C, P, and CP violating triple product Asymmetries

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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; mesons, hadrons and bosons.
- **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

$K_{S,L} \to \pi^+\pi^-e^+e^-$	$\Lambda_c \to \mathcal{BP}$	$H \to 4\ell$
$D^0 \to K^+K^-\pi^+\pi^-$	$\Lambda_c \to \mathcal{BV}$	$Z \to 4\ell$
$D_s^+ \to K_S^0 K^-\pi^+\pi^-$	$\Lambda_b \to \Lambda J\psi$	$Z \to b\bar{b}b\bar{b}$
$B \to J\psi K^*$	$\mathcal{B}$ = Baryon	$ZH \to \ell^+\ell^- q\bar{q}$
$B_s \to J\psi\phi$	$\mathcal{P}$ = Pseudoscalar	$W^\pm H \to \ell^\pm \nu q\bar{q}$
	$\mathcal{V}$ = Vector	

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

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

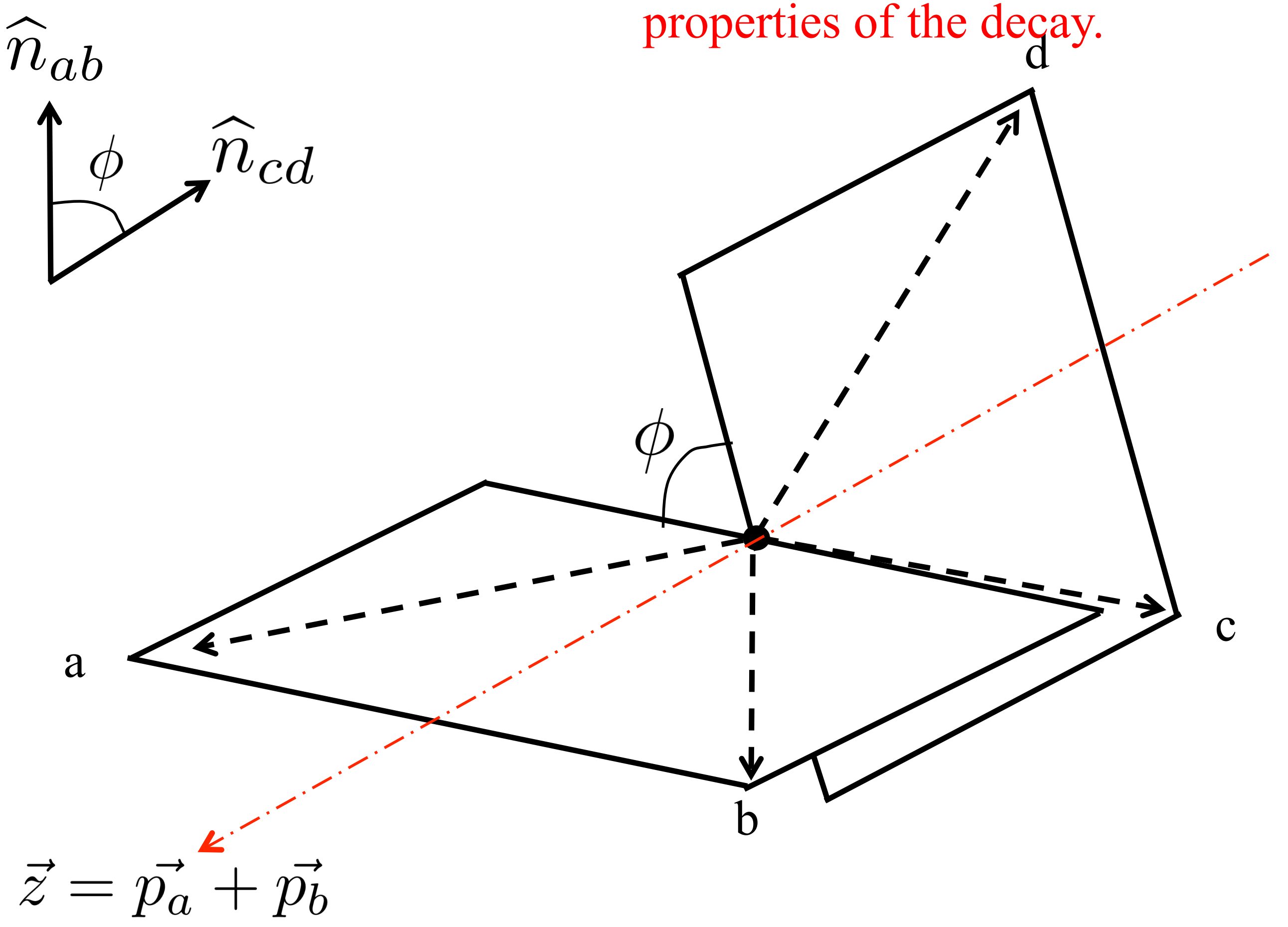
- Tests of T violation using neutral mesons amongst other quantum mechanical systems are now possible. Entanglement is a useful tool to facilitate such studies as described elsewhere:

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...

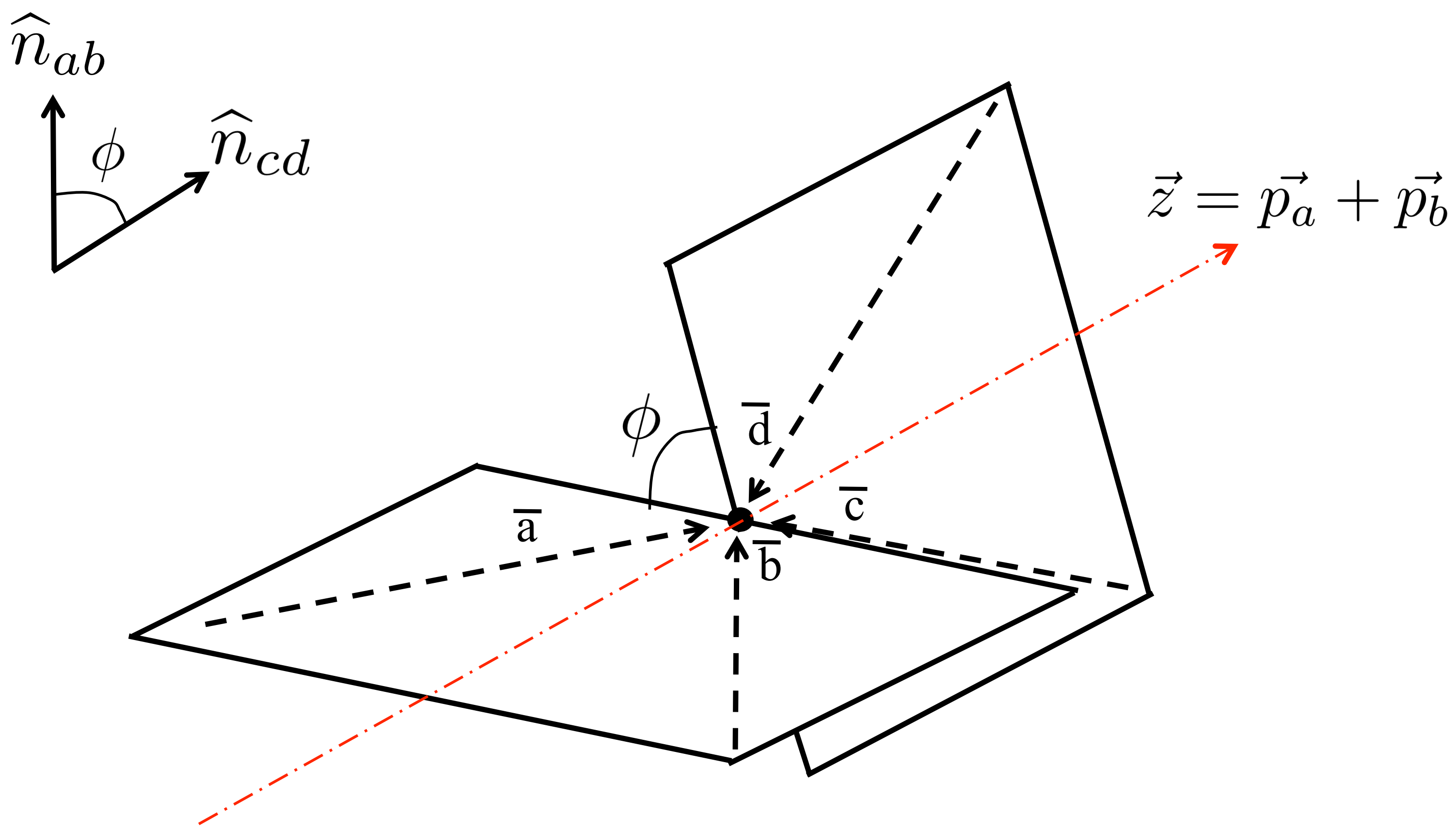
Reference Plot: $M \to abcd$

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.



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

$abcd \to M$

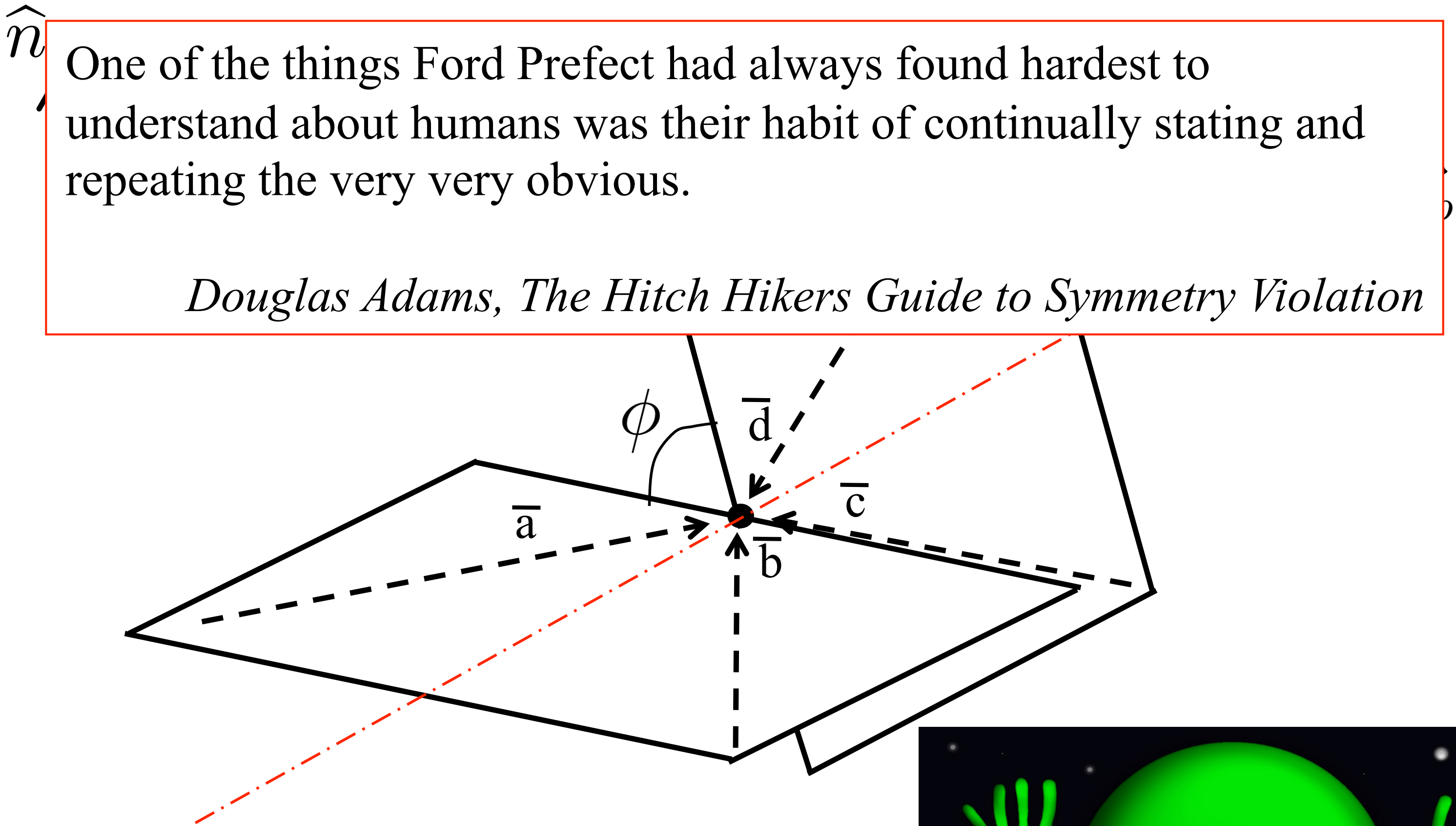


T Conjugate:

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



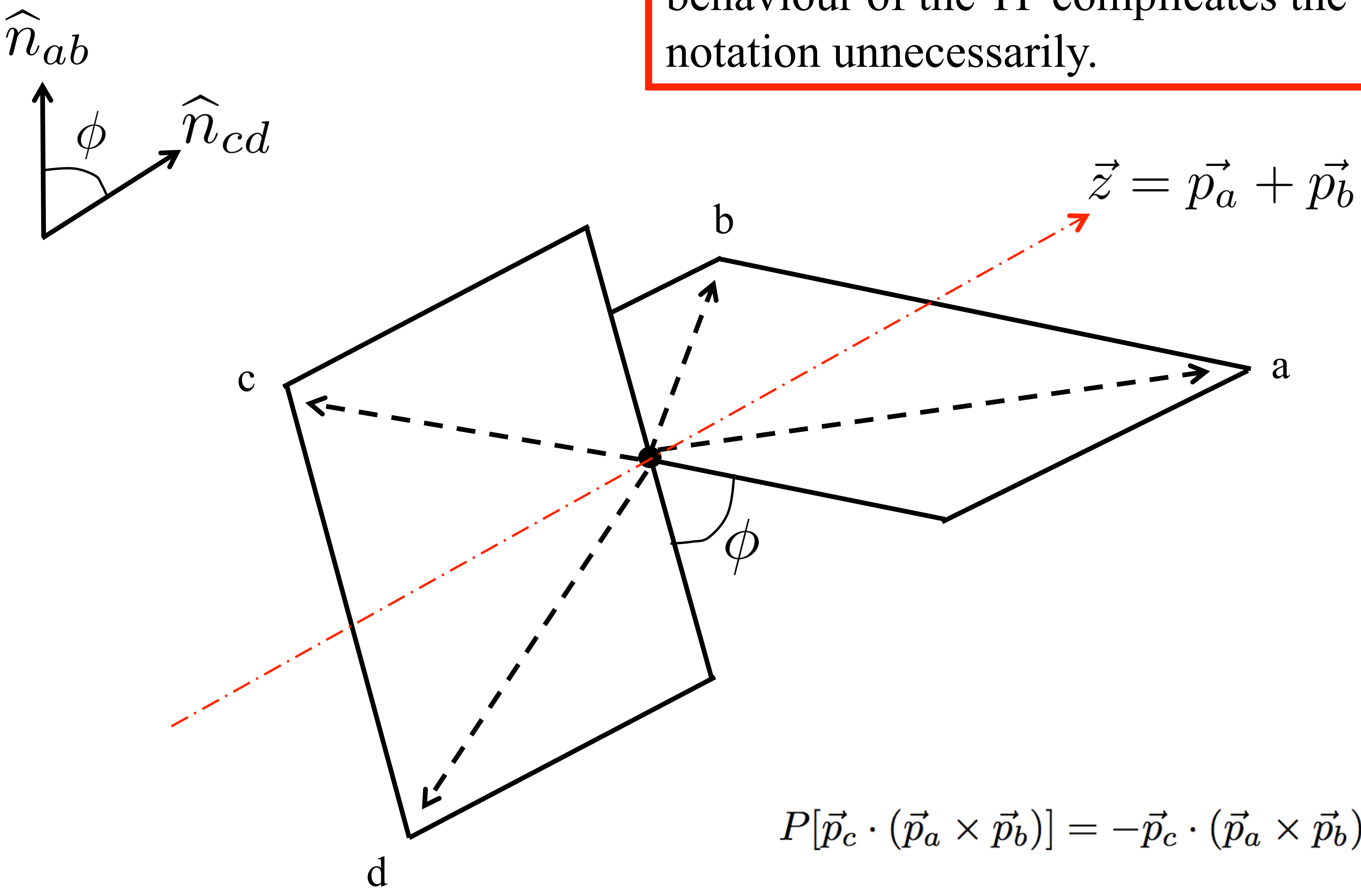
T Conjugate:

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: $M \rightarrow abcd$

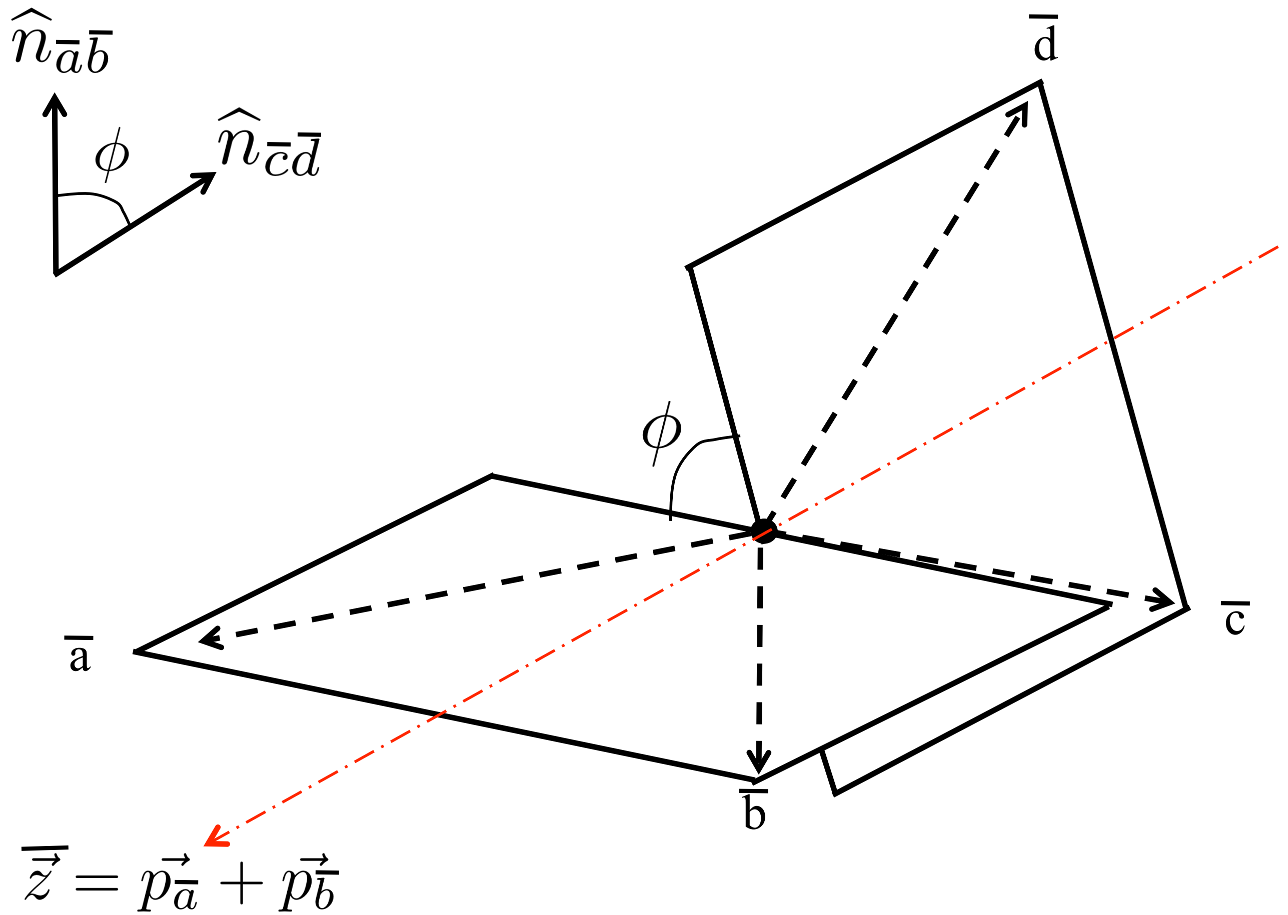
This is what is really being used for the T-odd triple products. Using the T-odd behaviour of the TP complicates the notation unnecessarily.



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

Spatial inversion

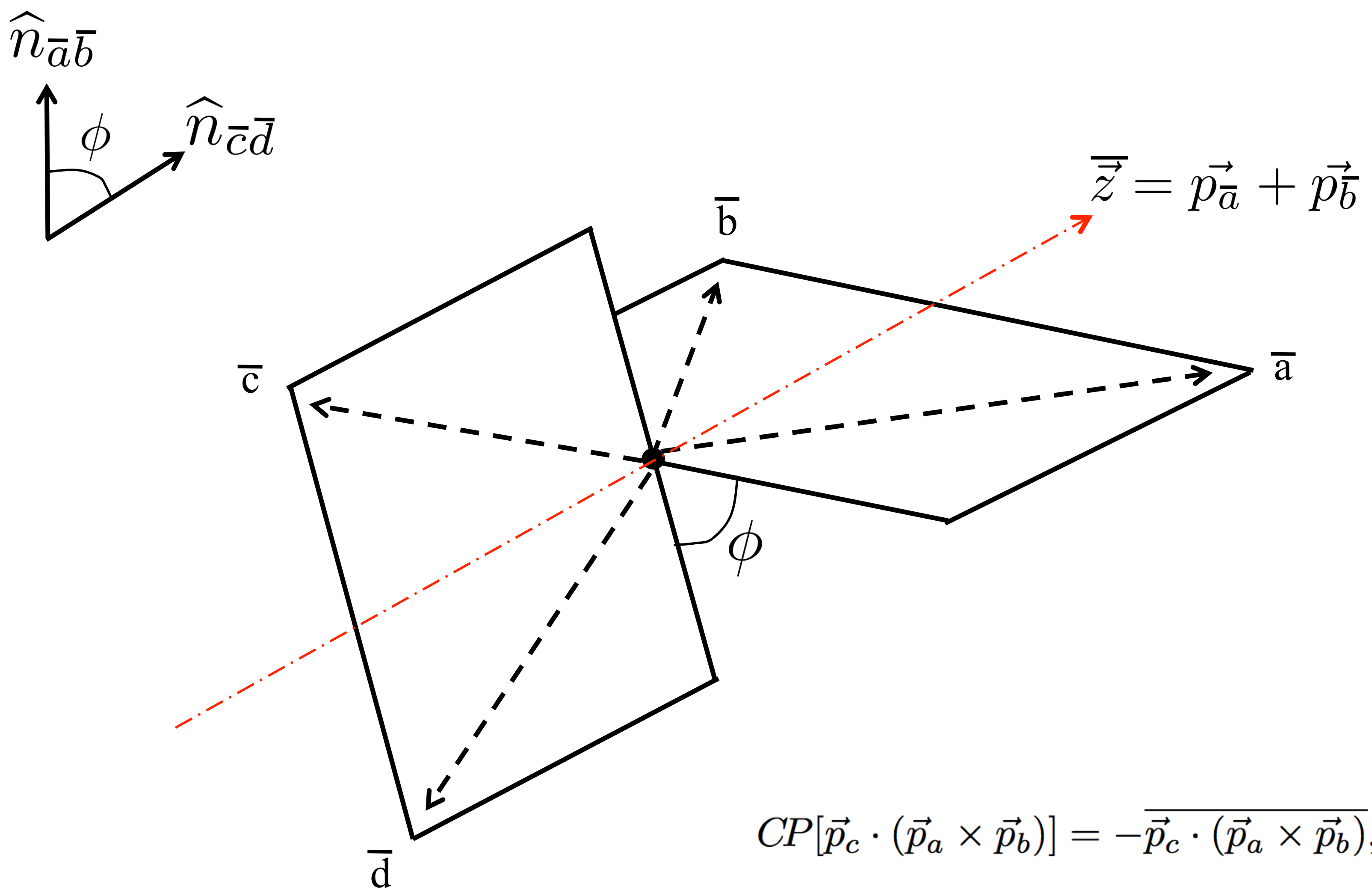
Under C Operation: $\overline{M} \rightarrow \overline{abcd}$



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

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.

$$\psi = \vec{p}_c \cdot (\vec{p}_a \times \vec{p}_b) \longrightarrow$$

use the sign of ψ in the absence of an understanding of the decay

  - 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.

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

- Theory predicted a 14% asymmetry for the K_L mode as the result of the following pattern of interfering amplitudes:
  - Radiative decay of the CP violating (conserving) process: $K_{L(S)} \to \pi^+\pi^-$
  - Photon conversion from $K_{L(S)} \to \pi^+\pi^-\gamma$
  - CP conserving magnetic dipole component.
  - CP conserving short distance component related to $s\bar{d} \to e^+e^-$

- Bottom line:
  - K_L decay should be CP violating.
  - K_S decay should be CP conserving.

P. Heiliger and L. M. Sehgal, Phys. Rev. D 48 (1993) 4146[Phys. Rev. D 60 (1999) 079902].

K_L decays

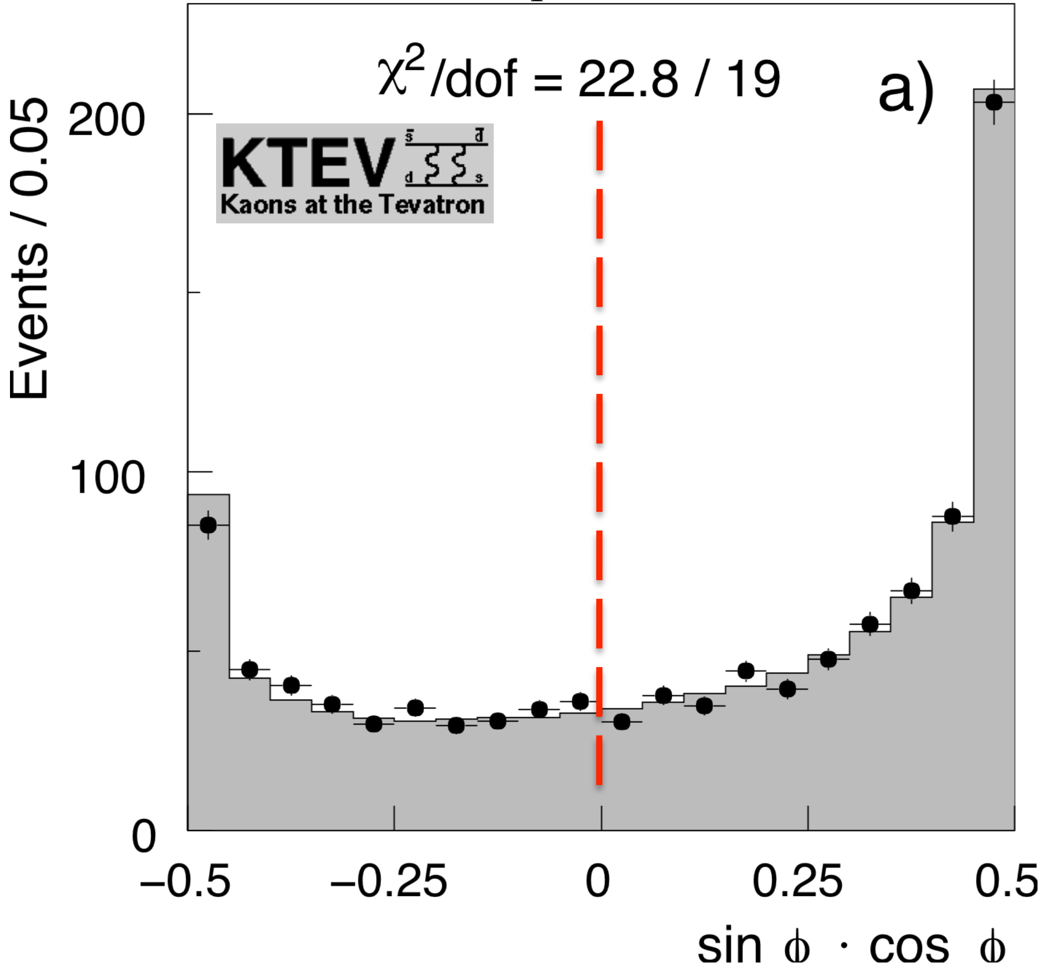
- There is a single asymmetry that tests P and CP simultaneously for:

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

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

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

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



- c.f $\varepsilon_K \sim 10^{-3}$ and $\varepsilon'_K \sim 10^{-6}$

- As KTeV first discovered, the K_L decay violates both P and CP.

K_S decays

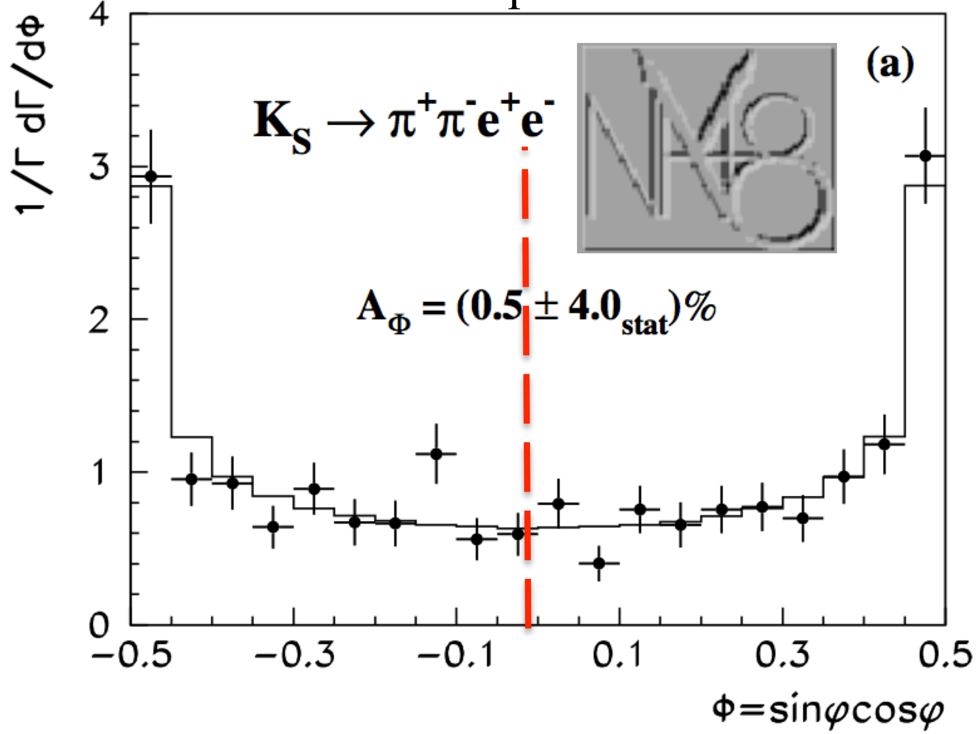
- There is a single asymmetry that tests P and CP simultaneously for:

See EPJC 30 p33 2003

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

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

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



- NA48 confirmed that the K_S decay is consistent with both P and CP conservation, 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

AB arXiv:1408.3813

- 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)

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

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

- C derived asymmetries:

  (C even triple product asymmetries)

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

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

- CP derived asymmetries:

  (CP odd triple product asymmetries)

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

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

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)

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

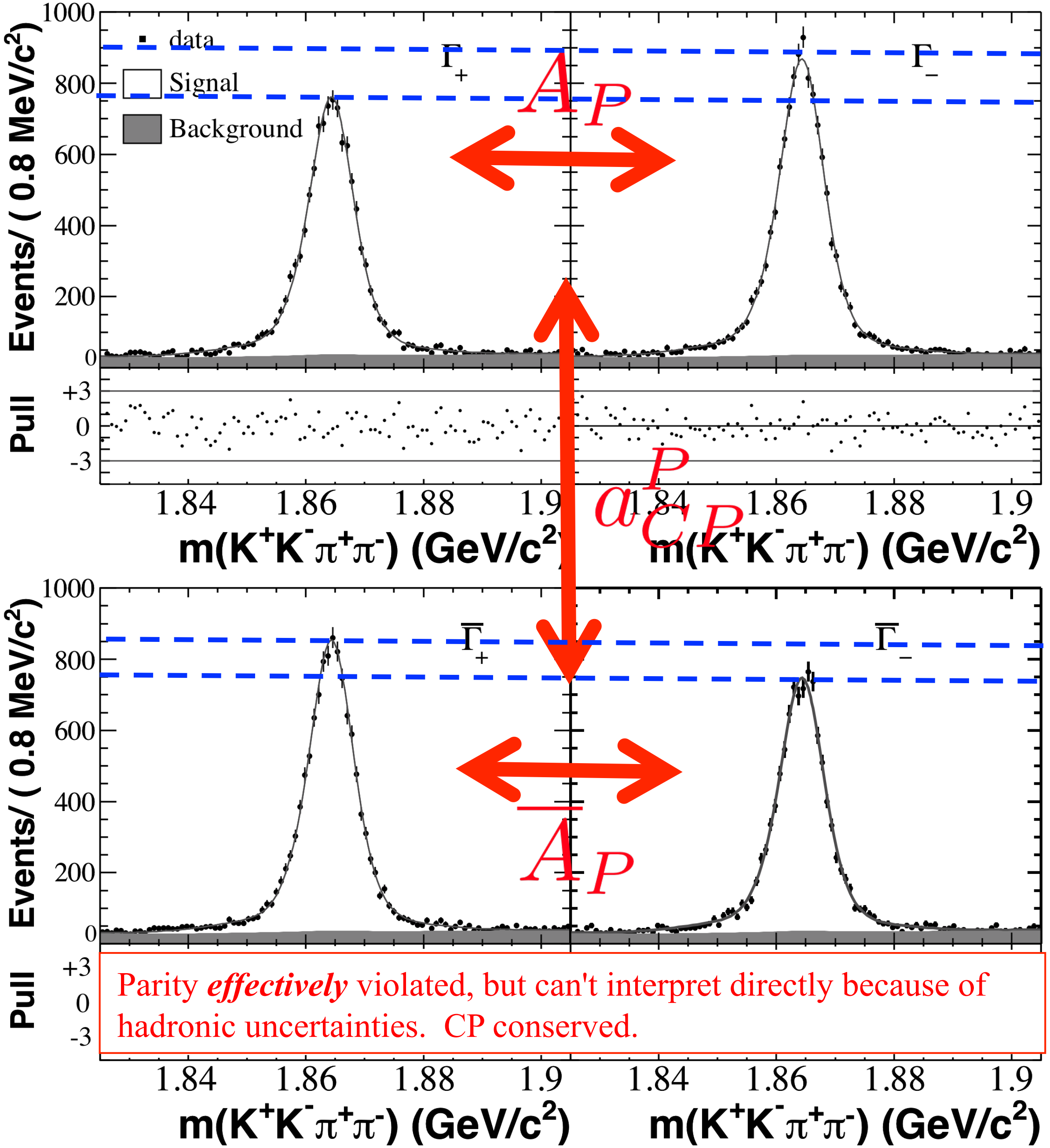
3) of the form $M^0 = \overline{M}^0; \ \overline{abcd} = abcd$, e.g.: (1 asymmetry)

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

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

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

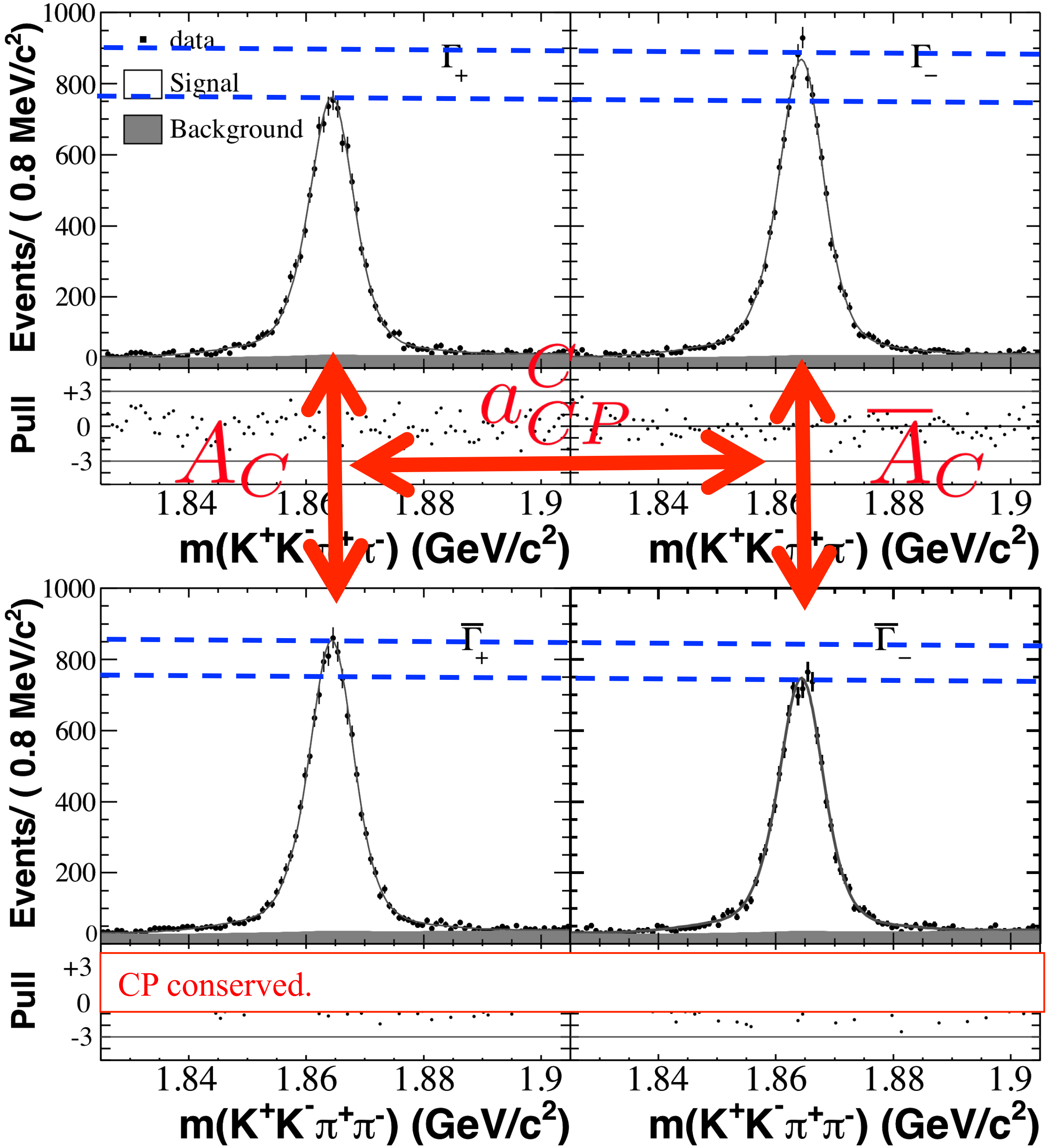
BaBar data
arXiv:1003.3397



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

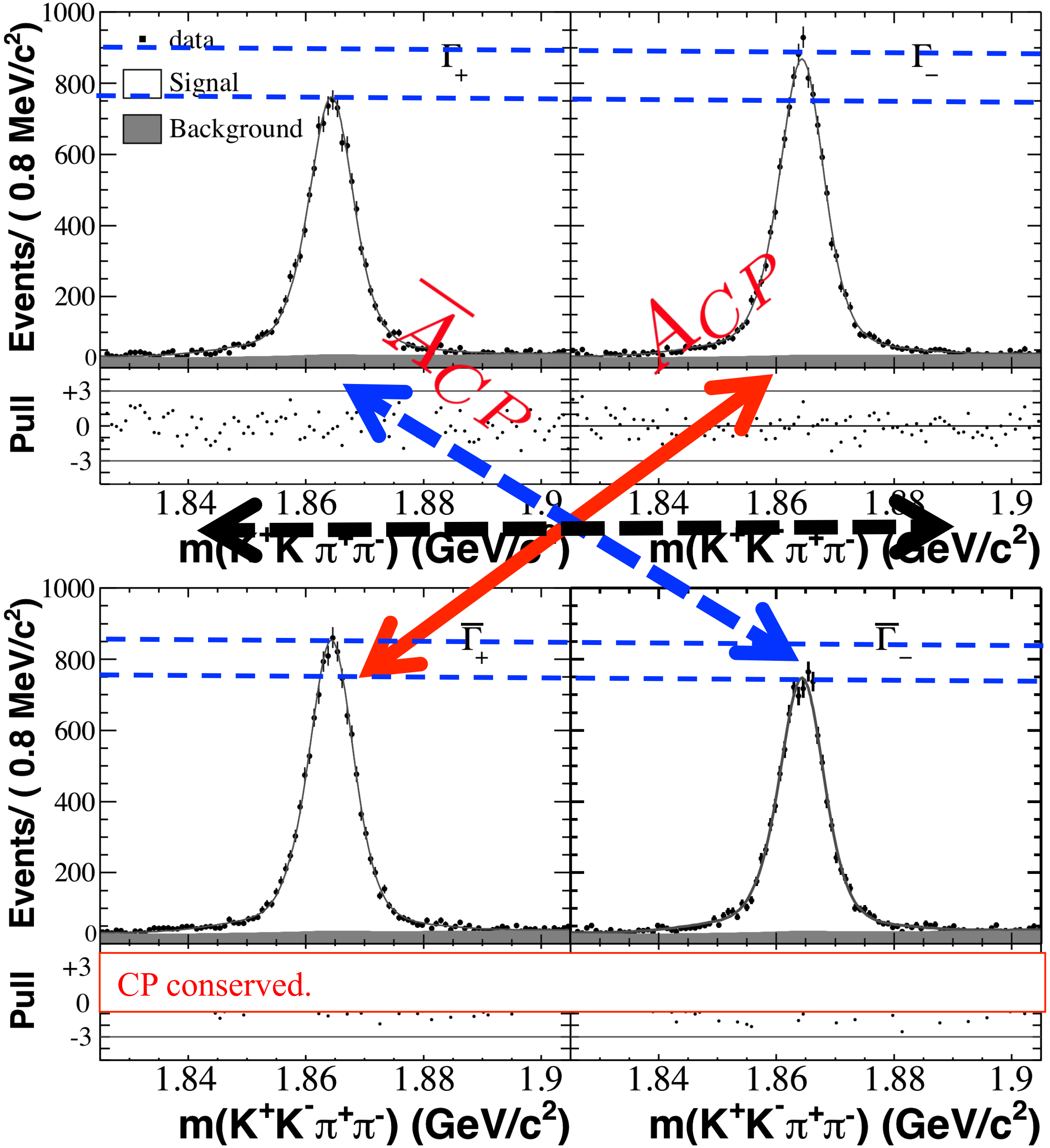
$D^0 \to K^+K^-\pi^+\pi^-$

BaBar data
arXiv:1003.3397



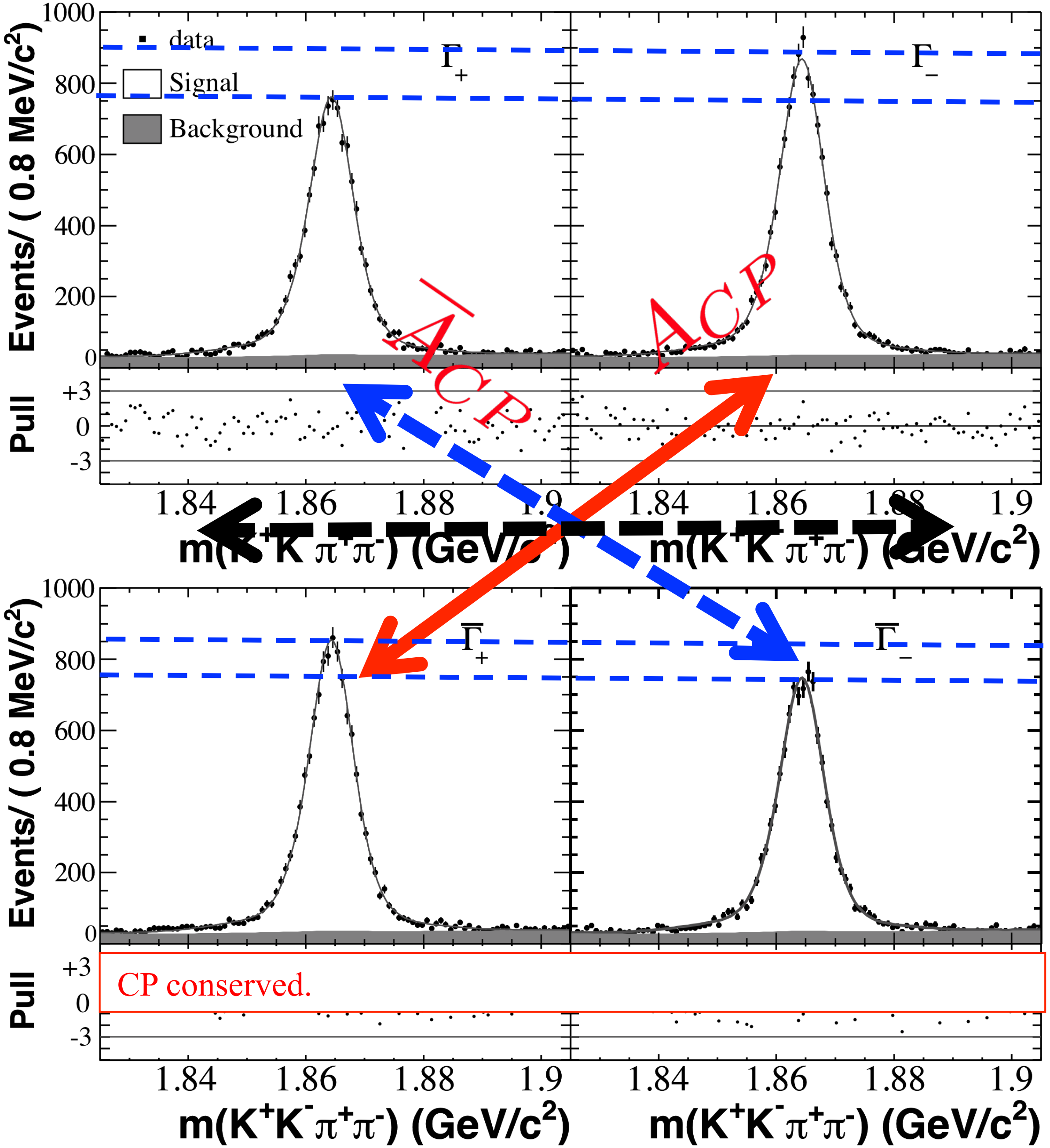
$D^0 \to K^+K^-\pi^+\pi^-$

BaBar data
arXiv:1003.3397



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

BaBar data
arXiv:1003.3397



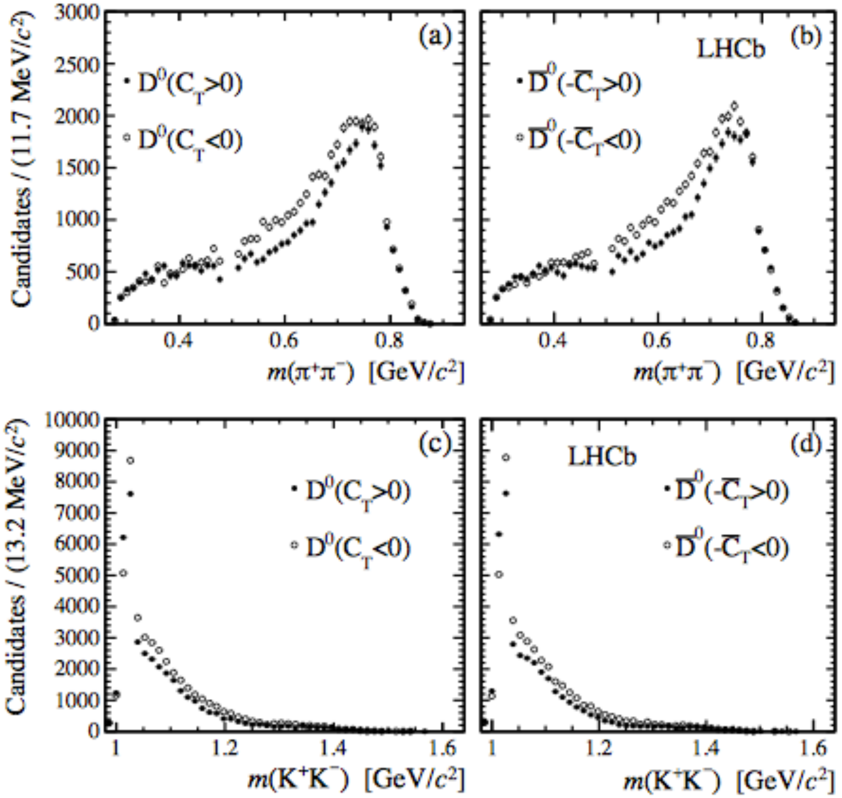
Asymmetry	$D^0 \to K^+K^-\pi^+\pi^-$
A_P	$-0.069 \pm 0.007\,(9.8)$ [7.5]
$\overline{A}_P$	$0.071 \pm 0.007\,(10.1)$ [8.8]
a_C^P	$0.001 \pm 0.005\,(0.2)$ [0.2]
a_{CP}^P	$-0.070 \pm 0.005\,(14.0)$ [13.5]
A_C	$0.060 \pm 0.007\,(8.6)$ [8.3]
$\overline{A}_C$	$-0.079 \pm 0.007\,(11.3)$ [10.8]
a_P^C	$0.070 \pm 0.005\,(14.0)$ [13.5]
a_{CP}^C	$-0.009 \pm 0.005\,(1.8)$ [1.8]
A_{CP}	$-0.008 \pm 0.007\,(1.1)$ [1.0]
$\overline{A}_{CP}$	$-0.010 \pm 0.008\,(1.3)$ [1.1]
a_P^{CP}	$0.001 \pm 0.005\,(0.2)$ [0.2]
a_C^{CP}	$-0.009 \pm 0.005\,(1.8)$ [1.8]

- Pattern of asymmetries driven by non-zero strong phases.
- This can be understood using a naive model; but more data and an amplitude analysis required for a deep understanding of the data.

LHCb results

see arXiv:1408.1299

- In addition to measuring over the whole phase space; LHCb can probe different hh mass combinations.

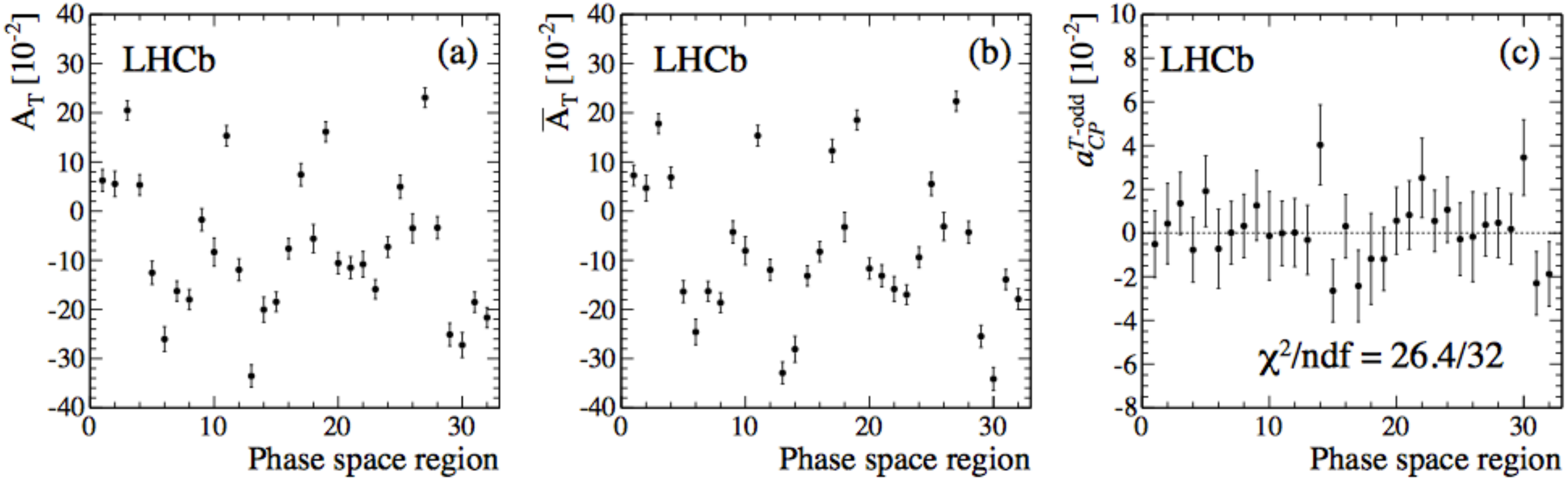


- Clear asymmetries are seen.
- Resonant structures exist in m(KK) and m(pipi)
- But the Kpi combinations are not probed
- The 4-body phase space will include KK, pipi, and Kpi combinations, so the general analysis of this final state will become rather complicated as data increases:
  - see CLEO: Phys. Rev. D **85**, 122002 (2012); Durieux, Grossman arXiv:1508.03054.

$$A_T = (-7.18 \pm 0.41(\text{stat}) \pm 0.13(\text{syst}))\%,$$
$$\overline{A}_T = (-7.55 \pm 0.41(\text{stat}) \pm 0.12(\text{syst}))\%,$$
$$a_{CP}^{T\text{-odd}} = (\;\;0.18 \pm 0.29(\text{stat}) \pm 0.04(\text{syst}))\%,$$

LHCb results

- There is a definite pattern of large violations varying as a function of phase space:
  - Requires an amplitude analysis to elaborate further on the sources of symmetry violation.
  - LHCb are working on this: (see Durieux, Grossman arXiv:1508.03054)



What is being measured?

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

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

$r=a_1/a_2$

- 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.

A final word on charm decays

- Is there a lesson to be learned from kaons?
  - The asymmetry in kaons was found by looking at the interference of something that is completely CP violating with CP conserving amplitudes.
  - $\pi\pi ee$ is an unambiguous final state to define the analysis with; consider looking for this!
  - It will be hard to interpret, but easier than anything people are trying to measure today.
- Hadronic systems have ambiguity from combinatorics;
  - A 4-body amplitude analysis of (12)(34) requires consideration of (14)(23) at the same time [interference].
  - Will be very hard to understand what is being measured in an all hadronic final state.

$\Lambda_b \rightarrow \Lambda J/\psi$

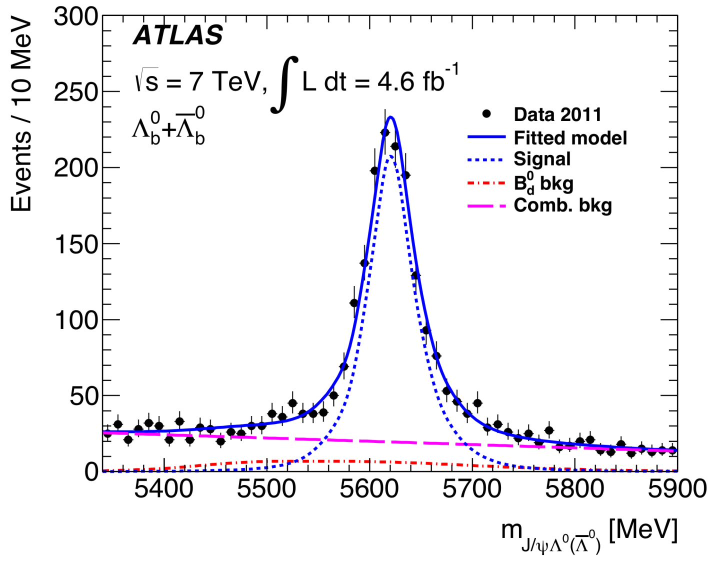
Class 1 decay

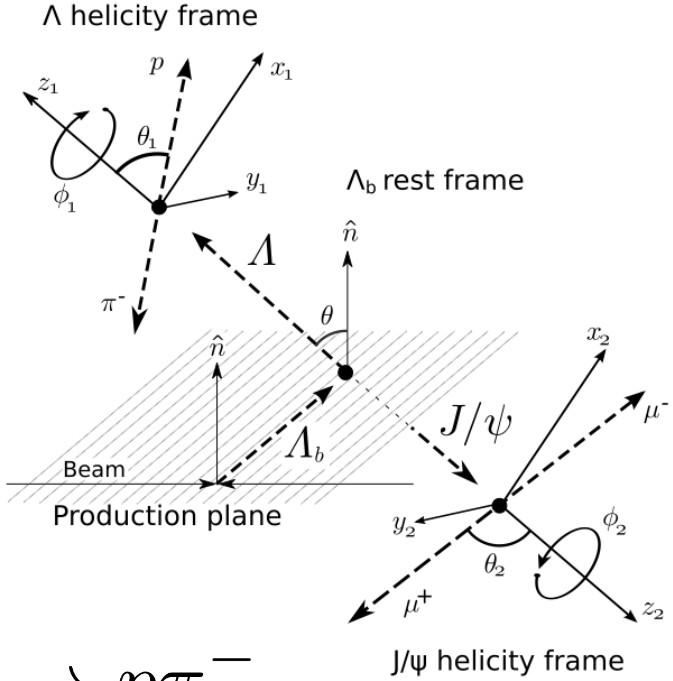
- The LHC experiments have searched for P violation in this decay (measuring α_b).

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.

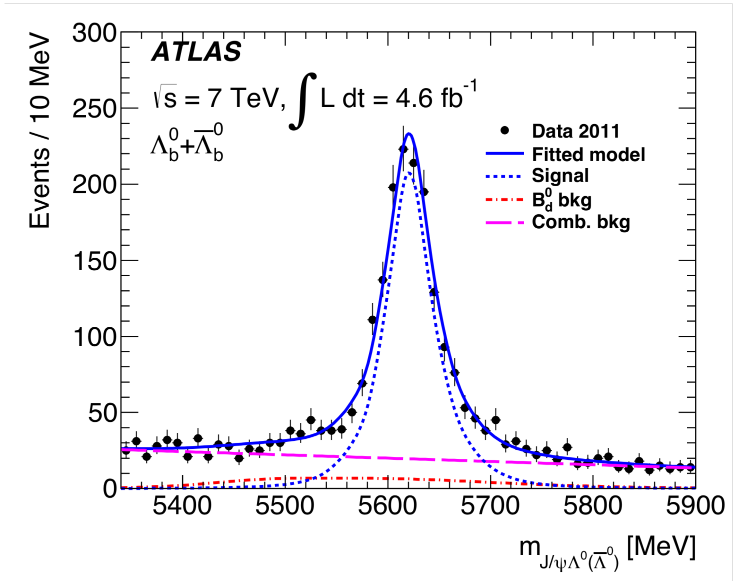
arXiv:1404.1071 [Phys. Rev. D **89**, 092009 (2014)]





- Self tagging final state via: $\Lambda^0 \rightarrow p\pi^-$
- 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

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

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

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

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

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

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

- 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
  - *This energy scale could be high enough to make reasonable predictions of the triple product asymmetries.*

$D \to VV$

- 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 $\overline{A}_T$

- 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.

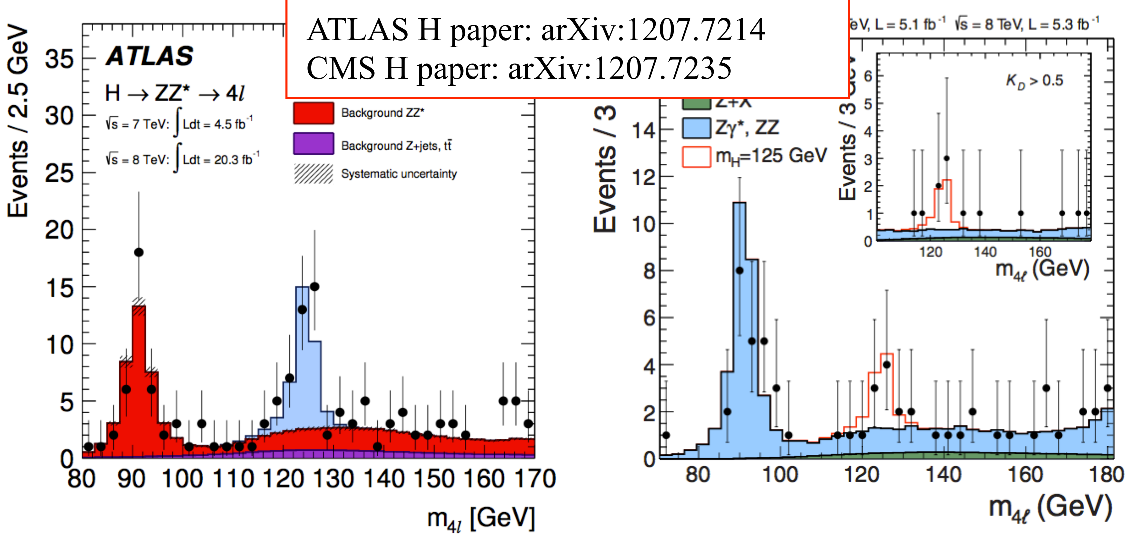
Consider 4 body decays of bosons

- We can perform similar measurements of Z and H decays, as well as associated production (VH) decays.
  - In the case of H; the starting point is to assume that we have a SM Higgs.
    - Consistent with data so far, but obviously not yet conclusive.
  - Any non-zero effect would be new physics (i.e. not just from a SM Higgs).
    - i.e. the outcome of a measurement is interesting if SM, and very interesting if not SM.
  - Requires (only a little bit of) a stretch of the imagination.
    - By the time these measurements will be possible, the SM properties of H would be confirmed (or not).

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

Class 3 decay

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



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.

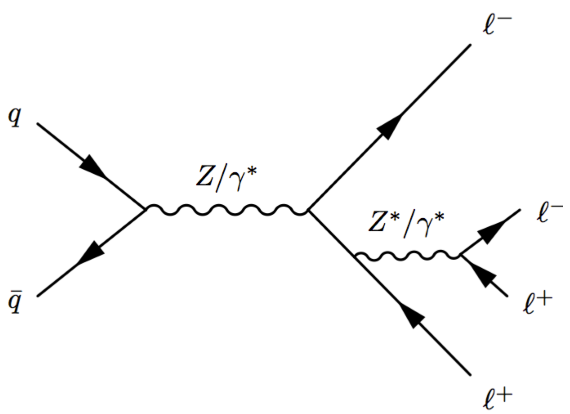
Data sample	$H \to \mu^+\mu^-e^+e^-$
Run 1 ($\sim 25\,\text{fb}^{-1}$)	0.38
Run 2 ($\sim 125\,\text{fb}^{-1}$)	0.11
Run 3 ($\sim 300\,\text{fb}^{-1}$)	0.07
HL-LHC ($\sim 3000\,\text{fb}^{-1}$)	0.02

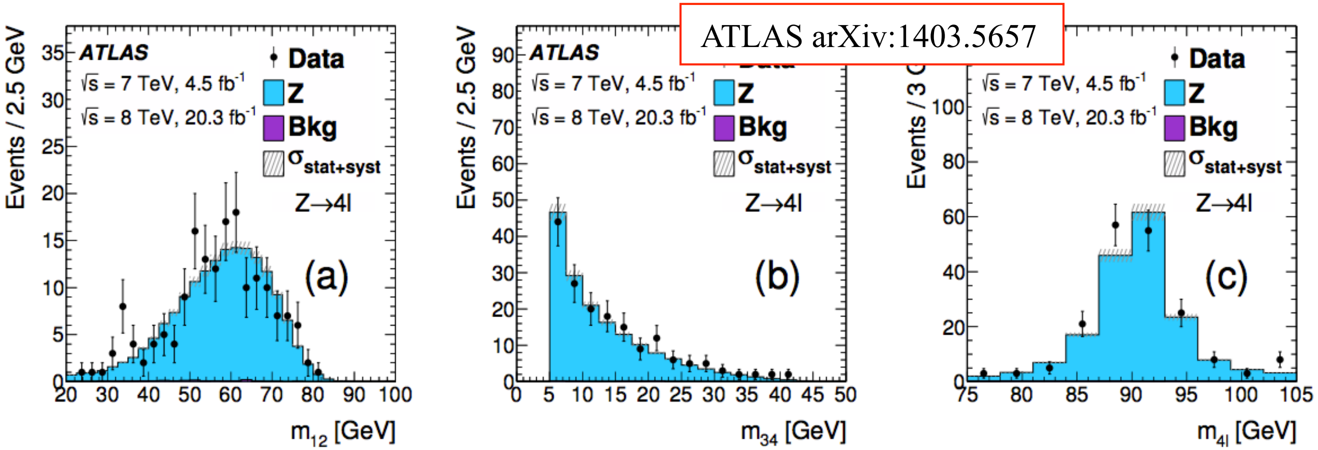
est. asym. precision

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

Class 3 decay

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





- 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	$Z^0 \to \mu^+\mu^-e^+e^-$ (est. asym. precision)
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

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:

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

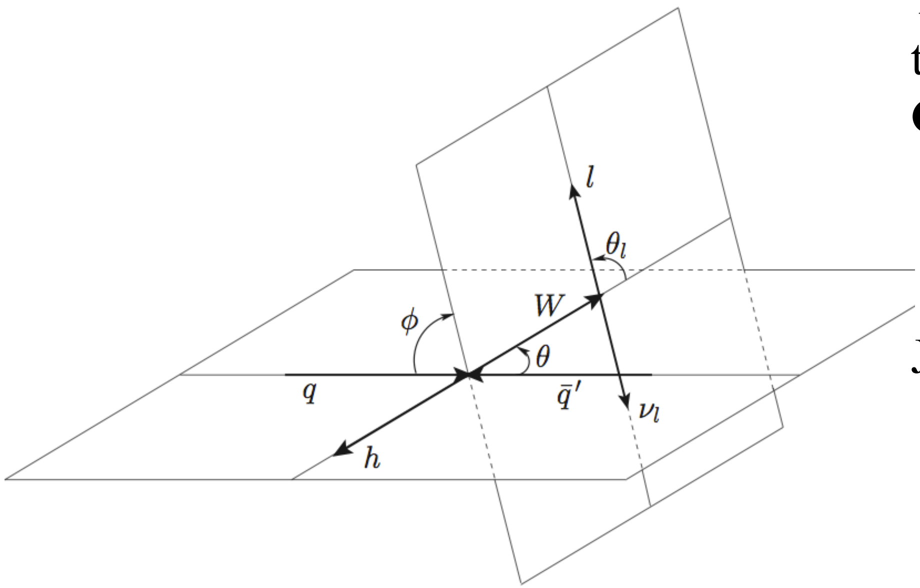
  - 76,000 events running at 250 GeV.
  - 50,000 events running at 500 GeV.
- This sample size would yield statistical precisions of 1.5-2% for inclusive measurements, and 2.6-3.3% for exclusive ones on the P and CP asymmetry.
- FCC-ee and CEPC would be ~5 times more precise.

Up-Down CP asymmetry for WH

- Generally Higgs couplings $hV_\mu V_\nu$ BSM could be CPV at high scales.

$$-ig_V m_V \left[A_V \eta_{\mu\nu} + B_V p_{1\nu} p_{2\mu} + C_V \epsilon_{\mu\nu\alpha\beta} p_1^\beta p_2^\alpha\right]$$

  - Third coupling C_V is CP violating.
  - SM predicts A=1, B=C=0 at tree level.
    - C_Z is already constrained to be small, so $H \to ZZ$ will have small or no effect. $H \to WW$ may be more promising.
  - Now back to VH: Consider the 1 lepton case:



The script $\mathcal{A}$'s depend on masses of bosons and the form factors; **γ provides information on CP violation**;

$$\hat{A}_{\rm CP} \equiv \frac{\hat{\sigma}_{\phi>0} - \hat{\sigma}_{\phi<0}}{\hat{\sigma}_{\phi>0} + \hat{\sigma}_{\phi<0}} = -\frac{9\pi}{16} \sin\gamma \left(\frac{\mathcal{A}_T \mathcal{A}_L}{2\mathcal{A}_T^2 + \mathcal{A}_L^2}\right)$$

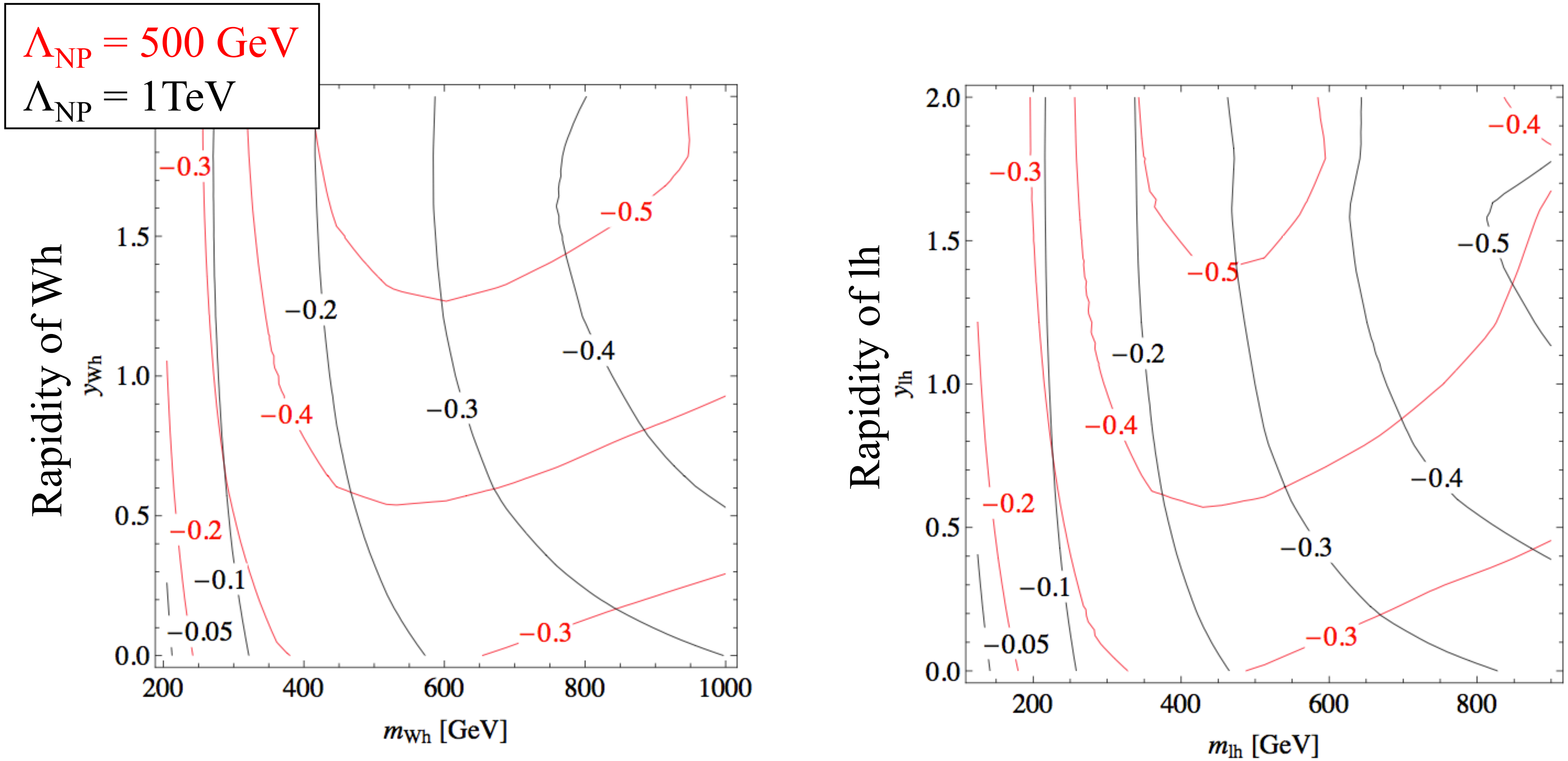
Just have to measure the rate asymmetry:

$$A_{\rm CP} \equiv \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Delaunay, Perez, Sandres, Skiba, PRD 89, 035004 (2014) [arXiv:1308.4930]

Up-Down CP asymmetry for WH

- Large asymmetries can be manifest for modest Λ_{NP}.



mass ofWlh

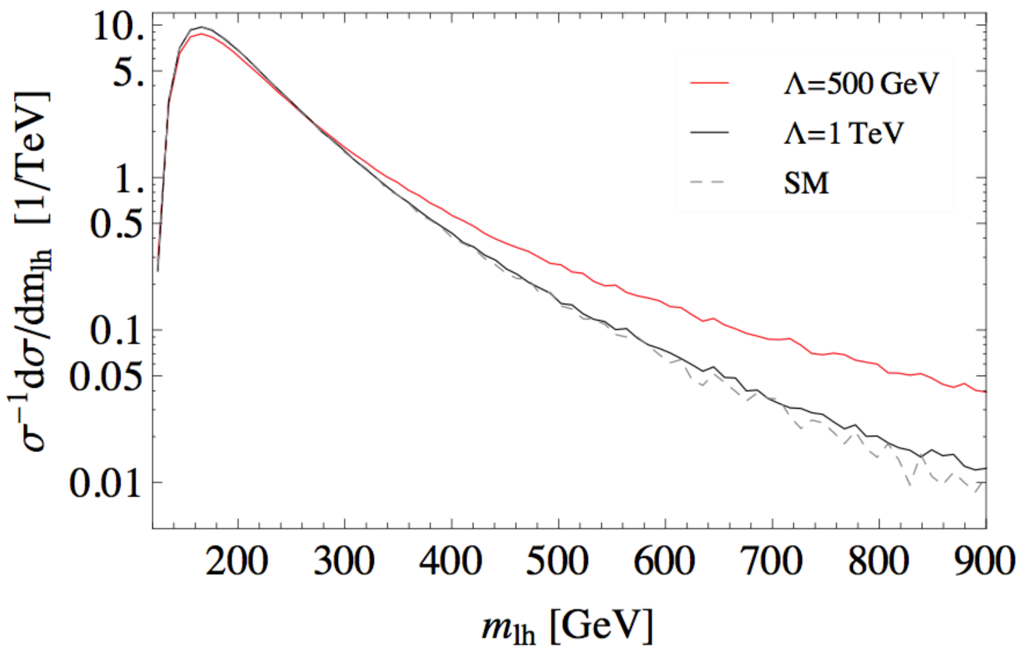
mass of lh

- Won't require too much data to start making a credible measurement; even evidence for WH would make this an interesting exercise.

Delaunay, Perez, Sandres, Skiba, PRD 89, 035004 (2014) [arXiv:1308.4930]

Up-Down CP asymmetry for WH

- To construct the triple product we make some assignment; charge of the W daughters is trivial; charge of the H daughters requires jet charge to be well known.
  - Without that information we can still learn about the presence of new physics by just looking at the rate as a function of mass.



Delaunay, Perez, Sandres, Skiba, PRD 89, 035004 (2014) [arXiv:1308.4930]

WH and ZH production in Run 2/3

- Measurements become viable when we have evidence for a signal.

- The CM frame of the ZH system can be reconstructed experimentally; enabling a measurement should we see evidence for the decay.
  - The precision achievable depends on luminosity delivered and S/B, but the measurement technique is straightforward. Unfortunately C_Z is expected to be zero, so we won't see an asymmetry.

- The CM frame for WH is not fully reconstructed; can use mass constraints to vertex WH signal and estimate the CM frame.
  - How well will this work ?

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→4b).
- These permit systematic tests of the C, P, and CP symmetry nature of the Standard Model and searches for new physics.