Photon Helicity in $b \to s\gamma$ Decays towards New Physics Search

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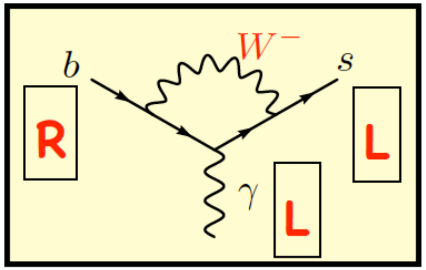
1st LHCb Physics Frontier
14-15 Dec 2019

OUTLINE

- Photon polarization in $b \to s\gamma$



- Recent Progresses on photon polarization
- Novel Approach to determine the photon helicity

  Wang, Yu, Zhao, 1909.13083

- Summary

BEYOND SM: THREE FRONTIERS

- High Energy Frontier:
  Tevatron, LHC…
  Direct search

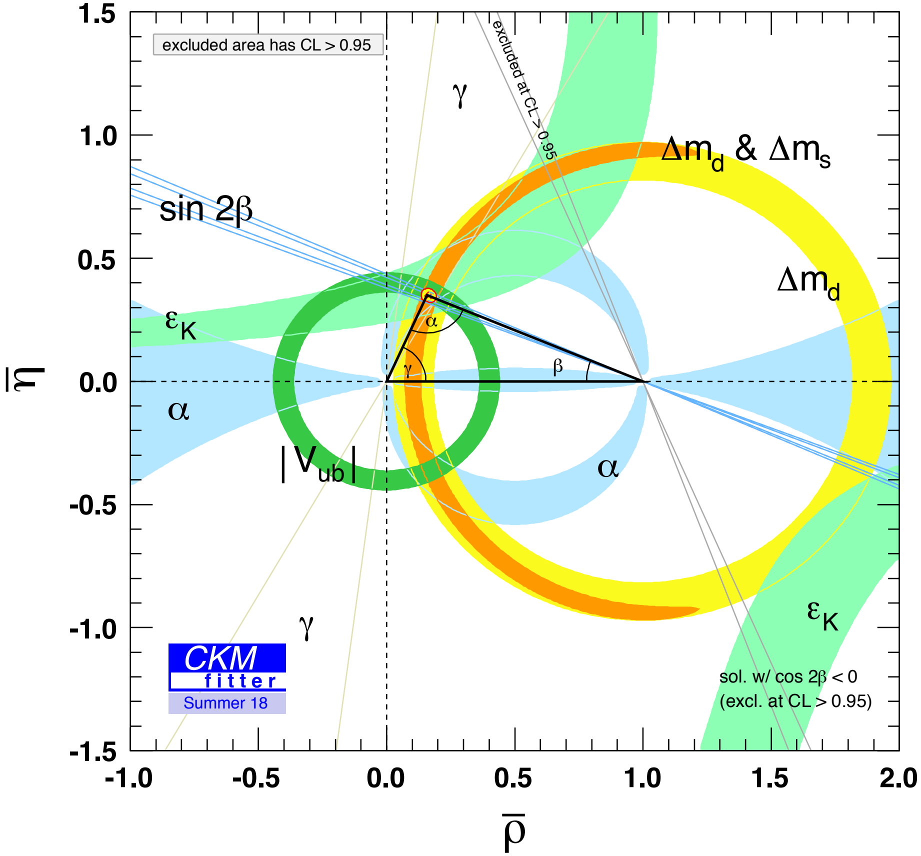
- High Precision Frontier:
  B factories Tau/charm
  factory …
  indirect search

BEYOND SM: INTENSITY FRONTIER

If the LHC/xxx did not discover any new particle beyond SM, precision study becomes an ideal platform to detect NP effects.

If the LHC/xxx discovers new elementary particles beyond SM, then precision physics will be necessary to constrain the underlying framework.

BOTTOM PHYSICS



- Looks great, but can be deceived (tension)
- O(10%-15%) NP is still allowed

R_K/R_K* ANOMALY:

$$R_{K^*}[q^2_{\rm min}, q^2_{\rm max}] \equiv \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 d\Gamma(B\to K^*\mu^+\mu^-)/dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 d\Gamma(B\to K^* e^+ e^-)/dq^2},$$

q^2:invariant mass of lepton pair

Observable	SM results	Experimental data	
$R_K : q^2 = [1,6]\mathrm{GeV}^2$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$	2.6 Sigma
$R^{\rm low}_{K^*} : q^2 = [0.045, 1.1]\ \mathrm{GeV}^2$	$0.920^{+0.007}_{-0.006}$	$0.66^{+0.11}_{-0.07} \pm 0.03$	2.3 Sigma
$R^{\rm central}_{K^*} : q^2 = [1.1, 6]\ \mathrm{GeV}^2$	0.996 ± 0.002	$0.69^{+0.11}_{-0.07} \pm 0.05$	2.5 Sigma

SM: Geng, et.al, 1704.05446

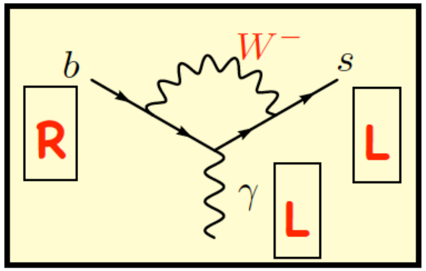
LHCb: PRL, 113, 151601(2014)
LHCb: 1705.05802

Anomalies in heavy flavor:
New Physics or QCD contaminations ?

Photon polarization in $b \to s\gamma$

PHOTON POLARIZATION OF $b \to s\gamma$

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



W-boson couples only left-handed ⟷ γ from $b \to s\gamma$ should be mostly left-handed

- ✓ $b \to s\gamma$: left-handed polarization
- ✓ $\bar{b} \to \bar{s}\gamma$: right-handed polarization

HOW DO WE MEASURE THE POLARIZATION?

- Time-dependent measurements:
  - ✓ $B_d \to K_s \pi^0 \gamma$, $B_d \to \rho\gamma$
  - ✓ $B_d \to K_s \pi^+ \pi^- \gamma$
  - ✓ $B_s \to K^+ K^- \gamma$

LHCb(2013):
$P_{\Lambda b}$ is "small" :
(0.06±0.07±0.02)

- Angular distribution :
  - ✓ Baryonic decays: $\Lambda_b \to \Lambda\gamma$, request the polarization of Λ_b or Λ
  - ✓ $B \to K_{res}\ (\to K\pi\pi)\gamma$

NEW PHYSICS CONTRIBUTIONS IN $b \to s\gamma$

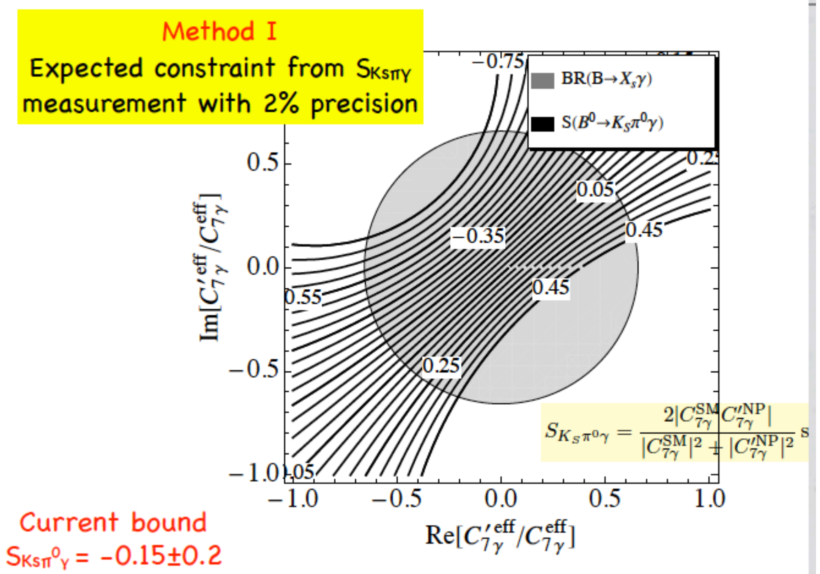
$$\mathcal{M}(b \to s\gamma) \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[\underbrace{(C_{7\gamma}^{\rm SM} + C_{7\gamma}^{\rm NP}) \langle \mathcal{O}_{7\gamma} \rangle}_{\propto \mathcal{M}_L} + \underbrace{C_{7\gamma}^{\prime \rm NP} \langle \mathcal{O}_{7\gamma}^\prime \rangle}_{\propto \mathcal{M}_R}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

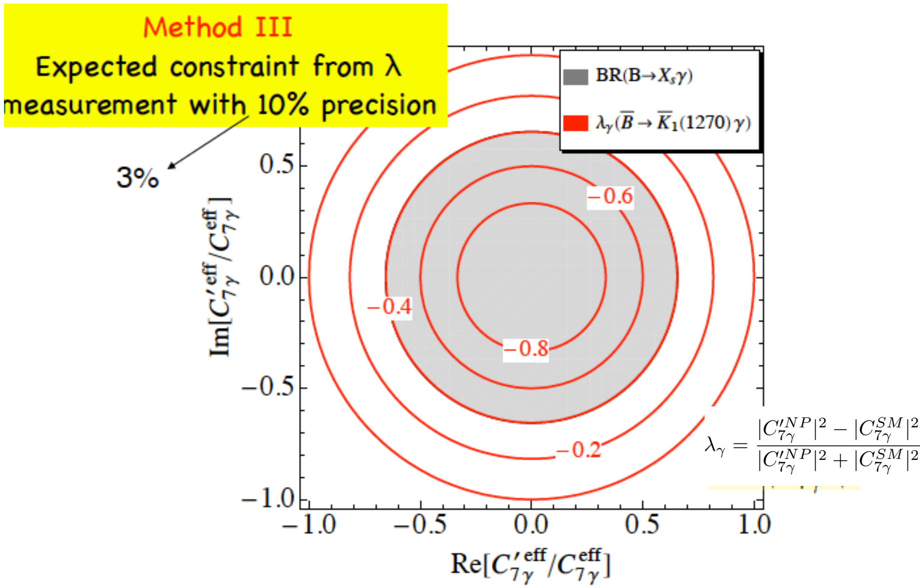
Note:

In NP, $C_{7\gamma}^{NP}$ and/or $C'_{7\gamma}{}^{NP}$ can be complex numbers!

We only consider $C'_{7\gamma}{}^{NP}$ in the following.

COMPLEMENTARITY





Discovering NP: Competitive
Constraining NP: Complementary

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Angular distribution of B→K$_1$γ→(Kππ)γ

$$\lambda_\gamma \equiv \frac{|\mathcal{A}(\bar{B} \to \bar{K}_{1R}\gamma_R)|^2 - |\mathcal{A}(\bar{B} \to \bar{K}_{1L}\gamma_L)|^2}{|\mathcal{A}(\bar{B} \to \bar{K}_{1R}\gamma_R)|^2 + |\mathcal{A}(\bar{B} \to \bar{K}_{1L}\gamma_L)|^2}$$

$$= \frac{|C'^{NP}_{7\gamma}|^2 - |C^{SM}_{7\gamma}|^2}{|C'^{NP}_{7\gamma}|^2 + |C^{SM}_{7\gamma}|^2}$$

In SM, $\lambda_\gamma \simeq -1$

K1

$K_1(1270)$

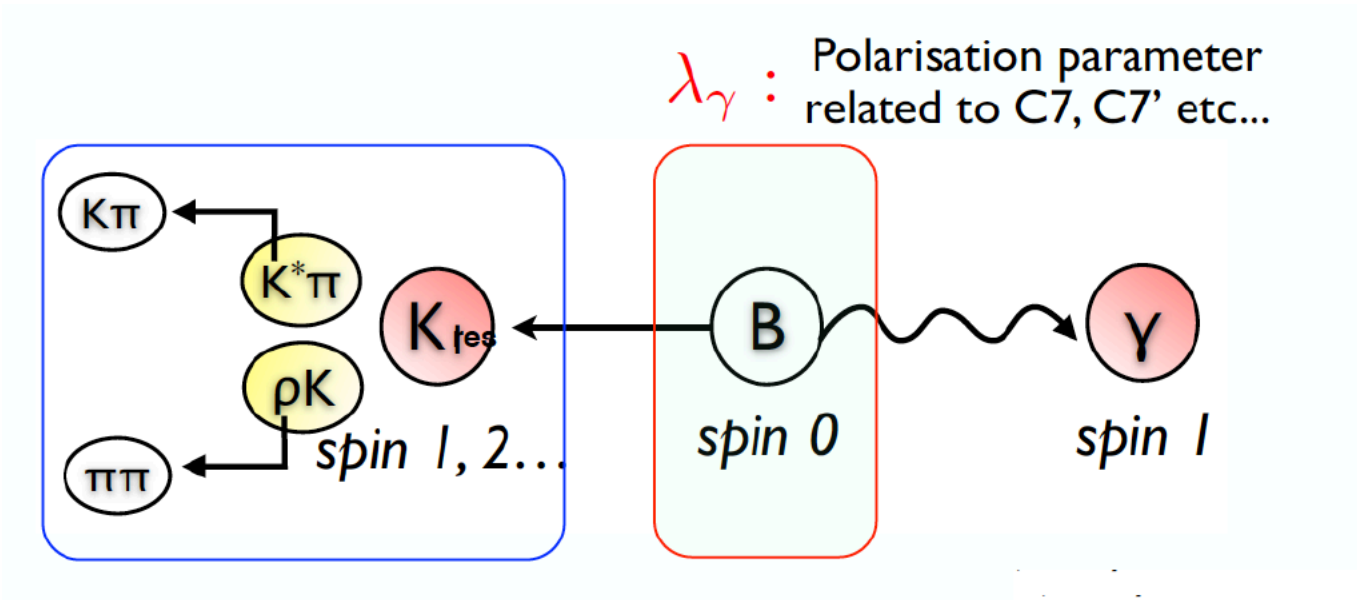
$I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1272 \pm 7$ MeV [l]
Full width $\Gamma = 90 \pm 20$ MeV [l]

$K_1(1270)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\rho$	(42 ± 6) %	46
$K_0^*(1430)\pi$	(28 ± 4) %	†
$K^*(892)\pi$	(16 ± 5) %	302
$K\omega$	(11.0 ± 2.0) %	†
$K f_0(1370)$	(3.0 ± 2.0) %	†
γK^0	seen	539

ANGULAR DISTRIBUTION FOR $b \to s\gamma$

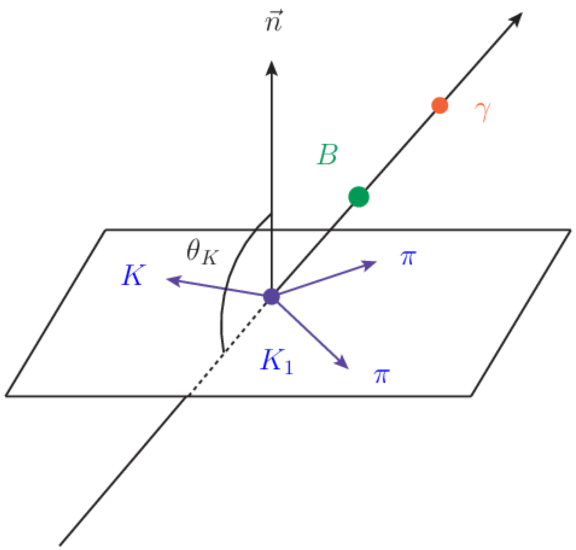
B meson is a spin-0 hadron:
Photon polarization is equivalent to the polarization of Kaon resonance!



Up-down asymmetry for K1

Angular distribution:

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



- ✓ Cos(θ_K): Parity Odd
- ✓ Positive and negative helicities contribute with different signs.

$$\frac{d\Gamma_{K_1\gamma}}{d\cos\theta_K} = \frac{|A|^2|\vec{J}|^2}{4} \times \left[1 + \cos^2\theta_K + 2\lambda_\gamma \cos\theta_K \frac{\mathrm{Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}\right].$$

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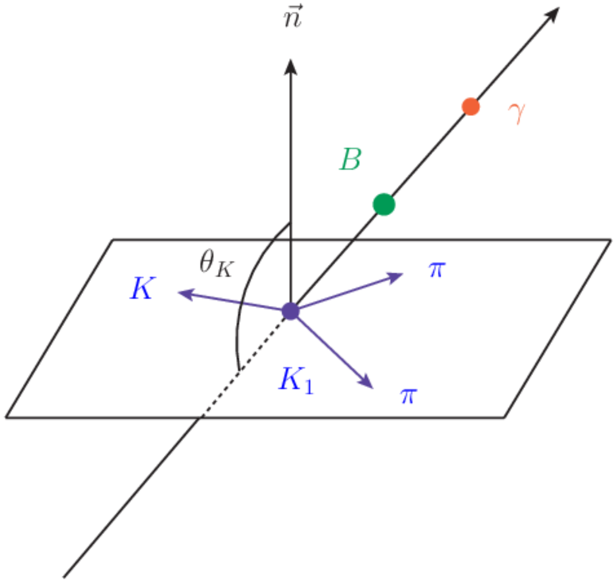

- ✓ To measure λγ, we need to know the decay factor $\mathrm{Im}\left[\vec{n}.(\vec{J}\times\vec{J}^*)\right]/|\vec{J}|^2$
- ✓ Non-zero decay factor requires imaginary part
- ✓ Source of imaginary part: Breit-Wigner

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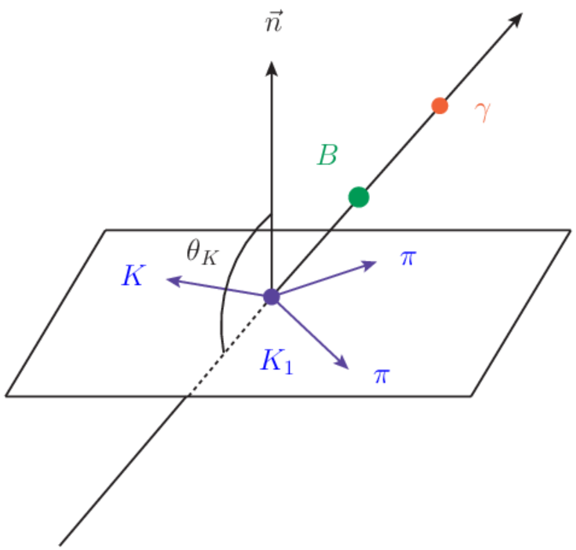
Up-down asymmetry for K1

$$\mathcal{A}_{\mathrm{UD}} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\Gamma(B\to K_1\gamma)}{d\cos\theta_K}}{\left[\int_0^1 + \int_{-1}^0\right] d\cos\theta_K \frac{d\Gamma(B\to K_1\gamma)}{d\cos\theta_K}}$$

$$= \lambda_\gamma \frac{3}{4}\frac{\mathrm{Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}$$



- ✓ To measure λγ, we need to know the decay factor $Im[\vec{n}.(\vec{J}\times\vec{J}^*)]/|\vec{J}|^2$
- ✓ Non-zero decay factor requires imaginary part
- ✓ Source of imaginary part: Breit-Wigner

To extract photon helicity,
we have to reliably understand decay mechanism,
but…

GENERATOR FOR $K_{RES} \rightarrow K\pi\pi$ 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 $K_1 \rightarrow K\pi\pi$ comes from quasi-two-body decay, e.g. $K_1 \rightarrow K^*\pi$, $K_1 \rightarrow \rho K$, 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

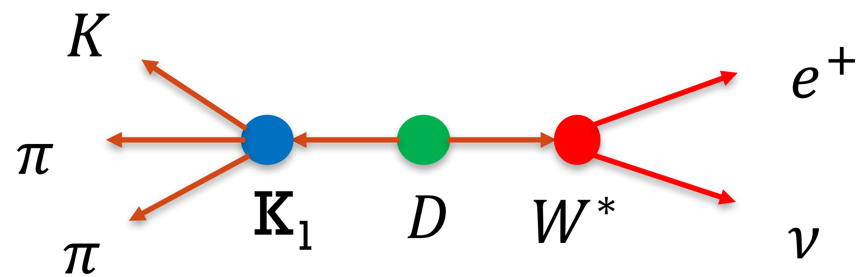
Lesser parameters

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

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

From Emi Kou

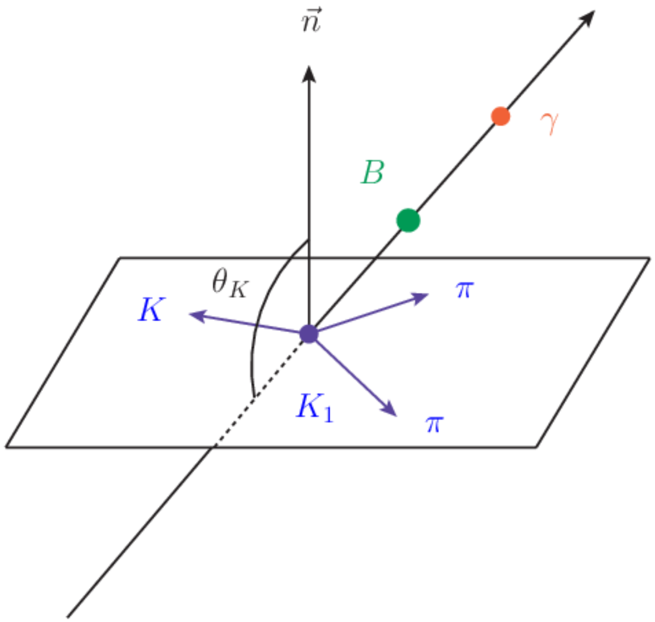
Semileptonic $D \to K\pi\pi e^+\nu$:

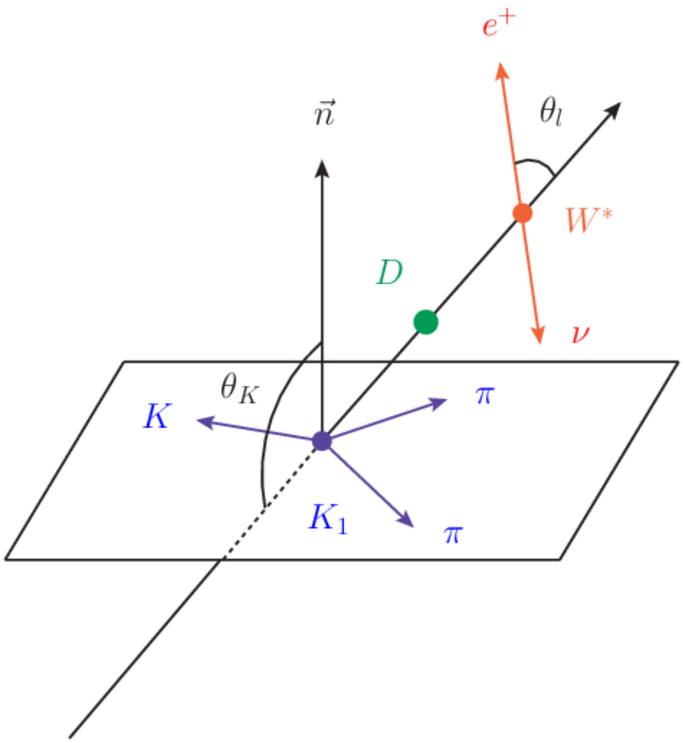


$\mathbf{B_s}, \tau$

WW, F.S. Yu, Z.X.Zhao, 1909.13083

$B \to K_1(K\pi\pi)\gamma$ VS $D \to K_1(K\pi\pi)e^+\nu$





Polarization of γ: +, -

Polarization of W^*: +, -, 0, t

t: timelike, $\sim p_{W^*}$

$D \to K_1(\to K\pi\pi)e^+\nu$

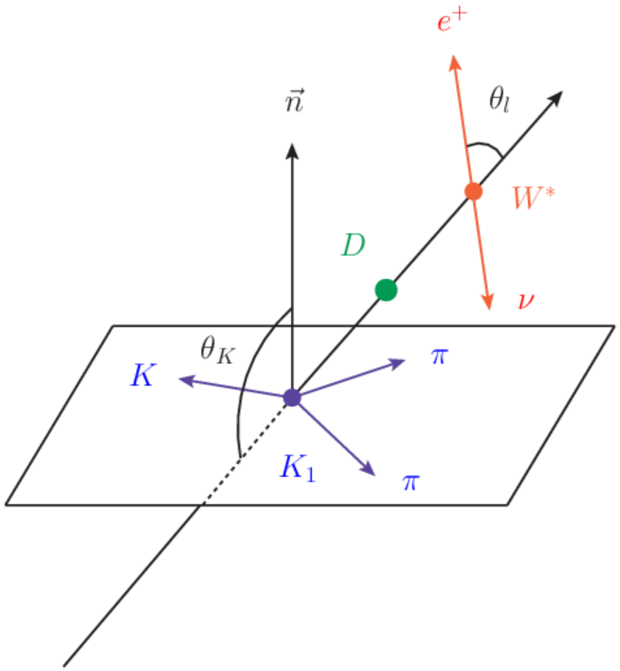
Angular Distributions:

$$\begin{aligned}\frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_K d\cos\theta_l} &= d_1[1+\cos^2\theta_K\cos^2\theta_l] \\ &+ d_2[1+\cos^2\theta_K]\cos\theta_l \\ &+ d_3\cos\theta_K[1+\cos^2\theta_l] \\ &+ d_4\cos\theta_K\cos\theta_l \\ &+ d_5[\cos^2\theta_K+\cos^2\theta_l].\end{aligned}$$

The angular coefficients are given as:

$$\begin{aligned} d_1 &= \frac{1}{2}|\vec{J}|^2(4|c_0|^2+|c_-|^2+|c_+|^2), \\ d_2 &= -|\vec{J}|^2(|c_-|^2-|c_+|^2), \\ d_3 &= -\mathrm{Im}\,[\vec{n}\cdot(\vec{J}\times\vec{J}^*)](|c_-|^2-|c_+|^2), \\ d_4 &= 2\mathrm{Im}\,[\vec{n}\cdot(\vec{J}\times\vec{J}^*)](|c_-|^2+|c_+|^2), \\ d_5 &= -\frac{1}{2}|\vec{J}|^2(4|c_0|^2-|c_-|^2-|c_+|^2).\end{aligned}$$

$D \to K_1(\to K\pi\pi)e^+\nu$: RATIO OF UP-DOWN ASYMMETRIES



Parity Odd: $\cos\theta_K$

$$\cos\theta_K(|c_+|^2 - |c_-|^2)\mathrm{Im}[n\cdot\vec{(}J\times J^*)]$$

Parity Violation: $\cos\theta_l$

$$\cos\theta_l(|c_+|^2 - |c_-|^2)|\vec{J}|^2$$

RATIO OF UP-DOWN ASYMMETRIES

$$\mathcal{A}'_{\rm UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_K}}{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_l}}$$

$$D \to K_1(\to K\pi\pi)e^+\nu$$

$$\mathcal{A}'_{\rm UD} = \frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}$$

$$\mathcal{A}_{UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}}{\left[\int_0^1 + \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}}$$

$$= \lambda_\gamma \frac{3}{4}\frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}$$

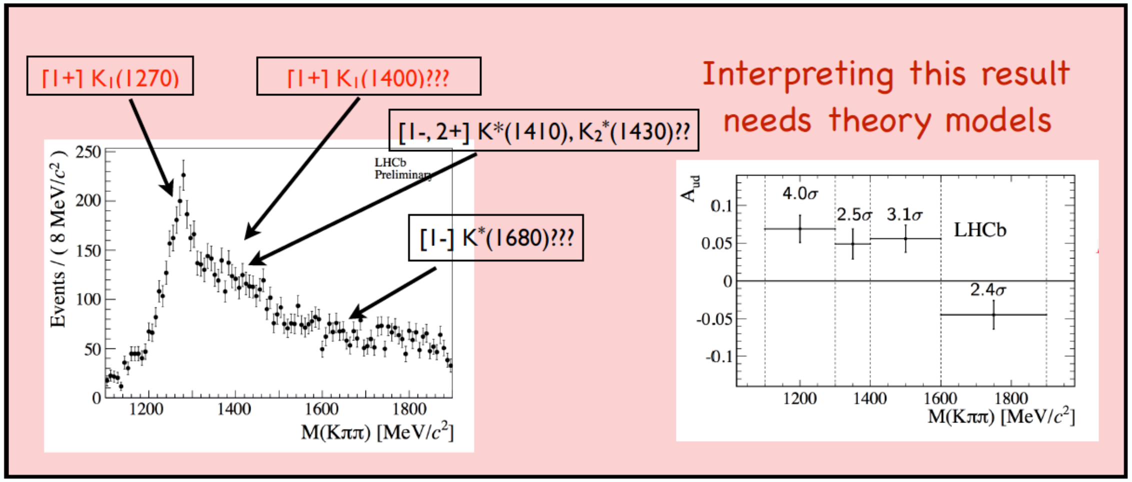
$$B \to K_1(\to K\pi\pi)\gamma$$

RATIO OF UP-DOWN ASYMMETRIES

$$\lambda_\gamma = \frac{4}{3}\frac{\mathcal{A}_{UD}}{\mathcal{A}'_{\mathrm{UD}}}$$

LHCb result on up-down asymmetry

LHCb PRL ('14)



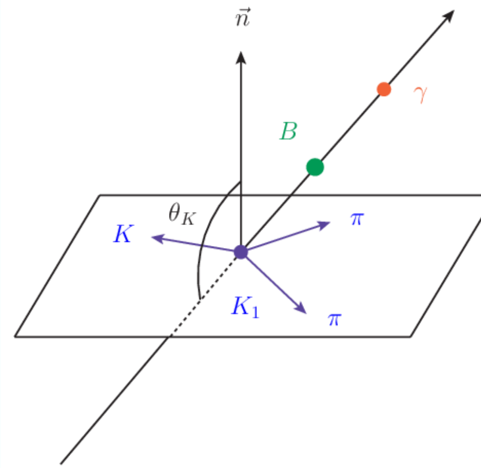


TABLE I. Legendre coefficients obtained from fits to the normalized background-subtracted $\cos\hat{\theta}$ distribution in the four $K^+\pi^-\pi^+$ mass intervals of interest. The up-down asymmetries are obtained from Eq. (4). The quoted uncertainties contain statistical and systematic contributions. The $K^+\pi^-\pi^+$ mass ranges are indicated in GeV$/c^2$ and all the parameters are expressed in units of 10^{-2}. The covariance matrices are given in Ref. [22].

	[1.1,1.3]	[1.3,1.4]	[1.4,1.6]	[1.6,1.9]
c_1	6.3 ± 1.7	5.4 ± 2.0	4.3 ± 1.9	-4.6 ± 1.8
c_2	31.6 ± 2.2	27.0 ± 2.6	43.1 ± 2.3	28.0 ± 2.3
c_3	-2.1 ± 2.6	2.0 ± 3.1	-5.2 ± 2.8	-0.6 ± 2.7
c_4	3.0 ± 3.0	6.8 ± 3.6	8.1 ± 3.1	-6.2 ± 3.2
$\mathcal{A}_{\rm ud}$	6.9 ± 1.7	4.9 ± 2.0	5.6 ± 1.8	-4.5 ± 1.9

$$\mathcal{A}_{\rm UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\Gamma(B\to K_1\gamma)}{d\cos\theta_K}}{\left[\int_0^1 + \int_{-1}^0\right] d\cos\theta_K \frac{d\Gamma(B\to K_1\gamma)}{d\cos\theta_K}} = \lambda_\gamma \frac{3}{4}\frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}.$$

PROSPECT

[1.1-1.3]GeV:

LHCb:
PRL112.161801(2014)

$$\mathcal{A}_{UD} = (6.9 \pm 1.7) \times 10^{-2}$$

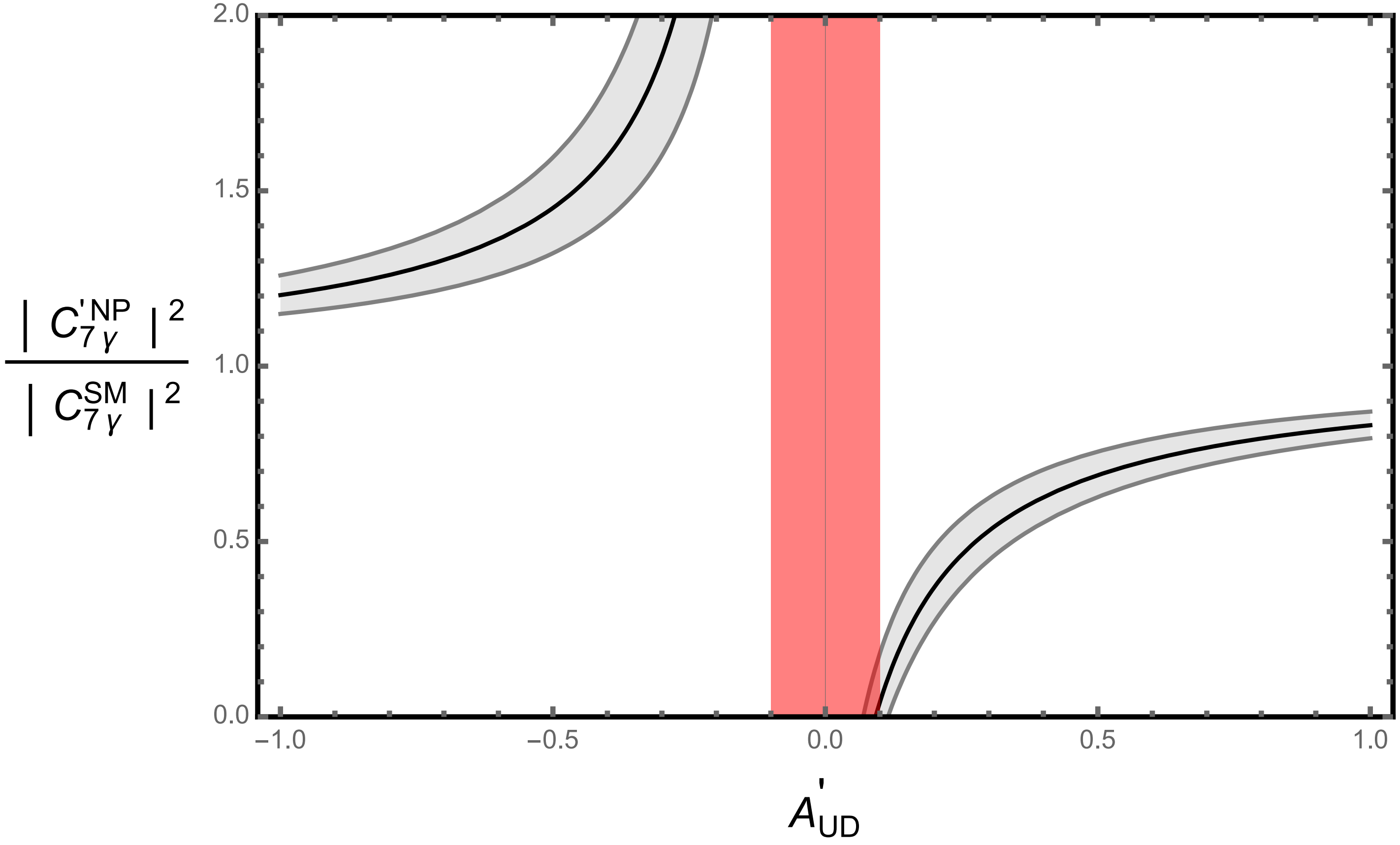
If SM

$$A'_{UD} = (9.2 \pm 2.3) \times 10^{-2}$$

A significant deviation from the above value would be a clear signal for new physics beyond SM.

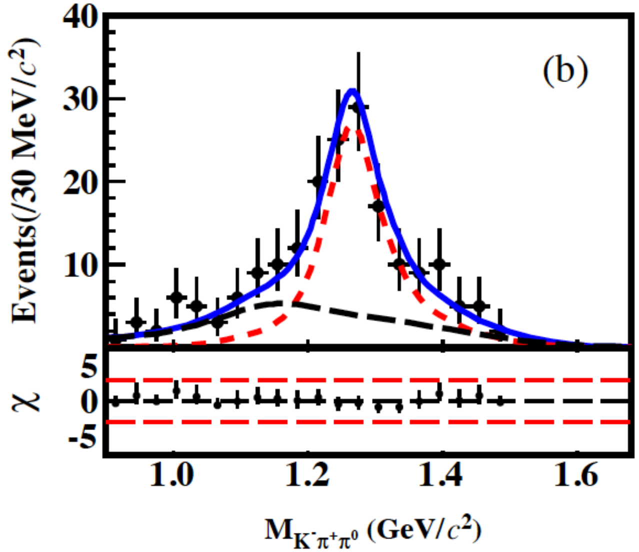
PROSPECT

Dependence of $C_{7\gamma}^{\prime NP}$ on ratio of up-down asymmetries



$D \to K_1(\to K\pi\pi)e^+\nu$ FROM BESIII

BESIII: 1907.11370



$$\mathcal{B}(D^+ \to \overline{K}_1^0 e^+\nu) = (2.3 \pm 0.26 \pm 0.18 \pm 0.25) \times 10^{-3}.$$

BESIII, Belle**II, LHCb, Super Tau-Charm in future?**

SUMMARY

Heavy Flavor Physics: indirect search for NP

Photon polarization in $b \to s\gamma$: unique to probe right-handed couplings

Model-independent extraction using $D \to K_1 e^+ \nu$

- ✓ Photon polarization in a model-independent way: NP?
- ✓ BESIII, BelleII, LHCb, Super tau-charm, CEPC?

Thank you very much!

INCLUDING MORE K_J RESONANCES

The angular distribution for $D \to K_{res}(\to K\pi\pi)e^+\nu$

$$\frac{d\hat{\Gamma}}{d\cos\theta_K d\cos\theta_l} = \sum_{K_J=K_1,K_1^*,K_2,K_{12}^I} \frac{d\hat{\Gamma}_{K_J l\nu}}{d\cos\theta_K d\cos\theta_l}$$

$K^*(1410)$

$$\frac{d\hat{\Gamma}_{K_1^* l\nu}}{d\cos\theta_K d\cos\theta_l} = (|c''_+|^2 + |c''_-|^2)\sin^2\theta_K(1+\cos^2\theta_l)$$
$$+2(|c''_+|^2 - |c''_-|^2)\sin^2\theta_K\cos\theta_l + 4|c''_0|^2\cos^2\theta_K\sin^2\theta_l$$

INCLUDING MORE K_J RESONANCES

$K_2^*(1430)$

$$\frac{d\hat{\Gamma}_{K_2 l\nu}}{d\cos\theta_K d\cos\theta_l} = |c_0'|^2 \frac{3}{2}\sin^2(2\theta_K)\sin^2\theta_l|\vec{K}|^2$$
$$+2|c_1'|^2\cos^4\frac{\theta_l}{2}\{|\vec{K}|^2(\cos^2\theta_K+\cos^2 2\theta_K)$$
$$+2\cos\theta_K\cos 2\theta_K \mathrm{Im}[\vec{n}\cdot(\vec{K}\times\vec{K}^*)]\}$$
$$+2|c_{-1}'|^2\sin^4\frac{\theta_l}{2}\{|\vec{K}|^2(\cos^2\theta_K+\cos^2 2\theta_K)$$
$$-2\cos\theta_K\cos 2\theta_K \mathrm{Im}[\vec{n}\cdot(\vec{K}\times\vec{K}^*)]\}$$

The $K_1 - K_2$ interference

$$\frac{d\hat{\Gamma}_{K_{12}^I l\nu}}{d\cos\theta_K d\cos\theta_l}$$
$$= -4\sqrt{3}\sin^2(\theta_K)\cos\theta_K\sin^2\theta_l \mathrm{Re}[c_0(c_0')^*\vec{J}\cdot\vec{K}^*]$$
$$-8\cos^4\frac{\theta_l}{2}\{\frac{1}{2}(3\cos^2\theta_K-1)\mathrm{Im}[c_+(c_+')^*\vec{n}\cdot(\vec{J}\times\vec{K}^*)]$$
$$+\cos^3\theta_K \mathrm{Re}[c_1(c_1')^* * (\vec{J}\cdot\vec{K}^*)]\}$$
$$-8\sin^4\frac{\theta_l}{2}\{\frac{1}{2}(1-3\cos^2\theta_K)\mathrm{Im}[c_-(c_-')^*\vec{n}\cdot(\vec{J}\times\vec{K}^*)]$$
$$+\cos^3\theta_K \mathrm{Re}[c_{-1}(c_{-1}')^*(\vec{J}\cdot\vec{K}^*)]\}.$$