Amplitude Analysis of D Decays into Three Hadrons in the LHCb Experiment

Fernanda Abrantes, Sandra Amato, Juan Baptista, Carla Göbel, Erica Polycarpo, Alberto Reis

UFRJ CBPF PUC RIO

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Outline

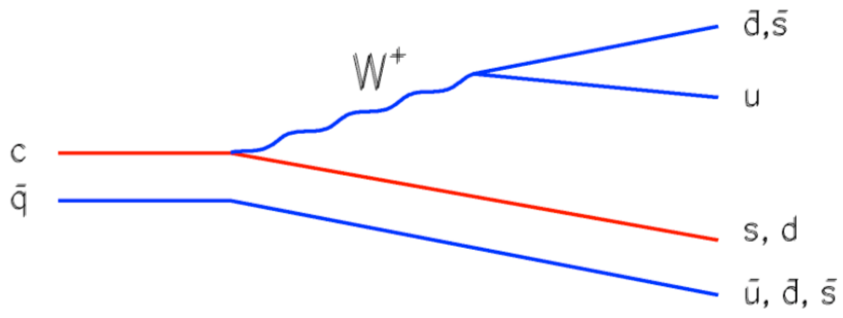
- Introduction: Three-body decays
- Decay Amplitude: Basic Concepts
- Ongoing analyses
- Conclusions and Perspectives

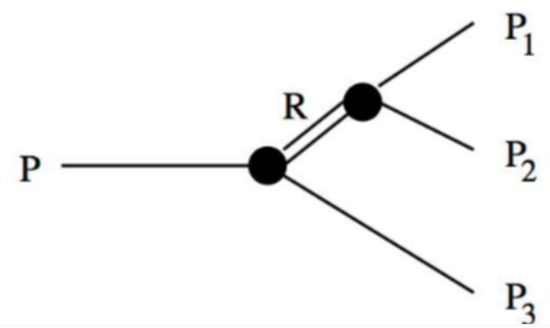
Introduction

Introduction

- D-mesons decaying weakly to hadrons lie in a semi-perturbative/non-perturbative QCD regime
- Three body decay usually treated as quasi-2-body processes
- Resonances produced very often together with the weak process

$$c \to (s, d)\, q\, \bar{q}$$





$$P \to RP_3 \to (P_1P_2)P_3$$

- Dynamics studied through its Dalitz Plot - contains all information

Described by the independent variables (invariants)

$$S_{12} = m_{12}^2 = (p_1 + p_2)^2$$
$$S_{13} = m_{13}^2 = (p_1 + p_3)^2$$

Decay Rate:

$$\frac{d\Gamma}{ds_{12}\, ds_{13}} = \frac{1}{(2\pi)^3 32 M^3} |\mathcal{A}|^2$$

Introduction

- Dalitz Plot has been a fundamental tool to study the dynamics of decay processes
- Provides important information of hadronic processes, such as:
    - Revealing and understanding resonances in different final states
    - Study the dynamics of the scalar sector (not well understood)
    - Search and Study of CP violation in the charm sector

This work presents the status of our ongoing analyses with RUN1 data from the LHCb

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

$D^+_{(s)} \rightarrow \pi^-\pi^+\pi^+$

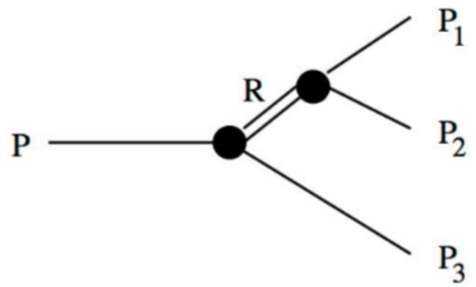
$D^+ \rightarrow K^-K^+K^+$

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

Decay Amplitude: Basic Concepts

Decay Amplitude

Traditional approach: Isobar Model $D \to h_1^- h_2^+ h_3^+$



For each resonant sub-channel:

$$\mathcal{A}_i = F_D F_R \times \mathcal{M}_i^J \times BW_i$$

form factors — angular function — resonance propagator

$$\mathcal{A}(P \to RP_3 \to (P_1P_2)P_3) = \mathcal{A}(P \to RP_3) \times BW_{R,12} \times \mathcal{A}(R \to P_1P_2)$$
$$= F_D F_R (-2|\vec{p_1}||\vec{p_3}|)^J P_J(cos\theta_{13}) \times BW_{R,12}$$

Coherent sum of each individual resonance amplitude

$$\mathcal{A} = a_{nr} e^{i\delta_{nr}} + \sum_j a_j e^{i\delta_j} \mathcal{A}_j$$

δ_j : accommodate weak and strong phases

a_j : magnitude of each mode

Amplitude Analyses Challenges

Isobar model may provide a good description under limited conditions:

- ★ When the resonances are relatively narrow and not overlapping
  - usually not the case for $K\pi$ and $\pi\pi$ S-waves where many broad resonant states coexist at energies below 2GeV
- ★ When analyzing data without "not so high" statistics
  - Not the case for the current huge amount of charm decays at LHCb!

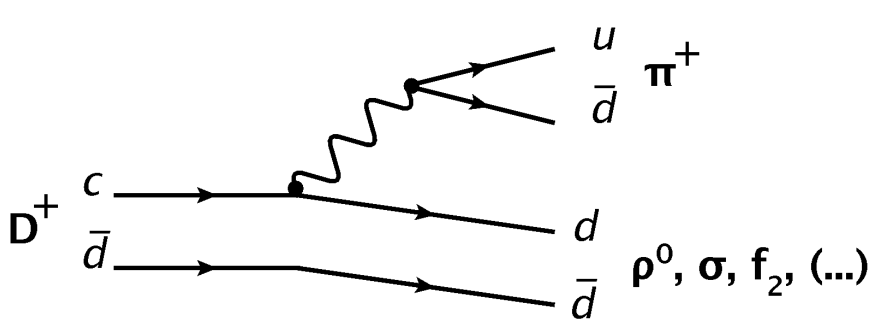
Goal: better description of decay processes

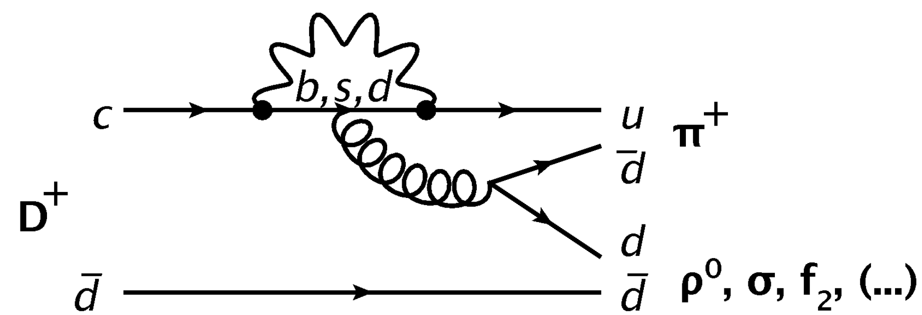
- Challenges: semi-perturbative/non-perturbative processes for charm decays
- How to handle the broad S-wave states
- Final state interactions

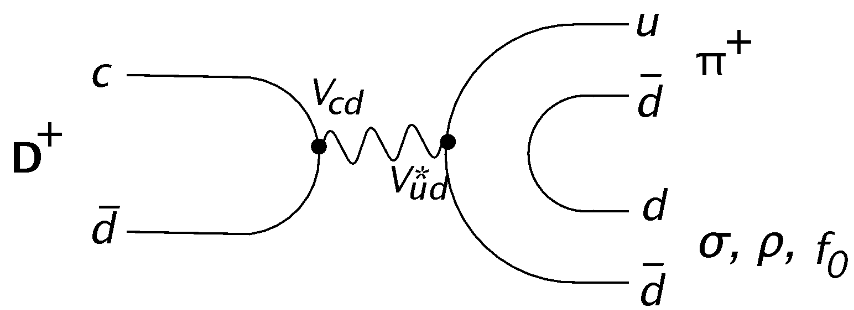
Ongoing analyses

$D^+ \to \pi^-\pi^+\pi^+$ Amplitude Analysis

Cabibbo-suppressed decay

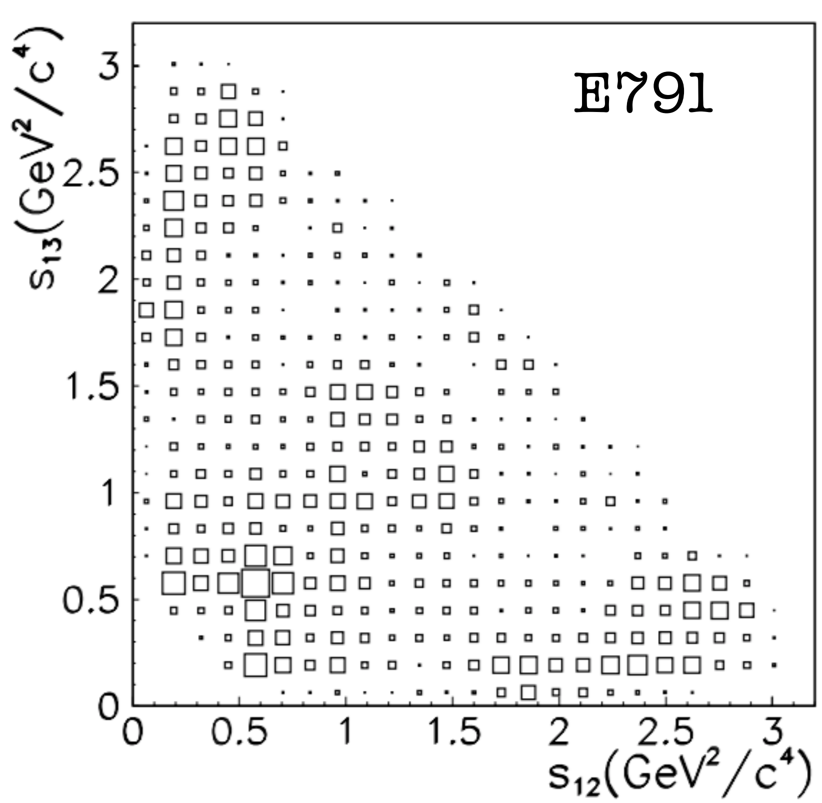




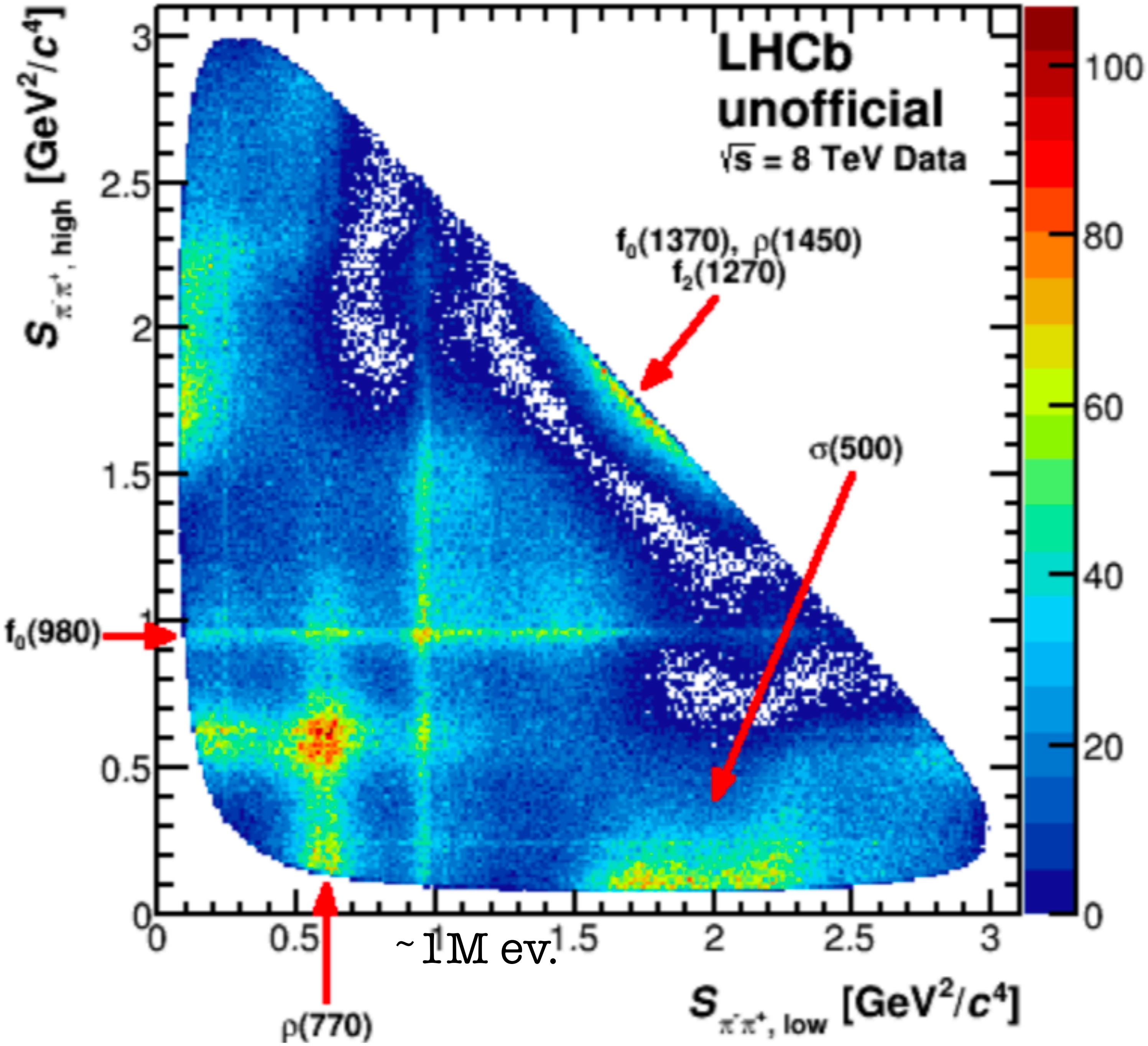


- Previous Dalitz analyses has shown important contribution of ππ S-wave
- σ (500) seen for the first time in decays by E791 with BW parametrization
- Focus parametrized using K-matrix PLB 585 (2004) 200
- Complicated structure of the S-wave: better formulation needed

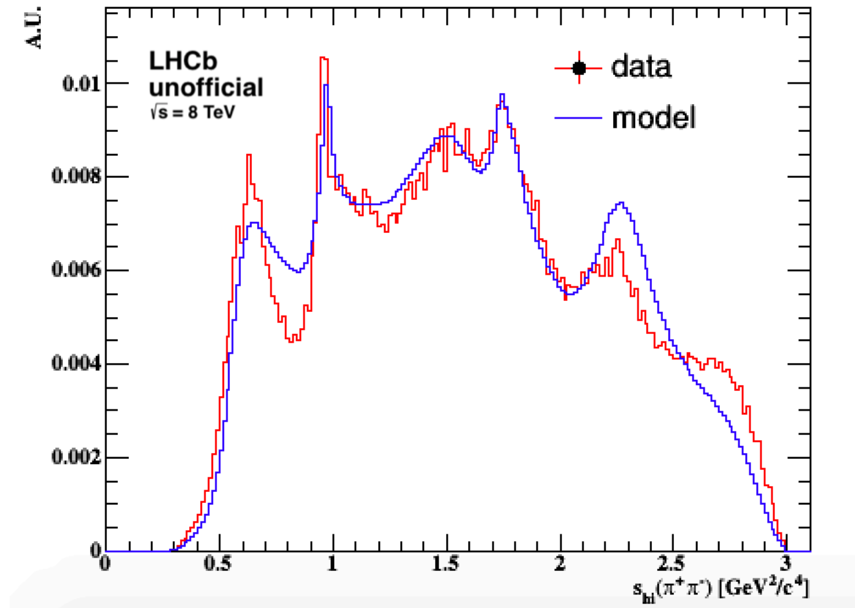
PRL 86 (2001) 770

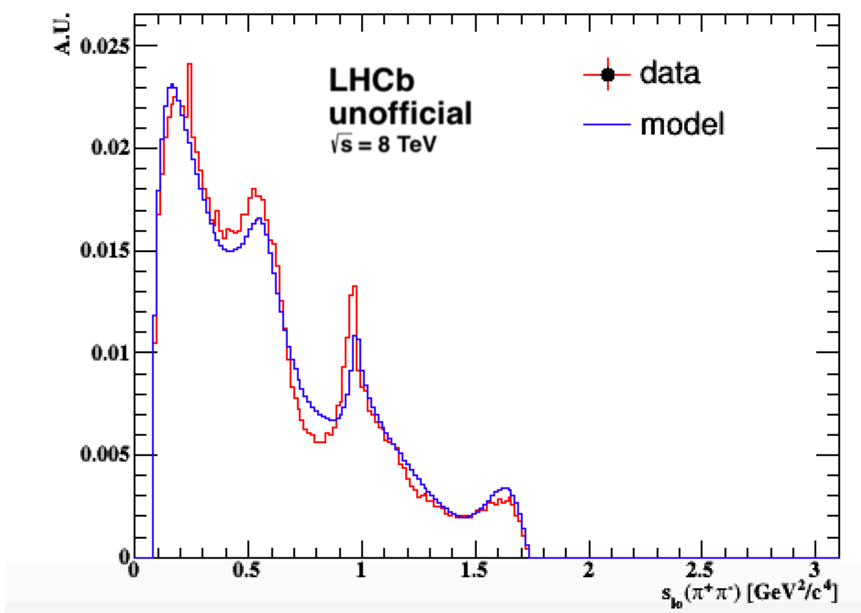


$D^+ \to \pi^-\pi^+\pi^+$ Amplitude Analysis



Model: $f_0(980)$, σ, ρ (770) GS
$f_2(1270)$, $f_0(1500)$,NR, ρ(1450)





- ★Over 1M events with high purity
- ★Many interest features seen by eye
- ★ρ-ω mixing
- ★Challenging analysis

- Isobar really limited here
- Other approaches must be taken in account!

$D^+ \longrightarrow \pi^-\pi^+\pi^+$ Amplitude Analysis

Perspectives:

PWA

$$\mathcal{S} = s(\sqrt{s_{ij}}) \times \mathcal{M}_0^J(p^*, p_0^*) F_D(q^*, r_D, 0)$$

- Sum of partial waves , truncated at the D-wave
- ππ mass spectrum divided into n-1 slices
- parameterized by an interpolation between the n endpoints in the complex plane

$$\mathcal{A}_{S-wave}(m_{\pi^+\pi^-}) = c_i e^{i\phi_i}_{i=1,\dots,n}$$

K-matrix

Dynamics is dominated by two-body processes, meaning that the S-wave does not interact with the rest of the products in the final state

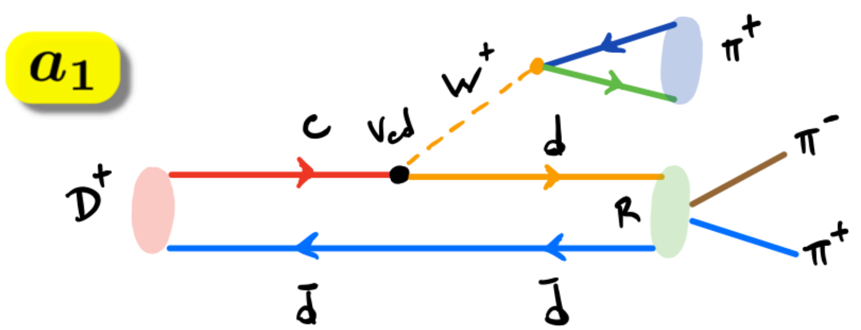
$$\hat{K}^{-1} = \hat{T}^{-1} + i\rho \longrightarrow \mathcal{F}_u = \sum_{v=1}^{n} [I - i\hat{K}\rho]^{-1}_{uv} . \hat{P}_v$$

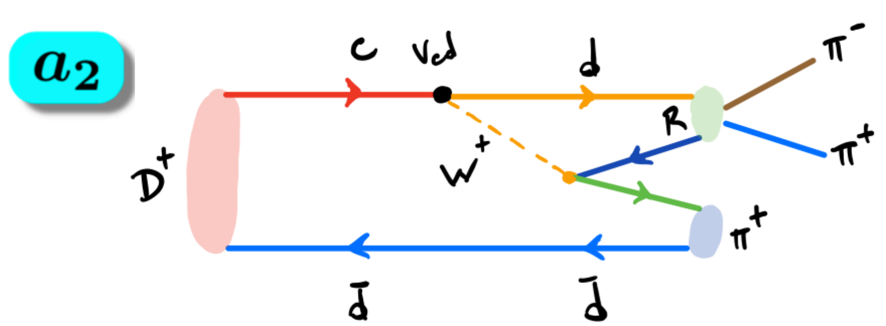
$$\mathcal{F}_1 = \sum_{\alpha=1}^{N} \mathcal{A}_\alpha + \sum_{v=1}^{n} \mathcal{A}_{SVP,v}$$

$$\mathcal{A}_\alpha(s) = \frac{\beta_\alpha}{m_\alpha^2 - s} \sum_{v=1}^{n} [I - i\hat{K}\rho]^{-1}_{1v} g_v^{(\alpha)}$$

$$\mathcal{A}_{SVP,v}(s) = \frac{m_0^2 - s_0^{prod}}{s - s_0^{prod}} [I - i\hat{K}\rho]^{-1}_{1v} f_v^{prod}$$

Factorization





$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM} C_i(\mu) \hat{O}_i$$

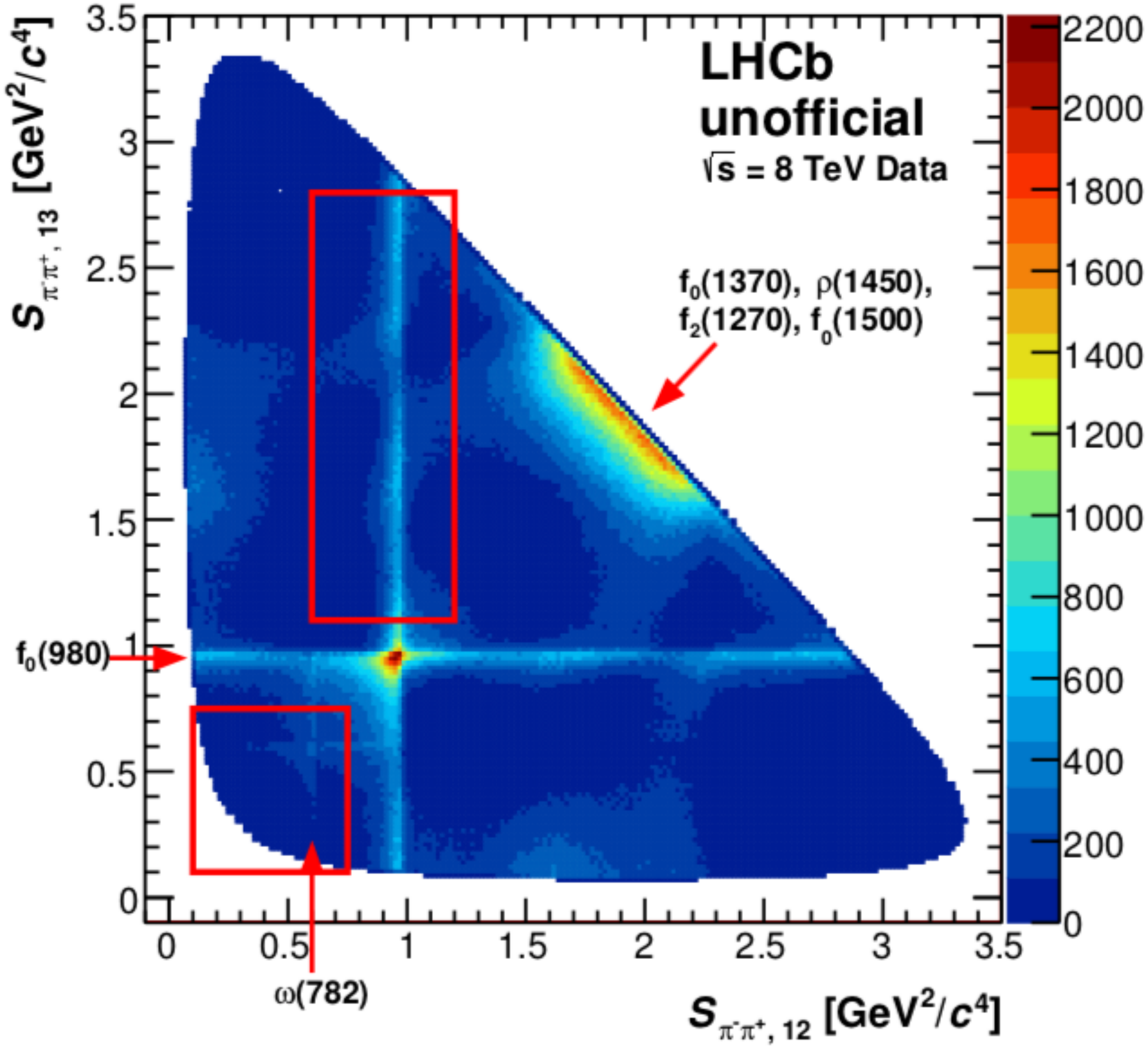
$$\hat{O}_1 = \bar{s}\gamma_\mu(1-\gamma_5)c\,\bar{u}\gamma_\mu(1-\gamma_5)d$$

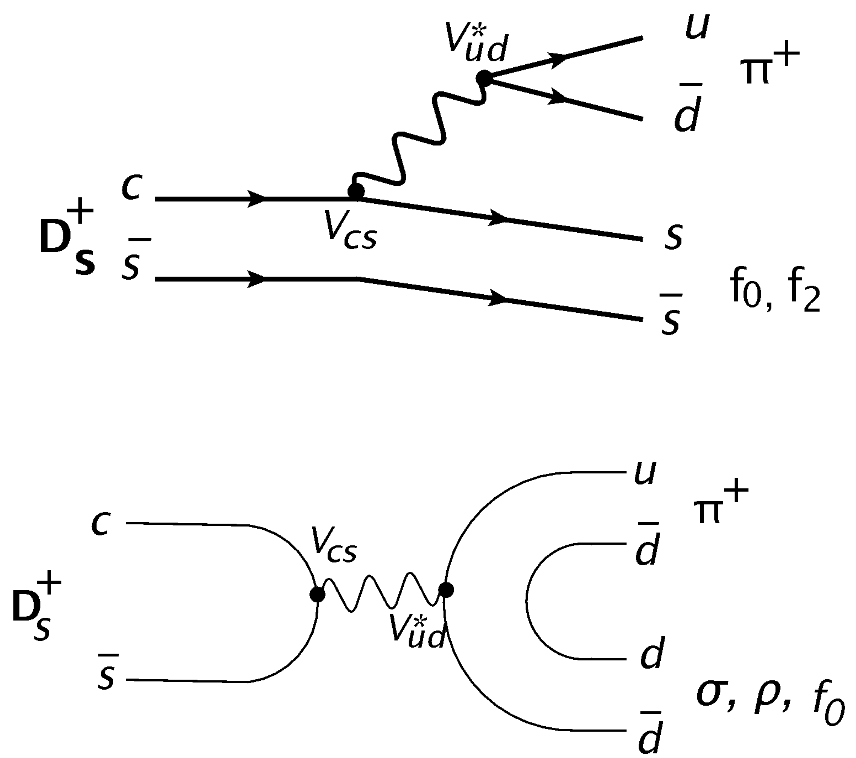
$$\langle \pi^-\pi^+\pi^+ | \mathcal{H}_{eff} | D^+ \rangle = \frac{G_F}{\sqrt{2}} V_{cd} V_{ud}^* (a_1 A_1 + a_2 A_2) = \frac{G_F}{\sqrt{2}} V_{cd} V_{ud}^* (a_1 \langle \pi^-\pi^+ | \bar{d}\gamma^\mu(1-\gamma_5)c | D^+ \rangle \langle \pi^+ | \bar{u}\gamma_\mu(1-\gamma_5)d | 0 \rangle$$

$$+ a_2 \langle \pi^-\pi^+ | \bar{d}\gamma_\mu(1-\gamma_5)d | 0 \rangle \langle \pi^+ | \bar{u}\gamma^\mu(1-\gamma_5)c | D^+ \rangle$$

Boito et al. PRD 96, 113003 (2017)

$D^+_s \longrightarrow \pi^-\pi^+\pi^+$ Amplitude Analysis

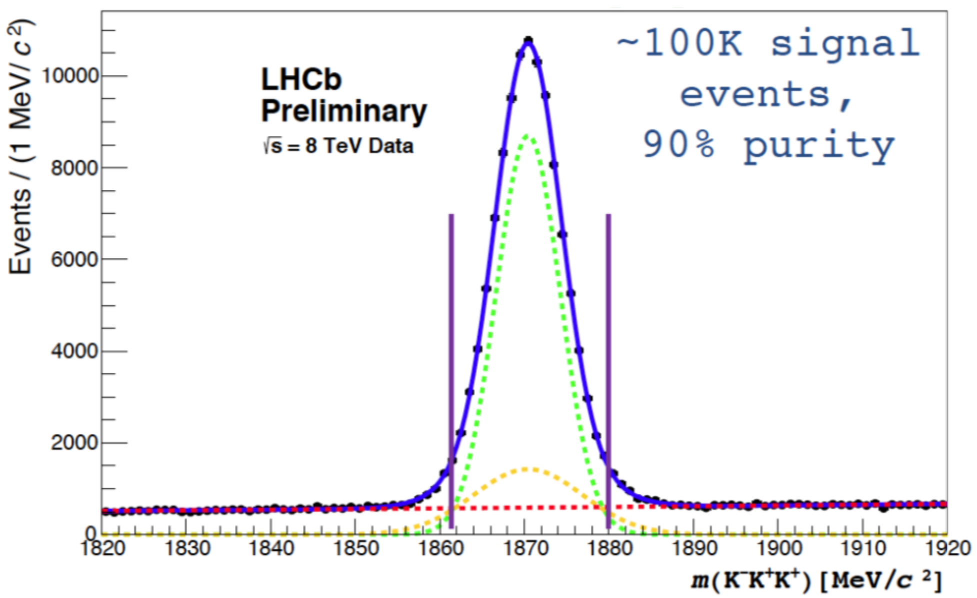


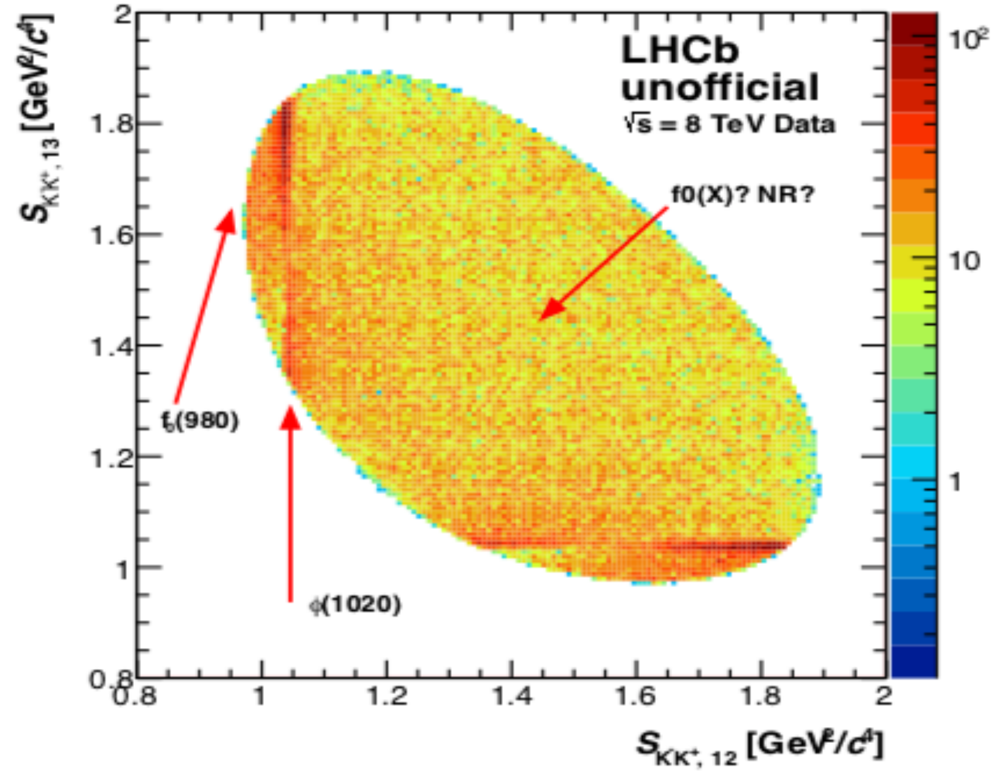


- Different decay path
- Clear contribution of $f_0(980)$; and ω
- Goal: Study and compare S-wave in D^+ and D_s

$D^+ \to K^-K^+K^+$ Amplitude Analysis

Doubly Cabibbo-suppressed decay

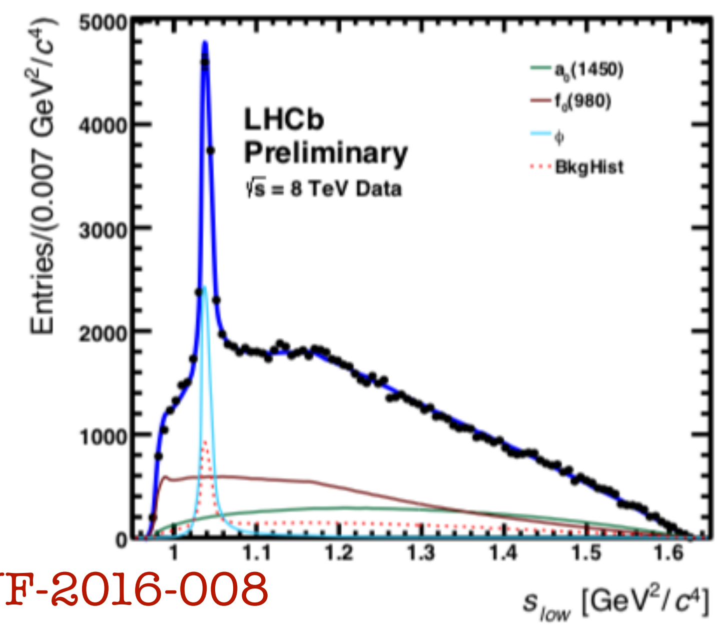


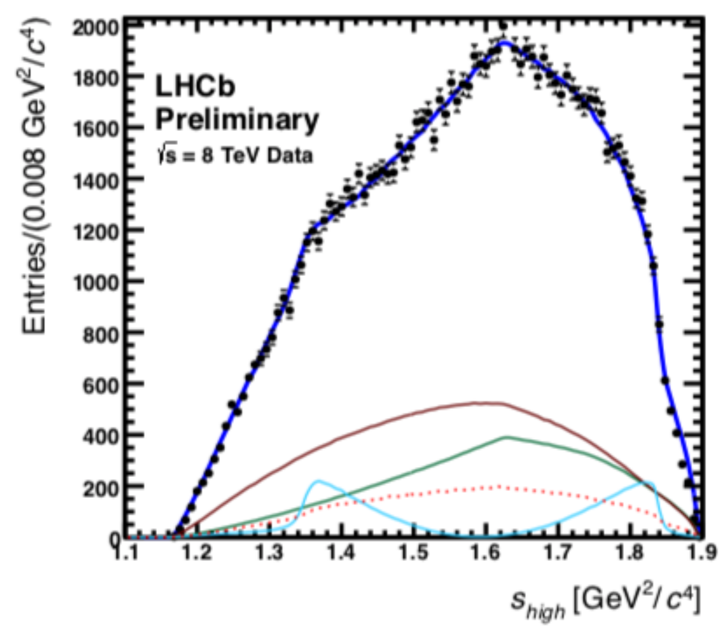


With Isobar Model, just a few resonances are needed:

- ✓ $f_0(980)$, ~29.9%
- ✓ $\varphi(1020)$, ~6.5%
- ✓ $a_0(1450)$, ~18.6% (or $f_0(X)$ ~22%)

Model: $f_0(980)$, $\varphi(1020)$, $a_0(1450)$



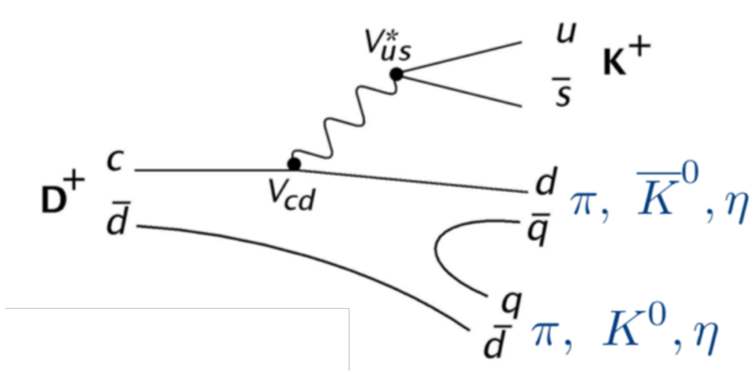


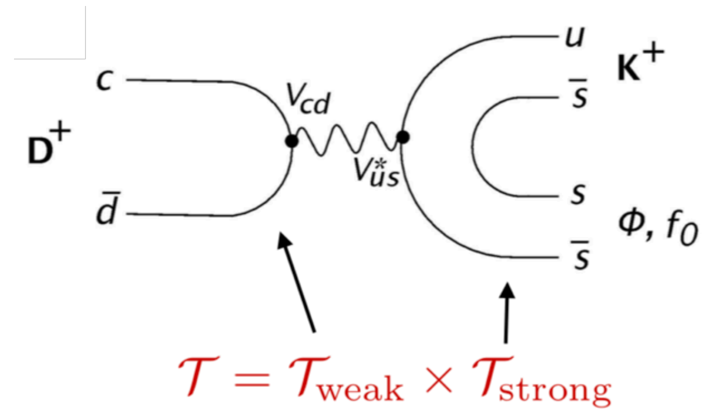
LHCb-CONF-2016-008

$D^+ \to K^-K^+K^+$ Triple M

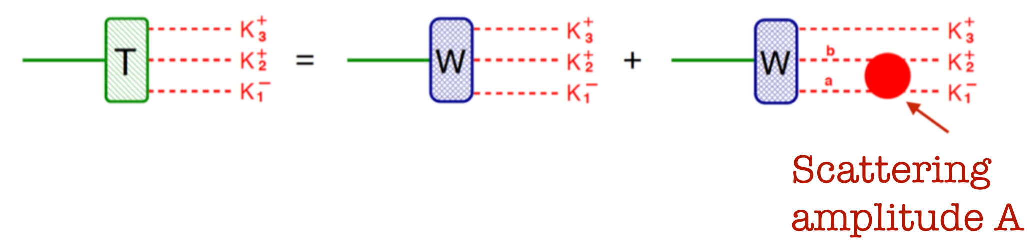
Tree level amplitude:
- Cannot form phi
- Cannot form K^+K^- directly

Factorization of the weak and strong components: possible only for the annihilation topology





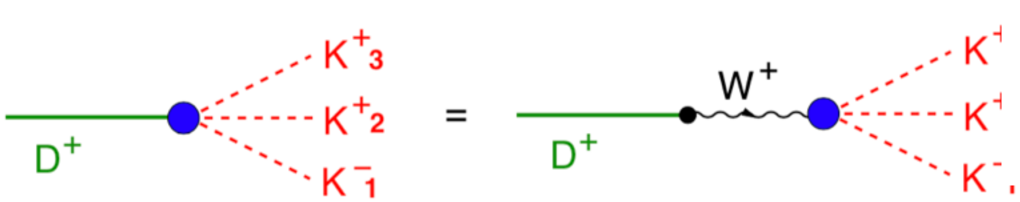
annihilation:



✓ Key hypothesis: annihilation topology dominates!

✓ Strong amplitude calculated on solid theoretical grounds: ChPT

Decay amplitude for annihilation topology:



$$\mathcal{T} = \langle (KKK)^+ | T | D^+ \rangle = \underbrace{\langle (KKK)^+ | A_\mu | 0 \rangle}_{\text{MMM amplitude}} \langle 0 | A^\mu | D^+ \rangle .$$

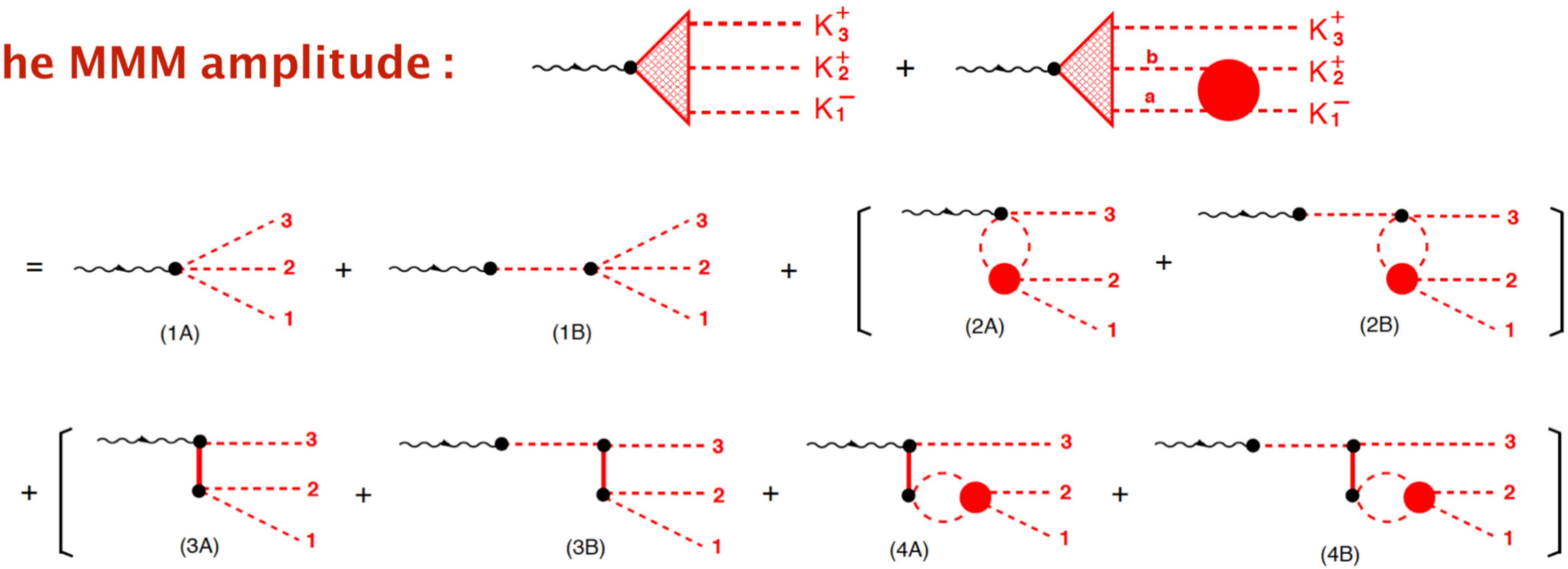
$$\langle 0 | A^\mu | D^+(P) \rangle = -i\, G_F \sin^2\theta_C\, F_D\, P^\mu = \text{const}.$$

MMM amplitude

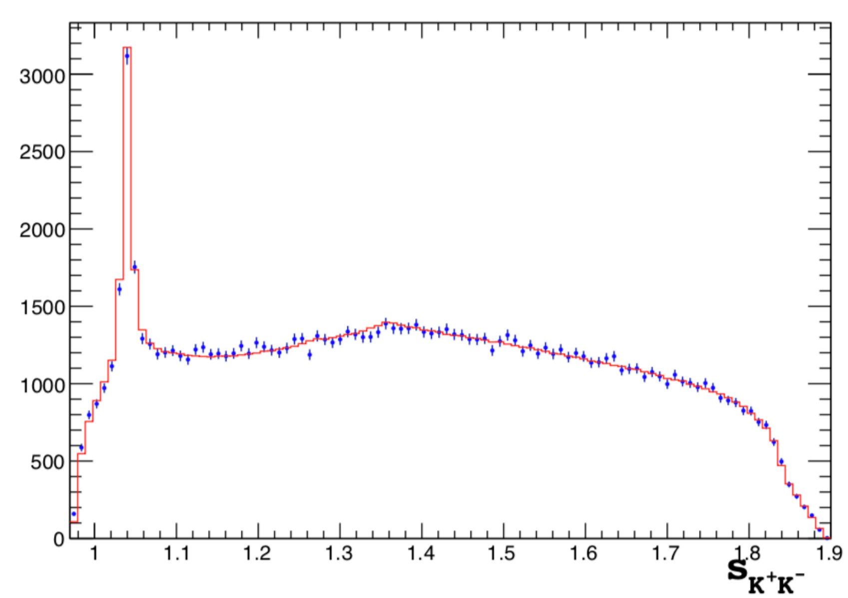
PoS Hadron2017 (2018) 044. Robilotta, Aoude, Reis

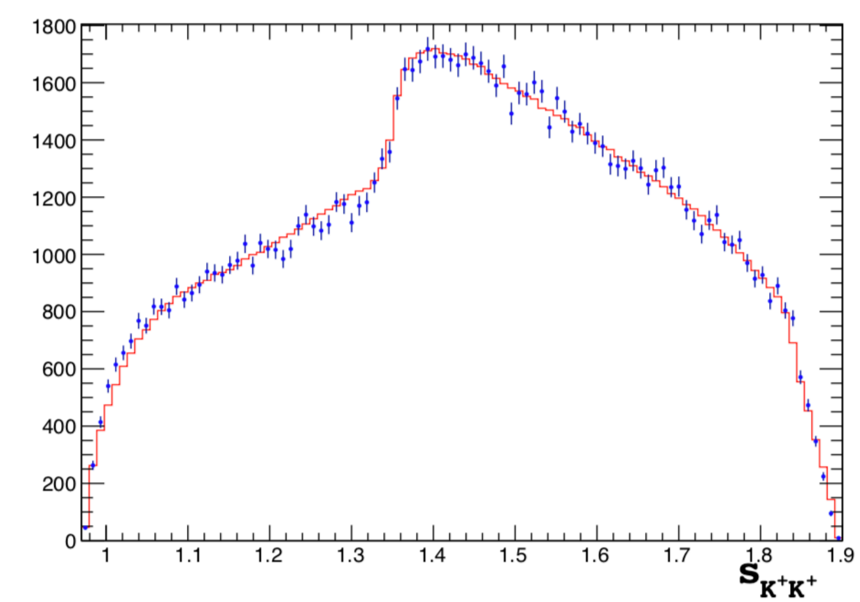
$D^+ \to K^-K^+K^+$ Triple M

the MMM amplitude :

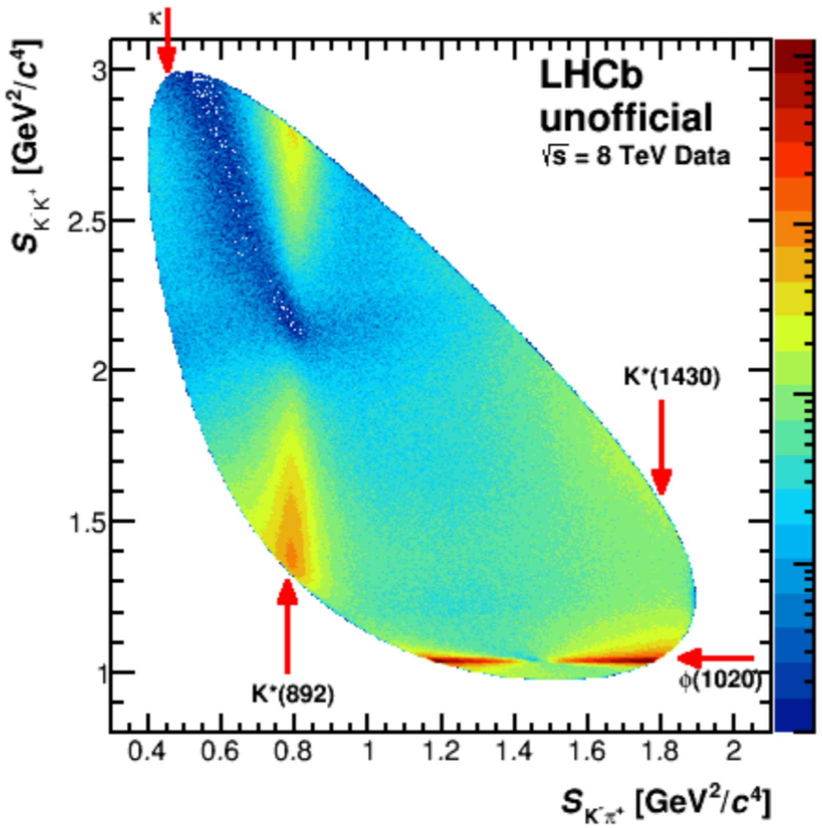


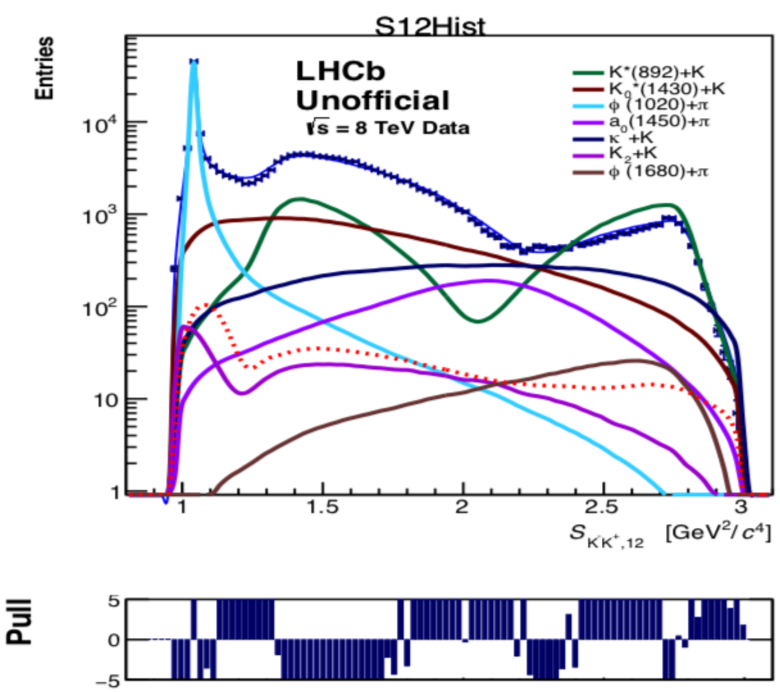
- Already implemented
- Final result to be published soon

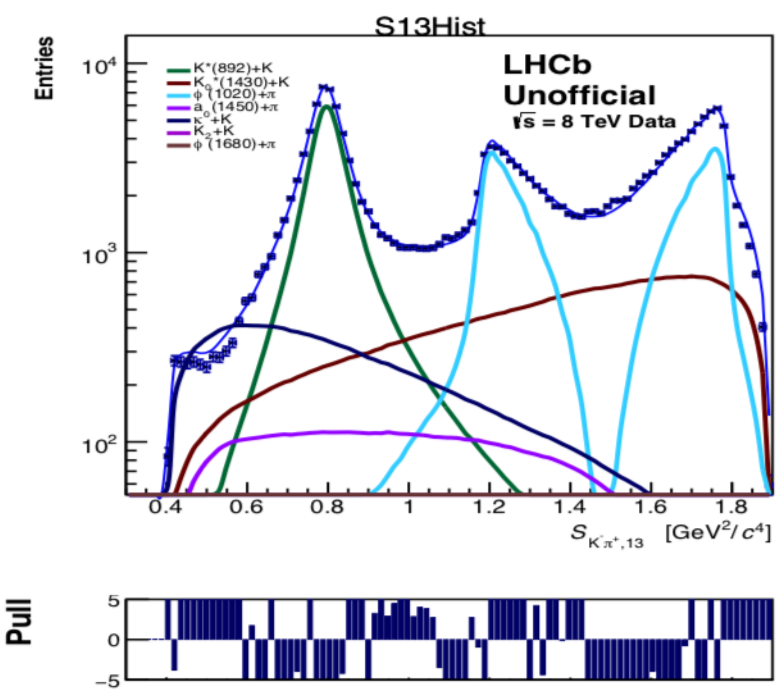




$D^+ \to K^- K^+ \pi^+$ Amplitude Analysis







- High purity ~ 99%
- Huge sample, even though the isobar model seems to be appropriate
- For run1 analyses just part of the data (~500k events)
- Demanding of accurate model for resonance lineshapes
- S-wave in both KK and Kπ system
- Very challenging

Conclusions and Perspectives

- Amplitude analyses as powerful tool to understand the dynamics of multibody decays
- Charm physics has entered precision era

  Control of experimental systematics is challenging

- From the theory side, need better understanding for better modelling

  Also very challenging!

- LHCb is putting a lot of effort on many amplitude analyses if c- and b-hadrons (both mesons and baryons!)
- LHCb Rio Charm group currently studying: $D^+ \to K^-K^+K^+$, $D^+ \to K^-K^+\pi^+$, $D_s^+ \to \pi^-\pi^+\pi^+$, $D_s^+ \to \pi^-\pi^+\pi^+$

Perspectives:

- Comprehensive study of D→hhh in run 2
  - CP violation searches in Cabibbo- and Doubly Cabibbo-Supressed decays
  - Amplitude analyses
- Work along with theoreticians: new inputs necessary

Thank you!