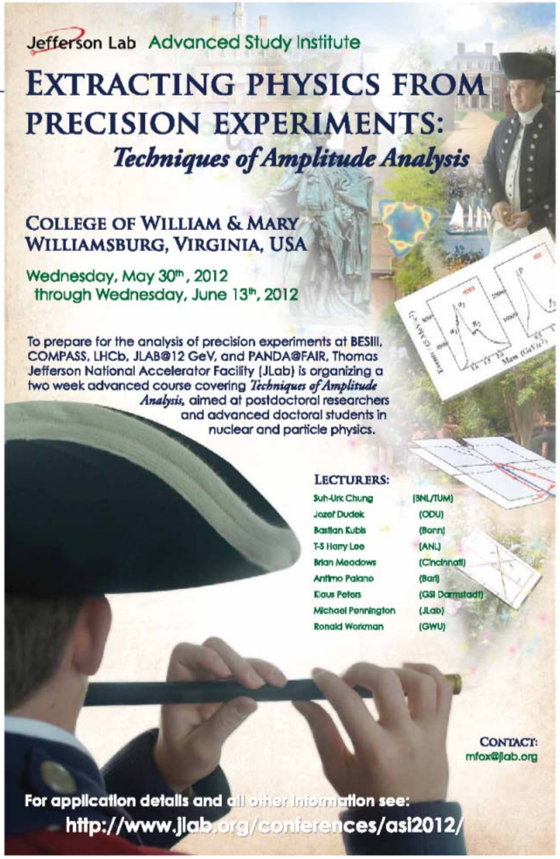
Amplitude Analysis
An Experimentalists View

*Lectures at the "Extracting Physics from Precision Experiments
Techniques of Amplitude Analysis"*



Jefferson Lab Advanced Study Institute

EXTRACTING PHYSICS FROM PRECISION EXPERIMENTS:
Techniques of Amplitude Analysis

COLLEGE OF WILLIAM & MARY
WILLIAMSBURG, VIRGINIA, USA

Wednesday, May 30th, 2012
through Wednesday, June 13th, 2012

To prepare for the analysis of precision experiments at BESIII, COMPASS, LHCb, JLAB@12 GeV, and PANDA@FAIR, Thomas Jefferson National Accelerator Facility (JLab) is organizing a two week advanced course covering *Techniques of Amplitude Analysis*, aimed at postdoctoral researchers and advanced doctoral students in nuclear and particle physics.

LECTURERS:

Suh-Urk Chung	(BNL/TUM)
Jozef Dudek	(ODU)
Bastian Kubis	(Bonn)
T-S Harry Lee	(ANL)
Brian Meadows	(Cincinnati)
Antimo Palano	(Bari)
Klaus Peters	(GSI Darmstadt)
Michael Pennington	(JLab)
Ronald Workman	(GWU)

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mfox@jlab.org

For application details and all other information see:
http://www.jlab.org/conferences/asi2012/

Klaus Peters

GSI Darmstadt and GU Frankfurt

Williamsburg, June 2012

The Course

4 Lectures

Introduction

Mission / Amplitude Analysis Concepts and Procedures / Use Cases

Kinematics and more

Dalitz-Plots / Observables / Coordinate Systems / Examples

K-Matrix

Derivation / Examples / Properties / Fitting / Interpretation

Experiments

Selection / Background / Numerical Issues / Goodness-of-Fit / Computers

The Course

6 Lectures

Introduction

Mission / Amplitude Analysis Concepts and Procedures / Use Cases

Kinematics and more

Dalitz-Plots / Observables / Coordinate Systems / Examples

Spin

…

Dynamics

…

K-Matrix

Derivation / Examples / Properties / Fitting / Interpretation

Experiments

Selection / Background / Numerical Issues / Goodness-of-Fit / Computers

Books

Dynamics

J.M. Blatt & V.F. Weisskopf – *Theoretical Nuclear Physics*

J.R. Taylor – *Scattering Theory*

M.L. Goldberger & K.M. Watson – *Collision Theory*

J. Gillespie – *Final State Interactions*

H. Burkhardt – *Dispersion Relation Dynamics*

Kinematics and more

M. Nikolic – *Kinematics and Multiparticle Systems*

E. Byckling & K. Kajantie – *Particle Kinematics*

Spin

M.E. Rose – *Elementary Theory of Angular Momentum*

Overview

D.V. Bugg (Edtitor) – Nato School on *Hadron Spectroscopy and the Confinement Problem*

Reviews and Articles

General

R.S. Longacre – *Techniques in Meson Spectroscopy,* BNL 49445

K. Peters – *A Primer on Partial Wave Analysis,* Int.J.Mod.Phys. A21 (2006) 5618-5624

Spin

S.U. Chung – *Spin Formalisms,* CERN Yellow Report 71-8

V. Filippini et al. – *Covariant Spin Tensors in Meson Spectroscopy,* PRD 51(1995) 2247

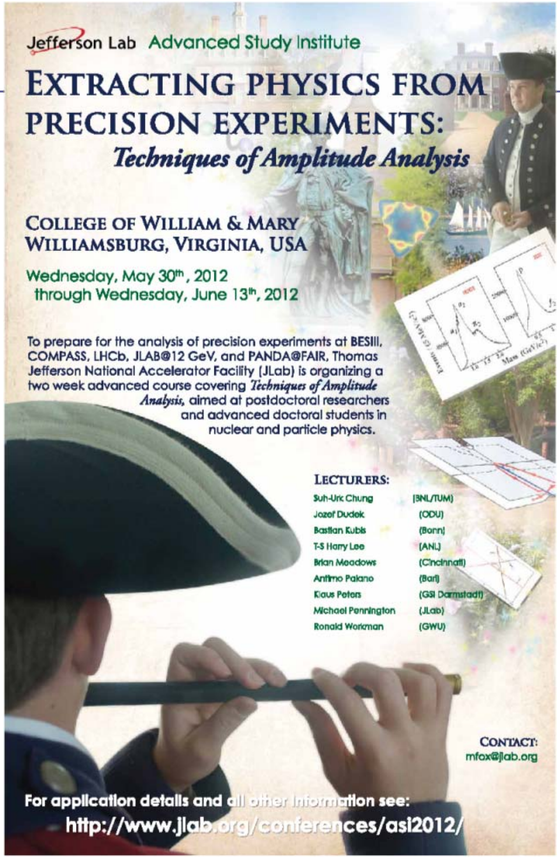
Dynamics

S.U. Chung et al. – *Partial wave analysis in K matrix formalism,* Annalen Phys. 4 (1995) 404-430

F.v. Hippel, C. Quigg – *Centrifugal-Barrier Effect in Resonance Partial Decay Widths, Shapes, and Production Amplitudes* , PRD 5 (1972) 624

I.J.R Aitchison – *K-matrix Formalism For Overlapping Resonances*, Nucl.Phys. A189 (1972) 417-423

K. Peters



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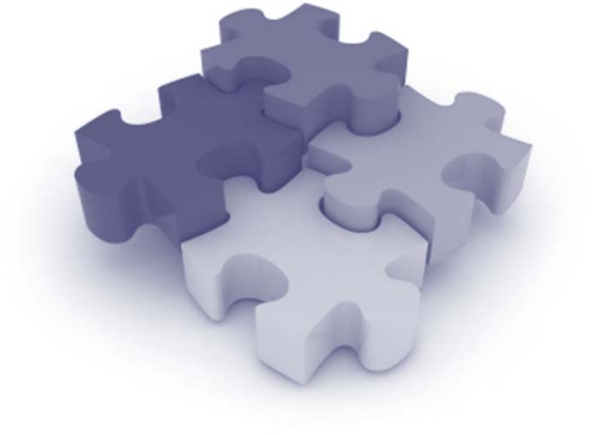
Part I

Introduction

Introduction



Mission

Concepts

Procedures

Use Cases

What is the mission ?

Particle physics at small distances is quite well understood

- One Boson Exchange, Heavy Quark Limits

This is not true at large distances

- Hadronization, Light mesons
- are barely understood compared to their abundance

Understanding interaction/dynamics of light hadrons will

- improve our knowledge about non-perturbative QCD
- parameterizations will give provide
  toolkit to analyze heavy quark processes
- thus an important tool also for precise standard model tests

We need

- Appropriate parameterizations for the multi-particle phase space
- A translation from the parameterizations to effective degrees of freedom for a deeper understanding of QCD

Intermediate State Mixing

- Many states may contribute to a final state
  - not only ones with well defined (already measured) properties
  - not only expected ones
- Many mixing parameters are poorly known
  - *K*-phases
  - SU(3) phases
- In addition
  - also *D/S* mixing (b_1, a_1 decays)

Isoscalar Mixing:

strong Int.: I^G und J^{PC} identical

η-η′ or f_2- f_2’ and/or Glueballs

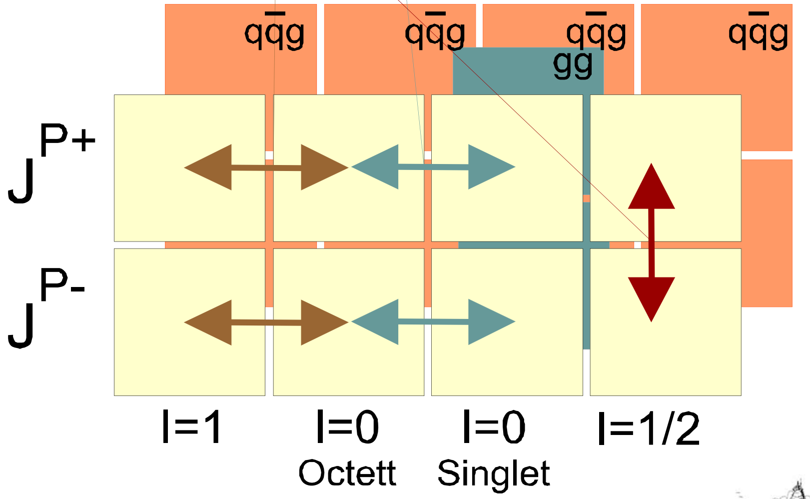
I=0/I=1-Mixing:

elm. Int.: ΔI=1 : ρ-ω

Kaonmixing:

strong Int.: C undef., I^G and J^P identical

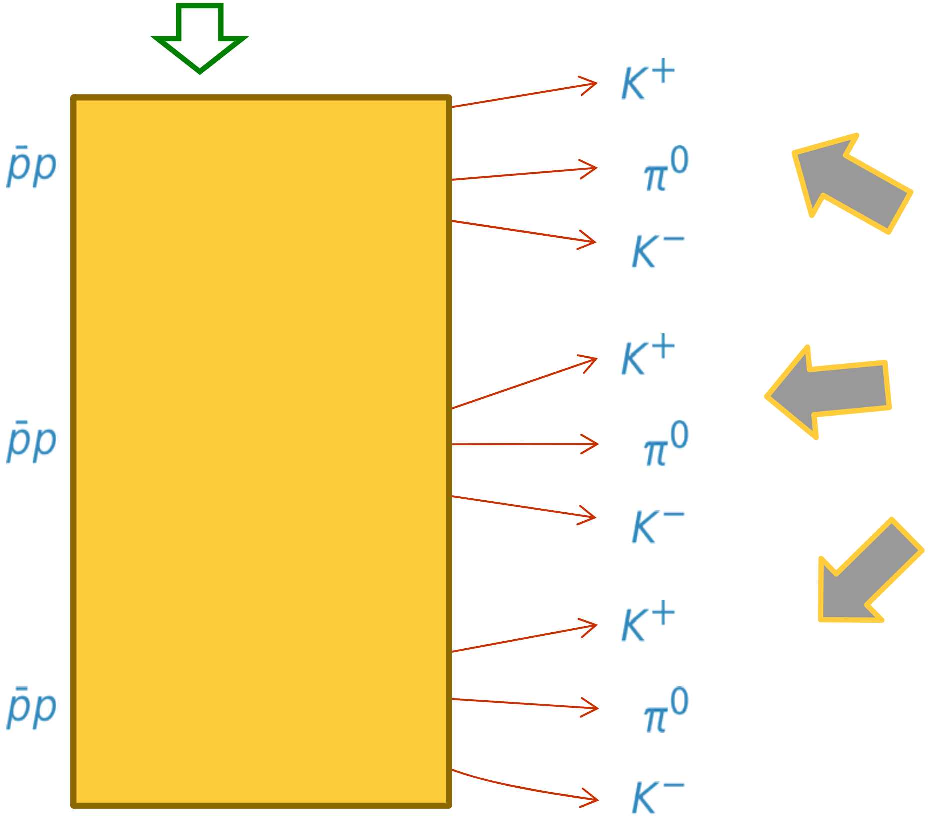
K_{1A}-K_{1B}



The Need for Partial Wave Analysis

Example: Consider the reaction $\bar{p}p \rightarrow K^+K^-\pi^0$

What *really* happened…



What you see is
always the same …

…
etc.

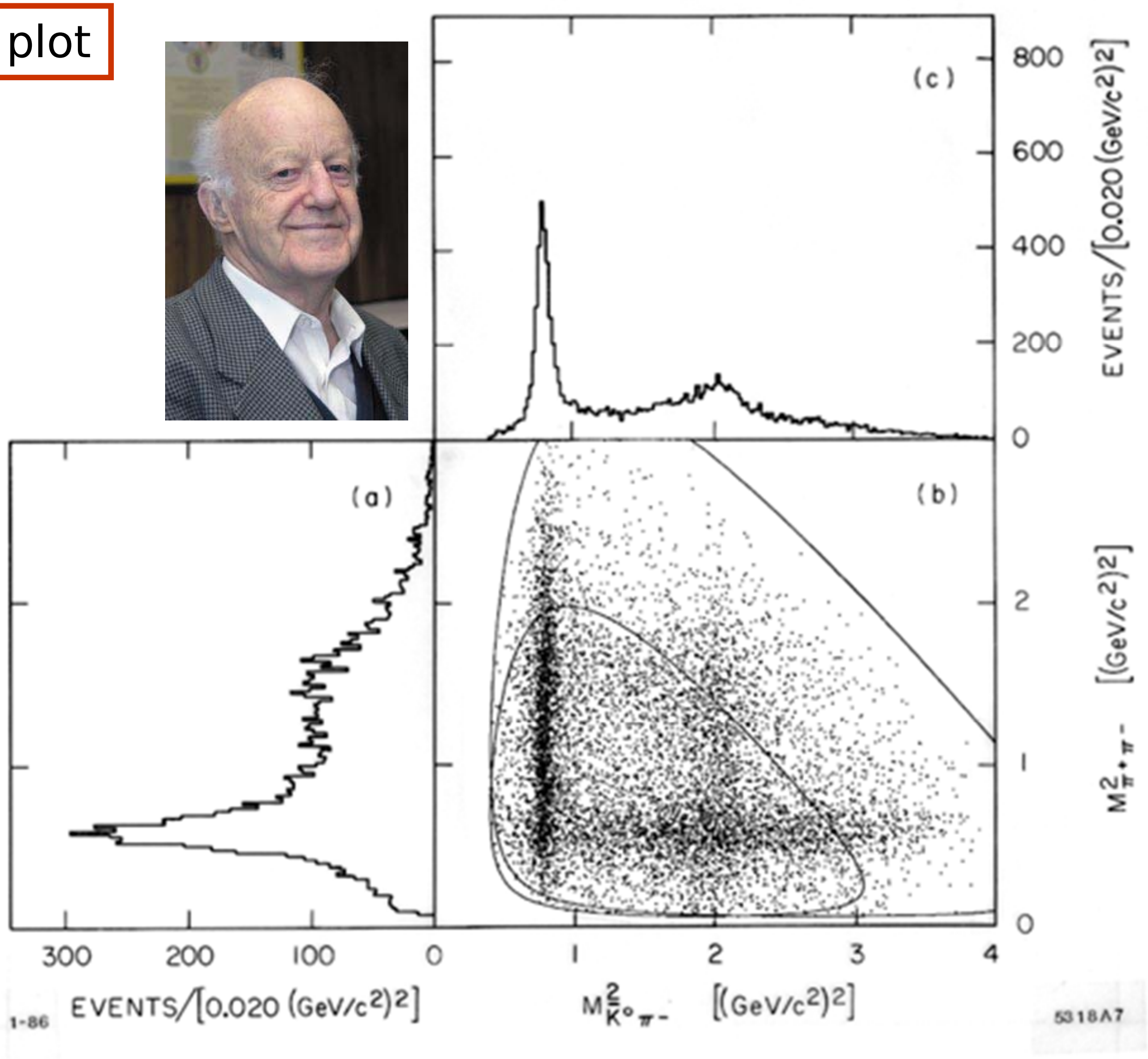
PWA = technique to find
out what happens in between

Goal

- For whatever you need the parameterization of the *n*-Particle phase space
  - It contains the static properties of the unstable (resonant) particles within the decay chain like
    - mass
    - width
    - spin and parities
  - as well as properties of the initial state
  - and some constraints from the experimental setup/measurement
- The main problem is, you don‘t need just a good description, you need the right one
  - Many solutions may look alike, but only one is right

n-Particle Phase space, *n*=3

Dalitz plot



But…

the mission is way more general,

…there are many more questions, which can only be answered with a correct phase space description

whenever states mix and an need to be unambiguously disentangled

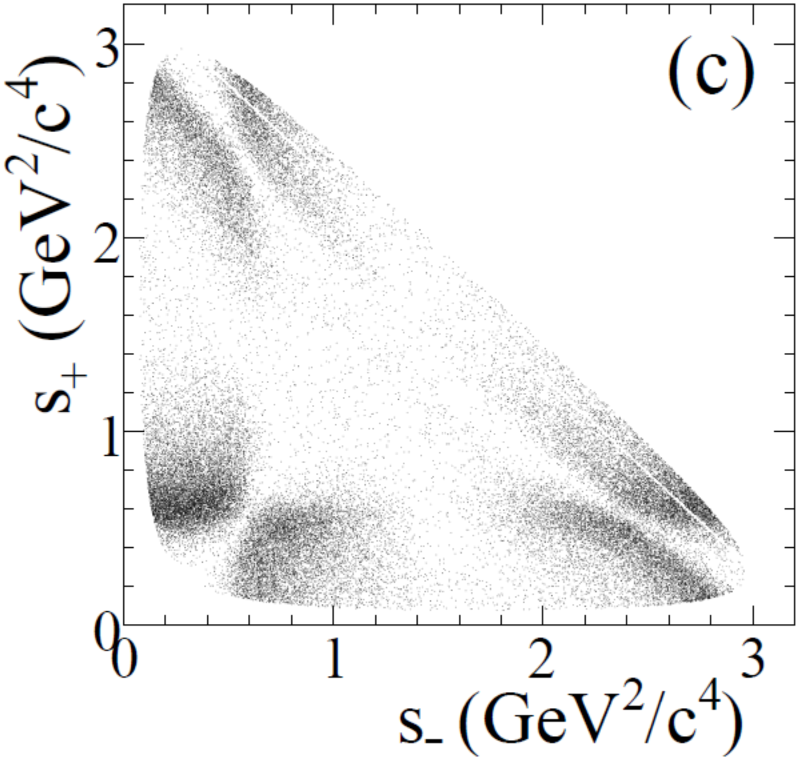
the focus then moves away
from masses and line shapes to yields and phases

example: $D^0\bar{D}^0$-Mixing and CPV

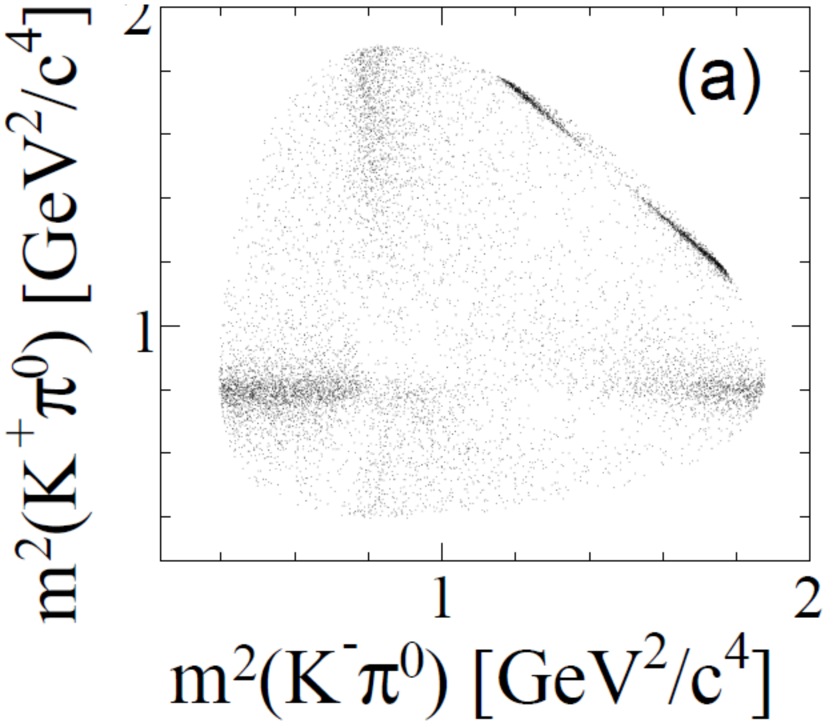
Data from BaBar

$D^0 \rightarrow h^+h^-\pi^0$, $h=K,\pi$

$D^0 \longrightarrow \pi^-\pi^+\pi^0$



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



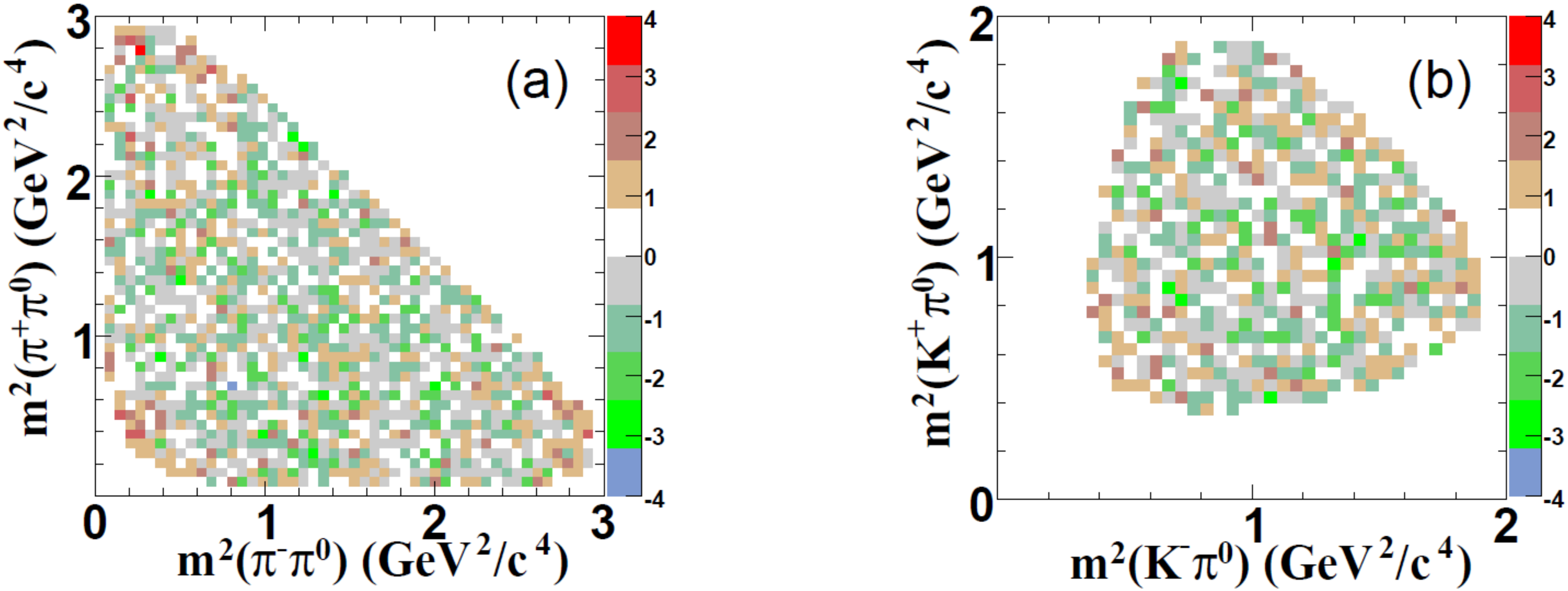
search for asymmetry in production cross section
or in branching fractions

example: $D^0\bar{D}^0$-Mixing and CPV

Data from BaBar

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

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



χ^2-distribution shows: no observed CP-violation

not enough statistics to verify SM prediction

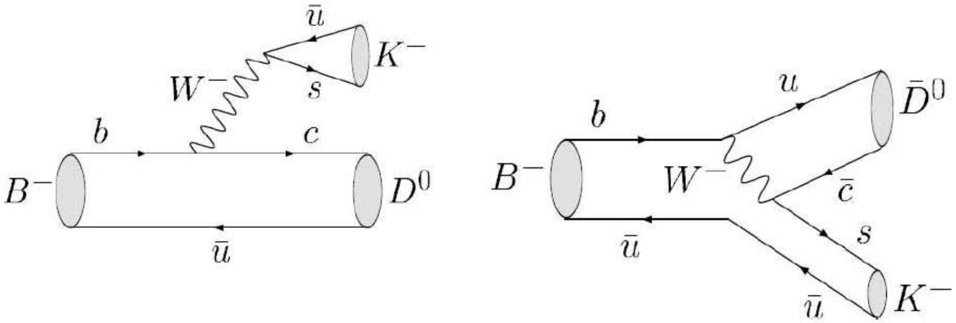
example: CKM Angle γ in $B^- \to D^0 K^-$ (+c.c.)

Direct *CP* violation in interference between $b \to c\bar{u}s,\ u\bar{c}s$

$B^- \to \widetilde{D}^{(*)0} K^{(*)-}$

Interference, if

$D^0 \to f \leftarrow \bar{D}^0$



$$\frac{\mathcal{A}(B^- \to \bar{D}^0 K^-)}{\mathcal{A}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \gamma)}, \qquad \frac{\mathcal{A}(B^+ \to D^0 K^+)}{\mathcal{A}(B^+ \to \bar{D}^0 K^+)} = r_B e^{i(\delta_B + \gamma)}$$

r_B Ratio of magnitudes of amplitudes, small

δ_B *CP* invariant strong phase

Most sensitive channel to date: $\widetilde{D}^0 \to K_S^0 \pi^+ \pi^-$:

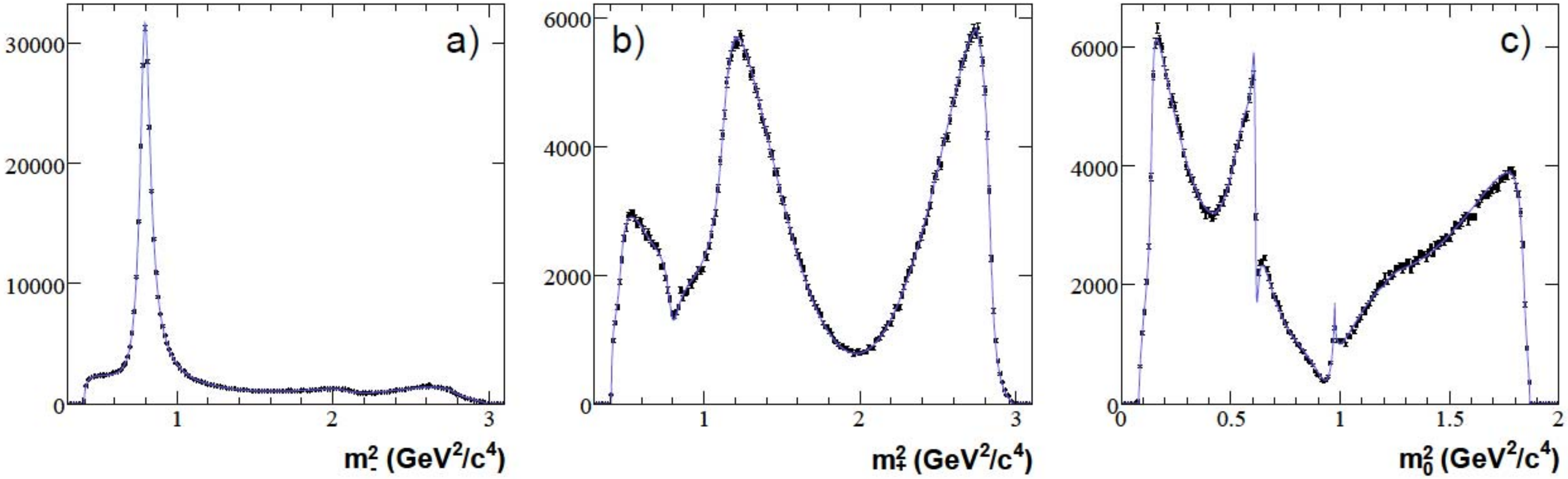
GGSZ, Phys. Rev. D **68**, 054018 (2003), BP, Eur. Phys. Jour. **47**, 347 (2006)

Requires a detailled understanding of the D^0 decay as input

Quality

High Quality is needed

and achievable…



this lecture is basically about how to model the input for such fits

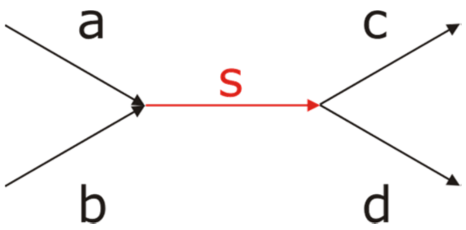
to reveal all the physics of a multi-particle reaction

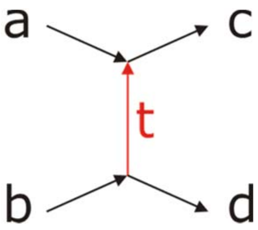
How to obtain this in an effective way?

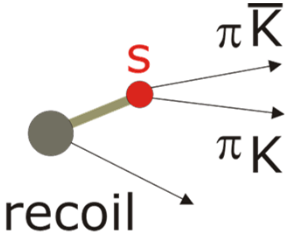
Important aspects...

General considerations
Course of action
Phase space
Observables
Hypotheses
Background
Fitting
Mathematical problems
Quality Assurance

Experimental Techniques







Scattering Experiments

πN - *N** measurement

πN - meson spectroscopy

E818, E852 @ AGS, GAMS
Compass, VES

pp meson threshold production

WASA @ Celsius, COSY

pp or *π*p in the central region

WA76, WA91, WA102

γN – photo production

Cebaf, Mami, Elsa, Graal

"At-rest" Experiments

p̄*N* @ rest at LEAR

Asterix, Obelix, Crystal Barrel
PANDA

J/ψ decays

MarkIII,DM2,BES,CLEO-c

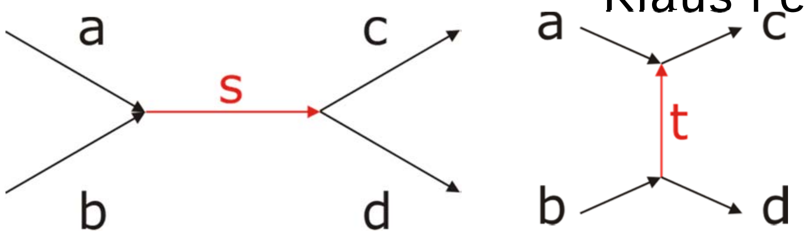
ϕ(1020) decays

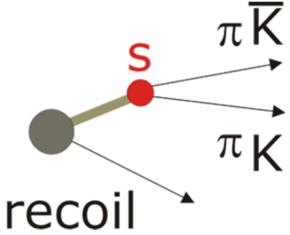
Kloe @ Dafne, VEPP

D and D_s decays

FNAL, Babar, Belle, Belle-II

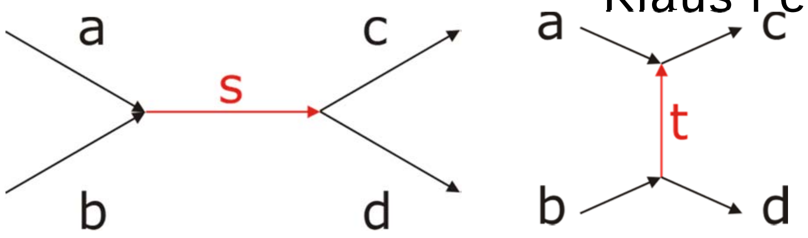
Experimental Techniques





Scattering Experiments	“At-rest” Experiments
partial waves decomposition → via moment analysis	ad-hoc introduction of waves
systematic studies to limit #waves	ad-hoc introduction of dynamic amplitudes (“resonances”)
dynamics appear as amplitude variations	systematic studies to limit #waves and #resonances
resonance parameters from fits to amplitudes	resonance parameters appear as fit parameters

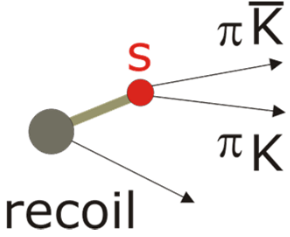
Experimental Techniques



Scattering Experiments

exchange model needed

ad−hoc intermediate resonances
→ parameters fixed for wave decomposition



“At-rest” Experiments

independent of production model

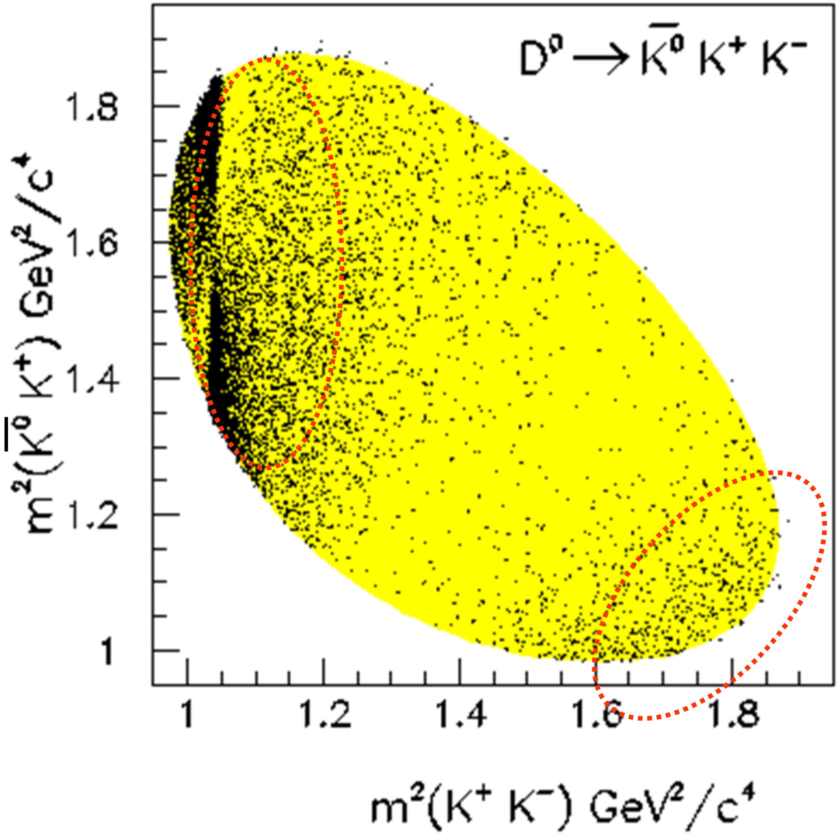
intermediate resonances treated
→ identically to final state resonances

crossing bands may provide high resolution interferometer

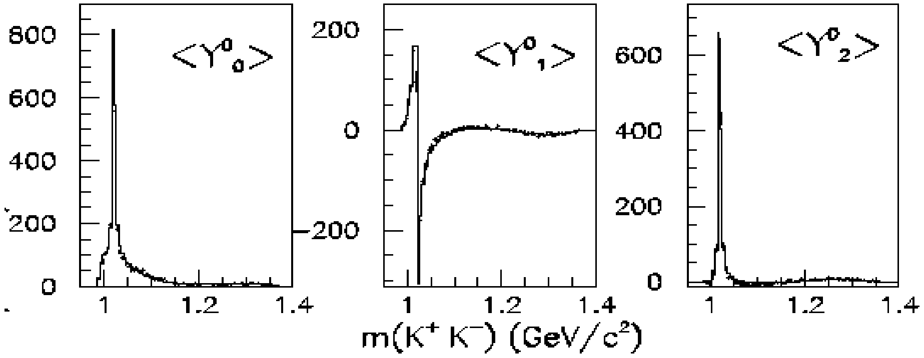
Momentum Analysis in a Dalitz Plot

see M. Pappagallo, Charm06

$$\begin{cases} \sqrt{4\pi}\left\langle Y_0^0 \right\rangle = S^2 + P^2 \\ \sqrt{4\pi}\left\langle Y_1^0 \right\rangle = 2\left|S\right|\left|P\right|\cos\varphi_{SP} \\ \sqrt{4\pi}\left\langle Y_2^0 \right\rangle = \frac{2}{\sqrt{5}}P^2 \end{cases}$$



In some cases it‘s possible if no sharp bands overlap



General considerations (I)

Which processes take place?

Interactions?

Basic processes – scattering vs. decay – which scattering

(Physics of) Initial State – recoils – inclusive/exclusive

Physics background

Leading effects

Scales?

Dynamics – range parameters

Approximations – low energy or threshold expansions

do scales differ for different sub-processes?

factorization of dynamics, like in open-charm decays

General considerations (II)

What are conserved properties?

kinematics

energy/momentum conservation

kinematicaly fitted data?

quantum numbers

quark/isospin conservation/symmetries

good and bad quantum numbers (isospin, parity, CP)

impact on spin formalisms

interferences of Feynman graphs

phase space

full set of observables?

integrate over part of the phase-space

Properties

	Helicity	**Transversity**	**Canonical**
property	possibility/simplicity		
partial wave expansion	simple	complicated	complicated
parity conservation	no	yes	yes
crossing relation	no	good	bad
specification of kinematical constraints	no	yes	yes

Example: Isospin Dependence

$\bar{p}p$ initial states differ in isospin

$$^1S_0 \qquad I^G(J^{PC}) = 1^-(0^{-+})$$

$$^3S_1 \qquad I^G(J^{PC}) = 0^+(1^{--})$$

Calculate isospin Clebsch-Gordan

$$\rho^0\pi^0 \;\rightarrow\; (1010|00) = -\sqrt{\frac{1}{3}}$$

$$\rho^0\pi^0 \;\rightarrow\; (1010|10) = 0$$

$$\rho^\pm\pi^\mp \;\rightarrow\; (1(\pm 1)\ 1(\mp 1)|00) = \sqrt{\frac{1}{3}}$$

$$\rho^\pm\pi^\mp \;\rightarrow\; (1(\pm 1)\ 1(\mp 1)|10) = \pm\sqrt{\frac{1}{2}}$$

$^1S_0$ destructive interferences

$^3S_1$ $\rho^0\pi^0$ forbidden

General considerations (III)

What are the relevant parameters?

Order of magnitude

relevant for coding?

leading terms?

[[Parameter too small, different formulation]]

[[Examples only smallest L]]

Relations

are the parameters related to each other? (D/S, phases, …)

which one is the master and which the slave?

Normalization/Constraints

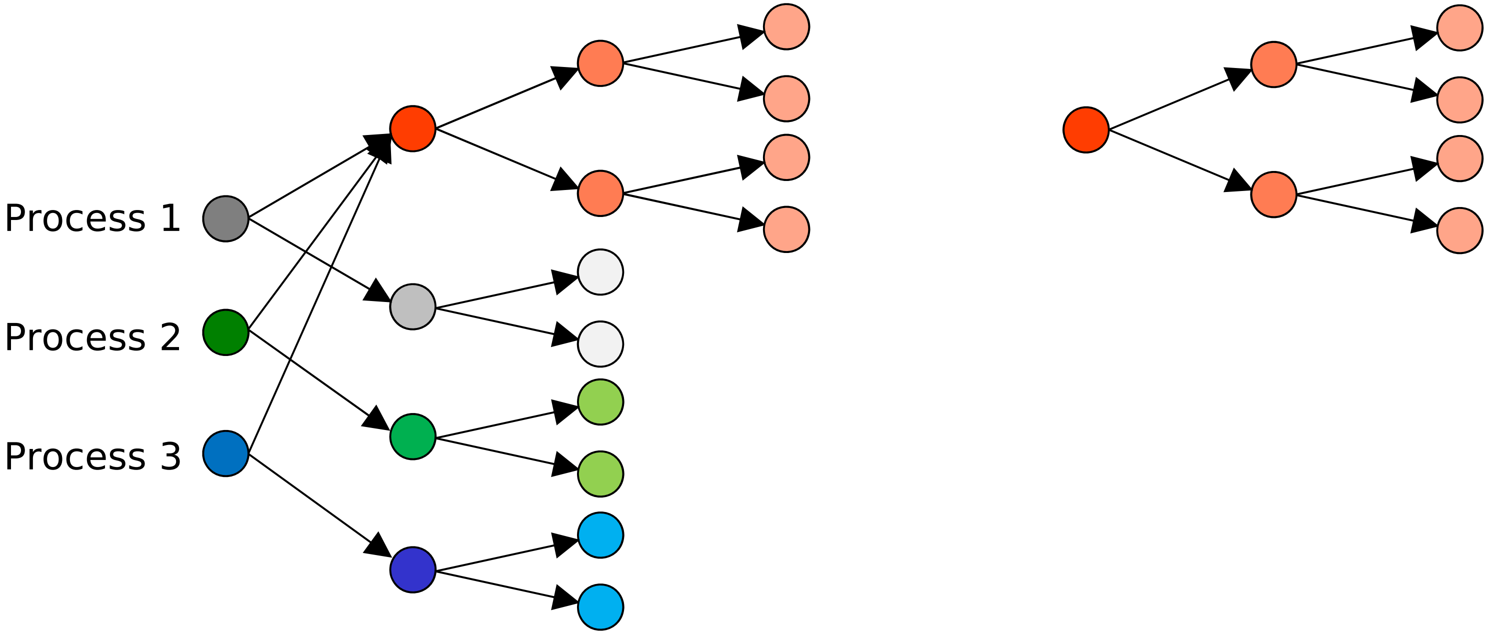
[[Example relations]]

[[Example couplings normalized to 1]]

General considerations (IV)

Can the process be factorized or simplified?

Whole tree needed? or is a leave sufficient



Rules

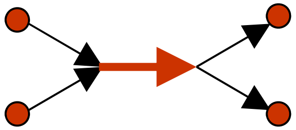
which rules/conditions can be used to formulate the model

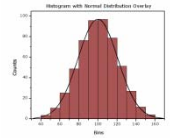
which rules/conditions have to be applied during the fit

e.g. what is fixed by definitions

Course of action

- Data Analysis
- Modelling
- Fitting
- Quality Assurance
- Review and Publication





Course of action (I)

Data analysis

Data

extract relevant data set(s) with appropriate statistics, high purity and high efficiency

MC

signal MC, may be mixed due to experimental conditions

Background

extract from data and/or generate via Monte Carlo data sets from potential background channels

Representation

represent the data in *n*-tupels of relevant (transformed?) observables for the fit and the visualization

Course of action (II)

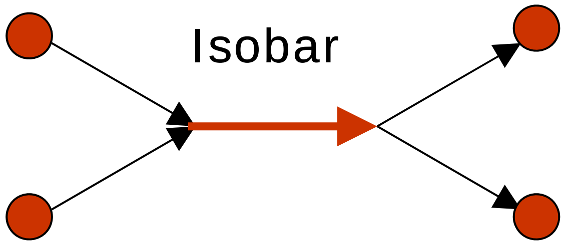
Modelling

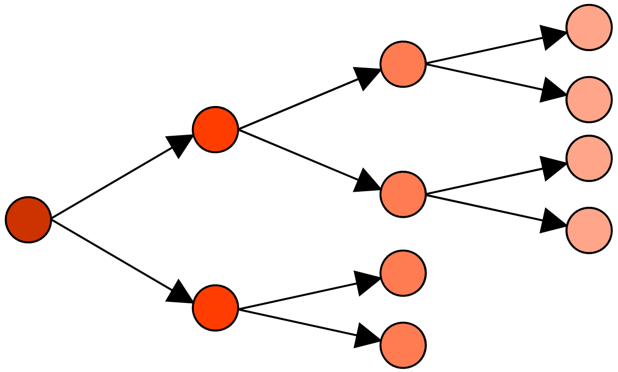
Data

Visual inspection of the data !!

Physics

create list of hypotheses (incl. production, spins, dynamics and if so, background)





Mathematics

optimize the mathematical form

may improve speed and may reduce numerical instabilities

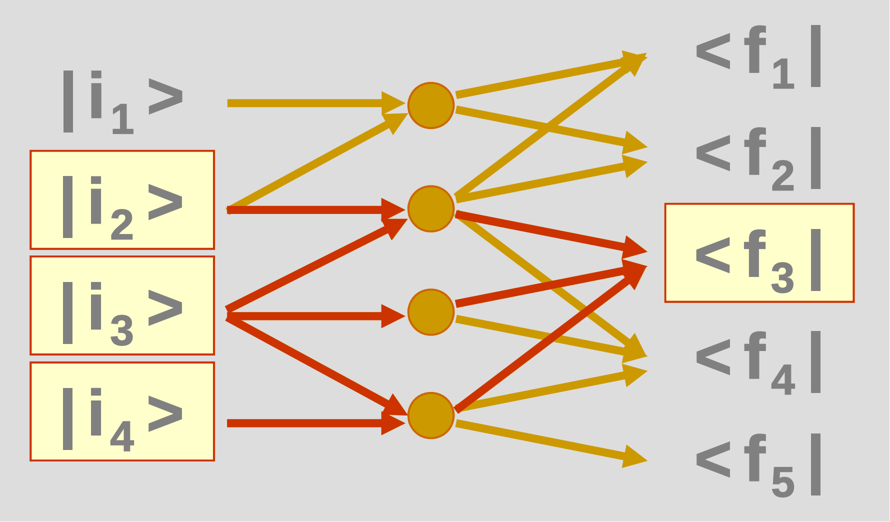
Reduced Amplitudes (I)

of parameters explodes with
increasing number of initial and final states

forget about the tree, reduce amplitude to the final state of interest

feed by many initial and several intermediate states

spin density matrix ρ_{mn}



Reduced Amplitudes (II)

Caveat:

Two channels may interfere in one tree,
but may not in another

thus measured rate I has different formalisms

Coherent

$$I=|A+e^{i\phi}B|^2 = |A|^2+|B|^2 +2[\mathrm{Re}(AB^*)\sin\varphi+\mathrm{Im}(AB^*)\cos\varphi]$$

Incoherent

$$I=|A|^2+|B|^2$$

Effective coherence

$$I=|A|^2+|B|^2 + C\,[\mathrm{Re}(AB^*)\sin\varphi +\mathrm{Im}(AB^*)\cos\varphi]$$

$(C=-2,\ldots,2)$

Course of action (III)

Fitting

fit model(s) to the data

likelihood definition, what is to be minimized

(max. Likelihood, Chi2,…)

needs a strategy to find the best solution

systematic studies for a variety of hypotheses

vary initial stats, resonances, parameterizations

need a strategy for each fit

optimizer (gradient/random/genetic)

sequence (different optimizers, fixation and release of parameters)

criteria for convergence and termination

Course of action (IV)

Quality Assurance

Documentation

excellent documentation! is the key

what was done? formulae!

(intermediate) results!

Validation

validation of the result (for example with toy MC)

Significance

scrutinize the significance of new findings

check various methods to investigate the goodness-of-fit

Errors

determination of statistical and systematic errors

Course of action (V)

Review and Publication

review

process which may lead to a reanalysis at various entry points

publication

publish only things you are confident about

there is an undefined border where

the experiment ends and the theoretical bias starts

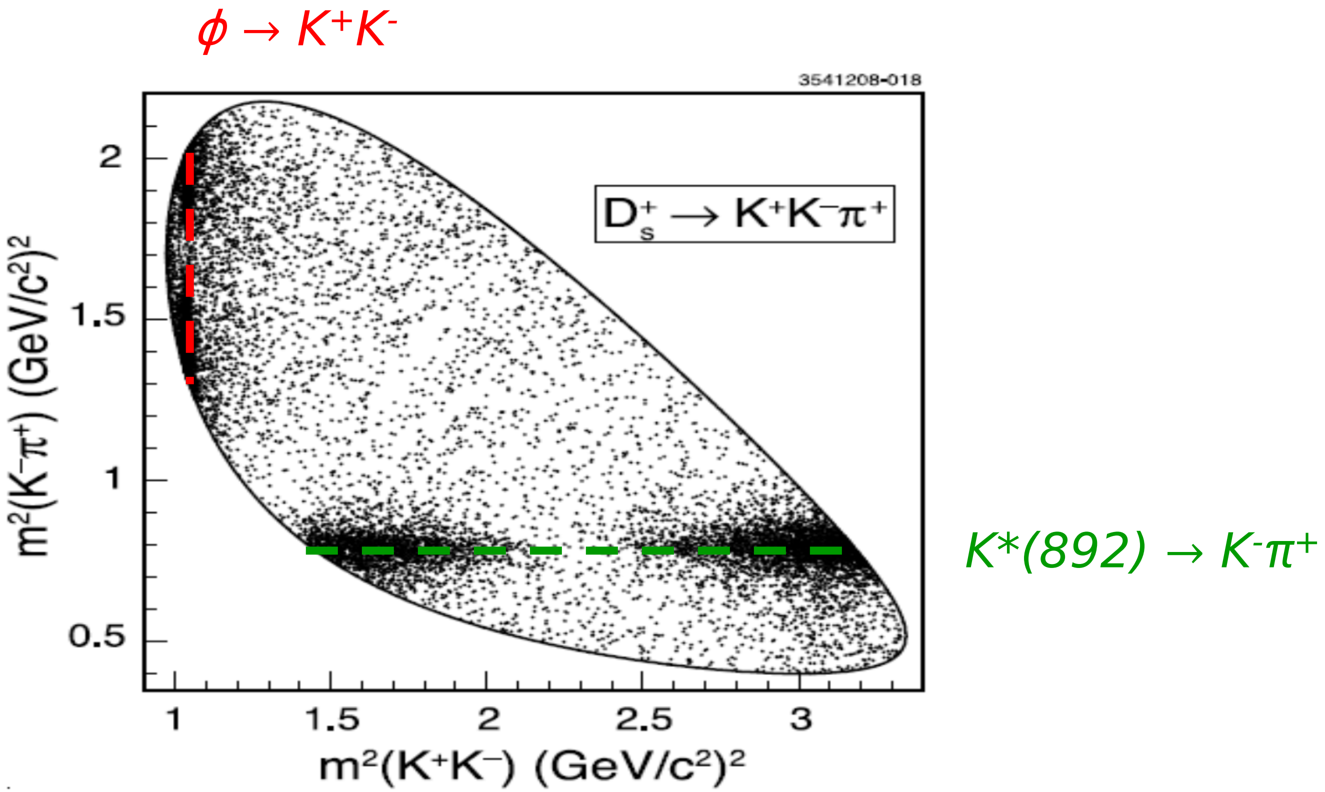
Phase space

visual inspection of the phase space distribution

are the structures?

structures from signal or background?

are there strong interferences, threshold effects, potential resonances?



Kinematical Reflections

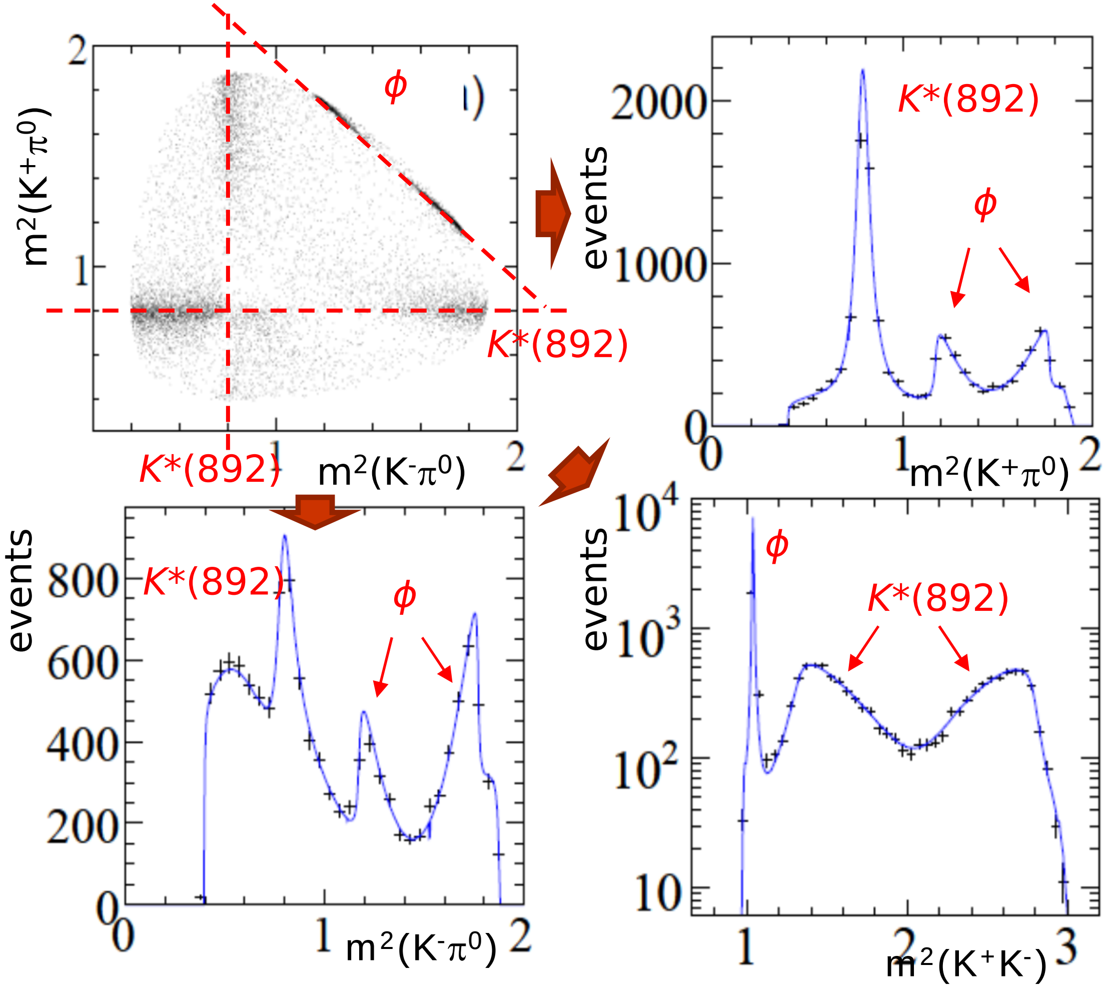
Kinematic situation can produce mass peaks not being true resonances ➔ called Reflections

Example:

Dalitz plot of

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

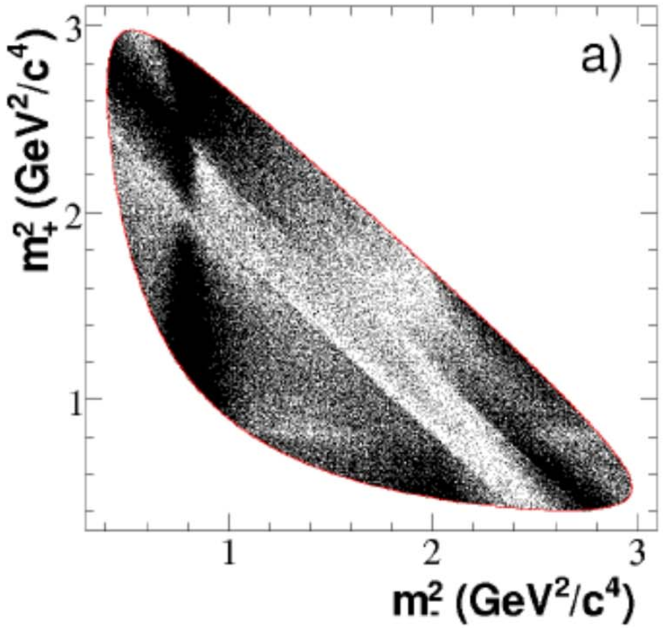
in this case „fakes“ are simple to spot...

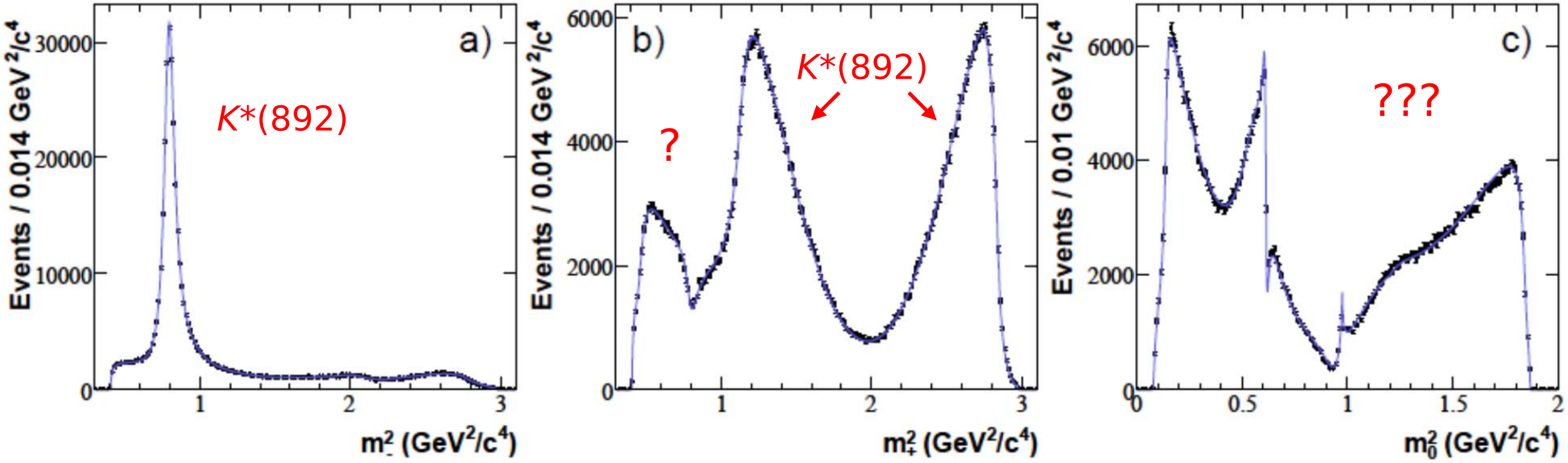


Kinematical Reflections, cont‘d

… but it can be much less obvious!

Example: $D_s^+ \rightarrow K_S^0 \pi^+ \pi^-$




K*(892)

?

K*(892)

???

Obervables

Observables should be aligned with the problem/process

is polarization relevant?

is dynamics present in all particle pairs?

are there isolated structures or regions with strong correlations?

Typical observables are

*m*² (*s*)

invariant mass square,

Mandelstam *s*

T

kinetic energy

cos*θ*

decay angle of

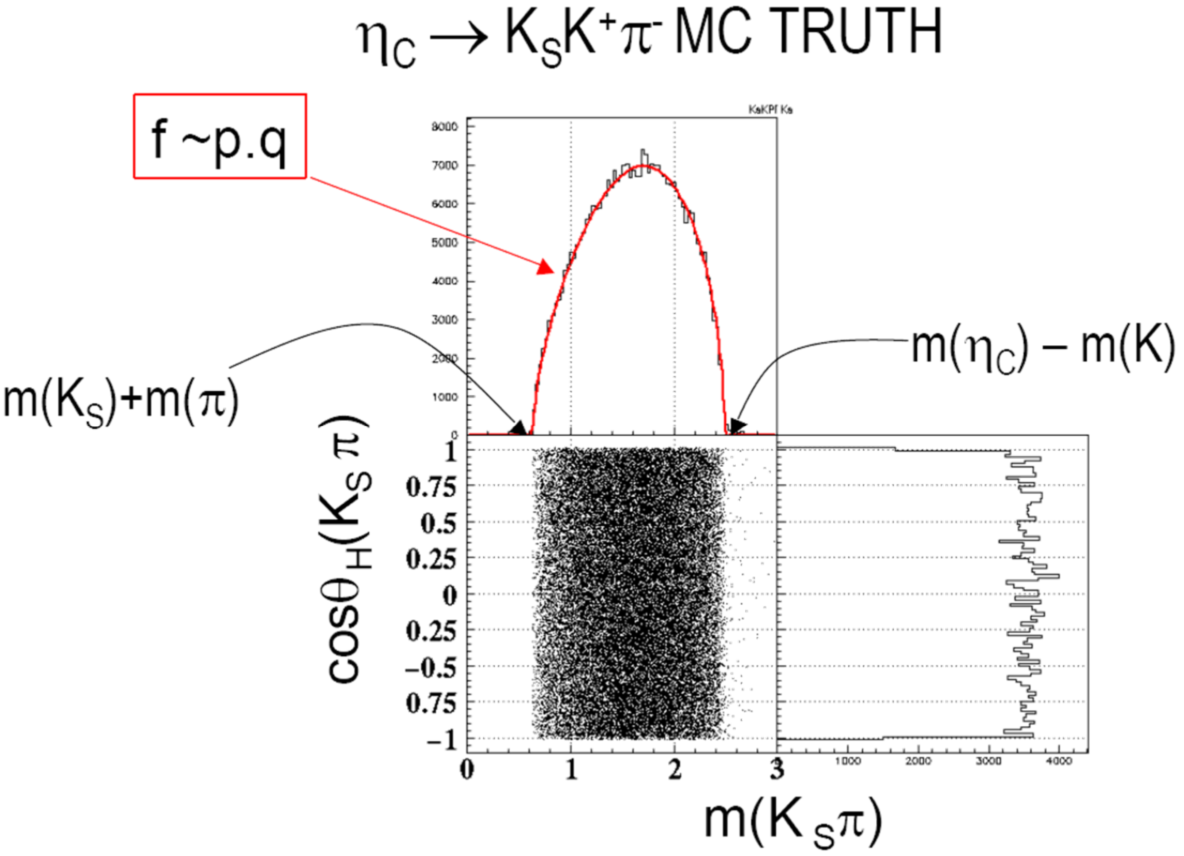
resonances

cos*ψ*

angle between

decay places,

….. a.m.o.m.



Observables, cont'd

are there symmetries in the phase space?

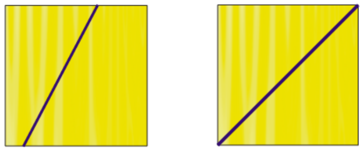
unique assignment of phase space coordinates
is important to avoid double counting

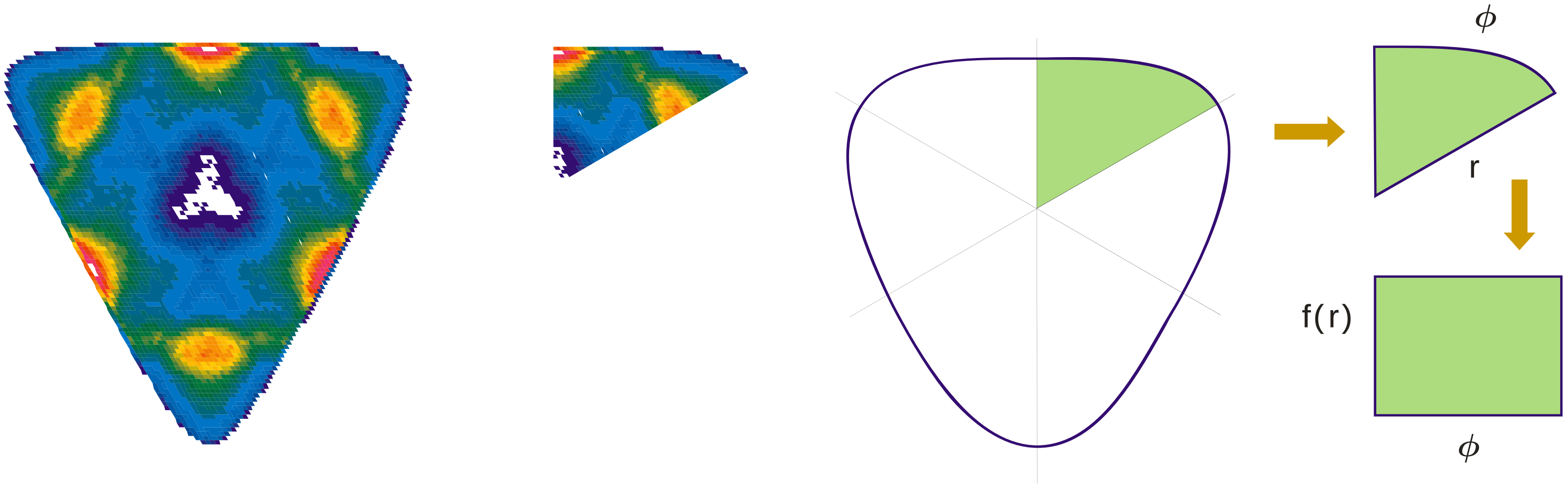
transformation necessary?

Most Dalitz plots are symmetric:

Problem: sharing of events

Possible solution: transform DP





Hypotheses

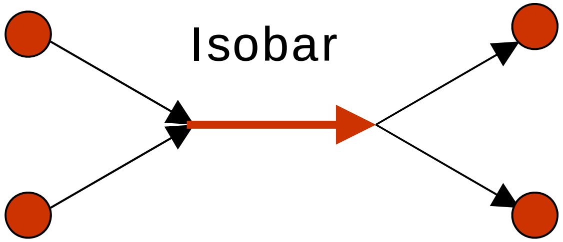
- Select basic model
  - usually isobar model, is not appropriate in all cases
  - rescattering, t-channel and Deck effects may lead to artifacts
- Select formalism to handle the spin
  - select basis (helicity reflectivity, canonical....)
  - or tensors (Zemach, covariant or Lorentz-invariant)
  - depends on the process and the goals
- Select set of dynamical functions
  - which resonances and thresholds are known
  - which do you guess from inspection
  - how much freedom is needed,
    how well do I know the processes involved
  - analysis of angular moments might be helpful as a start
- Selection of parameters and optimization

First results may indicate that the assumptions
are wrong and one has to start over

Isobar Model

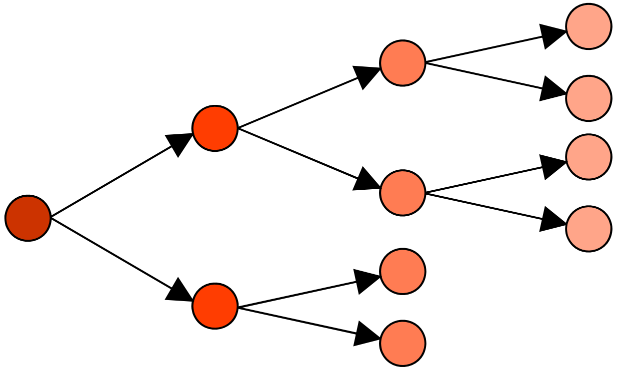
Generalization

- construct any many-body system as a tree of subsequent two-body decays
- the overall process is dominated by two-body processes
- the two-body systems behave identical in each reaction
- different initial states may interfere



We need

- need two-body "spin"-algebra
  - various formalisms
- need two-body scattering formalism
  - final state interaction, e.g. Breit-Wigner



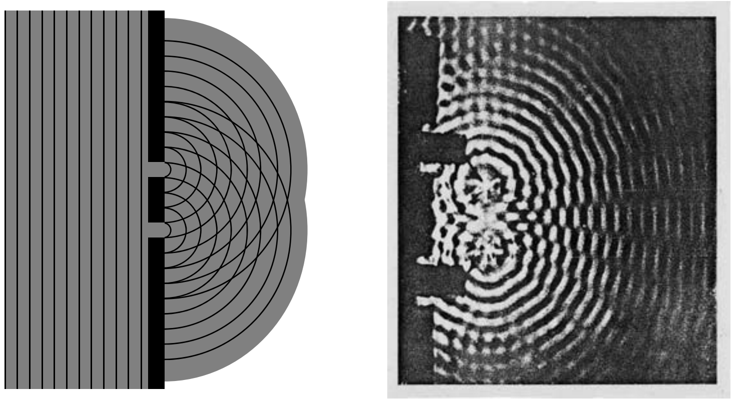
Interference problem

PWA

The phase space diagram in hadron physics shows a pattern due to interference and spin effects

This is the unbiased measurement

What has to be determined ?



Analogy Optics ⇔ PWA

\# lamps ⇔ # level

\# slits ⇔ # resonances

positions of slits ⇔ masses

sizes of slits ⇔ widths

but only if spins
are properly assigned

bias due to hypothetical
spin-parity assumption

Optics

$$I(x) = \left|A_1(x) + A_2(x)e^{\iota\varphi}\right|^2$$

Dalitz plot

$$I(m) = \left|A_1(m) + A_2(m)e^{\iota\varphi}\right|^2$$

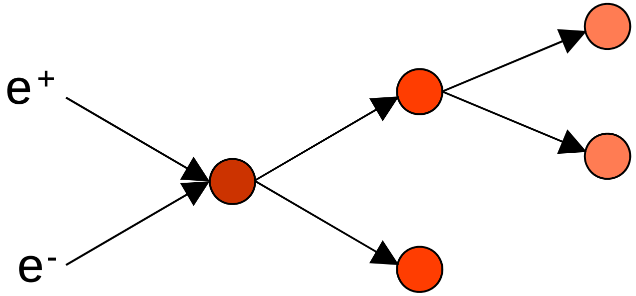
Use Cases #1 of 4: Hadron Decays

Reactions (examples)

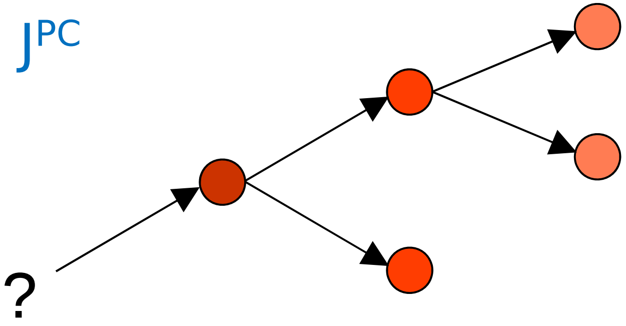
$J/\psi \rightarrow$ 3 hadrons (e.g. $\pi\pi\pi$)

$D_s \rightarrow$ 3 hadrons (e.g. $K\bar{K}\pi$)

Typical Graphs



Initial state has a well defined J^{PC}



J/ψ $J^{PC}= 1^{--}$

D_s $J^{PC}= 0^{-+}$

Focus/Mission/Goal

Properties of intermediate resonances (J^{PC}, mass, width, decay ratios)

spin-parity of the decaying particle

Typical Experiments

Tau-Charm Factories, B-Factories

Use Cases #1 of 4: Hadron Decays (cont’d)

Procedure

Formulate spin-dependent amplitude

using all available constraints

hadronics decays conserve P, weak decays don‘t

Formulate dynamics (resonance cocktail)

with guesses for the properties (if not sufficiently well known)

Fit the parameters of the model to the data

Repeat for various hypothesis and identify the „best solution“

Use Cases #2 of 4: $p\bar{p}$ annihilation

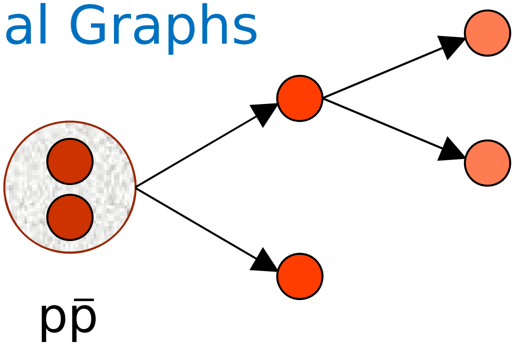
Reactions (examples)

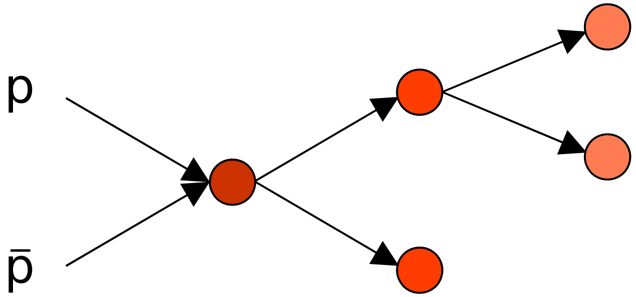
$p\bar{p}$ → 3 hadrons (at rest)

$p\bar{p}$ → 3 hadrons (in flight)

Initial state is a mixture of well defined J^{PC}'s

Typical Graphs





Focus/Mission/Goal

Properties of intermediate resonances (J^{PC}, mass, width, decay ratios)

Typical Experiments

Asterix and Crystal Barrel @ LEAR

Proton-Antiproton Annihilation @ Rest

Atomic initial system

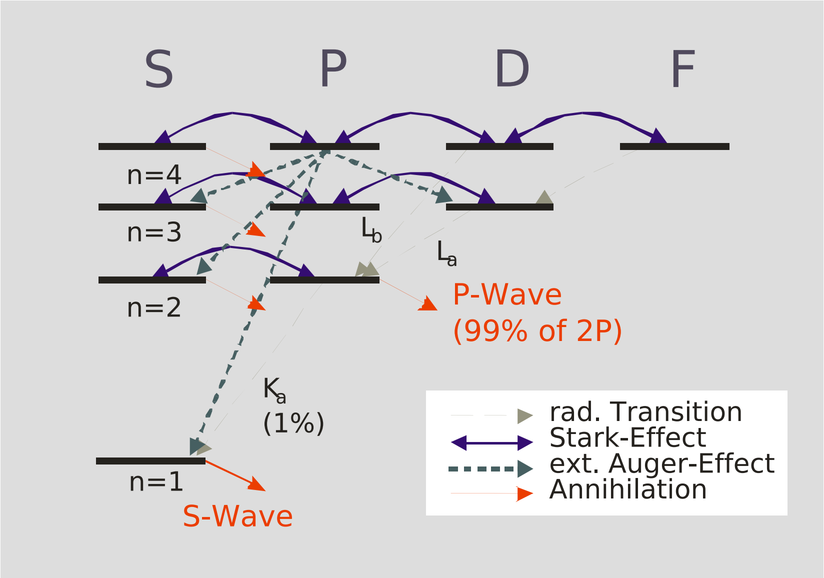
- formation at high *n, l* (*n*~30)
- slow radiative transitions
- de-excitation through collisions (Auger effect)
- Stark mixing of *l*-levels (Day, Snow, Sucher, 1960)

Advantages

- J^{PC} varies with target density
- isospin varies with n (d) or p target
- incoherent initial states
- unambiguous PWA possible

Disadvantages

- phase space very limited
- small kaon yield



	J^{PC}		I^G	L	S
$^1S_0$	0^{-+}	pseudo scalar	$1^-;0^+$	0	0
$^3S_1$	1^{--}	vector	$1^+;0^-$	0	1
$^1P_1$	1^{+-}	axial vector	$1^+;0^-$	1	0
$^3P_0$	0^{++}	scalar	$1^-;0^+$	1	1
$^3P_1$	1^{++}	axial vector	$1^-;0^+$	1	1
$^3P_2$	2^{++}	tensor	$1^-;0^+$	1	1

Use Cases #2 of 4: $p\bar{p}$ annihilation (cont’d)

Very similar to hadron decays for $p\bar{p}$ at rest

Procedure

Formulate spin-dependent amplitude

using all available constraints

but for a couple of possible initial states !

hadronics decays conserve P, weak decays don‘t

Formulate dynamics (resonance cocktail)

with guesses for the properties (if not sufficiently well known)

Fit the parameters of the model to the data

Repeat for various hypothesis and identify the „best solution“

Proton-Antiproton Annihilation in Flight

Annihilation in flight

- scattering process:
  no well defined initial state
- maximum angular momentum
  rises with energy

Advantages

- larger phase space
- formation experiments

Disadvantages

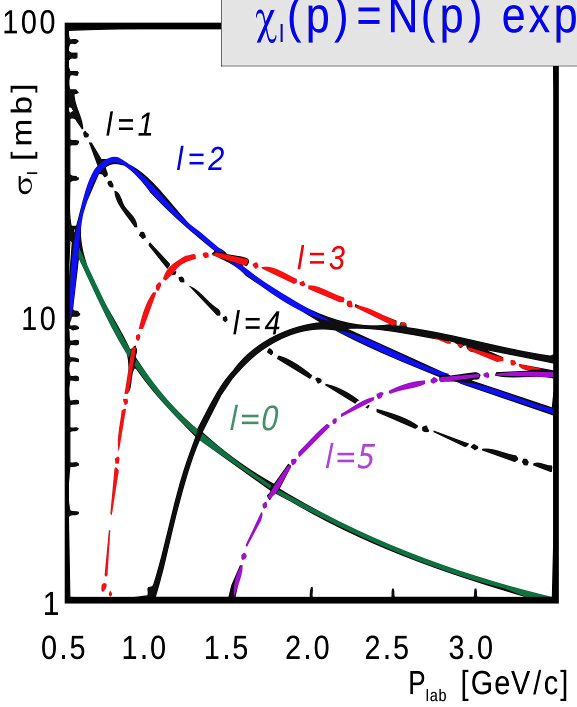
- many waves interfere
  with each other
- many waves due
  to large phase space

$$\sigma_{ann}=\Sigma_l\sigma_l$$

$$\sigma_l(p)=(2l+1)\ \pi\ [1-\exp(-\chi_l(p))]\ /\ p^2$$

$$\chi_l(p)=N(p)\ \exp(-3l(l+1)/4p^2R^2)$$

with $R^2=\langle r^2\rangle$ (Baryon)



ang. mom. l
$l \sim p_{cms}/0.2$ GeV/c

Scattering Amplitudes in p̄p in Flight (II)

$$H^J_{\nu_1\nu_2} = \sum_{L,S} \frac{\sqrt{2L+1}}{\sqrt{2J+1}} \left(L0S\nu\middle|J\nu\right)\left(s_1\nu_1 s_2 -\nu_2\middle|S\nu\right)\left(JMLS\middle|\mathrm{M}\middle|JM\right)$$

using all constraints leads to 4 incoherent sets of coherent amplitudes

Singlett even L	J^{PC}	L	S	H_{++}	H_{+-}
$^1S_0$	0^{-+}	0	0	Yes	No
$^1D_2$	2^{-+}	2	0	Yes	No
$^1G_4$	4^{-+}	4	0	Yes	No

Singlett odd L	J^{PC}	L	S	H_{++}	H_{+-}
$^1P_1$	1^{+-}	1	0	Yes	No
$^1F_3$	3^{+-}	3	0	Yes	No
$^1G_5$	5^{+-}	5	0	Yes	No

Triplett even L	J^{PC}	L	S	H_{++}	H_{+-}
$^3S_1$ ↕	1^{--}	0	1	Yes	Yes
$^3D_1$	1^{--}	2	1	Yes	Yes
$^3D_2$	2^{--}	2	1	Yes	Yes
$^3D_3$	3^{--}	2	1	Yes	Yes

Triplett odd L	J^{PC}	L	S	H_{++}	H_{+-}
$^3P_0$	0^{++}	1	1	Yes	No
$^3P_1$	1^{++}	1	1	No	Yes
$^3P_2$ ↕	2^{++}	1	1	Yes	Yes
$^3F_2$	2^{++}	3	1	Yes	No
$^3F_3$	3^{++}	3	1	No	Yes
$^3F_4$	4^{++}	3	1	Yes	Yes

and only 2 of them contribute to a particular exclusive final state

Use Cases #3 of 4: Diffractive Production

Reactions (examples)

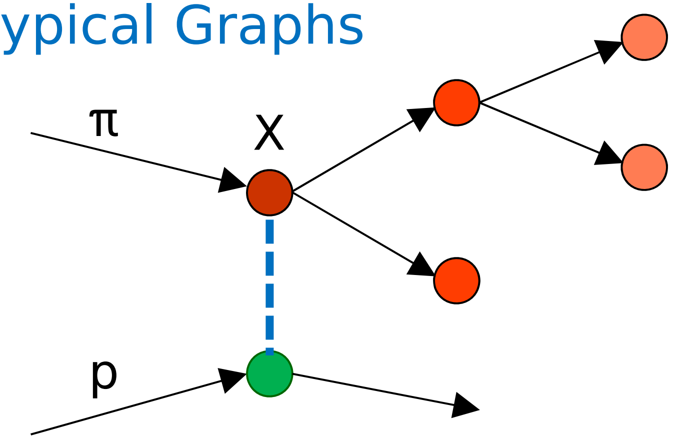
πp → 3 hadrons p,n

unknown initial state

scattering process

expressed in terms of moments

Typical Graphs



Focus/Mission/Goal

Properties of X (J^{PC}, mass, width, decay ratios)

Typical Experiments

E852 at AGS (BNL) or COMPASS at CERN

Use Cases #3 of 4: Diffr. Production (cont’d)

Procedure

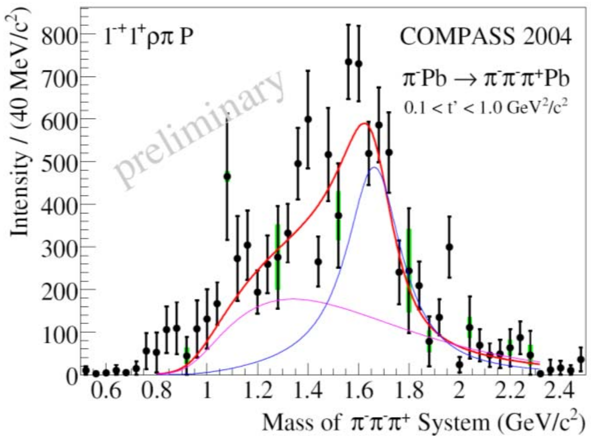
π^--beam and t-exchange produce X

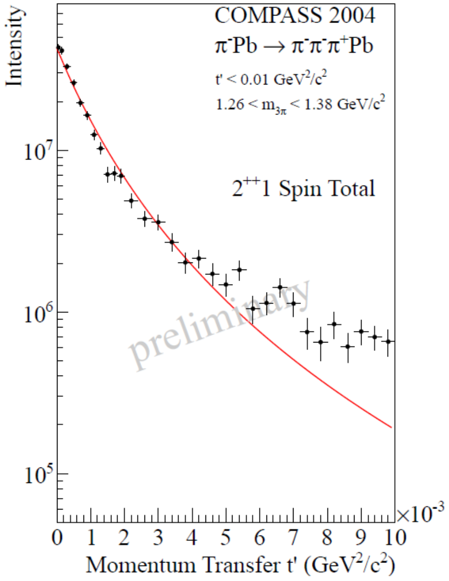
- Partitioning in bins of m(3π)
- Potentially also binning in t.

Wave ~$t^m e^{-bt}$ → background as function of t

Formulate spin-dependent amplitude and dynamics for the intermediate resonance cocktail

with best guesses for the properties





Mass dependent fits

performed for a fixed m(3pi) (and may be t) and all fits result in moments (and errors) per bin, which are then translated into wave content

The result of one slice is then input (start value) for the next slice to be fitted.

Use Cases #4 of 4: Photo-production

Reactions (examples)

γ p → 3 hadrons p,n

known initial states

scattering process

finally expressed in terms of moments

→ very similar to diffractive production for high energies and multi-hadron final states

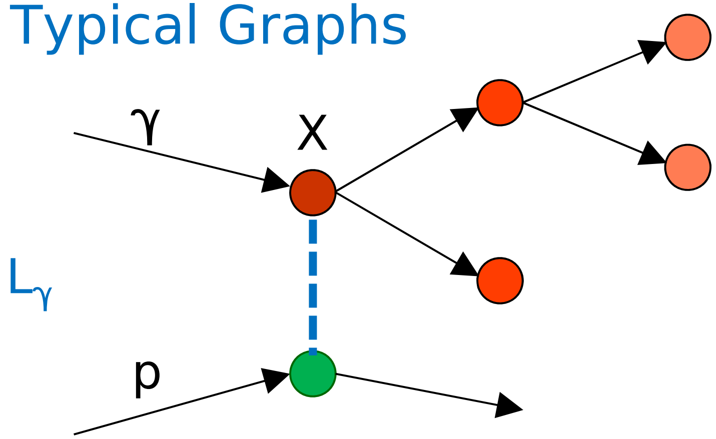
Focus/Mission/Goal

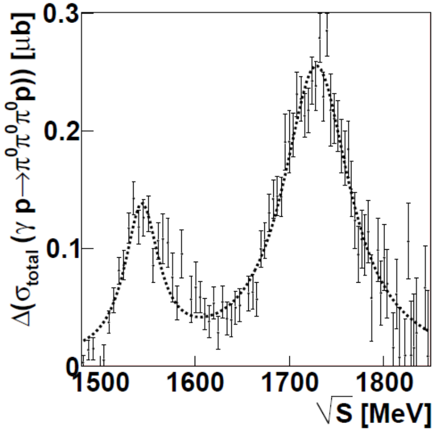
Properties of X (J^{PC}, mass, width, decay ratios)

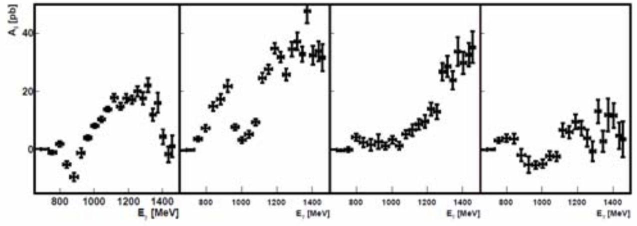
Typical Experiments

Crystal Barrel at ELSA or Gluex/Clas12 @ Jlab12

Typical Graphs



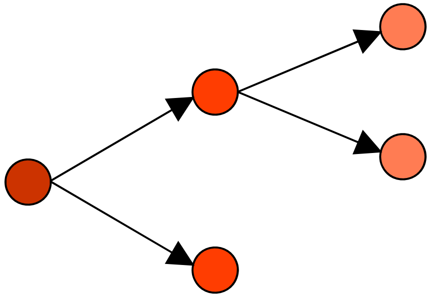




Summary

Use cases are different

There **IS** a common aspect



and for each decay we need a proper formulation in our model

and we always have to fit our model to the data

THANK YOU

for today