Model-Independent Determination of Photon Helicity in Exclusive Radiative $b \to s\gamma$ Decays

赵振兴
内蒙古大学

In collaboration with Wei Wang, Fu-Sheng Yu, 1909.13083

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Outline

- Heavy Quark Physics
- Photon polarization in $b \to s\gamma$
- Recent Progresses on photon polarization measurements
- Model-independent extraction using $D \to K_1 e^+ \nu$
- Summary

the Standard Model(SM)

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

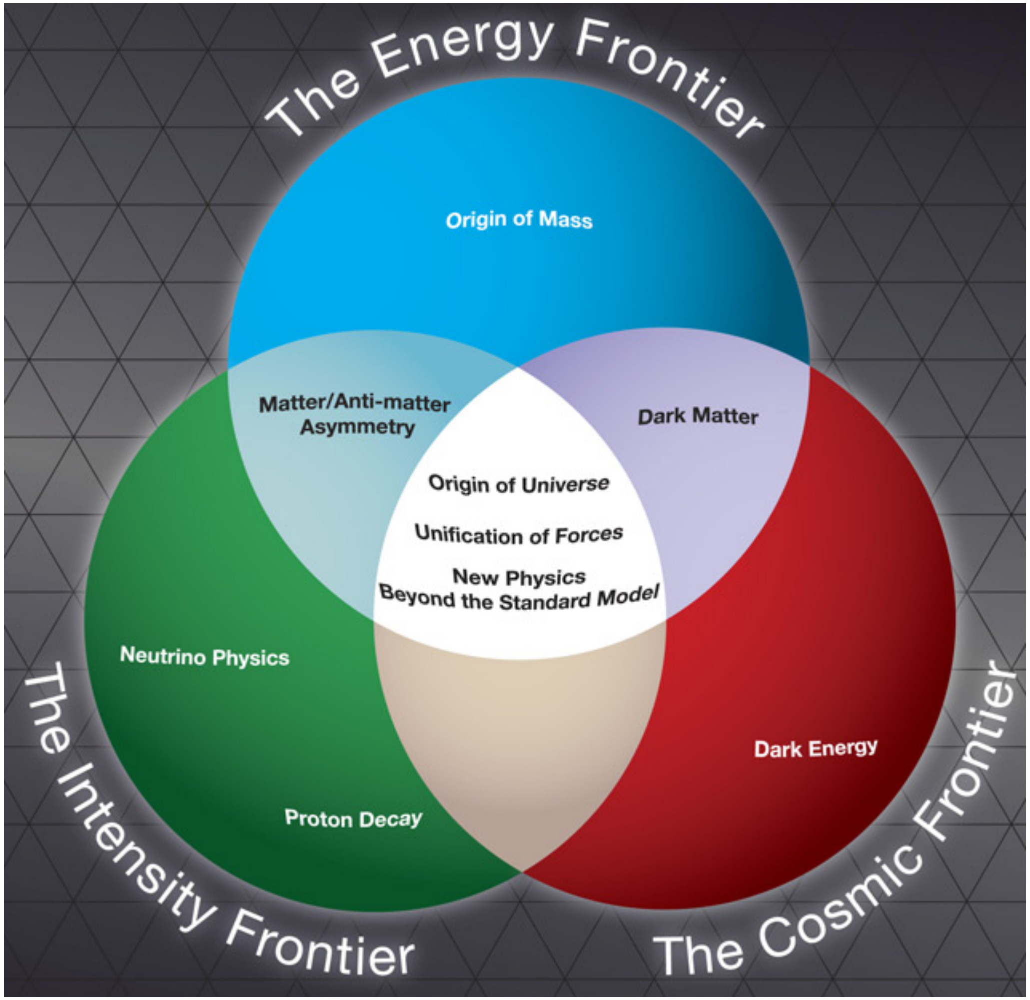
Beyond SM

- Neutrino: Mass, Dirac or Majorana Fermion
- Dark Matter: 27%
- Dark Energy
- …
- Hierarchy problem?
- …

Beyond SM: Three Frontiers

Tevatron, LHC…
Direct search

B factories
Tau/charm
factory …
indirect search



Beyond SM: Indirect search

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)

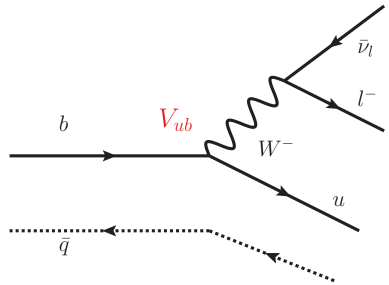
The measurement of the frequency of $B - \bar{B}$ oscillations allowed to predict the large top quark mass
(various authors in the late 80's)

(direct discovery of the bottom quark in 1977 at Fermilab)
(direct discovery of the top quark in 1995 at Fermilab)

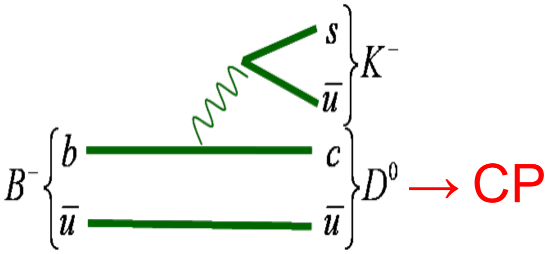
Heavy Flavor Bottom Physics

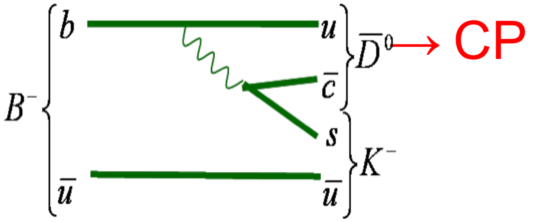
- Extract the SM parameters:

  Vub, Vcb, Weak Phases

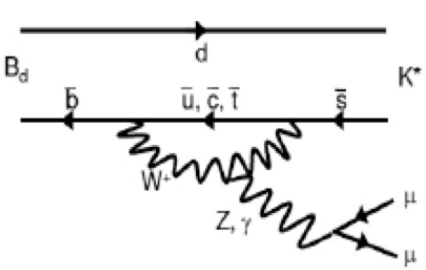


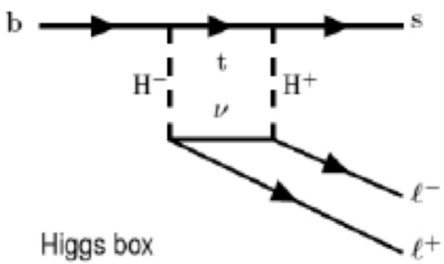
- Test SM: unitary triangle





- Hunt for NP: Rare Decays





Bottom Physics: Unitary Triangle

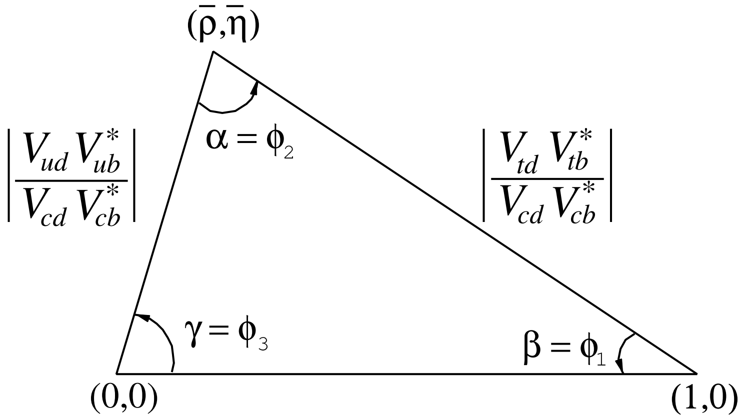
➢ Charged currents involving quarks:

$$J^{\mu}W_{\mu}^{+} = -\frac{g}{\sqrt{2}}\overline{U_L^i}\gamma^{\mu}W_{\mu}^{+}V_{CKM}D_L^i$$

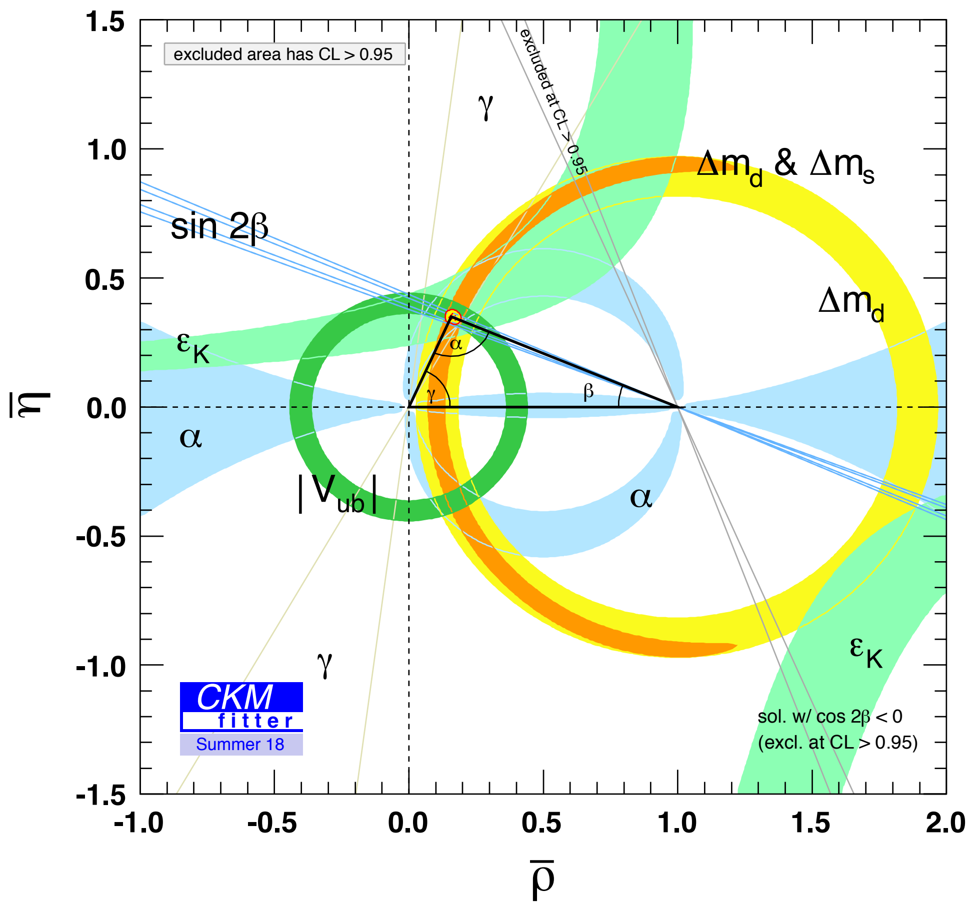
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity:

$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$



Bottom Physics: status



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

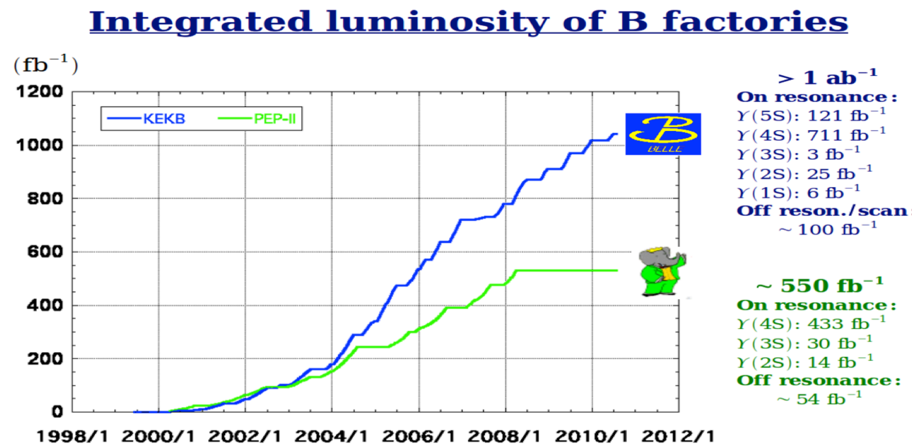
High Precision

Bottom Physics: Prospect

Experiments provided many analyses

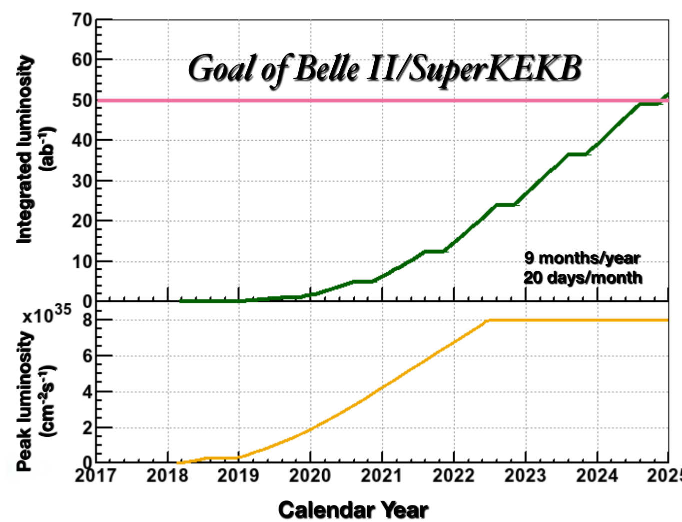
3.1 GeV e^+
9 GeV e^-

3.5 GeV e^+
8 GeV e^-



10^9 events, leading to Nobel in 2008

10^{11} events, what will happen?

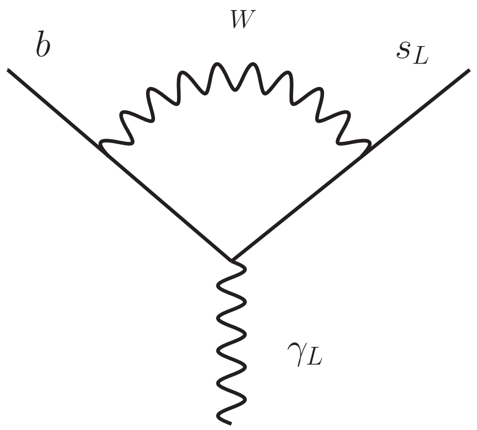


Ongoing Experiments

Photon polarization in $b \to s\gamma$

Photon polarization of $b \to s\gamma$

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



In SM,

- $b \to s\gamma_L$ (BSM with right-handed)
- $\bar{b} \to \bar{s}\gamma_R$ (BSM with right-handed)

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 $b \to s\gamma$

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

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

Angular analysis of B➔$K_1\gamma$➔(Kππ)γ

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

$$\simeq \frac{|C_{7R,NP}|^2 - |C_{7L,SM}|^2}{|C_{7R,NP}|^2 + |C_{7L,SM}|^2}$$

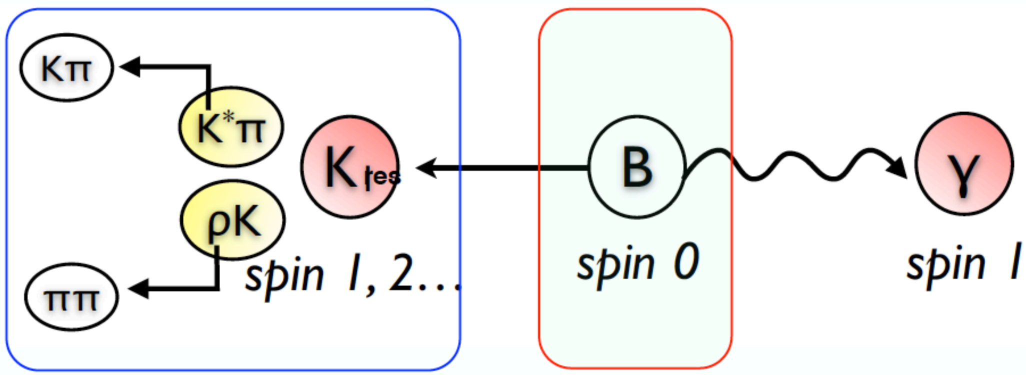
In SM, $\lambda_\gamma \simeq -1$

Angular distribution method

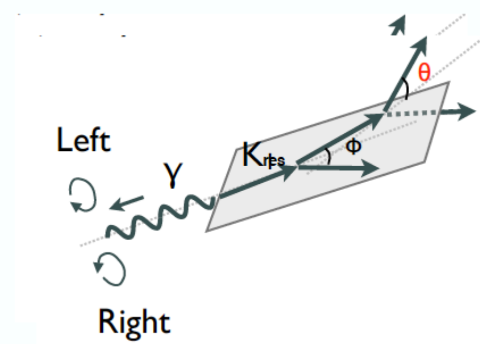
Gronau, Grossman, Pirjol, Ryd PRL88('01)

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.

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

Up-down asymmetry for K1

Angular distribution:

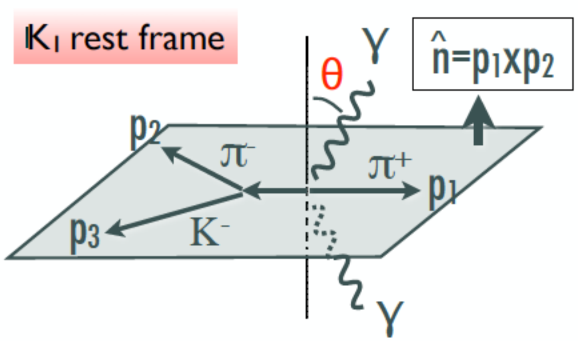
Gronau,Grossman, Pirjol, Ryd PRL88('01)

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

Up-down asymmetry for K1

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

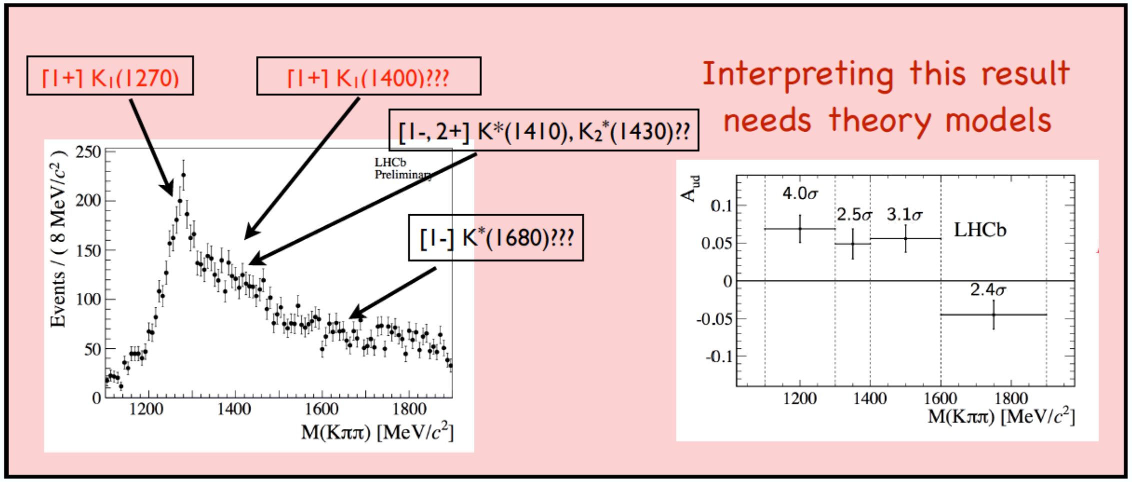
$$= \lambda_\gamma \frac{3}{4} \frac{\mathrm{Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}$$

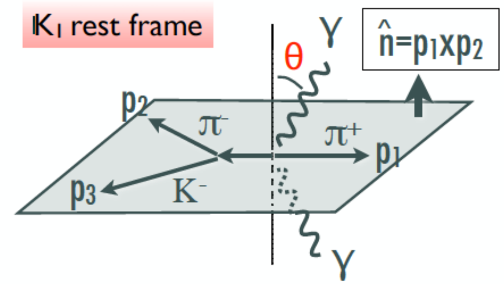


- ✓ To measure λγ, we need to know the decay factor $Im[\vec{n}.(\vec{J}\times\vec{J}^*)]/|\vec{J}|^2$
- ✓ Non-zero decay factor requires imaginary part
- ✓ Source of imaginary part: Breit-Wigner

LHCb result on up-down asymmetry

LHCb PRL ('14)





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

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
$\mathcal{A}_{\mathrm{ud}}$	6.9 ± 1.7	4.9 ± 2.0	5.6 ± 1.8	-4.5 ± 1.9

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

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

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+)

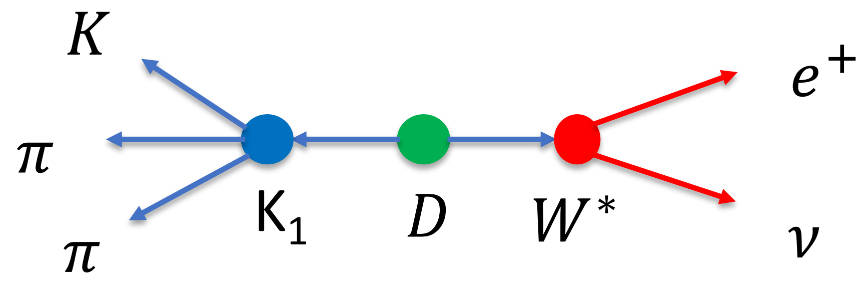
A. Kotenko, B. Knysh talk at Lausanne WS '17

Lesser parameters

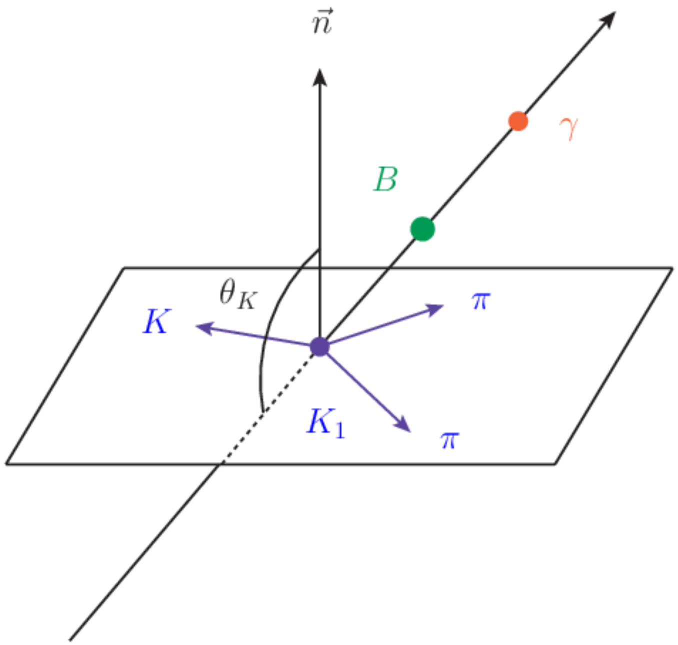
- Known to decay mainly $K_{res} \rightarrow K^*\pi$, ρK
- Only 1 form factor for each resonance

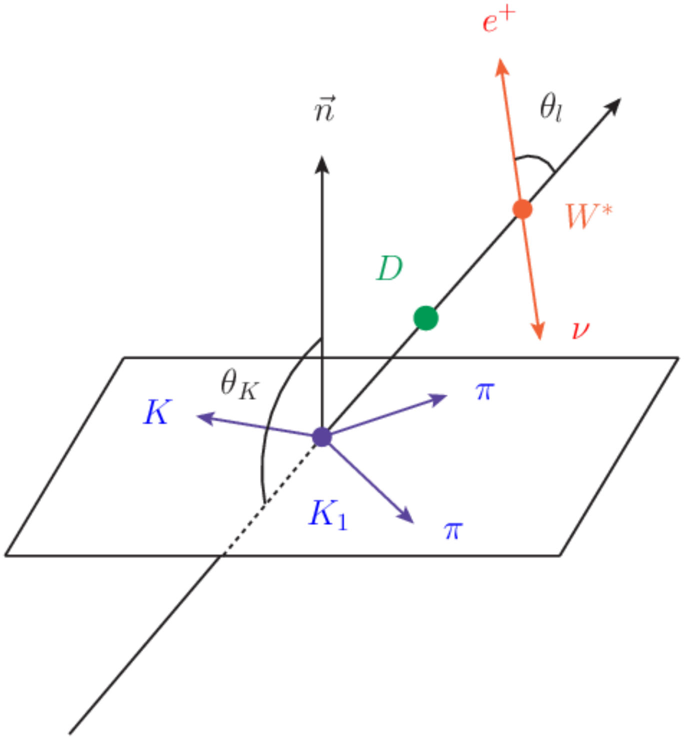
On total 10 complex couplings needed (20 real number)!

Semileptonic $D \rightarrow K\pi\pi e^{+}\nu$



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





Polarization of γ: +, -

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

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

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

$$B \to K_1\gamma$$

$$\begin{array}{lcccc} \text{case 1:} & \gamma \leftarrow & B & \rightarrow K_1 \\ & \Leftarrow & & \Rightarrow \end{array}$$

$$\begin{array}{lcccc} \text{case 2:} & \gamma \leftarrow & B & \rightarrow K_1 \\ & \Rightarrow & & \Leftarrow \end{array}$$

$$D \to K_1 W^*$$

$$\begin{array}{lcccc} \text{case 1:} & W^* \leftarrow & D & \rightarrow K_1 \\ & \Leftarrow & & \Rightarrow \end{array}$$

$$\begin{array}{lcccc} \text{case 2:} & W^* \leftarrow & D & \rightarrow K_1 \\ & \Rightarrow & & \Leftarrow \end{array}$$

$$\begin{array}{lcccc} \text{case 3:} & W^* \leftarrow & D & \rightarrow K_1 \\ & 0 & & 0 \end{array}$$

timelike polarization $\sim m_l$

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

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:

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

Up-down asymmetries

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

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

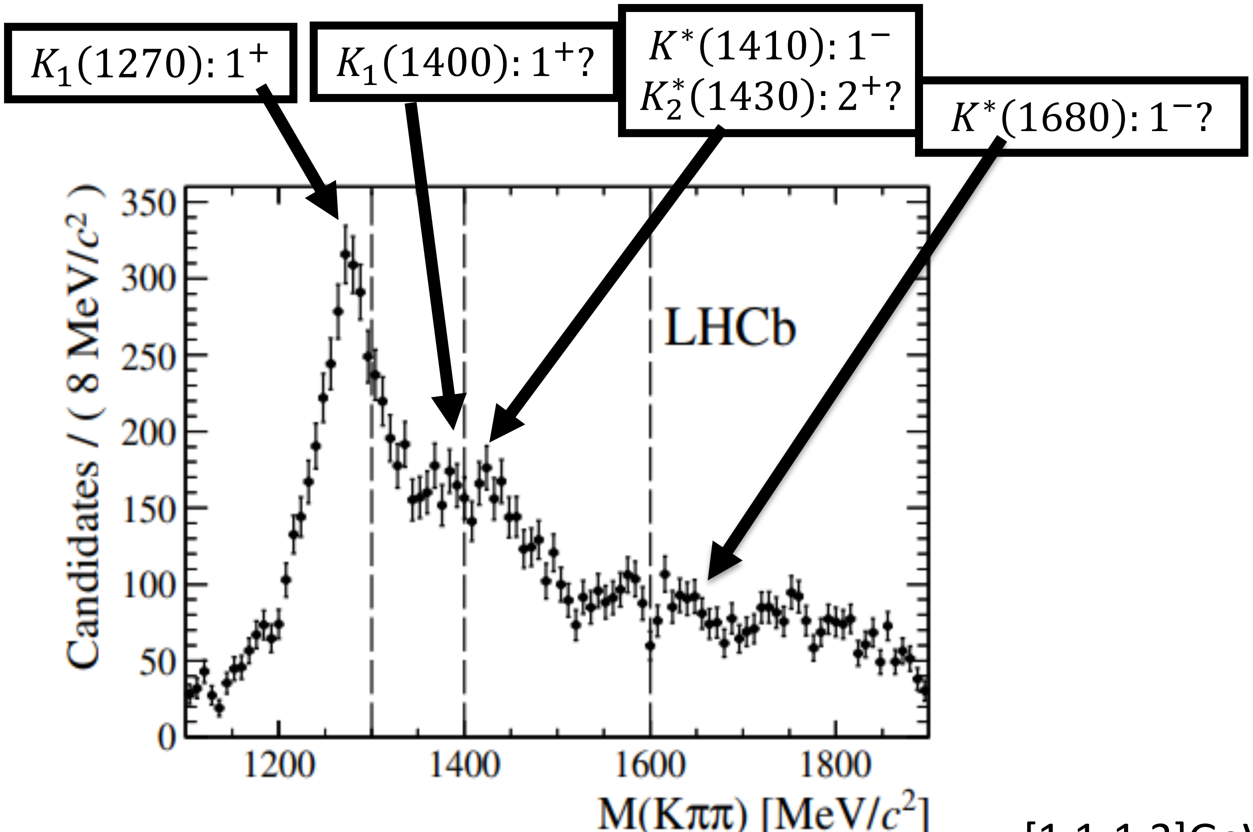
$$\mathcal{A}'_{\rm UD} = \frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}$$

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

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

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

$Pros$pect at BESIII & BelleII



LHCb: PRL112.161801(2014)

[1.1-1.3]GeV:

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

Prospect

[1.1-1.3]GeV:

LHCb: PRL112.161801(2014)

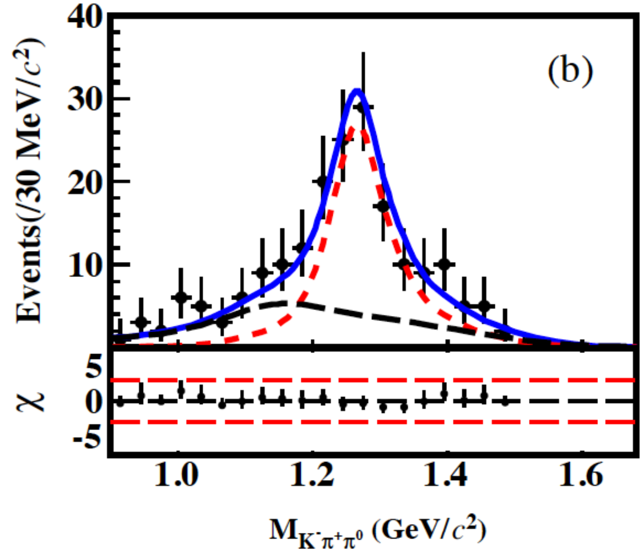
$$\mathcal{A}_{UD} = (6.9 \pm 1.7) \times 10^{-2}$$

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

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

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

- ✓ Hadron inputs
- ✓ Photon polarization in a model-independent way: NP?
- ✓ BESIII, BelleII, LHCb, Super Tau-Charm, CEPC in future?

Thank you very much!

backup

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

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