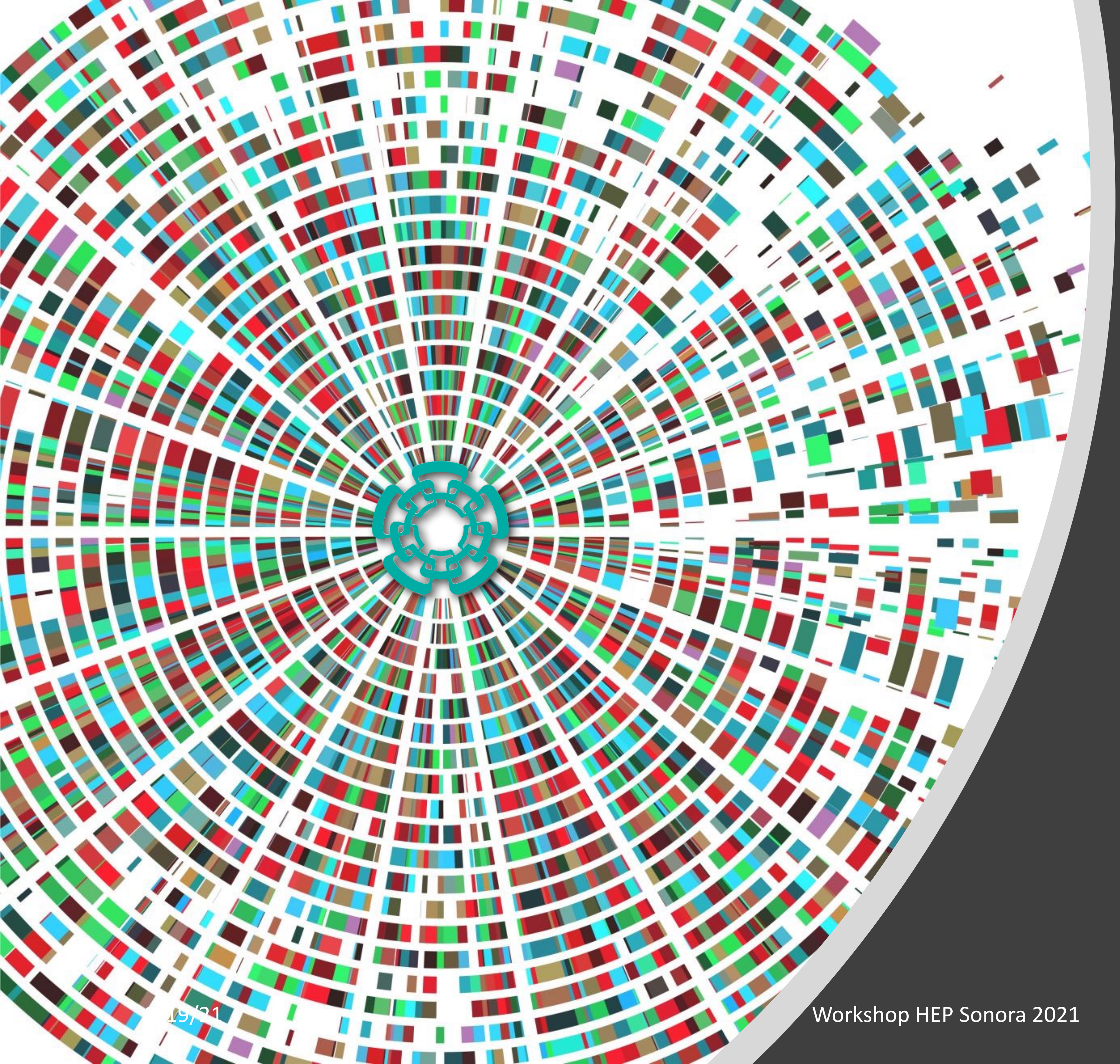


Belle II physics

Eduard De La Cruz Burelo

Department of Physics

CINVESTAV

XIX Mexican School of Particles and Fields

Disclaimer

The talk was prepared thinking on the students in the audience. So, I kept everything as basic as I could.

Many parts of this talk are based on previous talks by colleagues at the Belle II experiment. Particularly, thanks to Tom Browder, Ami Rostomyan, Francesco Tenchini, Navid K. Rad, and Alejandro De Yta.

Belle II

What is Belle II?

Belle II is an international collaboration

- Belle II detectors is based in Japan in the SuperKEKB collider
- Belle II now has grown to ~1000 researchers from 26 countries
- Around 330 are students
- Mexico joined Belle II in July 2013
- First collisions in 2018.

B factories …

- The B Factories focused on establishing large CP violation in the B Meson System in the SM and constraints on the CKM matrix.
- PEP II/BaBar stopped in 2008 while KEKB/Belle completed operations in 2010.

Parameters			PEP-II	KEKB
Beam energy		(GeV)	9.0 (e^-), 3.1 (e^+)	8.0 (e^-), 3.5 (e^+)
Beam current		(A)	1.8 (e^-), 2.7 (e^+)	1.2 (e^-), 1.6 (e^+)
Beam size at IP	x	(μm)	140	80
	y	(μm)	3	1
	z	(mm)	8.5	5
Luminosity		(cm^{-2} s^{-1})	1.2×10^{34}	2.1×10^{34}
Number of beam bunches			1732	1584
Bunch spacing		(m)	1.25	1.84
Beam crossing angle		(mrad)	0 (head-on)	±11 (crab-crossing)

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

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

A single irreducible complex phase explains all CPV

Some history…

The B factory experiments, Belle and BaBar, discovered large CP violation in the B system in 2001, compatible with the SM and provided a large range of CKM measurements. These provided the experimental foundation for the 2008 Nobel Prize to Kobayashi and Maskawa.

In the meantime, the LHC was constructed in 2008, ATLAS and CMS completely changed the nature of high energy physics. Of particular importance was the landmark discovery in 2012 of the Higgs boson.

This discovery was recognized by the 2013 Physics Nobel Prize to Englert and Higgs.

Complementarity

- ATLAS and CMS and the LHC, known as high pT experiments, established tight constraints on direct production of high mass particles (e.g. M(Z'), M(W')>3 TeV, vector-like fermions > 800 GeV) and limits on SUSY. This *search* continues with the high luminosity LHC.
- Paradigm shift: inspired by intriguing results from LHCb and the potential of Belle II, the possibility of finding new physics in flavor has emerged as a *complementary* route to the LHC.

European strategy group (ESG) final report

The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***

The observed pattern of masses and mixings of the fundamental constituents of matter, quarks and leptons, remains a puzzle in spite of the plethora of new experimental results obtained since the last Strategy update. Studying the flavour puzzle may indicate the way to new physics with sensitivity far beyond what is reachable in direct searches, e.g. the evidence for the existence of the top quark that followed from the study of B-meson mixing. In addition, flavour physics and CP violation, which play a vital role in determining the parameters of the Standard Model, are explored by a wide spectrum of experiments all over the world. These include measurements of electric or magnetic dipole moments of charged and neutral particles, atoms and molecules, rare muon decays with high intensity muon beams at PSI, FNAL and KEK, rare kaon decays at CERN and KEK, and a variety of charm and/or beauty particle decays at the LHC, in particular with the LHCb experiment. New results are expected in the near future from the Belle II experiment at KEK in Japan and from LHCb (currently undergoing an upgrade) at CERN.

Counting particles or decays

$$N = L * \sigma * \left(\prod_{i=1}^{m} Br_i \right) * \varepsilon$$

- L : Luminosity
- σ : Cross section
- Br : Branching fractions
- ε : detector efficiency

Counting particles or decays

Detector

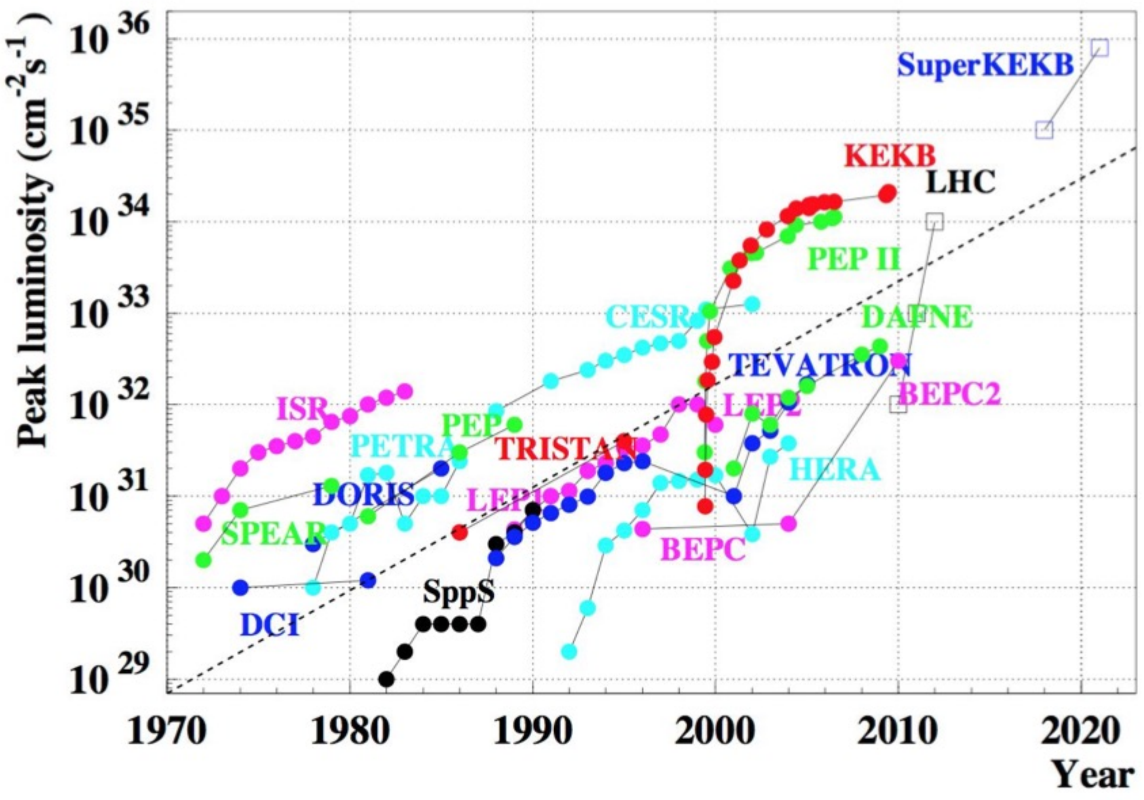
Accelerator

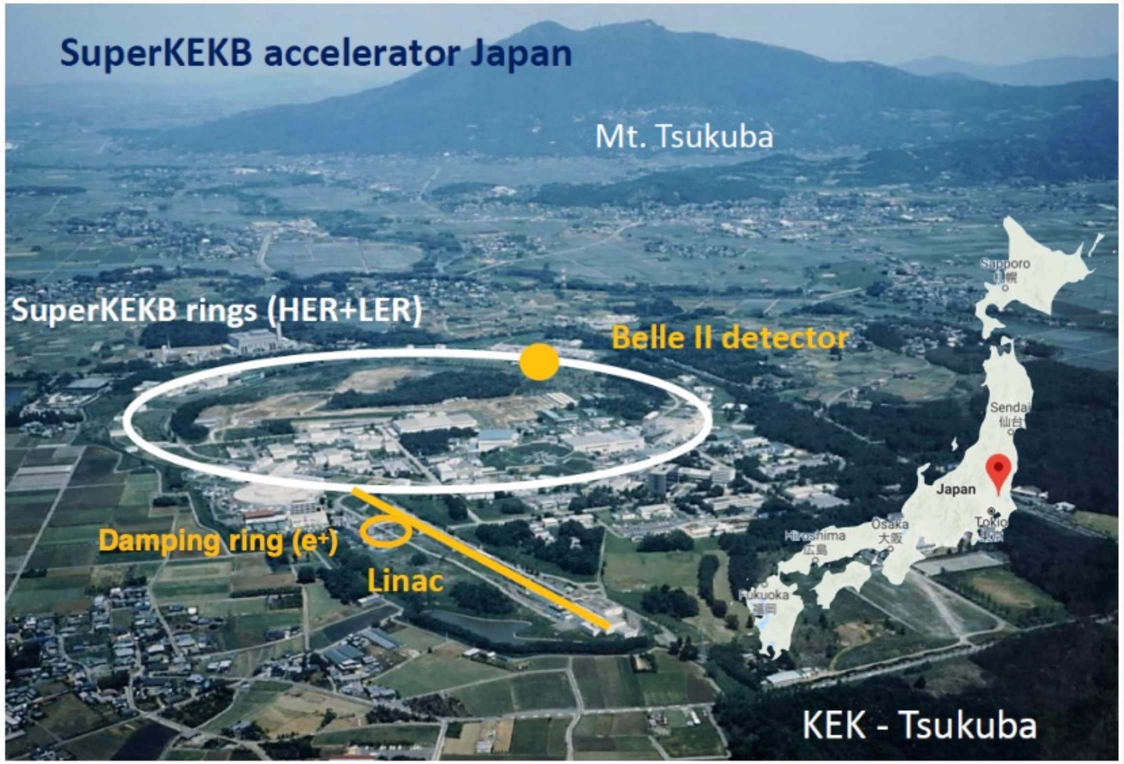
$$N = L * \sigma * \left(\prod_{i=1}^{m} Br_i \right) * \varepsilon$$

Nature

- L : Luminosity
- σ : Cross section
- Br : Branching fractions
- ε : detector efficiency

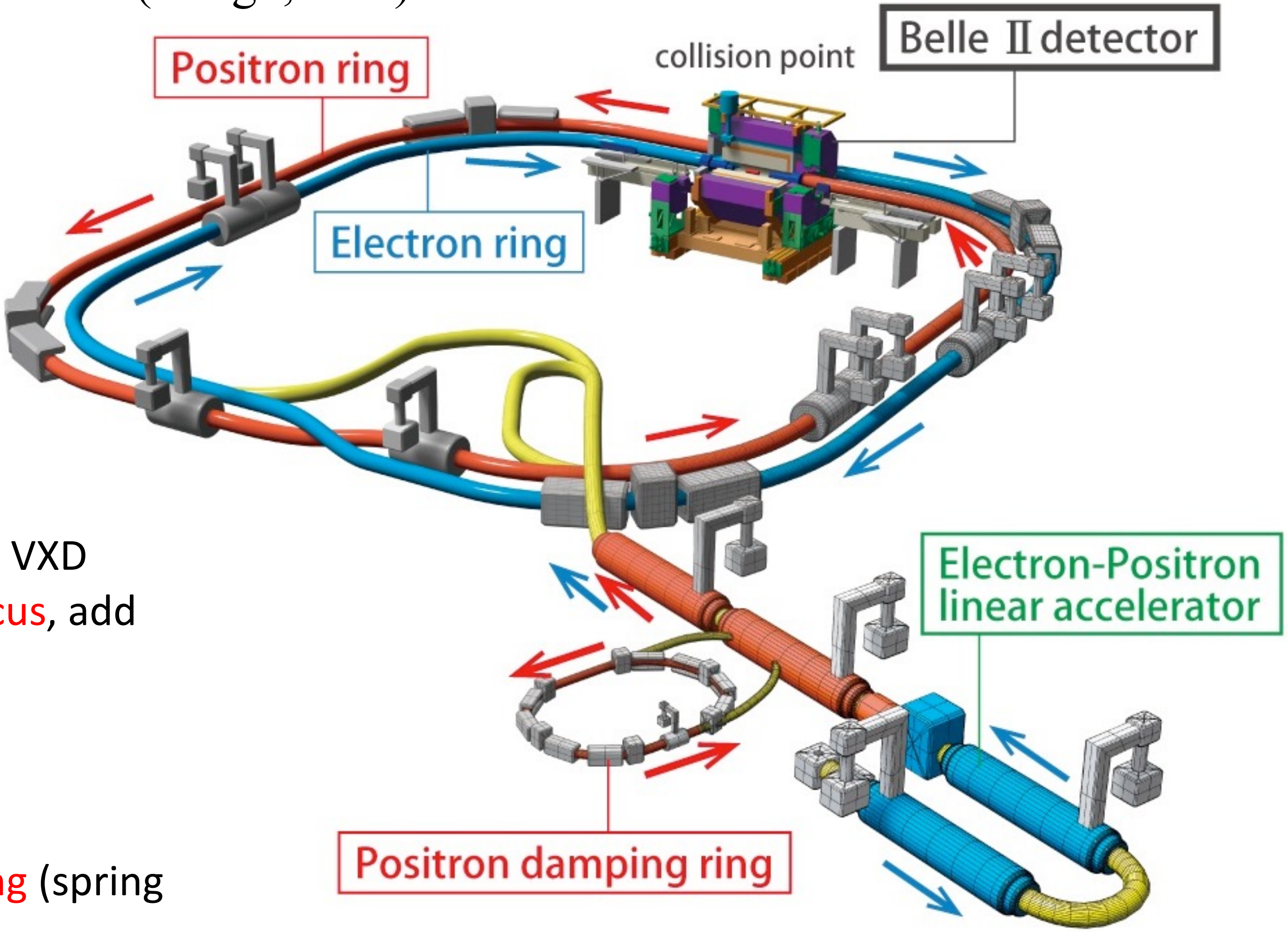
Ambitious Next Step at Luminosity Frontier: SuperKEKB





SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron (e^+e^-) rather than proton-proton (pp)). Operates on the Upsilon(4S) resonance with 7 GeV(e-) on 4 GeV(e+) beams.

$L(\text{design},2020) = 6.5 \times 10^{35}/\text{cm}^2/\text{sec}$



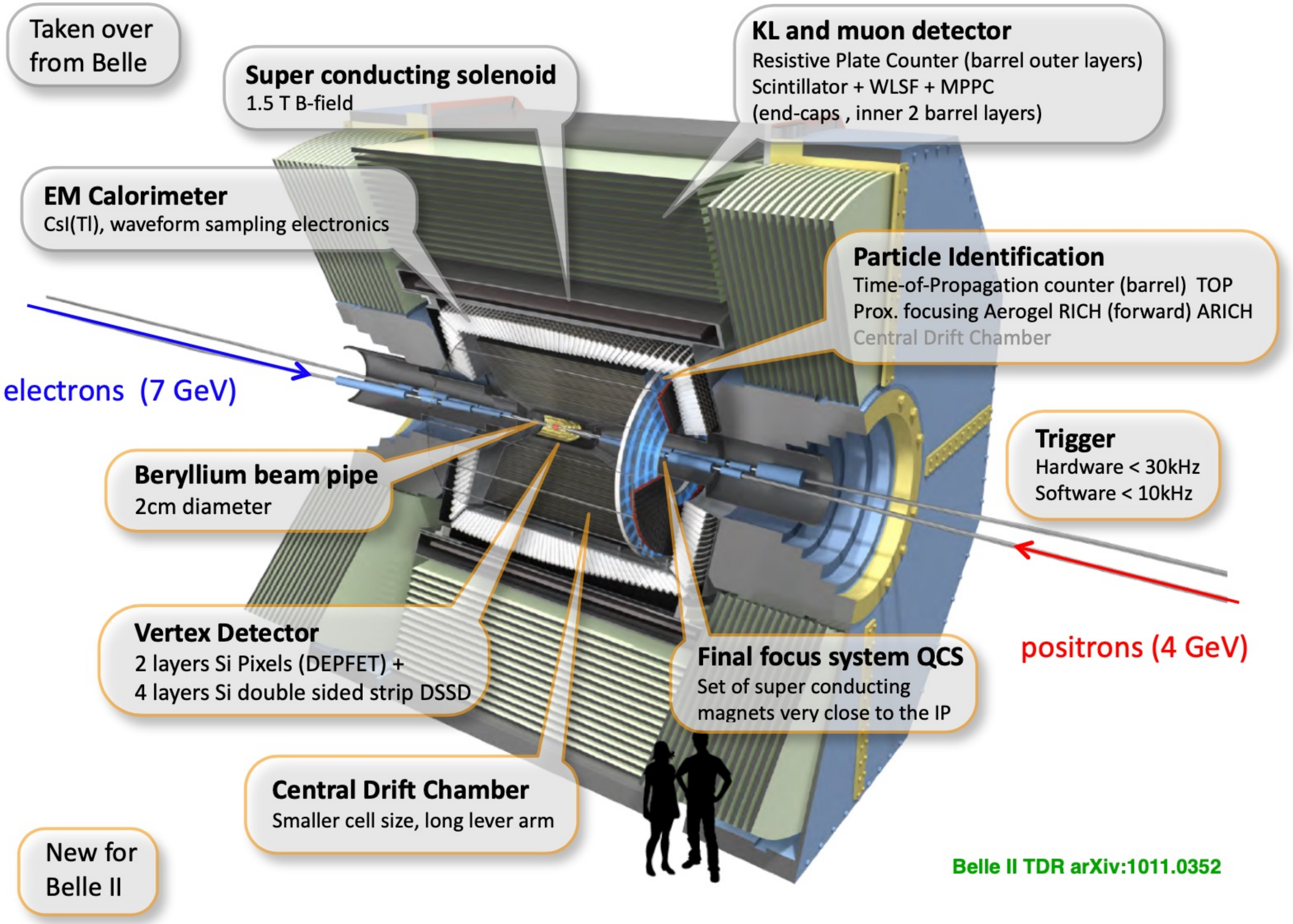
Phase 1:
Background, Optics Commissioning
Feb-June 2016.
Brand new
3 km positron ring.

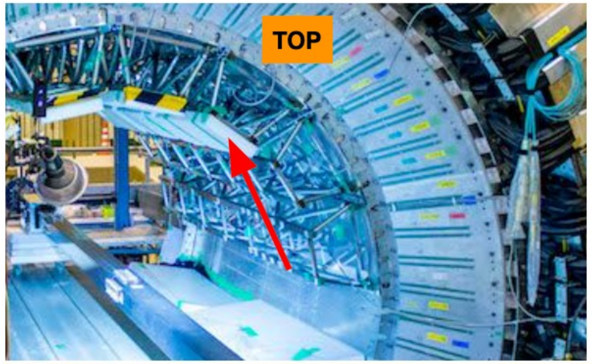
Phase 2: Pilot run without VXD
Superconducting Final Focus, add positron damping ring,
First Collisions (0.5 fb^{-1}).
April 27-July 17, 2018

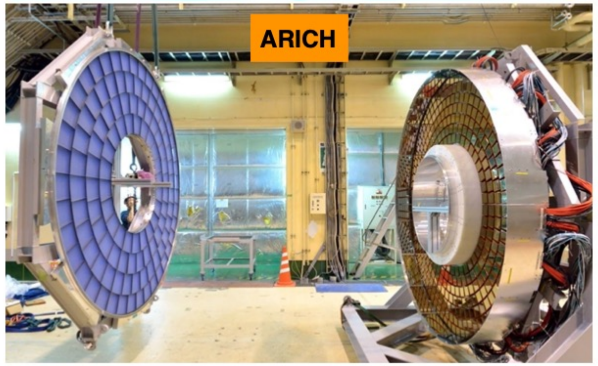
Phase 3: → Physics running (spring 2019 to present).
Have integrated 213 fb^{-1} so far.

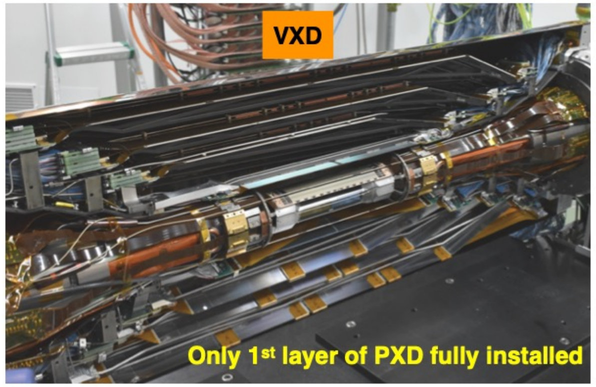
Accelerator innovations: nano-beams and crab waist optics (*rather than large beam currents*)

Belle II Detector









Physics at Belle II

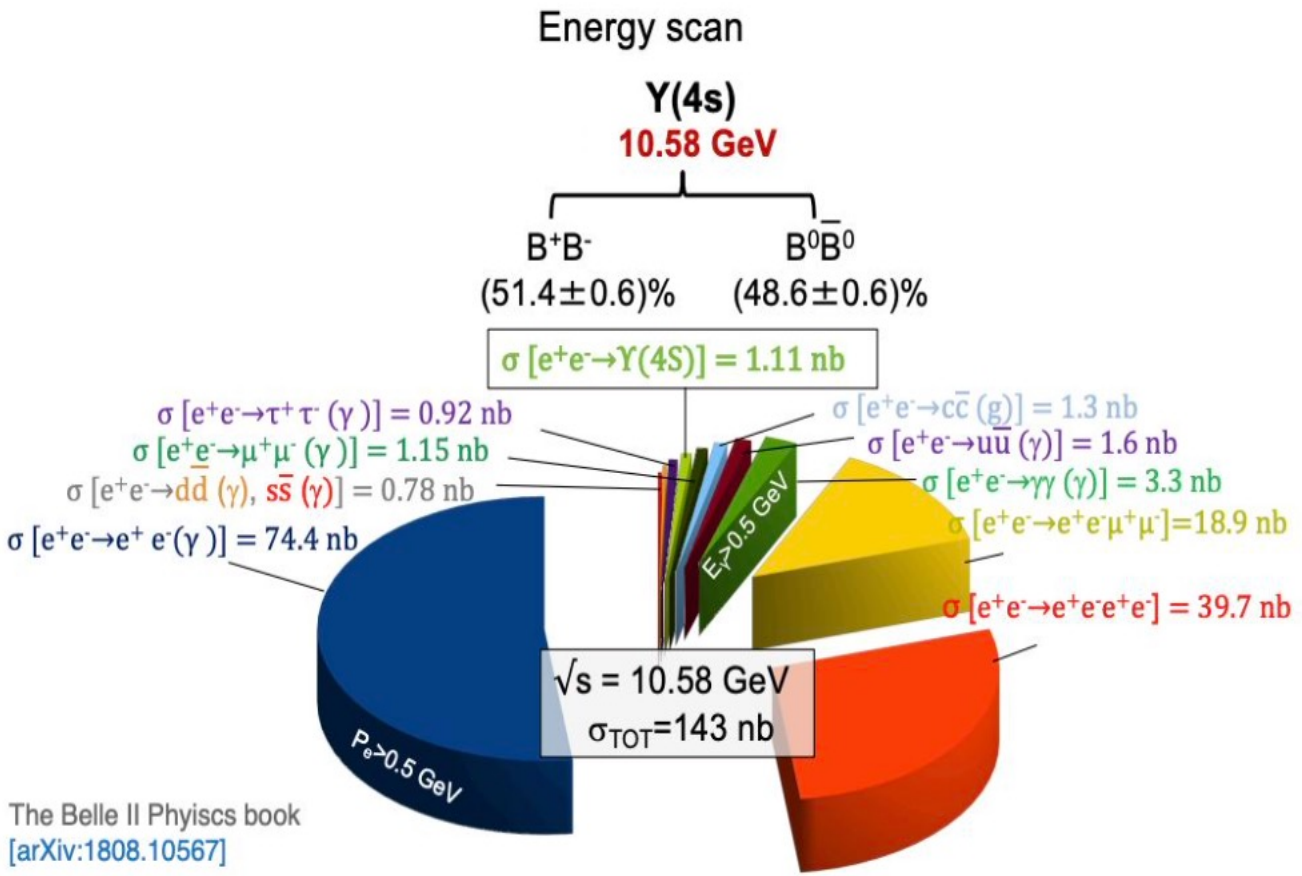
- Not *just* a B-factory!
  - τ, c, and b pairs have similar cross sections at $\sqrt{s}$ = 10.58 GeV

$\sigma(e^+e^- \to \Upsilon(4S)) = 1.11$ nb

$\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb

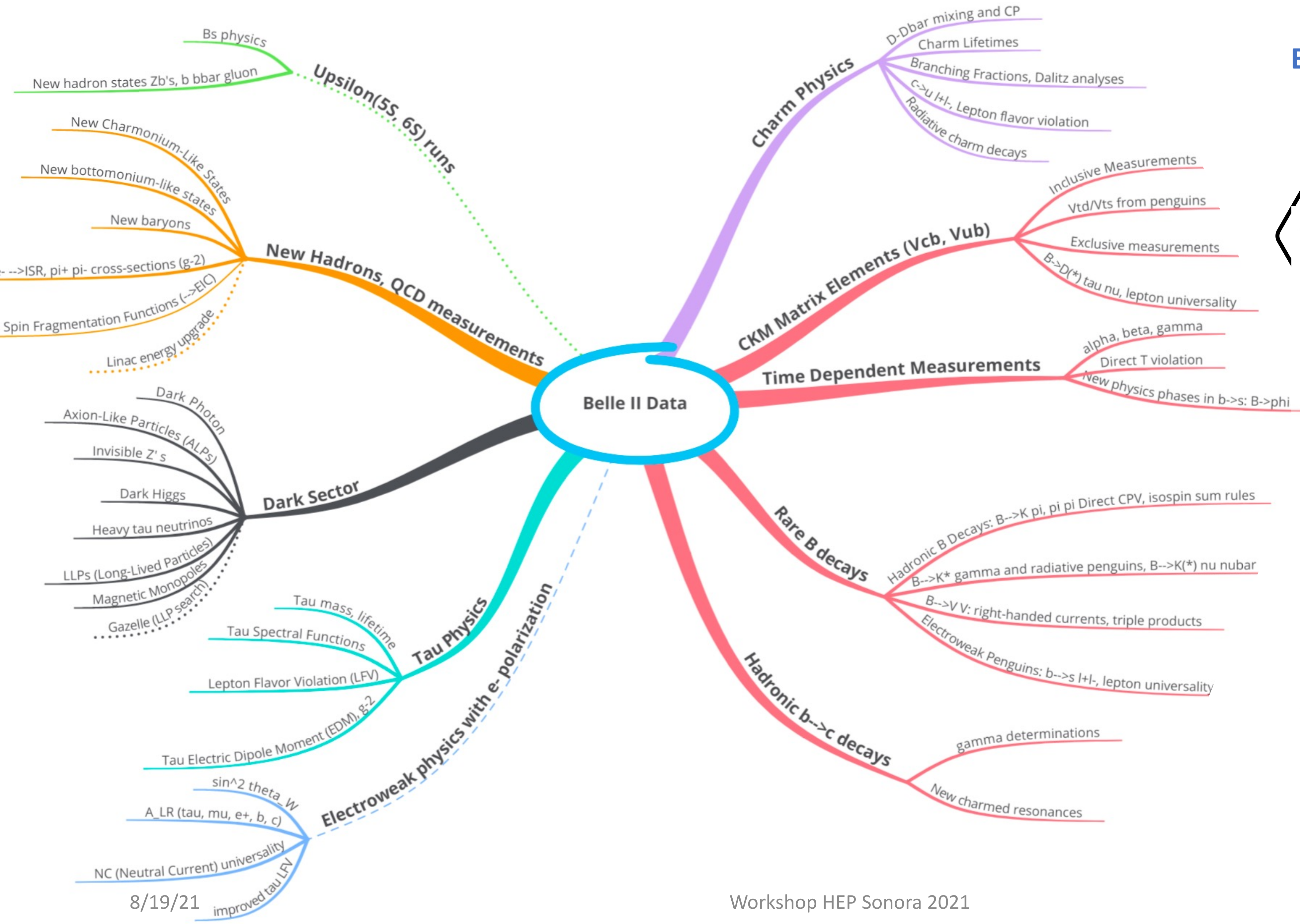
$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb

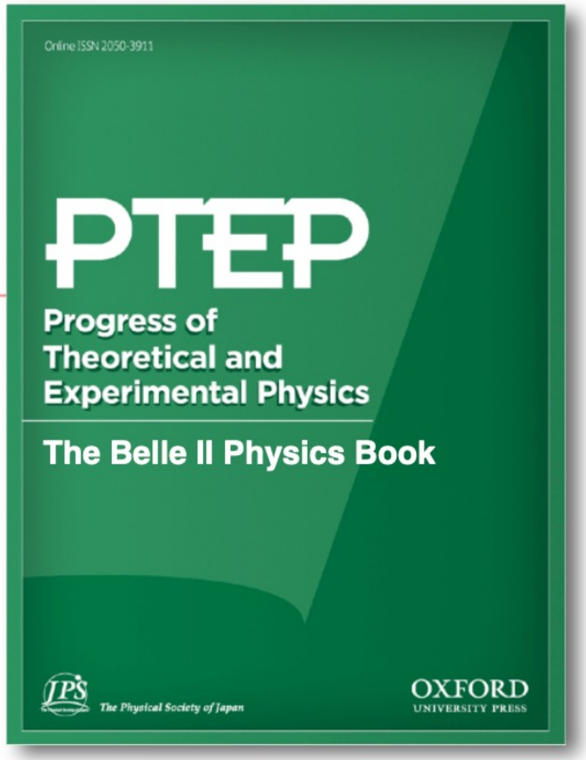
- Wide physics program
  - precision measurements of time-dependent CPV and CKM parameters
  - searches for lepton flavor universality/number violations
  - dark-sector searches
  - and many more



The Belle II Phyiscs book
[arXiv:1808.10567]

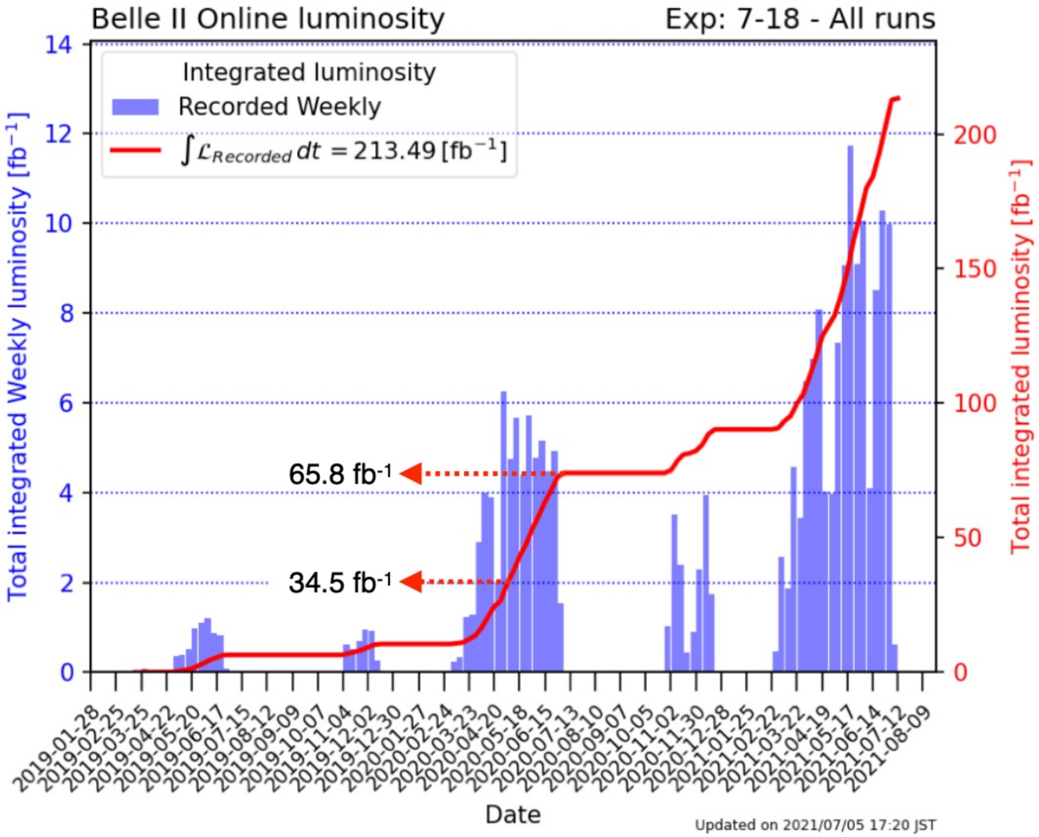
Belle II Physics mind map

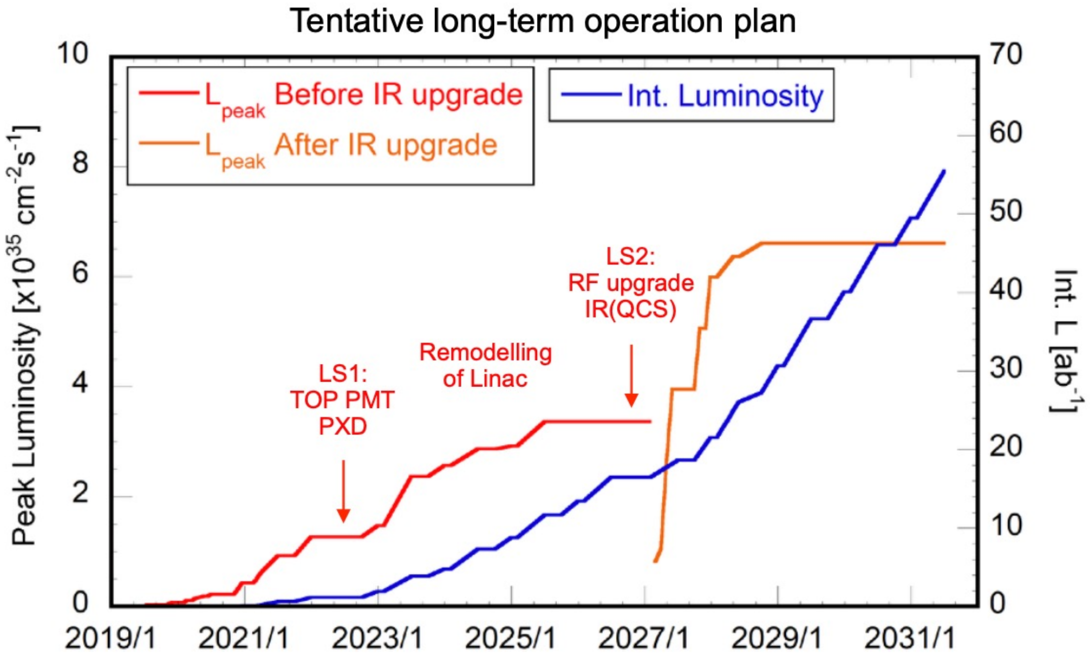




Prog. Theor. Exp. Phys. 2019, 123C01
arXiv:1808.10567

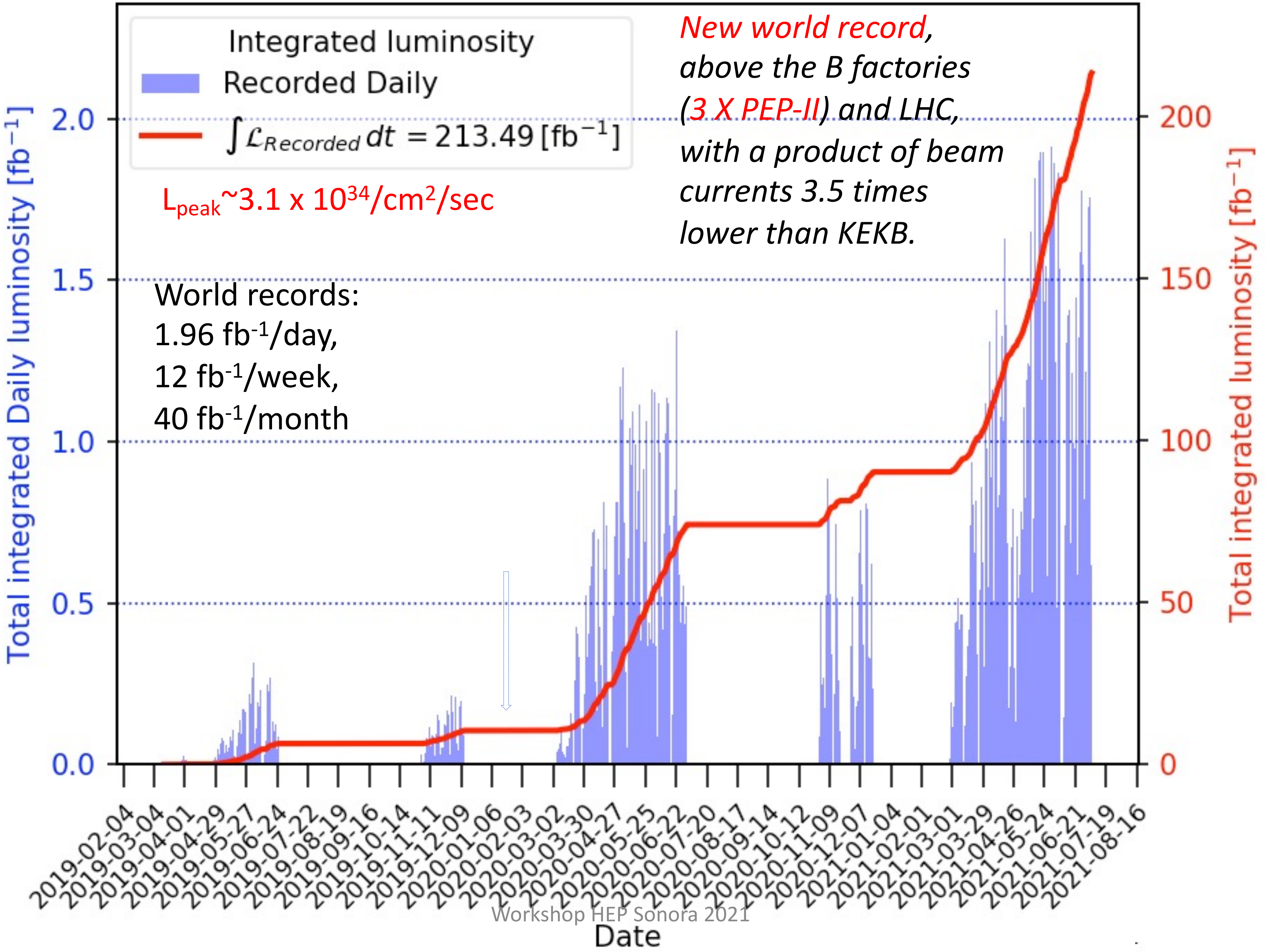
Luminosity: status and plans





- Very successful data taking throughout the pandemic
  - overall data taking efficiency of **89.5%**
  - collected up to 12 fb^{-1} per week: Super-B factory mode
- Current working plan follows the KEK Roadmap2020
  - LS1 in 2022 for PXD & TOP-PMT replacement
  - options for a possible IR upgrade ≳2026 under study

Belle II Integrated Luminosity



FAQ: How can an international experiment and accelerator operate during a global pandemic ?

SuperKEKB/Belle II was and is operating during the COVID-19 pandemic with protocols in place to maximize safety and minimize the risk of infection. Difficult with travel restrictions and a very heavy load on a skeleton crew at KEK (~40 people).

Developed a "social distancing" scheme for on-site shifts in the Belle II and SuperKEKB control rooms. Mobilized remote shifters around the world – depended heavily on internet chat utilities for communication and monitoring.

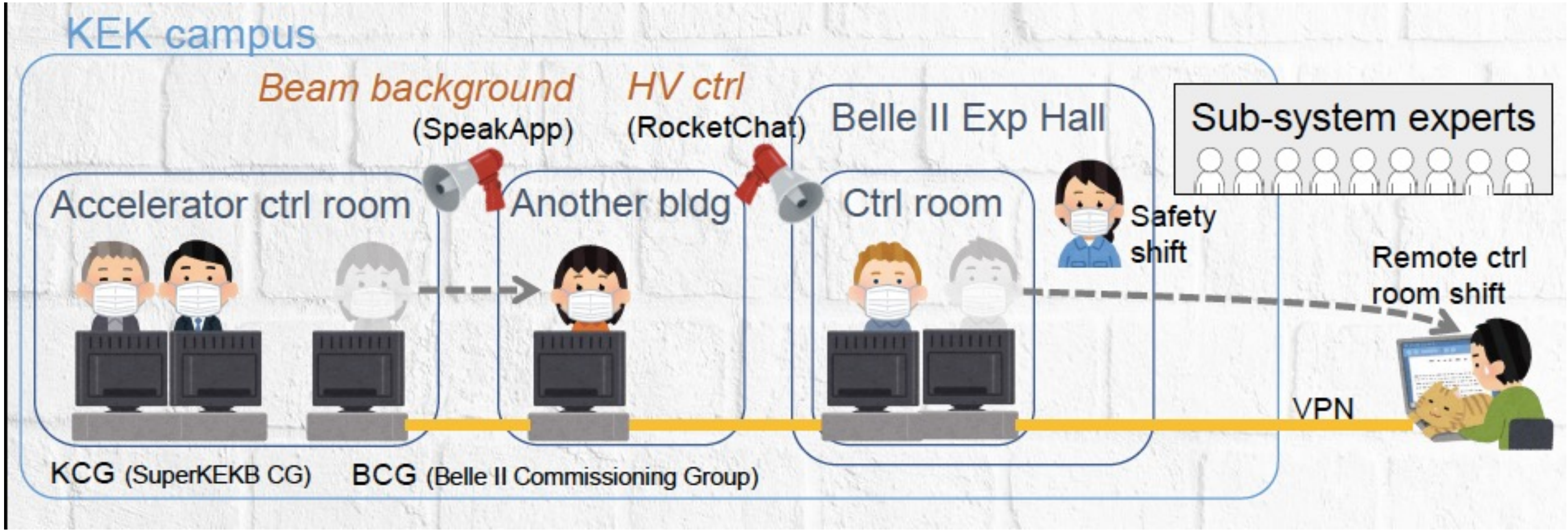
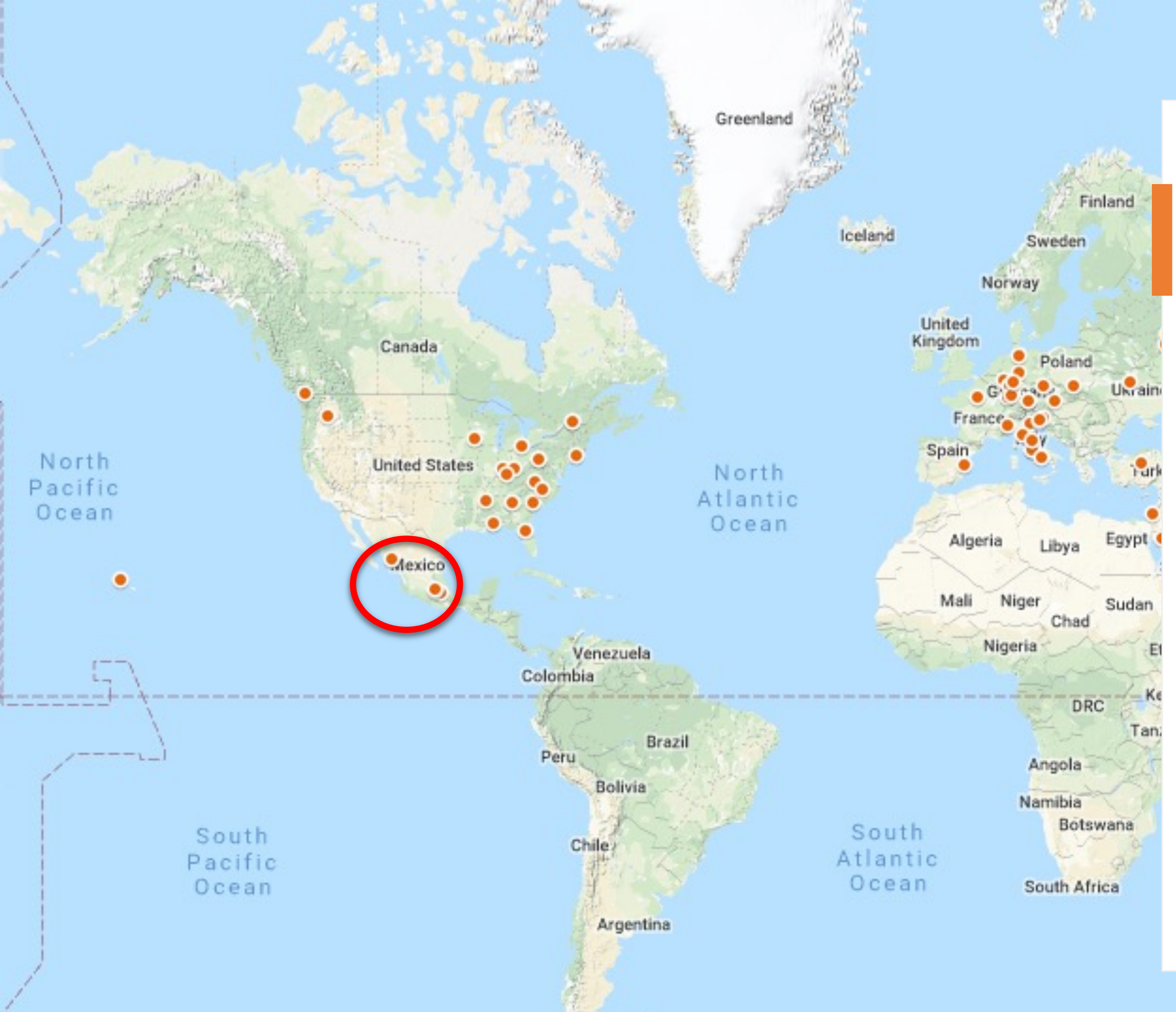


Figure credit: K. Matsuoka

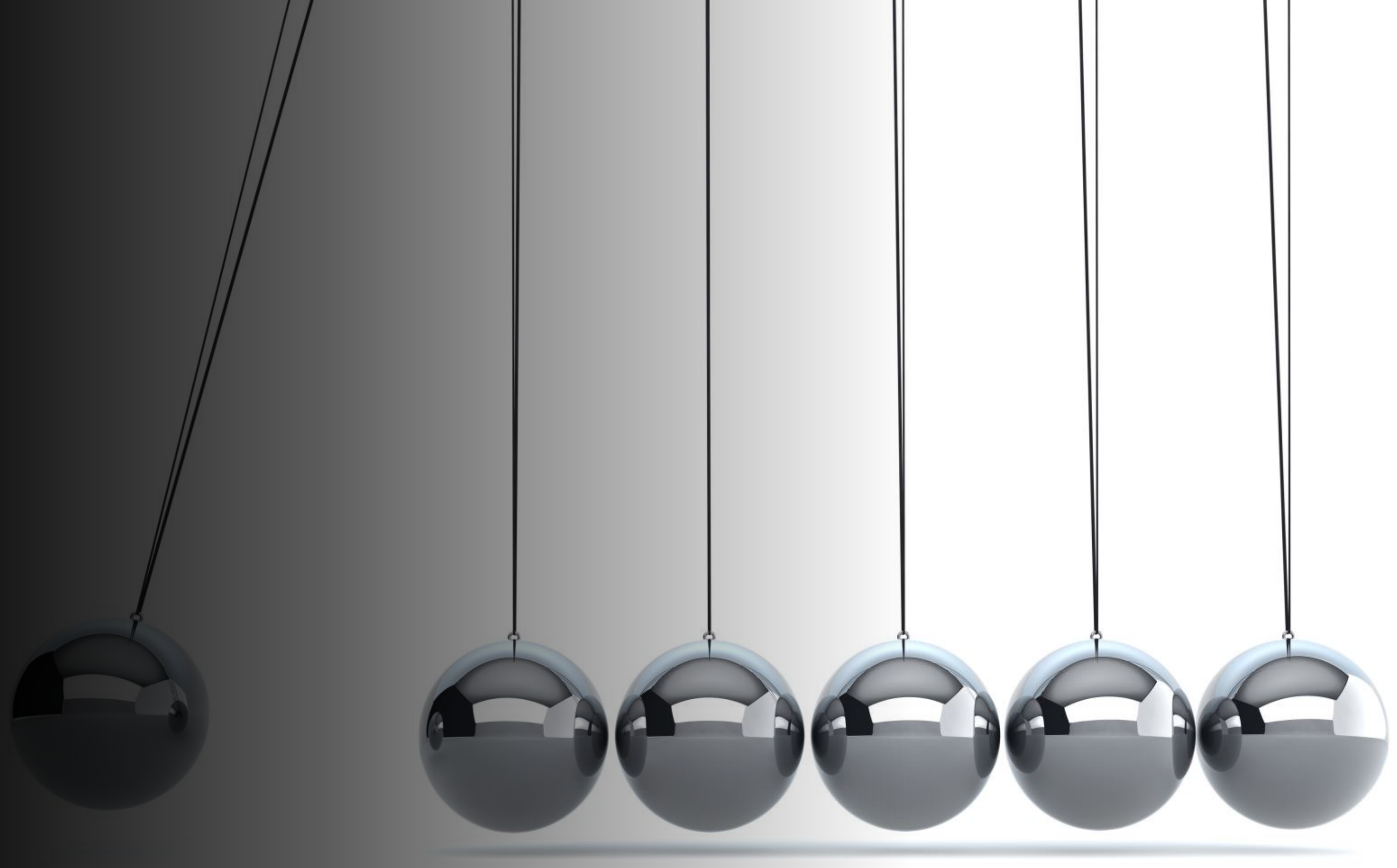


Mexico @ Belle II

- Cinvestav: 3+5
- Universidad Autónoma de Sinaloa: 2 + 1
- IF UNAM: 1+1

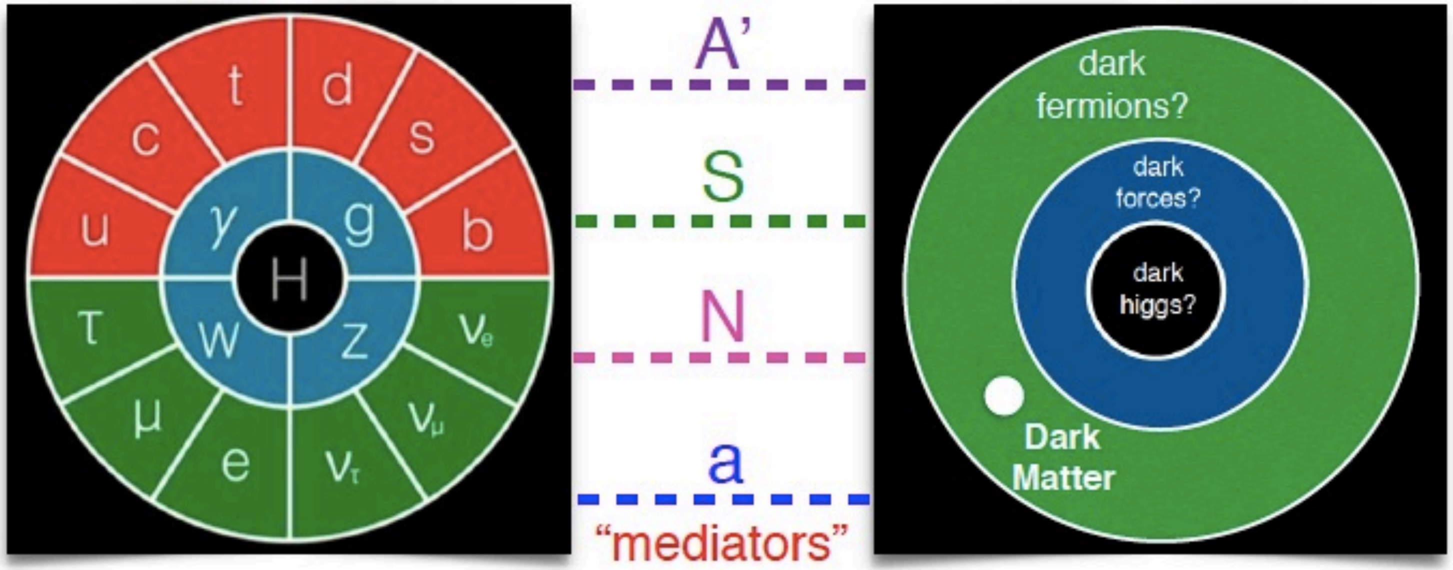
Mexico @ Belle II

Some first physics finding from Belle II



From a pre-Snowmass meeting

How to gain access to the dark sector?



Only a few interactions exist that are allowed by Standard Model symmetries:

"mediators"	"portal interactions"
Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

We will look at several examples of these mediators in early Belle II data including a special Z' and an axion. Prospects for a dark photon will be mentioned.

S.Gori

Dark Sector:

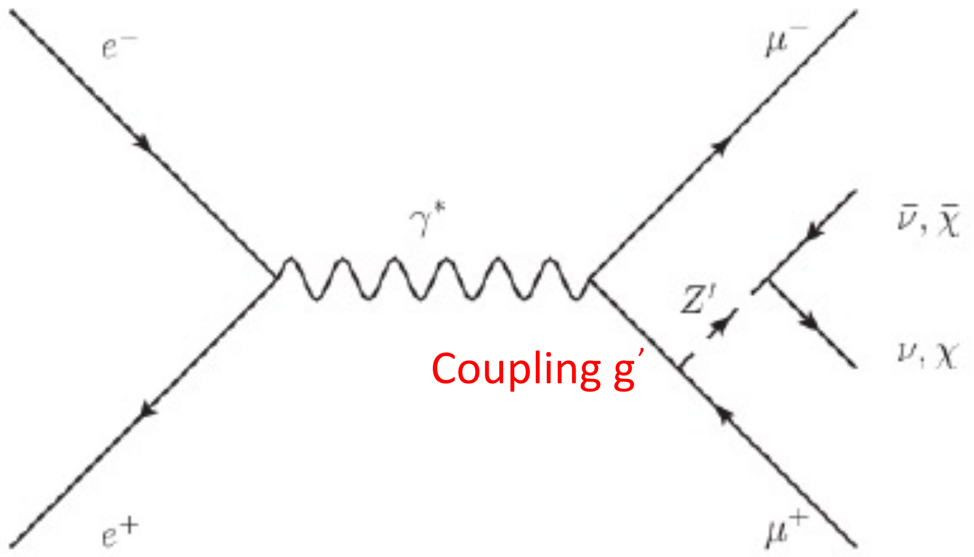
Previously limited by Triggering, QED backgrounds and theoretical imagination. *Now new possibilities of triggering, more bandwidth.*

There are a variety of possible dark sector portal particles: Vector, Scalar, Pseudo-scalars.

Belle II First Physics. A novel result on the dark sector (Z' →nothing) recoiling against di-muons *or* an electron-muon pair. *Both possibilities are poorly constrained at low Z' mass and in the first case, could explain the muon g-2 anomaly.*

They may decay to lepton pairs, photon pairs, or Invisible particles

Also examine a *lepton flavor violating* NP signature in the dark sector



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  - dark-sector searches
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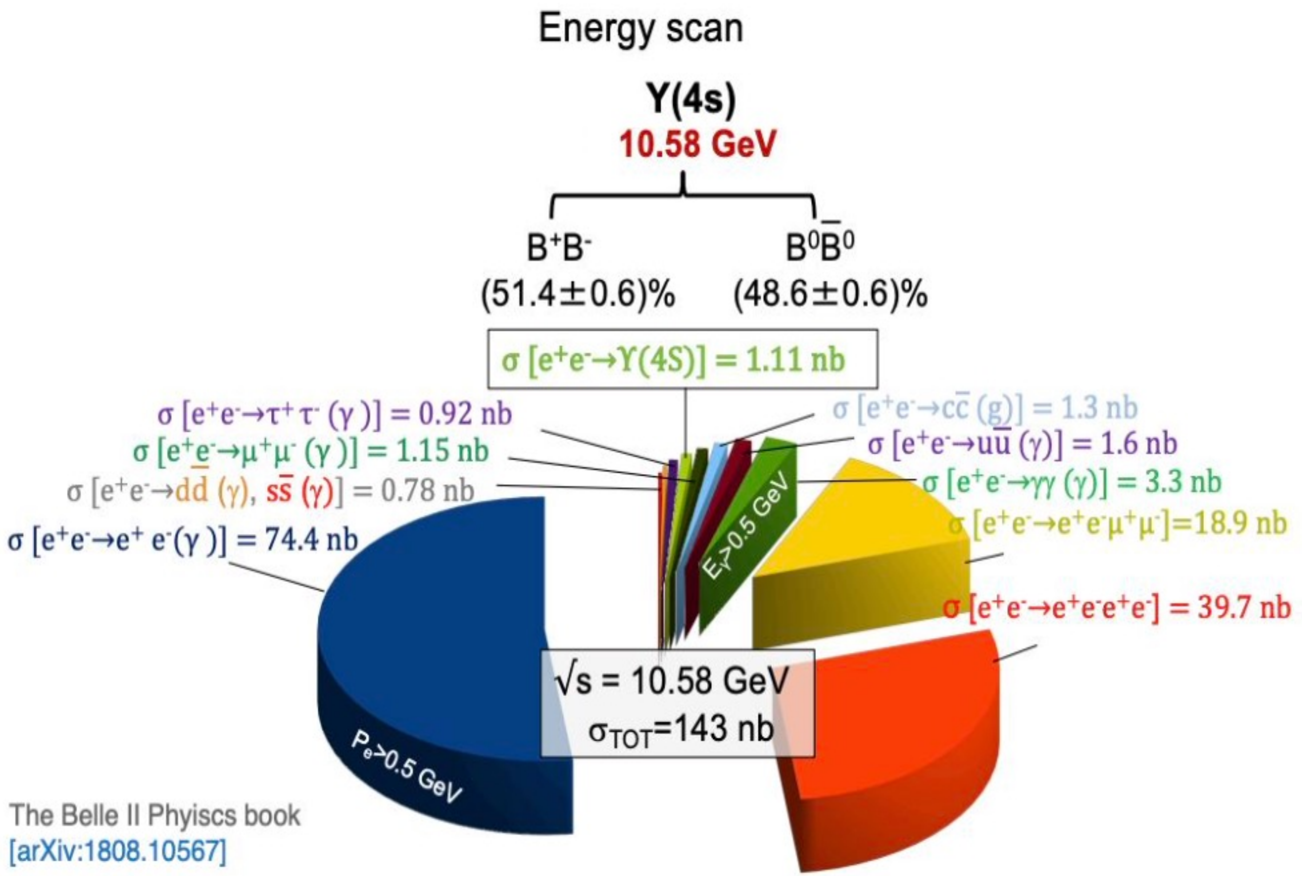
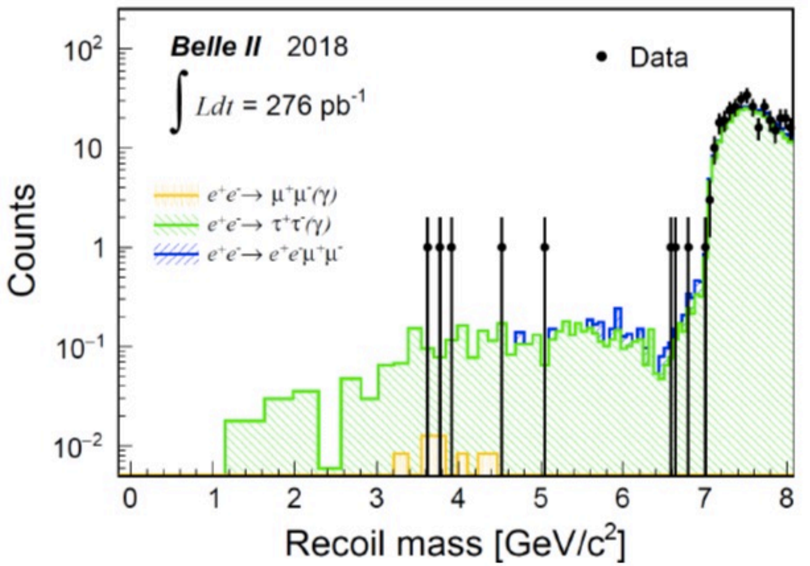
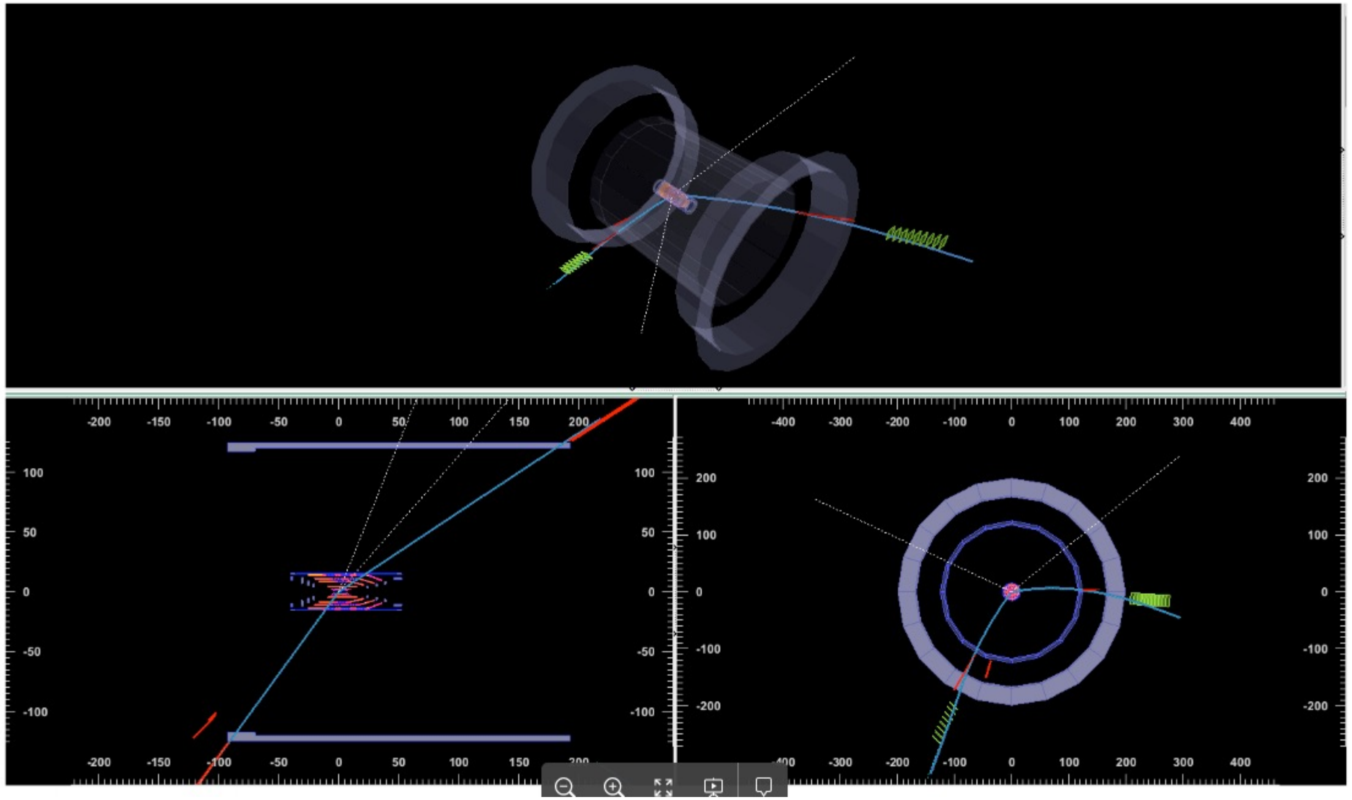


The Belle II Phyiscs book
[arXiv:1808.10567]

Monte Carlo simulation of a Z' →invisible event

- Bkg dominated by
- e^+e^- →τ+ τ- γ

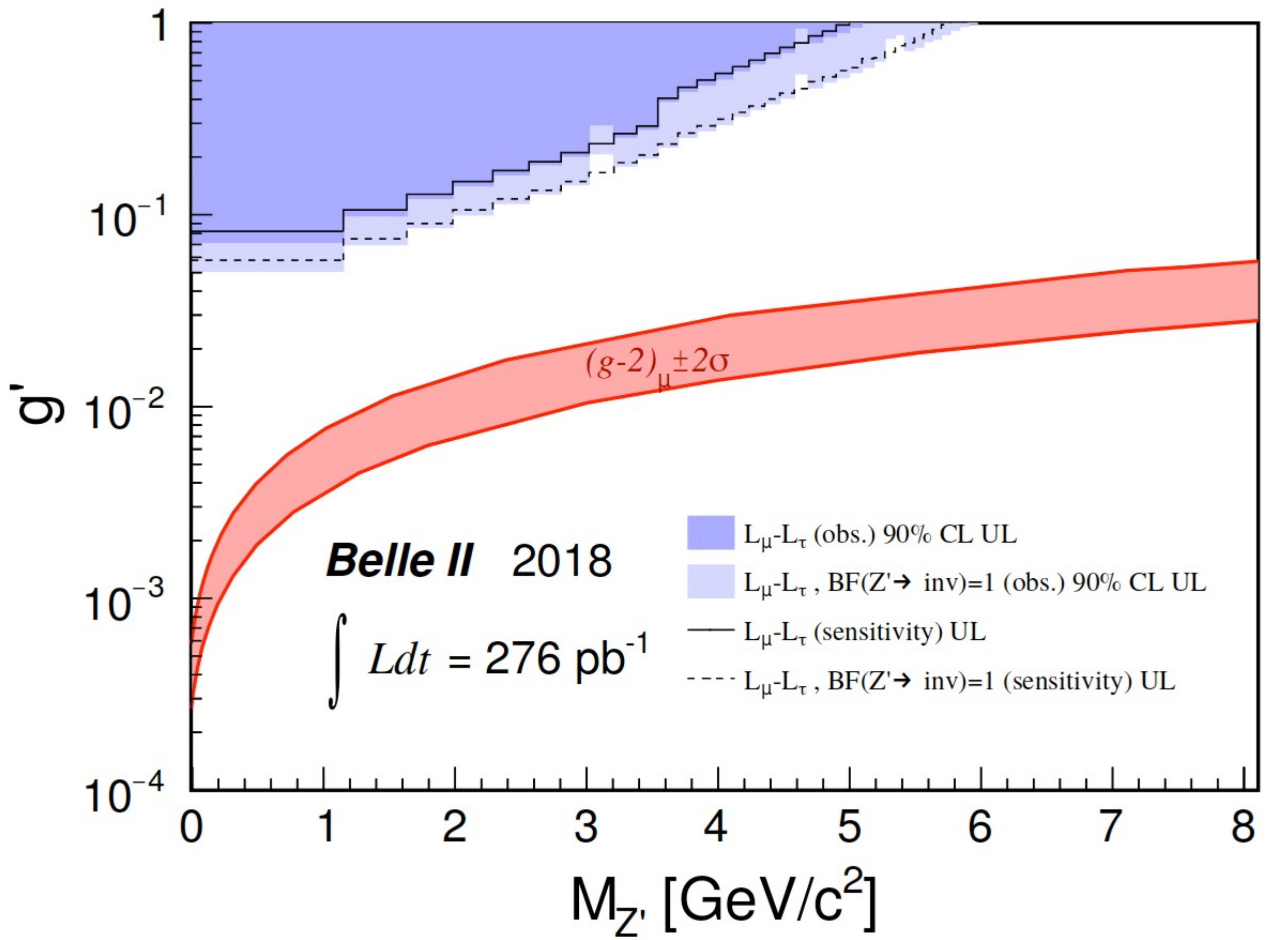




However, in data we do not find any excess in recoil mass.

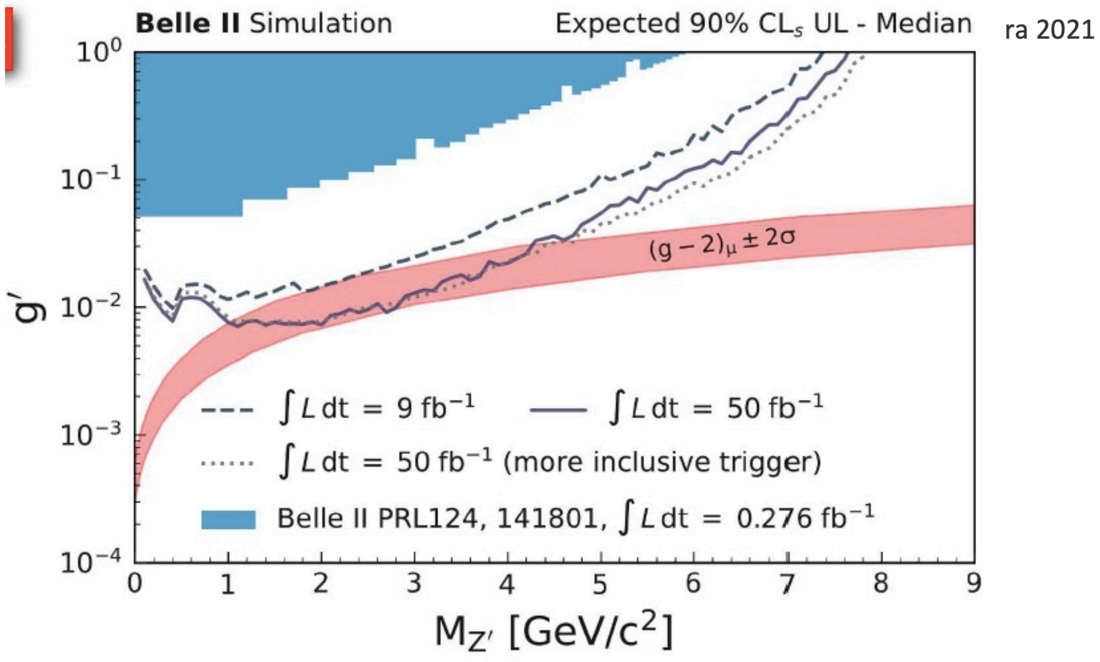
With 278 pb^{-1} from the Phase 2 "pilot run"

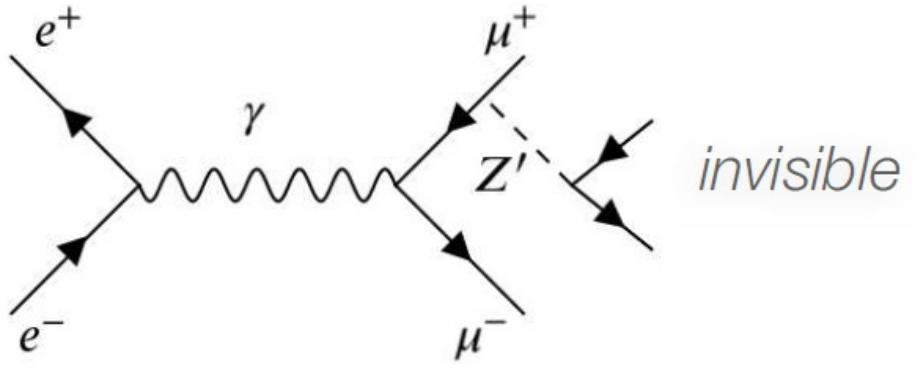
- I. Adachi et al. (Belle II Collaboration)
- Phys. Rev. Lett. 124, 141801 – PRL Editor's Choice



Near term prospects for Z' →invisible

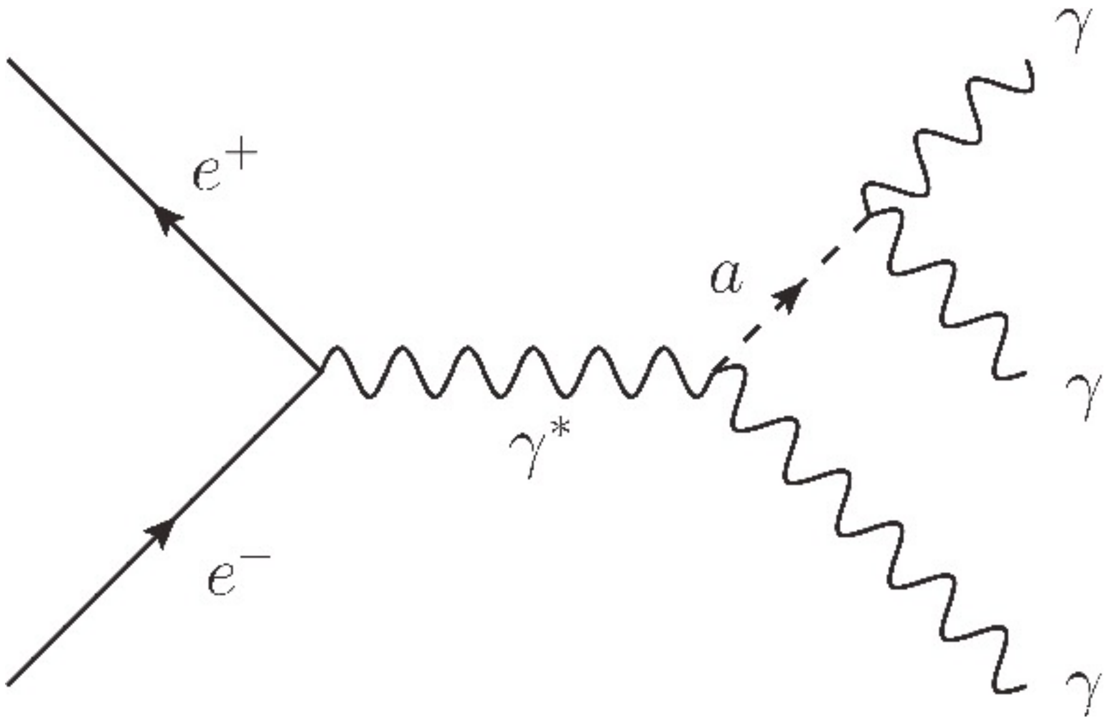
- Uses Phase 3 data on tape. Adding in KLM triggers may allow us to "break through" the g-2 band.



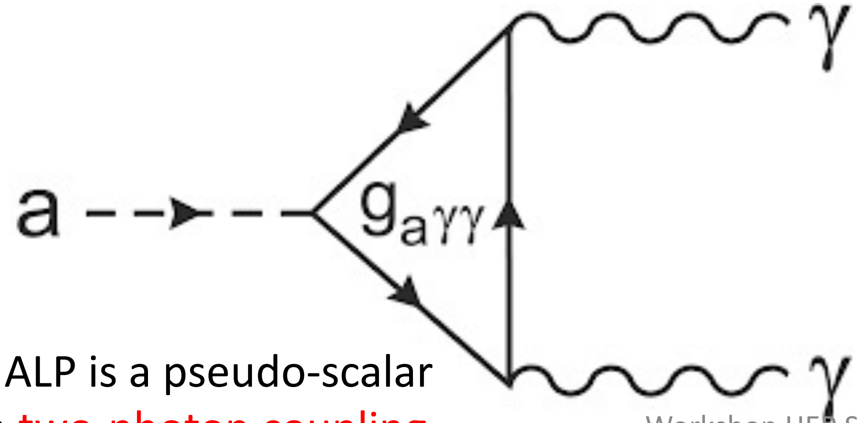


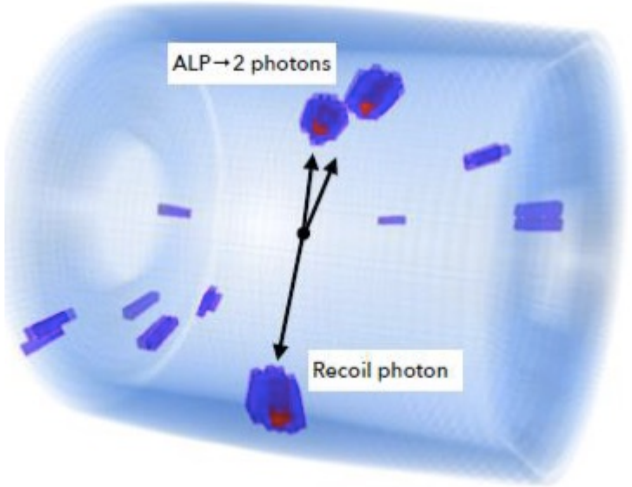
Search for ALPs (Axion Like Particles) at Belle II

An extra term was introduced in the QCD Lagrangian by Peccei, Quinn to solve the strong CP problem in 1977. Wilczek introduced a particle interpretation called the Axion. Expected to be very light (microeV or millieV).



Examine the three photon final state:





The ALP is a pseudo-scalar with two-photon coupling

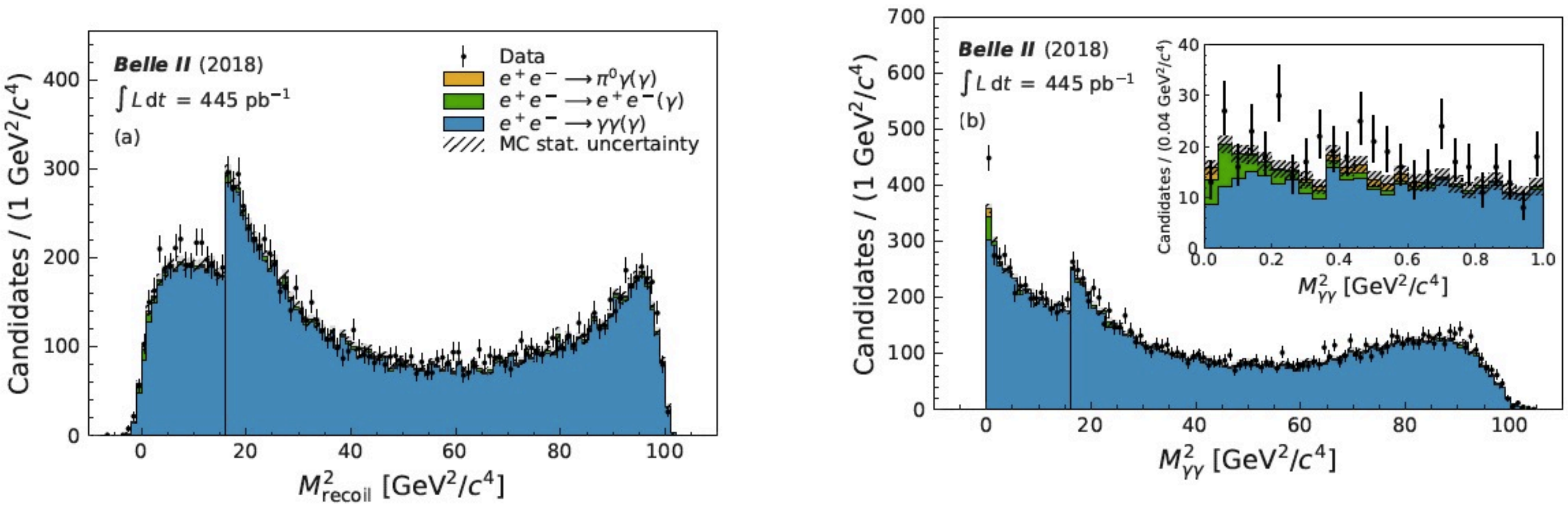


FIG. 1. $M^2_{\rm recoil}$ distribution (a) and $M^2_{\gamma\gamma}$ distribution (b) together with the stacked contributions from the different simulated SM background samples. For $M^2 \leq 16\ \mathrm{GeV}^2/c^4$, the selection is $E_\gamma > 1.0$ GeV; for $M^2 > 16\ \mathrm{GeV}^2/c^4$, it is $E_\gamma > 0.65$ GeV. Simulation is normalized to luminosity. The inset in (b) shows a zoom of the low-mass region $M^2_{\gamma\gamma} < 1\,\mathrm{GeV}^2/c^4$.

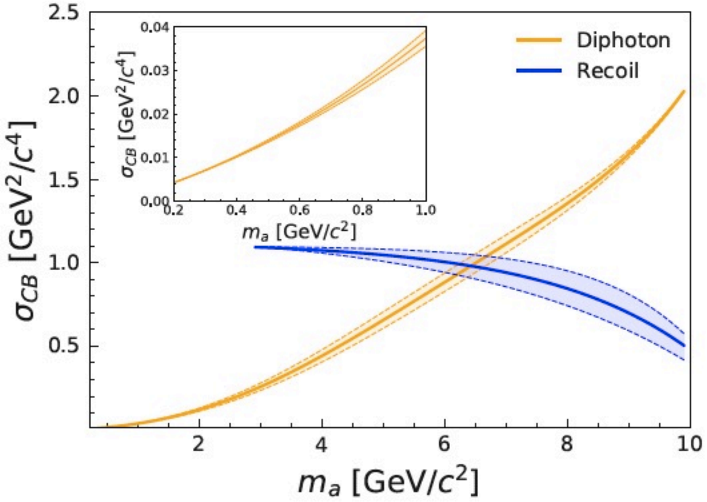
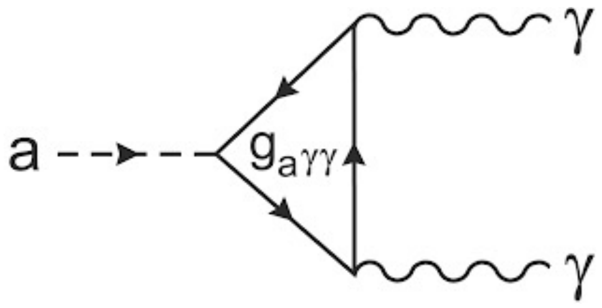


FIG. 2. $M^2_{\gamma\gamma}$ and $M^2_{\rm recoil}$ resolutions with uncertainty as a function of ALP mass m_a. The inset shows a zoom of the low-mass region $m_a < 1\,\mathrm{GeV}/c^2$.

$$e^+e^- \to \gamma a \to \gamma(\gamma\gamma)$$

We fit M(γγ)^2 in bins at low mass and M(recoil)^2 at high mass. No significant excess is found.

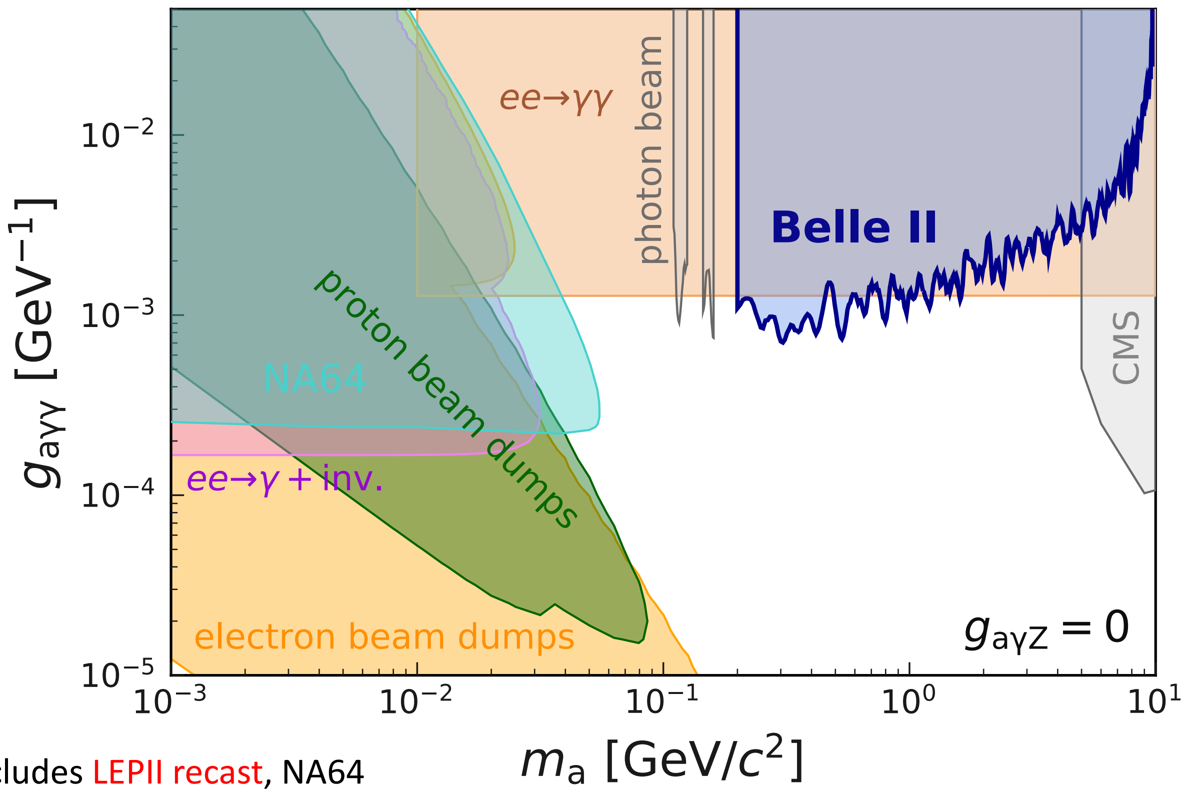
The Belle II mass range is *200 MeV to 9.7 GeV*, *far above* the keV mass range suggested by the Xenon1T excess. https://arxiv.org/abs/2006.09721



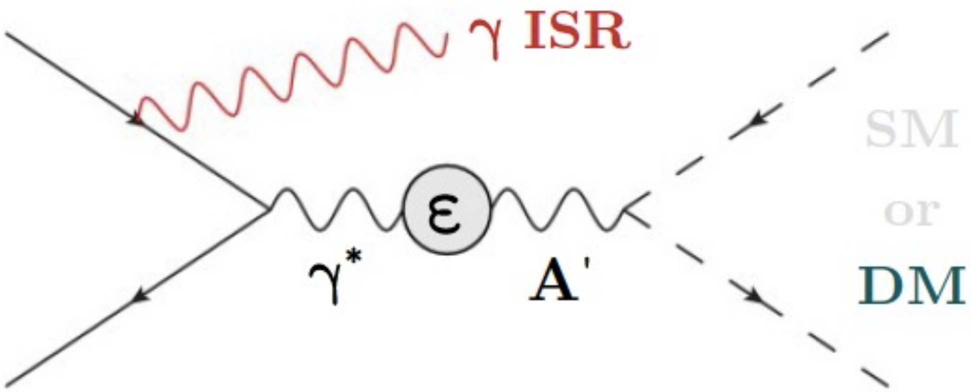
F. Abudinén *et al.* (Belle II Collaboration)
Phys. Rev. Lett. 125, 161806 (2020)

Final ALPS results with 445 pb^{-1} of pilot run (Phase 2) data

Plan to update with two orders of magnitude more data→one order of magnitude improvement in g



Revised plot includes LEPII recast, NA64

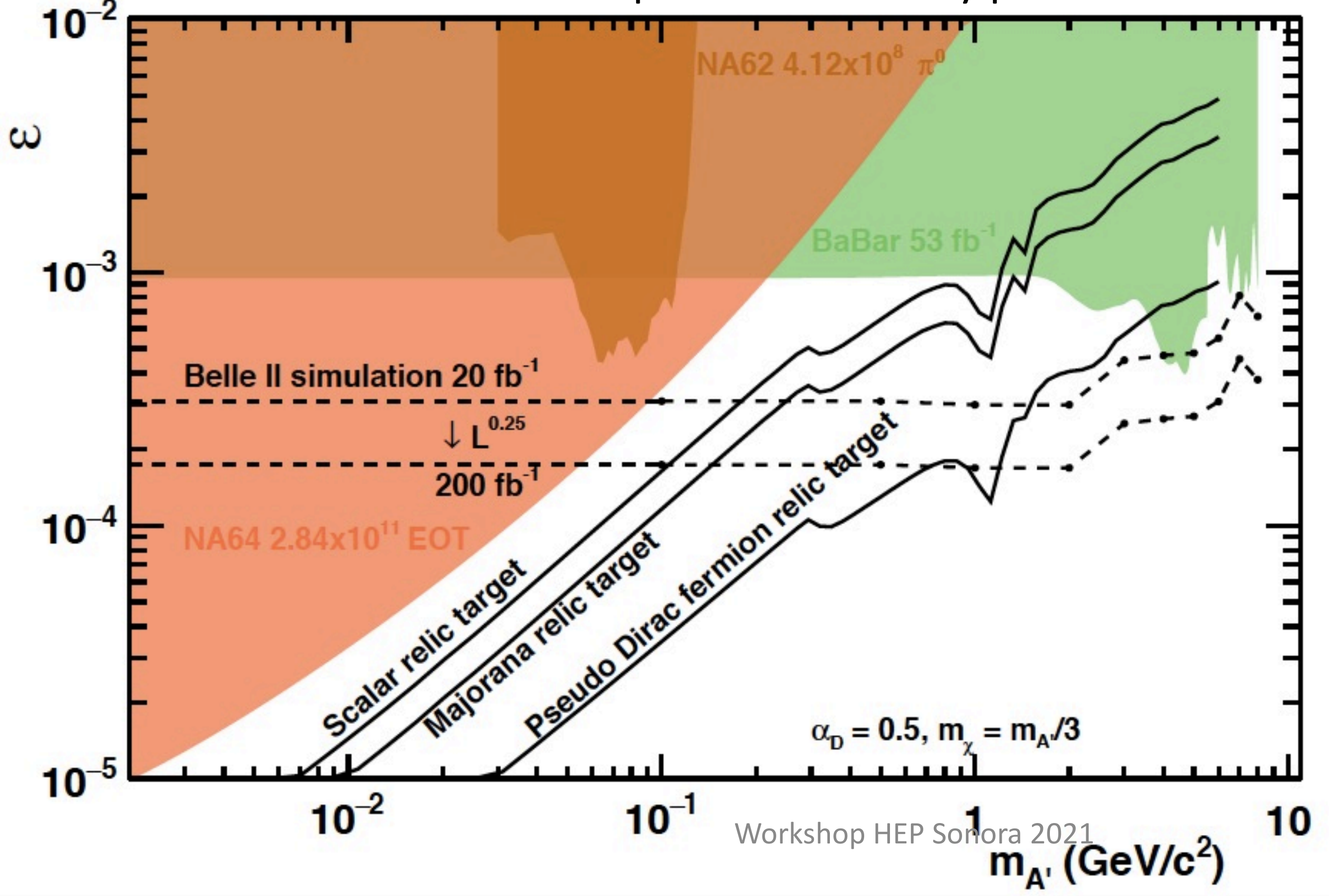


Sensitivity for the "dark photon" with the signature: e+e- → γ + nothing

- a bump in the recoil mass:

$$E_\gamma = \frac{s - m_{A'}^2}{2\sqrt{s}}$$

Latest dark photon sensitivity plot



This is the most difficult dark sector signature (in progress).

Belle II physics by Mexican groups

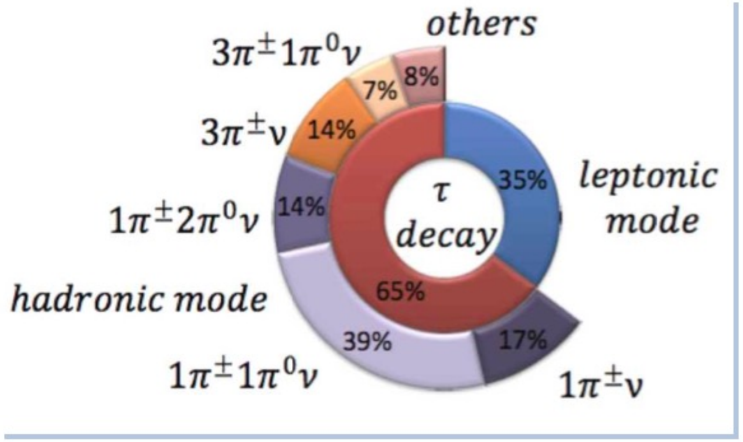
- Tau physics
- Exotics
- Rare decays

Mexican measurements involvement

- Tau lepton mass
- LFV tau to lepton + boson
- LFV tau to 3leptons
- LFV tau to mu gamma

τ -Physics at Belle II

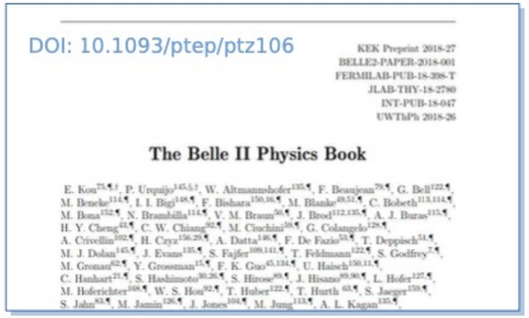
- Why τ ***physics***?
  - Large production cs: $\sigma(e^+e^- \to \tau^+\tau^-)$ = 0.9 nb (τ –factory)
  - The τ is the only lepton massive enough to decay into hadrons:
    - Leptonic decays: BR ~ 35%
    - Hadronic decays: BR ~ 65%



- τ **physics** program
  Rich program of precision SM measurements and new physics searches @ Belle II

Some ongoing physics analyses @ Belle II:

- Precision SM measurements / Indirect NP searches (deviations from the SM)
  - Mass
  - Lifetime
  - Lepton universality in $\tau \to l\nu\nu$ decays
  - τ EDM and MDM
  - $\tau \to ee e\nu\nu$
  - CP violation $\tau \to K_S\pi\nu$
- Direct NP searches (forbidden / strongly suppressed decays)
  - $\tau \to l\,\alpha$
  - $\tau \to l\,\phi$
  - $\tau \to l\,\gamma$
  - $\tau \to \mu\mu\mu$
  - $\tau \to l\pi^0$
  - $\tau \to lhh$


DOI: 10.1093/ptep/ptz106

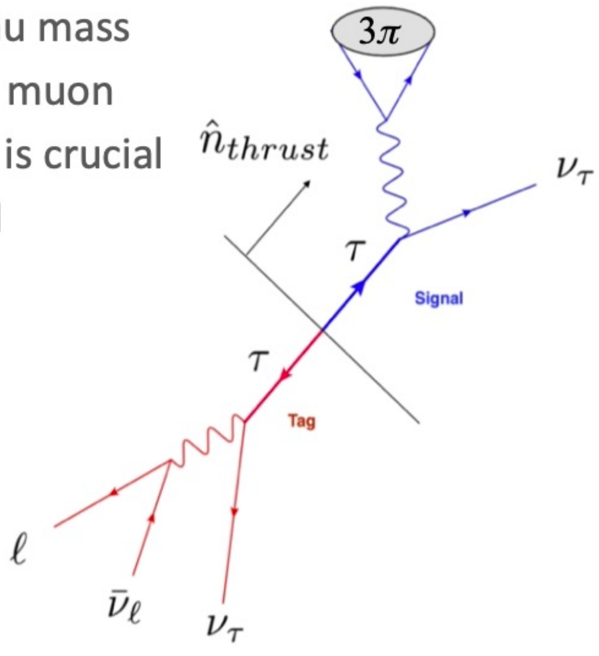
KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

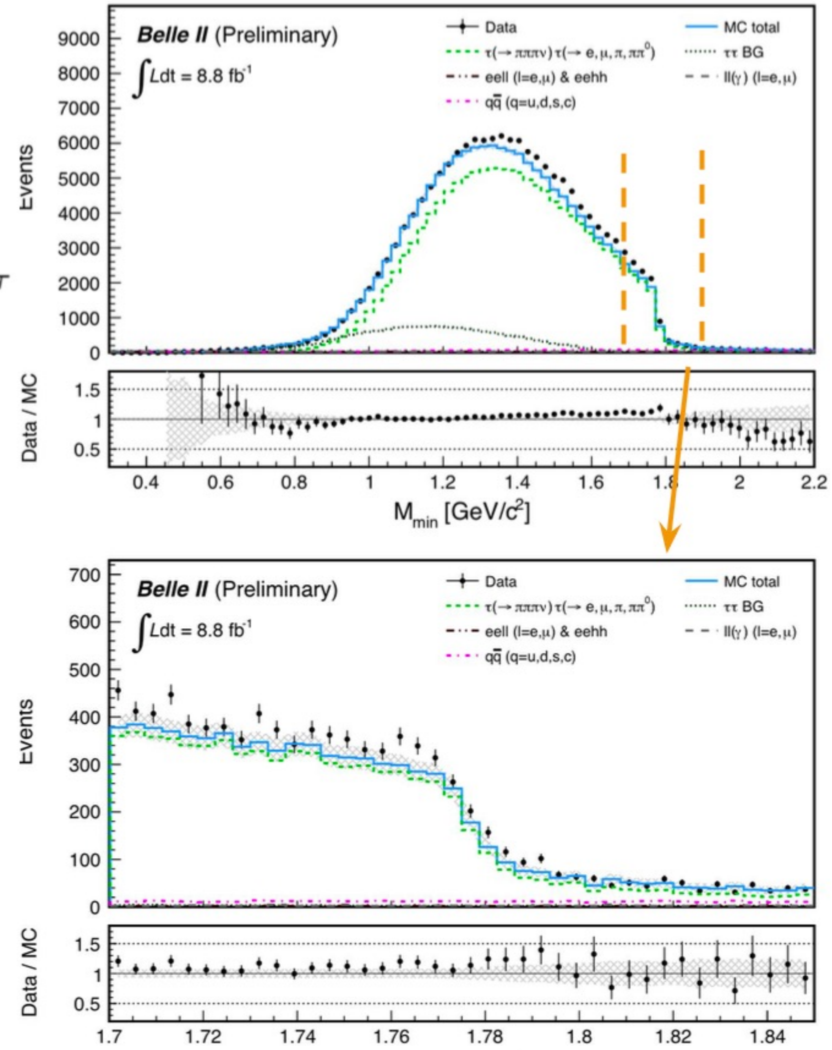
The Belle II Physics Book

Tau lepton mass measurement:

- **Motivation:**
  - ~10^3 worse relative precision in tau mass compared to that of electron and muon
  - A precise tau mass measurement is crucial for lepton universality tests of SM
- **Topology:**
  - 3x1 decays of the τ are used
  - signal: $\tau^- \to \pi^+\pi^-\pi^+\nu_\tau$
  - tag: $\tau^- \to \ell\nu_\ell\nu_\tau,\ \pi^-\nu_\tau,\ \pi^-\pi^0\nu_\tau$
- **Pseudomass variable (M_{min}) :**
  - calculated from 4-momentum of the 3π system
  - kinematic edge exploited to extract the mass:

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau$$



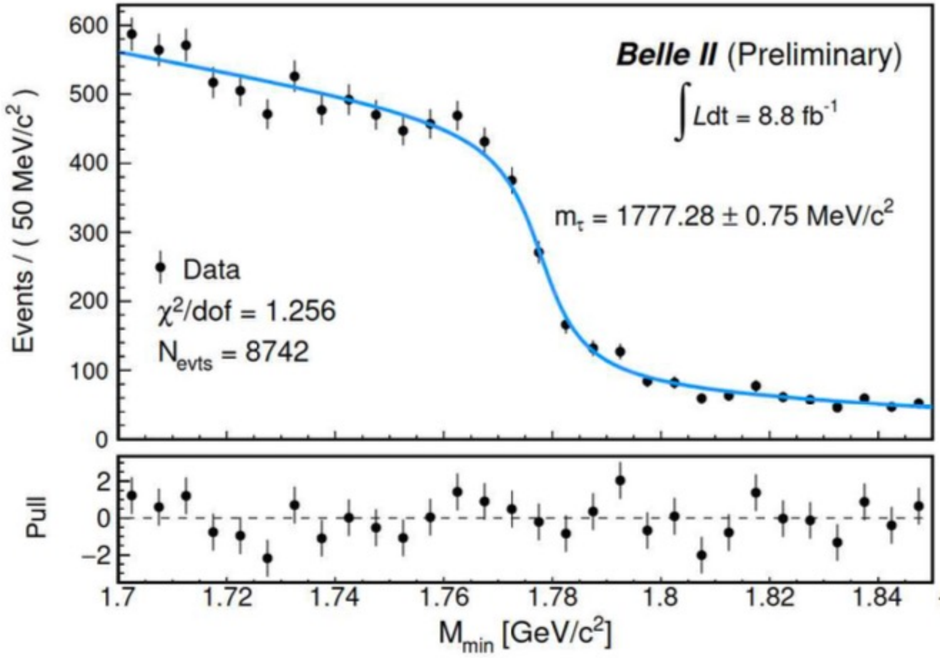


Tau lepton mass measurement

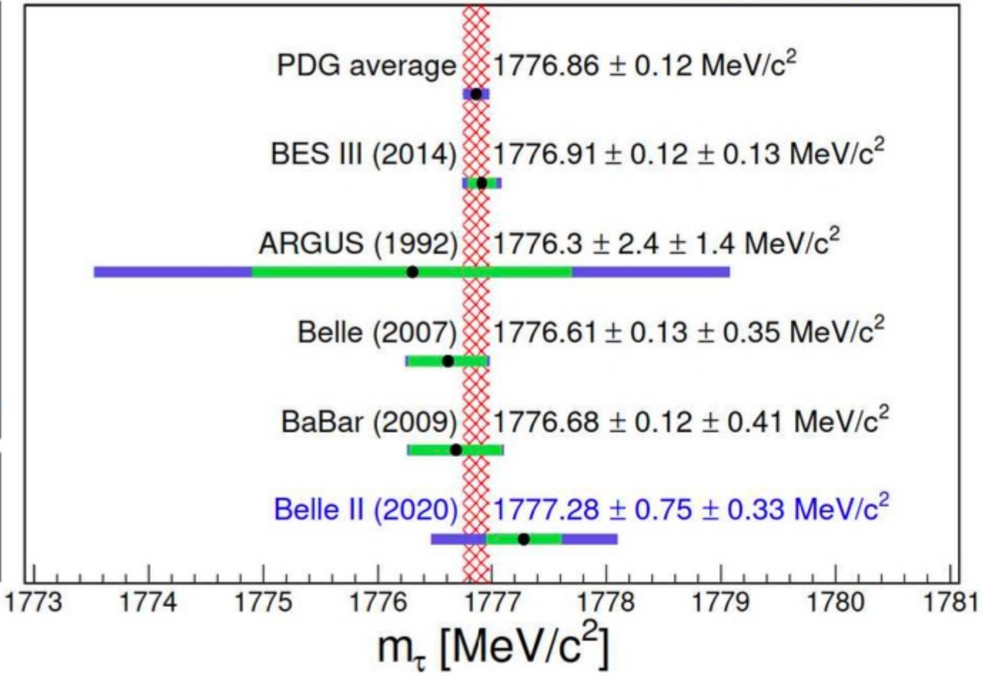
- An empirical p.d.f. is used to estimate the τ lepton mass, m_τ:

$$F(M,\vec{P}) = (P_3 + P_4 \cdot M) \cdot \tan^{-1}[(M - P_1)/P_2] + P_5 \cdot M + 1$$

- P_1 is the estimator of the τ lepton mass.



arXiv:2008.04665



$m_\tau = 1777.28 \pm 0.75_{stat} \pm 0.33_{sys}$ MeV/c²

- Consistent with previous measurements!
- Belle II has similar systematic error as Belle

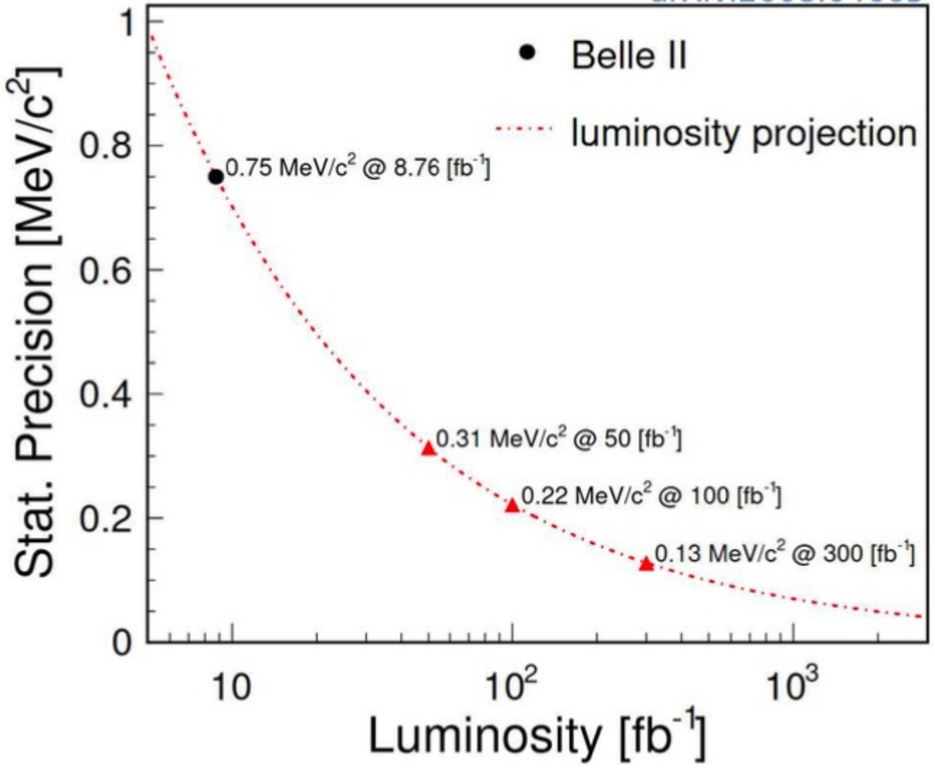
Tau lepton mass measurement

- Dominant systematic uncertainty due to the track momentum scale, but it is expected to be reduced

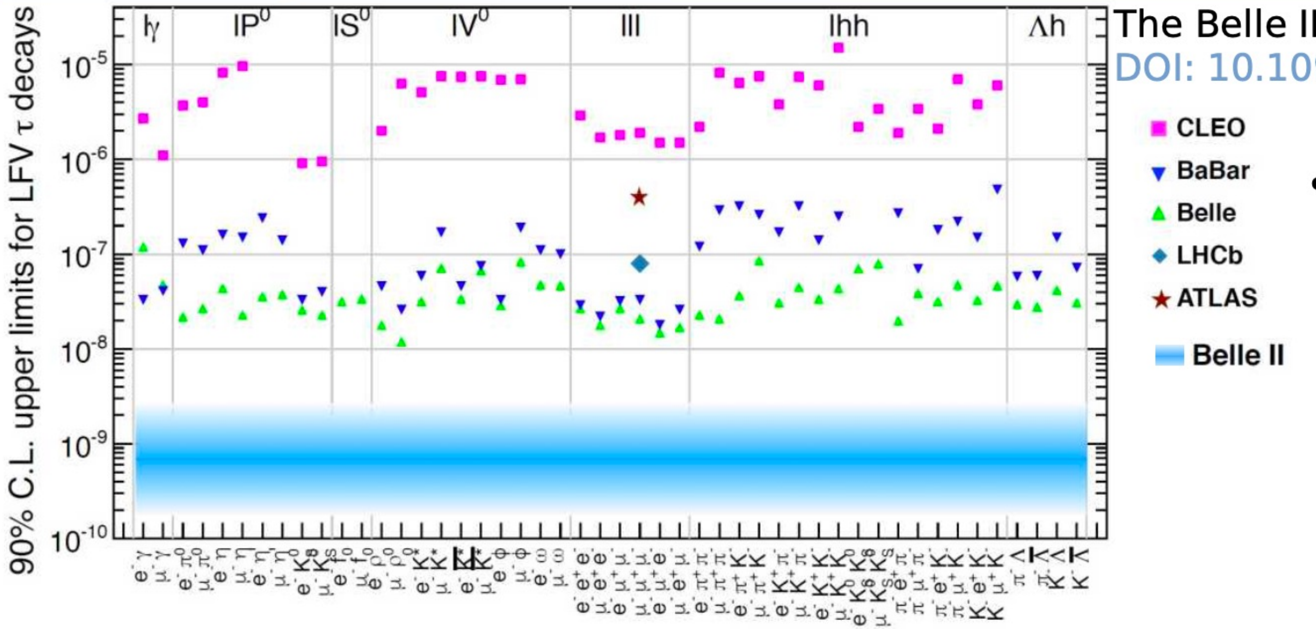
Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

- A scenario with a total systematic uncertainty reduced is expected in the near future

arXiv:2008.04665



- With the present level of systematic uncertainties, this measurement is expected to be statistically dominated until around 50 fb^{-1} of data.
- With around 300 fb^{-1} of data, systematic uncertainties would dominate the measurement.



The Belle II Physics Book,
DOI: 10.1093/ptep/ptz106

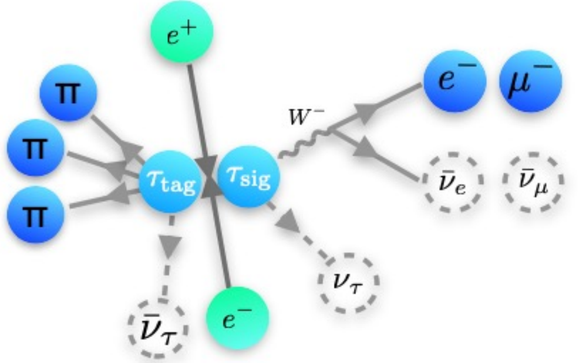
- Thanks to the large mass of the τ, we have an extensive variety of decay modes to explore

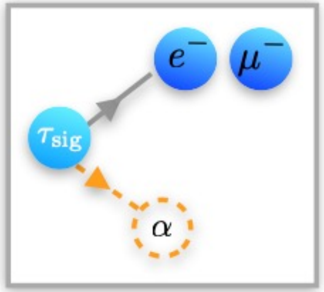
- LFV decays of the τ are strongly suppressed in the SM
  Br ~ $O(10^{-54})$
- Many NP models predict LFV decays of the τ at a measurable rate
  Br ~ $O(10^{-10})$ - $O(10^{-7})$
- Any observation of LFV is a clear indication of NP

- Golden channels:
  - $\tau \to \mu\mu\mu$
  - $\tau \to \mu\gamma$

  Work in progress
- Belle II is expected to push the current bounds further by more than one order of magnitude.

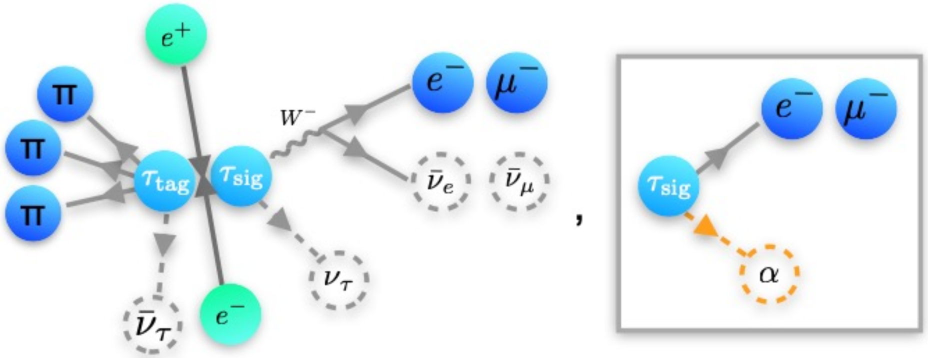
LFV decay $\tau \to \ell + \alpha$(invisible)



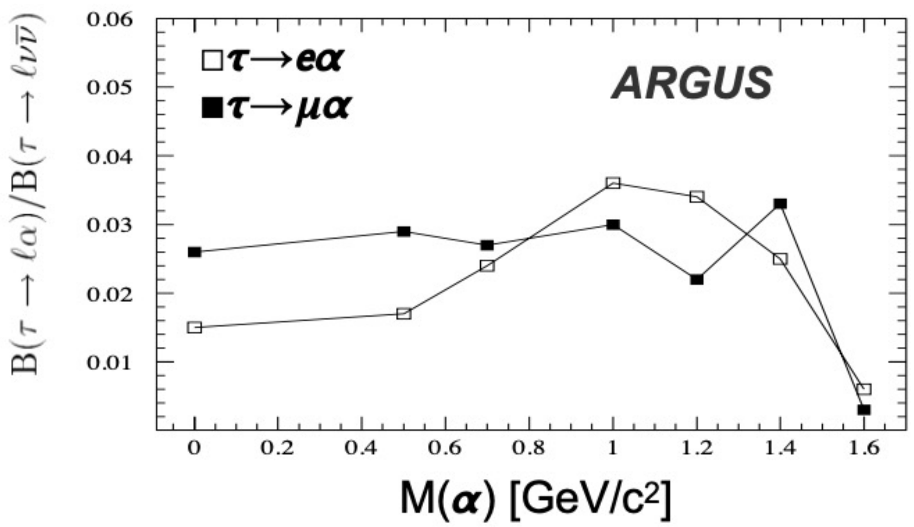


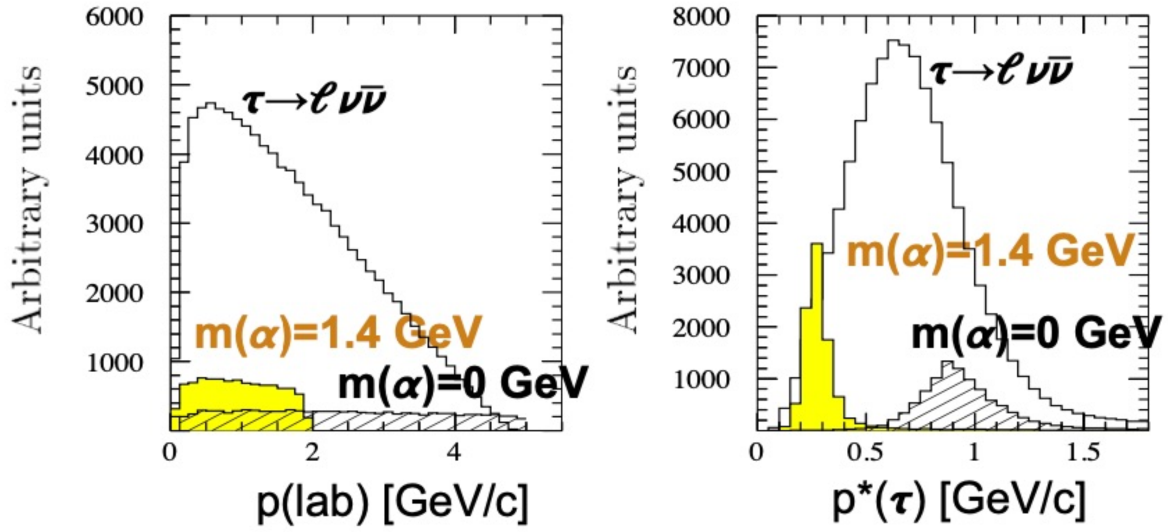
- Search for the two body decay $\boldsymbol{\tau \to e/\mu + \alpha}$ where $\boldsymbol{\alpha}$ is an unobserved particle (missing energy).
- LFV process which is not present in the SM but appears in several NP models e.g. as a Goldstone boson.
- Model independent search - minimal assumptions are made on the nature of $\boldsymbol{\alpha}$.
- We present preliminary MC studies and provide UL(95% CL) projections for the $\boldsymbol{\tau \to e\alpha}$ channel measurement at Belle II.

Previous Searches



- **Mark III (1985, 9.4 pb^{-1})**
- **ARGUS (1995, 476 pb^{-1})**
- Here the lepton momentum is studied in the τ rest frame, where it manifests as a peak against the SM $\tau \to \ell\nu\nu$ background.

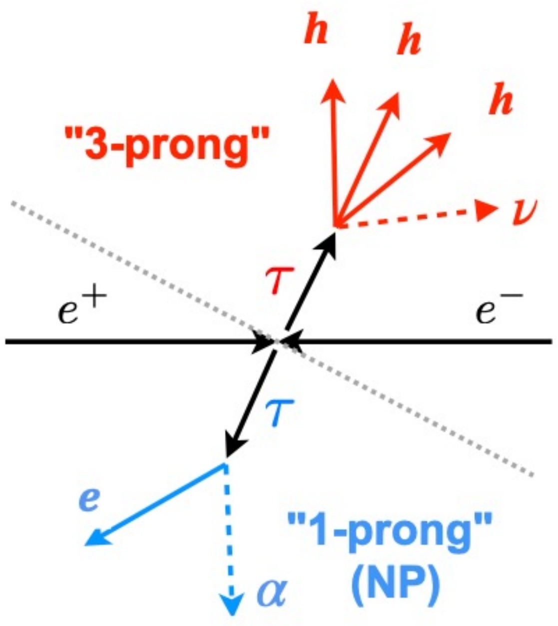


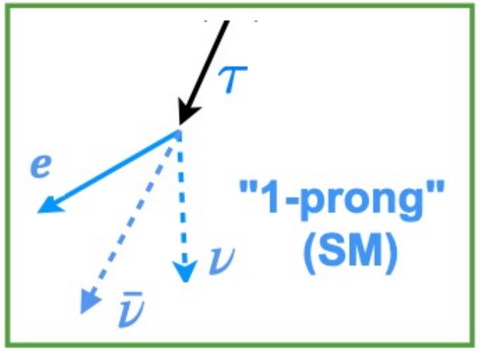


Z.Phys. C68 (1995) 25-28

Event Reconstruction

- 3x1-prong decay: $\tau \rightarrow e\alpha$ **(signal)** , $\tau \rightarrow 3\pi\nu$ **(tag)**
  - Exactly 4 good tracks required.
  - Hemisphere separation using thrust vector $\vec{T} = max\left(\sum_i \frac{\vec{p_i} \cdot \hat{T}}{|p_i|}\right)$
- Dominant background: SM $\tau \rightarrow e\nu\nu$ **(irreducible)**
  - Since we don't know **M(α)** we optimise for the SM.
- Other BG: $\tau\tau$ (non-3x1), BBbar, qqbar, ee(γ), μμ(γ), ee$\ell\ell$, beam
- Initially rejected by:
  - **Vertex fit** of the 3-prong tag (reject displaced vertices).
  - **Veto** neutral pions and gamma (qqbar, beam bg).





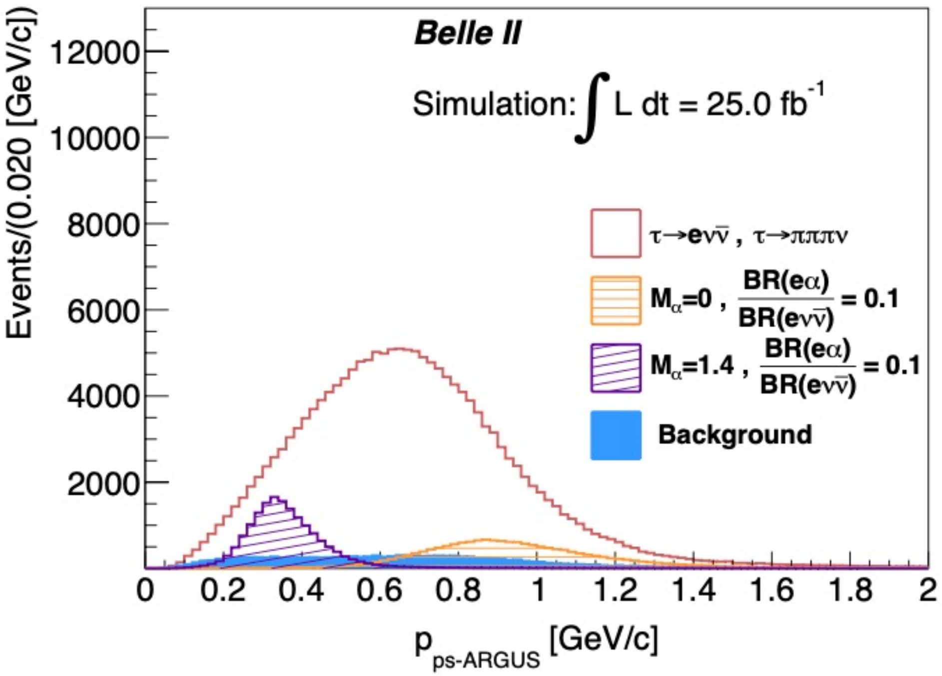
Tracks
-3< dz<3 cm
dr < 1 cm

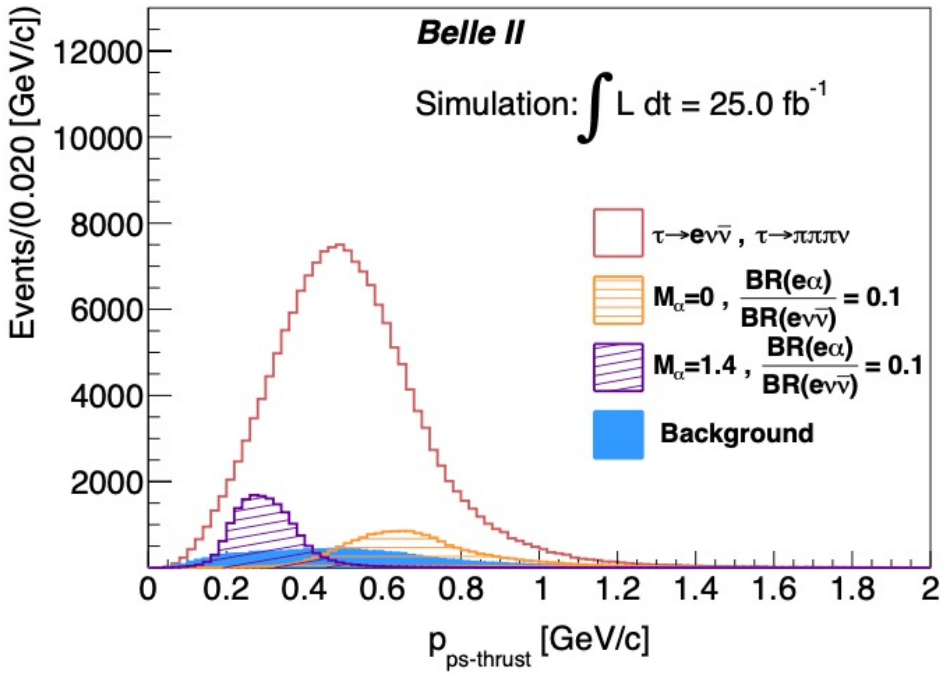
PID
e: E/p > 0.8
π: E/p < 0.8

Photons
Within tracking acceptance and
E(γ) > 100 MeV
115<M(γγ)<152 MeV
or
E(γ)>200 MeV

Spectrum in the Pseudo-Rest Frame

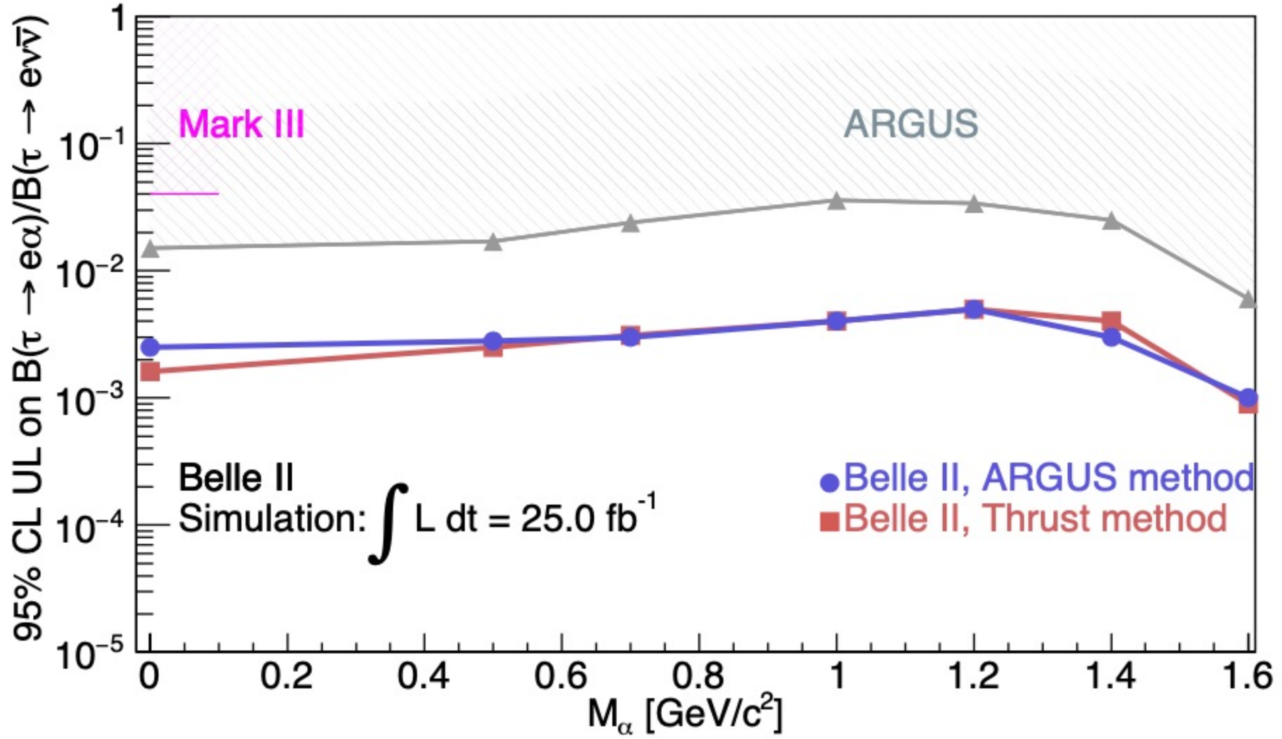
- In the signal $\boldsymbol{\tau}$ rest frame, the **e** momentum for $\boldsymbol{\tau} \rightarrow \mathbf{e}\boldsymbol{\alpha}$ will be a monoenergetic peak; the boost to the $\boldsymbol{\tau}$ frame is unknown, so we approximate:
- $E_\tau = \sqrt{s}/2$
- ARGUS method: $\hat{p}_\tau \approx -\hat{p}_{3\pi}$
- Thrust method: $\hat{p}_\tau \approx \hat{T}$





Previous Measurements and MC Estimations

- UL is provided for the ratio $Br(\tau \rightarrow e\alpha)/Br(\tau \rightarrow e\nu\nu)$



	UL(95% c.l.)		
$M(\alpha)$ [GeV/c^2]	ARGUS (1995)	Argus method	Thrust method
0	0.015	0.0025	0.0016
0.5	0.017	0.0028	0.0025
0.7	0.024	0.003	0.0031
1.0	0.036	0.004	0.004
1.2	0.034	0.005	0.005
1.4	0.025	0.003	0.004
1.6	0.006	0.001	0.0009

BELLE2-NOTE-PL-2020-018

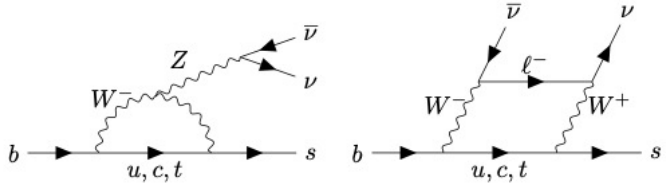
- No systematics effects are taken into account at this stage.

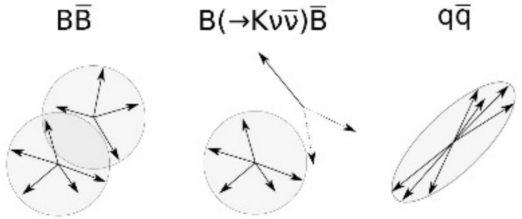
Many other things going on in Belle II

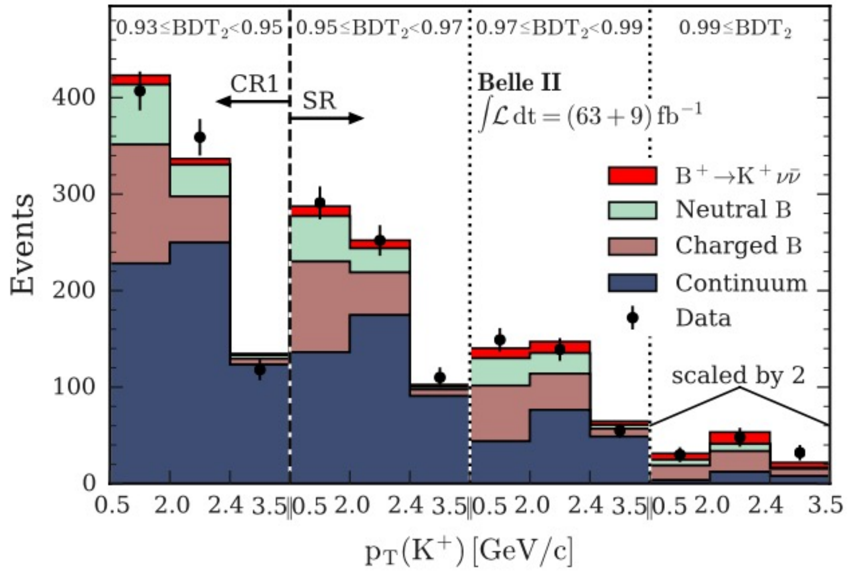
Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$

Belle II

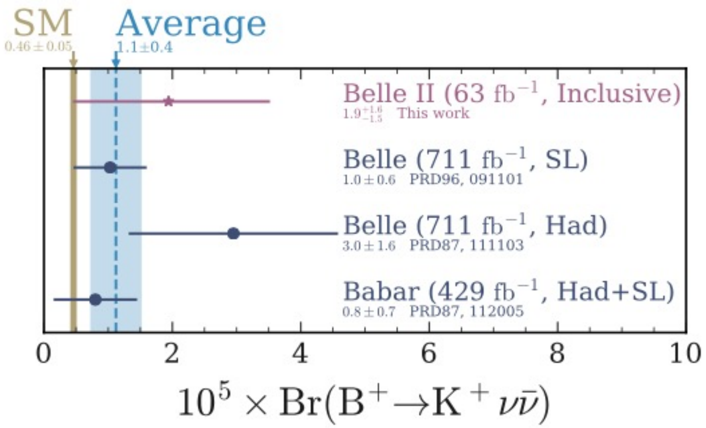
arXiv: 2104.12624, submitted to PRL





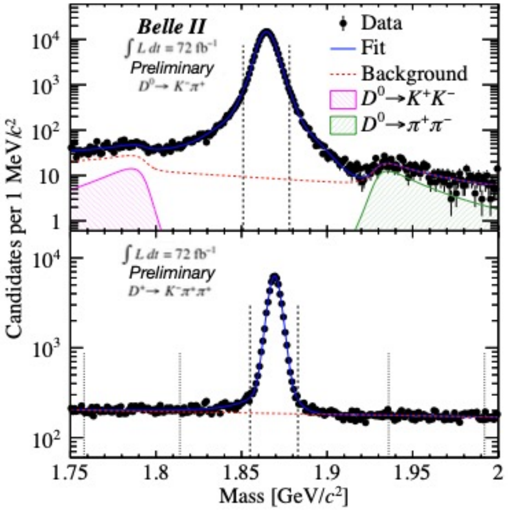


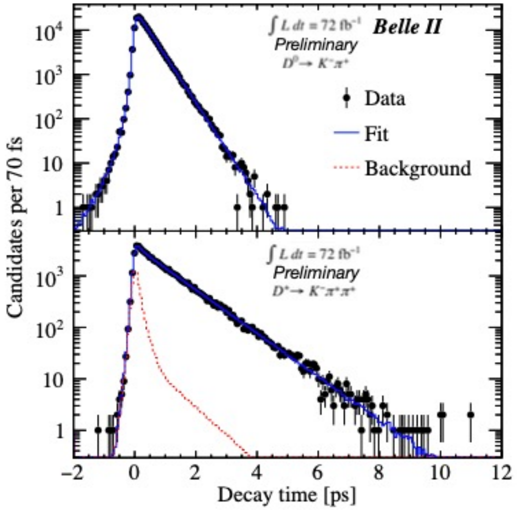
- Flavour-Changing Neutral Current process that has not yet been observed
  - no photon contribution → much cleaner theoretical prediction $\mathscr{B}(B^{\pm} \to K^{\pm}\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$
- Previous searches based on tagged analyses
  - semi-leptonic tag: $\varepsilon_{sig} \sim 0.2\%$ (Belle)
  - hadronic tag: $\varepsilon_{sig} \sim 0.04\%$ (BaBar)
- New approach by Belle II based on an inclusive tag
  - no explicit reconstruction of the second B-meson
  - use BDTs to exploit distinctive topological features of $B^{\pm} \to K^{\pm}\nu\bar{\nu}$
  - much higher efficiency of $\varepsilon_{sig} \sim 4.3\%$ resulting in increased sensitivity per luminosity
- Further improvements are underway
  - more data (already have 3x more on tape)
  - additional channels ($B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K^0_S\nu\bar{\nu}$, …)
  - improved/extended classifiers (neural networks)
- Events of different tagging methods are statistically independent and can be combined



D^0 and D^+ Lifetime Measurements

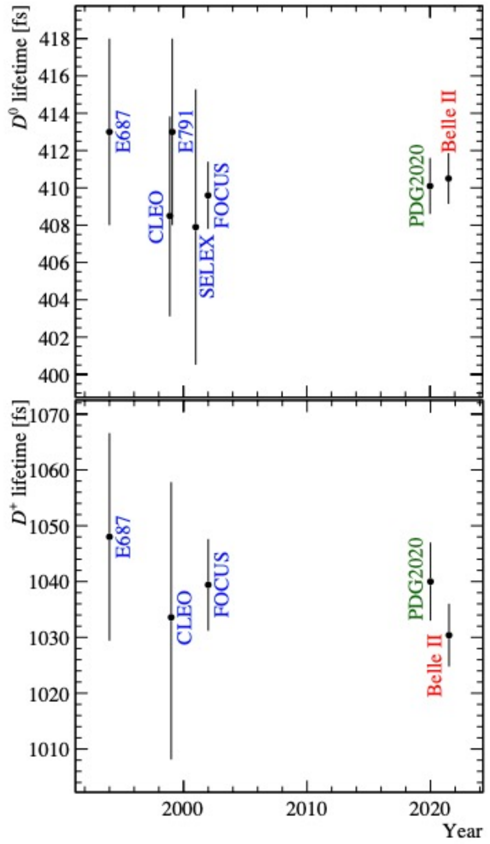
to be submitted to PRL





Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Statistical	1.1	4.7
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total systematic	0.8	3.1

	Belle II	World average
$\tau(D^0)$	$(410.5 \pm 1.1 \pm 0.8)$ fs	(410.1 ± 1.5) fs
$\tau(D^+)$	$(1030.4 \pm 4.7 \pm 3.1)$ fs	(1040 ± 7) fs



- Select high-purity samples of D^*-tagged $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays
- Fit the distribution of the decay time with accurate modelling of the resolution
  - dominant systematic uncertainties come from residual mis-alignment (D^0) and from background modelling (D^+)
  - results not yet limited by systematics
- Preliminary results consistent with, and more precise than, respective world averages
- Demonstration of excellent vertexing capabilities of Belle II

Remarks

- Belle II is working well and is now producing physics. SuperKEKB has broken the world-luminosity record and is now a "Super B Factory".
- *World-leading results already on the dark sector* (Search for Z'→invisible and ALPs PRL's)
- A number of b→s processes have hints of NP. (New: pay attention to B→K ν νbar, Belle II has demonstrated improved sensitivity). Along with B→$D^{(*)}$ τ ν, these will be studied in detail at Belle II in the coming years.
- *A decade-long program of discoveries ahead*. Belle II is fully engaged in the rare and precision and dark sector frontiers, and instrumentation, computing and accelerator frontiers.