CKM Physics in $e^+e^-$ Colliders

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KEK
CKM 2018 @ Heidelberg
Sep. 17, 2018
Contents

• Status of Belle II experiment.

• Results from BaBar and Belle.

Belle II before Phase 2 (2018 Mar)

Belle II go to beamline (2017/4/11)
Two B Factories

**BaBar @ PEP-II**
- 9 GeV $e^-$ + 3.1 GeV $e^+$

**Belle @ KEKB**
- 8 GeV $e^-$ + 3.5 GeV $e^+$

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$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$ (\(\sigma = 1.1 \text{nb}\))

Integrated Luminosity [fb\(^{-1}\)]

Luminosity

1 fb\(^{-1}\) \(\sim 10^6\) $B\overline{B}$ @ \(\Upsilon(4S)\)

Total \(\sim 1040\) fb\(^{-1}\)

Peak $2.11 \times 10^{34}\) cm\(^{-2}\) s\(^{-1}\)

On resonance:
- \(\Upsilon(5S)\): 121 fb\(^{-1}\)
- \(\Upsilon(4S)\): 711 fb\(^{-1}\)
- \(\Upsilon(3S)\): 3 fb\(^{-1}\)
- \(\Upsilon(2S)\): 24 fb\(^{-1}\)
- \(\Upsilon(1S)\): 6 fb\(^{-1}\)

Off resonance, scan:
\(~ 100\) fb\(^{-1}\)

Total 550 fb\(^{-1}\)

Peak $1.21 \times 10^{34}\) cm\(^{-2}\) s\(^{-1}\)

On resonance:
- \(\Upsilon(4S)\): 433 fb\(^{-1}\)
- \(\Upsilon(3S)\): 30 fb\(^{-1}\)
- \(\Upsilon(2S)\): 14 fb\(^{-1}\)

Off resonance:
\(~ 54\) fb\(^{-1}\)

These data are taken till 2010.
Belle II experiment with SuperKEKB started!

- SuperKEKB targeting $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$
  ($\times 40$ of Belle)
  ✓ “Nano beam scheme”:
    $\times 1/20$ beam size (~50nm)
    $\times 2$ beam current (2-3 A)
- Belle II spectrometer.
  ✓ New type of vertex and PID detector.
- Phase 2 Operation in 2018.

**Phase 1 (2016)** without Belle II
**Phase 2 (2018)** with Belle II (no VXD)
**Phase 3 (2019-)** with full Belle II
SuperKEKB

Replace short dipoles with longer ones (LER)

Larger crossing angle
2\(\phi\) = 22 mrad \(\rightarrow\) 83 mrad

Smaller asymmetry
3.5 / 8 GeV \(\rightarrow\) 4 / 7 GeV

Add / modify RF systems for higher beam current

Positron source
New positron target / capture section

Low emittance gun
Low emittance electrons to inject

Damping ring

Low emittance positrons to inject

New beam pipe & bellows

New IR

Belle II

New superconducting / permanent final focusing quads near the IP

TiN-coated beam pipe with antechambers

Redesign the lattices of HER & LER to squeeze the emittance

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**Belle II Spectrometer**

**ECL**: CsI (TI), waveform sampling

**VXD**

- **PXD**: DEPFET (pixel)
- **SVD**: Silicon microstrip

**CDC**: drift chamber (small cells)

**KLM**: "KL and muon" RPC (barrel) + SiPM (end-cap, inner barrel)

**1.5T solenoid coil**

**PID**: Cherenkov ring image
- **TOP** (barrel): Quartz
- **ARICH** (endcap): Aerogel

- Operation at higher luminosity (background)
- New type of Vertex and PID detector.

**e^- (7GeV)**

**e^+ (4GeV)**

**ARICH** (during construction)
Phase II Operation

- The construction of SuperKEKB was completed.
- Belle II detector without vertex detectors.
Belle II First Collision

Belle II first collision at 0:46 on Apr. 26, 2018

Kobayashi @ First collisions ceremony
Phase 2 Operation

One day history of SuperKEKB (Jul 5, 2018)

- Mostly accelerator tuning.
- Physics run (in the midnight).
- Maximum luminosity $5.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$ (during accelerator study).
  - $1-2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ during physics run
Phase 2 Operation

- The main purpose of Phase II operation was the accelerator tuning and the study of nano beam scheme.
- Physics data were also taken: total data size 0.5 fb⁻¹
  - Understanding of the detector.
  - B mesons are reconstructed.

Potential BB candidate

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**Phase II Operation**

- The main purpose of Phase II operation was the accelerator tuning and the study of nano beam scheme.
- Physics data were also taken: total data size 0.5 fb⁻¹
  - Understanding of the detector.
  - B mesons are reconstructed.
Toward Phase 3

- The construction of SVD (inner vertex detector) is finished. Under commissioning outside Belle II.
- Will be installed to Belle II together with PXD (innermost pixel detector) towards the end of this year.
- Other maintenance, repair work is going on.

Phase III operation (physics run) starts in early 2019.
Let’s go back to BaBar and Belle

• Data were taken till 2008/2010.
• But the analysis is still active, and we have new results.
B Tagging Technique

• Reconstruction of B decay modes with one or more neutrinos in the final states.
• B mesons are produced in pair → Reconstruct or tag the other B.
  ✓ Full reconstruction: reconstruct the other B with hadronic modes.
  ✓ Semi-leptonic tag: tag the other B with semi-leptonic decays.
  ✓ Inclusive: reconstruct signal B and check if the rests are consistent with B.
  ✓ Unagged: do not tag the other B (applicable in case of one neutrino)
• In general, a method with high purity has low efficiency. Typical full reconstruction efficiency is O(0.1%).
• Effort to improve the performance, which directly affects the analysis sensitivity.

FEI (Full Event Interpretation)

Talk by M. Gelb (WG2)

New Result

B → ℓνγ by Belle
(first result w/ FEI)

Talk by M. Gelb (WG2)

Talk by R. Van Tonder (WG1)

[arXiv:1807.08680]
\( B \rightarrow D^{(*)}\tau\nu \)

- NP contribution is tree diagram?
  ✓ Sensitive to charged Higgs.
- Measure the branching ratio
  \[
  R(D^{(*)}) = \frac{BF(\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau)}{BF(\bar{B} \rightarrow D^{(*)}l^-\bar{\nu}_l)} \\
  (l^- = e^-, \mu^-)
  \]
  ✓ Cancel form factors.
  ✓ Cancel experimental systematics

- Several measurements from Belle and BaBar
  ✓ With different B tagging method → Independent sample
$B \rightarrow D^{(*)}\tau\nu$

- $3.8\,\sigma$ deviation from the SM
- $2.3\,\sigma$ in $R(D)$
- $3.0\,\sigma$ in $R(D^*)$

- More precise
- Other observables (polarization)
For more precise measurement of $B \rightarrow D^{(*)}\tau\nu$

- More statistics $\rightarrow$ Belle II
- Better understanding of the systematics
  ✓ Dominant systematic error: the uncertainty of $B \rightarrow D^{**}\ell\nu (D^{**}\tau\nu)$.

Measurement of $B \rightarrow D^{(*)}\pi\ell\nu$ at Belle

[PRD98, 012005 (2018)]

- Hadronic tag.
- Simultaneous fit on $B \rightarrow D\pi\ell\nu$ and $B \rightarrow D^*\pi\ell\nu$. 

\[ B \rightarrow D^{(*)}\pi\ell\nu \]

<table>
<thead>
<tr>
<th>Results</th>
<th>HFLAV2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \rightarrow D^-\pi^+\ell^+\nu )</td>
<td>((4.55 \pm 0.27 \pm 0.39) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^0 \rightarrow D^0\pi^-\ell^+\nu )</td>
<td>((4.05 \pm 0.36 \pm 0.41) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^+ \rightarrow D^{*-}\pi^+\ell^+\nu )</td>
<td>((6.03 \pm 0.43 \pm 0.38) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^0 \rightarrow D^0\pi^-\ell^+\nu )</td>
<td>((6.46 \pm 0.53 \pm 0.52) \times 10^{-3})</td>
</tr>
</tbody>
</table>

- Consistent with HFLAV.
- Precision is similar or slightly better compared to HFLAV2016.
- Main source of systematic errors are tag efficiency for charged modes, and PID, tracking efficiency for neutral modes.
  - ✓ Can be improved with luminosity (but not an easy work).
τ Polarization in $B \to D^* \tau \nu$

- Effect of the NP can appear in the polarization.
- Belle measured τ polarization in $B \to D^* \tau \nu$
  - Hadronic tag (full reconstruction)
  - Hadronic τ decays.
  - 2 bins of $\cos(\theta_{\text{hel}})$

$P_{\tau}(D^*) = -0.38 \pm 0.51^{\text{stat.}} +0.21_{-0.16}^{\text{syst.}}$

SM : $P_{\tau}(D^*) = -0.497\pm0.013$

Consistent with the SM at 0.6σ
D* Polarization in $B \rightarrow D^* \tau\nu$

New Result

$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{\text{hel}}(D^*)} = \frac{3}{4}[2F_L^{D^*} \cos^2(\theta_{\text{hel}}(D^*)) + (1 - F_L^{D^*}) \sin^2(\theta_{\text{hel}}(D^*))]$

- Inclusive reconstruction
- All $\tau$ decays can be used.
- Efficiency highly depends on $\cos\theta_{\text{hel}}(D^*)$.
- 3 bins of $\cos\theta_{\text{hel}}(D^*)$.

$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.03$

Consistent with SM ($\sim 0.45$) within $2\sigma$

$M(\text{tag})$ for one mode with $-0.67 < \cos\theta_{\text{hel}}(D^*) < 0.33$. 

Talk by K. Adamczyk (WG2)
EW Penguin B Decays

• $b \to s \ell^+ \ell^-$: Electroweak penguin (or box) diagram.
  ✓ Sensitive to $C_7$, $C_9$, $C_{10}$.
• “Anomalies” seen:
  ✓ Lepton Flavour Universality.
  ✓ Angular variable

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu\mu)}{\mathcal{B}(B^+ \to K^+ ee)}$$

LHCb result

$$R_K = 0.745 \pm 0.090_{-0.074} \pm 0.036 \quad (2.6\sigma \text{ from SM})$$

[PRL 113 (2014) 151601]

$$R_{K^*} : 2.1\text{-}2.4\sigma \text{ deviation from SM.}$$

LHCb, JHEP08(2017)055
EW Penguin B Decays

Belle measured $P_5'$ separately for muon and electron modes.

- $\sim 3\sigma$ deviation
- LHCb/ATLAS/CMS results from muon modes.

- 2.6$\sigma$ deviation in the muon mode.
- 1.1$\sigma$ in the electron mode.

[PRL 118, 11801 (2017)]
EW Penguin B Decays

New results in a few more related modes.

\[ B^0 \rightarrow K^{*0}\mu^\pm e^\mp \]
- Deviation in \( R(K) \), \( R(K^*) \) by LHCb.
- LFU violation \( \rightarrow \) LFV

\[ B^{-} \rightarrow \Lambda\bar{\nu}\nu \]
- \( b \rightarrow s\nu\bar{\nu} \) : FCNC process
- SM : \( B = (7.9 \pm 1.9) \times 10^{-7} \)
- Hadronic B tag

B\( (B^0 \rightarrow K^{*0}\mu^\pm e^\mp) < 1.8 \times 10^{-7} \)  

B\( (B^- \rightarrow \Lambda\bar{\nu}\nu) < 3.0 \times 10^{-5} \)
Radiative B Decay ($b \rightarrow s \gamma$)

- Penguin diagram (FCNC process).
- Good agreement between theory and experiments.
  - Strong constraint to New Physics

$B(B \rightarrow X_s \gamma; E_\gamma > 1.6\text{GeV})$

\[ = (3.32 \pm 0.15) \times 10^{-4} \quad \text{[HFLAV2018]} \]
\[ = (3.36 \pm 0.23) \times 10^{-4} \quad \text{[Misiak 2015]}^{\dagger} \]

$^{\dagger}$ Misiak et al, PRL 114, 221801, (2015)

- $A_{CP}$ of $B \rightarrow X_s \gamma$ is an interesting probe for NP, but has small (~2%) theoretical uncertainty.
- $\Delta A_{CP}$ (difference of $A_{CP}$ between charged and neutral B) is a cleaner probe.

\[
\Delta A_{CP}(B \rightarrow X_s \gamma) \equiv A_{CP}(B^+ \rightarrow X_s^+ \gamma) - A_{CP}(B^0 \rightarrow X_s^0 \gamma)
\]
$B \rightarrow X_s \gamma$

- Sum of 38 $X_s$ modes with $M(X_s) < 2.8$ GeV.
  - 11 of them are flavour non specific modes.
- 8 $M_{bc}$ distributions (including 3 from off-resonance) are simultaneously fitted.

$\Delta_{0-} = (+1.70 \pm 1.39 \pm 0.87 \pm 1.15)\%$

$\Delta A_{CP} = (+1.26 \pm 2.40 \pm 0.67)\%$

Constraint NP: 

$$\Delta A_{CP} \approx 4\pi^2 \alpha_s \frac{\Lambda_{78}}{m_b} \text{Im} \left( \frac{C_8}{C_7} \right)$$
Unitarity Triangle

\[ \sin 2\phi_1 \]

\[ |V_{ub}| \]

\[ \rho \]

\[ \phi_2 \]

\[ \phi_3 \]

\[ \Delta m_d \] and \[ \Delta m_s \]

\[ \epsilon_K \]

\[ \text{excluded area has CL > 0.95} \]

\[ \text{sol. w/ \cos 2\theta_1 < 0} \]

\[ \text{(excl. at CL > 0.95)} \]
\[ \cos(2\beta) \text{ in } B \to D(\ast)h^0 \]

- \( \sin 2\beta \) is precisely measured, but trigonometric ambiguity exists for \( \beta \).
- Time-dependent Dalitz analysis of \( B \to D(\ast)h^0 \), \( D \to K_S\pi^+\pi^- \) (\( h = \pi^0, \eta, \omega \)) can resolve it.
- Joint Babar + Belle analysis.  
  ✓ 471 + 772 M BB

\[ \sin(2\beta) = 0.80 \pm 0.14 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \pm 0.03 \text{ (model)} \]
\[ \cos(2\beta) = 0.91 \pm 0.22 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.07 \text{ (model)} \]
\[ \beta = (22.5 \pm 4.4 \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.6 \text{ (model)})^0 \]

- First evidence of \( \cos 2\beta > 0 \).

Talk by B.Pal (WG4)
\[ |V_{ub}| \text{ and } |V_{cb}| \]

- \(|V_{ub}| \text{ and } |V_{cb}| \) measurements are done using semi-leptonic decays \( b \rightarrow u\ell\nu, c\ell\nu \).

- Two approaches: inclusive and exclusive

Inclusive Semi-leptonic

\[
\bar{B} \rightarrow V_{cb} X_c \rightarrow W^- \ell^- \bar{\nu}
\]

BF \( \sim \) 25%

- QCD corrections to parton level decay rate
- Operator Product Expansion (OPE) in \( \alpha_s \) and \( \Lambda/m_b \)

Exclusive Semi-leptonic

\[
\bar{B} \rightarrow V_{cb} D^* \rightarrow W^- \ell^- \bar{\nu}
\]

specify hadrons (experimentally clean)

- QCD contributions parametrized in form factors
- Lattice QCD (high \( q^2 \)) or LCSR (low \( q^2 \))
Discrepancy between inclusive and exclusive measurements

**inclusive measurements**

Average $|V_{ub}|$:
- Inclusive: $|V_{ub}| = (4.49 \pm 0.16) \times 10^{-3}$
- Exclusive: $|V_{ub}| = (3.72 \pm 0.19) \times 10^{-3}$

Average $|V_{cb}|$:
- Inclusive: $|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$
- Exclusive: $|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3}$
Untagged $B \rightarrow D^* \ell \nu$

- New result of untagged analysis of $B \rightarrow D^* \ell \nu$ was presented at ICHEP.
- Simultaneous fit to $\cos\theta_\ell$, $\cos\theta_V$, $\chi$, $w$ (hadronic recoil) to extract form factors and $F(1) |V_{cb}|$.
- Two form factor parametrization, CLN [NPB530, 153 (1998)] and BGL [PRL74, 463 (1995)] are used.
  - CLN was mainly used in previous measurements.

$N(B \rightarrow D^*\text{ev}) = 91381$
$N(B \rightarrow D^*\mu\nu) = 89965$

Bonus: Lepton Flavor Universality test

$$\frac{\mathcal{B}(B^0 \rightarrow D^*-e^+\nu)}{\mathcal{B}(B^0 \rightarrow D^*-\mu^+\nu)} = 1.01 \pm 0.01 \pm 0.03$$
Untagged $B \to D^* \ell \nu$

Fit for BGL parametrizations for $B \to D^* \mu \nu$

- $w$
- $\cos \theta_\ell$
- $\cos \theta_\nu$
- $\chi$

**World average**

- $|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ (inclusive)
- $|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3}$ (exclusive)

**CLN:** $|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$

**BGL:** $|V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$

Some hint of inclusive/exclusive discrepancy?

Talk by K. Lieret (WG2) and C. Schwanda (WG2)
More Results, Talks

- $B \to \mu \nu$ (untagged) [PRL 121, 031801 (2018)]
  
  Talk by A. Sibidanov (WG2)

- $B \to \ell \nu \gamma$ (hadronic tag with Full Event Interpretation)

  New Result
  Talk by M. Gelb (WG2)

- CPV of $B \to J/\psi \pi^0$, $B \to K_S \pi^0 \pi^0$

  Talk by B. Pal (WG4)

- Inclusive $B \to X_u \ell \nu$ (electron energy endpoint)
  [PRD 95, 072001 (2017)]

- Charmless B decays, $\gamma(=\phi_3)$, …..

  and

- Prospects for Belle II
Summary

• Belle II started. Phase 2 operation completed this year.
  ✓ First collision.
  ✓ Accelerator study, but some physics data are taken.
  ✓ B mesons are reconstructed.

• New results from BaBar and Belle.
  ✓ D* polarization in B → D*τν.
  ✓ cos(2β) in B → D(*)h^0
  ✓ |V_{cb}| from B → D*ℓν
  ✓ ….

• Belle II Phase 3 (physics run) starts next year, and we expect first physics results soon. Stay tuned.
Backup
SuperKEKB and Belle II

- SuperKEKB
  - New beam pipe & bellows
  - Low emittance positrons to inject
  - Damping ring
  - Low emittance gun
  - Low emittance electrons to inject
  - Add / modify RF systems for higher beam current

- Belle II
  - New IR
  - New positron target / capture section

~ 7 m
~ 7.5 m

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## SuperKEKB Parameter

<table>
<thead>
<tr>
<th>parameters</th>
<th>KEKB</th>
<th></th>
<th>SuperKEKB</th>
<th></th>
<th>units</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LER</td>
<td>HER</td>
<td>LER</td>
<td>HER</td>
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<tr>
<td>Beam energy</td>
<td>$E_b$</td>
<td>3.5</td>
<td>8</td>
<td>4</td>
<td>7</td>
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<td>Half crossing angle</td>
<td>$\phi$</td>
<td>11</td>
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<td>41.5</td>
<td></td>
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<tr>
<td>Horizontal emittance</td>
<td>$\varepsilon_x$</td>
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<td>24</td>
<td>3.2</td>
<td>5.0</td>
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<td>Emittance ratio</td>
<td>$\kappa$</td>
<td>0.88</td>
<td>0.66</td>
<td>0.27</td>
<td>0.25</td>
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<td>Beta functions at IP</td>
<td>$\beta_x^<em>/\beta_y^</em>$</td>
<td>1200/5.9</td>
<td></td>
<td>32/0.27</td>
<td>25/0.31</td>
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<tr>
<td>Beam currents</td>
<td>$I_b$</td>
<td>1.64</td>
<td>1.19</td>
<td>3.60</td>
<td>2.60</td>
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<tr>
<td>beam-beam parameter</td>
<td>$\xi_y$</td>
<td>0.129</td>
<td>0.090</td>
<td>0.0886</td>
<td>0.0830</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$</td>
<td>$2.1 \times 10^{34}$</td>
<td></td>
<td>$8 \times 10^{35}$</td>
<td></td>
</tr>
</tbody>
</table>

- Small beam size & high current to increase luminosity
- Large crossing angle
- Change beam energies to solve the problem of LER short lifetime
Belle II

- At least, the same performance as Belle in higher luminosity.
- Better performance if important for physics

SVD: 4 DSSD lyr + 4 DSSD lyr
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)
The Geography of the International Belle II collaboration

Belle II now has grown to ~800 researchers from 25 countries

This is rather unique in Japan and Asia. The only comparable example is the T2K experiment at JPARC, which is also an international collaboration

Youth and potential: There are ~267 graduate students in the collaboration
We are on the Y(4S) resonance and recording B anti-B pairs with ~99% efficiency.

Event Topology tells us we are seeing B’s

B pairs produced at rest in the CM with no extra particles
Examples of Physics Competition and Complementarity

Use publicly available LHCb projections.
Angular Analysis of $B \rightarrow K^* \ell^+ \ell^-$

Angular distribution in $B \rightarrow K^* \ell^+ \ell^-$ ($K^* \rightarrow K\pi$)

\[
\frac{1}{d\Gamma/dq^2} \left[ \frac{d^4\Gamma}{d\cos\theta_{\ell} \, d\cos\theta_K \, d\phi \, dq^2} \right]
= \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K \right. \\
+ \frac{1}{4} (1 - F_L) \sin^2\theta_K \cos 2\theta_\ell \\
- F_L \cos^2\theta_K \cos 2\theta_\ell + S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\
+ S_6 \sin^2\theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \left. \right]
\]

- 8 variables: $F_L$ (longitudinal polarization of $K^*$) and $S_j$ (j=3,4,5,6,7,8,9)
- ✓ function of $q^2$

\[ q^2 = M(\ell^+ \ell^-)^2 \]