CP violation in multi-body B decays @ LHCb

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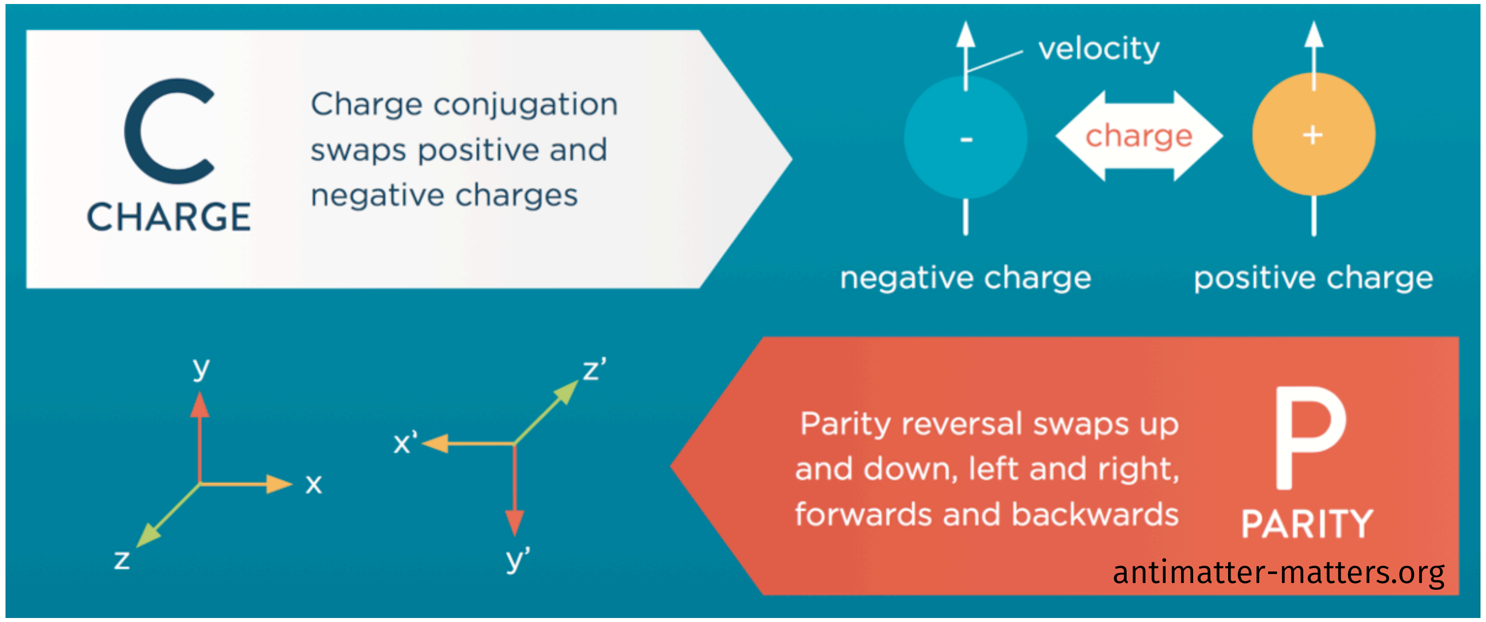
CP violation

- Describes a violation of a combination **charge conjugation** and **parity inversion**, which transforms a particle into its antiparticle



- Violation is a fundamental difference between **matter** and **anti-matter**
- Very well constrained in the Standard Model, so interesting to study
- But the SM parameter is **not enough** to describe the observed imbalance of matter and anti-matter (by a factor of 10^7!)

CP violation

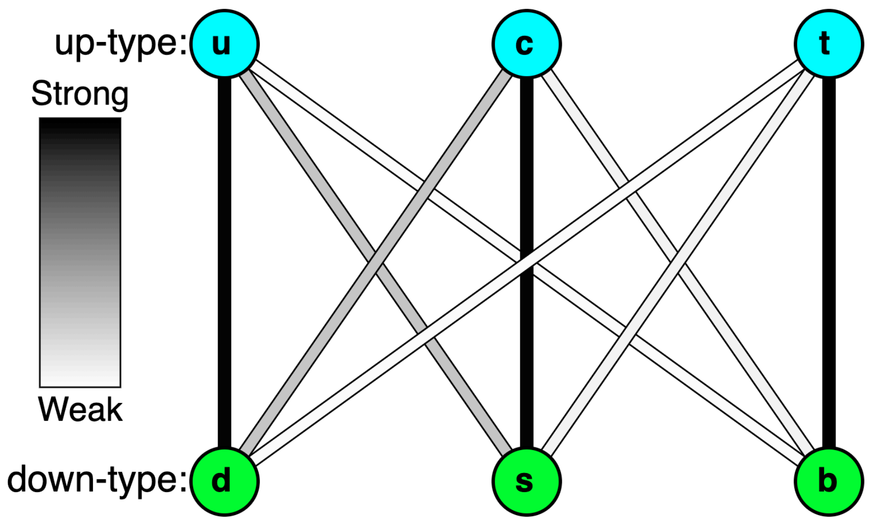
- In the **Standard Model**:

Arises from a single phase in the

Cabibbo-Kobayashi-Maskawa (CKM) matrix

that describes **transitions** between quark flavours

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



- Can compare different determinations of the SM parameter to constrain New Physics

CP violation in B decays

- Three types: CPV in **mixing**, CPV in **decay**, and CPV in the **interference between mixing and decay**

- In decay - rate asymmetry:

'Weak' phase difference, changes sign under CP

$$
\begin{aligned}
\mathcal{A}_{CP} &= \frac{\Gamma(\overline{B} \to \overline{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \overline{f}) + \Gamma(B \to f)} \\
&= \frac{2|A_1||A_2| \sin\delta \sin\phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos\delta \cos\phi},
\end{aligned}
$$

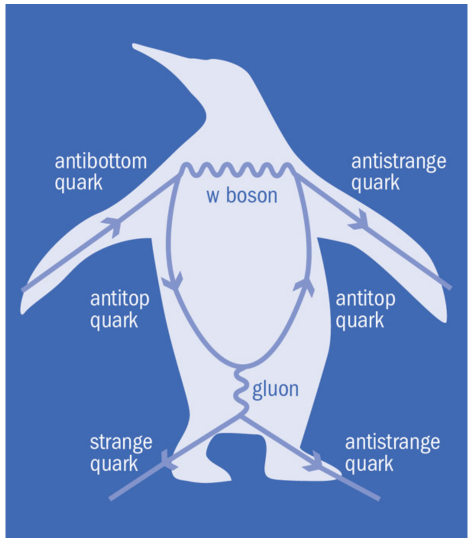
'Strong' phase difference, invariant under CP

CP violation in decay

- **Weak phase** arises from the CKM phase in the **Standard Model**

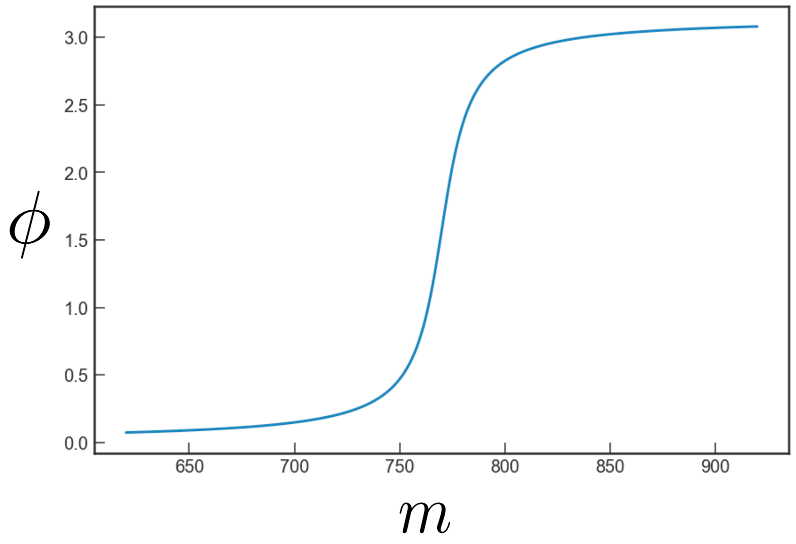
- Strong phase difference can arise from:

Competing **tree** and **penguin** diagram contributions



Final state **re-scattering** effects

Phase evolution of intermediate resonances



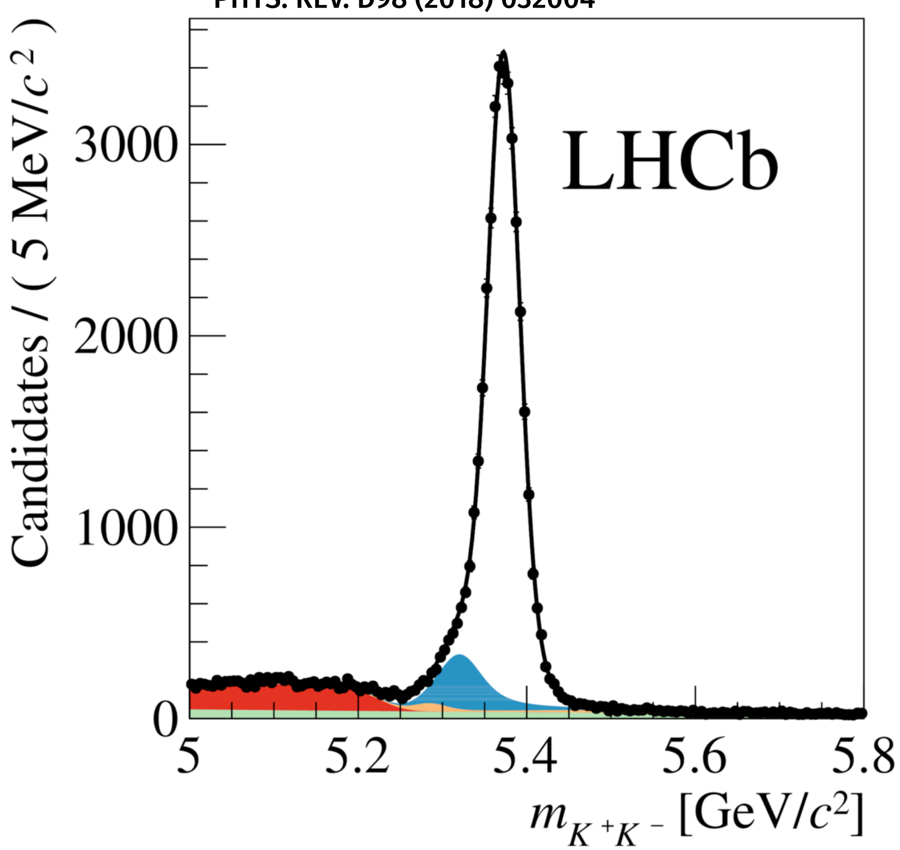
Only available in multi-body decays!

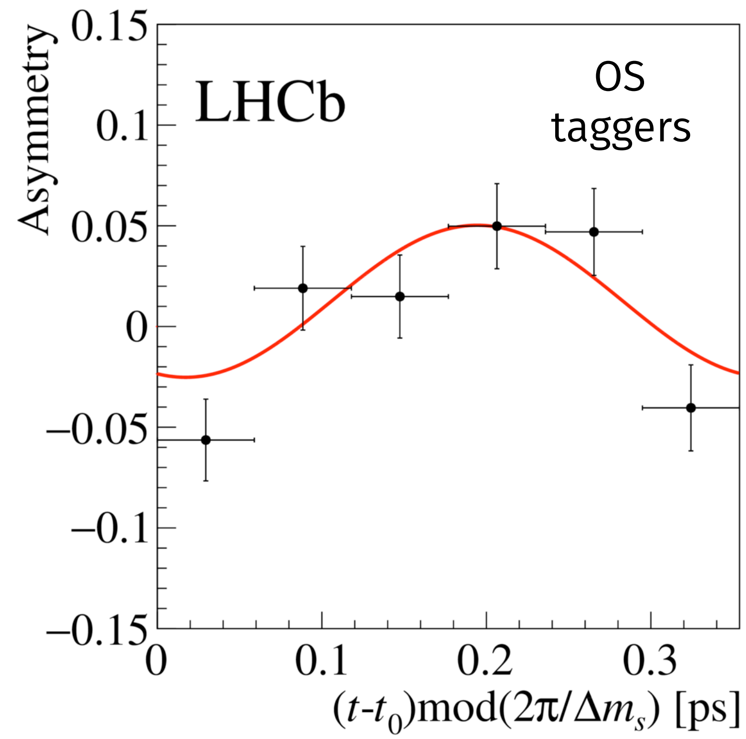
CP violation in two-body decays

- Most studies of CP violation are in **two-body decays**
- These analyses are **very advanced**, time dependent, with **very large** data sizes:

$$B^0_{(s)} \to h^+ h^-$$

PHYS. REV. D98 (2018) 032004





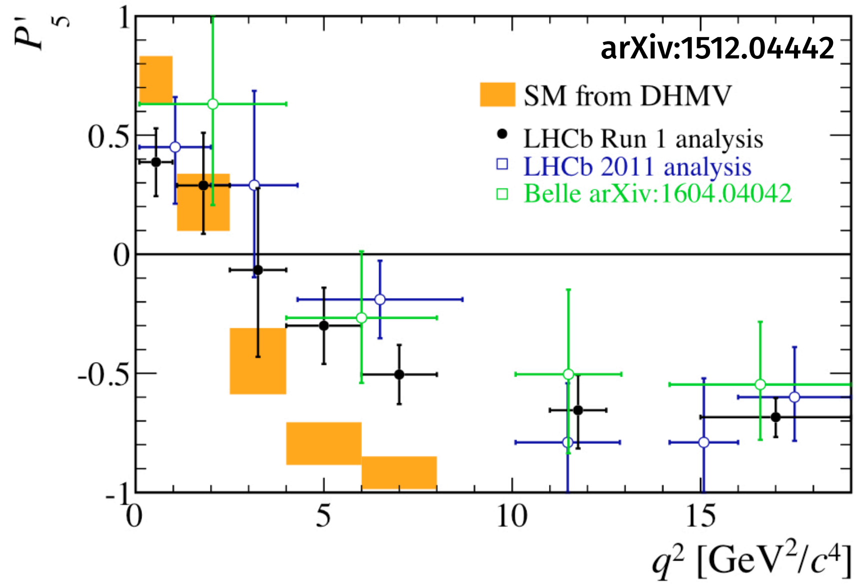
$$\begin{aligned}
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01, \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01, \\
C_{K^+K^-} &= 0.20 \pm 0.06 \pm 0.02, \\
S_{K^+K^-} &= 0.18 \pm 0.06 \pm 0.02, \\
A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10, \\
A^{B^0}_{CP} &= -0.084 \pm 0.004 \pm 0.003, \\
A^{B^0_s}_{CP} &= 0.213 \pm 0.015 \pm 0.007,
\end{aligned}$$

- For three-body decays, the situation is **less well established**

Why **model** multi-body decays?

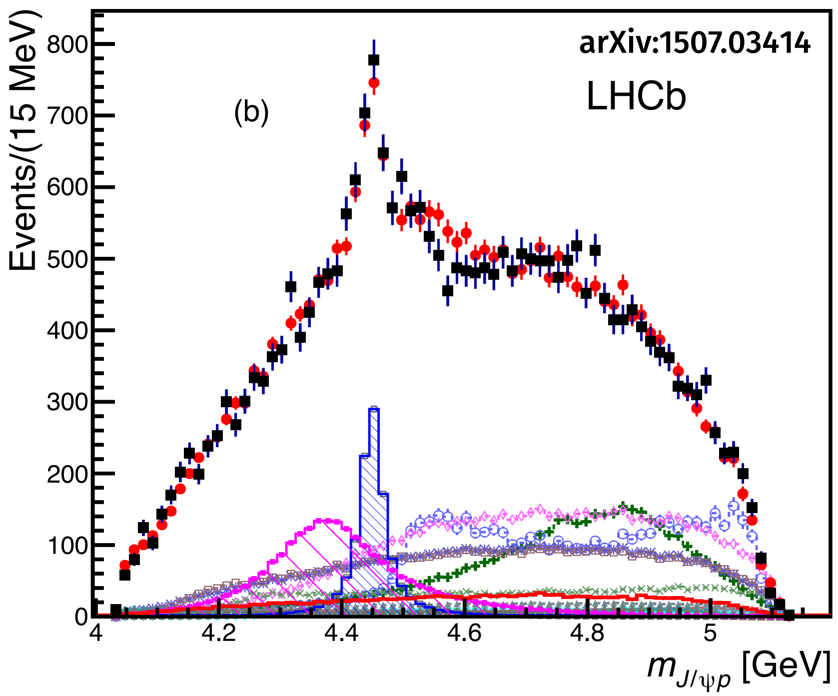
- Model parameters can have new physics interpretations

$B^0 \to K^*(892)^0 \mu^+ \mu^-$



- Searches for new, exotic hadronic resonances

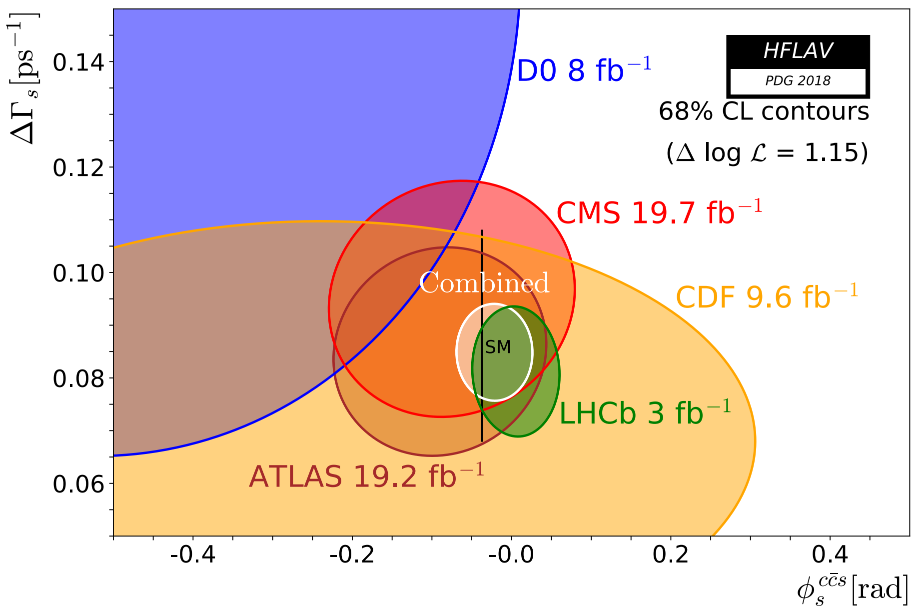
Pentaquarks in $\Lambda_b^0 \to P_c^+ K^-$



Why **model** multi-body decays?

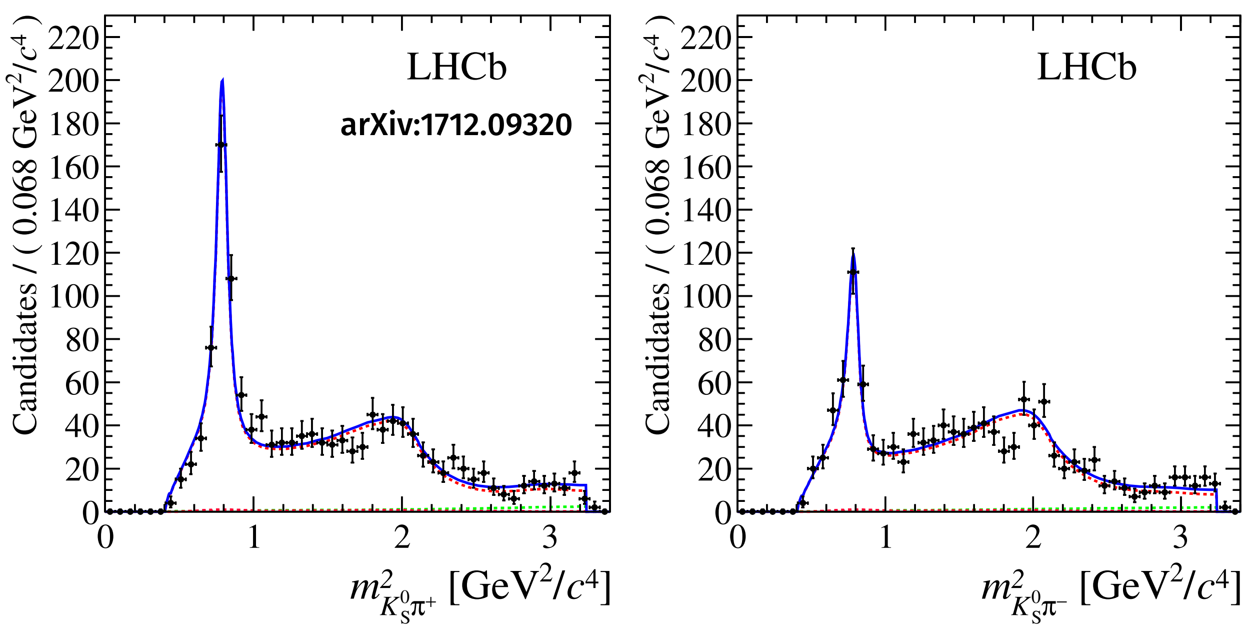
- Extract $B^0_{(s)}$ mixing parameters

$B^0_s \to J/\psi K^+ K^-,\ B^0_s \to J/\psi \pi^+ \pi^-$

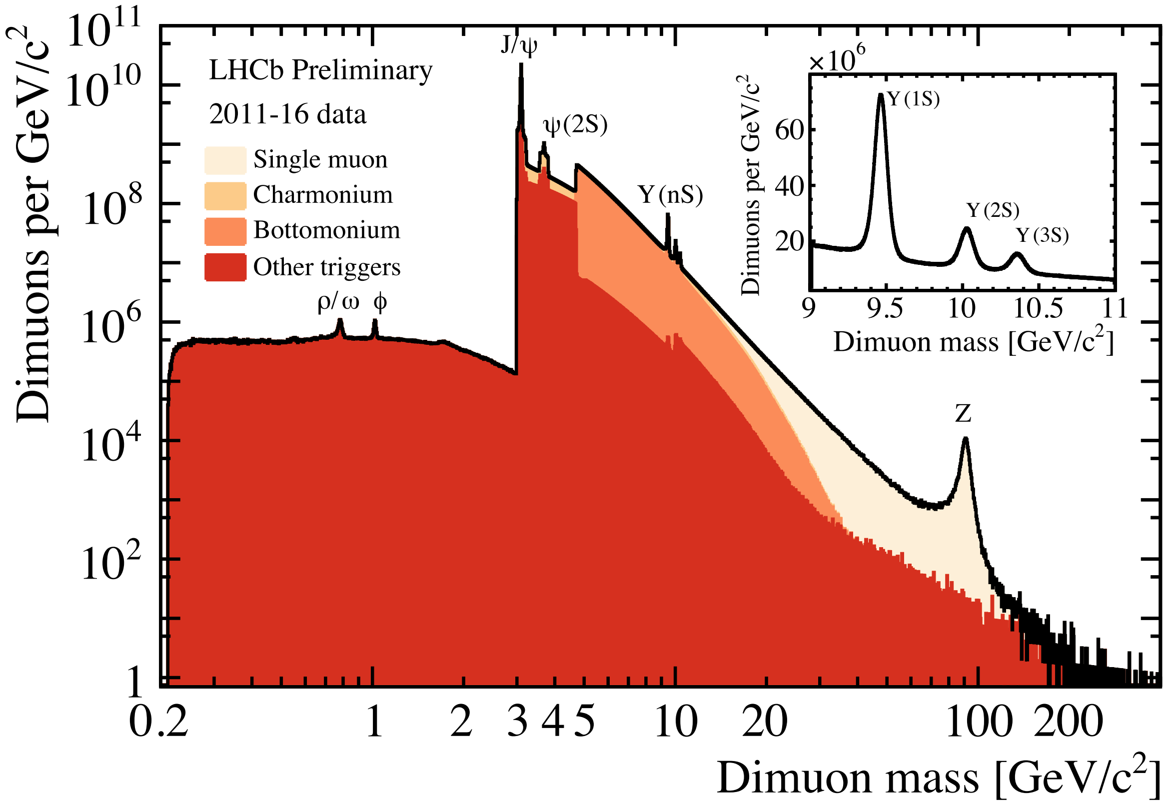


- Study CP violation

CP violation in $B^0 \to K^{*+}(K^0_S\pi^+)\pi^-$



Resonances



- For practical purposes, are states that have a **short lifetime** compared to the detector resolution

$$\tau = \frac{1}{\Gamma} \propto \left[\sum_i^{\text{channels}} \Gamma_i \right]^{-1}$$

- Short lifetimes imply **large widths**, and for hadronic resonances, decays via the **strong force** (unless OZI suppressed)

- For an isolated resonance, the mass lineshape is described by the relativistic Breit-Wigner function....

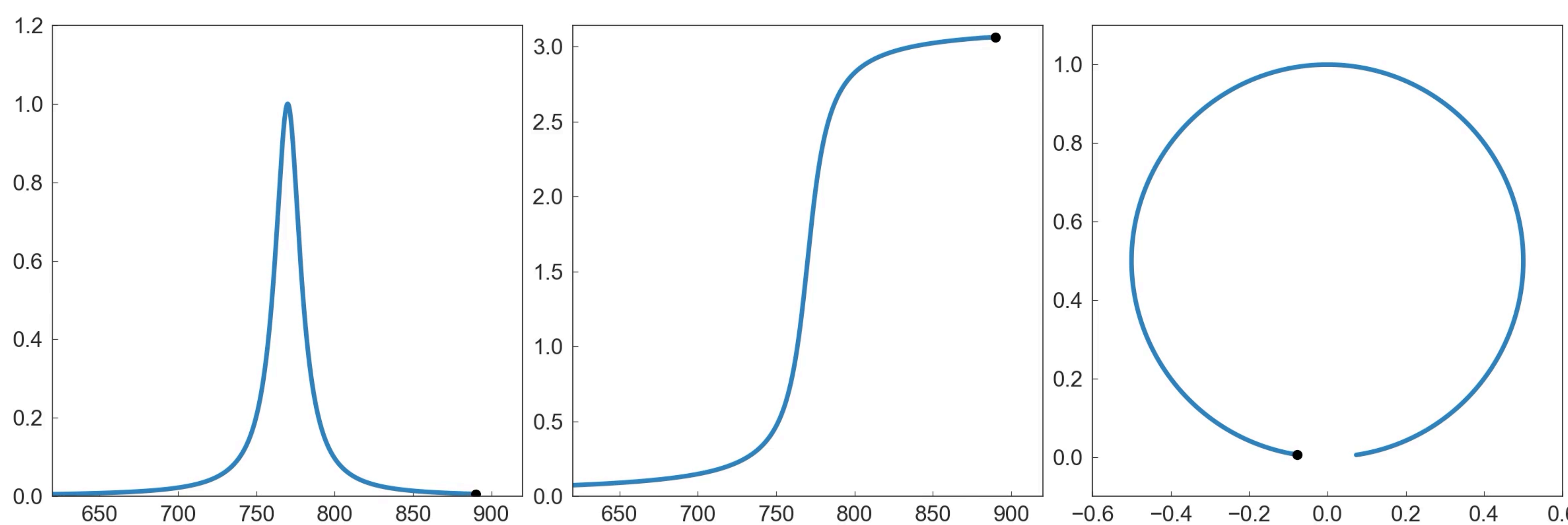
Relativistic Breit-Wigner

$$R(m) = \frac{1}{(m_0^2 - m^2) - i m_0 \Gamma_0}$$

For:

$$m_0 = 770\,\mathrm{MeV}$$
$$\Gamma_0 = 20\,\mathrm{MeV}$$

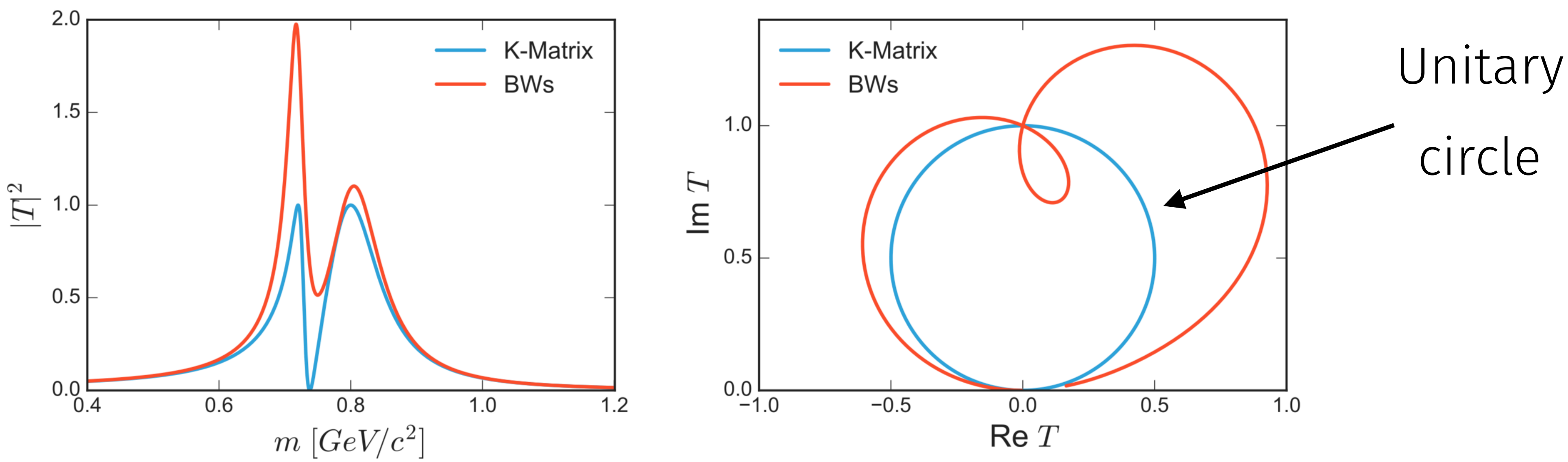
$\lvert R(m)\rvert^2$	$\arg\left[R(m)\right]$	$\mathrm{Re}[R(m)]\,,\ \mathrm{Im}[R(m)]$
Intensity	**Phase**	**Argand diagram**



Problems with this

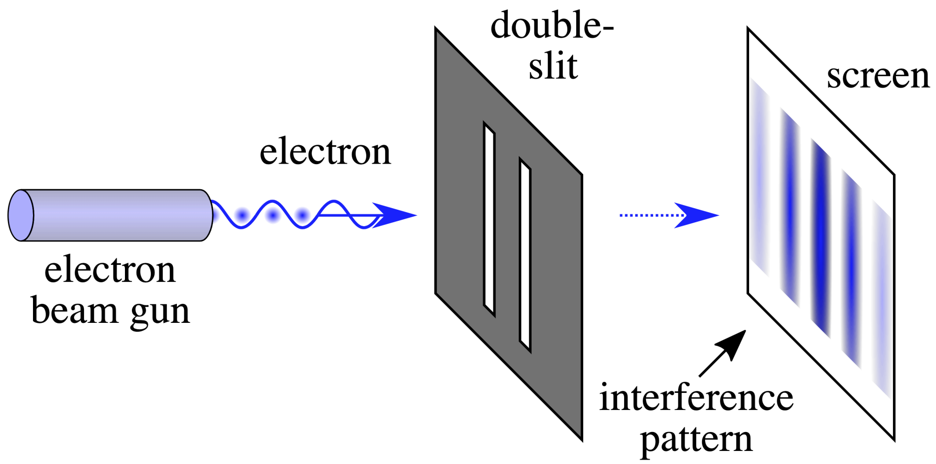
- Resonances near **open decay channels** see a drop in amplitude due to conservation of **unitarity** - total probability to decay to **all** channels must be conserved

- Unitarity is also violated for nearby **overlapping resonances** of the same spin



- 'Pole' masses and widths of resonances **near thresholds** are also not well replicated by Breit-Wigner lineshapes

The double slit experiment



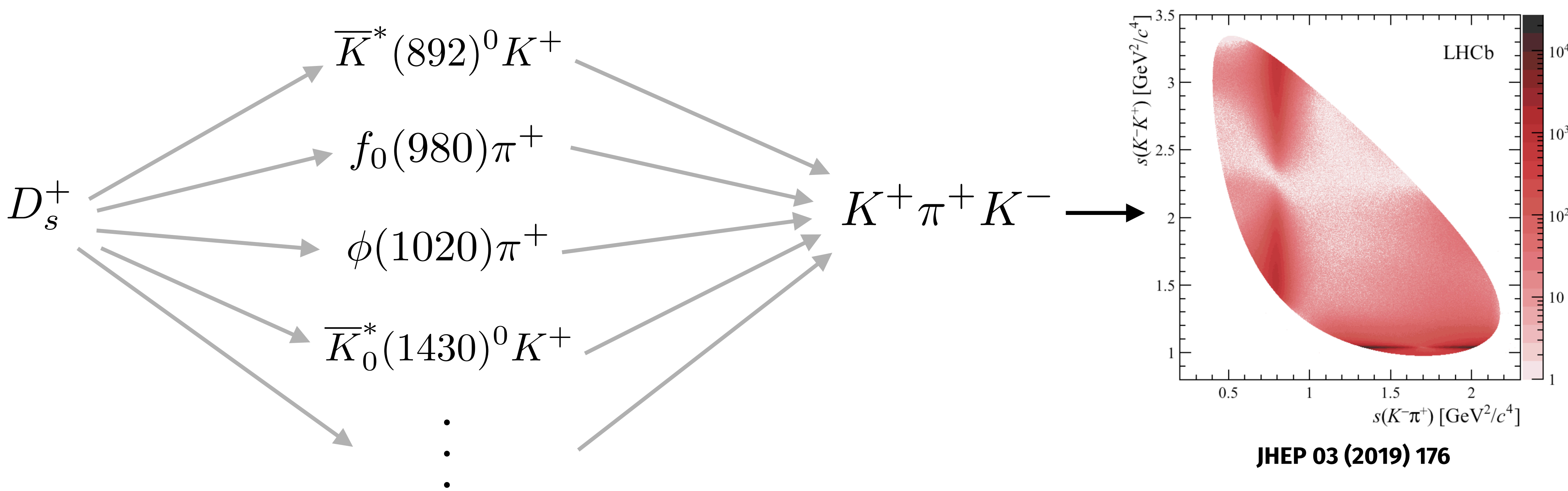
Interference

term

$$\langle x_1 \mid x_2 \rangle = \sum_j^{\text{slits}} \langle x_1 \mid \text{slit}_j \rangle \langle \text{slit}_j \mid x_2 \rangle = \sum_j^{\text{slits}} \Phi_j e^{i\theta_j} \Rightarrow |\langle x_1 \mid x_2 \rangle|^2 = \sum_j \Phi_j^2 + \boxed{I(\theta)}$$

“ In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics. ”

The double slit experiment



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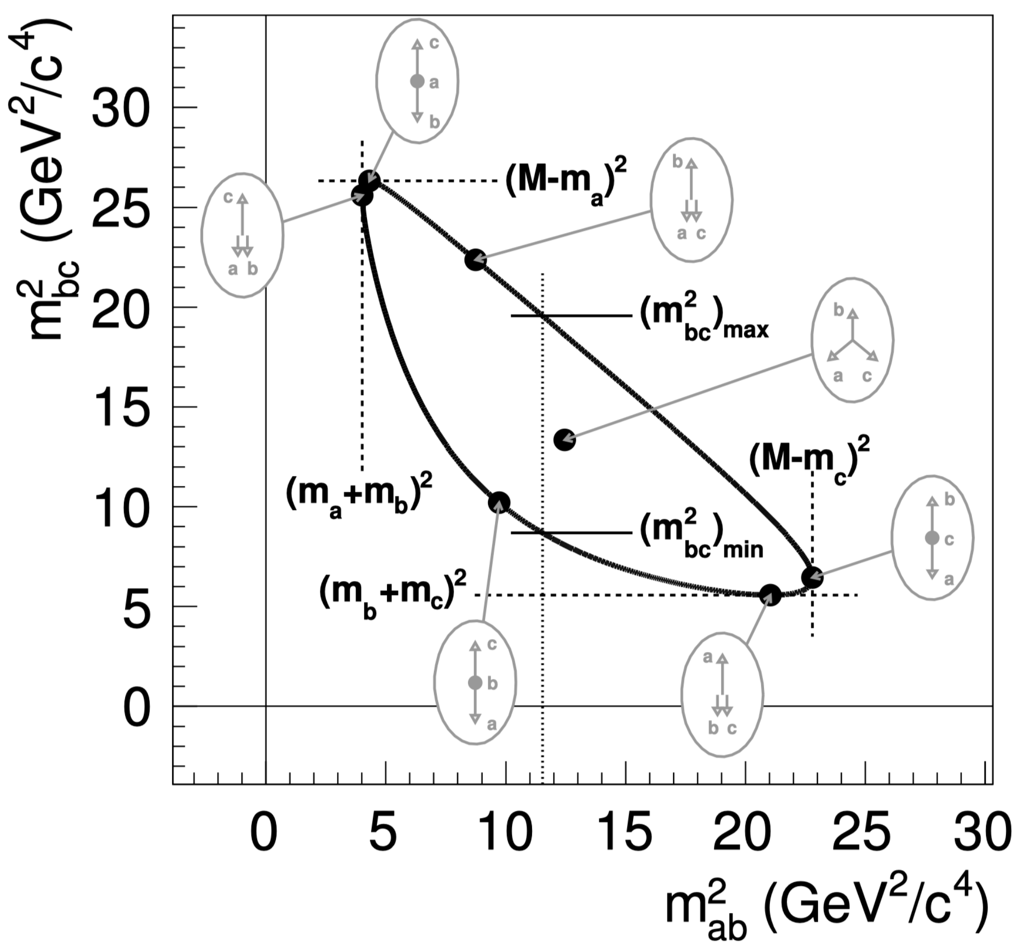
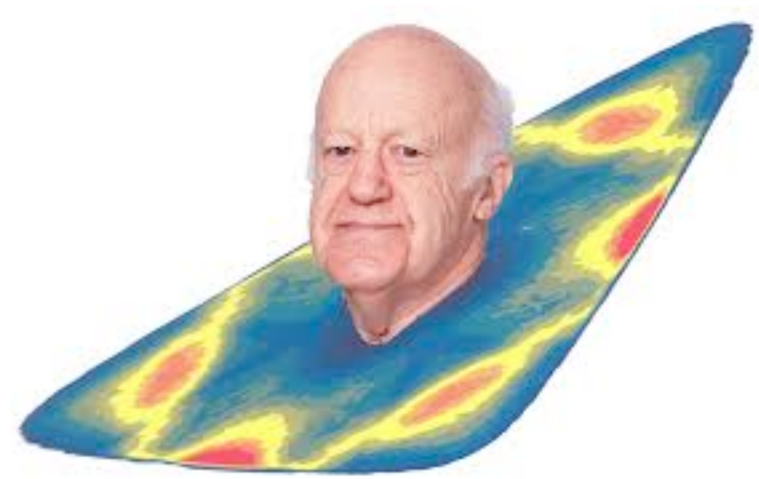
The Dalitz plot

- For a **three-body** decay to scalars with known masses: $B \to a\,b\,c$

Only **two** independent degrees of freedom

- Choose these to be any two-body invariant masses: the **Dalitz** plot





Named after Richard Dalitz, after his work on the '$\tau - \theta$ puzzle'

Amplitude models

- A good assumption is that the resonance is produced far from the third hadron - amplitude is a **sum over intermediate two-body resonance decays**

Phase-space dependent part

$$\boxed{\mathcal{A}(m_{13}^2, m_{23}^2) = \sum_j c_j F_j(m_{13}^2, m_{23}^2),}$$

$|A|^2$ is the observed data distribution

$c_j = |c_j| e^{i\theta}$

Describes relative contribution of resonance j (complex)

Amplitude models

- Each resonant component is the product of a few terms:

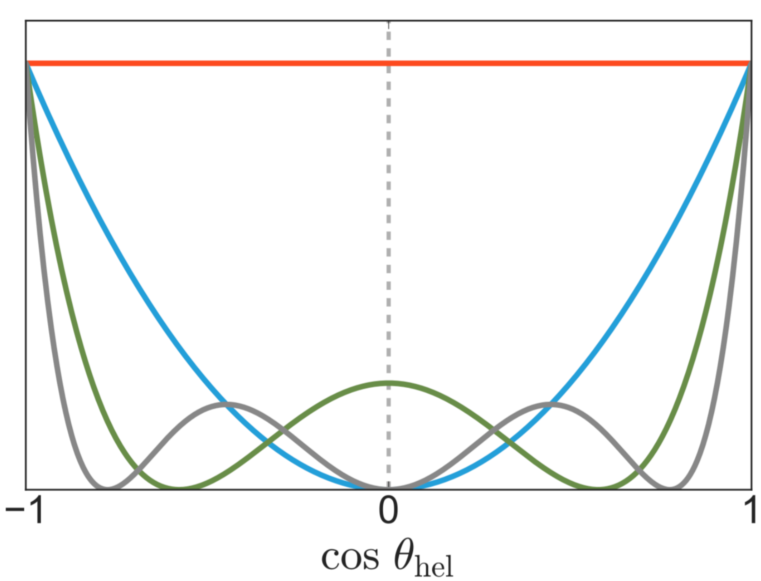
Mass lineshape

(e.g., relativistic Breit-Wigner)

$$\boxed{F(m_{13}^2, m_{23}^2) = T(m_{13}) \cdot Z(\vec{p}, \vec{q}, L) \cdot X(pr_{\mathrm{BW}}, L) \cdot X(qr_{\mathrm{BW}}, L).}$$

Angular momentum conservation terms

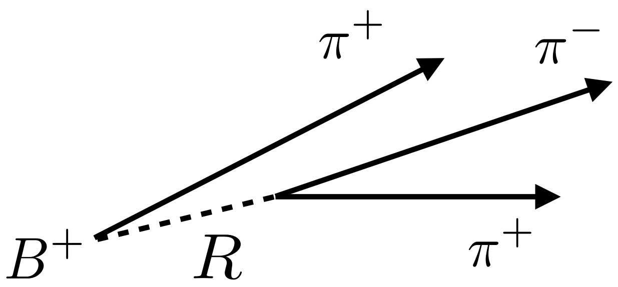
Form factors to account for the finite size of the mesons



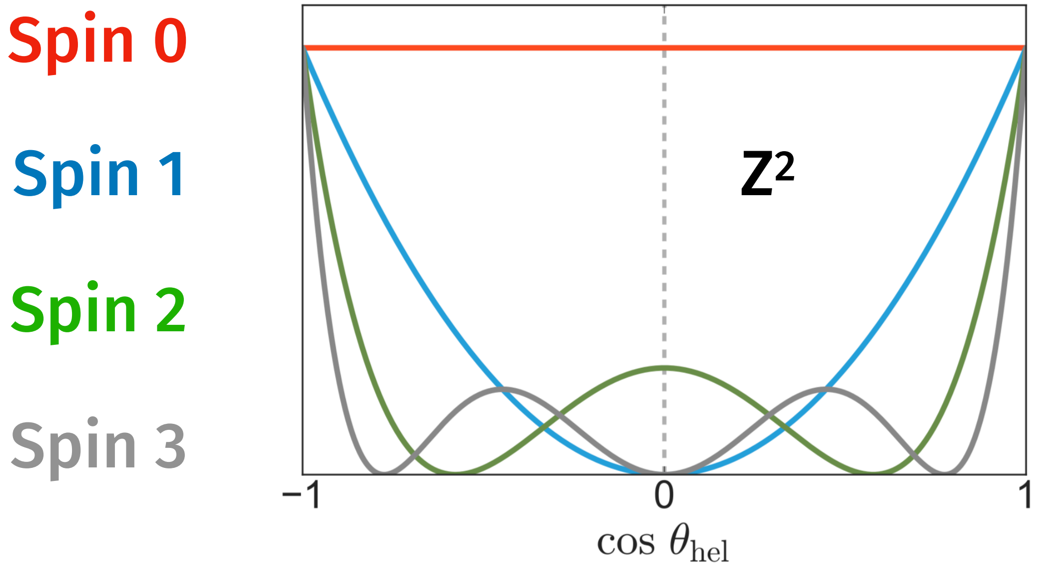
$$\begin{aligned}
L = 0 \ : \ X(z) &= 1\,, \\
L = 1 \ : \ X(z) &= \sqrt{\frac{1+z_0^2}{1+z^2}}\,, \\
L = 2 \ : \ X(z) &= \sqrt{\frac{z_0^4+3z_0^2+9}{z^4+3z^2+9}}\,, \\
L = 3 \ : \ X(z) &= \sqrt{\frac{z_0^6+6z_0^4+45z_0^2+225}{z^6+6z^4+45z^2+225}}
\end{aligned}$$

Angular momentum factors

- Angular momentum terms conserve angular momentum
- Depend on the the **relative angular momentum** between the resonance R and the third hadron (equivalent to the **spin of R**)
- Depend on the **(helicity) angle** between these two in rest frame of R



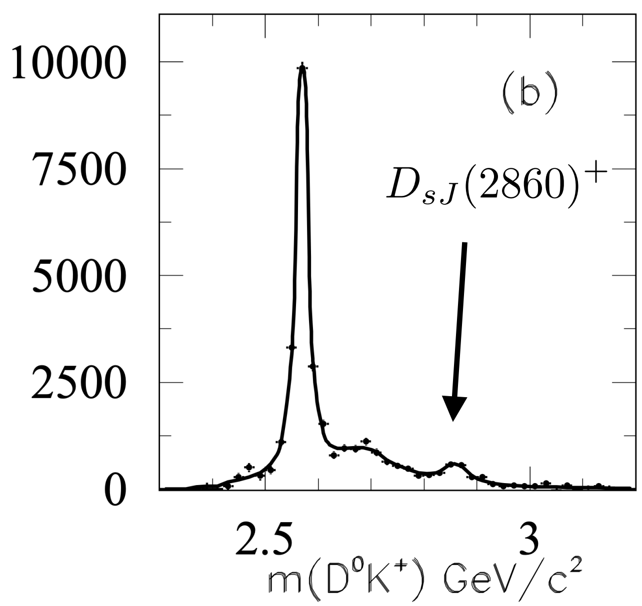
- (Squared) Legendre polynomials in $\cos\theta_{\mathrm{hel}}$



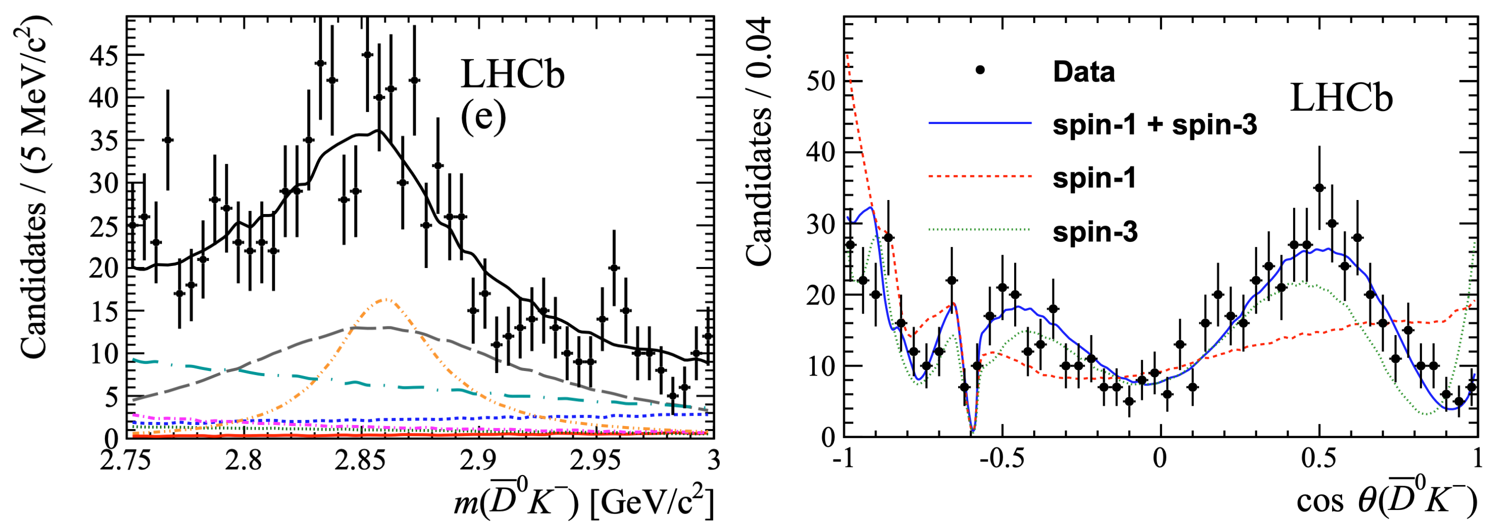
Angular momentum factors

- Proportional to the second invariant mass squared in the Dalitz plot, mass lineshape separate resonances in **mass**, angular momentum terms separate resonances in **spin**

Turns out to be two overlapping resonances of different spin!



Phys.Rev.Lett.97:222001, 2006



Phys. Rev. Lett. 113, 162001 (2014)

BaBar - inclusive $e^+e^- \to D^0K^+X$, **no** angular momentum information

LHCb - amplitude analysis of $B^0 \to \overline{D}^0 K^- \pi^+$ **with** angular momentum information

Interference terms

- Distribution in $\cos\theta_{\mathrm{hel}}$ is determined by the **interferences** (relative phases) between resonances

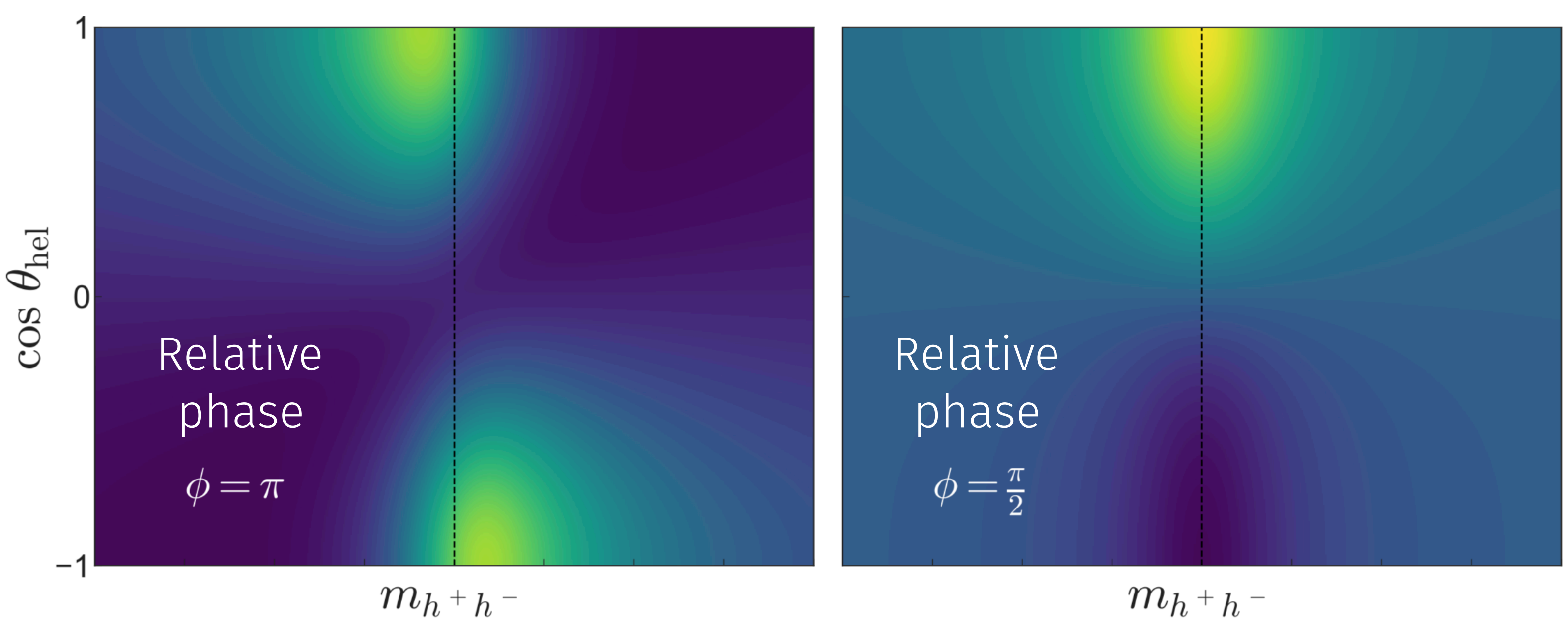
With just two components:

$$
\begin{aligned}
|\mathcal{A}|^2 &= |T_1(m^2)Z_1(\theta) + T_2(m^2)Z_2(\theta)|^2 \\
&= Z_1^2[Re(T_1)^2 + Im(T_1)^2] + Z_2^2[Re(T_2)^2 + Im(T_2)^2] \\
&\quad \boxed{+\boxed{2Z_1Z_2}[Re(T_1)Re(T_2) + Im(T_1)Im(T_2)],}
\end{aligned}
$$

Product of the two angular momentum terms

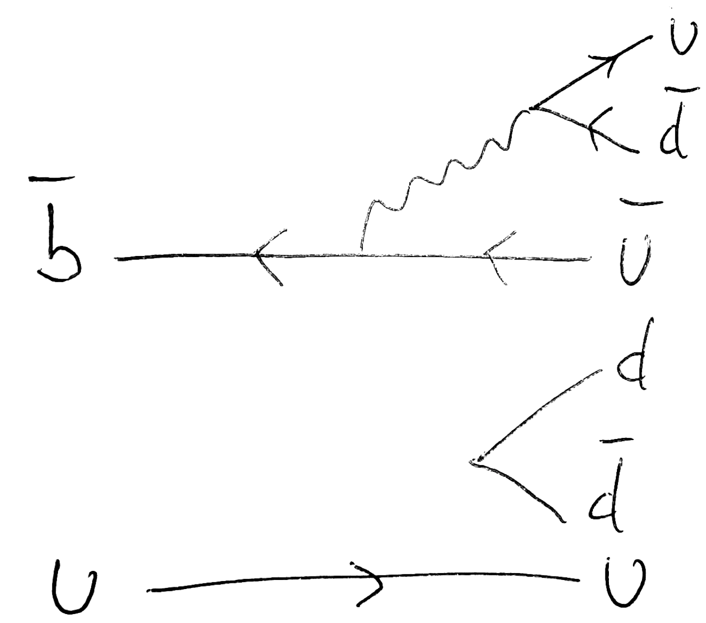
Interference term

Spin 0
+
Spin 1



$B^+ \to \pi^+\pi^+\pi^-$

- **Interesting *a priori* for QCD**: the lightest bound states decay to two pions

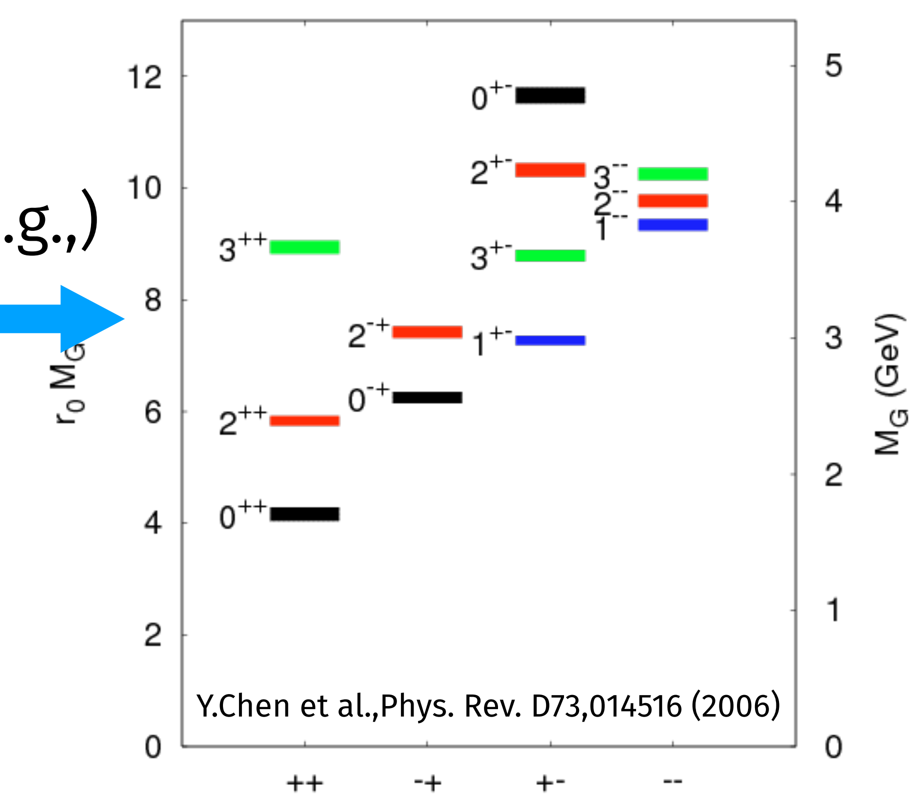


- Scalars in particular are complicated to model:

  Entire PDG review article dedicated to this:

  http://pdg.lbl.gov/2019/reviews/rpp2018-rev-scalar-mesons.pdf

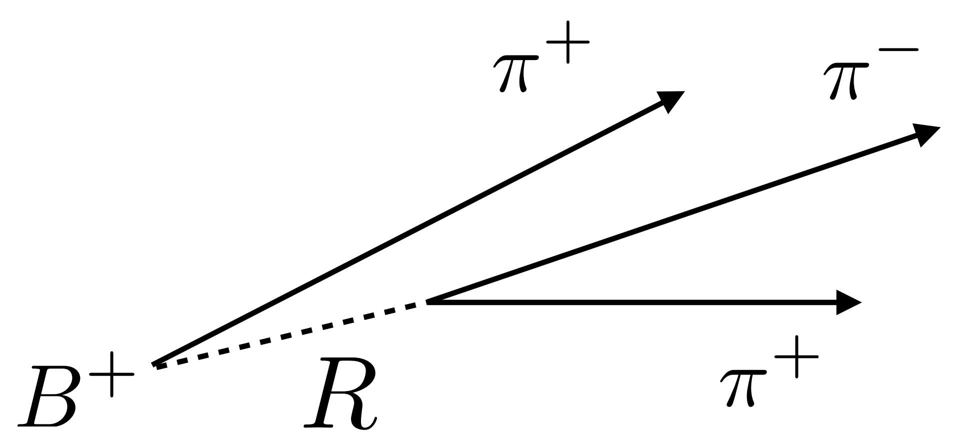
- Spectrum contains the very broad $f_0(500)$ (or σ) meson
- Lattice QCD puts the **lightest 'glueball'** somewhere here (e.g.,)
- Many resonance **decay channels** opening up (e.g., $K\overline{K}, \eta\eta$)
- Everything is close to **production threshold**



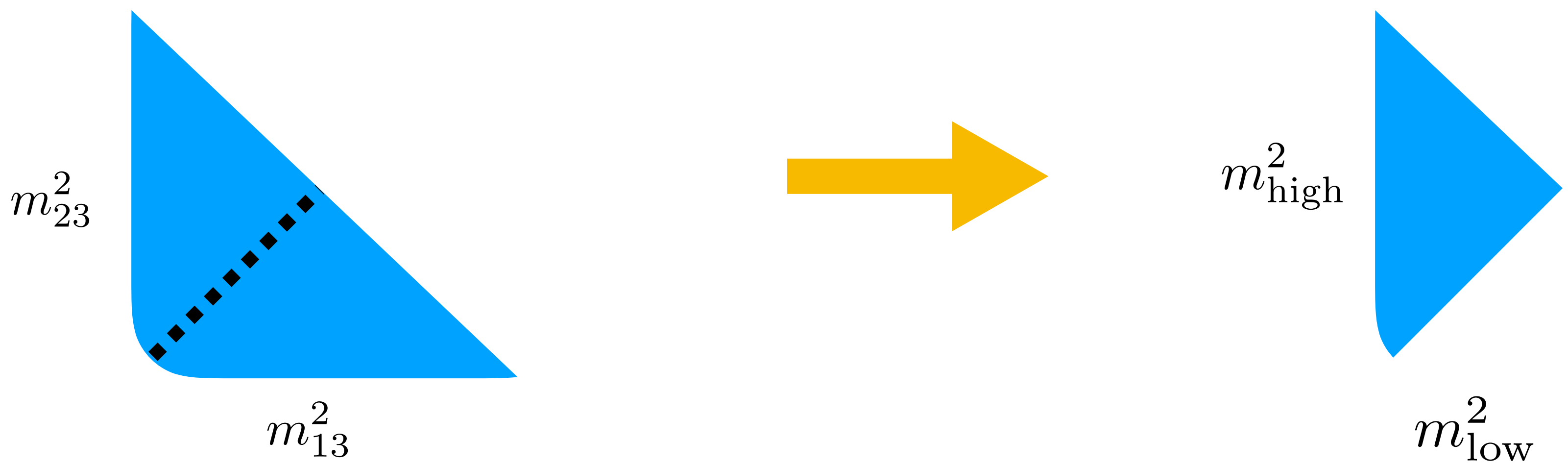
Almost all assumptions used when modelling hadrons are violated!

$B^+ \to \pi^+\pi^+\pi^-$

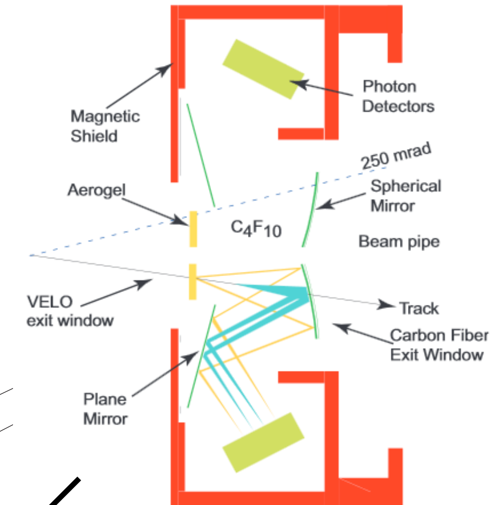
- Only expect resonances in the $\pi^+\pi^-$ spectrum

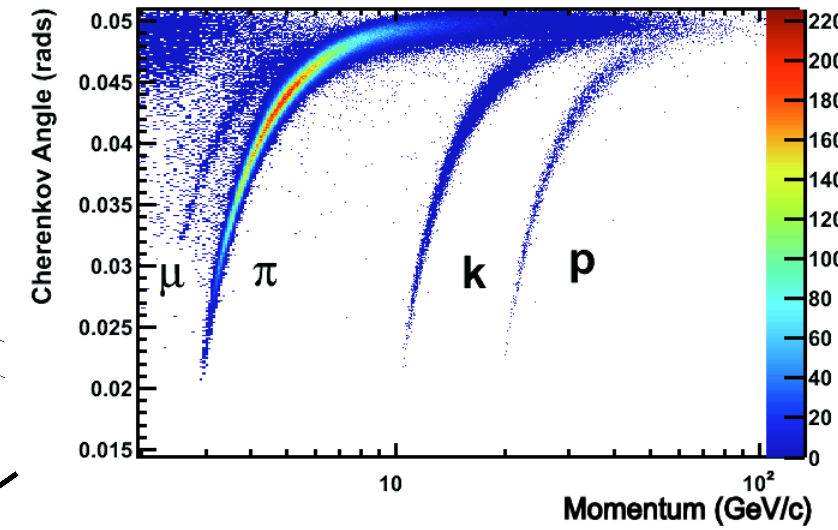


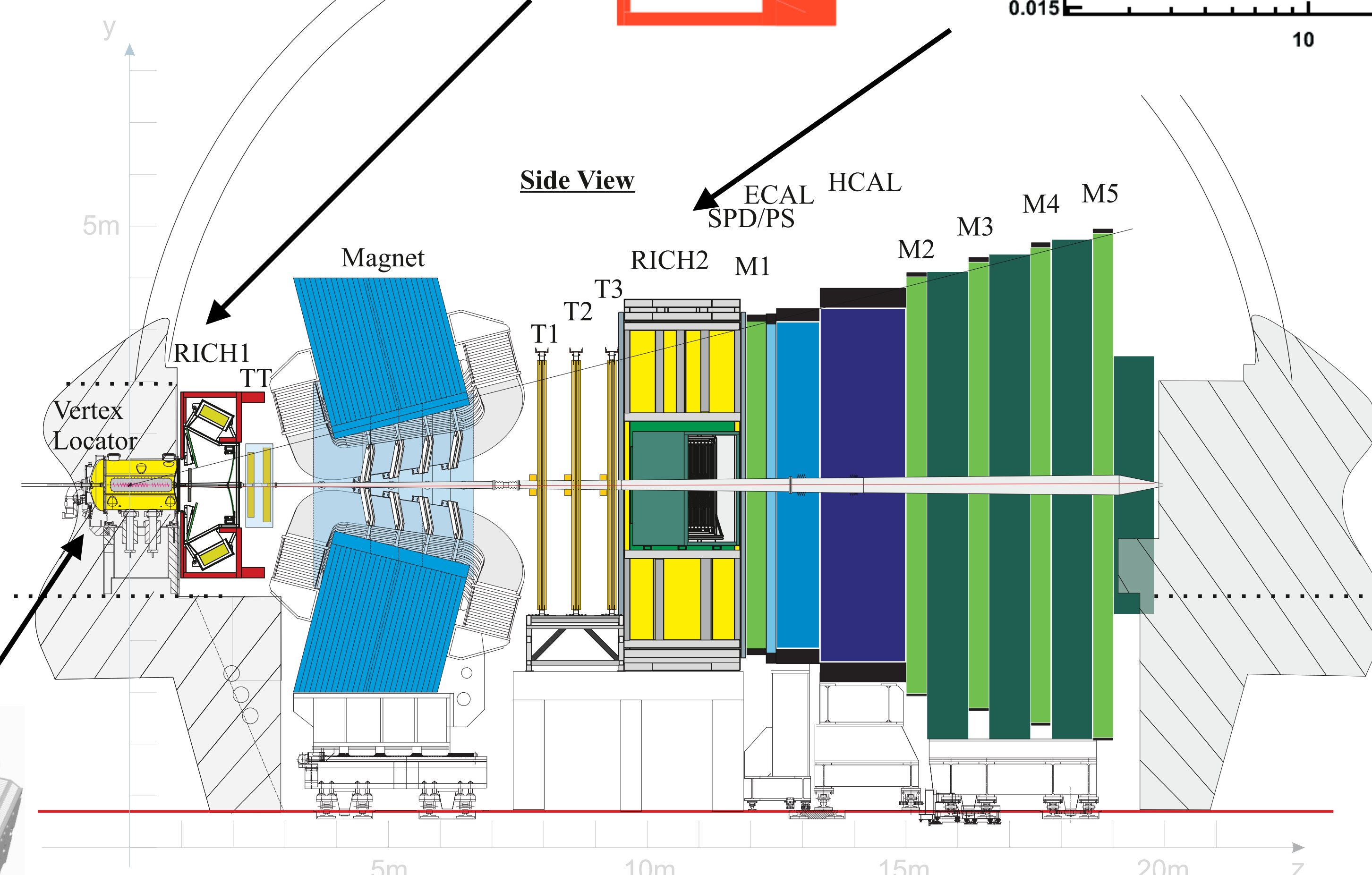
- Amplitude invariant under exchange of same-sign π^+ - mirror symmetry about $m_{13} = m_{23}$ in the Dalitz plot (not a unique choice)

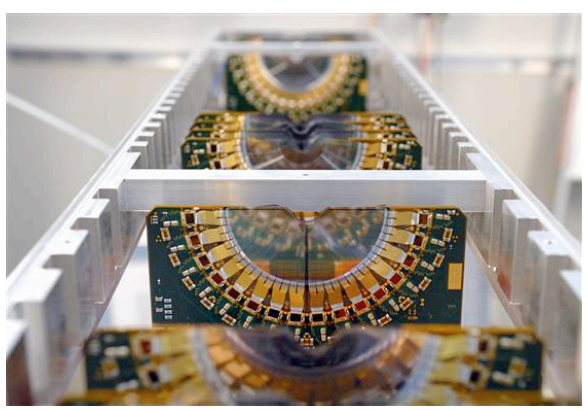


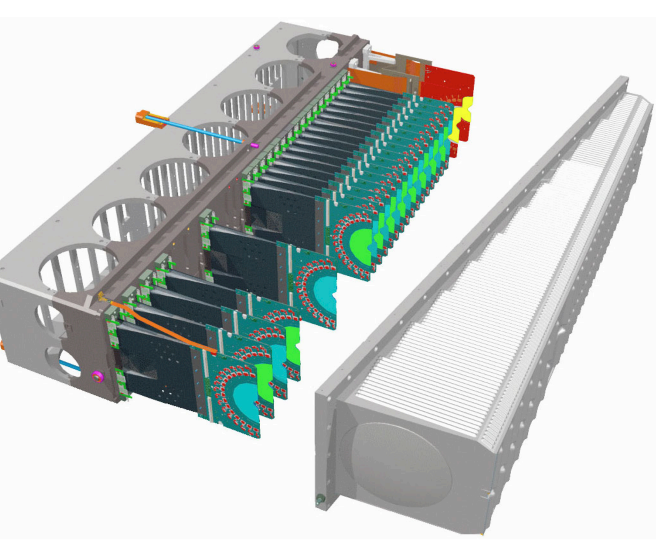
The LHCb experiment

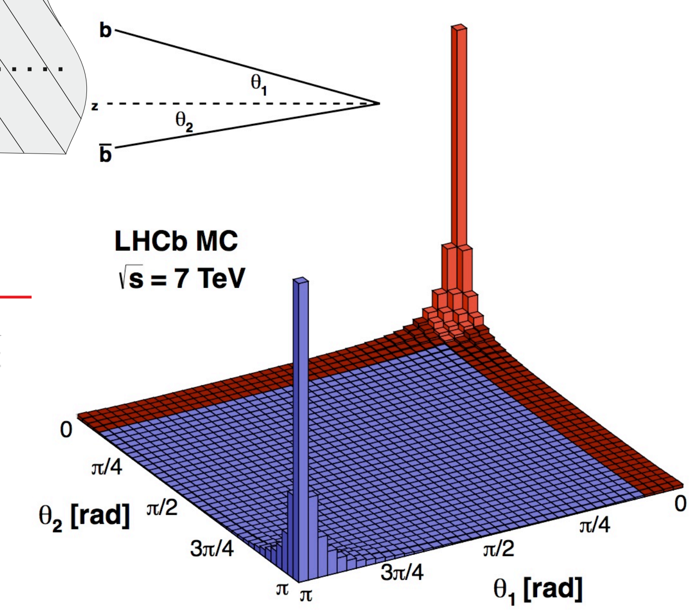






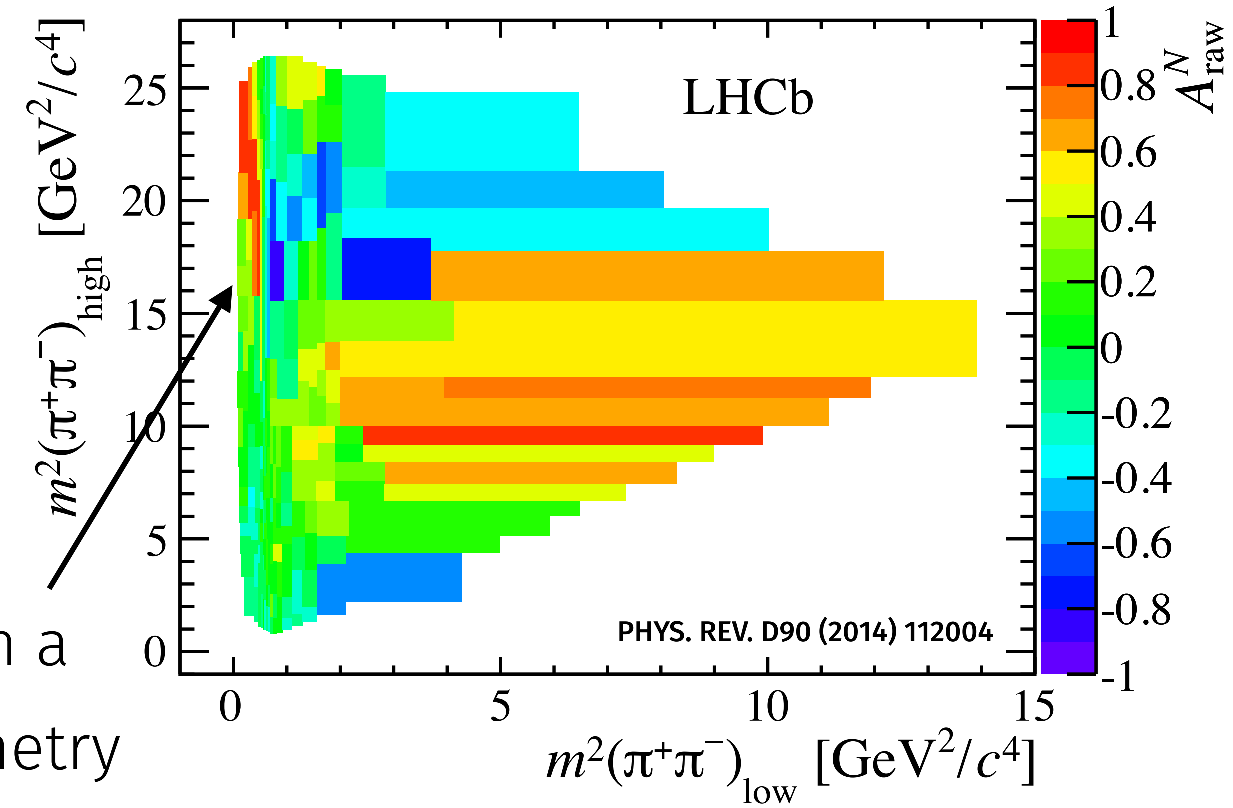






$B^+ \to \pi^+\pi^+\pi^-$

- Previous analysis - calculate CP asymmetry in **bins** of the Dalitz plot:



Not associated with a resonance CP asymmetry (would be axis aligned)

- Downside of this: Have to **guess** at what physics is generating these!

$B^+ \to \pi^+\pi^+\pi^-$

LHCb-PAPER-2019-017,018

- **New** analysis (3 fb^{-1} of Run 1 LHCb data):

  Construct an explicit **amplitude model** for the decay

- **Three** approaches, that differ in the S-wave (spin-0) description:

  'K-matrix':
  Single unitarity conserving model, with parameters from scattering data

  'Isobar':
  Individual hand-engineered components for each contribution, does not conserve unitarity

  'Quasi-model-independent':
  Fit for a magnitude and phase in bins of the phase-space

The ‘K-matrix’ S-wave model

Sum over
resonance poles

https://arxiv.org/abs/hep-ph/0204328

Phase space

Production vector

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

Rescattering matrix

Describes initial B ‘production’ state, and propagation into all final states:

$$\hat{K}_{uv}(s) = \left(\sum_{\alpha=1}^{N} \frac{g_u^{(\alpha)} g_v^{(\alpha)}}{m_\alpha^2 - s} + f_{uv}^{\mathrm{scatt}} \frac{m_0^2 - s_0^{\mathrm{scatt}}}{s - s_0^{\mathrm{scatt}}} \right) f_{A0}(s)$$

Parameters from
scattering data (fixed)

$$\hat{P}_v(s) = \sum_{\alpha=1}^{N} \frac{\beta_\alpha g_v^{(\alpha)}}{m_\alpha^2 - s} + f_v^{\mathrm{prod}} \frac{m_0^2 - s_0^{\mathrm{prod}}}{s - s_0^{\mathrm{prod}}}$$

Parameters from
extracted from fit

The ‘K-matrix’ S-wave model

Poles

Parameters from scattering data (fixed)

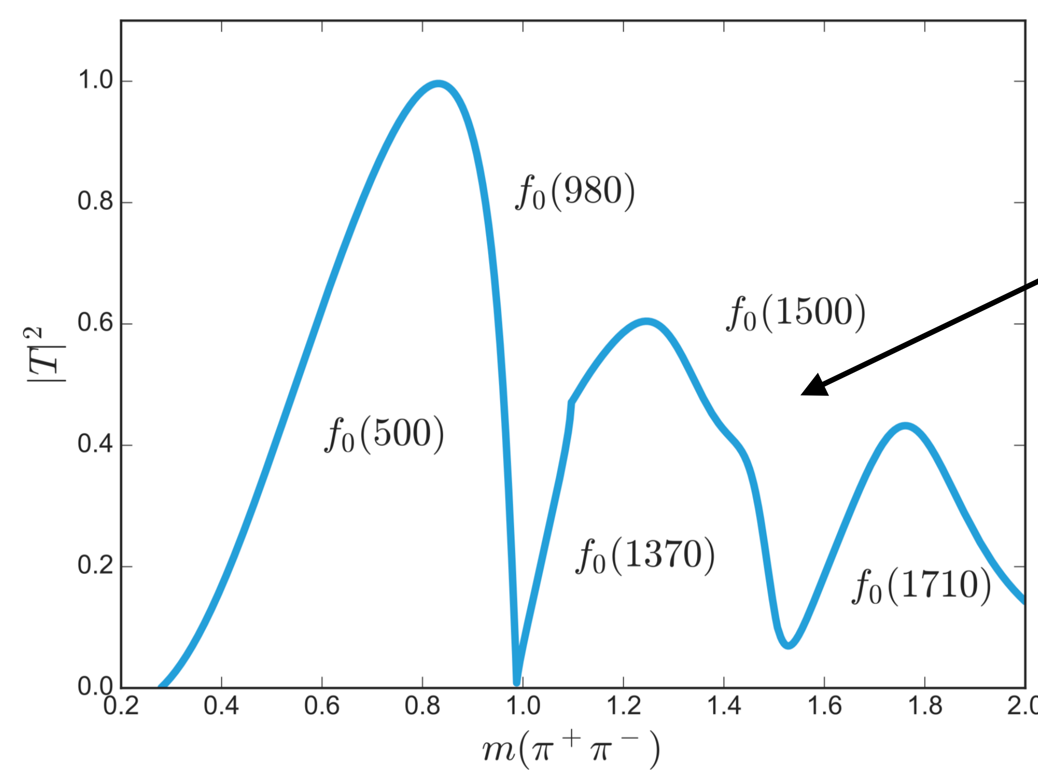
α	m_α	$g_1^{(\alpha)}[\pi\pi]$	$g_2^{(\alpha)}[K\bar{K}]$	$g_3^{(\alpha)}[4\pi]$	$g_4^{(\alpha)}[\eta\eta]$	$g_5^{(\alpha)}[\eta\eta']$
1	0.65100	0.22889	−0.55377	0.00000	−0.39899	−0.34639
2	1.20360	0.94128	0.55095	0.00000	0.39065	0.31503
3	1.55817	0.36856	0.23888	0.55639	0.18340	0.18681
4	1.21000	0.33650	0.40907	0.85679	0.19906	−0.00984
5	1.82206	0.18171	−0.17558	−0.79658	−0.00355	0.22358

s_0^{scatt}	f_{11}^{scatt}	f_{12}^{scatt}	f_{13}^{scatt}	f_{14}^{scatt}	f_{15}^{scatt}
−3.92637	0.23399	0.15044	−0.20545	0.32825	0.35412

s_0^{prod}	m_0^2	s_A	s_{A0}
−3.0	1.0	1.0	−0.15

Channels

Couplings



Describes entire S-wave in a single model

The 'Isobar' S-wave model

$$A_{\text{source}}(m) = [1 + (m/\Delta^2_{\pi\pi})]^{-1}[1 + (m/\Delta^2_{KK})]^{-1}$$

$$A_{\text{scatt}}(m) = A_{\text{source}}(m)\, f_{\text{rescatt}}(m).$$

$$f_{\text{rescatt}}(m) = \sqrt{1-\eta(m)^2}e^{2i\delta(m)}$$

Phase

$$\cot\delta = c_0\, \frac{(s-M_s^2)(M_f^2-s)}{M_f^2 s^{1/2}}\, \frac{|k_2|}{k_2^2},$$

Inelasticity

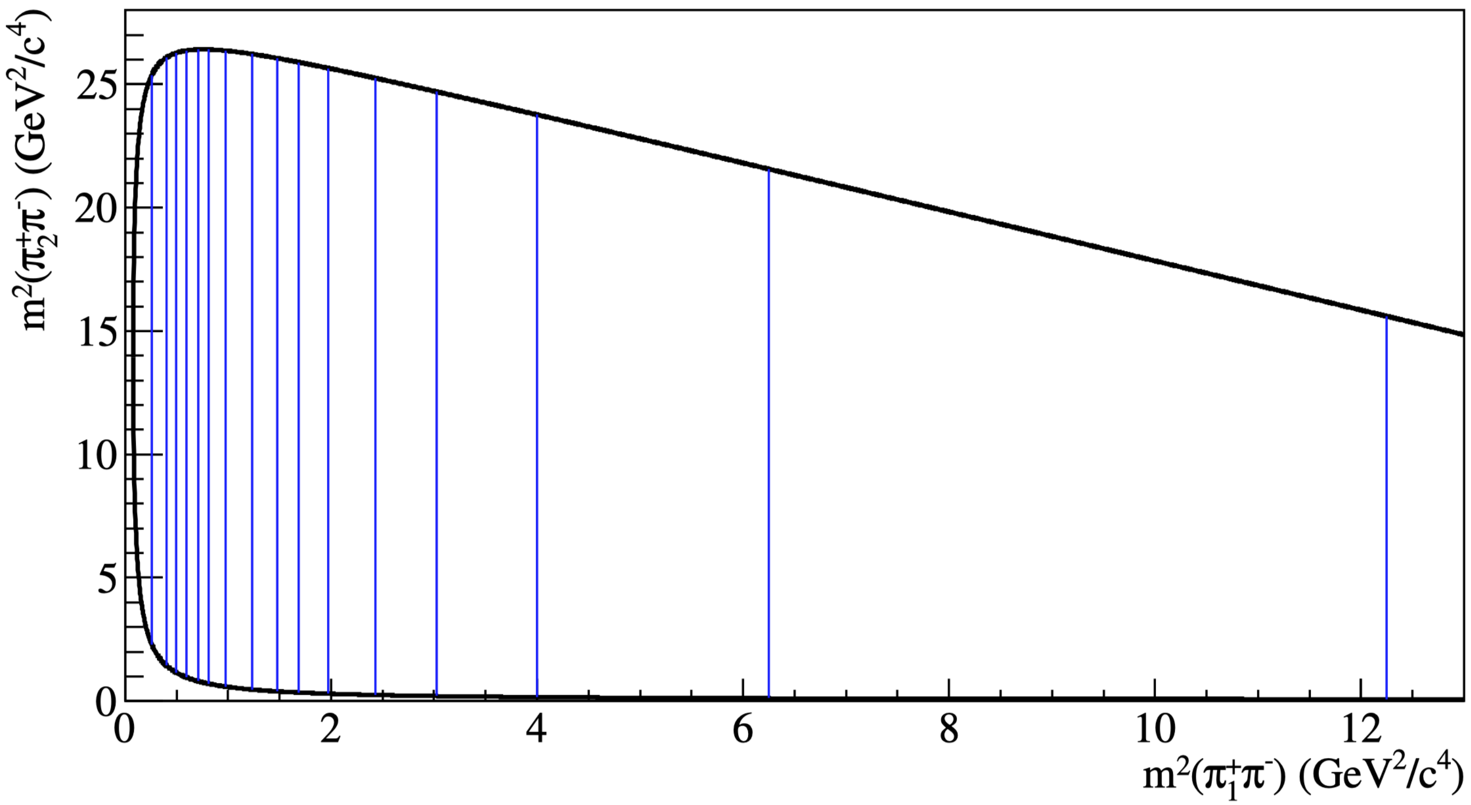
$$\eta = 1 - \left(\epsilon_1 \frac{k_2}{s^{1/2}} + \epsilon_2 \frac{k_2^2}{s}\right)\, \frac{M'^2 - s}{s}$$

$$k_2 = \frac{\sqrt{s-4m_K^2}}{2};$$

Parameters from $\pi\pi \to \pi\pi$ and $\pi\pi \to KK$ scattering data

The ‘QMI’ S-wave model

- 17 bins - 14 below the charm veto, 3 above

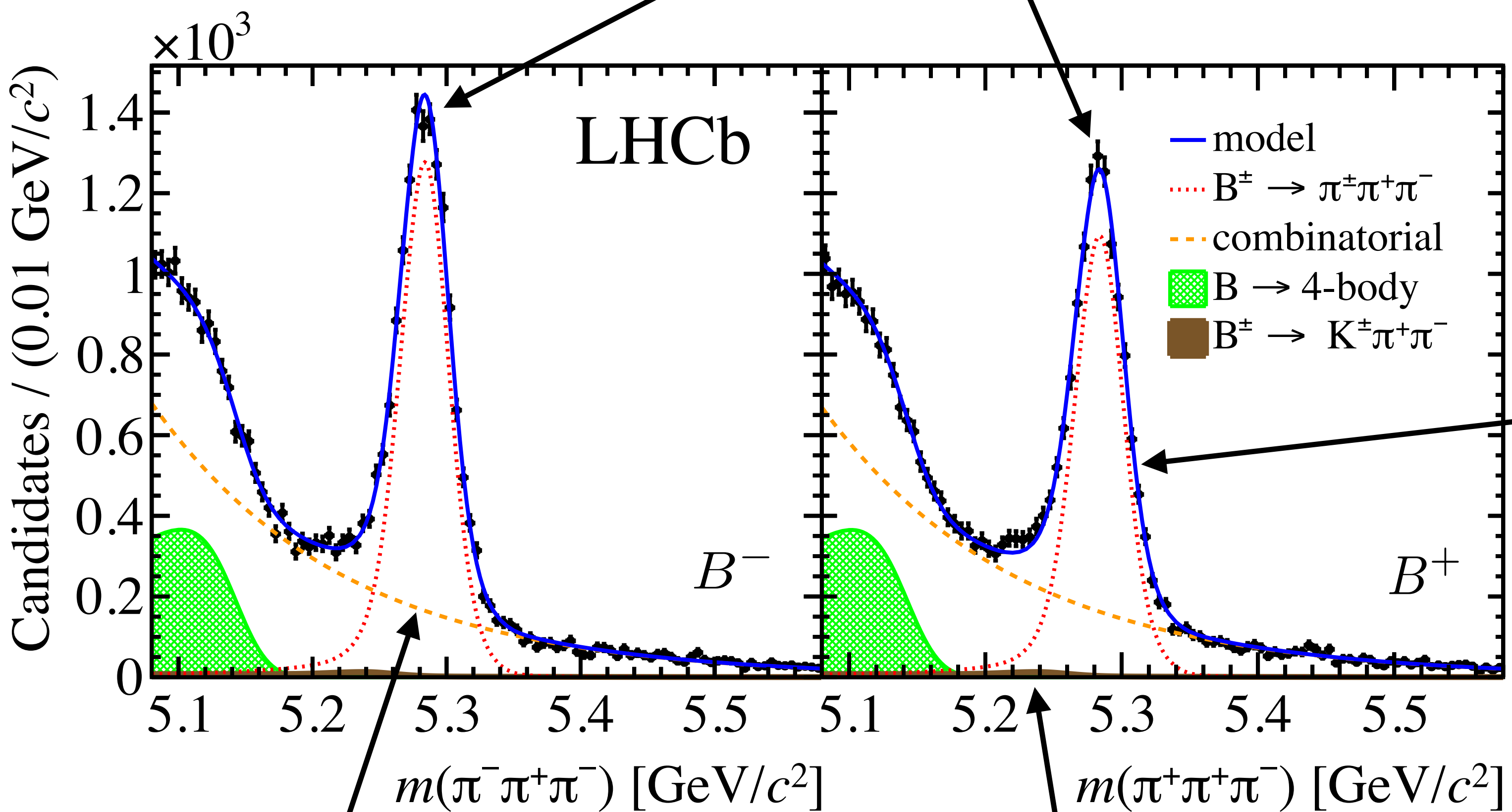


- Fit an independent magnitude and phase in each bin

$B^+ \to \pi^+\pi^+\pi^-$

- Invariant mass fit of $\pi^+\pi^+\pi^-$

Some phase-space integrated asymmetry



Signal yield of around 20,000 candidates

Largest background from random pions

Other background from $B^+ \to K^+\pi^+\pi^-$ include in the model

Model construction

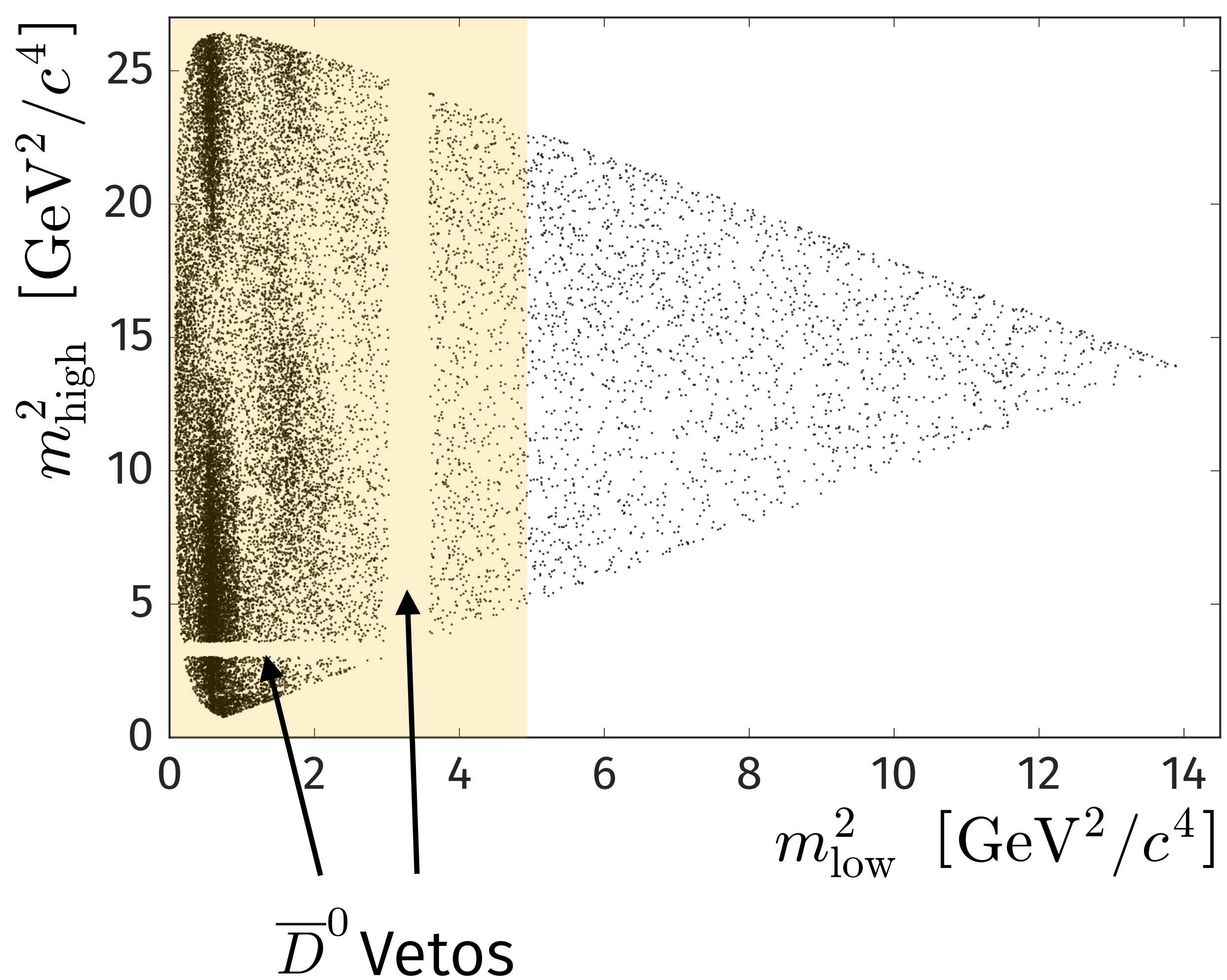
- Start with components identified by the BaBar analysis of this mode, that used 20x fewer decays **Phys. Rev. D72 (2005) 052002**

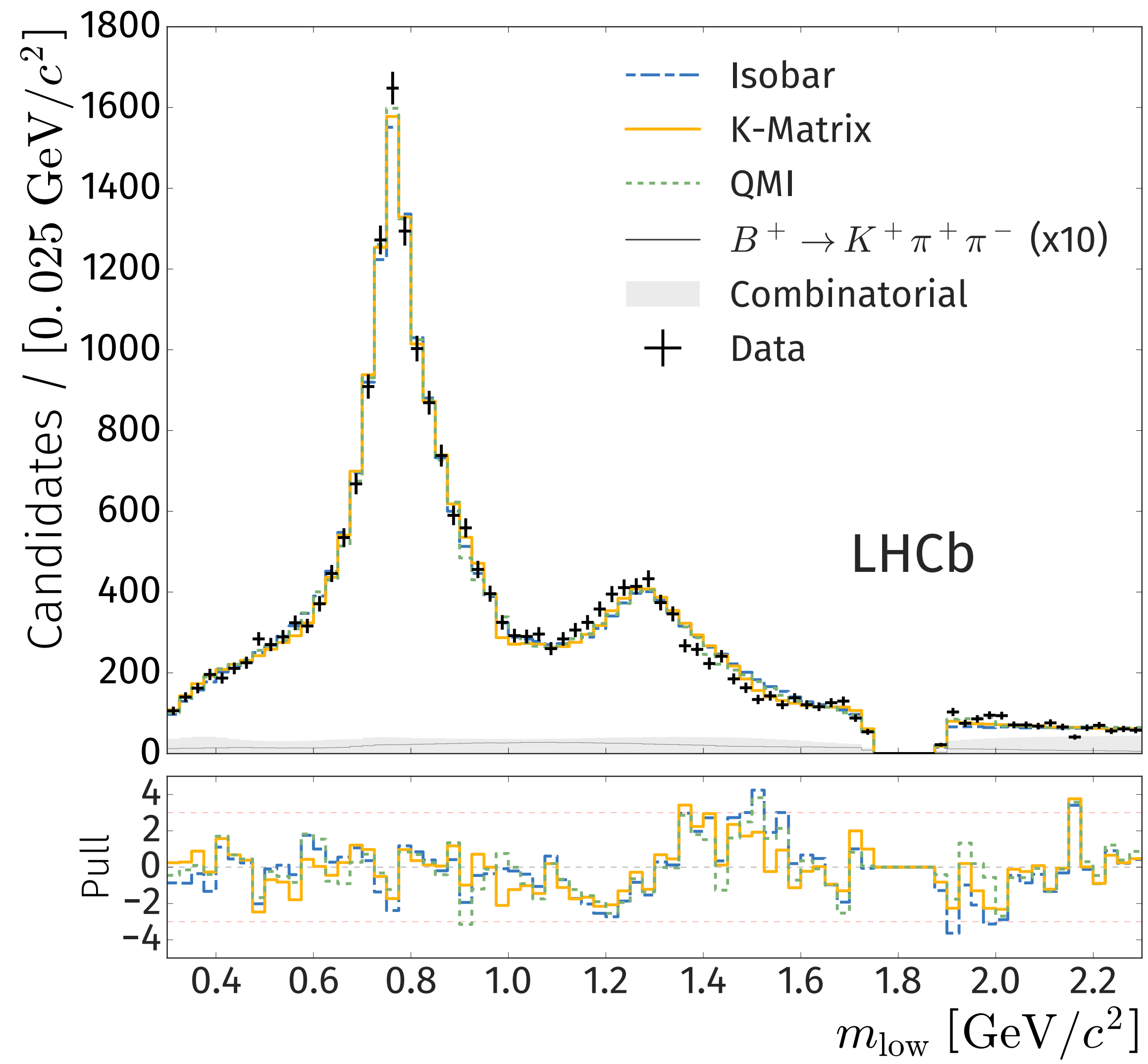
- Include additional components based on a **likelihood ratio test**, with a threshold of 10 units of negative log-likelihood for inclusion

More accurate model for $\rho(770)^0$ width

S-wave	(See previous slide)
$\rho(770)^0$	**Gounaris-Sakurai model**
$\omega(782)$	Relativistic Breit-Wigner
$f_2(1270)$	Relativistic Breit-Wigner
$\rho(1450)^0$	Relativistic Breit-Wigner
$\rho_3(1690)^0$	Relativistic Breit-Wigner

$B^+ \to \pi^+\pi^+\pi^-$

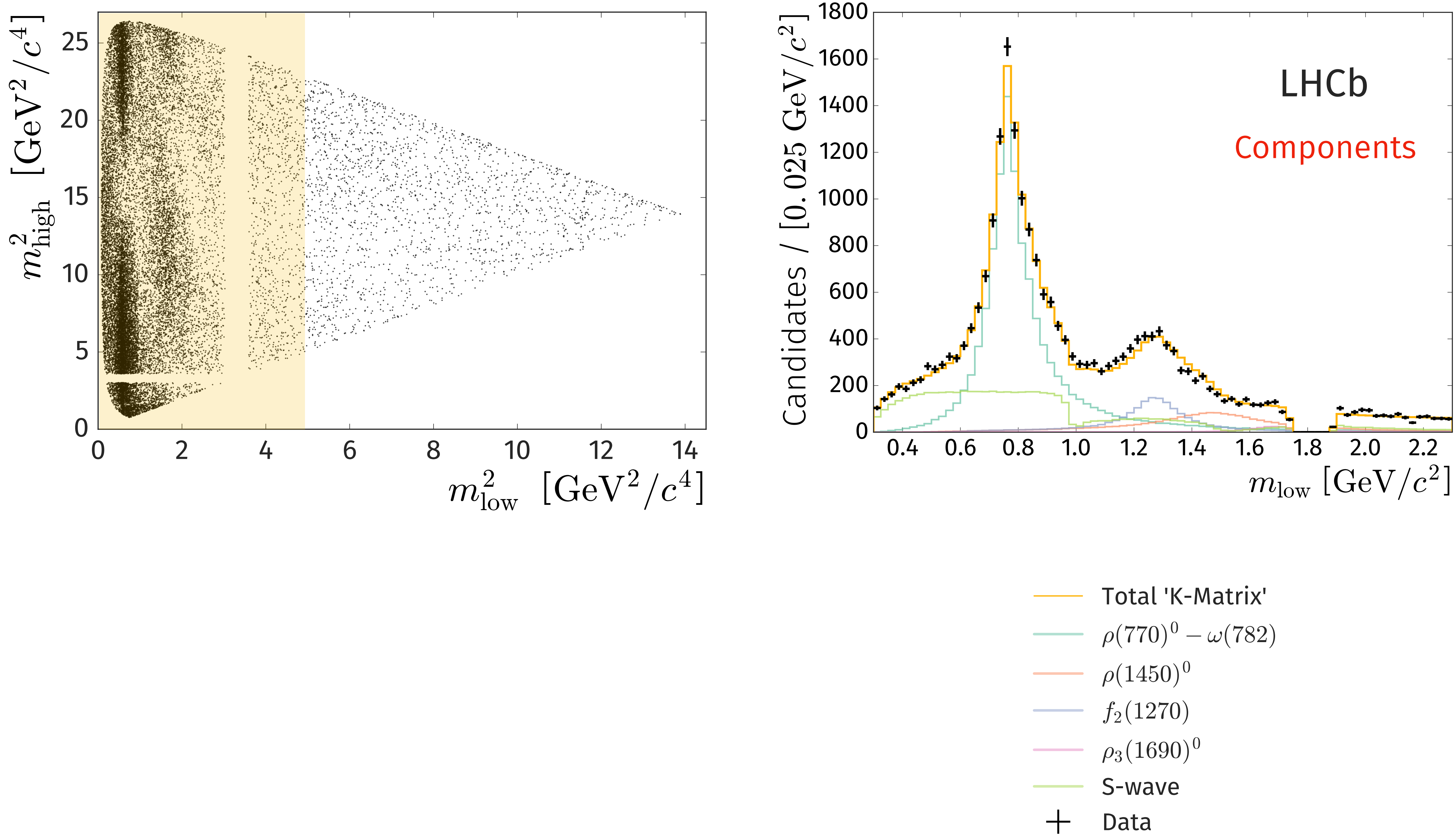




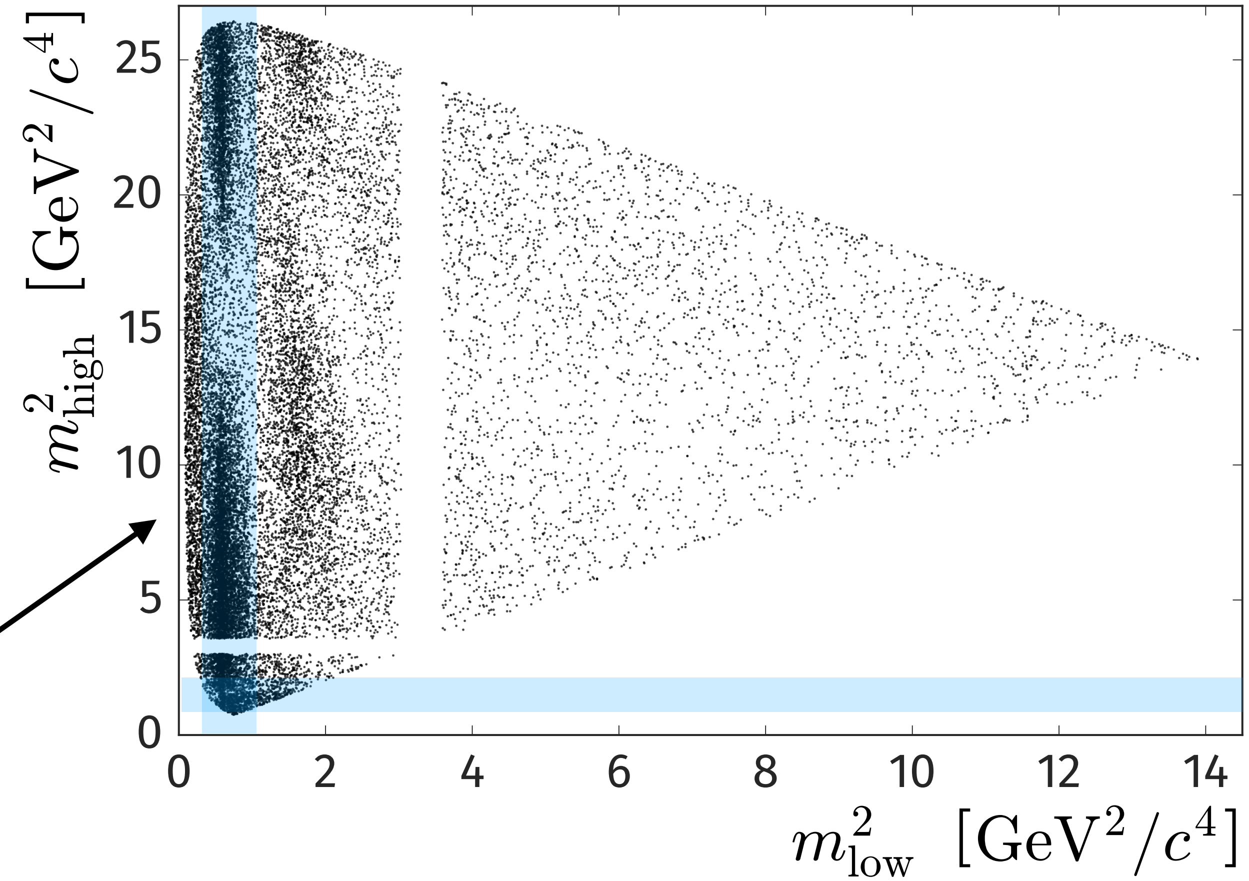
Weak decays to $\pi^+\pi^-$ and $K^+\pi^-$,

very narrow resonances

$B^+ \to \pi^+\pi^+\pi^-$

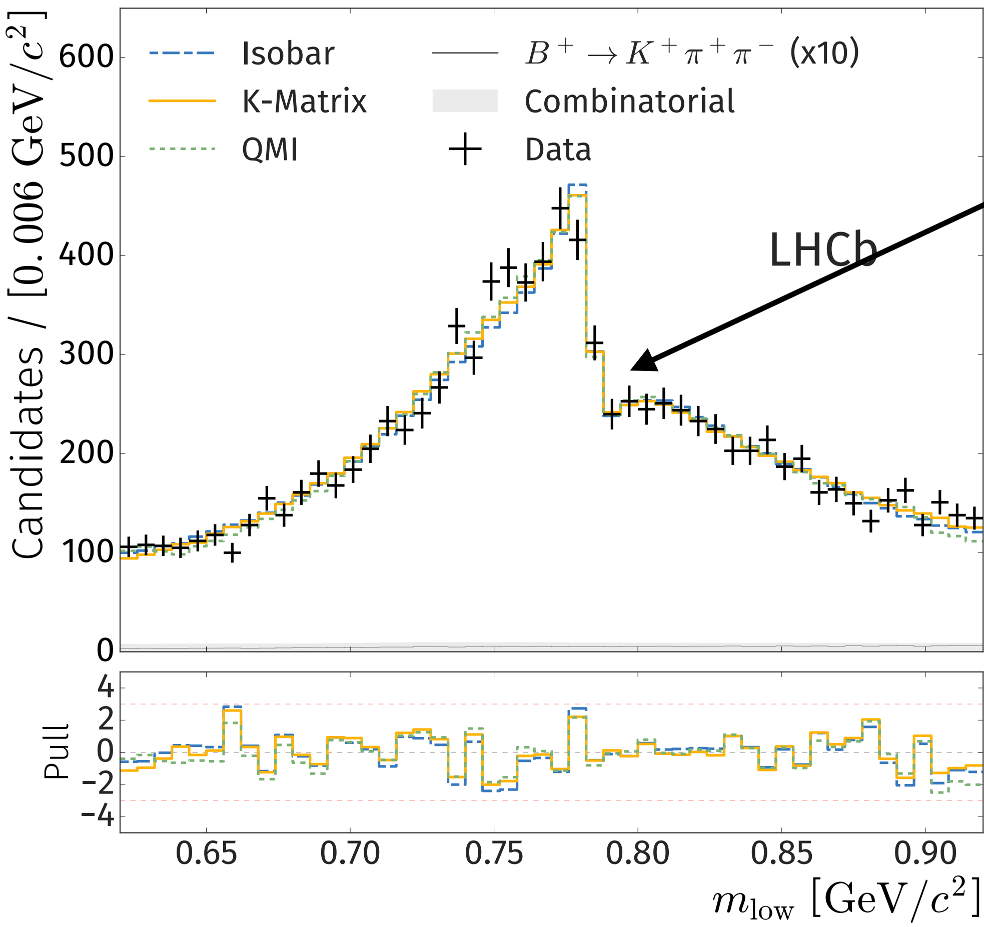


m^2_{high} [GeV$^2/c^4$]
m^2_{low} [GeV$^2/c^4$]
Candidates / [0.025 GeV/c^2]
m_{low} [GeV/c^2]
LHCb
Components
Total 'K-Matrix'
$\rho(770)^0 - \omega(782)$
$\rho(1450)^0$
$f_2(1270)$
$\rho_3(1690)^0$
S-wave
Data


m^2_{high} $[\mathrm{GeV}^2/c^4]$
25
20
15
10
5
0
0
2
4
6
8
10
12
14
m^2_{low} $[\mathrm{GeV}^2/c^4]$

$\rho(770)^0$

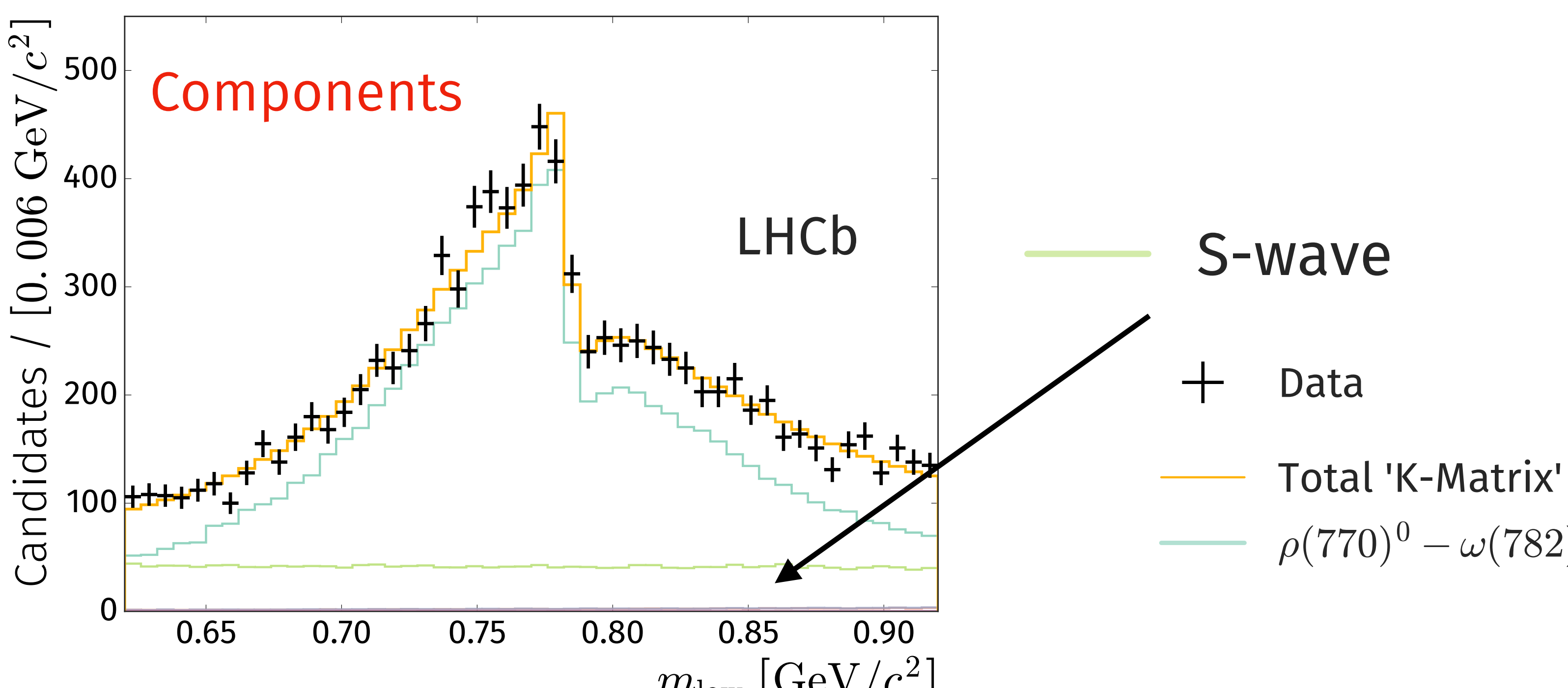
$\rho(770)^0$

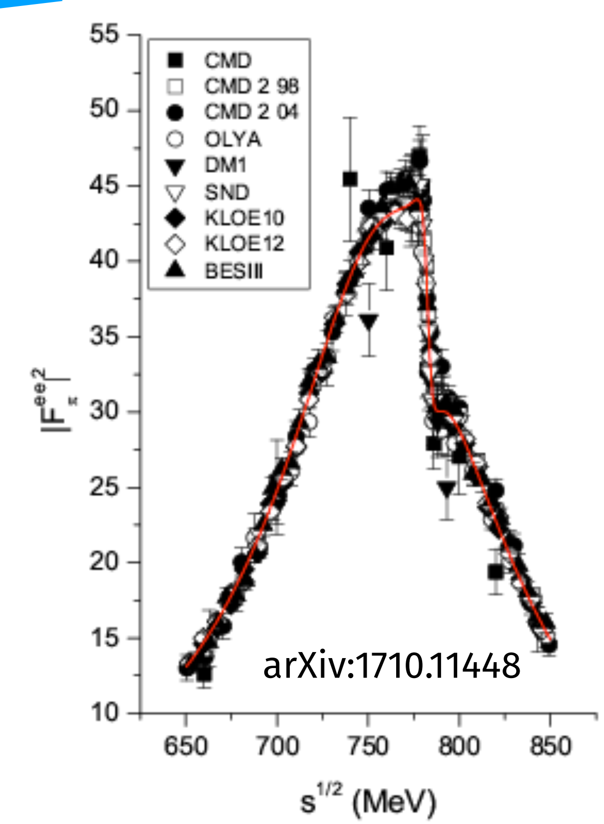


$\rho(770)^0 \; - \; \omega(782)$
Mixing

$\omega(782)$ is forbidden to decay to $\pi^+\pi^-$ due to isospin conservation

However, it can **mix** with the $\rho(770)^0$, causing a drop in the $\rho(770)^0$ amplitude above the mass of the $\omega(782)$

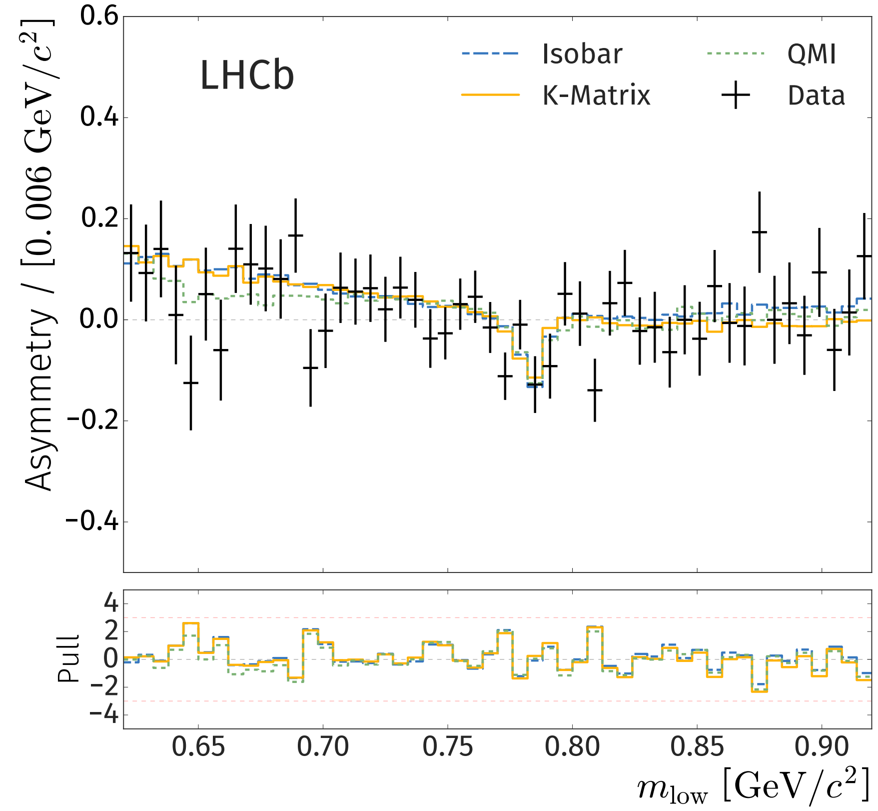




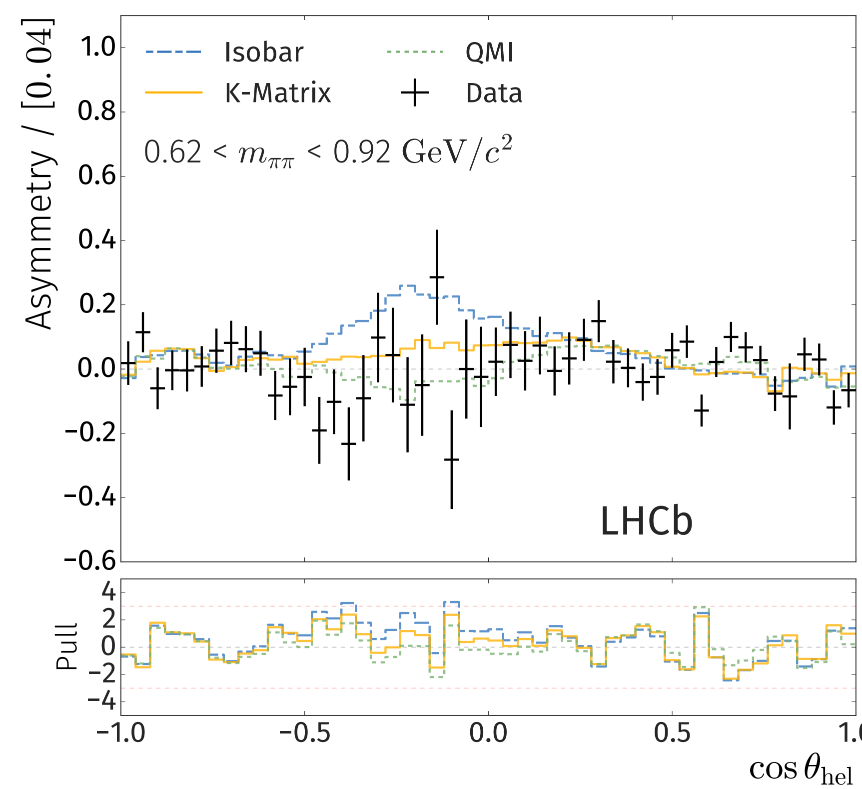
$\rho(770)^0$

- Very little asymmetry in this region as a function of **mass**:

$$\Rightarrow A_{\mathrm{CP}}(\rho(770)^0) \to 0$$



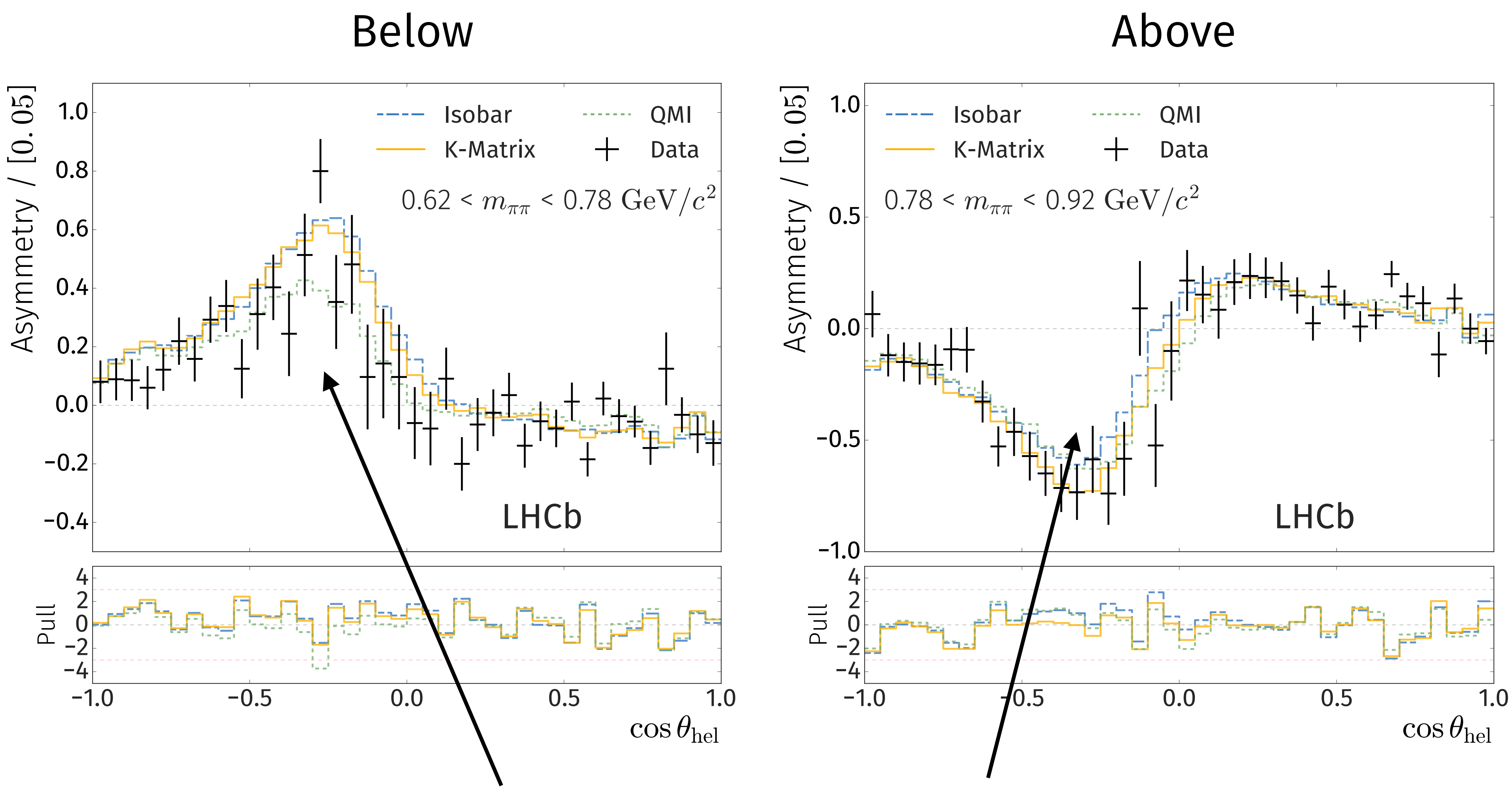
- Also very little asymmetry as a function of **helicity angle**...



- ...so where is the CP violation?

$\rho(770)^0$

- Below and above the $\rho(770)^0$ mass:



Almost perfect cancellation!

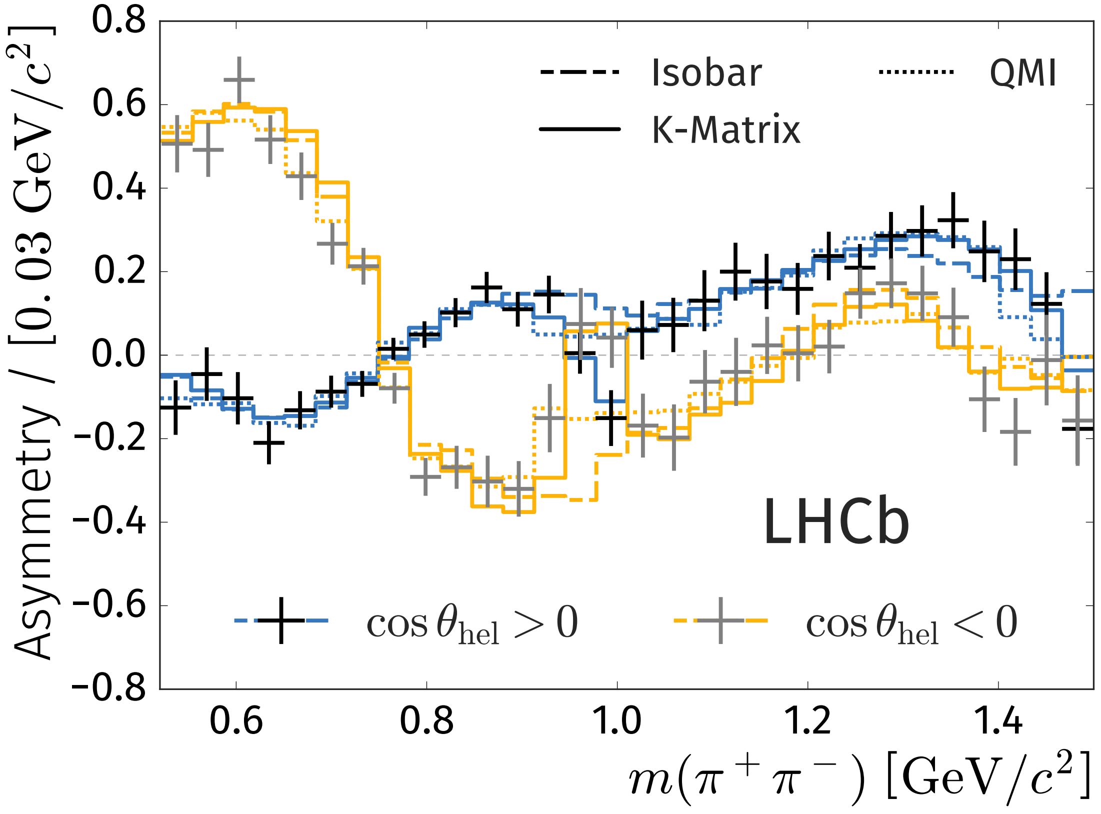
$\rho(770)^0$

- But why?

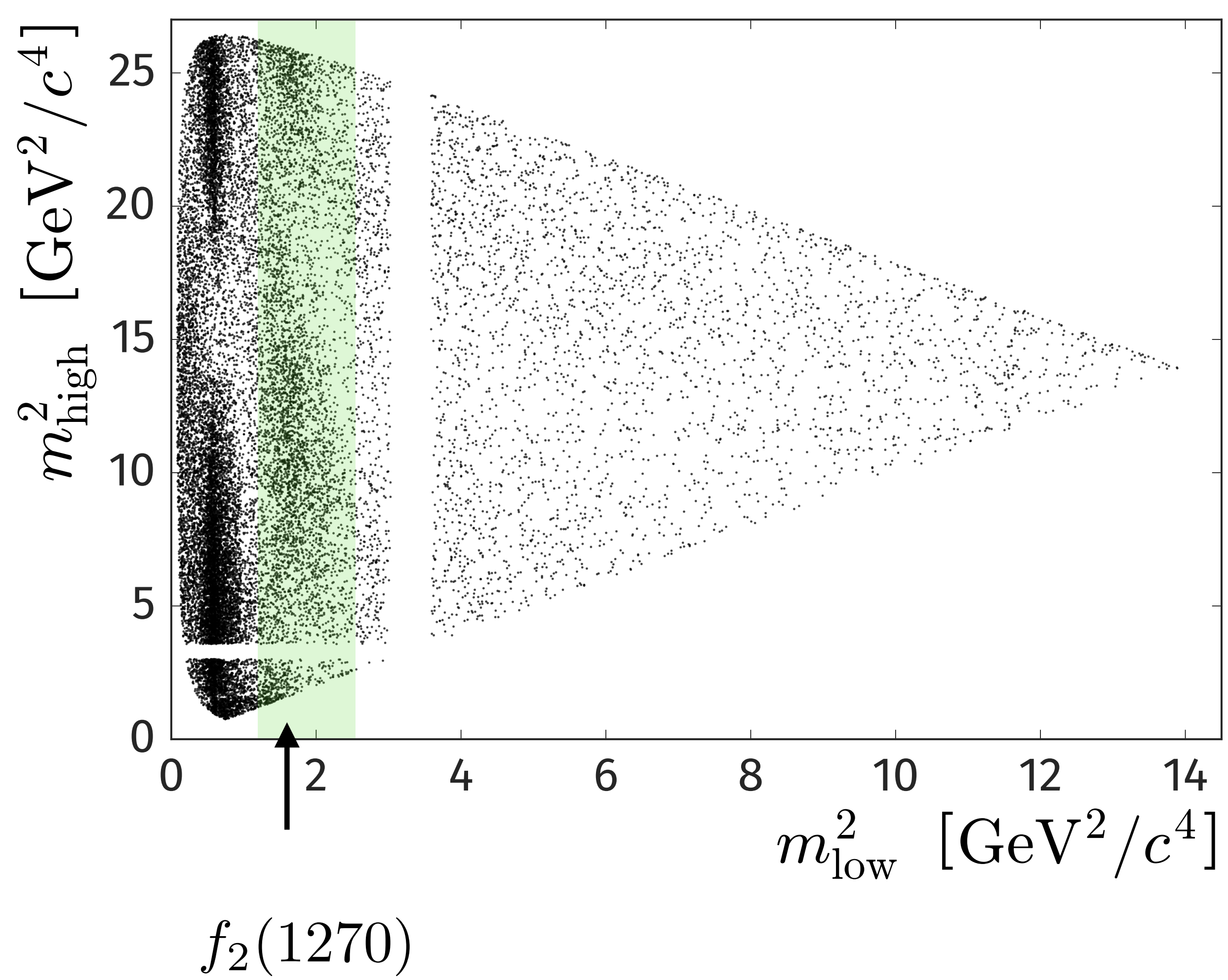
This region is dominated by slowly varying spin 0, and the rapidly varying spin-1 $\rho(770)^0$

Interference term between these is $\sim \cos\theta_{\rm hel}$, when projecting on mass (integrating over $\cos\theta_{\rm hel}$) this term **vanishes!**

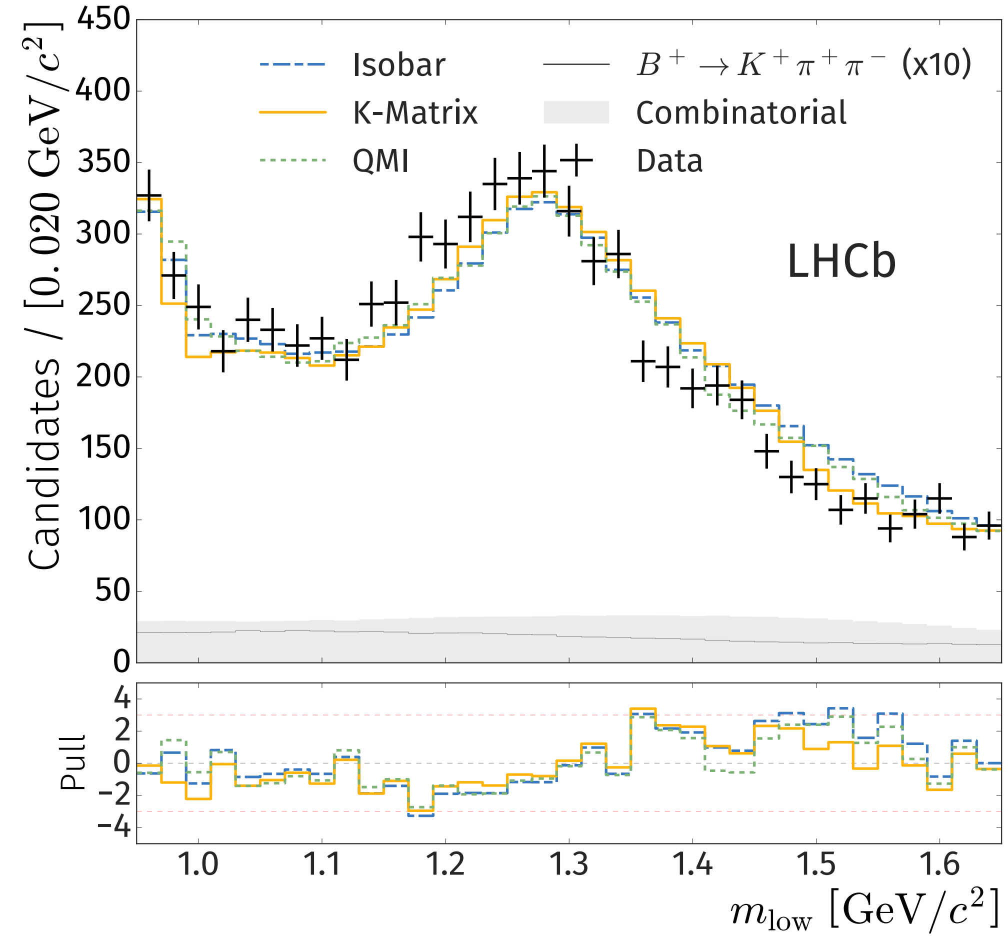
CP violation is driven by the **strong phase** of the resonance, varies as a function of mass, symmetric about the pole



$B^+ \to \pi^+\pi^+\pi^-$

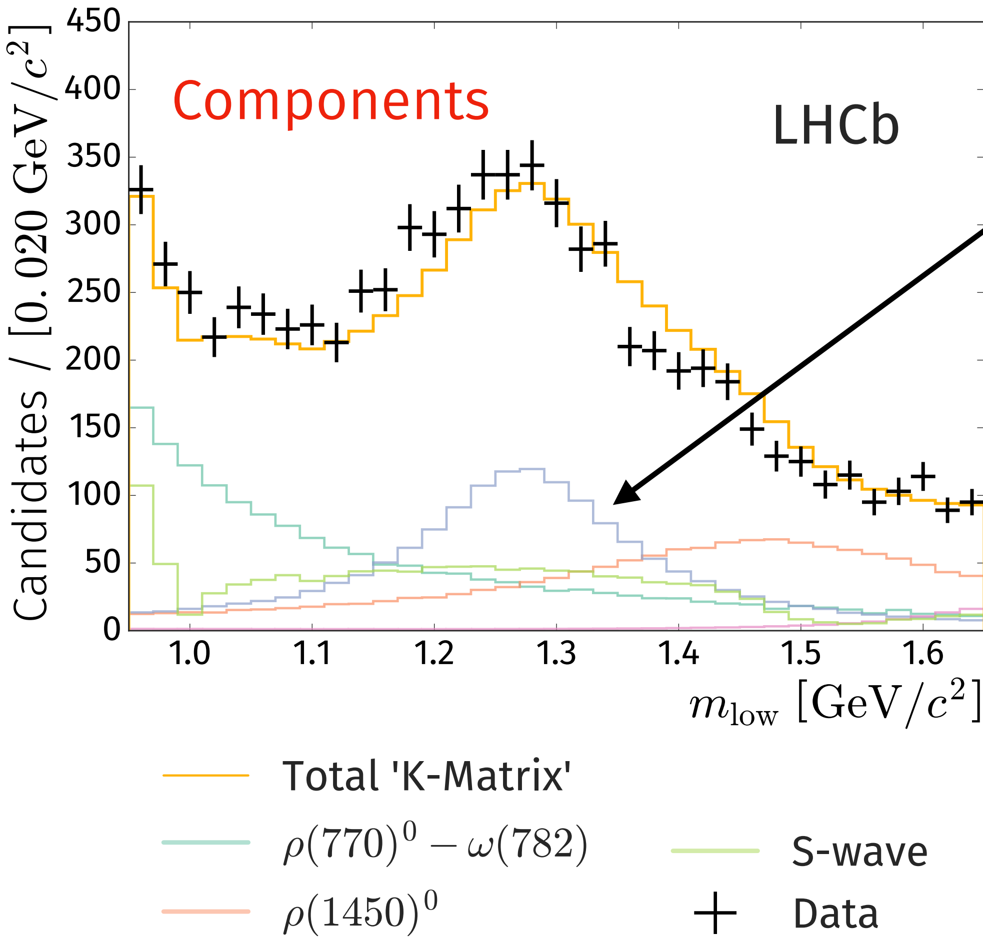


$m^2_{\rm high}$ [GeV$^2/c^4$]
$m^2_{\rm low}$ [GeV$^2/c^4$]
$f_2(1270)$



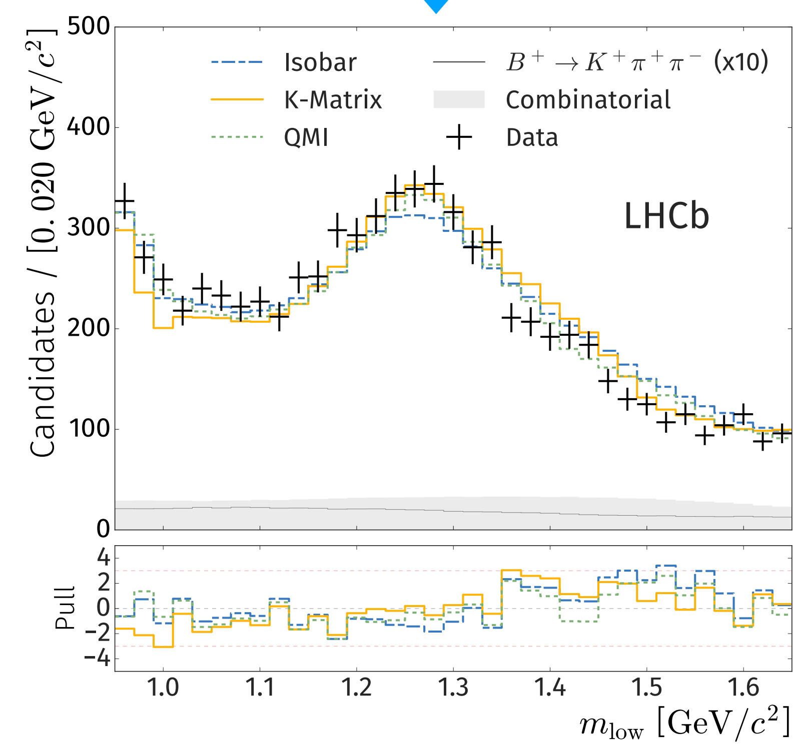
Isobar
K-Matrix
QMI
$B^+ \to K^+\pi^+\pi^-$ (x10)
Combinatorial
Data
LHCb
Candidates / [0.020 GeV/c^2]
Pull
$m_{\rm low}$ [GeV/c^2]

$f_2(1270)$



$f_2(1270)$

- Fit quality is not too good in this region, looks like $f_2(1270)$ mass is **'shifted'**
- With a **free mass parameter**, this ends up being around **1255 ± 4 MeV**, with the PDG average being **1275.5 ± 0.8 MeV**



- Plausible that observed resonance properties depend on the **production environment** - most from the PDG measurements were **not** B decays

$f_2(1270)$

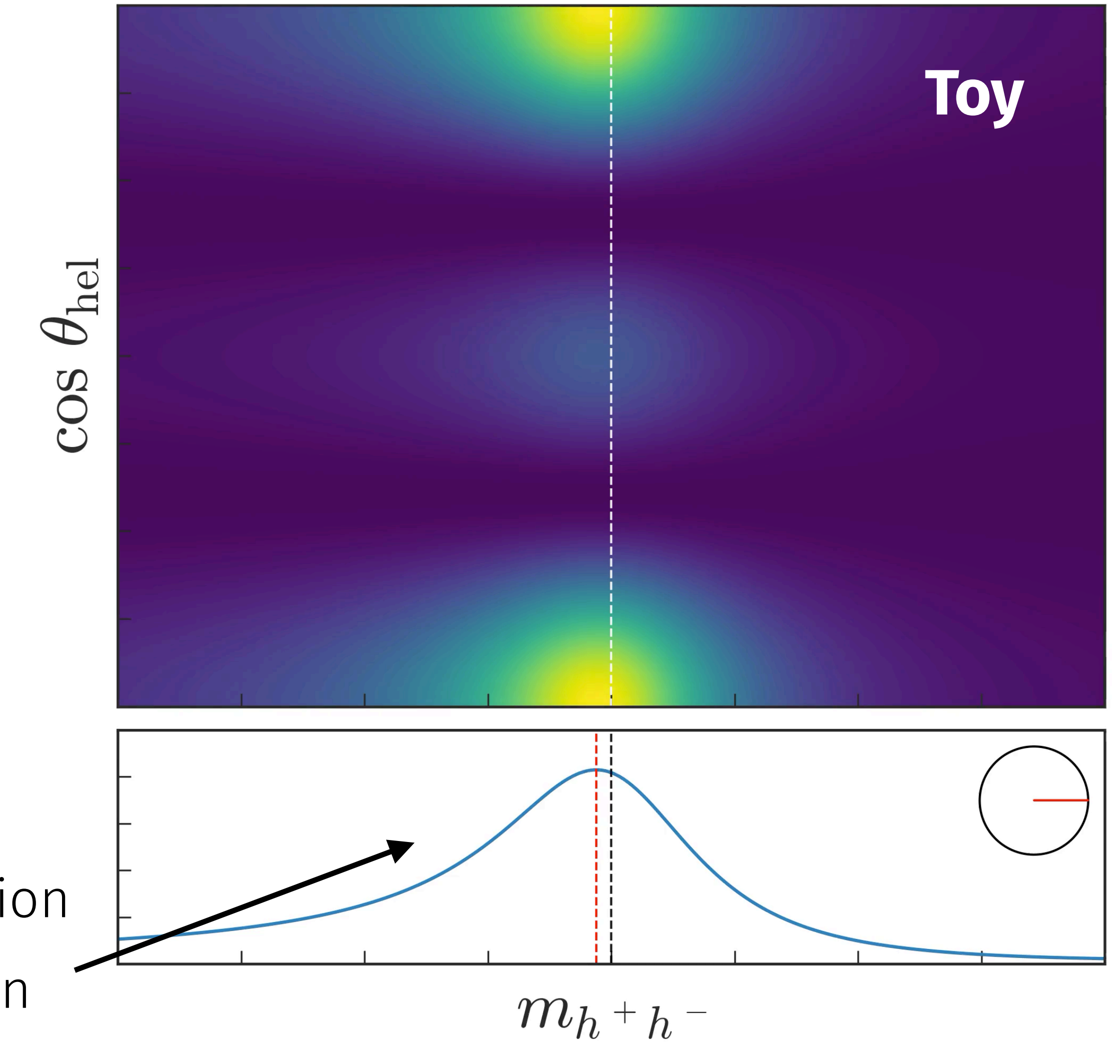
- **Also** plausible that this is due to the interference with an **additional** spin-2 state

- Interferences with other spin states **cancel** when integrating over helicity

- This additional resonance can change the **'observed'** peak position…

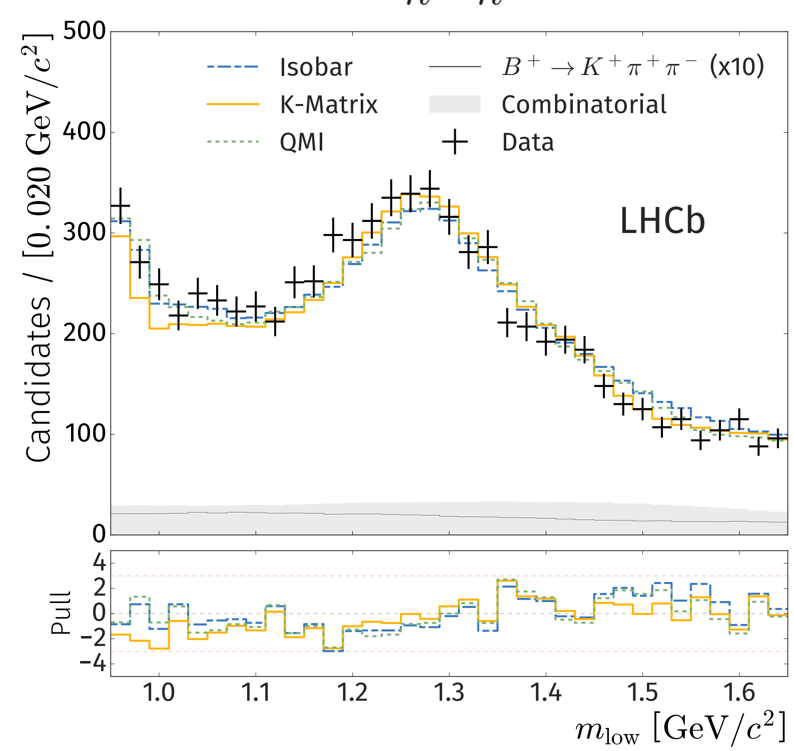
- …but as long as we include it in the model, we always get the right mass value!

Dominant resonance
(additional broad state not visible)



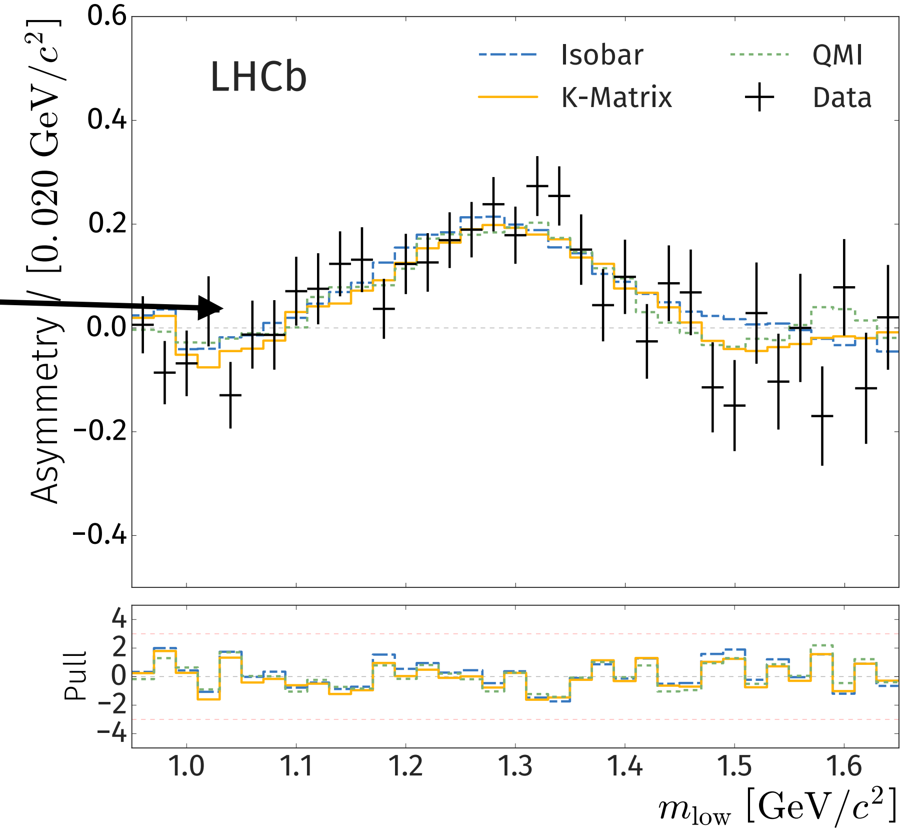
Peak position depends on relative phase

With an additional f_2

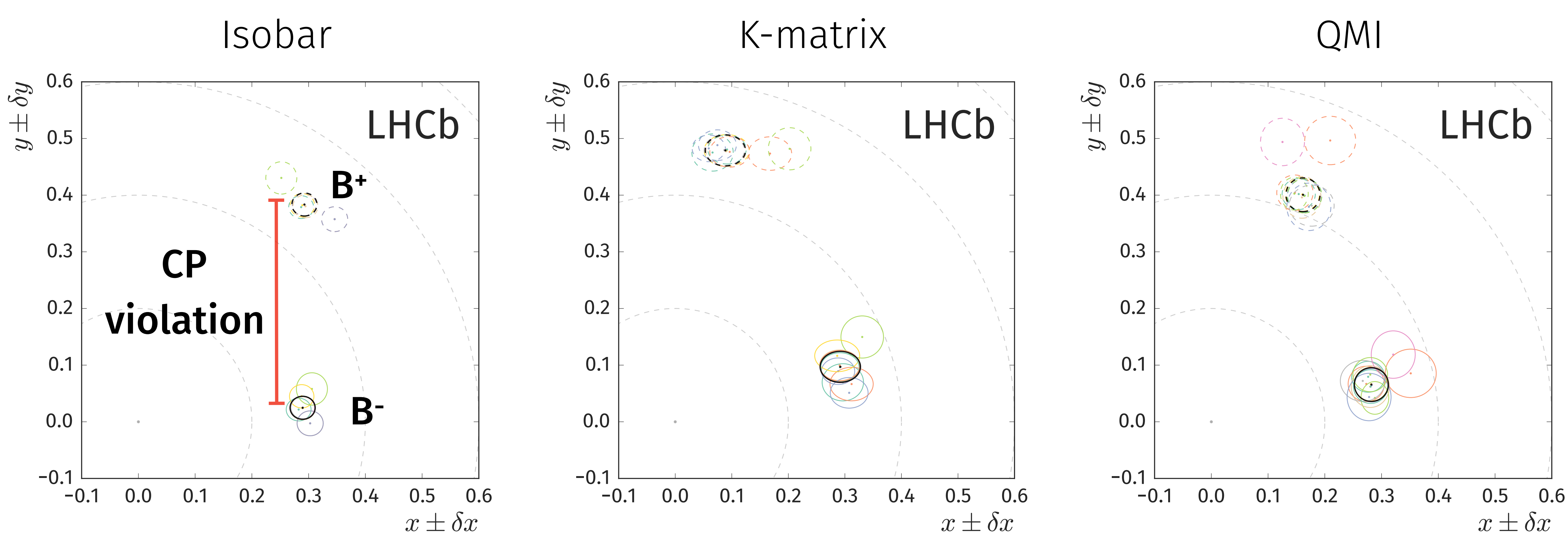


$f_2(1270)$

- Very large asymmetry in this region, associated with the $f_2(1270)$ component, an A_{CP} of around 40% in all models

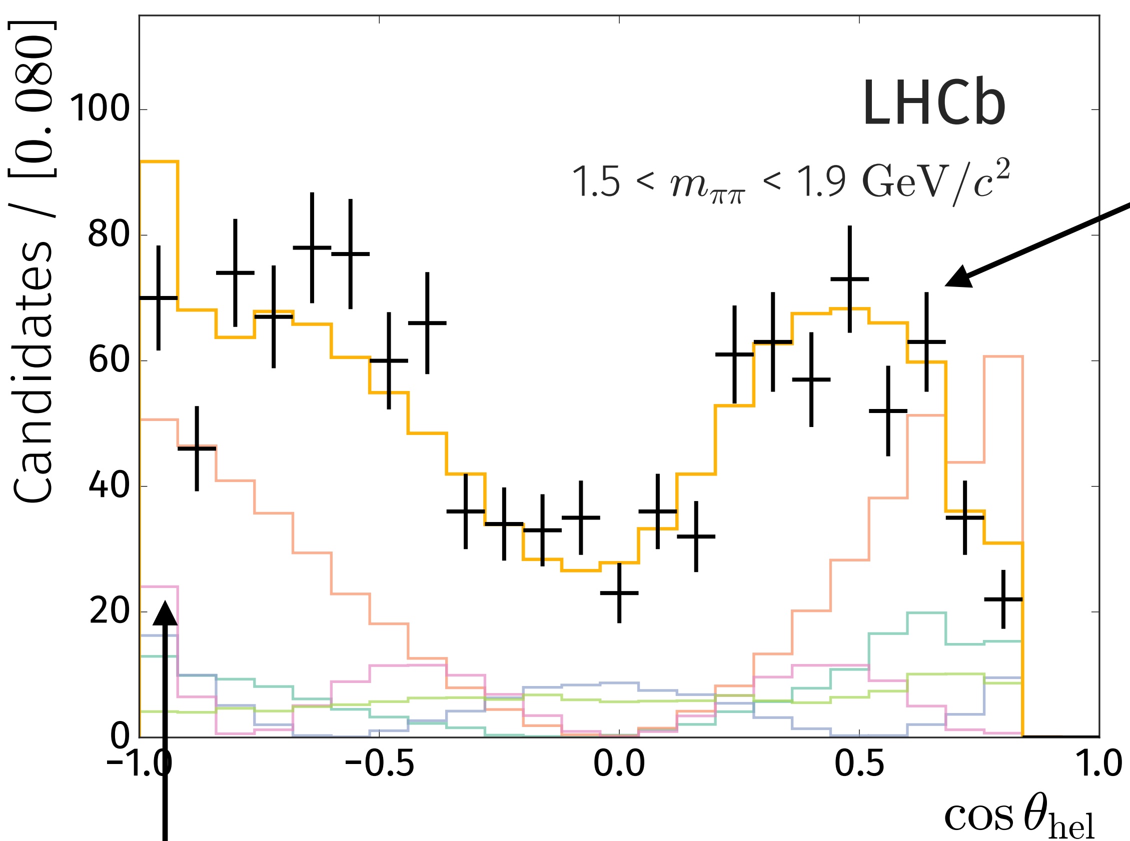


- Robust to systematic effects
- One of the largest CP asymmetries ever observed!



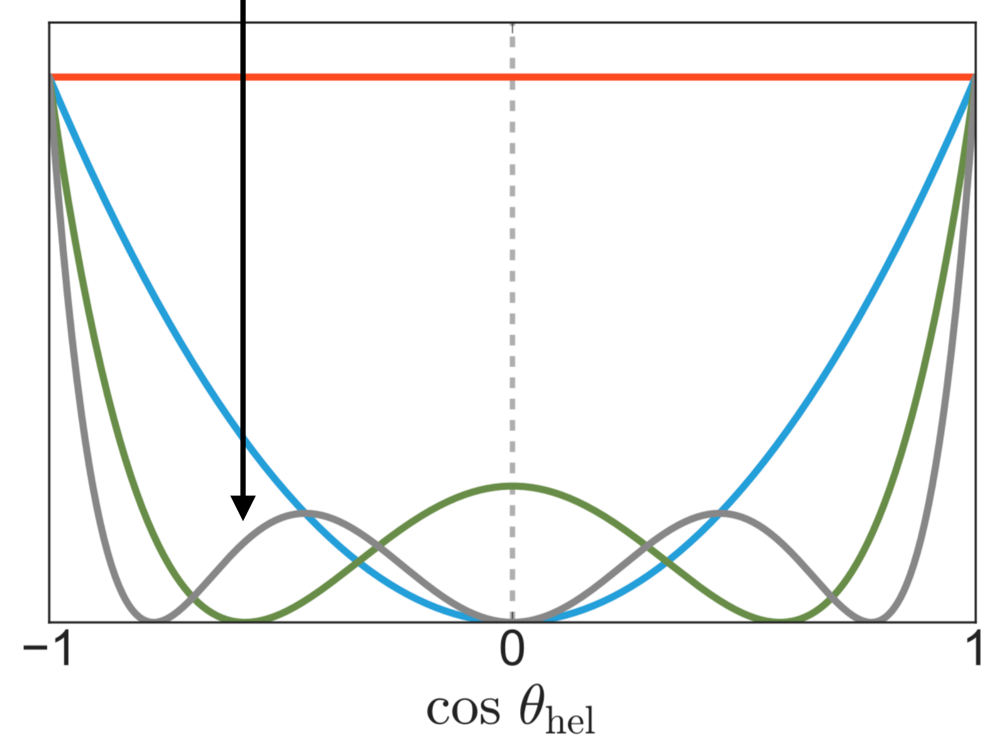
$\rho_3(1690)$

- Interesting distribution in the helicity angle around 1700 MeV



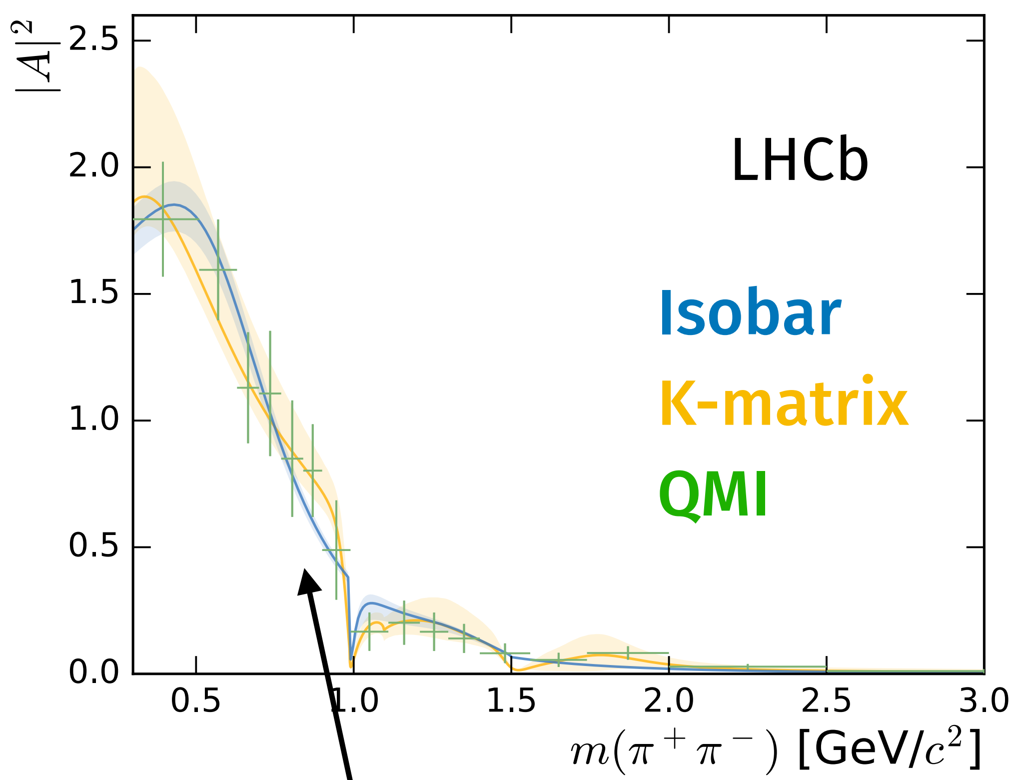
$\rho_3(1690)$ contribution

- Four lobe structure characteristic of a spin-3 resonance



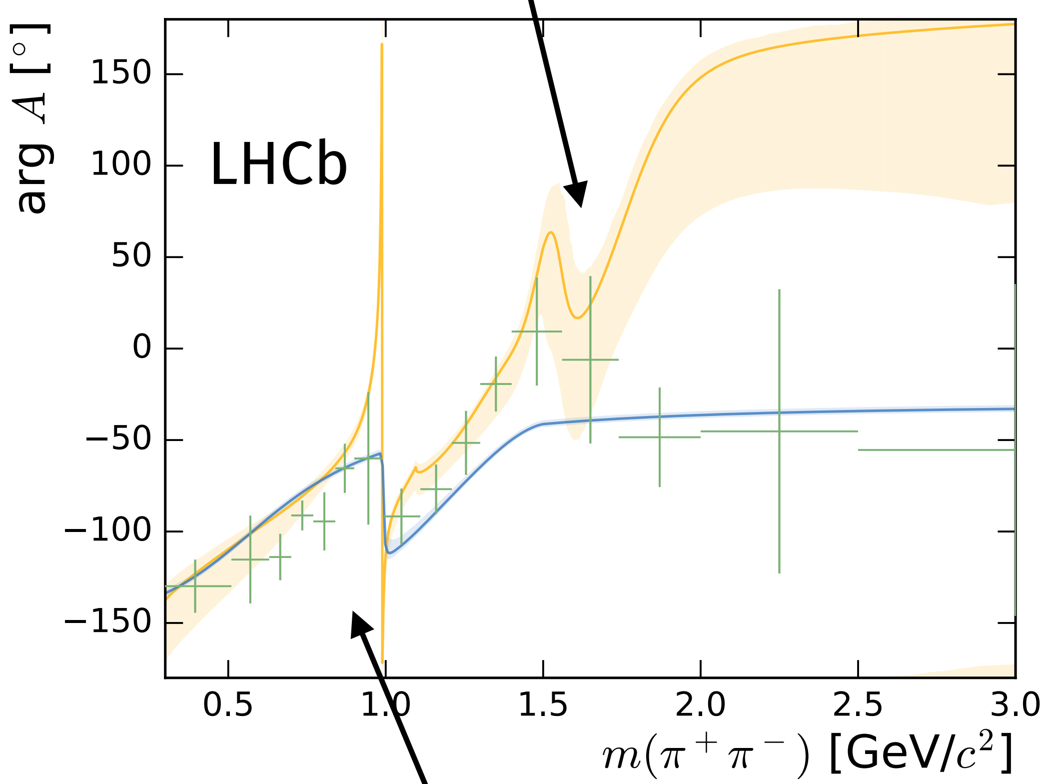
- Unfortunately not quite 5σ, lots of background in this region

S-wave model projections - comparisons



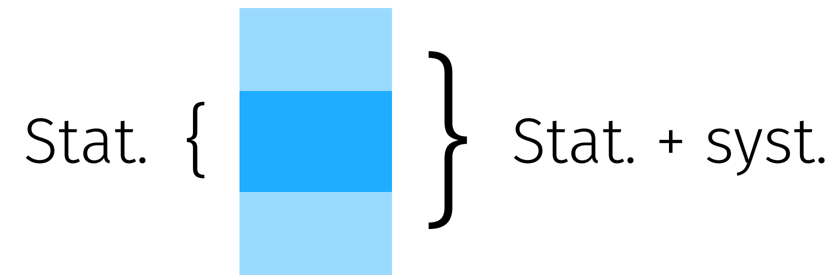
Agreement between magnitudes is very good

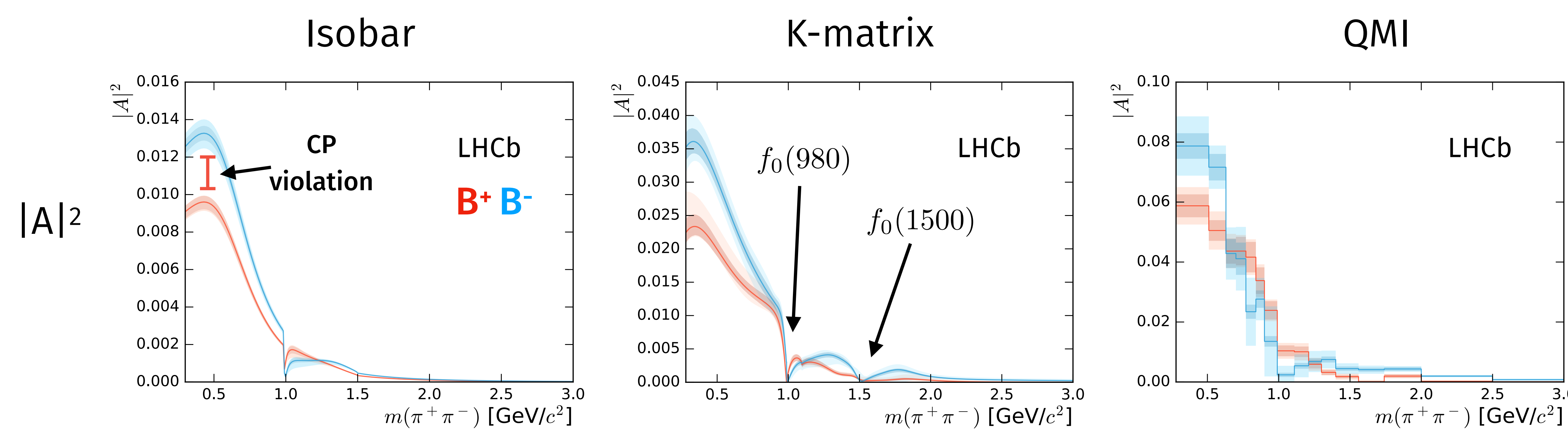
No $f_0(1500)$ in the isobar model



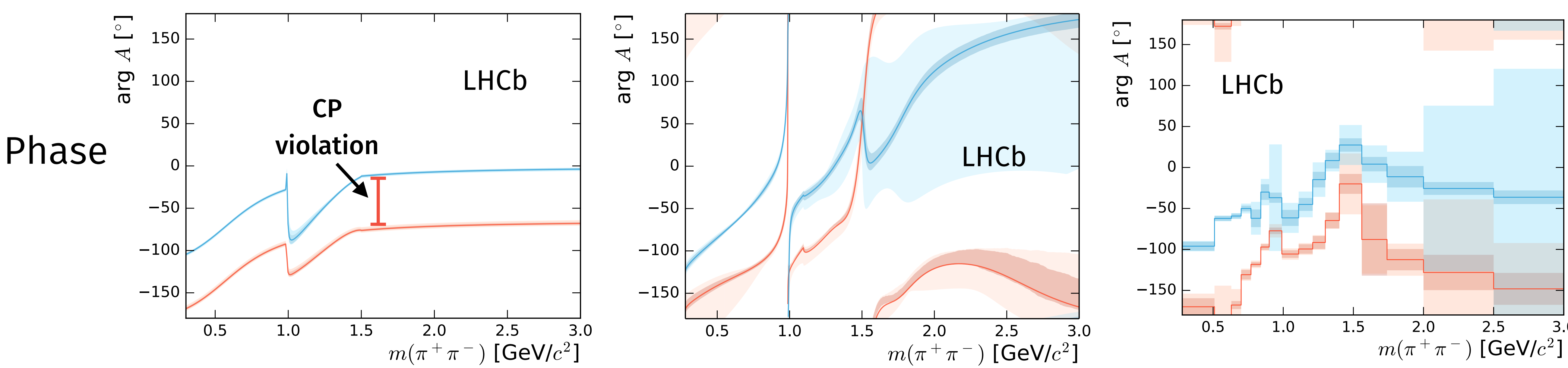
Phases are harder to get right, models rely on different assumptions

S-wave model projections





CP violation is pretty evident here!

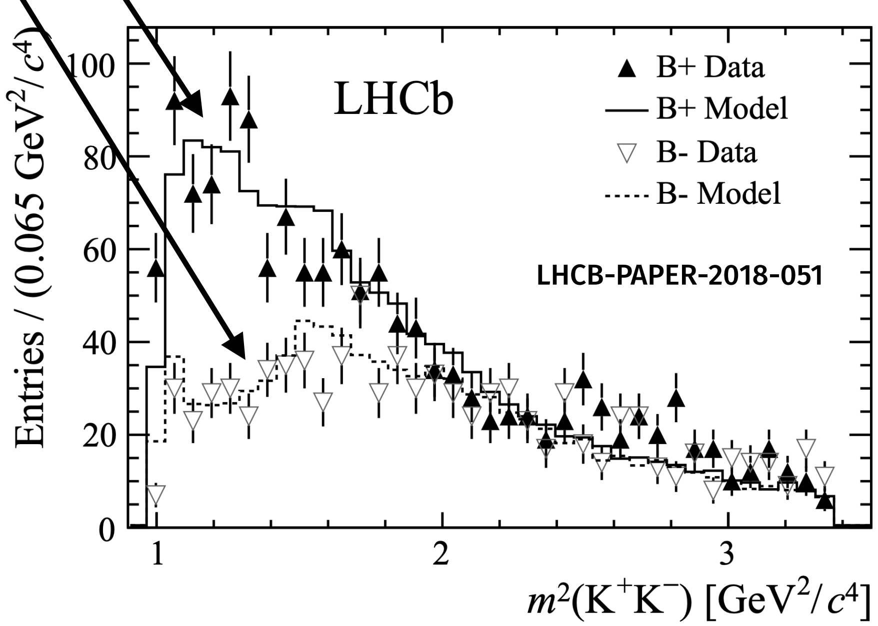


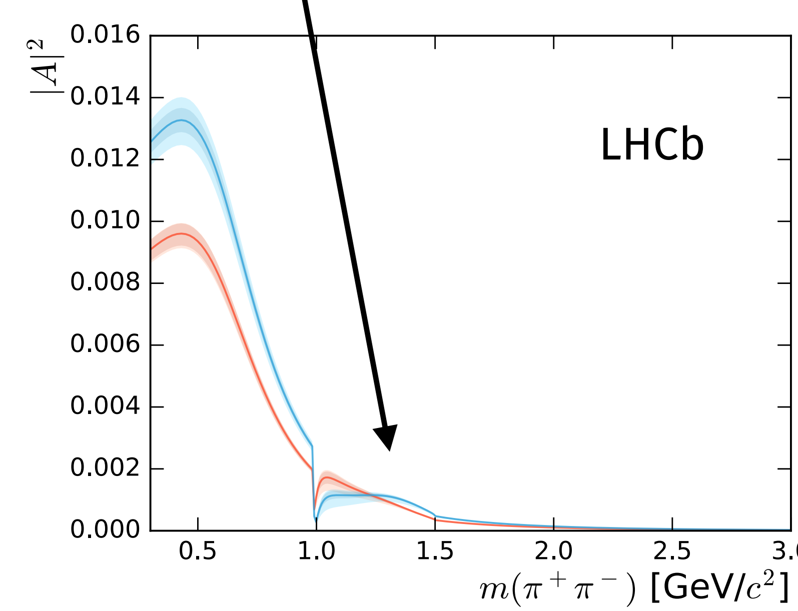
Correspondence with $B^+ \to K^+\pi^+K^-$

- Possible for strong phase generation via **final-state re-scattering**: $\pi^+\pi^- \leftrightarrow K^+K^-$

  This would imply that there is a relation between the scalar components of the $B^+ \to K^+\pi^+K^-$ and $B^+ \to \pi^+\pi^+\pi^-$ decays

- Large CP asymmetry observed in the re-scattering (~1.0 - ~1.5 GeV) range in $B^+ \to K^+\pi^+K^-$ of around 66%, but less in $B^+ \to \pi^+\pi^+\pi^-$





- To gain more information on this phenomenon would required a **coupled channel** analysis of both decay modes

Numerical results

- **Fit-fractions** - the rate if only this component contributed

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$55.5 \pm 0.6 \pm 0.7 \pm 2.5$	$56.5 \pm 0.7 \pm 1.5 \pm 3.1$	$54.8 \pm 1.0 \pm 1.9 \pm 1.0$
$\omega(782)$	$0.50 \pm 0.03 \pm 0.03 \pm 0.04$	$0.47 \pm 0.04 \pm 0.01 \pm 0.03$	$0.57 \pm 0.10 \pm 0.12 \pm 0.12$
$f_2(1270)$	$9.0 \pm 0.3 \pm 0.8 \pm 1.4$	$9.3 \pm 0.4 \pm 0.6 \pm 2.4$	$9.6 \pm 0.4 \pm 0.7 \pm 3.9$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 0.4 \pm 1.9$	$10.5 \pm 0.7 \pm 0.8 \pm 4.5$	$7.4 \pm 0.5 \pm 3.9 \pm 1.1$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.5 \pm 0.1$
S-wave	$25.4 \pm 0.5 \pm 0.7 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

$$\mathcal{F}_j = \frac{\int_{\mathrm{PhSp}} |A_j|^2 + |\overline{A}_j|^2 d\mathrm{PhSp}}{\int_{\mathrm{PhSp}} |\sum_j A_j|^2 + |\sum_j \overline{A}_j|^2 d\mathrm{PhSp}}$$

- Quasi-two-body **CP asymmetries** - asymmetry of a single component

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 1.2 \pm 1.5$	$+4.2 \pm 1.5 \pm 2.6 \pm 5.8$	$+4.4 \pm 1.7 \pm 2.3 \pm 1.6$
$\omega(782)$	$-4.8 \pm 6.5 \pm 6.6 \pm 3.5$	$-6.2 \pm 8.4 \pm 5.6 \pm 8.1$	$-7.9 \pm 16.5 \pm 14.2 \pm 7.0$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 3.6 \pm 4.4$	$+42.8 \pm 4.1 \pm 2.1 \pm 8.9$	$+37.6 \pm 4.4 \pm 6.0 \pm 5.2$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 7.0 \pm 35.7$	$+9.0 \pm 6.0 \pm 10.8 \pm 45.7$	$-15.5 \pm 7.3 \pm 14.3 \pm 32.2$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 13.5 \pm 24.1$	$-35.7 \pm 10.8 \pm 8.5 \pm 35.9$	$-93.2 \pm 6.8 \pm 8.0 \pm 38.1$
S-wave	$+14.4 \pm 1.8 \pm 2.1 \pm 1.9$	$+15.8 \pm 2.6 \pm 2.1 \pm 6.9$	$+15.0 \pm 2.7 \pm 4.2 \pm 7.0$

$$A_{\mathrm{CP}}^j = \frac{|\overline{A}_j|^2 - |A_j|^2}{|\overline{A}_j|^2 + |A_j|^2}$$

Summary

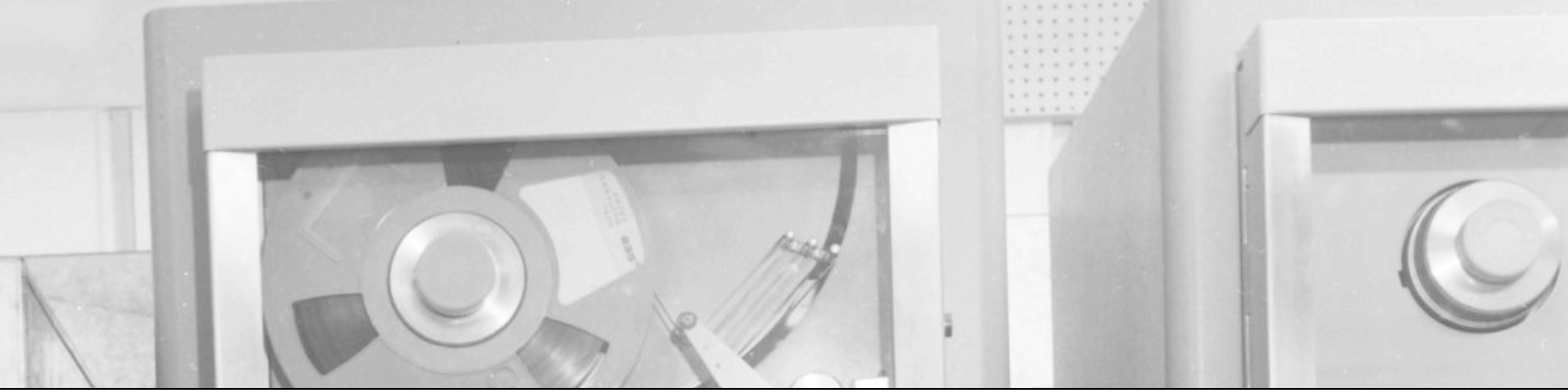
- Multi-body decays are the place to study CP violation

    Access to overlapping resonances **enhances CP violation**, but also permits measurements of the relative phases

- Observations of large CP violation, and the **first observation** of CP violation in the interference between resonances

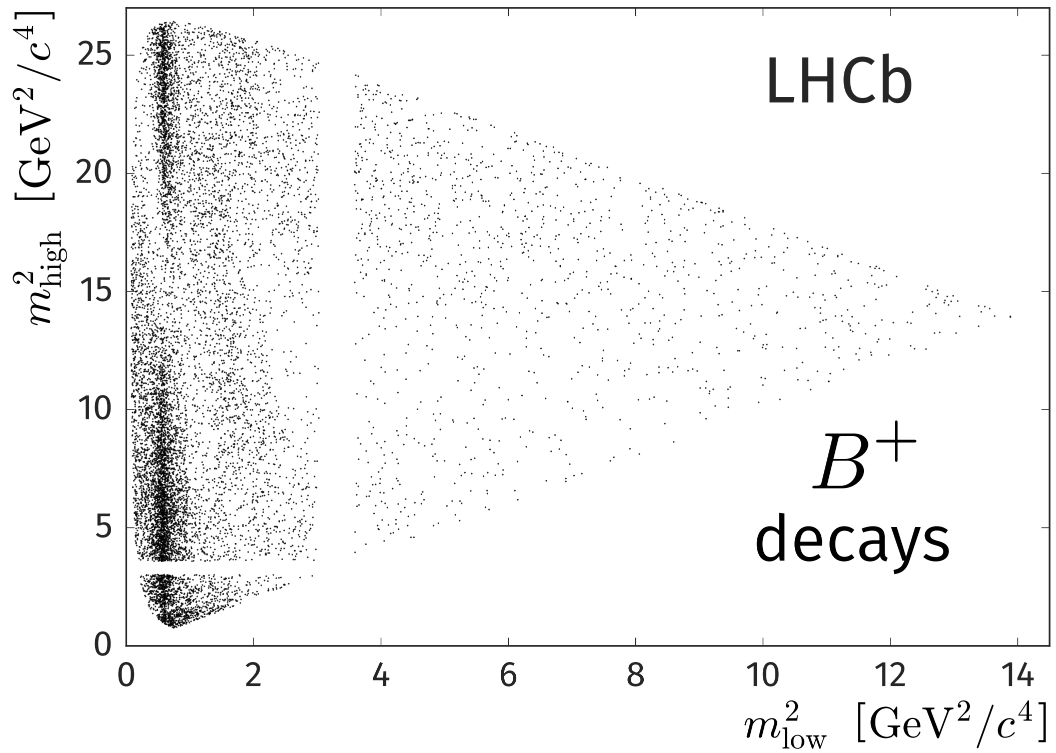
    Provides information on how CP violation manifests in practice - useful for understanding the (essential) **QCD components**, and informs **future studies** (e.g., in charm and baryon decays)

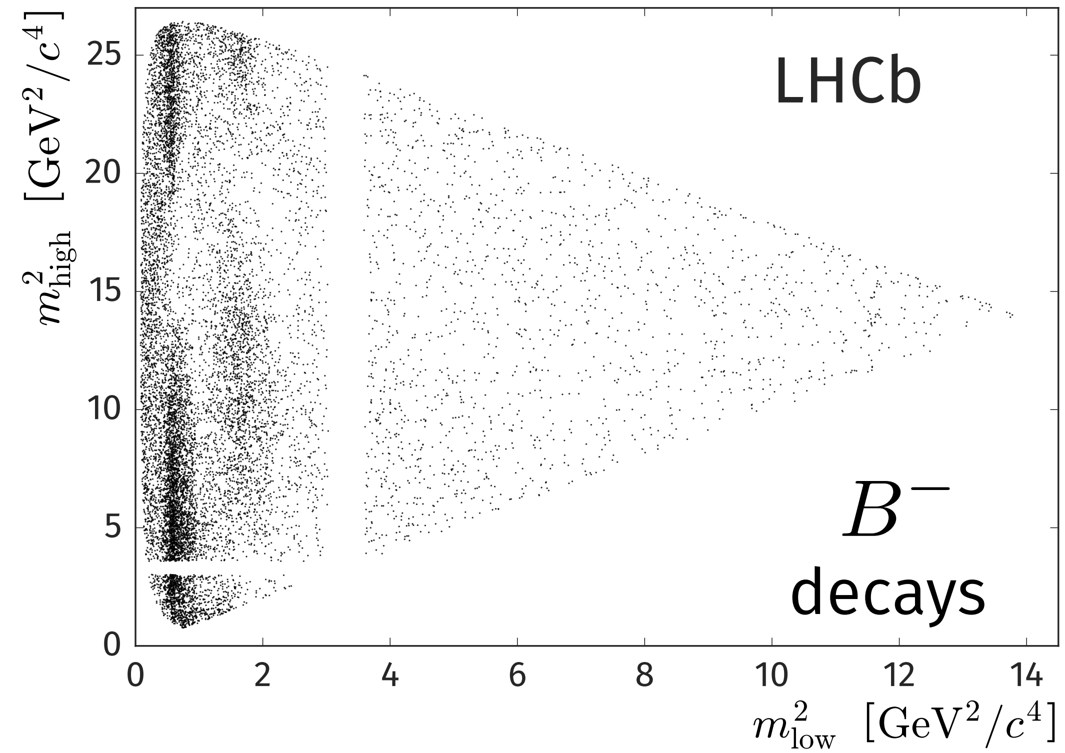
- Future studies will investigate the interplay between the $B^+ \to \pi^+\pi^+\pi^-$ and the $B^+ \to K^+\pi^+K^-$ decay with Run 2 data

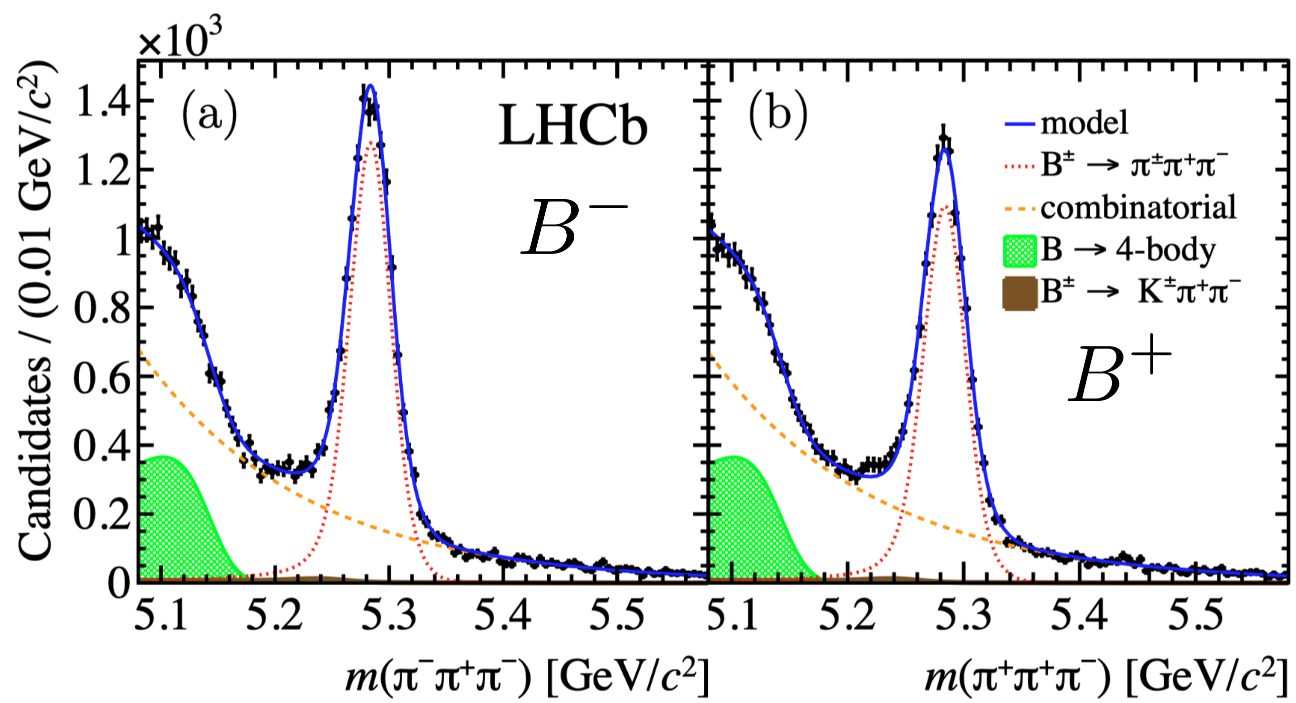


Backup

$B^+ \to \pi^+\pi^+\pi^-$


LHCb
B^+
decays
m^2_{high} [GeV$^2/c^4$]
m^2_{low} [GeV$^2/c^4$]


LHCb
B^-
decays
m^2_{high} [GeV$^2/c^4$]
m^2_{low} [GeV$^2/c^4$]


×10³
(a)
LHCb
B^-
(b)
model
$B^\pm \to \pi^\pm\pi^+\pi^-$
combinatorial
$B \to$ 4-body
$B^\pm \to K^\pm\pi^+\pi^-$
B^+
Candidates / (0.01 GeV/c^2)
$m(\pi^-\pi^+\pi^-)$ [GeV/c^2]
$m(\pi^+\pi^+\pi^-)$ [GeV/c^2]

f2 width

(a) (b) (c)

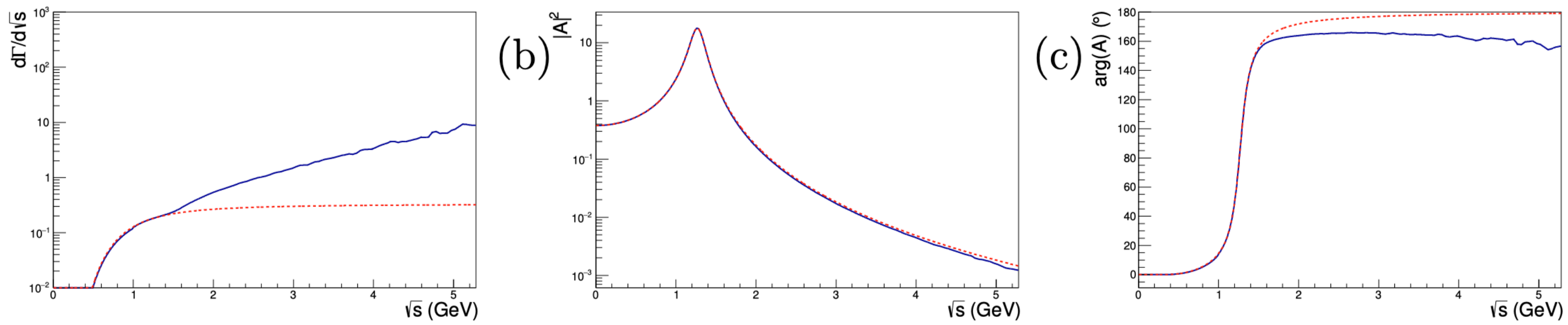
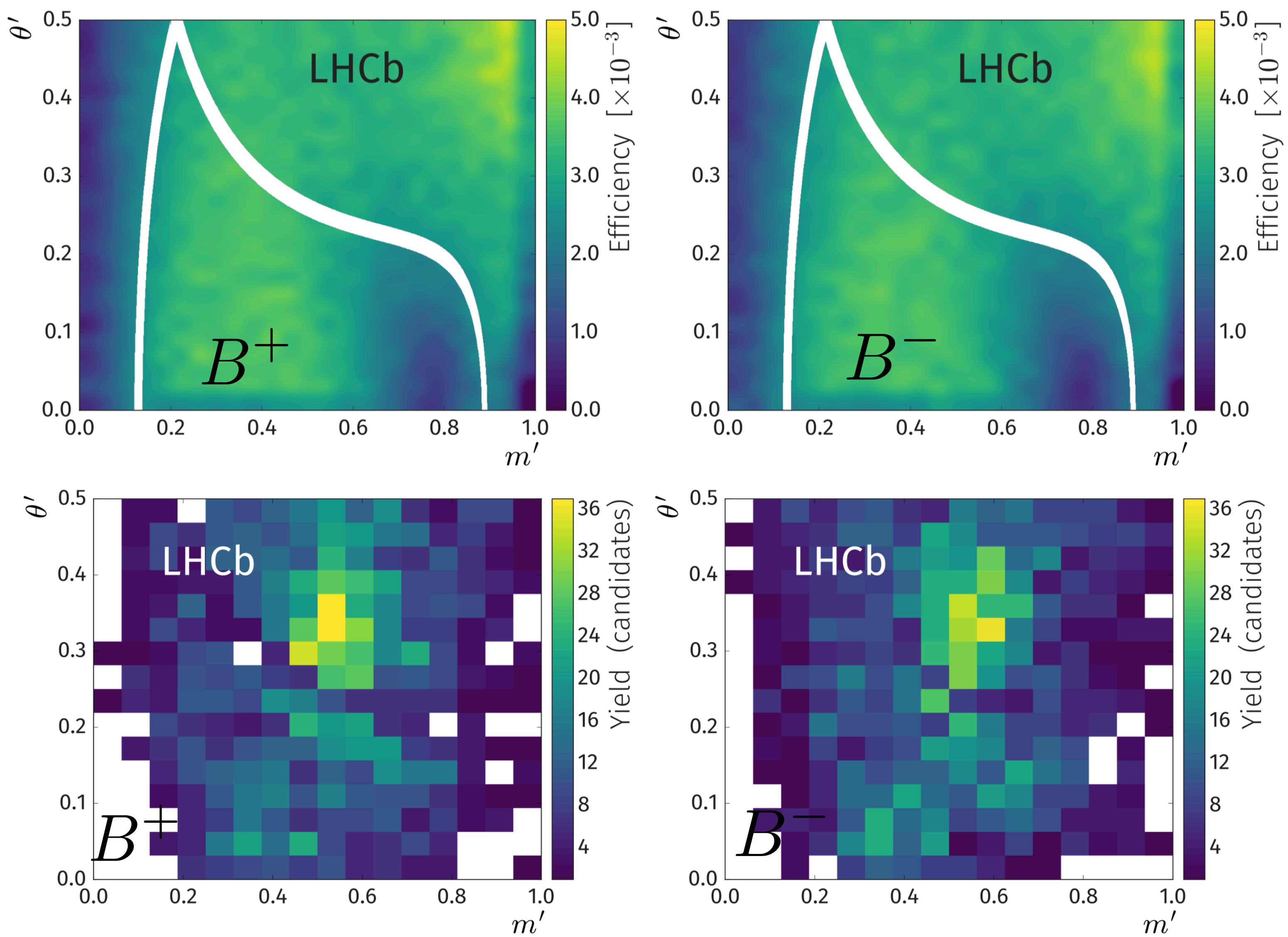


Figure 99: Comparison of the mass-dependence of the (a) $f_2(1270)$ total width (blue) with its $\pi^+\pi^-$ partial width (red), and its effects on (b), the Breit-Wigner amplitude-squared and (c) the Breit-Wigner phase

Backgrounds and efficiencies



$B^+ \to K^+\pi^+\pi^-$