Amplitude analysis of $B^+ \to K^+ \pi^- \pi^+ \gamma$ decays at LHCb

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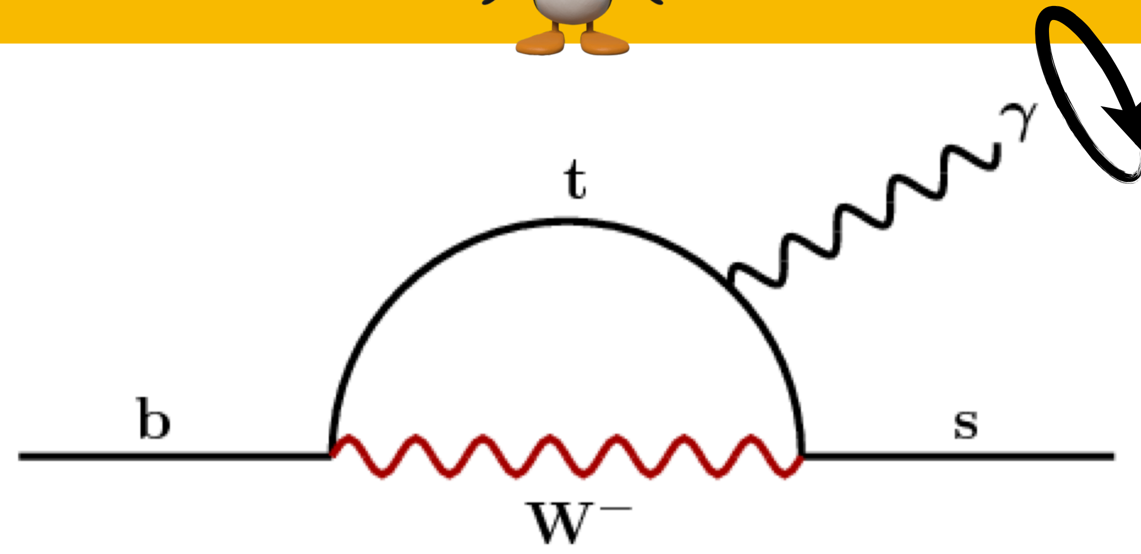
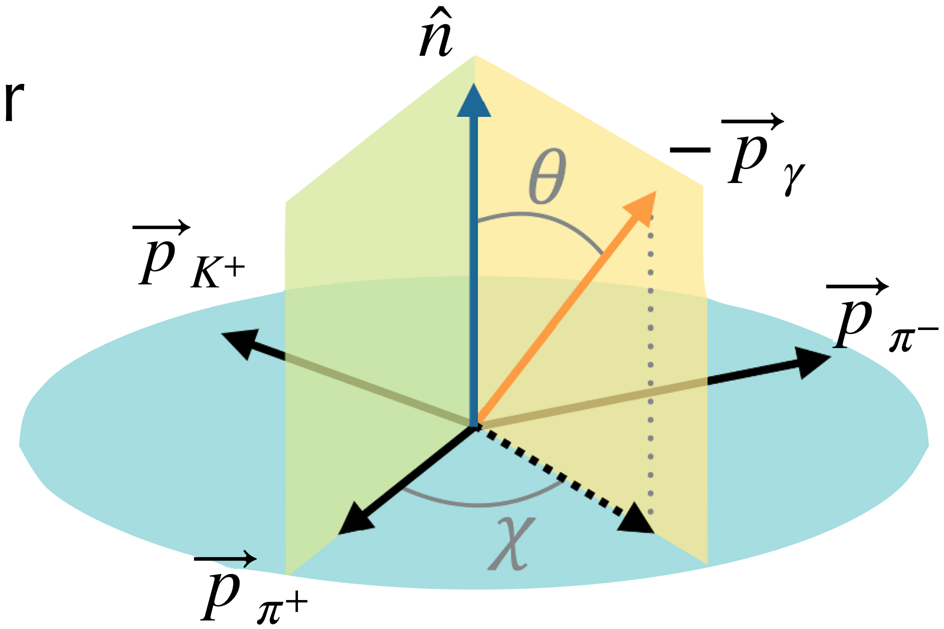
$b \to s\,\gamma$



- Like $b \to s\,\ell\ell$, forbidden at tree level in the SM
- Due to the chiral nature of the weak interaction, γ mostly left-handed in the SM
- BSM effects in loop could enhance right-handed contribution
- Recent measurement results are SM-compliant:
  - $B^0 \to K^{*}ee$ at low q^2 (ee invariant mass): arXiv: 2010.06011
  - $\Lambda_b^0 \to \Lambda\gamma$: PAPER-2021-030 (in preparation)

$B^+ \to K^+\pi^-\pi^+\gamma$: a photon polarisation lab



- Sensitive to the photon polarisation parameter due to
  A. Three hadrons in the final state

     → Parity-odd triple product , proportional to photon polarisation parameter λ_γ

  B. Interferences in the hadronic decay chain

     → Triple product does not cancel in differential decay rate

- final state: 4 four-vectors 16

  - 4 mass constraints -4

  - four-momentum conservation -4

  - choice of reference frame -3

  = 5 dimensional phase space

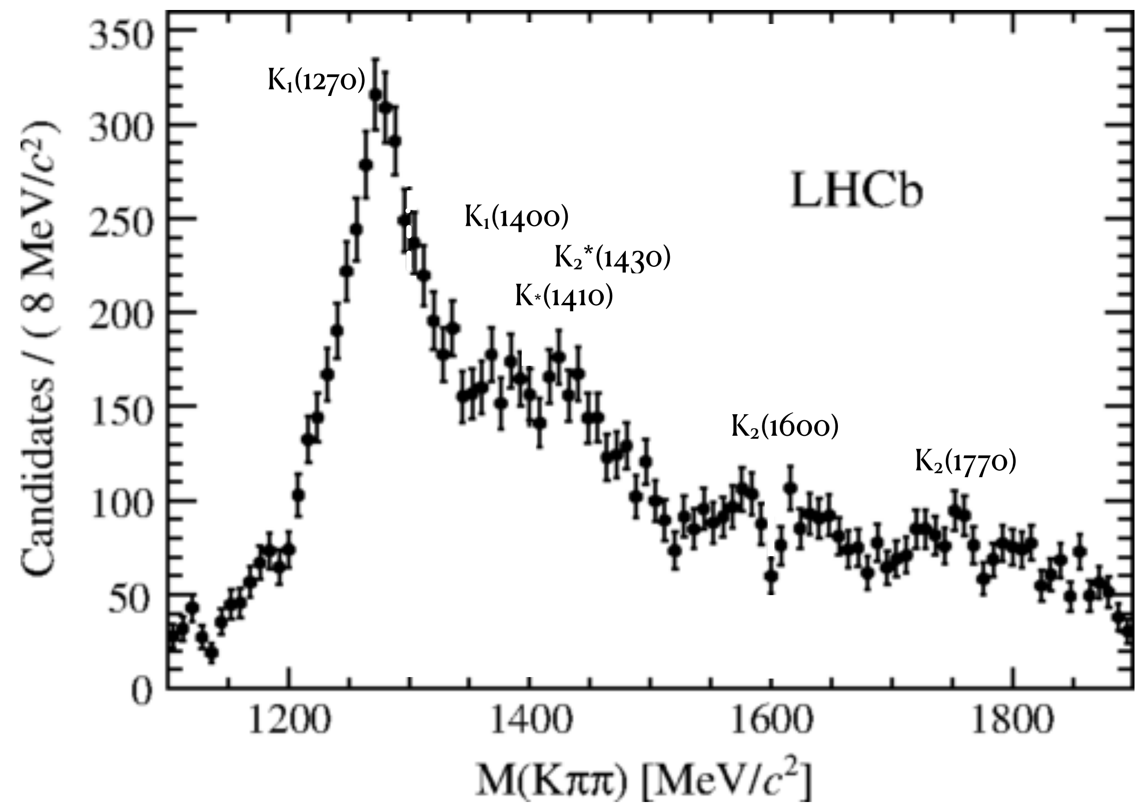
The differential decay rate

- By construction, $-1 \leq \lambda_\gamma \leq +1$
- In the SM, $\lambda_\gamma = +1$ up to corrections of order $\frac{m_s^2}{m_b^2}$
- Differential decay rate
  $d\Gamma(B \to K\pi\pi\gamma) \propto |\mathcal{M}_\mathrm{R}|^2 + |\mathcal{M}_\mathrm{L}|^2 + \lambda_\gamma(|\mathcal{M}_\mathrm{R}|^2 - |\mathcal{M}_\mathrm{L}|^2)$
- $\mathcal{M}_\mathrm{R/L} = \sum_k a_k e^{i\phi_k} \mathcal{A}_{k,\mathrm{R/L}}$
- a_k, ϕ_k: relative magnitude and phase
- Decay amplitude $\mathcal{A}_{k.R/L}$ = (intermediate resonances) × (angular momentum dependence)
- Interference between decay chains → $|\mathcal{M}_R|^2 \neq |\mathcal{M}_L|^2$

  → λ_γ measurable in $B^+ \to K^+\pi^-\pi^+\gamma$ decays

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

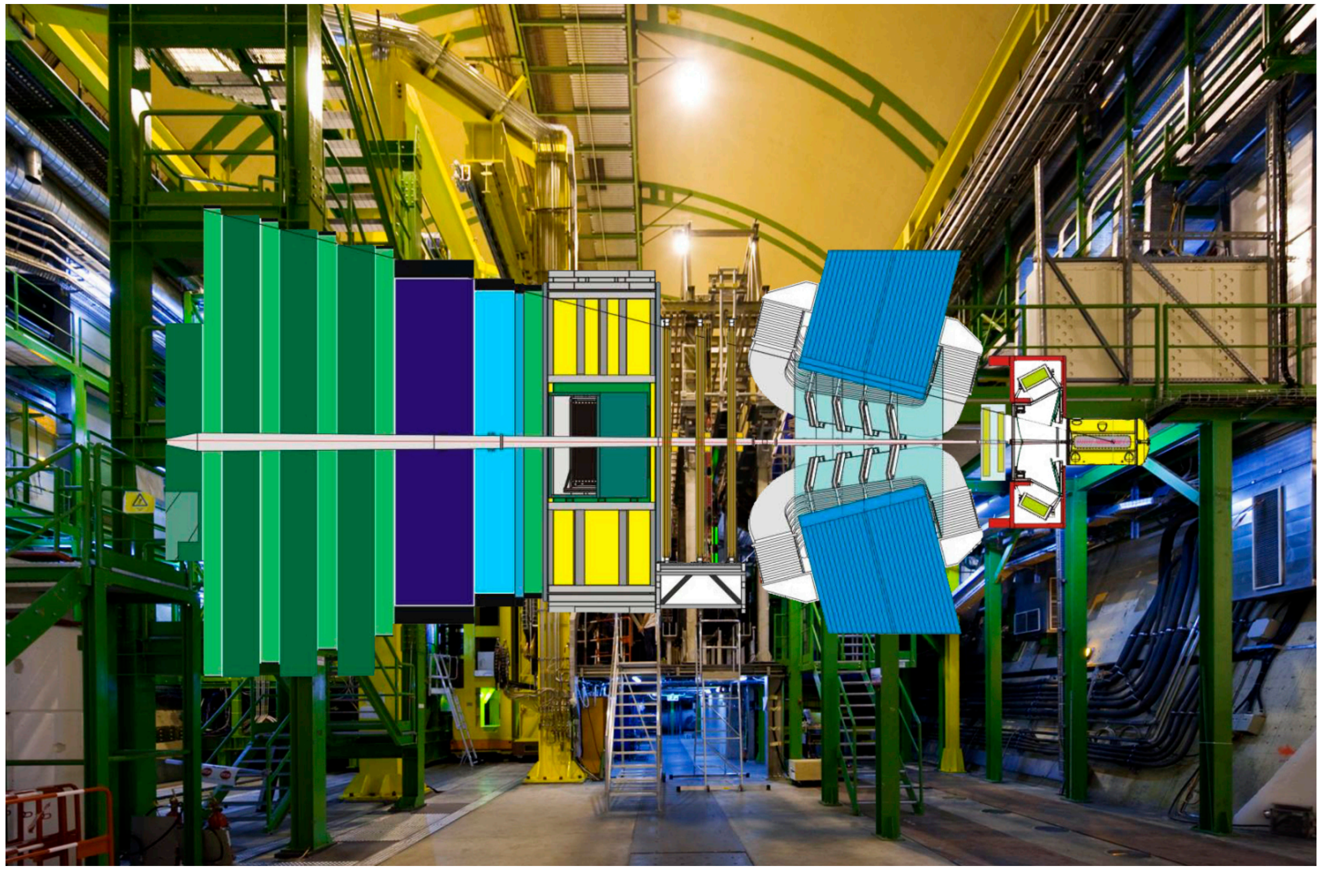
- Non-zero photon polarisation parameter observed at LHCb: arXiv: 1402.6852 using up-down asymmetry proportional to λ_γ
- Content of hadronic decay system poorly known → unknown proportionality coefficient
- Amplitude fit: use all degrees of freedom of the system to extract
  - photon polarisation parameter
  - content of the hadronic system: a_k, ϕ_k and choice of model
- Model building: Iteratively pick significant resonance channels to include in the fit



J^P	Amplitude k
1^+	$K_1(1270)^+ \to K^*(892)^0\pi^+$
	$K_1(1270)^+ \to K^+\rho(770)^0$
	$K_1(1270)^+ \to K^+\omega(782)^0$
	$K_1(1270)^+ \to K^*(1430)^0\pi^+$
	$K_1(1400)^+ \to K^*(892)^0\pi^+$
1^-	$K^*(1410)^+ \to K^*(892)^0\pi^+$
	$K^*(1680)^+ \to K^*(892)^0\pi^+$
	$K^*(1680)^+ \to K^+\rho(770)^0$
2^+	$K_2^*(1430)^+ \to K^*(892)^0\pi^+$
	$K_2^*(1430)^+ \to K^+\rho(770)^0$
	$K_2^*(1430)^+ \to K^+\omega(782)^0$
2^-	$K_2(1580)^+ \to K^*(892)^0\pi^+$
	$K_2(1580)^+ \to K^+\rho(770)^0$
	$K_2(1770)^+ \to K^*(892)^0\pi^+$
	$K_2(1770)^+ \to K^+\rho(770)^0$
	$K_2(1770)^+ \to K_2^*(1430)^0\pi^+$
	$K_2(1770)^+ \to K^+f_2(1270)^0$

Data and simulation samples

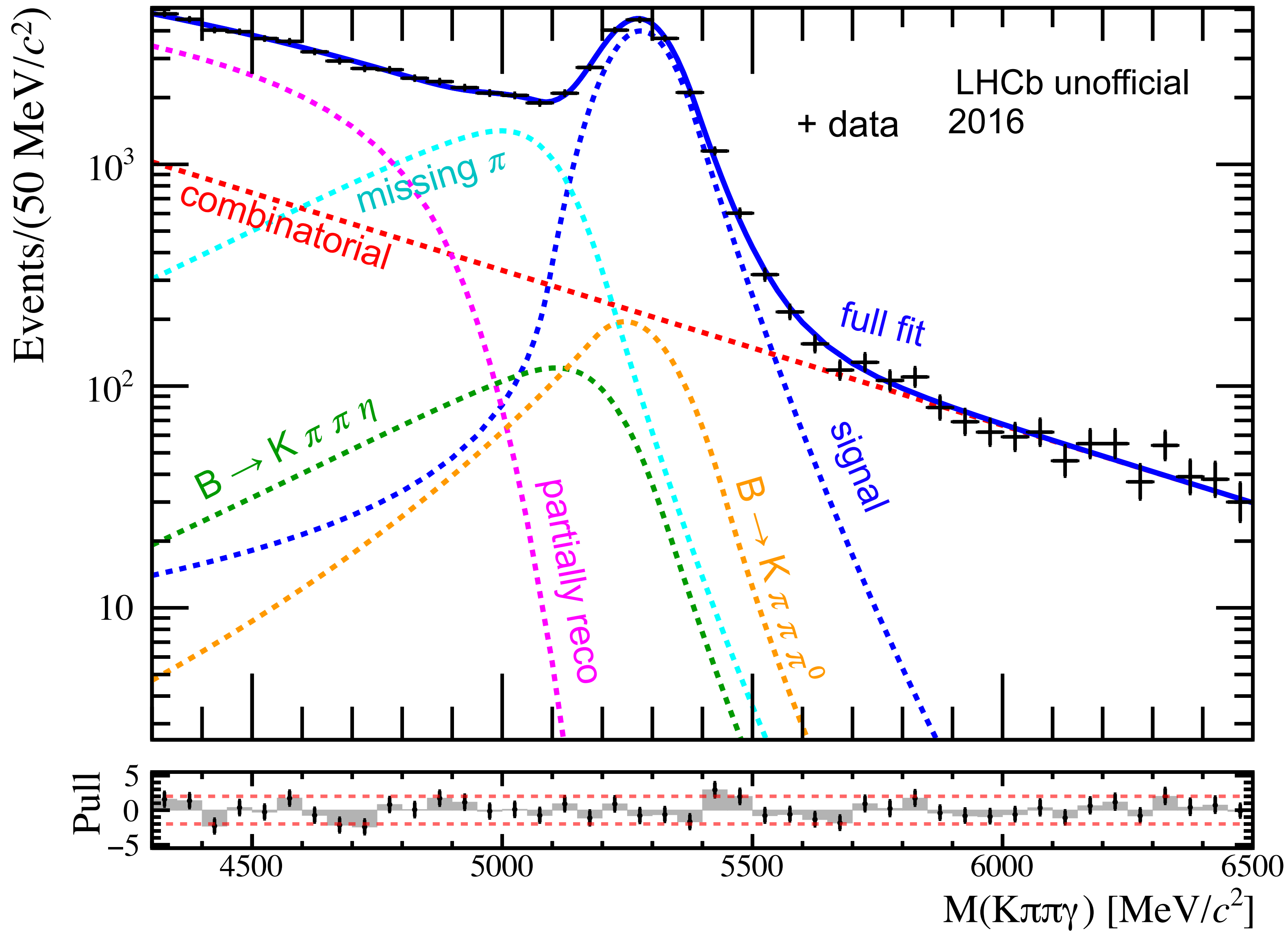
- Data collected by the LHCb experiment in 2011, 2012, 2016, 2017, 2018
- Monte Carlo (MC) simulated events for signal and background sources used to estimate as well as remove background contributions
- Radiative B decay candidates reconstructed as $B^+ \to K^+ \pi^- \pi^+ \gamma$ decays
- Selection criteria include
  - general event quality
  - particle identification
  - invariant mass vetoes
  - ML classifier to reject combinatorial background



Mass fit for background subtraction

- Invariant mass distributions of signal and backgrounds from data and MC
- Assign weights to events based on orthogonal functions

  → Background-subtracted (signal-like) data sample



- Statistical power of weighted sample smaller than pure signal sample would be

Status and outlook

- All data and MC samples available
- Background subtraction to be finalised
- With 40 000 signal events, estimated statistical uncertainty on photon polarisation parameter 0.014 [arXiv:1902.09201]; we have O(70 000)
- Model building strategy for the amplitude fit to be tested and finalised
- Systematic uncertainties from signal model, resolution and accuracy of kinematic variables, etc to be computed
- Stay tuned for the photon polarisation in $B^+ \to K^+\pi^-\pi^+\gamma$ decays!

Backup: PDF details

- $\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{ts}^{*} V_{tb} (C_7 \mathcal{O}_{7,L} + C_7' \mathcal{O}_{7,R})$; $\lambda_\gamma = \frac{|C_7^{\text{eff}}|^2 - |C_7'|^2}{|C_7^{\text{eff}}|^2 + |C_7'|^2}$
- Signal function $\mathcal{P}_{\text{s}} = \frac{(1+\lambda_\gamma)}{2} |\mathcal{M}_{\text{R}}|^2 + \frac{(1-\lambda_\gamma)}{2} |\mathcal{M}_{\text{L}}|^2$ dependent on four-momenta x by $\mathcal{M}_{\text{R/L}} = \sum_k a_k e^{i\phi_k} \mathcal{A}_{k,\text{R/L}}(x)$
- Fit pdf $\mathcal{F}(x\,|\,\Omega) = \frac{\xi(x)\mathcal{P}_{\text{s}}(x\,|\,\Omega)\Phi_4(x)}{\int \xi(x)\mathcal{P}_{\text{s}}(x\,|\,\Omega)\Phi_4(x)\mathrm{d}x}$
- $\Omega = (\lambda_\gamma, \{a_k\}, \{\phi_k\})$
- Normalisation integral performed using MC sample generated with model $\mathcal{P}_{\text{gen}}$
- $\frac{\int \xi(x)\mathcal{P}_{\text{s}}(x\,|\,\Omega)\Phi_4(x)\mathrm{d}x}{\int \xi(x)\mathcal{P}_{\text{gen}}(x)\Phi_4(x)\mathrm{d}x} = \frac{1}{N_{\text{sel}}} \sum_j^{N_{\text{sel}}} \frac{\mathcal{P}_s(x_j\,|\,\Omega)}{\mathcal{P}_{\text{gen}}(x_j)}$
- Efficiency ξ taken into account by applying selection on integration sample

Backup: Offline selection

Variable	2011–2012	2016–2017	Unit
Photon E_{T}	> 3000	> 3000	MeV
B meson p_{T}	> 5000	> 4000	MeV/c
B meson isolation $\Delta\chi^2$	> 5	> 5	
γ/π^0 separation	> 0.7	> 0.7	
γ confidence level	> 0.2	> 0.2	
$\mathrm{ProbNN}_K(K^+) \times (1 - \mathrm{ProbNN}_\pi(K^+))$	> 0.2	> 0.2	
$\mathrm{ProbNN}_\pi(\pi^+) \times (1 - \mathrm{ProbNN}_K(\pi^+))$	> 0.2	> 0.2	
$\mathrm{ProbNN}_\pi(\pi^-) \times (1 - \mathrm{ProbNN}_K(\pi^-))$	> 0.2	> 0.2	
$K\pi\pi$ mass	$\in [1100, 1900]$	$\in [1100, 1900]$	MeV/c^2
$K^+\pi^-\pi^0$ mass	> 2200	> 2200	MeV/c^2
$\pi^+\pi^0$ mass	> 1100	> 1100	MeV/c^2

Event quality

PID

$B^+ \to \bar{D}^0(\to K^+\pi^-\pi^0)\rho^+(\to \pi^+\pi^0)$ **veto**

$D_s^+ \to K^+\pi^-\pi^+$ **veto**

+ BDT to reject combinatorial background trained on signal MC and upper-mass sideband data

Backup: Background subtraction

- Know the shapes of all species (signal, backgrounds) that make up the sample in a discriminating variable
- Use these shapes to define orthogonal weight functions
- Each event is assigned a weight for each species according to its value in the discriminating variable
- The signal-weighted sample has the correct distribution in any variable that is independent of the discriminating variable
- Discriminating variable: *B* candidate invariant mass

$$w_k(m_{B\text{cand}}) = \frac{\sum_{i=1}^{N(\text{species})} C_{ki} f_i(m_{B\text{cand}})}{\sum_{i=1}^{N(\text{species})} N_i f_i(m_{B\text{cand}})} \qquad C_{kl}^{-1} = \int \mathrm{d}m \frac{f_k(m) f_l(m)}{\sum_{i=1}^{N(\text{species})} N_i f_i(m)}$$

Following M. Schmelling, based on R. J. Barlow, *Event Classification Using Weighting Methods*, J. Comput. Phys. 72, 202 (1987), doi:10.1016/0021-9991(87)90078-7 and M. Pivk, F. R. Le Diberder, *sPlot: A statistical tool to unfold data distributions,* Nucl. Instrum. Meth. A555 (2005) 356, arXiv:physics/0402083.

Backup: Isobar model