

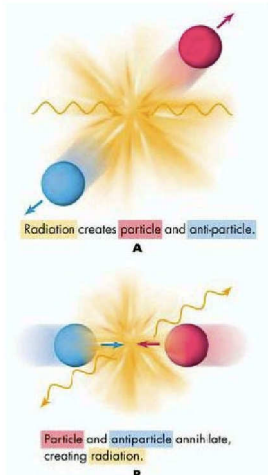
HOW TO MASTER LIGHT MESON DYNAMICS:

from hadron spectroscopy to CP phases

June 15, 2018 | Christoph Hanhart | IKP/IAS Forschungszentrum Jülich



MATTER EXCESS



In the early universe:

matter:antimatter as
1 000 000 001:1 000 000 000

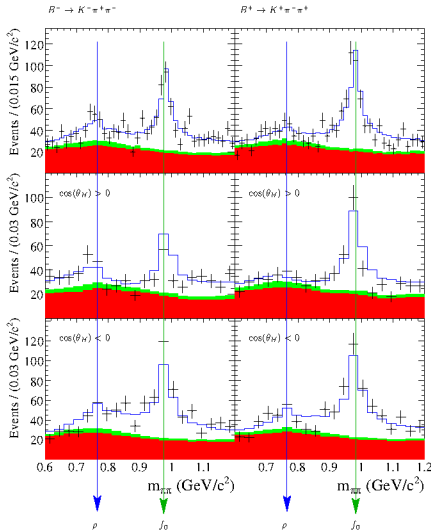
Problem: The Standard Model falls short by several orders of magnitude!

→ What is missing?

Look for the needle in the haystack



SENSITIVE OBSERVABLES



Here: $B^\pm \rightarrow K^\pm \pi^\mp \pi^\pm$

BABAR (2008); Belle (2006)

- 3.7σ in ρK
- 3.5σ in $f_2(1270)K$
- 1.8σ in $f_0(980)K$

Consistent with SM

Important next steps:

- Improve analysis and thus sensitivity
- Study D decays
→ SM prediction tiny



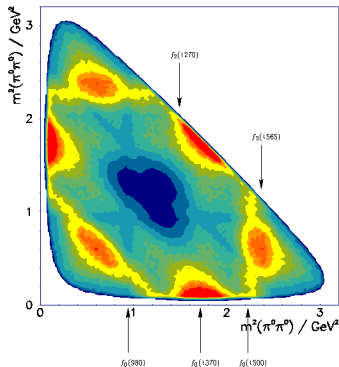
WHY DALITZ PLOTS?

CP violation shows up as a phase

⇒ most visible in environments with strong phase variation

Example Dalitz plot: $\bar{p}p \rightarrow 3\pi^0$ from Chrystal Barrel

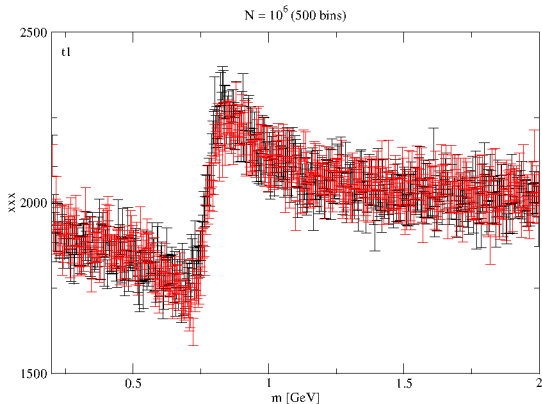
from Chrystal Barrel ($\bar{p}p$ at rest); download: <http://www-meg.phys.cmu.edu/cb/pi03.html>



ILLUSTRATION

Employing hadronic input drastically increases sensitivity!

$$N/\bar{N} = \alpha + \beta \operatorname{Re} \left\{ \exp(\pm i\delta_{CP}) \frac{1}{m^2 - M_{\text{res}}^2 + iM_{\text{res}}\Gamma_{\text{res}}} \right\}$$

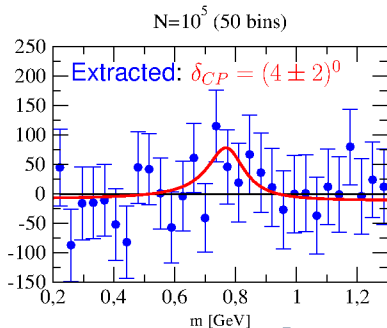
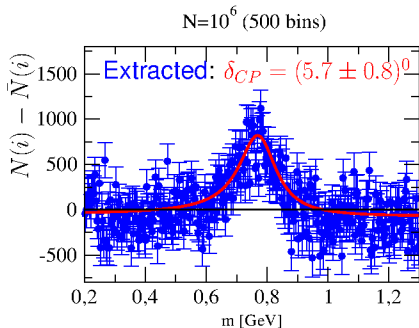


ILLUSTRATION

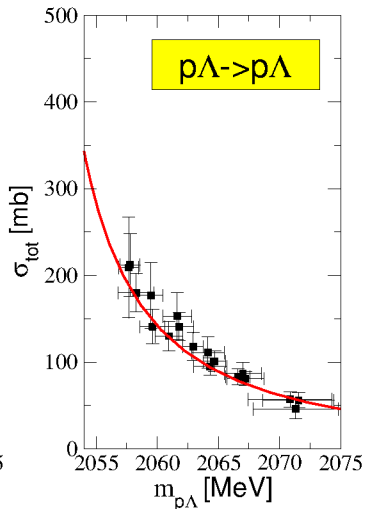
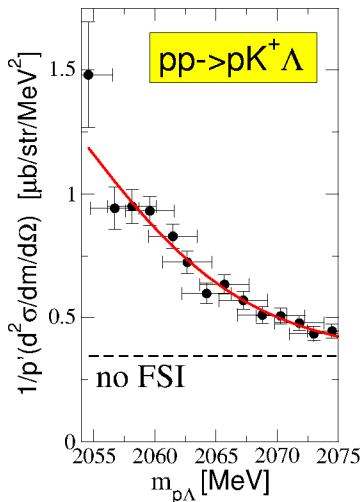
with this

$$N - \bar{N} = \delta_{CP} \times \left(\frac{2\beta M_{\text{res}} \Gamma_{\text{res}}}{(m^2 - M_{\text{res}}^2)^2 + (M_{\text{res}} \Gamma_{\text{res}})^2} \right) + \mathcal{O}(\delta_{CP}^2)$$

Input: $\delta_{CP} = 5^0$; $M_{\text{res}} = 0.77 \text{ GeV}$; $\Gamma_{\text{res}} = 0.15 \text{ GeV}$



PRODUCTION VS. SCATTERING



R. Siebert et al. (1994); G. Alexander et al. (1968)

In general: not identical, but related



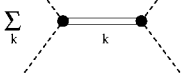
MODELING HADRON PHYSICS

Standard treatment: **sum of Breit-Wigners**

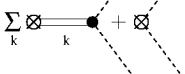
Propagator: $iG_k(s) = \text{diagram} = i/(s - M_k^2 + iM_k\Gamma_k)$



Scattering: $\sum_k \text{diagram} = \sum_k ig_k^2 G_k(s)$



Production: $\sum_k \text{diagram} + \text{diagram} = (\sum_k ig_k G_k(s)\alpha_k) + i\beta$



Problems:

- Wrong threshold behavior (cured by $\Gamma = \Gamma(s)$)
- Violates unitarity $\longrightarrow$ **wrong phase motion**
- Parameters reaction dependent
only pole positions and residues universal!



IMPOSING UNITARITY

- Properly constructed models fit to large sets of data

a la Bonn-Gatchina, J'ulich-Bonn, SAID

- or recent parametrization of near threshold cross sections

C.H. et al., PRL 115(2015)202001 and Guo et al. PRD93(2016)074031

- or **Dispersion Theory**: Starting point: Im-part of form factor F_i

$$\text{Im}(F_i) = \sum_k T_{ik}^* \sigma_k F_k \quad \rightarrow \text{Dispersion Integral}(s)$$

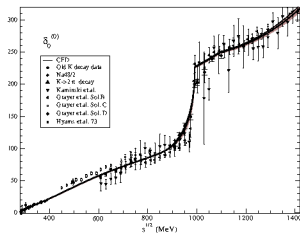
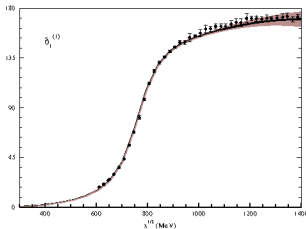
for **single channel** $\rightarrow$ **Watson theorem** and **Omnès function**

$$\Omega(s) = \exp \left(\frac{s}{\pi} \int_{4m_\pi^2}^{\infty} ds' \frac{\delta(s')}{s'(s' - s - i\epsilon)} \right) \quad \text{and} \quad F(s) = P(s)\Omega(s)$$

- $\Omega(s)$ is **universal and fixed** in elastic regime
- $P(s)$ **reaction specific** and contains e.g.
higher thresholds, inelastic resonances, left-hand cuts



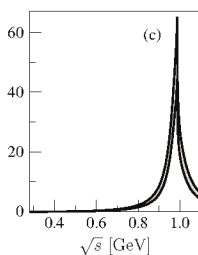
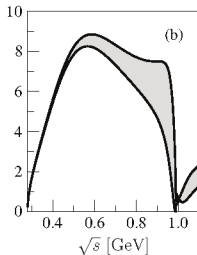
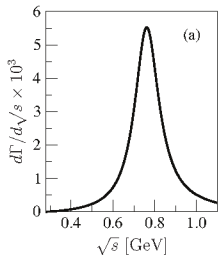
STATUS $\Omega(s)$: $\pi\pi$ S- AND P-WAVES



Give for $\tau \rightarrow \mu \pi \pi$ $\Omega_1^+(s)(p+p')^\mu = \langle \pi \pi | \bar{q} \gamma^\mu q | 0 \rangle$

$\Gamma_\pi^n(s) = \langle \pi \pi | \langle \bar{u}u + \bar{d}d \rangle / 2 | 0 \rangle$

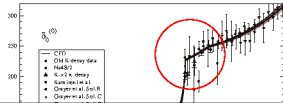
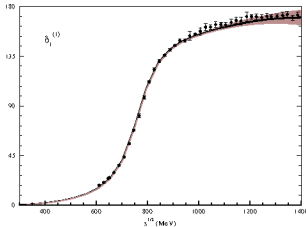
$\Gamma_\pi^S(s) = \langle \pi \pi | \bar{3}s | 0 \rangle$



δ : Garcia-Martin et al., PRD83(2011)074004; FF's: Daub et al., JHEP01(2013)179



STATUS $\Omega(s)$: $\pi\pi$ S- AND P-WAVES



Region of uncertainty - see also

Caprini et al., EPJC72(2012)1860

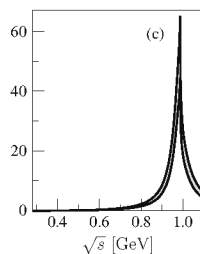
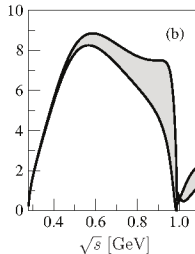
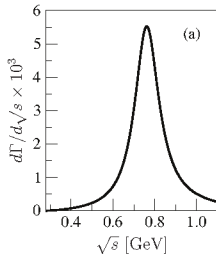
Büttiker et al., EPJC33(2004)409

Dai, Pennington, PRD90(2014)036004

Give for $\tau \rightarrow \mu \pi \pi$ $\Omega_1^+(s)(p+p')^\mu = \langle \pi \pi | \bar{q} \gamma^\mu q | 0 \rangle$

$\Gamma_\pi^\eta(s) = \langle \pi \pi | (\bar{u}u + \bar{d}d) / 2 | 0 \rangle$

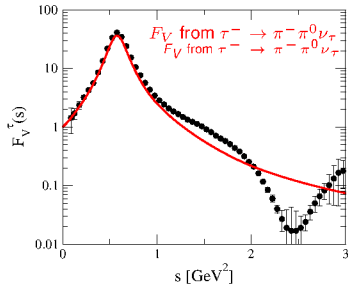
$\Gamma_\pi^S(s) = \langle \pi \pi | \bar{3}s | 0 \rangle$



δ : Garcia-Martin et al., PRD83(2011)074004; FF's: Daub et al., JHEP01(2013)179



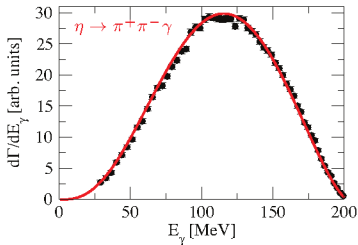
UNIVERSALITY OF FSI



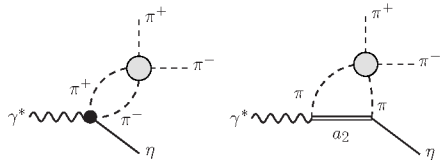
red lines: p-wave Omnes

× kinematic factors

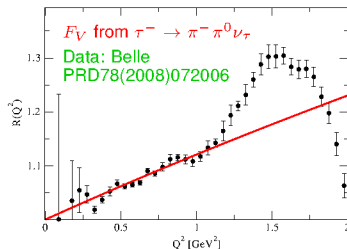
- bulk described properly
- there are deviations
 $\rightarrow P(s)$ not constant!



We need to add for η -decay:



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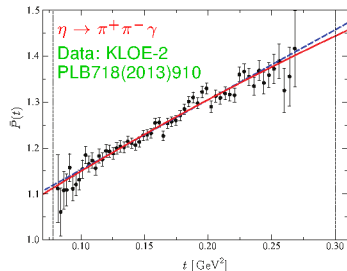


We write $F_V(Q^2) = R(Q^2)\Omega(Q^2)$

We find

- $R(Q^2)$ linear for $Q^2 < 1 \text{ GeV}^2$
- deviations by ρ' & ρ''

G.H. et al., EPJC73(2013)2668



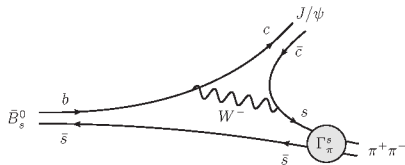
Inclusion of left-hand cut from
 $a_2(1320)$ for $\eta \rightarrow \pi \pi \gamma$

$$F_{a_2}(s_{\pi\pi}) = \Omega(s_{\pi\pi}) \left\{ A(1 + \alpha_{\Omega}[a_2] s_{\pi\pi}) + \frac{\cos \delta_1(s') \tilde{F}_{a_2}(s')}{|\Omega(s')|} + \frac{s_{\pi\pi}^2}{\pi} \int_{4m_\pi^2}^{\infty} \frac{ds'}{s'^2} \frac{\sin \delta_1(s') \tilde{F}_{a_2}(s')}{|\Omega(s')|(s' - s_{\pi\pi})} \right\},$$

Kubis and Plenter, EPJC75(2015)283



APPLICATION: $\bar{B}_{s/d}^0 \rightarrow J/\psi \pi \pi$



- $\bar{B}_s^0$: clean $\bar{s}s$ source
- $\bar{B}_d^0$: clean $\bar{d}d$ source
- $\pi J/\psi$ interactions negligible
→ no left-hand cuts

Ideal testing ground for formalism

e.g. for $\bar{B}^0$ -decay:

- phenomenological analysis: inclusion of BW-functions for $f_0(500)$, $\rho(770)$, $\omega(782) \rightarrow$ **14 parameters**
- dispersive approach for S - and P -waves $\rightarrow$ **3-4 parameters**
3 normalizations; eventually allowing for additional slope

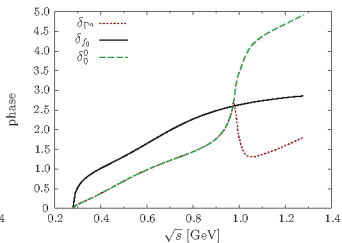
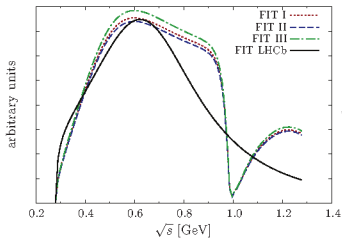
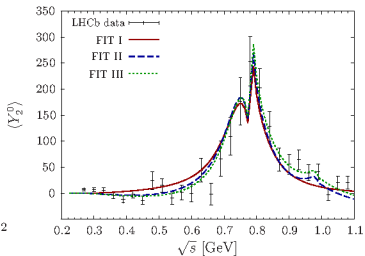
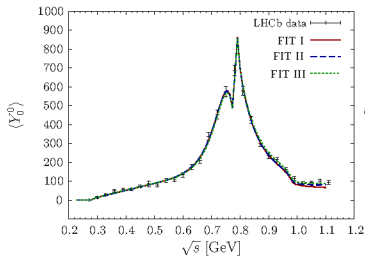
LHCb, PRD90(2014)012003

Daub, C.H., Kubis, JHEP1602(2016)009

→ Fits with even of higher quality and proper phase motion!



RESULTS FOR $\bar{B}^0 \rightarrow J/\psi \pi \pi$



RESULTS FOR $\bar{B}^0 \rightarrow J/\psi \pi \pi$

- The absence of the $f_0(980)$ in the LHCb fit was interpreted as incompatibility with tetraquark structure (at 8σ)

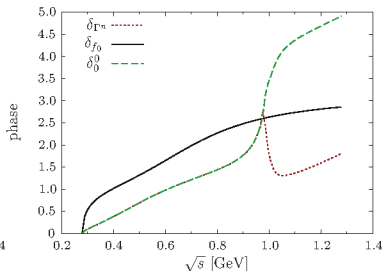
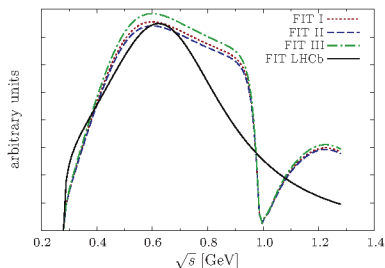
R. Aaij et al. (LHCb Collaboration) PRD90(2014)012003

- Re-analysis shows that this conclusion was premature

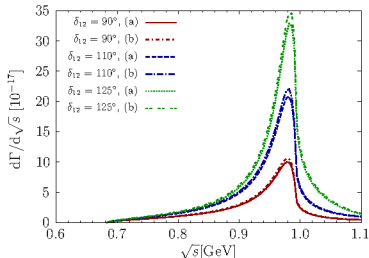
Daub, C.H., Kubis, JHEP1602(2016)009

- Light scalars consistent with two-meson states

For a review on had.-molecules: F. K. Guo et al., Rev. Mod. Phys. 90(2018)015004



OUTLOOK

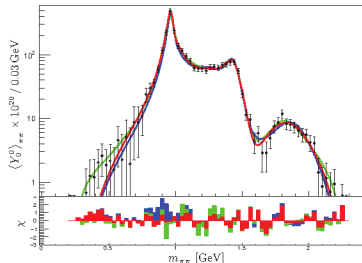


Data for $\bar{B}_d^0 \rightarrow J/\psi \pi \eta$ will allow one to **fix final uncertainty in $\eta\pi$ scattering phase shifts**

Albaladejo et al., JHEP1704(2017)010

employing

Albaladejo & Moussallam EPJC75(2015)488



Analysis of $B_s \rightarrow J/\psi \pi\pi$ extended to higher energies: shown fits **by LHCb, 2 res., 3 res.**

Ropertz et al., in preparation

Data: LHCb, PRD89(2014)092006

adapting formalism of

C.H., PLB715(2012)170



SUMMARY

- **States** are characterized by their **pole positions and residues**
- **Breit-Wigner** fits should in general be **avoided**
- Where ever possible **phase information** should be employed
 - either via **dispersion theory**

for other examples see, e.g.,

$\gamma\gamma \rightarrow \pi\pi$: Hoferichter et al. 2011, Moussallam 2011, Mao et al. 2009, Pennington et al. 2008

$\omega/\phi \rightarrow \pi\pi\pi$: Niecknig, Kubis, Schneider 2012, Danilkin et al. (2015)

- or via **models consistent with analyticity and unitarity**

coupled channel analyses for πN , $\pi\pi N$, γN a la Bonn-Gatchina, Jülich-Bonn, SAID

The theoretical tools are becoming available to

- **extract the hadron spectrum** from data in a controlled way
- treat hadronic **final state interactions rigorously**
- **hunt for physics beyond the Standard Model**

