Introduction to Dalitz Plot Analysis

Tim Gershon
University of Warwick

479.WE-Heraeus-Seminar
Physics at LHCb
26 April 2011
What Is a Dalitz Plot?

- Visual representation of
  - the phase-space of a three-body decay
    - involving only spin-0 particles
    - (term often abused to refer to phase-space of any multibody decay)
- Named after its inventor, Richard Dalitz (1925–2006):
  - “On the analysis of tau-meson data and the nature of the tau-meson.”
    - R.H. Dalitz, Phil. Mag. 44 (1953) 1068
    - (historical reminder: tau meson = charged kaon)
- For scientific obituary, see
  - I.J.R. Aitchison, F.E. Close, A. Gal, D.J. Millener,
“Equilaterial representation”

Connection between scattering and decay processes provides a solid theoretical ground for describing some hadronic effects – “Watson's theorem”
In case anyone is wondering ...

- Previous plot shows $p\bar{p} \rightarrow \pi^0\pi^0\pi^0$ from Crystal Barrel experiment (LEAR)
  - C.Amsler et al., EPJC 23 (2002) 29
- Highly symmetrized because 3 identical bosons in the final state
  - symmetric under interchange of any 2 $\pi^0$
“Right-angled representation”

Removes some of the symmetry ... but easier for most software to handle
(Most decays that we are interested in are not so symmetric anyway)
Retains & heightens intuitive connection between visualisation and kinematics

Lorentz invariant phase-space of three-body decay

\[ d\Omega \sim ds_{12} ds_{13} \]
Dalitz plots as visualiser of kinematics

- Illustration for $D \rightarrow K_S \pi^+ \pi^-$
  - green & blue: $K^*(892)$ (vector)
  - cyan & magenta: $K^*_2(1430)$ (tensor)
  - yellow: $\rho(770)$ (vector)
  - red: $f_0(980)$ (scalar)

- but main advantage of Dalitz plots is ability to exploit inference between different resonances
Some examples of Dalitz plots

\[ D^0 \rightarrow K_s \pi^+\pi^- \]
BaBar PRL 105 (2010) 081803

\[ D_{s}^+ \rightarrow \pi^+\pi^-\pi^+ \]
BaBar PRD 79 (2009) 032003

Note symmetries

K*, interference

\[ m^2(\pi^+\pi^-) \] (GeV^2/c^4)

\[ s_+ \] (GeV^2/c^4)

\[ s_- \] (GeV^2/c^4)

\[ m^2(\pi^+\pi^-) \] (GeV^2/c^4)

(b) \[ f_0 \]
Some examples of Dalitz plots

\[ B^+ \rightarrow D^-\pi^+\pi^+ \]
Belle PRD 69 (2004) 112002

\[ B^+ \rightarrow K^+K^+K^- \]
Belle PRD 71 (2005) 092003

Note symmetries

\[ D_2^* \]

\[ \Phi, \text{ nonresonant} \]
Why are we so interested in Dalitz plots?

- **Condition for DCPV:** $|\bar{A}/A| \neq 1$
- **Need** $\bar{A}$ and $A$ **to consist of** (at least) **two parts**
  - with different weak ($\varphi$) and strong ($\delta$) phases
- **Often realised by** “tree” and “penguin” diagrams

\[
A = |T|e^{i(\delta_T - \phi_T)} + |P|e^{i(\delta_P - \phi_P)}
\]
\[
\bar{A} = |T|e^{i(\delta_T + \phi_T)} + |P|e^{i(\delta_P + \phi_P)}
\]
\[
A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2 |T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2 |T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}
\]

**Example:** $B \to K\pi$

(weak phase difference is $\gamma$)

---

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*Introduction to Dalitz Plot Analysis*
Why are we so interested in Dalitz plots?

- Condition for DCPV: $|\bar{A}/A|\neq 1$

Problem with two-body decays:
- 2 observables ($B$, $A_{CP}$)
- 4 unknowns ($|T|$, $|P|$, $\delta_T - \delta_P$, $\phi_T - \phi_P$)

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2 |T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2 |T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}$$

Example: $B \rightarrow K\pi$
(weak phase difference is $\gamma$)

Feynman tree (a) and penguin (b) diagrams for the $B^0_d \rightarrow K^+\pi^-$ decay
Direct CP violation in $B \to K\pi$

• Direct CP violation in $B \to K\pi$ sensitive to $\gamma$
  too many hadronic parameters $\Rightarrow$ need theory input

NB. interesting deviation from naïve expectation

$$A_{CP}(K^- \pi^+) = (-9.8^{+1.2}_{-1.1})\% \quad A_{CP}(K^- \pi^0) = (5.0 \pm 2.5)\%$$

$$\Delta (A_{CP}) = (-14.8 \pm 2.8)\%$$

HFAG averages
BABAR PRD 76 (2007) 091102 & arXiv:0807.4226; also CDF

and now LHCb!
(results not in average yet)

Could be a sign of new physics …
… but need to rule out possibility of larger
than expected QCD corrections
Dalitz plot analysis

- **Amplitude analysis** to extract directly information related to the phase at each Dalitz plot position
- Most commonly performed in the “isobar model”
  - sum of interfering resonances
  - each described by Breit-Wigner (or similar) lineshapes, spin terms, etc.
  - fit can be unbinned, but has inherent model dependence
- Alternative approaches aiming to avoid model dependence usually involve binning
  - partial wave analysis
Pros and cons of Dalitz plots

**Pros**

- More observables ($B & A_{CP}$ at each Dalitz plot point)

- Using isobar formalism, can express total amplitude as coherent sum of quasi-two-body contributions

$$A(m_{12}^2, m_{23}^2) = \sum_r c_r F_r(m_{12}^2, m_{23}^2)$$

  - where $c_r$ & $F_r$ contain the weak and strong physics, respectively

  - n.b. each $c_r$ is itself a sum of contributions from tree, penguin, etc.

- **Interference provides additional sensitivity to CP violation**

**Cons**

- Need to understand hadronic ($F_r$) factors
  - lineshapes, angular terms, barrier factors, ...

- Isobar formalism only an approximation

- Model dependence

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Introduction to Dalitz Plot Analysis
B^+ \rightarrow K^+ \pi^+ \pi^-

Model includes:
- K^{*0}(892)\pi^+, K_2^{*0}(1430)\pi^+
- (K\pi)_0^*\pi^+ (LASS lineshape)
- \rho^0(770)K^+, \omega(782)K^+, f_0(980)K^+, f_2(1270)K^+, \chi_{c0}K^+
- f_X(1300)K^+, phase-space nonresonant

BaBar PRD 78 (2008) 012004
See also Belle PRL 96 (2006) 251803
TABLE II: Summary of measurements of branching fractions (averaged over charge conjugate states) and CP asymmetries. Note that these results are not corrected for secondary branching fractions. The first uncertainty is statistical, the second is systematic, and the third represents the model dependence. The final column is the statistical significance of direct CP violation determined as described in the text.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fit fraction (%)</th>
<th>(B(B^+ \to \text{Mode})(10^{-6}))</th>
<th>(A_{\text{CP}}) (%)</th>
<th>DCPV sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+\pi^-\pi^+) total</td>
<td></td>
<td>54.4 ± 1.1 ± 4.5 ± 0.7</td>
<td>2.8 ± 2.0 ± 2.0 ± 1.2</td>
<td></td>
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<tr>
<td>(K^<em>(892)\pi^+); (K^</em>(892) \to K^+\pi^-)</td>
<td>13.3 ± 0.7 ± 0.7 ± 0.4/9.0</td>
<td>7.2 ± 0.4 ± 0.7 ± 0.3/0.5</td>
<td>+3.2 ± 5.2 ± 1.1 ± 1.2/0.7</td>
<td>0.9σ</td>
</tr>
<tr>
<td>((K\pi)^0\pi^+); ((K\pi)^0 \to K^+\pi^-)</td>
<td>45.0 ± 1.4 ± 1.2 ± 12.9/0.2</td>
<td>24.5 ± 0.9 ± 2.1 ± 7.0/1.1</td>
<td>+3.2 ± 3.5 ± 2.0 ± 2.7/1.9</td>
<td>1.2σ</td>
</tr>
<tr>
<td>(\rho^0(770)K^+); (\rho^0(770) \to \pi^+\pi^-)</td>
<td>6.54 ± 0.81 ± 0.58 ± 0.69/0.26</td>
<td>3.56 ± 0.45 ± 0.43 ± 0.38/0.15</td>
<td>+44 ± 10 ± 4.5/1.3</td>
<td>3.7σ</td>
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<tr>
<td>(f_0(980)K^+); (f_0(980) \to \pi^+\pi^-)</td>
<td>18.9 ± 0.9 ± 1.7 ± 2.8/0.6</td>
<td>10.3 ± 0.5 ± 1.3 ± 1.5/0.4</td>
<td>-10.6 ± 5.0 ± 1.1 ± 3.4/1.0</td>
<td>1.8σ</td>
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<tr>
<td>(\chi_{c0}K^+); (\chi_{c0} \to \pi^+\pi^-)</td>
<td>1.29 ± 0.19 ± 0.15 ± 0.12/0.03</td>
<td>0.70 ± 0.10 ± 0.10 ± 0.06/0.02</td>
<td>-14 ± 15 ± 3 ± 1/5</td>
<td>0.5σ</td>
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<td>(K^+\pi^-\pi^+) nonresonant</td>
<td>4.5 ± 0.9 ± 2.4± 0.6/1.5</td>
<td>2.4 ± 0.5 ± 1.3 ± 0.3/0.8</td>
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<tr>
<td>(K^<em>_2(1430)\pi^+); (K^</em>_2(1430) \to K^+\pi^-)</td>
<td>3.40 ± 0.75 ± 0.42 ± 0.99/0.13</td>
<td>1.85 ± 0.41 ± 0.28 ± 0.54/0.08</td>
<td>+5 ± 23 ± 4 ± 18/7</td>
<td>0.2σ</td>
</tr>
<tr>
<td>(\omega(782)K^+); (\omega(782) \to \pi^+\pi^-)</td>
<td>0.17 ± 0.24 ± 0.03 ± 0.05/0.08</td>
<td>0.09 ± 0.13 ± 0.02 ± 0.03/0.04</td>
<td>—</td>
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</tr>
<tr>
<td>(f_2(1270)K^+); (f_2(1270) \to \pi^+\pi^-)</td>
<td>0.91 ± 0.27 ± 0.11 ± 0.24/0.17</td>
<td>0.50 ± 0.15 ± 0.07 ± 0.13/0.09</td>
<td>-85 ± 22 ± 13 ± 22/2</td>
<td>3.5σ</td>
</tr>
<tr>
<td>(f_X(1300)K^+); (f_X(1300) \to \pi^+\pi^-)</td>
<td>1.33 ± 0.38 ± 0.86 ± 0.04/0.14</td>
<td>0.73 ± 0.21 ± 0.47 ± 0.02/0.08</td>
<td>+28 ± 26 ± 13 ± 7/5</td>
<td>0.6σ</td>
</tr>
</tbody>
</table>

- \(f_X(1300)K^+\), phase-space nonresonant

Evidence for direct CP violation
But significant model dependence
\[ B^+ \to K^+ \pi^+ \pi^- \]

Evidence for direct CP violation
But significant model dependence

Huge potential for LHCb ...
... but need to reduce model dependence
Sources of model dependence

- Lineshapes
  - coupled channels, threshold effects, etc.
- Isobar formalism
  - “sum of Breit-Wigners” model violates unitarity
  - problem most severe for broad, overlapping resonances
    - even talking about “mass” and “width” for such states is not strictly correct (process dependent) – can only be defined by pole position
- Nonresonant contributions
  - such terms are small for D decays, but are found to be large for some B decays (not well understood why)
  - interference with other (S-wave) terms can lead to unphysical phase variations
Are methods used for D decay Dalitz plots also valid for B decays?

\[ D \rightarrow K^- \pi^+ \pi^0 \quad \text{B} \rightarrow K^- \pi^+ \pi^0 \]

Same model as D decay

D Dalitz plot on same scale

Image credit: Brian Meadows
How to address model dependence?

- Model independent methods
  - Dalitz plot anisotropy ("Miranda" method)
  - binned D Dalitz plots for measurement of $\gamma$ in $B\to DK$ (and charm mixing & CP violation)
  - partial wave analysis

- More robust (but still model dependent) methods
  - K-matrix approach
  - use of scattering data to constrain phase variation (Watson's theorem) – e.g. LASS shape for $(K\pi)$ S-wave
  - input from theory (chiral symmetry, dispersion relations)

More details in talks of Christoph Hanhart and Leonard Lesniak in parallel session on Thursday
“Miranda” procedure a.k.a. Dalitz plot anisotropy

\[ D_P S_{CP} \equiv \frac{N(i) - \bar{N}(i)}{\sqrt{N(i) + \bar{N}(i)}} \]

Toy model (using \( B^+ \rightarrow K^+\pi^+\pi^- \))

- Without CP violation
  - Gaussian
- With CP violation
  - Not Gaussian

- Good model-independent way to identify CP violation
  - could be sufficient to identify non-SM physics in, e.g., charm decays
- Constant (DP independent) systematic asymmetries can be accounted for
- Can isolate region of the Dalitz plot where CP violation effects occur

But does not provide quantitative measure of weak phase
Example partial wave analysis:

\[ D_s^+ \rightarrow K^+ K^- \pi^+ \ (\text{BaBar}) \]

Plot \( m(K^+ K^-) \), weighting events by factors

\[ Y_{L,0}(\cos \theta_{KK})/\epsilon \]

to obtain “moments \( <Y_{L,0}(m)> \)”

\[
\sqrt{4\pi} \langle Y_0^0 \rangle = \frac{|S|^2 + |P|^2}{2}, \\
\sqrt{4\pi} \langle Y_2^0 \rangle = \frac{|P|^2}{\sqrt{5}}, \\
\sqrt{4\pi} \langle Y_4^0 \rangle = 2 |S||P| \cos \phi_{SP}
\]

\( \phi(1020) \)

\( K^*(892) \)

\(~101K\) Events

96% purity

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Example partial wave analysis:

\[ \mathbf{D}_s^+ \rightarrow \mathbf{K}^+ \mathbf{K}^- \pi^+ \ (\text{BaBar}) \]

(Aproximately) model-independent information on the KK S-wave magnitude and phase

Ambiguity in \( \phi_{SP} \) resolved by knowledge of \( \phi(1020) \) phase variation

Seems process independent?

From \( K^+K^- \) cross channel

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Quasi-model-independent partial wave analysis

- Pioneered by E791 (B. Meadows) in $D^+ \rightarrow K^-\pi^+\pi^+$
- Describe S-wave by complex spline (many free parameters)
- Example: $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ from BaBar
ππ S-wave comparison

Data points from BaBar
ππ S-wave comparison

Prediction from theory: Kaminski et al. PRD77:054015,2008
Extracting weak phases from Dalitz plots

- Many methods exist in the literature
  - some have been used by the B factories
    - most results are statistically limited
    - in some cases model uncertainties are an issue
  - still plenty of room for good new ideas
- Examples (there are many more!)
  - Snyder-Quinn method to measure $\alpha$ from $B \rightarrow \pi^+\pi^-\pi^0$
  - GGSZ/BP method to measure $\gamma$ from $B^\pm \rightarrow DK^\pm$ with $D \rightarrow K_S\pi^+\pi^-$
  - Measurement of charm oscillation parameters using $D \rightarrow K_S\pi^+\pi^-$
  - Various methods to measure $\gamma$ from three-body charmless B decays ($B_{\{u,d,s\}} \rightarrow \pi\pi\pi$, $K\pi\pi$, $KK\pi$, $KKK$)
  - Penguin-free measurements of $\beta$ & $\beta_s$ from $D\pi^+\pi^-$ & $DK^+K^-$, respectively
B → π⁺π⁻π⁰ − B factory results

• Results from
  • BaBar, 375 M BB pairs: PRD 76 (2007) 012004

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B → π⁺π⁻π⁰ – B factory results

• Results from
  • BaBar, 375 M BB pairs: PRD 76 (2007) 012004

Contour from B → π⁺π⁻π⁰ only

Including also information on B⁺ → ρ⁺π⁰ and B⁺ → ρ⁰π⁺
$B^\pm \rightarrow DK^\pm$ with $D \rightarrow K_S\pi^+\pi^-$

Interference between $b \rightarrow u$ and $b \rightarrow c$ amplitudes when $D$ is reconstructed in final state common to $D^0$ and $\bar{D}^0$ provides sensitivity to $\gamma$

$$|M_{\pm}(m_+^2, m_-^2)|^2 = |f_D(m_+^2, m_-^2) + re^{i\delta_B \pm i\phi_3} f_D(m_-^2, m_+^2)|^2$$

Model ($f_D(m_+^2, m_-^2)$) taken from measurements of $|f_D|^2$ using flavour tagging $D^*$ decays – model dependence

BaBar obtain

$$\gamma = (68^{+15}_{-14} \pm 4 \pm 3)^\circ$$
(from $DK^-$, $D^*K^-$ & $DK^{*-}$)

Belle obtain

$$\phi_3 = (78^{+11}_{-12} \pm 4 \pm 9)^\circ$$
(from $DK^-$ & $D^*K^-$)

PRL 105 (2010) 121801

PRD 81 (2010) 112002
\[ B^\pm \rightarrow DK^\pm \text{ with } D \rightarrow K_S\pi^+\pi^- \]

Solution – bin the Dalitz plot and use \( \psi(3770) \rightarrow D\bar{D} \) events (CLEOc, BES) to measure per-bin phases


(unusual bin shapes to attempt to optimise sensitivity)

\[ M_i^\pm = h\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x\pm c_i + y\pm s_i)\} \]

\[ x_\pm = r_B \cos(\delta_B \pm \phi_3) \]
\[ y_\pm = r_B \sin(\delta_B \pm \phi_3) \]

\( c_i, s_i \) measured by CLEO

PRD 82, 112006 (2010)

First model independent measurement of \( \gamma \) in this mode by Belle

\[ \phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)° \]
Looking ahead

• I hope I have already convinced you that there is great physics potential in Dalitz plot analysis

• But there are also considerable challenges
  • theoretical (hadronic effects, etc.)
  • experimental
    – Dalitz plot dependent effects:
    – Efficiency
    – Background
    – Mass resolution
    – Misreconstruction effects …

• I leave the details to the parallel session speakers, but …
Motivation for “Les Nabis”

- From I. Bigi, “Hadronization — the Unsung Hero rather than the alleged Villain in the Tale of CP Violation”, proceedings of Hadron '05

- “We expect confidently that New Physics surfaces at the TeV scale. Yet we have to aim beyond ‘merely’ establishing the existence of New Physics – our goal has to be to identify its salient features. The discovery potential in B decays is essential, not a luxury. Yet due to the past ‘unlikely’ success of the CKM description one cannot count on massive manifestations of New Physics. Therefore we need high accuracy both on the experimental and theoretical side in heavy flavour studies. This requires a better quantitative understanding of hadronization to exhaust the discovery potential in B decays.”

- “The expertise required to attain an essential goal – namely to exhaust the discovery potential in heavy flavour transitions by harnessing low-energy hadronization – does exist or can be acquired with no need for a breakthrough. However it tends to reside in a community all too often disjoint from the heavy flavour community – this has to change!”
Erm, What is “Les Nabis”?

- A group of experimentalists and theorists, drawn from both particle/heavy flavour and nuclear/hadronic physics communities, set up to address issues in Dalitz plot analysis with the aim of obtaining both qualitative and quantitative information on weak phases and CP violation

- Theory:

- Experiment:

  (This is the list on the Nabis web page – apologies for any omissions)
OK, but why is it called “Les Nabis”?

• From the manifesto (yes, really):
  
  • “Les Nabis” means “the Prophets” in Hebrew, and this name had been adopted by a group of post-impressionist artists who set the pace for paintings and graphics in France in the 1890s. With some of us harbouring a similar sense of modesty as those artists, we found a re-incarnation of “Les Nabis” an appropriate motto for our group and its efforts. This is further strengthened by the fact that one work by a central member of the original “Les Nabis” seems to show a (somewhat artistically enhanced) image of a Dalitz plot – it is “The Talisman” by Paul Sérusier. We have chosen it as our logo.
Summer school

- School on Amplitude Analysis in Modern Physics: from hadron spectroscopy to CP phases
- August 1-5, 2011 at Physikzentrum Bad Honnef, Germany
  - http://www2.fz-juelich.de/ikp/workshops/LesNabis/index.shtml

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Introduction to Dalitz Plot Analysis

Preliminary program August 1-5, 2011

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<tbody>
<tr>
<td>09:00</td>
<td>Introduction</td>
<td>Theory I</td>
<td>Experiment I</td>
<td>Experiment II</td>
<td>Theory II</td>
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<td>Experiment II</td>
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<td>14:00</td>
<td>Experiment I</td>
<td>Discussion I</td>
<td>Discussion II</td>
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Introduction (NN)

Theory I (Jose Pelaez): Dispersion Theory

Theory II (Thomas Mannel): CP violation in the Standard Model

Experiment I (Klaus Peters): Phenomenological Tools

Experiment II (Timothy Gershon): Precision Experiments/Data Analysis

Supplementary I: Regge Theory

Supplementary II: Chiral Perturbation Theory

Supplementary III: Experimental Issues
Summary

- Dalitz plot analyses provide promising methods to measure weak phases and CP violation
- Many attractive features …
- … but significant complications due to model dependence
- Need progress on several fronts
  - Understand better \((\pi\pi), (K\pi), (KK), (D\pi), (DK)\) systems
  - “Nonresonant” contributions and 3-body unitarity
  - Methods to combat model-dependence
  - Nabis initiative set up to try to address this
- Many new possibilities opening up with LHCb
For more details, please come to the parallel session

**Thursday 28 April 2011**

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker/Institution</th>
<th>Title/Topics</th>
<th>PDF</th>
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<tbody>
<tr>
<td>14:00 - 14:35</td>
<td>Christoph Hanhart (Juelich)</td>
<td>Theoretical issues in Dalitz plot analysis</td>
<td>pdf</td>
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<td>14:35 - 15:05</td>
<td>Marco Pappagallo (Bari)</td>
<td>Charm Dalitz plot analyses</td>
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<td>15:05 - 15:30</td>
<td>Carla Gobel (Rio)</td>
<td>Model independent approaches to DP analysis</td>
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<td>15:50 - 16:20</td>
<td>Coffee</td>
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<td>16:20 - 16:50</td>
<td>Jussara Miranda (Rio)</td>
<td>Dalitz plot analyses of charmless B decays</td>
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<td>16:50 - 17:25</td>
<td>Leonard Lesniak (Krakow)</td>
<td>Model for charmless B decay Dalitz plots</td>
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<td>17:25 - 17:50</td>
<td>Anton Poluektov (Warwick)</td>
<td>B-&gt;Dhh' Dalitz plot analyses</td>
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<td>17:50 - 18:10</td>
<td>Daniel Johnson (Oxford)</td>
<td>Use of binned Dalitz plots to measure gamma at LHCb</td>
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<td>18:10 - 18:30</td>
<td>Paras Naik (Bristol)</td>
<td>Four-body Amplitude Analyses at LHCb</td>
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