Triple-product Asymmetries
A Snowmass Letter of Interest

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Triple products

- Processes with more than three final-state particles

  Assuming final state spin/polarizations not directly measured

- Four-body final state has 5 kinematic variables

  Possible choice: 2 invariant masses + 3 helicity angles

Differential decay rate: $\dfrac{d^5\Gamma}{dq_{12}^2\ dq_{34}^2\ d\cos\theta^*\ d\cos\theta_\ell\ d\chi} \propto |\mathcal{M}|^2$

$$|\mathcal{M}|^2 = \sum_j K_i(q_{12}^2, q_{34}^2)\ f_i(\theta^*, \theta_\ell, \chi)$$

Triple-products: $f_i \propto \sin\chi = (\hat{n}_{12} \times \hat{n}_{34}) \cdot \hat{z}$

$\hat{n}_{ij}$ defines plane containing final states i, j

$\chi =$ azimuthal angle about decay axis

Triple-product Asymmetries

- Coefficients of TP angular functions: $K_i \propto \mathrm{Re/Im}(A_a A_b^*)$
  Helicity amplitudes A_a contain physics information
- TP Asymmetry: $X = \mathrm{Im}(A_a A_b^* - \bar{A}_a \bar{A}_b^*)$
  $\rightarrow$ $\bar{A}$ represents CP conjugate of A
  $\rightarrow$ $\bar{X} = -X \Rightarrow X$ is CP-odd
- Compare Γ and $\bar{\Gamma}$ $\rightarrow$ find non-zero true CP-Violating TPAs
- In order to observe CP violation
  $\Rightarrow$ measure a non-zero true TPAs
- $d\Gamma + d\bar{\Gamma}$ contains TPAs
  TP terms $\propto \sin\chi$ $\rightarrow$ flip sign from process to anti-process

Potential for discovery

- Form of true-CPV TP terms: *Phases* $\rightarrow$ *δ (CP-even), ϕ (CP-odd)*

  $\mathrm{Im}(A_a A_b^*) = |A_a||A_b| \sin(\Delta\delta_{ab} + \Delta\phi_{ab})$

- Strong-phase differences not needed for non-zero TPAs

  $\Rightarrow \quad \mathrm{Im}(A_a A_b^* - \bar{A}_a \bar{A}_b^*) = 2|A_a||A_b| \cos(\Delta\delta_{ab}) \sin(\Delta\phi_{ab})$

- Single CP-odd phase in the SM $\Rightarrow$ $\Delta\phi = 0$ $\Rightarrow$ TPAs vanish

- Measurement of non-zero CPV TPA $\rightarrow$ *unambiguous signal*

  $\Rightarrow$ New ϕ beyond the SM $\Rightarrow$ *New source of CPV*

- Measure event-distribution asymmetry in $\sin\chi$

$$A_{\mathrm{TP}} = \frac{N(\sin\chi > 0) - N(\sin\chi < 0)}{N(\sin\chi > 0) + N(\sin\chi > 0)}$$

Need for theory progress

- In the event of observation of TPAs

  $\rightarrow$ Model based theory predictions for TPAs

  $\rightarrow$ Analysis of theoretical cleanliness of observables

  (hadronic uncertainties in determination of new CP-odd phase?)
- TPAs may be observed in semi-leptonic B decay modes
  - $B \rightarrow K^* \ell^- \ell^+$ (precision?)
  - $B \rightarrow D^* \mu(\tau) \nu_{\mu(\tau)}$ (additional observables?)
- Hadonic B decay modes: $B \rightarrow K^* \bar{K}^*$
- Identify other multi-body channels $\rightarrow$ optimum for experiments?
- Meson mixing and time-dependence effects?

Summary

- New sources of CP violation (BSM) are necessary
- CPV can help distinguish models
- Angular asymmetries are a great target
- True TPAs need new CP-odd phase only (~~strong phase~~)
- Non-zero measurement for true-CPV TPAs $\Rightarrow$ *New physics*
- Theory progress needed:

  $\rightarrow$ find optimal processes for searches

  $\rightarrow$ interpret data/search results to quantify NP

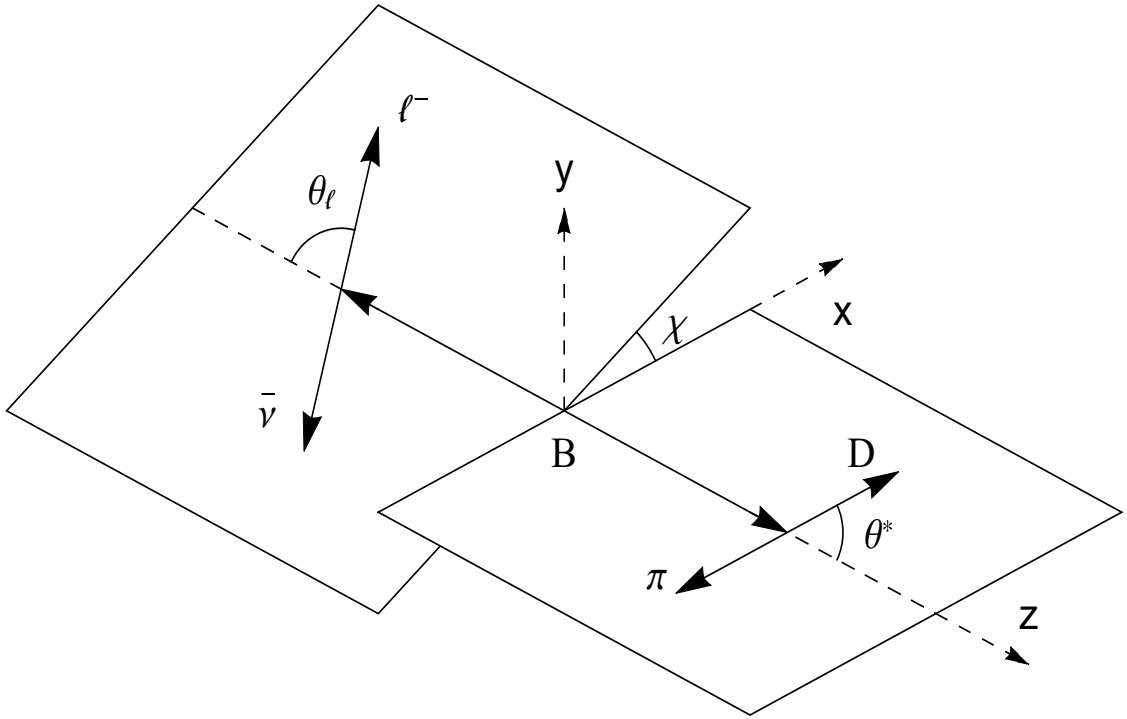
References

- Valencia, PRD 39, 3339 (1989)
- Datta and London, arXiv:hep-ph/0303159
- Bensalem, Datta, and London, arXiv:hep-ph/0205009, arXiv:hep-ph/0208054
- Datta, Duraisamy, and London, arXiv:1103.2442
- Datta, Duraisamy, and London, arXiv:1207.4495
- **BB**, Datta, Duraisamy, and London, arXiv:1306.1911
- Alok et al. (with **BB**), arXiv:1703.09247
- **BB**, Datta, Kamali, and London, arXiv:1903.02567
- **BB**, Datta, Kamali, and London, arXiv:2005.03032

Thank You!

Back-up Slides

Angular distribution in $B \to D^* \ell \bar{\nu}$



- 4-body decay through D^* intermediate $\Rightarrow$ (5 - 1 =) 4 parameters
- Invariant mass (q^2) and angles ($\theta^*, \theta_\ell, \chi$)