Belle II group report

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on behalf of (and with contributions from) HEPHY Belle II group

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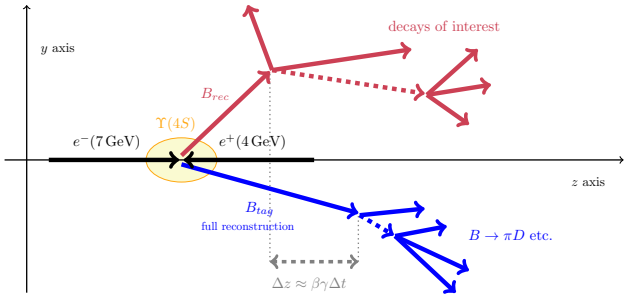
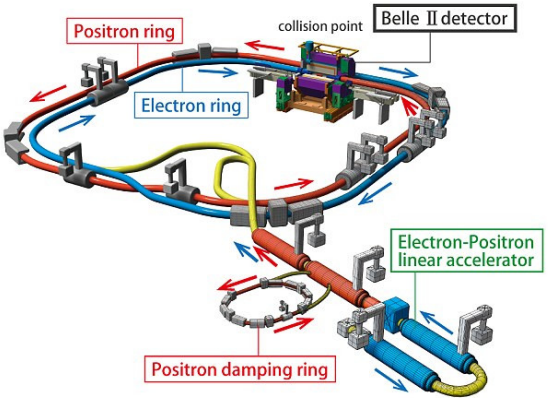
Introduction & Motivation

- Experiment: an asymmetrical e^+e^- SuperKEKB collider and Belle II spectrometer
- Started operation in 2018
- Designed for studies of rare decays of B and D mesons and τ leptons
- Mainly operates at $\Upsilon(4S)$ resonance energy: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Aim at 50-times more collected data than Belle $\to$ New rare processes discoveries?



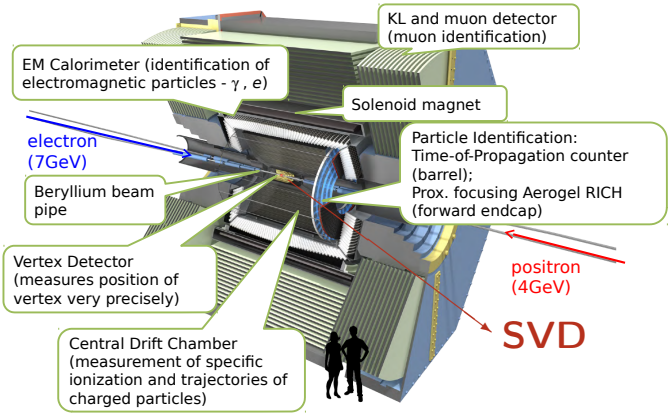
SuperKEKB

- Located at KEK in Tsukuba, Japan
- It uses a 3 km long underground tunnel
- Beam energies:
  $E_{\text{electron}} = 7\,\text{GeV}$
  $E_{\text{positron}} = 4\,\text{GeV}$
- It is designed to collect data at energies between 9.46 GeV and 11.25 GeV
- The target final luminosity is $8 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$ (40-times higher than KEKB)



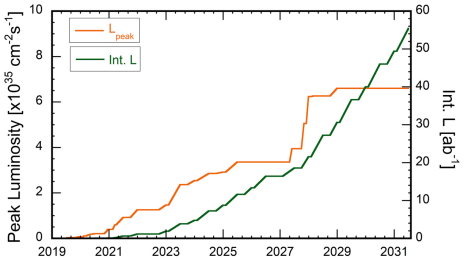
Belle II Spectrometer

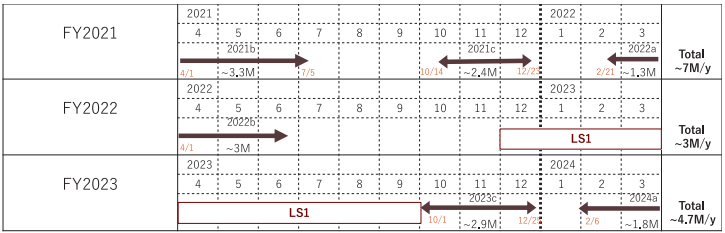
- Requirements:
  - Spatial limitations: has to fit into the Belle shell
  - Radiation damage: 10- to 20-times higher beam background
- Measurements of impact parameters by Vertex Detector (VXD): Pixel Detector (PXD) and **Silicon Vertex Detector (SVD)**



Data taking plans

- 6-7 months/year (depending on electricity cost)
- Long-term plan (right): Peak luminosity in early 2030s
- Aim to collect $\sim$500 fb^{-1} before long shutdown in 2023





Experiment timeline

Feb 2016	First turns of the SuperKEKB positron and electron beams
Feb 2018	Detector commissioning phase; First Belle II paper!
Feb 2019	First physics runs
Jun 2021	Luminosity record of $3.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
~2024/25	Surpassing Belle int. luminosity: collecting data sample of $1\,\mathrm{ab}^{-1}$
2026+	Long shutdown and vertex detector upgrade
in ~10y.	Reaching peak luminosity and data sample

HEPHY Belle II team

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Manca Mrvar, postdoc

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Daniel Dorner, PhD s.

Hannes Kößl, master s.

Gianluca Inguglia, PI

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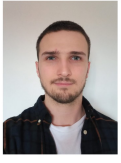
Geraldine Raeuber, PhD s.

Lukas Goldschmied, Master s.

Huw Haigh, PhD s.



Paul Feichtinger, PhD s.

Petar Rados, postdoc

Matthias Maurer master s.

Abdul Basith, postdoc, from 03/22

Markus Friedl, PI

Christian Irmler

Richard Thalmeier

Hao Yin

Belle II group at HEPHY

Hardware

- Silicon Vertex Detector (SVD) installed in 2018
- Vertex detector upgrade in $\sim$2023
- SVD upgrade in 2026+

Software & Detector operation

- Several active SVD experts
- SVD reconstruction and detector operation software
- SVD and control room shifts

Performance studies

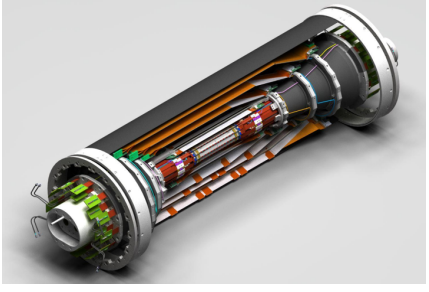
- Lepton ID
- Trigger
- Tracking
- Hadron ID
- + more

Physics analyses

- Semileptonic decays: $b \to c$ transitions
- $b \to s\ell\ell$ physics
- τ physics
- Dark matter
- Phenomenology

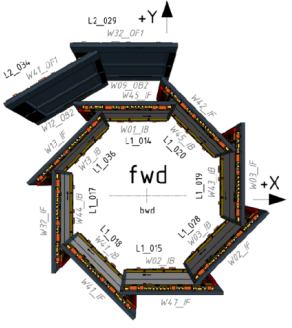
Vertex Detector (VXD)

- Consists of two semiconductor detectors:
  - Pixel Detector (PXD): two layers of pixel silicon detectors
  - **Silicon Vertex Detector (SVD)**: four layers of double-sided silicon strips
- Signal detection through ionizing radiation that produces free charge carriers
- Vertex position can be measured with a high resolution of 10 µm



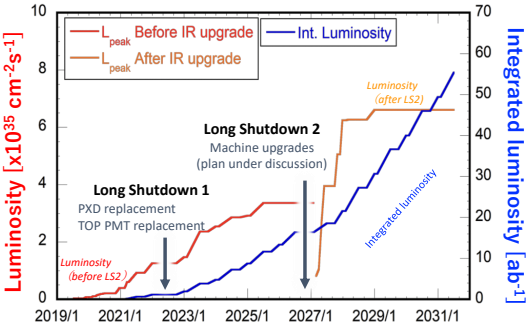
PXD design → reality (production problems):

- L1 with 8 ladders → all installed (one bad)
- L2 with 12 ladders → only 2 installed



Vertex Detector: Upgrade Timeline

- Long Shutdown 1 scheduled for 2023
- Long Shutdown 2 scheduled for 2026+ (exact date not yet fixed):
  - SuperKEKB upgrade foreseen
  - Several options for a major upgrade of the VXD under discussion



2023 Intervention: Add PXD L2

Sounds simple, but requires many actions:

- Open Belle II detector on both sides
- Uncable and extract full VXD
- Remove both SVD halves
- Test SVD halves || prepare new beam pipe + full PXD
- Attach SVD halves
- Test full VXD
- Insert and cable up full VXD
- Close Belle II detector

In Tsukuba B4 (ARICH cleanroom, VXD tent)

Actions involving SVD **(HEPHY)**

Overall duration: ∼9 months

2023 Intervention: COVID19

- Problem: visiting Japan is de facto impossible
- Not only for actual intervention, but also for exercising procedures (on dummies)
- Remote reviews: 15 Feb 2021, 27 Oct 2021 $\rightarrow$ But not the same quality as in-person

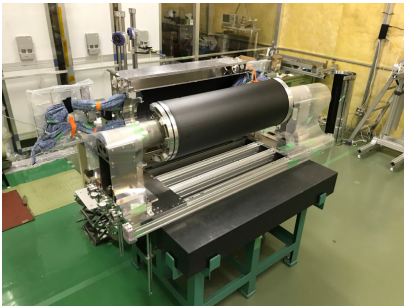


Figure: Dummy for exercising removal of SVD halves.

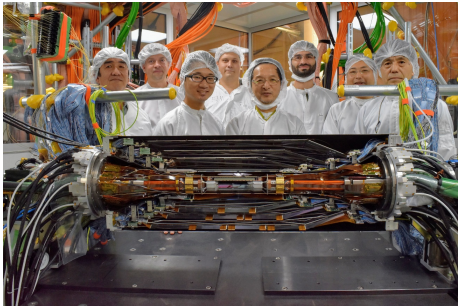


Figure: First half of SVD attached (3 Oct 2018).

VXD2026+ Upgrade Motivation

Limitations of current VXD:

- Tolerance for beam-induced background
- Level 1 trigger latency (limited by SVD)
- Tracking and vertexing performance
- Lifetime of PXD (DEPFET) is limited

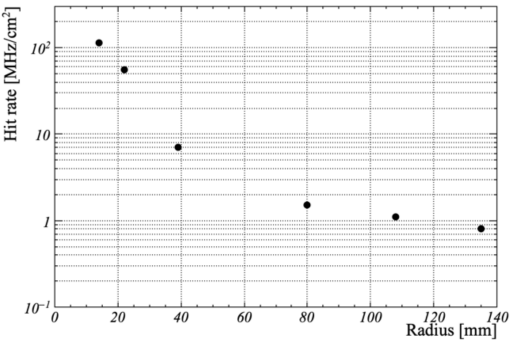


Figure: Required hit rate tolerance vs. radius for upgrade.

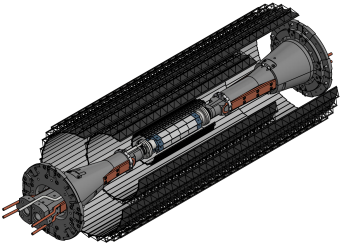
VXD2026+ Upgrade Option

Several sensor technologies and concepts under discussion, R&D ongoing:

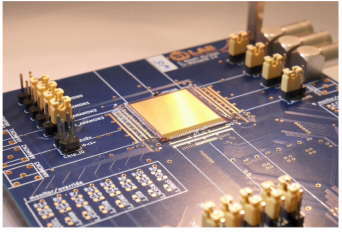
- **Thin DSSD sensor**
  - Similar to existing SVD, but with thinner/smaller sensors
  - Target: outer layers (L3–L5); Japanese initiative
- **DEPFET pixel sensor**
  - Similar to existing pixel detectors
  - Target: inner layers (L1, L2); German initiative
- **Silicon-on-isolator pixel (SOIPIX) sensor**
  - Different pixel detectors
  - Japanese effort
- **Depleted monolithic active pixels sensors (DMAPS)**
  - Monolithic pixel sensor in CMOS technology
  - Target: all layers; European initiative (including **HEPHY**)

CMOS VXD Concept

- Ladder / stave design
  - 5 straight layers (to keep the design simple)
  - Inspired by ALICE upgrade
  - Possible fields of **HEPHY contribution**: **mechanics, cooling**



- Chip design
  - Based on TowerJazz-Monopix2 (Bonn et al.)
  - OBELIX chip for Belle II **(HEPHY contribution)**



CKM matrix and $|V_{cb}|$

- $|V_{cb}|$ governs the rate of the dominant weak quark transition $b \to c$
- $|V_{cb}| \approx 0.04$ with 2% rel. uncertainty
- Measured from $B \to X_c \ell \nu_\ell$ decays:
  - *Inclusive*: sensitive to all $X_c \ell \nu_\ell$ final states
  - *Exclusive*: based on single mode, such as $B \to D^* \ell \nu_\ell$ or $B \to D^0 \ell \nu_\ell$

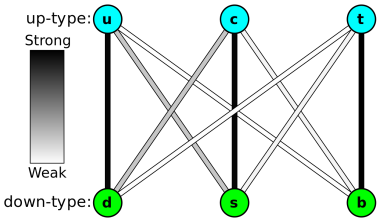


Figure: Quark weak interactions.

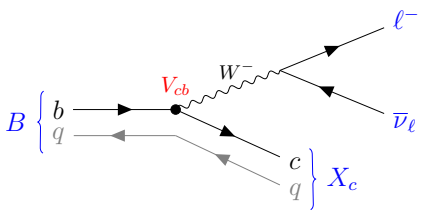
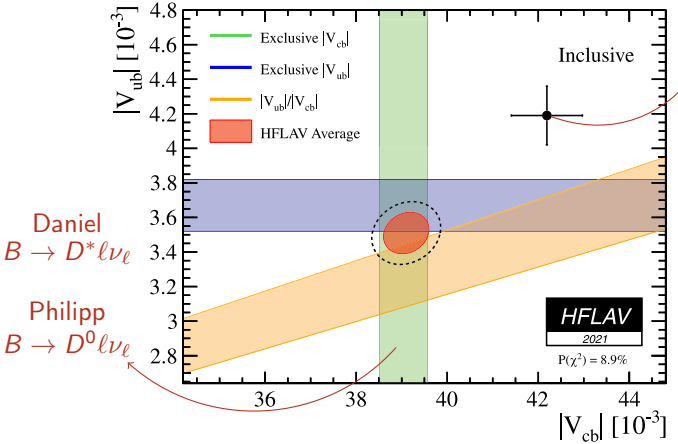


Figure: Feynman diagram of $b \to c$ decays.

Theoretical motivation: The current status $|V_{cb}|$

- 3.3σ tension between exclusive and inclusive determinations of $|V_{cb}|$
- Precise measurement is crucial for ongoing precision B physics program



Manca
$B \to X_c \ell \nu_\ell$

Daniel
$B \to D^* \ell \nu_\ell$

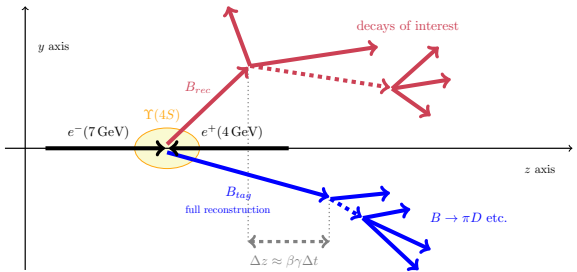
Philipp
$B \to D^0 \ell \nu_\ell$

Possible reasons:

- An experimental issue with the exclusive or the inclusive measurement?
- A problem in the theory input?
- Physics beyond the Standard Model?

(Un)tagged analysis

- $e^+e^- \to \Upsilon(4S) \to B_{rec}B_{tag}$
- Decay products boosted in e^- direction
- B_{rec}: decays of interest
- B_{tag}: reconstructed to provide more kinematic restrictions



Tagging techniques

Purity

Efficiency

Untagged analysis

Inclusive
$B \to$ anything
$\epsilon \approx \mathcal{O}(100\,\%)$
Large statistics and backgrounds

Semileptonic
$B \to D^{(*)}\ell\nu$
$\epsilon \approx \mathcal{O}(1\,\%)$
Mid-range reconstruction efficiency; less information

Hadronic
$B \to$ hadrons
$\epsilon \approx \mathcal{O}(0.1\,\%)$
Clean sample of B_{sig}; low B_{tag} efficiency

Tagged analysis

Untagged studies of $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell(\ell = e, \mu)$

[Daniel] [arXiv:2008.07198]

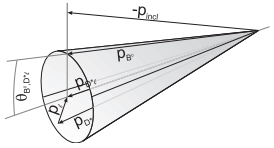
$\hookrightarrow D^0\pi_s^+$

$\hookrightarrow K^-\pi^+$

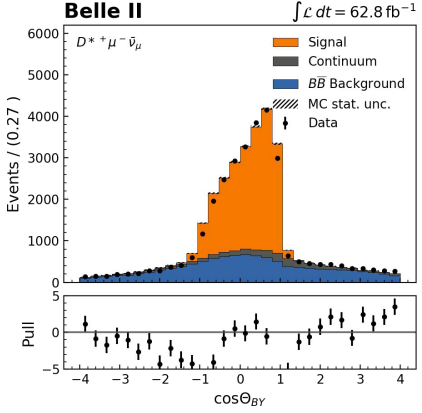
Main objectives

Determinations of $|V_{cb}|$ and A_{FB}

- Separation between e and μ channel
- Long decay chain: four kinematic observables
- Main fitting variable is $\cos\theta_{BY}$ ($Y = D^*\ell$)



- Fitting with three MC distributions:
  - Signal events
  - $B\bar{B}$ backgrounds
  - Continuum ($e^+e^- \to q\bar{q}$)



Branching fraction and lepton universality

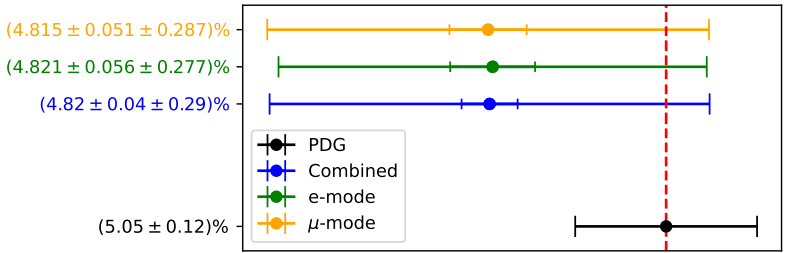
[Daniel]
[arXiv:2008.07198]

Branching fraction $\mathcal{B}$:

- Separate for e and μ channel
- Combined

Lepton universality:

- Probed by ratio of $\mathcal{B}_e/\mathcal{B}_\mu = 1.001 \pm 0.016$



→ Working towards $|V_{cb}|$ measurement!

Lepton forward-backward asymmetry A_{FB}

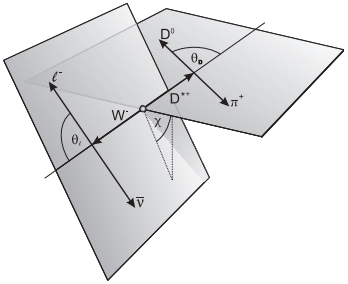
[arXiv:2104.02094v1]

$$A_{FB} = \frac{\Gamma_F - \Gamma_B}{\Gamma_F + \Gamma_B}$$

Γ ... semileptonic width

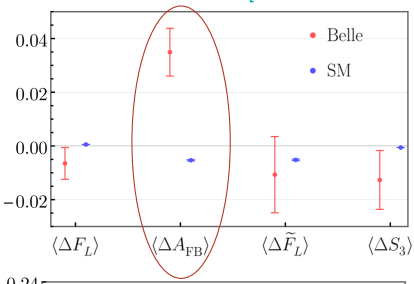
$F \equiv \cos\theta_\ell > 0$

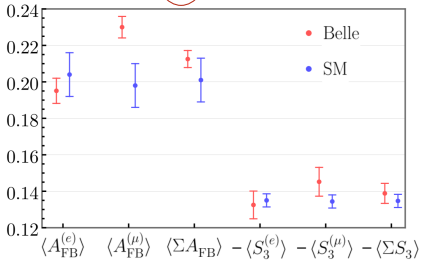
$B \equiv \cos\theta_\ell < 0$



discrepancy of 3.9σ

$\Delta A_{FB} \equiv A_{FB}^{\mu} - A_{FB}^{e}$





Untagged studies of $\bar{B}^- \to D^0 \ell^- \bar{\nu}_\ell$: Comparison to $B \to D^*$ decay

$\hookrightarrow K^- \pi^+$

Similarities:

- Measurement of branching fractions and $|V_{cb}|$
- Separation between e and μ channel
- Main fitting variable is $\cos\theta_{BY}$ ($Y = D^0\ell$)

Differences:

	$B \to D^0 \ell \nu_\ell$	$B \to D^*(\to D^0\pi_s)\ell\nu_\ell$
Theory	Scalar meson 1 form factor free parameter ρ 1 kinematic variable w	Vector meson 3 form factor parameters ρ, R1(1), R2(2) 4 kinematic variables w, θ_ℓ, θ_V, χ
Experiment	Large downfeed from $D^*\ell\nu_\ell$ Smaller branching fraction No slow pion	Clean sample by cutting on $m_{D^*} - m_{D^0}$ Large systematic error from slow pion

Untagged studies of $\bar{B}^- \to D^0 \ell^- \bar{\nu}_\ell (\ell = e, \mu)$

[Philipp]
[arXiv:2110.02648]

Main objectives

Determinations of branching fractions and $|V_{cb}|$

- Fitting with four MC distributions:
  - Signal events
  - $\bar{B}^0 \to D^* \ell \nu_\ell$ background
  - Other $B\bar{B}$ backgrounds
  - Continuum ($e^+e^- \to q\bar{q}$)

Results:

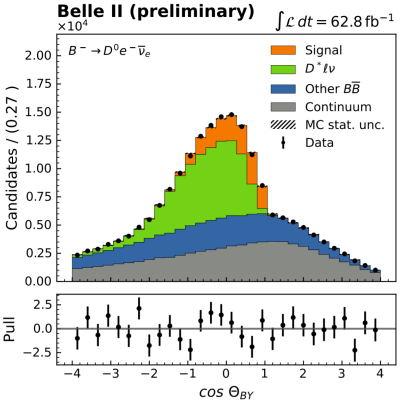
$\mathcal{B}(\bar{B}^- \to D^0 \ell^- \bar{\nu}_\ell) = (2.29 \pm 0.05(\text{stat.}) \pm 0.08(\text{sys.}))\%$

World average

$\mathcal{B}(\bar{B}^- \to D^0 \ell^- \bar{\nu}_\ell) = (2.35 \pm 0.03(\text{stat.}) \pm 0.09(\text{sys.}))\%$

Lepton universality

$R(e/\mu) = \frac{\mathcal{B}(\bar{B}^- \to D^0 e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B}^- \to D^0 \mu^- \bar{\nu}_\mu)} = 1.04 \pm 0.05(\text{stat.}) \pm 0.03(\text{sys.})$

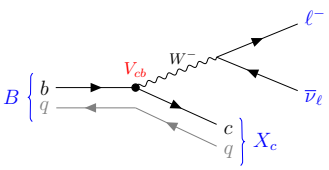


Inclusive $B \to X_c \ell \nu_\ell (\ell = e, \mu)$ studies

[Manca]
[arXiv:2111.09405]

Main objectives

Determinations of **(partial) branching ratios**, $|V_{cb}|$ and **moments of** lepton energy, E_ℓ, and lepton invariant mass, q^2 ($q = p_\ell + p_\nu$).



Untagged approach: the only known particle is ℓ.

NEUTRINO MOMENTUM: $p_\nu = (|p_{\text{miss}}|, \vec{p}_{\text{miss}})$

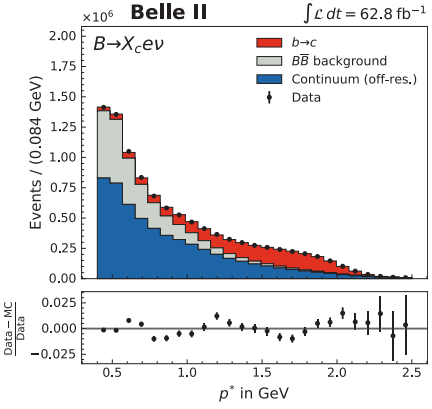
Excluding events where other particles have (most likely) been lost:

- × Missing momentum outside of the detector acceptance
- × Large charge imbalance
- ✓ M^2_{miss} close to zero
- × Missing energy close to zero

Inclusive $B \to X_c \ell \nu_\ell (\ell = e, \mu)$ results

[Manca]
[arXiv:2111.09405]

- Three templates (shapes) are used for fitting:
  - **Signal (MC)**: events that include ℓ, ν_ℓ and c-quark containing meson
  - **Continuum**: shape of off-resonance data
  - **$B\bar{B}$ backgrounds (MC)**: $b \to u$, secondary leptons, fake leptons, other lepton candidates



BRANCHING RATIOS

$$\mathcal{B}(B \to X_c e \nu_e) = (9.97 \pm 0.03_{stat} \pm 0.38_{sys})\%$$
$$\mathcal{B}(B \to X_c \mu \nu_\mu) = (9.47 \pm 0.05_{stat} \pm 0.45_{sys})\%$$

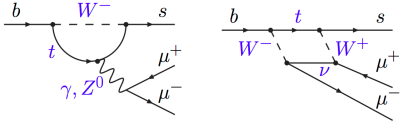
COMBINED BRANCHING RATIO

$$\mathcal{B}(B \to X_c \ell \nu_\ell) = (9.75 \pm 0.03_{stat} \pm 0.47_{sys})\%$$

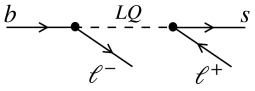
Main systematic uncertainties: modelling of $B \to X_c \ell \nu_\ell$ and lepton ID corrections.

$b \to s\ell\ell$ studies

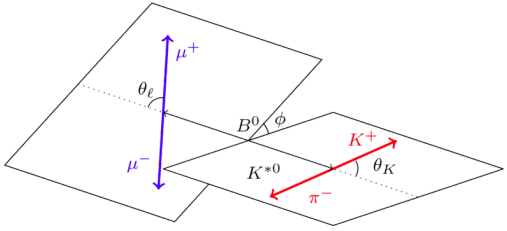
Flavour Changing Neutral Currents in the SM are forbidden processes at tree level that proceeds via loops



and are sensitive to new physics



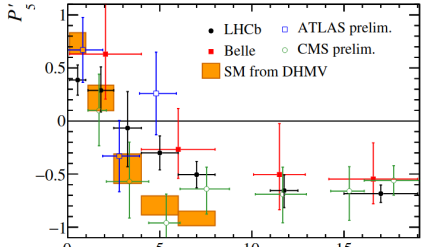
Angular observables can be used to constrain NP effects



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

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

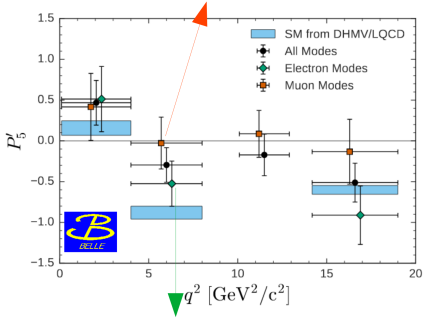
$b \to s\ell\ell$ studies



[arXiv:1808.02990]

- Uncertainty on P_5' dominated by the sample size
- At Belle (II) both μ and e channels can be measured
- Belle: e seems to be more SM-like than μ channel
- Belle II measurement:
  - More aggressive MVA approach
  - Probe new physics
  - Determine (in)compatibility of e and μ channel

$P_5'(B \to K^* \mu^+ \mu^-) = -0.03^{+0.31}_{-0.30}(stat.) \pm 0.09(sys.)$



$P_5'(B \to K^* e^+ e^-) = -0.52^{+0.28}_{-0.26}(stat.) \pm 0.03(sys.)$

[arXiv:1612.05014]

[Matthias et al.]

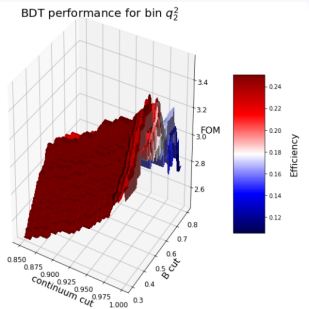
$b \to s\ell\ell$ studies at Belle II

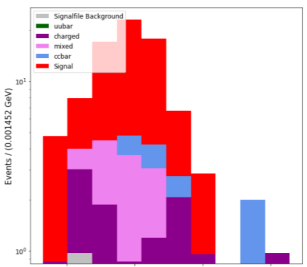
- Development of ntuples (in collaboration with Mainz):
  - Reconstruction using Belle II MC data
- Preparation and cleaning of data for **B**oosted **D**ecision **T**rees
  - Applying selections and corrections
- Suppression of background using 2-step BDTs for each q^2 bin
  - xgboost with Bayesian Optimization and 10-fold cross validation

Results: Purity is much higher than at Belle, but the efficiency is slightly lower

q^2 [GeV]	$0.1 < q^2 < 4.0$	$4.0 < q^2 < 8.0$	$10.09 < q^2 < 12.9$	$14.18 < q^2 < 19.0$	Total
$\epsilon_{\text{Belle II}}$	10.6% ± 2.8%	15.8% ± 3.8%	14.9% ± 4.0%	17.3% ± 3.6%	14.5% ± 1.8%
$\epsilon_{\text{Belle I}}$	16.75%	18.23%	11.37%	12.90%	15.78% ± 0.16%
$\text{Purity}_{\text{Belle II}}$	68.0%	89.8%	62.8%	64.8%	70.0%
$\text{Purity}_{\text{Belle I}}$	49.7%	48.2%	45.8%	76.1%	47.2%

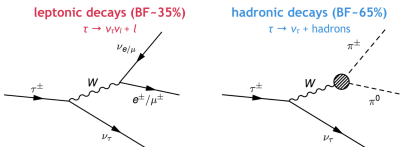
Next step: Maximize efficiency, giving up some purity → Statistically dominated measurement

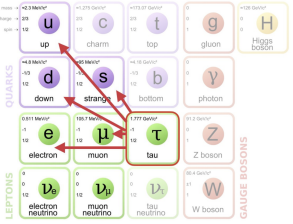


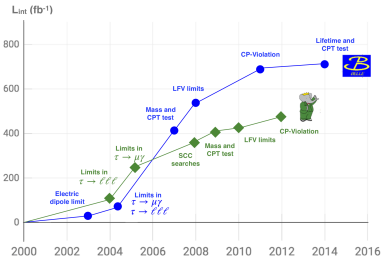


Tau Lepton Physics at Belle II

The τ is the only lepton massive enough to decay into hadrons.







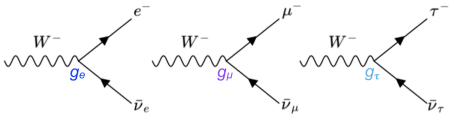
Belle II aims to a sample of $\sim 4.6 \times 10^{10}$ τ-pair events $\to$ a unique environment to study τ physics with high precision!

HEPHY plays a leading role in several τ physics topics:

1. LFU violation search in 3x1 & 1x1 prong τ-pair decays
2. V_{us} measurement with taus
3. Search for $\tau \to \ell\alpha$ (invisible)

Lepton Flavour Universality (LFU)

LFU $\to$ couplings of leptons to W bosons are flavour independent: $g_e = g_\mu = g_\tau$



Anomalies in quark sector:

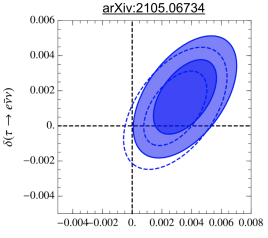
- R(D)-R(D*) (3.1σ)
- R(K) (3.1σ)
- P_5' in $B \to K^* \mu\mu$ (3.4σ)
- $B_s \to \phi\ell\ell$ (3.6σ)
- and more...

and in lepton sector:

- $(g\text{-}2)_\mu$ (4.2σ)
- and also for e (2.5σ)

Hints of a new fundamental interaction that violates LFU?

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} = R_\mu$$

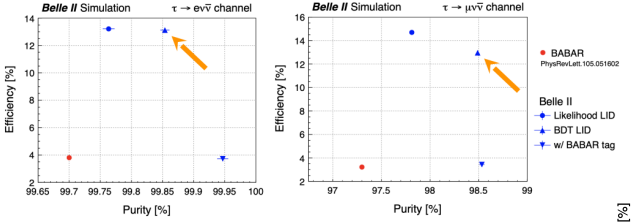


- Global fits to $\tau \to e\nu\bar{\nu}$ and $\tau \to \mu\nu\bar{\nu}$ ratios $\to$ 2σ tension with SM
- New Physics could enter in a variety of ways: LFU violating Z', singly charged scalar, W' + many more
- Will this tension become more significant with better precision on R_μ? Only Belle II can provide answers!

Search for LFUV in 3x1 decays

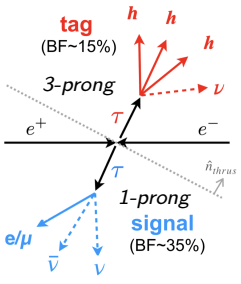
[Petar et al.]

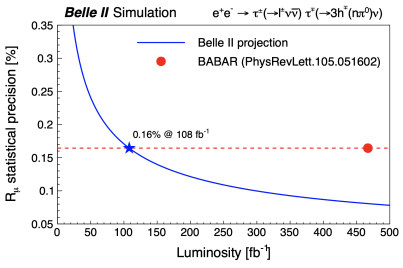
- Current leading measurement comes from BaBar ($467\,\text{fb}^{-1}$)
- Belle II developed a cut-based selection with ~4x higher efficiency and better purity (further 2x boost from MVA)



Sensitivity studies suggest Belle II can match BaBar statistical error with only ~$100\,\text{fb}^{-1}$ of data!

Limiting factor is the lepton ID performance → Collaboration with the LID performance group to bring down the uncertainties to a competitive level.

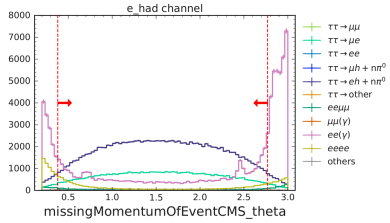




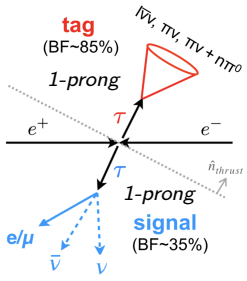
Search for LFUV in 1x1 decays

- Current world leading measurement comes from CLEO ($3.55\,\text{fb}^{-1}$)
- Multiple modes combined into one R_μ measurement

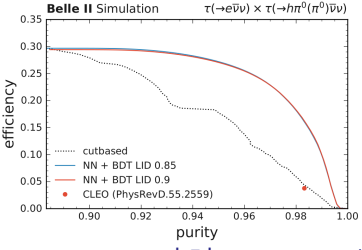
mode	signal τ	tag τ
$\mu \times \mu$	$\mu\overline{\nu}\nu$	$\mu\overline{\nu}\nu$
$e \times \mu$	$e\overline{\nu}\nu$	$\mu\overline{\nu}\nu$
$e \times e$	$e\overline{\nu}\nu$	$e\overline{\nu}\nu$
$\mu \times h$	$\mu\overline{\nu}\nu$	$h\overline{\nu}\nu$
$e \times h$	$e\overline{\nu}\nu$	$h\overline{\nu}\nu$
$\mu \times \rho$	$\mu\overline{\nu}\nu$	$h\pi^0(\pi^0)\overline{\nu}\nu$
$e \times \rho$	$e\overline{\nu}\nu$	$h\pi^0(\pi^0)\overline{\nu}\nu$



[Paul et al.]



- Main backgrounds: $ee \to \ell\ell(\gamma)$, $ee \to ee\ell\ell$
- Suppressed by utilising missing E / p in τ-pair events
- Higher purity and efficiency than CLEO, depending on mode
- Limiting factor are lepton ID systematic uncertainties



V_{us} measurement

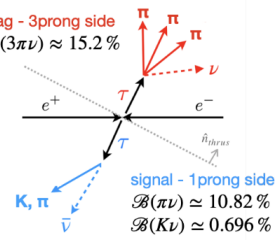
[Géraldine et al.]

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

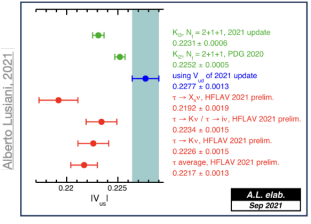
- Methods for the V_{us} parameter extraction:
  1. τ **exclusive**

$$R_{Kl\pi} = \frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)} = \frac{f_K^2 \left|V_{us}\right|^2}{f_\pi^2 \left|V_{ud}\right|^2} \left(\frac{1 - m_K^2/m_\tau^2}{1 - m_\pi^2/m_\tau^2}\right)^2 (1 + \delta_{LD})$$

  2. τ inclusive (strange vs. non-strange)
  3. CKM matrix unitarity
  4. K^0 decays, e.g. $K_L^0 \to \pi^- e^+ \nu$



- Tension between different approaches is observed



- BaBar measurements from 2010:

	π	K
N^D	369091	25123
Purity	78.7%	76.6%
Total Efficiency	0.324%	0.330%
Particle ID Efficiency	74.6%	84.6%

Phys. Rev. Lett. 105, 051602 (2010)

- Aim at surpassing their purity and efficiency

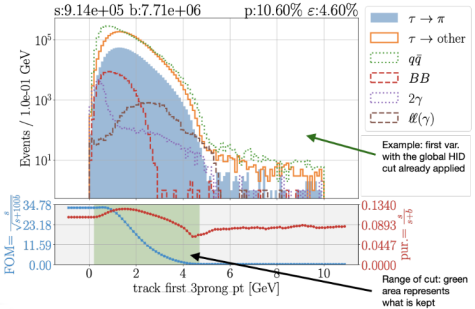
V_{us} measurement

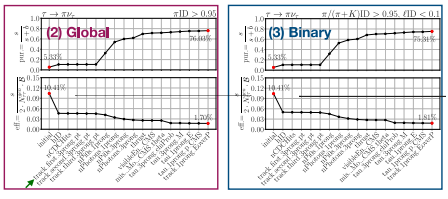
[Géraldine et al.]

Many backgrounds, e.g. $q\bar{q}$, $\tau \to$ other, ...

- Suppression by rectangular cuts, optimized by FOM
- Additional strategy needed in the K channel since purity is not sufficient

	(1) BaBar	(2) Global	(3) Binary	Δ_{12}	Δ_{13}
π purity	78.7	76.03	75.31	-2.67	-3.39
π efficiency	0.324	1.70	1.81	+1.376	+1.486
K purity	76.6	49.95	43.95	-26.65	-32.65
K efficiency	0.330	1.91	2.03	+1.58	+1.7



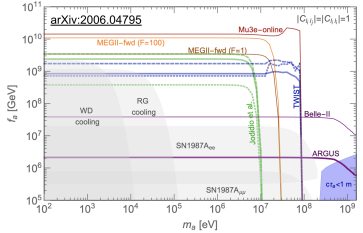


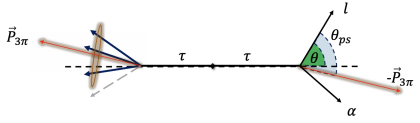
- The first studies of the difference between two ways of identifying particles:
  - GLOBAL hadron ID (6 input variables)
  - BINARY hadron ID (two input variables + lepton veto)
- Better purity achieved by global hadron ID

Search for $\tau \to \ell + \alpha$ (invisible)

[Petar et al.]

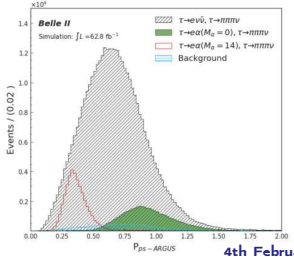
Search for $\tau \to e\alpha$ & $\tau \to \mu\alpha$ (α = BSM invisible particle). Best result is from ARGUS (1995, 476 pb^{-1}).





Signature: 2-body signal decay will manifest as a bump in the τ pseudo-rest frame momentum, on top of the SM 3-body $\tau \to \ell\nu\nu$ background.

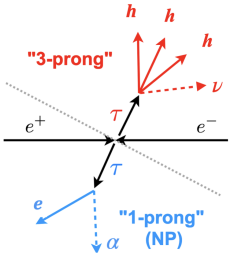
- This LFV decay appears in several NP models: light ALP, LFV Z' + many more
- Cannot access τ rest frame directly due to neutrino $\to$ Two approximations:
  1. $E_\tau = \sqrt{s}/2$
  2. $\vec{n}_\tau \approx -\vec{n}_{3\pi} = -\sum_{i=1}^{3} \frac{\vec{p}_\pi^{\,i}}{|\vec{p}_{3\pi}|}$

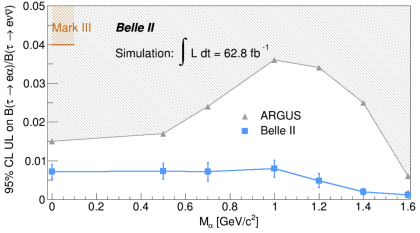


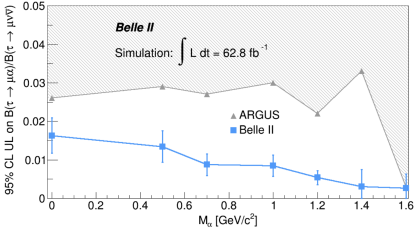
Search for $\tau \to \ell + \alpha$ (invisible)

[Petar et al.]

- Selections optimized on SM $\tau \to \ell\nu\nu$ to achieve high efficiency of 12.7% (16.2%) and purity of 95.9% (92.0%) in e (μ) channels
- Leading systematic unc. from trigger and lepton ID efficiencies
- Data/MC validation in sidebands and partially unblinded data
- Expect a world-leading upper limit on $\mathcal{B}(\tau \to \ell\alpha)/\mathcal{B}(\tau \to \ell\nu\bar{\nu})$ with 62.8 fb^{-1} of Belle II data:

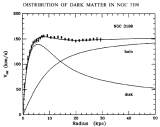


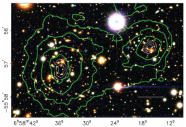


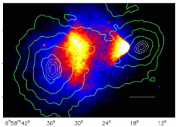


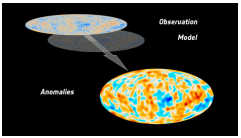
Aiming for a paper for Moriond 2022.

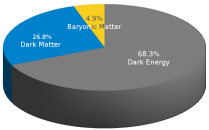
Can we use Belle II to investigate dark matter?



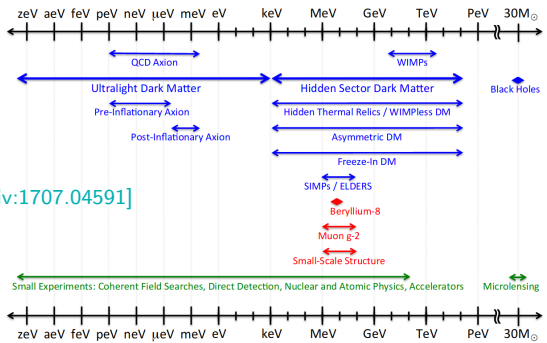






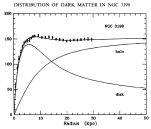


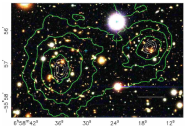
Dark Sector Candidates, Anomalies, and Search Techniques

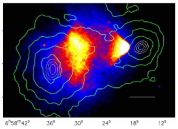


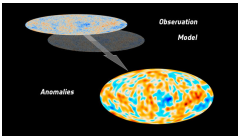
[arXiv:1707.04591]

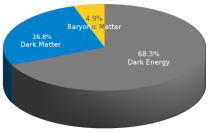
Searching for Dark Matter and Forces @ Belle/Belle II







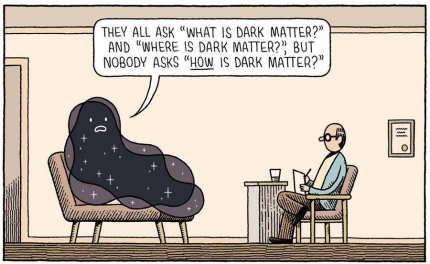




Search for events with missing energy, particle disappearance, dark forces, single/multi-photon final state events, etc.

Some ongoing searches at Belle II:

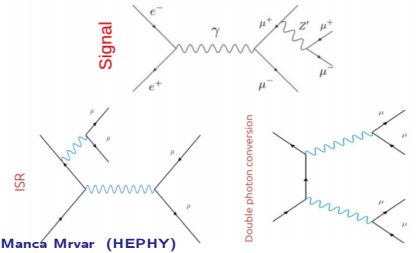
- Dark photon, visible and invisible decays
- Light Z' boson, visible and invisible decays
- Dark higgs boson
- Magnetic monopoles
- Axion like particles
- Long lived particles

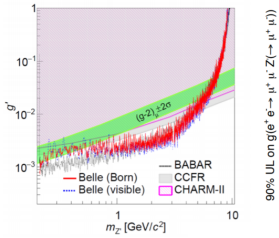


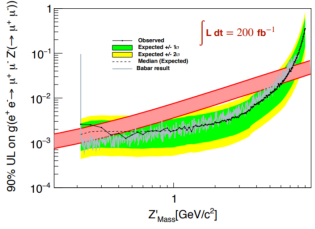
$Z' \to \mu\mu$ (prompt)

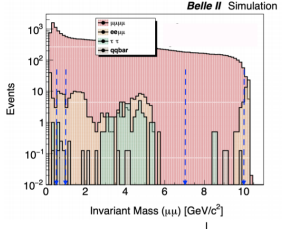
[Rajesh et al.]

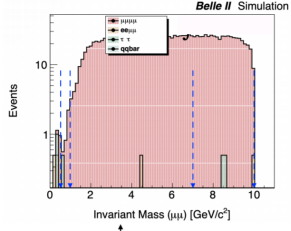
- Searches by BaBar and Belle using 514 fb^{-1} and 711 fb^{-1} of data [arXiv:1606.03501, arXiv:2109.08596]
- Plan to achieve better performance by using aggressive background suppression (Multilayer Perceptron Neural Network)
- The main challenging backgrounds are $\mu\mu\mu\mu$, $\mu\mu(\gamma)$, double photon conversion, etc.









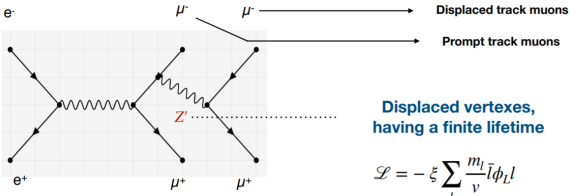


The Blue arrow dashed line shows different MLP training regions.

After applying MLP

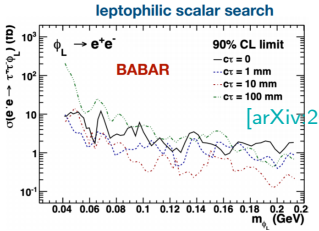
$Z' \to \mu\mu$ (displaced)

[Rajesh et al.]



Displaced vertexes, having a finite lifetime

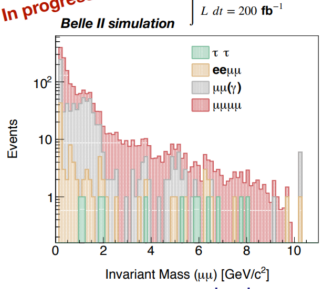
$$\mathscr{L} = -\xi \sum_l \frac{m_l}{v} \bar{l} \phi_L l$$



[arXiv:2005.01885]

- First search by BaBar with $\Phi_L \to$ For low values of coupling constant could lead to displacing vertex
- Plan to search for the same final state as for the prompt case and displacing vertices
- Most of the backgrounds are prompt by nature and rejected by the displacing of the signals
- The most challenging part is to trigger the signal events $\to$ Unavailability of displaced track triggers in Belle II

Study In progress...

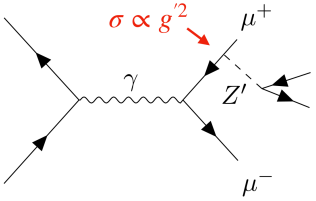


Expected backgrounds

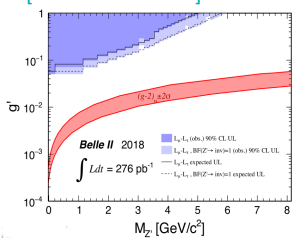
$Z' \to$ invisible

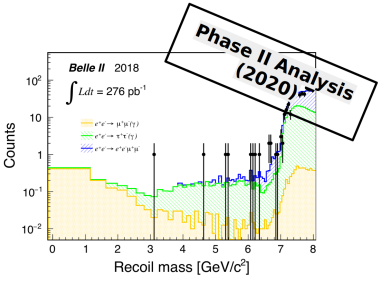
[Huw et al.]

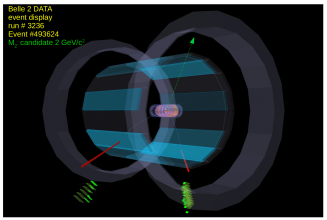
- U(1)' extension of SM $\to$ New massive gauge boson
- Couples to μ and τ leptons ($L_\mu - L_\tau$) via g'
- First published Belle II result in 2018 using 276 pb^{-1}
- Z' decays invisibly to neutrinos OR dark matter
- Event reconstruction: $\mu^+\mu^-$–pair with some missing energy (recoil mass from muons) with photon veto



[arXiv:1912.11276]





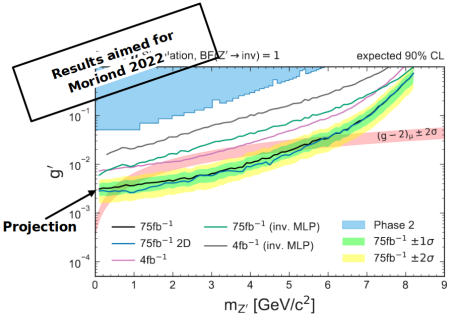


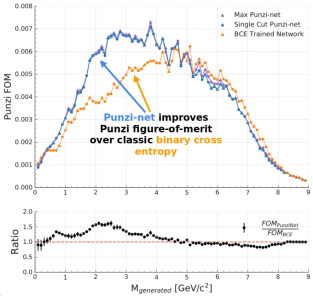
Could explain $(g\text{-}2)_\mu$

$Z' \to$ invisible

[Huw, Paul et al.]

- Bump hunt of squared recoil mass distribution
- Event selection using specially developed 'Punzi-net'
- Updated study using ≈300-times larger dataset near publishing
- Will probe g' parameter space associated with $(g\text{-}2)_\mu$





Punzi-Net

- Trained with BCE then with Punzi-loss*
- Maximise sensitivity across search space
- Single cut to output for all

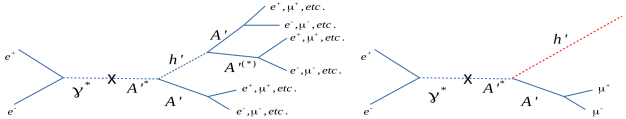
* Punzi-loss: A non-differentiable metric approximation for sensitivity optimisation in the search for new particles [arXiv:2110.00810]

Higgs-Strahlung

[Michel et al.]

[arXiv:0903.0363]

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



h'= dark Higgs,
A'= dark photon

Higgs-strahlung process

- $M_{h'} > 2M_{A'}$: $h' \to A'A'$; Very low background
  - Exclusive: 3 charged track pairs with same invariant M and total E of the event
  - Inclusive: 2 charged track pairs, same invariant M, third A' from 4-mom. of e^+e^-
- $M_{A'} < M_{h'} < 2M_{A'}$: $h' \to A'A'^*$
- $M_{h'} < M_{A'}$: h' (very) long lived

Phenomenology

[Gianluca et al.]

Combining observables in tau with other particles to test LFU in charged currents via combined/global fits

Testing Lepton Flavor Universality with Pion, Kaon, Tau, and Beta Decays [arXiv:2111.05338]

D. Bryman, V. Cirigliano, A. Crivellin, and G.I. (Accepted for publication in the Annu. Rev. Nucl. Part. Sci. , Vol 72, 2022)

We select all relevant and latest (up to autumn 2021) results from π, K, τ, β decays and perform a combined fit to constrain LFU in charged currents:

$$\mathcal{L} \supset -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L \nu_j W_\mu^- \left(\delta_{ij} + \epsilon_{ij}\right) + h.c.$$

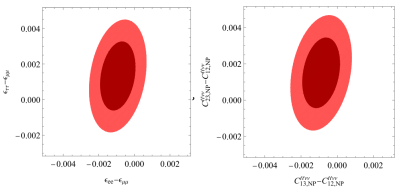


FIG. 2. Left: Global fit in the $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ vs. $\epsilon_{ee} - \epsilon_{\mu\mu}$ plane, including kaon, pion, and tau decays, quantifying LFU in the charged current. Right: Global fit in the $C_{23}^{\rm NP} - C_{12}^{\rm NP}$ vs. $C_{13}^{\rm NP} - C_{12}^{\rm NP}$ plane from leptonic tau and muon decays. Uncertainties are shown for one (dark color) and two (lighter color) standard deviations.

$$\frac{g_\mu}{g_e} = 1 + \epsilon_{\mu\mu} - \epsilon_{ee} = 1.0009 \pm 0.0006\,,$$
$$\frac{g_\tau}{g_\mu} = 1 + \epsilon_{\tau\tau} - \epsilon_{\mu\mu} = 1.0013 \pm 0.0013\,, \text{and}$$
$$\frac{g_\tau}{g_e} = 1 + \epsilon_{\tau\tau} - \epsilon_{ee} = 1.0022 \pm 0.0013\,.$$

Our global fit results are consistent with the SM at the 2σ level $\rightarrow$ No LFUV in charged currents.

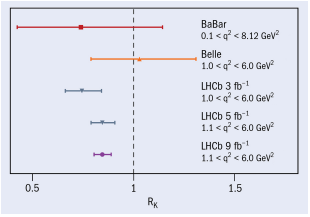
We acknowledge the need of improved LFU tests in leptonic and hadronic tau decays at Belle II.

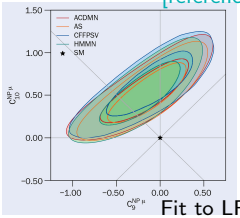
[Gianluca, Paul et al.]

Phenomenology

$b \to s\ell\ell$ and $Z' \to$ invisible – is the invisible Z' causing B anomalies?

[reference]





Fit to LFU+$B_s \to \mu\mu$

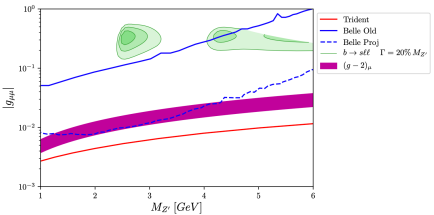
Can be explained combined to the muon anomaly, dark matter and by a Z' boson:
Ex1: Explaining Dark Matter and B Decay Anomalies with an $L_\mu L_\tau$ Model [ArXiv:1609.04026]
Ex2: A light dimuon resonance in B decays [ArXiv:1809.11061]

In "Towards a no-go theorem for light Z' explanations of the $b \to s\mu^-\mu^-$ anomalies", W. Altmannshofer, A. Crivellin, A. Manzari and G.I. (currently being prepared for submission)

We introduced a generic Z' model

$$\mathcal{L}_{Z'} \supset \left(g^V_{\mu\mu}\bar{\mu}\gamma^\mu\mu + g^A_{\mu\mu}\bar{\mu}\gamma^\mu\gamma_5\mu + g^L_{sb}\bar{s}\gamma^\mu P_L b + g^R_{sb}\bar{s}\gamma^\mu P_R b\right) Z'_\mu$$

and found that Huw's analysis should either discover a Z' boson and confirm it as the cause of $b \to s\ell\ell$ tensions, or reject it!



Summary and outlook

SuperKEKB/Belle II:

- The experiment has successfully completed its 3rd year of data taking and accumulated $268\,\text{fb}^{-1}$ of $\Upsilon(4S)$ data
- Vertical beta squeezing down to 0.8 mm was demonstrated and a record luminosity of $3.81 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ (Dec 23, 2021) was achieved
- While operation conditions are very difficult due to the energy price surge and COVID-19 the collaboration is trying hard to meet the expectations of the community

Belle II @ HEPHY

- HEPHY plays a major role at various levels of the experiment
- We make diverse contributions to experimental hardware, software and physics analysis
- Our work has won a series of grants (ERC, 2x Stand-alone, Lise-Meitner, Schrödinger, Jennifer2; worth $\sim$2.5 M EUR)

We strongly believe that precision physics will pave the way to discoveries that were not seen at the energy frontier yet – stay tuned!

BACKUP

Core activities: Search of new physics:

- Lepton Flavour Universality violation and precision CKM metrology in tau decays → Geraldine, Lukas, Paul, Petar
- Dark sector and dark matter searches → Huw, Paul, Rajesh (and Michel, borrowed to BNL)
- Lepton Flavour Universality violation in B *to* Abdul (from March), Matthias, new PhD student (ASAP)
- Phenomenology connecting all our experimental activities → Gianluca

Services to the Collaborations and management roles:

- Coordination of the Belle II Performance Group + tracking → Petar
- Coordination of the Belle II Statistics Advisory Committee → Gianluca
- Trigger+tracking studies → Rajesh, Huw
- Lepton and Hadron identification analysis → Geraldine, Paul, Rajesh
- Software and Machine Learning tools development → Huw, Paul
- Coordination of the Belle Dark Sector group → Gianluca

Funding ($\sim$2 MEUR since 2018):

- Michel Bertemes, FWF – Schroedinger Program, "Charming direct CP Violation", BNL-HEPHY 2022-2024
- Gianluca Inguglia, ERC StG. "InterLeptons", 2020-2025
- Gianluca Inguglia, FWF Standalone Program, "Search for dark matter and dark forces at Belle II", 2018-2023

Conferences:

- Interplay between Particle and Astroparticle Physics, IPA 2022 – Sept 5-9 Vienna
- Anomalies and precision in the Belle II Era, Sept. 6-8 2021 Vienna