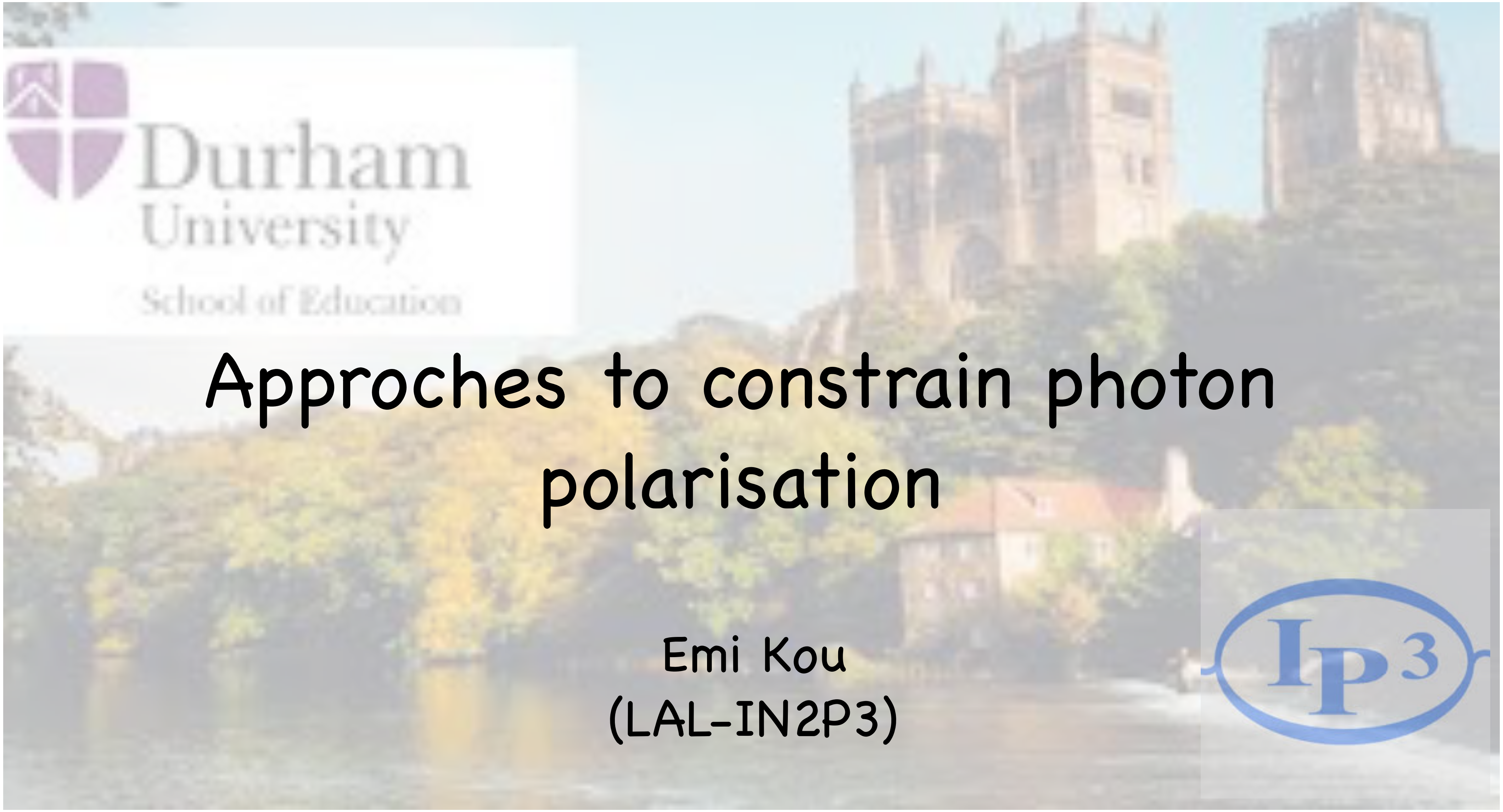


Approches to constrain photon polarisation

Emi Kou
(LAL-IN2P3)

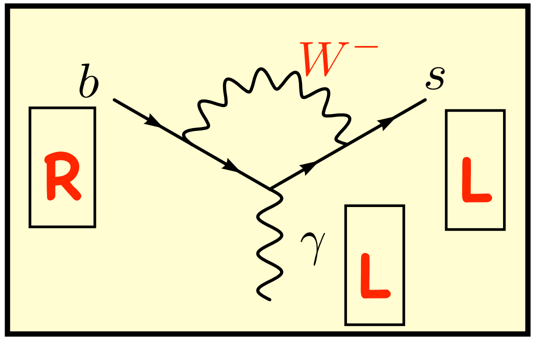
in memories of Jame Stirling and Mike Pennington

Towards the Ultimate Precision in Flavour Physics
@ Durham, 2-4 April 2019

Photon polarisation of $b \rightarrow s\gamma$

Photon polarisation of $b \rightarrow s\gamma$ process

- The photon polarisation of the $b \rightarrow s\gamma$ process has an unique sensitivity to BSM with right-handed couplings.
- However, the photon polarisation has never been measured at a hight precision so far: an important challenge for LHCb (and its upgrade) and Belle II.



In SM

W-boson couples only left-handed

⇔

γ of $b \rightarrow s\ \gamma$ should be circularly-polarised

✍ $b \rightarrow s\ \gamma_L$ (left-handed polarisation)

✍ $\bar{b} \rightarrow \bar{s}\ \gamma_R$ (right-handed polarisation)

How do we measure the polarisation?!

- Time dependent CP asymmetry

Atwood, Gronau, Soni PRL79
Atwood, Gershon, Hazumi, Soni PRD 05

  - ✓ $B_d \rightarrow K_S \pi^0 \gamma$, $B_d \rightarrow \rho \gamma$ (Belle II) **<— Golden channel of Belle II**
  - ✓ $B_d \rightarrow K_S \pi^+ \pi^- \gamma$ (Belle II)
  - ✓ $B_d \rightarrow K_S \phi \gamma$, $K_S \eta \gamma$
  - ✓ $B_s \rightarrow K^+ K^- \gamma$ (LHCb)

- Angular distribution (require more than 4 body final state)

Kruger, Matias PRD71
Becirevic, Schneider, NPB854

  - ✓ Transverse asymmetry in $B_d \rightarrow K^* l^+ l^-$(called $A_T^{(2)}$, $A_T^{(im)}$) (LHCb)
  - ✓ $B \rightarrow K_{res}(\rightarrow K\pi\pi)\gamma$ (called λ_γ)(Belle II/LHCB)
  - ✓ $\Lambda_b \rightarrow \Lambda^{(*)}\gamma$ (LHCb)

Gronau et al PRL88
E.K. Le Yaouanc, Tayduganov PRD83

Gremm et al.'95, Mannel et al '97, Legger et al '07, Oliver et al '10

For recent theoretical works, see
S. de Boer & G. Hiller, Eur.Phys.J. C78 (2018)
J. Gratrex, R. Zwicky arXiv:1807.01643

How do we measure the polarisation?!

- Time dependent CP asymmetry
  - ✓ $B_d \to K_S\pi^0\gamma$, $B_d \to \rho\gamma$ (Belle II)
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  - ✓ $B \to K_{res}(\to K\pi\pi)\gamma$ (called λ_γ)(Belle II/LHCB)
  - ✓ $\Lambda_b \to \Lambda^{(*)}\gamma$ (LHCb)

new

Martin et.al. arXiv:1902.04870

✍ Λ_b turned out to be un-polarised in LHCb

✍ Possibility in Ξ^-_b ?

How do we measure the polarisation?!

- Time dependent CP asymmetry
  - ✓ $B_d \to K_S \pi^0 \gamma$, $B_d \to \rho\gamma$ (Belle II)
  - ✓ $B_d \to K_S \pi^+ \pi^- \gamma$ (Belle II)
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  - ✓ $B \to K_{res}(\to K\pi\pi)\gamma$ (called λ_γ)(Belle II/LHCB)
  - ✓ $\Lambda_b \to \Lambda^{(*)}\gamma$ (LHCb)

new

V. Bellee et.al. arXiv:1902.0920 *S.Akar et.al. arXiv:1802.09433*

✍ Challenges to resolve $K_1 \to K\pi\pi$ system

✍ New observable in TDCPV

Current status on the constraint on the right-handed contribution

We can write the amplitude including RH contribution as:

$$\mathcal{M}(b\to s\gamma)\simeq -\frac{4G_F}{\sqrt{2}}V_{ts}^{*}V_{tb}\left[\underbrace{(C_{7\gamma}^{\rm SM}+C_{7\gamma}^{\rm NP})\langle\mathcal{O}_{7\gamma}\rangle}_{\propto\mathcal{M}_L}+\underbrace{C_{7\gamma}^{\prime\rm NP}\langle\mathcal{O}_{7\gamma}^{\prime}\rangle}_{\propto\mathcal{M}_R}\right]$$

We have a constraint from inclusive branching ratio measurement:

$$Br(B\to X_S\gamma)\propto|C_{7\gamma}^{\rm SM}+C_{7\gamma}^{\rm NP}|^2+|C_{7\gamma}^{\prime\rm NP}|^2$$

While the polarization measurement carries information on

$$\frac{\mathcal{M}_R}{\mathcal{M}_L}\simeq\frac{C_{7\gamma}^{\prime\rm NP}}{C_{7\gamma}^{\rm SM}+C_{7\gamma}^{\rm NP}}$$

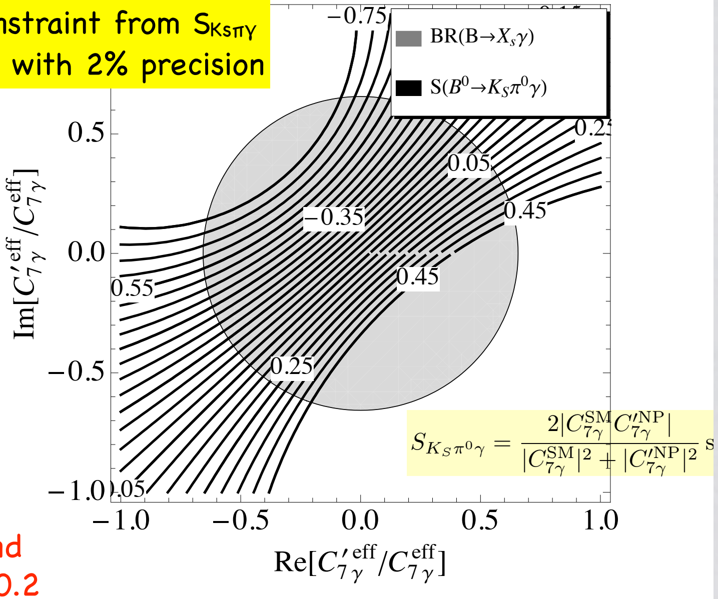
Note: new physics contributions, $C_{7\gamma}{}^{\rm NP}$ and/or $C'_{7\gamma}{}^{\rm NP}$ can be complex numbers!

A.Tayduganov et al. JHEP 1208

Prospect...

Method I

Expected constraint from $S_{K_S\pi\gamma}$ measurement with 2% precision



$$S_{K_S\pi^0\gamma} = \frac{2|C^{\rm SM}_{7\gamma}C'^{\rm NP}_{7\gamma}|}{|C^{\rm SM}_{7\gamma}|^2+|C'^{\rm NP}_{7\gamma}|^2}$$

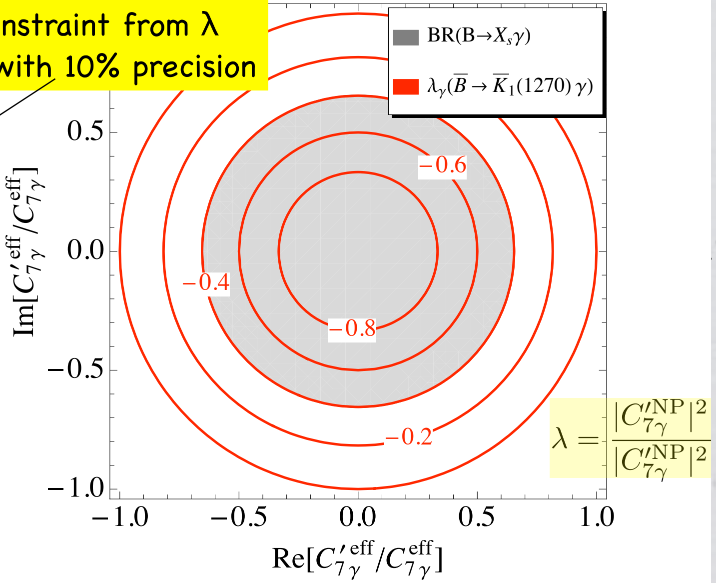
Current bound

$S_{K_S\pi^0\gamma}$ = -0.15±0.2

Method III

Expected constraint from λ measurement with 10% precision

3%

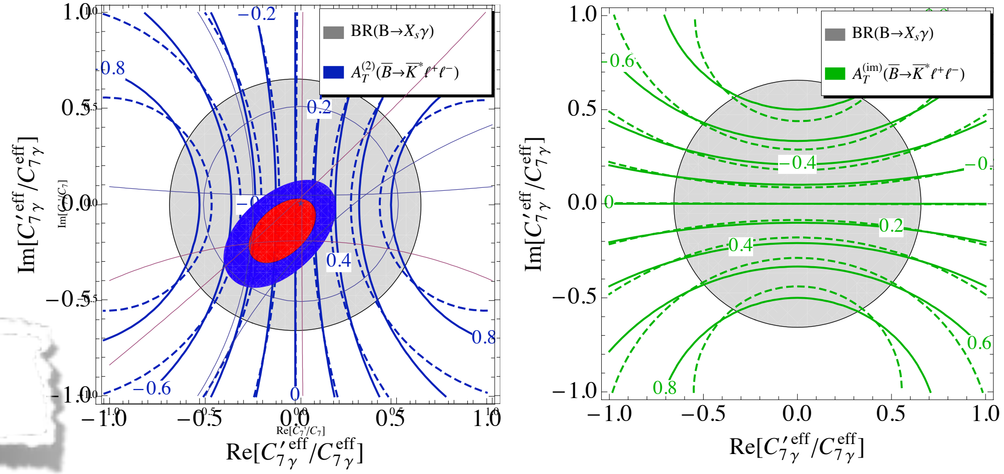


$$\lambda = \frac{|C'^{\rm NP}_{7\gamma}|^2}{|C'^{\rm NP}_{7\gamma}|^2}$$

Method II

Expected constraint from

$A_T^{(2)}$, $A_T^{(\rm im)}$ measurement with 10% precision



LHCb measurement
JHEP '15

It turned out that Method I with $B_s \to K^+K^-\gamma$ gives similar constraints.

$C'^{\rm NP}_{7\gamma} \neq 0$, $C^{\rm NP}_{7\gamma} = 0$

Becirevic, EK, Le Yaouanc, Tayduganov JHEP 1208

Recent progresses on the baryonic mode

Measuring photon polarisation with Λ_b decay

$$\boxed{\frac{1}{N}\frac{dN}{d\cos\theta_p d\cos\theta_{\Lambda^{(*)}}} \propto 1 - \alpha_{\Lambda^{(*)}} P_{\Lambda_b}\cos\theta_p\cos\theta_{\Lambda^{(*)}} - \alpha_\gamma \alpha_{\Lambda^{(*)}}\cos\theta_p - \alpha_\gamma P_{\Lambda_b}\cos\theta_{\Lambda^{(*)}}}$$

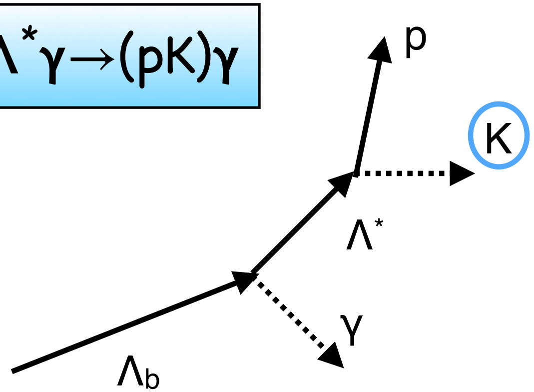
Λ^* spin 1/2 example

α_γ : photon polarisation, related to C_7'/C_7

$\alpha_{\Lambda^{(*)}}$: $\Lambda^{(*)}, \alpha_\Lambda = 0.642 \pm 0.013$

P_{Λ_b} : Λ_b polarisation

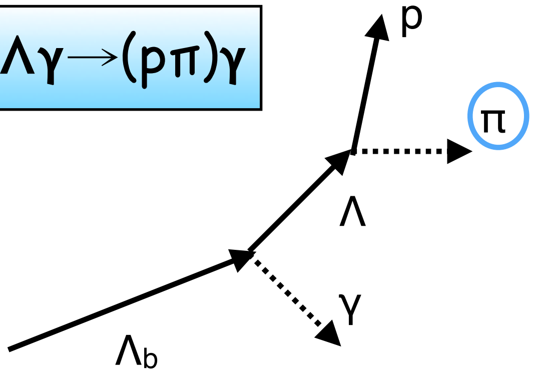
$\Lambda_b \rightarrow \Lambda^* \gamma \rightarrow (pK)\gamma$



$$\frac{1}{N}\frac{dN}{d\cos\theta_p d\cos\theta_\Lambda} \propto 1 - \alpha_\gamma P_{\Lambda_b}\cos\theta_\Lambda$$

Weak decay followed by Strong decay
→ need non-zero polarisation of Λ_b

$\Lambda_b \rightarrow \Lambda \gamma \rightarrow (p\pi)\gamma$



$$\frac{1}{N}\frac{dN}{d\cos\theta_p d\cos\theta_\Lambda} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$$

Weak decay followed by Weak decay
→ works with zero polarisation of Λ_b

Measuring photon polarisation with Λb decay

$$\frac{1}{N}\frac{dN}{d\cos\theta_p d\cos\theta_{\Lambda^{(*)}}} \propto 1 - \alpha_{\Lambda^{(*)}} P_{\Lambda_b}\cos\theta_p\cos\theta_{\Lambda^{(*)}} - \alpha_\gamma\alpha_{\Lambda^{(*)}}\cos\theta_p - \alpha_\gamma P_{\Lambda_b}\cos\theta_{\Lambda^{(*)}}$$

Λ* spin 1/2 example

α_γ : photon polarisation, related to C_7'/C_7

$\alpha_{\Lambda^{(*)}}$: $\Lambda^{(*)}, \alpha_\Lambda = 0.642 \pm 0.013$

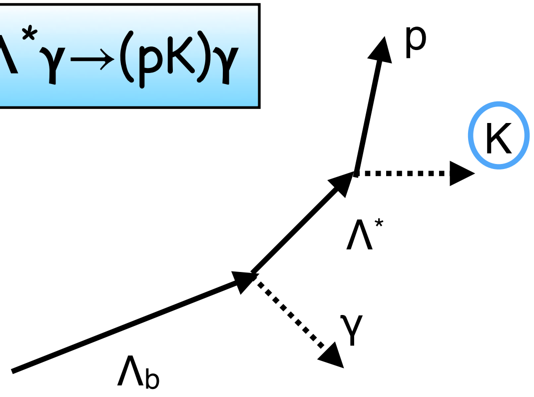
LHCb PLB ('13)

P_{Λ_b} : Λ_b polarisation

LHCb found PΛb is "small" :

(0.06±0.07±0.02)

Λb→Λ*γ→(pK)γ

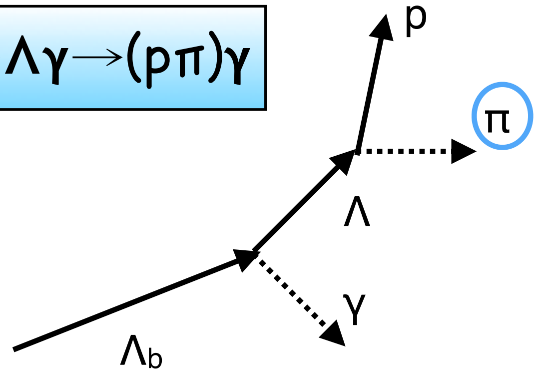


$$\frac{1}{N}\frac{dN}{d\cos\theta_p d\cos\theta_{\Lambda}} \quad \alpha_\gamma P_{\Lambda_b}\cos\theta_\Lambda$$

Weak decay followed by Strong decay → need non-zero polarisation of Λb

Λ life time is very long and challenging to detect it experimentally.

Λb→Λγ→(pπ)γ



$$\frac{1}{N}\frac{dN}{d\cos\theta_p d\cos}$$

Weak decay followed by Weak decay → works with zero polarisation of Λb

Measuring photon polarisation with Λ_b decay

$$\frac{1}{N}\frac{dN}{d\cos\theta_p d\cos\theta_{\Lambda(*)}} \propto 1 - \alpha_{\Lambda(*)} P_{\Lambda_b}\cos\theta_p\cos\theta_{\Lambda(*)} - \alpha_\gamma\alpha_{\Lambda(*)}\cos\theta_p - \alpha_\gamma P_{\Lambda_b}\cos\theta_{\Lambda(*)}$$

Λ^* spin 1/2 example

Martin et.al. arXiv:1902.04870, see also talk by C. Benito

- ✍ LHCb observed $\Lambda_b\to\Lambda\gamma\to(p\pi)\gamma$: (65±13) events (1fb^{-1} data)!
- ✍ Sensitivity to α_Λ is 15 % at Run II (with ~10^3 events)
- ✍ Idea of using $\Xi^-_b\to\Xi^-\gamma\to(\Lambda\pi^-)\gamma$ examined:
  - ~1/15 suppressed production rate
  - but similar sensitivity for α_Ξ, 20%, possible

Some brainstorming ?

- ✎ Can't we produce polarised Λ_b ?
- ✎ Are there other b baryons which make tracks ?
- ✎ Roles of azimuthal angles?
- ✎ Symmetry relations to remove P_{Λ_b} dependence?
- ✎ How about Λ_c radiative days ?

Angular analysis of $B \rightarrow K_{res}\gamma \rightarrow (K\pi\pi)\gamma$

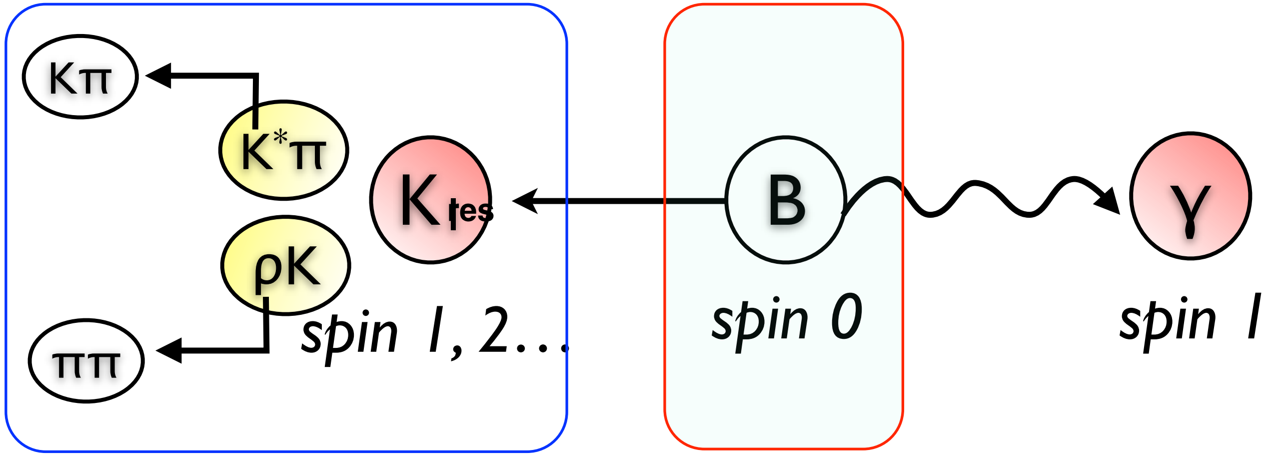
Angular distribution method

Gronau, Grossman, Pirjol, Ryd PRL88('01)

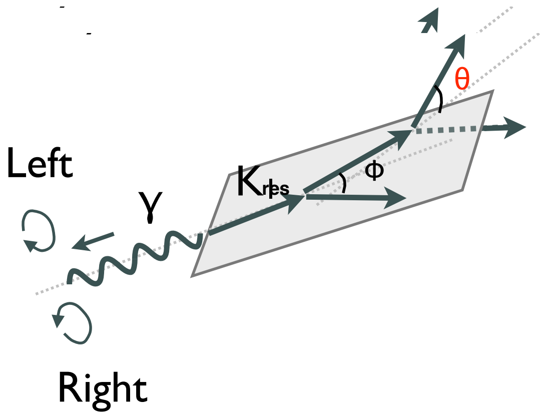
Photon polarisation = Recoiling K1 polarisation

—> measure it from K_{res} decay angular distribution

λ_γ : Polarisation parameter related to C7, C7' etc...



3 body decay necessary



** K_1 may decay through $(K\pi)_S\pi$, too.*

Example of K_1^+ (1270,1400)→$K^+\pi^+\pi^-$

We need to know the angular distribution of K_{res} in advance

K1→Kππ decay amplitude

$$\vec{\mathcal{J}}(s, s_{13}, s_{23}) = C_1(s, s_{13}, s_{23})\vec{p}_1 - C_2(s, s_{13}, s_{23})\vec{p}_2$$

$$K_1^+(1270/1400) \to \underbrace{\underbrace{\pi^-(p_1)\pi^+}_{\rho^0}(p_2)K^+}_{K^{*0}}(p_3)$$

Main 2 isobars

K1->[ρK, K*π]->Kππ

Angular distributions

$$\mathcal{W}(s, s_{13}, s_{23}, \cos\theta, \phi) \propto 2a - (a + a_1 \cos 2\phi + a_2 \sin 2\phi) \sin^2\theta + \lambda_\gamma b \cos\theta$$

$$a(s, s_{13}, s_{23}) = |C_1|^2|\vec{p}_1|^2 + |C_2|^2|\vec{p}_2|^2 - \mathrm{Re}[C_1C_2^*]\vec{p}_1 \cdot \vec{p}_2$$

$$a_1(s, s_{13}, s_{23}) = (|C_1|^2|\frac{|\vec{p}_1|}{|\vec{p}_2|} + |C_2|^2|\frac{|\vec{p}_2|}{|\vec{p}_1|})\vec{p}_1 \cdot \vec{p}_2 - \mathrm{Re}[C_1C_2^*]\vec{p}_1 \cdot \vec{p}_2$$

$$a_2(s, s_{13}, s_{23}) = (|C_1|^2|\frac{|\vec{p}_1|}{|\vec{p}_2|} - |C_2|^2|\frac{|\vec{p}_2|}{|\vec{p}_1|})\vec{p}_1 \times \vec{p}_2$$

$$b(s, s_{13}, s_{23}) = -4\mathrm{Im}[C_1C_2^*]\vec{p}_1 \times \vec{p}_2]$$

Imaginary part is needed to measure λ_γ

Up-down asymmetry for K_1^+ (1270,1400)

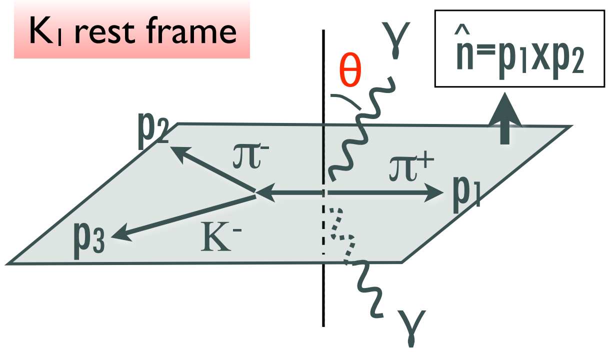
Example of K1 (ϕ angle integrated) Gronau, Grossman, Pirjol, Ryd PRL88('01)

$$\mathcal{W}(s, s_{13}, s_{23}, \cos\theta) \propto a(s, s_{13}, s_{23})(1+\cos^2\theta) + \lambda_\gamma b(s, s_{13}, s_{23})\cos\theta$$

Up-down asymmetry

$$\mathcal{A}_{UD} \equiv \frac{\int_0^1 \mathcal{W}(s, s_{13}, s_{23}, \cos\theta) d\cos\theta - \int_{-1}^0 \mathcal{W}(s, s_{13}, s_{23}, \cos\theta) d\cos\theta}{\int_{-1}^1 \mathcal{W}(s, s_{13}, s_{23}, \cos\theta) d\cos\theta}$$

$$= \lambda_\gamma \frac{3}{8} \frac{b(s, s_{13}, s_{23})}{a(s, s_{13}, s_{23})}$$



- » To measure λ_γ, we need to know the factor ***b/a***
- » Non-zero **b** requires imaginary part
- » Source of imaginary part: Breit-Wigner of isobars as well as K_1's

Theory prediction for up-down asymmetry

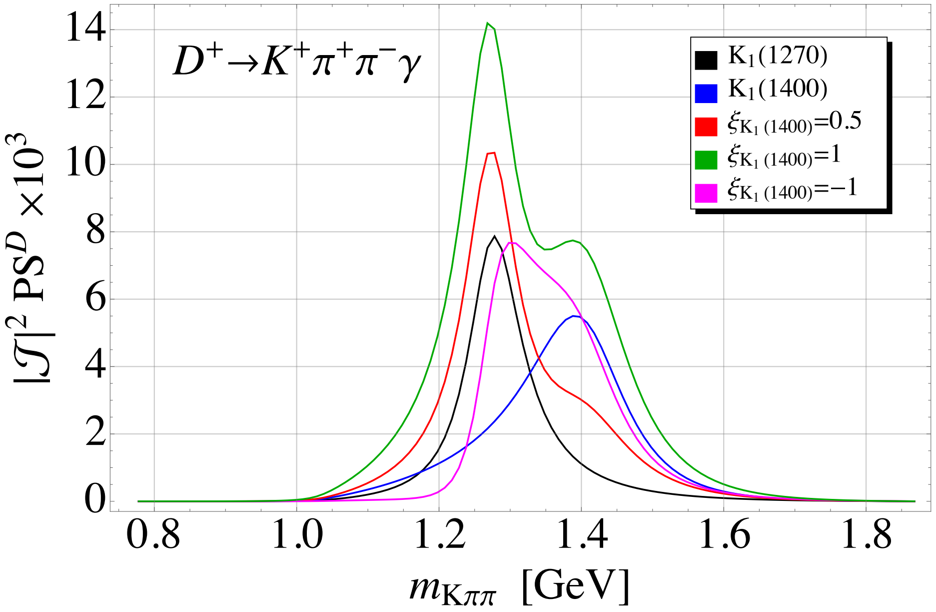
K1→Kππ is studied in detail at ACMMOR experiment

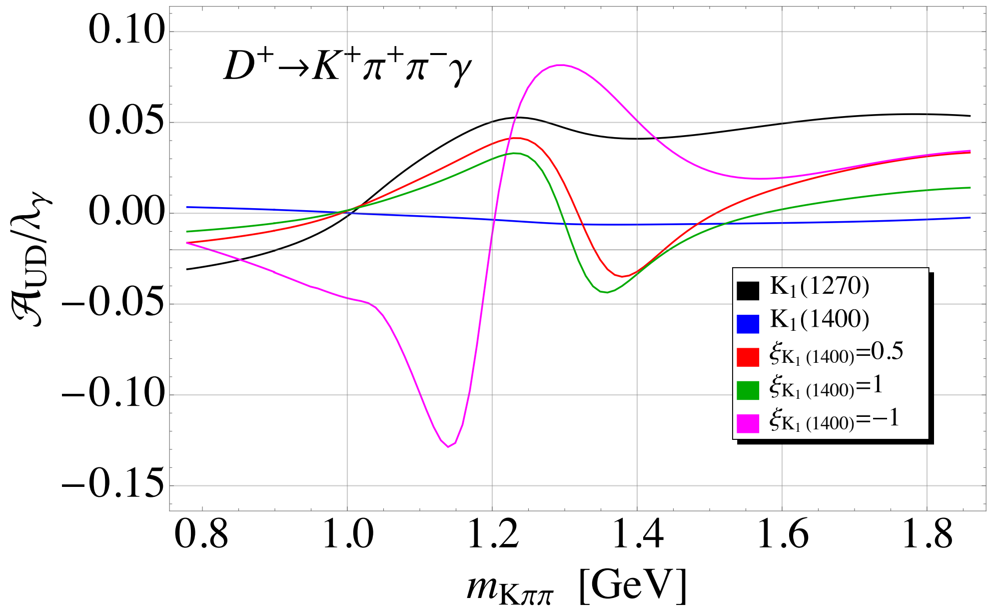
Using the fitted parameters, we can predict A_{UD}/λ_γ for K1(1270) and K1(1400)

Daum et al, Nucl Phys, B187 ('81), A.Tayduganov, EK, Le Yaouanc PRD '13

Recently, the result is shown for D decay (but it is the same for B decay)

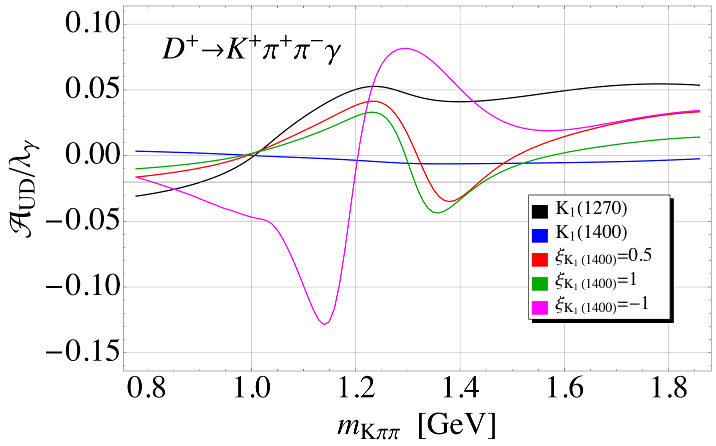
N. Adolph, G. Hiller, A. Tayduganov 1812.04679





Previous experiments indicate small K1(1400) but the ration has to be measured.

Origin of the up-down asymmetry



N.Adolph et.al 1812.04679

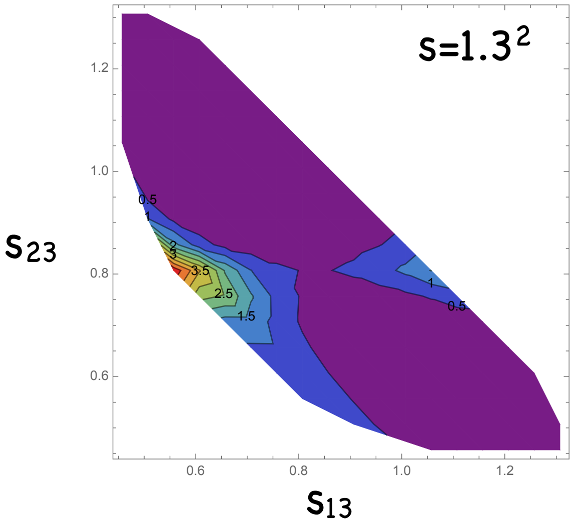
Non-zero asymmetry requires an interference of resonances.

✓K1(1270) decays through both [ρK, K*π] isobars.

✓K1(1400) decays through mostly [K*π] isobar.

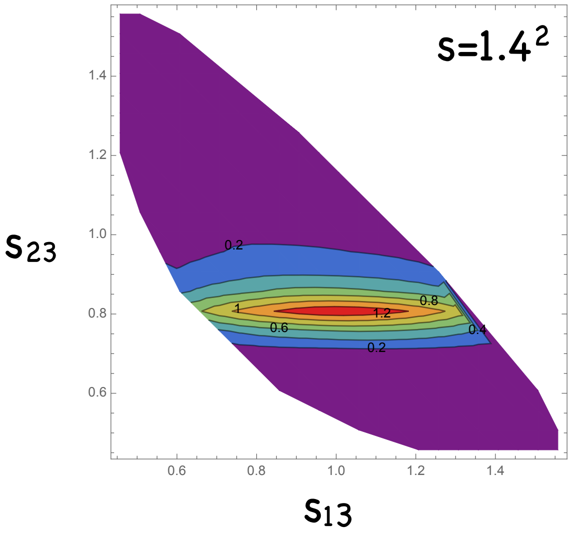
$$K_1^+(1270/1400) \longrightarrow \underbrace{\underbrace{\pi^-(p_1)\pi^+}_{\rho^0}(p_2)K^+}_{K^{*0}}(p_3)$$

K1(1270) Dalitz



We see both [ρK, K*π]

K1(1400) Dalitz

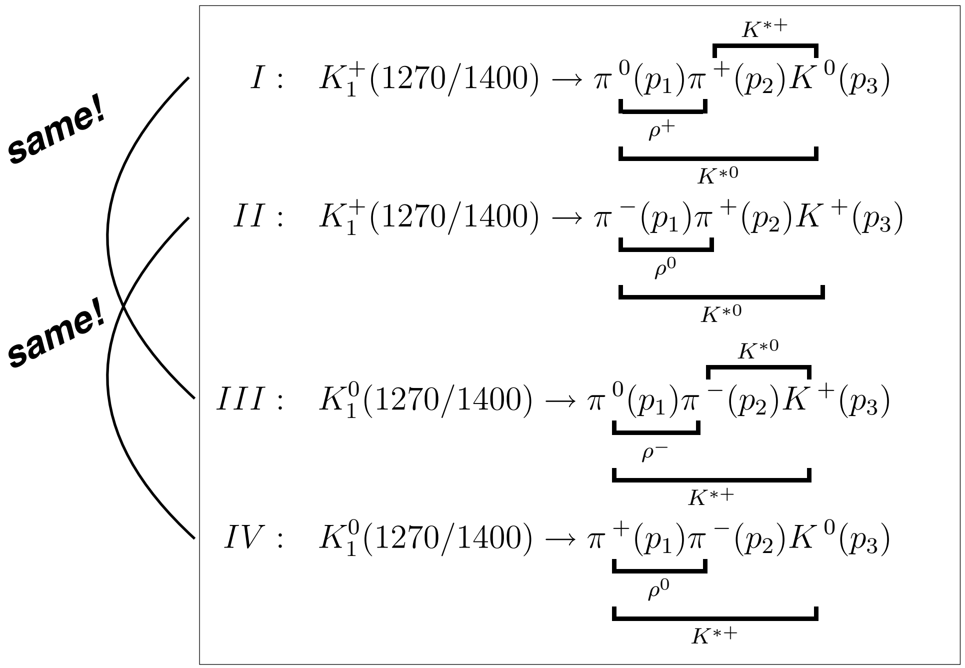


We almost only see K*π

Combining with neutral modes

Good news for Belle

- » LHCb has a large data sample for $B^+ \to K_1^+\gamma \to K^+\pi^+\pi^-\gamma$
- » But for final states with neutral particle, Belle (II) is better!
- » In general, Br, A^{UD} are larger for neutral modes.



$$I: \quad K_1^+(1270/1400) \to \underbrace{\underbrace{\pi^0(p_1)\pi}_{\rho^+}\overbrace{{}^+(p_2)K^0}^{K^{*+}}}_{K^{*0}}(p_3)$$

$$II: \quad K_1^+(1270/1400) \to \underbrace{\underbrace{\pi^-(p_1)\pi}_{\rho^0}{}^+(p_2)K^+}_{K^{*0}}(p_3)$$

$$III: \quad K_1^0(1270/1400) \to \underbrace{\underbrace{\pi^0(p_1)\pi}_{\rho^-}\overbrace{{}^-(p_2)K^+}^{K^{*0}}}_{K^{*+}}(p_3)$$

$$IV: \quad K_1^0(1270/1400) \to \underbrace{\underbrace{\pi^+(p_1)\pi}_{\rho^0}{}^-(p_2)K^0}_{K^{*+}}(p_3)$$

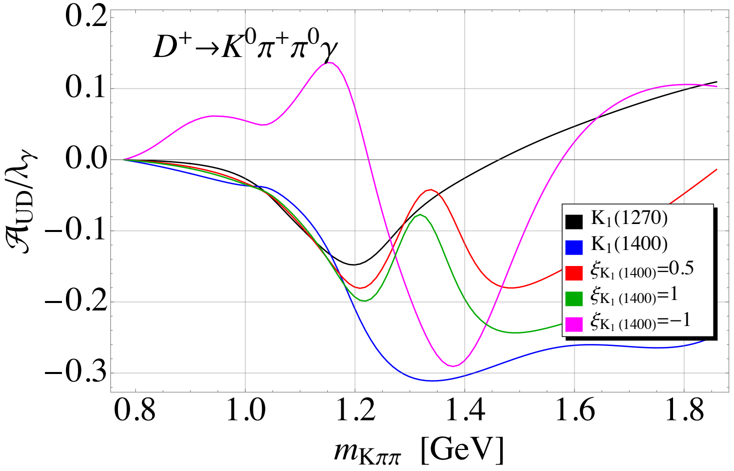
Babar'05

TABLE I: Results of the fit for $B \to K\pi\pi\gamma$, for $m_{K\pi\pi} < 1.8\ \mathrm{GeV}/c^2$. The first error is statistical, the second systematic. The yields do not include the channel crossfeeds, which are included in the fit to obtain the branching fractions.

	Channel	Yield	Branching Fraction (10^{-5})
II	$K^+\pi^-\pi^+\gamma$	899 ± 38	$2.95 \pm 0.13 \pm 0.20$
III	$K^+\pi^-\pi^0\gamma$	572 ± 31	$4.07 \pm 0.22 \pm 0.31$
IV	$K^0\pi^+\pi^-\gamma$	176 ± 20	$1.85 \pm 0.21 \pm 0.12$
I	$K^0\pi^+\pi^0\gamma$	164 ± 15	$4.56 \pm 0.42 \pm 0.31$

adding each π0: loss of efficiency x 0.4-0.5
adding each K0: loss of efficiency x 0.25

Up-down asymmetry for K_1^0 (1270,1400)→$K^+\pi^0\pi^-$

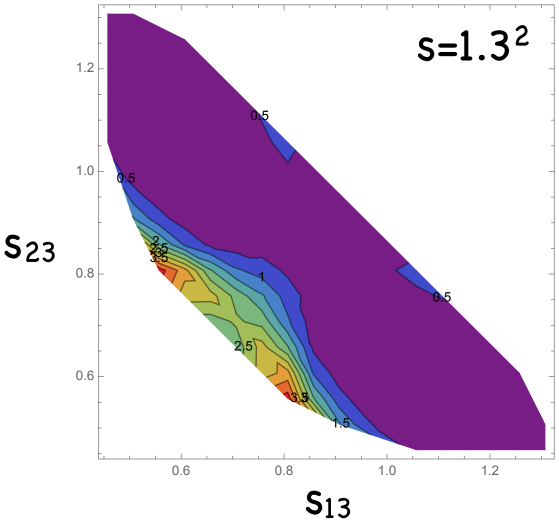


N.Adolph et.al 1812.04679

✓K1(1270) decays through both [ρK, 2K*π] isobars.
✓K1(1400) decays through mostly [2K*π] isobar.

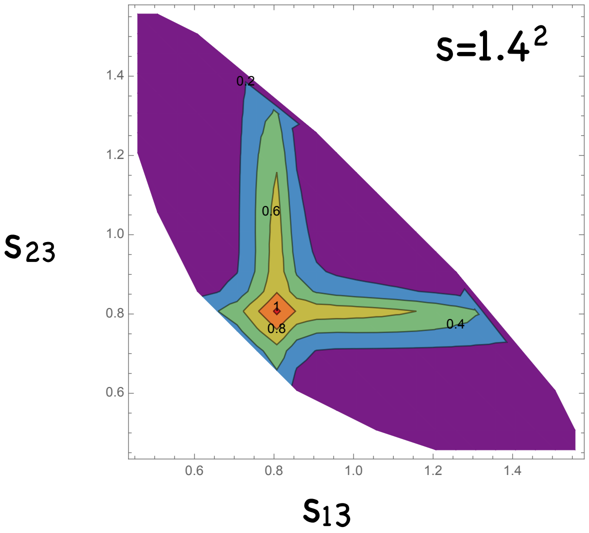
$$K_1^0(1270/1400) \to \underbrace{\underbrace{\pi^0(p_1)\pi}_{\rho^-}\overbrace{{}^{-}(p_2)K}^{K^{*0}}}_{K^{*+}}{}^{+}(p_3)$$

K1(1270) Dalitz



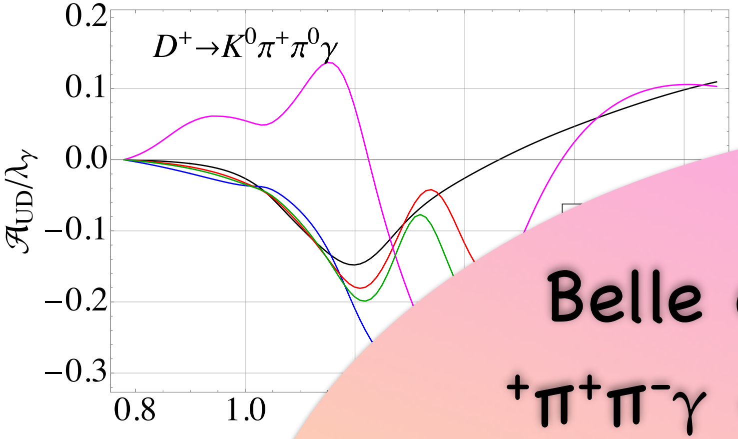
We see both [ρK, 2K*π]

K1(1400) Dalitz



We see almost only 2K*π

Up-down asymmetry for K_1^0 (1270,1400)$\rightarrow K^+\pi^0\pi^-$



ugh both [ρK, 2K*π] isobars.

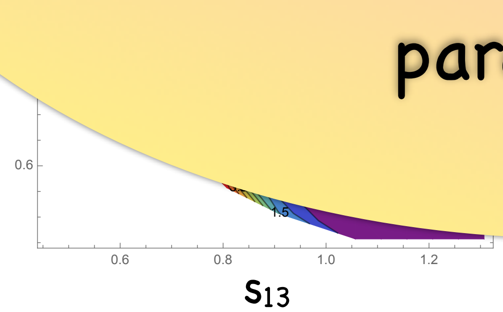
stly [2K*π] isobar.

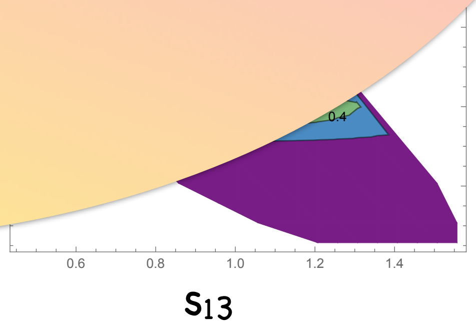
)

N.Ad

Belle combined analysis of [$K^+\pi^+\pi^-\gamma$ & $K^+\pi^-\pi^0\gamma$] is interesting

- Gaining statistics (x~1.5)
- Gaining sensitivity to photon polarisation (neutral mode x~2)
- Isospin relation provides extra information to constraint hadronic parameters



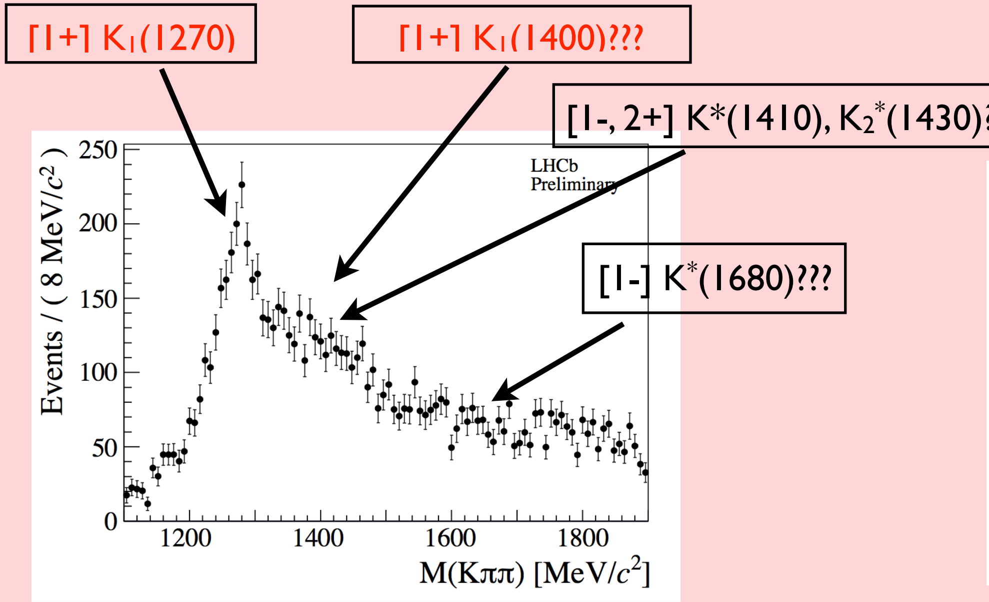


We see both [ρK, 2K*π]

We see almost only 2K*π

LHCb result on up-down asymmetry

LHCb PRL ('14)

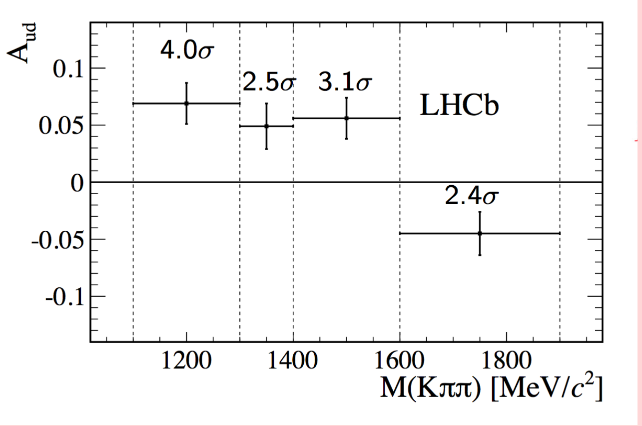

[1+] $K_1(1270)$

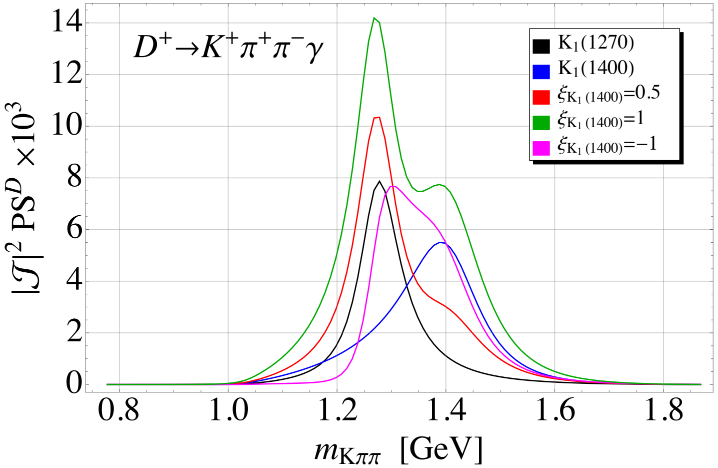
[1+] $K_1(1400)$???

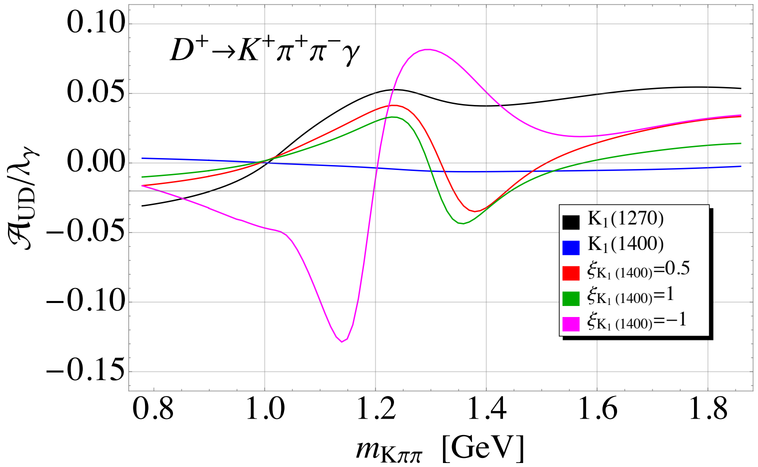
[1-, 2+] $K^*(1410)$, $K_2^*(1430)$??

[1-] $K^*(1680)$???

Interpreting this result needs theory models







LHCb result on up-down asymmetry

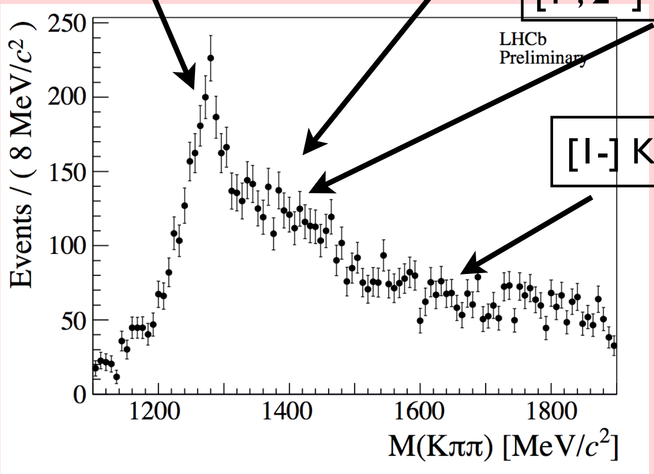
LHCb PRL ('14)

[1+] K₁(1270)

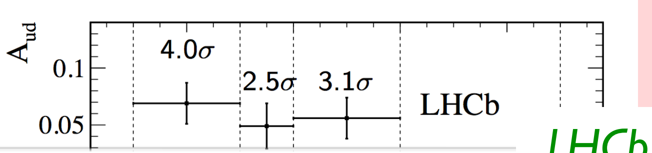
[1+] K₁(1400)???

[1-, 2+] K*(1410), K₂*(1430)??

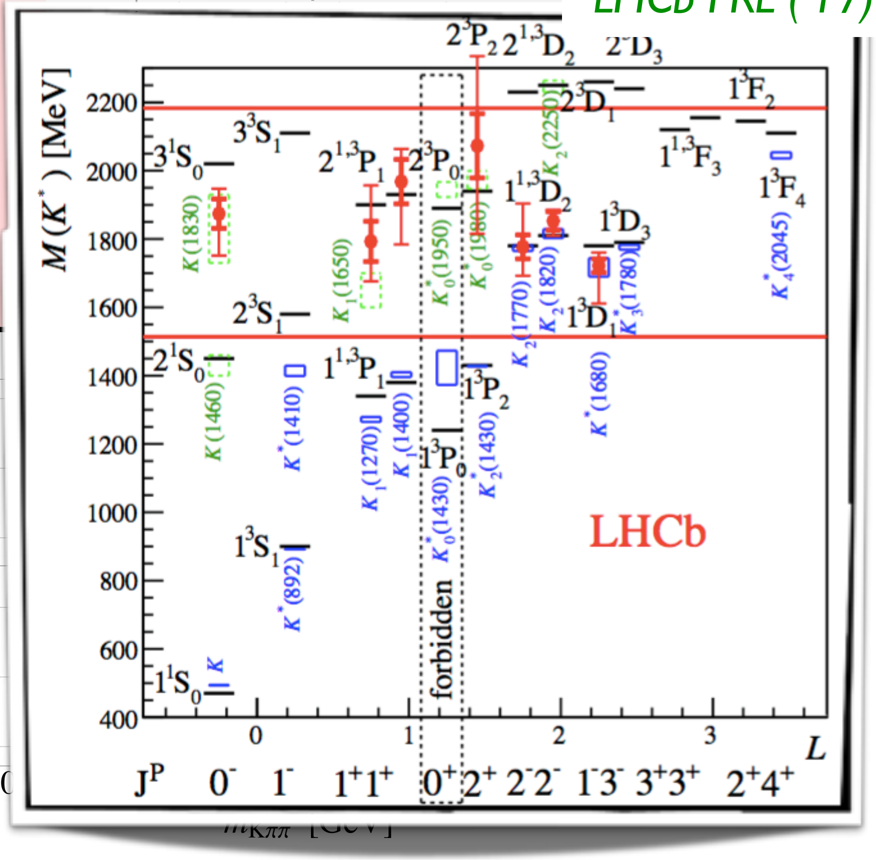
[1-] K*(1680)???

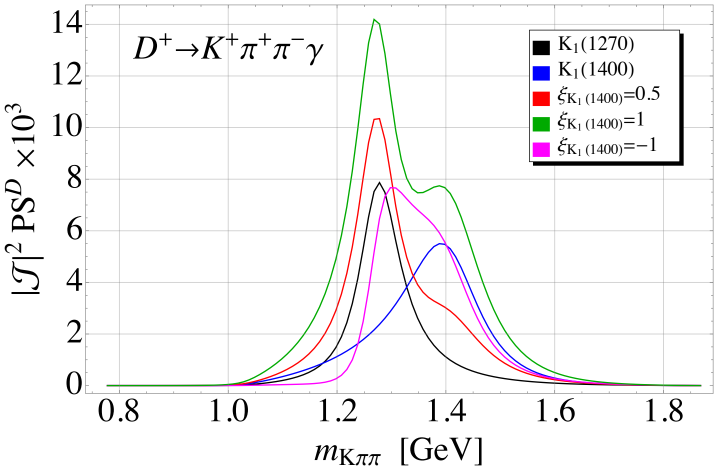


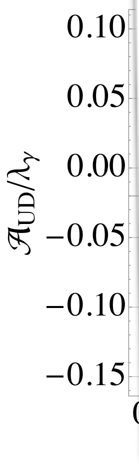
Interpreting this result needs theory models



LHCb PRL ('17)





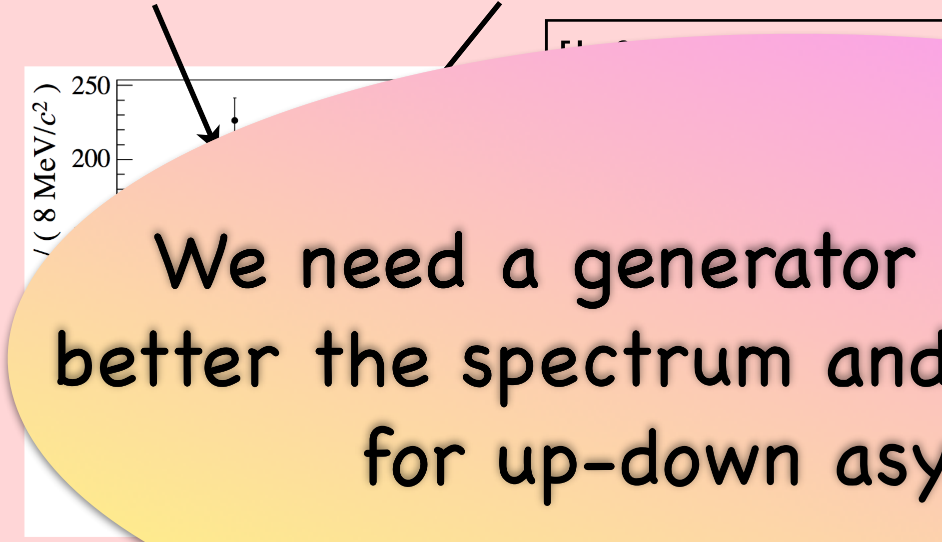


LHCb result on up-down asymmetry

LHCb PRL ('14)

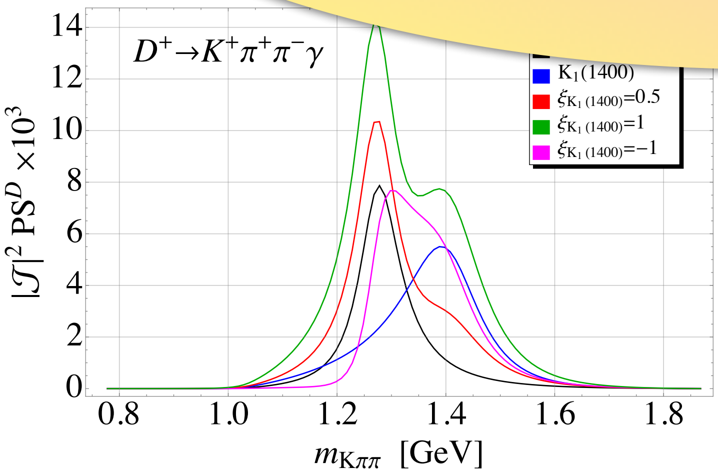
[1+] K₁(1270)

[1+] K₁(1400)???

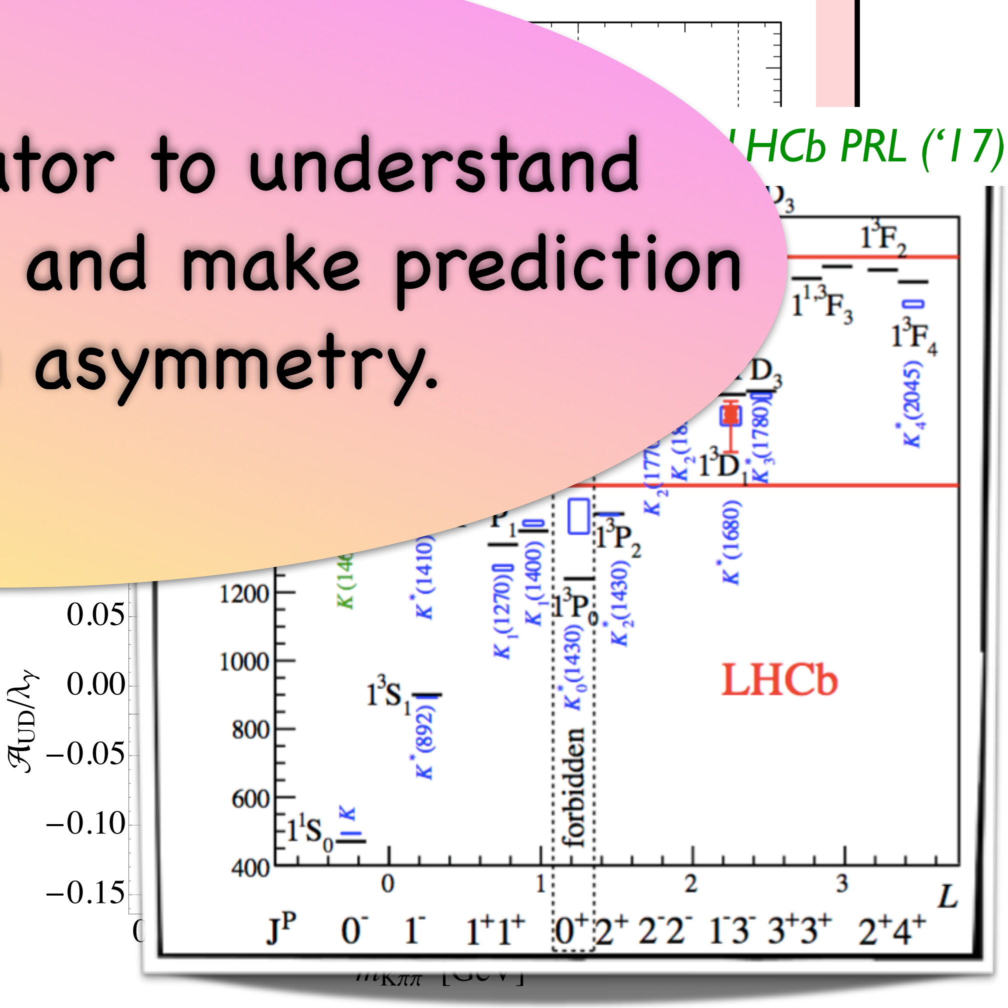


Interpreting this result needs theory models

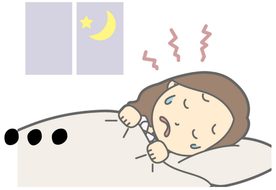
We need a generator to understand better the spectrum and make prediction for up-down asymmetry.



LHCb PRL ('17)



Generator for K_{res}→$K\pi\pi$ decays…



see also M. Gronau, D. Pirjol, Phys.Rev. D96 (2017)

1. $K1_{1270}(1+)$ & $K1_{1400}(1+)$ decays based on quark model

A.Tayduganov, EK, Le Yaouanc PRD '13

Assume K_1→$K\pi\pi$ comes from quasi-two-body decay, e.g. K_1→$K^*\pi$, K_1→ρK, then, J function can be written in terms of:

- 4 form factors (S,D partial wave amplitudes)

2. $K^*_{1410,\ 1680}(1-)$ and $K2_{1430}$ (2+)

A. Kotenko, B. Knysh talk at Lausanne WS '17

Lesser parameters

- Known to decay mainly K_{res}→$K^*\pi$, ρK
- Only 1 form factor for each resonance

On total 10 complex couplings needed (20 real number)!

Generator for K_{res}→$K\pi\pi$ decays...

Gampola

A. Kotenko, B. Knysh E.K. talk at Lausanne WS '17

"Form-Factor" method

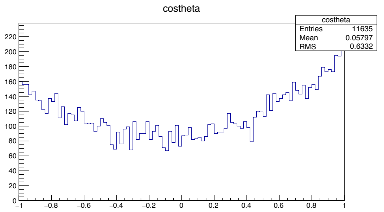
$$\begin{aligned}\mathcal{W}^{K_1}(s,s_{13},s_{23},\theta,\phi) &= -A_1^{K_1}(1+\cos^2\theta)+\lambda_\gamma B^{K_1}\cos\theta\\ &+ (A_2^{K_1}\cos 2\phi + A_3^{K_1}\sin 2\phi)\sin^2\theta\end{aligned}$$

$$\mathcal{W}^{K^*}(s,s_{13},s_{23},\theta,\phi) = A^{K^*}\sin^2\theta$$

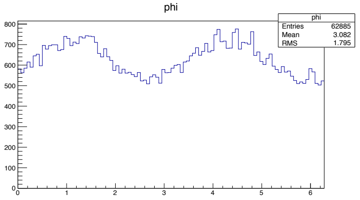
$$\begin{aligned}\mathcal{W}^{K_2}(s,s_{13},s_{23},\theta,\phi) &= A^{K_2}+\lambda_\gamma B^{K_2}\cos\theta\\ &+ C_1^{K_2}\sin^2\theta + D_1^{K_2}\sin^4\theta + \lambda_\gamma E^{K_2}\sin^2\theta\cos\theta\\ &+ (C_2^{K_2}\sin^2\theta + D_2^{K_2}\sin^4\theta)\cos 2\phi\end{aligned}$$

$$\begin{aligned}\mathcal{W}^{K_1K^*}(s,s_{13},s_{23},\theta,\phi) &= A^{K_1K^*}+\lambda_\gamma E^{K_1K^*}\cos\theta + D_1^{K_1K^*}\sin^2\theta\\ &+ (B_1^{K_1K^*}\sin\phi + B_2^{K_1K^*}\cos\phi)\sin\theta\\ &+ \lambda_\gamma(C_1^{K_1K^*}\sin\phi + C_2^{K_1K^*}\cos\phi)\sin\theta\cos\theta\\ &+ (D_2^{K_1K^*}\cos 2\phi + D_3^{K_1K^*}\sin 2\phi)\sin^2\theta\end{aligned}$$

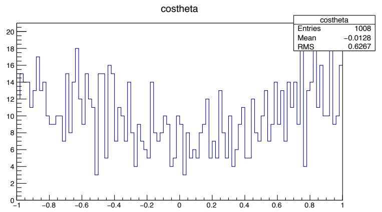
$$\begin{aligned}\mathcal{W}^{K_1K_2}(s,s_{13},s_{23},\theta,\phi) &= A_1^{K_1K_2}+\lambda_\gamma A_2^{K_1K_2}\cos\theta\\ &+ B_1^{K_1K_2}\sin^2\theta + \lambda_\gamma C_1^{K_1K_2}\sin^2\theta\cos\theta + D_1^{K_1K_2}\sin\cdot\theta\\ &+ (B_2^{K_1K_2}\cos 2\phi + B_3^{K_1K_2}\sin 2\phi)\sin^2\theta +\\ &+ \lambda_\gamma(C_2^{K_1K_2}\sin\phi +\\ &+ D_2^{K_1K_2}\cos 2\phi\sin^4\end{aligned}$$



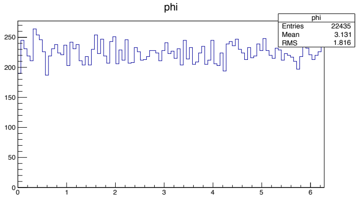
$1.3 < \sqrt{s} < 1.4$



$K_1^{1270}: A_1\cdot sin(2\phi) + B_1\cdot cos(2\phi)$

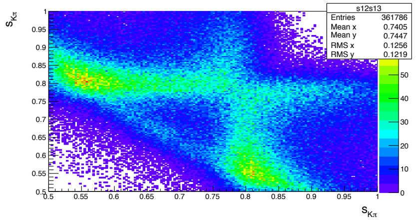


$1.6 < \sqrt{s} < 1.9$

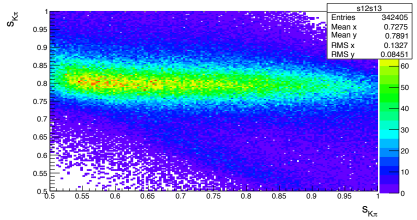


$K^{*1410}: A_3$

$$\begin{aligned}\mathcal{W}^{K_2K^*}(s_{13},s_{23},\theta,\phi) &= A_1^{K_2K^*}+\lambda_\gamma A_2^{K_2K^*}\cos\theta +\\ &+ B_1^{K_2K^*}\sin^2\theta + C_1^{K_2K^*}\sin^4\theta + \lambda_\gamma D^{K_2K^*}\sin^2\theta\cos\theta\\ &+ \left(B_2^{K_2K^*}\sin^2\theta + C_2^{K_2K^*}\sin^4\theta\right)\cos 2\phi\\ &+ \lambda_\gamma(E_1^{K_2K^*}\sin\phi + E_2^{K_2K^*}\cos\phi)\sin\theta\cos\theta\\ &+ (F_1^{K_2K^*}\sin\phi + F_2^{K_2K^*}\cos\phi)\cos 2\theta\sin\theta\end{aligned}$$



$K^0\pi^+\pi^0$ and $K^+\pi^-\pi^0$



$K^+\pi^+\pi^-$ and $K^0\pi^-\pi^+$

The functions, $A_i^{K_res}$, $B_i^{K_res}$, $C_i^{K_res}$ $\cdots$, are the functions of the Dalitz variables

Generator for K_{res}→Kππ decays…

MINTII

V. Belle, P. Pais talk at Lausanne WS '17, V. Bellee et.al. arXiv:1902.0920

"Covariant-Tensor" method

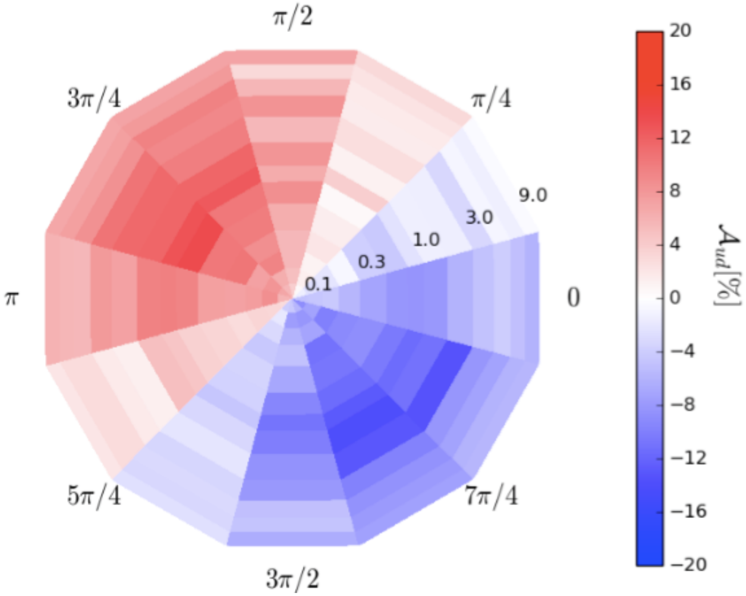
$$\boxed{\begin{aligned}\mathcal{A}^k_{\mathrm{R}}(\boldsymbol{x}) &= B_{L_B}(q_B(\boldsymbol{x}),0)\mathcal{T}^k_i(\boldsymbol{x})\mathcal{T}^k_j(\boldsymbol{x})\mathcal{S}^k_{ij,\mathrm{R}}(\boldsymbol{x})\,,\\ \mathcal{A}^k_{\mathrm{L}}(\boldsymbol{x}) &= P_i(-1)^{J_i-1}B_{L_B}(q_B(\boldsymbol{x}),0)\mathcal{T}^k_i(\boldsymbol{x})\mathcal{T}^k_j(\boldsymbol{x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

Applied by BESIII & LHCb e.g. to
D->Kπππ mode arXiv:1903.06316
D->Kπππ mode EPJC 78
B->J/ψKππ mode Thesis by D'argent

$$\mathcal{T}(s,q,L) = \frac{\sqrt{c}\;B_L(q,0)}{m_0^2 - s - im_0\Gamma(s,q,L)}$$

$$\mathcal{S}^{ij,m_\gamma} = \sum_{m_i,m_j} \langle P_2P_3|\mathcal{M}|R_j(m_j)\rangle\langle R_j(m_j)P_1|\mathcal{M}|R_i(m_i)\rangle\langle R_i(m_i)\gamma(m_\gamma)|\mathcal{M}|B\rangle$$

Decay chain	Spin factor
$B\to A\gamma, A\to VP_1, V\to P_2P_3$	$\epsilon^*_\alpha(\gamma)P^{\alpha\beta}_{(1)}(A)L_{(1)\beta}(V)$
$B\to A\gamma, A[D]\to VP_1, V\to P_2P_3$	$\epsilon^*_\alpha(\gamma)L^{\alpha\beta}_{(2)}(A)L_{(1)\beta}(V)$
$B\to A\gamma, A\to SP_1, S\to P_2P_3$	$\epsilon^{*\alpha}(\gamma)L_{(1)\alpha}(A)$
$B\to V_1\gamma, V_1\to V_2P_1, V_2\to P_2P_3$	$\epsilon^*_\alpha(\gamma)P^{\alpha\kappa}_{(1)}(V_1)\epsilon_{\kappa\lambda\mu\nu}L^{\lambda}_{(1)}(V_1)u^{\mu}_{V_1}P^{\nu\xi}_{(1)}(V_1)L_{(1)\xi}(V_2)$
$B\to T_-\gamma, T_-\to VP_1, V\to P_2P_3$	$L_{(1)\alpha}(B)\epsilon^*_\beta(\gamma)P^{\alpha\beta\lambda\mu}_{(2)}(T_-)L_{(1)\lambda}(T_-)P_{(1)\mu\nu}(T_-)L^{\nu}_{(1)}(V)$
$B\to T_-\gamma, T_-\to SP_1, S\to P_2P_3$	$L_{(1)\alpha}(B)\epsilon^*_\beta(\gamma)L^{\alpha\beta}_{(2)}(T_-)$
$B\to T_+\gamma, T_+\to VP_1, V\to P_2P_3$	$\epsilon_{\kappa\lambda\mu\nu}u^{\kappa}_{T_+}L_{(1)\alpha}(B)\epsilon^*_\beta(\gamma)P^{\alpha\beta\lambda\xi}_{(2)}(T_+)L^{\mu}_{(2)\xi}(T_+)P^{\nu\rho}_{(1)}(T_+)L_{(1)\rho}(V)$



Up-down asymmetry $\mathcal{A}_{ud}$ for simulated samples of $B^+\to K_1(1270)^+\gamma$ decays governed by two amplitudes only, $K_1(1270)^+\to K^+\rho(770)^0$ and $K_1(1270)^+\to K^*(892)^0\pi^+$, shown as a function of the generated ratio of fractions (radial coordinate, from 0.1 to 9.0) and phase difference between the two amplitudes (polar coordinate).

Generator for $K_{res} \rightarrow K\pi\pi$ decays…

STAY TUNED!

☑ MINTII vs Gampola comparison is going well (Second workshop next week).

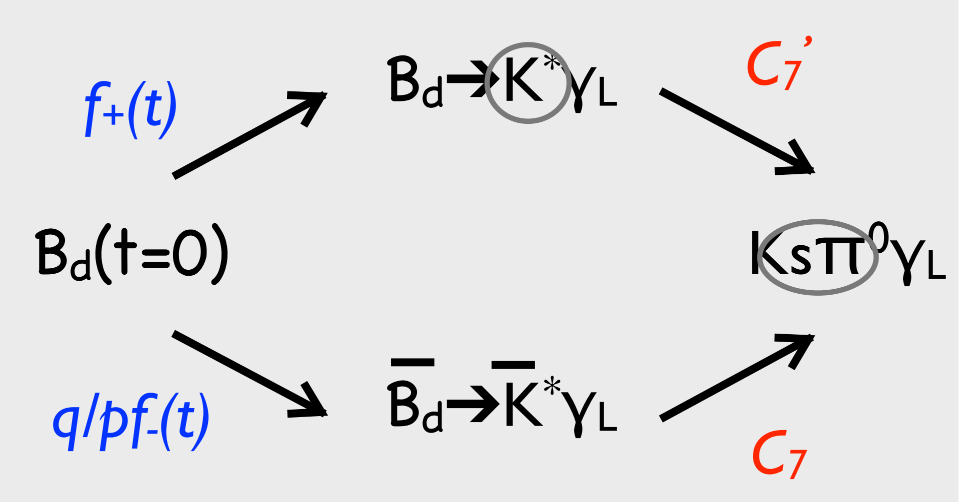
☑ Now that the generator is ready, we can start the full angular and Dalitz variable fit (5 dimensional fit) to determine simultaneously photon polarisation and hadronic parameters.

☑ This will improve significantly the sensitivity to the photon polarisation.

☑ The generators can be extended to apply to the other processes including kaonic resonances (e.g. tau-> K pi pi nu).

Time dependent analysis of $B \to K_{res}\gamma \to (K\pi\pi)\gamma$

Time dependent CPV method



$f_+(t)$

$B_d \rightarrow K^* \gamma_L$

C_7'

$B_d(t=0)$

$K_S \pi^0 \gamma_L$

$q/p f_-(t)$

$\bar{B}_d \rightarrow \bar{K}^* \gamma_L$

C_7

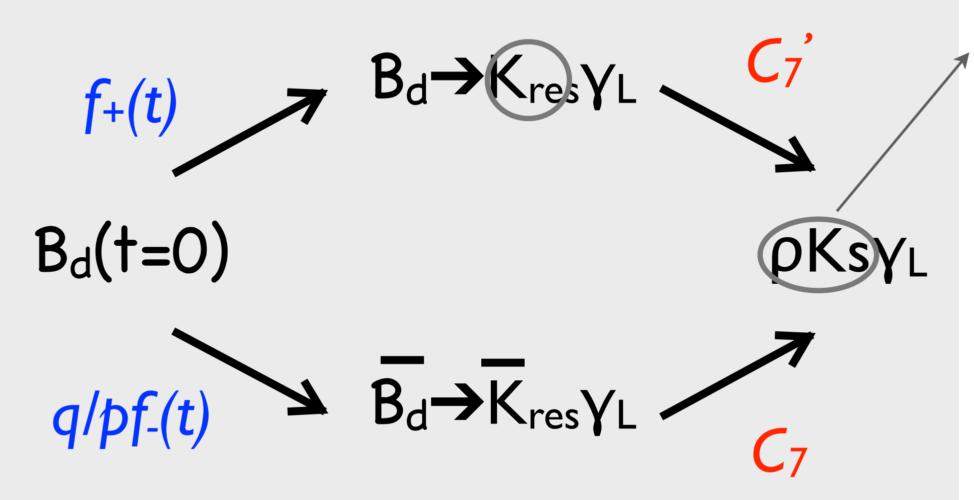
Atwood, Gronau, Soni, PRL 79 (1997)
Atwood, Gershon, Hazumi, Soni, PRD71 (2005)

- In SM C_7' is negligibly small, so the interference does not occur (no CPV).
- Thus, observation of CPV is a signal beyond the SM.

Time dependent CPV method

$K_S\pi^+\pi^-\gamma_L$ Atwood, Gronau, Soni, PRL 79 (1997)

Atwood, Gershon, Hazumi, Soni, PRD71 (2005)



$f_+(t)$

$B_d \rightarrow K_{res}\gamma_L$

C_7'

$B_d(t=0)$

$\rho K_S\gamma_L$

$q/p f_-(t)$

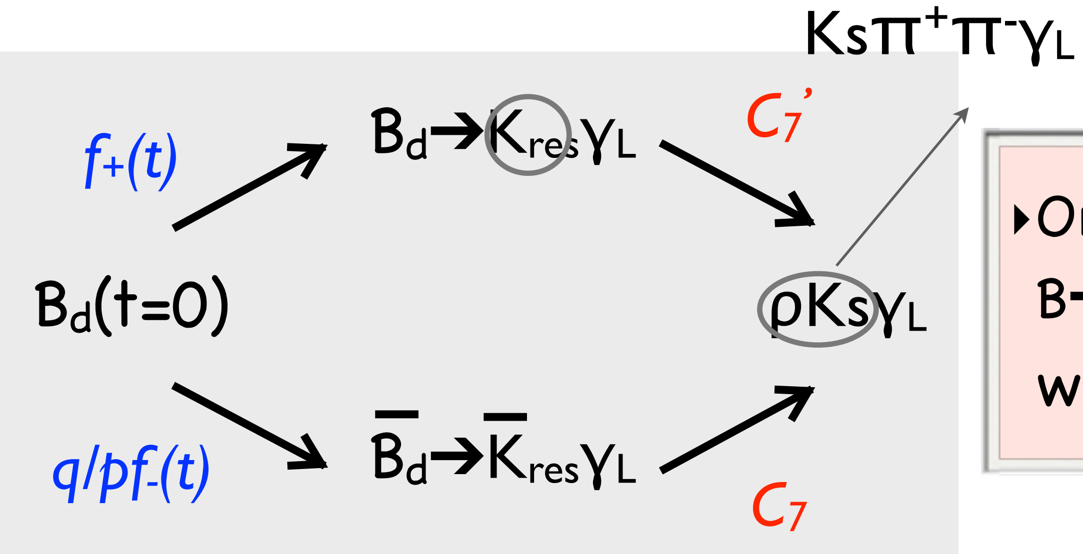
$\overline{B}_d \rightarrow \overline{K}_{res}\gamma_L$

C_7

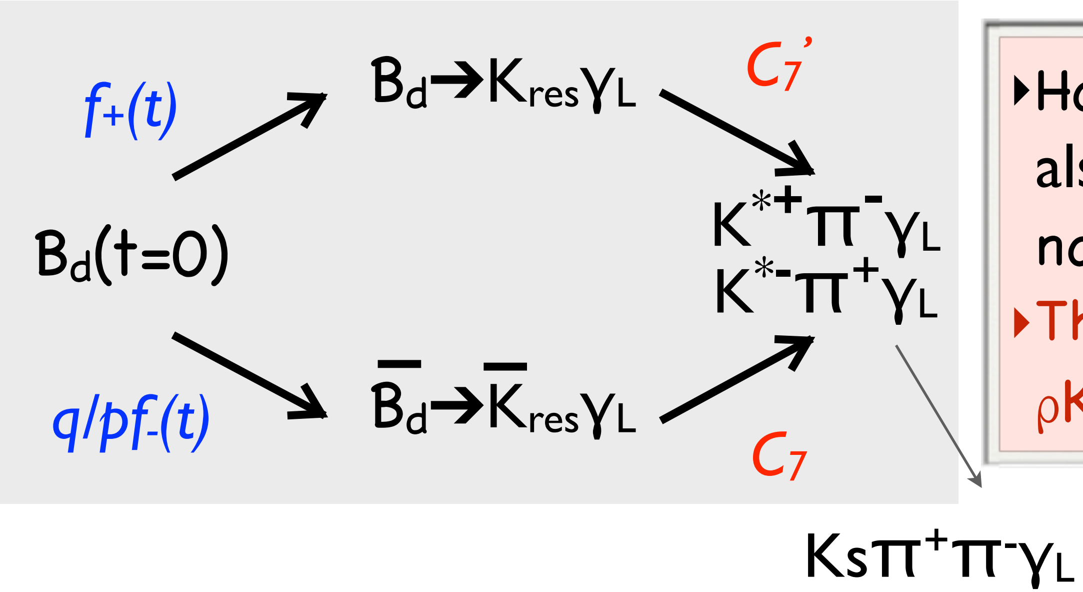
- One can do the same study using $B \rightarrow \rho K_S\gamma_L$ channel (CP eigenstate) with final state $K_S\pi^+\pi^-\gamma_L$.

Time dependent CPV method

Atwood, Gronau, Soni, PRL 79 (1997)
Atwood, Gershon, Hazumi, Soni, PRD71 (2005)



- One can do the same study using $B \rightarrow \rho K_S \gamma_L$ channel (CP eigenstate) with final state $K_S\pi^+\pi^-\gamma_L$.



- However, $K_S\pi^+\pi^-\gamma_L$ final state can also come from $K^*\pi$ channel, which is not CP eigenstate.
- This can "dilute" the CP violation from $\rho K_S \gamma_L$ channel.

Time dependent CPV formula

Time dependent CPV (measurable)

$$S_{K_S\pi^+\pi^-} = \frac{2Im\left[\frac{q}{p}\left(\frac{c}{c'^*}\right)\right]}{(1+|\frac{c}{c'}|^2)}$$

Photon polarization

$$\times \frac{\sum_{\lambda=L,R}\left\{-|A_\lambda^{\rho K_S}|^2 + \mathrm{Re}\left[A_\lambda^{*K^{*-}\pi^+} A_\lambda^{K^{*+}\pi^-}\right] + \mathrm{Re}\left[A_\lambda^{*\kappa^-\pi^+} A_\lambda^{\kappa^+\pi^-}\right] - 2\mathrm{Re}[A_\lambda^{*\rho K_S} A_\lambda^{K^{*+}\pi^-}] - 2\mathrm{Re}[A_\lambda^{*\rho K_S} A_\lambda^{\kappa^+\pi^-}]\right\}}{\sum_{\lambda=L,R}\left\{|A_\lambda^{\rho K_S}|^2 + |A_\lambda^{*K^{*+}\pi^-}|^2 + |A_\lambda^{*\kappa^+\pi^-}|^2 + 2\mathrm{Re}[A_\lambda^{*\rho K_S} A_\lambda^{K^{*+}\pi^-}] + 2\mathrm{Re}[A_\lambda^{*\rho K_S} A_\lambda^{\kappa^+\pi^-}]\right\}}$$

=D dilution factor

Dilution factor to be extracted from the resonance study (angular analysis)

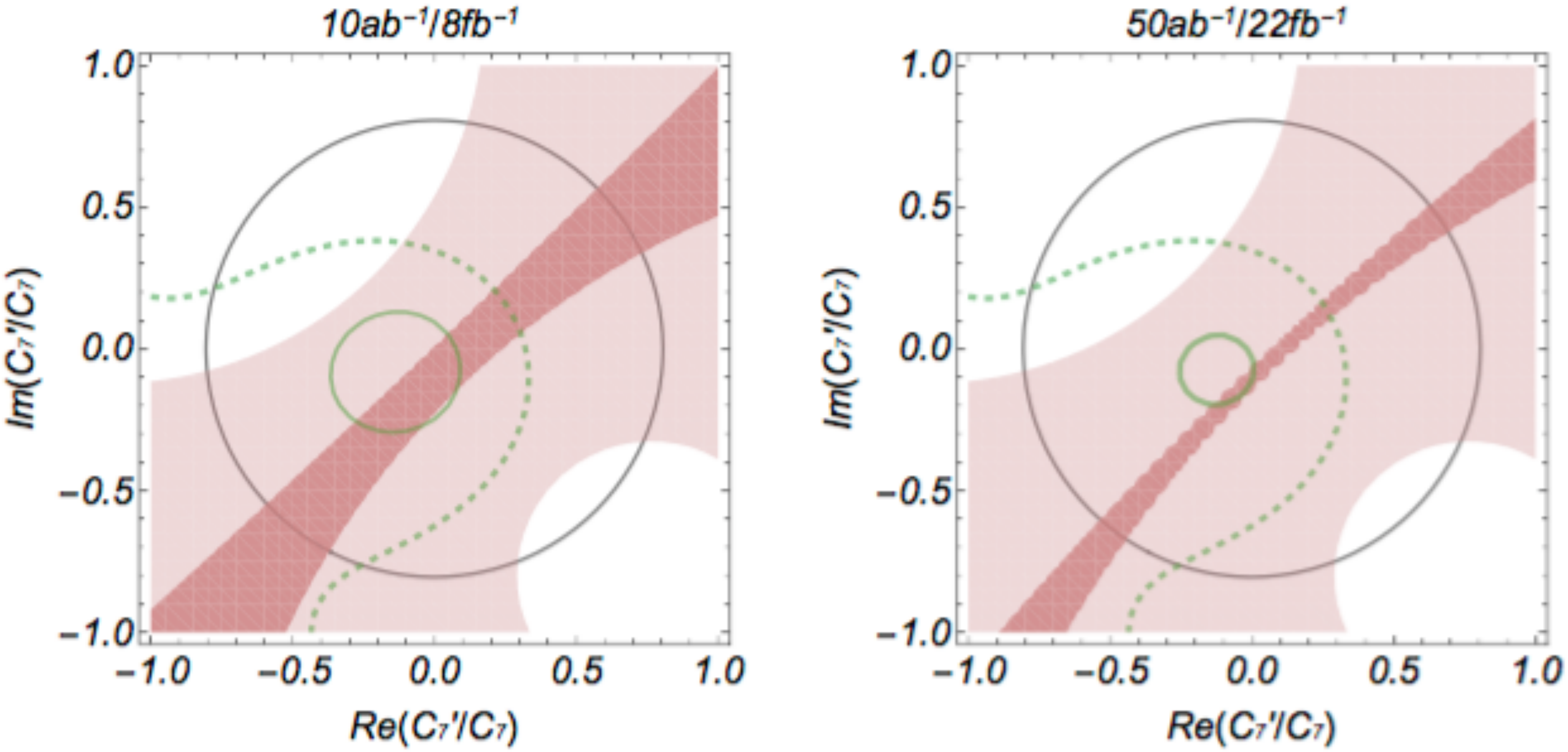
Belle: Phys.Rev.Lett. 101 (2008), Babar: Phys.Rev. D93 (2016)

- Note: a null-test can be performed without dilution factor (i.e. $S_{K_S\pi^+\pi^-\gamma} \neq 0$ is immediately a discovery of new physics!)

Time dependent analysis

$B_d \rightarrow K_S \pi^0 \gamma$ vs $B_d \rightarrow K_S \pi^+ \pi^- \gamma$

S. Akar, E. Ben-Haim, J. Hebinger, E.K. F.Yu
arXiv:1802.09433



Red: Belle II golden channel $B_d \rightarrow K_S \pi^0 \gamma$

Green: LHCb B->K*ee angular analysis

Time dependent analysis

$B_d \to K_S \pi^0 \gamma$ vs $B_d \to K_S \pi^+ \pi^- \gamma$

S. Akar, E. Ben-Haim, J. Hebinger, E.K. F. Yu
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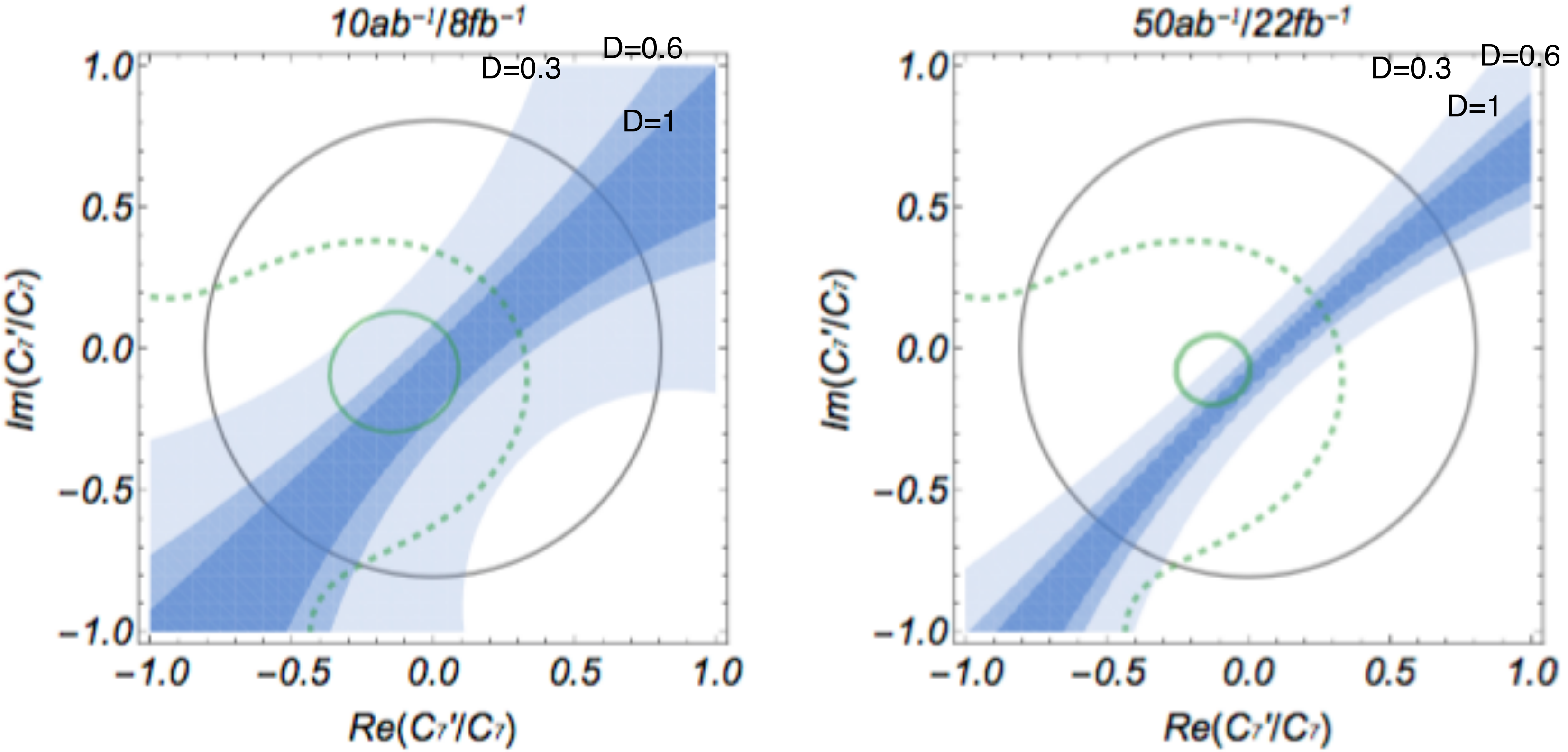


Blue: Belle II $B_d \to K_S \pi^+ \pi^- \gamma$ (without Dalitz information)
Green: LHCb B->K*ee angular analysis

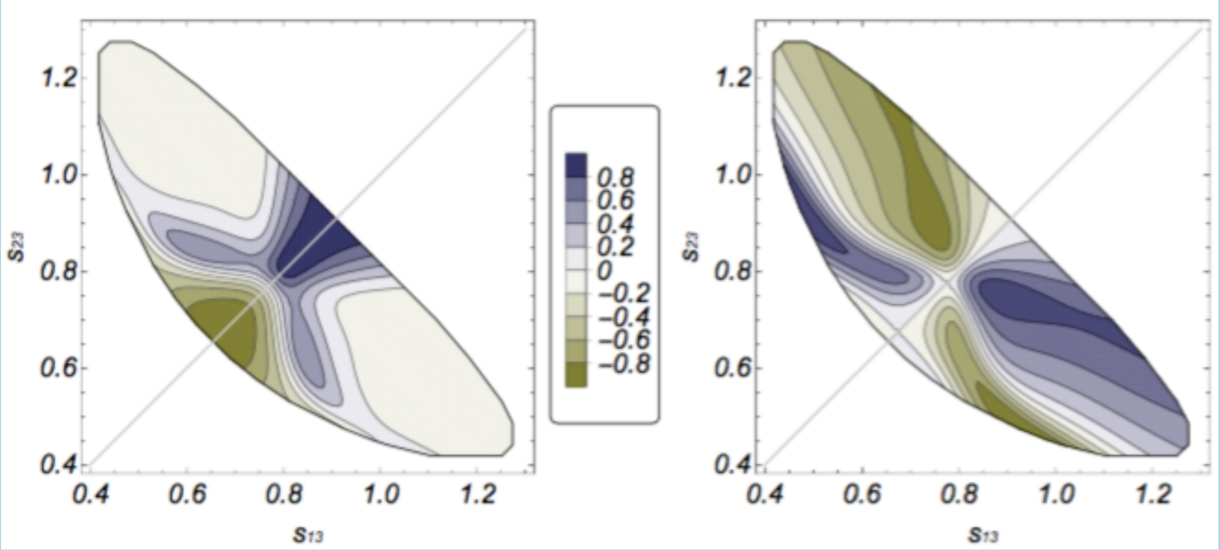
$B_d \to K_S\pi^+\pi^-\gamma$: new observable!

S. Akar, E. Ben-Haim, J. Hebinger, E.K. F.Yu
arXiv:1802.09433

$$S_{K_S\pi^+\pi^-} = \frac{2Im\left[\frac{q}{p}\left(\frac{c}{c'^*}\right)\right]}{\left(1+|\frac{c}{c'}|^2\right)}$$

$$\times \frac{\sum_{\lambda=L,R}\left\{-|A_\lambda^{\rho K_S}|^2 + \mathrm{Re}\left[A_\lambda^{*K^{*-}\pi^+} A_\lambda^{K^{*+}\pi^-}\right] + \mathrm{Re}\left[A_\lambda^{*\kappa^-\pi^+} A_\lambda^{\kappa^+\pi^-}\right] - 2\mathrm{Re}[A_\lambda^{*\rho K_S} A_\lambda^{K^{*+}\pi^-}] - 2\mathrm{Re}[A_\lambda^{*\rho K_S} A_\lambda^{\kappa^+\pi^-}]\right\}}{\sum_{\lambda=L,R}\left\{|A_\lambda^{\rho K_S}|^2 + |A_\lambda^{*K^{*+}\pi^-}|^2 + |A_\lambda^{*\kappa^+\pi^-}|^2 + 2\mathrm{Re}[A_\lambda^{*\rho K_S} A_\lambda^{K^{*+}\pi^-}] + 2\mathrm{Re}[A_\lambda^{*\rho K_S} A_\lambda^{\kappa^+\pi^-}]\right\}}$$

=D: dilution factor



Re[D(s12,s23)] **Im[D(s12,s23)]**

Im[D] is symmetric so it becomes zero when integrating over the Dalitz space

In previous studies, Dilution factor was Dalitz integrated. Without integration, we have two observables (Re and Im of Dilution factor). Using these information, we can resolve the ambiguity and constrain both real and imaginary part of C7/C7'.

$B_d \to K_S \pi^+ \pi^- \gamma$: new observable!

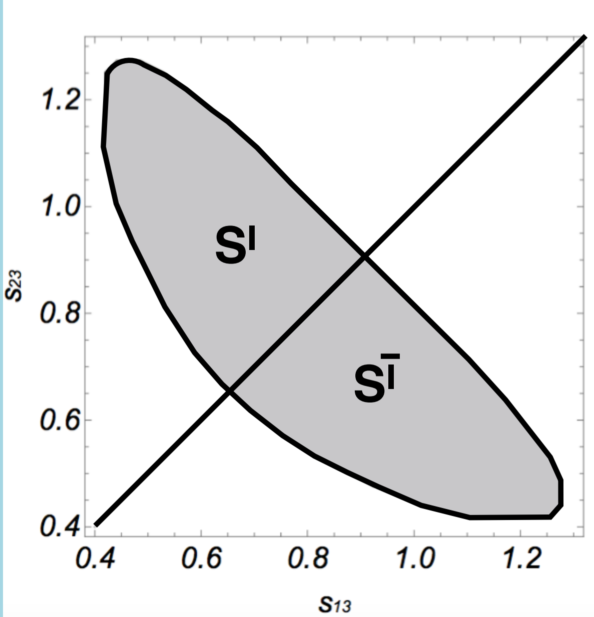
S. Akar, E. Ben-Haim, J. Hebinger, E.K. F.Yu
arXiv:1802.09433

$$S_{K_S\pi^+\pi^-} = \frac{2Im\left[\frac{q}{p}\left(\frac{c}{c'^*}\right)\right]}{\left(1+|\frac{c}{c'}|^2\right)}$$

$$\times\frac{\sum_{\lambda=L,R}\left\{-|A_\lambda^{\rho K_S}|^2 + \mathrm{Re}\left[A_\lambda^{*K^{*-}\pi^+}A_\lambda^{K^{*+}\pi^-}\right] + \mathrm{Re}\left[A_\lambda^{*\kappa^-\pi^+}A_\lambda^{\kappa^+\pi^-}\right] - 2\mathrm{Re}[A_\lambda^{*\rho K_S}A_\lambda^{K^{*+}\pi^-}] - 2\mathrm{Re}[A_\lambda^{*\rho K_S}A_\lambda^{\kappa^+\pi^-}]\right\}}{\sum_{\lambda=L,R}\left\{|A_\lambda^{\rho K_S}|^2 + |A_\lambda^{*K^{*+}\pi^-}|^2 + |A_\lambda^{*\kappa^+\pi^-}|^2 + 2\mathrm{Re}[A_\lambda^{*\rho K_S}A_\lambda^{K^{*+}\pi^-}] + 2\mathrm{Re}[A_\lambda^{*\rho K_S}A_\lambda^{\kappa^+\pi^-}]\right\}}$$

=D: dilution factor

$S_{KS\pi+\pi-\gamma}$



For example,

- measure the CPV parameter $S_{KS\pi+\pi-\gamma}$ for upper (S^I) and lower ($S^{\bar{I}}$) part of Dalitz plane separately.
- then, we can compose two observables:

$$S^+ \equiv S^I_{\pi^+\pi^-K^0_S\gamma} + S^{\bar{I}}_{\pi^+\pi^-K^0_S\gamma}$$

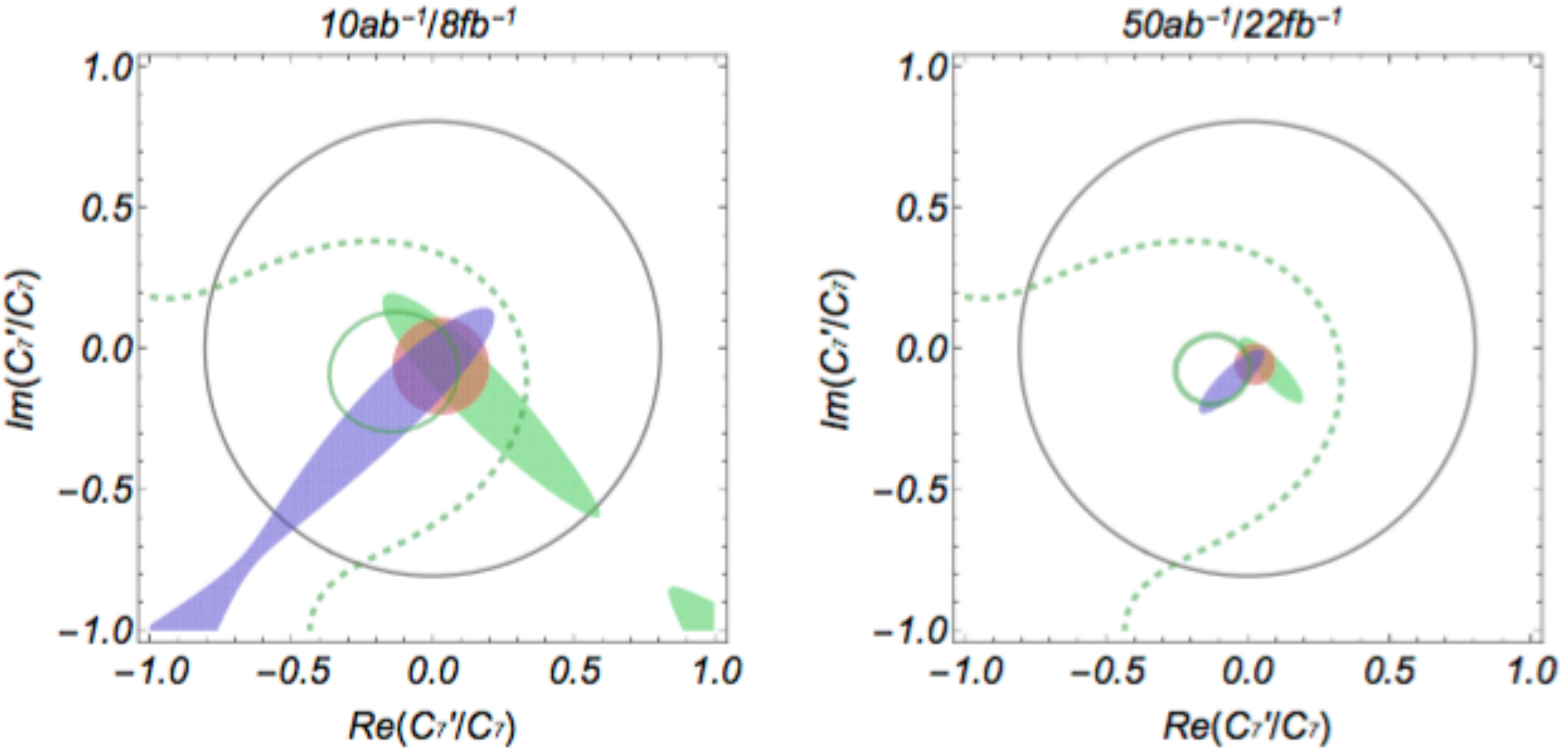
$$S^- \equiv S^I_{\pi^+\pi^-K^0_S\gamma} - S^{\bar{I}}_{\pi^+\pi^-K^0_S\gamma}$$

Similar to the GGSZ method, PRD68 (2003)

For model independent analysis, see
Le Yaouanc, A.Tayduganov, EK, PLB '16

$B_d \rightarrow K_S \pi^+ \pi^- \gamma$: new observable!

S. Akar, E. Ben-Haim, J. Hebinger, E.K. F. Yu
arXiv:1802.09433



Purple : in case Re[D] > Im[D]
Green: in case Re[D] < Im[D]
Red: in case Re[D] = Im[D]

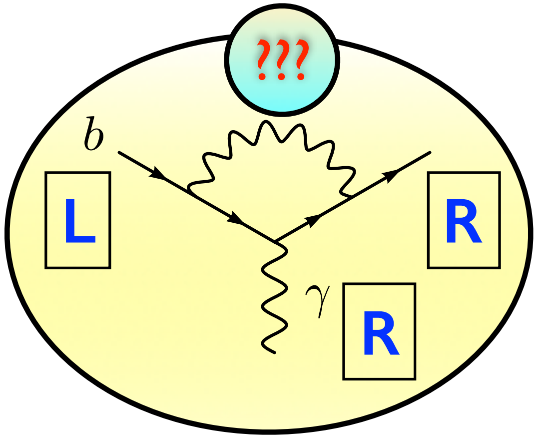
Conclusions

- There have been many progresses in photon polarisation determination of the $b \rightarrow s\gamma$ process.
- $B \rightarrow K\pi\pi\gamma$ channel is motivated by its large data sample. Also $B \rightarrow K\pi\pi\gamma$ is the simplest possible channel for angular analysis.
- The angular analysis method determines the photon polarisation by measuring the Kaonic resonance polarization. Thus, the challenge is to understand the $K_{res} \rightarrow K\pi\pi$ decays very precisely.
- Simultaneous fit of angles and Dalitz variables is crucial and a lot of efforts are put in such works by LHCb/Belle/BelleII.

- For the time dependent analysis, $B_d \rightarrow K_S\pi^+\pi^-\gamma$ channel requires an extraction of the dilution factor D, which is the challenges for this channel (though it can be obtained as a byproduct of the angular analysis).
- We showed that $B_d \rightarrow K_S\pi^+\pi^-\gamma$ has an advantage compared to $B_d \rightarrow K_S\pi^0\gamma$ (golden-)channel since the Dalitz distribution can provide extra information, which provides more information, such as both the real/imaginary parts of the C7′/C7.

Backup

Right-handed: which NP model?



- What types of new physics models?

For example, models with right-handed neutrino, or custodial symmetry in general induces the right handed current.

Left-Right symmetric model (W_R)

Blanke et al. JHEP1203

SUSY GUT model δ_{RR} mass insertion

Girrbach et al. JHEP1106

- Which flavour structure?

The models that contain new particles which change the chirality inside of the b→sγ loop can induce a large chiral enhancement!

Left-Right symmetric model: mt/mb

Cho, Misiak, PRD49, '94
Babu et al PLB333 '94

SUSY with δ_{RL} mass insertions: m_{SUSY}/mb

Gabbiani, et al. NPB477 '96
Ball, EK, Khalil, PRD69 '04

NP signal beyond the constraints from Bs oscillation parameters possible.

Model independent analysis

Use of B->J/psi Kππ channel

Le Yaouanc, A. Tayduganov, EK, PLB '16

$$\mathcal{W}^V(s_{13},s_{23},\cos\theta,\phi)_s \equiv a^V + (a_1^V + a_2^V\cos 2\phi + a_3^V \sin 2\phi)\sin^2\theta + b^V\cos\theta$$

$$V = J/\psi, \gamma$$

$$\mathcal{W}^V(s_{13},s_{23},\cos\theta,\phi)_s = \frac{\sum_{s_z} |\mathcal{A}^V_{s_z}(s)|^2 \left|\vec{\epsilon}_{K_{1s_z}} \cdot \vec{\mathcal{J}}_{K_1}(s_{13},s_{23})_s\right|^2}{\int ds_{13}\int ds_{23}\int d(\cos\theta)\int d\phi \sum_{s_z} |\mathcal{A}^V_{s_z}(s)|^2 \left|\vec{\epsilon}_{K_{1s_z}} \cdot \vec{\mathcal{J}}_{K_1}(s_{13},s_{23})_s\right|^2}$$

$$\begin{aligned}
a^V(s,s_{13},s_{23}) &= N_s^V \xi_a^V \left[|c_1|^2 + |c_2|^2 - 2\mathrm{Re}(c_1 c_2^*)\cos\delta\right] ,\\
a_1^V(s,s_{13},s_{23}) &= N_s^V \xi_{a_i}^V \left[|c_1|^2 + |c_2|^2 - 2\mathrm{Re}(c_1 c_2^*)\cos\delta\right] ,\\
a_2^V(s,s_{13},s_{23}) &= N_s^V \xi_{a_i}^V \left[(|c_1|^2 + |c_2|^2)\cos\delta - 2\mathrm{Re}(c_1 c_2^*)\right]\\
a_3^V(s,s_{13},s_{23}) &= N_s^V \xi_{a_i}^V \left[(|c_1|^2 - |c_2|^2)\sin\delta\right] ,\\
b^V(s,s_{13},s_{23}) &= -N_s^V \xi_b^V \left[2\mathrm{Im}(c_1 c_2^*)\sin\delta\right] ,
\end{aligned}$$

$$\begin{aligned}
\xi_a^V(s) &\equiv \frac{|\mathcal{A}_+^V(s)|^2 + |\mathcal{A}_-^V(s)|^2}{2} ,\\
\xi_{a_i}^V(s) &\equiv \frac{-(|\mathcal{A}_+^V(s)|^2 + |\mathcal{A}_-^V(s)|^2) + 2|\mathcal{A}_0^V(s)|^2}{4}\\
\xi_b^V(s) &\equiv \frac{|\mathcal{A}_+^V(s)|^2 - |\mathcal{A}_-^V(s)|^2}{2} .
\end{aligned}$$

Preliminary result on the simultaneous fit

EK & F. Le Diberder B2TiP workshop 2015

- ❖ Photon polarization is sensitive to the imaginary part of the K1 decay amplitudes

$$b^{\gamma} \propto \langle \mathrm{Im}(\hat{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^{*})) \rangle \left[|C_7'|^2 - |C_7|^2 \right]$$

- ❖ The imaginary part comes from interference of different resonances (either initial or intermediate states).
- ❖ These are very difficult to predict theoretically and the simultaneous fit is the most powerful!

The error matrix for simultaneous fit

$$E = \begin{array}{cl} \left(\begin{array}{c|cccc} 0.034 & -0.133 & -0.021 & -0.067 & 0.007 \\ \hline & 0.040 & 0.260 & 0.630 & -0.320 \\ & & 0.019 & 0.395 & -0.470 \\ & & & 0.680 & -0.405 \\ & & & & 0.180 \end{array} \right) & \begin{array}{l} \longleftarrow \text{Photon polarization} \\ \longleftarrow \text{K1(1270)/K1(1270) separation} \\ \longleftarrow (K\pi)_{\text{s-wave}} \text{ contributions} \\ \longleftarrow \text{K1 mixing angle c.f. } (60\pm10)^{\circ} \\ \longleftarrow \text{Damping factor c.f. } (4\pm0.5) \end{array} \end{array}$$

Preliminary result!

At ~3% level sensitivity to all 5 parameters (5k events)!

ω method: optimal observable beyond A^{UD}

Davier, Duflot, Le Diberder, Rouge, PLB306 '93,
Atwood, Soni, PRD45 '92

$$\mathcal{W}(s, s_{13}, s_{23}, \cos\theta) \propto a(s, s_{13}, s_{23})(1+\cos^2\theta) + \lambda_\gamma b(s, s_{13}, s_{23})\cos\theta$$

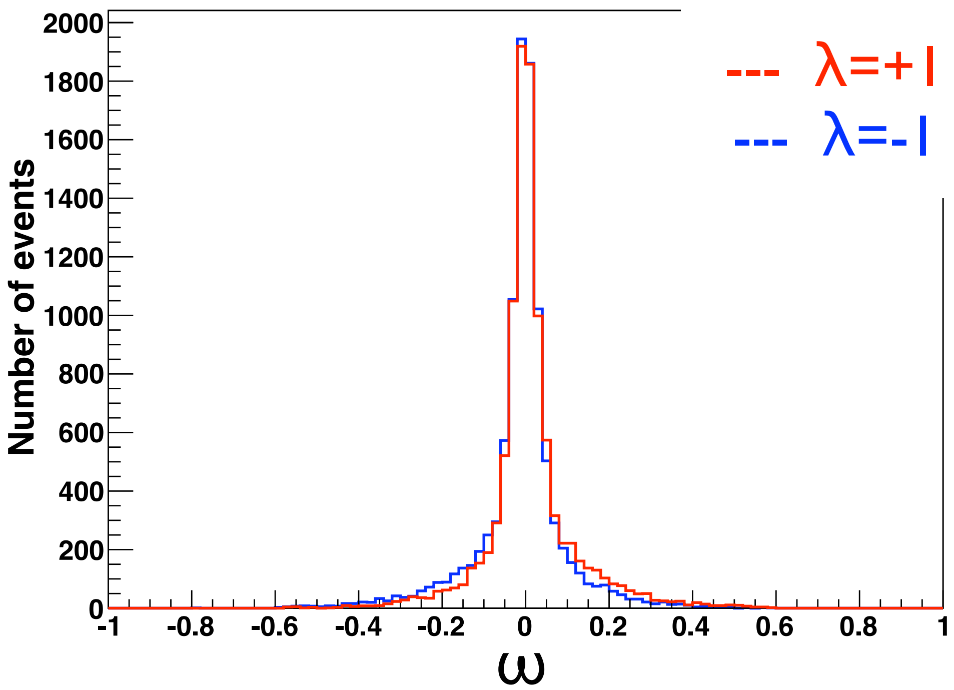
$$\boxed{\omega(s, s_{13}, s_{23}, \cos\theta) \equiv \frac{b(s, s_{13}, s_{23})\cos\theta}{a(s, s_{13}, s_{23})(1+\cos^2\theta)}}$$

How to use the ω variable?

For each event $\xi_i(s,s_{13},s_{23},\cos_\theta)$:

1. Compute the ω value **knowing the function J $(s,s_{13},s_{23},\cos_\theta)$**.
2. Make a ω distribution.
3. Polarization is then obtained!

$$\boxed{\lambda = \frac{\langle\omega\rangle}{\langle\omega^2\rangle}} \quad \boxed{\sigma_\lambda^2 = 1/N\langle\left(\frac{\omega}{1+\lambda_\gamma^{\rm fit}\omega}\right)^2\rangle}$$



EK, Le Yaouanc, A. Tayduganov, PRD83 ('11)

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How to use the ω variable?

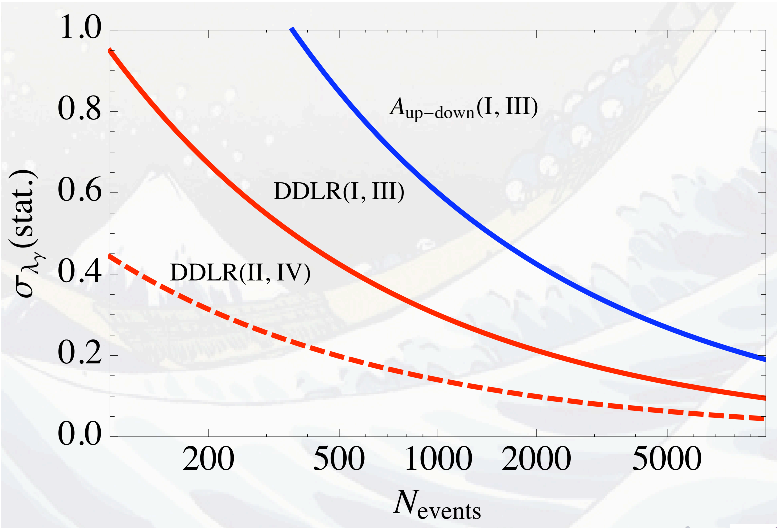
For each event $\xi_i(s, s_{13}, s_{23}, \cos_\theta)$:

1. Compute the ω value knowing the function J $(s, s_{13}, s_{23}, \cos_\theta)$.
2. Make a ω distribution.
3. Polarization is then obtained!

$$\boxed{\lambda = \frac{\langle\omega\rangle}{\langle\omega^2\rangle}}$$

$$\boxed{\sigma_\lambda^2 = 1/N\langle\left(\frac{\omega}{1+\lambda_\gamma^{\text{fit}}\omega}\right)^2\rangle}$$

EK, Le Yaouanc, A. Tayduganov, PRD83 ('11)



ω method reduces the statistical errors in λ by a factor of two comparing to A^{UD}

Combining diff. charged modes

Thesis Tayduganov '11

Babar'05

same!

same!

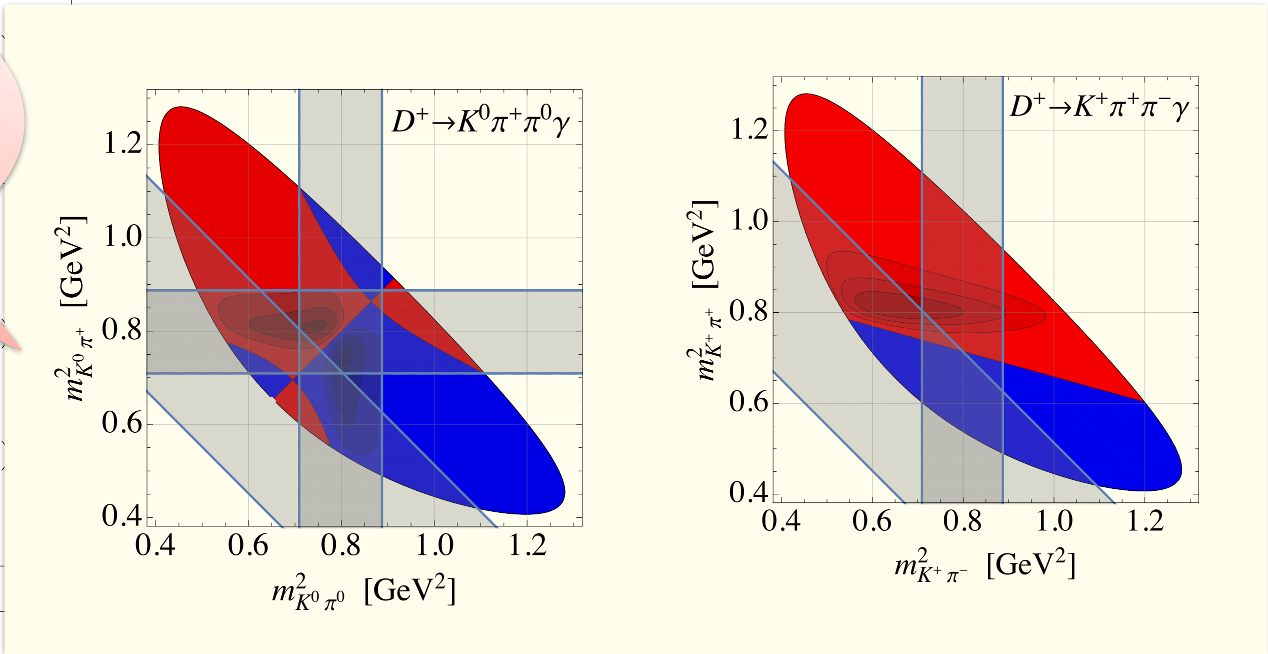
$I :$

II

$III : \quad K_1^0(1270/1400) \to \underbrace{\underbrace{\pi^0(p_1)\pi^-}_{\rho^-}(p_2)K^+}_{K^{*+}}(p_3$

$IV : \quad K_1^0(1270/1400) \to \underbrace{\underbrace{\pi^+(p_1)\pi^-}_{\rho^0}(p_2)K^0}_{K^{*+}}(p_3$

We multiply sign[s13-s23] for charged case.



same!

same!

$$\mathcal{M}_I(K_1^+ \to \pi^0(p_1)\pi^+(p_2)K^0(p_3)) = \frac{\sqrt{2}}{3}\mathcal{M}^{K^{*0}}_{(P_1P_3)P_2} - \frac{\sqrt{2}}{3}\mathcal{M}^{K^{*+}}_{(P_2P_3)P_1} + \frac{1}{\sqrt{3}}\mathcal{M}^{\rho^+}_{(P_1P_2)P_3} \tag{2.29a}$$

$$\mathcal{M}_{II}(K_1^+ \to \pi^-(p_1)\pi^+(p_2)K^+(p_3)) = -\frac{2}{3}\mathcal{M}^{K^{*0}}_{(P_1P_3)P_2} - \frac{1}{\sqrt{6}}\mathcal{M}^{\rho^0}_{(P_1P_2)P_3} \tag{2.29b}$$

$$\mathcal{M}_{III}(K_1^0 \to \pi^0(p_1)\pi^-(p_2)K^+(p_3)) = \frac{\sqrt{2}}{3}\mathcal{M}^{K^{*+}}_{(P_1P_3)P_2} - \frac{\sqrt{2}}{3}\mathcal{M}^{K^{*0}}_{(P_2P_3)P_1} + \frac{1}{\sqrt{3}}\mathcal{M}^{\rho^-}_{(P_1P_2)P_3} \tag{2.29c}$$

$$\mathcal{M}_{IV}(K_1^0 \to \pi^+(p_1)\pi^-(p_2)K^0(p_3)) = -\frac{2}{3}\mathcal{M}^{K^{*+}}_{(P_1P_3)P_2} - \frac{1}{\sqrt{6}}\mathcal{M}^{\rho^0}_{(P_1P_2)P_3} \tag{2.29d}$$