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

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ÉCOLE POLYTECHNIQUE
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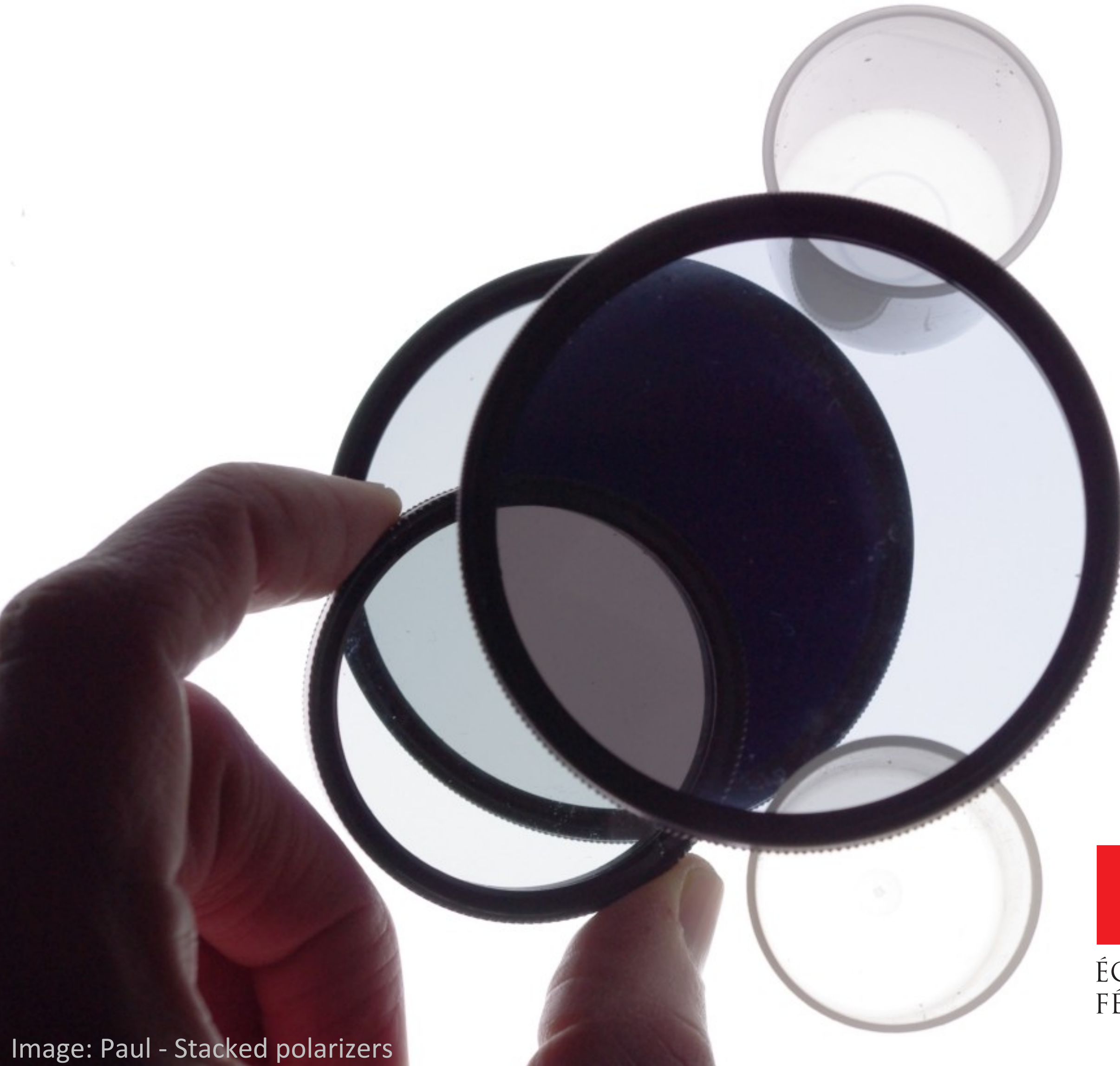
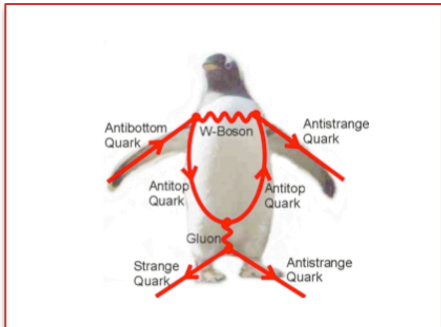
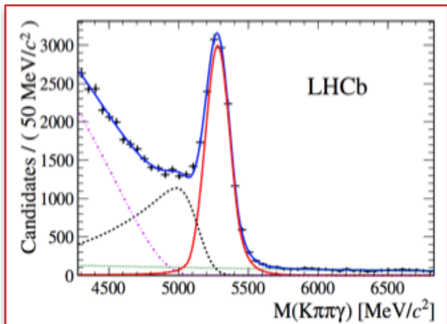


Image: Paul - Stacked polarizers

Outline

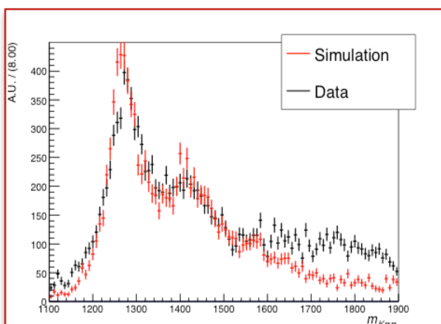


Photon polarisation in radiative B decays



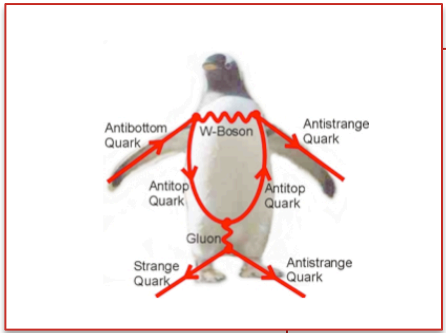
Observation of non-zero photon polarisation in B→Kππγ decays

3D amplitude analysis of the Kππ system



Proof of concept for a measurement of the photon polarisation using a 5D amplitude analysis of the Kππγ system

Outline



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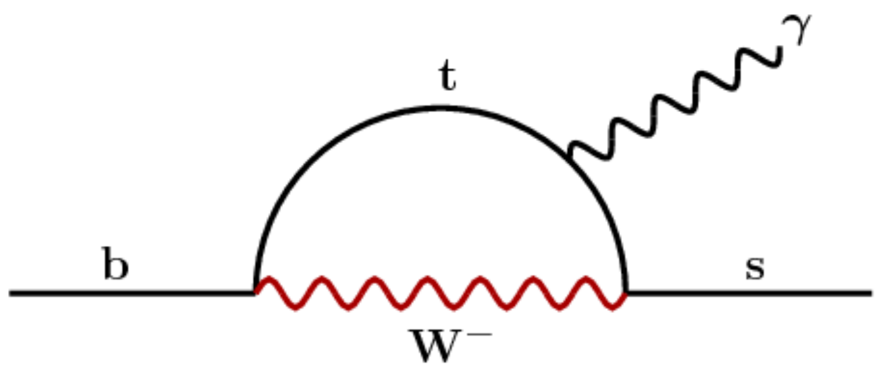
Radiative B decays

- 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 $b \to s\gamma$ transitions

- The decay amplitude for $b \to s\gamma$ transitions is proportional to:

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

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:

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

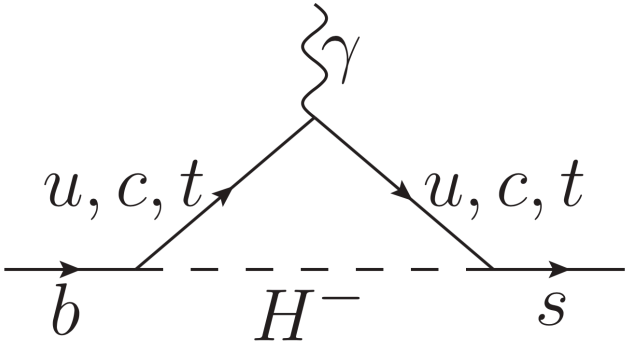
- The photon polarisation parameter λ_γ is defined as:

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

In SM, $\lambda_\gamma \cong 1$ (with corrections of $O(m_s^2/m_b^2)$) for decays of a B^+ meson

Photon polarisation: a probe for NP

- NP processes could introduce right-handed currents, hence modifying the photon polarisation (e.g. Charged Higgs models as in arXiv:1208.1251v2)

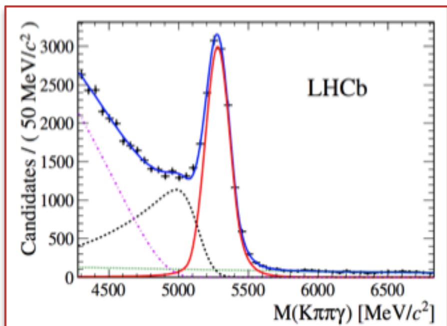


- The measurement of the photon polarisation is a test of the SM but it has not been done yet

- Maybe some new penguins around !

Outline

Photon polarisation in radiative B decays



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

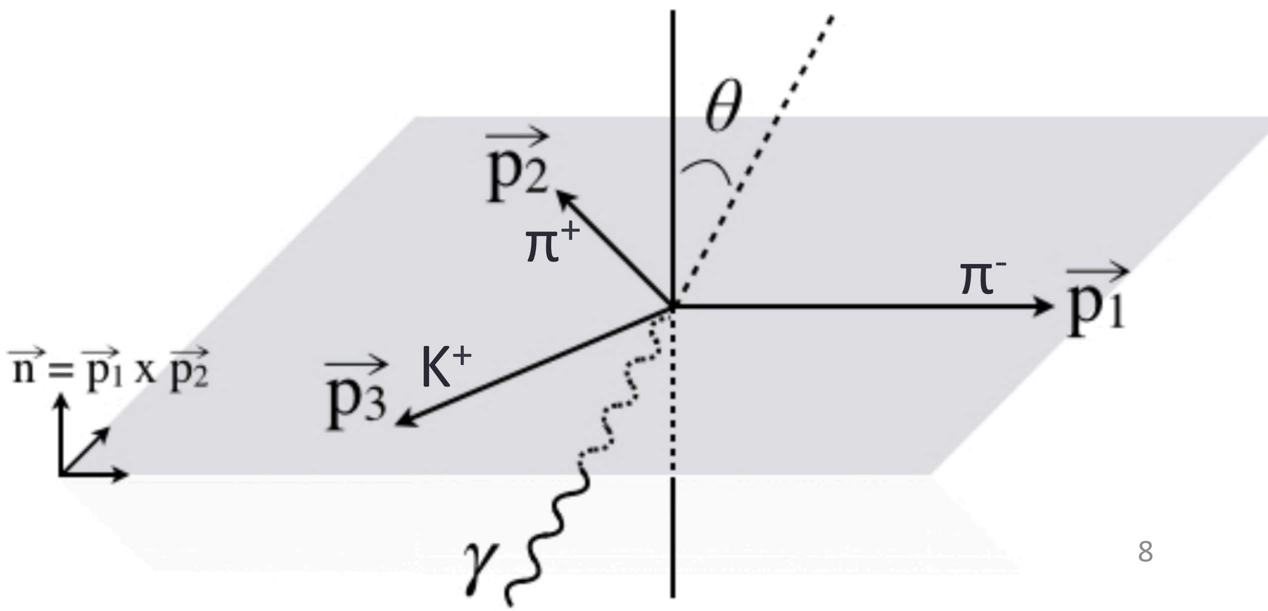
3D amplitude analysis of the Kππ system

Proof of concept for a measurement of the photon polarisation using a 5D amplitude analysis of the Kππγ system

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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$$\frac{|c^{\text{weak}}_R|^2 - |c^{\text{weak}}_L|^2}{|c^{\text{weak}}_R|^2 + |c^{\text{weak}}_L|^2} = \frac{|C'_7|^2 - |C_7|^2}{|C'_7|^2 + |C_7|^2} = \lambda_\gamma$$

Photon polarisation parameter

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

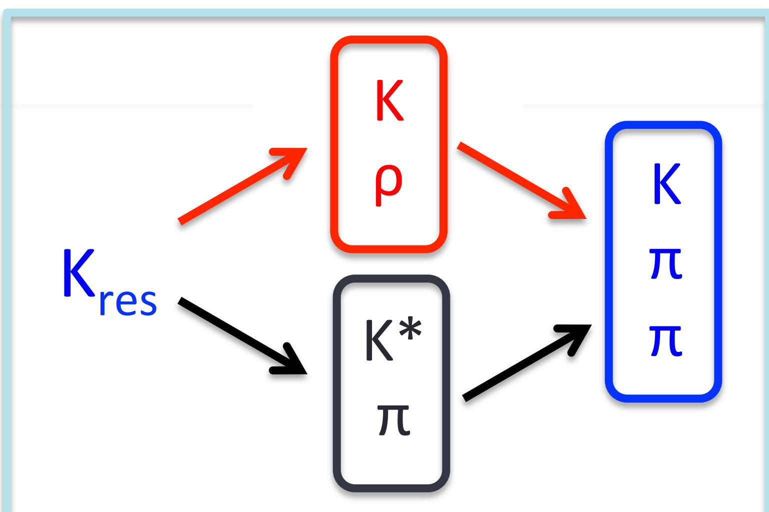
In the case of a single 1^+ resonance:

[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]

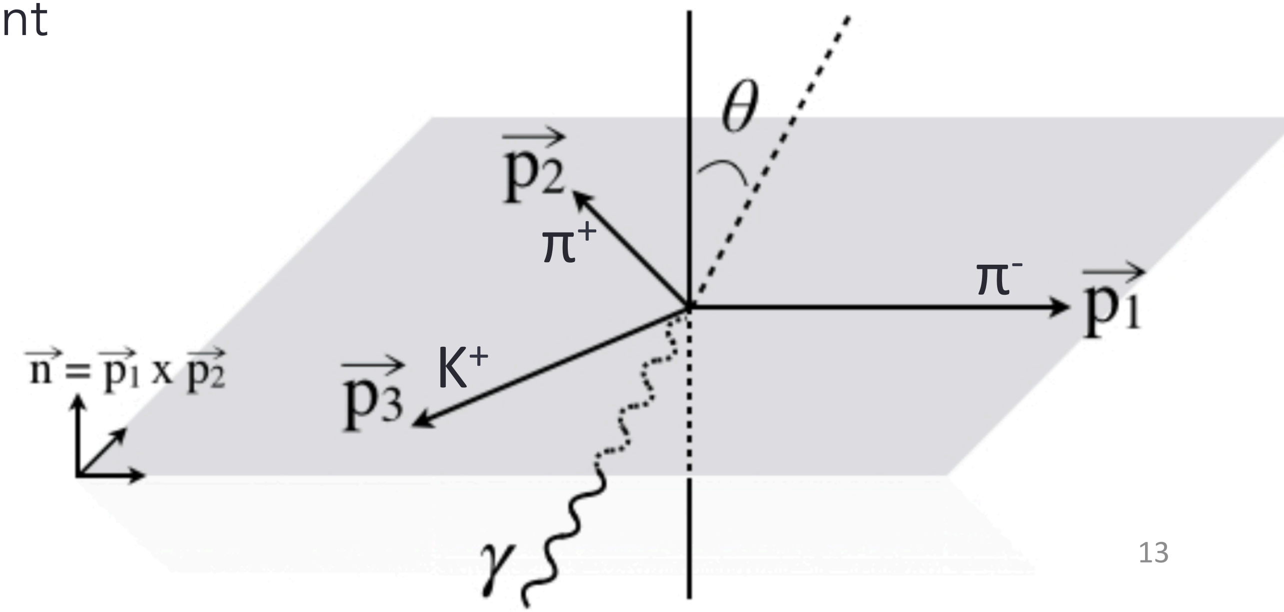
As the $K^+\pi^-\pi^+$ system is not known, **simplification is needed !**

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

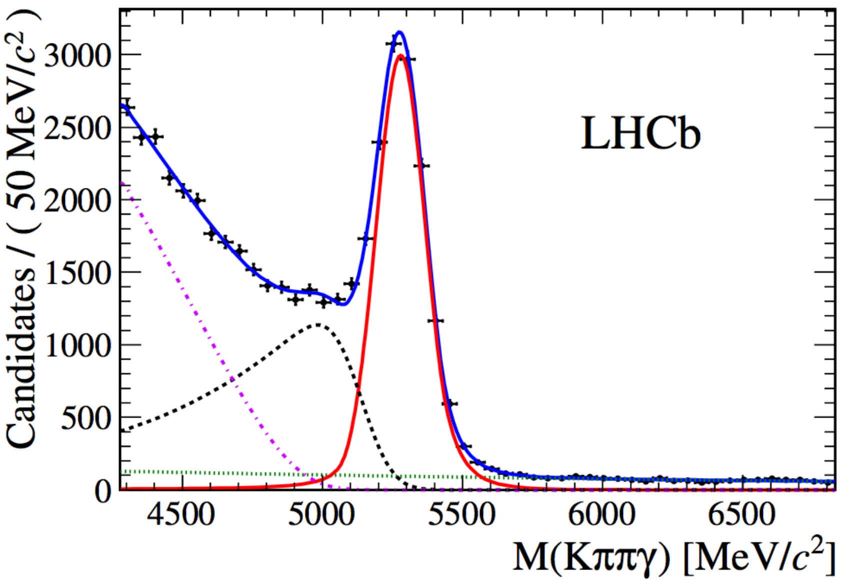
The idea is to integrate over the Dalitz plot and the angular distribution to obtain the up-down asymmetry:

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

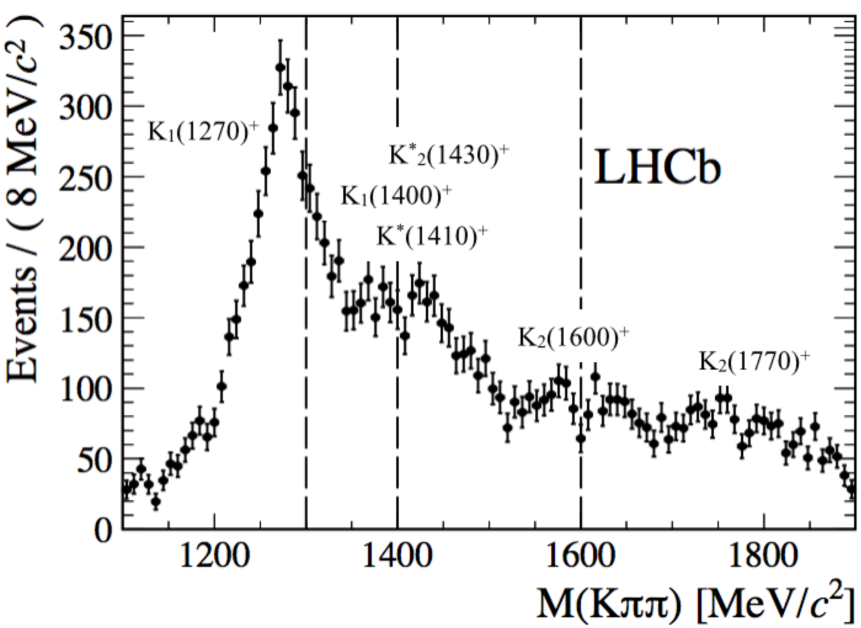
where C takes into account the integrations and depends on the $K\pi\pi$ system content



Selection of the B→Kππγ events



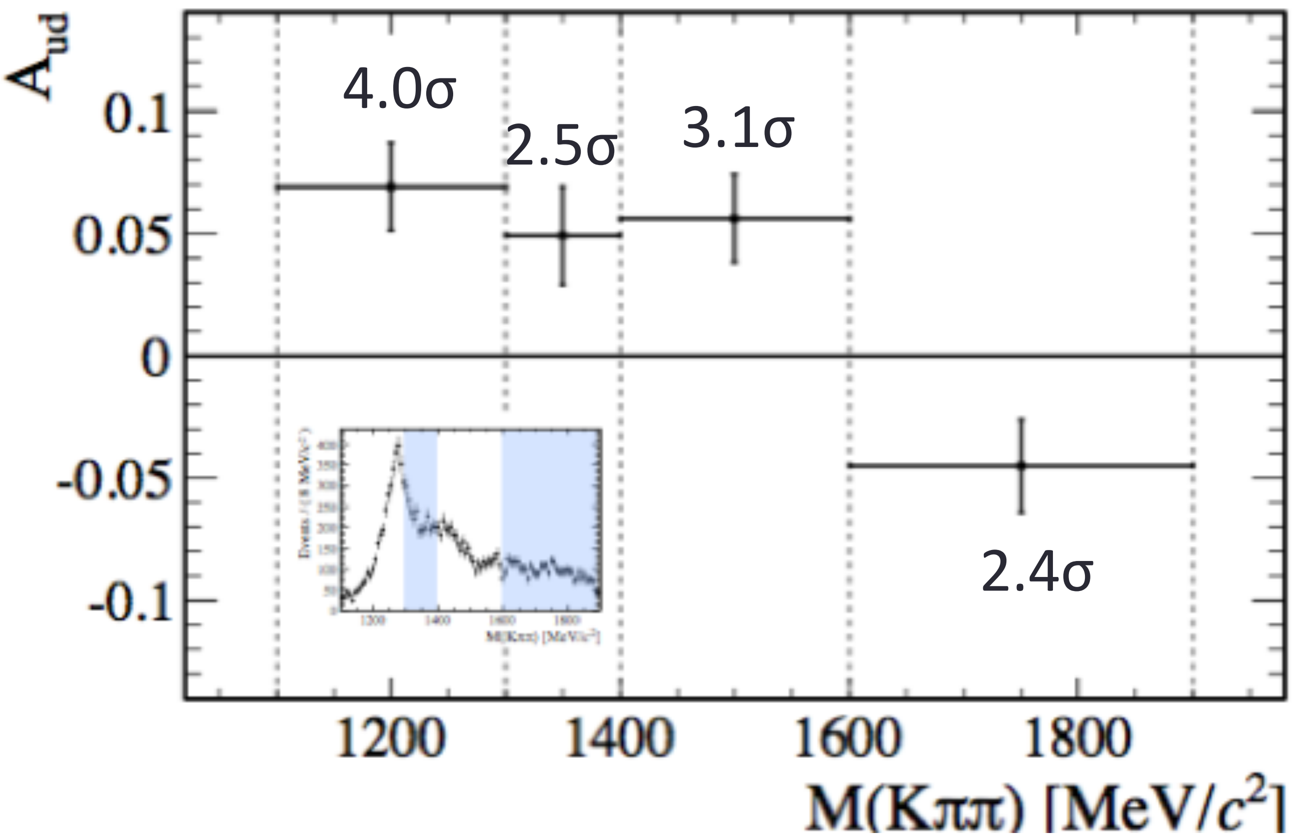
[PRL 112, 161801 (2014)]
Signal
Combinatorial background
Missing pion background
Partially reconstructed background
Total fit
Data



- 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 and divided in m(Kππ) bins

Observation of λ_γ

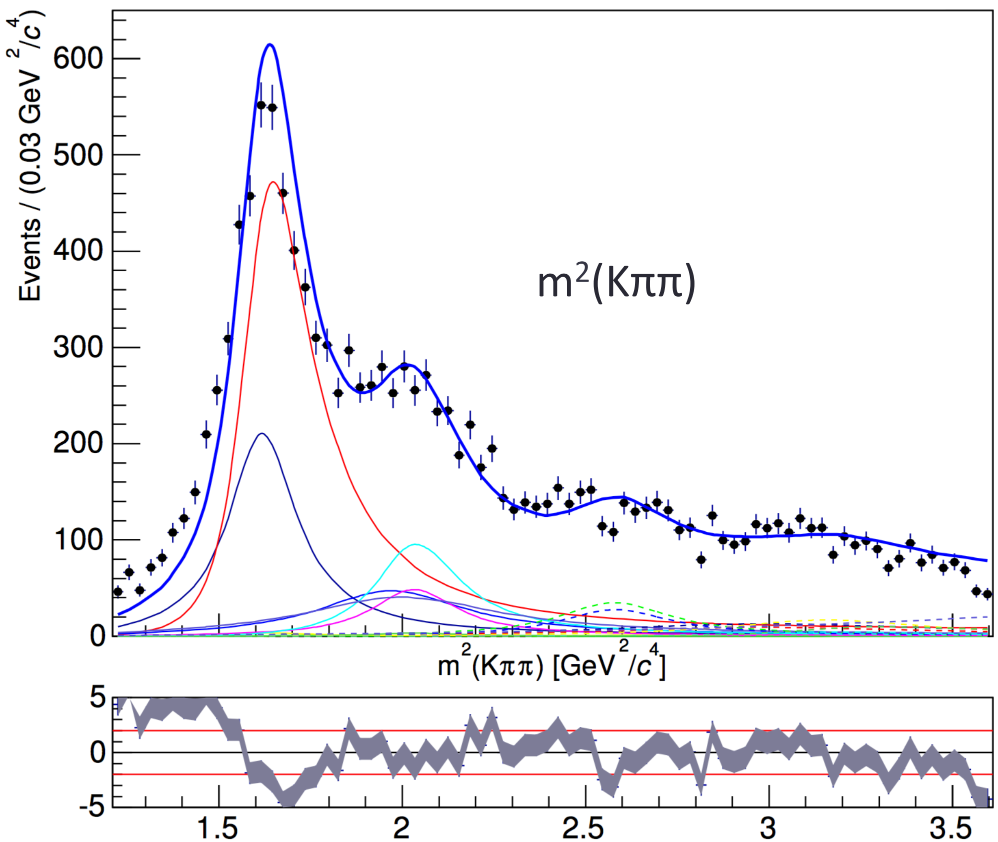
- In each m(Kππ) bin, the cos θ distribution is fitted
- As **A_{ud} is proportional to λ_γ**:
  Observation of a non-zero photon polarisation with A_{ud} different from 0 at 5.2 σ .
- Missing knowledge of the Kππ system to make a measurement

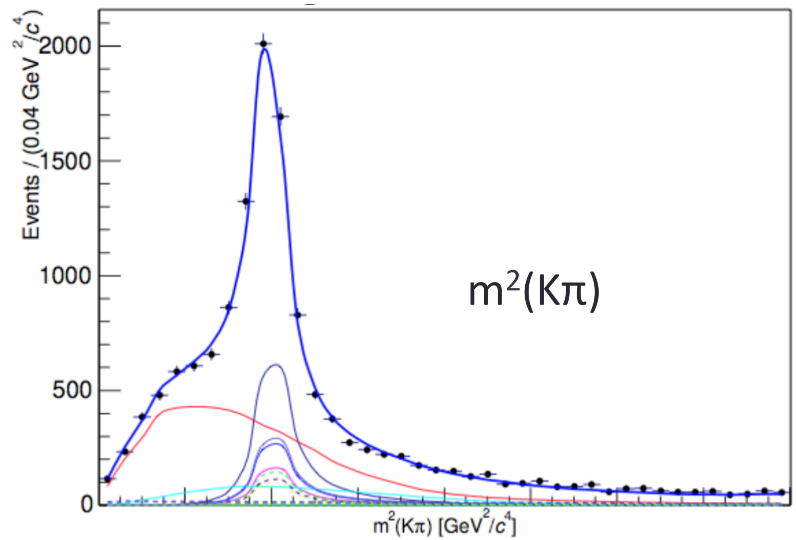


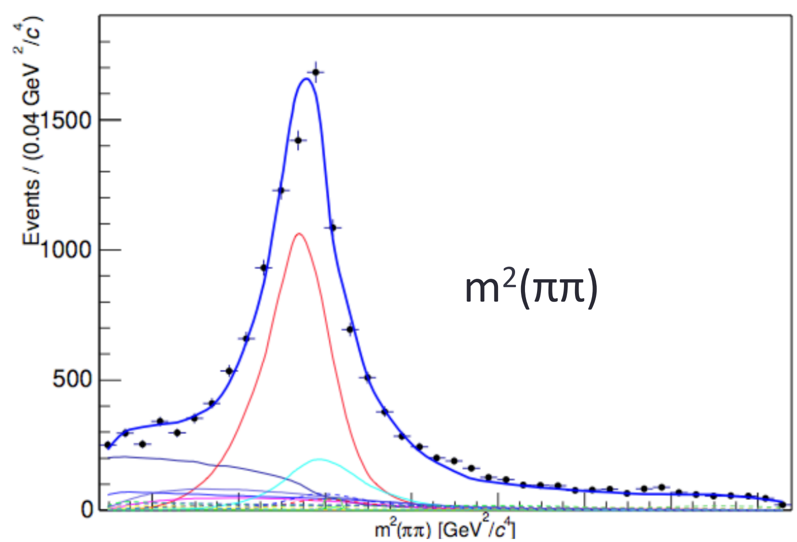
[PRL 112, 161801 (2014)]

Amplitude analysis of the Kππ system

- 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 (including resonances with $J^P = 1^+, 1^-, 2^+, 2^-$)



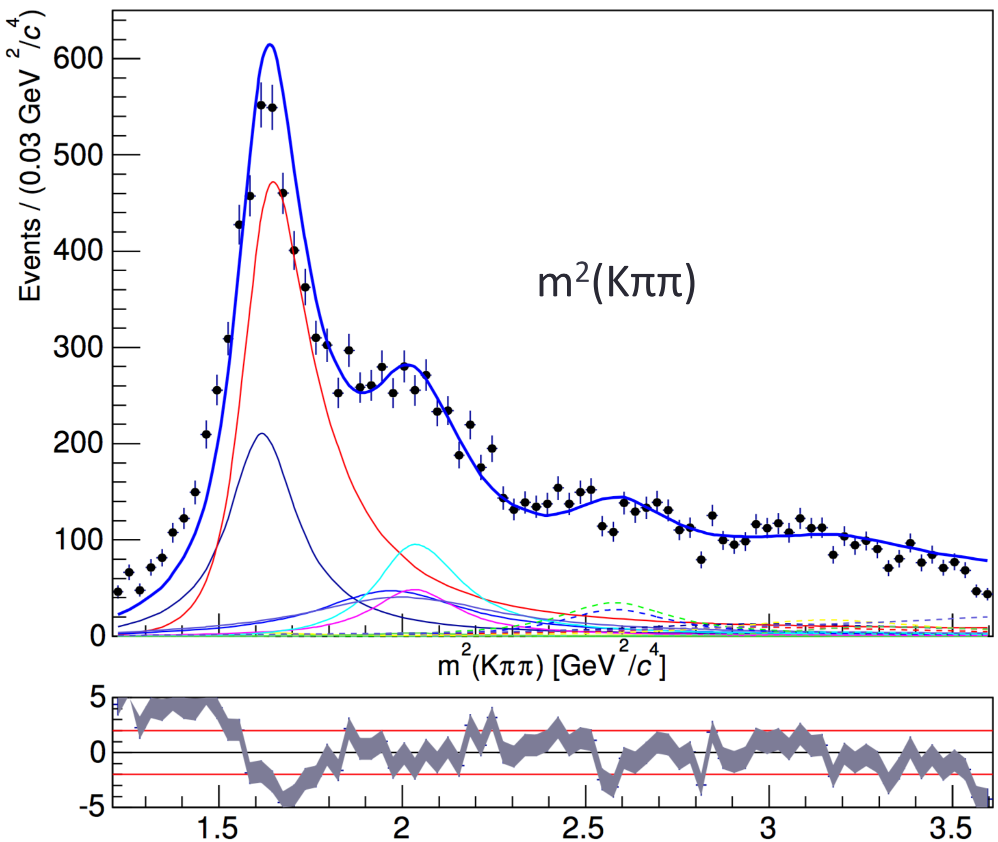


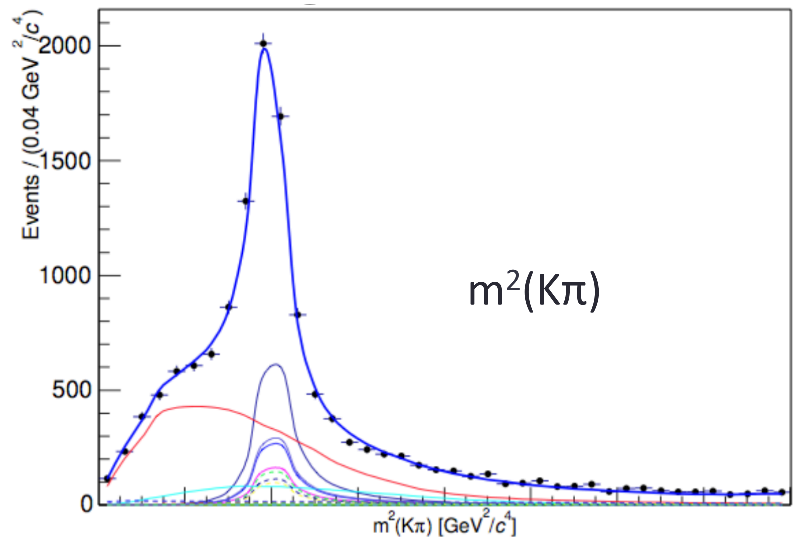


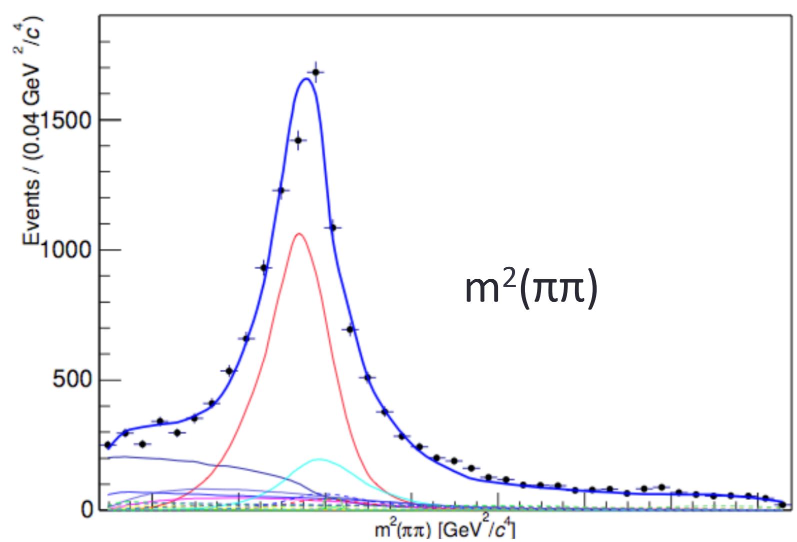
[CERN-THESIS-2015-287]

Amplitude analysis of the Kππ system

- The 2 main amplitudes are
  K(1270) → $K^{*}\pi$ and
  K(1270) → K ρ







[CERN-THESIS-2015-287]

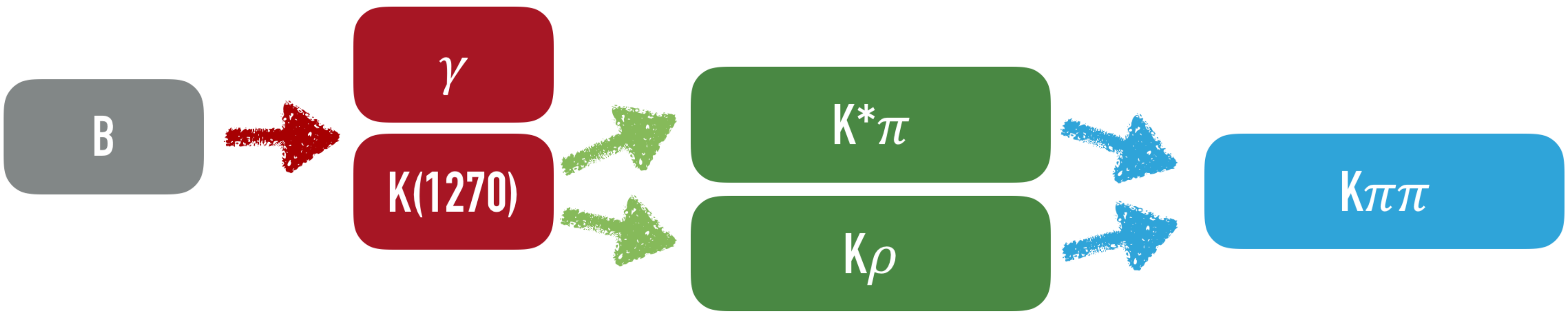
Relating A_{UD} with the Kππ system

Toys using a simple model with two amplitudes (and their interference):

$\mathcal{A}(B^+ \rightarrow K(1270)\ (\rightarrow K^*\ (\rightarrow K^+\pi^-)\ \pi^+)\ \gamma) = \mathcal{A}_{K^*\pi}$

$\mathcal{A}(B^+ \rightarrow K(1270)\ (\rightarrow \rho\ (\rightarrow \pi^-\pi^+)\ K^+)\ \gamma) = \mathcal{A}_{\rho K}$

Systems described by (r, $\Delta\varphi$) such that $\mathcal{A}_{\rho K}/\mathcal{A}_{K^*\pi} = r \times e^{i\Delta\varphi}$



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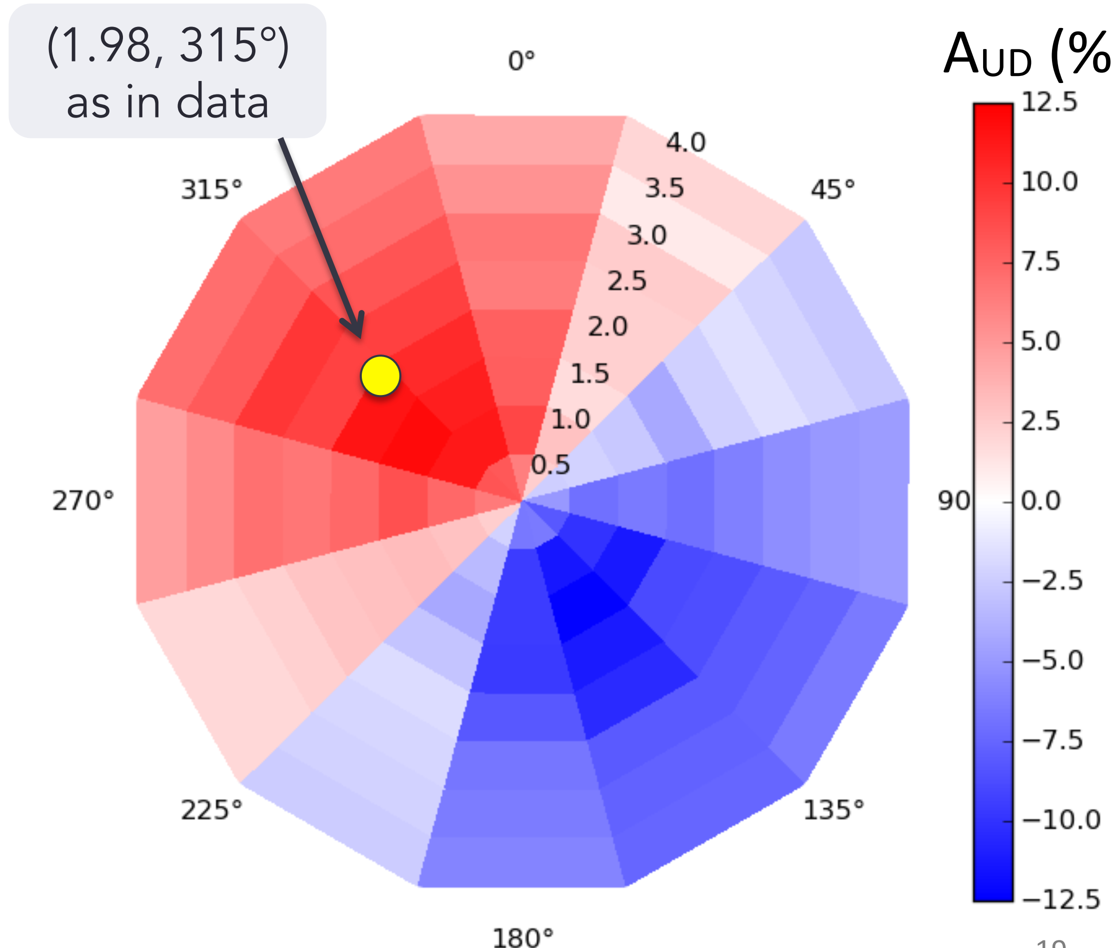
Systems described by (r, $\Delta\varphi$) such that $\mathcal{A}_{\rho K}/\mathcal{A}_{K^*\pi} = r \times e^{i\Delta\varphi}$

Radius: Ratio of amplitudes r

Phase: Difference of phase between the two amplitudes $\Delta\varphi$

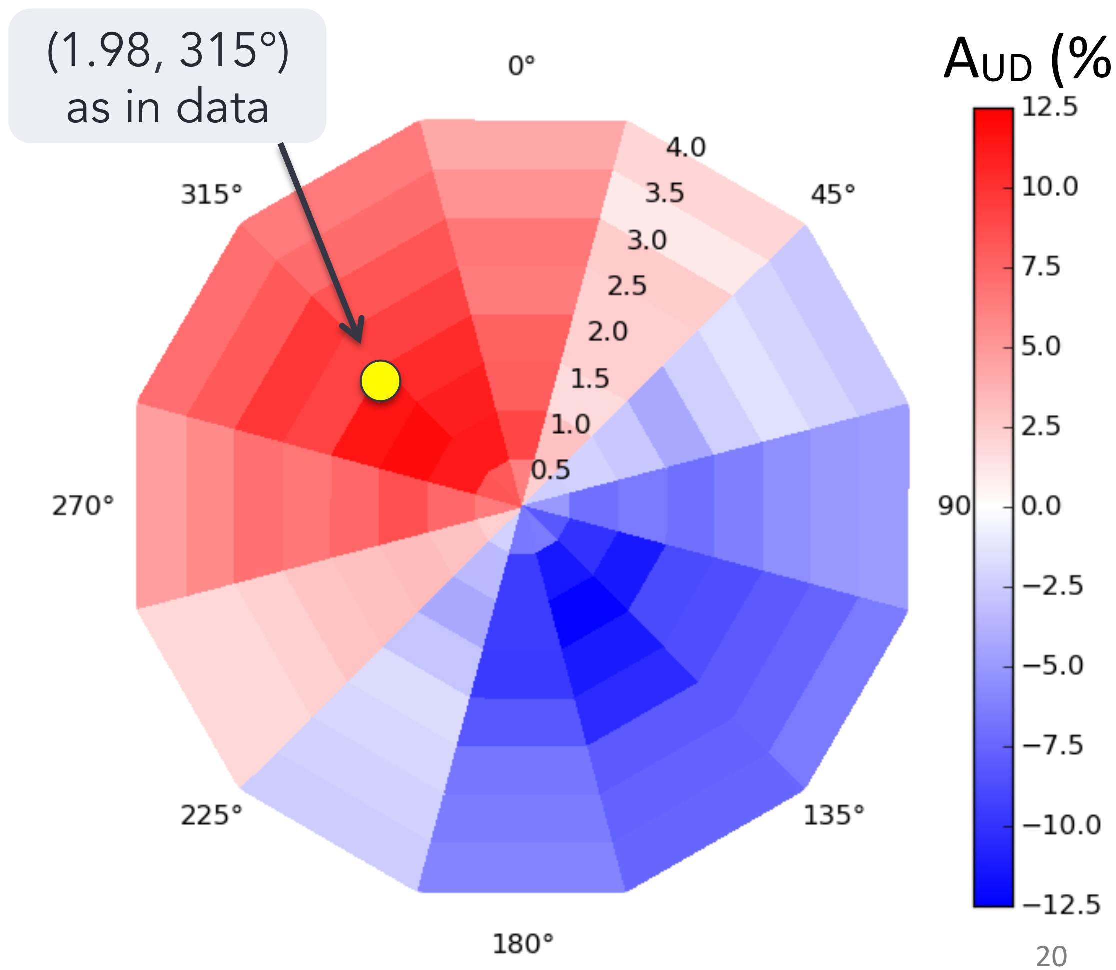
Color scale:
Up-down asymmetry in %
(for samples generated with $\lambda_\gamma = 1$)



Limits of the measurement of A_{UD}

From theory: $A_{UD} = C.\ \lambda_\gamma$

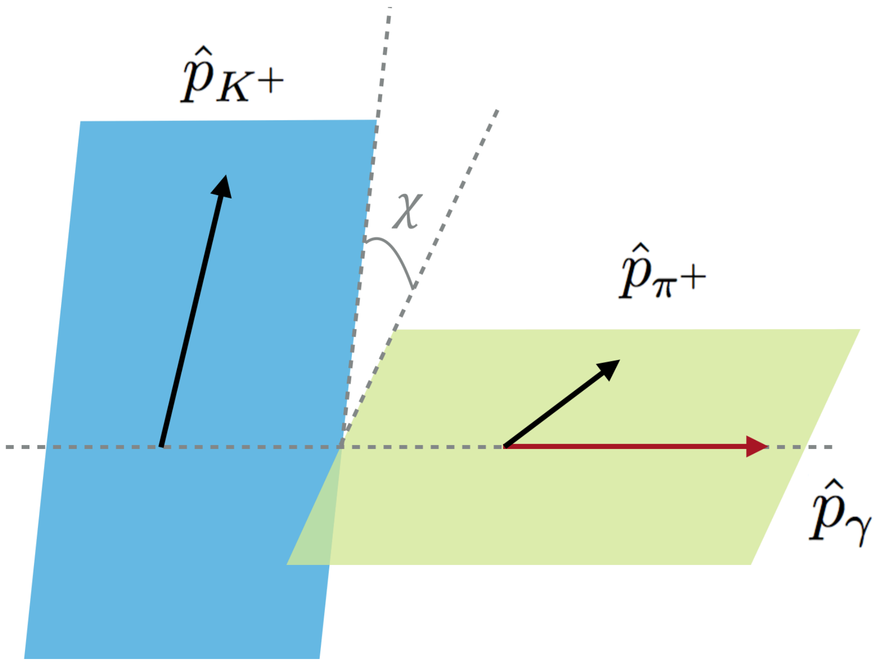
In regions where $A_{UD} = 0$, there is no sensitivity to the photon polarisation

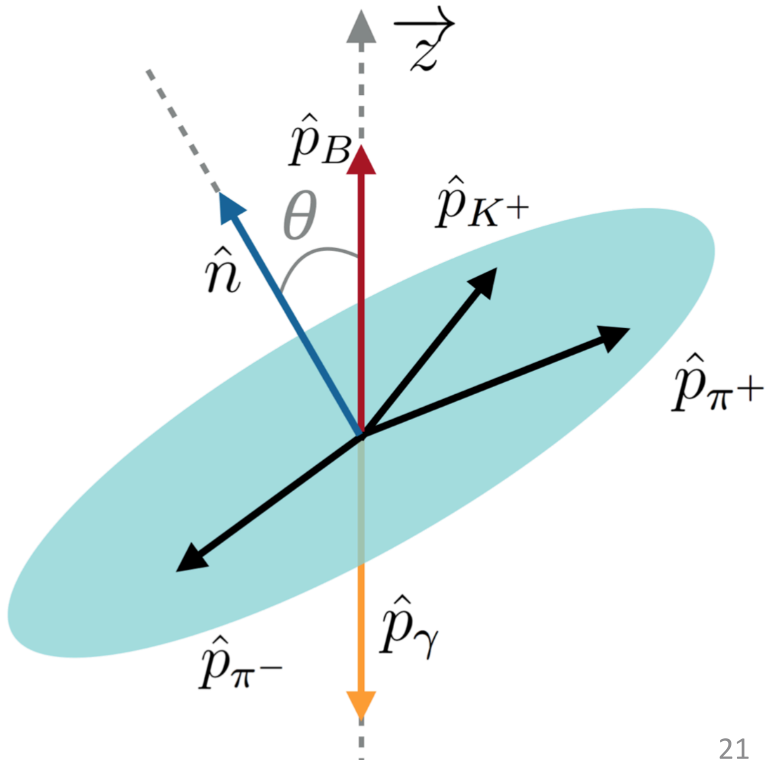


How to measure the photon polarisation parameter?

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

→ Use of the squared masses + the angles (θ and χ) describing the orientation of the Kππ system with respect to the photon





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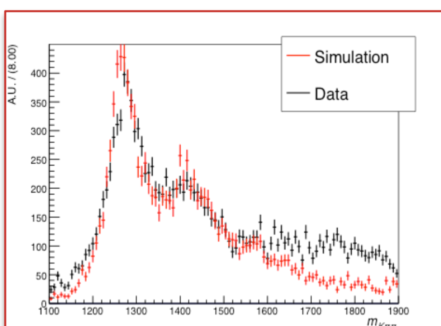
Photon polarisation in radiative B decays

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

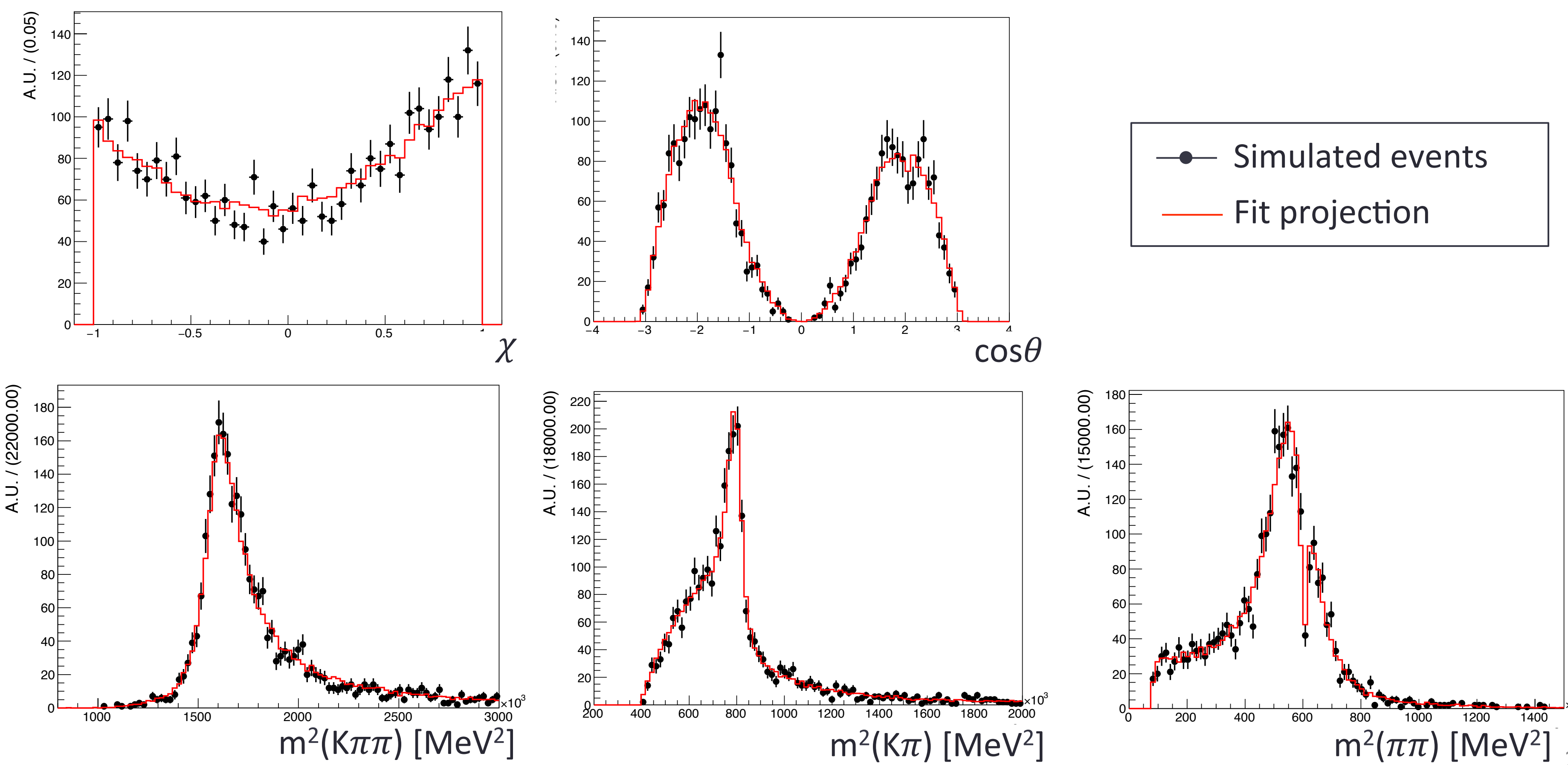
3D amplitude analysis of the Kππ system



Proof of concept for a measurement of the photon polarisation using a 5D amplitude analysis of the Kππγ system

Toy studies with a 2-amplitude model in 5D

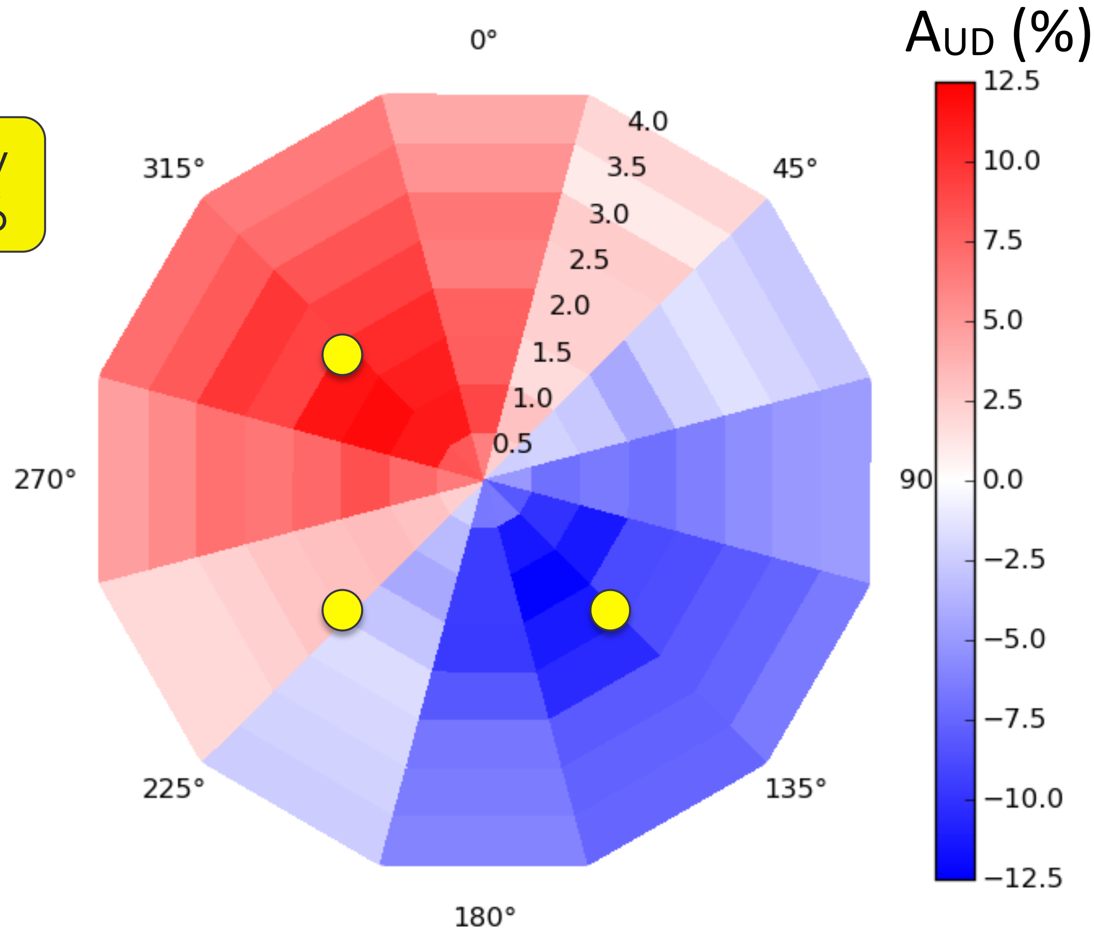
- Now possible using a dedicated piece of software [arXiv:1201.5716]
- Toy studies with a **2-amplitude model** containing K(1270) → $K^{*}\pi$ and K(1270) → $K\rho$ with (r, $\Delta\varphi$) corresponding to data and $\lambda_\gamma = 1$
- **3 free parameters** of the fit: r, $\Delta\varphi$ and λ_γ
- The fitted parameters are compatible with the generated ones



Advantage of the 5D fit

On a simplified 2-amplitude model:
Similar error on the photon polarisation parameter independently of the phase difference between amplitudes

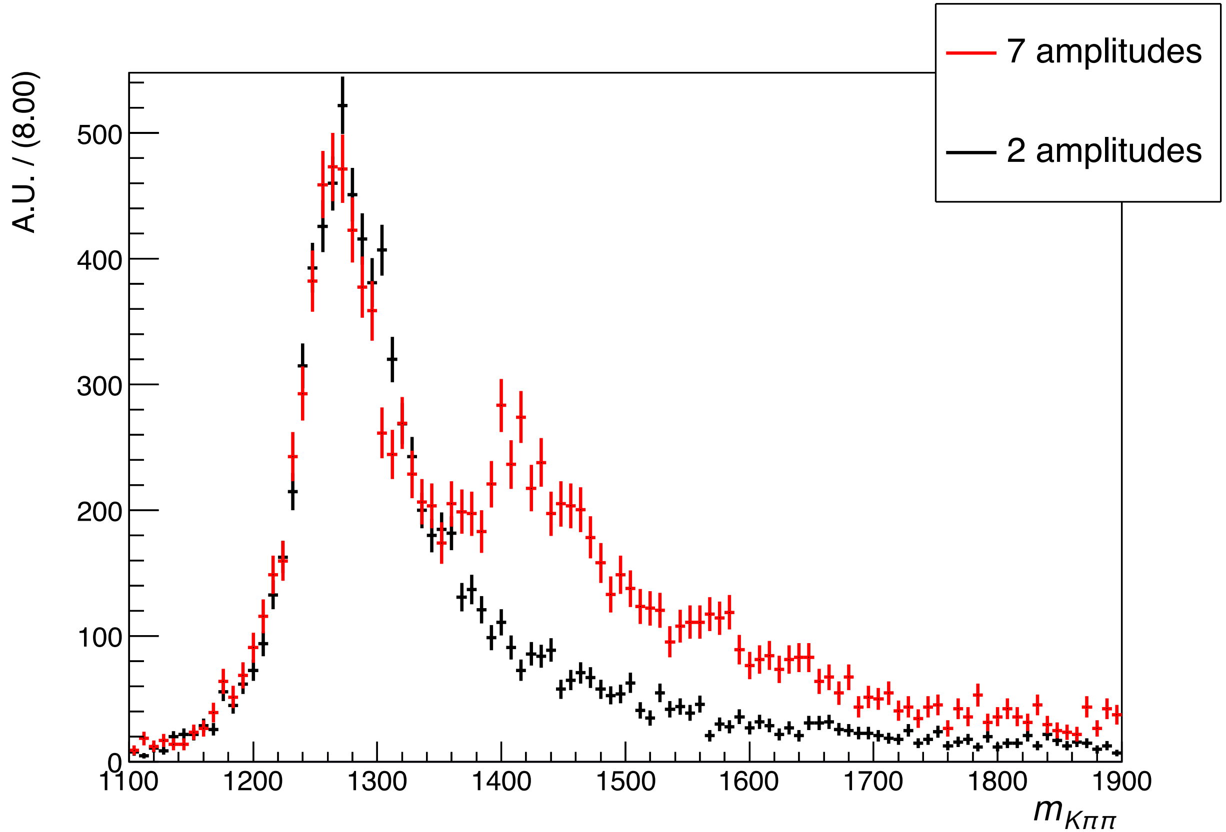
Uncertainty on λ_γ ~0.06



Generating a realistic $K\pi\pi\gamma$ system

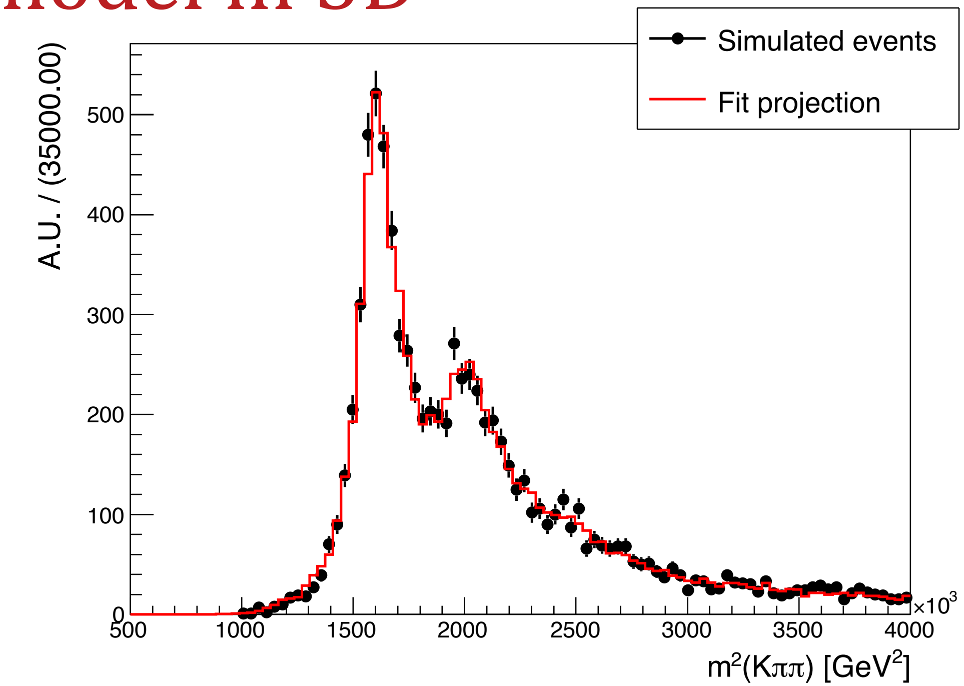
- Using our knowledge of the Kππ system, we can generate more realistic simulated samples

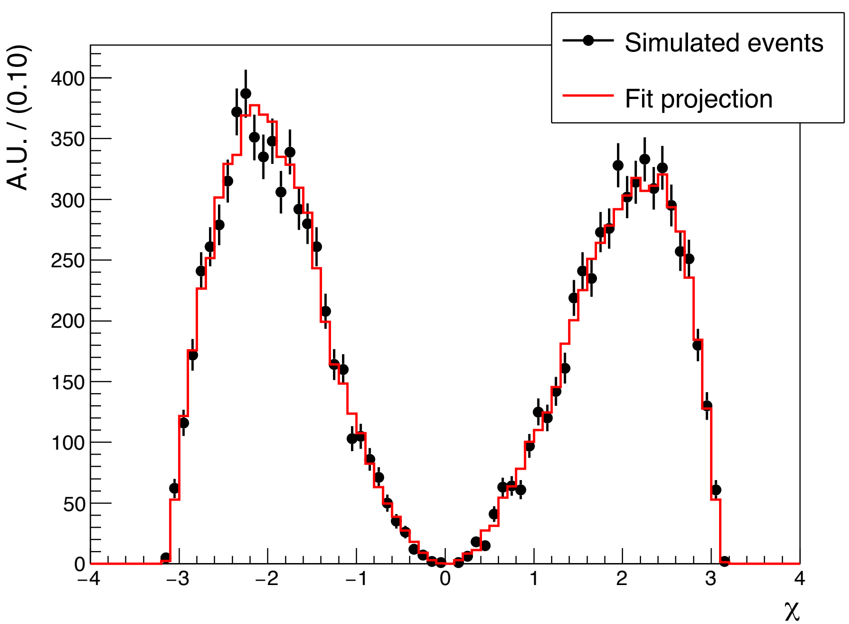
7 amplitudes:
- $K(1270) \to K^{*}\pi$
- $K(1270) \to K\rho$
- $K(1400) \to K^{*}\pi$ } 1^{+}
- $K(1410) \to K^{*}\pi$ } 1^{-}
- $K_2(1430) \to K^{*}\pi$
- $K_2(1430) \to K\rho$ } 2^{+}
- $K_2(1580) \to K^{*}\pi$ } 2^{-}

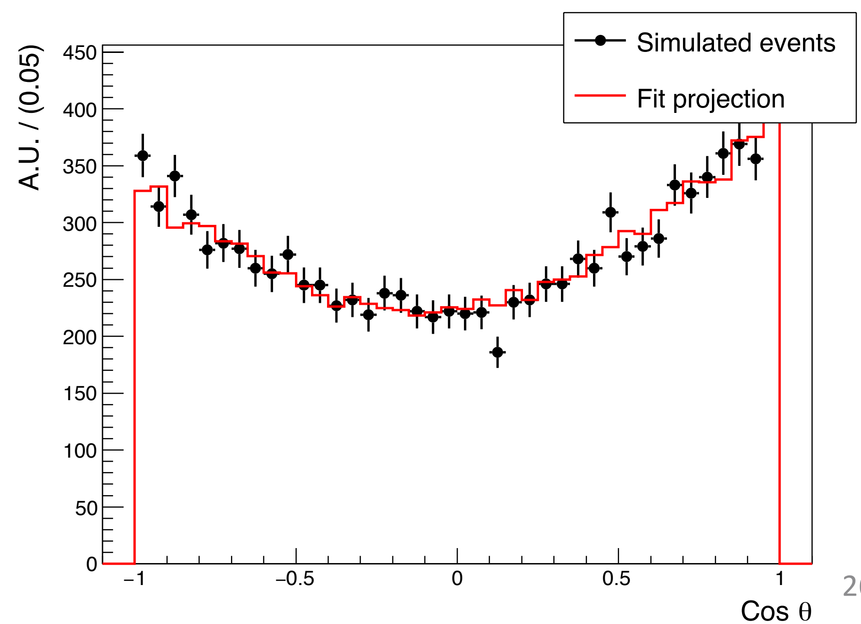


Fitting a realistic model in 5D

- Generate samples of pure signal with 7 amplitudes and $\lambda_\gamma = 1$, fit with 13 free parameters
- Uncertainty on $\lambda_\gamma \sim 0.03$ from toy studies (no background)







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**

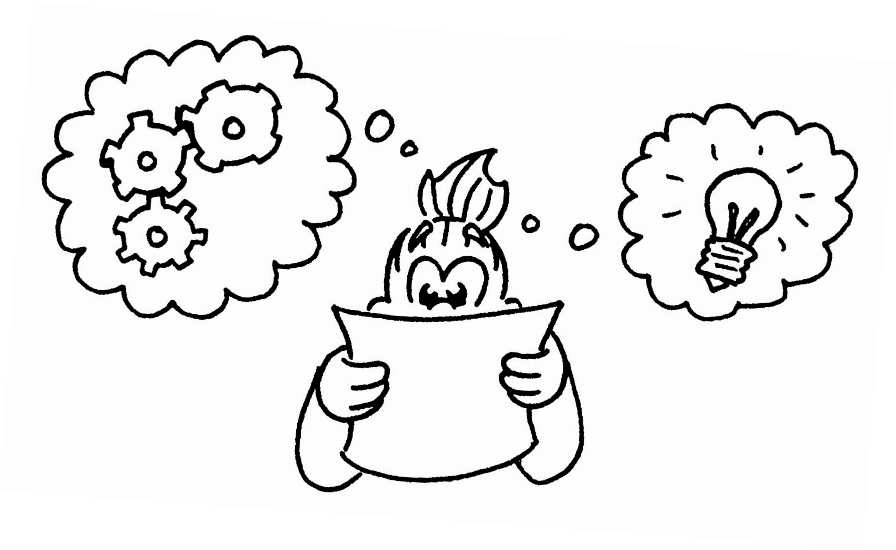
- The **knowledge of the $K\pi\pi$ system** has been dramatically improved thanks to the 3D fit

- Toy studies have shown that λ_γ **can be accessed by performing a 5D fit of the $B \to K\pi\pi\gamma$ decays**, and that the sensitivity does not depend much on the configuration of the $K\pi\pi$ system

- **Realistic models** of the $K\pi\pi$ system can be generated and fitted

- Nexts steps:
  - **Include backgrounds**
  - **Fit data** from LHCb Run1 and 2

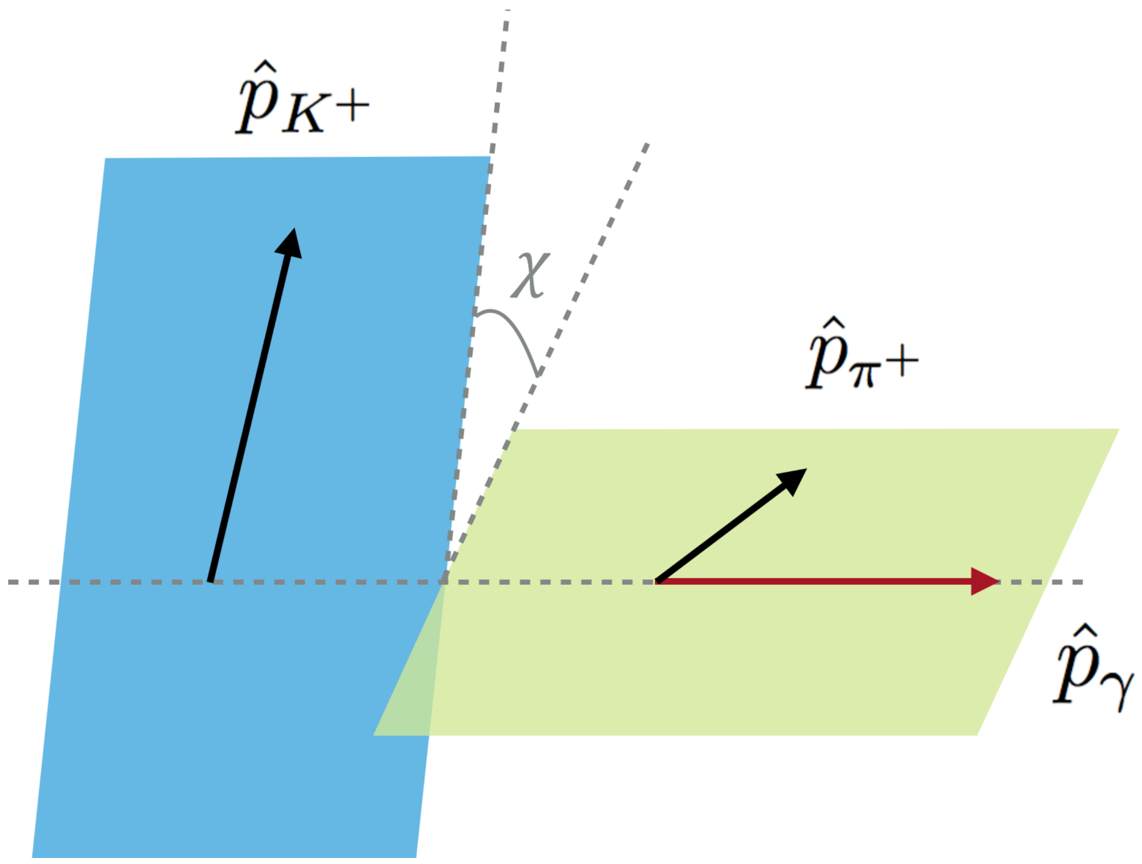
Thanks for your attention



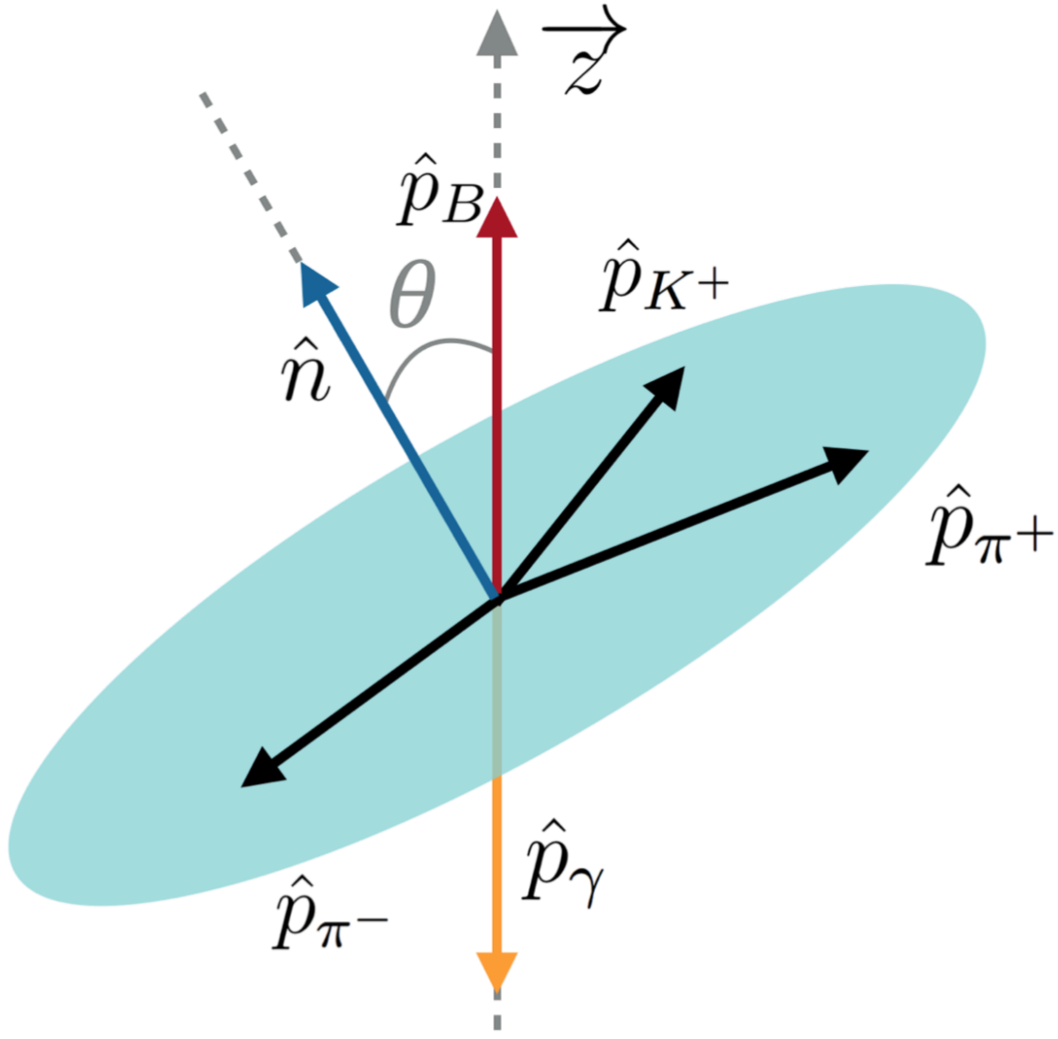
DEFINITION OF THE χ VARIABLE

$$\sin\chi = [(\hat{p}_\gamma \times \hat{p}_{\pi^+}) \times (\hat{p}_\gamma \times \hat{p}_{K^+})] \cdot (\hat{p}_\gamma + \hat{p}_{K^+})$$

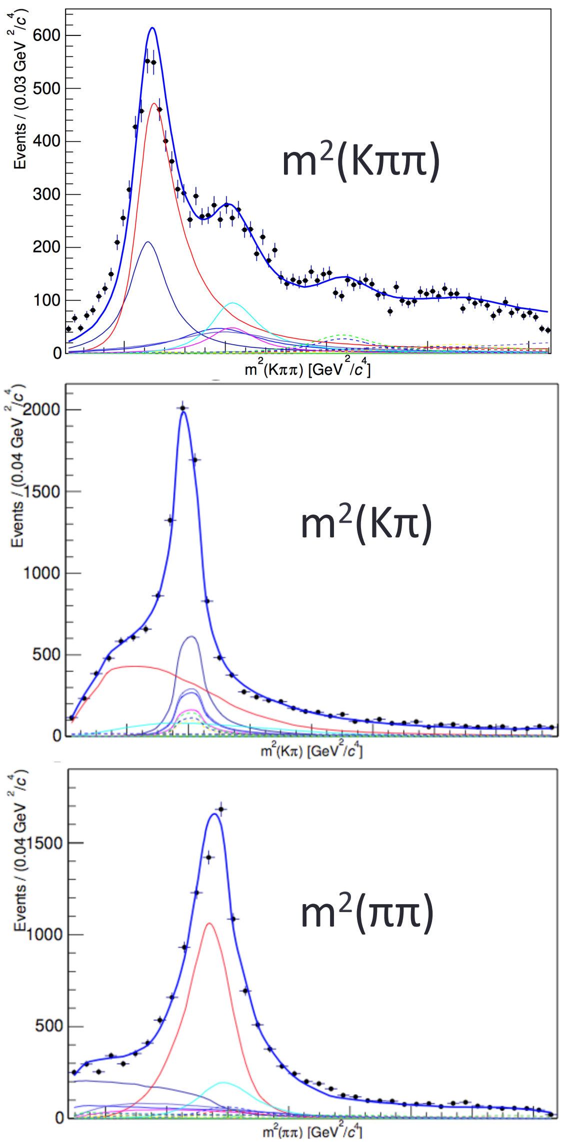
$$\cos\chi = (\hat{p}_\gamma \times \hat{p}_{\pi^+}) \cdot (\hat{p}_\gamma \times \hat{p}_{K^+})$$



DEFINITION OF THE COSθ VARIABLE



Amplitude analysis of the Kππ system

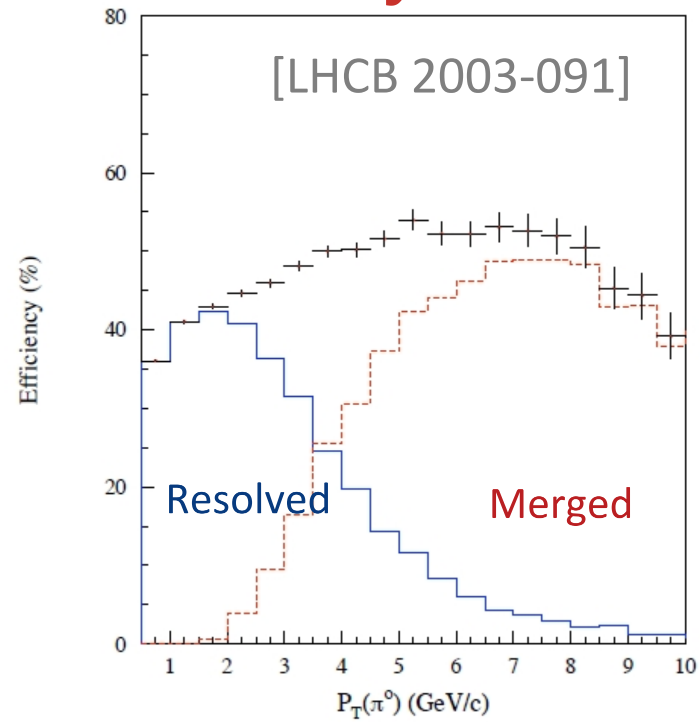


[CERN-THESIS-2015-287]

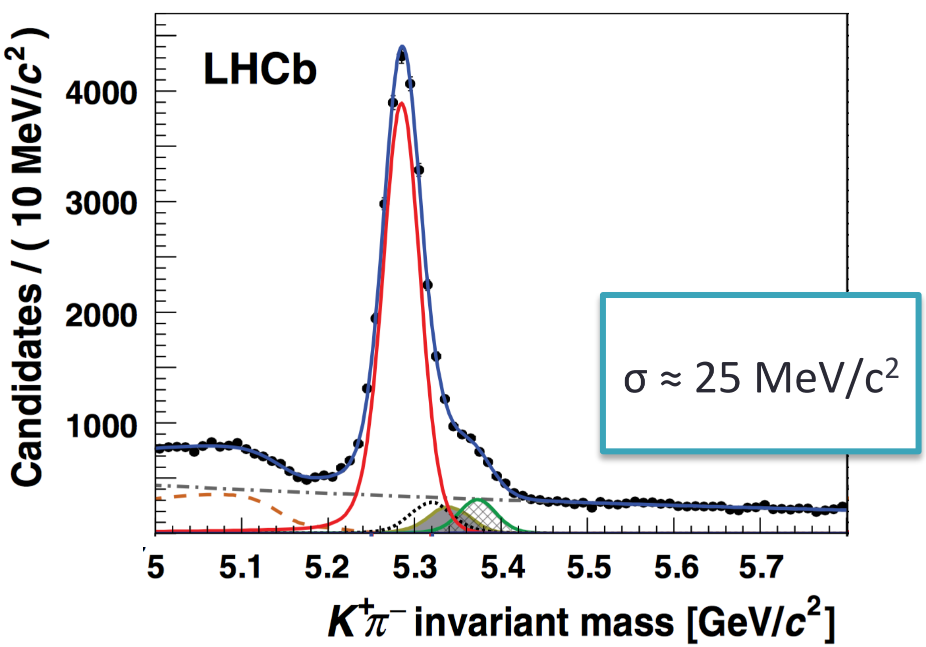
	Decay channel k	Modulus	Phase [rad]	FF_k (10^{-2})
1^+	$K_1(1270)^+ \to K^*(892)^0\pi^+$	1 (fixed)	0 (fixed)	16.8 ± 0.9
	$K_1(1270)^+ \to K^+\rho(770)$	1.747 ± 0.049	-0.91 ± 0.028	$39.9\,^{+0.6}_{-0.7}$
	$K_1(1270)^+ \to K^+\omega(782)$	0.302 ± 0.085	0.302 ± 0.27	$0.068\,^{+0.028}_{-0.180}$
	$K_1(1270)^+ \to K^*(1430)^0\pi^+$	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

Main challenges for radiative decays

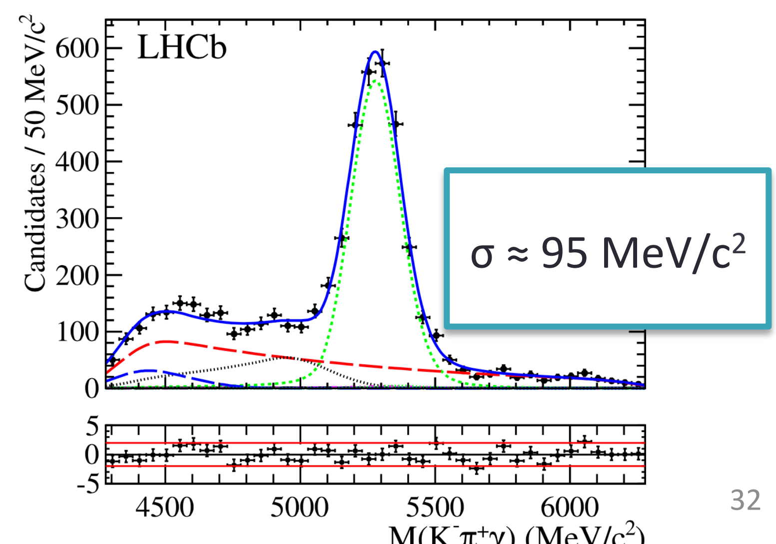
- High level of **background in pp collisions**
- For energies above 4 GeV the two clusters from $\boldsymbol{\pi^0 \rightarrow \gamma\gamma}$ are reconstructed as a single cluster in the calorimeter
- Mass **resolution dominated by photon** reconstruction



[PRL 110 (2013) 221601]



[Nucl. Phys. B 867 (2012)]



Adding resonances is not so simple

➢ A 7-amplitude model reproduces well the data between 1200 and 1600 MeV