Investigation for photon polarisation in $B \to K\pi\pi\gamma$ decays at LHCb

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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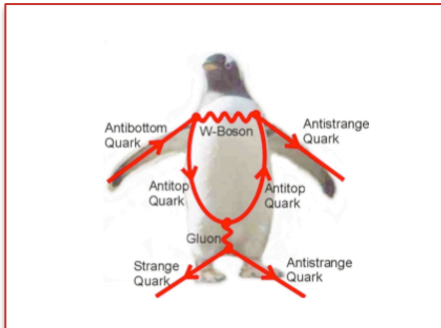
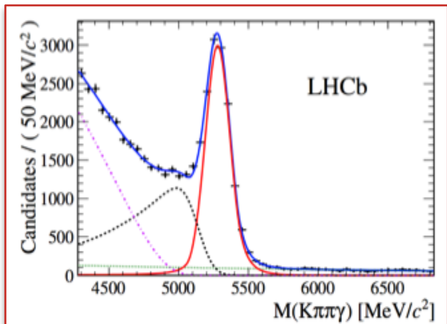
Outline

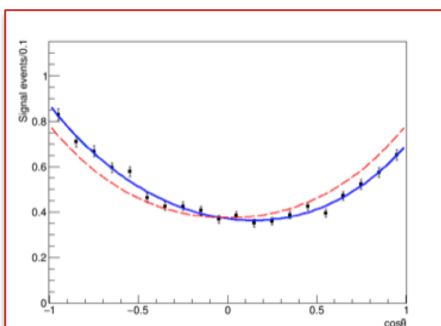


Photon polarisation in radiative B decays



Observation of non-zero photon polarisation in B→Kππγ decays

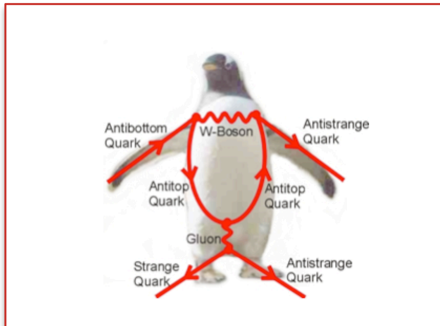
Amplitude analysis of the Kππ system



Generating amplitudes in 5D

Studies of the up-down asymmetry

Photon polarisation in b → sγ transitions



Photon polarisation in radiative B decays

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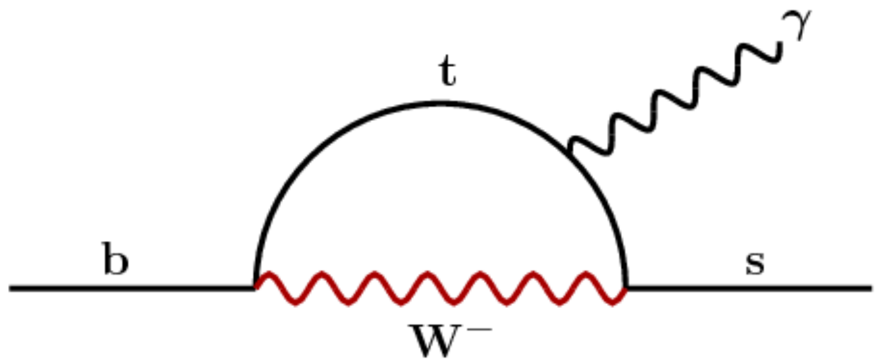
Radiative B decays

- FCNC with a final state photon
- The $b \to s\gamma$ transition occurs through a penguin loop



- In the SM, the photon in $b \to s\gamma$ transitions is mostly left-handed

Photon polarisation in SM b → sγ transitions

- The decay amplitude for b → sγ transitions is proportional to:

$$\langle f|\mathcal{H}_{\rm eff}|i\rangle = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}{}^* \left[C_7^{\rm eff}(m_b)\langle f|\mathcal{O}_7(m_b)|i\rangle + C_7'{}^{\rm eff}(m_b)\langle f|\mathcal{O}_7'(m_b)|i\rangle\right]$$

Coupling to left-handed photon

Coupling to right-handed photon

[arXiv:1206.1502]

- In SM, Wilson coefficients C_7 and $C_{7'}$ are such that:

$$C_{7'}/C_7 \cong m_s/m_b \cong 0.02$$

- The photon polarisation parameter λ_γ is defined as the asymmetry between the right and left components:

$$\lambda_\gamma = \frac{|C_7'|^2 - |C_7|^2}{|C_7'|^2 + |C_7|^2}$$

In SM, $\lambda_\gamma \cong -1$ (with corrections of $O(m^2_s/m^2_b)$) for decays of a b quark

Photon polarisation: a probe for NP

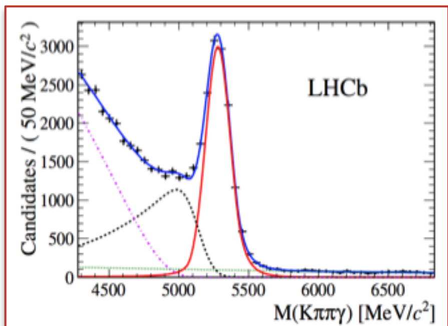
- NP processes could introduce right handed currents, hence modifying the photon polarisation

- The photon polarisation is a test for SM but it has never been measured

- Maybe some new penguins around !

Up-Down asymmetry in B→Kππγ decays

Photon polarisation in radiative B decays



Observation of non-zero photon polarisation in B→Kππγ decays

Amplitude analysis of the Kππ system

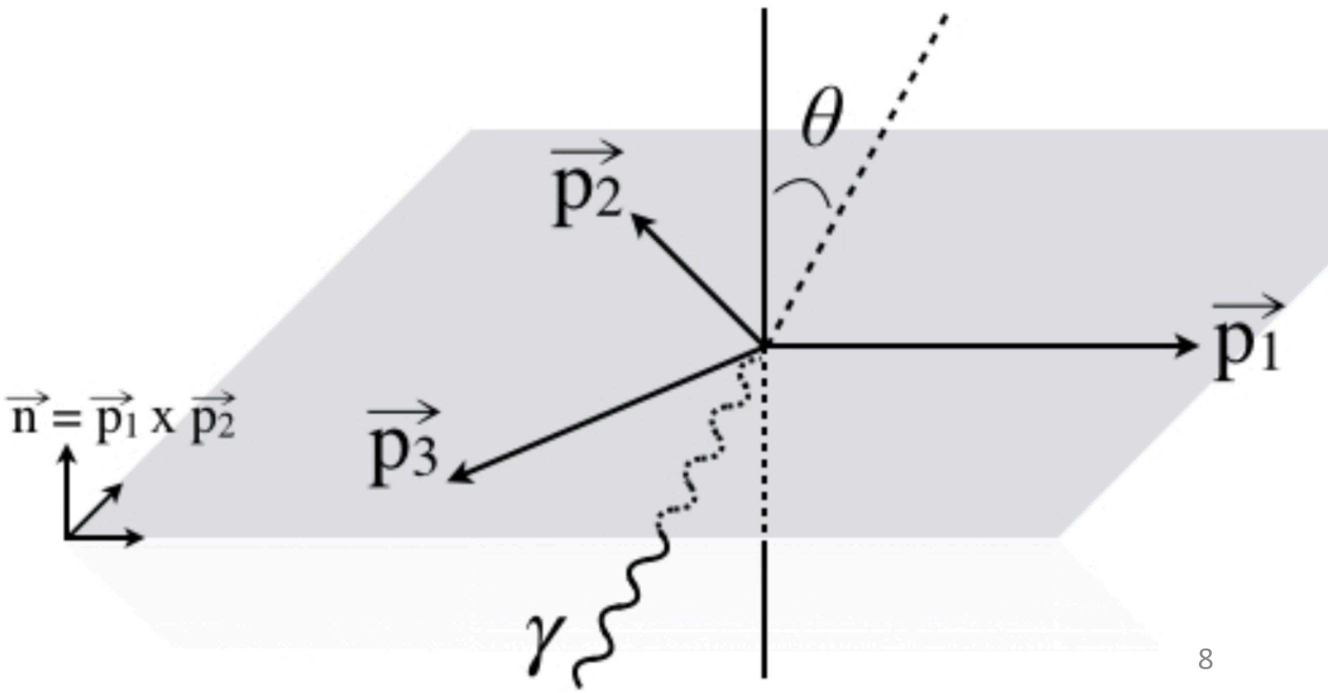
Generating amplitudes in 5D

Studies of the up-down asymmetry

Why do we need 3 hadrons in the final state?

Minimum number of tracks needed to build a P-odd quantity proportional to the photon polarisation using the final state momenta

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



$B^+ \to K^+_{res}(K\pi\pi)\gamma$ decay rate

- Decay rate for the $B^+ \to K^+_{res}$ ($\to K^+\pi^-\pi^+$) γ decay:

[Gronau *et al*, PRD66 (2002) 054008]

$$\mathrm{d}\Gamma(B \to K\pi\pi\gamma) = \left| \sum_k \frac{c^{\mathrm{weak}}_{k,R} \times A^{\mathrm{strong}}_{k,R}}{m^2_{K\pi\pi} - m^2_k - i m_k \Gamma_k} \right|^2 + \left| \sum_k \frac{c^{\mathrm{weak}}_{k,L} \times A^{\mathrm{strong}}_{k,L}}{m^2_{K\pi\pi} - m^2_k - i m_k \Gamma_k} \right|^2$$

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[Gronau *et al*, PRD66 (2002) 054008]

$$d\Gamma(B \to K\pi\pi\gamma) = \left|\sum_k \frac{c^{\text{weak}}_{k,R} \times A^{\text{strong}}_{k,R}}{m^2_{K\pi\pi} - m^2_k - im_k\Gamma_k}\right|^2 + \left|\sum_k \frac{c^{\text{weak}}_{k,L} \times A^{\text{strong}}_{k,L}}{m^2_{K\pi\pi} - m^2_k - im_k\Gamma_k}\right|^2$$

$$\lambda_\gamma = \frac{|c^{\text{weak}}_R|^2 - |c^{\text{weak}}_L|^2}{|c^{\text{weak}}_R|^2 + |c^{\text{weak}}_L|^2}$$

Photon polarisation parameter

$$\lambda_\gamma = \frac{|C'_7|^2 - |C_7|^2}{|C'_7|^2 + |C_7|^2}$$

How to access λ_γ in $B^+ \to K^+_{res}(K\pi\pi)\gamma$ decays ?

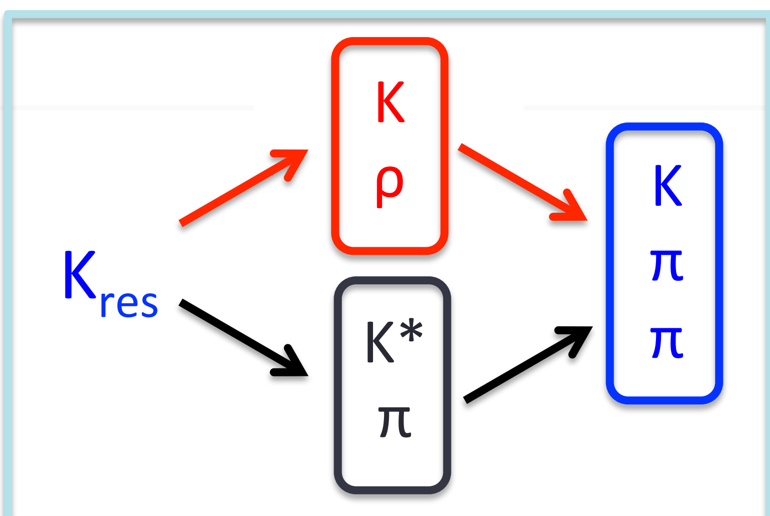
In the case of a single 1^+ resonance:

[Gronau *et al*, PRD66 (2002) 054008]

interference !

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

invariant mass dependencies



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

Adding resonances is not so simple

Adding more resonances (1^+, 2^+, 1^-), the formula gets complex:

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos\theta} = |A|^2\left\{\frac{1}{4}|\vec{J}|^2(1+\cos^2\theta) + \frac{1}{2}\lambda_\gamma \mathrm{Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]\cos\theta\right\}$$

$$+ \quad |B|^2\left\{\frac{1}{4}|\vec{K}|^2(\cos^2\theta+\cos^2 2\theta) + \frac{1}{2}\lambda_\gamma \mathrm{Im}[\vec{n}\cdot(\vec{K}\times\vec{K}^*)]\cos\theta\cos 2\theta\right\} + |C|^2\frac{1}{2}\sin^2\theta$$

$$+ \quad \left\{\frac{1}{2}(3\cos^2\theta-1)\mathrm{Im}[AB^*\vec{n}\cdot(\vec{J}\times\vec{K}^*)] + \lambda_\gamma \mathrm{Re}[AB^*(\vec{J}\cdot\vec{K}^*)]\cos^3\theta\right\} \quad .$$

[Gronau *et al*, PRD66 (2002) 054008]

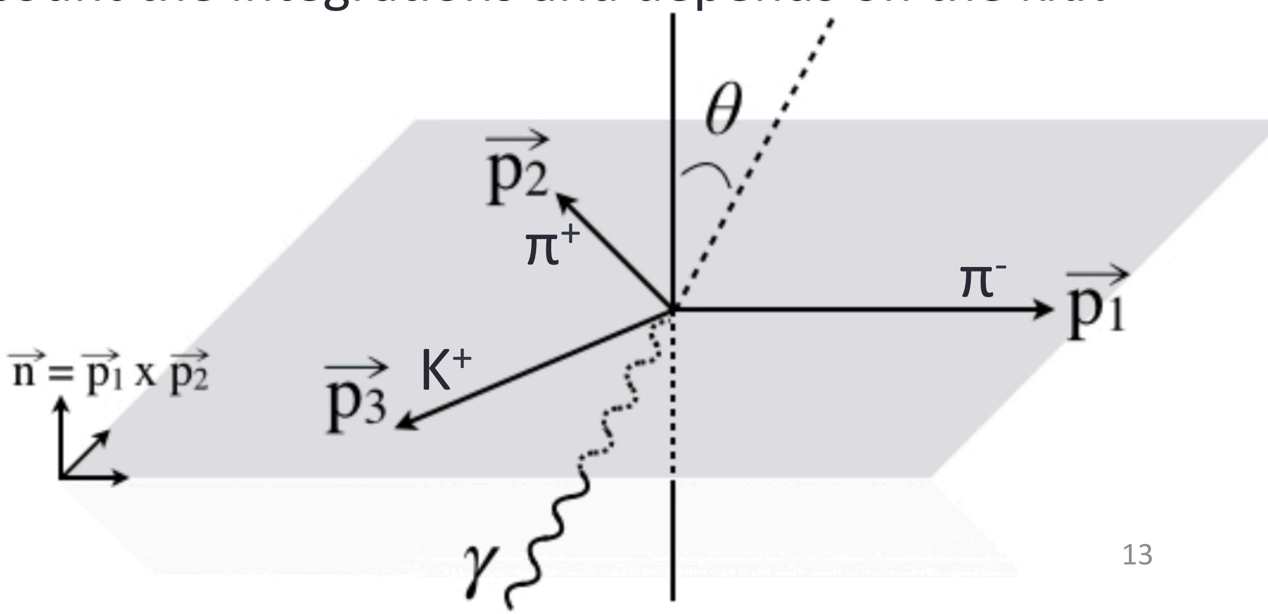
As the $K^+\pi^-\pi^+$ system is not known, **simplification is needed** !

How to access λ_γ in $B^+ \to K^+_{res}(K\pi\pi)\gamma$ decays ?

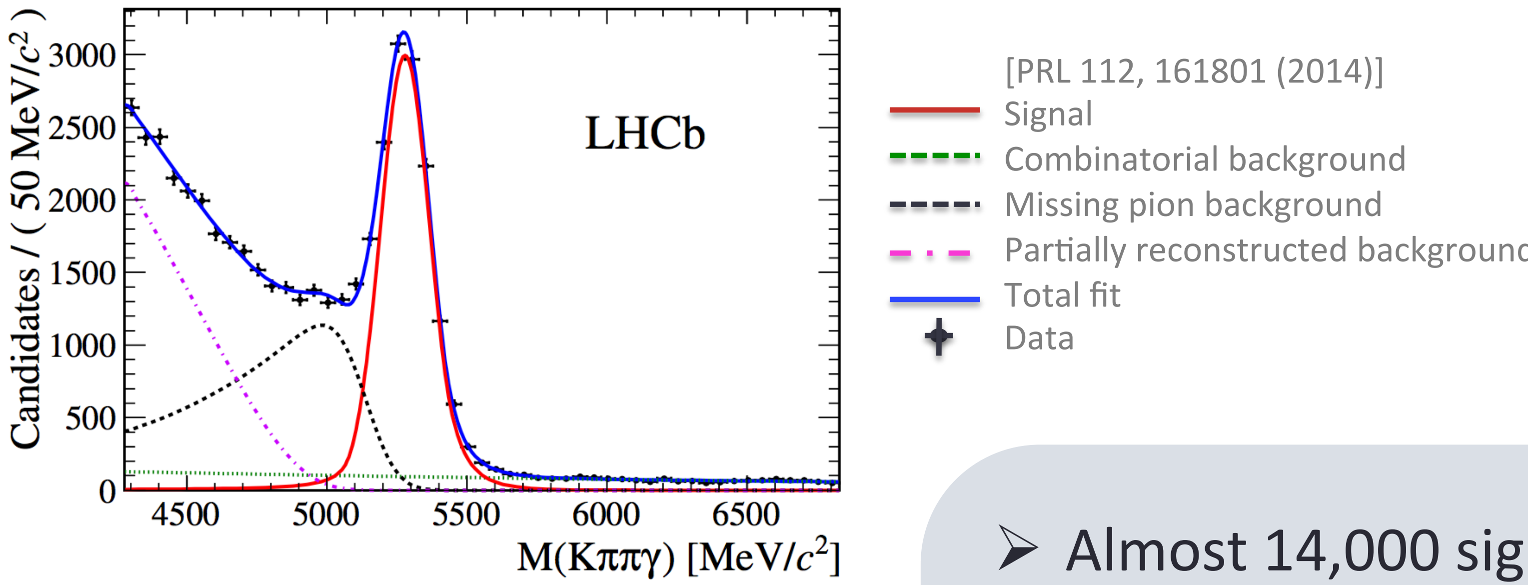
The idea is to **integrate over the Dalitz plot and the angular distribution** to obtain the up-down asymmetry:

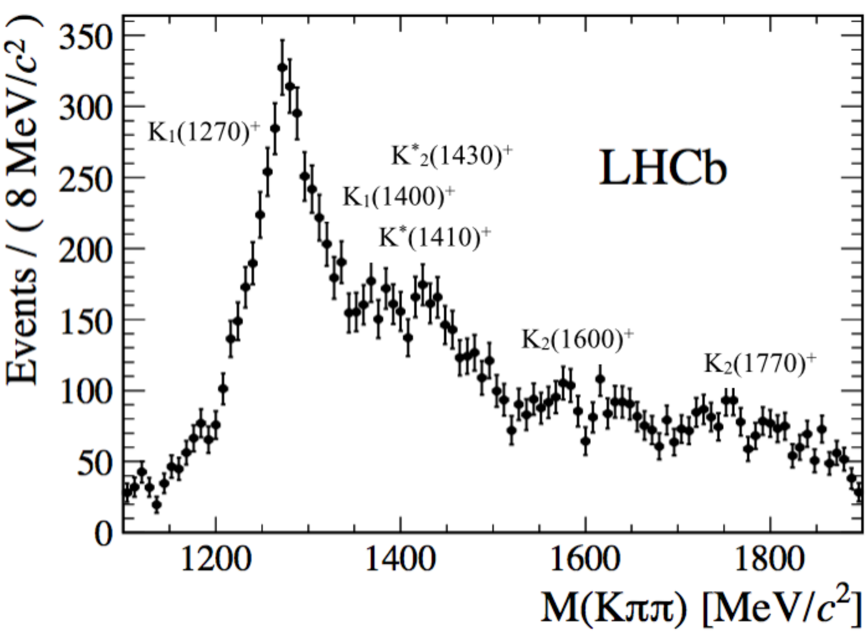
$$\mathcal{A}_{ud} \equiv \frac{\int_0^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} - \int_{-1}^0 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}}{\int_{-1}^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}} = C\lambda_\gamma$$

Where C takes into account the integrations and depends on the Kππ system content



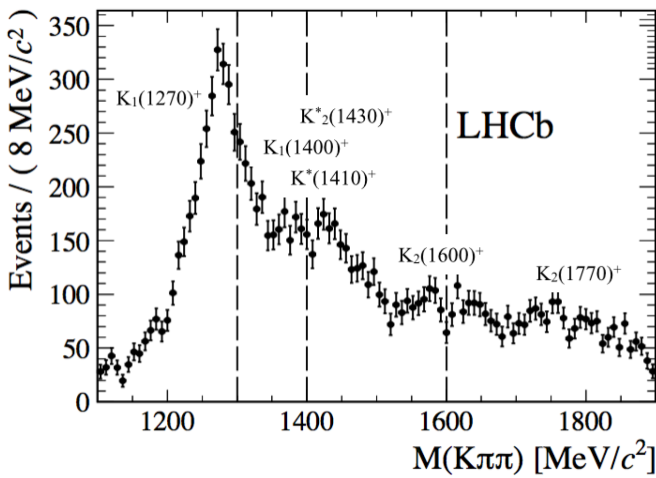
Selection of the B→Kππγ events





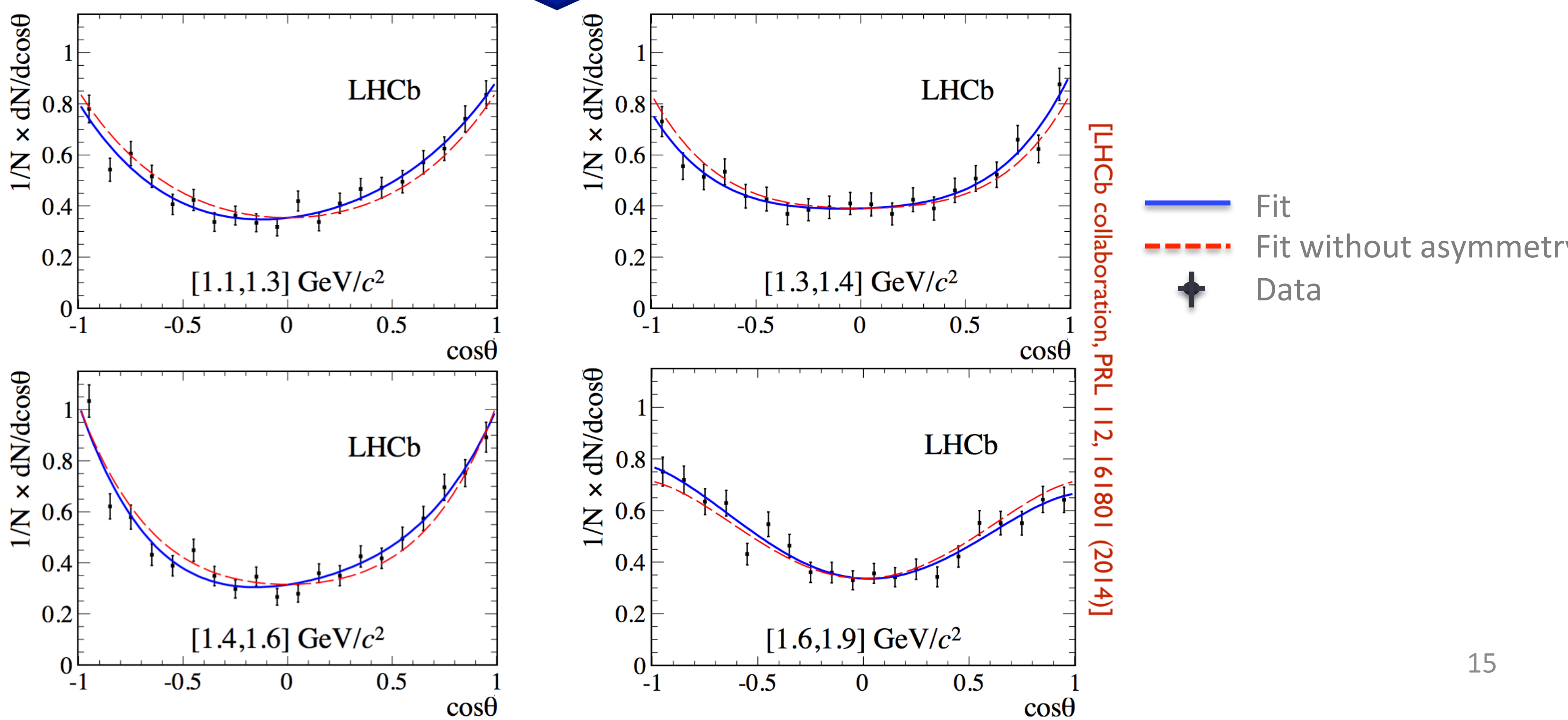
- Almost 14,000 signal events are reconstructed and selected in the full 3 fb^{-1} LHCb Run 1 data sample
- The background-subtracted Kππ mass spectrum is obtained

Observation of λ_γ



- The $K\pi\pi$ mass spectrum is obtained and divided in bins of m($K\pi\pi$)
- In each bin, the cos θ distribution is fitted

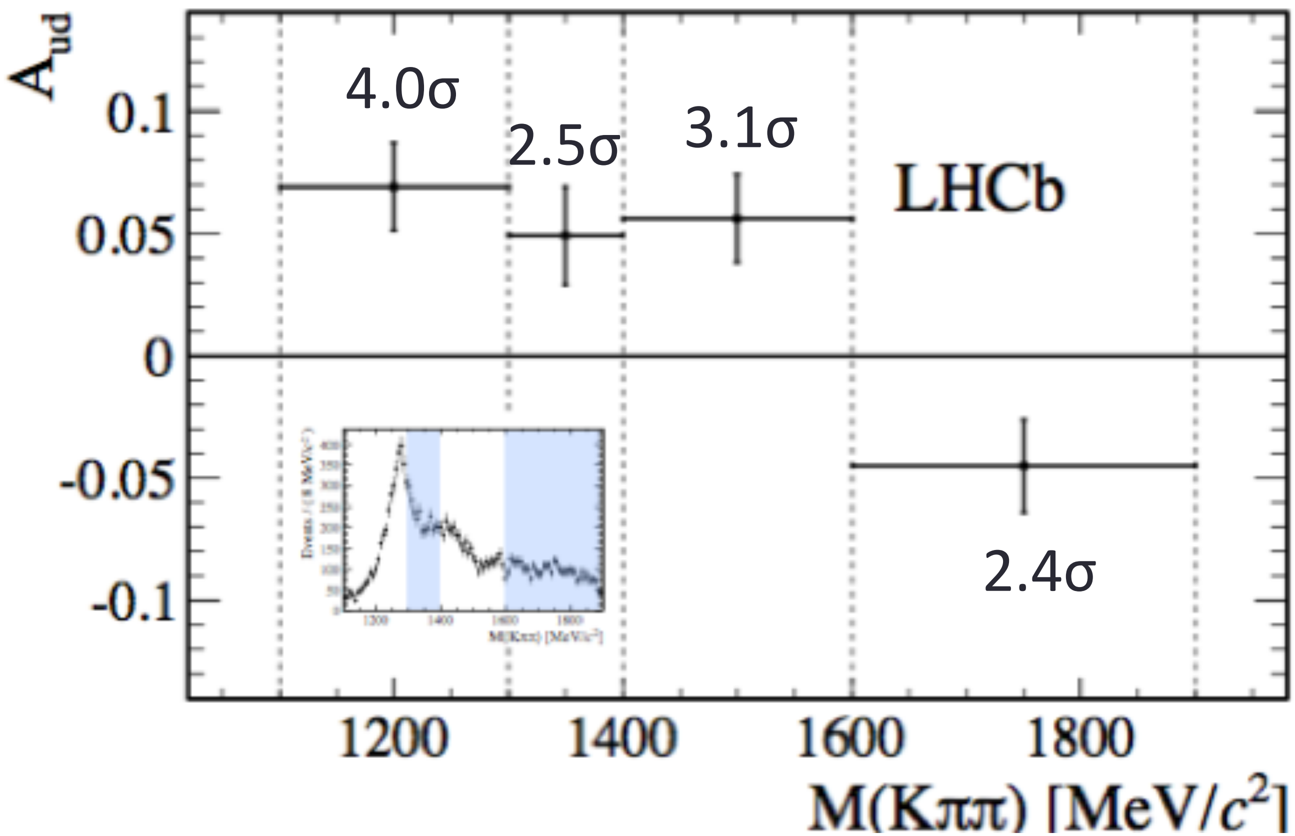
[PRL 112, 161801 (2014)]



[LHCb collaboration, PRL 112, 161801 (2014)]

Observation of λ_γ

- Up-down asymmetry expected to be proportional to λ_γ

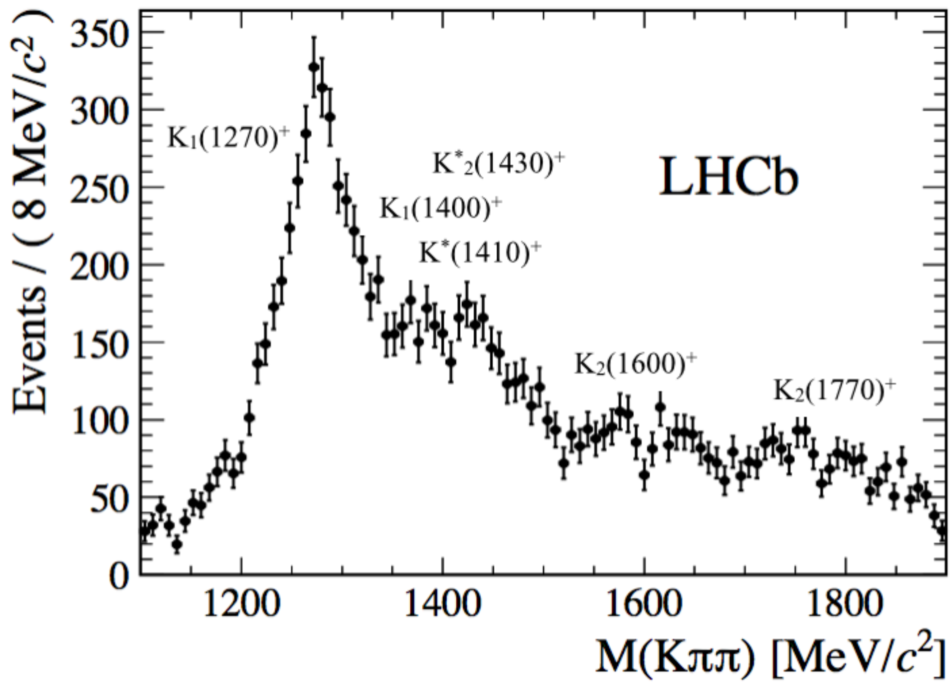


[PRL 112, 161801 (2014)]

- **Observation of a non-zero photon polarisation** with A_{ud} different from 0 at **5.2σ**.

Towards a measurement of λ_γ

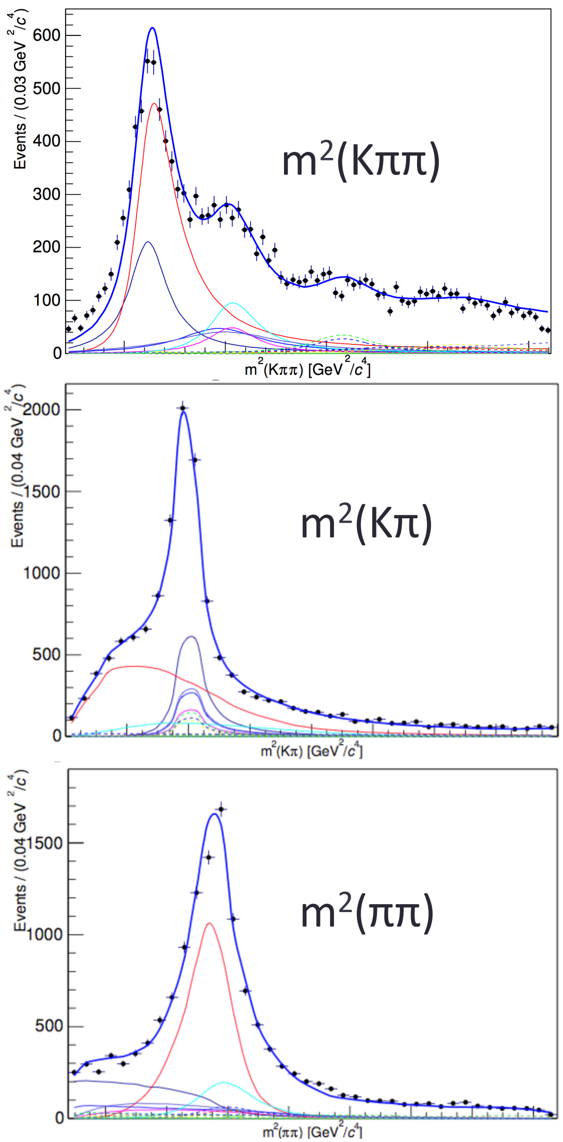
- To measure the value of λ_γ, we need to know the proportionnality coefficient *C* between A_{ud} and λ_γ.
- This coefficient depends on the content of the Kππ system



[PRL 112, 161801 (2014)]

- Missing knowledge of the Kππ system to make a measurement

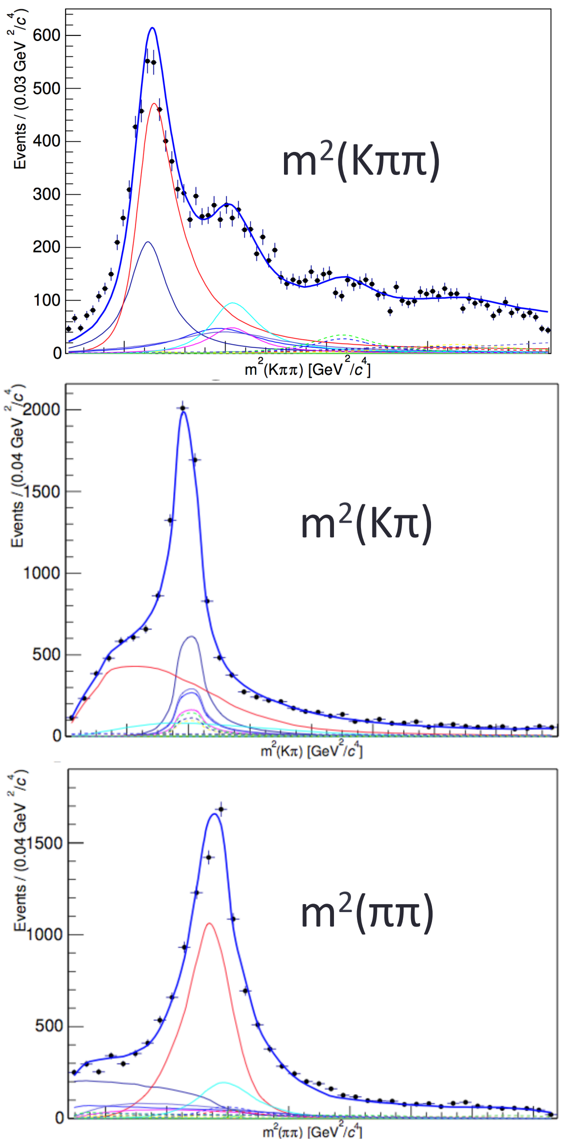
Amplitude analysis of the Kππ system



[CERN-THESIS-2015-287]

- Fit of the three invariant masses squared $m^2(K\pi\pi)$, $m^2(K\pi)$ and $m^2(\pi\pi)$, integrating on the angles
- Using 18 amplitudes

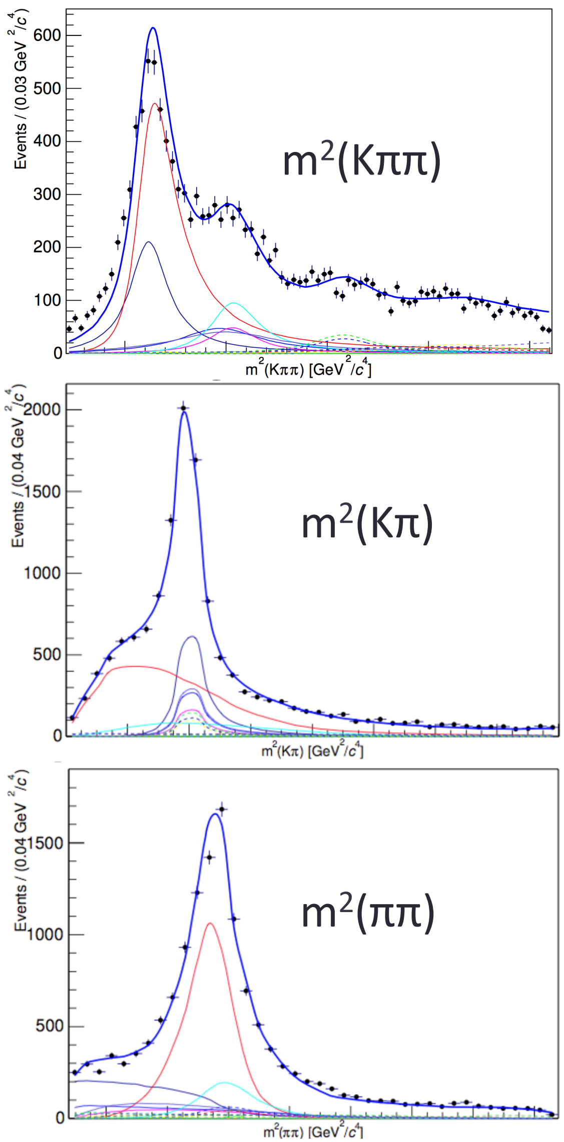
Amplitude analysis of the Kππ system



[CERN-THESIS-2015-287]

	Decay channel k	Modulus	Phase [rad]	FF_k (10^{-2})
1^+	$K_1(1270)^+ \to K^*(892)^0\pi^+$	1 (fixed)	0 (fixed)	16.8 ± 0.9
	$K_1(1270)^+ \to K^+\rho(770)$	1.747 ± 0.049	-0.91 ± 0.028	$39.9^{+0.6}_{-0.7}$
	$K_1(1270)^+ \to K^+\omega(782)$	0.302 ± 0.085	0.302 ± 0.27	$0.068^{+0.028}_{-0.180}$
	$K_1(1270)^+ \to K^*(1430)^0\pi^+$	0.382 ± 0.055	-1.637 ± 0.162	$0.69^{+0.22}_{-0.20}$
	$K_1(1400)^+ \to K^*(892)^0\pi^+$	0.42 ± 0.022	-0.755 ± 0.053	7.8 ± 0.8
1^-	$K^*(1410)^+ \to K^*(892)^0\pi^+$	0.479 ± 0.042	0 (fixed)	$8.4^{+2.8}_{-3.3}$
	$K^*(1680)^+ \to K^*(892)^0\pi^+$	0.219 ± 0.022	0.443 ± 0.124	$3.5^{+1.7}_{-2.1}$
	$K^*(1680)^+ \to K^+\rho(770)$	0.112 ± 0.01	1.403 ± 0.221	2.4 ± 0.4
2^+	$K_2^*(1430)^+ \to K^*(892)^0\pi^+$	0.509 ± 0.034	0 (fixed)	4.8 ± 1.0
	$K_2^*(1430)^+ \to K^+\rho(770)$	0.511 ± 0.026	1.798 ± 0.09	9.0 ± 0.8
	$K_2^*(1430)^+ \to K^+\omega(782)$	0.332 ± 0.078	-2.353 ± 0.236	$0.30^{+0.13}_{-0.26}$
2^-	$K_2(1600)^+ \to K^*(892)^0\pi^+$	0.172 ± 0.01	2.883 ± 0.119	$4.4^{+0.9}_{-1.0}$
	$K_2(1600)^+ \to K^+\rho(770)$	0.095 ± 0.012	2.442 ± 0.129	$3.33^{+0.34}_{-0.50}$
	$K_2(1770)^+ \to K^*(892)^0\pi^+$	0.107 ± 0.008	0 (fixed)	$3.0^{+0.6}_{-0.8}$
	$K_2(1770)^+ \to K^+\rho(770)$	0.018 ± 0.005	2.527 ± 0.266	$0.23^{+0.08}_{-0.32}$
	$K_2(1770)^+ \to K_2^*(1430)^0\pi^+$	0.087 ± 0.009	-2.06 ± 0.128	$0.67^{+0.10}_{-0.09}$
	$K_2(1770)^+ \to K^+f_2(1270)^0$	0.17 ± 0.007	-0.174 ± 0.088	$1.30^{+0.15}_{-0.16}$
	Non resonant	0.051 ± 0.002	0 (fixed)	4.1 ± 0.5

Amplitude analysis of the Kππ system



[CERN-THESIS-2015-287]

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- The 2 main amplitudes are **K(1270) → K*π** and **K(1270) → Kρ** with a ratio of modulus of **1.78** and a phase difference of **-0.91 rad**

Limits of the amplitude analysis

- The previous study brought **knowledge of the $K\pi\pi$ system**

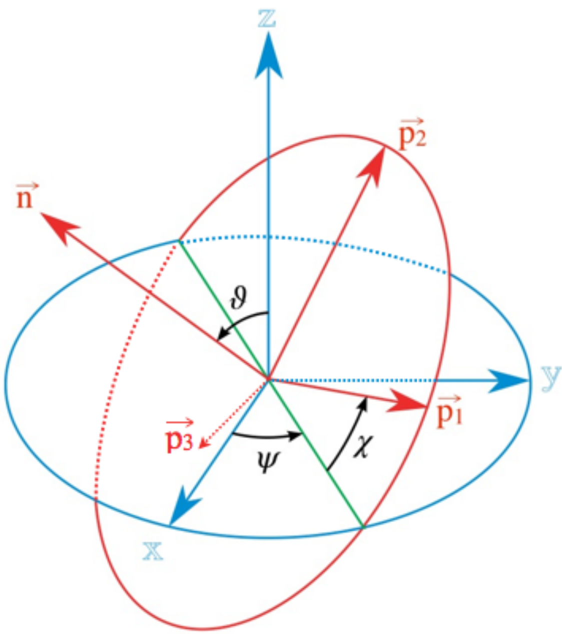
- **Main limitation: use of 3 dimensions ($m^2(K\pi\pi)$, $m^2(K\pi)$, $m^2(\pi\pi)$)**

→ Not sensitive to the photon polarisation that appears in the angular variables

- **To measure the photon polarisation, a fit in 5 dimensions is necessary**

→ Use of the squared masses +

θ (polar angle) and χ (azimuthal angle)



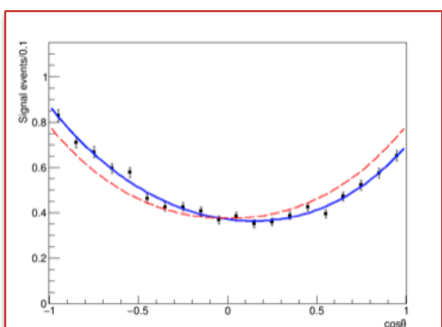
A tool to generate and fit in 5D is needed: MINT [arXiv:1201.5716]

Relating A_{ud} to the interferences and λ_γ

Photon polarisation in radiative B decays

Observation of non-zero photon polarisation in B→Kππγ decays

Amplitude analysis of the Kππ system



Generating amplitudes in 5D

Studies of the up-down asymmetry

Modelling the Kππ system in 5D

- Using our knowledge of the Kππ system, we can generate in 5D simulated samples close to the data
- A model with 9 amplitudes reproduces well the lower part of the $m^2(K\pi\pi)$ spectrum

9 amplitudes:

- $K(1270) \to K^*\pi$ [S]
- $K(1270) \to K^*\pi$ [D]
- $K(1270) \to K\rho$
- $K(1400) \to K^*\pi$

} 1+

- $K(1410) \to K^*\pi$

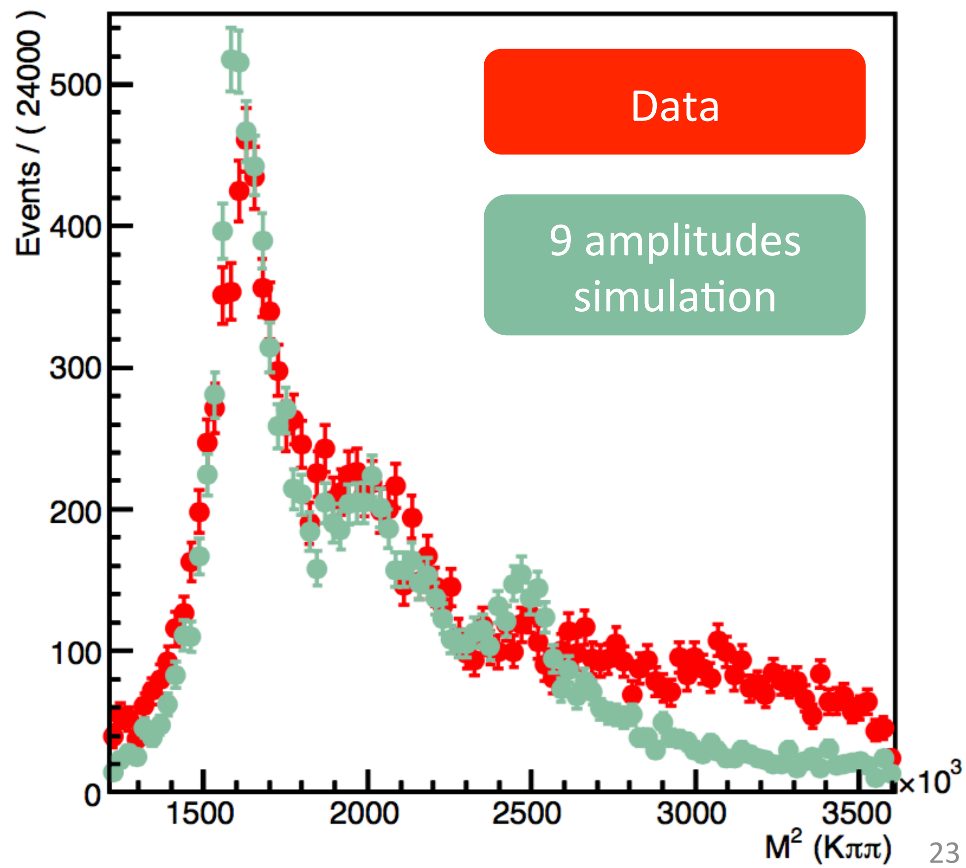
} 1-

- $K_2(1430) \to K^*\pi$
- $K_2(1430) \to K\rho$

} 2+

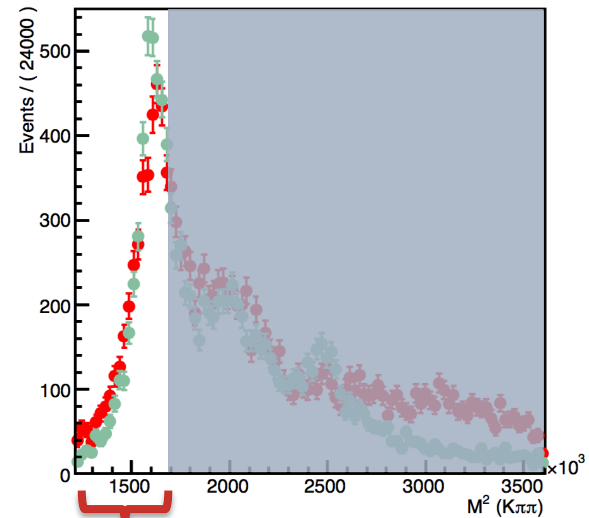
- $K_2(1580) \to K^*\pi$
- $K_2(1580) \to K\rho$

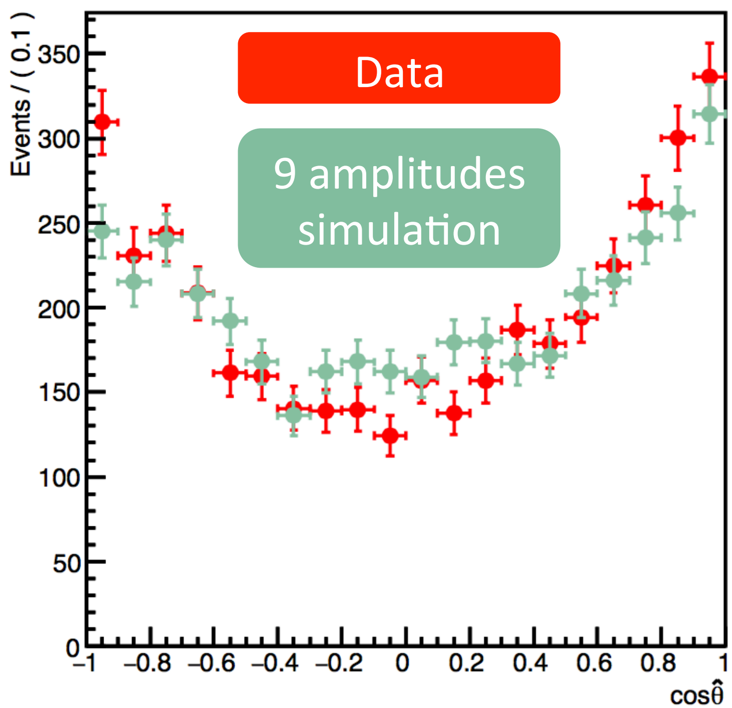
} 2-

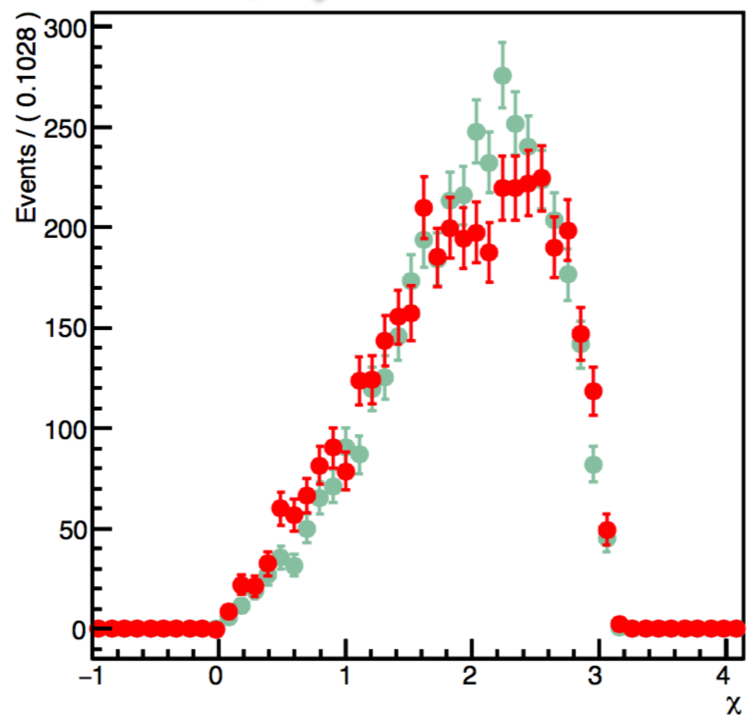


Modelling the Kππ system in 5D

- The angular distributions (that were not considered in the 3D fit) are reasonably well reproduced in the lower part of the $m^2(K\pi\pi)$ spectrum

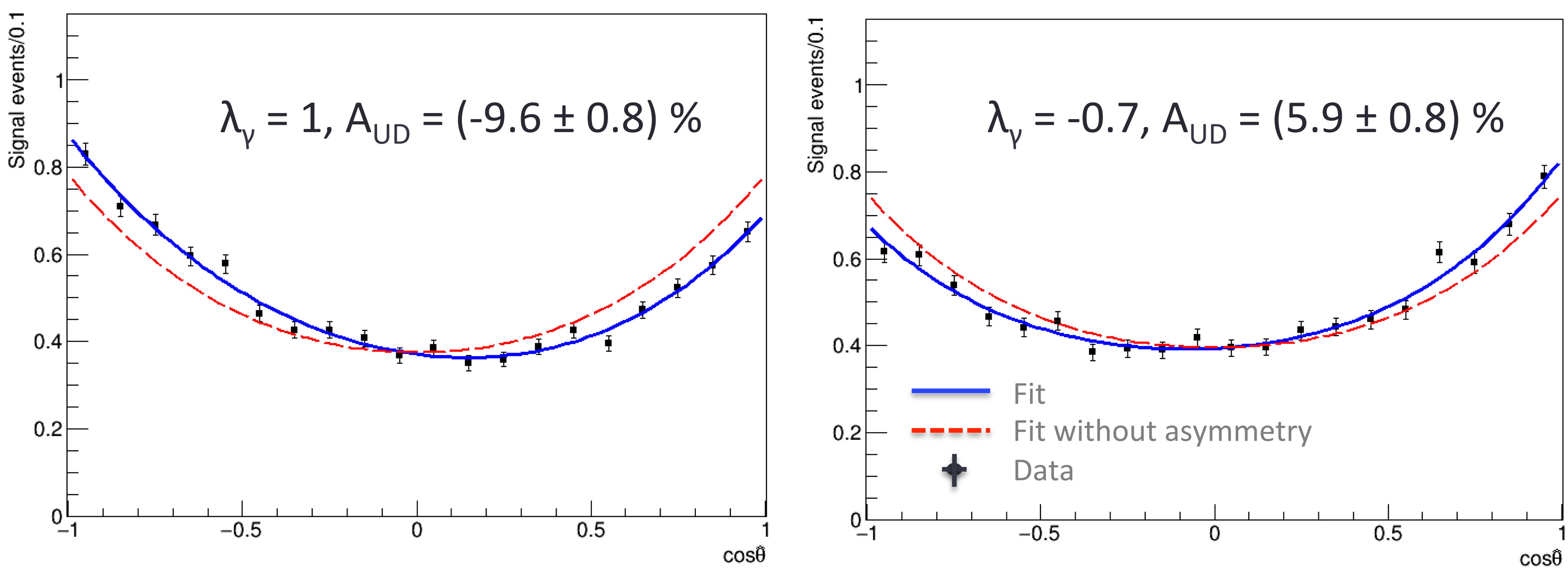






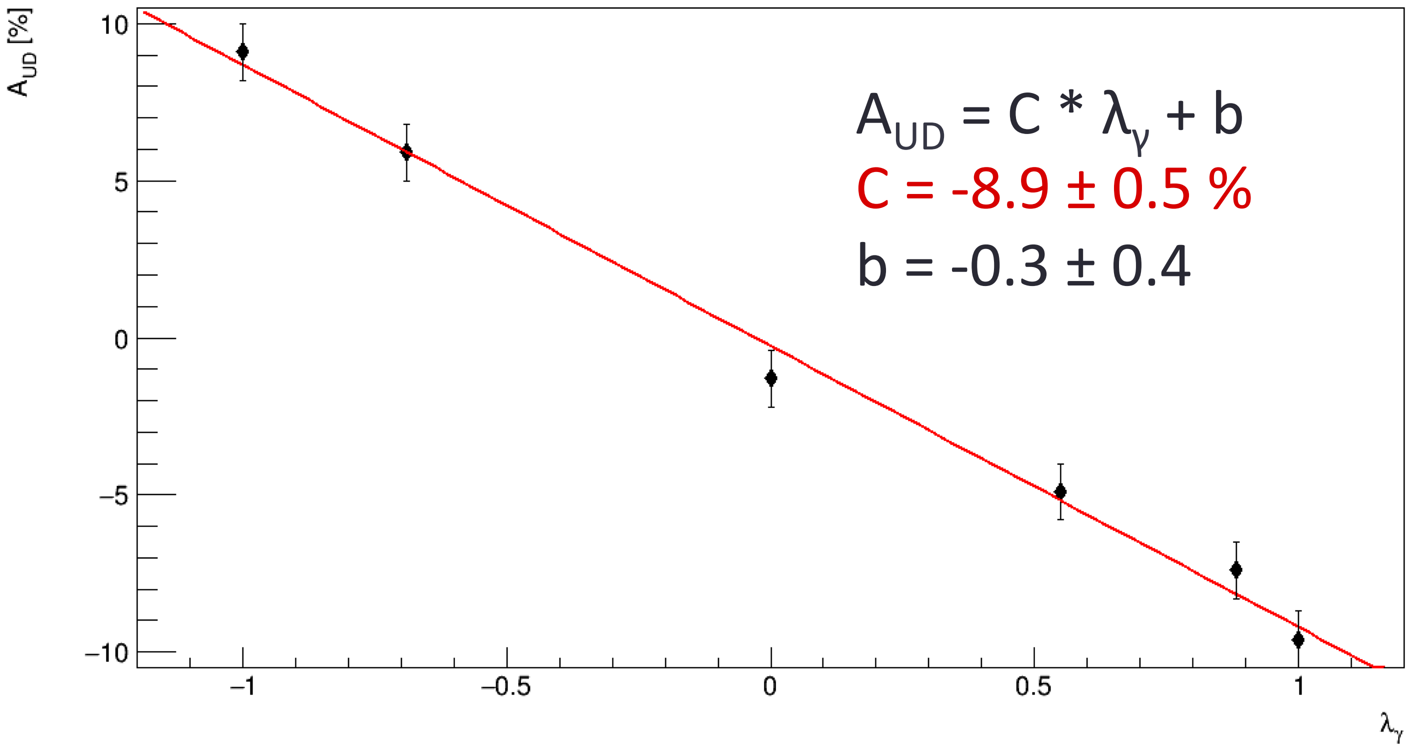
Relating A_{UD} and λ_γ

- The λ_γ parameter is first set to 1
- Simulated events are generated using a simple model with 2 amplitudes: **K(1270) → Kρ** and **K(1270) → K*π** with the complex ratio observed in data
- The up-down asymmetry is computed by fitting the cos θ distribution



Relating A_{UD} and λ_γ

- The dependance of A_{UD} and λ_γ is obtained and is linear
- From theory: $A_{UD} = C.\ \lambda_\gamma$



A_{UD} as a function of λ_γ for toy samples of 10k events generated with K(1270) → Kρ and K(1270) → $K^*\pi$ amplitudes (complex ratio corresponding to data)

Conclusion

- The study of the up-down asymmetry in $B \to K\pi\pi\gamma$ decays has lead to **the observation of a non-zero photon polarisation**

- The **knowledge of the Kππ system** has been dramatically improved thanks to the **3D fit**

- A **5D simulation of the $B \to K\pi\pi\gamma$** events has been obtained and has allowed to compute the **proportionality coefficient between A_{UD} and λ_γ** in a simplified case

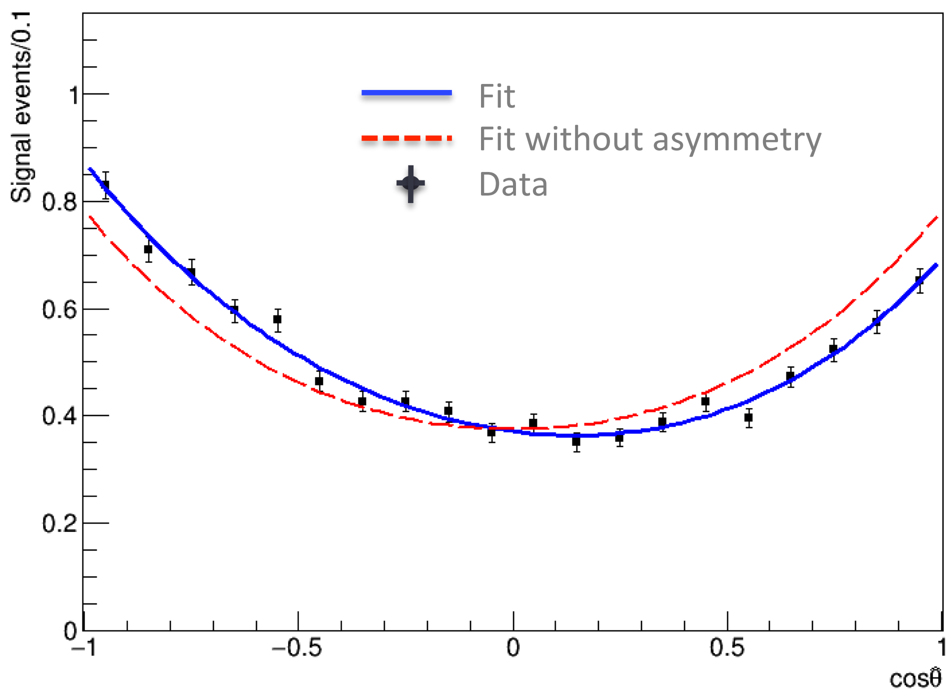
- Next step: **Fitting in 5D** !

Back-up

Thanks for your attention

Relating A_{UD} with the interference pattern

- The up-down asymmetry can also be computed as a function of the complex ratio of the two amplitudes considered
- Several sets of simulated events are generated varying the ratio of modulus and the phase difference between amplitudes



A_{UD} = (-9.6 ± 0.8) %

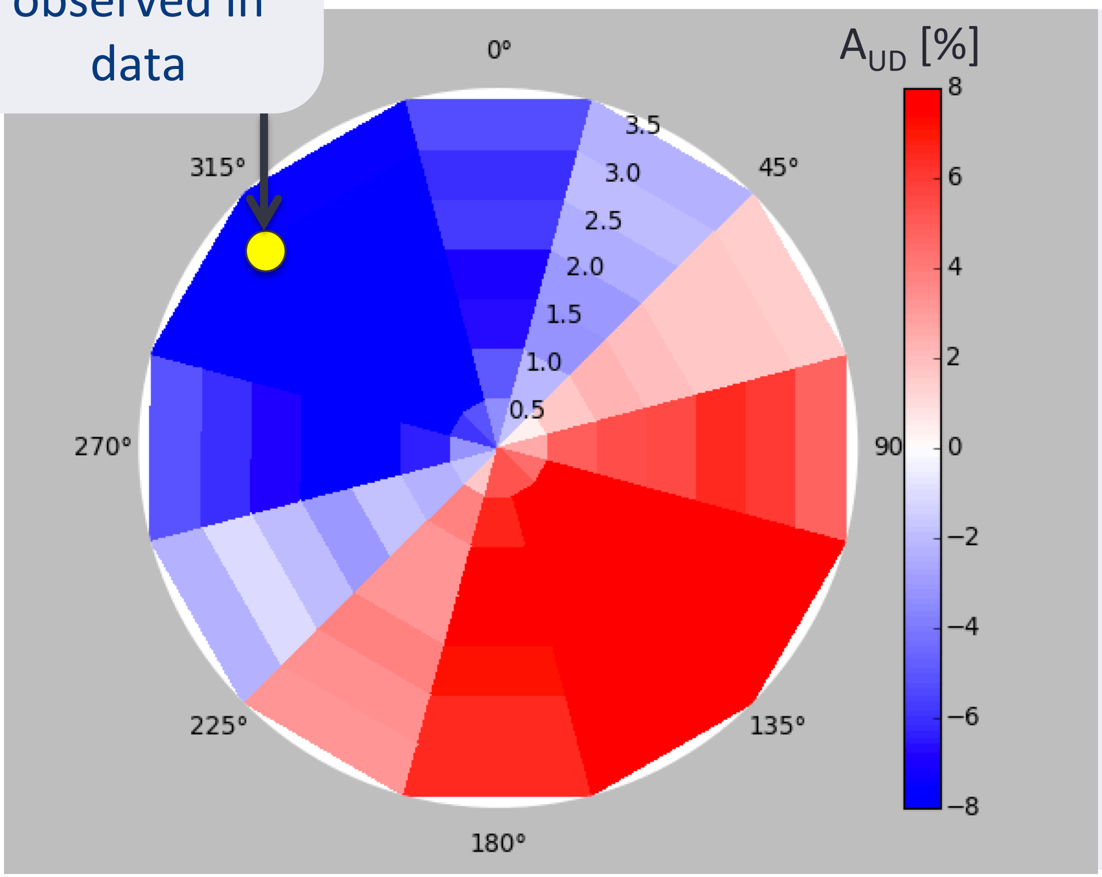
Example: Up-down asymmetry for the complex ratio of amplitudes seen in data ($\lambda_\gamma = 1$)

Relating A_{UD} with the interference pattern

- In some regions of the interference pattern, A_{UD} is zero

-> A_{UD} is not always sensitive to λ_γ

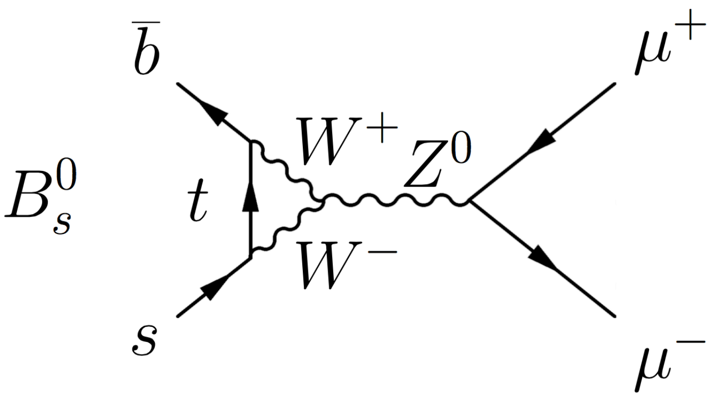
Ratio of amplitudes observed in data



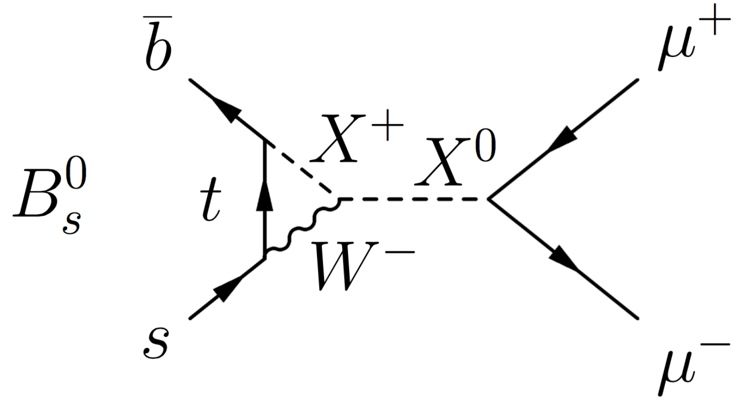
Up-Down asymmetry as a function of the complex ratio between the $K(1270) \to K\rho$ and $K(1270) \to K^{*}\pi$ amplitudes for $\lambda_\gamma = 1$

Rare B decays

- Flavour changing neutral currents with ΔF = 1 are forbidden at tree level in the SM
- Occur through loops (boxes, penguin loops) which may receive contributions from new physics (NP)
- For e.g., for $B_s^0 \to \mu^+\mu^-$:



SM process



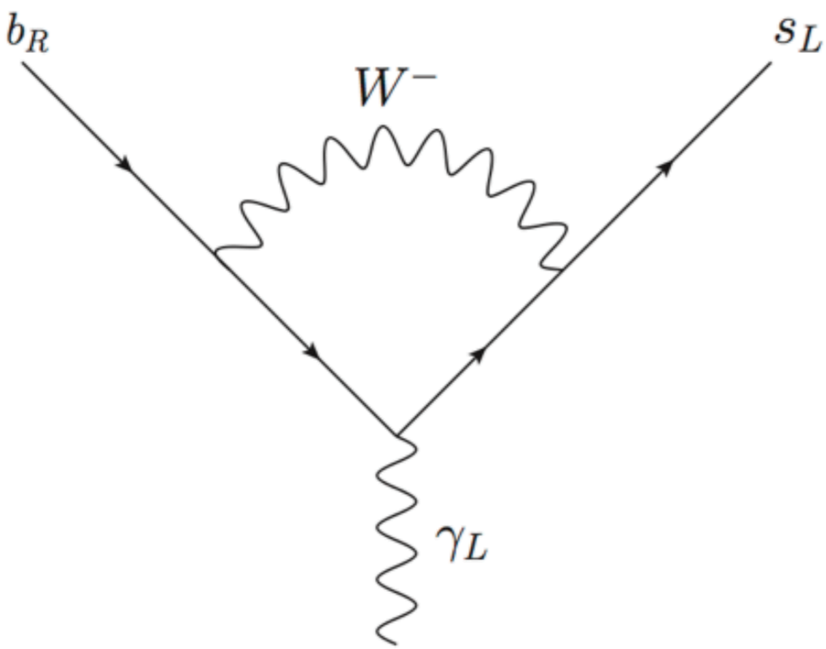
NP process

[*Nature* **522**, 68–72 (04 June 2015)]

- Rare decays are used for indirect searches of NP:
  - Suppressed in the SM
  - Sensitive to NP

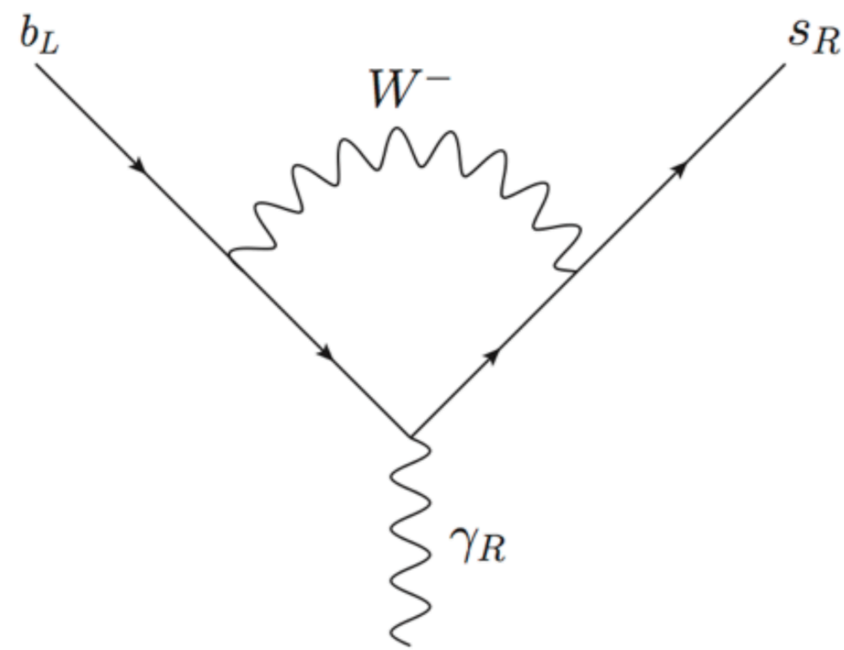
Photon polarisation in b → sγ transitions

- In the SM, the photon in b → sγ transitions is mostly left handed because the W couples left-handedly



Leading contribution

$$m_b \bar{s}_L \sigma_{\mu\nu} q^\nu b_R$$

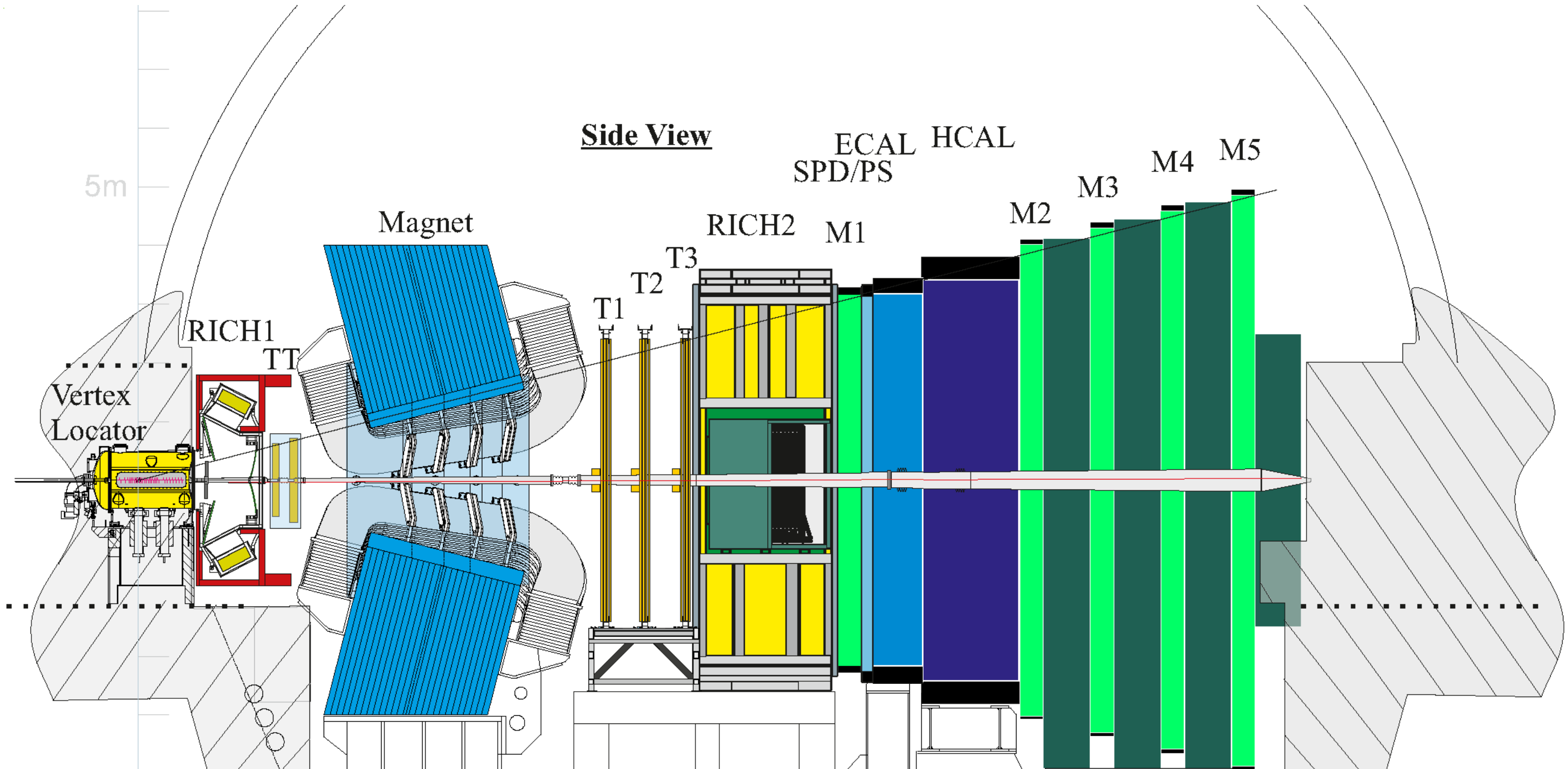


Contribution with chirality flip

$$m_s \bar{s}_R \sigma_{\mu\nu} q^\nu b_L$$

The LHCb detector

- Forward spectrometer dedicated to heavy flavour physics at LHC



Tracking:

✓ $\Delta p/p \approx 0.5\text{-}1$ % in the full momentum range

✓ $\sigma_\tau \approx 45$ fs and $\sigma_{IP} \approx 20$ µm for high-p_T tracks

Particle identification: K/π separation over 2-100 GeV/c ($\varepsilon_K \approx 90\%$ and $p_{\text{mis-id}\ \pi \to K} \approx 5\%$)

Calorimeter system: $\sigma_E/E \approx 10\%/\sqrt{E} + 1\%$

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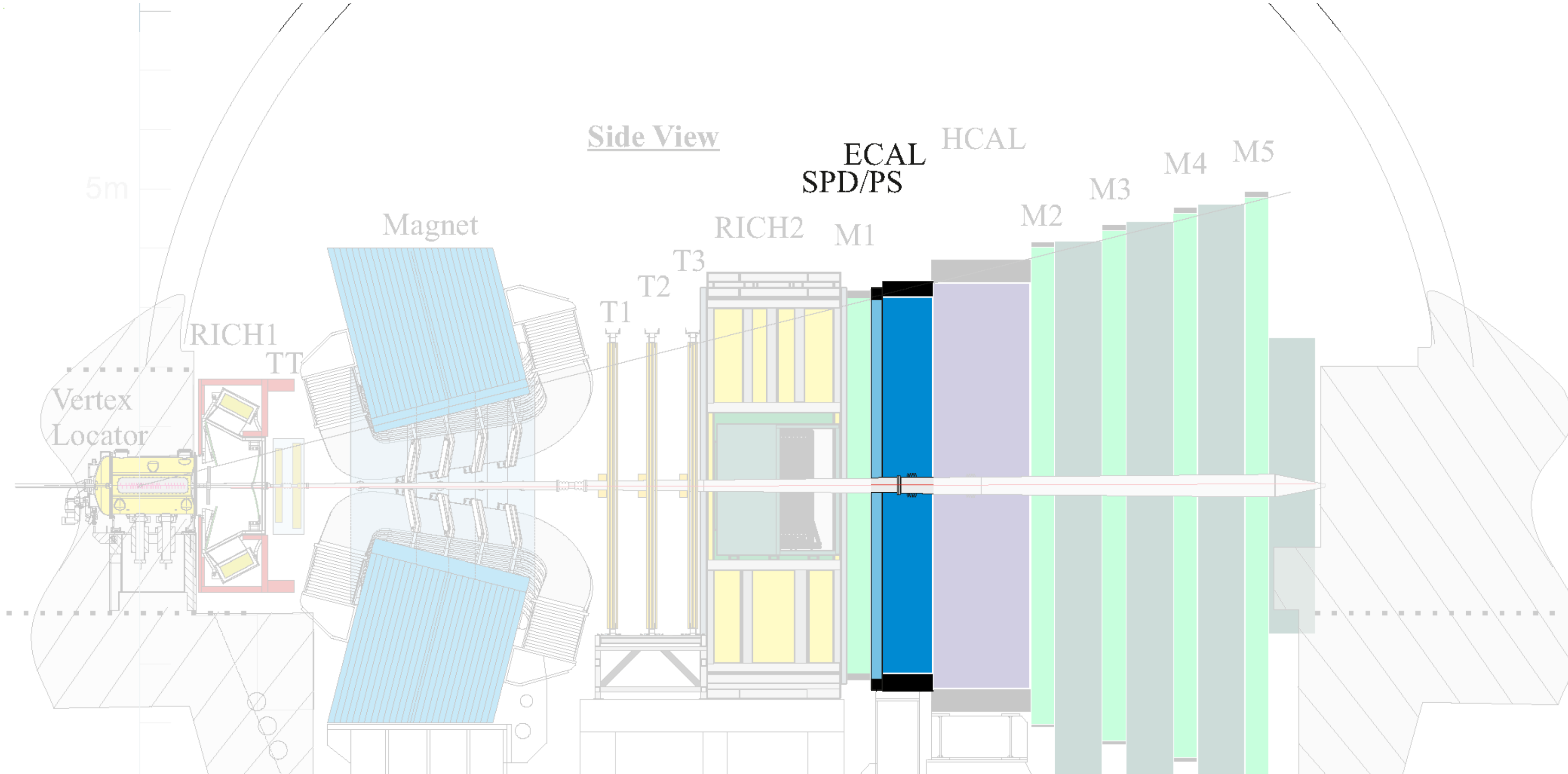

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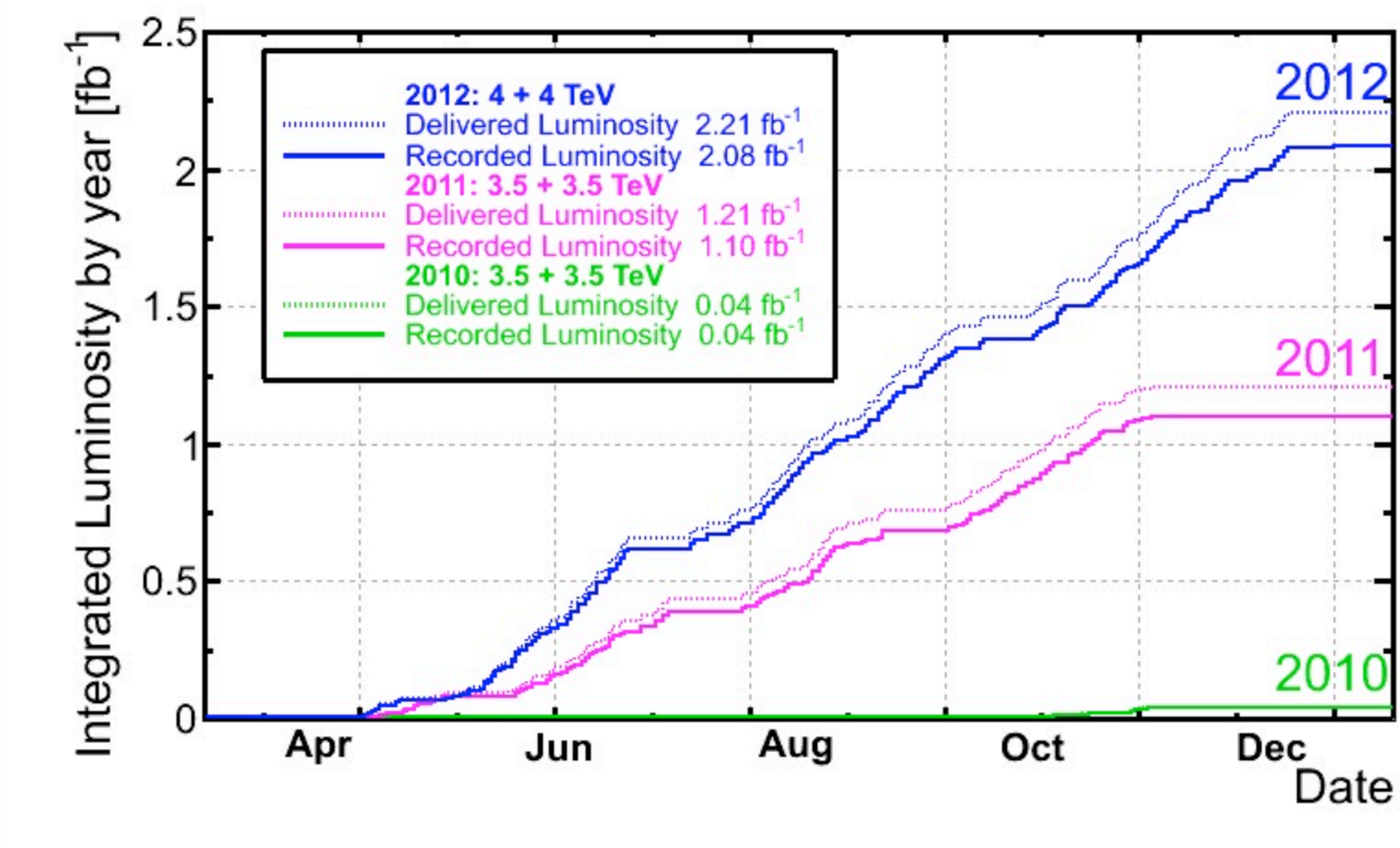
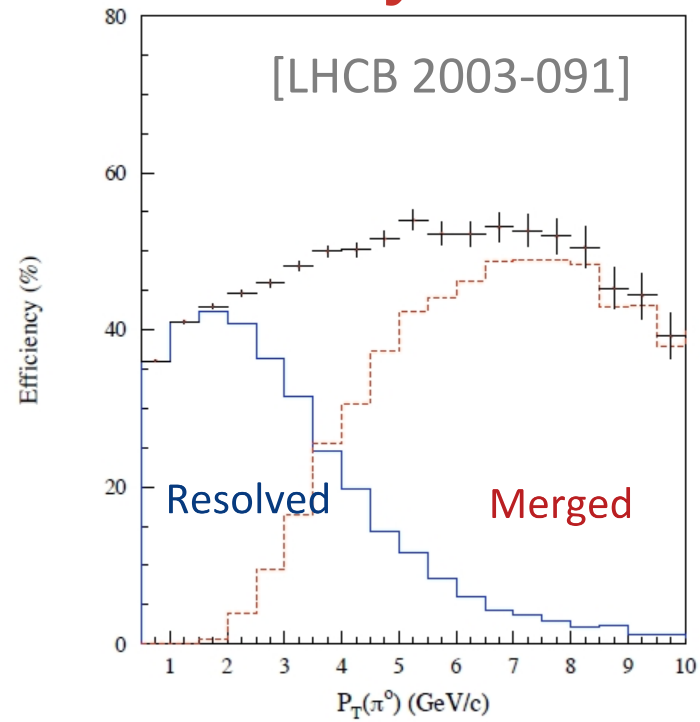
Operations

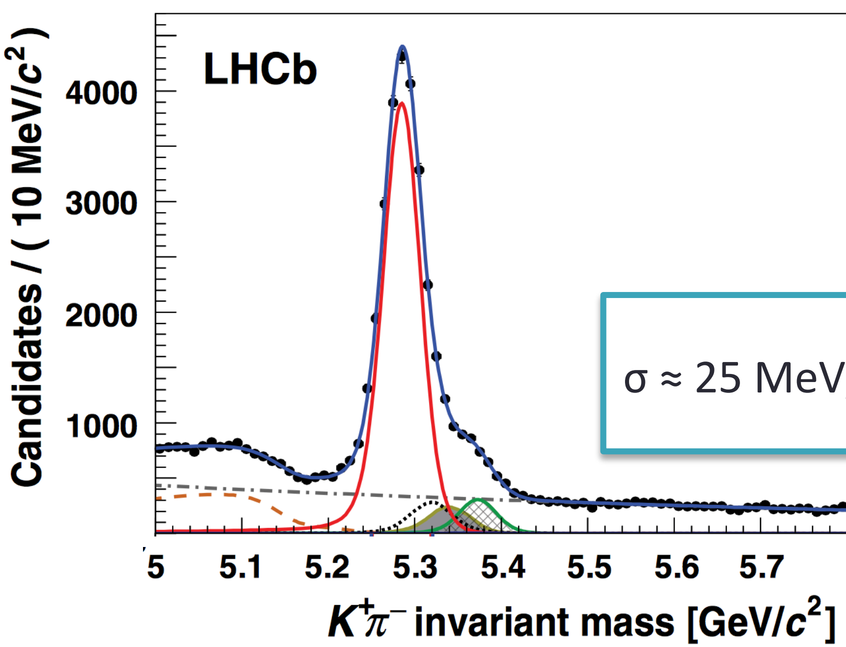
- Data taking: 2009 – 2012 (Run 1, integrated luminosity of $3fb^{-1}$)
- Now in Run 2: 2015 – 2018



Main challenges for radiative decays

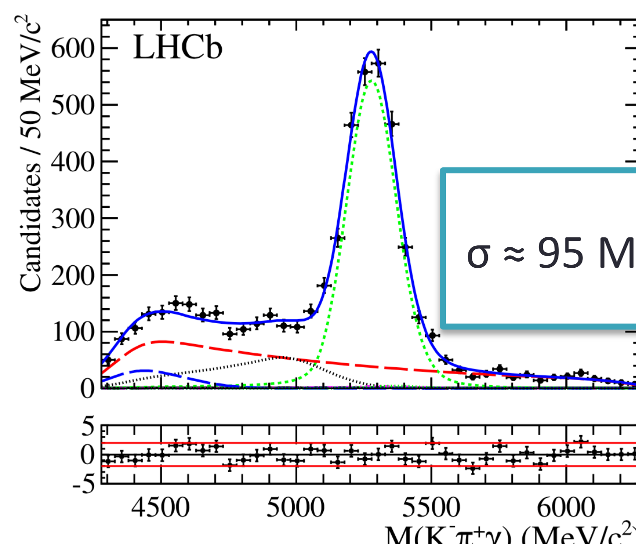
- High level of **background in pp collisions**
- For energies above 4 GeV the two clusters from $\pi^0 \rightarrow \gamma\gamma$ are reconstructed as a single cluster in the calorimeter
- Mass **resolution dominated by photon** reconstruction





σ ≈ 25 MeV/c²

[PRL 110 (2013) 221601]



σ ≈ 95 MeV/c²

[Nucl. Phys. B 867 (2012)]

Adding resonances is not so simple

The amplitude for a system containing (1^+, 2^+, 1^-) is:

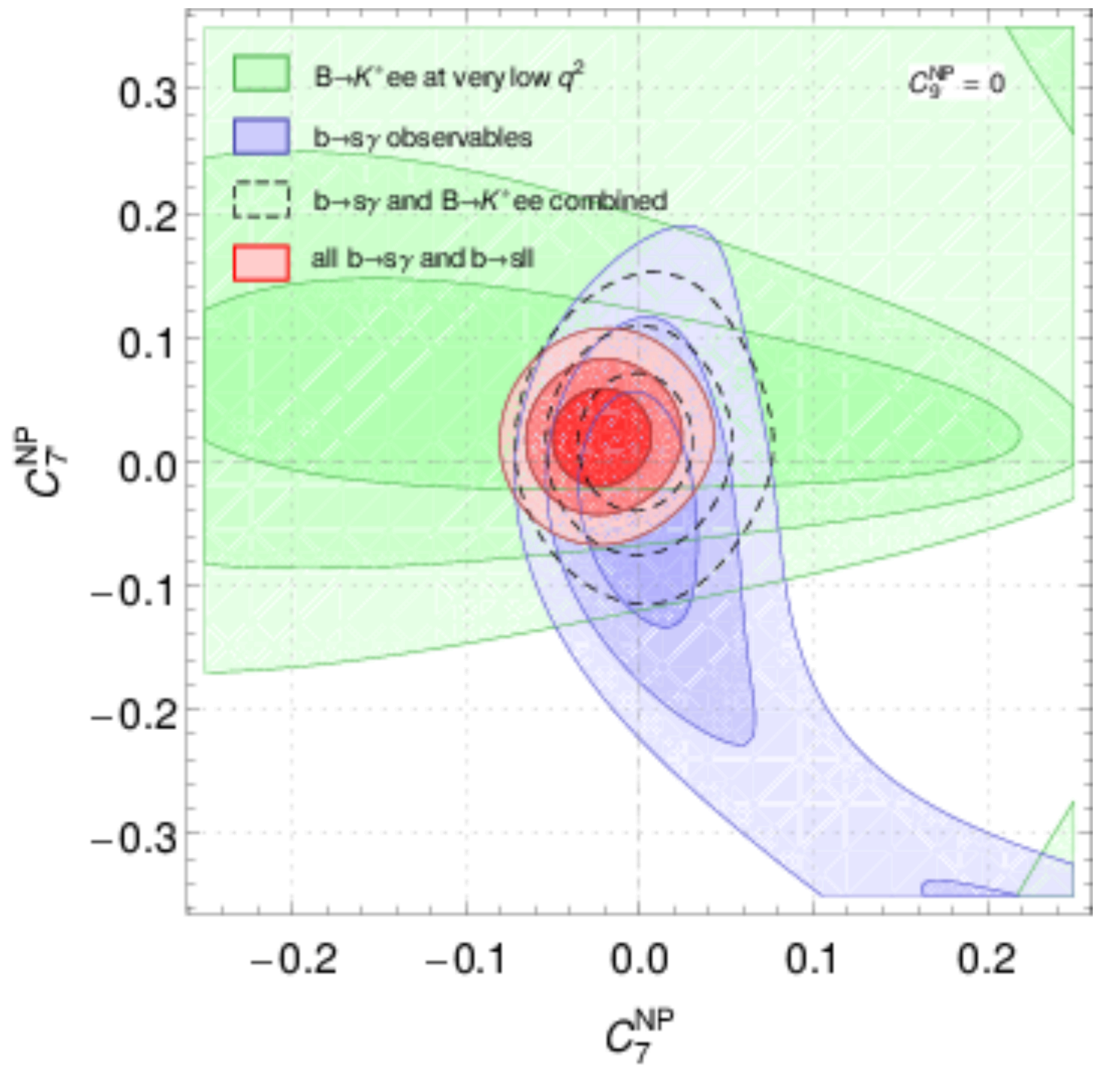
$$\mathcal{A}_{R,L}(\bar{B} \to \bar{K}\pi\pi\gamma_{R,L}) = A(\vec{\varepsilon}_\pm \cdot \vec{J}) \pm B\left((\vec{\varepsilon}_\pm \cdot \vec{n})(\vec{\varepsilon}_0 \cdot \vec{K}) + (\vec{\varepsilon}_\pm \cdot \vec{K})(\vec{\varepsilon}_0 \cdot \vec{n})\right) \pm C(\vec{\varepsilon}_\pm \cdot \vec{n})$$

where A, B and C are constant obtained after factorizing out the terms depending on the polarisatiuon and the final state momenta in the respective expressions of the amplitudes of the 1+, 2+ and 1- resonances.

The vectors are defined using the final state momenta:

$$\begin{aligned} \vec{J} &= C_1\vec{p}_1 - C_2\vec{p}_2 \quad , \\ \vec{K} &= |\vec{p}_1 \times \vec{p}_2|\,\{\vec{p}_1[B_{K^*}(s_{23}) + \kappa_\rho B_\rho(s_{12})] + \vec{p}_2[B_{K^*}(s_{13}) + \kappa_\rho B_\rho(s_{12})]\} \end{aligned}$$

Constraints on C_7 and $C_{7'}$



[arXiv: 1510.04239]

Likelihood function

- Function to be minimized

$$\mathcal{L} = -2 \cdot ln\left(\prod_{data} \mathcal{L}_i\right)$$

$$\mathcal{L}_i = \frac{y_i \cdot (|\sum\limits_{amp} c_j \cdot A_j|^2)}{\sum\limits_{m \in MC} \frac{y_m}{N_{MC}} \sum\limits_{m \in MC} \frac{w_m \cdot |\sum\limits_{amp} c_j \cdot A_{jm}|^2}{\sum\limits_{k \in MC} w_k}}$$

Amplitudes

- Amplitudes are products of spin factor and Breit-Wigner distributions

$$A_{K(1270)\to K\rho} = \mathcal{S}_f(B \to V_0 A(\to P_1 V(\to P_2 P_3)))\, BW(K(1270) \to K\rho) BW(\rho \to \pi\pi)$$

$$A_{K(1270)\to K^*\pi} = \mathcal{S}_f(B \to V_0 A(\to P_1 V(\to P_2 P_3)))\, BW(K(1270) \to K^*\pi) BW(K^* \to K\pi)$$

Spin-factors

- Spin factors:

$$\mathcal{S}_f(B \to V_0 A(\to P_1 V(\to P_2 P_3))) = \epsilon^*_\alpha(V_0) P^{\alpha\beta}_{(1)}(A) L_{(1)\beta}(V)$$

Conjugated polarisation vector

Spin1 projection tensor

Encodes the state of pure angular momentum 1 of the 2-particles system coming from V

Spin-factors

- where:

$$\epsilon^{\mu}(p, m = \mp 1) = \frac{\pm 1}{\sqrt{2}} \begin{pmatrix} 0 \\ \pm\frac{p_z}{E} + (1 - \frac{p_z}{E})(\frac{p_y}{p_x^2 + p_y^2})(\pm p_y - i p_x) \\ -i\frac{p_z}{E} + (1 - \frac{p_z}{E})(\frac{p_x}{p_x^2 + p_y^2})(\pm p_y - i p_x) \\ \frac{\sin(\arccos\frac{p_z}{E})}{p_x^2 + p_y^2}(\mp p_x + i p_y) \end{pmatrix}$$

$$P^{\mu\nu}_{(1)}(p) = \sum_m \epsilon^{\mu}(p, m)\epsilon^{*\nu}(p, m) = -g^{\mu\nu} + \frac{p^{\mu}p^{\nu}}{M^2}$$

$$L^{\mu}_{(1)}(p_R, q_R) = -P_{(1)\mu\nu}(p_R) q^{\nu}_R$$