Using an amplitude analysis to measure the photon polarisation in B→Kππγ decays

V. Bellee, F. Blanc, P. Pais, A. Puig, O. Schneider, K. Trabelsi, G. Veneziano

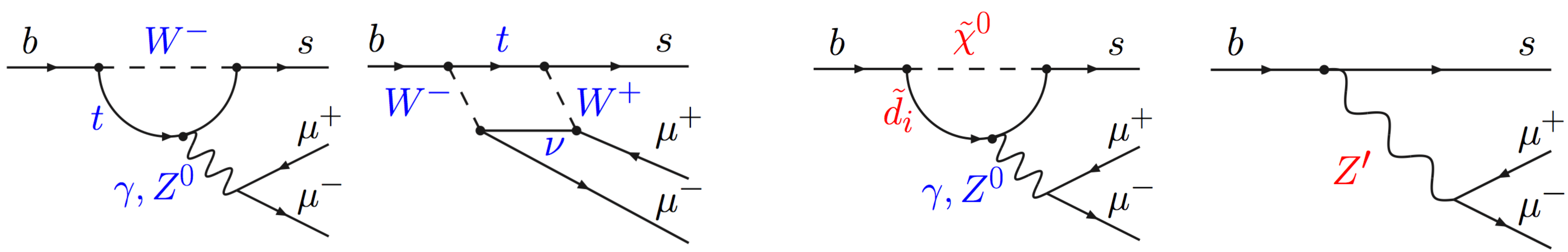
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

DESY Pizza (+HEP) Seminar

November 27, 2019

Rare Decays

- 'Flavour-changing neutral current' (FCNC) transitions
- Proceed via electroweak loops; suppressed in the SM
- New particles could also contribute at loop level



Potential effects observed via:

- Anomalies in decay rates, differential branching fraction measurements
- Analyses of angular distributions
- Tests of lepton flavour universality and lepton flavour violation

Parametrising Radiative Decays

Effective Hamiltonian described by an operator product expansion

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1}^{8} \underbrace{C_i(\mu) Q_i(\mu)}_{\text{left handed}} + \sum_{i=7}^{8} \underbrace{C'_i(\mu) Q'_i(\mu)}_{\text{right handed (suppressed in the SM)}} \right)$$

- The operators Q_i encode long-distance effects

Q_{1-6} SM 4-quark operators

$$Q_7^{(\prime)} = \frac{e}{16\pi^2} m_b (\bar{s}_{L/R} \sigma_{\mu\nu} b_{R/L}) F^{\mu\nu}$$

Electromagnetic dipole operator

$$Q_8^{(\prime)} = \frac{g_s}{16\pi^2} m_b (\bar{s}_{L/R} \sigma_{\mu\nu} T^a b_{R/L}) G^{a\mu\nu}$$

Chromomagnetic dipole operator

Parametrising Radiative Decays

Effective Hamiltonian described by an operator product expansion

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\underbrace{\sum_{i=1}^{8} C_i(\mu) Q_i(\mu)}_{\text{left handed}} + \underbrace{\sum_{i=7}^{8} C_i'(\mu) Q_i'(\mu)}_{\text{right handed (suppressed in the SM)}} \right)$$

- The Wilson coefficients encode perturbative, short-distance effects
- Define an effective Wilson coefficient C_7^{eff}:

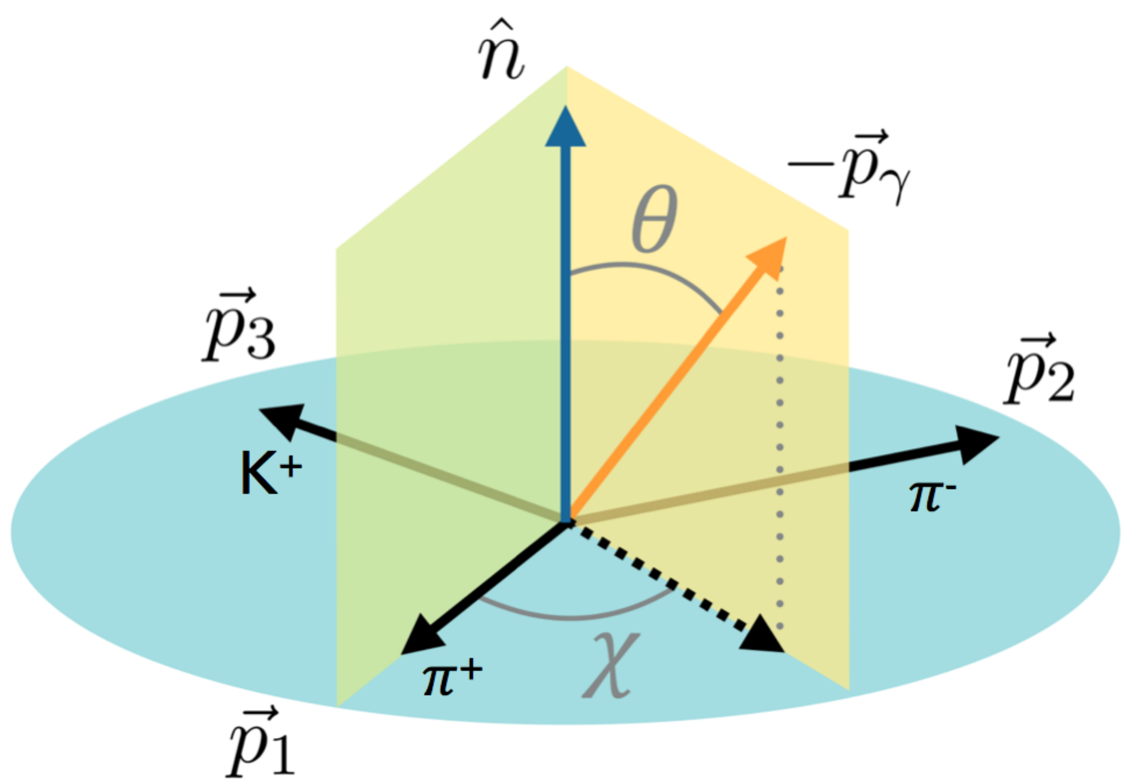
$$C_7^{\text{eff}}(\mu) = C_7(\mu) + \sum_{i=1}^{6} y_i C_i(\mu)$$

- In the SM, $C_7'/C_7^{\text{eff}} = m_s/m_b \sim 0.02$
  - Left-handed photons are dominant
- NP contributions could enhance fraction of right-handed photons

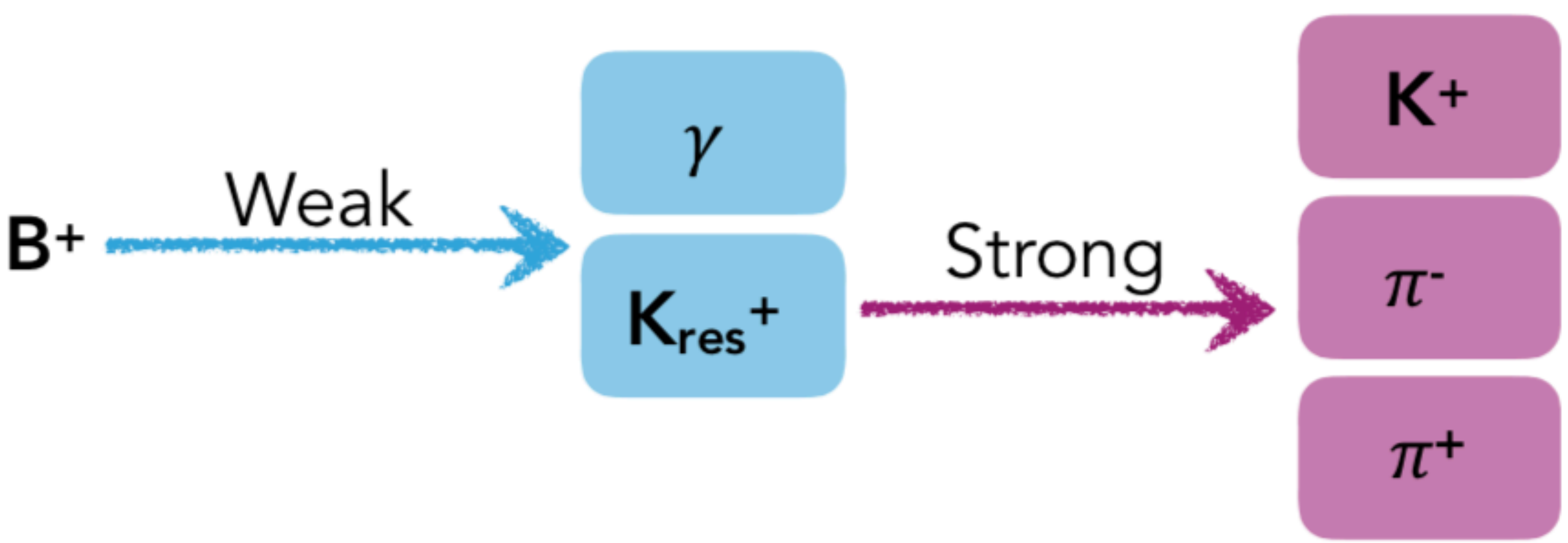
Photon Polarisation in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ Decays

The $K\pi\pi\gamma$ final state can be described in terms of 5 independent variables:

- Three invariant masses (**$m^2(K\pi\pi)$**, **$m^2(K\pi)$** and **$m^2(\pi\pi)$**)
- Two angular variables (**χ** and **θ**) that describe the orientation of the photon with respect to the hadronic plane



This is a $\bar{b}\rightarrow\bar{s}$ transition; in the SM, photons are expected to be predominantly right-handed

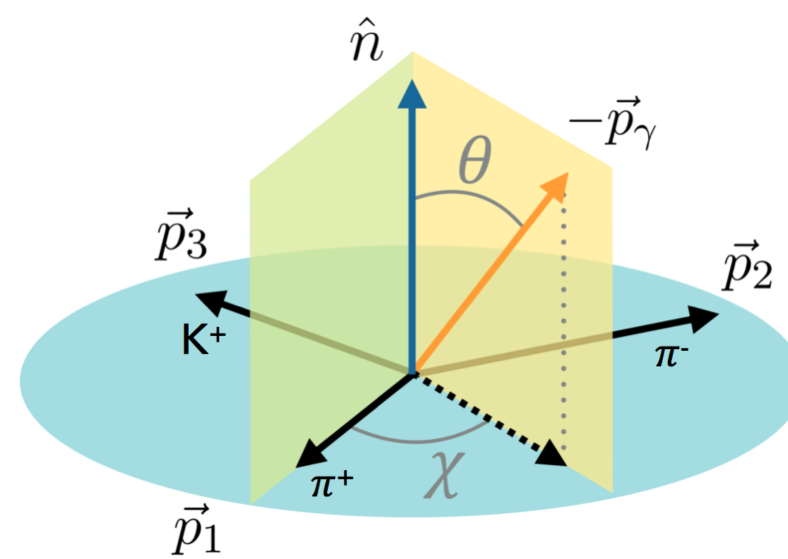


Photon Polarisation in $B^+ \to K^+\pi^-\pi^+\gamma$ Decays

Can measure the photon polarisation using the recoil hadron distribution:

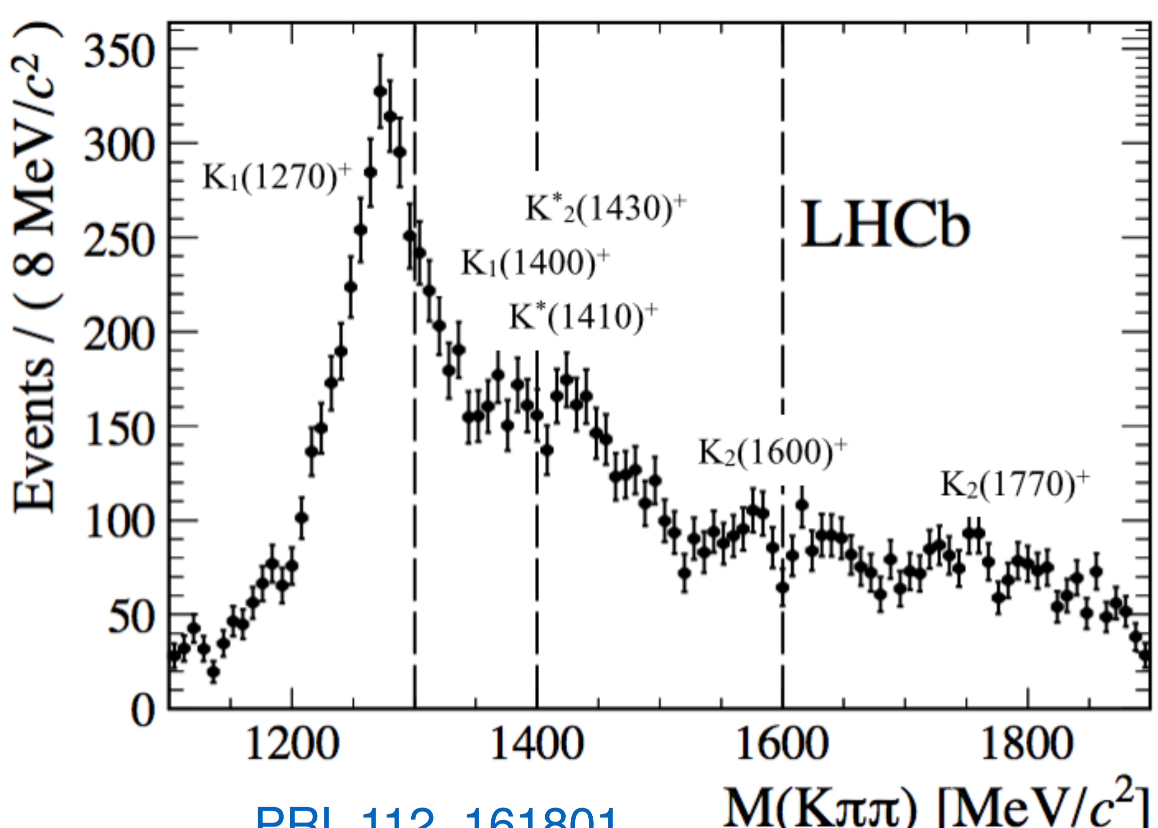
- Photon helicity is odd under parity
- Need three tracks in the final state; can form a parity-odd triple product from final-state particle momenta

$$\vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2)$$



- Requires interference between various decay amplitudes that contribute to the final state

Gronau et. al:
PRL 88, 051802
PRD 66, 054008



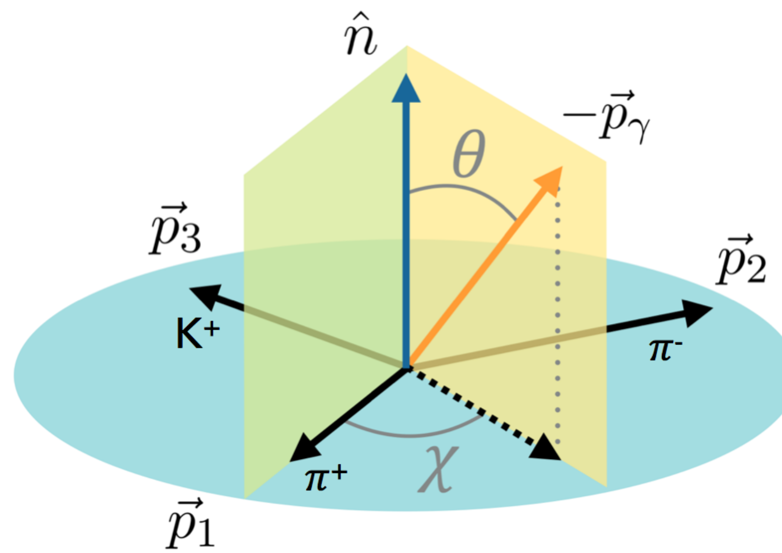
PRL 112, 161801

- System populated by a multitude of resonances
  - Interferences give sensitivity to photon polarisation parameter
  - Very complex!

PHOTON POLARISATION IN $B^+ \to K^+\pi^-\pi^+\gamma$ DECAYS

Simplify the problem:

- Compute an up-down asymmetry (between the number of photons emitted on one side and on the other of the Kππ decay plane
- Proportional to photon polarisation parameter

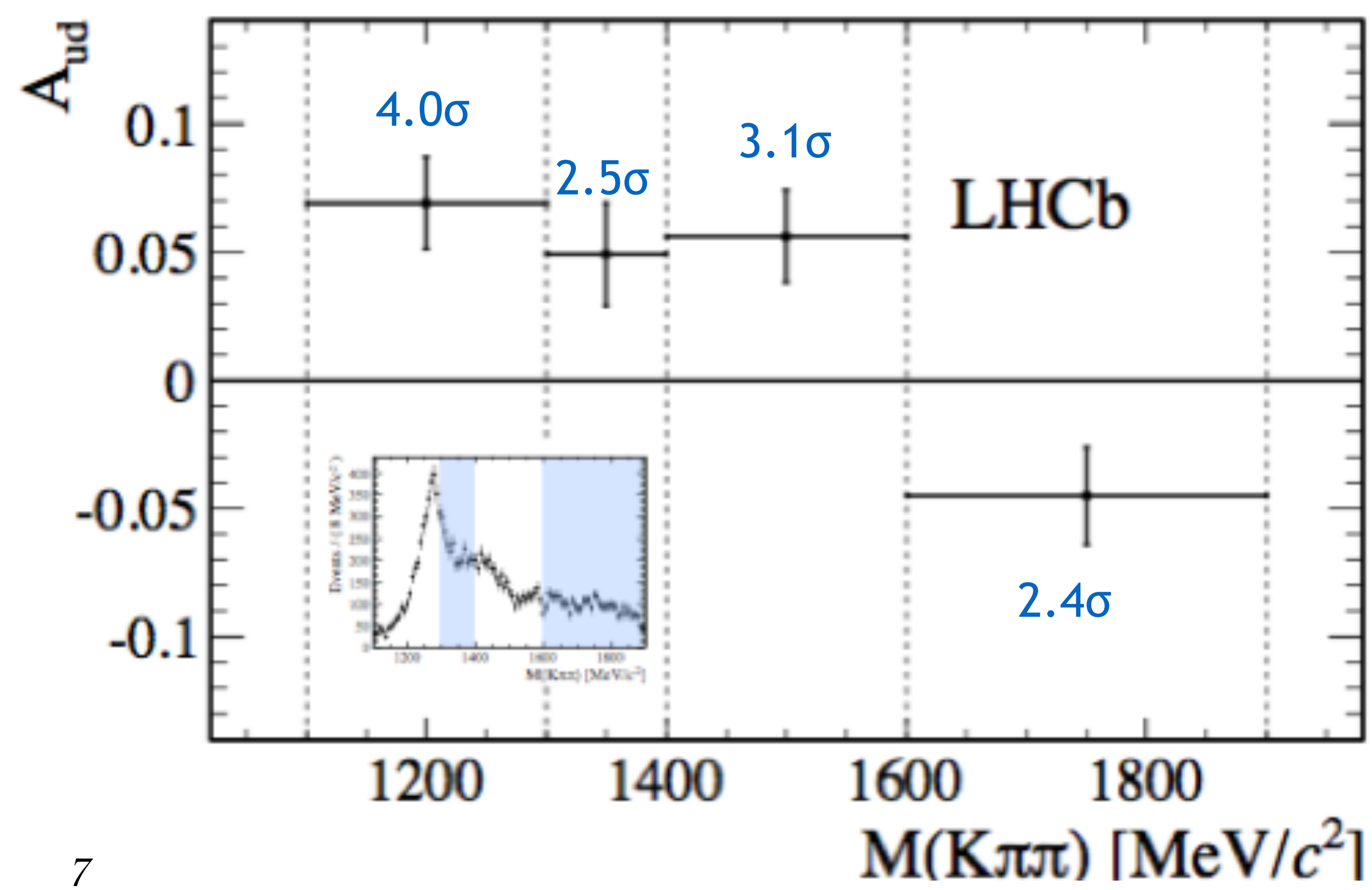


$$\mathcal{A}_{\rm ud} \equiv \frac{\int_0^1 {\rm dcos}\,\theta \frac{{\rm d}\Gamma}{{\rm dcos}\,\theta} - \int_{-1}^0 {\rm dcos}\,\theta \frac{{\rm d}\Gamma}{{\rm dcos}\,\theta}}{\int_{-1}^1 {\rm dcos}\,\theta \frac{{\rm d}\Gamma}{{\rm dcos}\,\theta}} = C\lambda_\gamma$$

PRL 112, 161801

- 14,000 signal events selected from full LHCb Run 1 dataset
- Cosθ fit performed in four m(Kππ) bins

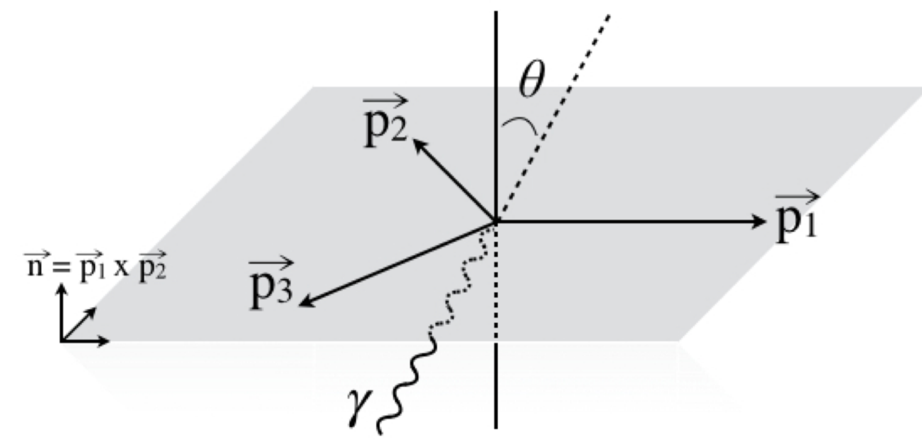
First observation of a non-zero photon polarisation in b→sγ transitions (**5.2σ** significance)



Photon Polarisation in $B^+ \to K^+\pi^-\pi^+\gamma$ Decays

Simplify the problem:

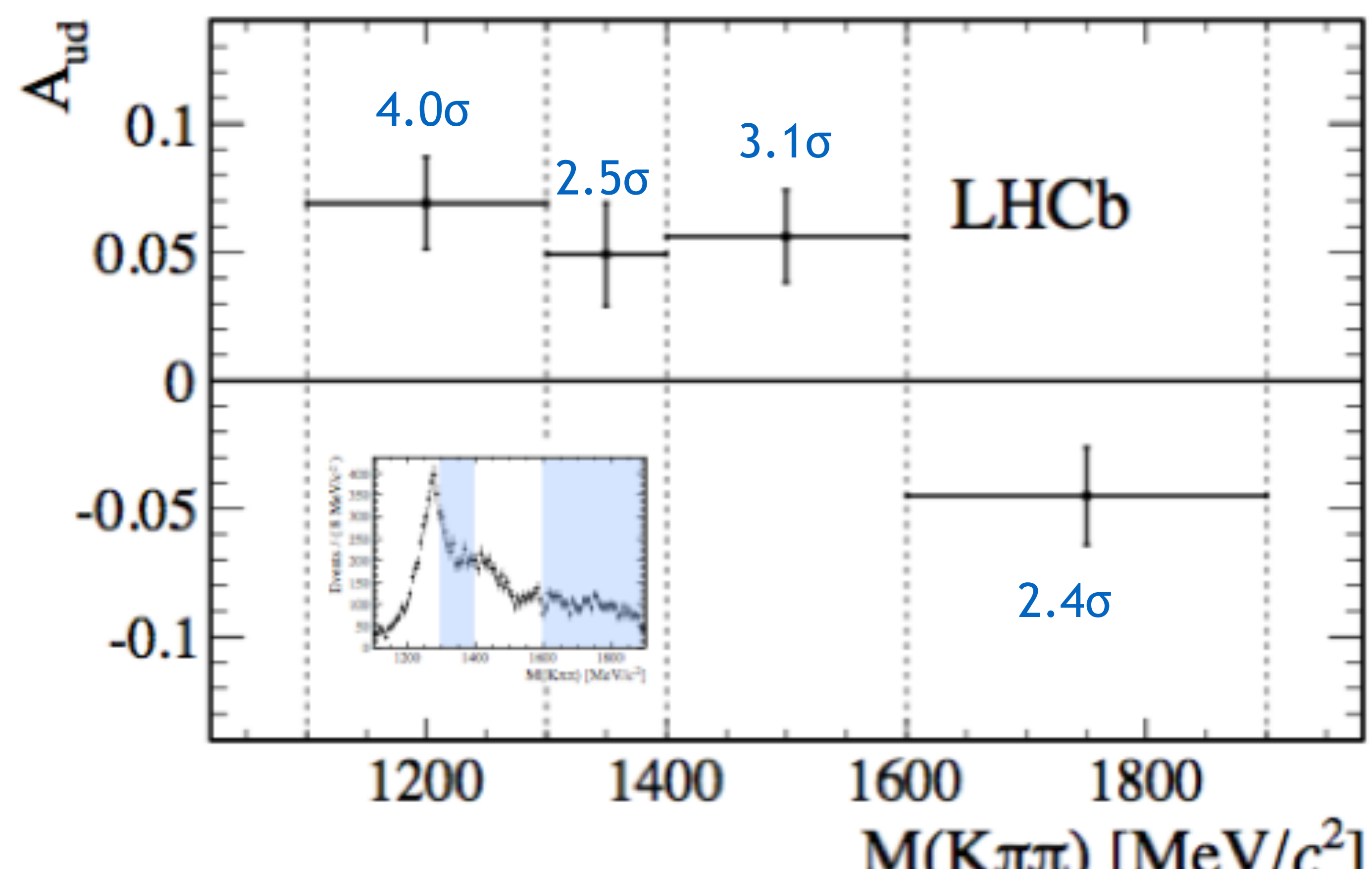
- Compute an up-down asymmetry (between the number of photons emitted on one side and on the other of the Kππ decay plane
- Proportional to photon polarisation parameter



$$\mathcal{A}_{\rm ud} \equiv \frac{\int_0^1 {\rm d}\cos\theta \frac{{\rm d}\Gamma}{{\rm d}\cos\theta} - \int_{-1}^0 {\rm d}\cos\theta \frac{{\rm d}\Gamma}{{\rm d}\cos\theta}}{\int_{-1}^1 {\rm d}\cos\theta \frac{{\rm d}\Gamma}{{\rm d}\cos\theta}} = C\lambda_\gamma$$

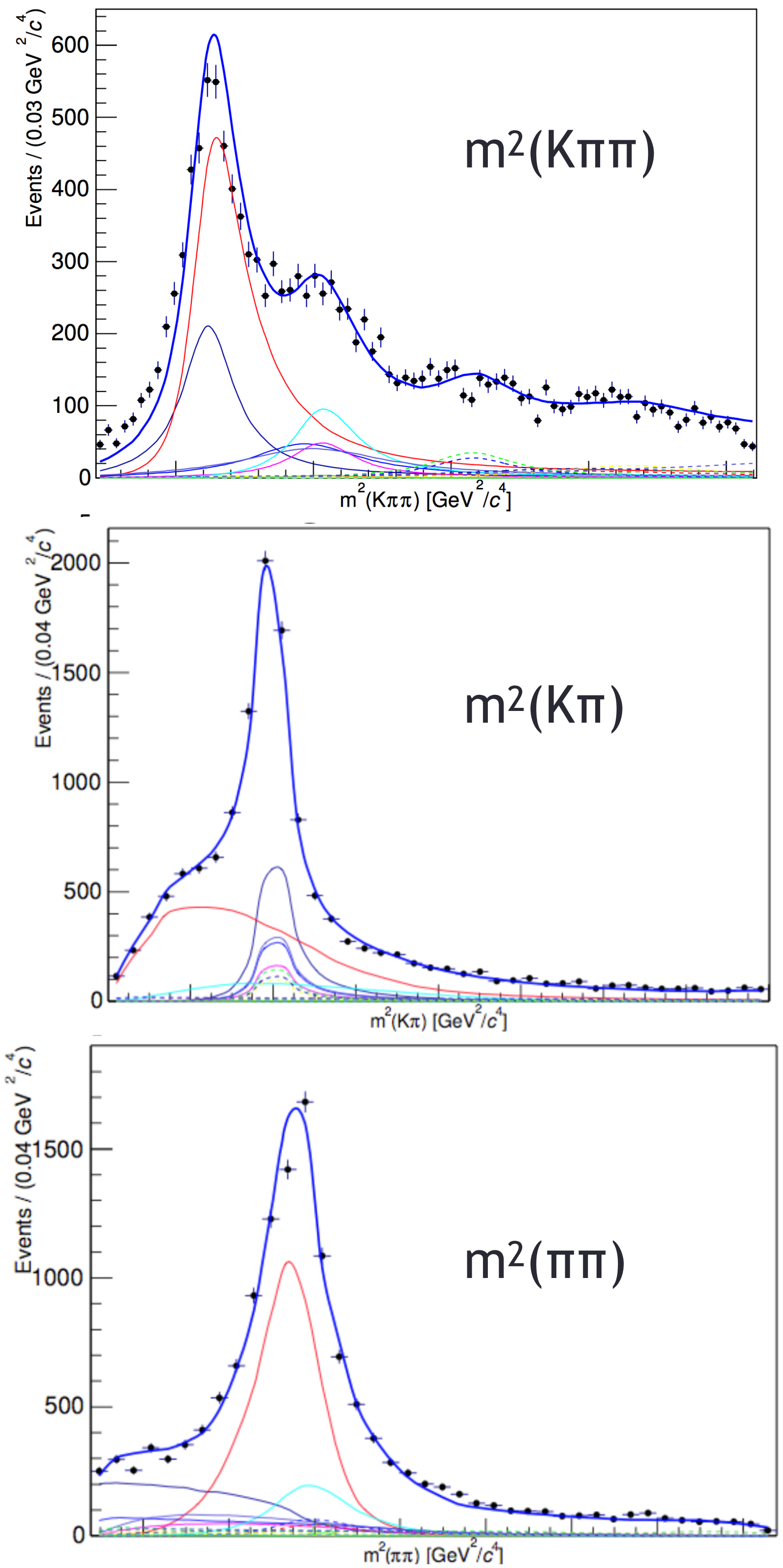
PRL 112, 161801

> Cannot translate this to a value of the photon polarisation parameter without exact knowledge of the resonances that populate the system
>
> Need a full amplitude analysis



3-D Amplitude Analysis of the $K\pi\pi$ System

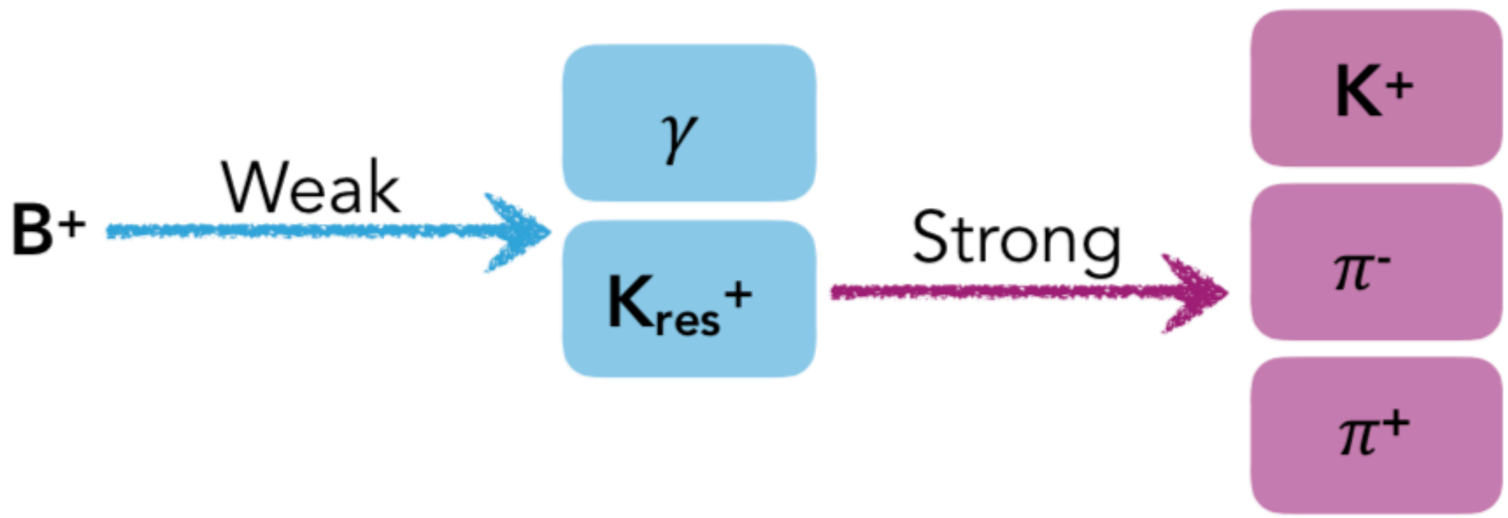
CERN-THESIS-2015-287



Integrate over photon angular variables; fit in terms of invariant masses $m^2(K\pi\pi)$, $m^2(K\pi)$ and $m^2(\pi\pi)$

Decay channel k	$\mathcal{R}e[f_k]$	$\mathcal{I}m[f_k]$	FF_k (10^{-2})
$K_1(1270)^+ \to K^*(892)^0\pi^+$	1 (fixed)	0 (fixed)	16.8 ± 0.9
$K_1(1270)^+ \to K^+\rho(770)^0$	1.072 ± 0.050	-1.379 ± 0.047	$39.9\,^{+0.6}_{-0.7}$
$K_1(1270)^+ \to K^+\omega(782)^0$	0.288 ± 0.086	0.090 ± 0.081	$0.068\,^{+0.028}_{-0.180}$
$K_1(1270)^+ \to K^*(1430)^0\pi^+$	-0.025 ± 0.062	-0.381 ± 0.055	$0.69\,^{+0.22}_{-0.20}$
$K_1(1400)^+ \to K^*(892)^0\pi^+$	0.306 ± 0.024	-0.288 ± 0.020	7.8 ± 0.8
$K^*(1410)^+ \to K^*(892)^0\pi^+$	-0.479 ± 0.042	0 (fixed)	$8.4\,^{+2.8}_{-3.3}$
$K^*(1680)^+ \to K^*(892)^0\pi^+$	0.198 ± 0.020	0.094 ± 0.028	$3.5\,^{+1.7}_{-2.1}$
$K^*(1680)^+ \to K^+\rho(770)^0$	0.019 ± 0.025	0.1104 ± 0.0097	2.4 ± 0.4
$K_2^*(1430)^+ \to K^*(892)^0\pi^+$	-0.509 ± 0.034	0 (fixed)	4.8 ± 1.0
$K_2^*(1430)^+ \to K^+\rho(770)^0$	-0.115 ± 0.047	0.497 ± 0.024	9.0 ± 0.8
$K_2^*(1430)^+ \to K^+\omega(782)^0$	-0.234 ± 0.072	-0.236 ± 0.084	$0.30\,^{+0.13}_{-0.26}$
$K_2(1600)^+ \to K^*(892)^0\pi^+$	-0.1666 ± 0.0088	0.044 ± 0.021	$4.4\,^{+0.9}_{-1.0}$
$K_2(1600)^+ \to K^+\rho(770)^0$	-0.073 ± 0.011	0.061 ± 0.013	$3.33\,^{+0.34}_{-0.50}$
$K_2(1770)^+ \to K^*(892)^0\pi^+$	0.1072 ± 0.0078	0 (fixed)	$3.0\,^{+0.6}_{-0.8}$
$K_2(1770)^+ \to K^+\rho(770)^0$	-0.0147 ± 0.0044	0.0103 ± 0.0050	$0.23\,^{+0.08}_{-0.32}$
$K_2(1770)^+ \to K_2^*(1430)^0\pi^+$	-0.041 ± 0.012	-0.0772 ± 0.0077	$0.67\,^{+0.10}_{-0.09}$
$K_2(1770)^+ \to K^+f_2(1270)^0$	0.1673 ± 0.0071	-0.029 ± 0.015	$1.30\,^{+0.15}_{-0.16}$
Non resonant	-0.0511 ± 0.0021	0 (fixed)	4.1 ± 0.5

Photon Polarisation in $B^+ \to K^+\pi^-\pi^+\gamma$ Decays



Differential decay rate for a particular decay mode $B^+ \to K_{res}^{+(i)}\gamma \to K^+\pi^-\pi^+\gamma$:

$$\frac{d\Gamma(B^+ \to K^+\pi^-\pi^+\gamma)}{ds} = |\sum_i c^i_{\mathrm{R}} B^i(s) A^i_{\mathrm{R}}|^2 + |\sum_i c^i_{\mathrm{L}} B^i(s) A^i_{\mathrm{L}}|^2$$

Decay amplitude for $B^+ \to K_{res}^{+(i)}\gamma$

Propagator for $K_{res}^{+(i)}$

Decay amplitude for $K_{res}^{+(i)} \to K^+\pi^-\pi^+$

The photon polarisation parameter λ_γ for a decay mode *i* is then defined as:

$$\lambda^i_\gamma \equiv \frac{|c^i_{\mathrm{R}}|^2 - |c^i_{\mathrm{L}}|^2}{|c^i_{\mathrm{R}}|^2 + |c^i_{\mathrm{L}}|^2}$$

Gronau et. al:
PRL 88, 051802
PRD 66, 054008

PHOTON POLARISATION IN $B^+ \to K^+\pi^-\pi^+\gamma$ DECAYS

Use parity invariance of the strong interaction to relate the amplitudes for emitting left- and right- handed photons:

$$\langle K_{\mathrm{res}}^{+(i)R}\gamma_R|\mathcal{O}_{7R}|B^+\rangle = \mathcal{P}_i(-1)^{(J_i-1)}\langle K_{\mathrm{res}}^{+(i)L}\gamma_L|\mathcal{O}_{7L}|B^+\rangle$$

PRL 88, 051802
PRD 66, 054008

The weak amplitudes are then proportional to the Wilson coefficients:

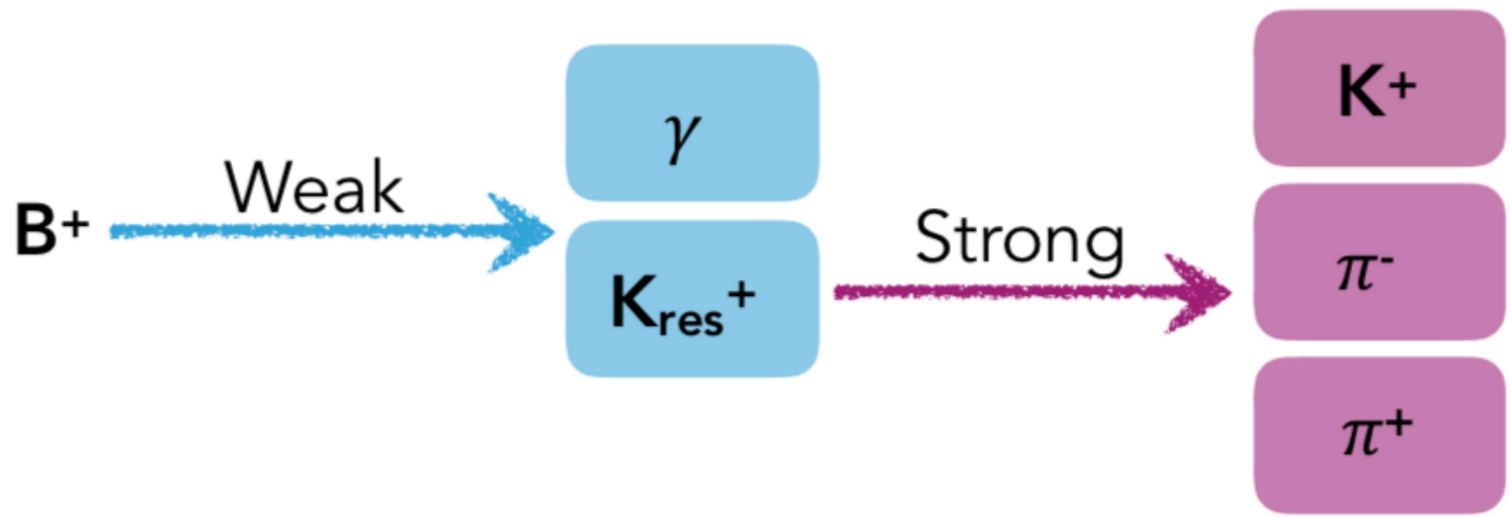
$$\begin{pmatrix} c_{\mathrm{R}}^i \\ c_{\mathrm{L}}^i \end{pmatrix} = -\frac{4G_{\mathrm{F}}}{\sqrt{2}} V_{tb}V_{ts}^* \begin{pmatrix} C_7^{\mathrm{eff}}\, g^i(0) \\ C_7'\, P_i(-1)^{J_i-1}\, g^i(0) \end{pmatrix}$$

hadronic matrix element of O_7

We can therefore derive λ_γ in terms of the Wilson coefficients:

$$\frac{|c_{\mathrm{R}}^i|}{|c_{\mathrm{L}}^i|} = \frac{|C_{7\mathrm{R}}|}{|C_{7\mathrm{L}}|} \quad \Longrightarrow \quad \lambda_\gamma^i = \frac{|C_{7\mathrm{R}}|^2 - |C_{7\mathrm{L}}|^2}{|C_{7\mathrm{R}}|^2 + |C_{7\mathrm{L}}|^2} \equiv \lambda_\gamma$$

λ_γ is the same for all decay modes



Can rewrite the total decay rate for all decay modes $B^+ \to K_{res}^+\gamma \to K^+\pi^-\pi^+\gamma$:

$$d\Gamma(B^+ \to K_{\rm res}^{+(i)}\gamma \to K^+\pi^-\pi^+\gamma) \propto (|\mathcal{M}_{\rm R}|^2 + |\mathcal{M}_{\rm L}|^2) + \lambda_\gamma(|\mathcal{M}_{\rm R}|^2 - |\mathcal{M}_{\rm L}|^2)$$

Right handed amplitudes

Photon polarisation parameter

$$\frac{|C_7^{\rm eff}|^2 - |C_7'|^2}{|C_7^{\rm eff}|^2 + |C_7'|^2} \equiv \lambda_\gamma$$

Left handed amplitudes

B→Kππγ FORMALISM

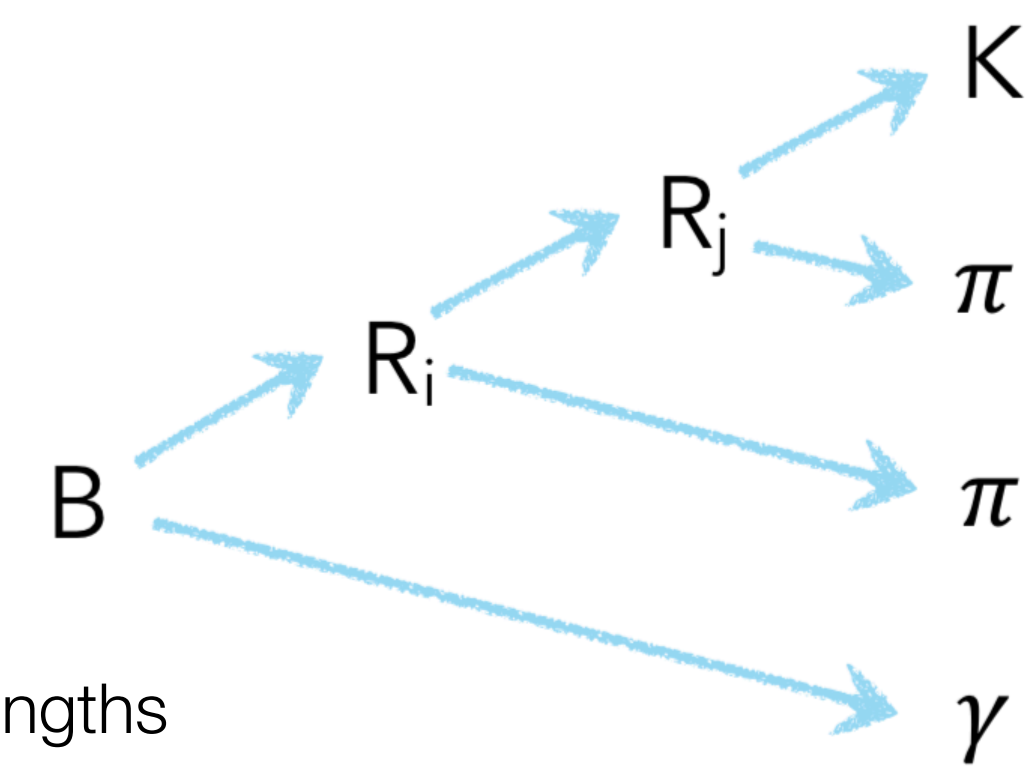
arxiv:1902.09201

$$d\Gamma(B^+ \to K^{+(i)}_{\text{res}}\gamma \to K^+\pi^-\pi^+\gamma) \propto (|\mathcal{M}_{\text{R}}|^2 + |\mathcal{M}_{\text{L}}|^2) + \lambda_\gamma(|\mathcal{M}_{\text{R}}|^2 - |\mathcal{M}_{\text{L}}|^2)$$

Use the isobar model to construct decay amplitudes

$$\mathcal{M}_{\text{R/L}} = \sum_k f_k \mathcal{A}_{k,\text{R/L}}(\boldsymbol{x})$$

$$f_k = a_k e^{i\phi_k}$$



The complex coefficients f_K encode relative strengths and phases for each amplitude

B→Kππγ FORMALISM

arxiv:1902.09201

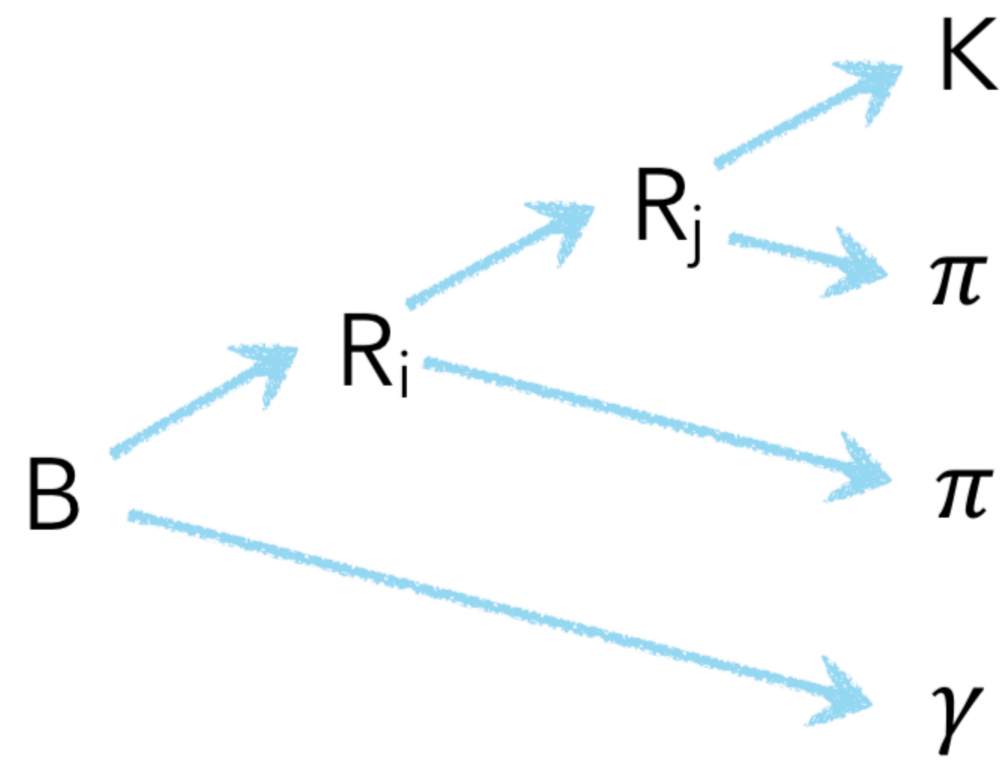
$$\mathcal{A}^k_{\mathrm{R}}(\boldsymbol{x}) = B_{L_B}(q_B(\boldsymbol{x}),0)\mathcal{T}^k_i(\boldsymbol{x})\mathcal{T}^k_j(\boldsymbol{x})\mathcal{S}^k_{ij,\mathrm{R}}(\boldsymbol{x})$$

$$\mathcal{A}^k_{\mathrm{L}}(\boldsymbol{x}) = P_i(-1)^{J_i-1}B_{L_B}(q_B(\boldsymbol{x}),0)\mathcal{T}^k_i(\boldsymbol{x})\mathcal{T}^k_j(\boldsymbol{x})\mathcal{S}^k_{ij,\mathrm{L}}(\boldsymbol{x})$$

Resonance propagators

Barrier factor for a B meson of angular momentum L

Spin factors
Encode the phenomenology of the decay, computed with the covariant formalism



B→Kππγ FORMALISM (RECAP)

The (normalised) probability density function for B→Kππγ decays:

arxiv:1902.09201

PRL 88, 051802
PRD 66, 054008

$$\mathcal{F}(\boldsymbol{x}|\Omega) = \frac{\xi(\boldsymbol{x})\mathcal{P}_{\rm s}(\boldsymbol{x}|\Omega)\Phi_4(\boldsymbol{x})}{\int \xi(\boldsymbol{x})\mathcal{P}_{\rm s}(\boldsymbol{x}|\Omega)\Phi_4(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x}}$$

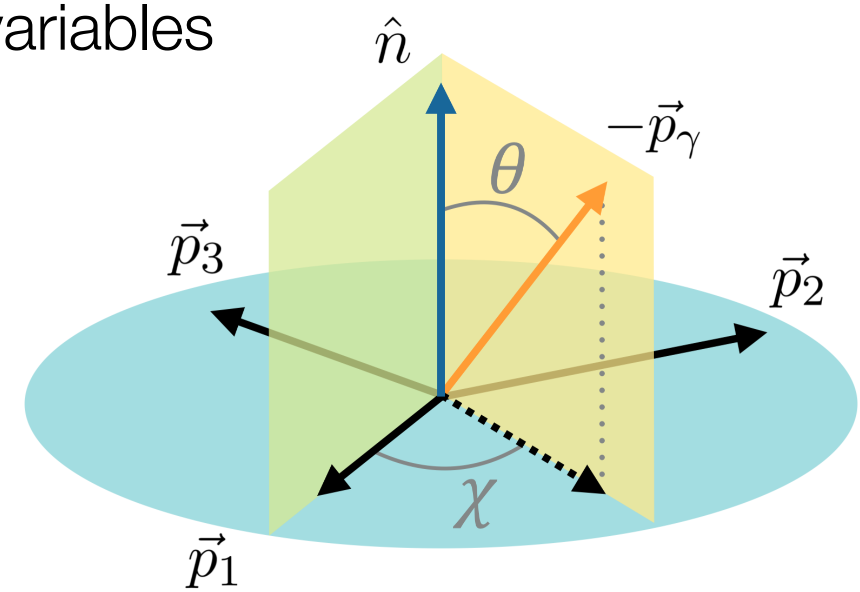
where

$\boldsymbol{x} = (m^2_{K^+\pi^-\pi^+}, m^2_{K^+\pi^-}, m^2_{\pi^-\pi^+}, \cos\theta, \chi)$: phase space variables

$\Omega = \lambda_\gamma, \{a_k\}, \{\phi_k\}$: fit parameters

$\xi(\boldsymbol{x})$: efficiency

$\Phi_4(\boldsymbol{x})$: phase space volume



The signal function P_s encodes the dependence on λ_γ

$$\mathcal{P}_{\rm s} = \frac{(1+\lambda_\gamma)}{2}|\mathcal{M}_{\rm R}|^2 + \frac{(1-\lambda_\gamma)}{2}|\mathcal{M}_{\rm L}|^2$$

B→Kππγ Amplitude Analysis: Method

arxiv:1902.09201

The (normalised) probability density function for B→Kππγ decays:

$$\mathcal{F}(\boldsymbol{x}|\Omega) = \frac{\xi(\boldsymbol{x})\mathcal{P}_{\mathrm{s}}(\boldsymbol{x}|\Omega)\Phi_4(\boldsymbol{x})}{\int \xi(\boldsymbol{x})\mathcal{P}_{\mathrm{s}}(\boldsymbol{x}|\Omega)\Phi_4(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x}}$$

This PDF is implemented in a modified version of the MINT2 generator-fitter framework

- Enables generation of multi-amplitude models with interferences, performs unbinned maximum likelihood minimisation

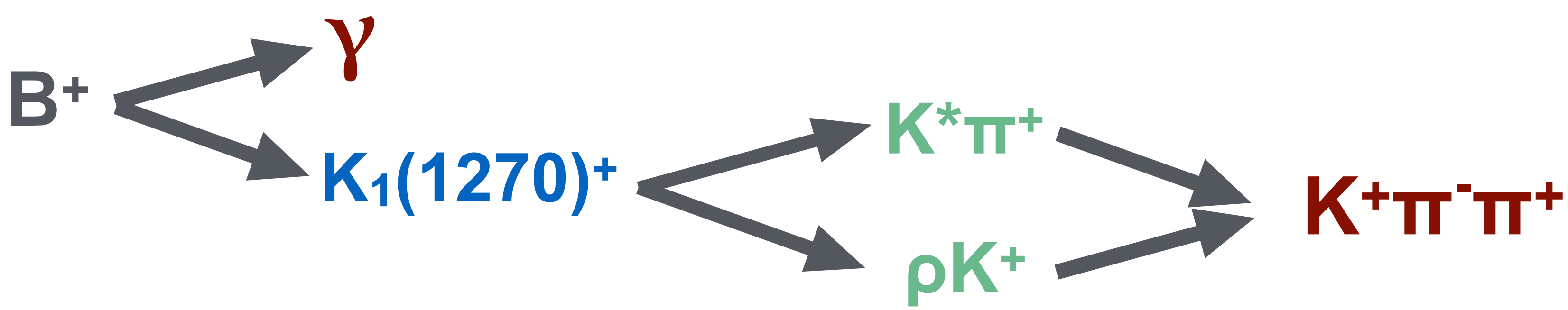
The normalisation integral is computed numerically using MC generated events according to an approximate PDF P_{gen}:

$$\int \xi(\boldsymbol{x})\mathcal{P}_s(\boldsymbol{x})\phi_4(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x} = \frac{I_{\mathrm{gen}}}{N_{\mathrm{sel}}}\sum_{j}^{N_{\mathrm{sel}}}\frac{\mathcal{P}_s(\boldsymbol{x}_j)}{\mathcal{P}_{\mathrm{gen}}(\boldsymbol{x}_j)}$$

The term $I_{\mathrm{gen}} = \int \xi(\boldsymbol{x})\mathcal{P}_{\mathrm{gen}}(\boldsymbol{x})\phi_4(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x}$ is independent of all fit parameters, so can be neglected in the minimisation

$B^+ \to K^+\pi^-\pi^+\gamma$ with Two Decay Amplitudes

- Test the method with a simplified, two-amplitude model:



- System described by three free parameters:
    - The relative fraction **r** between the two amplitudes
    - Their phase difference **Δϕ**
    - The photon polarisation parameter $\boldsymbol{\lambda_\gamma}$

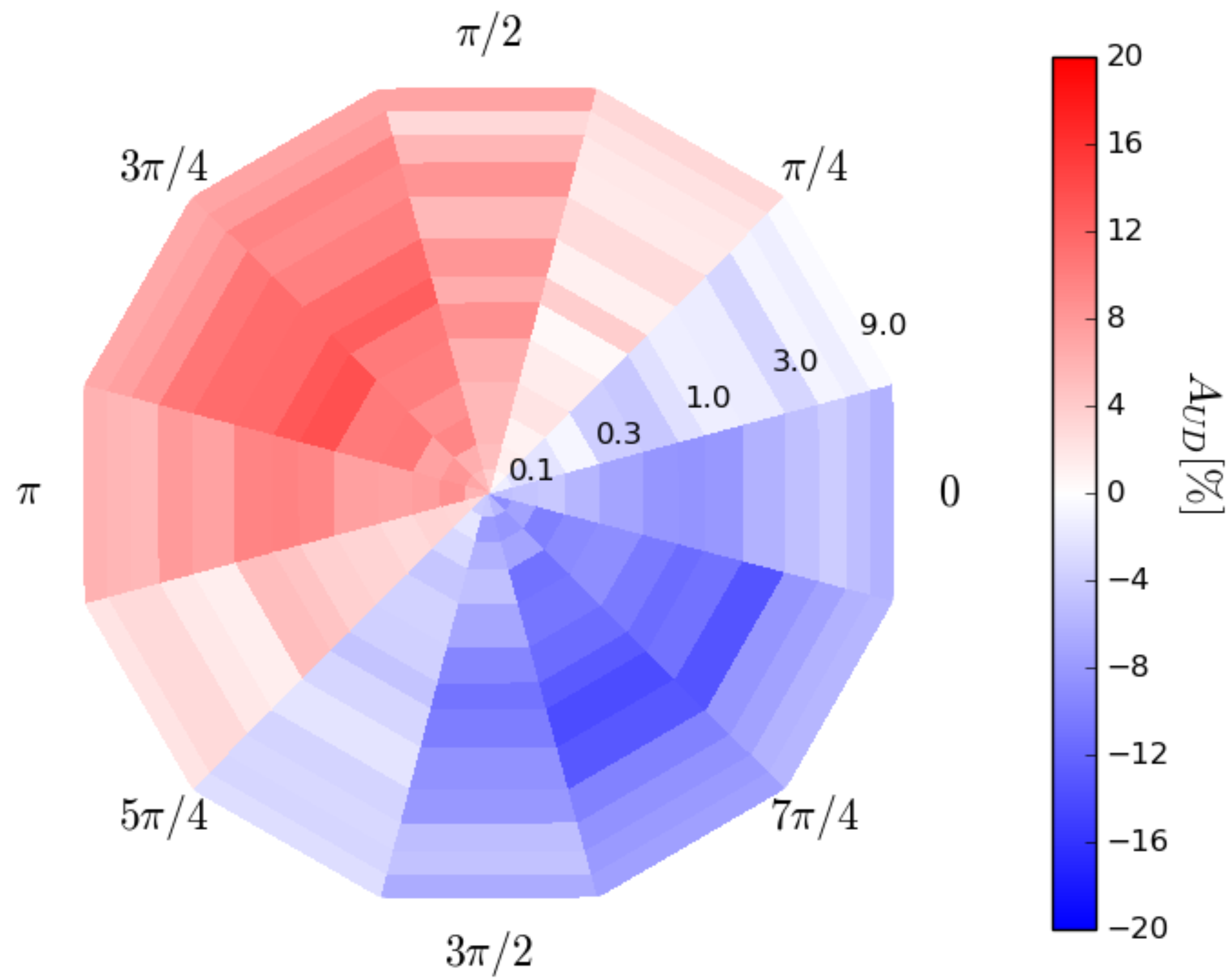
- Study performance of the fit for a range of model parameters
    - At each point, 10 data sets of 8000 events each are generated and fit

Reminder: Limitations of A_{ud}

The up-down asymmetry A_{ud} is proportional to λ_γ

- The proportionality constant C depends on the resonance content of the system
- Cannot calculate λ_γ from up-down asymmetry without full characterisation of the resonances

- As an illustration, use the two amplitude model
- Generate samples for a range of relative fractions and phases between the amplitudes; λ_γ=1 (always)
- For each generated sample, calculate A_{ud}
- Up-down asymmetry varies as a function of the relative fraction and phase
  - Regions where A_{ud} =0, so no sensitivity to λ_γ

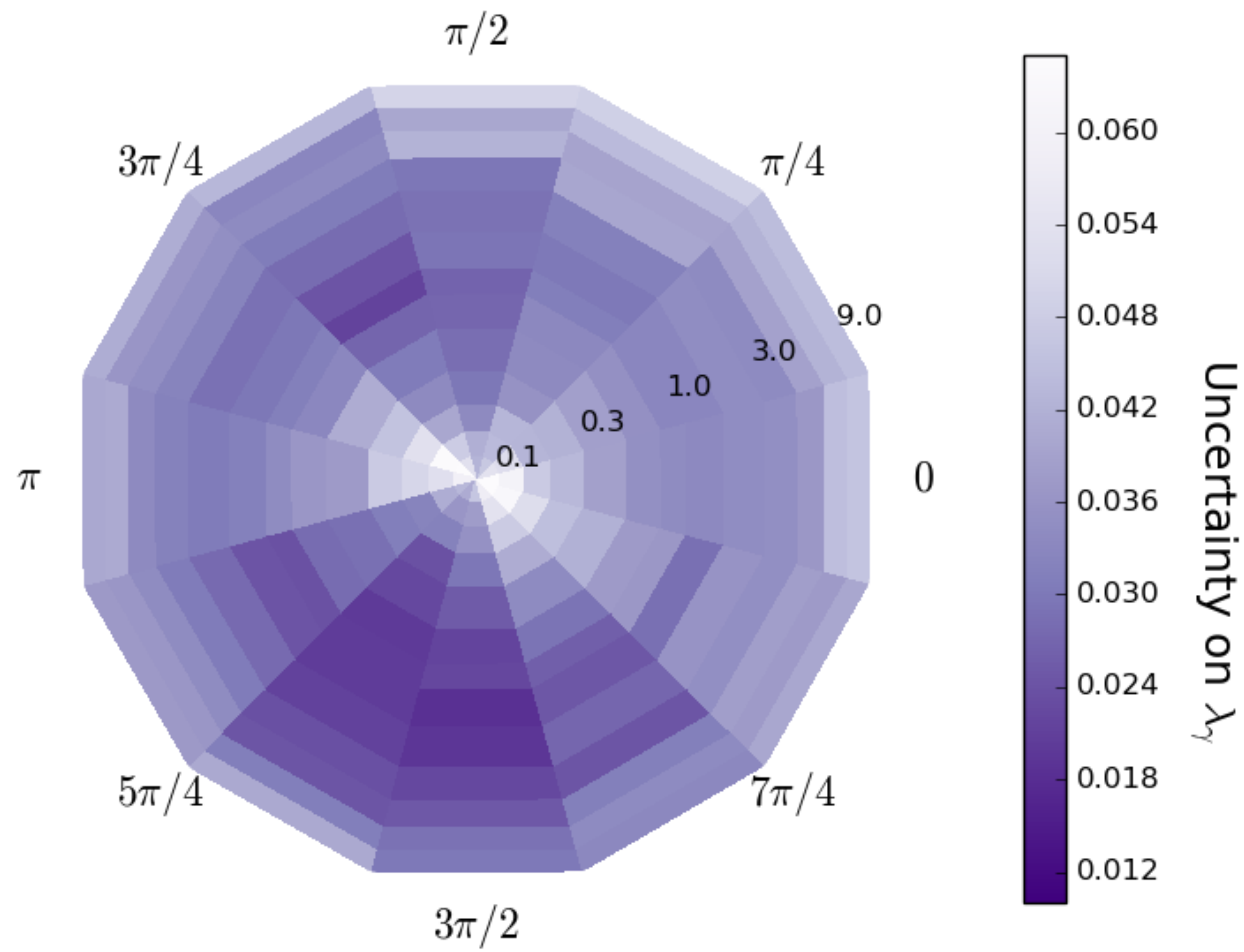


$B^+ \to K^+\pi^-\pi^+\gamma$: Two-Amplitude Model

arxiv:1902.09201

- Use MINT to perform amplitude fits for the same generated data sets
- Fits mostly converge with no errors
  - Resulting fit parameters are centred around the 'true' (generated) values

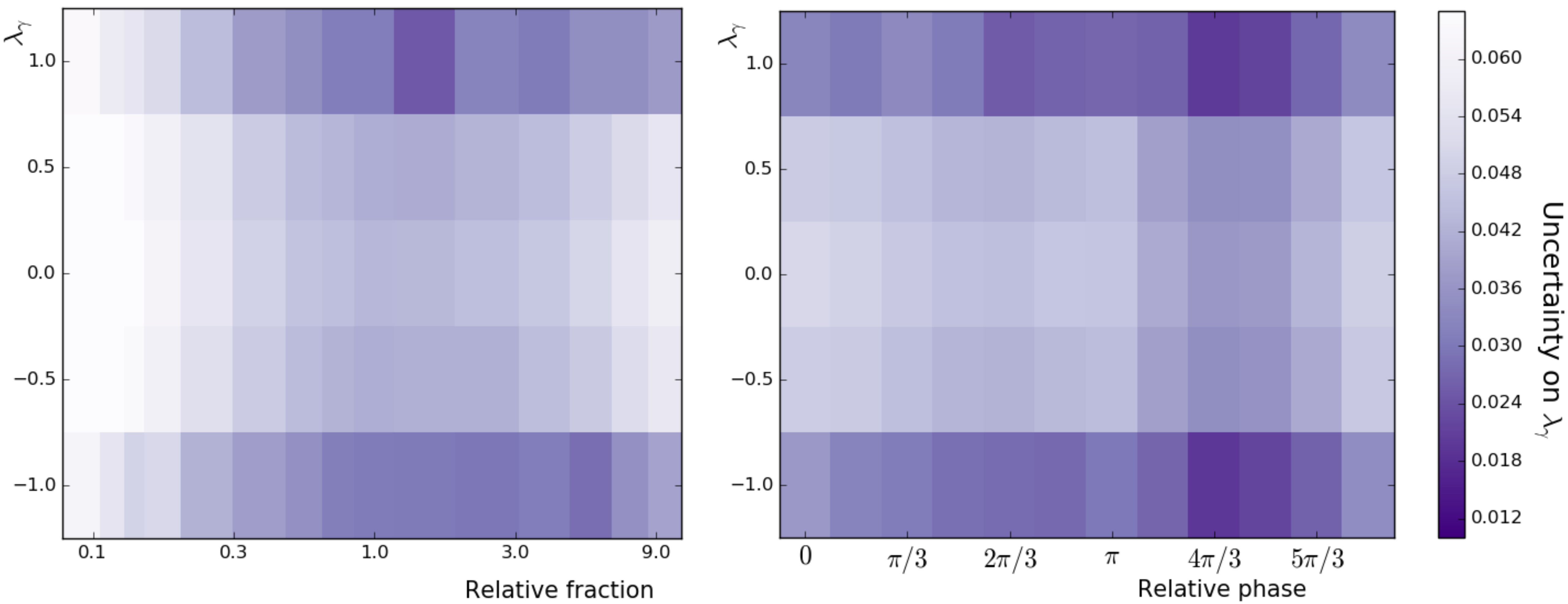
- The method is sensitive to all data points studied
- Variations in uncertainty on seen as a function of both r and Δϕ
  - Uncertainty is highest when one amplitude is dominant, tending towards a single amplitude model



$B^+ \to K^+\pi^-\pi^+\gamma$: Two-Amplitude Model

arxiv:1902.09201

- Repeat the previous test for ranges of (r, λ_γ) and ($\Delta\phi$, λ_γ)
- Fit is sensitive to all values studied
  - The uncertainty on λ_γ increases as values tend towards 0



$B^+ \to K^+\pi^-\pi^+\gamma$: Two-Amplitude Model

- More detailed check of behaviour of the fit:
  - Perform 100 fits for a subset of points for each of the previous plots
  - Check distributions of fit parameters, associated errors, and pull parameter g:

$$\text{if (fit result)} \leq \text{(true value)}: \quad g = \frac{\text{(true value)} - \text{(fit result)}}{\text{(positive error)}}$$

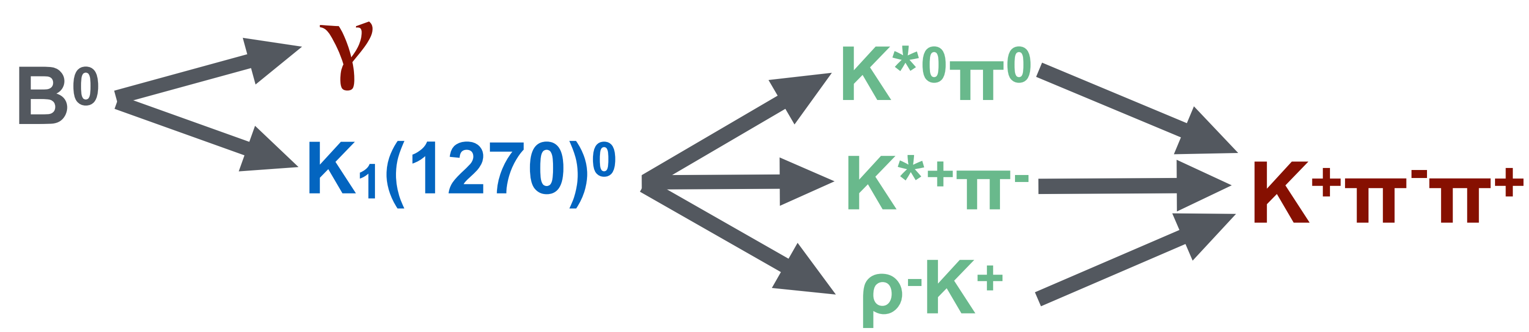
$$\text{otherwise:} \quad g = \frac{\text{(fit result)} - \text{(true value)}}{\text{(negative error)}}$$

- Pull distributions are unbiased with widths mostly consistent with unity in all cases

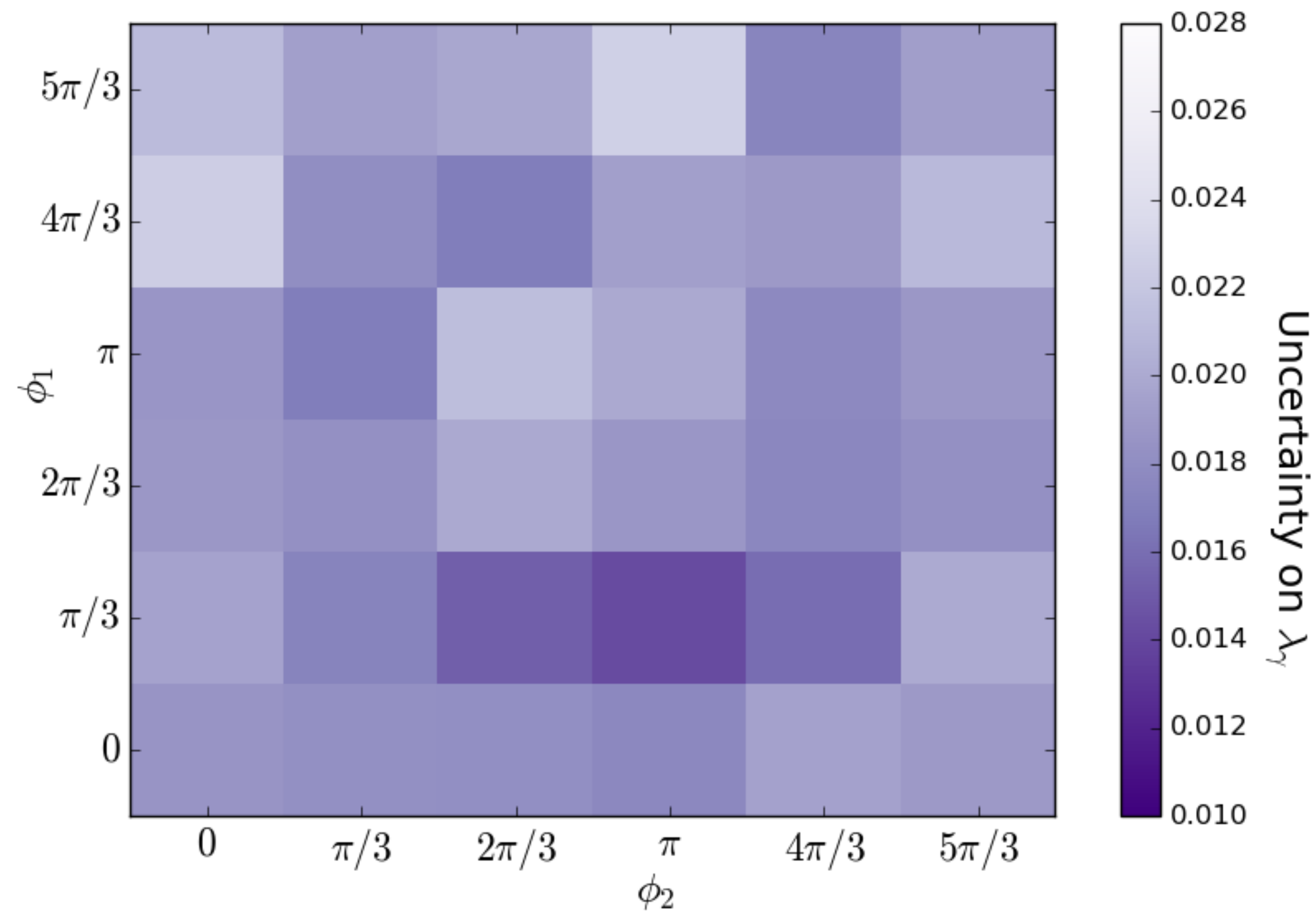
Parameter	True value	Mean value	Std deviation	μ_{pull}	σ_{pull}
a	2.02	2.020	0.04	0.01 ± 0.11	1.14 ± 0.07
ϕ	0.82	0.823	0.02	-0.09 ± 0.09	0.94 ± 0.07
λ_γ	1	1.001	0.04	-0.09 ± 0.12	1.17 ± 0.08
a	2.02	2.023	0.04	-0.06 ± 0.11	1.17 ± 0.07
ϕ	0.82	0.823	0.03	-0.13 ± 0.09	0.97 ± 0.06
λ_γ	0.875	0.870	0.04	0.11 ± 0.11	1.17 ± 0.08
a	2.02	2.022	0.04	-0.03 ± 0.09	1.03 ± 0.07
ϕ	0.82	0.822	0.03	-0.07 ± 0.09	0.92 ± 0.06
λ_γ	0.75	0.741	0.04	0.20 ± 0.09	1.03 ± 0.07

$B^0 \to K^+\pi^-\pi^0\gamma$: Three-Amplitude Model

- Perform a similar test with $B^0 \to K^+\pi^-\pi^0\gamma$ decays arxiv:1902.09201
  - Gronau et. al. noted an increased sensitivity in up-down symmetry with additional interference terms, would the same hold true for a full amplitude analysis?



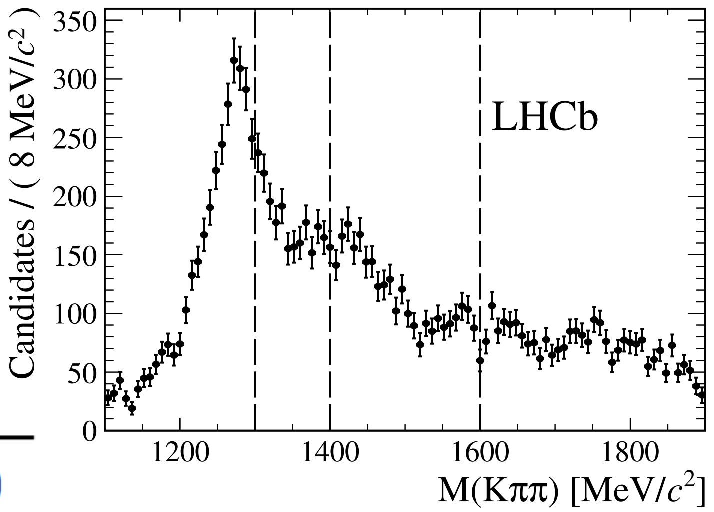
- Generated ratios of fit fractions ~1, λ_γ=1
- Scan over a range of relative phases
- Uncertainties within the range seen for the charged mode



$B^+ \to K^+\pi^-\pi^+\gamma$: Realistic Model

CERN-THESIS-2015-287

- Build a model with 15 decay amplitudes
- Generate 100 datasets with 14000 events each, (r, Δϕ) generated values chosen correspond to 3-dimensional amplitude fit results from LHCb Run1 data analysis

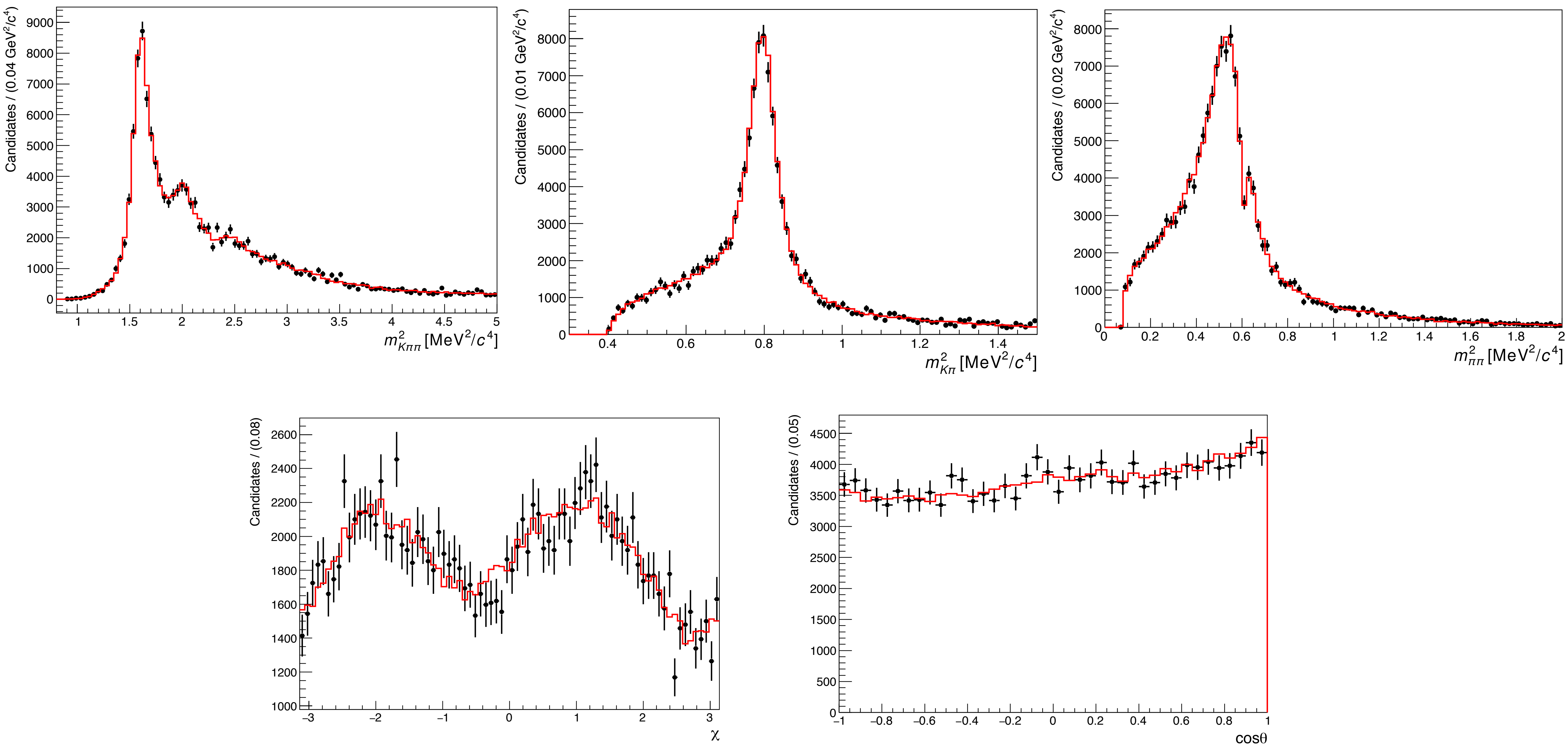


J^P	Amplitude k	a_k	ϕ_k	Fraction (%)
1^+	$K_1(1270)^+ \to K^*(892)^0\pi^+$ [S-wave]	1 (fixed)	0 (fixed)	15.3
	$K_1(1270)^+ \to K^*(892)^0\pi^+$ [D-wave]	1.00	−1.74	0.6
	$K_1(1270)^+ \to K^+\rho(770)^0$	2.02	−0.91	37.9
	$K_1(1400)^+ \to K^*(892)^0\pi^+$	0.59	−0.76	7.4
1^-	$K^*(1410)^+ \to K^*(892)^0\pi^+$	0.11	0.00	7.9
	$K^*(1680)^+ \to K^*(892)^0\pi^+$	0.05	0.44	3.4
	$K^*(1680)^+ \to K^+\rho(770)^0$	0.04	1.40	2.3
2^+	$K_2^*(1430)^+ \to K^*(892)^0\pi^+$	0.28	0.00	4.5
	$K_2^*(1430)^+ \to K^+\rho(770)^0$	0.47	1.80	8.9
2^-	$K_2(1580)^+ \to K^*(892)^0\pi^+$	0.49	2.88	4.2
	$K_2(1580)^+ \to K^+\rho(770)^0$	0.38	2.44	3.2
	$K_2(1770)^+ \to K^*(892)^0\pi^+$	0.35	0.00	2.8
	$K_2(1770)^+ \to K^+\rho(770)^0$	0.08	2.53	0.2
	$K_2(1770)^+ \to K_2^*(1430)^0\pi^+$	0.07	−2.06	0.6

$B^+ \to K^+\pi^-\pi^+\gamma$: Realistic Model

arxiv:1902.09201

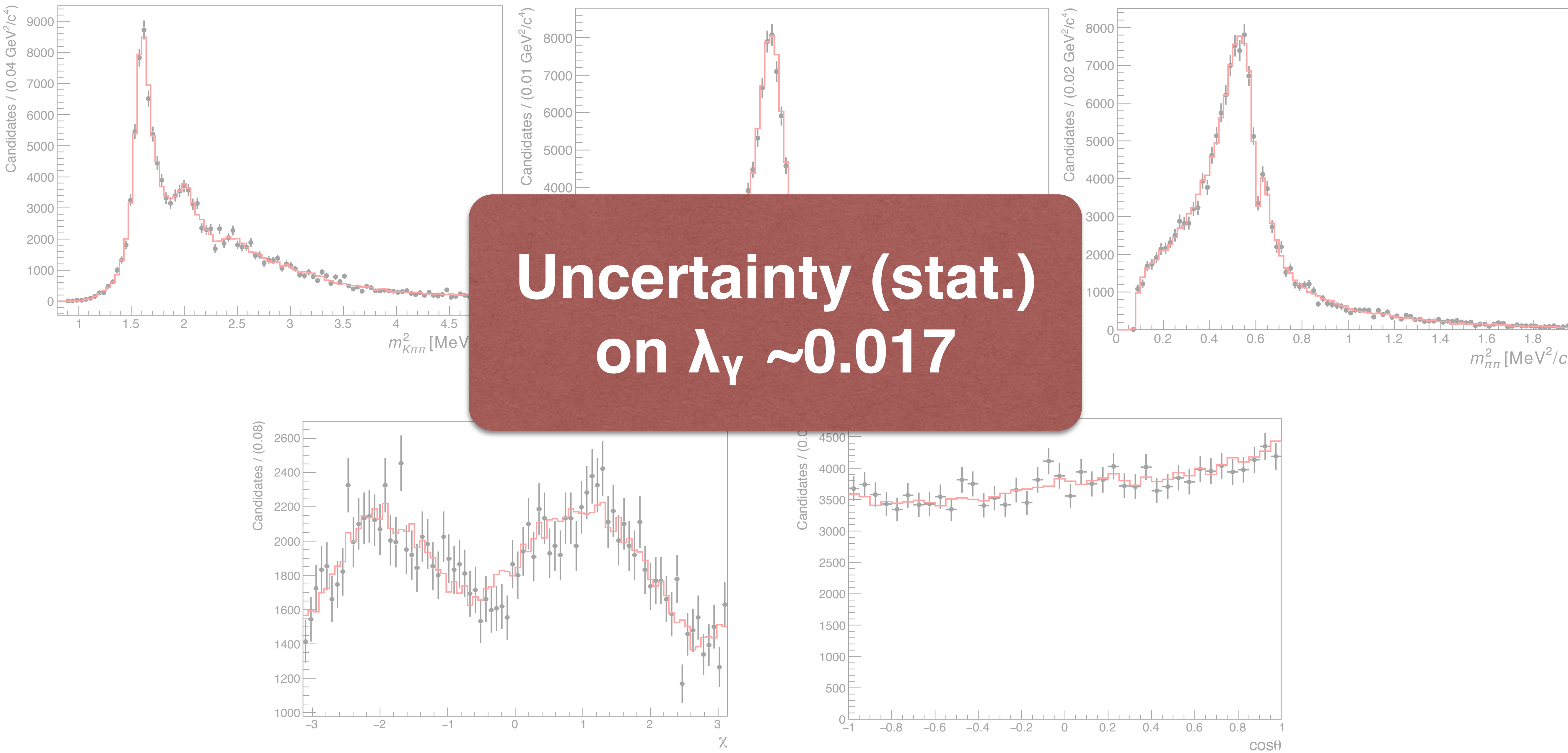
- Fits converge, pulls mostly unbiased, with unit width
- Sample fit projection shown below:



$B^+ \to K^+\pi^-\pi^+\gamma$: REALISTIC MODEL

arxiv:1902.09201

- Fits converge, pulls mostly unbiased, with unit width
  - Pull width for λ_γ slightly greater than unity, correct average uncertainty from fit to compensate



Uncertainty (stat.) on λ_γ ~0.017

$B^0 \to K^+\pi^-\pi^0\gamma$: Realistic Model

arxiv:1902.09201

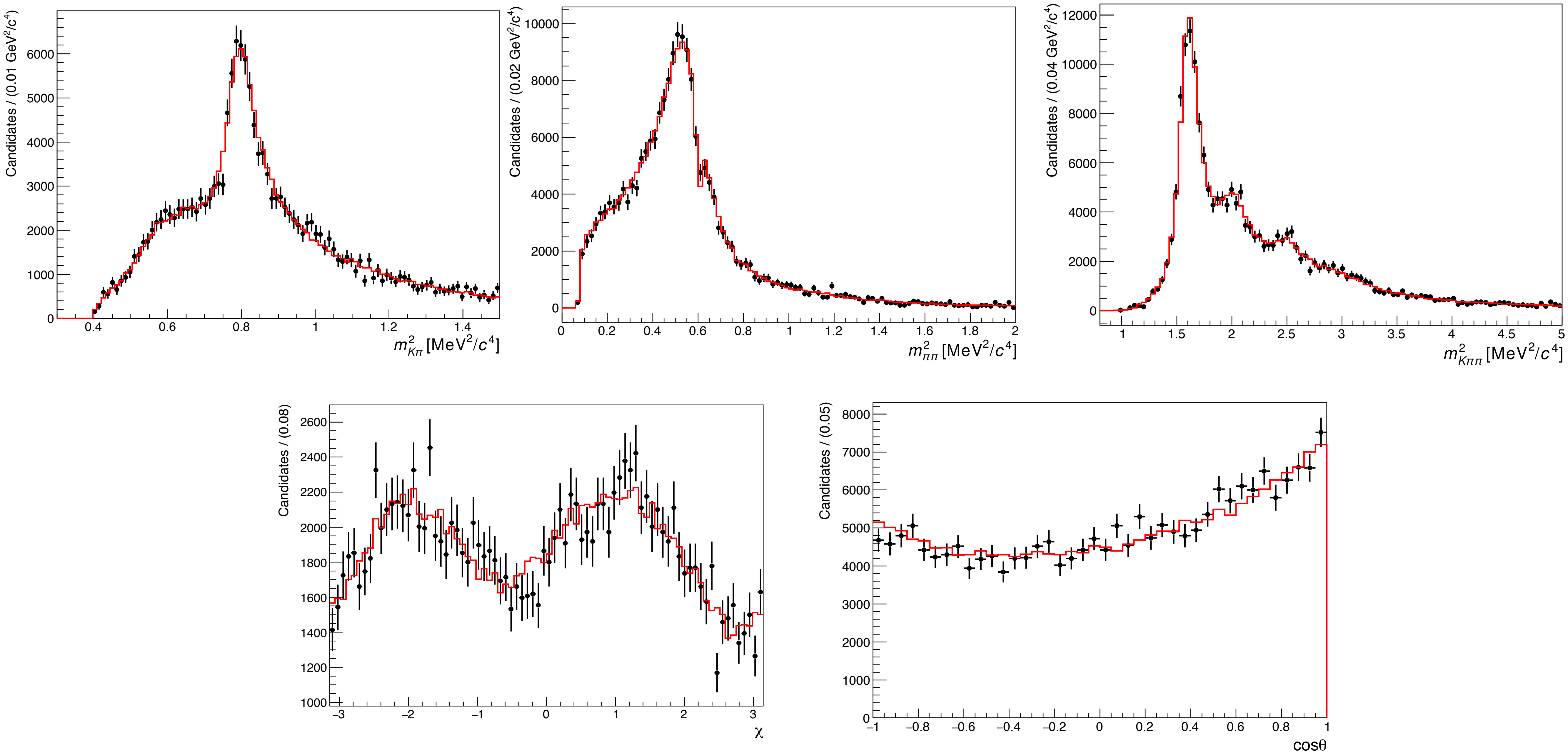
- Build analogous model for $B^0 \to K^+\pi^-\pi^0\gamma$ decays
- Generate and fit 100 data sets with 10000 events each

J^P	Amplitude k	a_k	ϕ_k	Fraction (%)
1^+	$K_1(1270)^0 \to K^*(892)^0\pi^0$ [S-wave]	1(fixed)	0 (fixed)	8.0
	$K_1(1270)^0 \to K^*(892)^+\pi^-$ [S-wave]	1.01	0.00	8.0
	$K_1(1270)^0 \to K^*(892)^+\pi^-$ [D-wave]	0.98	-1.74	0.3
	$K_1(1270)^0 \to K^*(892)^0\pi^0$ [D-wave]	0.99	-1.74	0.3
	$K_1(1270)^0 \to K^+\rho(770)^-$	2.86	-0.91	39.7
	$K_1(1400)^0 \to K^*(892)^+\pi^-$	0.60	-0.76	3.8
	$K_1(1400)^0 \to K^*(892)^0\pi^0$	0.59	-0.76	3.8
1^-	$K^*(1410)^0 \to K^*(892)^+\pi^-$	0.11	0.00	3.9
	$K^*(1410)^0 \to K^*(892)^0\pi^0$	0.11	0.00	3.9
	$K^*(1680)^0 \to K^*(892)^+\pi^-$	0.05	0.44	1.7
	$K^*(1680)^0 \to K^*(892)^0\pi^0$	0.05	0.44	1.7
	$K^*(1680)^0 \to K^+\rho(770)^-$	0.06	1.40	2.4
2^+	$K_2^*(1430)^0 \to K^*(892)^+\pi^-$	0.27	0.00	2.3
	$K_2^*(1430)^0 \to K^*(892)^0\pi^0$	0.27	0.00	2.3
	$K_2^*(1430)^0 \to K^+\rho(770)^-$	0.63	1.80	8.9
2^-	$K_2(1580)^0 \to K^*(892)^+\pi^-$	0.49	2.88	2.2
	$K_2(1580)^0 \to K^*(892)^0\pi^0$	0.49	2.88	2.2
	$K_2(1580)^0 \to K^+\rho(770)^-$	0.54	2.44	3.2
	$K_2(1770)^0 \to K^*(892)^+\pi^-$	0.35	0.00	1.5
	$K_2(1770)^0 \to K^*(892)^0\pi^0$	0.35	0.00	1.5
	$K_2(1770)^0 \to K^+\rho(770)^-$	0.11	2.53	0.2
	$K_2(1770)^0 \to K_2^*(1430)^+\pi^-$	0.07	-2.06	0.3
	$K_2(1770)^0 \to K_2^*(1430)^0\pi^0$	0.07	-2.06	0.3

$B^0 \to K^+\pi^-\pi^0\gamma$: Realistic Model

arxiv:1902.09201

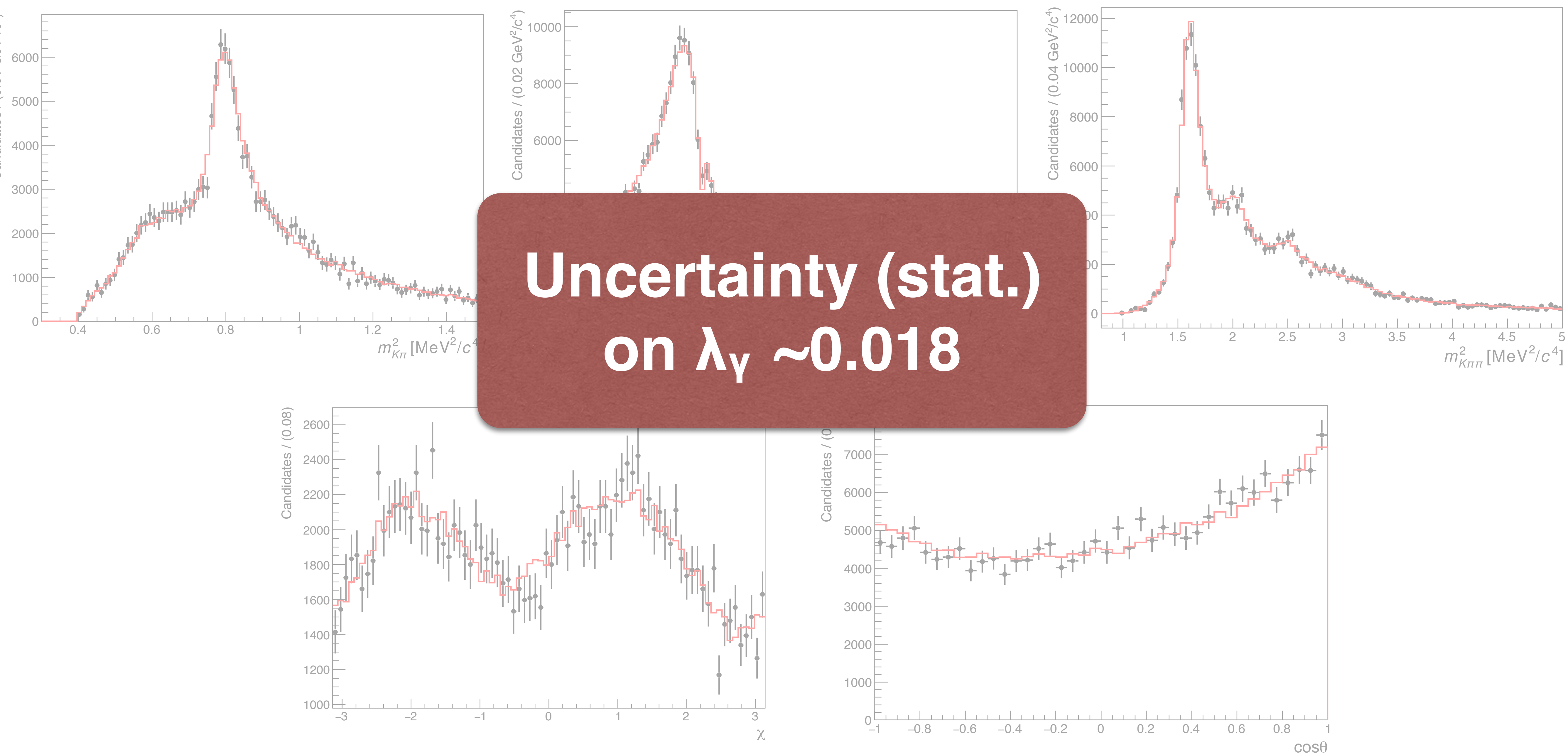
- Fits converge, pulls mostly unbiased, with unit width
- Sample fit projection shown below:



$B^+ \to K^+\pi^-\pi^+\gamma$: Realistic Model

arxiv:1902.09201

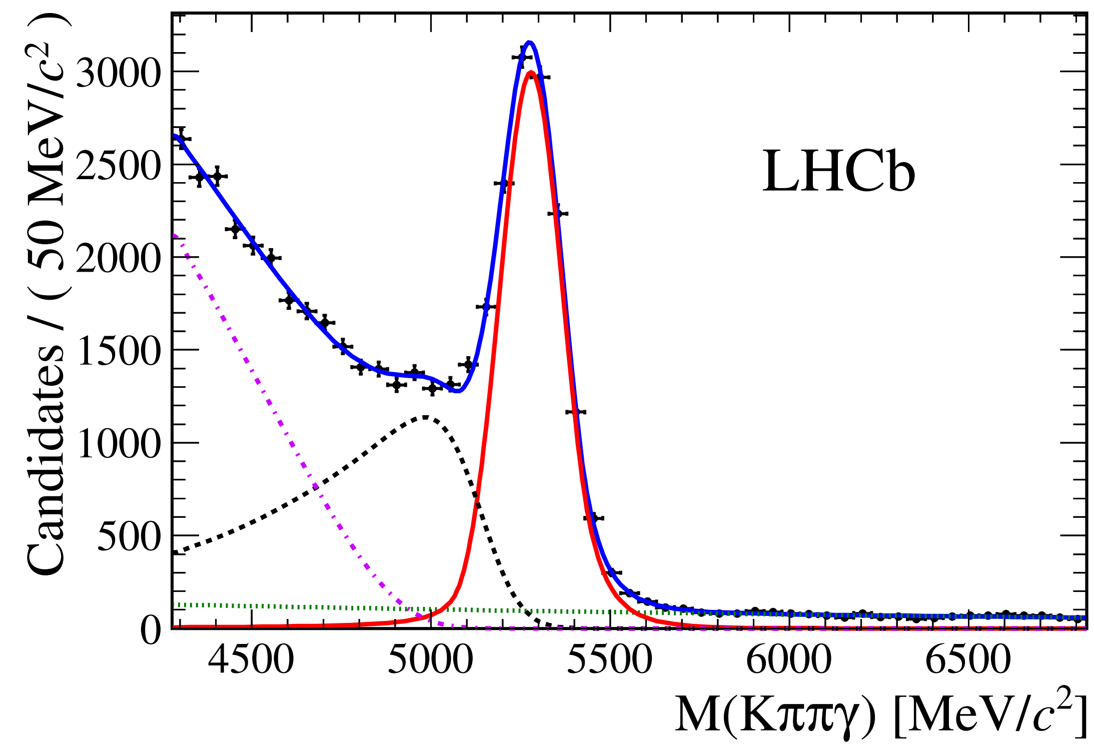
- Fits converge, pulls mostly unbiased, with unit width
  - Pull width for λ_γ slightly greater than unity, correct average uncertainty from fit to compensate



Uncertainty (stat.) on λ_γ ~0.018

Prospects for Photon Polarisation Measurements

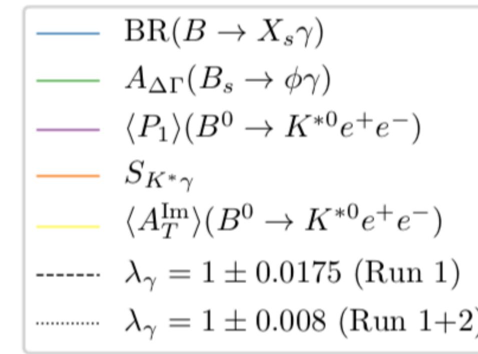
- Sensitivity to photon polarisation parameter studied for both simplified and realistic signal-only models
  - The method is sensitive to both simplified and realistic models with reasonable values of $(r, \Delta\phi, \lambda_\gamma)$ in the ideal, signal-only case
- LHCb has collected ~6.4 fb^{-1} of data during 2011, 2012, 2016 and 2017
  - Expect around 50000 $B^+ \to K^+\pi^-\pi^+\gamma$ signal events
  - Signal-only toy studies show an expected statistical sensitivity of ~0.01
- Full analysis ongoing with LHCb Run 1 + partial Run 2 data set
  - Event selection + mass fits finalised
  - Pieces in place to proceed with amplitude analysis with data



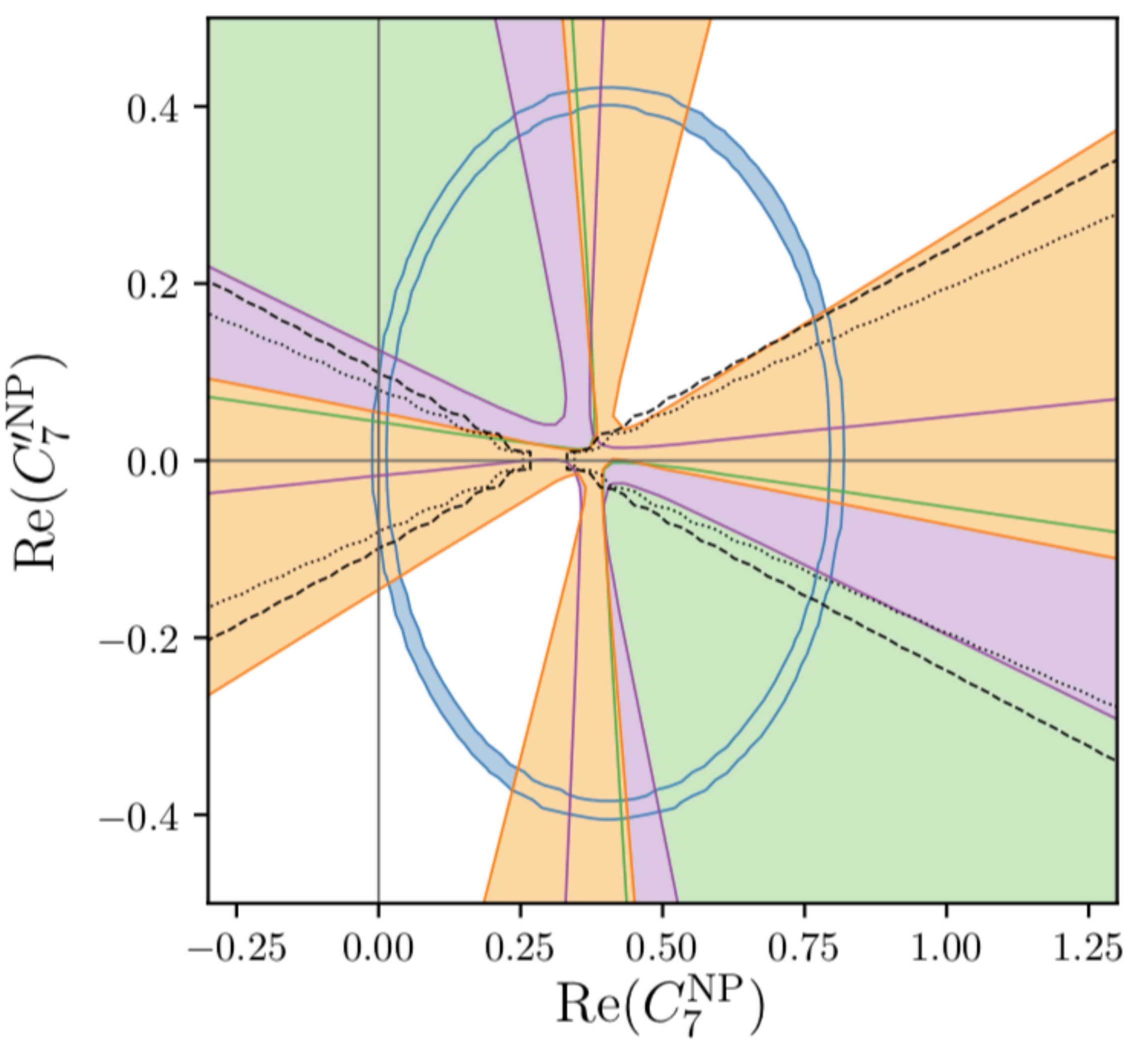
- Belle-II could expect around 10000 $B^0 \to K^+\pi^-\pi^0\gamma$ signal events with ~5 ab^{-1}
  - Signal-only toy studies show an expected statistical sensitivity of ~0.018

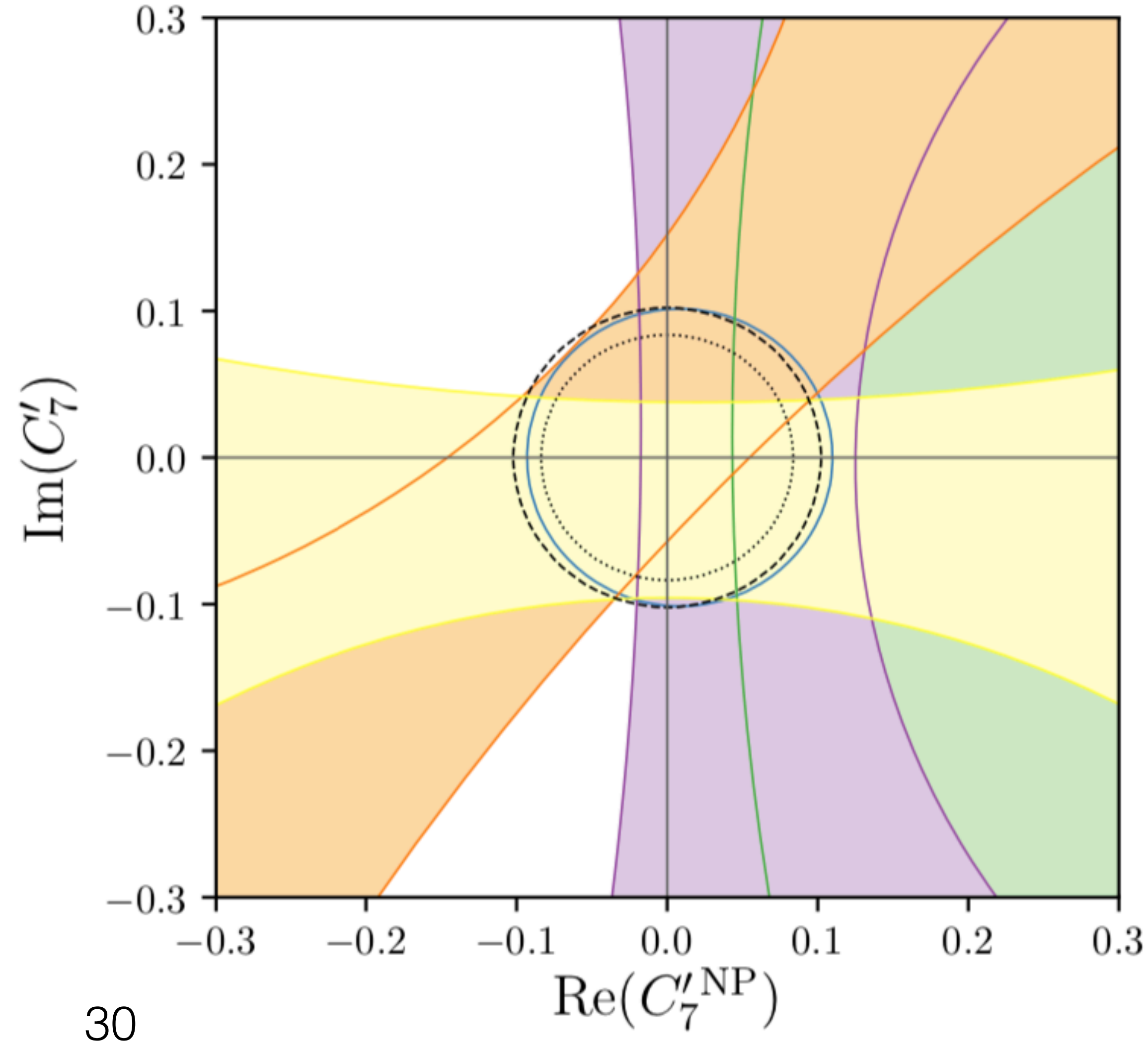
Interpretation in terms of Wilson Coefficients

- Sensitivity to photon polarisation parameter from these decays provides complementary information to that from complementary analyses
  - In particular, could help resolve ambiguities in Re(C7')



A. Puig
flavio: D. Straub et al.
JHEP 04 (2017) 027





Interpretation in terms of Wilson Coefficients

- However, interpretation may not be quite as straightforward
  - Reminder - weak decay amplitudes written in terms of the Wilson coefficients

$$\begin{pmatrix} c^i_{\mathrm{R}} \\ c^i_{\mathrm{L}} \end{pmatrix} = -\frac{4G_{\mathrm{F}}}{\sqrt{2}} V_{tb} V^*_{ts} \begin{pmatrix} C_7^{\mathrm{eff}}\, g^i(0) \\ C'_7\, P_i (-1)^{J_i - 1}\, g^i(0) \end{pmatrix}$$

  - Could define a single photon polarisation parameter for all decay modes

$$\lambda^i_\gamma = \frac{|C_{7\mathrm{R}}|^2 - |C_{7\mathrm{L}}|^2}{|C_{7\mathrm{R}}|^2 + |C_{7\mathrm{L}}|^2} \equiv \lambda_\gamma$$

Interpretation in terms of Wilson Coefficients

- Could have non-negligible contributions from other operators

$$\begin{pmatrix} c^i_{\mathrm{R}} \\ c^i_{\mathrm{L}} \end{pmatrix} = -\frac{4G_{\mathrm{F}}}{\sqrt{2}} V_{tb} V^*_{ts} \begin{pmatrix} C^{\mathrm{eff}}_7 \, g^i(0) + h^i_{\mathrm{R}} \\ C'_7 \, P_i (-1)^{J_i - 1} \, g^i(0) + h^i_{\mathrm{L}} \end{pmatrix}$$

- How could we deal with this?
  - Theoretical estimation of $h_{R/L}$?
  - Treat them as nuisance parameters in the analysis
  - Compute the photon polarisation parameter in different invariant mass bins
  - Check compatibility between channels with different contributions, like $B^+ \to K^+\pi^-\pi^+\gamma$ and $B^0 \to K^+\pi^-\pi^0\gamma$ decays

Interpretation in terms of Wilson Coefficients

- Could have non-negligible contributions from other operators

$$\begin{pmatrix} c_{\mathrm{R}}^i \\ c_{\mathrm{L}}^i \end{pmatrix} = -\frac{4G_{\mathrm{F}}}{\sqrt{2}} V_{tb} V_{ts}^* \begin{pmatrix} C_7^{\mathrm{eff}}\, g^i(0) + h_{\mathrm{R}}^i \\ C_7'\, P_i (-1)^{J_i - 1}\, g^i(0) + h_{\mathrm{L}}^i \end{pmatrix}$$

- How could we deal with this?
  - Theoretical estimation of $h_{R/L}$?
  - Treat them as nuisance parameters in the analysis
    →**technically challenging**
  - Compute the photon polarisation parameter in different invariant mass bins
    →**difficult due to long tails of (broad) high mass resonances**
  - Check compatibility between channels with different contributions, like $B^+ \to K^+\pi^-\pi^+\gamma$ and $B^0 \to K^+\pi^-\pi^0\gamma$ decays
    ✓ **For now, the way to go**

SUMMARY

- PDF that describes B→Kππγ decays implemented in a generator-fitter framework
  - Generated single amplitude MC samples validated (where possible) against EvtGen
- Sensitivity to photon polarisation parameter studied for both simplified and realistic signal-only models
  - Ideal case: signal-only samples with perfect efficiency
  - The method is sensitive to both simplified and realistic models with reasonable values of (r, $\Delta\phi$, λ_γ)
- Amplitude analysis method can be used to study both charged and neutral decay modes
- Analysis of charged decay mode with LHCb data sample ongoing

BACKUP

Parametrising FCNC Transitions

Effective Hamiltonian for radiative b-> s gamma transitions:

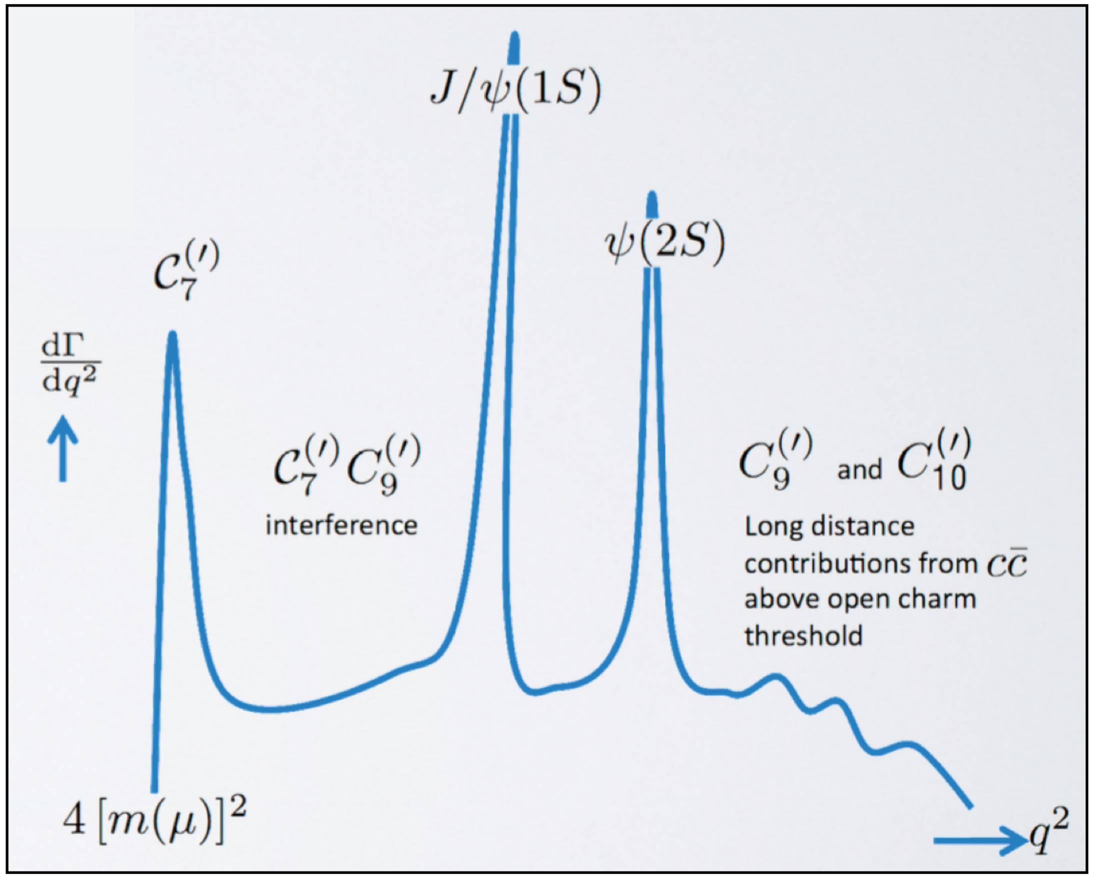
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

Operators (O_i) - long-distance effects (non-perturbative)

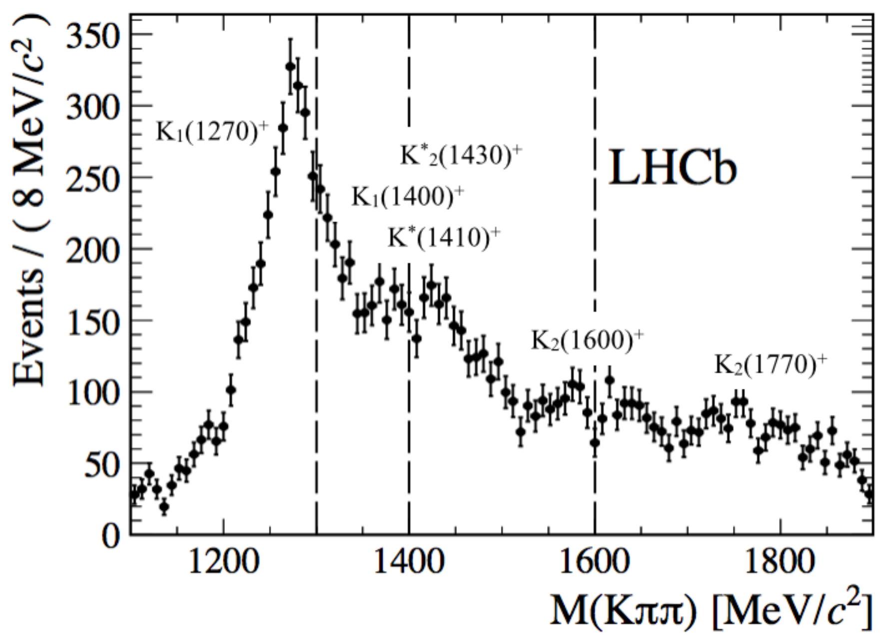
Wilson coefficients (C_i) - perturbative, short-distance physics

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

different regions of q^2 probe different processes

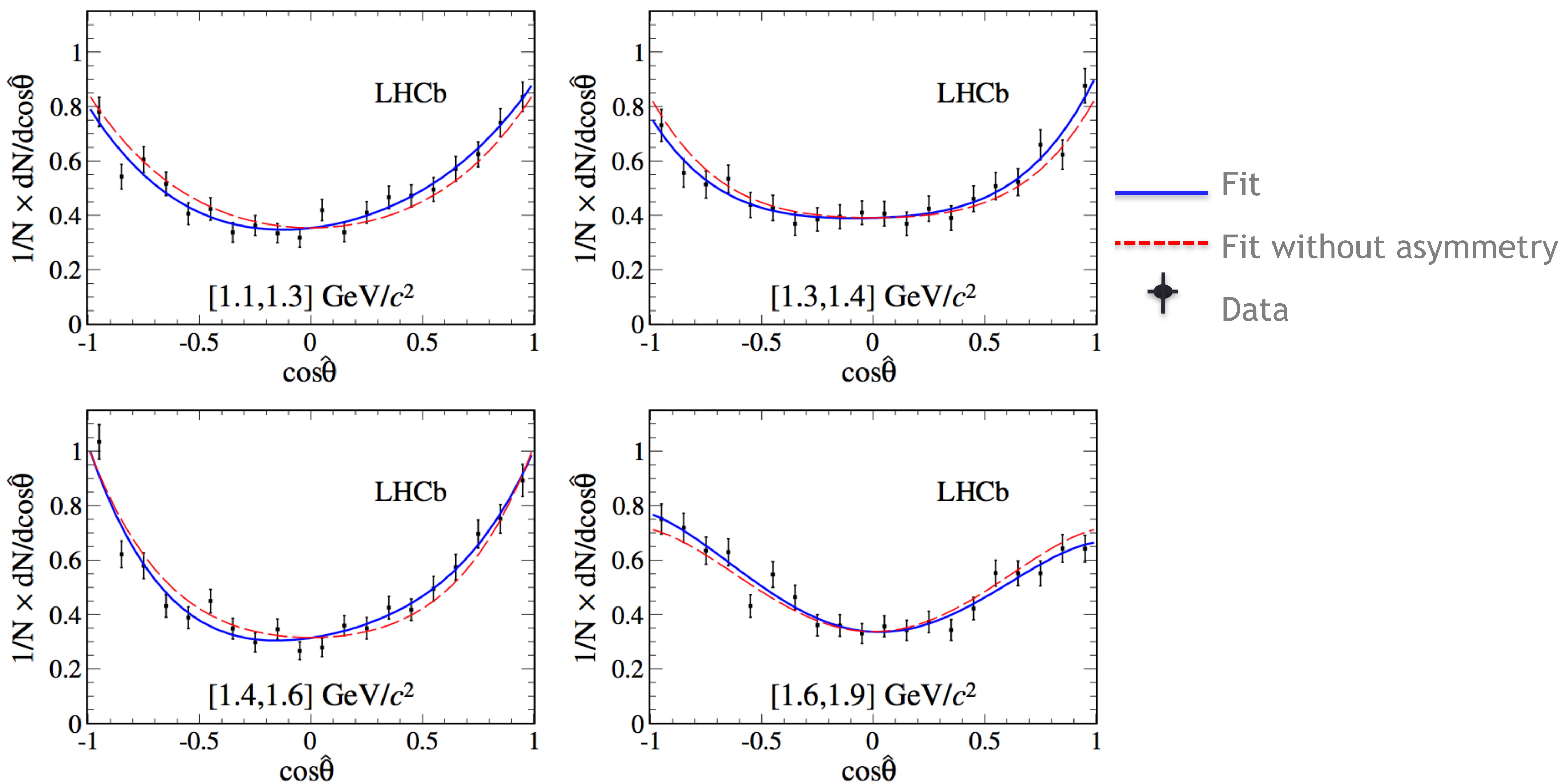


MEASURING THE UP-DOWN ASYMMETRY



PRL 112, 161801

- 14,000 events selected from full LHCb Run 1 dataset
- Obtained background-subtracted Kππ mass spectrum
- Cosθ fit performed in four m(Kππ) bins



Two-Amplitude Model

Decay rate for a system with a single 1^+ resonance:

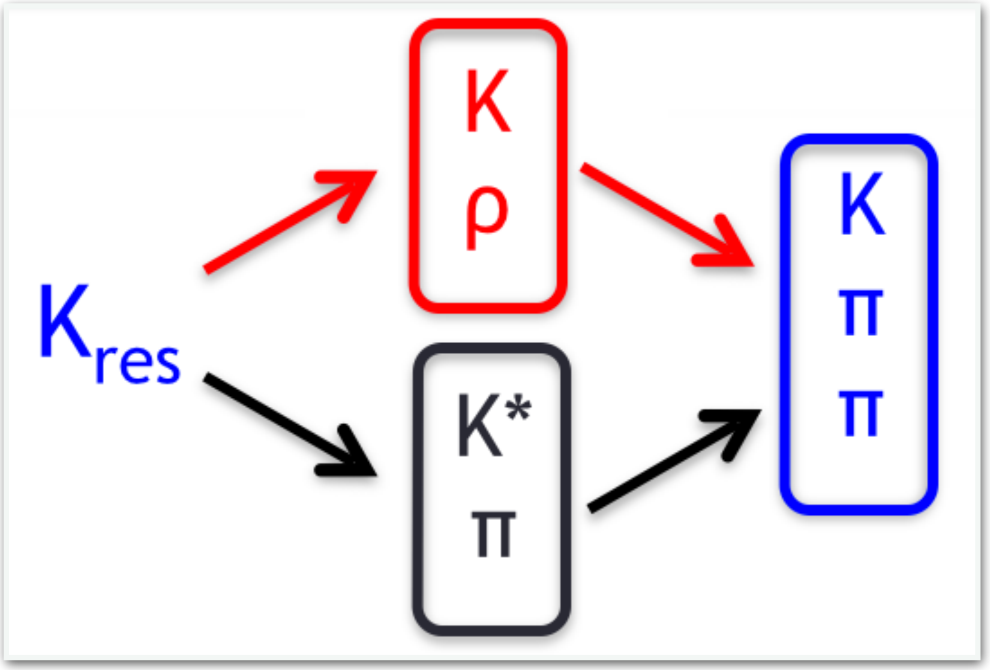
[Gronau et al, PRD66 (2002) 054008]

$$\frac{d\Gamma(B \to K\pi\pi\gamma)}{ds\, ds_{13}\, ds_{23}\, d\cos\theta} \propto \frac{1}{2}|\vec{\mathcal{J}}|^2(1+\cos^2\theta) + \lambda_\gamma \cos\theta\, \mathrm{Im}[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)]$$

invariant mass dependencies

where $s \to m^2(K\pi\pi)$, $s_{13} \to m^2(K\pi)$ and $s_{23} \to m^2(\pi\pi)$

Interferences between decay modes



B→Kππγ Amplitude Analysis: Method

Notes on the normalisation integral and its implementation in MINT arxiv:1902.09201

- Makes use of 'importance sampling', i.e. sample the function more frequently in regions where its value is large (to minimise uncertainties)
  - Use a mix of approximate signal events with a small amount of phase space events
- Explicit functional form of the efficiency not needed (non-trivial to parametrise in five dimensions)
- Often need a large number of official (full-chain) MC simulated events in order to obtain good precision on the fit
- Generation of normalisation MC toy events + computation of integrals for more complicated models takes up the majority of CPU time in MINT

$$\int \xi(\boldsymbol{x})\mathcal{P}_s(\boldsymbol{x})\phi_4(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x} = \frac{I_{\text{gen}}}{N_{\text{sel}}}\sum_j^{N_{\text{sel}}} \frac{\mathcal{P}_s(\boldsymbol{x}_j)}{\mathcal{P}_{\text{gen}}(\boldsymbol{x}_j)}$$

More details on the (practical) challenges of amplitude analyses in Albert's talk

Photon Polarisation in $B^+ \to K^+ \pi^- \pi^+ \gamma$ Decays

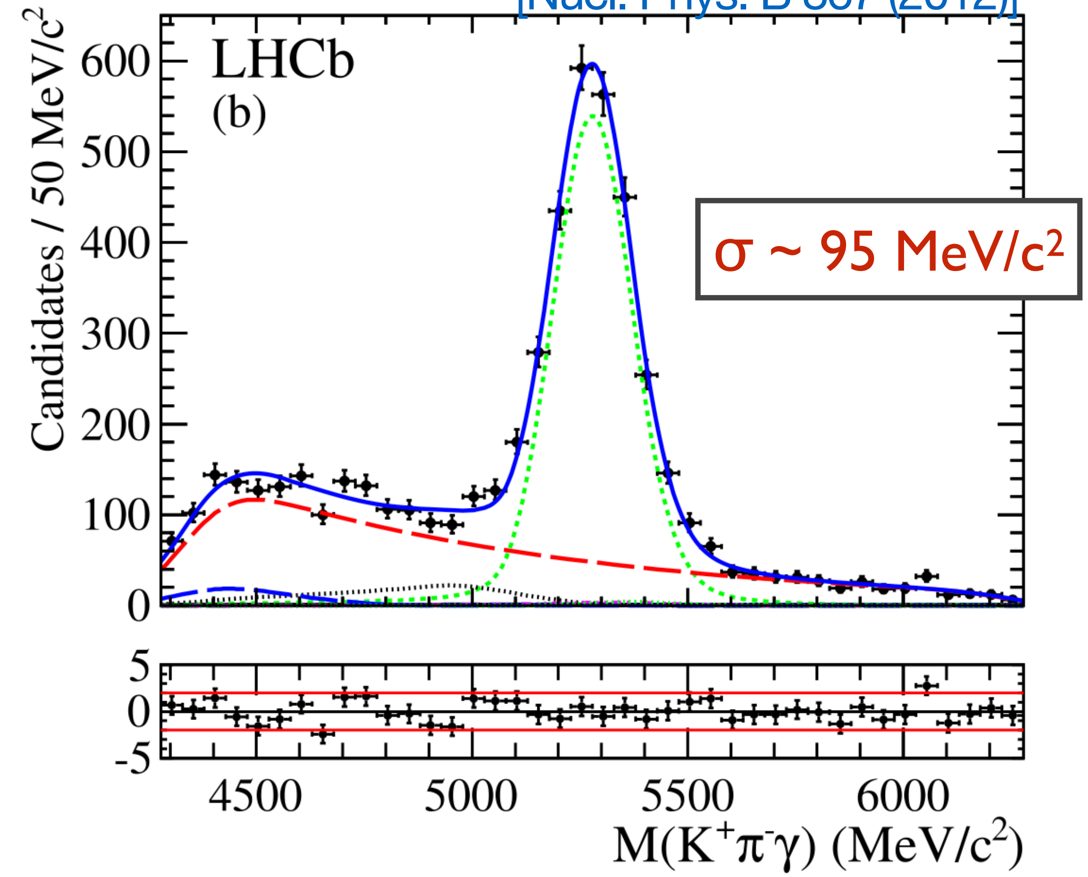
Fit pull values for realistic model:

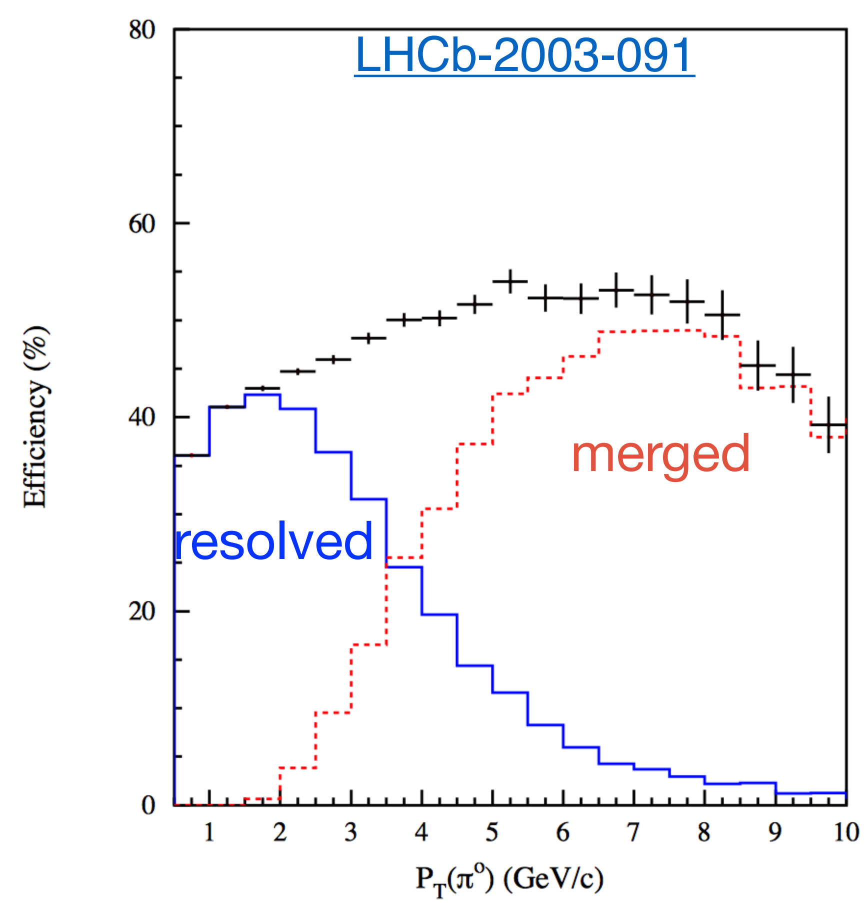
Amplitude k	Magnitude a_k		Phase ϕ_k	
	μ_{pull}	σ_{pull}	μ_{pull}	σ_{pull}
$K_1(1270)^+ \to K^*(892)^0 \pi^+$ [D-wave]	0.12 ± 0.10	0.97 ± 0.07	-0.01 ± 0.10	1.02 ± 0.07
$K_1(1270)^+ \to K^+ \rho(770)^0$	0.08 ± 0.09	0.91 ± 0.06	0.02 ± 0.11	1.08 ± 0.07
$K_1(1400)^+ \to K^*(892)^0 \pi^+$	-0.44 ± 0.09	0.95 ± 0.06	0.87 ± 0.10	1.06 ± 0.07
$K^*(1410)^+ \to K^*(892)^0 \pi^+$	-0.45 ± 0.09	0.94 ± 0.06	0.06 ± 0.10	1.04 ± 0.07
$K^*(1680)^+ \to K^*(892)^0 \pi^+$	0.04 ± 0.09	0.94 ± 0.06	0.02 ± 0.10	1.08 ± 0.07
$K^*(1680)^+ \to K^+ \rho(770)^0$	-0.02 ± 0.11	1.11 ± 0.07	0.02 ± 0.10	1.05 ± 0.07
$K_2^*(1430)^+ \to K^*(892)^0 \pi^+$	0.51 ± 0.10	1.07 ± 0.07	0.45 ± 0.09	0.86 ± 0.06
$K_2^*(1430)^+ \to K^+ \rho(770)^0$	0.36 ± 0.09	0.98 ± 0.07	-0.01 ± 0.09	0.94 ± 0.06
$K_2(1580)^+ \to K^*(892)^0 \pi^+$	-0.39 ± 0.10	1.03 ± 0.07	-0.06 ± 0.11	1.10 ± 0.07
$K_2(1580)^+ \to K^+ \rho(770)^0$	0.04 ± 0.09	0.90 ± 0.06	0.14 ± 0.10	0.97 ± 0.07
$K_2(1770)^+ \to K^*(892)^0 \pi^+$	0.08 ± 0.11	1.11 ± 0.07	-0.10 ± 0.12	1.21 ± 0.08
$K_2(1770)^+ \to K^+ \rho(770)^0$	-0.13 ± 0.10	0.97 ± 0.06	-0.04 ± 0.09	0.97 ± 0.06
$K_2(1770)^+ \to K_2^*(1430)^0 \pi^+$	0.17 ± 0.10	1.05 ± 0.07	0.05 ± 0.10	1.01 ± 0.07

Experimental Challenges

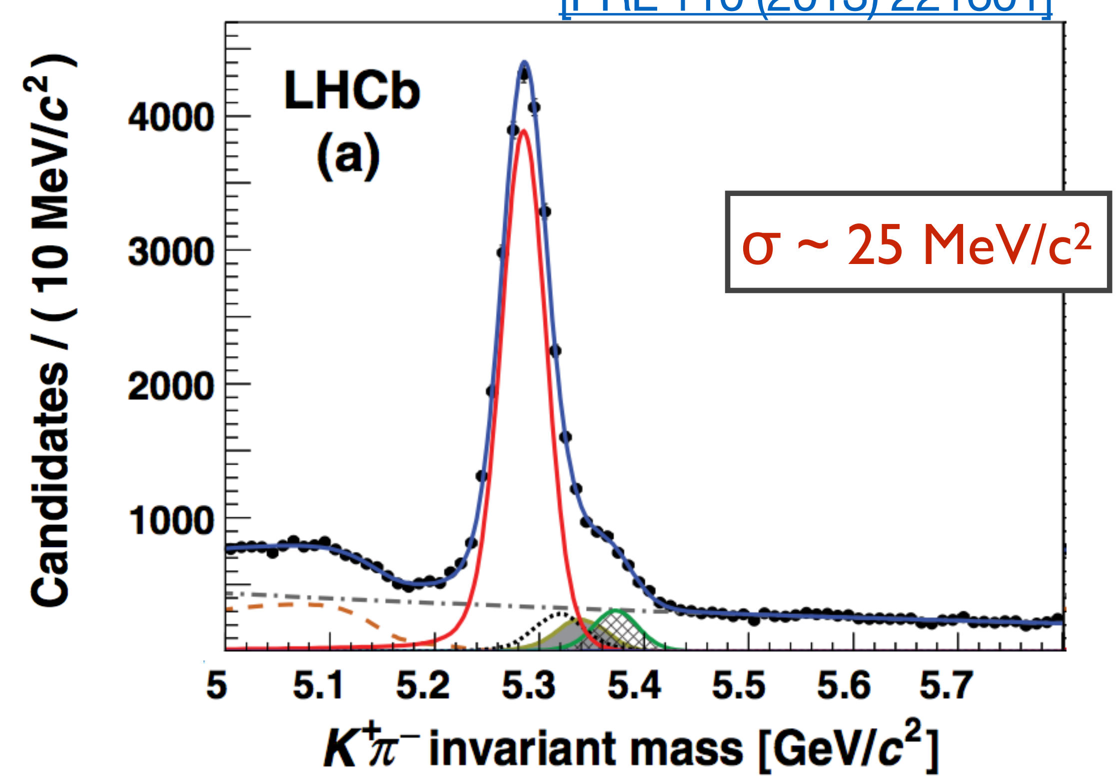
- Mass resolution dominated by photon reconstruction
  - **σ~95 MeV/c²** for B→K*γ decays, compared to ~25 MeV/c² for B→Kπ decays.
- Backgrounds:
  - Above transverse energies of 4 GeV, $\pi^0 \to \gamma\gamma$ reconstructed as a single cluster in the calorimeter
  - Combinatorial: *O*(10) reconstructed photons per event

[Nucl. Phys. B 867 (2012)]





[PRL 110 (2013) 221601]



Experimental Challenges

Without analysis improvements, many analyses would be systematics-limited by Run 5

Primary known/expected sources of systematic uncertainty:

- Partially reconstructed background, due to large invariant mass resolution
  - Correlation between decay time and reconstructed mass in $B_s \to \phi\gamma$ decays
  - Uncertainty in background modeling in A_{cp} and branching fraction measurements
  - Effects on angular distributions in $K\pi\pi\gamma$ decays
- Detector effects
  - Decay time resolution for C,S measurements in tagged $B_s \to \phi\gamma$ analysis
  - Detection asymmetry in A_{cp} measurement
- Modeling of acceptances
  - Main source of uncertainty for $\Lambda_b \to \Lambda^0\gamma$ angular analysis