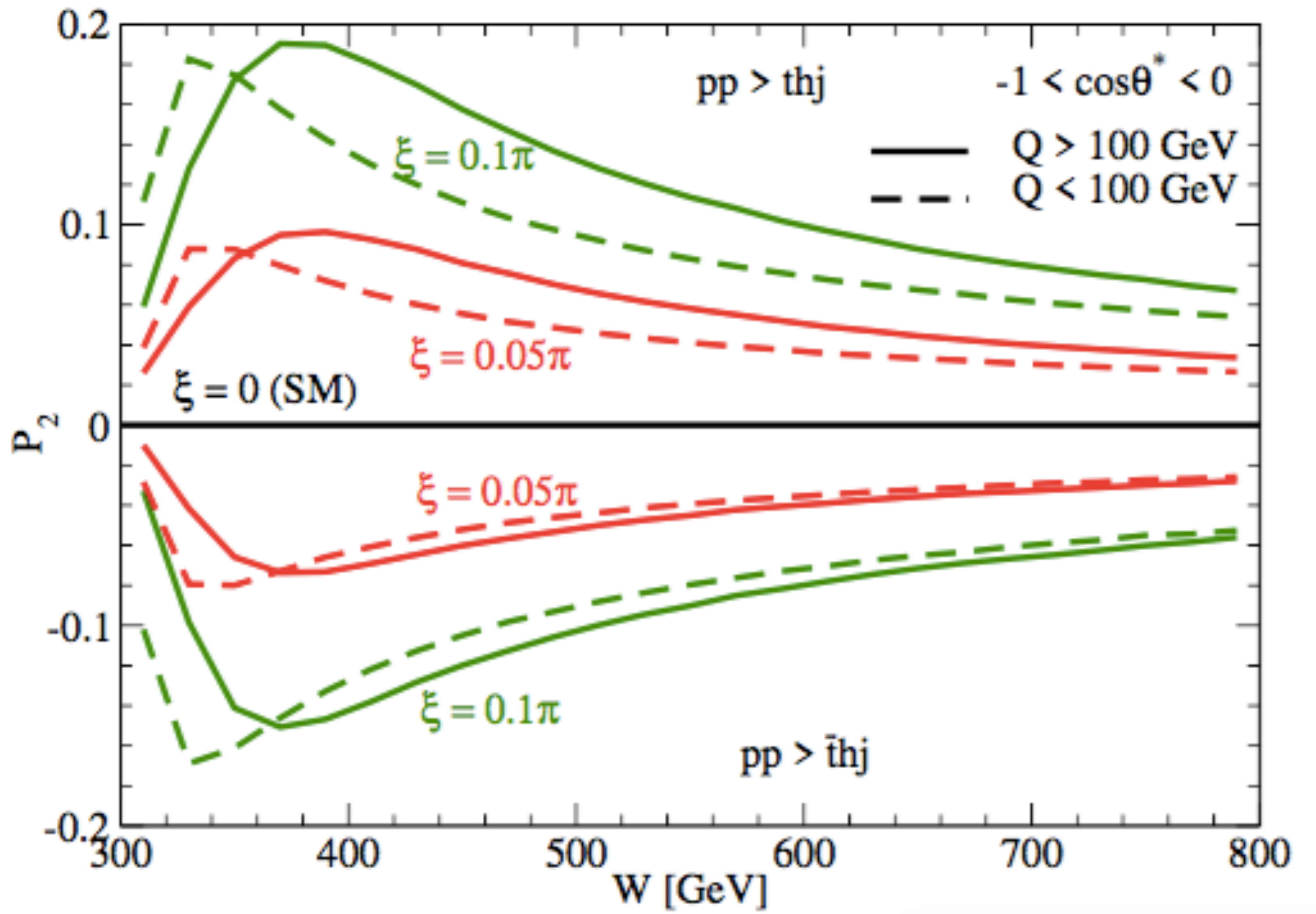
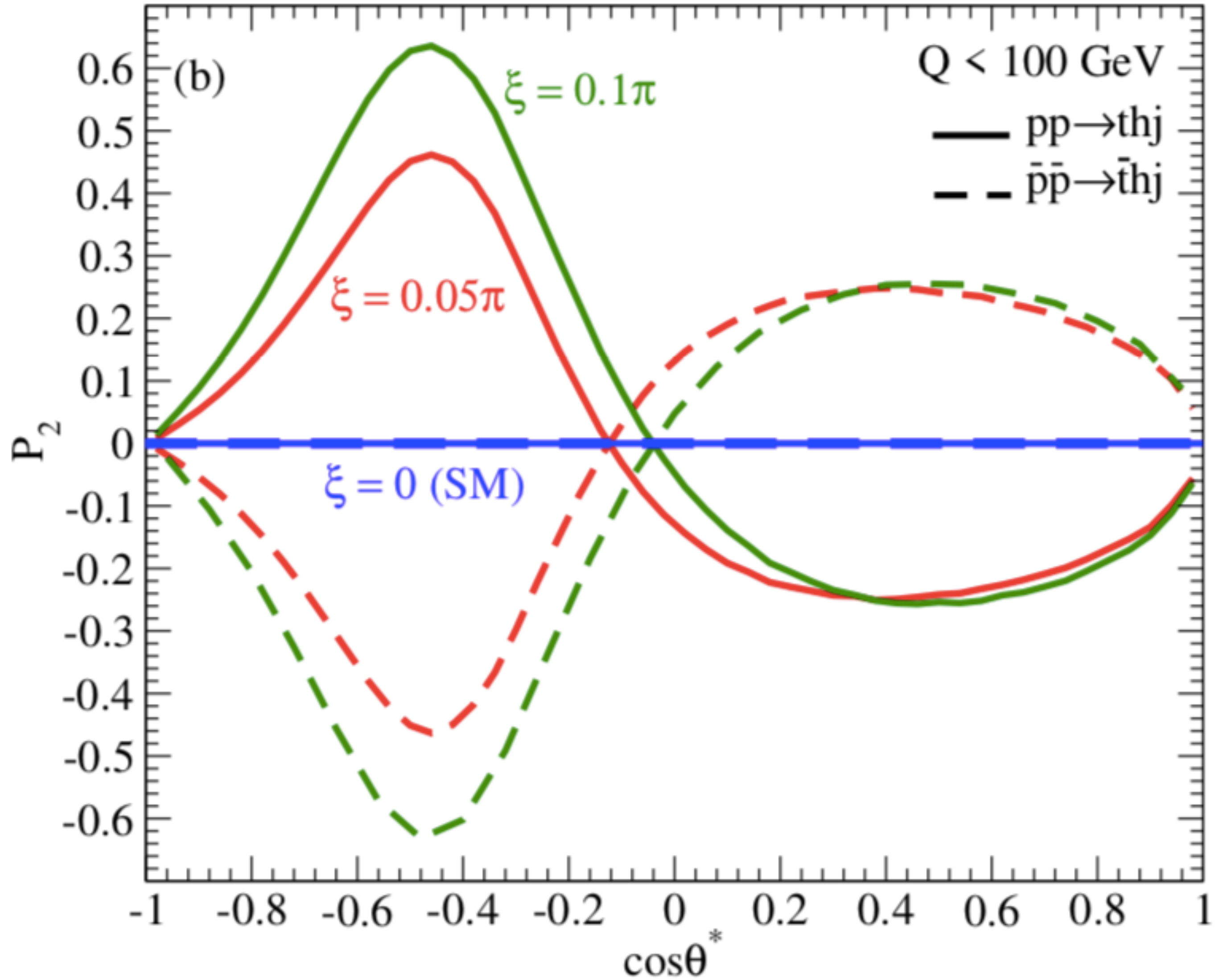


FIG. 15: P_2 v.s. W for $pp \to thj$ (a) and $pp \to \bar{t}hj$ (b) in the region $-1 < \cos\theta^* < 0$. The green curves are for $\xi = 0.1\pi$, while the red curves are for $\xi = 0.05\pi$. The soid curves are for $Q > 100$ GeV, while the dashed curves are for $Q < 100$ GeV.



$$pp \to thj \quad (ub \to dth) \quad \xleftrightarrow{\text{CP}} \quad \bar{p}\bar{p} \to \bar{t}hj \quad (\bar{u}\bar{b} \to \bar{d}\bar{t}h)$$

In thj and $\bar{t}$hj production at the LHC, longitudinal contributions ($W^{\pm}(\lambda=0)$) dominate.

$$W^{+}(\lambda = 0) + b \to t + h \quad \xleftrightarrow{\text{CP}} \quad W^{-}(\lambda = 0) + \bar{b} \to \bar{t} + h$$

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	

0.0051 ✓

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

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.

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

- Polarization can be measured by using the density matrix.

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

- Polarization perpendicular to the scattering plane measures the relative phase between the two helicity amplitudes

$$P_2 = \frac{-2\mathrm{Im}(M_+ M_-^*)}{|M_+|^2 + |M_-|^2} \;\propto \sin \xi_{htt}$$

- We find significant asymmetry reaching A_ϕ ~+8%(th),−10%($\bar{t}$h), whereas P_2~+18% (th), −15% ($\bar{t}$h) for xi=0.1pi. All the asymmetries change sign if xi is negative.

IWATE COLLIDER SCHOOL 2024

26 FEBRUARY - 2 MARCH, 2024

Appi highland, Iwate, Japan

Registration fee

FREE and local expenses will be supported.
(No support for travel fees.)

Eligibility

Mainly for graduate students and postdoc fellows
(Max. 25 participants in person)

Venue

ANA Crowne Plaza Resort Appi Kogen

Application submission deadline

8 December, 2023

Website

https://ics.sgk.iwate-u.ac.jp/

Contact

ics2024@iwate-u.ac.jp

Overview

Students will learn a variety of topics in collider physics via lectures and tutorials. Long lunch break for skiing and discussions are planned.

Lecturers:

- Celine Degrande (Louvain, Belgium)
- Rikkert Frederix (Lund, Sweden)
- Fabio Maltoni (Louvain, Belgium)
- Olivier Mattelaer (Louvain, Belgium)
- Marco Zaro (Milan, Italy) etc.

Organizers:

- Kaoru Hagiwara (KEK)
- Daniel Jeans (KEK)
- Fabio Maltoni (UC Louvain / Bologna)
- Kentarou Mawatari (Chair, Iwate U.)
- Shinya Narita (Iwate U.)
- Yajuan Zheng (Iwate U.)