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

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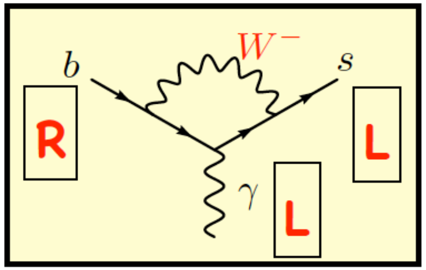
OUTLINE

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



- Recent Progresses on photon polarization

- Model-independent extraction with semileptonic decays

- Summary

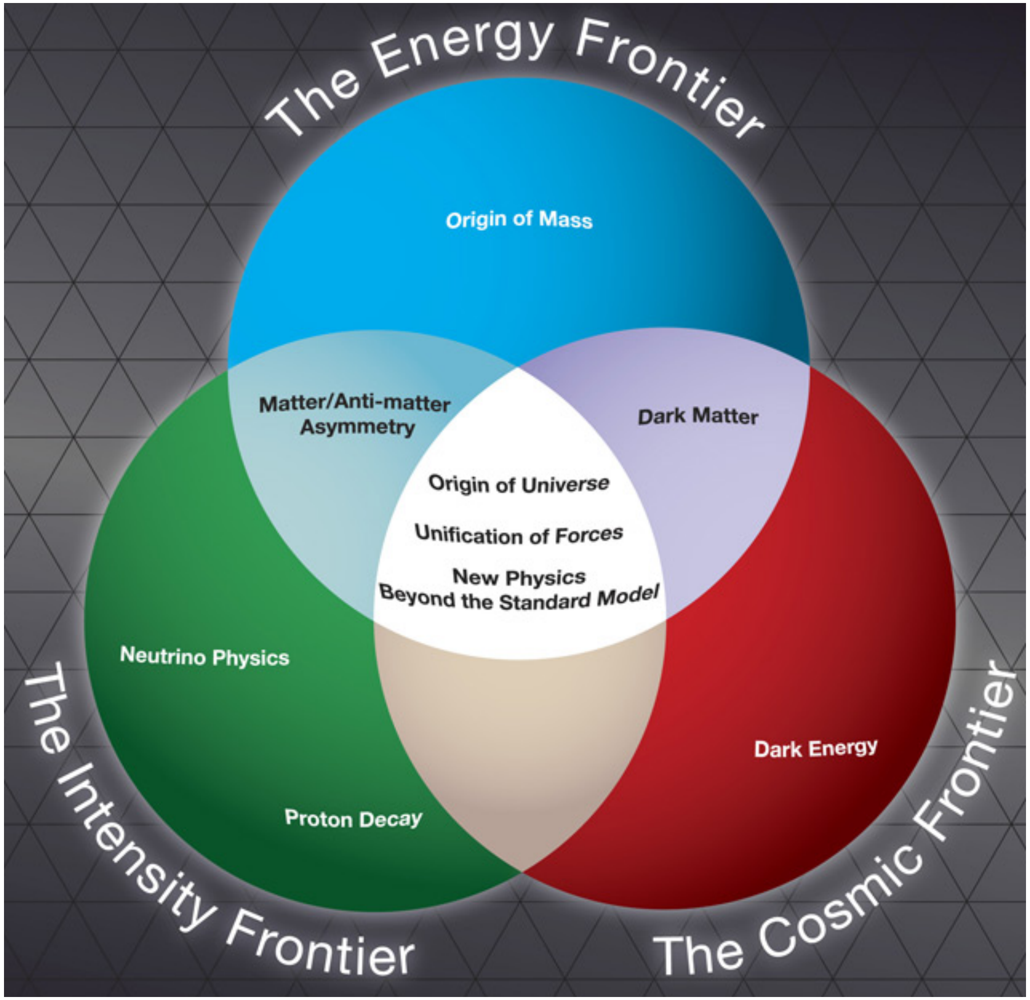
THE STANDARD MODEL(SM)

- 1960-1970s
- Gauge Field Theory: SU(3)xSU(2)xU(1)
- Fermion：
  - ✓quark
  - ✓lepton
- Bosons：
  - ✓Gauge boson
  - ✓Higgs boson

BEYOND SM: THREE FRONTIERS

Tevatron, LHC…
Direct search

B factories
Tau/charm
factory …
indirect search



BEYOND SM: INTENSITY FRONTIER

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

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

INDIRECT SEARCH FROM HISTORY

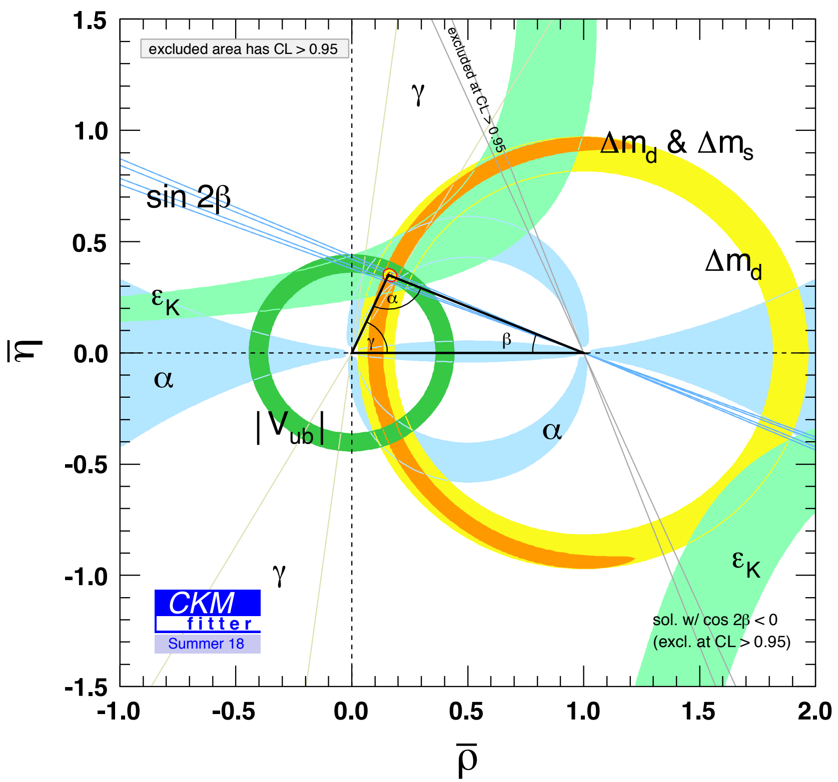
The tiny branching ratio of the decay $K_L \to \mu^+\mu^-$
led to the prediction of the charm quark to suppress FCNCs
(Glashow, Iliopoulos, Maiani 1970)

The measurement of the frequency of kaon anti-kaon oscillations allowed a successful prediction of the charm quark mass
(Gaillard, Lee 1974)
(direct discovery of the charm quark in 1974 at SLAC and BNL)

The observation of CP violation in kaon anti-kaon oscillations let to the prediction of the 3rd generation of quarks
(Kobayashi, Maskawa 1973)

The measurement of the frequency of $B - \bar{B}$ oscillations allowed to predict the large top quark mass
(various authors in the late 80's)
(direct discovery of the bottom quark in 1977 at Fermilab)
(direct discovery of the top quark in 1995 at Fermilab)

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

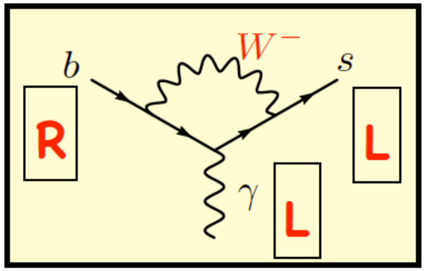
LHCb: PRL, 113, 151601(2014)
LHCb: 1705.05802

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 to the polarization of Λ_b or Λ
  - ✓ $B \to K_{res}\,(\to K\pi\pi)\gamma$

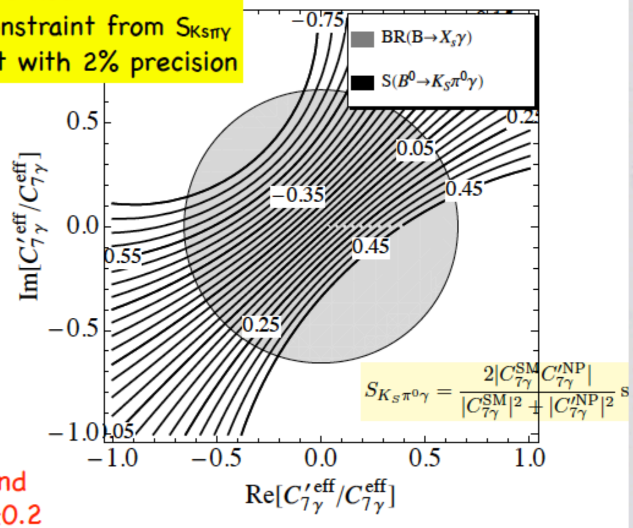
NEW PHYSICS CONTRIBUTIONS IN $b \to s\gamma$

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

Note: new physics contributions,
$C_{7\gamma}^{NP}$ and/or $C'^{NP}_{7\gamma}$ can be complex numbers!
We only consider $C'^{NP}_{7\gamma}$ in the following.

COMPLEMENTARITY

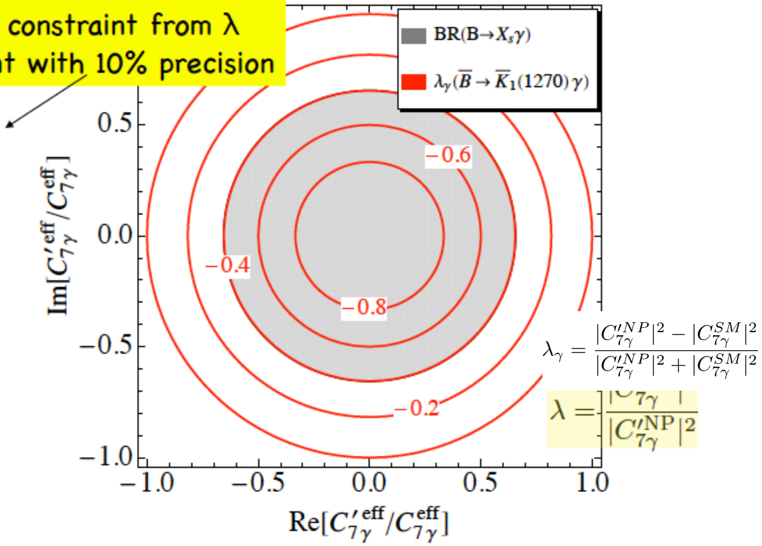
Method I
Expected constraint from $S_{K_S\pi\gamma}$ measurement with 2% precision



Current bound
$S_{K_S\pi^0\gamma} = -0.15 \pm 0.2$

Method III
Expected constraint from λ measurement with 10% precision

3%



Discovering NP: Competitive
Constraining NP: Complementary

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Angular distribution of B→$K_1\gamma$→(Kππ)γ

$$\lambda_\gamma \equiv \frac{|\mathcal{A}(\bar{B}\to\bar{K}_{1R}\gamma_R)|^2 - |\mathcal{A}(\bar{B}\to\bar{K}_{1L}\gamma_L)|^2}{|\mathcal{A}(\bar{B}\to\bar{K}_{1R}\gamma_R)|^2 + |\mathcal{A}(\bar{B}\to\bar{K}_{1L}\gamma_L)|^2}$$
$$= \frac{|C_{7\gamma}^{\prime NP}|^2 - |C_{7\gamma}^{SM}|^2}{|C_{7\gamma}^{\prime NP}|^2 + |C_{7\gamma}^{SM}|^2}$$

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

K1

$K_1(1270)$

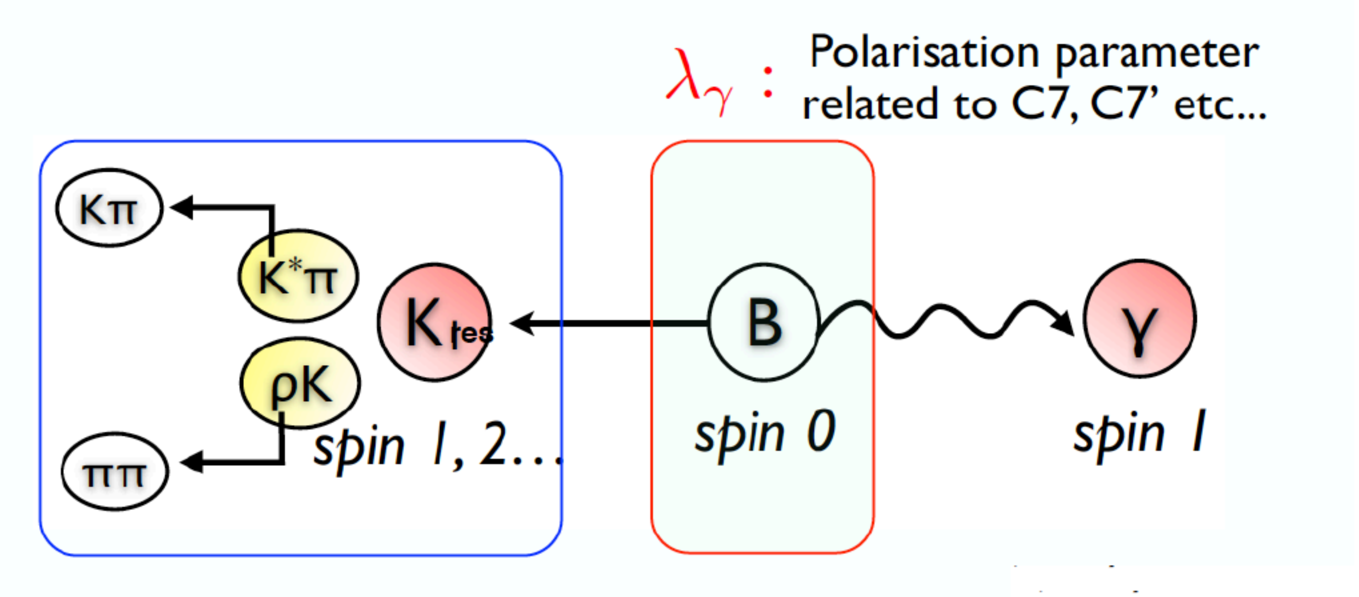
$I(J^P) = \frac{1}{2}(1^+)$

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:

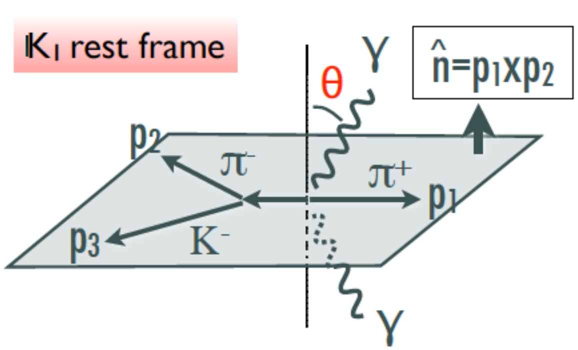
Gronau,Grossman, Pirjol, Ryd PRL88('01)

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

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}→$K\pi\pi$ 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)

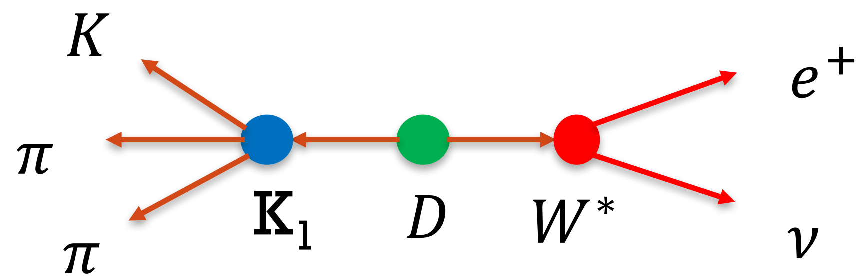
2. $K^*_{1410,\ 1680}(1-)$ and $K2_{1430}$ (2+) *A. Kotenko, B. Knysh talk at Lausanne WS '17*

> 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)!

From Emi Kou

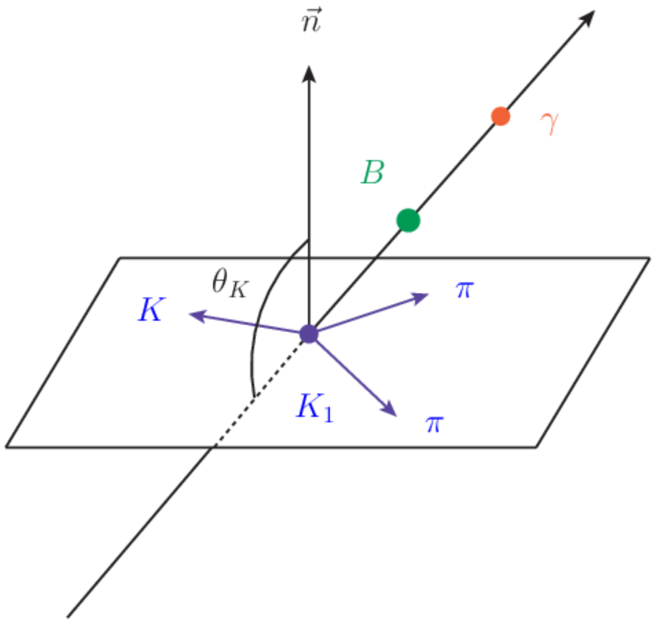
Semileptonic $D \to K\pi\pi e^+\nu$:

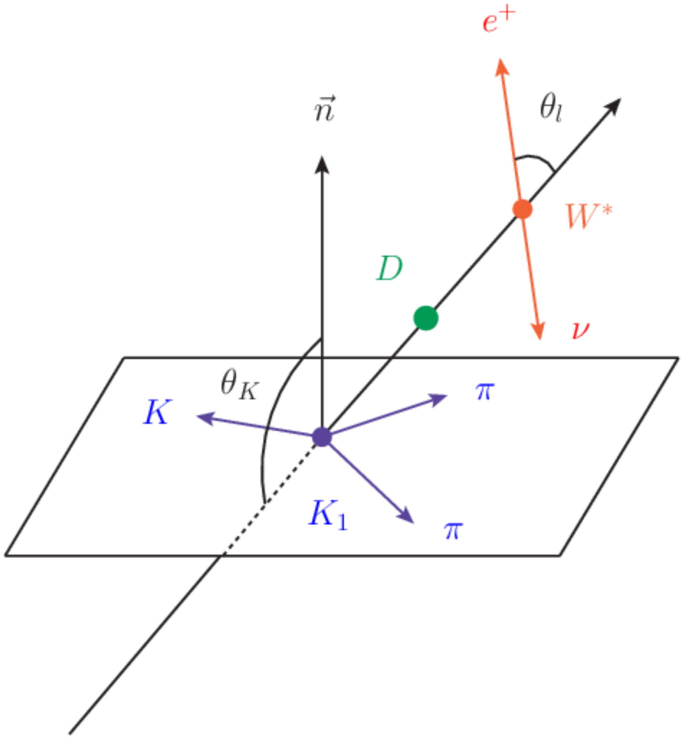


Bs, tau

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, $\sim p_{W^*}$

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

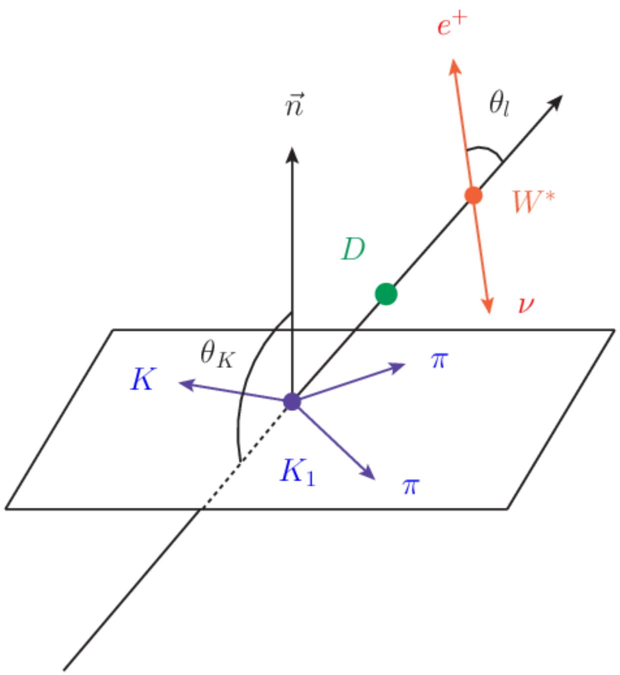
Angular Distributions:

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

The angular coefficients are given as:

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

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

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

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

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

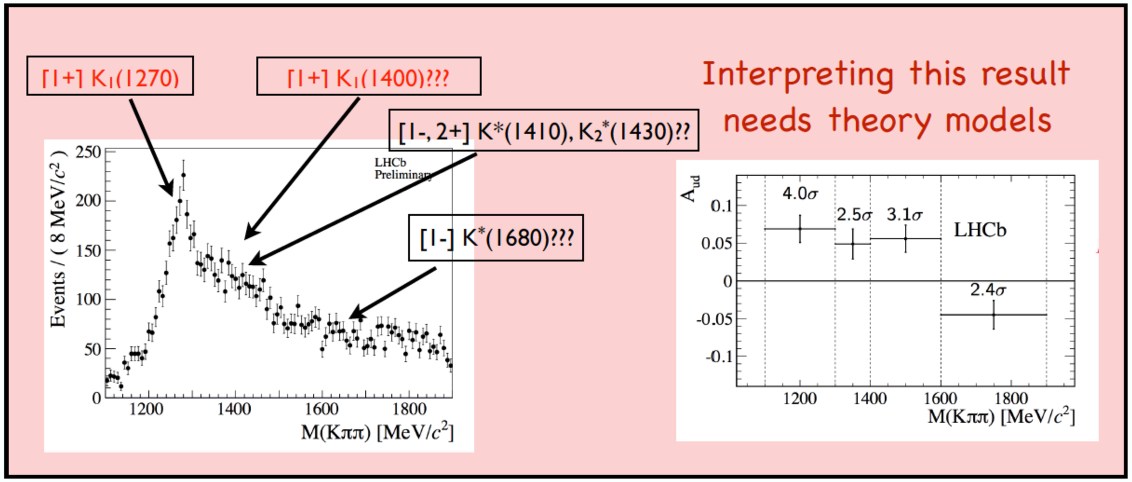
$$\mathcal{A}_{UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}}{\left[\int_0^1 + \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}}$$

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

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

LHCb result on up-down asymmetry

LHCb PRL ('14)



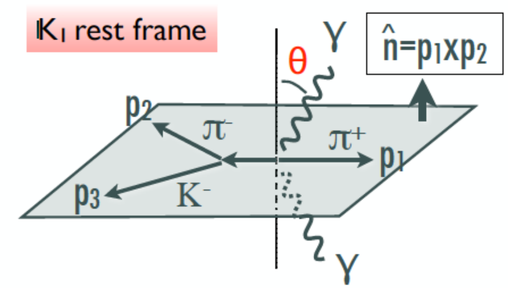


TABLE I. Legendre coefficients obtained from fits to the normalized background-subtracted $\cos\hat{\theta}$ distribution in the four $K^+\pi^-\pi^+$ mass intervals of interest. The up-down asymmetries are obtained from Eq. (4). The quoted uncertainties contain statistical and systematic contributions. 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
$\mathcal{A}_{ud}$	6.9 ± 1.7	4.9 ± 2.0	5.6 ± 1.8	-4.5 ± 1.9

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

PROSPECT

[1.1-1.3]GeV:

LHCb:
PRL112.161801(2014)

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

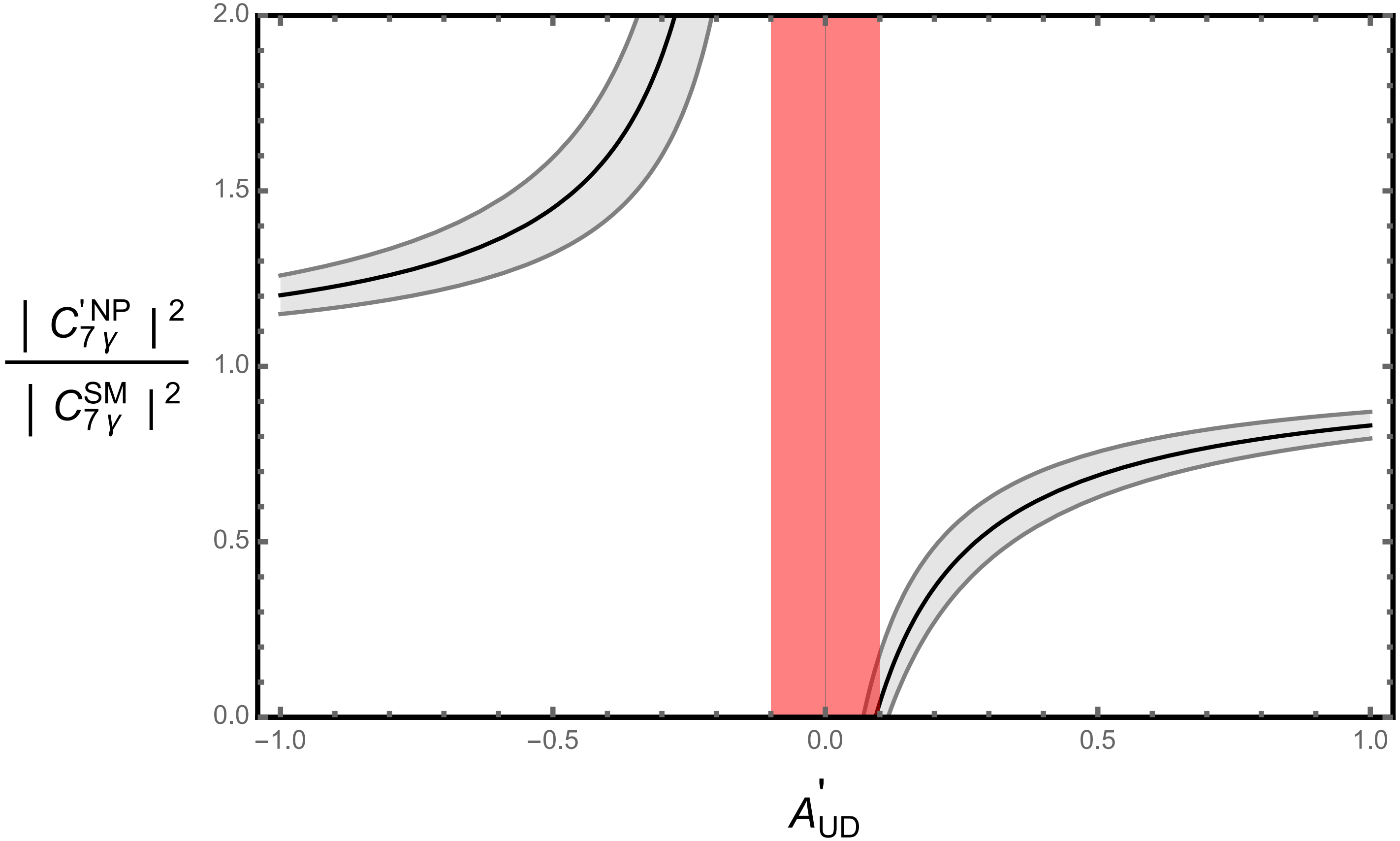
If SM

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

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

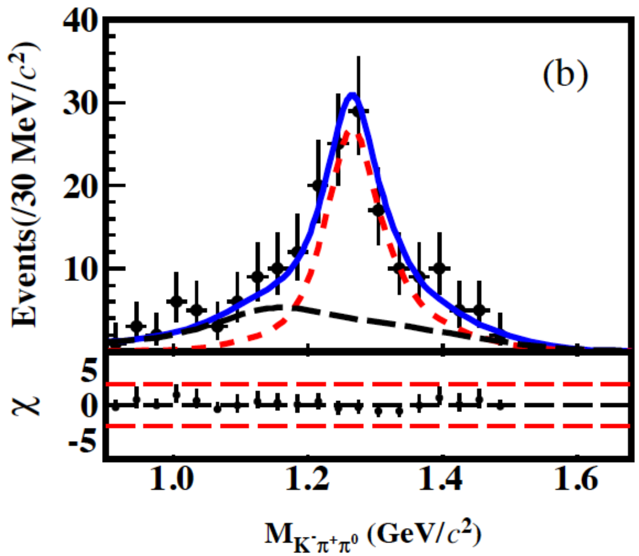
PROSPECT

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, BelleII, LHCb, Super Tau-Charm, CEPC 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

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