C, P, and CP violating triple product Asymmetries

Charm 2015
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Outline

- **Introduction**
  - A brief motivation for studying discrete symmetries

- **Triple product (TP) asymmetry tests**
  - Old notation
  - A different viewpoint description
  - Applications to various systems

- **Summary**

Introduction

- Discrete symmetries are at the heart of our understanding of fundamental physics.
- The symmetries C, P, T and their combinations play an important role in modern physics.
- The following pattern is observed:

	Stong	Electromagnetic	Weak	New Physics
P	conserved	conserved	violated	?
C	conserved	conserved	violated	?
T	conserved	conserved	violated	?
CP	conserved	conserved	violated	?
CPT	conserved	conserved	conserved	?

- 50 years of measurements of CP violation in quarks are consistent with each other; just not enough to resolve the matter-antimatter asymmetry observed in the Universe.
- Can we learn something useful from systematic tests of all of these symmetries?
- TPs can be used to probe P, C, and CP.

Introduction

- Need to test a reference process against the symmetry transformed one; where S=(C, P, T, CP, CPT); e.g.

$$A_{\mathcal{S}} = \frac{P(\mathcal{S}|reference\rangle) - P(|reference\rangle)}{P(\mathcal{S}|reference\rangle) + P(|reference\rangle)}$$

c.f. CP asymmetries constructed from CP conjugate processes.

- The problem resides in identifying conjugate pairs of processes that can be experimentally distinguished.
  - Given strong and EM conserve these symmetries we want to identify weak decays (for quarks) that can be transformed under C, P, CP, T, CPT, and focus on conjugate pairs of decays.
  - Failing that we have to control hadronic uncertainties so that we can interpret measurements.
  - It is also worth testing our knowledge of the other forces, searching for new physics that may violate these symmetries.

Formalism

- Consider the decay of some particle to a 4-body final state

$$M \to abcd$$

- TP asymmetries can be used to probe symmetry conservation in the longitudinal polarisation of these decays.

Dreitlein and Primakoff, Phys. Rev. 124 (1961) 268.

- Some example decays that can test the SM and be used to search for new physics:

Low energy → High energy

$$K_{S,L} \to \pi^+\pi^-e^+e^-$$
$$D^0 \to K^+K^-\pi^+\pi^-$$
$$D_s^+ \to K_S^0K^-\pi^+\pi^-$$
$$B \to J\psi K^*$$
$$B_s \to J\psi\phi$$

$$\Lambda_c \to \mathcal{B}\mathcal{P}$$
$$\Lambda_c \to \mathcal{B}\mathcal{V}$$
$$\Lambda_b \to \Lambda J\psi$$

$\mathcal{B}$ = Baryon
$\mathcal{P}$ = Pseudoscalar
$\mathcal{V}$ = Vector

$$H \to 4\ell$$
$$Z \to 4\ell$$
$$Z \to b\bar{b}b\bar{b}$$
$$ZH \to \ell^+\ell^-q\bar{q}$$
$$W^\pm H \to \ell^\pm\nu q\bar{q}$$

See AB arXiv:1408.3813 and refs therein.

Traditional view

- The nomenclature in the literature often interchanges the T-odd nature of a CP violating the TP with the jargon "T violation".

  i.e. rather than considering $T(M \to abcd) = abcd \to M$

  there is a mix of language in the literature where the "T-volation" is jargon for

  $$T\left(p_c \cdot (p_a \times p_b)\right) = -p_c \cdot (p_a \times p_b)$$

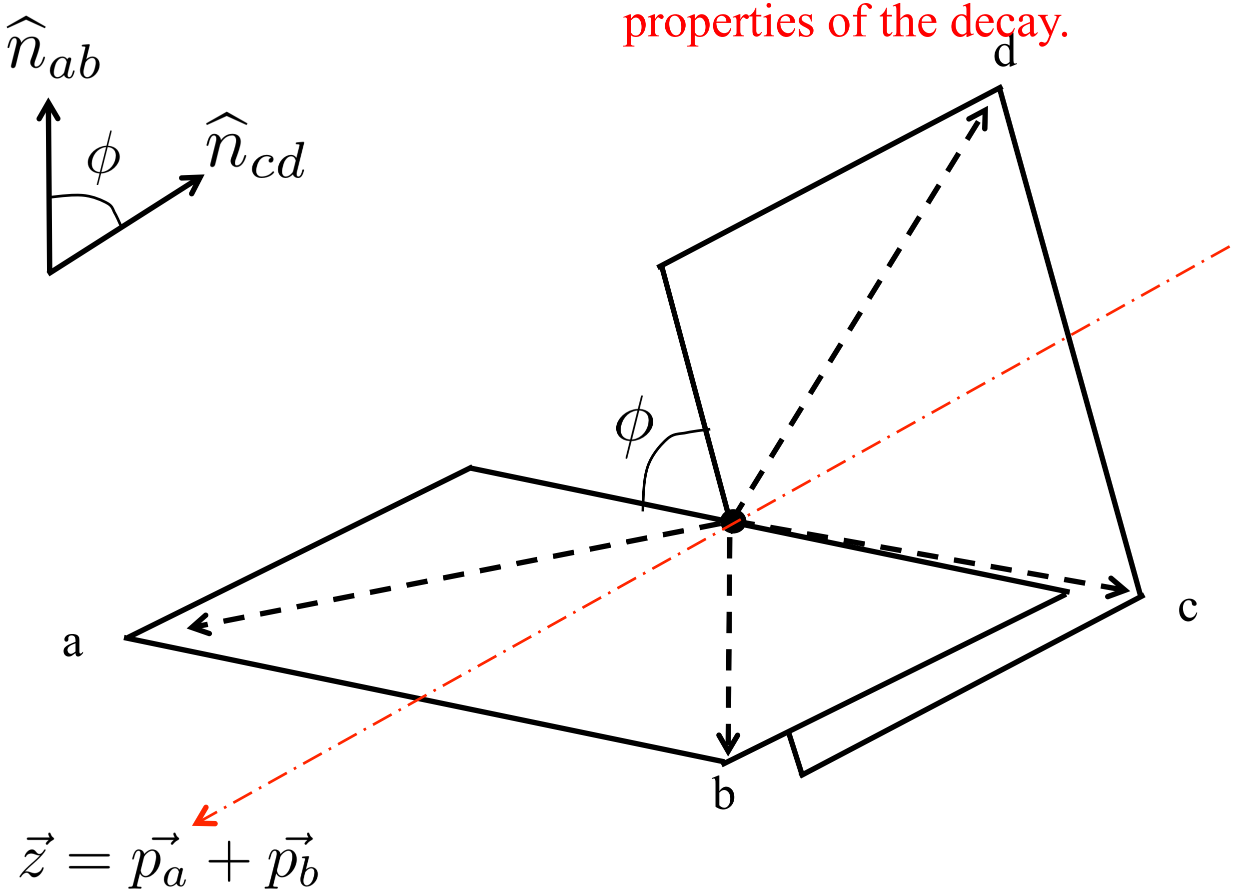
- Tests of T violation using neutral mesons amongst other quantum mechanical systems are now possible. Entanglement is a useful tool to facilitate such studies as described elsewhere:

Banuls & Bernabeu [PLB **464** 117 (1999); PLB **590** 19 (2000)]; Alverex & Szynkman [hep-ph/0611370]; Bernaneu, Martinez-Vidal, Villanueva-Perez [JHEP **1208** 064 (2012)]; AB, Inguglia, Zoccali [arXiv:arXiv:1302.4191]; Applebaum et al, [arXiv:1312.4164]; Schubert et al., arXiv:1401.6938; Ed. AB et al arXiv:1406.6311; Fidecaro, Gerber, Ruf, arXiv:1312.3770; Schubert, arXiv:1409.5998;Dadisman, Gardner, Yan, arXiv:1409.6801; ... and references therein.

- But it is still worth looking at what most measurements use...

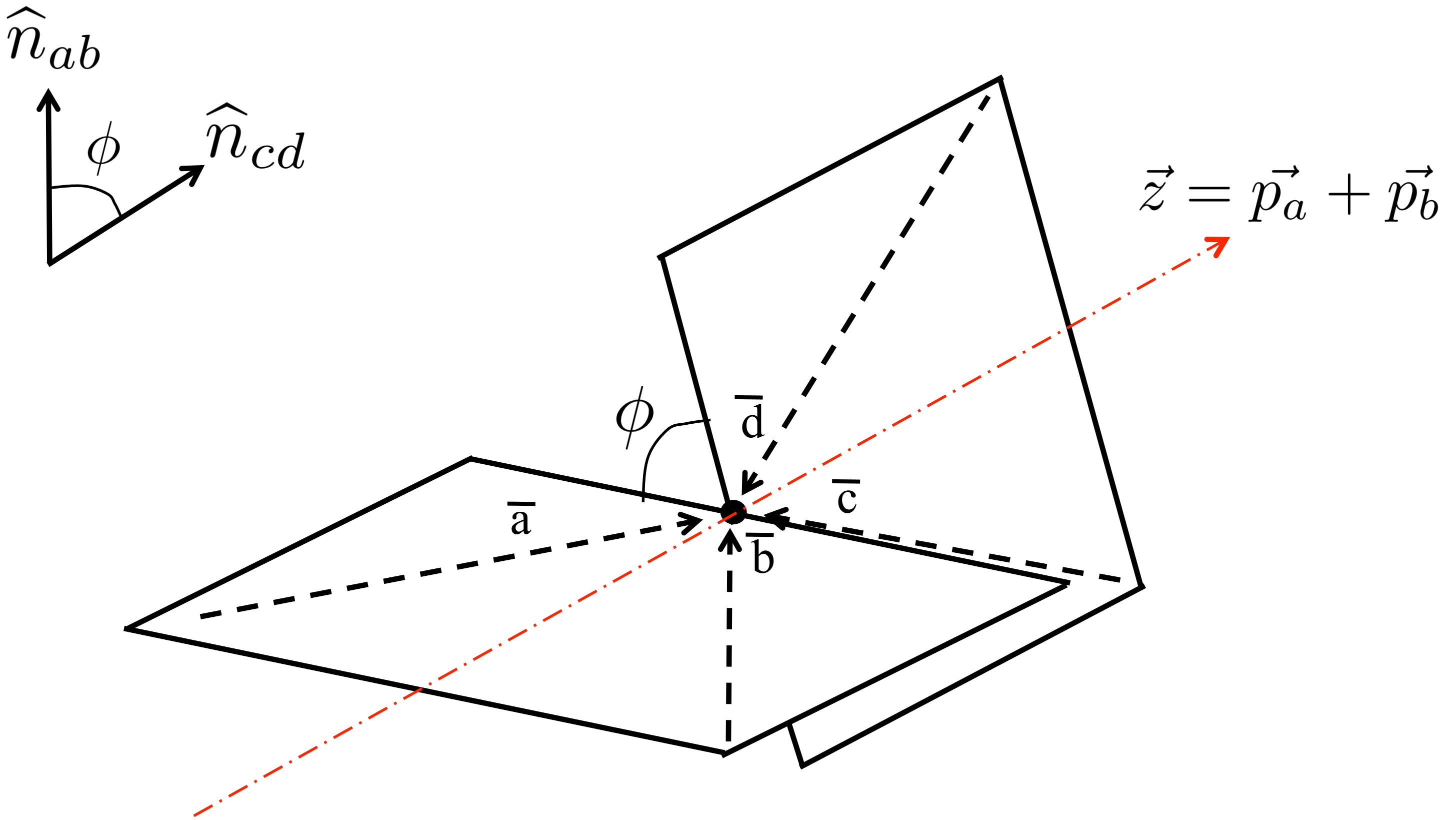
Reference Plot: $M \rightarrow abcd$

We can construct a TP for some decay, from three of the four particles in the final state.   The angular distribution can then be used to test symmetry properties of the decay.



$$[\vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b)]$$

$abcd \to M$

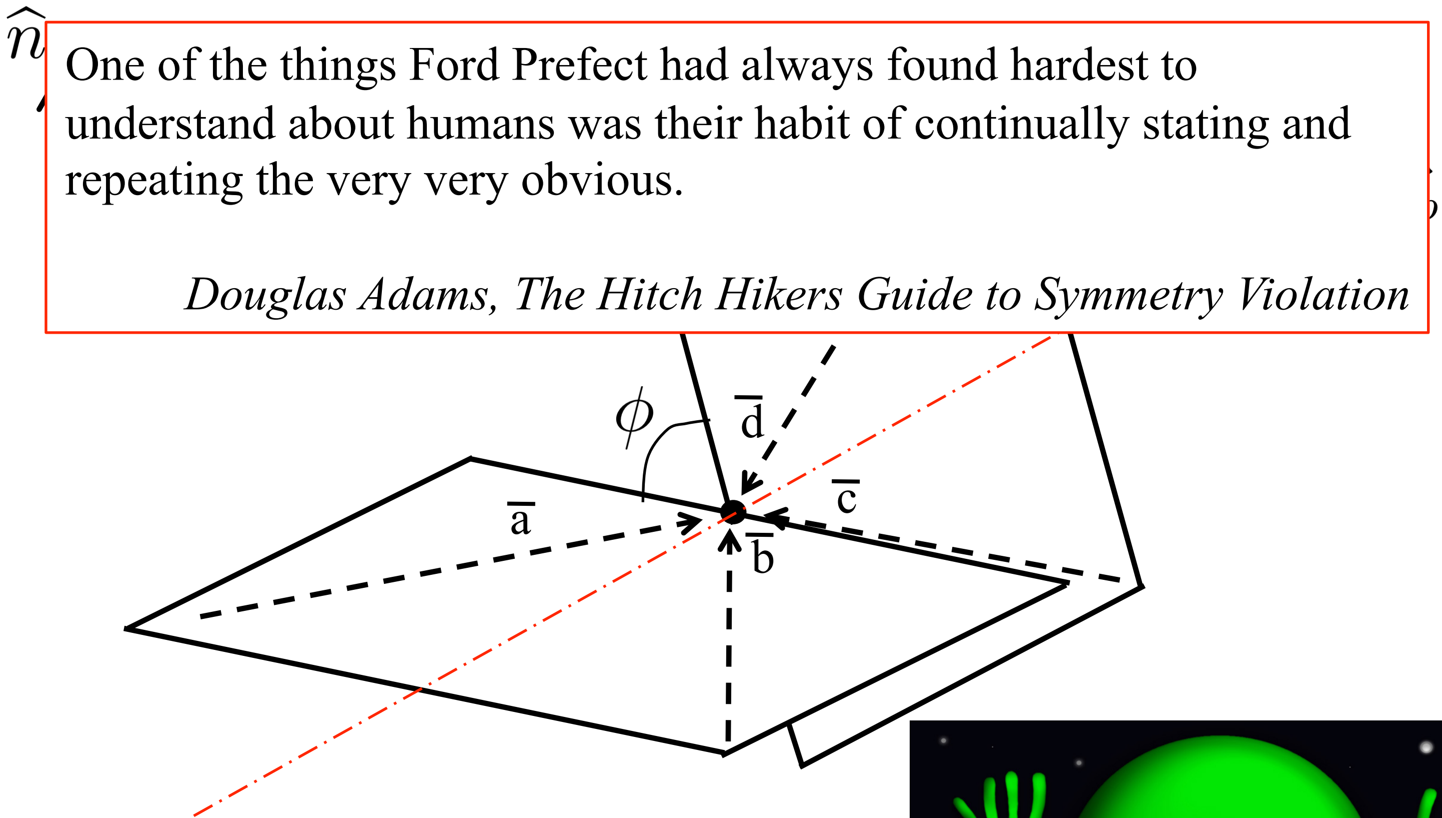


T Conjugate:

THIS NEVER HAPPENS ...

One of the things Ford Prefect had always found hardest to understand about humans was their habit of continually stating and repeating the very very obvious.

Douglas Adams, The Hitch Hikers Guide to Symmetry Violation



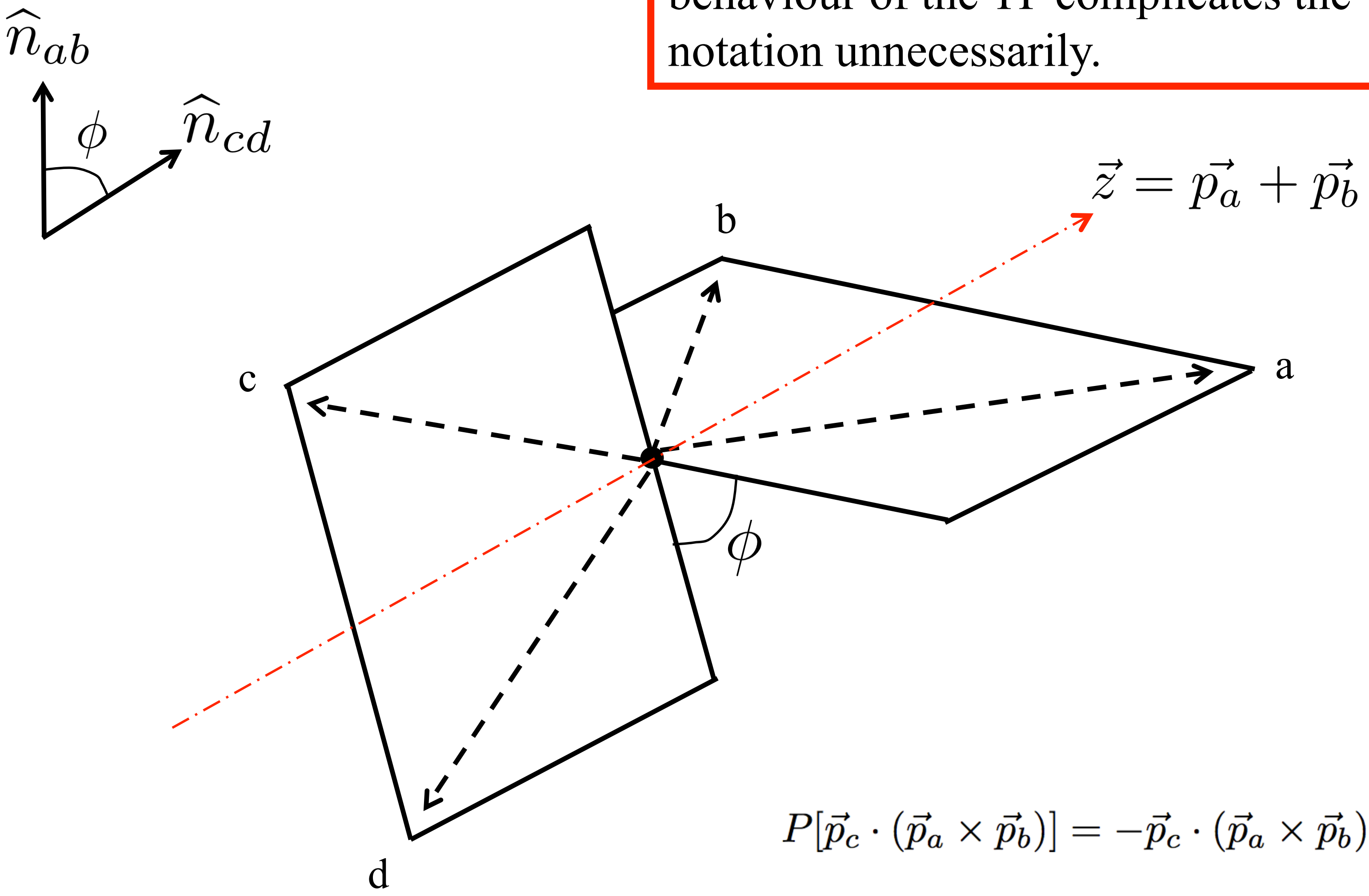
~~T Conjugate:~~

Can construct a P Conjugate that acts the same way on the triple product, and is physical.

- Now we can proceed to look at the problem from the viewpoint of P, C, and CP directly...

Under P Operation: $M \to abcd$

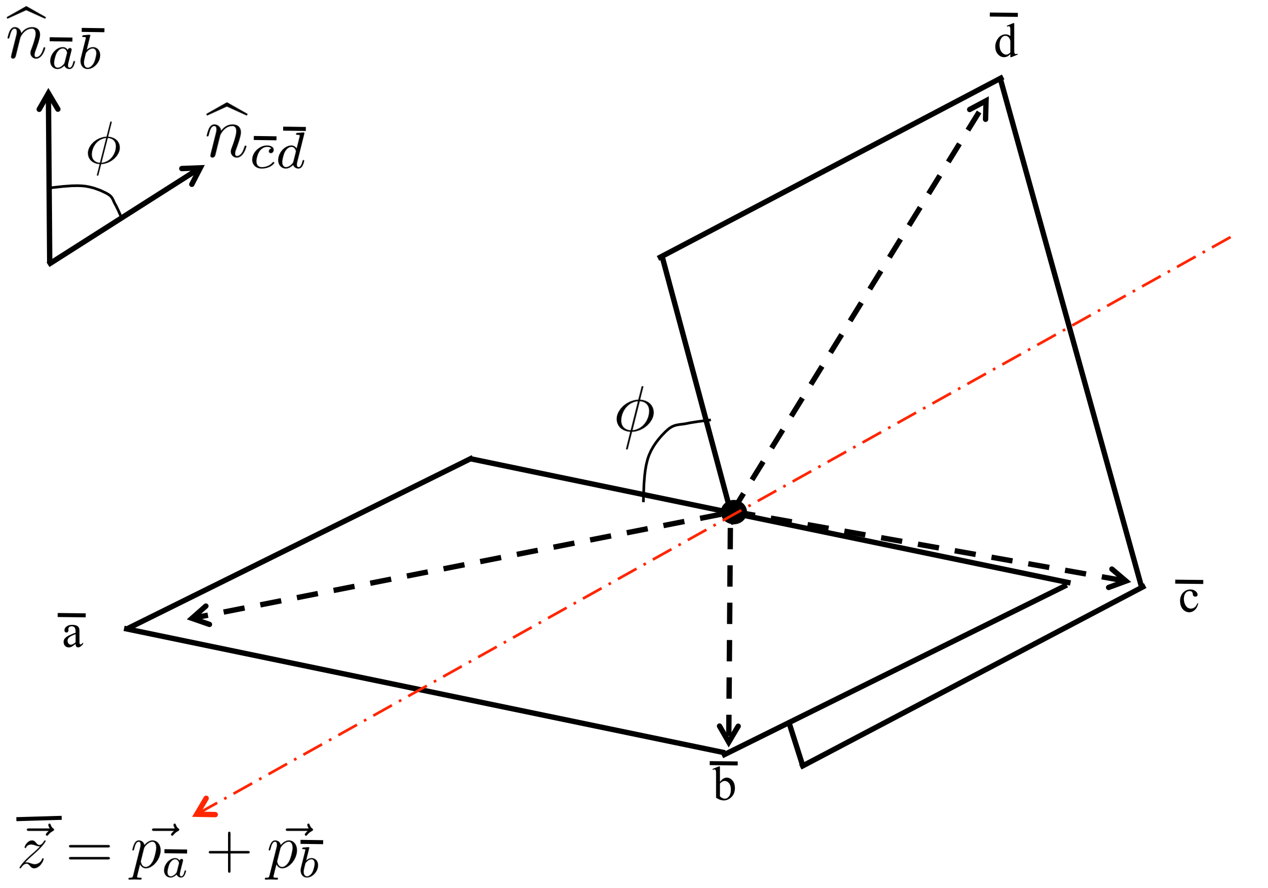
This is what is really being used for the T-odd triple products. Using the T-odd behaviour of the TP complicates the notation unnecessarily.



$$P[\vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b)] = -\vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b),$$

Spatial inversion

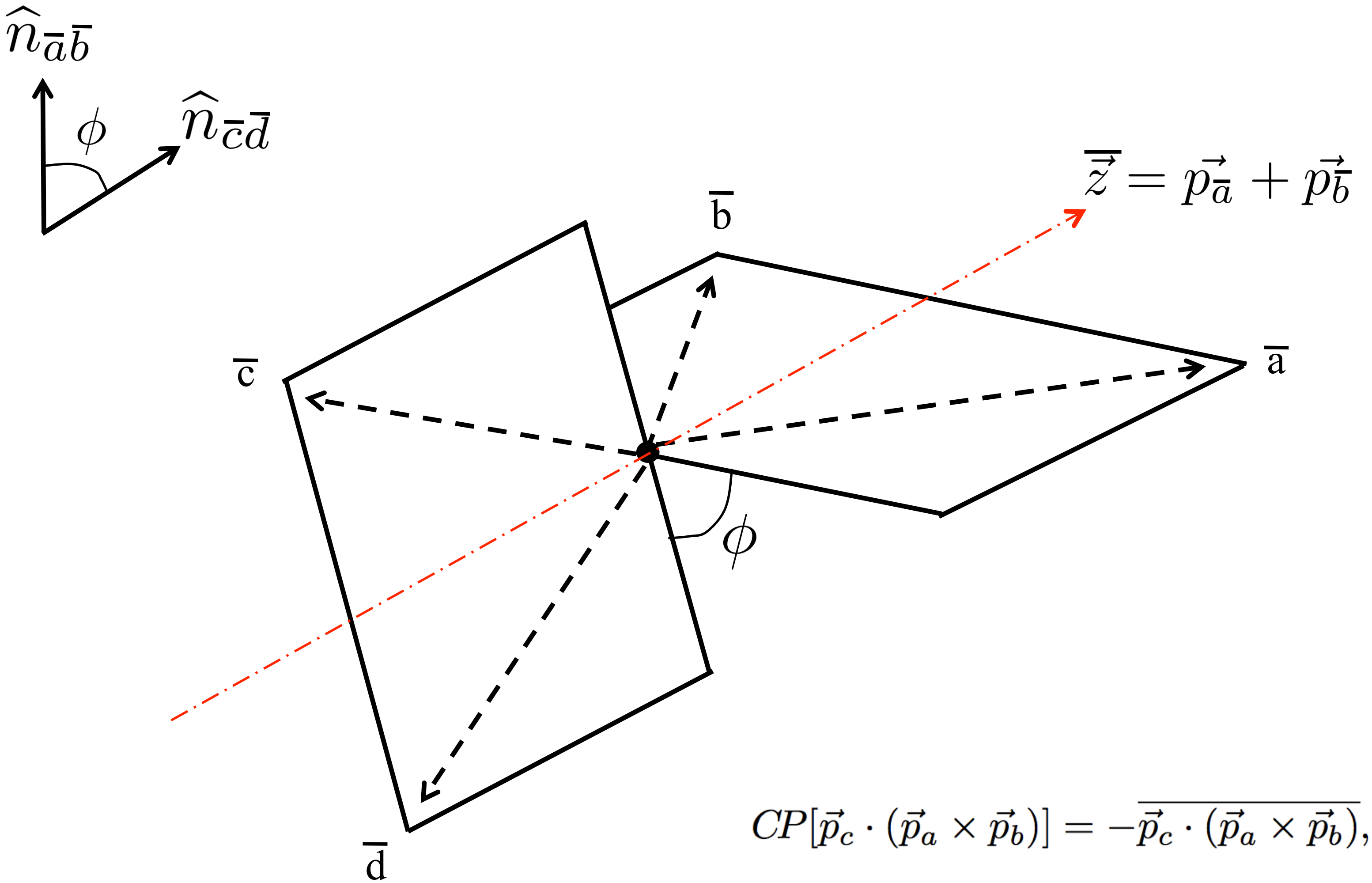
Under C Operation: $\overline{M} \rightarrow \overline{abcd}$



$$C[\vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b)] = \overline{\vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b)},$$

Change particles to antiparticles

Under CP Operation: $\overline{M} \rightarrow \overline{abcd}$



$$CP[\vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b)] = -\overline{\vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b)},$$

Change particles to antiparticles and spatially invert

TP asymmetries

- These are either computed in an un-normalised way (in which case the sign of the asymmetry is important), or normalised, so that one can study the asymmetry as a function of the angle between the two decay planes of particles.
  - Look at 4 body decays, and compute the triple product using the momenta in the CM system: e.g.

$$\psi = \vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b) \longrightarrow \text{use the sign of } \psi$$

  - Depending on the mode the following may be of interest

$$\sin\phi \;=\; (\widehat{n}_{ab} \times \widehat{n}_{cd}) \cdot \widehat{z}.$$

$$\sin 2\phi = \sin\phi \cos\phi$$

    This requires normalisation of the triple product and understanding of the decay dynamics.
- Both approaches are used in the literature.

K_L decays

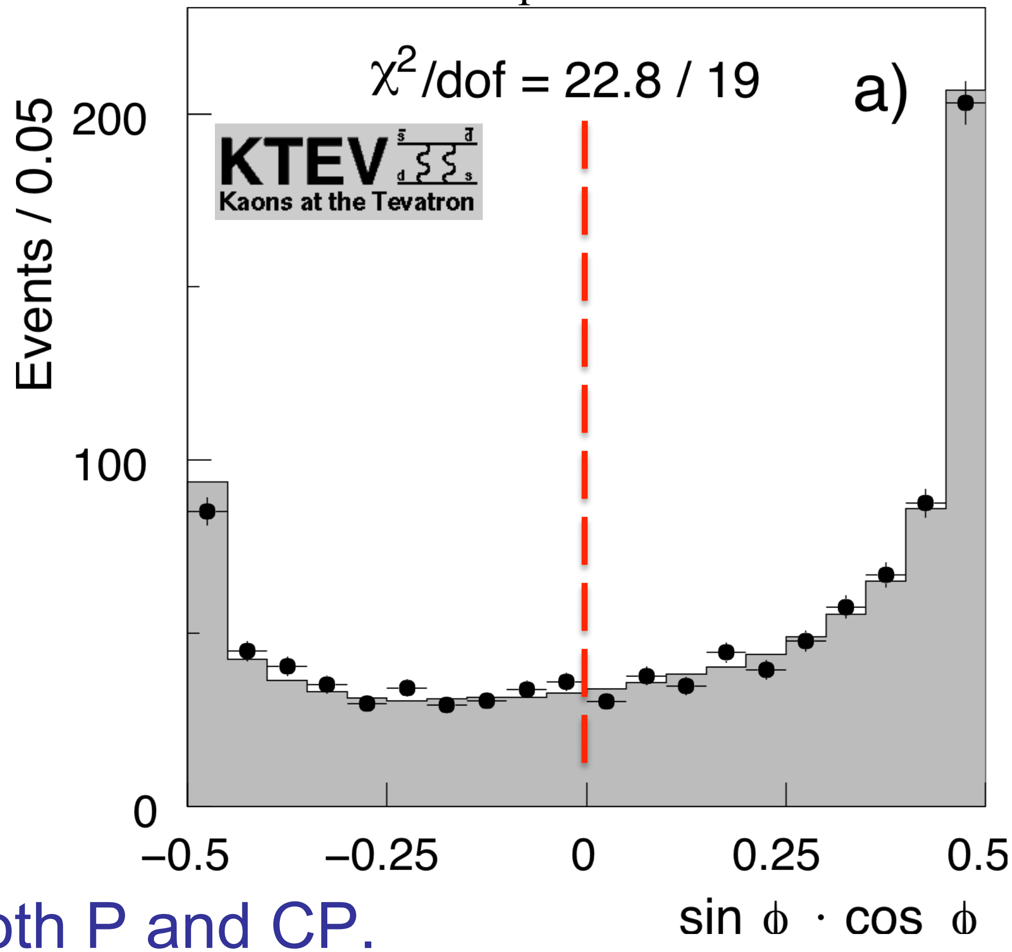
- There is a single asymmetry that tests P and CP simultaneously for:

$$K_L \rightarrow \pi^+\pi^-e^+e^-$$

$$A = \frac{N_{\sin\phi\cos\phi\,>\,0.0} - N_{\sin\phi\cos\phi\,<\,0.0}}{N_{\sin\phi\cos\phi\,>\,0.0} + N_{\sin\phi\cos\phi\,<\,0.0}}$$

$$A = (13.6 \pm 1.4 \pm 1.5)\%\ \text{KTeV}$$
$$A = (14.2 \pm 3.0 \pm 1.9)\%\ \text{NA48}$$
$$A = (13.7 \pm 1.5)\%\ \text{PDG}$$

KTeV: Phys.Rev.Lett.96:101801,2006
NA48: EPJC 30 p33 2003



- c.f $\varepsilon_K \sim 10^{-3}$ and $\varepsilon'_K \sim 10^{-6}$
- This K_L decay violates both P and CP.

K_S decays

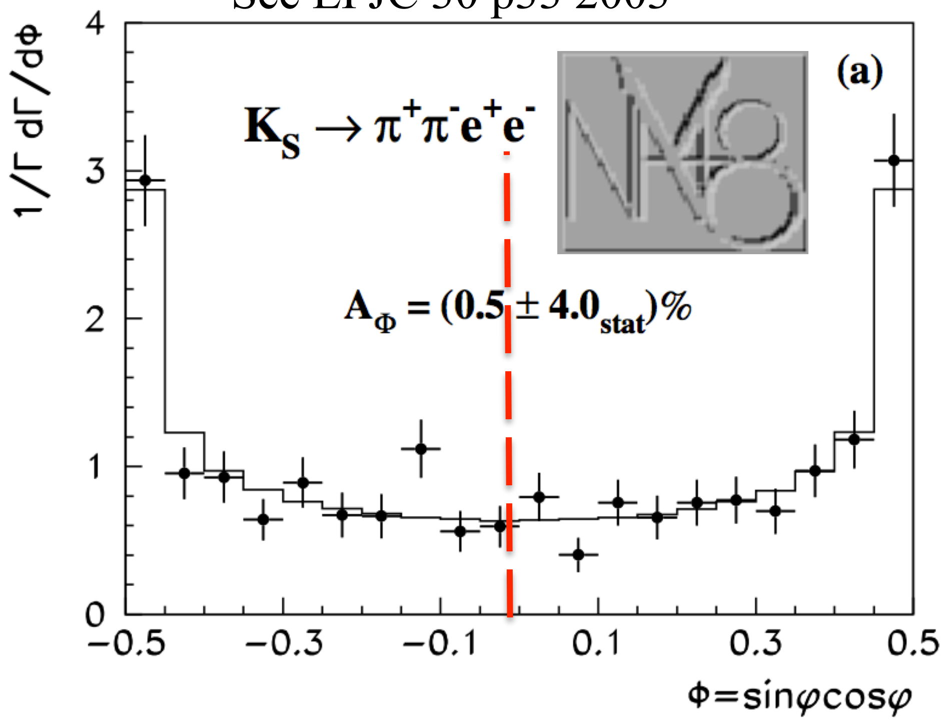
- There is a single asymmetry that tests P and CP simultaneously for:

See EPJC 30 p33 2003

$$K_S \rightarrow \pi^+ \pi^- e^+ e^-$$

$$A = \frac{N_{\sin\phi\cos\phi\ >\ 0.0} - N_{\sin\phi\cos\phi\ <\ 0.0}}{N_{\sin\phi\cos\phi\ >\ 0.0} + N_{\sin\phi\cos\phi\ <\ 0.0}}$$

$$A = (0.5 \pm 4.0)\%$$



- This K_S decay is consistent with both P and CP, in contrast to the K_L system.

- Nomenclature often used (Γs are new, C_T > < 0 are old)

Particles:

$$\Gamma_+ \equiv N(C_T > 0),$$ Positive values of the TP

$$\Gamma_- \equiv N(C_T < 0).$$ Negative values of the TP

Anti-particles:

$$\overline{\Gamma}_+ \equiv N(-\overline{C}_T < 0),$$ Positive values of the TP

$$\overline{\Gamma}_- \equiv N(-\overline{C}_T > 0).$$ Negative values of the TP

- Symmetry conjugates of the Γs

$$\begin{aligned}
P(\Gamma_+) &= \Gamma_- & C(\Gamma_+) &= \overline{\Gamma}_+ & CP(\Gamma_+) &= \overline{\Gamma}_- \\
P(\Gamma_-) &= \Gamma_+ & C(\Gamma_-) &= \overline{\Gamma}_- & CP(\Gamma_-) &= \overline{\Gamma}_+ \\
P(\overline{\Gamma}_+) &= \overline{\Gamma}_- & C(\overline{\Gamma}_+) &= \Gamma_+ & CP(\overline{\Gamma}_+) &= \Gamma_- \\
P(\overline{\Gamma}_-) &= \overline{\Gamma}_+ & C(\overline{\Gamma}_-) &= \Gamma_- & CP(\overline{\Gamma}_-) &= \Gamma_+
\end{aligned}$$

Brief reminder of what is being measured

- Can measure 12 asymmetries in terms of four rates:

$$\Gamma_+, \Gamma_-, \overline{\Gamma}_+, \overline{\Gamma}_-$$

  - 6 Asymmetries are computed from considering C, P, and CP on these rates.
  - A further 6 asymmetries are computed by constructing asymmetries from the "other" symmetries.
- These are summarised on the next pages:
  - The P and CP derived asymmetries sample different regions of phase space.
  - The C asymmetries sample the same region.
- BaBar have measured these for D^0, D^+ and D_s^+ decays.

See AB arXiv:1408.3813

Asymmetries

- P derived asymmetries:

(P odd triple product asymmetries)

$$A_P = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}, \quad \overline{A}_P = \frac{\overline{\Gamma}_+ - \overline{\Gamma}_-}{\overline{\Gamma}_+ + \overline{\Gamma}_-}$$

- C derived asymmetries:

(C even triple product asymmetries)

$$A_C = \frac{\overline{\Gamma}_- - \Gamma_-}{\overline{\Gamma}_- + \Gamma_-}, \quad \overline{A}_C = \frac{\overline{\Gamma}_+ - \Gamma_+}{\overline{\Gamma}_+ + \Gamma_+}$$

- CP derived asymmetries:

(CP odd triple product asymmetries)

$$A_{CP} = \frac{\overline{\Gamma}_+ - \Gamma_-}{\overline{\Gamma}_+ + \Gamma_-}, \quad \overline{A}_{CP} = \frac{\overline{\Gamma}_- - \Gamma_+}{\overline{\Gamma}_- + \Gamma_+}$$

Asymmetries

AB arXiv:1408.3813

There are only 9 distinct conditions for non-zero asymmetries, however denominators are all different, so there are 12 distinct asymmetries.

- ## P derived asymmetries:

(P odd triple product asymmetries)

$$A_P = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}, \quad \overline{A}_P = \frac{\overline{\Gamma}_+ - \overline{\Gamma}_-}{\overline{\Gamma}_+ + \overline{\Gamma}_-}$$

$$\Rightarrow$$

$$a_C^P = \frac{1}{2}\left(A_P - \overline{A}_P\right)$$

$$a_{CP}^P = \frac{1}{2}\left(A_P + \overline{A}_P\right)$$

- ## C derived asymmetries:

(C even triple product asymmetries)

$$A_C = \frac{\overline{\Gamma}_- - \Gamma_-}{\overline{\Gamma}_- + \Gamma_-}, \quad \overline{A}_C = \frac{\overline{\Gamma}_+ - \Gamma_+}{\overline{\Gamma}_+ + \Gamma_+}$$

$$\Rightarrow$$

$$\boxed{a_P^C = \frac{1}{2}(A_C - \overline{A}_C)}$$

$$a_{CP}^C = \frac{1}{2}(A_C + \overline{A}_C)$$

- ## CP derived asymmetries:

(CP odd triple product asymmetries)

$$A_{CP} = \frac{\overline{\Gamma}_+ - \Gamma_-}{\overline{\Gamma}_+ + \Gamma_-}, \quad \overline{A}_{CP} = \frac{\overline{\Gamma}_- - \Gamma_+}{\overline{\Gamma}_- + \Gamma_+}$$

$$\Rightarrow$$

$$\boxed{\begin{aligned} a_P^{CP} &= \frac{1}{2}(A_{CP} - \overline{A}_{CP}) \\ a_C^{CP} &= \frac{1}{2}(A_{CP} + \overline{A}_{CP}), \end{aligned}}$$

Classes of decay

- There are three classes of decay:

1) of the form $\overline{M} \neq M; \ \overline{abcd} \neq abcd$, e.g.: (12 asymmetries)

$$D^+ \to K_S^0 K^- \pi^+ \pi^-$$
$$D_s^+ \to K_S^0 K^- \pi^+ \pi^-$$

2) of the form $\overline{M} \neq M; \ \overline{abcd} = abcd$, e.g.: (12 asymmetries)

$$D^0 \to K^+ K^- \pi^+ \pi^-$$

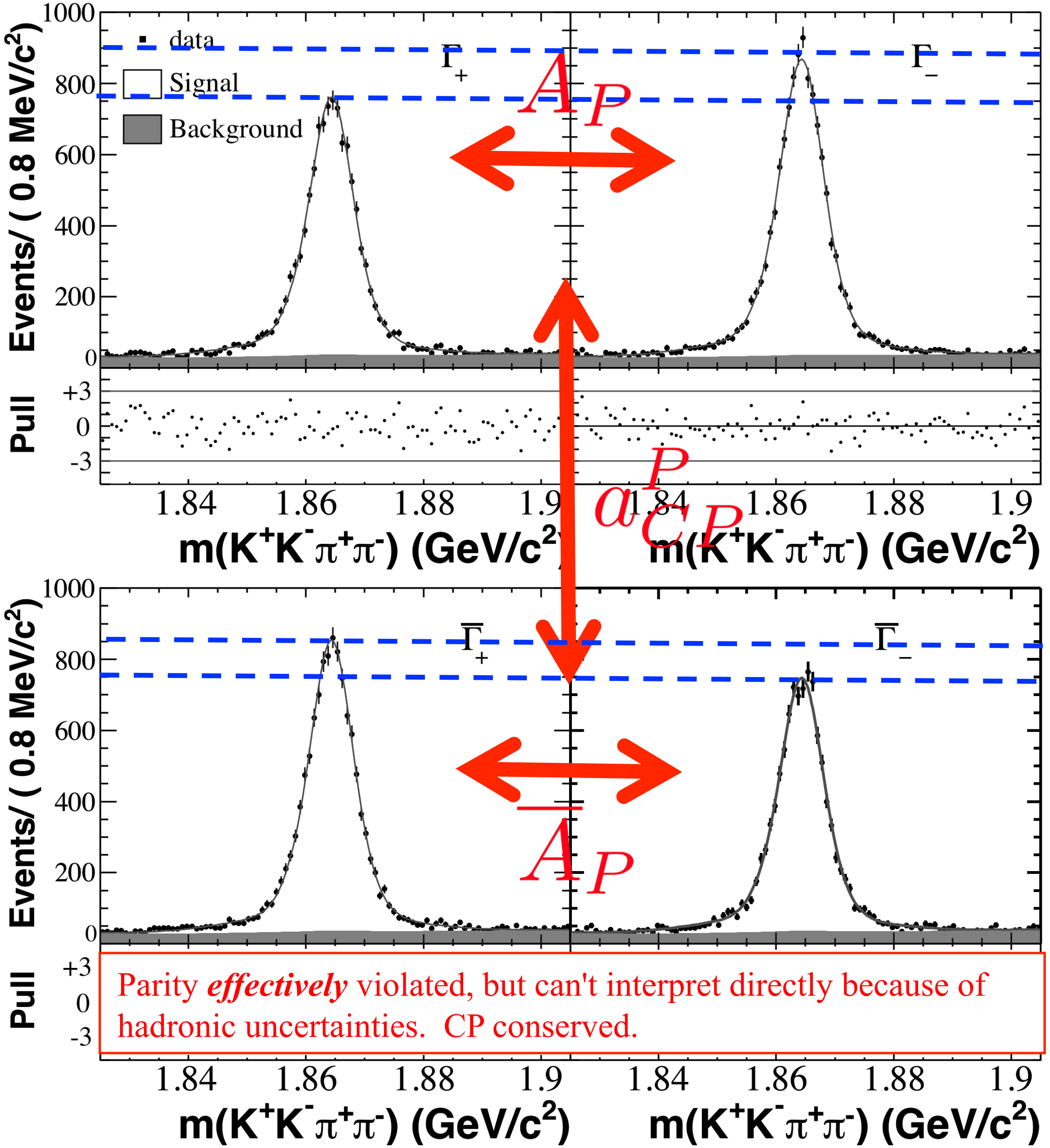
3) of the form $M^0 = \overline{M}^0; \ \overline{abcd} = abcd$, e.g.: (1 asymmetry)

$$K_{S,L} \to \pi^+ \pi^- e^+ e^-$$

$$\boxed{A_{P,CP} = \frac{\langle\Gamma\rangle_+ - \langle\Gamma\rangle_-}{\langle\Gamma\rangle_+ + \langle\Gamma\rangle_-}.}$$

$D^0 \rightarrow K^+K^-\pi^+\pi^-$

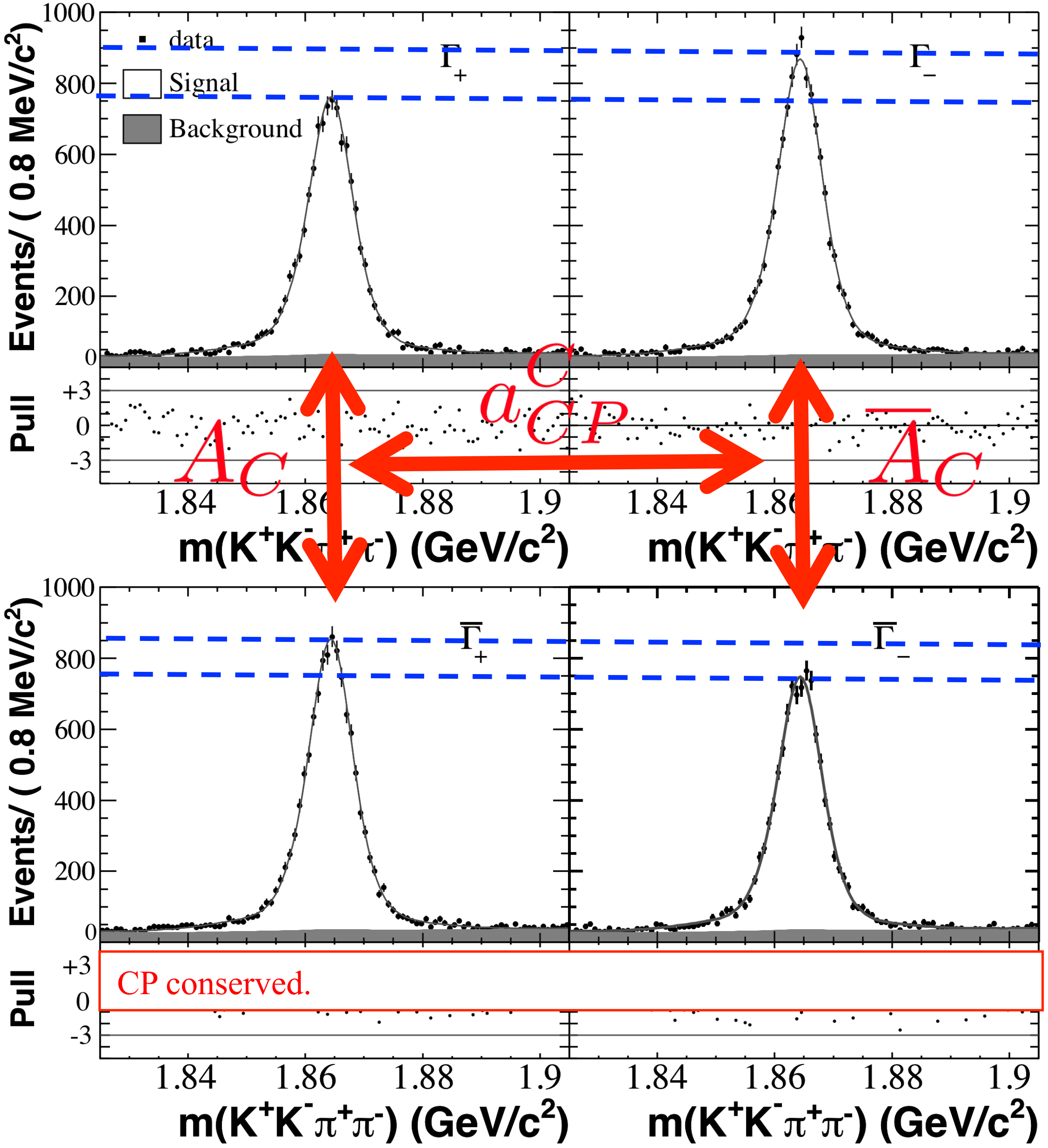
BaBar data
arXiv:1003.3397



Parity ***effectively*** violated, but can't interpret directly because of hadronic uncertainties. CP conserved.

$D^0 \to K^+K^-\pi^+\pi^-$

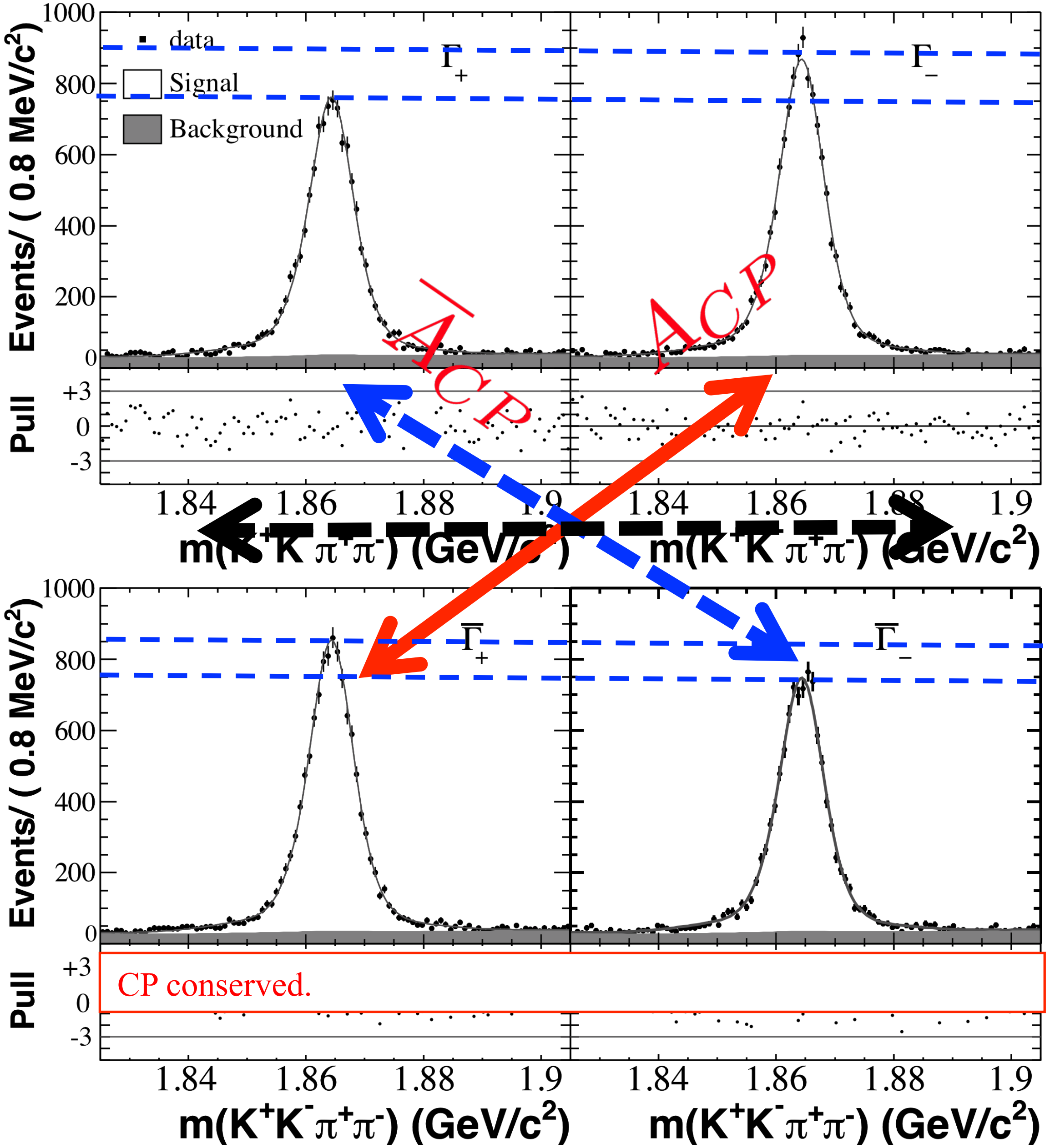
BaBar data
arXiv:1003.3397



$D^0 \to K^+K^-\pi^+\pi^-$

Charge-Parity

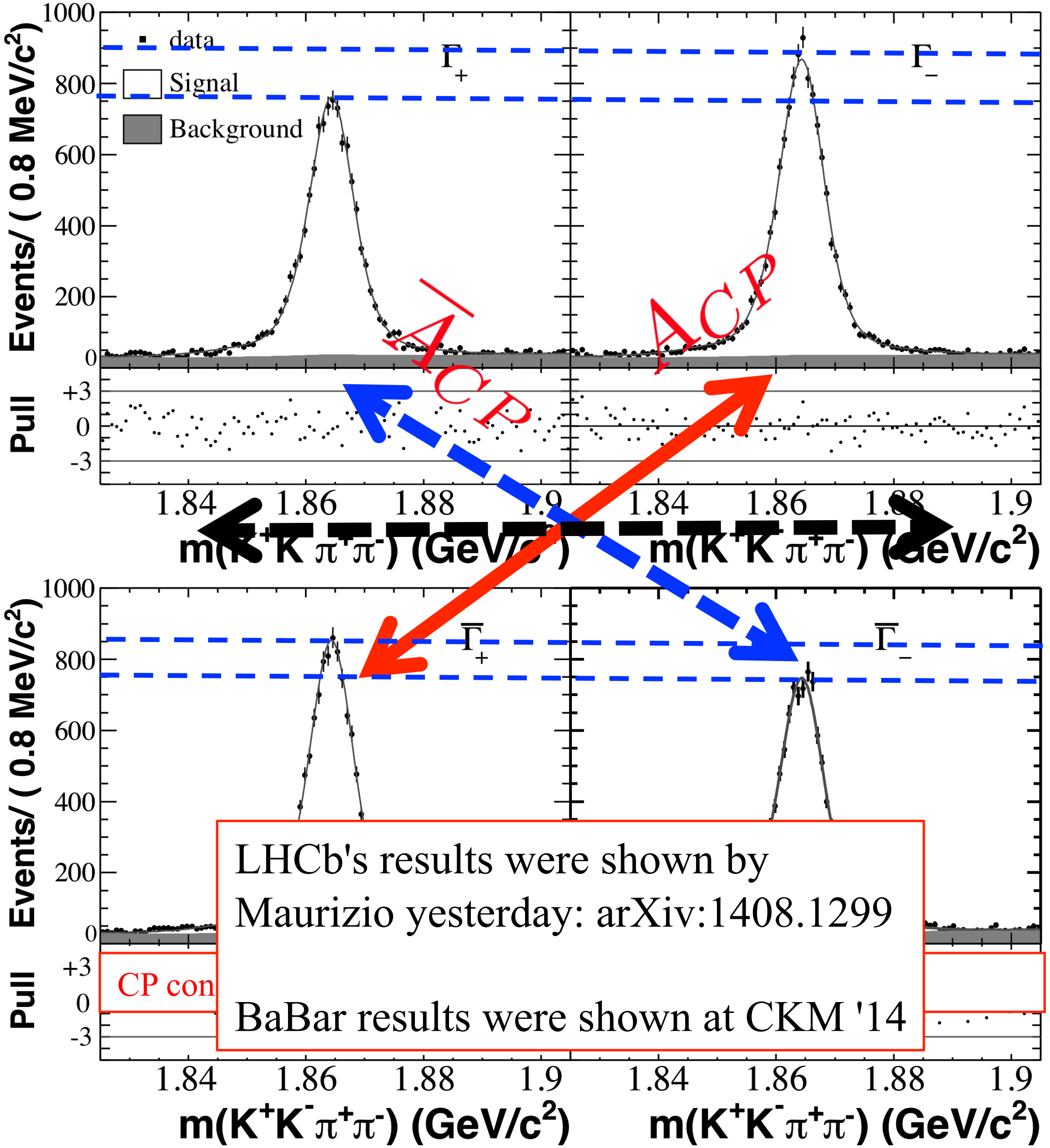
BaBar data
arXiv:1003.3397



$D^0 \to K^+K^-\pi^+\pi^-$

Charge-Parity

BaBar data
arXiv:1003.3397



CP con

LHCb's results were shown by
Maurizio yesterday: arXiv:1408.1299

BaBar results were shown at CKM '14

What is being measured?

- Assume a naive model: two interfering amplitudes with different weak and strong phases.

c.f. Zupan, Tuesday

$$\begin{aligned}
A_+ &= a_1 e^{i(\phi_1+\delta_{1,+})} + a_2 e^{i(\phi_2+\delta_{2,+})}, \\
A_- &= a_1 e^{i(\phi_1+\delta_{1,-})} + a_2 e^{i(\phi_2+\delta_{2,-})}, \\
\overline{A}_+ &= a_1 e^{i(-\phi_1+\delta_{1,+})} + a_2 e^{i(-\phi_2+\delta_{2,+})}, \\
\overline{A}_- &= a_1 e^{i(-\phi_1+\delta_{1,-})} + a_2 e^{i(-\phi_2+\delta_{2,-})},
\end{aligned}$$

$r=a_1/a_2$

- These are functions of the sine and cosines of differences in weak and strong phases; e.g.

$$\begin{aligned}
A_P &\propto r\sin\Delta\phi(\sin\Delta\delta_- - \sin\Delta\delta_+) + r\cos\Delta\phi(\cos\Delta\delta_+ - \cos\Delta\delta_-) \\
\overline{A}_P &\propto r\sin\Delta\phi(\sin\Delta\delta_+ - \sin\Delta\delta_-) + r\cos\Delta\phi(\cos\Delta\delta_+ - \cos\Delta\delta_-) \\
A_C^P &\propto [(2r^2\cos\Delta\phi\sin[\Delta\delta_- - \Delta\delta_+]) + r(1+r^2)(\sin\Delta\delta_- - \sin\Delta\delta_+)]\sin\Delta\phi \\
A_{CP}^P &\propto (\cos\Delta\delta_- - \cos\Delta\delta_+)(r^2(\cos\Delta\delta_- + \cos\Delta\delta_+) + r(1+r^2)\cos\Delta\phi) \\
A_C &\propto 2r\sin[\Delta\delta_-]\sin[\Delta\phi] \\
\overline{A}_C &\propto 2r\sin[\Delta\delta_+]\sin[\Delta\phi] \\
A_P^C &\propto r\left[(1+r^2)(\sin\Delta\delta_- - \sin\Delta\delta_+) + 2r\cos\Delta\phi\sin[\Delta\delta_- - \Delta\delta_+]\right]\sin\Delta\phi \\
A_{CP}^C &\propto r\left[(1+r^2)(\sin\Delta\delta_- + \sin\Delta\delta_+) + 2r\cos\Delta\phi\sin[\Delta\delta_- + \Delta\delta_+]\right]\sin\Delta\phi \\
A_{CP} &\propto r\cos\Delta\phi(\cos\Delta\delta_+ - \cos\Delta\delta_-) + r\sin\Delta\phi(\sin\Delta\delta_+ + \sin\Delta\delta_-) \\
\overline{A}_{CP} &\propto r\cos\Delta\phi(\cos\Delta\delta_- - \cos\Delta\delta_+) + r\sin\Delta\phi(\sin\Delta\delta_+ + \sin\Delta\delta_-) \\
A_C^{CP} &\propto r\left[(1+r^2)(\sin\Delta\delta_- + \sin\Delta\delta_+) + 2r\cos\Delta\phi\sin(\Delta\delta_- + \Delta\delta_+)\right]\sin\Delta\phi \\
A_P^{CP} &\propto r(\cos\Delta\delta_+ - \cos\Delta\delta_-)[r(\cos\Delta\delta_- + \cos\Delta\delta_+) + (1+r^2)\cos\Delta\phi]
\end{aligned}$$

Some non-zero asymmetries require non-zero weak phase differences (i.e. not all of them can give FSI induced signatures).

e.g. A_C and $\overline{A}_C$

What is being measured?

- Minimal conditions for non-zero asymmetries in this model:

Asymmetry	Minimum conditon for a non-zero value
## A_P	$(\Delta\phi \neq 0$ and $\Delta\delta_\pm \neq 0)$ OR $(\Delta\delta_\pm$ and $\Delta\phi$ not maximal$)$
## $\overline{A}_P$	$(\Delta\phi \neq 0$ and $\Delta\delta_\pm \neq 0)$ OR $(\Delta\delta_\pm$ and $\Delta\phi$ not maximal$)$
** A_C^P	$\Delta\phi \neq 0$ and $\Delta\delta_\pm \neq 0$
## A_{CP}^P	$\Delta\delta_\pm$ not maximal
** A_C	$\Delta\phi \neq 0$ and $\Delta\delta_- \neq 0$
** $\overline{A}_C$	$\Delta\phi \neq 0$ and $\Delta\delta_+ \neq 0$
** A_P^C	$\Delta\phi \neq 0$ and $\Delta\delta_\pm \neq 0$
** A_{CP}^C	$\Delta\phi \neq 0$ and $\Delta\delta_\pm \neq 0$
## A_{CP}	$(\Delta\phi \neq 0$ and $\Delta\delta_\pm \neq 0)$ OR $(\Delta\delta_\pm$ and $\Delta\phi$ not maximal$)$
## $\overline{A}_{CP}$	$(\Delta\phi \neq 0$ and $\Delta\delta_\pm \neq 0)$ OR $(\Delta\delta_\pm$ and $\Delta\phi$ not maximal$)$
** A_C^{CP}	$\Delta\phi \neq 0$ and at least one of $\Delta\delta_\pm \neq 0$
## A_P^{CP}	$\Delta\delta_\pm$ not maximal (not $n\pi/2$, with odd n)

- ** means non-zero is driven by a weak phase difference.
- ## means non-zero asymmetry can be driven by FSI only.

$\Lambda_b \to \Lambda J/\psi$

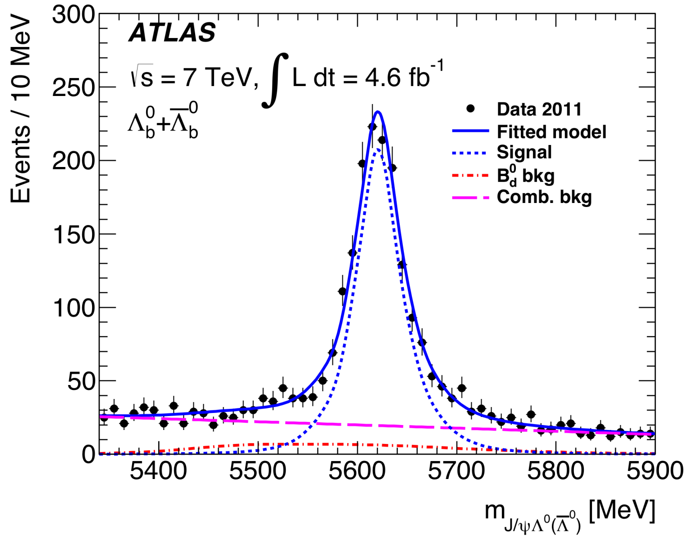
Class 1 decay

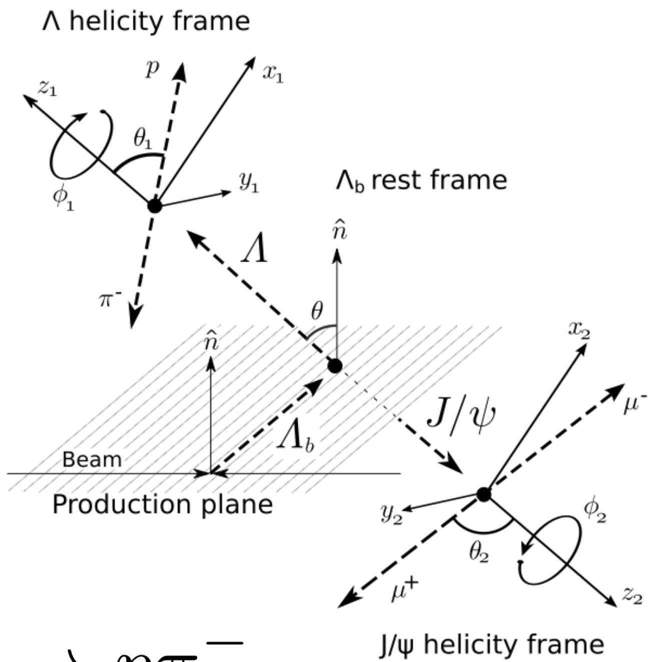
- The LHC experiments have searched for P violation in this decay (measuring α_b).

c.f. Cronin and Overseth's classic $\Lambda \rightarrow p\pi$ measurement

- e.g. ATLAS have 1400 Λ_b's; LHCb has a larger sample.

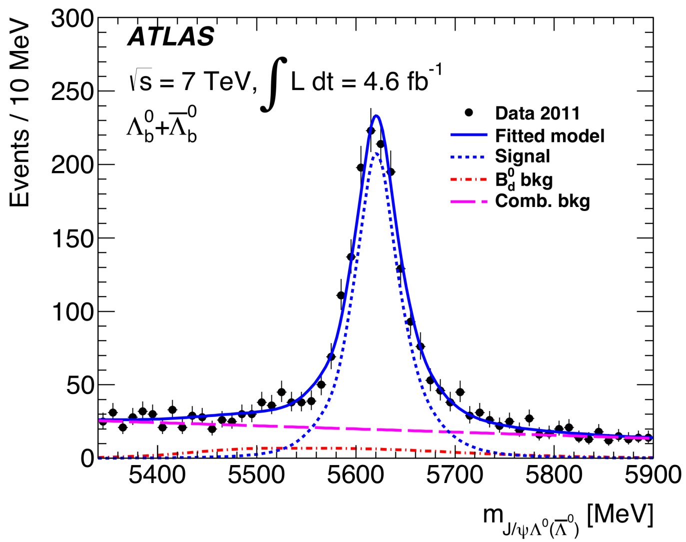
arXiv:1404.1071 [Phys. Rev. D **89**, 092009 (2014)]





- Self tagging final state via: $\Lambda^0 \to p\pi^-$
- Statistical precision on asymmetries ~3.8% is achievable with ATLAS; LHCb could do a bit better.
- A test bed for understanding soft QCD vs weak effects.

Measurement of parity violation in $\Lambda_b \to J/\psi\Lambda$



- Clean signal peak found in data.

ATLAS EXPERIMENT

$$\alpha_b = 0.30 \pm 0.16(\mathrm{stat}) \pm 0.06(\mathrm{syst}),$$

$$|a_+| = 0.17^{+0.12}_{-0.17}(\mathrm{stat}) \pm 0.09(\mathrm{syst}),$$

$$|a_-| = 0.59^{+0.06}_{-0.07}(\mathrm{stat}) \pm 0.03(\mathrm{syst}),$$

$$|b_+| = 0.79^{+0.04}_{-0.05}(\mathrm{stat}) \pm 0.02(\mathrm{syst}),$$

$$|b_-| = 0.08^{+0.13}_{-0.08}(\mathrm{stat}) \pm 0.06(\mathrm{syst}).$$

- Negative helicity states of Λ^0 preferred.
- Both Λ^0 and J/ψ are highly polarised.
- consistent with LHCb:

arXiv:1302.5578

$$\alpha_b = 0.05 \pm 0.17 \pm 0.07$$

- c.f. with:
  - Factorisation: α_b = -0.17 to -0.14
  - HQET: α_b = 0.78

arXiv:1404.1071 [Phys. Rev. D **89**, 092009 (2014)]

$D \to VV$

- Studied for BES III (arXiv:0912.3068v2) using the traditional nomenclature (so 3 asymmetries; one being a P-odd CP violating quantity).
- The matrix element consists of S, P and D components:

$$
\begin{aligned}
\mathcal{M} &\equiv as + bd + icp \\
&= a\epsilon_1^* \cdot \epsilon_2^* + \frac{b}{m_1 m_2}(p \cdot \epsilon_1^*)(p \cdot \epsilon_2^*) \\
&\quad + i\frac{c}{m_1 m_2}\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^* k_\gamma p_\delta
\end{aligned}
$$

$$
\begin{aligned}
a &= \sum_j a_j e^{i\delta_{sj}} e^{i\phi_{sj}} \\
b &= \sum_j b_j e^{i\delta_{dj}} e^{i\phi_{dj}} \\
c &= \sum_j c_j e^{i\delta_{pj}} e^{i\phi_{pj}}
\end{aligned}
$$

- One can two construct P asymmetries from the sign of triple products of the form

$$
\mathcal{A}_T = \frac{\Gamma(\vec{k} \cdot \vec{\epsilon}_1^* \times \vec{\epsilon}_2^* > 0) - \Gamma(\vec{k} \cdot \vec{\epsilon}_1^* \times \vec{\epsilon}_2^* < 0)}{\Gamma(\vec{k} \cdot \vec{\epsilon}_1^* \times \vec{\epsilon}_2^* > 0) + \Gamma(\vec{k} \cdot \vec{\epsilon}_1^* \times \vec{\epsilon}_2^* > 0}
$$

+ CP conjugate called $\overline{\mathrm{A}}_{\mathrm{T}}$

- If strong phase differences are large we can manifest non-zero asymmetries even for zero weak phase difference.

$D \to VV$

Kang, Li arXiv:0912.3068v2

- The corresponding CP asymmetry has the form

$$\frac{1}{2}(\mathcal{A}_T + \bar{\mathcal{A}}_T) \propto \frac{1}{2}[Im(ac^*) - Im(\bar{a}\bar{c}^*)] \; = \sum_{i,j} a_i c_j \sin(\phi_{si} - \phi_{pj}) \cos(\delta_{si} - \delta_{pj})$$

- The corresponding C asymmetry is orthogonal

$$\frac{1}{2}(\mathcal{A}_T - \bar{\mathcal{A}}_T) \propto \frac{1}{2}[Im(ac^*) + Im(\bar{a}\bar{c}^*)] \; = \sum_{i,j} a_i c_j \cos(\phi_{si} - \phi_{pj}) \sin(\delta_{si} - \delta_{pj})$$

- Statistical precisions below 1% are achievable using 20fb^{-1} of data with BES III for a number of modes:

VV	Br (%)	Eff. (ϵ)	Expected errors
$\rho^0\rho^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$	0.18	0.74	0.004
$\bar{K}^{*0}\rho^0 \to (K^-\pi^+)(\pi^+\pi^-)$	1.08	0.68	0.002
$\rho^0\phi \to (\pi^+\pi^-)(K^+K^-)$	0.14	0.26	0.006
$\rho^+\rho^- \to (\pi^+\pi^0)(\pi^-\pi^0)$	0.6^*	0.55	0.002
$K^{*+}K^{*-} \to (K^+\pi^0)(K^-\pi^0)$	0.08^*	0.55	0.006
$K^{*0}\bar{K}^{*0} \to (K^+\pi^-)(K^-\pi^+)$	0.048	0.62	0.002
$\bar{K}^{*0}\rho^+ \to (K^-\pi^+)(\pi^+\pi^0)$	1.33	0.59	0.001

- Similarly people have studied a number of baryon decay modes obtaining the estimated precisions given below.

BP	Br	Eff.(ϵ)	Expected errors at BES-III ($\times 10^{-2}$)
$\Lambda\pi^+ \to (p\pi^-)\pi^+$	6.8×10^{-3}	0.82	0.85
$\Lambda K^+ \to (p\pi^-)K^+$	3.2×10^{-4}	0.75	4.08
$\Lambda(1520)\pi^+ \to (pK^-)\pi^+$	8.1×10^{-3}	0.75	0.81
$\Sigma^0\pi^+ \to (\Lambda\gamma)\pi^+$	1.0×10^{-2}	0.62	0.80
$\Sigma^0 K^+ \to (\Lambda\gamma)K^+$	4.0×10^{-4}	0.56	4.23
$\Sigma^+\pi^0 \to (p\pi^0)\pi^0$	5.0×10^{-3}	0.60	1.15
$\Sigma^+\eta \to (p\pi^0)(\pi^+\pi^-\pi^0)$	8.2×10^{-4}	0.52	3.06
$\Xi^0 K^+ \to (\Lambda\pi^0)K^+$	2.6×10^{-4}	0.57	5.20

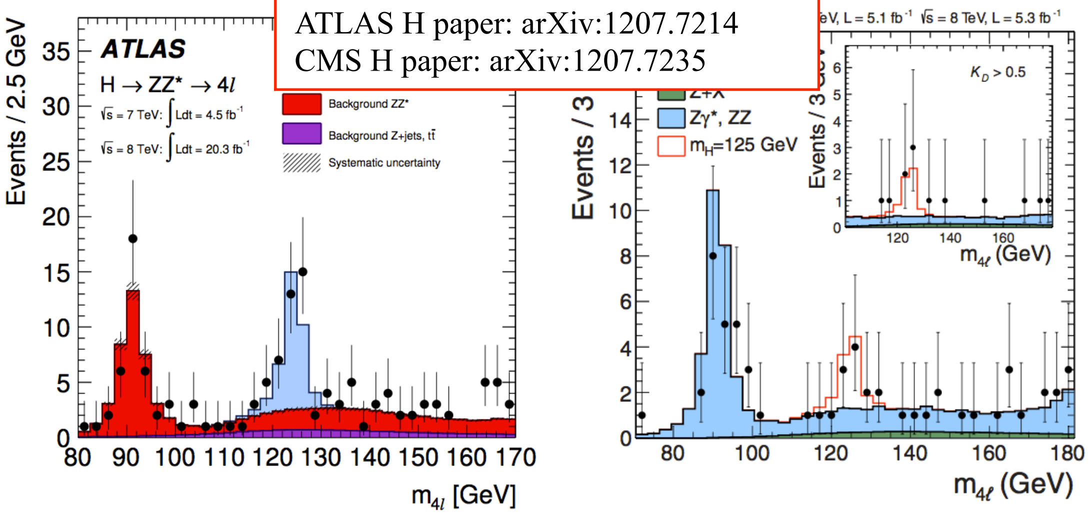
BV	Br	Eff.(ϵ)	Expected errors at BES-III ($\times 10^{-2}$)
$\Lambda\rho^+ \to (p\pi^-)(\pi^+\pi^0)$	$3.2\times10^{-2*}$	0.65	0.44
$\Sigma(1385)^+\rho^0 \to (\Lambda\pi^+)(\pi^+\pi^-)$	2.4×10^{-3}	0.69	1.55
$\Sigma^+\rho^0 \to (p\pi^0)(\pi^+\pi^-)$	$0.7\times10^{-2*}$	0.62	0.96
$\Sigma^+\omega \to (p\pi^0)(\pi^+\pi^-\pi^0)$	1.4×10^{-2}	0.49	0.76
$\Sigma^+\phi \to (p\pi^0)(K^+K^-)$	0.8×10^{-3}	0.52	3.10
$\Sigma^+K^{*0} \to (p\pi^0)(K^-\pi^+)$	0.7×10^{-3}	0.57	3.17

- Assuming 2.5×10^6 Λ_c pairs once can achieve sub-% level statistical precisions in many modes.
- Could be a promising way to systematically probe CP violation in baryon decays.
- Even if the LHC can perform many measurements, BES III or a Super τC experiment can provide complementary inputs.

$H \to \mu^+\mu^-e^+e^-$

Class 3 decay

- ATLAS and CMS have observed this state at run 1. Only a handful of events have been produced so far.



ATLAS H paper: arXiv:1207.7214
CMS H paper: arXiv:1207.7235

Based on the observed level of data it is possible to naively estimate the precision of asymmetries.
Trivial in the SM, but could be non-zero BSM.

- Estimates for the dominant μμee mode.
  - run 1 ~7 events
  - run 2 ~84 events
  - run 3 ~200 events
  - High luminosity LHC ~1000 ev.

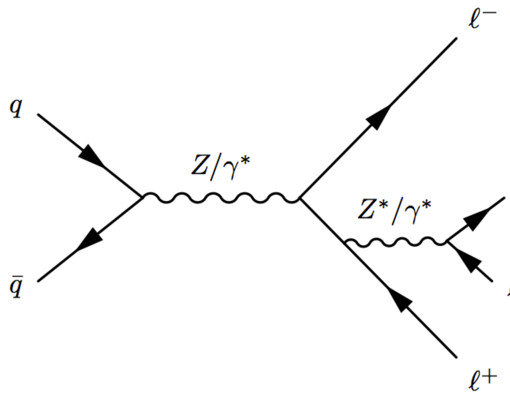
Data sample	$H \to \mu^+\mu^-e^+e^-$
Run 1 ($\sim 25\,\mathrm{fb}^{-1}$)	0.38
Run 2 ($\sim 125\,\mathrm{fb}^{-1}$)	0.11
Run 3 ($\sim 300\,\mathrm{fb}^{-1}$)	0.07
HL-LHC ($\sim 3000\,\mathrm{fb}^{-1}$)	0.02

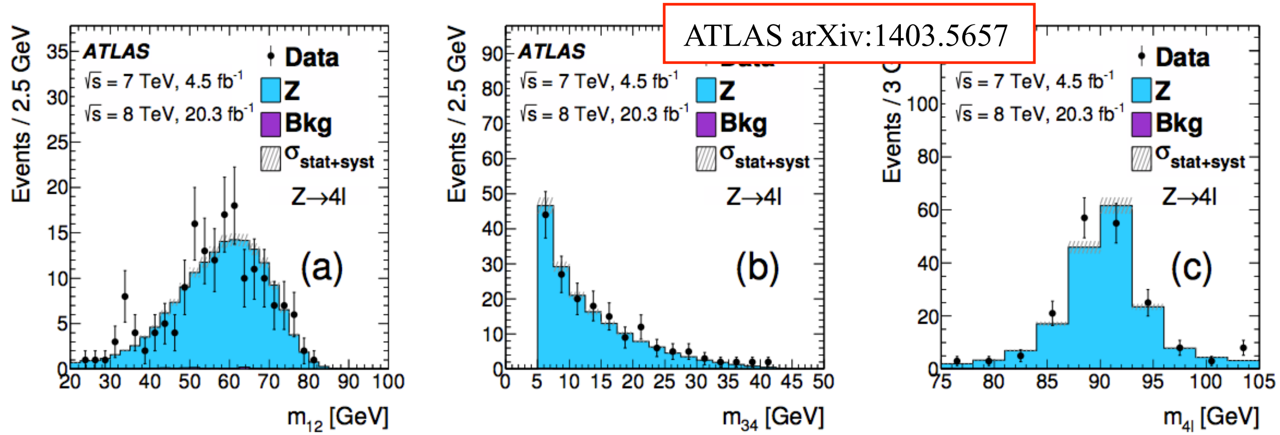
est. asym. precision

$Z \to \mu^+\mu^-e^+e^-$

Class 3 decay

- More copious than the previous example.
- Experimentally easier final state to study than the 4j mode studied at LEP.





ATLAS arXiv:1403.5657

- Estimates for the dominant μμee mode.
  - run 1 ~66 events
  - run 2 ~560 events
  - run 3 ~1350 events
  - High luminosity LHC ~13.5k ev.

Data sample	$Z^0 \to \mu^+\mu^-e^+e^-$
Run 1 ($\sim 25\,\mathrm{fb}^{-1}$)	0.12
Run 2 ($\sim 125\,\mathrm{fb}^{-1}$)	0.04
Run 3 ($\sim 300\,\mathrm{fb}^{-1}$)	0.03
HL-LHC ($\sim 3000\,\mathrm{fb}^{-1}$)	0.01

est. asym. precision

VH (ZH) production

Class 3 decay

- WH and ZH have not been observed at the LHC; expect large backgrounds and possible observation at run 2.
- However the ILC expects to obtain large samples of ZH events; e.g.

$$e^+e^- \to ZH \to (\ell^+\ell^-)(b\bar{b})$$

  - Only one asymmetry of interest:

$$A_{P,CP} = \frac{\langle\Gamma\rangle_+ - \langle\Gamma\rangle_-}{\langle\Gamma\rangle_+ + \langle\Gamma\rangle_-}.$$

  - 76,000 events running at 250 GeV.
  - 50,000 events running at 500 GeV.
- This sample size would yield statistical precisions of 1.5-2% for inclusive measurements, and 2.6-3.3% for exclusive ones on the P and CP asymmetry.
- FCC-ee and CEPC would be ~5 times more precise.

Summary

- CP violation has been measured using triple product asymmetries.
  - This is a P-odd CP asymmetry (not T-odd).
  - ... a number of asymmetries have been overlooked.
- 12 quantities can be measured to test C, P, and CP symmetries at energy scales from light mesons to top.
  - Low energy systems are harder to interpret (FSI/soft QCD).
  - Intermediate systems (e.g. Λ_b) is at a scale where we should be able to test factorisation and HQET frameworks. Perhaps Λ_c decays are also useful for this.
  - High energy systems are theoretically clean; but some experimental final states are challenging (e.g. VH and $Z\rightarrow 4b$).
- These permit systematic tests of the C, P, and CP symmetry nature of the Standard Model and searches for new physics.