Photon polarisation in radiative b-hadron decays at LHCb

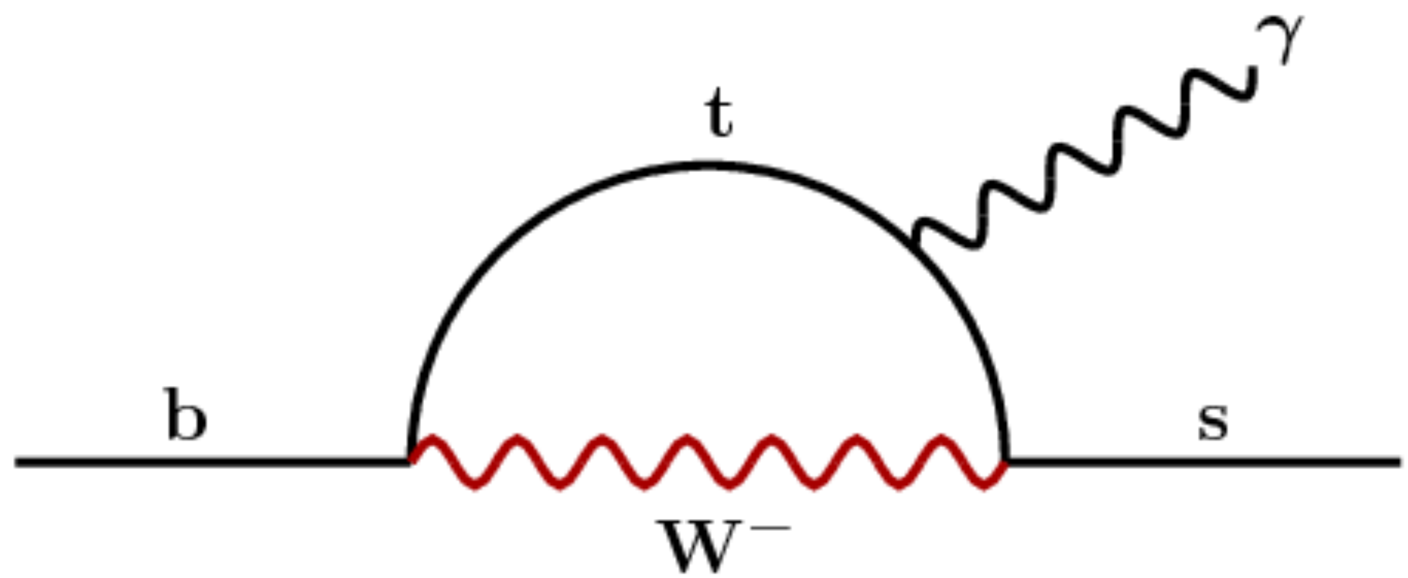
Violaine Bellée

SPS Annual Meeting

28–31 August 2018

Flavour-changing neutral current (FCNC) with a final-state photon

The b→sγ transition occurs through a penguin loop



Exclusive decays difficult from a theoretical point of view due to **form factors**

Sensitive to NP but need observables independent from form factors:

- CP and isospin asymmetries
- **Photon polarisation**

The effective hamiltonian for $b \to s\gamma$ transitions is proportional to:

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} (C_7 O_7 + C_7' O_7')$$

arXiv:1206.1502

Coupling to left-handed photon

Coupling to right-handed photon

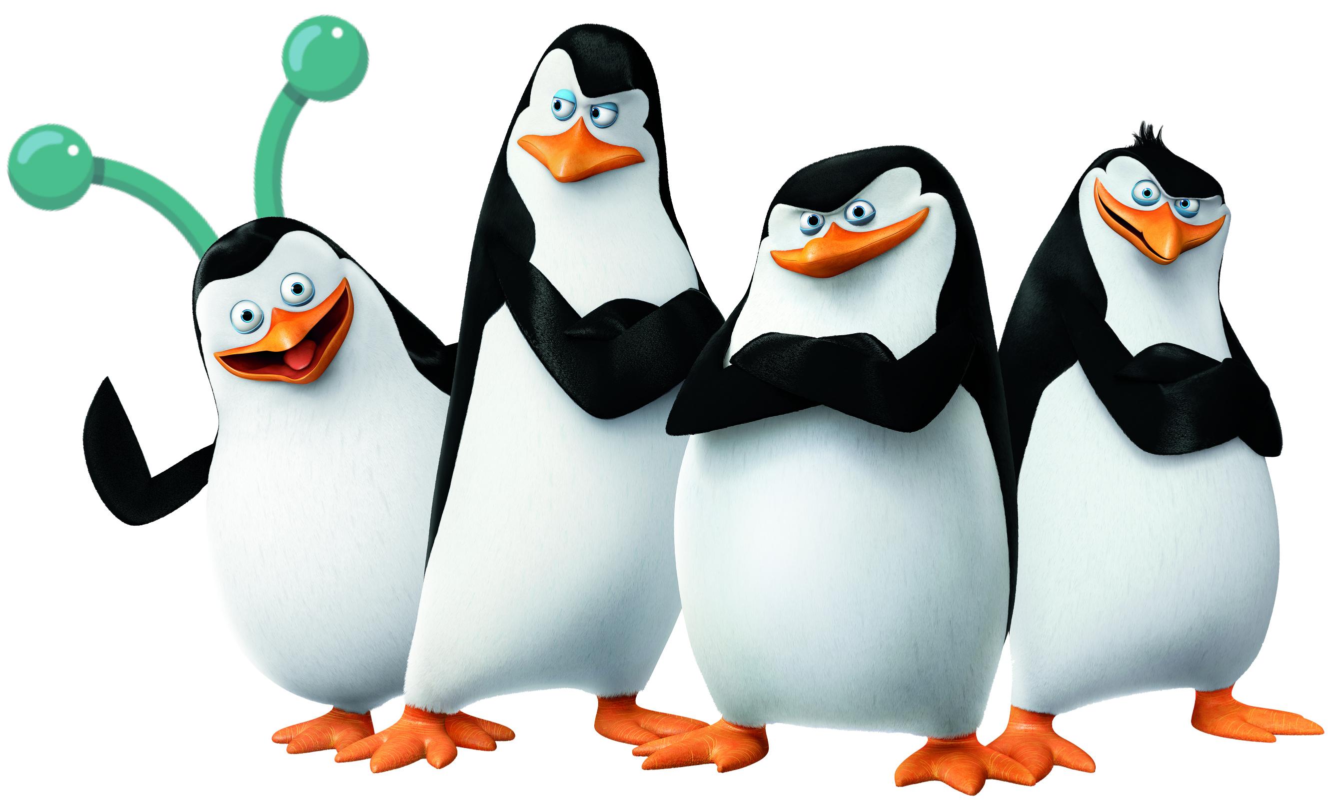
In SM, the Wilson coefficients C_7 and C_7' are such that

$C_7'/C_7 \simeq m_s/m_b \simeq 0.02$

The photon is mostly left-handed!

NP processes could introduce **right-handed currents**, hence modifying the value of C_7 and C_7'

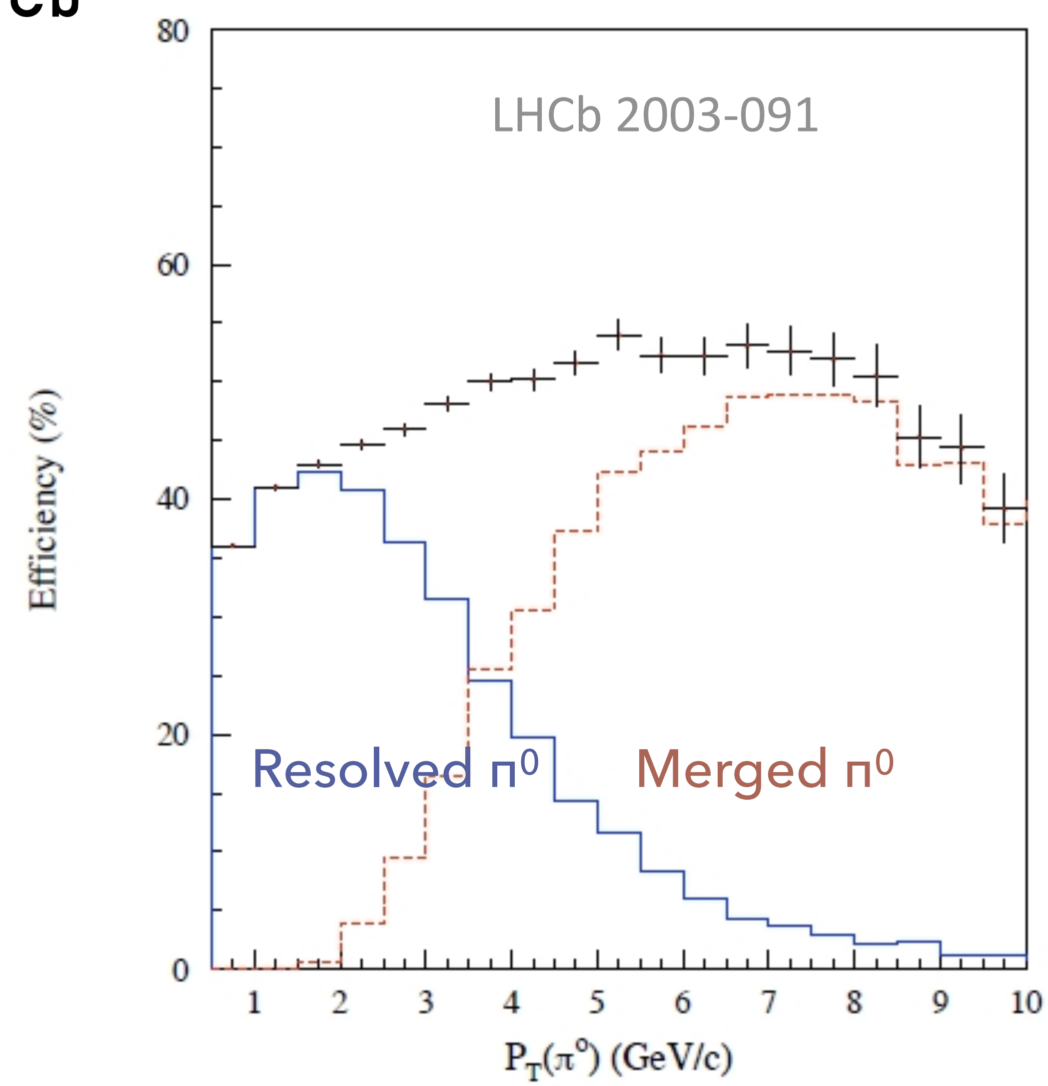
Maybe some **new penguins** around!



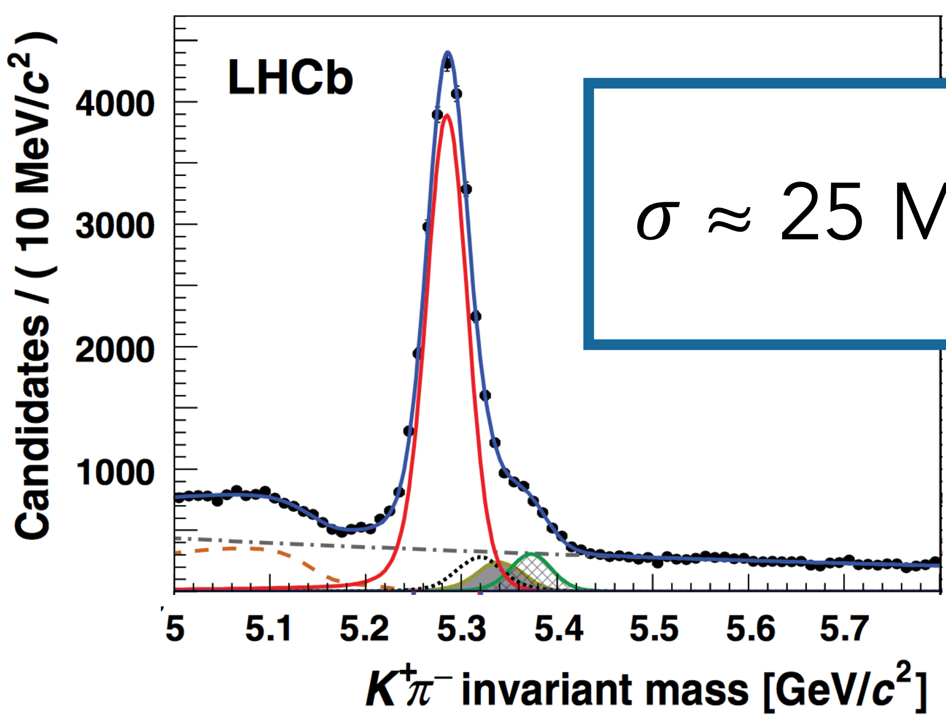
High level of background in pp collisions

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

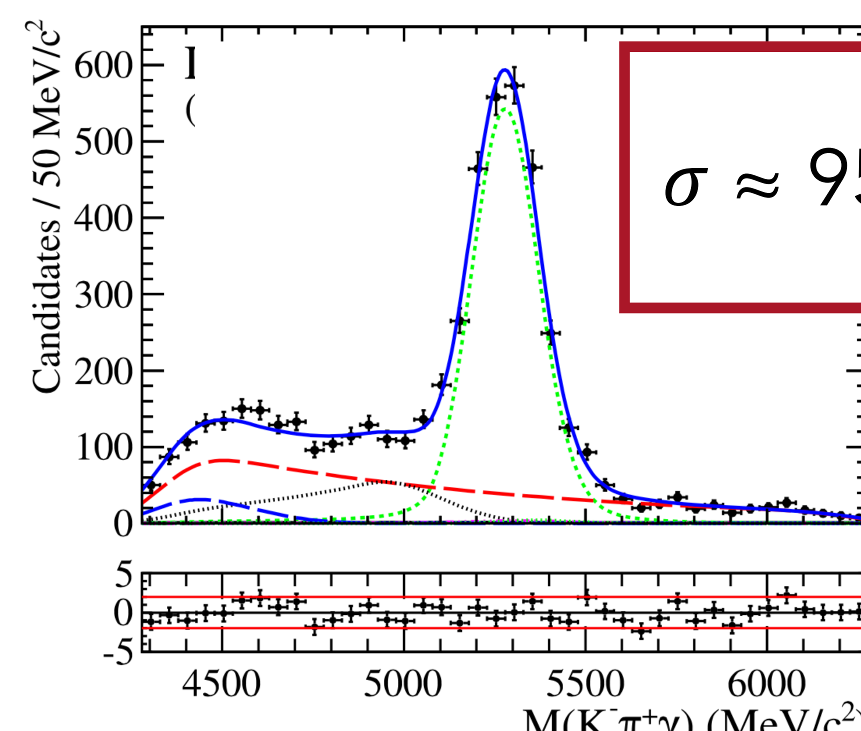


PRL 110 (2013) 221601



$\sigma \approx 25$ MeV/c^2

Nucl. Phys. B 867 (2012)



$\sigma \approx 95$ MeV/c2

Angular distributions in $\Lambda_b \to \Lambda\gamma$ decays

Time-dependent analysis of $B_s \to \phi\gamma$ decays

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

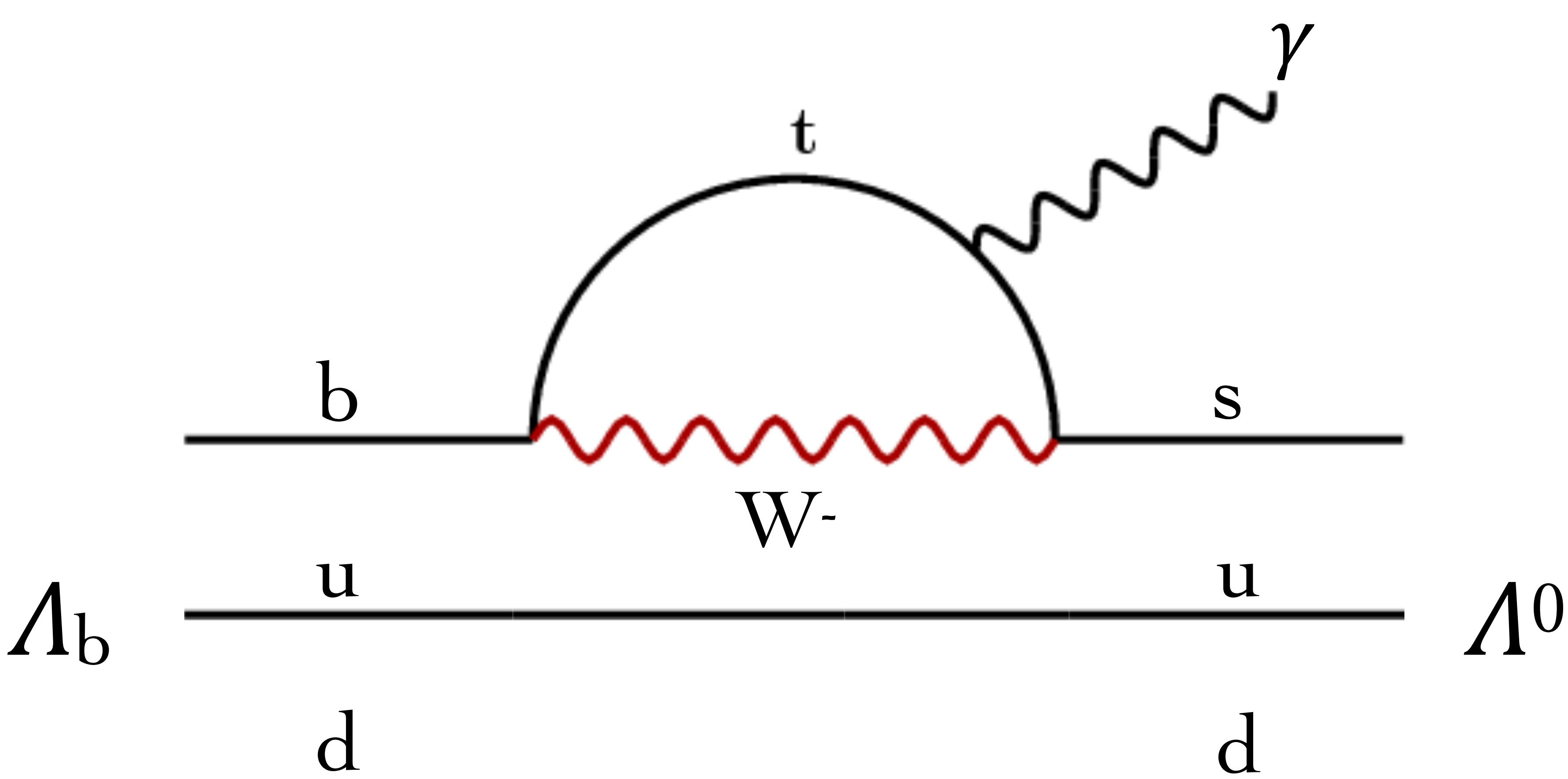
Angular distributions in $\Lambda_b \to \Lambda\gamma$ decays

Baryonic $b \to s\gamma$ transition

Not yet observed!

Expected BR: $(0.06\text{-}1)\times10^{-5}$ [arXiv:1705.07741]

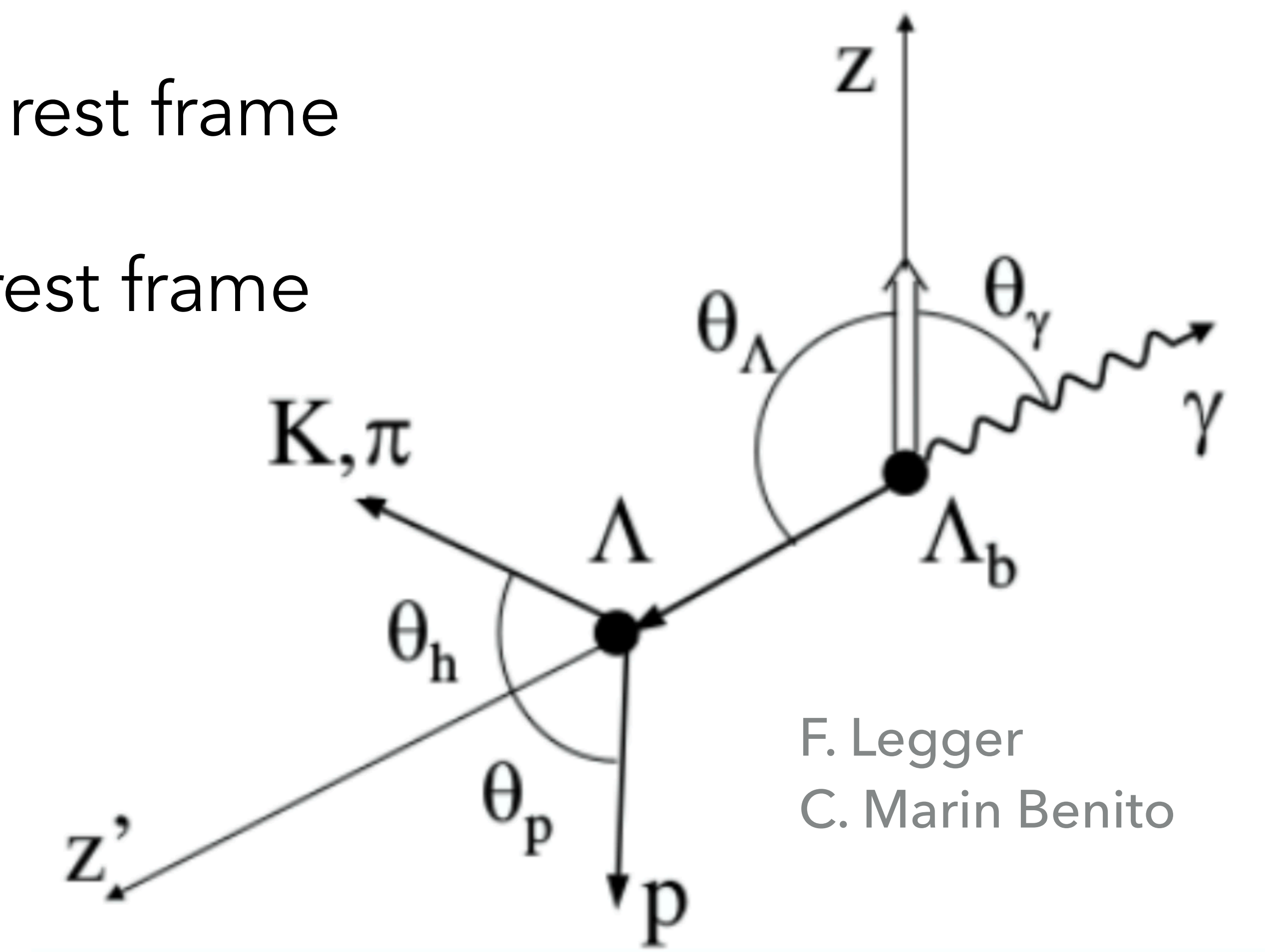
- **Can be reached at LHCb**



Angular distributions in $\Lambda_b \to \Lambda^{(*)}\gamma$ decays

Exploit the angular distributions in $\Lambda_b \to \Lambda^{(*)}(\to ph)\gamma$ decays:

- Angles θ_γ and θ_Λ defined in the Λ_b rest frame
- Angles θ_h and θ_p defined in the Λ rest frame



F. Legger
C. Marin Benito

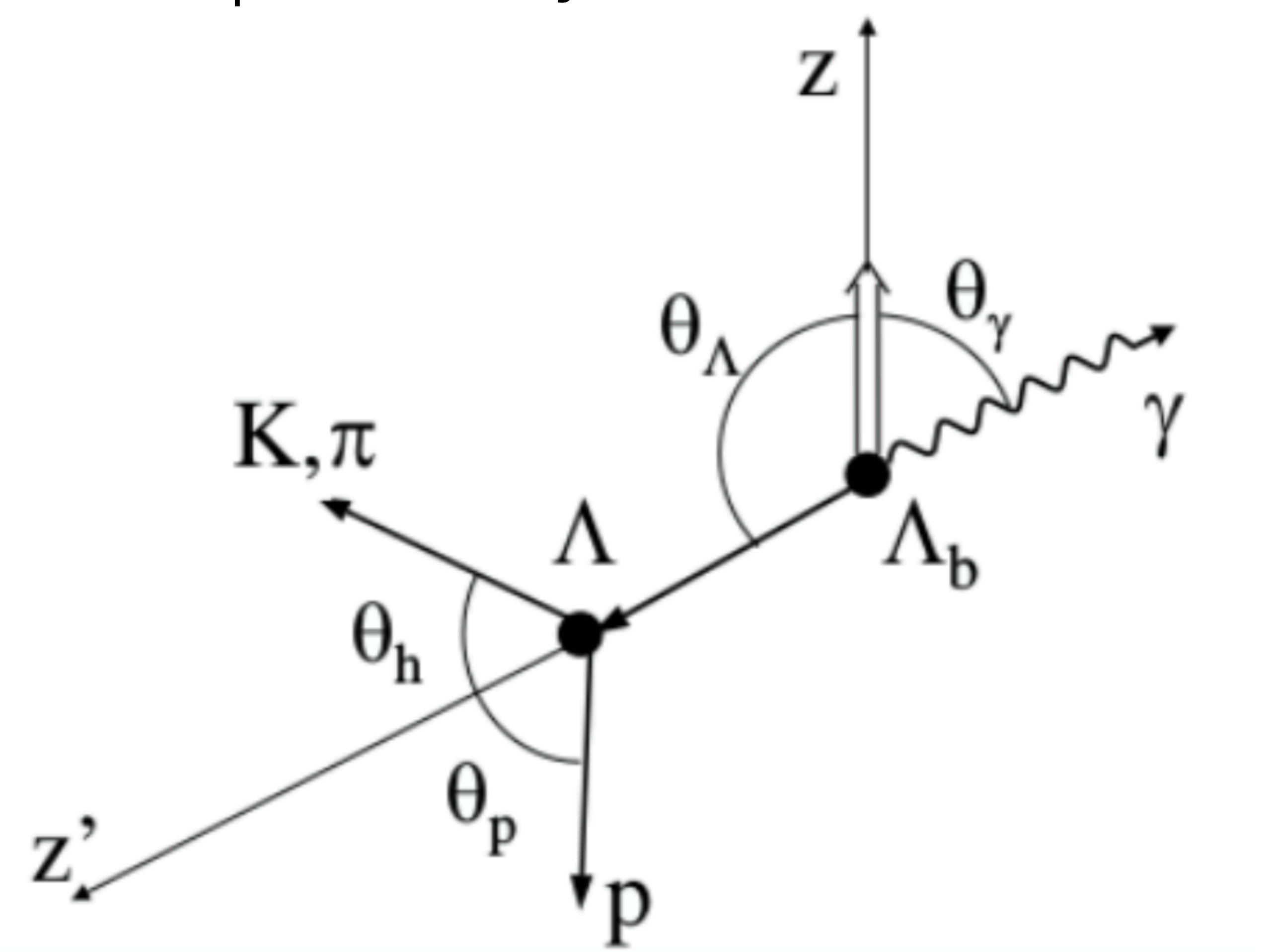
Angular distributions in $\Lambda_b \to \Lambda^{(*)}\gamma$ decays

Exploit the angular distributions in $\Lambda_b \to \Lambda^{(*)}(\to ph)\gamma$ decays:

Dependence on **C_7 and $C_{7'}$**

$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b^0} \cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} \cos\theta_p$$



Angular distributions in $\Lambda_b \to \Lambda^{(*)}\gamma$ decays

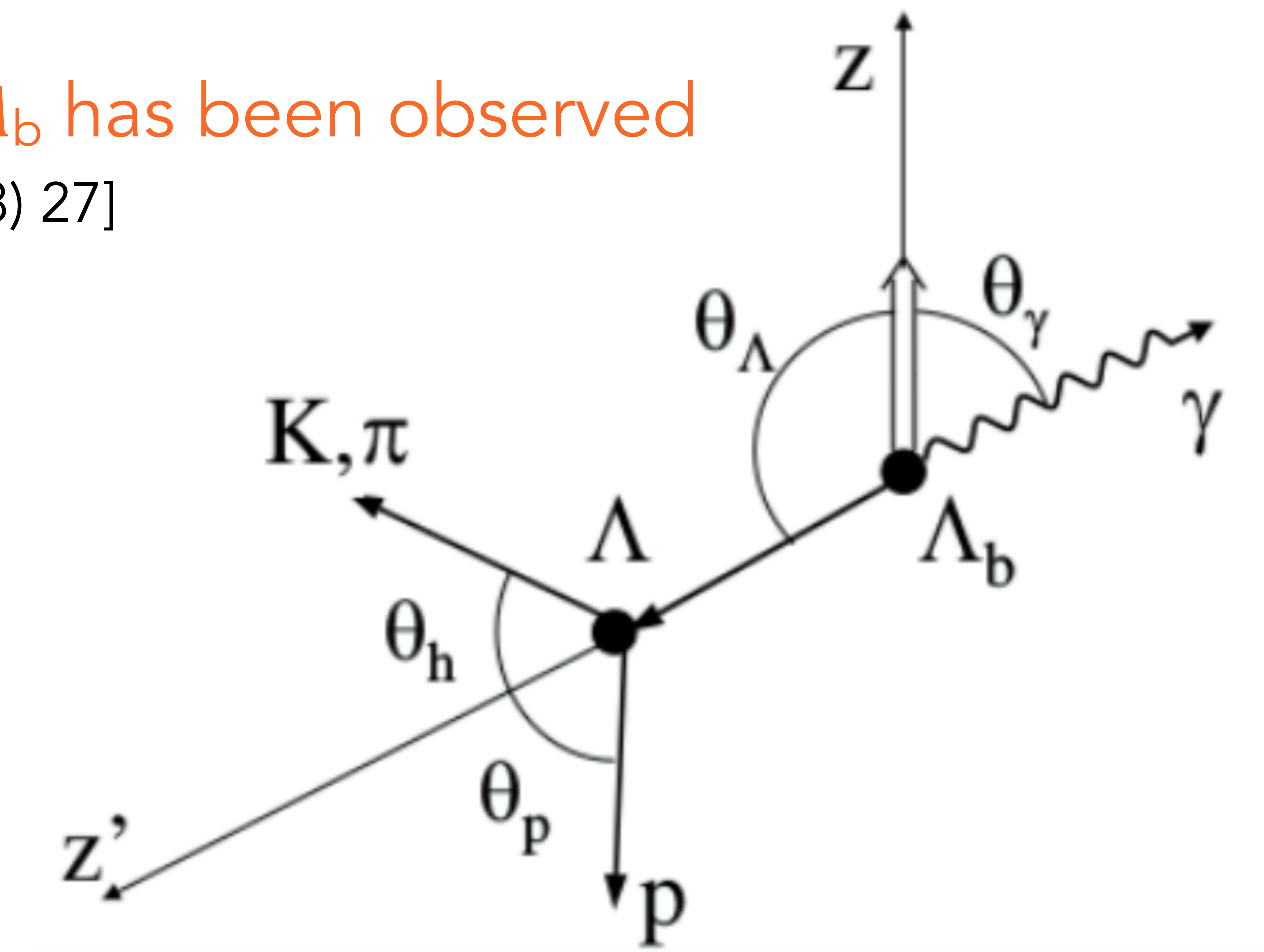
Challenges:

1) No significant **polarisation** of the Λ_b has been observed

Measured to be 0.06±0.07 [Phys. Lett. B724 (2013) 27]

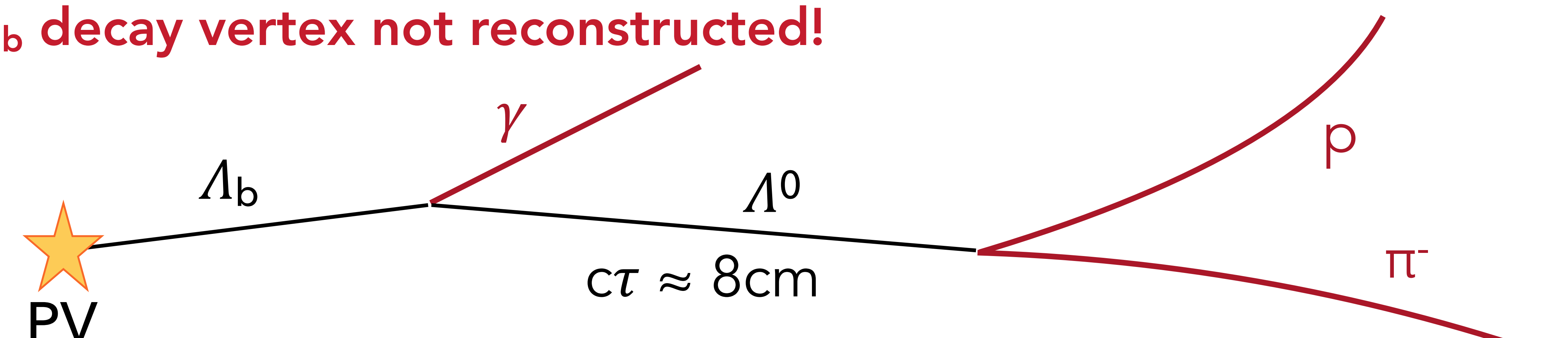
$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b^0} \cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} \cos\theta_p$$



2) **Proton asymmetry** expected to be **0** for $\Lambda^* \to pK$ (experimentally easier) so use $\Lambda \to p\pi$

3) Λ_b **decay vertex not reconstructed!**

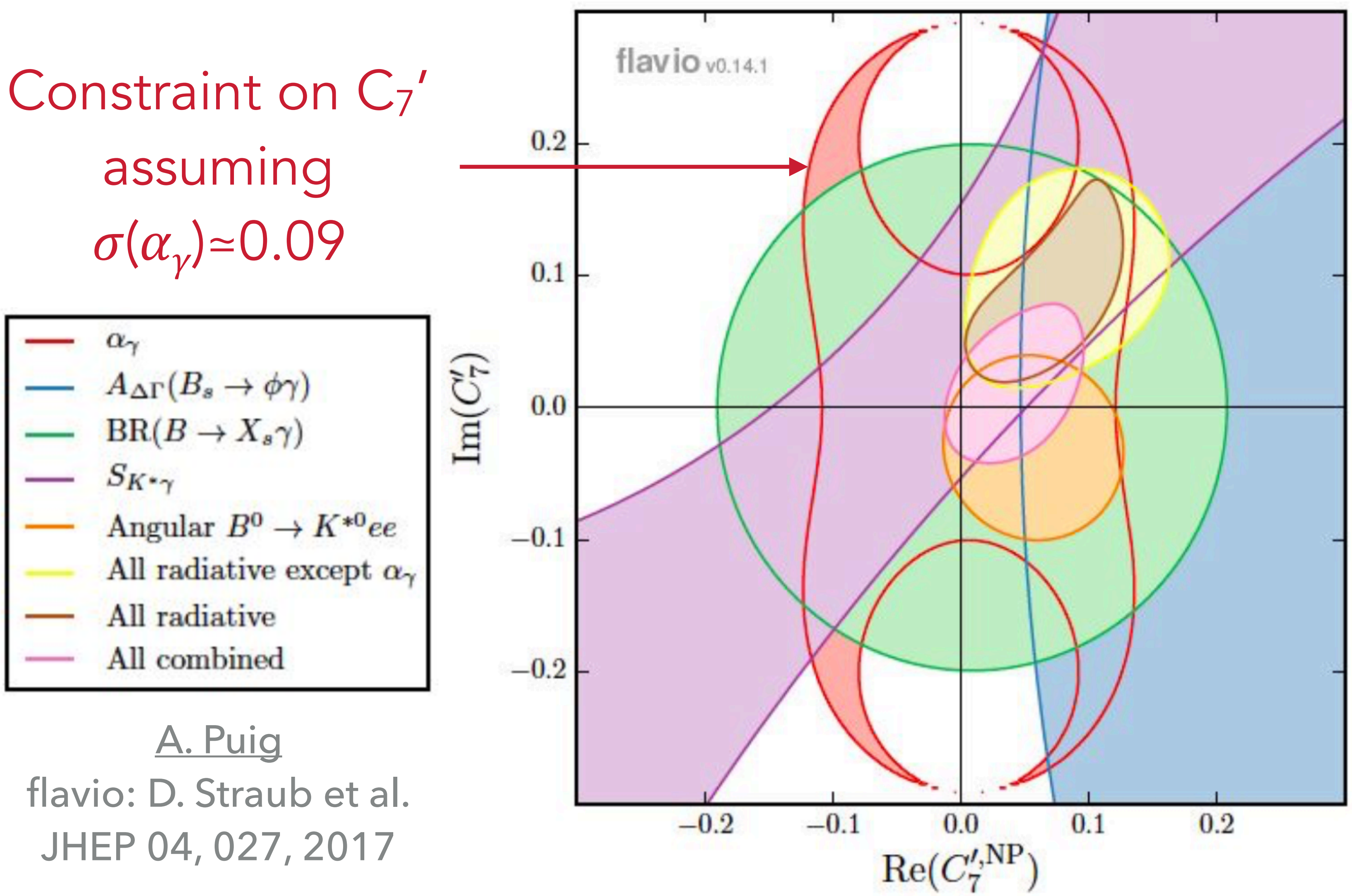


Angular distributions in $\Lambda_b \to \Lambda\gamma$ decays

Status:

- Search for $\Lambda_b \to \Lambda$ ($\to p\pi$) γ ongoing using LHCb 2016 data (1.7 fb^{-1})
- Plans to include full Run 2 data sample and perform angular analysis

Constraint on C_7' assuming $\sigma(\alpha_\gamma) \simeq 0.09$



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

Sensitivity of a fit to the $\cos\theta_p$ distribution estimated using samples with 1000 events (including resolution and acceptance effects)

Time dependent analysis of $B_s \to \phi\gamma$ decays

Time-dependent decay rates for $B_s \to \phi\gamma$ and $\bar{B}_s \to \phi\gamma$:

Phys. Lett. B664 (2008) 174

$$\Gamma_{B_s^0 \to \phi\gamma}(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}^{\Delta}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos\left(\Delta m_s t\right) - S\sin\left(\Delta m_s t\right)\right]$$

$$\Gamma_{\bar{B}_s^0 \to \phi\gamma}(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}^{\Delta}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C\cos\left(\Delta m_s t\right) + S\sin\left(\Delta m_s t\right)\right]$$

Depend on C_7 and C_7'

With:

- C: the direct *CP* asymmetry
- S: the asymmetry associated with B_s^0 - $\overline{B}_s^0$ mixing
- $\Delta\Gamma_s$ and Δm_s, the decay width and mass differences between the B_s^0 *CP* eigenstates

Untagged time dependent analysis of $B_s \to \phi\gamma$ decays

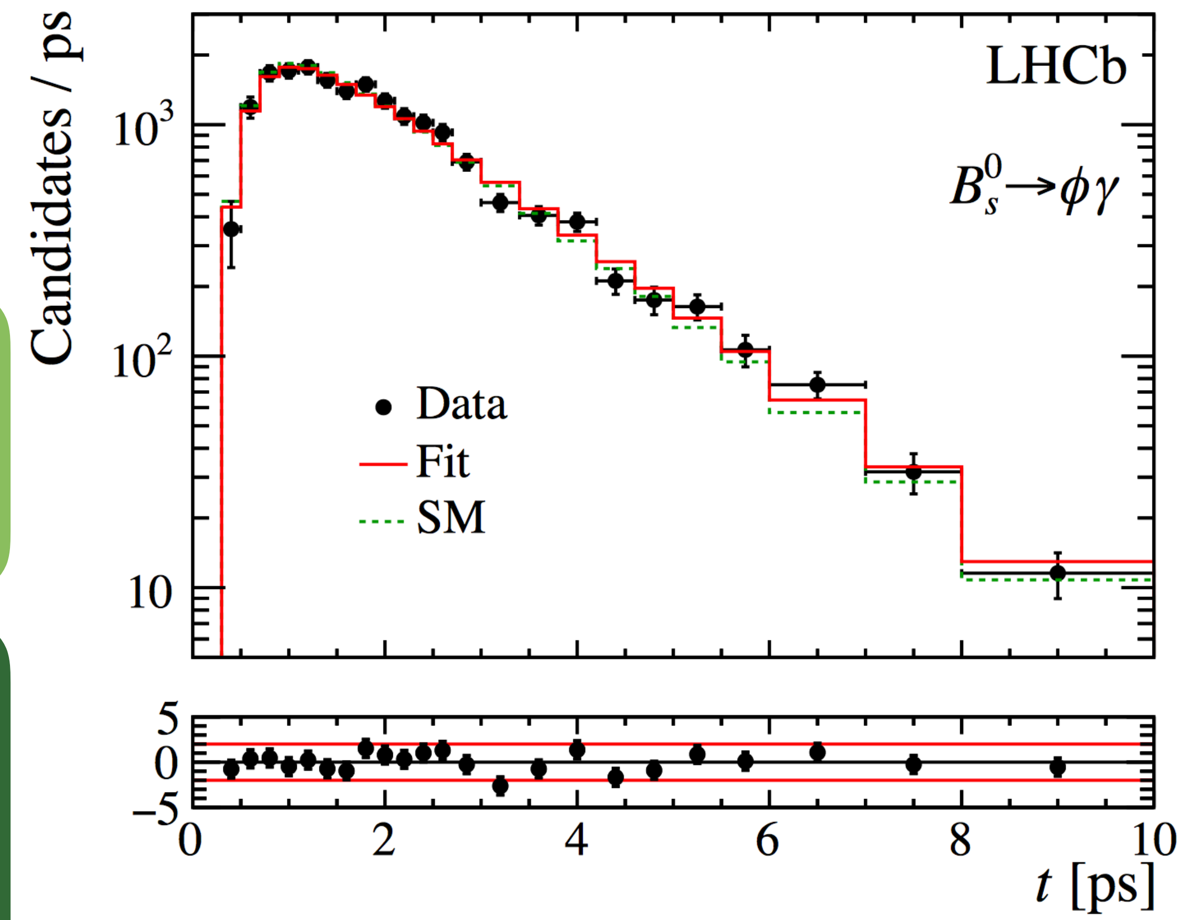
Separating B_s from B_s (flavour-tagging) is very challenging at LHCb!

1) Time-dependent untagged decay rate:

$$\Gamma(t) \propto e^{-\Gamma_{(s)}t}[\cosh(\frac{\Delta\Gamma_{(s)}}{2}t) - A^{\Delta}\sinh(\frac{\Delta\Gamma_{(s)}}{2}t)]$$

Phys. Lett. B664 (2008) 174

Phys. Rev. Lett. 118 (2017), 021801



Measurement using LHCb Run1 data

$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$$

Phys. Rev. Lett. 118 (2017), 021801

In agreement with SM

$$\mathcal{A}^{\Delta}_{\rm SM} = 0.047\,^{+0.029}_{-0.025}$$

Phys. Lett. B664 (2008) 174

2) Tagged analysis using LHCb Run1 data (3fb^{-1}) (ongoing)

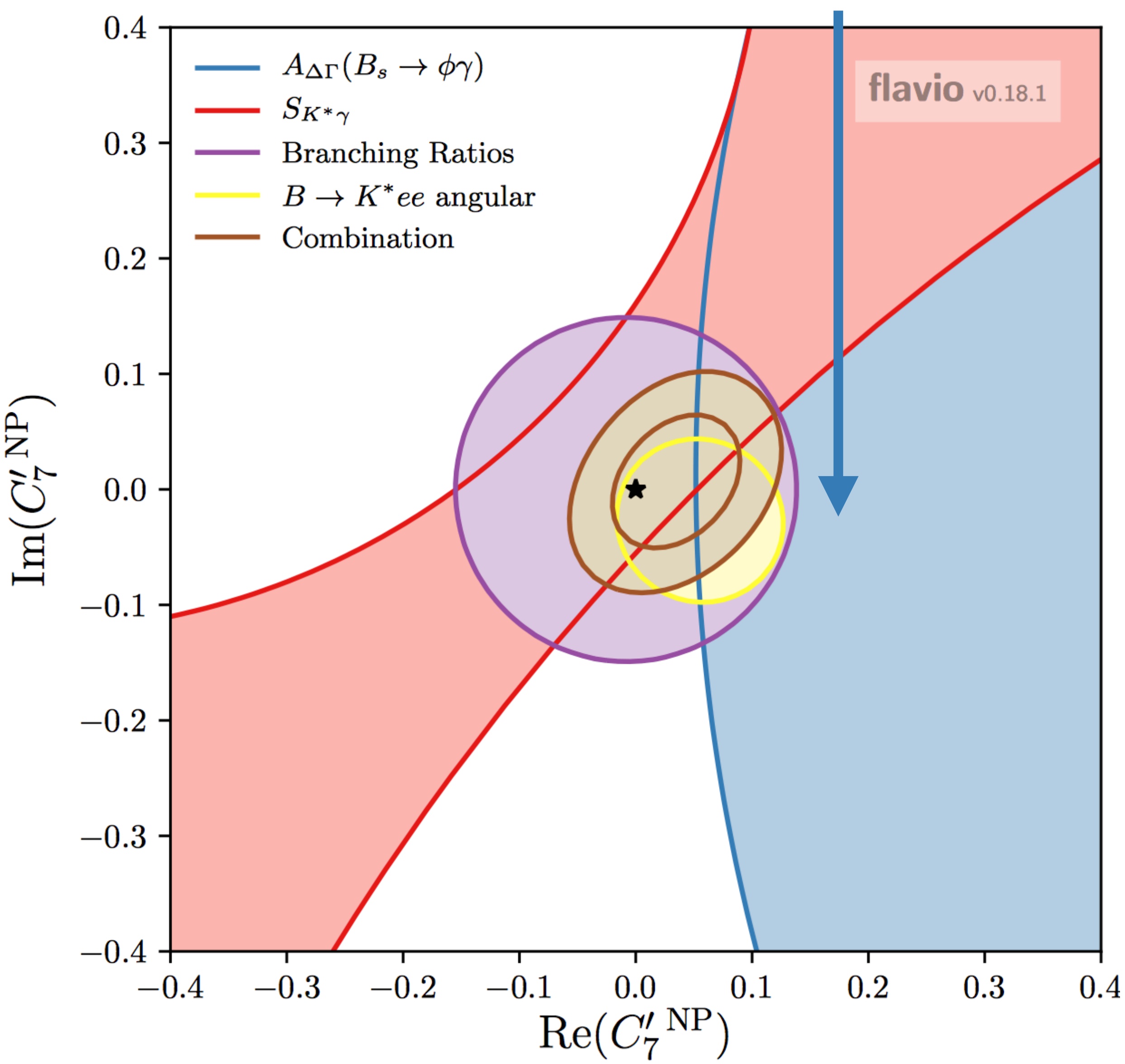
Additional challenge: Flavour-tagging is used for the first time in a radiative decay at LHCb (expect a tagging power ~4%)

Tagged time-dependent analysis of $B_s \to \phi\gamma$ decays

Sizeable improvements on the constraints on C_7 and C_7'

Already achieved

Untagged analysis (LHCb Run 1 data)

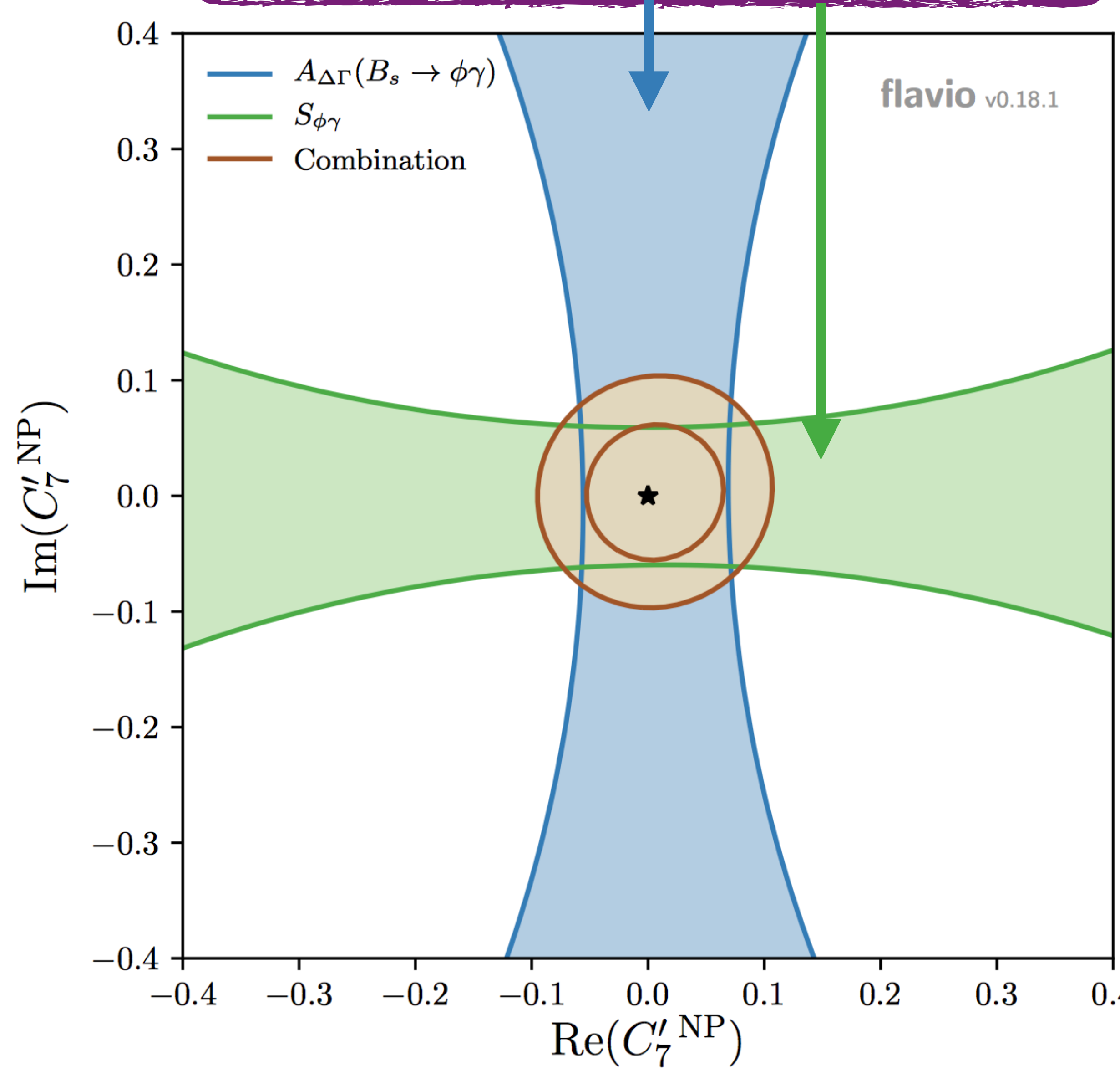


LHCC 2017 poster - C. Sánchez Mayordomo

Expectations

Tagged analysis (LHCb Run 2 data)

Assuming $\sigma(A^{\Delta}) \simeq \sigma(S) \simeq 0.2$



flavio: D.Straub et al.

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

Differential decay rate of $B^+ \to K^+\pi^-\pi^+\gamma$ decays:

Photon polarisation parameter

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

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

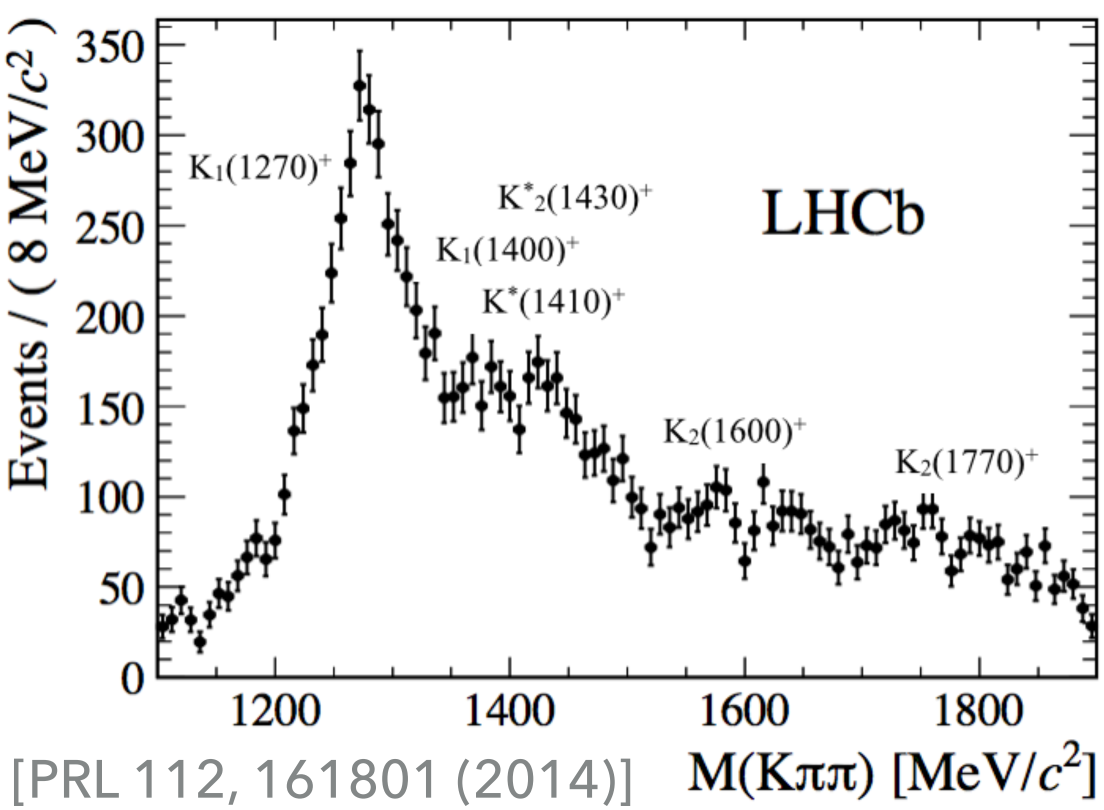
Amplitude associated with a right-handed photon

Amplitude associated with a left-handed photon

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

Differential decay rate of $B^+ \to K^+\pi^-\pi^+\gamma$ decays:

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



[PRL 112, 161801 (2014)]

Many kaonic resonances involved:

- Interferences give access to the photon polarisation parameter
- Complexity of the modelling of $\mathcal{M}_{\mathrm{R}}$ and $\mathcal{M}_{\mathrm{L}}$

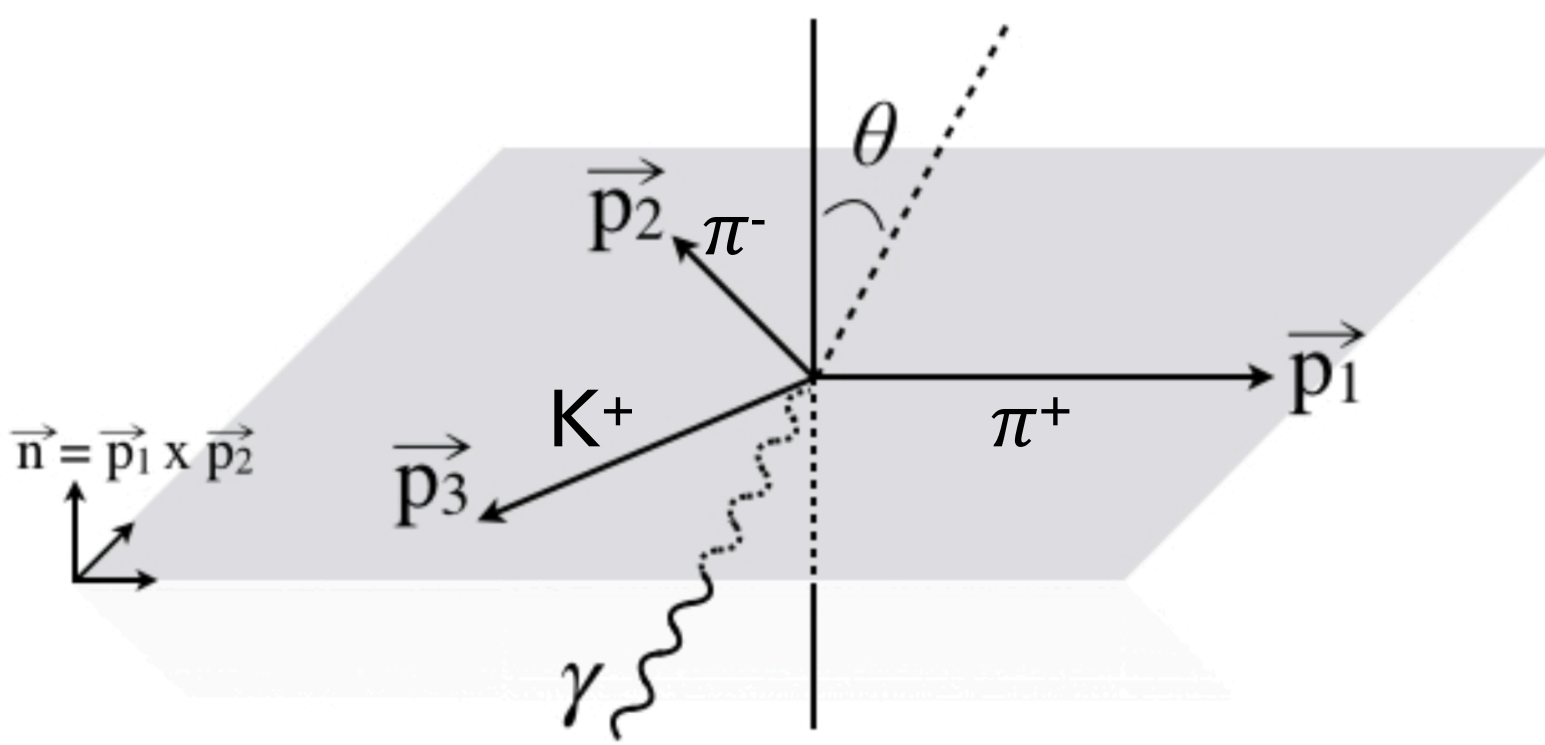
Up-down asymmetry in $B^+ \to K^+\pi^-\pi^+\gamma$ decays

First step: A simplified way to use $B^+ \to K^+\pi^-\pi^+\gamma$ decays

Measuring the **up-down asymmetry** (asymmetry between the number of photons emitted on one side and on the other of the $K\pi\pi$ decay plane), which is predicted to be **proportional** to λ_γ

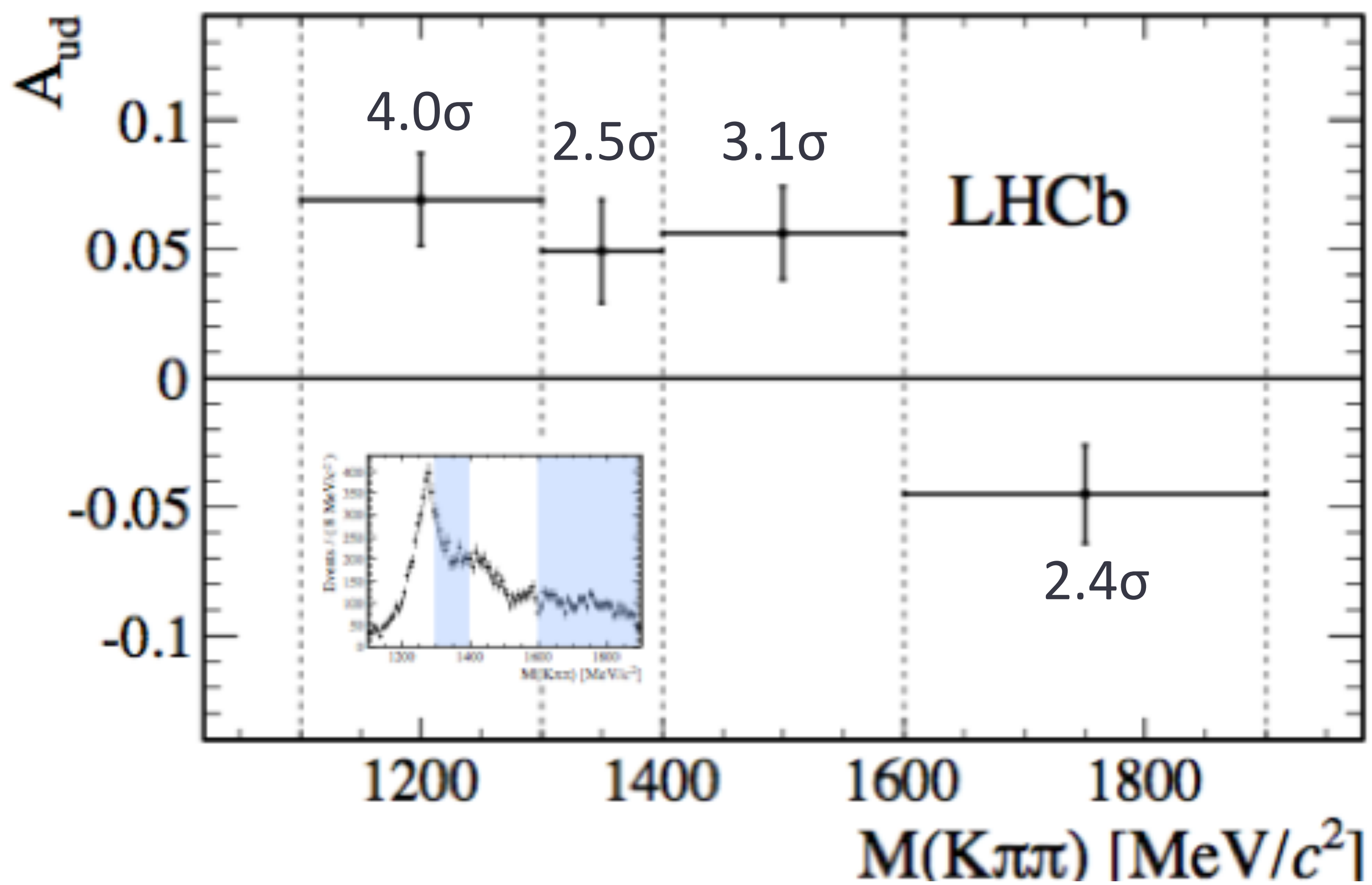
$$\mathcal{A}_{\rm ud} \equiv \frac{\int_0^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} - \int_{-1}^0 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}}{\int_{-1}^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}} = C\lambda_\gamma$$

where C depends on the content of the $K\pi\pi$ system



Up-down asymmetry in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ decays

Using 14,000 signal events reconstructed and selected in LHCb Run 1 data sample ($3fb^{-1}$), the up-down asymmetry is obtained in bins of M(Kππ)



[PRL 112, 161801 (2014)]

- As A_{ud} is proportional to λ_γ:
  Observation of a non-zero photon polarisation with A_{ud} different from 0 at 5.2σ.

- Extraction of value impossible due to unknown resonance content

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

Second step: Amplitude analysis

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

Principle:

1) Writing explicitly the left- and right-handed parts of the decay as a sum of amplitudes of subprocesses

$$\mathcal{M}_{\rm R/L} = \sum_k f_k \mathcal{A}_{k,{\rm R/L}}(X)$$

Complex fraction and amplitude
for the process k

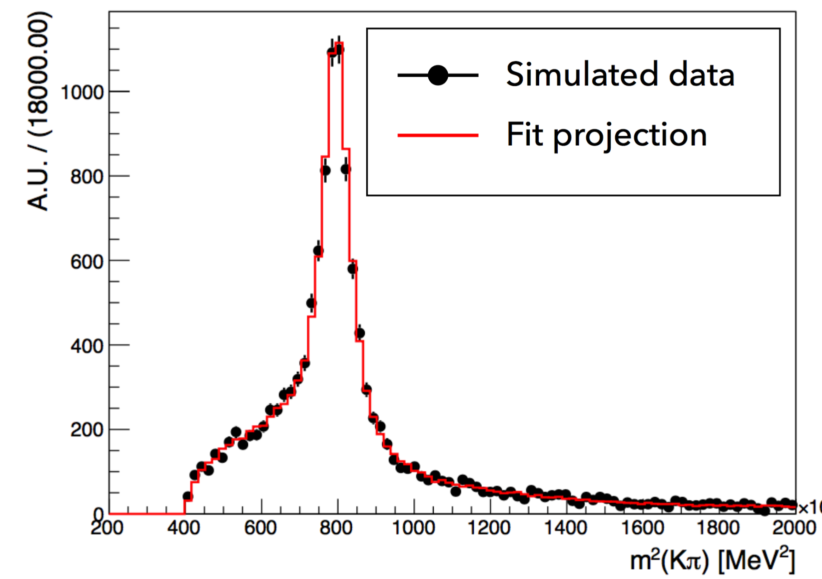
2) Fitting the selected events using **all kinematical variables** of the $B^+ \to K^+\pi^-\pi^+\gamma$ system and leaving as free parameters λ_γ and the complex fractions f_k

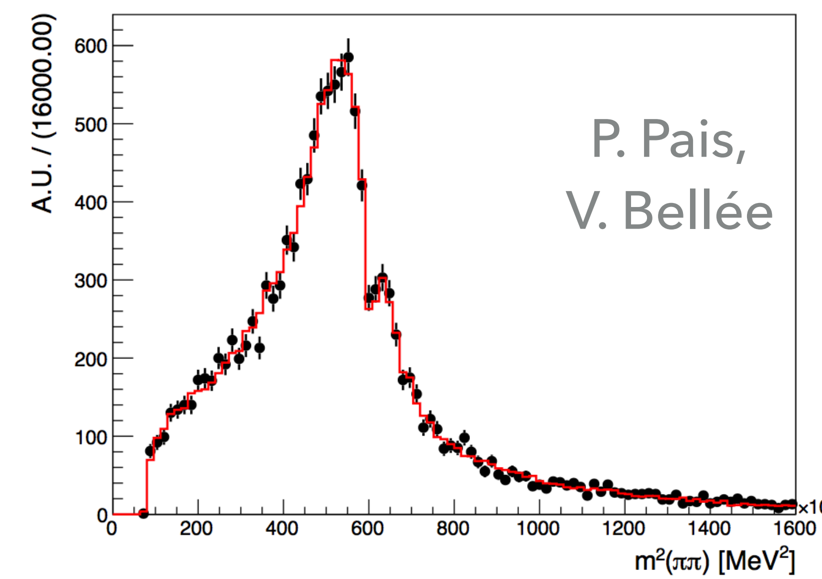
- Three invariant masses: m(Kππ), m(Kπ), m(ππ)
- Two angles that describe the orientation of the Kππ system with respect to the helicity vector of the photon: θ, χ

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

Sensitivity study

Using realistic models (containing up to 15 amplitudes) with 14,000 events
→ Reach **a sensitivity to λ_γ of 0.018** (in an ideal background-free case)





P. Pais,
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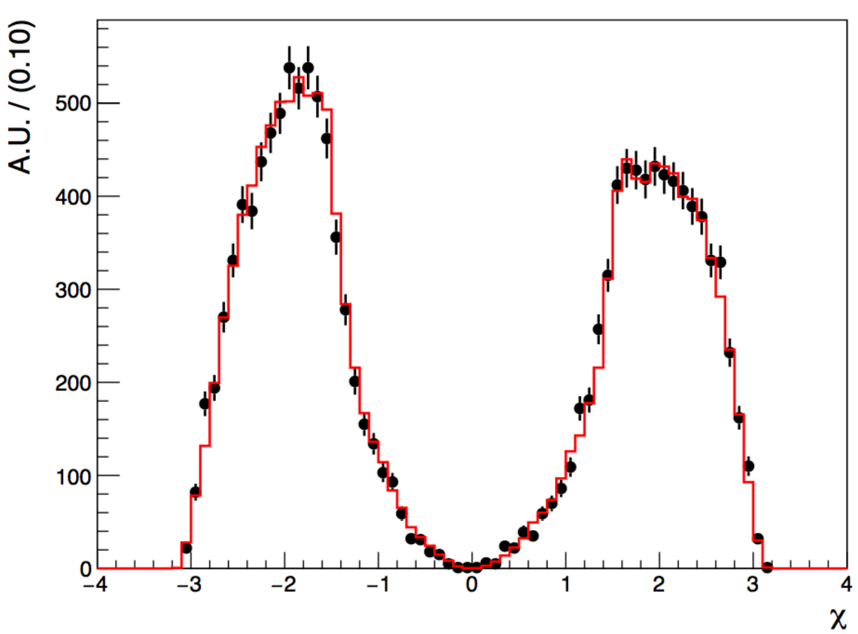
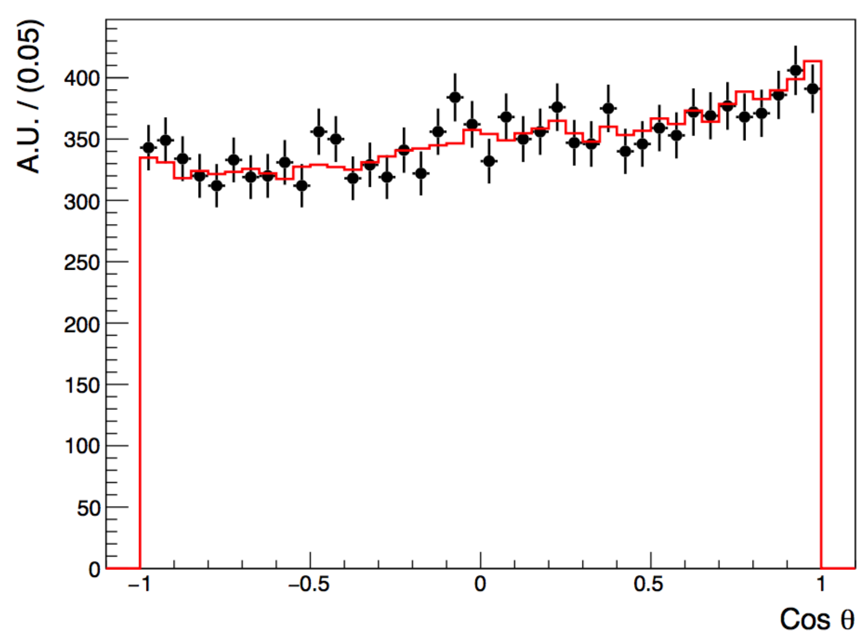
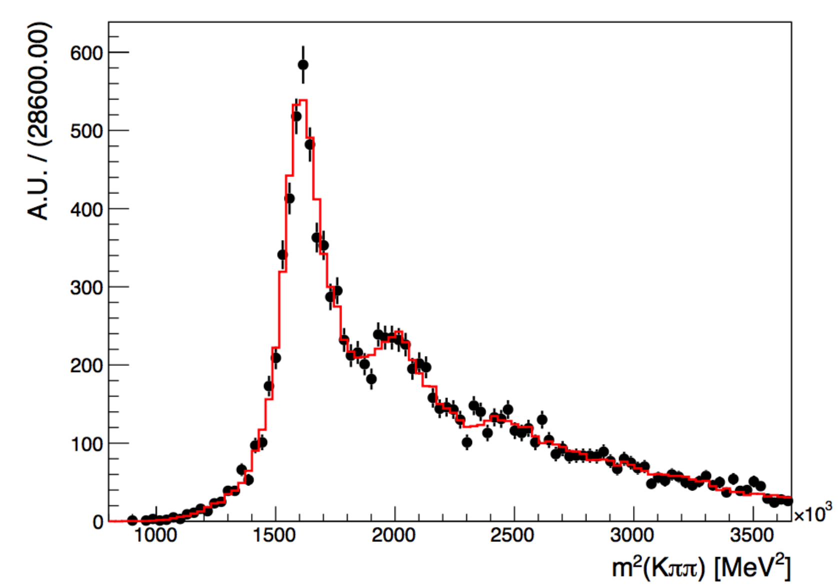


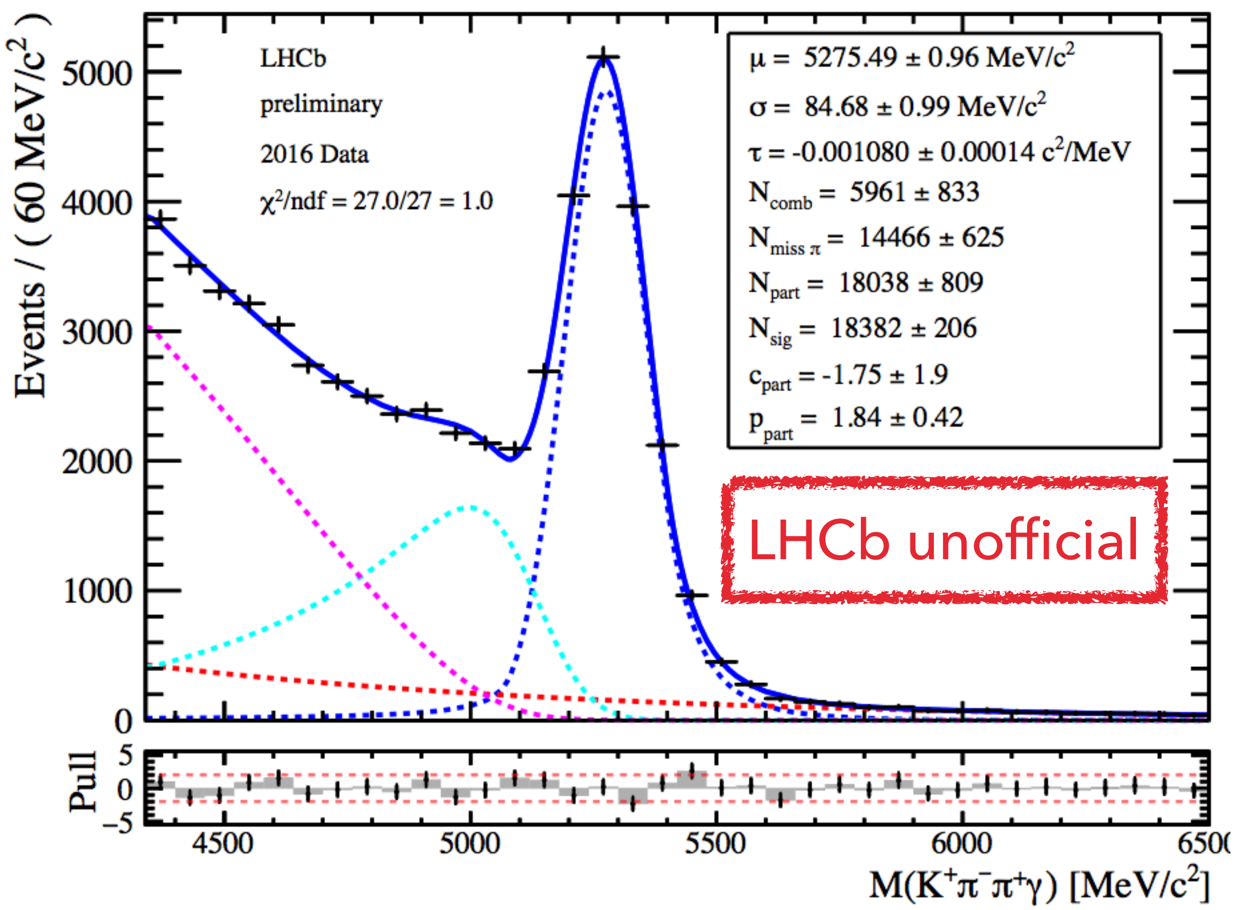


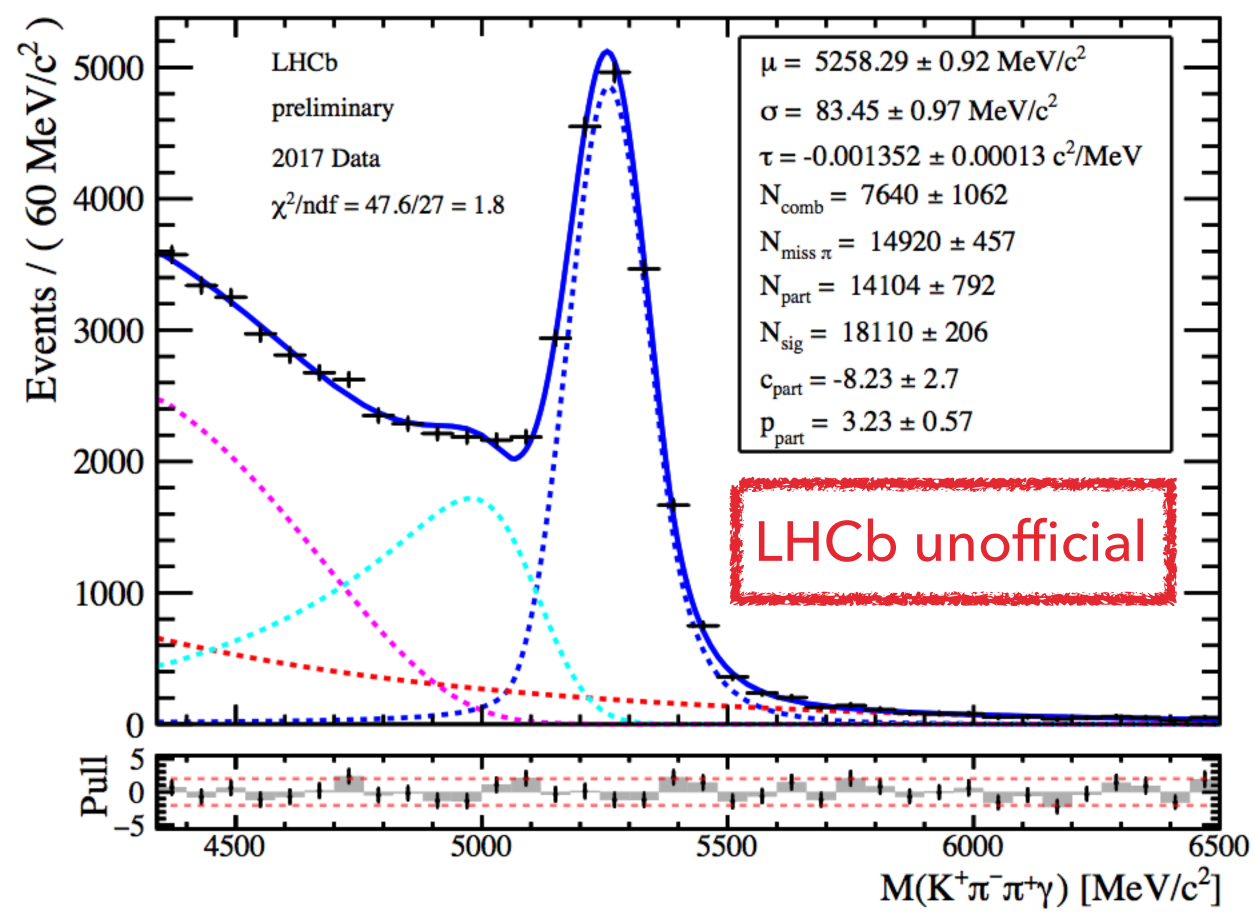


Amplitude analysis of $B^+ \to K^+\pi^-\pi^+\gamma$ decays

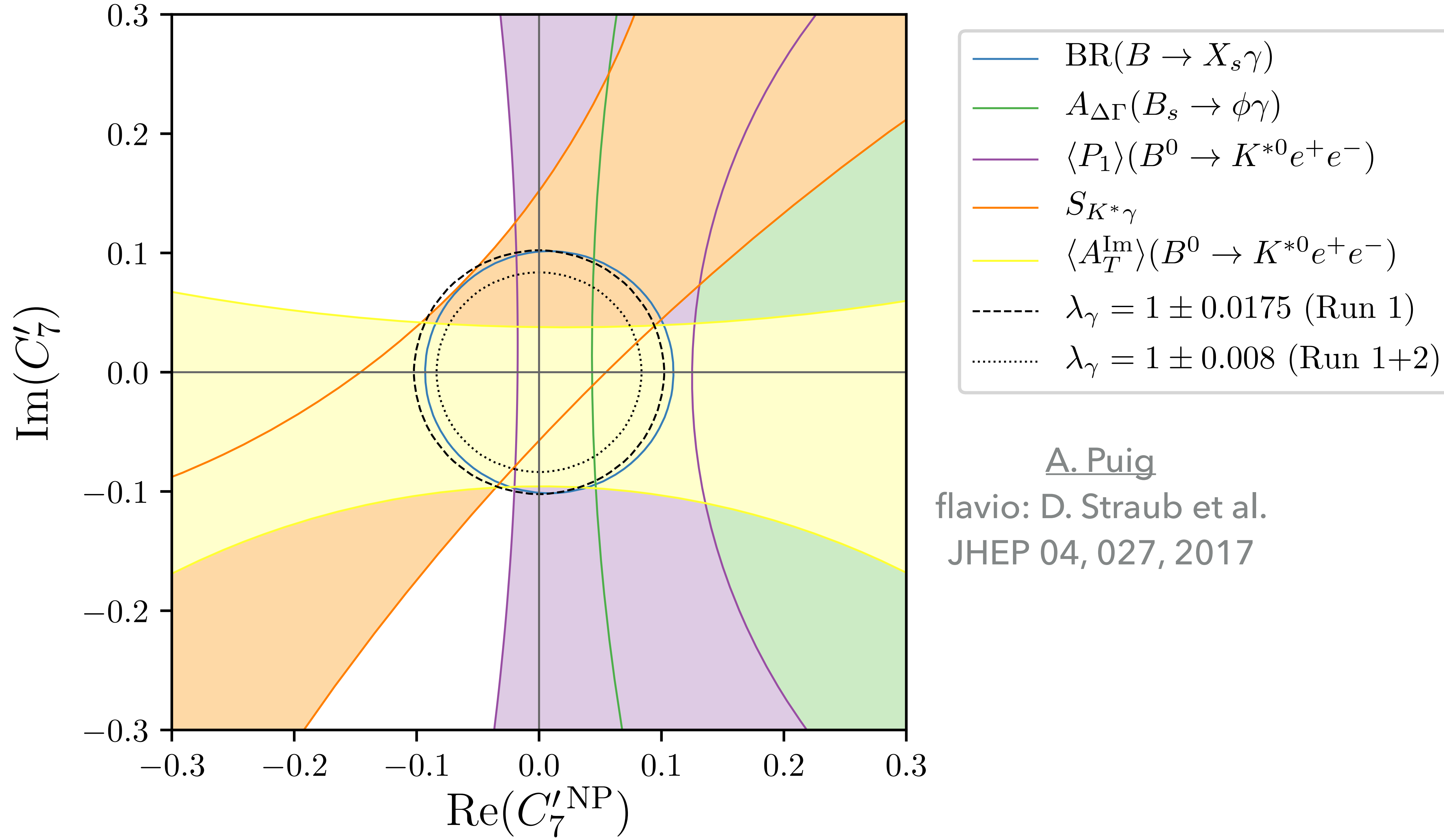
Selection of signal events in LHCb 2016+2017 data (ongoing)

→ Around 50,000 signal events available for the angular analysis (Run1 + Run2)





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



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

Competitive constraint on C_7'

SUMMARY

Despite a **very challenging environment**, the LHCb Collaboration is able to exploit radiative decays using a **wide variety of methods and channels**

THIS IS NOT THE END OF THE STORY!

In Run 2

- Exploit other baryonic decays ($\Xi_b \rightarrow \Xi\gamma$ and $\Omega_b \rightarrow \Omega\gamma$)
- Exploit other decays with three hadrons in the final state ($B^0 \rightarrow K_S\pi^-\pi^+\gamma$)

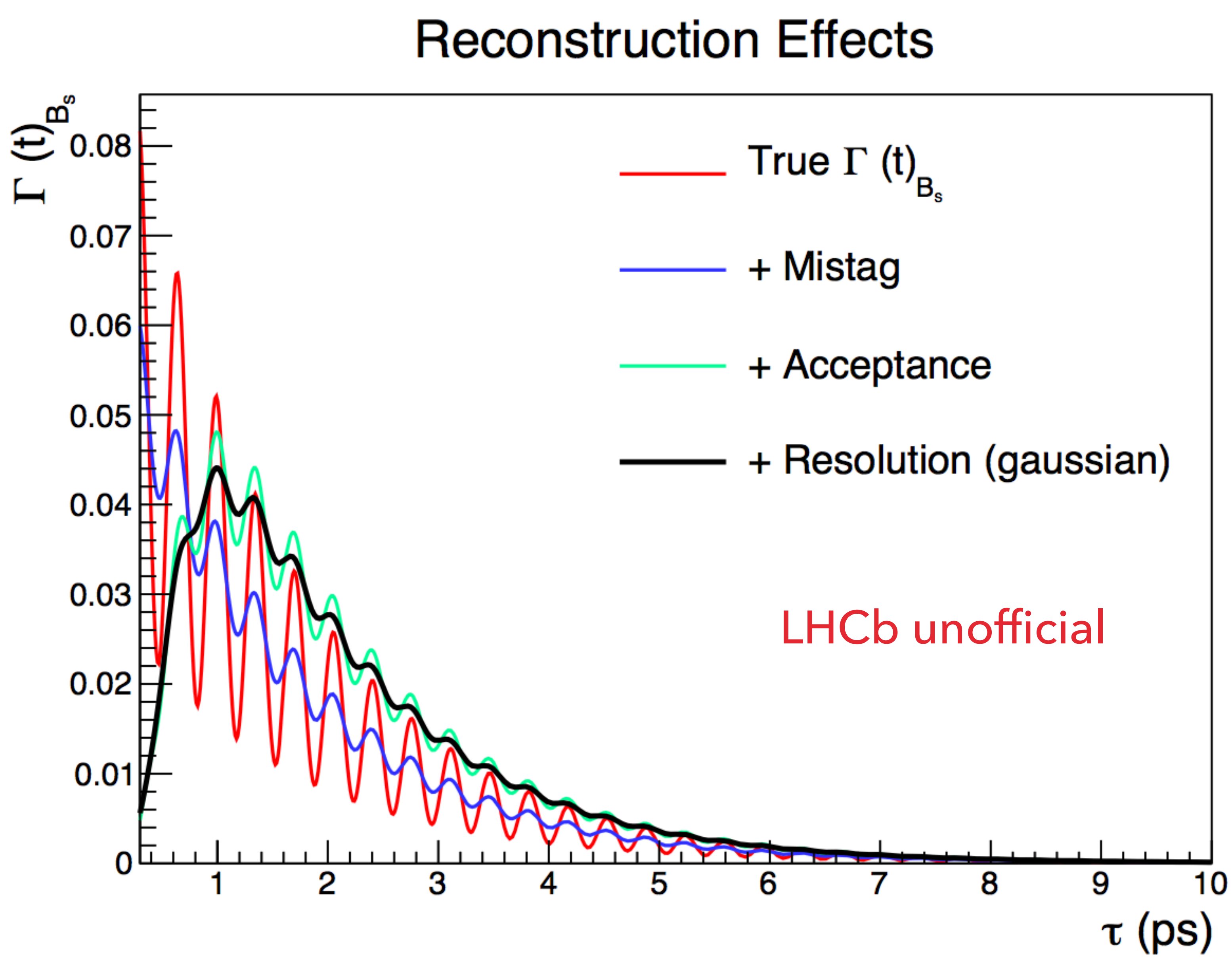
In the **LHCb upgrade phase** (target 50 fb^{-1} collected)

- **Larger data set**: Will improve statistical precision
- **New decays within reach**: CKM suppressed $b \rightarrow d\gamma$ transitions (e.g. $B \rightarrow \rho\gamma$)

BACK-UP

Tagged time-dependent analysis of $B_s \to \phi\gamma$ decays

Additional challenge: Flavour-tagging is used for the first time in a radiative decay at LHCb (expect a tagging power ~4%)



M. Calvo Gomez,
A Oyanguren Campos,
C. Remon Alepuz,
C. Sanchez Mayordomo

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

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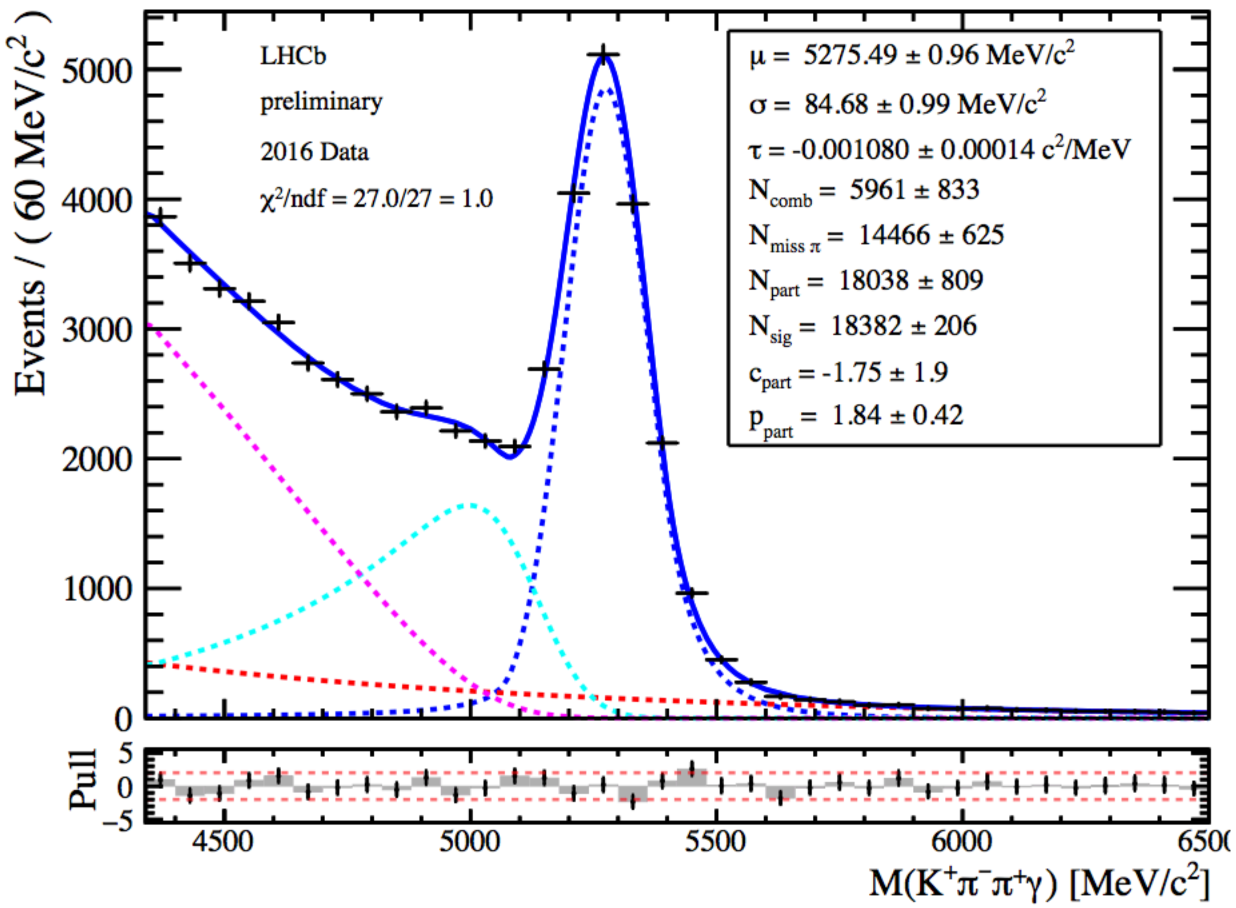
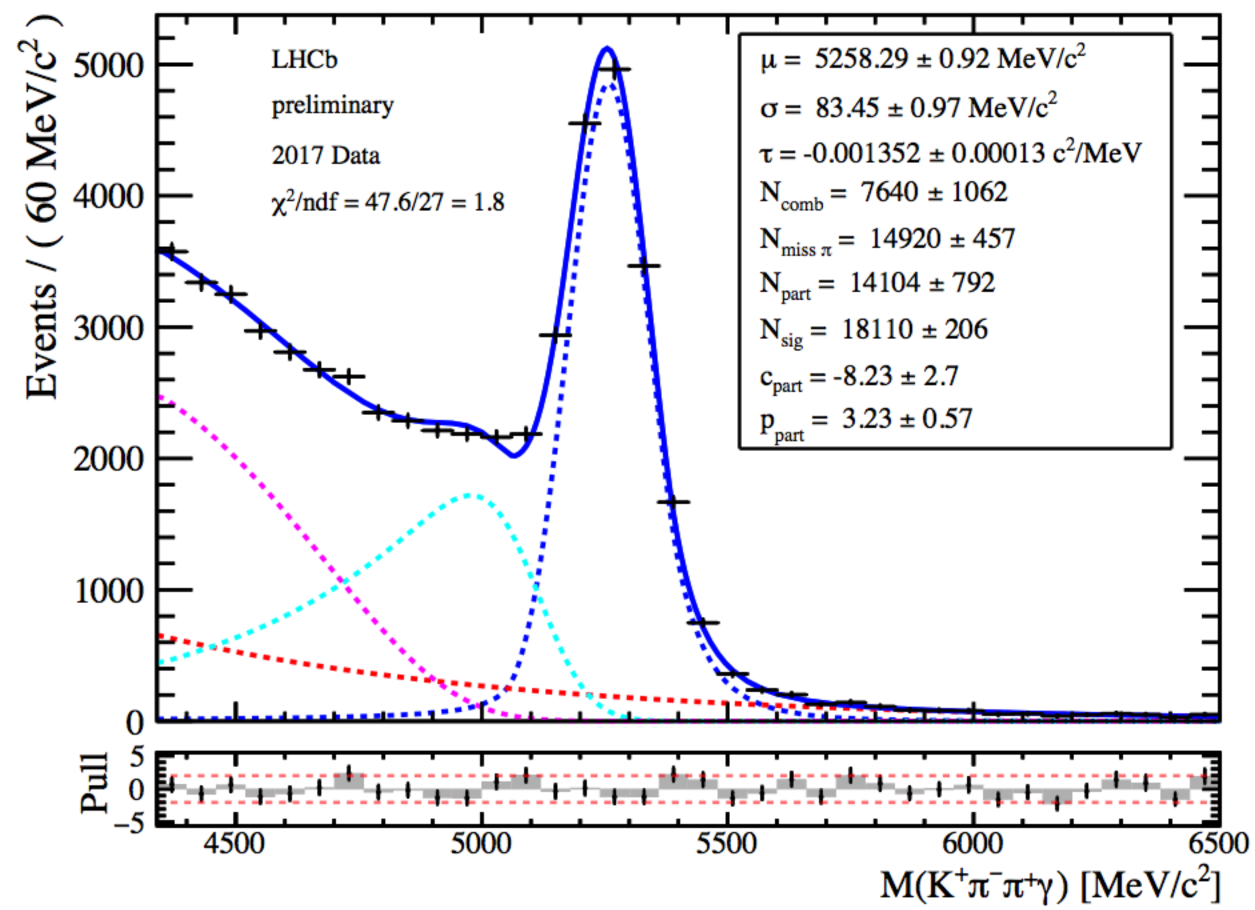
→ Around 50,000 signal events available for the angular analysis (Run1 + Run2)



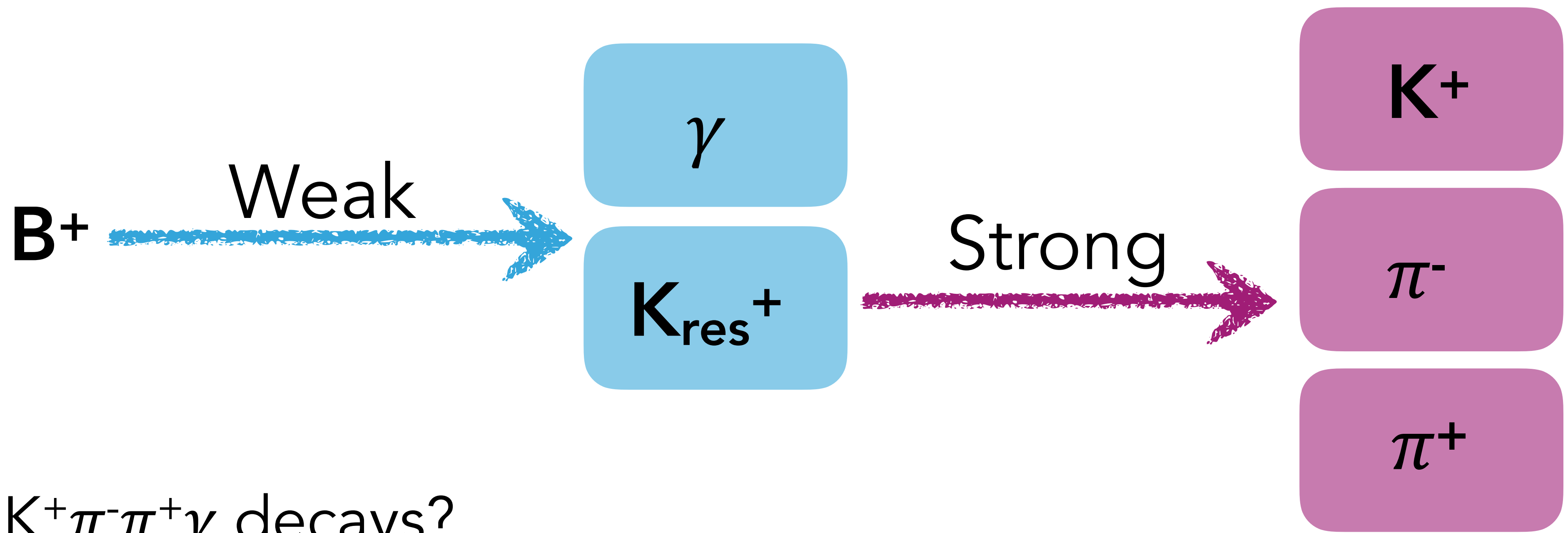


Cyrille Praz, EPFL Master Thesis

Main challenge: Presence of background with unknown angular distributions in the B mass region

→ Will require additional studies to allow background subtraction

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

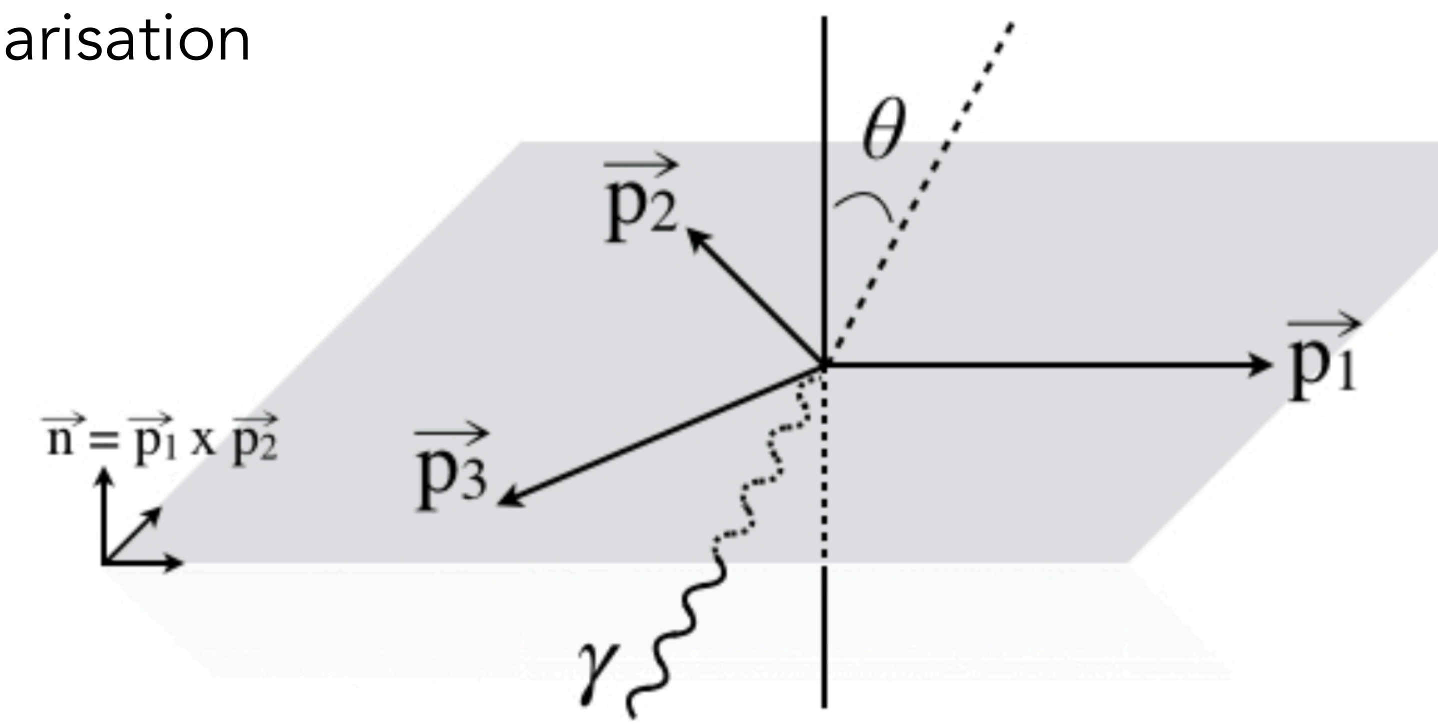


Why $B^+ \to K^+\pi^-\pi^+\gamma$ decays?

3 hadrons in the final state!

Minimum number of final state particles needed to build a P-odd triple product proportional to the photon polarisation

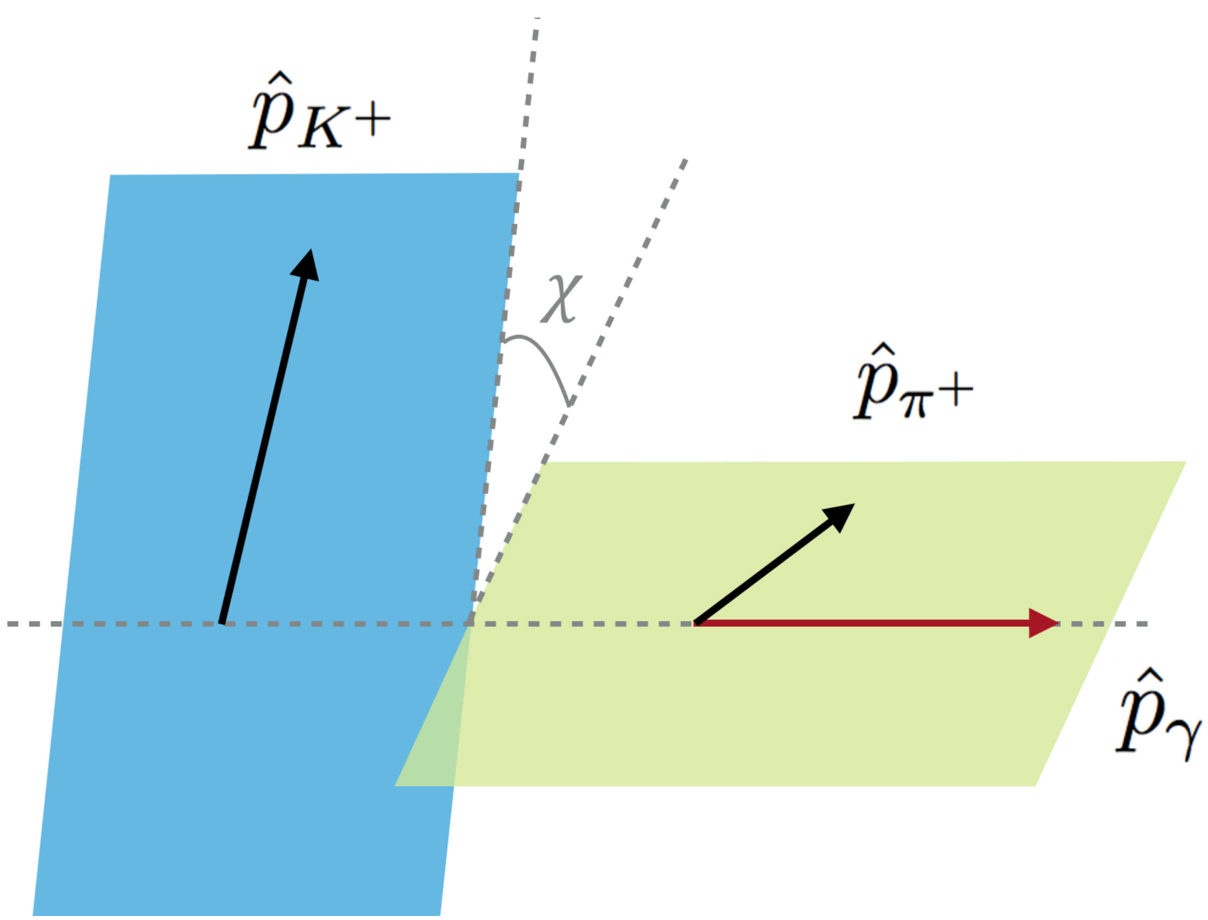
$$\boxed{\vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2)}$$

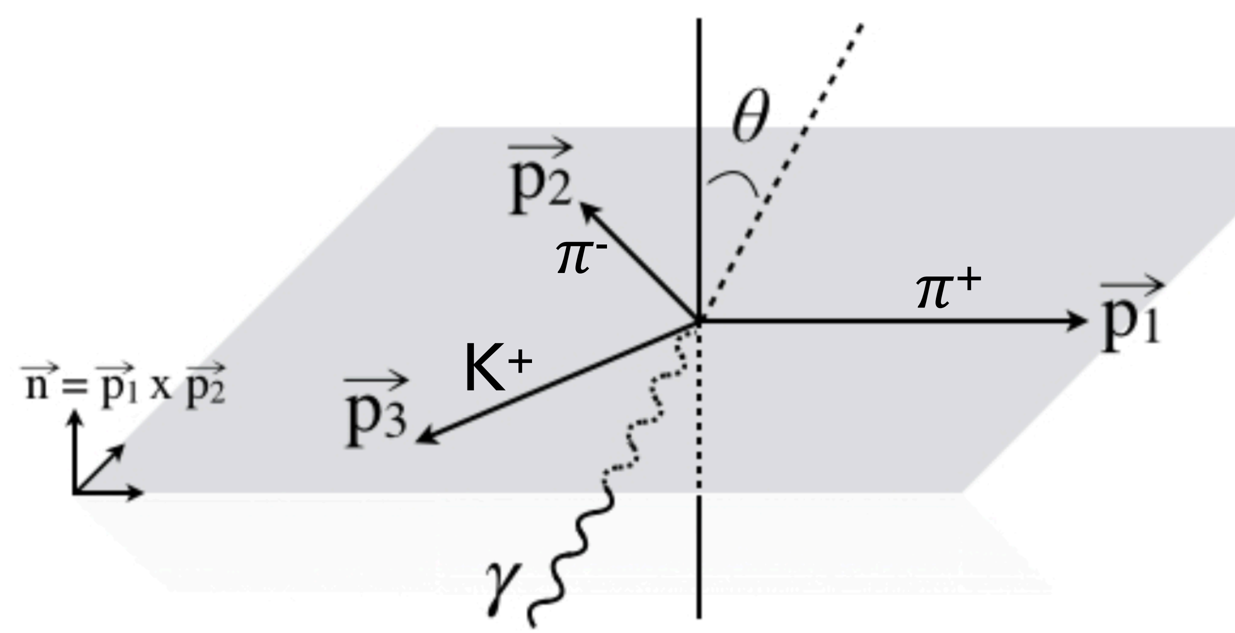


Amplitude analysis of B$^+ \to$ K$^+\pi^-\pi^+\gamma$ decays

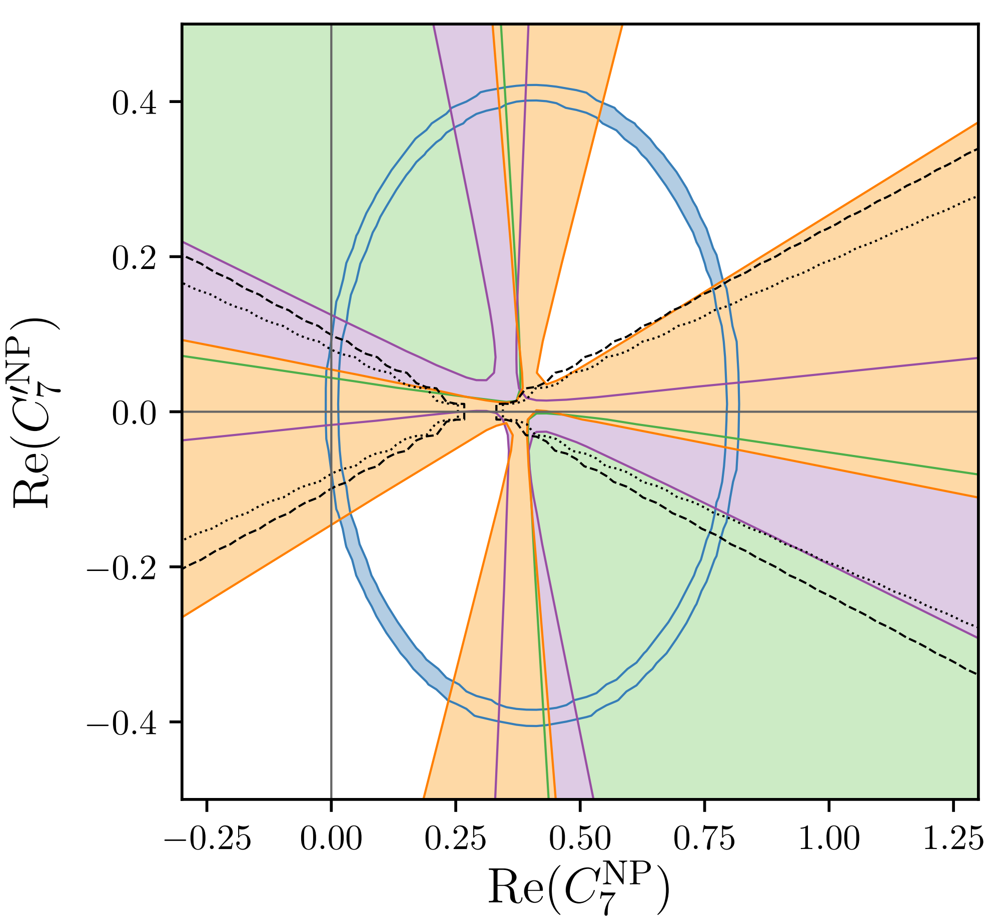
Degrees of freedom in the B$^+ \to$ K$^+\pi^-\pi^+\gamma$ system:

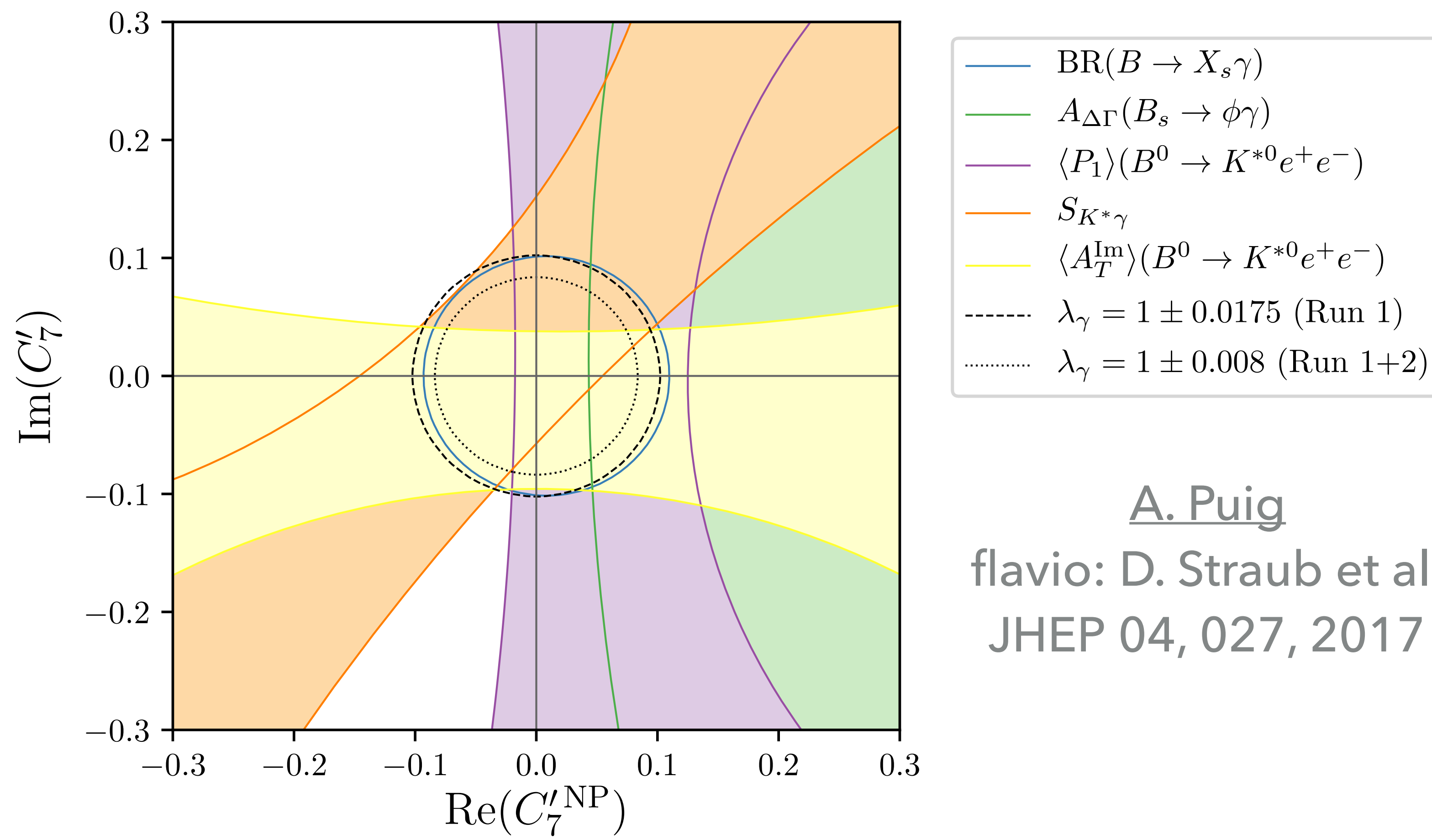
- Three invariant masses: m(Kππ), m(Kπ), m(ππ)
- Two angles that describe the orientation of the Kππ system with respect to the helicity vector of the photon: θ, χ





Amplitude analysis of $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ decays





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Breaks ambiguity in the determination of Re(C_7')

Competitive constraint on Re(C_7) and Re(C_7')