“Searching for new fundamental interactions at Belle II”

27/10/2020

Gianluca Inguglia
Some physics from Belle to Belle II

- B-factories have been the driving forces in the past decades to establish the CKM mechanism as origin of CP violation and in the search for new physics.

- Few anomalies in the recent years have been observed and large amount of data are required to understand if these are fluctuations or if new physics effects have been observed.

- Belle II will provide a complementary approach to new physics searches wrt other experiments.

- Rich program of flavor physics studies thanks to the high luminosity.

- Physics beyond flavor...
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- Physics beyond flavor...
To obtain x40 higher luminosity
Belle II Detector Elements

KL and muon detector:
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Particle Identification
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (fwd)

EM Calorimeter:
- CsI(Tl), waveform sampling

Electrons (7GeV)
- Beryllium beam pipe
  - 2cm diameter

Vertex Detector:
- 2 layers DEPFET + 4 layers DSSD
  - (1 in 2019)

Central Drift Chamber
- He(50%):C₆H₆(50%), small cells, long lever arm, fast electronics

Positrons (4GeV)
Belle II first collisions with full detector, 25\textsuperscript{th} March 2019

1\textsuperscript{st} e^+e^- \rightarrow \text{hadrons} event!
Belle II first collisions with full detector, 25th March 2019

1st $e^+e^- \rightarrow \bar{B}B$ event!
Belle II first collisions with full detector, 25th March 2019
SuperKEKB, the world’s “brightest” particle collider

KEK reclaims luminosity record

30 June 2020

Present record
$2.40 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
on June 21

World record!
$2.22 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
on June 15

Belle II Online luminosity

Exp: 7-8-10-12 - All runs

Integrated luminosity
- Recorded Daily
- $\int L_{\text{recorded}} \, dt = 74.10$ [fb$^{-1}$]

Total integrated luminosity [fb$^{-1}$]
Why a (super) B-factory?

The general aim of a B-factory is to study B mesons via the reaction

\[ e^+ e^- \rightarrow Y(4S) \rightarrow B \bar{B} \]

In general one of the two B mesons is tagged and the other is studied.

Entangled B meson pairs are produced in the decays of Y(4S)

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\[ t = 0 \]

\[ t = t_0 \]
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At the time \( t_0 \) in which the first meson decays, the wave function collapses into a specific and definite state: \( B^0 \bar{B}^0 \) vs. \( \bar{B}^0 B^0 \).
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\[ \Delta z = \Delta t \beta \gamma c \]

\[ \Delta \approx \Delta t \beta \gamma c \]

Why a (super) B-factory?
What happens when colliding $e^+e^-$ @Super-KEKB?
What happens when colliding $e^+e^- @ \text{Super-KEKB}$?

$$\sigma[e^+e^- \rightarrow e^+e^-(\gamma)] = 74.4 \text{ nb}$$

(51.99%)
What happens when colliding $e^+e^- @ \text{Super-KEKB}$?

- $\sigma[e^+e^- \rightarrow \gamma(4S)] = 1.05 \text{nb}$ (0.80%)
- $\sigma[e^+e^- \rightarrow \mu^+\mu^- (\gamma)] = 1.15 \text{nb}$ (0.91%)
- $\sigma[e^+e^- \rightarrow c\bar{c}(\gamma)] = 1.3 \text{nb}$
- $\sigma[e^+e^- \rightarrow \tau^+\tau^- (\gamma)] = 0.92 \text{nb}$ (0.64%)
- $\sigma[e^+e^- \rightarrow d\bar{d}(\gamma)] = 0.40 \text{nb}$ (0.28%)
- $\sigma[e^+e^- \rightarrow s\bar{s}(\gamma)] = 0.38 \text{nb}$ (0.27%)
- $\sigma[e^+e^- \rightarrow e^+e^- (\gamma)] = 74.4 \text{nb}$ (51.99%)
- $\sigma[e^+e^- \rightarrow e^+e^-\mu^+\mu^-] = 18.9 \text{nb}$ (13.21%)
- $\sigma[e^+e^- \rightarrow e^+e^-\mu^+\mu^-] = 39.7 \text{nb}$ (27.74%)
What happens when colliding $e^+e^-@Super$-KEKB?

- $\sigma[e^+e^-\rightarrow \Upsilon(4S)]=1.05\text{ nb}$ (0.73%)
- $\sigma[e^+e^-\rightarrow \mu^+\mu^- (\gamma)]=1.15\text{ nb}$ (0.80%)
- $\sigma[e^+e^-\rightarrow c\bar{c}(\gamma)]=1.3\text{ nb}$ (0.91%)
- $\sigma[e^+e^-\rightarrow u\bar{u}(\gamma)]=1.61\text{ nb}$ (1.13%)
- $\sigma[e^+e^-\rightarrow \gamma\gamma(\gamma)]=3.3\text{ nb}$ (2.31%)
- $\sigma[e^+e^-\rightarrow e^+e^-\mu^+\mu^-]=18.9\text{ nb}$ (13.21%)
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What happens when colliding $e^+e^-$ @Super-KEKB?

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Cross Section (nb)</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>$e^+e^+</td>
<td></td>
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</table><p>ightarrow e^+e^-$    | 74.4               | 51.99%     |
| $e^+e^+ightarrow \gamma\gamma$ | 3.3                | 2.31%      |
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### Physics process | Cross section [nb] | Cuts
--- | --- | ---
$\Upsilon(4S)$ | 1.05 ± 0.10 | -
w$\bar{u}$(γ) | 1.61 | -
d$\bar{d}$(γ) | 0.40 | -
s$\bar{s}$(γ) | 0.38 | -
$\alpha$γ(γ) | 1.30 | -
e$^+e^-$(γ) | 300 ± 3 (MC stat.) | $10^\circ < \theta_{e^+e^-} < 170^\circ$, $E_{e^+e^-} > 0.15$ GeV
γγ(γ) | 4.99 ± 0.05 (MC stat.) | $10^\circ < \theta_{\gamma\gamma} < 170^\circ$, $E_{\gamma\gamma} > 0.15$ GeV
$\mu^+\mu^-$ (γ) | 1.148 | -
$\mu^+\mu^-$ (γ) | 0.831 | $\mu^+\mu^-$'s (p > 0.5GeV) in CDC
$\mu^+\mu^-$ (γ) | 0.242 | $\mu^+\mu^-$'s (p > 0.5GeV) in CDC, $\geq 1$ γ ($E_{\gamma} > 0.5$GeV) in ECL
τ$^+\tau^-$ (γ) | 0.919 | -
$\nu\bar{\nu}$(γ) | 0.25 $\times$ 10$^{-3}$ | -
e$^+e^-e^+e^-$ | 39.7 ± 0.1 (MC stat.) | $W_{\ell\ell} > 0.5$GeV
e$^+e^-\mu^+\mu^-$ | 18.9 ± 0.1 (MC stat.) | $W_{\ell\ell} > 0.5$GeV

**Remember!!** \[ N = L \times \sigma \]

**Number of events of a process** | **Luminosity of an experiment**
--- | ---
| **Cross-section of the process to be studied in the specific experiment**

The Belle II physics program

- **New Hadrons, QCD measurements**
  - Spin Fragmentation Functions
  - New Charmonium-Like States
  - New bottomonium-like states
  - New baryons
  - e+e- -> ISR, pi+ pi- cross-sections (g-2)

- **Dark Sector**
  - Axion-Like Particles (ALPs)
  - Invisible Z
  - Dark Higgs
  - Heavy tau neutrino
  - LLPs (Long-Lived Particles)
  - Gazelle (LLP search)

- **Electroweak physics with e-polarization**
  - Tau mass, lifetime
  - Tau spectral functions
  - Lepton Flavor Violation (LFV)

- **Rare B decays**
  - Hadronic B Decays: B -> K pi, pi pi Direct CPV, isospin sum rules

- **Time Dependent Measurements**

- **Charm Physics**
  - D, Dbar mixing and CP
  - Charm Lifetimes
  - Branching Fractions, Dalitz analyses
  - B -> H, leptonic flavor violation

- **Radiative charm decays**

- **CKM Matrix elements (Vcb, Vub)**
  - Inclusive Measurements
  - Vtd/Vts from penguins
  - Exclusive measurements
    - B -> q' q tau nu, lepton universality
    - alpha, beta, gamma

- **Dark Photon**

- **Electroweak Penguins**
  - B -> V V; right-handed currents, triple products
  - B -> K* gamma and radiative penguins, B -> K(*) nu nubar

- **Hadronic b -> c decays**

- **New charmed resonances**

- **Upsilon(1S, 2S) runs**

- **Bs physics**

- **Improved tau**

- **A FB (tau, mu, e+, b, c)**
**Flavor anomalies**

Anomalies have been reported in many processes involving both quarks and leptons

- In the **quark sector** anomalies have been observed for example
  - **in** $b \rightarrow c l v$
    - $R(D) = BF[B \rightarrow D \tau^+ \nu_l] / BF[B \rightarrow D l^+ \nu_l]$ (l = e, µ), $\sim 1.4\sigma$
    - $R(D^*) = BF[B \rightarrow D^* \tau^+ \nu_l] / BF[B \rightarrow D^* l^+ \nu_l]$ (l = e, µ), $\sim 2.7\sigma$
    - In the $R(D)$-$R(D^*)$ plane $\sim 3.9\sigma$
  - **in** $b \rightarrow s l l$
    - $R(K) = BF[B^+ \rightarrow K^+ \mu^+ \mu^-] / BF[B^+ \rightarrow K^+ e^+ e^-]$ $\sim 2.5\sigma$
    - $R(K^{*0}) = BF[B^{0} \rightarrow K^{*0} \mu^+ \mu^-] / BF[B^{0} \rightarrow K^{*0} e^+ e^-]$ $\sim 2.2-2.5\sigma$
    - In the angular observables of $B \rightarrow K^* \mu^+ \mu^-$ $\sim 3.4\sigma$

- In the **lepton sector** anomalies have been observed for example
  - In the anomalous magnetic moment of the muon $(g-2)_\mu$ $\sim 3.8\sigma$
  - In the anomalous magnetic moment of the electron $\sim 2.5\sigma
Flavor anomalies, tensions in the standard model

Are these the hints of a new fundamental interaction that violates Lepton Flavour Universality?

“Lepton Flavor Universality refers to an intrinsic accidental property or symmetry of the SM under which the electroweak (gauge) bosons have the same couplings to the three generations of leptons, since the only physical difference between the three generations of leptons derives from Yukawa interactions between the lepton fields and the Higgs field” → The only difference between charged leptons is their mass.

The graphical compilation of anomalies was borrowed with permission from our collaborator Andreas Crivellin, https://arxiv.org/pdf/2002.07184.pdf
Flavor anomalies, tensions in the standard model

Are these the hints of a new fundamental interaction that violates Lepton Flavour Universality?

Lepton Flavor Universality from the perspective of a lepton flavor non-universal current:

”All leptons are equals, but some leptons are more equal than others...”

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Are these the hints of a new fundamental interaction that violates Lepton Flavour Universality?

- Should the observed flavor physics anomalies be due to new physics, are there other independent channels not well experimentally explored that might be affected by the same kind of new physics?
- Can these other channels be used to identify which new physics models are more suitable and which models are instead to be excluded or severely constrained?
- Is it possible to perform these measurements and tests in the clean but energy-limited environment of the Belle II experiment?

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The answer to all above questions is “yes” and we will focus on the following searches:

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Three unique experimental searches with leptons and missing energy in the final state

1. \( e^+e^- \rightarrow \mu^+\mu^- + Z' \)
2. \( e^+e^- \rightarrow \tau^+\tau^- + V_{\tau} \)
3. \( e^+e^- \rightarrow \nu_\mu(\nu_e) + Y(nS) \)
L-flavor preferential coupling: the $L_\mu - L_\tau$ model and a dark $Z'$

The model is a new gauge boson, $Z'$, which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g'\mu\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,L}\gamma^\mu Z'_\mu\nu_{\mu,L} + g'\bar{\nu}_{\tau,L}\gamma^\mu Z'_\mu\nu_{\tau,L}.$$  

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi} \left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right) \sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}} \theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$  

$$BR(Z' \to \text{invisible}) = \frac{2\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell)}{2\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) + \Gamma(Z' \to \mu\bar{\mu}) + \Gamma(Z' \to \tau\bar{\tau})}.$$
$Z' \rightarrow$ invisible, Belle II Event Display

$M_{Z'} = 1 \text{ GeV/c}^2$

$M_{Z'} = 4 \text{ GeV/c}^2$

$M_{Z'} = 8 \text{ GeV/c}^2$

$M_{Z'} = 9.7 \text{ GeV/c}^2$
Belle II Event Display

Belle 2 DATA
event display
run # 3236
Event #493624
$M_z$ candidate 2 GeV/c$^2$
L-flavor preferential coupling: the \( L_\mu - L_\tau \) model and a dark \( Z' \)

The model is a new gauge boson, \( Z' \), which couples to \( L_\mu - L_\tau \). The interaction Lagrangian is

\[
\mathcal{L} = -g' \mu \gamma^\mu Z'_{\mu} \mu + g' \tau \gamma^\mu Z'_{\mu} \tau - g' \tilde{\nu}_{\mu,L} \gamma^\mu Z'_{\mu} \nu_{\mu,L} + g' \tilde{\nu}_{\tau,L} \gamma^\mu Z'_{\mu} \nu_{\tau,L}.
\]

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\]

We already pioneered this search, PRL 124, 141801 (2020), arXiv:1912.11276

So, what can we do?
L-flavor preferential coupling: the $L_\mu$-$L_\tau$ model and a dark $Z'$

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Invisible decays of $Z'$ within the $L_\mu$-$L_\tau$ model

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New cutting-edge machine learning analysis techniques already developed at HEPHY, plan to go deeper...with more data..

![Graph showing signal and background separation](image)

![Diagram illustrating feature extraction and learning process](image)
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In the near term
L-flavor preferential coupling: the $L_\mu - L_\tau$ model and a dark $Z'$

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With lot of more data
Dark Higgs-strahlung @ Belle II


Higgs-strahlung process

h' = dark Higgs,
A' = dark photon

Higgs-strahlung: h' decays depending on $M_{h'}$ and $M_{A'}$. Measures the coupling constant of the dark photon to the dark Higgs, $\alpha_D$.

$M_{h'} > 2M_{A'}$: $h' \rightarrow A'A'$, Very low background.

- Exclusive: 3 charged tracks pairs with same invariant mass and total energy of the event.
- Inclusive: 2 charged tracks pairs, same invariant mass, third A' from 4-mom. of $e^+e^-$ system

$M_{A'} < M_{h'} < 2M_{A'}$: $h' \rightarrow A'A'^*$

$M_{h'} < M_{A'}$: h' (very) long lived.
Dark Higgs-strahlung @ Belle II with 10/fb


- Identical final state as for the invisible Z' search
- Low SM background
- Allows simultaneous search of a dark Higgs boson and of dark photon
- Existing limits only from KLOE

Current focus on $\mu^+\mu^+$+invisible final state, plans to extend to $e^+e^-$+invisible

Higgs-strahlung process $h'$=dark Higgs, $A'$= dark Photon

KLOE-2
Lepton flavor violating $Z'$ explanation of the muon anomalous magnetic moment

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We discuss a minimal solution to the long-standing $(g-2)_\mu$ anomaly in a simple extension of the Standard Model with an extra $Z'$ vector boson that has only flavor off-diagonal couplings to the second and third generation of leptons, i.e. $\mu, \tau, \nu_\mu, \nu_\tau$ and their antiparticles. A simplified model realization, as well as various collider and low-energy constraints on this model, are discussed. We find that the $(g-2)_\mu$-favored region for a $Z'$ lighter than the tau lepton is totally excluded, while a heavier $Z'$ solution is still allowed. Some testable implications of this scenario in future experiments, such as lepton-flavor universality-violating tau decays at Belle 2, and a new four-lepton signature involving same-sign di-muons and di-taus at HL-LHC and FCC-ee, are pointed out. A characteristic resonant absorption feature in the high-energy neutrino spectrum might also be observed by neutrino telescopes like IceCube and KM3NeT.

This is an Abelian symmetry group $L_\mu - L_\tau$ where LFV terms are allowed
Our "standard" Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g' \bar{\mu} \gamma^\mu Z'_\mu \mu + g' \bar{\tau} \gamma^\mu Z'_\mu \tau - g' \bar{\nu}_{\mu,L} \gamma^\mu Z'_\mu \nu_{\mu,L} + g' \bar{\nu}_{\tau,L} \gamma^\mu Z'_\mu \nu_{\tau,L}.$$

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+ \ell^-) = \frac{(g')^2 M_{Z'}}{12\pi} \left(1 + \frac{2M_{\ell}^2}{M_{Z'}^2}\right) \sqrt{1 - \frac{4M_{\ell}^2}{M_{Z'}^2}} \theta(M_{Z'} - 2M_{\ell}),$$

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Our "standard" $Z'$

The model is a new gauge boson, $Z'$, which couples to $L_{\mu} - L_{\tau}$. The interaction Lagrangian is

$$\mathcal{L} = -g' \bar{\mu} \gamma^{\mu} Z'_{\mu} \mu + g' \bar{\tau} \gamma^{\mu} Z'_{\mu} \tau - g' \bar{\nu}_{\mu, L} \gamma^{\mu} Z'_{\mu} \nu_{\mu, L} + g' \bar{\nu}_{\tau, L} \gamma^{\mu} Z'_{\mu} \nu_{\tau, L}.$$ 

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^{+} \ell^{-}) = \frac{(g')^2 M_{Z'}}{12\pi} \left(1 + \frac{2M_{\ell}^2}{M_{Z'}^2}\right) \sqrt{1 - \frac{4M_{\ell}^2}{M_{Z'}^2}} \theta(M_{Z'} - 2M_{\ell}),$$

$$\Gamma(Z' \to \nu_\ell \bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$
LFU tests in tau decays

\[ \mathcal{L}_{Z'} = g'_L \left( \bar{\mu} \gamma^\alpha P_L \tau + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\tau \right) Z'_\alpha \\
+ g'_R \left( \bar{\mu} \gamma^\alpha P_R \tau \right) Z'_\alpha + \text{H.c.} \]

\[ P_{L,R} = \left( 1 \mp \gamma^5 \right)/2 \]

Lepton doublets → \((\nu, l)_L\)

\[ L_\mu \leftrightarrow L_\tau, \]

Lepton singlets → \(l_R\)

\[ \mu_R \leftrightarrow \tau_R, \]

\[ B^\alpha \leftrightarrow B^\alpha, \]

\[ Z'^\alpha \leftrightarrow -Z'^\alpha \]

U(1)\(^Y\) gauge field

U(1)' gauge field

Our "standard" \(Z'\)

The model is a new gauge boson, \(Z'\), which couples to \(L_\mu - L_\tau\). The interaction Lagrangian is

\[ \mathcal{L} = -g' \bar{\mu} \gamma^\mu Z'_\mu \mu + g' \bar{\tau} \gamma^\mu Z'_\mu \tau - g' \bar{\nu}_{\mu,L} \gamma^\mu Z'_\mu \nu_{\mu,L} + g' \bar{\nu}_\tau, L \gamma^\mu Z'_\mu \nu_{\tau,L}. \]

The equations for the partial widths are,

\[ \Gamma(Z' \to \ell^+ \ell^-) = \frac{(g')^2 M_{Z'}}{12\pi} \left( 1 + \frac{2M^2_{\ell}}{M^2_{Z'}} \right) \sqrt{1 - \frac{4M^2_{\ell}}{M^2_{Z'}}} \theta(M_{Z'} - 2M_{\ell}), \]

\[ \Gamma(Z' \to \nu_\ell \bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}. \]
Taus at Belle II

A possible test of LFU in tau decays

\[ \left( \frac{g_\mu}{g_e} \right)_\tau = \sqrt{\frac{BF[\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau]} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}} \]
A possible test of LFU in tau decays

\[
\left( \frac{g_\mu}{g_e} \right)_\tau = \sqrt{\frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]} \frac{f(m_e^2/m^2_\tau)}{f(m^2_\mu/m^2_\tau)}}
\]

\[f(x) = -8x + 8x^3 - x^4 - 12x^2 \log x\]
A possible test of LFU in tau decays

\[ \left( \frac{g_\mu}{g_e} \right)_\tau = \sqrt{\frac{B F[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{B F[\tau^- \to e^- \bar{\nu}_e \nu_\tau]} \frac{f(m_\mu^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}} \]

\[ R_\mu = \frac{B F[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{B F[\tau^- \to e^- \bar{\nu}_e \nu_\tau]} \]

\[ f(x) = -8x + 8x^3 - x^4 - 12x^2 \log x \]

At Babar (Phys. Rev. Lett. 105 051602, ArXiv: 0912.0242 (2010)), with 500 fb^{-1}, \( R_\mu = 0.976 \pm 0.0016^{\text{stat}} \pm 0.0036^{\text{sys}} \)

And \( (g_\mu/g_e)_\tau = 1.0036 \pm 0.0020 \)

Can we improve this?
A possible test of LFU in tau decays

At Babar (Phys. Rev. Lett. 105 051602, ArXiv: 0912.0242 (2010)), with 500 fb$^{-1}$, $R_{\mu}=0.976 \pm 0.0016_{\text{stat}} \pm 0.0036_{\text{sys}}$

And $(g_\mu/g_e)_\tau = 1.0036 \pm 0.0020$

Can we improve this?
Yes, systematics dominated by PID due limited size of data and MC samples → the main sys. component will scale with the luminosity (of both data and MC)

Achieving per mille (or below) precision on $R_{\mu}$ will allow us, should $g_\mu/g_e=1.0036$ as measured by BaBar, to observe lepton flavor non-universal couplings at a precision $>5\sigma$
A possible test of LFU in tau decays: yet another Z’?

The sensitivity to a LFV Z’ depends on the level of systematics in the test of LFU in tau decays.
This is direct search for LFV in the decay of Y(nS) resonances (bb bound state).

CLEO Y(1S)

BaBar
leptonic $\gamma(3S) \to e\tau$ ($\chi^2/\text{ndf}=52.4/49$)
Lepton flavor violating quarkonium decays

Derek E. Hazard and Alexey A. Petrov

Phys. Rev. D 94, 074023 – Published 17 October 2016

“Any new physics model that incorporates flavor and involves flavor-violating interactions at high energy scales can be cast in terms of the effective Lagrangian of Eq. (1) at low energies. We argued that Wilson coefficients of this Lagrangian could be effectively probed by studying decays of quarkonium states with different spin-parity quantum numbers, providing complementary constraints to those obtained from tau and mu decays”

$$Y(nS) \rightarrow \tau\mu$$ decays at Belle 2

Leptons | Initial state (quark) | Wilson coefficient \((GeV^{-2})\) | \(C_{VL}^{\ell_1\ell_2}/\Lambda^2\) | \(C_{VR}^{\ell_1\ell_2}/\Lambda^2\) | \(C_{TL}^{\ell_1\ell_2}/\Lambda^2\) | \(C_{TR}^{\ell_1\ell_2}/\Lambda^2\)
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>(\ell_1\ell_2)</td>
<td>(Y(1S)) ((b))</td>
<td>(Y(2S)) ((b))</td>
<td>(Y(3S)) ((b))</td>
<td>(J/\psi) ((c))</td>
<td>(\phi) ((s))</td>
<td>(\mu\tau)</td>
</tr>
<tr>
<td>(\mu\tau)</td>
<td>(5.6 \times 10^{-6})</td>
<td>(4.1 \times 10^{-6})</td>
<td>(3.5 \times 10^{-6})</td>
<td>(5.5 \times 10^{-5})</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>(e\tau)</td>
<td>–</td>
<td>(4.1 \times 10^{-6})</td>
<td>(4.1 \times 10^{-6})</td>
<td>(1.1 \times 10^{-4})</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>(e\mu)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(1.0 \times 10^{-5})</td>
<td>(2 \times 10^{-3})</td>
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<td>(1.0 \times 10^{-5})</td>
<td>(2 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>(\mu\tau)</td>
<td>(4.4 \times 10^{-2})</td>
<td>(3.2 \times 10^{-2})</td>
<td>(2.8 \times 10^{-2})</td>
<td>(1.2)</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
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<td>(1 \times 10^4)</td>
<td></td>
</tr>
</tbody>
</table>
Y(nS) → τμ decays at Belle 2

Measurements dominated by BABAR [Y(2,3S)] and CLEO [Y(1S)]
Y(1S) → τμ decays at Belle 2

<table>
<thead>
<tr>
<th>CLEO-III</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 fb⁻¹ @ Y(1S) → 2.1 x10⁷ Y(1S)</td>
<td>13 fb⁻¹ @ Y(2S) → 98 x10⁶ Y(2S)</td>
</tr>
<tr>
<td>1.3 fb⁻¹ @ Y(2S) → 9.3 x10⁶ Y(2S)</td>
<td>26 fb⁻¹ @ Y(3S) → 116 x10⁶ Y(3S)</td>
</tr>
<tr>
<td>1.4 fb⁻¹ @ Y(3S) → 5.9 x10⁶ Y(3S)</td>
<td></td>
</tr>
</tbody>
</table>

We will look into ISR production, and decays, of Y(nS) from ISR with data collected at the Y(4S), unless samples collected at lower energy become available before 2024.

Taking into account the cross sections from ArXiv hep-ph/9910523 for ISR bottomonia production at the Y(4S) (respectively 0.019 nb for Y(1S), 0.015 nb for Y(2S) and 0.031 nb for Y(3S)) and the decay rate for Y(2,3S) → π⁺π⁻Y(1S)

- 3.1 x 10⁷ Y(3S)/ab⁻¹ of data collected at the Y(4S)
- 1.5 x 10⁷ Y(2S)/ab⁻¹ of data collected at the Y(4S) equivalent to
- 2.67 x 10⁶ Y(1S) from Y(3S) → π⁺π⁻Y(1S) /ab⁻¹ of data collected at the Y(4S)
- 1.39 x 10⁶ Y(1S) from Y(2S) → π⁺π⁻Y(1S) /ab⁻¹ of data collected at the Y(4S) equivalent to
- ~4 x 10⁶ Y(1S) available per ab⁻¹ collected at the Y(4S) with the ISR technique (vs. 1.6 x 10⁸ di-pion tagged Y(1S)/ab⁻¹ when taking data at the Y(3S))
We will look into ISR production, and decays, of $Y(nS)$ from ISR with data collected at the $Y(4S)$, unless samples collected at lower energy become available before 2024.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Production mode</th>
<th>Yields in 25 ab$^{-1}$</th>
<th>Total efficiency</th>
<th>N. of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(3S)$</td>
<td>$e^+e^- \rightarrow \gamma_{ISR}\Upsilon(3S)$</td>
<td>7.6×10$^8$</td>
<td>2%</td>
<td>1.5×10$^7$</td>
</tr>
<tr>
<td>$\Upsilon(2S)$</td>
<td>$e^+e^- \rightarrow \gamma_{ISR}\Upsilon(2S)$</td>
<td>3.8×10$^8$</td>
<td>2%</td>
<td>0.8×10$^7$</td>
</tr>
<tr>
<td>$\Upsilon(1S)$</td>
<td>$e^+e^- \rightarrow \gamma_{ISR}\Upsilon(1S)$</td>
<td>4.8×10$^8$</td>
<td>2%</td>
<td>1.0×10$^7$</td>
</tr>
<tr>
<td>total $\Upsilon(2S)$</td>
<td>$\Upsilon(3S)(ISR) \rightarrow \pi^+\pi^-\Upsilon(1S)$</td>
<td>2.1×10$^7$</td>
<td>4%</td>
<td>0.9×10$^7$</td>
</tr>
<tr>
<td>total $\Upsilon(1S)$</td>
<td>$\Upsilon(3S)(ISR) \rightarrow \pi^+\pi^-\Upsilon(1S)$</td>
<td>3.3×10$^7$</td>
<td>4%</td>
<td>1.3×10$^6$</td>
</tr>
<tr>
<td></td>
<td>$\Upsilon(2S)(ISR) \rightarrow \pi^+\pi^-\Upsilon(1S)$</td>
<td>6.8×10$^7$</td>
<td>4%</td>
<td>0.3×10$^7$</td>
</tr>
<tr>
<td></td>
<td>$\Upsilon(1S)$</td>
<td></td>
<td></td>
<td>1.4×10$^7$</td>
</tr>
</tbody>
</table>
$Y(nS) \to \tau \mu$ decays at Belle 2, examples of (untagged) ISR production

$e^+ e^- \to \gamma_{ISR} Y(3S), Y(3S) \to \pi^+ \pi^- Y(1S), Y(1S) \to \tau^+ \mu^-, \tau^+ \to e^+ \nu_e \bar{\nu}_\tau$

$e^+ e^- \to \gamma_{ISR} Y(2S), Y(2S) \to \pi^+ \pi^- Y(1S), Y(1S) \to \tau^+ \mu^-, \tau^+ \to e^+ \nu_e \bar{\nu}_\tau$

Not reconstructed
Intermediate or invisible
Reconstructed final state
Y(1S) → τμ decays at Belle 2

- 3.1 x 10^7 Y(3S)/ab^{-1} of data collected at the
- 1.5 x 10^7 Y(2S)/ab^{-1} of data collected at the
equivalent to
- 2.67 x 10^6 Y(1S) from Y(3S) → π^+π^-Y(1S)
- 1.39 x 10^6 Y(1S) from Y(2S) → π^+π^-Y(1S)
equivalent to
- ~4 x 10^6 Y(1S) available per ab^{-1} collected
(vs. 1.6 x 10^8 di-pion tagged Y(1S)/ab^{-1} when taking data at the Y(3S))
Recent contributions of team members

Search for Dark Higgsstrahlung in $e^+e^- \rightarrow \mu^+\mu^-$ and missing energy final states with the Belle II experiment [BELLE2-NOTE-PH-2020-048] (Physics, dark sector)

Search for an invisible $Z'$ in $e^+e^- \rightarrow \mu^+\mu^- + \text{missing energy}$ final states and background measurement for a search for a Lepton Flavour Violating invisible $Z'$ in $e^+e^- \rightarrow e^+\mu^- + \text{missing energy}$ final states with Phase 2 data [BELLE2-NOTE-PH-2019-002] (Physics, dark sector)

cLFV in bottomonium produced in processes with ISR at Belle II [BELLE2-NOTE-PH-2019-058] (Physics, bottomonium/cLFV)

L1 CDC trigger performance study targeting dark sector analyses with 2019 data [BELLE2-NOTE-TE-2020-014] (Technical, trigger)

Monitor of CDC trigger performance for low multiplicity events in Phase 3 data [BELLE2-NOTE-TE-2019-023] (Technical, trigger)

Performance of the CDC trigger for very low multiplicity studies in Phase 2 data [BELLE2-NOTE-TE-2018-017] (Technical, trigger)

Pion identification efficiency and lepton mis-id rates using tau events with 3-prong 1-prong topology [BELLE2-NOTE-TE-2020-001] (Technical, PID /Physics, tau)

Identification of muonic decays of tau pairs at the Belle II experiment through the implementation of machine learning algorithms [will appear soon] (Technical, ML/ Physics, tau)
New physics searches at different energy scale

GeV scale

EW scale

TEV scale

Thank you for your attention!