The Belle II Experiment: Status and Prospects

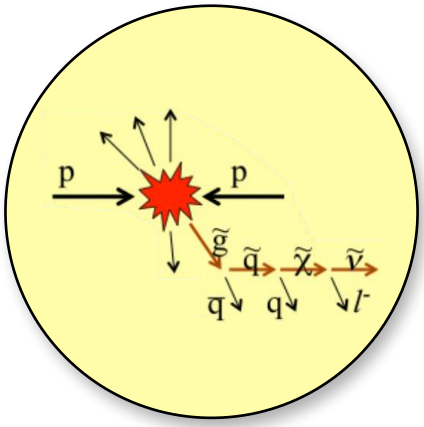
A.Passeri (INFN Roma Tre)
on behalf of the Belle II collaboration

EU grant 822070

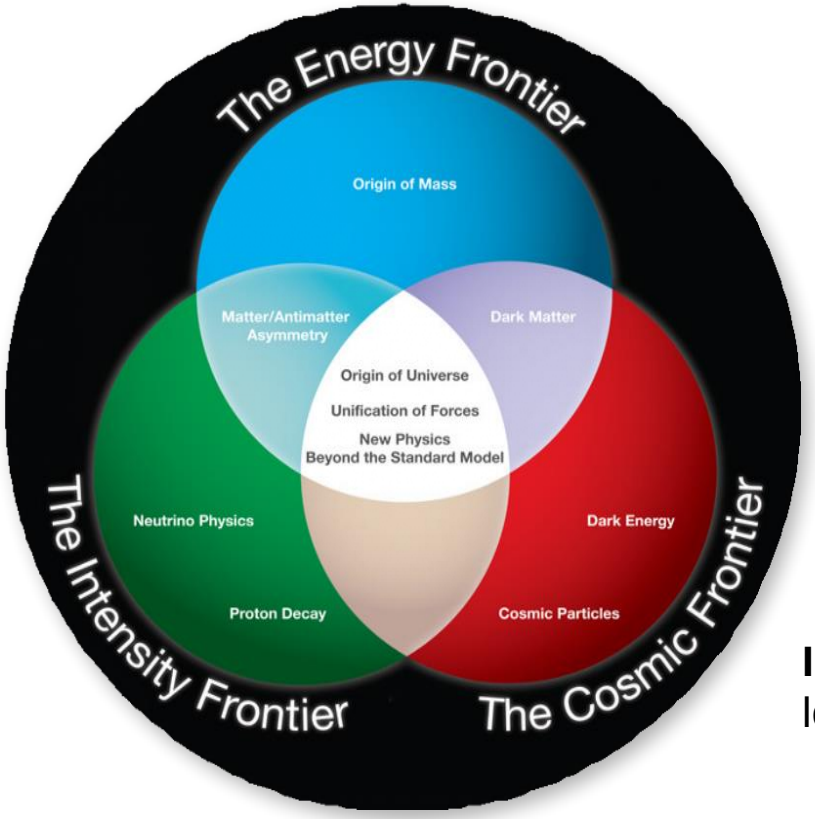
NuFact 2021 – Cagliari, september 8th 2021

Complementary Pathways to New Physics

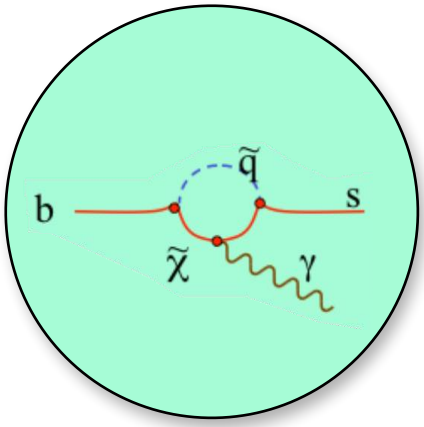
Energy frontier



Direct production of new particles



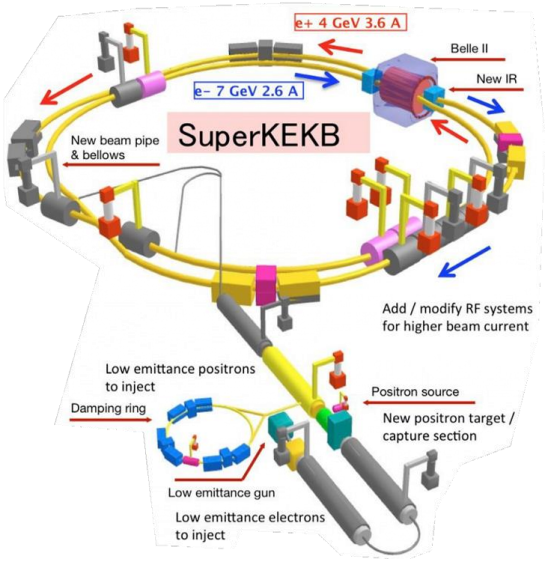
Intensity frontier



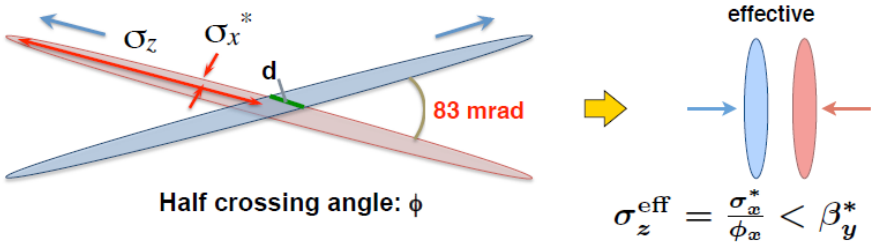
Indirect sensitivity through loops

- Presently no unambiguous evidence for Beyond Standard Model (BSM) physics at the high energy frontier
- Intensity frontier offers indirect sensitivity to very high scales

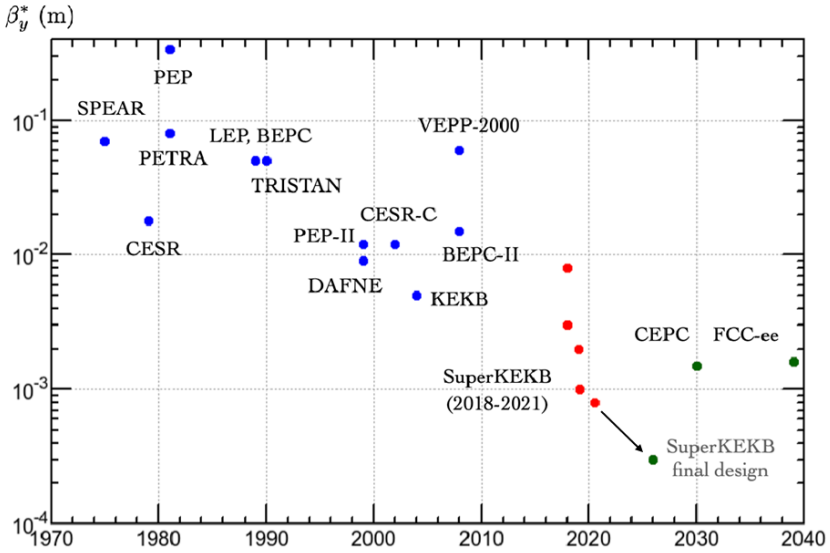
The SuperKEKB project



Nano-Beam scheme (P. Raimondi):
Squeeze beta function at the IP (β_x^*,β_y^*) and minimize longitudinal size of overlap region to avoid hourglass effect



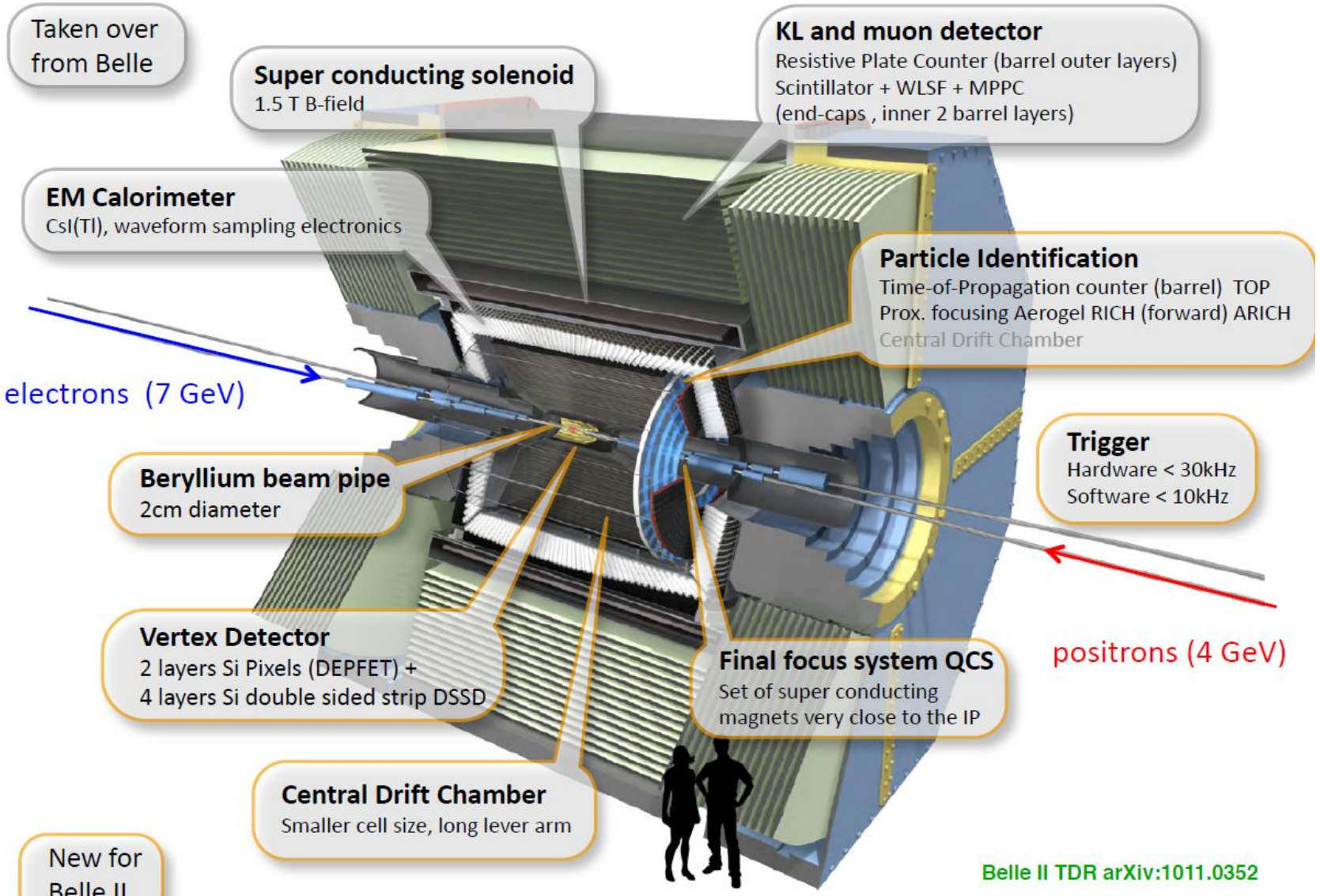
Strong focusing of beams down to vertical size of ~ **50 nm** requires **very low emittance beams** and **large crossing angle (83 mrad)**
⇒ Need **powerful** and **sophisticated final focus** system (QCS)
beam currents are also increased by a factor 1.5



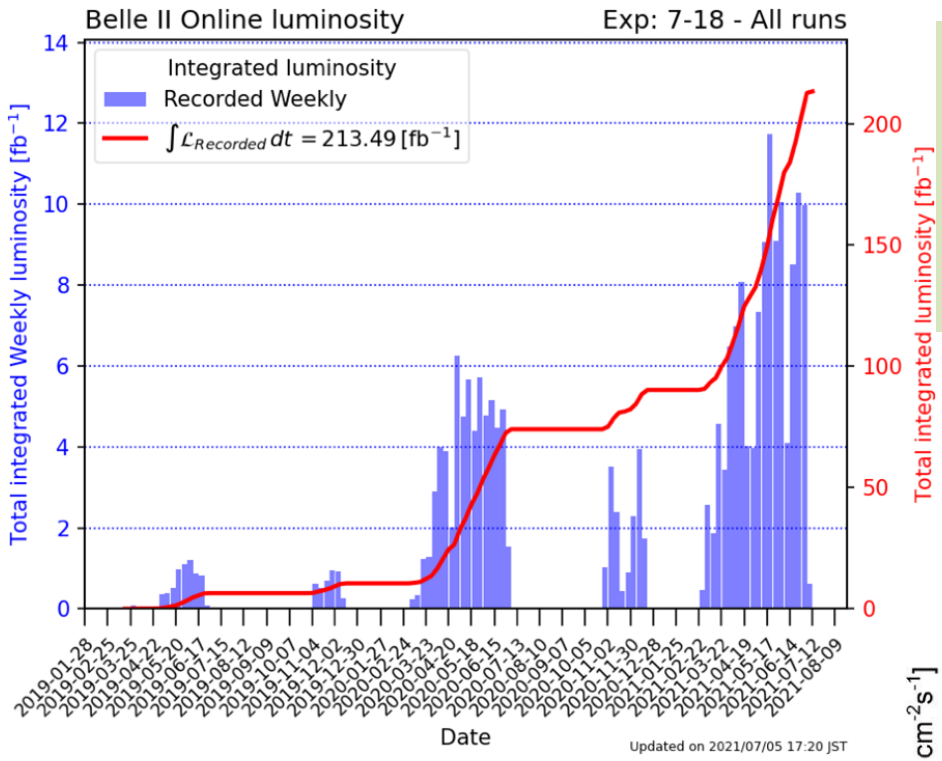
Project aims to a peak luminosity of 6x10^{35} cm^{-2}s^{-1}, 30 times more than KEKB.

Despite the challenging problems encountered for machine ramping up, vertical beta function has already been squeezed below 1 mm and **world record** reached in instantaneous luminosity of **3.12 x 10^{34}cm^{-2}s^{-1}** on June 22nd

The Belle II detector



Status of data taking and operation plan



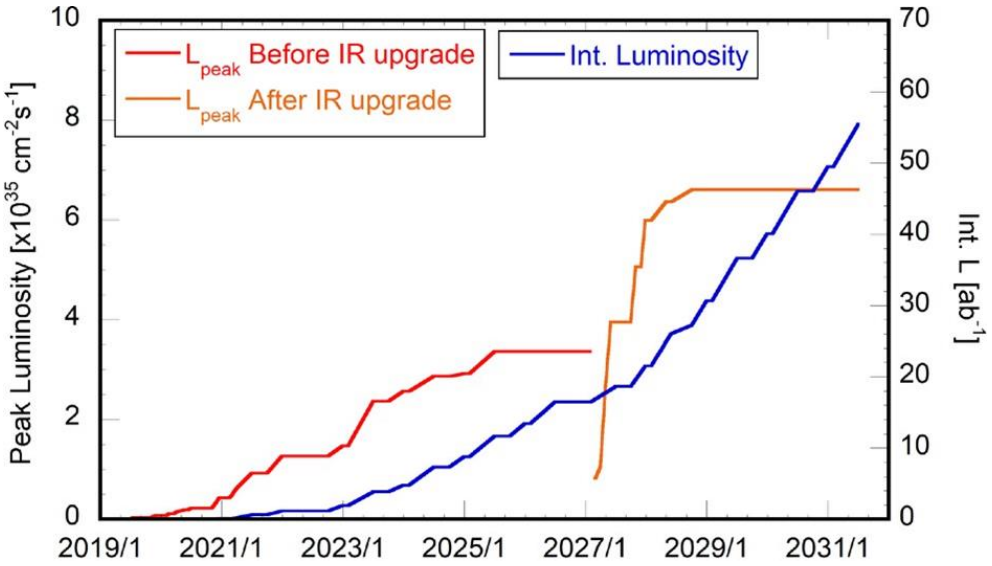
Despite the pandemic data taking has been very successful:

- 89.5% overall efficiency
- up to 12 fb^{-1} collected per week

According to KEK Roadmap 2020:

- Shutdown planned in 2022 for TOP-PMT replacement and PXD completion
- Possible IR upgrade after 2026 under study

Tentative long term operation plan



B factory advantages

Coherent and well defined initial state without additional interactions

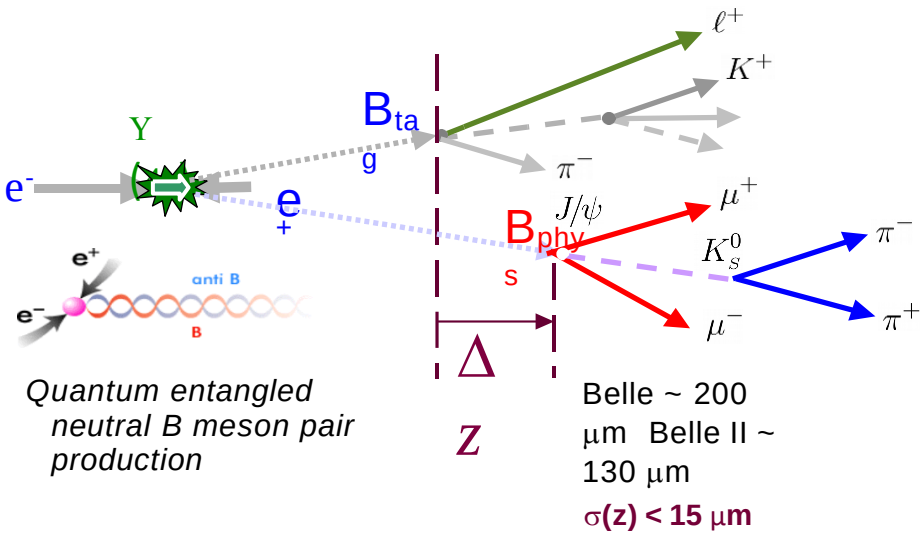
Low (physics) backgrounds, high trigger efficiency, little bias

Excellent neutral reconstruction (γ, π^0, η, K_S, K_L)

Kinematic good resolution → invisibles detection

Excellent vertex resolution

High performance flavour tagging



Many channels are unique to e^+e^- flavor factories. Absolute branching fractions can be measured

Can study rare and forbidden decays, invisible decays (incl. tau decays) asymmetries (CP, isospin) angular distributions

Systematics quite different from hadron machines in many areas complementary to LHCb

A wide physics program

The Belle II Physics Book
Prog. Theor. Exp. Phys. 2019, 123C01
arXiv:1808.10567

Dashed lines indicate potential extensions

Most relevant to this Conference:

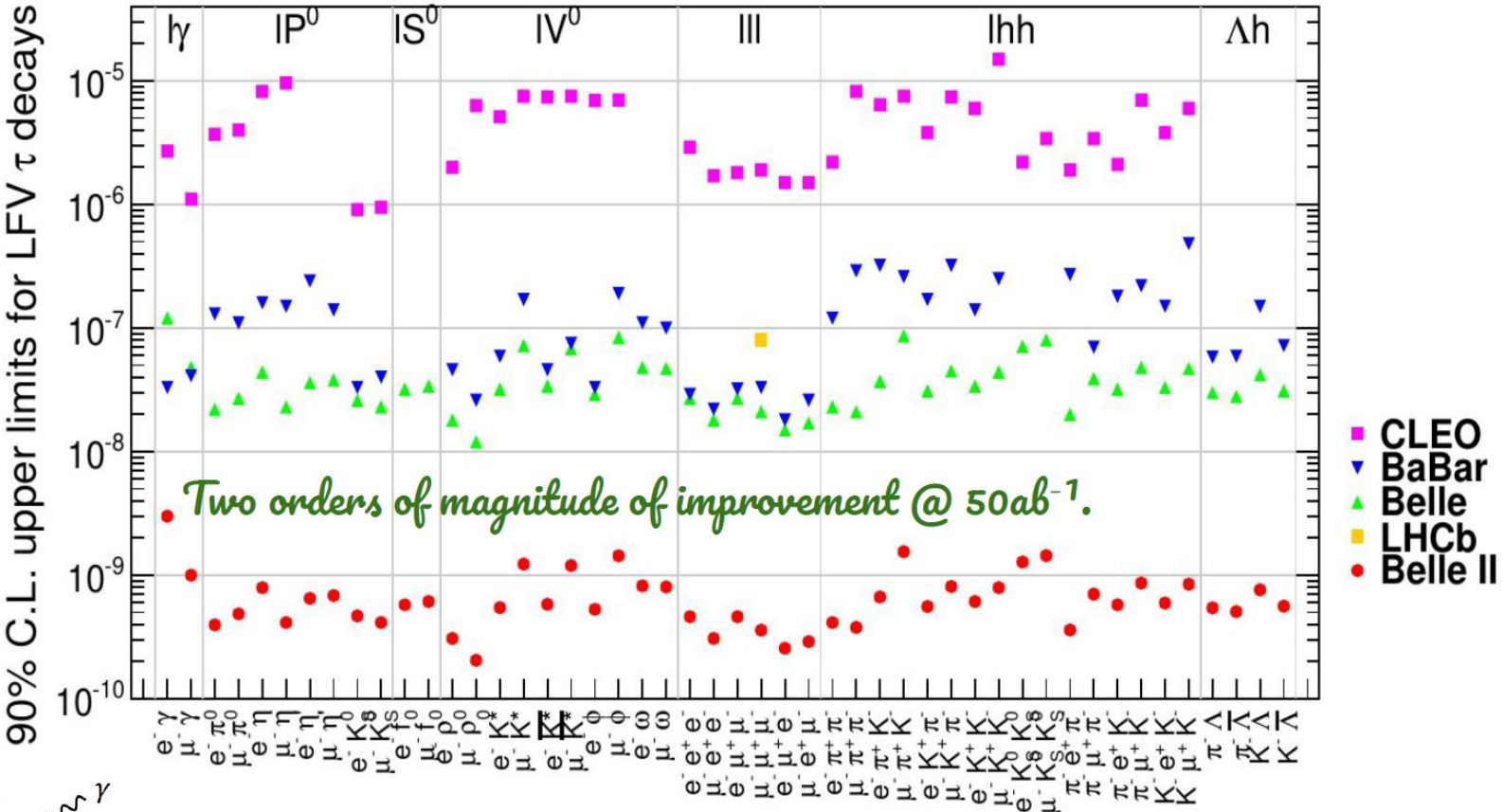
- Lepton Flavour Violation and taus
- Lepton universality tests and flavour anomalies
- Dark sector searches

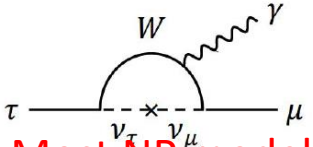
LFV and Tau decays

Perspectives for LFV searches @ Belle II

SuperKEKB is also a τ factory: cross section for ee→ττ events ~ 0.9 nb !

A variety of LFV channels available thanks to the large τ lepton mass:





In the SM τ LFV decays may happen only via ν oscillation at a rate of ~ 10^{-54}

Most NP models predicts LFV processes with BRs $10^{-7} \div 10^{-10}$, well inside Belle II sensitivity

τ LFV golden channels

$e^+e^- \rightarrow \tau^-\tau^+$

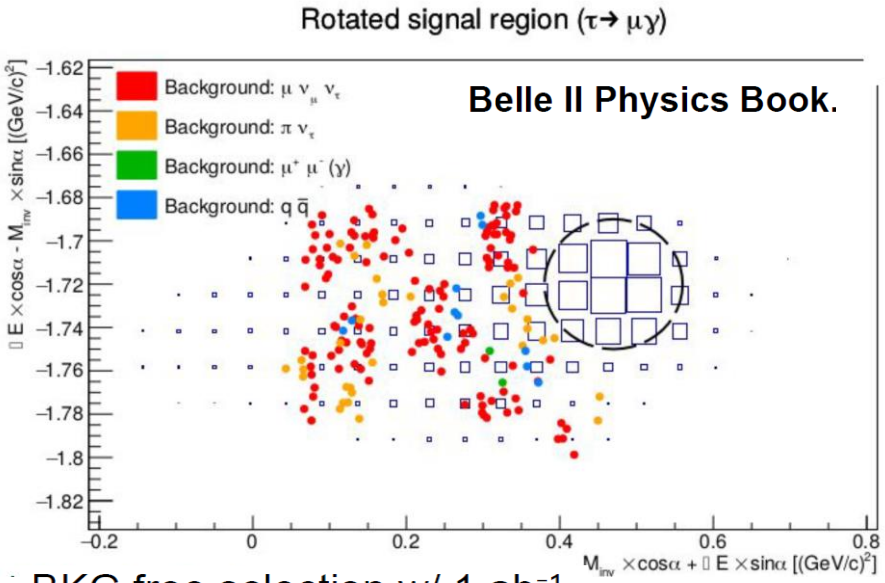
- 1 prong + missing(ν,γ)
- $\mu\gamma$, $\mu\mu\mu$ (LFV mode)

$$M_{inv}^{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - P_{\mu\gamma}^2}$$

$$\Delta E = E_{\mu\gamma}^{CM} - E_{beam}^{CM}$$

$$\begin{pmatrix} M_\tau^{'} \\ \Delta E^{'} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} M_\tau \\ \Delta E \end{pmatrix}$$

Events are fully reconstructed. «Rotation» of the 2 discriminant variables allows best signal-noise separation.

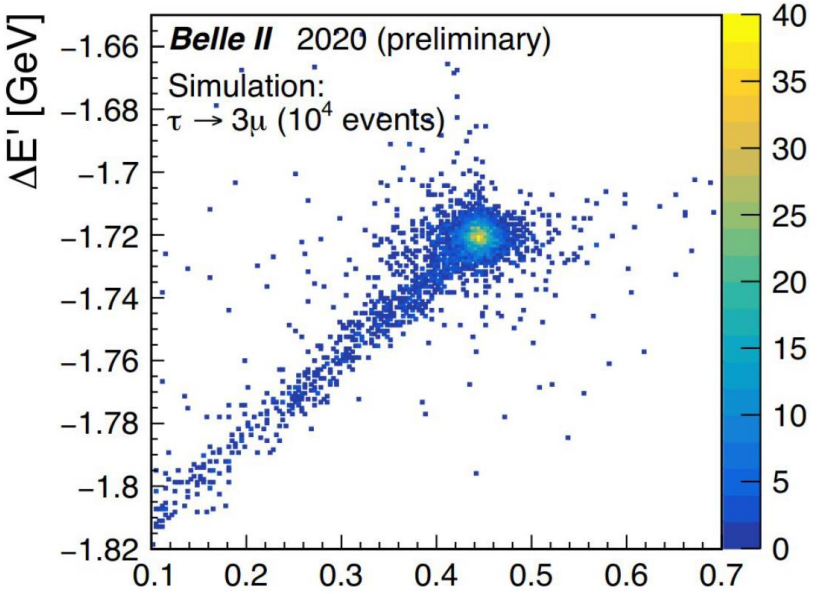


BKG free selection w/ 1 ab^{-1}.

BR($\tau \rightarrow \mu + \gamma$) < 2.72 x 10^{-8}

Improvement ~Belle limit/2.

(no sys. unc. included)

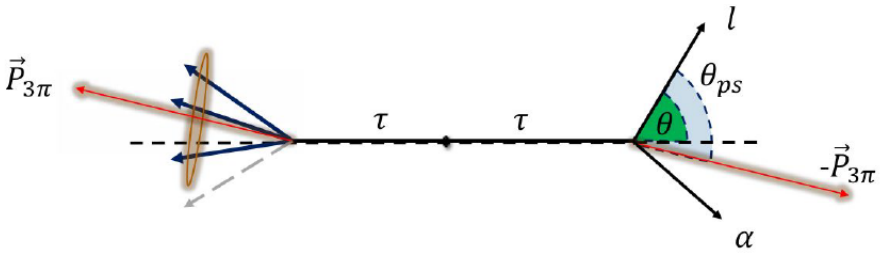


Belle: 2.1 x 10^{-8} (782fb^{-1}).

Belle II: ~10^{-10}.

Search for $\tau \rightarrow \ell\, \alpha$

α is a BSM invisible particle. Decay expected in several NP models. Previously searched by MARK III and ARGUS.
Use $\tau\tau$ events in 3+1 topology (4 tracks): $\tau \rightarrow 3\pi\nu + \tau \rightarrow$ 1 prong.



Look for α missing mass assuming:

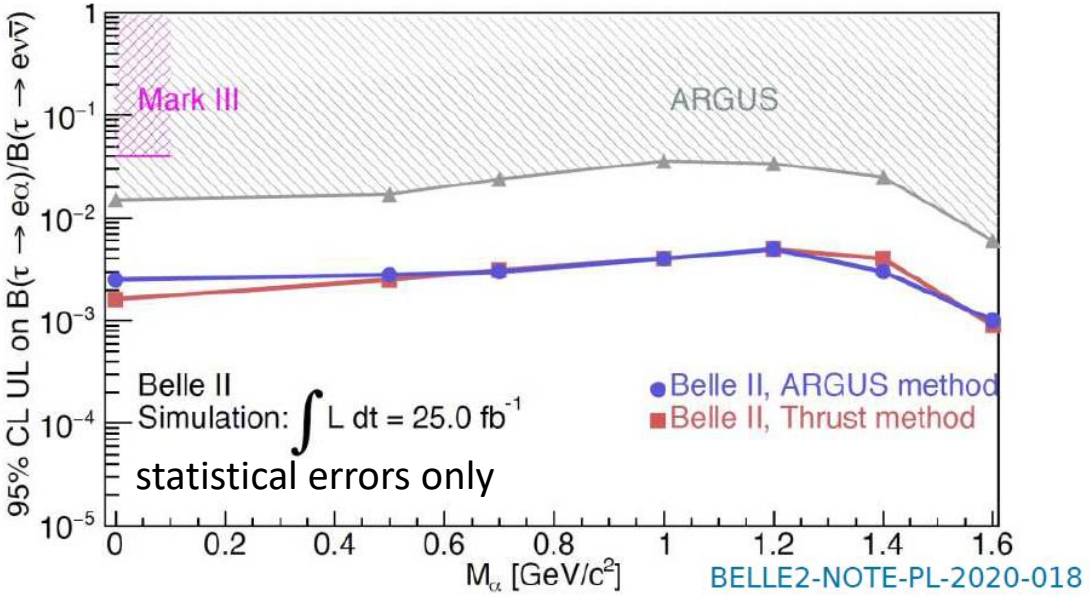
$\hat{p}_\tau \simeq -\hat{p}_{3\pi}$ $E_\tau = \sqrt{s}/2$ (ARGUS method)

or $\hat{p}_\tau \simeq \hat{V}_{thrust}$

Upper limit estimate for $\dfrac{BR(\tau \rightarrow l\alpha)}{BR(\tau \rightarrow l\nu\bar{\nu})}$

by fit to lepton momentum spectrum and hypothesis test for SM only and SM + NP. Frequentist approach.

1 order of magnitude improvement with 25 fb^{-1}. Study being finalized and completed with larger sample.



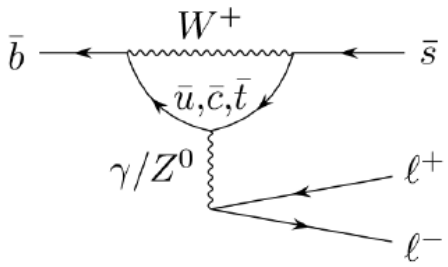
Lepton Flavour Universality Tests

b → sℓℓ transitions

Recent LHCb result show 3.1 σ tension with with SM predictions.

$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\text{stat})\ ^{+0.013}_{-0.012}\ (\text{syst})$

http://arxiv.org/abs/2103.11769



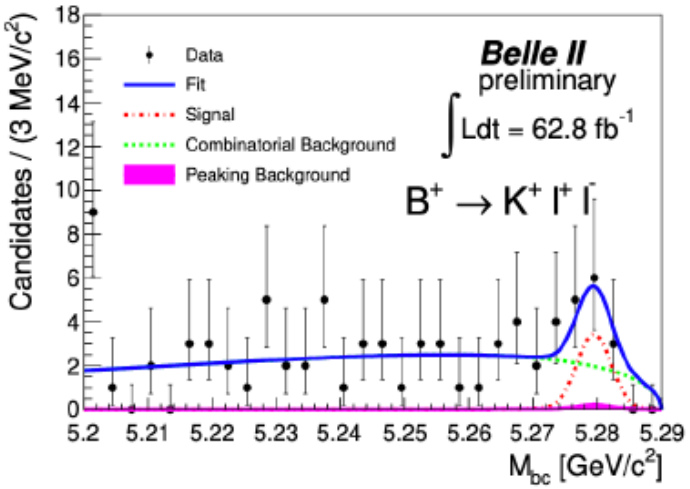
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

Belle II rediscovered $B^\pm \to K^\pm \ell^+ \ell^-$ in first data

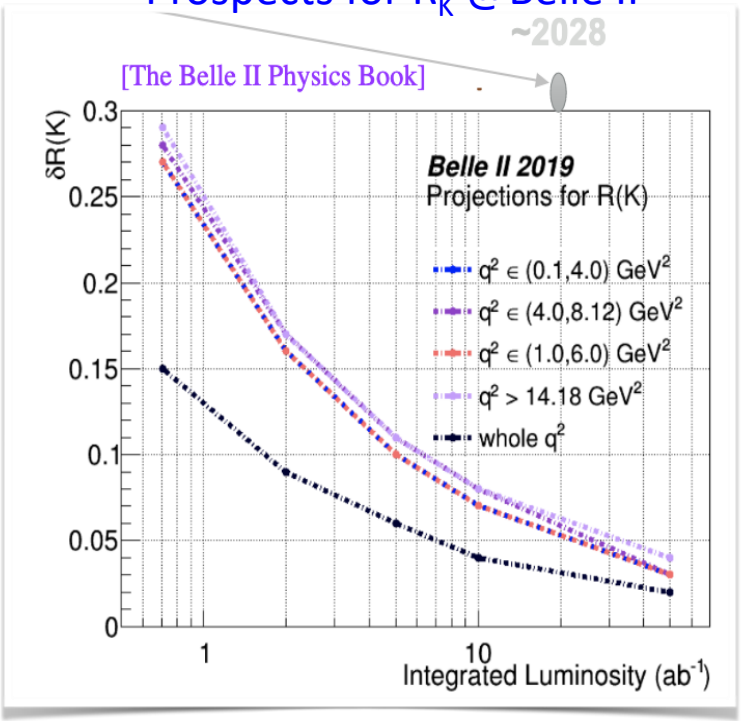
Observed $8.6^{+4.3}_{-3.9} \pm 0.4$ (stat./syst.) signal events in 2D fit (M_{bc}, ΔE)

$$M_{bc} = \sqrt{s/(4c^4) - p_B^{*2}/c^2}$$

$$\Delta E = E_B^{\ *} - \sqrt{s}/2$$



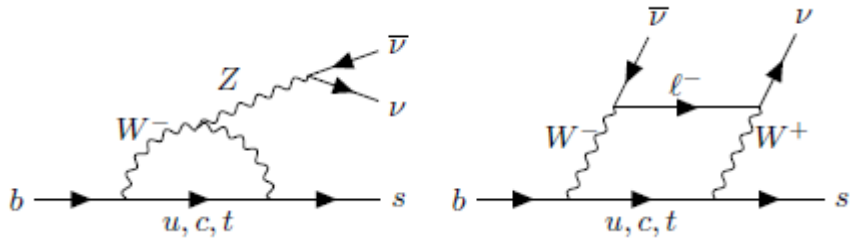
Prospects for R_K @Belle II



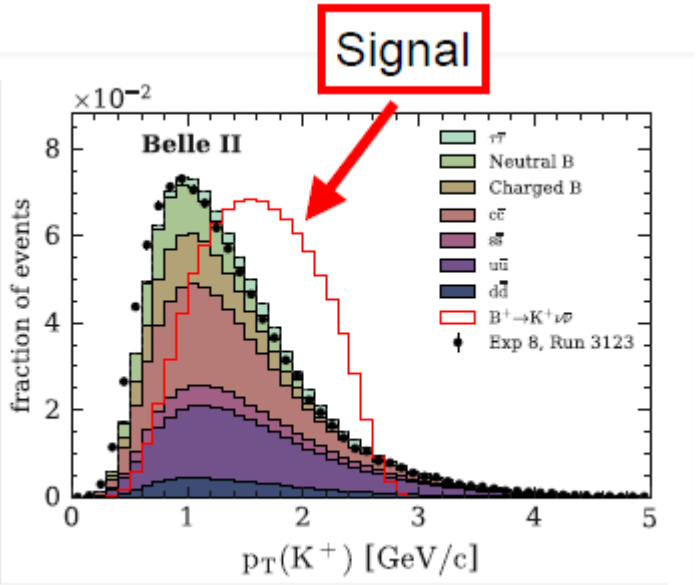
A much larger data sample (≥10 ab^{-1}) is needed to get the same accuracy of the actual measurement.

Already good results on complementary FCNC penguin decay: First Belle II paper on B physics!

Search for $B^{\pm} \rightarrow K^{\pm} \nu \nu$ arXiv 2104:12624

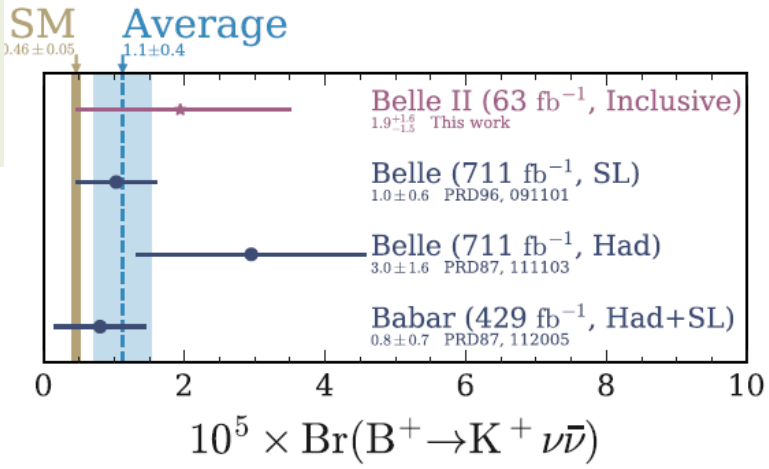


Cleaner theory prediction (no charm loop): BR=(4.6±0.6)x10^{-6}



New Belle II approach to increase signal efficiency:

- No explicit reconstruction of other B meson
- BDT used to select specific signal topology
- ε_{sig} ~ 4.3%, much higher than previous measurmts
- $B^+ \rightarrow J/\psi\, K^+$ used as validation channel



Same precision of previous searches with much smaller sample

Additional channels to be added (+ increased statistics, + better NN classifiers….)

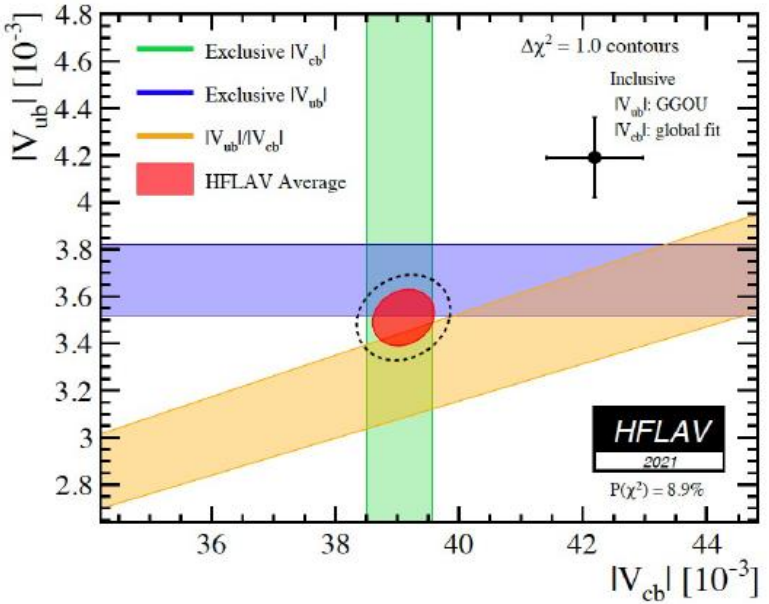
$|V_{ub}|$ and $|V_{cb}|$ CKM Matrix Elements

hflav.web.cern.ch

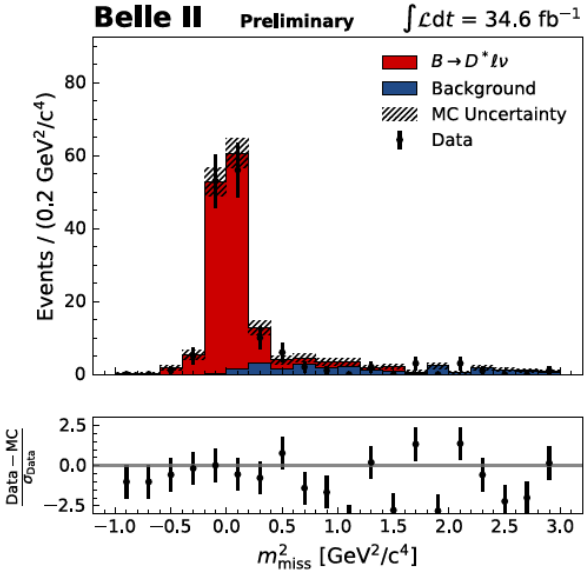
LFU may be behind the long standing tension between inclusive and exclusive determination of $|V_{ub}|$ and $|V_{cb}|$ (now about 3.3 σ)

Charged Higgs in 2HDM models or Leptoquarks can affect B→D BRs and $|V_{cb}|$.

Belle II has the capability to measure all the involved semileptonic decays with different techniques: tagged/untagged, inclusive/exclusive



FEI hadronic tag excl. $B^0 \to D^* \ell \nu$



Already several measurements performed with initial statistics. Exclusive B → D* ℓ ν is a key example:

Tagging efficiency improved w.r.t. Belle thanks to the **Full Event Interpretation** (FEI): hierarchical multivariate technique (>200 BDTs) to reconstruct B_{tag} side through $\mathcal{O}(10^3)$ different decay modes. **Comp. Softw. Big Sci. (2019) 3:6.**

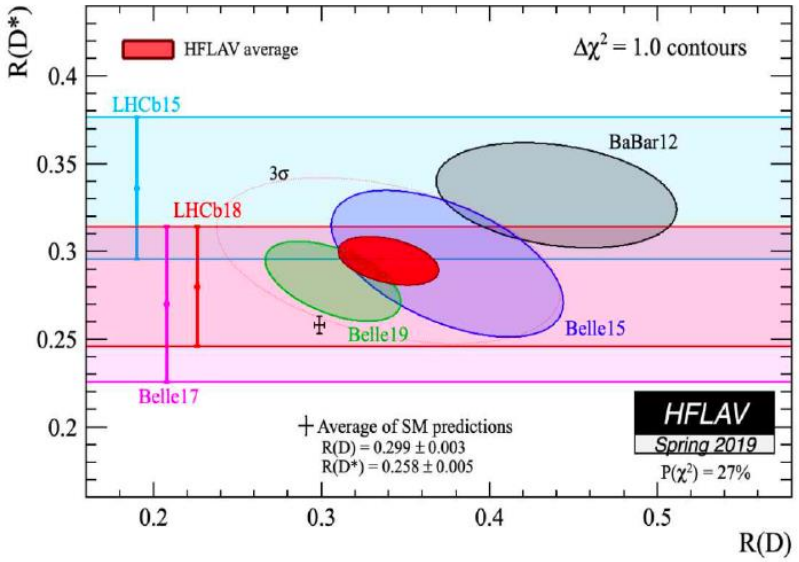
$$\mathcal{B}(\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}_l) = \left(4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s}\right) \%$$

Prospects for b→ c τ ν anomaly

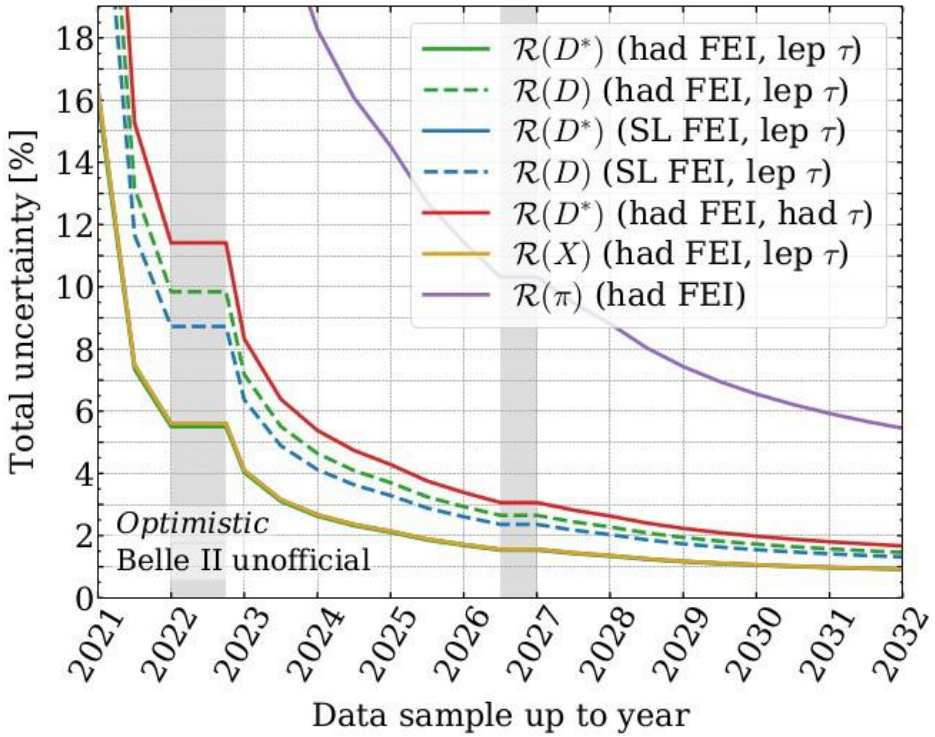
$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)} \tau \nu_\tau)}{\mathrm{Br}(B \to D^{(*)} \ell \nu_\ell)}$$

Denominator measurement well advanced. Numerator in progress via different tagging and τ decay channels.

3.1 σ deviation from SM



Bernlochner at al, arXiv 2101.83026



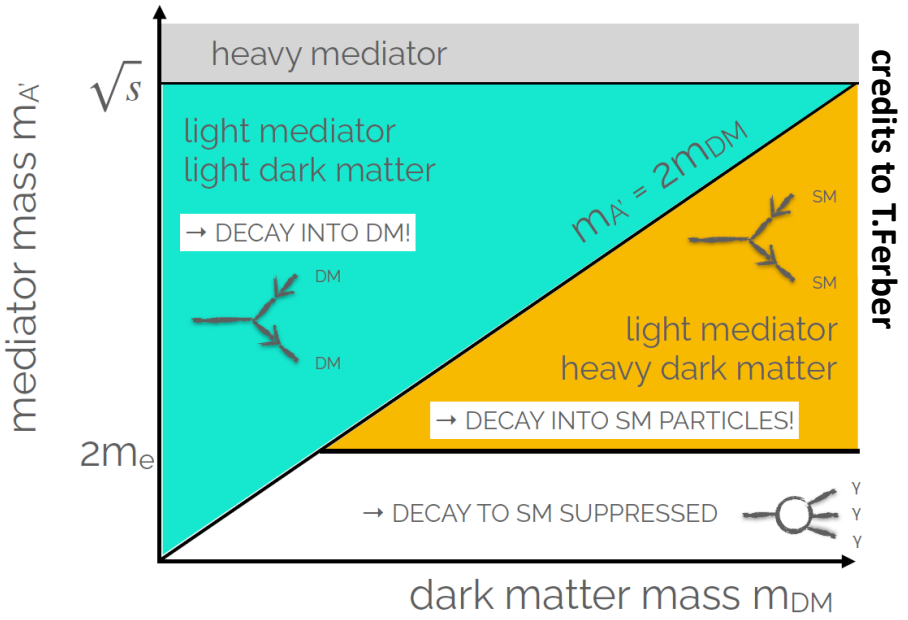
Belle II and LHCb can exploit many complementary channels. Final combined precision on R(D*) better than % expected

Dark sector searches

Dark sector searches @ Belle II

Depending on masses of DM particles and mediators different topologies are expected. Mediator's decay and/or missing energy signatures can be searched for.

Typical advantages of B factories very useful also for dark sector quest.



Many different models and possible channels can be investigated @ Belle II also with limited statistical samples.

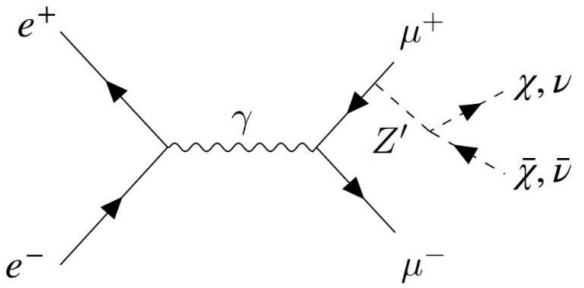
Two papers already published with very first data set:

- **Search for Z' decay in invisibles** *PRL **124** (2020) 141801*
- **Search for axion like particles (ALPs) strahlung** *PRL **125** (2020) 161806*

A number of other analyses in preparation

Search for Z' decay in invisibles

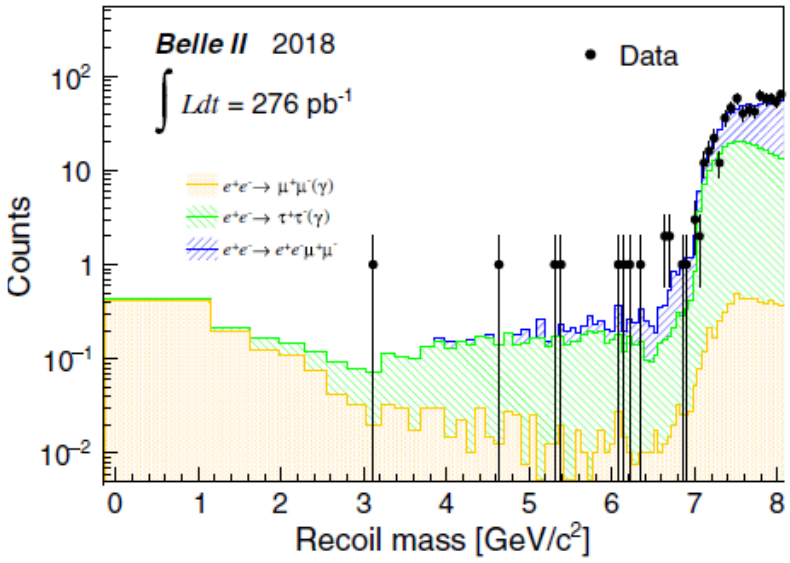
L_μ-L_τ model predicts a massive boson coupling only to 2nd and 3rd generation. May explain (g-2) and $R_{K(*)}$ anomalies.

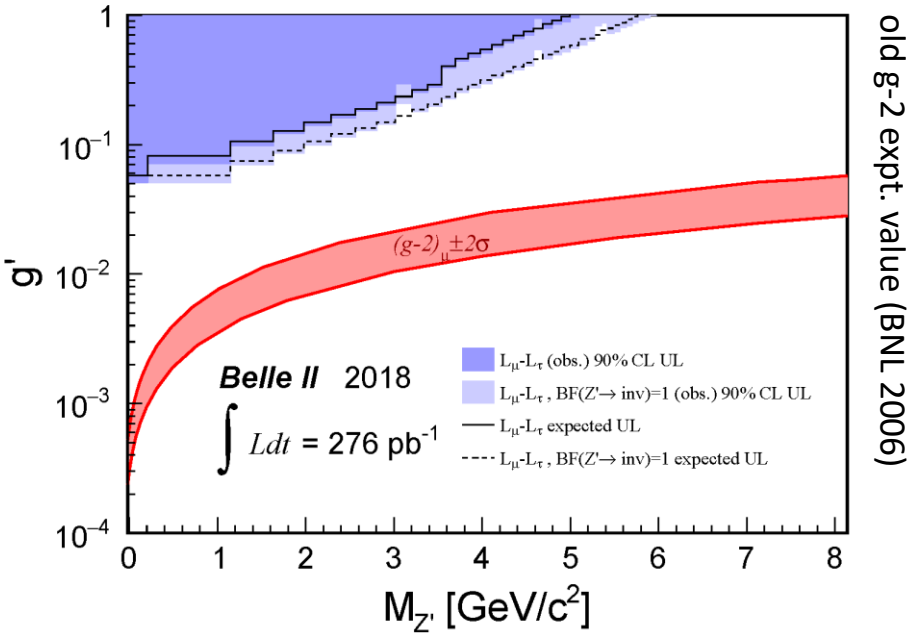


Z' decay into 2 muons already searched at BaBar, Belle II can improve it with $\mathcal{O}$(100 fb-1) sample.

First ever search for decay to invisibles:

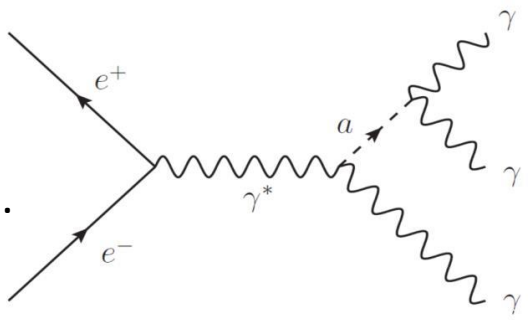
2 muons + missing energy final state. Background from $\mu\mu(\gamma)$, $\tau\tau(\gamma)$, $\mu\mu\tau\tau$ events.
Look for a peak in invariant mass of the system recoiling against $\mu\mu$.



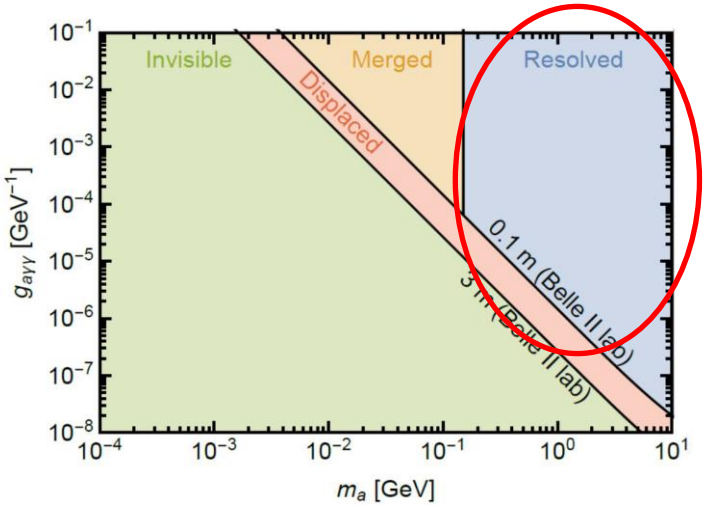


With 50 fb^{-1} sample (already on tape) sensitivity enough to start probing (g-2) band.

Search for Axion Like Particles



Pseudo-scalars coupling to bosons, appear in many BSM scenarios.
Can be both mediators or DM candidates.

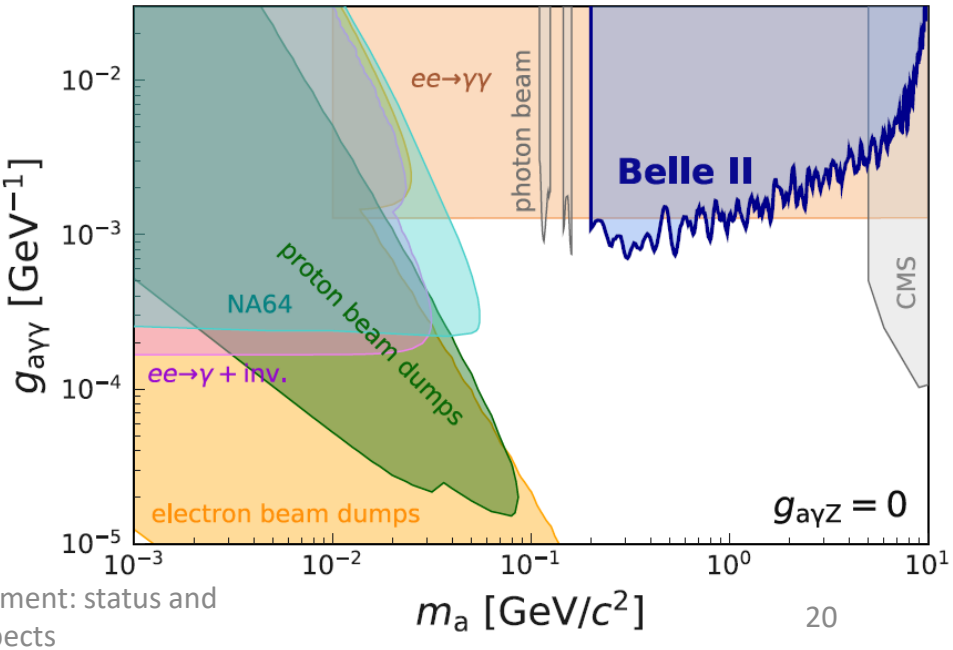


Belle II searched for ALP-strahlung with decay in 2 photons
Several topologies are possible depending on size of axion mass and coupling constant.

Resolved 3 γ final state searched for:

- 3 γ energy adds up to E_{beam}
- bump on di-photon mass searched
- Background from $\gamma\gamma(\gamma)$, $e^+e^-(\gamma)$, $P\gamma(\gamma)$

First ever result on ALPs from B factories.



Conclusions

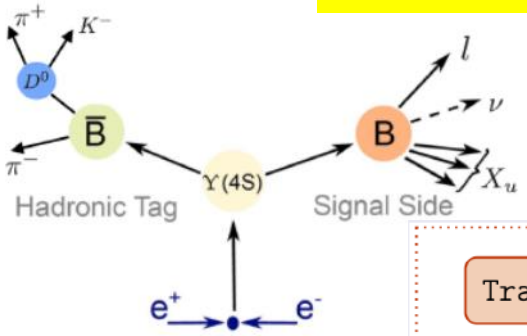
SuperKEKB has set a new world record in peak luminosity and is entering the regime of SuperB factory

The Belle II detector is performing very well and is already producing important physics results

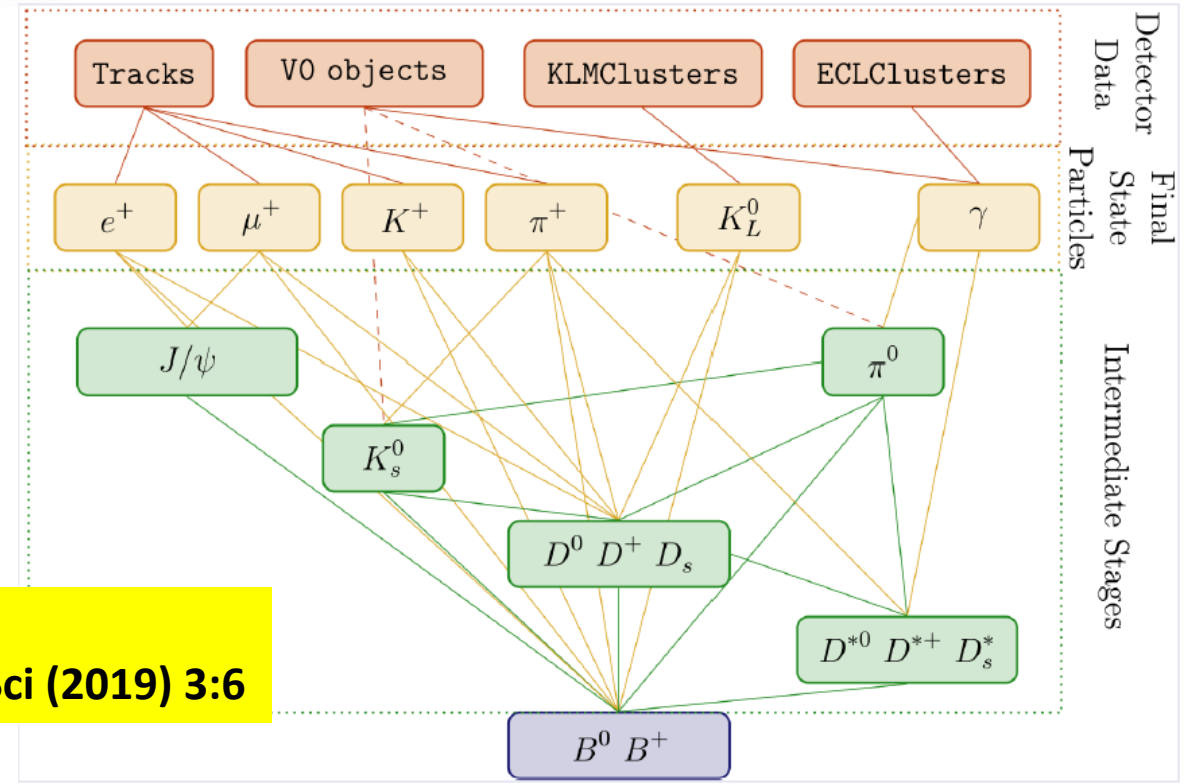
An extremely rich physics program will be accessible with Belle II data, to thoroughly probe BSM scenarios

SPARES

FEI: Full event interpretation, enhances by a factor of 2 the event tagging efficiency



A dedicated boosted decision tree for each step
More than 1000 B decay modes are reconstructed



T. Keck et al.,
Comput Softw Big Sci (2019) 3:6

Very powerful tool for all tagged analyses: high purity but usually low statistics
Untagged analyses by converse have high statistics, high background, and less kinematical constraints (Rest of the Event)

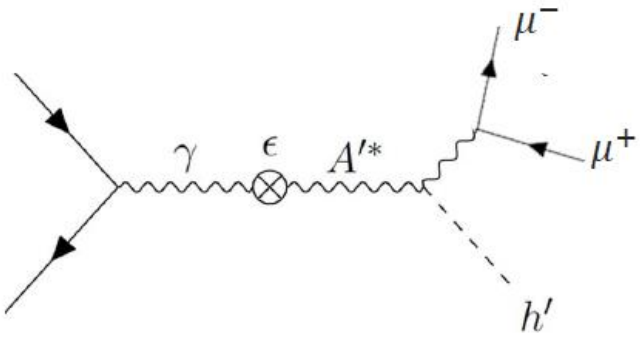
Status of B semileptonic decays BR measurement @Belle II

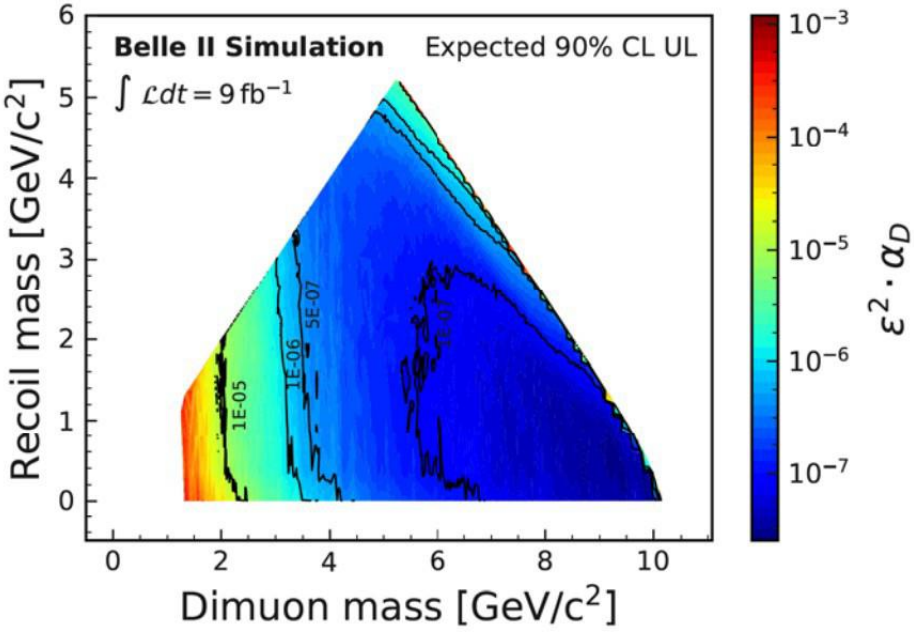
- With about 1/4 of the current dataset, Belle II has been able to measure extensively inclusive and exclusive semileptonic B decays, adopting untagged approaches and exploiting the Full Event Interpretation algorithm for tagged analyses

Channel	Result presented in the talk	$\lvert V_{xb}\rvert$ measurement in progress
$B \to X_u \ell \nu$	3σ observation (untagged)	
$B^0 \to \pi^- \ell \nu$	$BF = (1.58 \pm 0.43_{stat} \pm 0.07_{syst}) \times 10^{-4}$ (FEI hadronic)	$\lvert V_{ub}\rvert$ from partial branching fraction in q^2 bins
$B \to X_c \ell \nu$	$BF = (9.75 \pm 0.03_{stat} \pm 0.47_{syst})\%$ (untagged) Hadronic mass moments (FEI hadronic)	$\lvert V_{cb}\rvert$ from q^2 spectral moments (novel approach)
$\bar{B}^0 \to D^{*+} \ell^- \nu$	$BF = (4.60 \pm 0.05_{stat} \pm 0.48_{syst})\%$ (untagged) $BF = (4.51 \pm 0.41_{stat} \pm 0.52_{syst})\%$ (FEI hadronic)	$\lvert V_{cb}\rvert$ from partial branching fractions in hadronic recoil parameter bins
$B^- \to D^0 \ell^- \nu$	$BF = (2.29 \pm 0.05_{stat} \pm 0.08_{syst})\%$ (untagged)	

Dark higgs-strahlung search

Next to minimal dark photon model:
A' mass could be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson h ' to the theory





Belle II is exploring the *invisible h'* case in two muons and missing energy final state:

- **Signature:** a 2d peak in *recoil vs dimuon* mass;
- **Background** from QED processes: $\mu\mu(\gamma), \tau\tau(\gamma), ee\mu\mu$;

Very promising expectations even with the 2019 only dataset (~ 9 fb^{-1}).

- Accessing unconstrained region beyond the KLOE coverage;
- Probing non-trivial $\epsilon^2\ \alpha_D$ couplings.

Analysis to be finalized shortly (by end 2021).