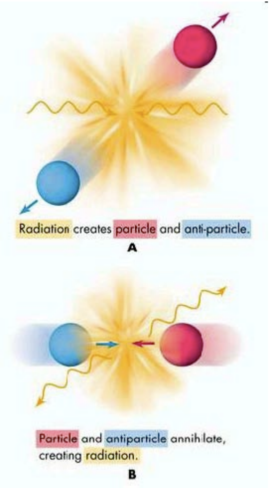
HOW TO MASTER LIGHT MESON DYNAMICS:

from hadron spectroscopy to CP phases

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

MATTER EXCESS



In the early universe:

matter:antimatter as

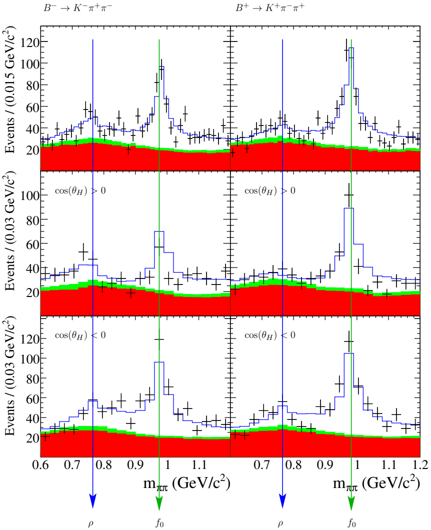
1 000 000 001:1 000 000 000

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

$\longrightarrow$ What is missing?

Look for the needle in the haystack

SENSITIVE OBSERVABLES



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

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
  $\longrightarrow$ SM prediction tiny

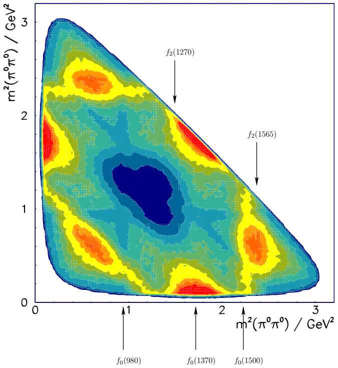
WHY DALITZ PLOTS?

CP violation shows up as a phase

$\Longrightarrow$ most visible in enviroments with strong phase variation

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

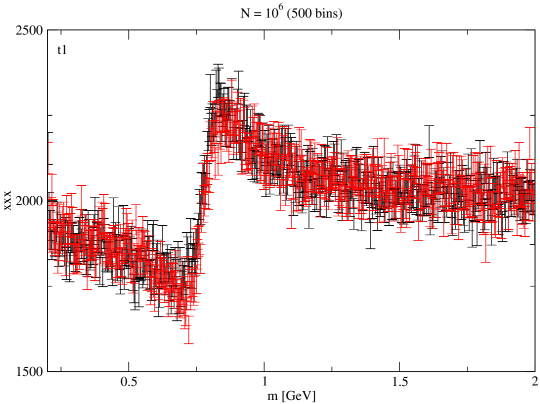
from Chrystal Barrel ($\bar{p}p$ at rest); download: http://www-meg.phys.cmu.edu/cb/pi03.html



ILLUSTRATION

Employing hadronic input drastically increases sensitivity!

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

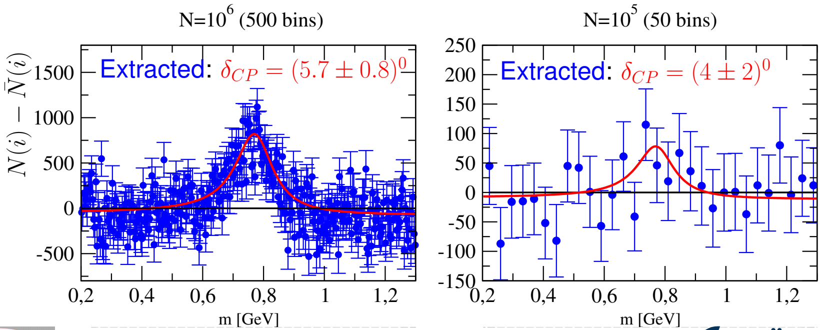


ILLUSTRATION

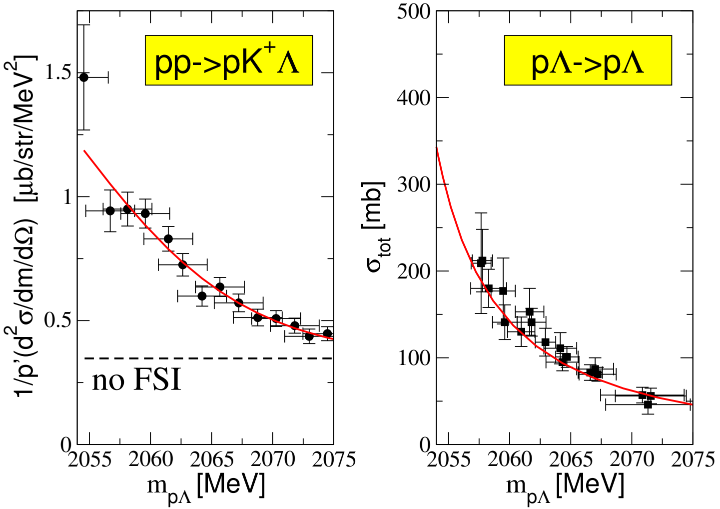
with this

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

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



PRODUCTION VS. SCATTERING



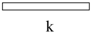
R. Siebert et al. (1994); G. Alexander et al. (1968)

In general: not identical, but related

MODELING HADRON PHYSICS

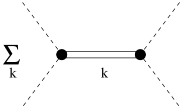
Standard treatment: sum of Breit-Wigners

Propagator: $iG_k(s) =$



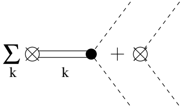
$= i/(s - M_k^2 + iM_k\Gamma_k)$

Scattering:



$= \sum_k ig_k^2 G_k(s)$

Production:



$= (\sum_k ig_k G_k(s)\alpha_k) + i\beta$

Problems:

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

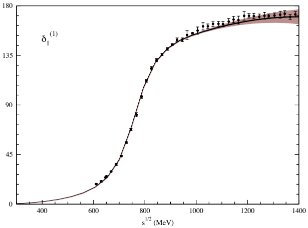
$$\mathrm{Im}(F_i) = \sum_k T_{ik}^* \sigma_k F_k \quad \to \text{Dispersion Integral(s)}$$

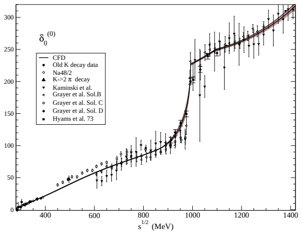
for single channel $\to$ Watson theorem and Omnès function

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

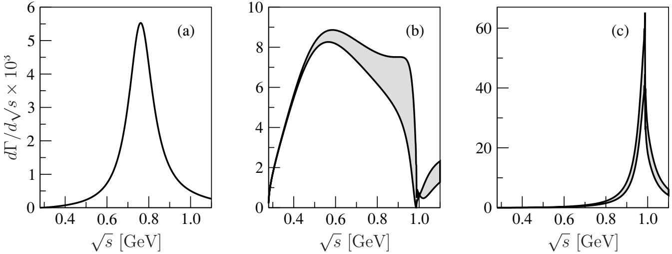
- $\Omega(s)$ is universal and fixed in elastic regime
- $P(s)$ reaction specific and contains e.g.
  higher thresholds, inelastic resonances, left-hand cuts

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



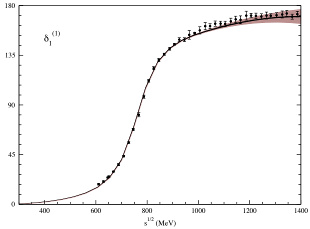


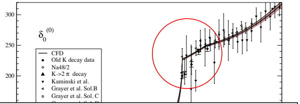
Give for $\tau \to \mu\pi\pi$ $\Omega_1^1(s)(p+p')^\mu = \langle\pi\pi|\bar{q}\gamma^\mu q|0\rangle$ $\Gamma_\pi^n(s) = \langle\pi\pi|(\bar{u}u+\bar{d}d)/2|0\rangle$ $\Gamma_\pi^s(s) = \langle\pi\pi|\bar{s}s|0\rangle$



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





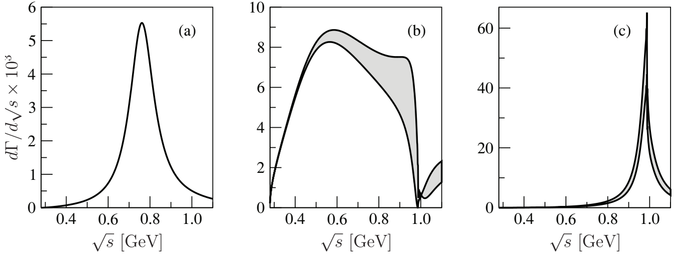
Region of uncertainty - see also

Caprini et al., EPJC72(2012)1860

Büttiker et al., EPJC33(2004)409

Dai, Pennington, PRD90(2014)036004

Give for $\tau \to \mu\pi\pi$ $\Omega_1^1(s)(p+p')^\mu = \langle\pi\pi|\bar{q}\gamma^\mu q|0\rangle$ $\Gamma_\pi^n(s) = \langle\pi\pi|(\bar{u}u+\bar{d}d)/2|0\rangle$ $\Gamma_\pi^s(s) = \langle\pi\pi|\bar{s}s|0\rangle$



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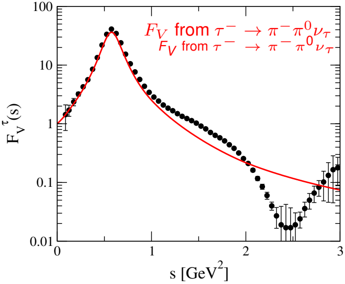
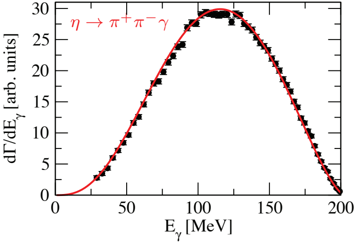
UNIVERSALITY OF FSI

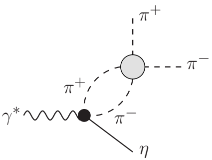


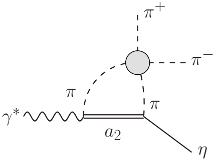
red lines: p-wave Omnes
$\times$ kinematic factors

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



We need to add for η-decay:





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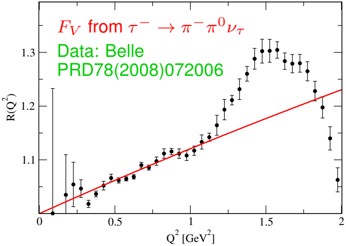
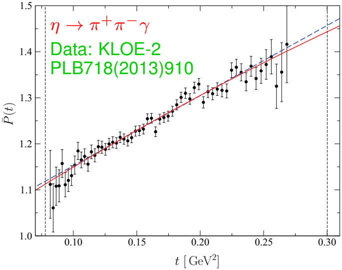


We write $F_V(Q^2) = R(Q^2)\Omega(Q^2)$

We find

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

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



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

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

Kubis and Plenter, EPJC75(2015)283

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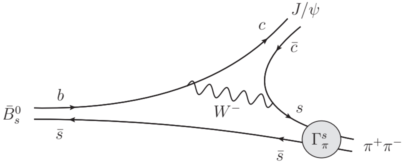
APPLICATION: $\bar{B}^0_{s/d} \to J/\psi\pi\pi$



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

Ideal testing ground for formalism

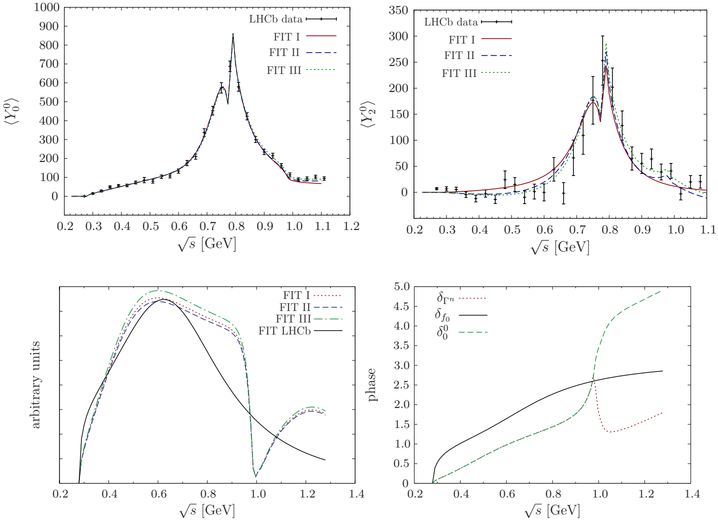
e.g. for $\bar{B}^0$-decay:

- phenomenological analysis: inclusion of BW-functions for
  $f_0(500)$, $\rho(770)$, $\omega(782)$ $\to$ 14 parameters   LHCb, PRD90(2014)012003
- dispersive approach for S- and P-waves $\to$ 3-4 parameters
  3 normalizations; eventually allowing for additional slope

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

$\to$ Fits with even of higher quality and proper phase motion!

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



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

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

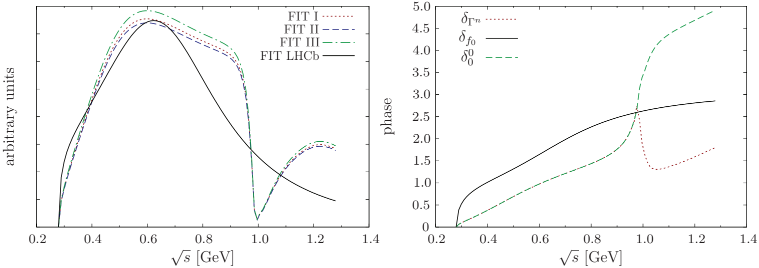
R. Aaij et al. (LHCb Collaboration) PRD90(2014)012003

- Re-analysis shows that this conclusion was premature

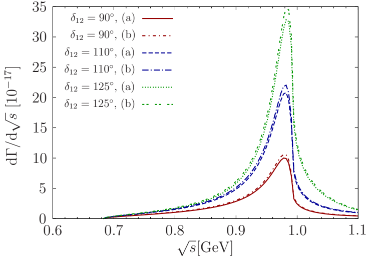
Daub, C.H., Kubis, JHEP1602(2016)009

- 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

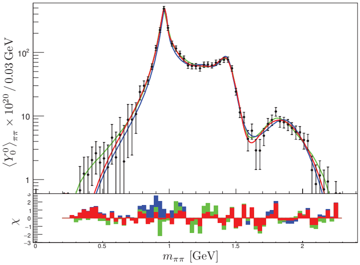


Data for $\bar{B}_d^0 \to J/\psi\pi\eta$ will allow one to fix final uncertainty in $\eta\pi$ scattering phase shifts

Albaladejo et al.,JHEP1704(2017)010

employing

Albaladejo & Moussallam EPJC75(2015)488



Analysis of $B_s \to J/\psi\pi\pi$ 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.,

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

    $\omega/\phi \to \pi\pi\pi$: 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