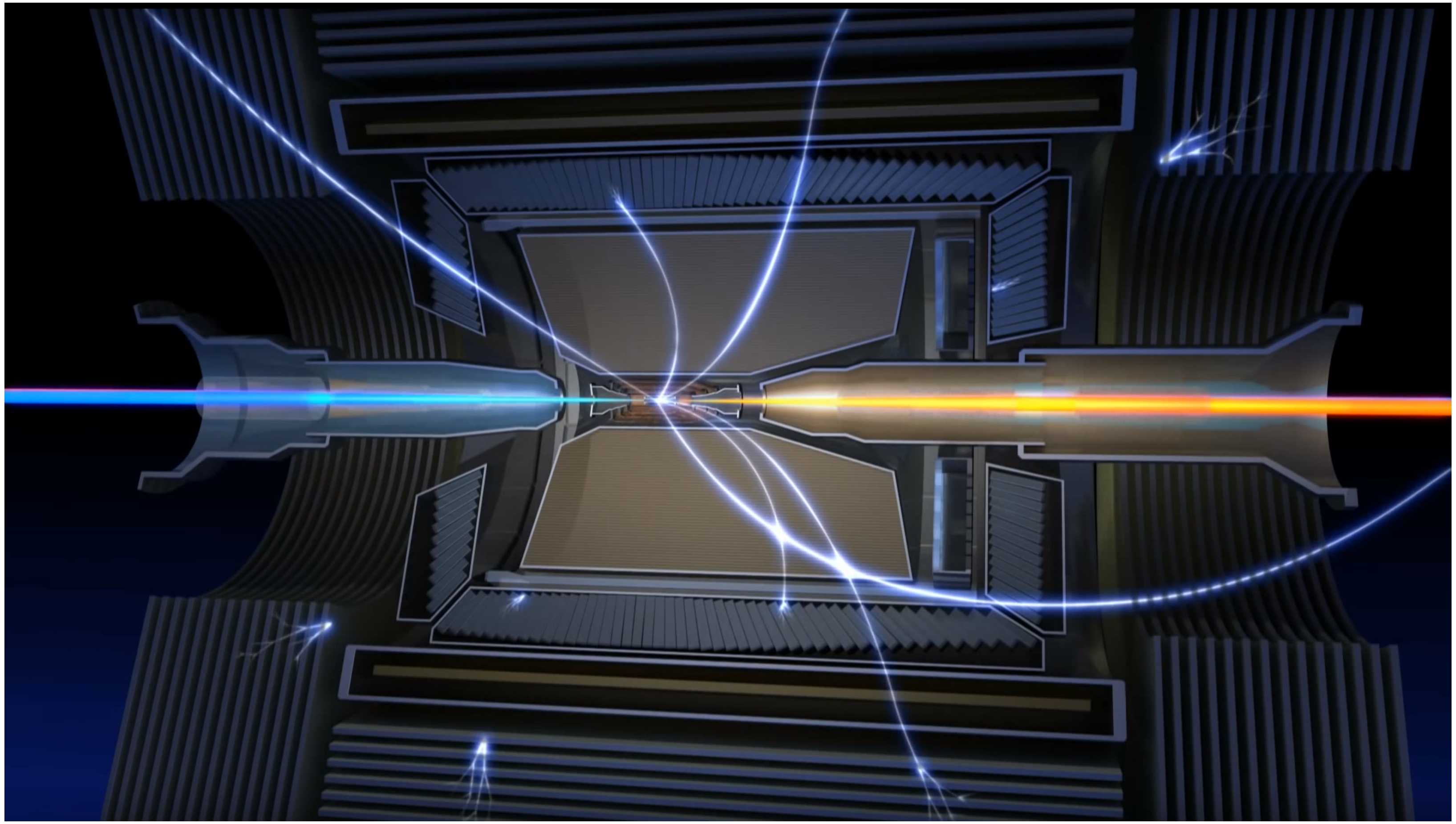
Belle II: Status and Prospects



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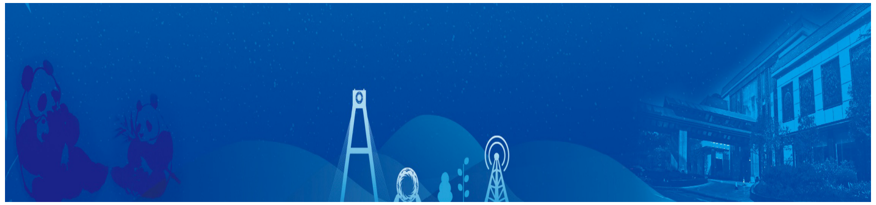
On behalf of Belle II

TeVPA 2021

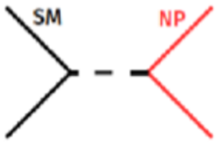
25-29 October 2021



Exploring this Universe

Energy frontier

Direct production of new particles - limited by beam energy (LHC – ATLAS, CMS)

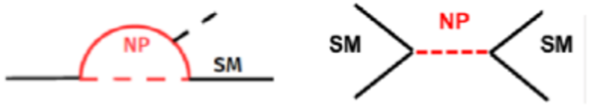


colliders

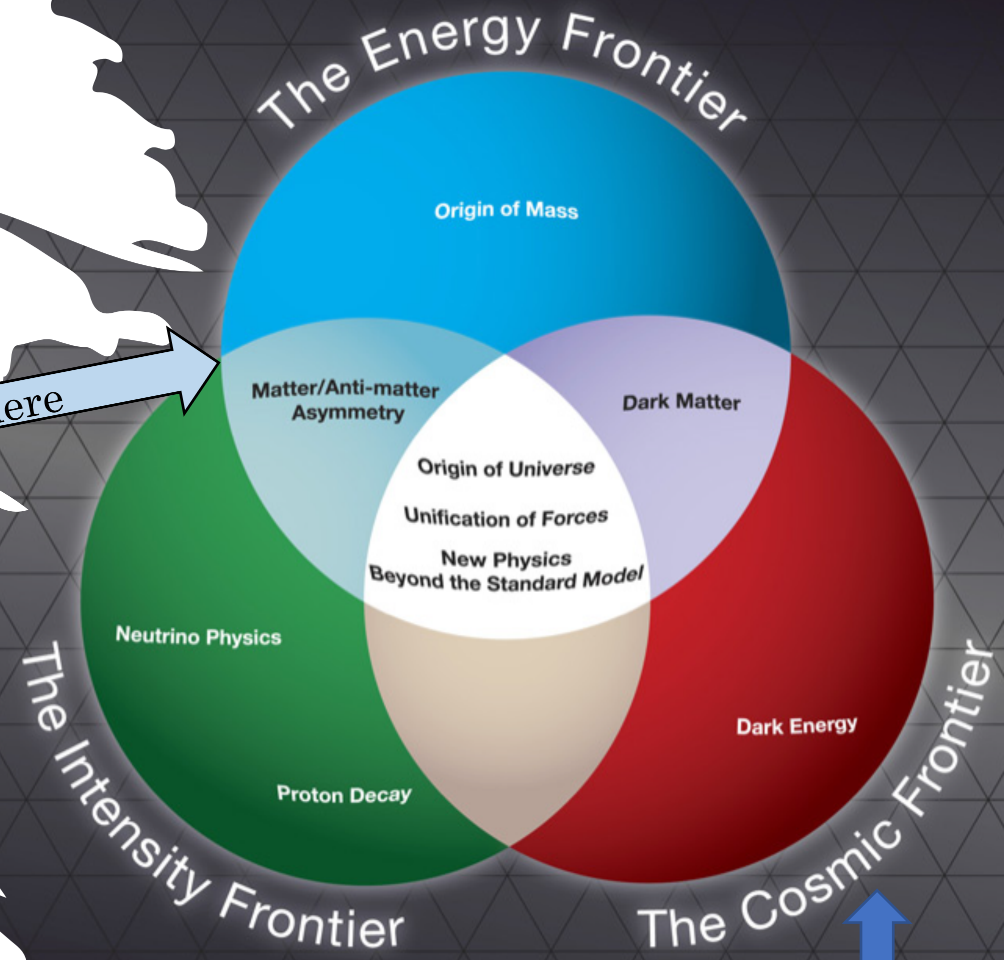
colliders contribute here

Intensity / precision frontier

New virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)



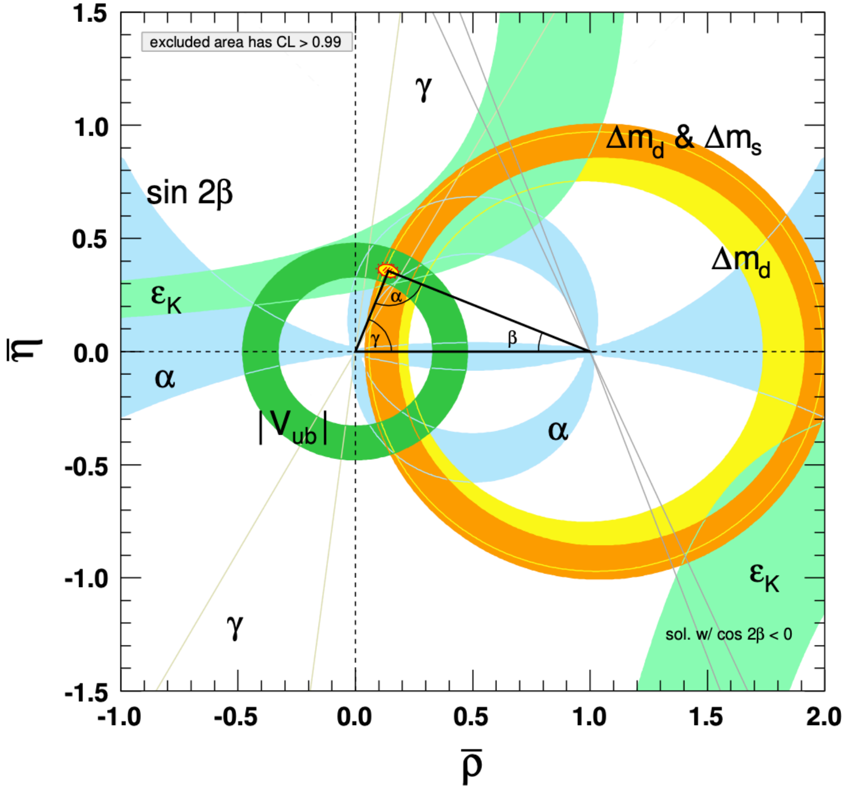
even if NP were not found in direct searches, NP effects could indirectly appear in high precision measurements

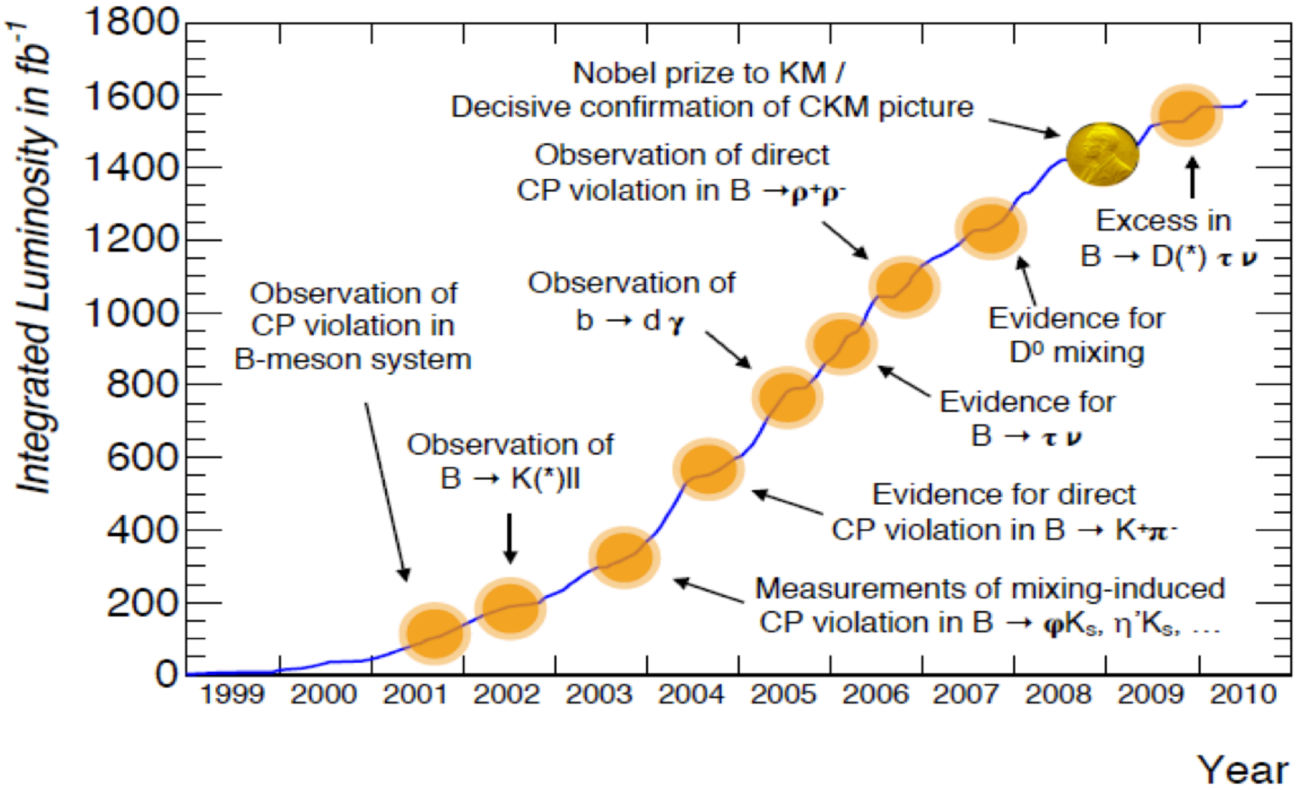


Numerous talks at this conference!

History recap

1964–2000: understand non-invariance of weak quark-interactions under particle-antiparticle exchange and inversion of spatial coordinates (CP violation).
2001: large CP violation observed in transitions of b-quark from e^+e^- colliders at the $\Upsilon(4S)$ mass energy (B factories) → success of standard model (SM) theory.
2001–: Use quark dynamics to probe indirectly beyond standard model (BSM) dynamics.

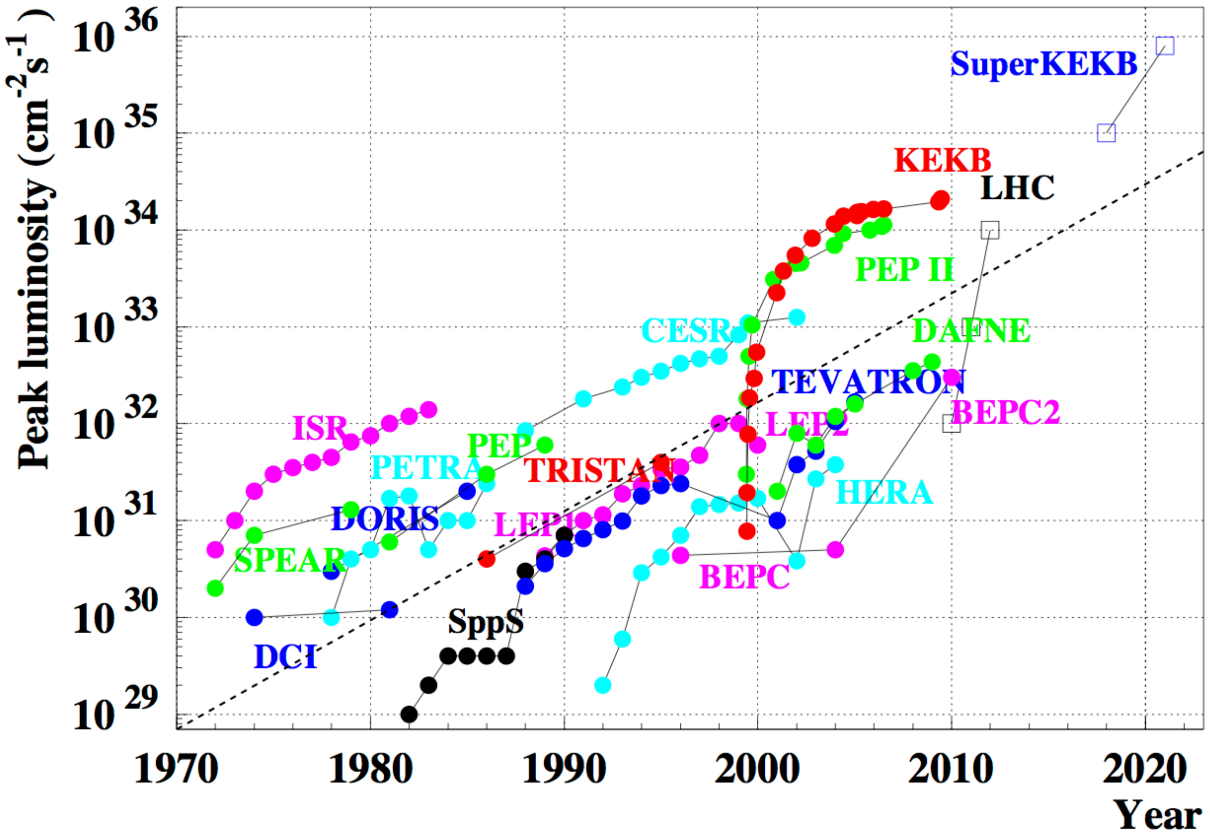




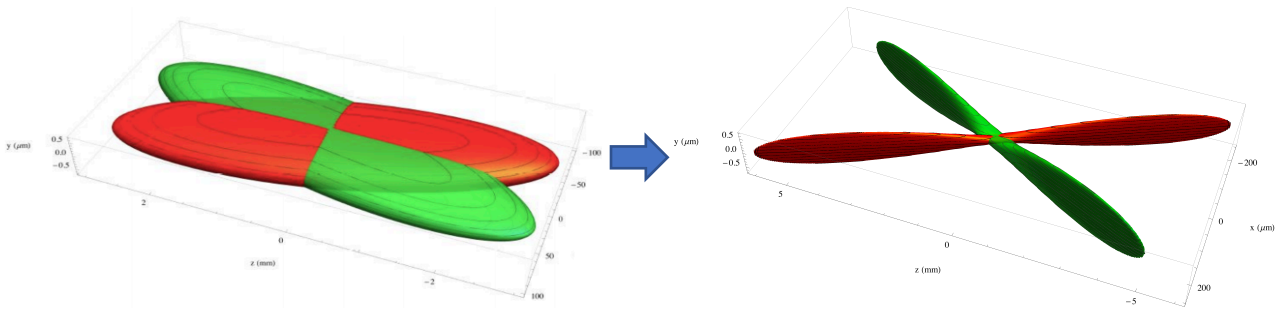
KEKB + Belle, PEP-II + BaBar, dedicated to searches for CP violation in B mesons, experimentally confirmed Kobayashi Maskawa mechanism.

First successful move on matter-antimatter asymmetry (not all accounted for).

SuperKEKB accelerator



Nano-beam Scheme:



Integrated luminosity expected 50 ab^{-1}.

x40 previous B factory.

Adopting beam squeezing and current increase as means to achieve higher luminosity, the project aims to a peak luminosity of 6×10^{35} cm^{-2}s^{-1}, 30 times more than KEKB.

On 22 June 2020, SuperKEKB set a new world record for peak luminosity: 3.1×10^{34}cm^{-2}s^{-1}.

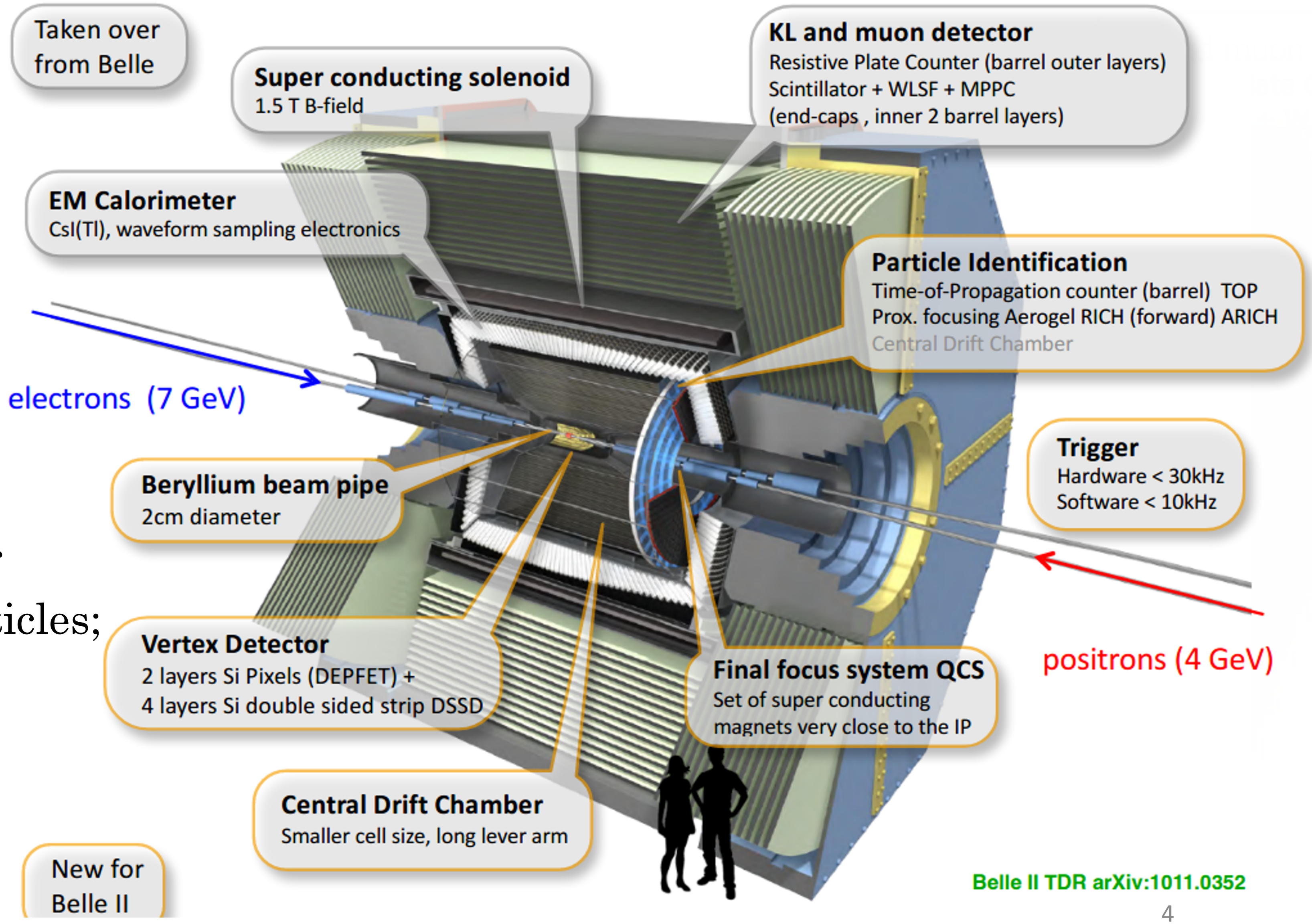
Belle II detector

Compared with Belle:

- Vertexing (decay time) resolution;
- Better momentum resolution;
- Slightly higher acceptance;
- More sophisticated trigger.

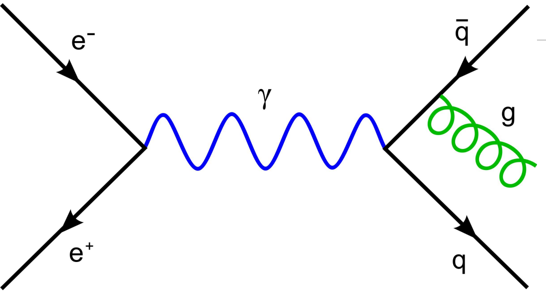
Compared with hadron colliders:

- low-background production of huge amounts of B/D/tau particles;
- kinematic constrains from e^+e^- production offer unique precision in final states with multiple neutrinos or π^0.



1100 members, 123 institutions, 26 countries

Belle II physics program



$e^+e^- \to B\,\bar{B}$: 1.05 nb
$e^+e^- \to \tau^+\tau^-$: 0.92 nb
$e^+e^- \to c\,\bar{c}$: 1.3 nb

Very rich topics

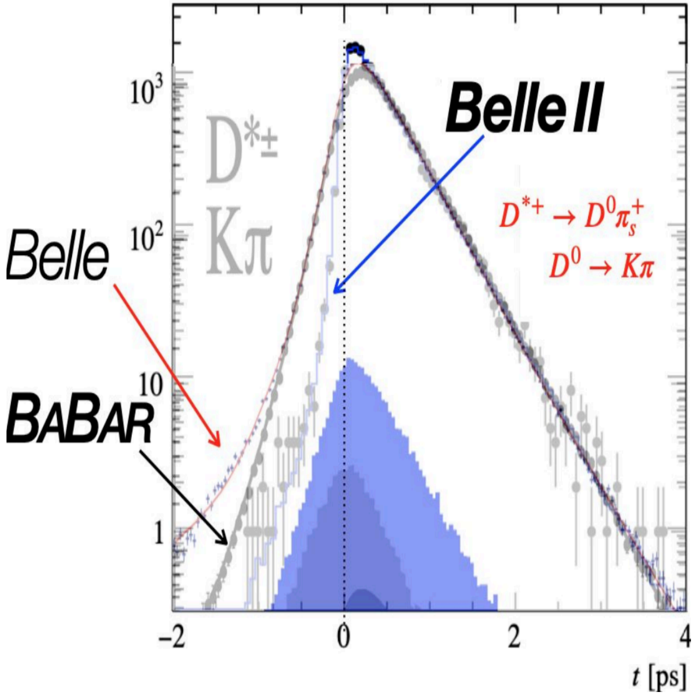
"The Belle II Physics Book"
[PTEP 2019 (2019) 12, 123C01](#)

D^0/D^+ lifetime

Motivation:

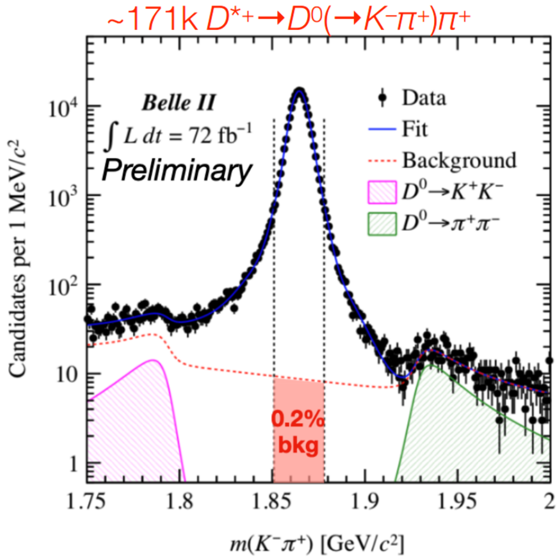
- Test of non-perturbative QCD
- Measured for the first time with sub-percent precision by FOCUS – 20 years ago
- No measurement from Belle/BaBar/LHCb
- D^+ lifetime is used as reference (LHCb)

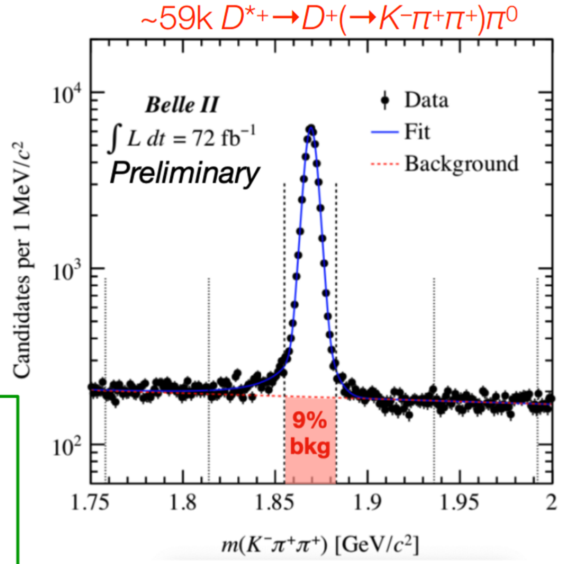
Analysis strategy:
2D fit of decay time and its uncertainty. All parameters extracted directly from the data.



Thanks to the good vertexing and high purity in the signal region.

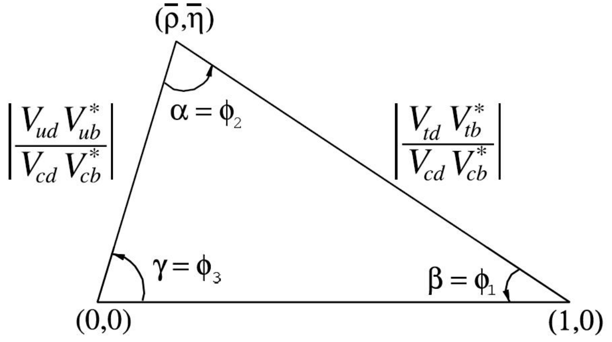
	Our result	WA
$\tau(D^0)$ =	$(410.5 \pm 1.1 \pm 0.8)$ fs	(410.1 ± 1.5) fs
$\tau(D^+)$ =	$(1030.4 \pm 4.7 \pm 3.1)$ fs	(1040 ± 7) fs



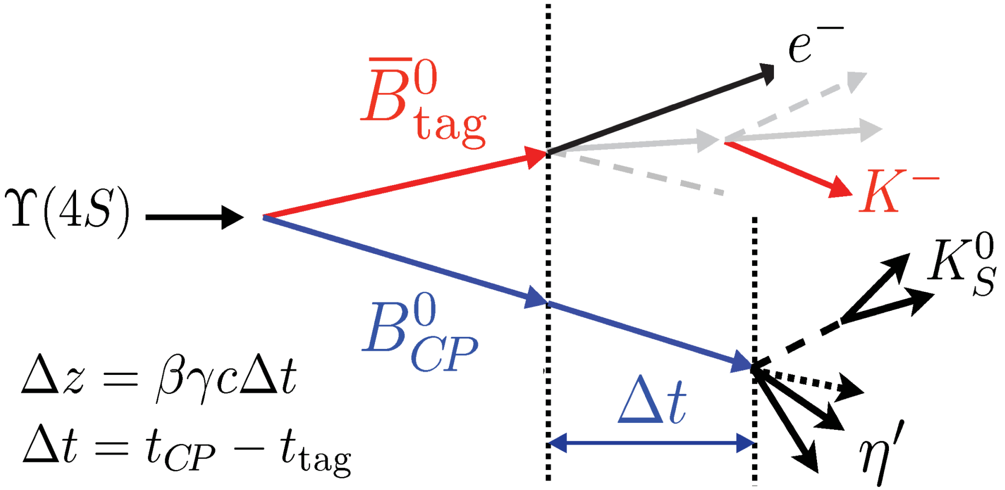


Accepted by PRL, arXiv: 2108.03216

Time dependent CPV in B decays, $\beta(\phi_1)$



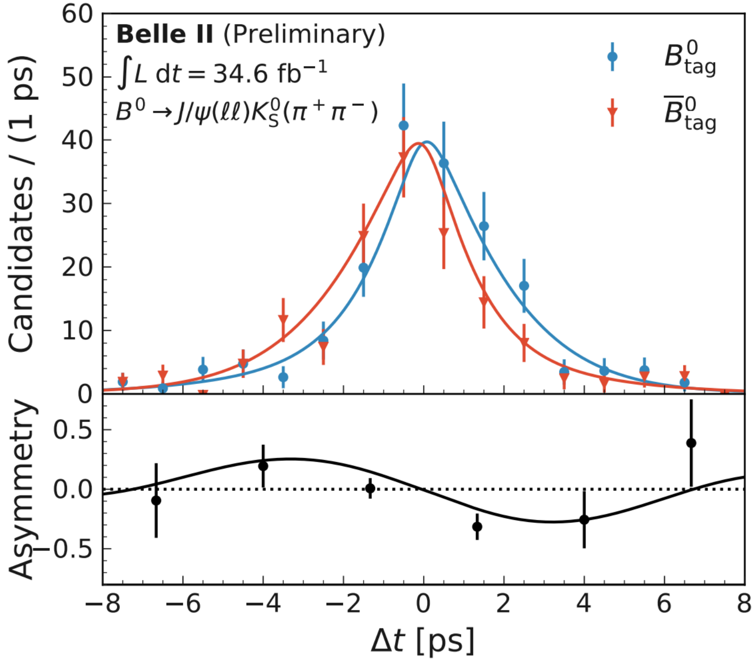
Measurement of CKM phase through the interference of B mixing amplitude with decay amplitude to a CP eigenstate.
(Flagship measurement of the B factories.)



<Δz> ~130 μm at Belle II

$$\begin{aligned} \mathcal{A}_f(\Delta t) &= \frac{\Gamma(\bar{B}^0(\Delta t)\to f) - \Gamma(B^0(\Delta t)\to f)}{\Gamma(\bar{B}^0(\Delta t)\to f) + \Gamma(B^0(\Delta t)\to f)} \\ &= S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t) \end{aligned}$$

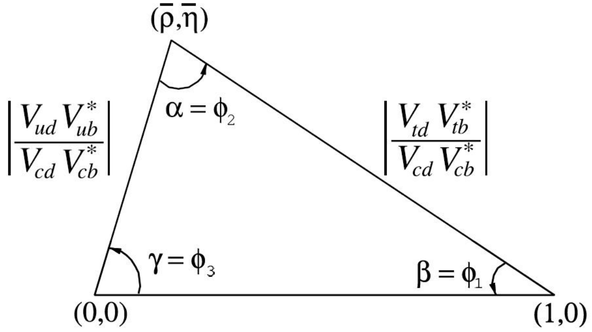
Ongoing analysis: $B^0 \to J/\psi(ee/\mu\mu)\, K_S$



S_f=sin $2\phi_1$=0.55 ± 0.21(stat.) ± 0.04(syst.)

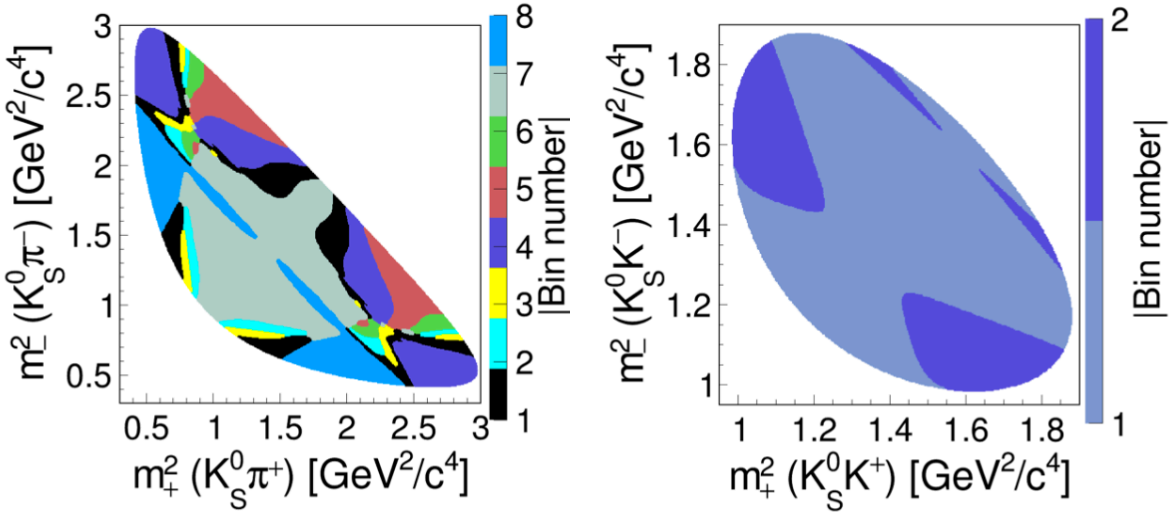
BELLE2-NOTE-PL-2020-011

Still very important at Belle II: ϕ_1 (current precision ~0.7°) is fundamental inputs of the CKM fit. We expect to improve by a factor of 5.

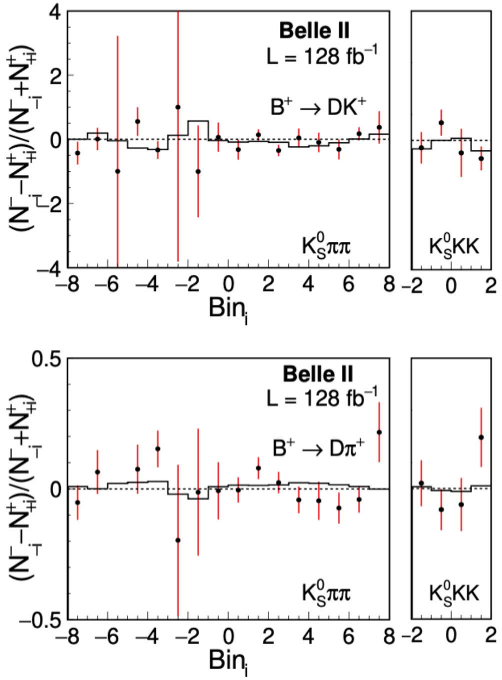


$\gamma\ (\phi_3)$

- Another fundamental input for the CKM fit, proceeding only through $B^- \to D^0 K^-$ tree level transitions;
- On this field, LHCb will have the upper hand, but Belle II will contribute in modes with neutrals in the final state;
- Good K-π separation is important to suppress the favored B → D π decays.



$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002\,,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,.$$

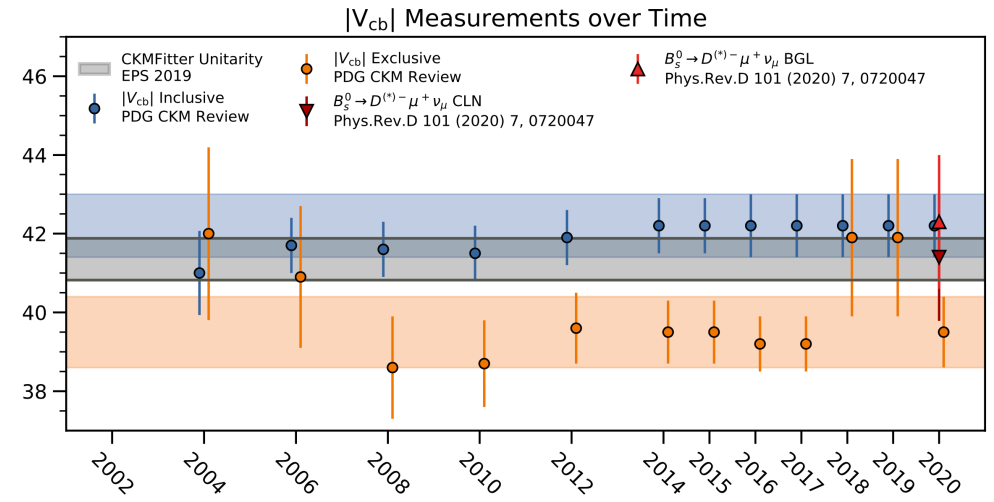


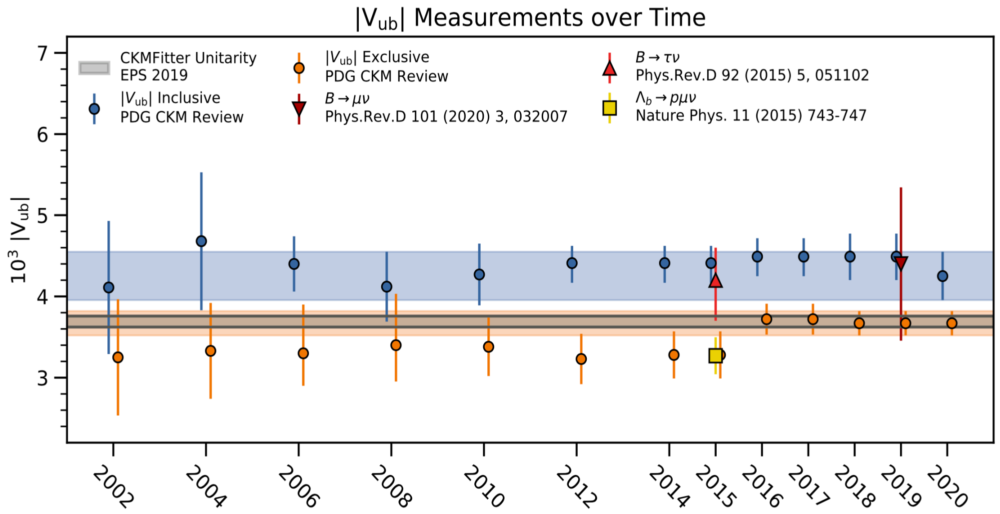
arXiv:2110.12125

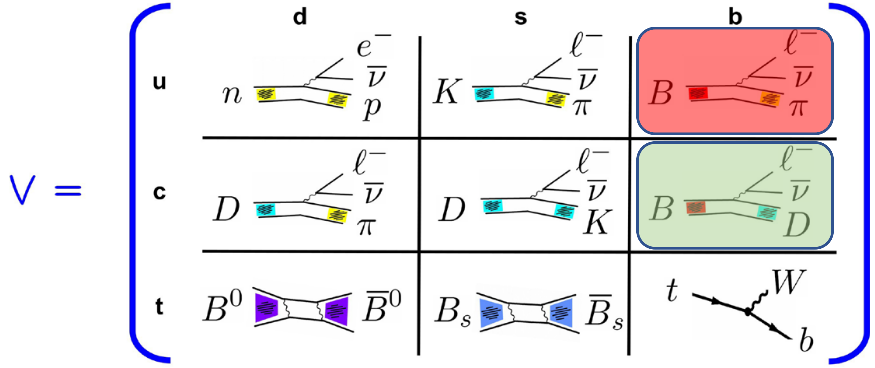
Model independent measurement (Dalitz plot analysis) of ϕ_3 by $B^+ \to D\left(K_S^0\, h^+\, h^-\right) h^+$ using Belle + Belle II data.

$$A_{B^+}\left(m_-^2, m_+^2\right) \propto A_{\bar{D}}\left(m_-^2, m_+^2\right) + r_B^{DK} e^{i\left(\delta_B^{DK} - \phi_3\right)} A_D\left(m_-^2, m_+^2\right)$$

CKM elements $|V_{cb}|$ and $|V_{ub}|$







Tree level nature of semi-leptonic B decays
→ SM gauges → key roles for $|V_{cb}|$ and $|V_{ub}|$.

Inclusive and exclusive determinations offer independent and complementary results
→ persistent tension between two approaches.

- $|V_{cb}|$ from $B \to X_c l\nu$, $B \to D^{(*)} l\nu$ $(l = e, \mu)$
- $|V_{ub}|$ from $B \to X_u l\nu$, $B \to \pi(\rho, \eta) l\nu$ $(l = e, \mu)$

Inclusive:

Observed $b \to u\ell\nu_\ell$ excess in data ($> 3\sigma$).

Exclusive:

$$\mathcal{B}(B^0 \to \pi^-\ell^+\nu_\ell) = [1.58 \pm 0.43 \pm 0.07] \times 10^{-4}$$

Preliminary, arXiv: 2103.02629

$|V_{cb}|$ cont'd

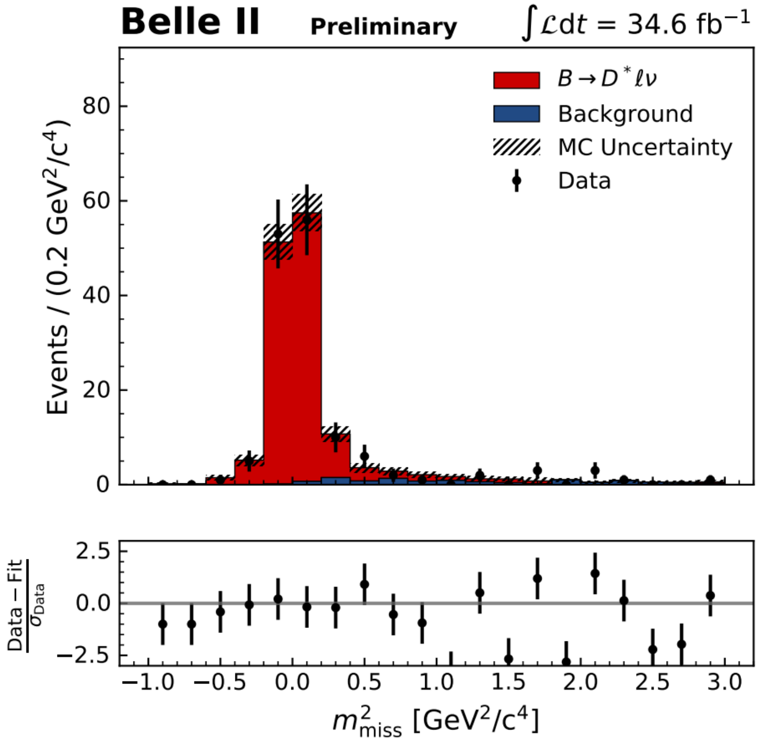
$$R_{D^{(*)}} \equiv \frac{\mathrm{Br}(B \to D^{(*)}\tau\,\bar{\nu_\tau})}{\mathrm{Br}(B \to D^{(*)}\ell\,\bar{\nu_\ell})_{\ell=e,\mu}}$$

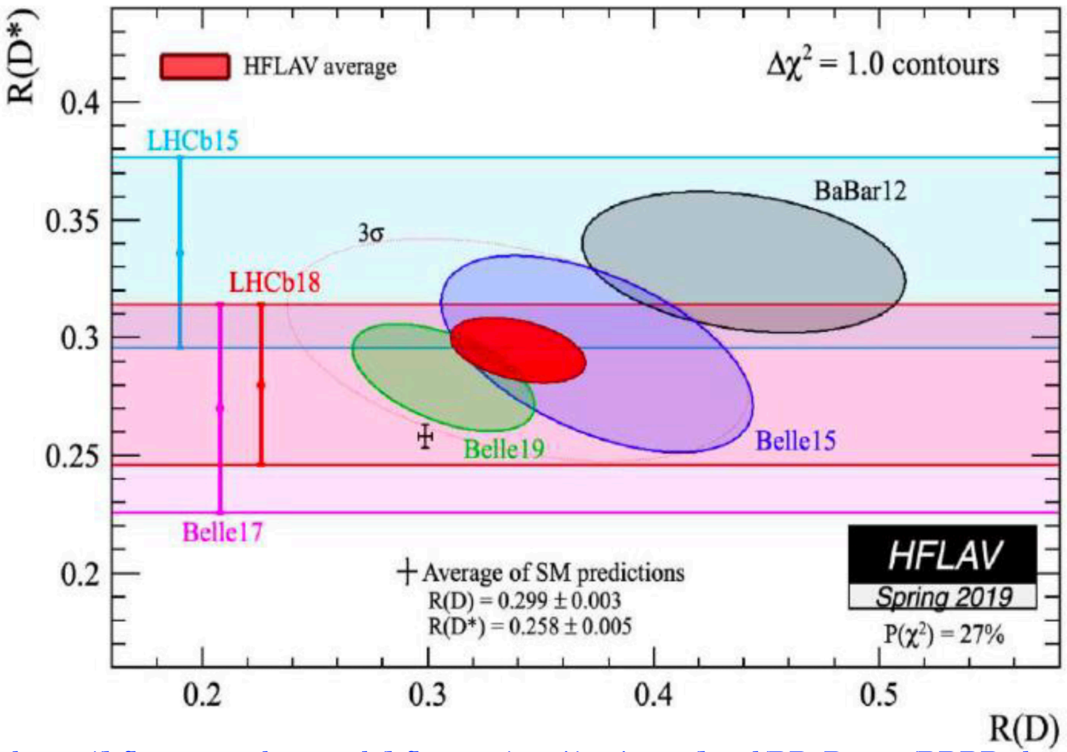
Lepton flavour universality (LFU) violated?

$R_D = 0.340 \pm 0.027 \pm 0.013$ $+1.4\sigma$ from SM

$R_{D^*} = 0.295 \pm 0.011 \pm 0.008$ $+2.5\sigma$ from SM

R_D/R_{D^*} combined $+3.08\sigma$ from SM





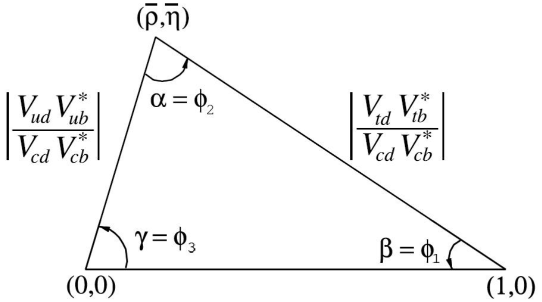
https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

Full Event Interpretation algorithm exploited, tagging B using over 100 hadronic decay modes.

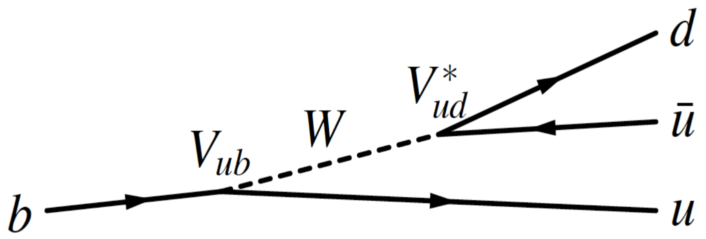
$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = (4.51 \pm 0.41_{\mathrm{stat}} \pm 0.27_{\mathrm{syst}} \pm 0.45_{\pi_s})\,\%$$

$\ell = e, \mu$

BELLE2-CONF-PH-2020-023



α (ϕ_2)



Unique Belle II capability to study all the $B \to \pi\,\pi, \rho\,\rho$ partner decays to determine α.

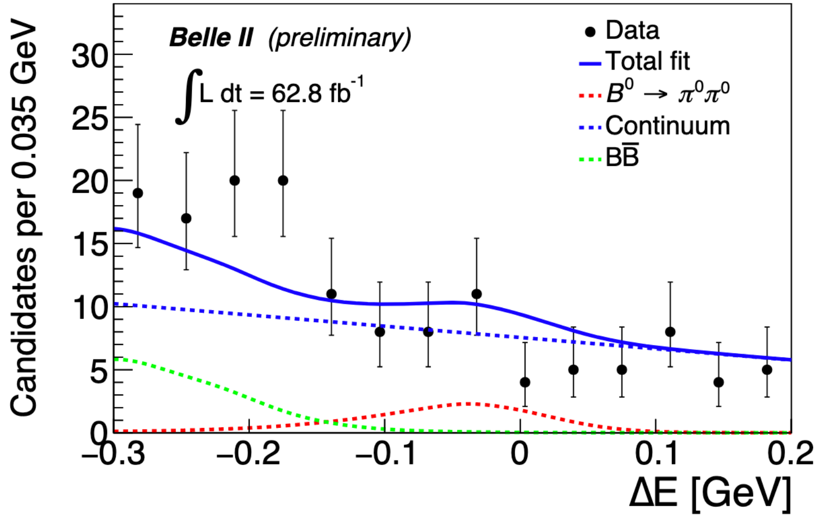
$B^0 \to \pi^0\pi^0$: very challenging because four γ's.

Train BDT to suppress background photons.

Unique Belle II reach.

$\mathscr{B}(B^0 \to \pi^0\pi^0) = [0.98^{+0.48}_{-0.39}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}$

arXiv:2107.02373

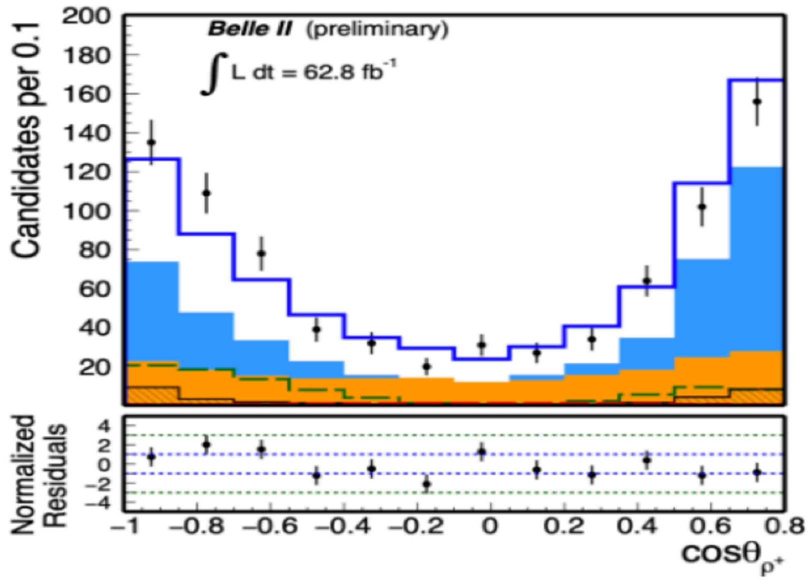


$B^+ \to \rho^+\rho^0$: π-only final state, large background because of ρ mass width. Additional challenge of angular analysis → 6D fit including helicity angles.

$f_L(B^+ \to \rho^+\rho^0) = 0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst})$

$\mathscr{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$

BELLE2-TALK-CONF-2021-013

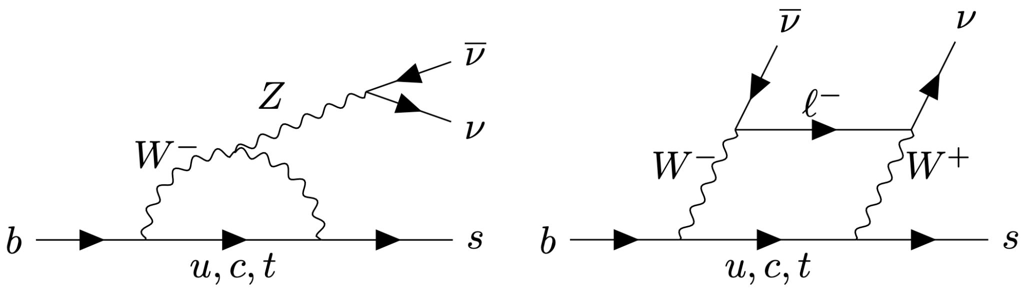


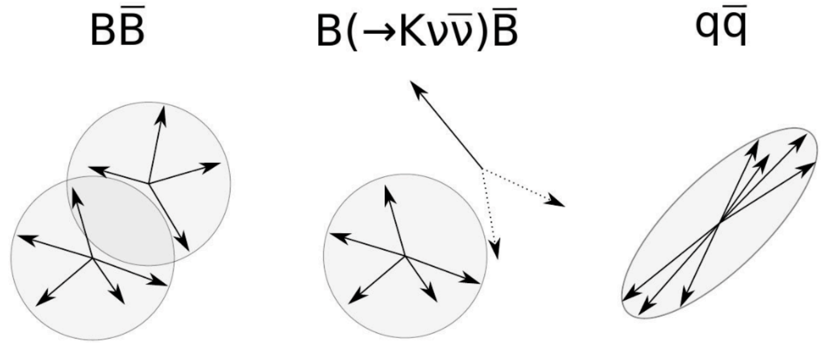
20% precision improvement wrt Belle at the same lumi!

Wrt BaBar's best (scaled): better on BF, same on f_L.

$B^+ \to K^+ \nu \bar{\nu}$

Flavor changing neutral-current.
The SM prediction of its Br is $(4.6 \pm 0.5)\times10^{-6}$.
Unobserved, but BSM could potentially enhance its Br.
Complementary probe to BSM from $b \to s\, l\, l$



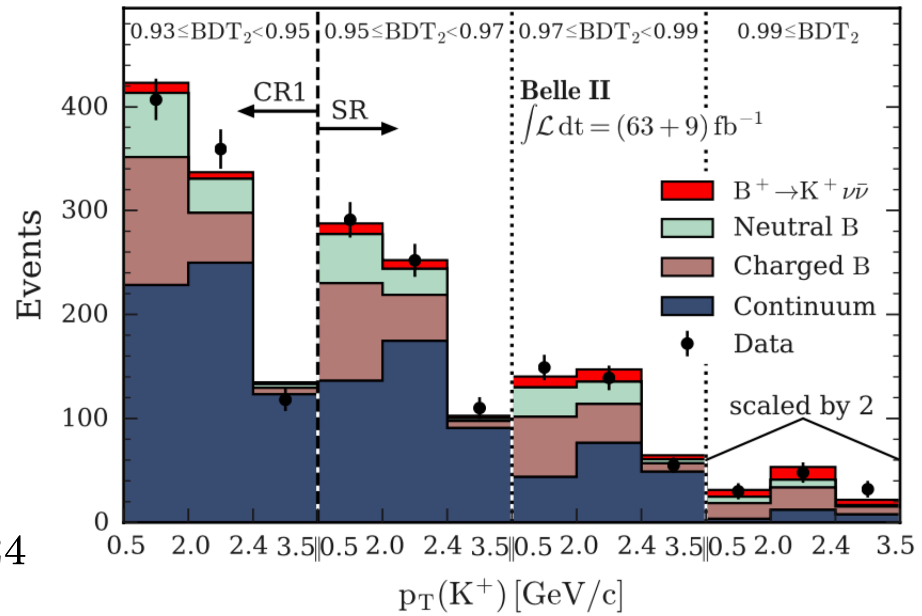


Previous analyses: tagged approach with limited signal efficiency:
- semileptonic tag (0.2% @ Belle, BaBar)
- hadronic tag (0.04% @ BaBar)

Belle II approach: **novel inclusive tagging** technique - signal efficiency 4.3%

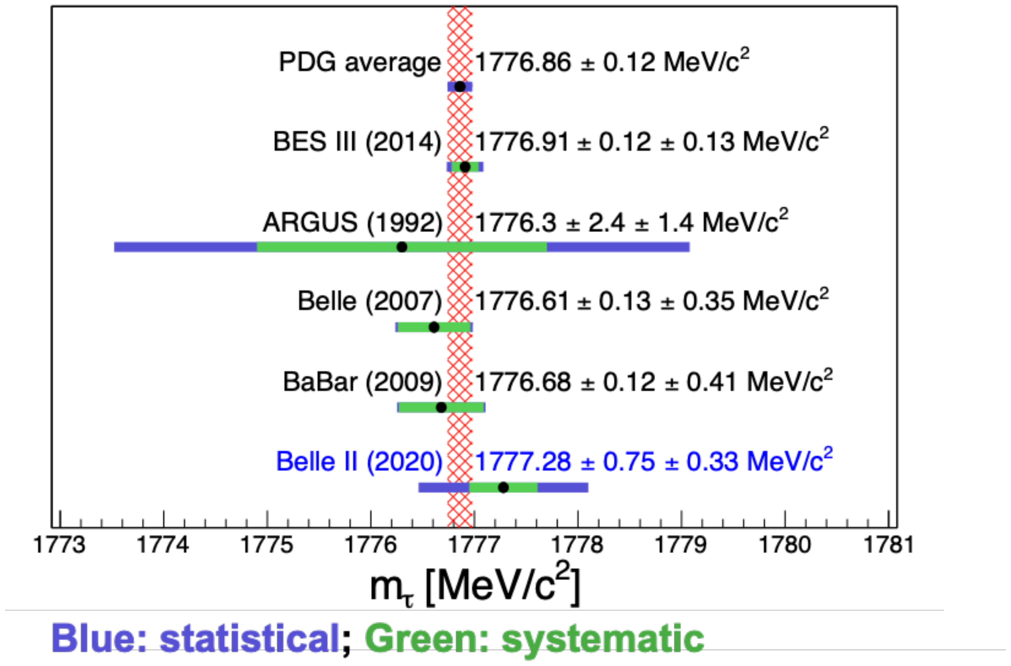
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (1.9^{+1.3+0.8}_{-1.3-0.7}) \times 10^{-5}$$

4.1×10^{-5} @90% CL



Accepted by PRL, arXiv:2104.12624

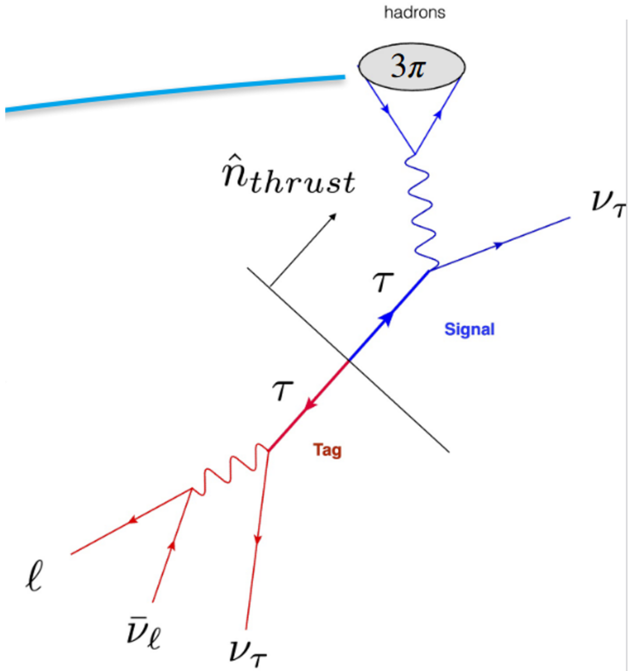
τ mass



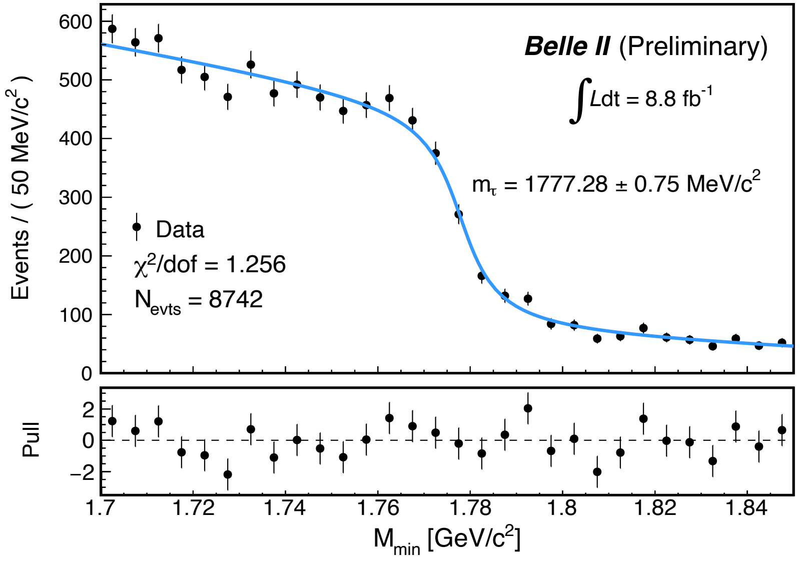
Two methods for measuring m_τ:

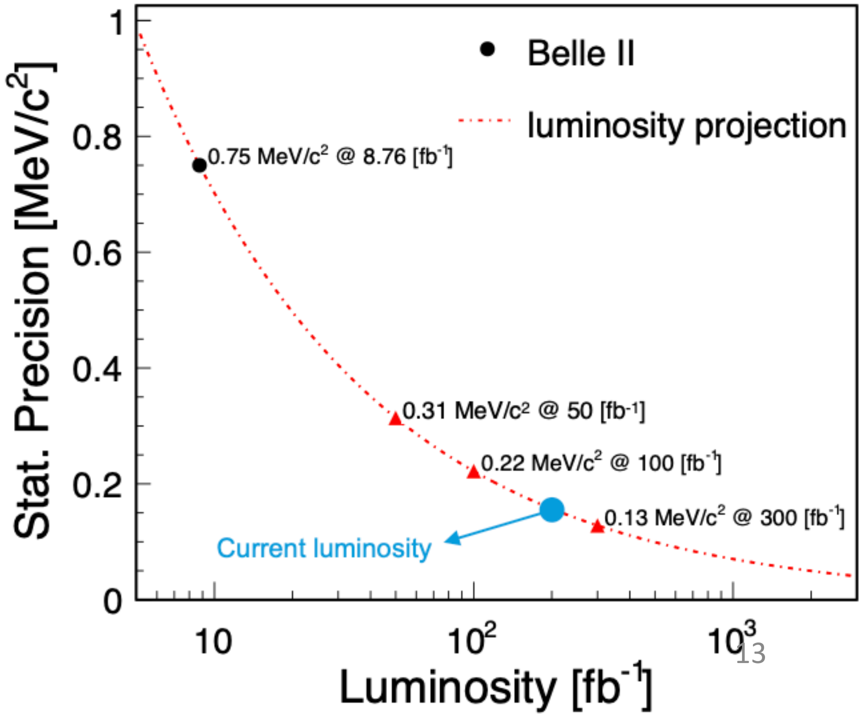
- Measurement in the production thresholds (DELCO, BES, KEDR, **BES III**).
- Pseudo-mass (M_{min}) distribution (ARGUS, OPAL, Babar, **Belle**).

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



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





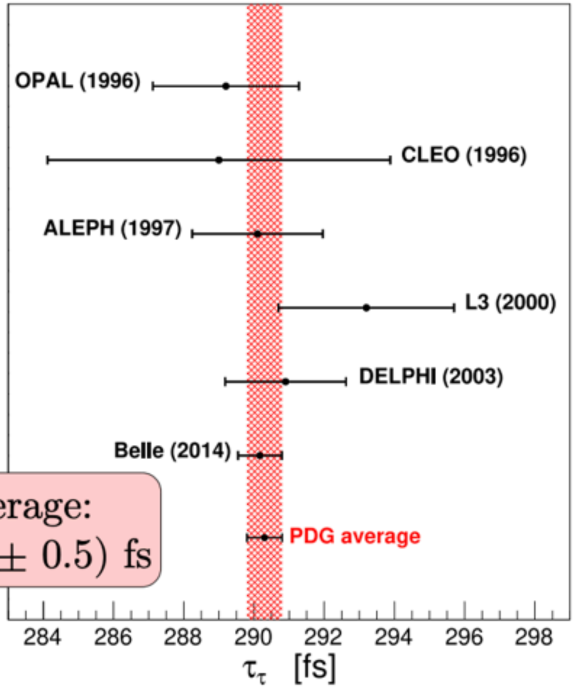
arXiv:2008.04665

τ lifetime

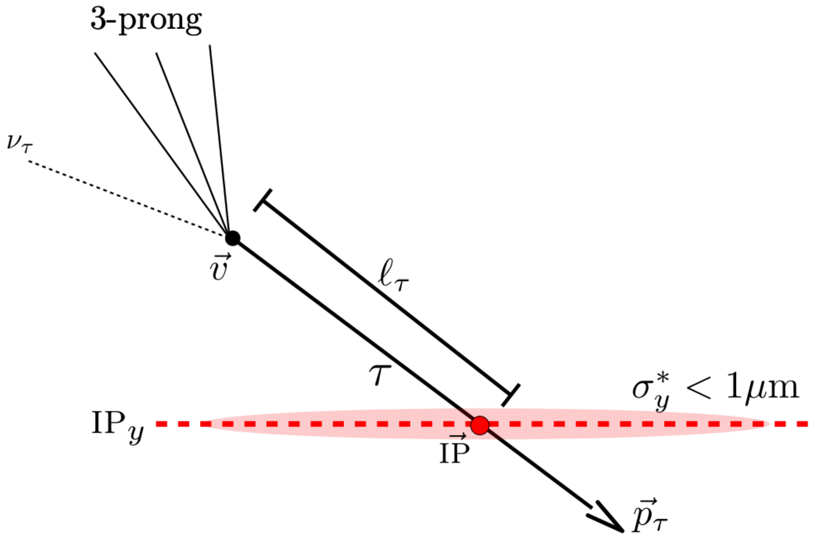
Important SM parameter. Its precision has implications in LFU, $\alpha_s(m_\tau)$, etc.

Previous measurements:

- Z-peak: LEP (DELPHI, L3, ALEPH, OPAL).
- Υ-peak: CLEO, BaBar, **Belle** [1].

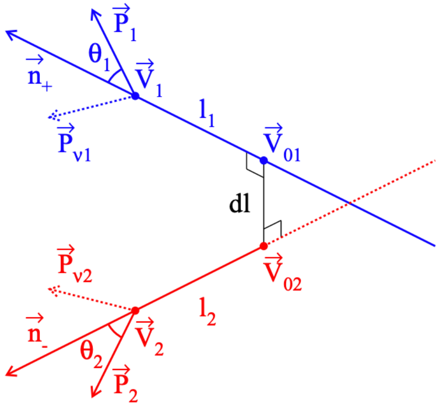


PDG average:
$\tau_\tau = (290.3 \pm 0.5)$ fs



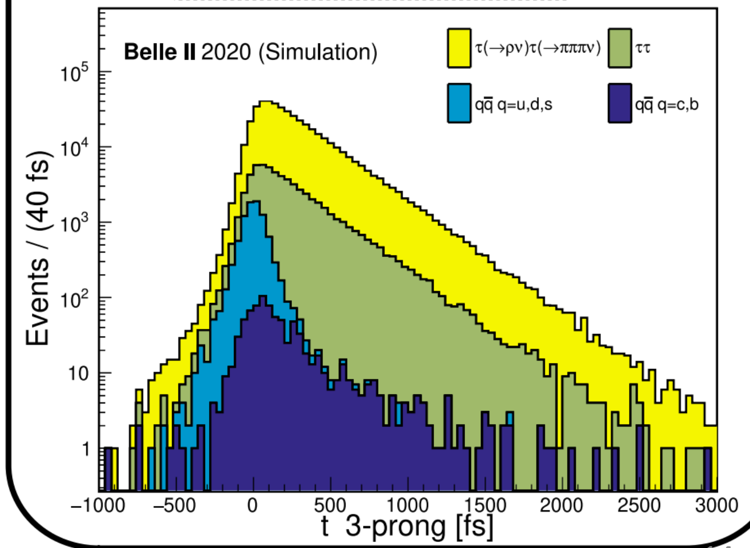
Strategy at Belle II:

1. Reconstruct vertex for 3-prong τ.
   Only one 3-prong = higher statistics.
2. Estimate the τ momentum $\vec{p}_\tau$.
   Hadronic decays in both sides.
3. Find the production vertex.
   Intersection of $\vec{p}_\tau$ with the plane IP_y.



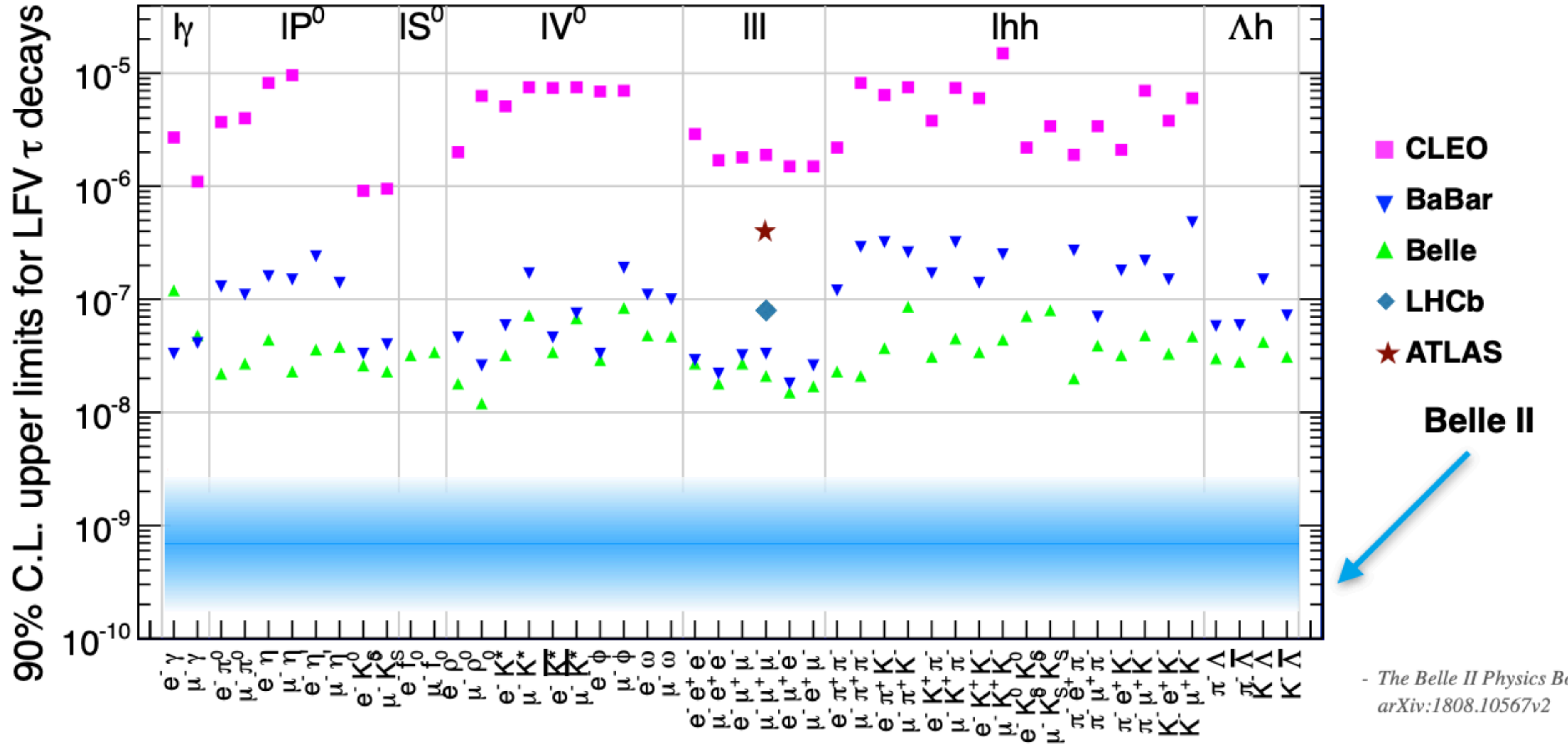
Proper decay time distribution

$$t = \ell_{3\text{-prong}} \frac{m_\tau}{|\vec{p}_{3\text{-prong}}|c}$$



[1] PRL 112, 031801 (2014), arXiv:1310.8503 [hep-ex]

Lepton flavor violation in τ



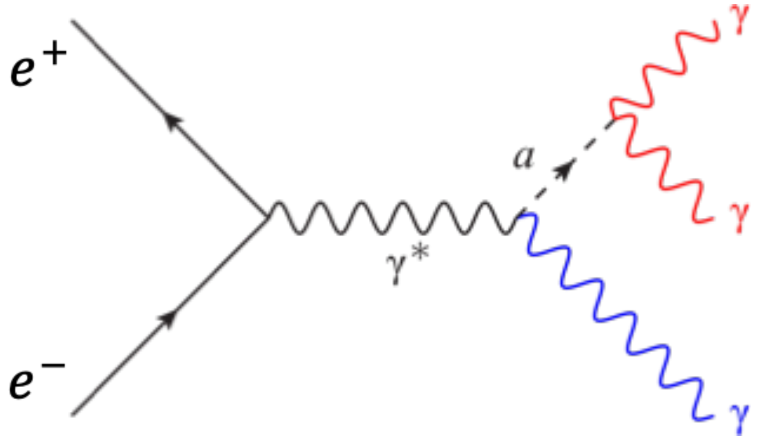
- *The Belle II Physics Book arXiv:1808.10567v2*

Super rare processes. With huger statistic (50 ab^{-1}), one more step approaching them.

Dark sector

Search for an axion like particle (ALP)

Signal: $e^+e^- \to \gamma_{recoil} + a\,(\to \gamma\,\gamma)$



PRL 125, 161806 (2020)

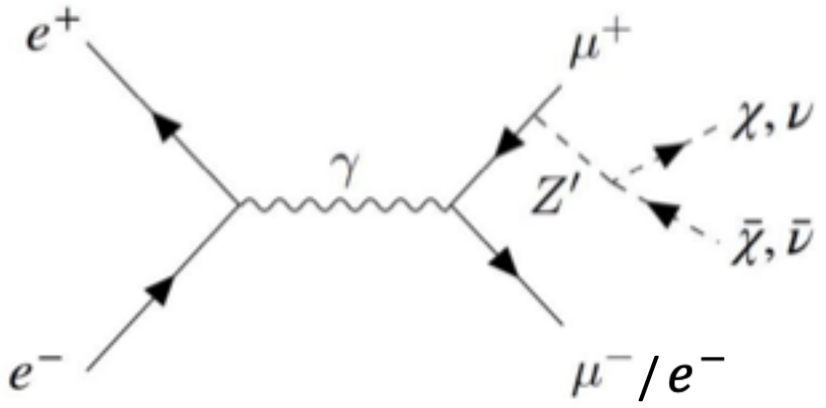
No evidence for ALP

$g_{a\gamma\gamma} \lesssim 10^{-3}\,(\mathrm{GeV}/c^2)^{-1}$ for $0.2 < m_a \leq 1\ \mathrm{GeV}/c^2$

Most restrictive to date for $0.2 < m_a < 1\ \mathrm{GeV}/c^2$.

Search for an Invisibly Decaying Z'

Signal: $e^+e^- \to \mu^+\mu^-(e^+\mu^-) +$ missing E



PRL 124, 141801 (2020)

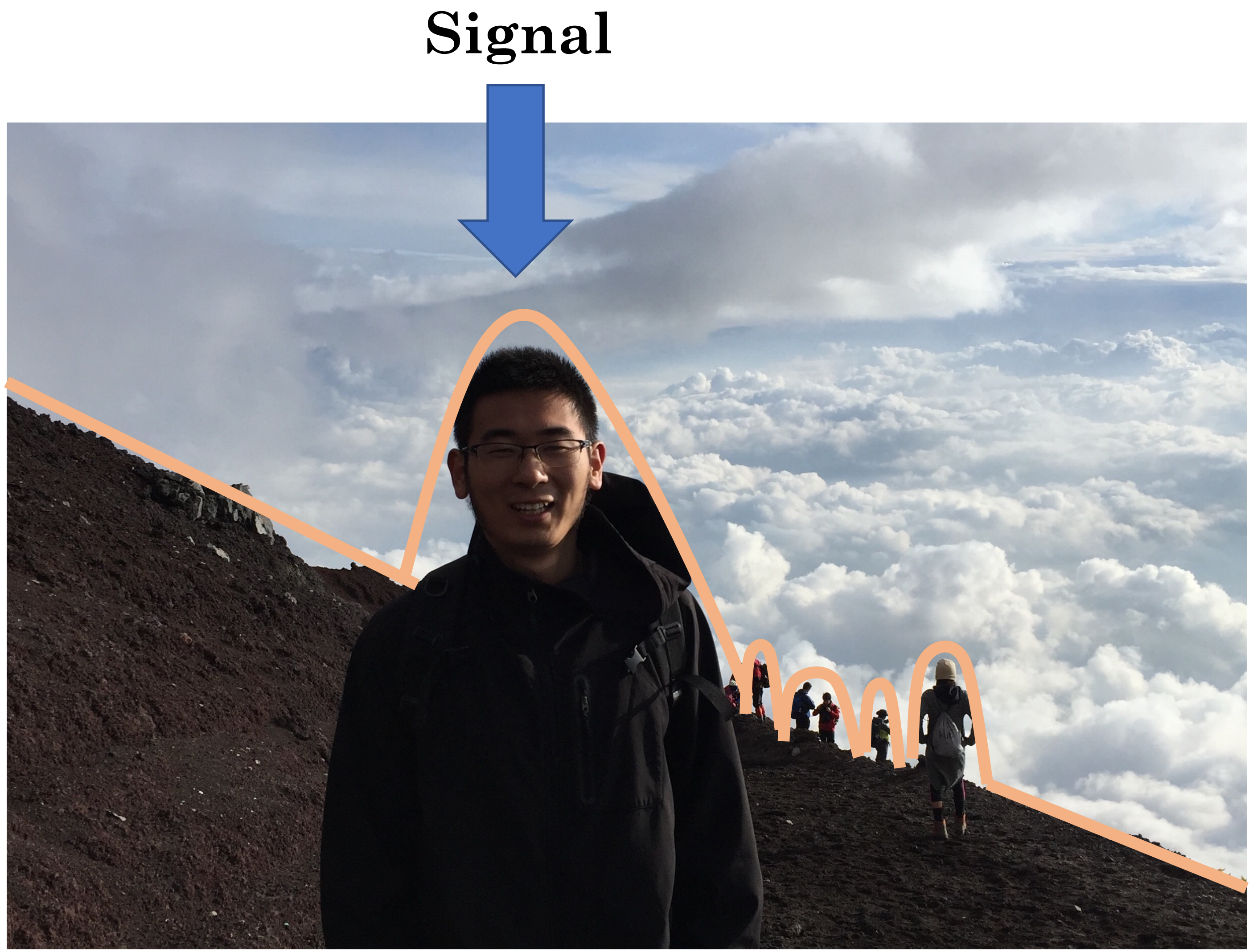
No evidence for Z'

$g_{Z'\ell\ell} < 5\times10^{-2}$...1 for $m_{Z'} \leq 6\ \mathrm{GeV}/c^2$

More details at Rajesh Maiti's talk, Dark sector physics at Belle II.

Summary

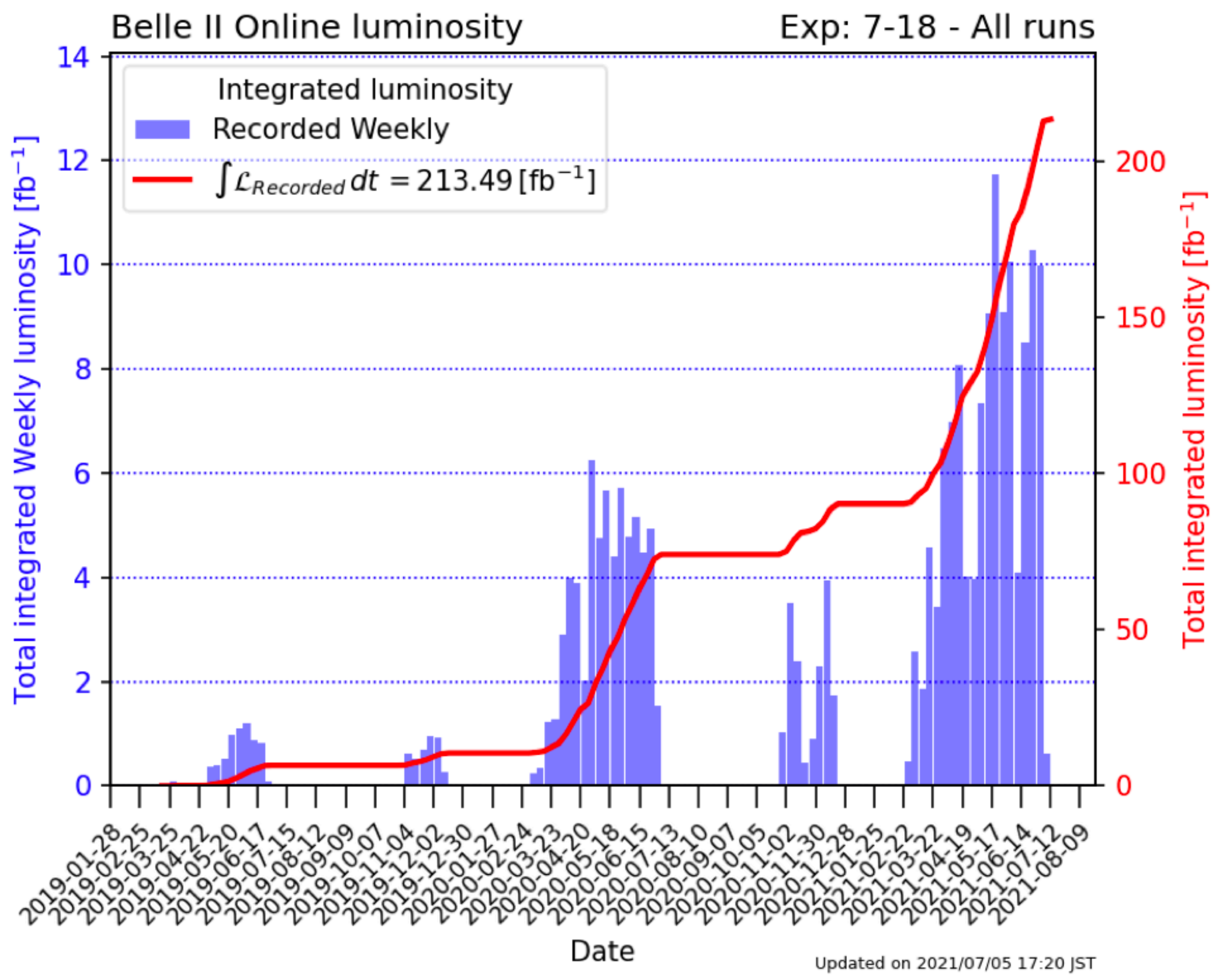
- A new-generation B-factory has set sail to produce billions of B, D, and tau decays over the next decade. A collaboration of 1100 members from 126 institutions over 26 countries built and operates Belle II, a dedicated state-of-the-art instrument to explore them.
- A rich program is ahead and early harvesting offers already impactful results: D lifetimes, $B^+ \to K^+ \nu \bar{\nu}$, ALP, Z', etc.
- Belle II will soon offer unique precision probes for BSM physics.



Thank you for your attention!

Back up

Data-taking so far



ACCELERATORS | NEWS

SuperKEKB raises the bar

22 August 2021

Record breaker The SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan. Credit: S. Takahashi / KEK

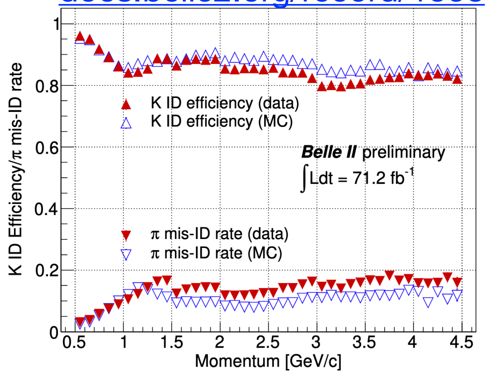
On 22 June, the SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan set a new world record for peak luminosity, reaching $3.1 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the Belle II detector. Until last year, the luminosity record stood at $2.1 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, shared by the former KEKB accelerator and the LHC. In the summer of 2020, however, SuperKEKB/Belle II surpassed this value with a peak luminosity of $2.4 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

https://cerncourier.com/a/superkekb-raises-the-bar/

A new world record!

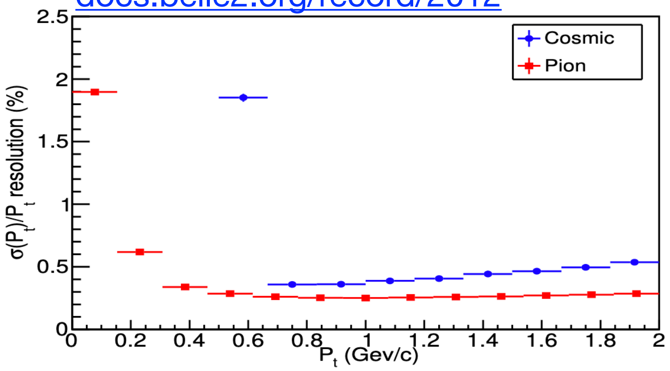
Performance overview

docs.belle2.org/record/1558



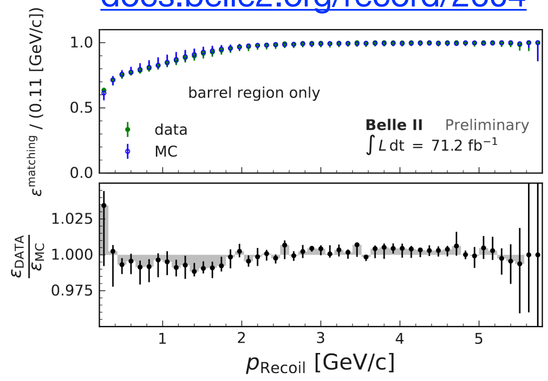
Strong charged particle identification.

docs.belle2.org/record/2012



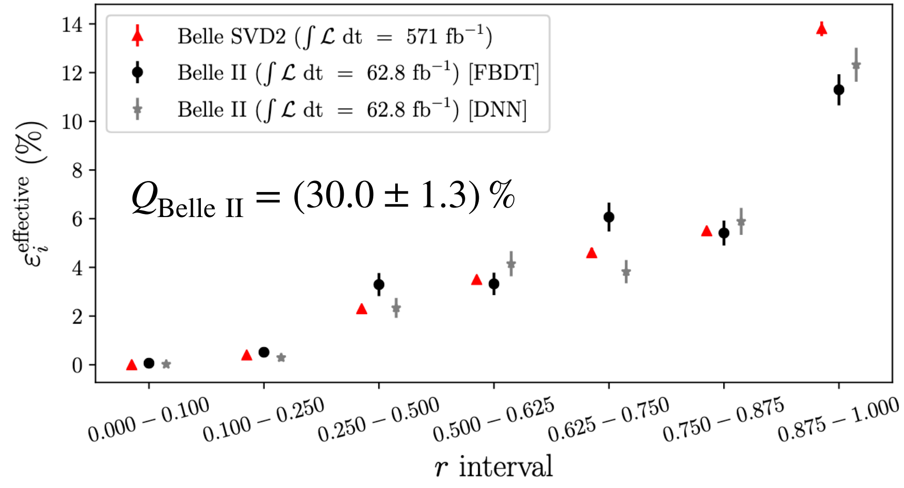
Good momentum resolution.

docs.belle2.org/record/2604



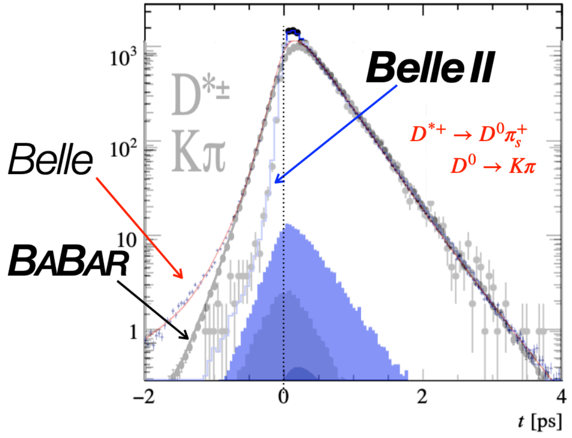
High ɣ efficiency.

To be submitted to EPJC



Flavor tagging efficiency comparable to Belle.

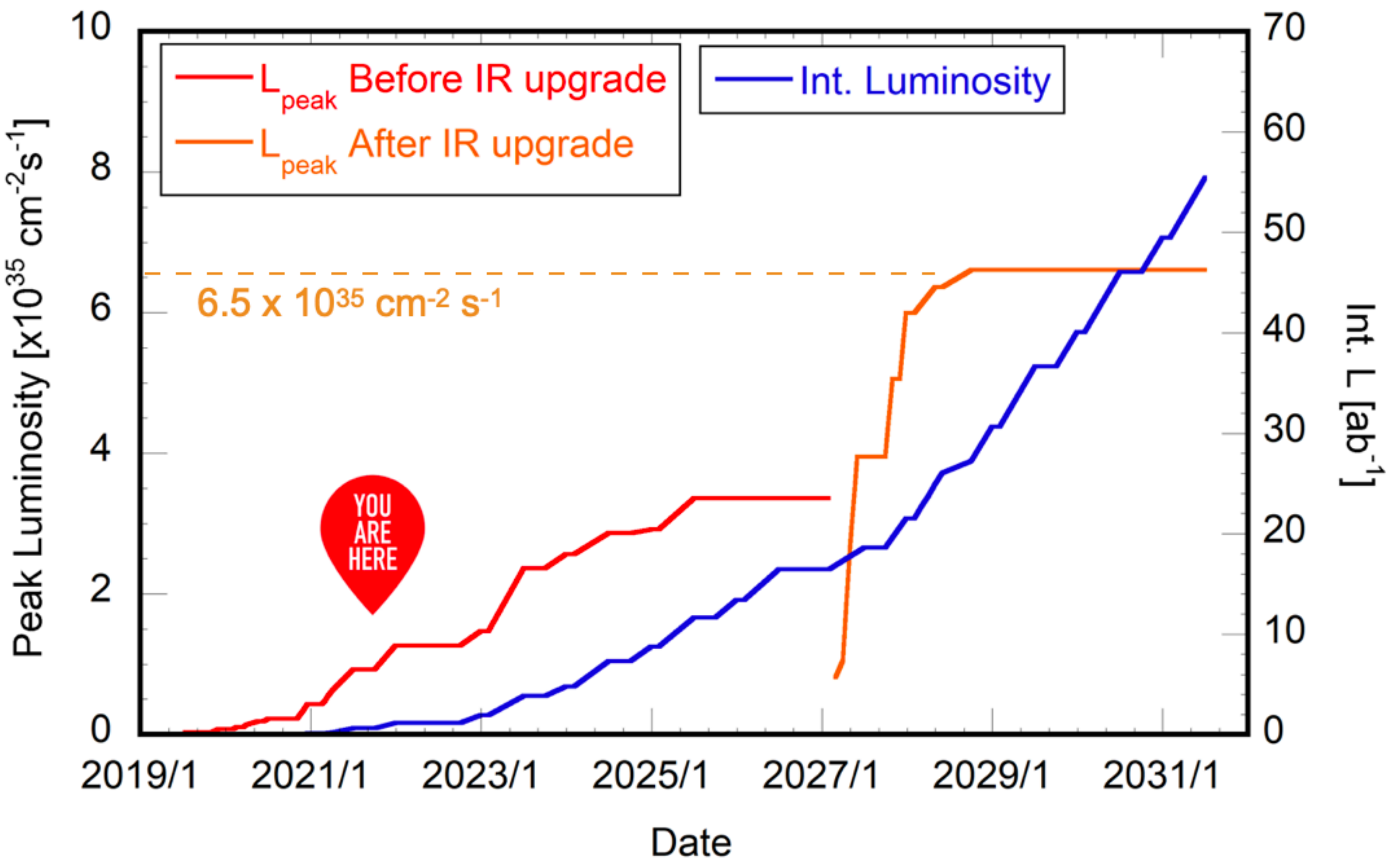
ICHEP 2020



Greatly improved time resolution compared to previous *B*-factories.

X

Belle II luminosity prospect



SM predictions for $R_{D^{(*)}}$

	R(D)	R(Di*)
D.Bigi, P.Gambino, Phys.Rev. D94 (2016) no.9, 094008 [arXiv:1606.08030 [hep-ph]]	0.299 ± 0.003	
F.Bernlochner, Z.Ligeti, M.Papucci, D.Robinson, Phys.Rev. D95 (2017) no.11, 115008 [arXiv:1703.05330 [hep-ph]]	0.299 ± 0.003	0.257 ± 0.003
D.Bigi, P.Gambino, S.Schacht, JHEP 1711 (2017) 061 [arXiv:1707.09509 [hep-ph]]		0.260 ± 0.008
S.Jaiswal, S.Nandi, S.K.Patra, JHEP 1712 (2017) 060 [arXiv:1707.09977 [hep-ph]]	0.299 ± 0.004	0.257 ± 0.005
Arithmetic average	**0.299 ± 0.003**	**0.258 ± 0.005**

CKM

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$