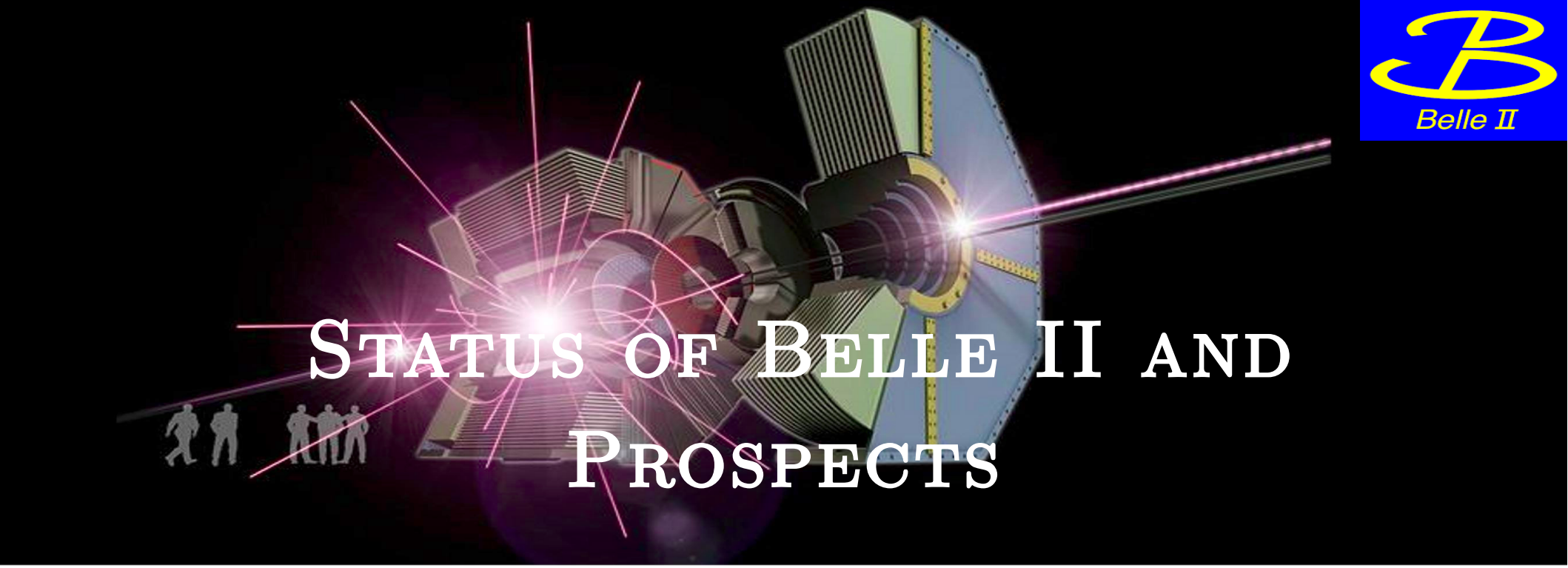


Status of Belle II and Prospects

FPCP 2021

Minakshi Nayak

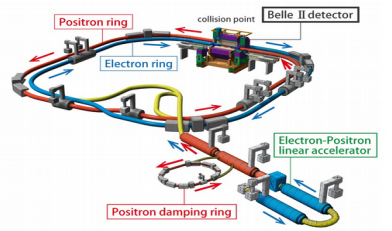
(for the Belle II collaboration)

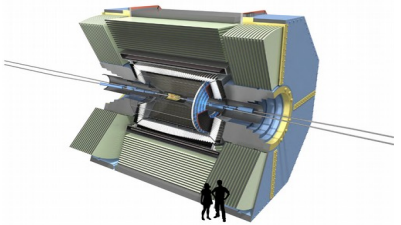
11th June, 2021

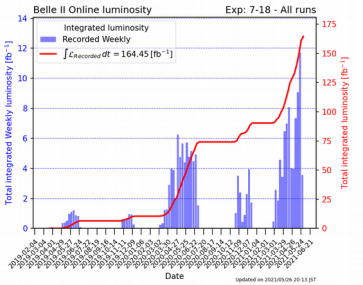
TEL AVIV UNIVERSITY

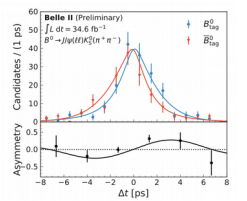
Talk Outline (focusing only on quark-flavor topics)

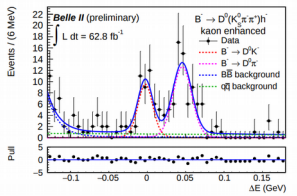
- **Experiment**
  - SuperKEKB
  - Belle II
- **Status**
  - Luminosity and data taking
  - Detector performances
  - Most recent physics results
- **Prospects**
  - Luminosity projection
  - Expected physics precisions
  - Future prospects

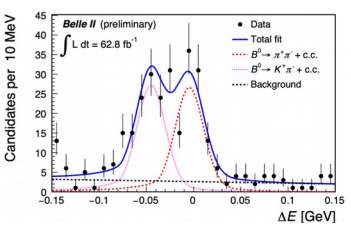


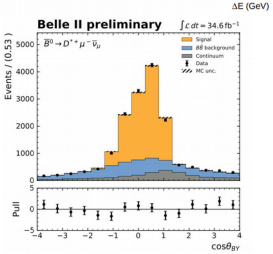


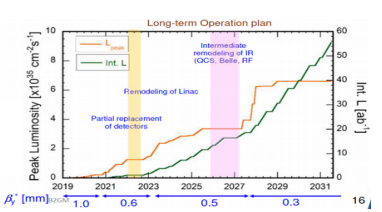


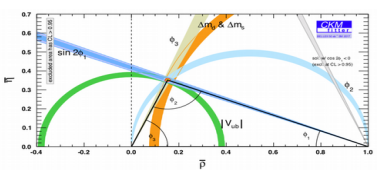


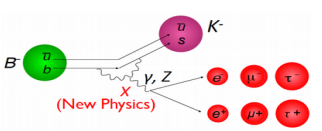


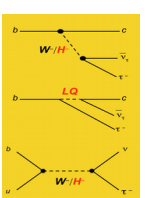


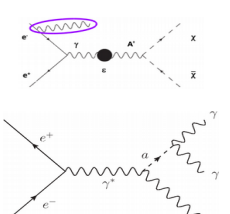




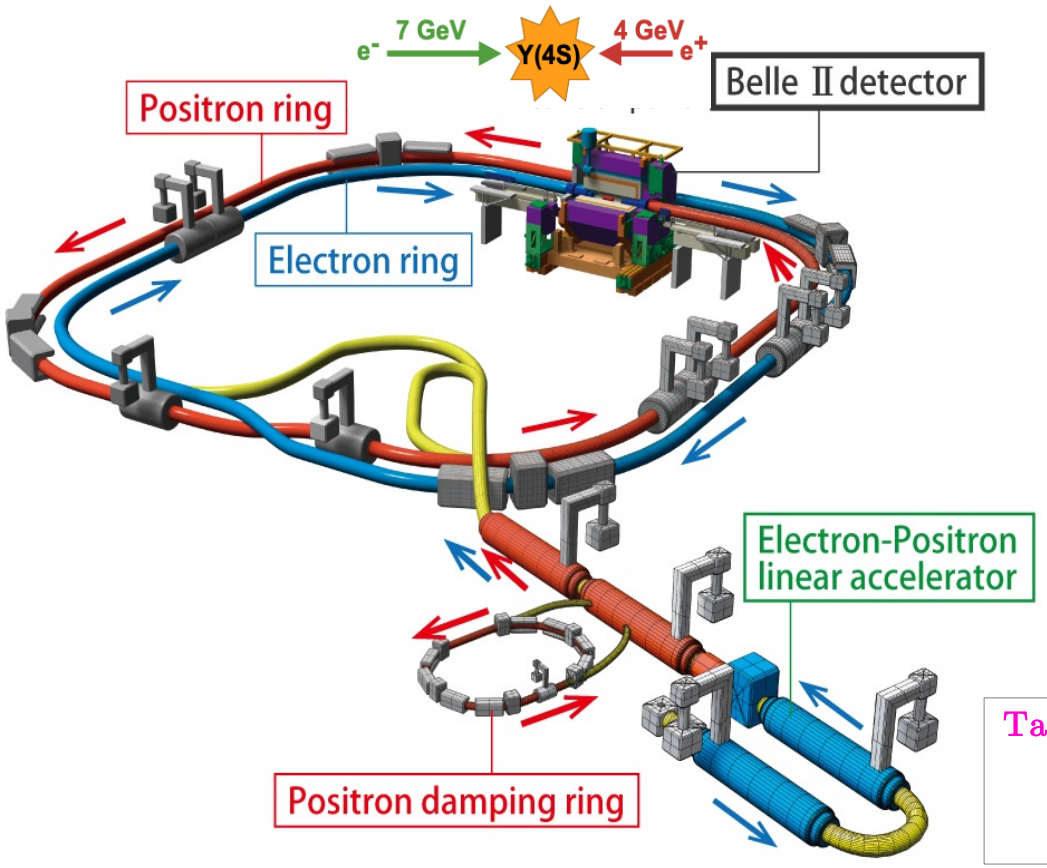


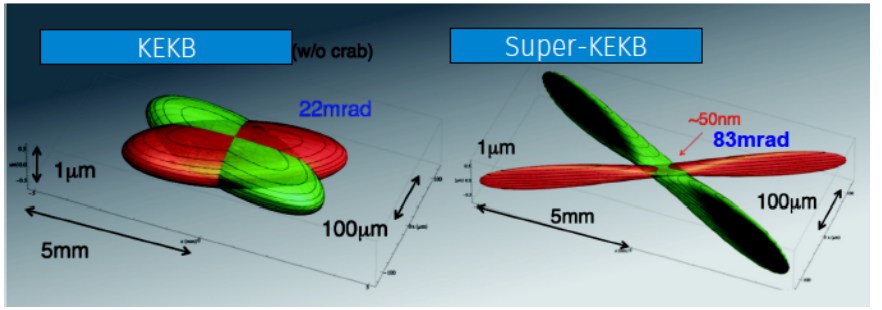






SuperKEKB Collider





Lorentz factor

Beam current

beam-beam parameter

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Geometrical reduction factor

Vertical beta function at the IP

Target: 50 ab^{-1} (50 x KEKB) by

× 1.5 higher beam current

× 20 lower βy^*

Consequences:

Deal with more severe background conditions

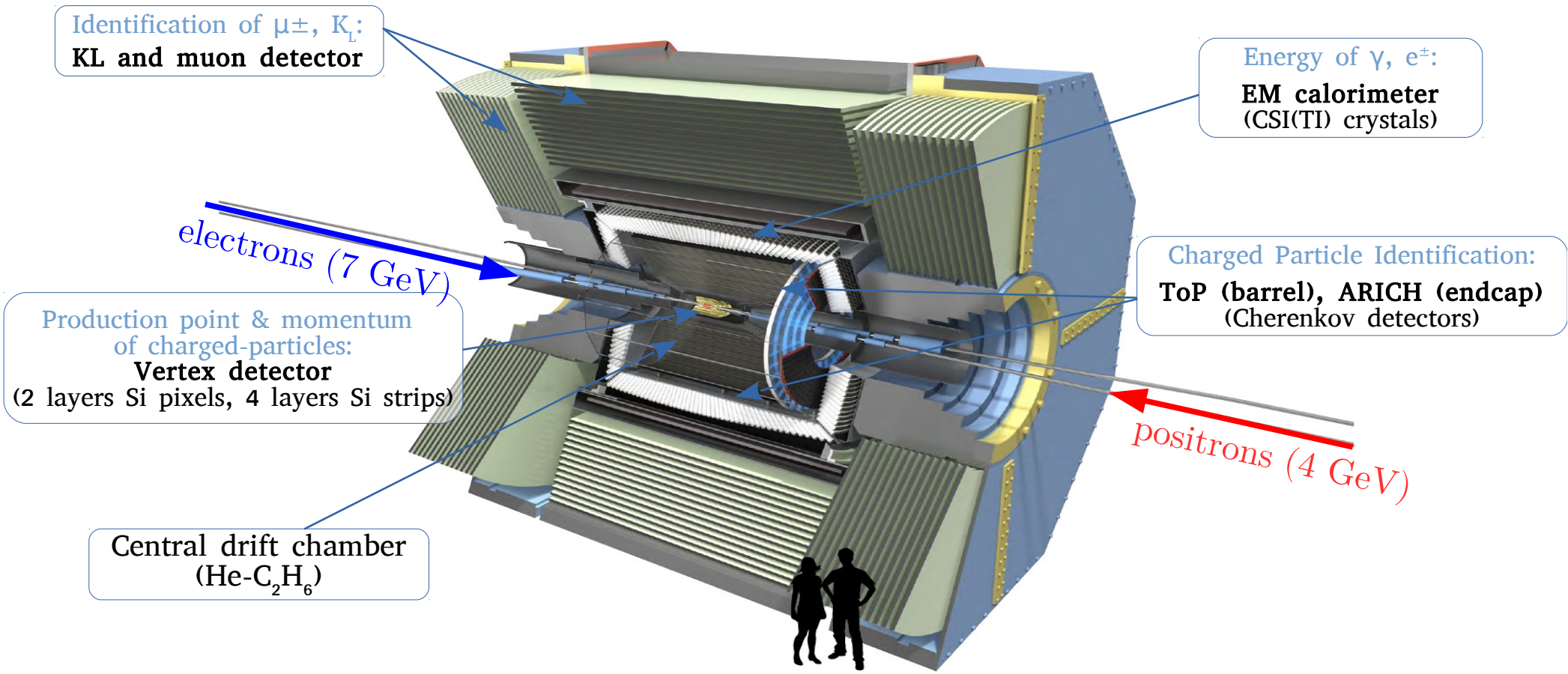
Lower boost ($\beta\gamma$: 0.43→0.28)

	Energy (GeV) LER/HER	β_y^* (mm) LER/HER	ε_x (nm) LER/HER	ξ_y LER/HER	φ (mrad)	I_{beam} (A) LER/HER	Luminosity ($cm^{-2}s^{-1}$) x 10^{34}
KEKB Achieved	3.5/8.0	5.9/5.9	18/24	0.13/0.09	11	1.6/1.2	2.11
SuperKEKB	4.0/7.0	0.27/0.3	3.2/2.4	0.09/0.09	41.5	2.8/2.0	65

Belle II detector upgrade

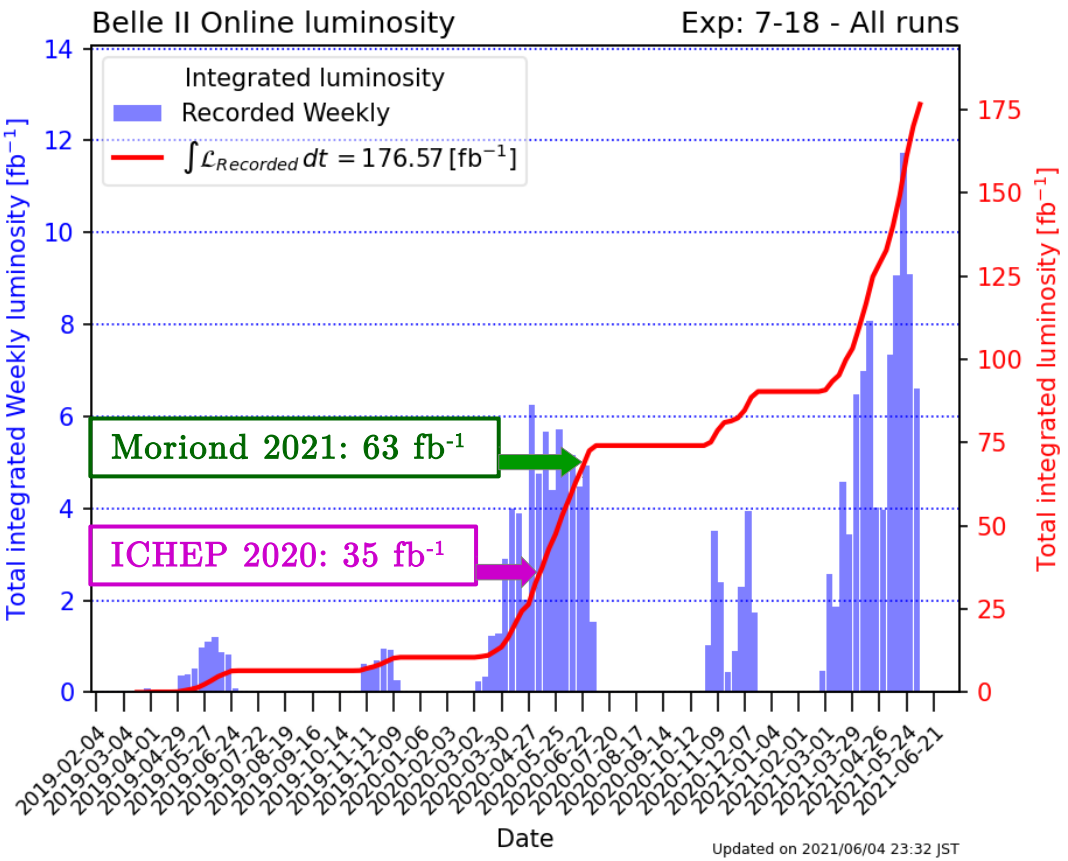
Belle II detector

New detector (only the structure, the super conducting magnets, and the crystals of the calorimeter are re-utilized)



Luminosity Status

- Achieved world record in June 2020 of instantaneous $L = 2.9 \times 10^{34} cm^{-2} s^{-1}$
- Regular data-taking since April 2019
- Despite Covid-19, collected ~*180 fb^{-1}* of data
- Belle: *1000 fb^{-1}*, *BaBar: 514 fb^{-1}*
- Already provided performance and physics results with 35 fb^{-1} and 63 fb^{-1} of data
- New results with 150 fb^{-1} coming soon



Mid-high momentum tracking performances

tag and probe with $e^+e^- \to \tau^+\tau^-$

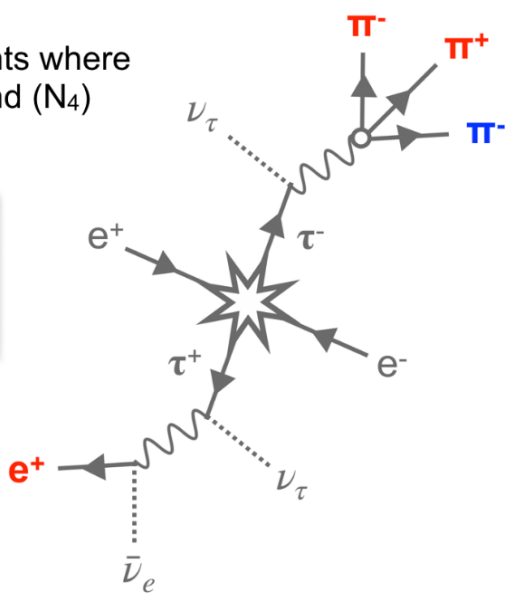
- Identify leptons on the tag-side
- Probe 3-prongs on the signal-side

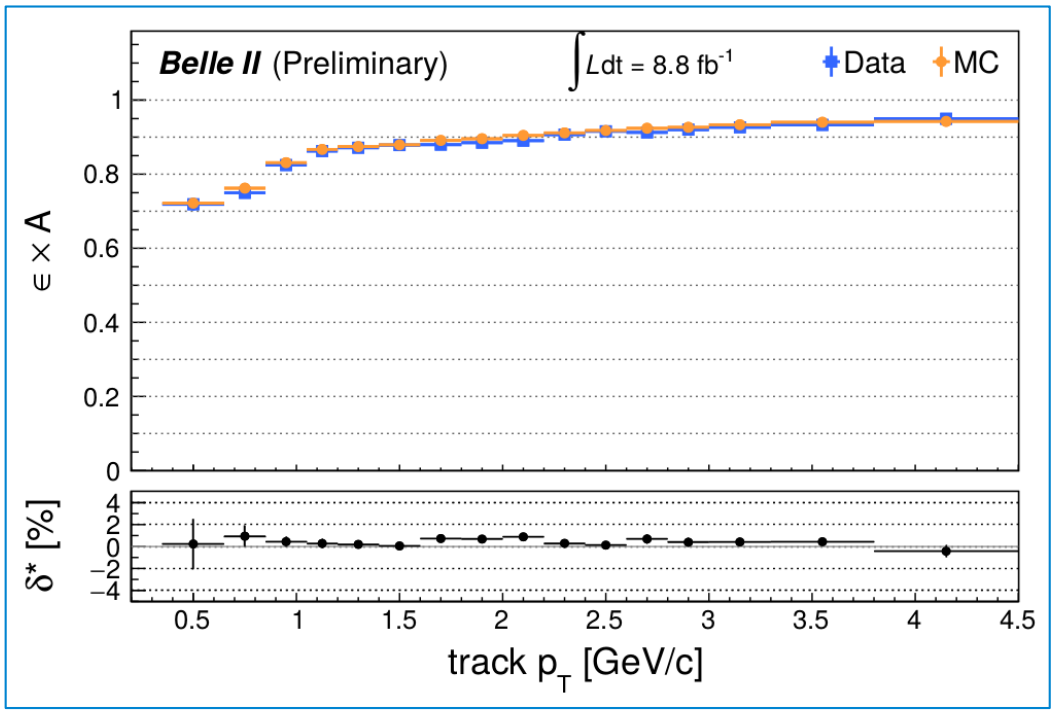
- **tag** = 3 good quality tracks with $\sum q = \pm 1$
- **probe** = look for 4th track that passes loose selections, and conserves charge ($\sum q = 0$)
- Count number of events where the probe track is found (N_4) and not found (N_3):

$$\epsilon \cdot A = \frac{N_4}{N_3 + N_4}$$

where:

- ϵ is tracking efficiency
- A is geometric acceptance





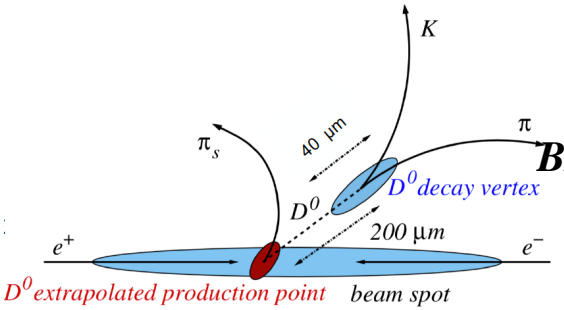
Data/MC disagreement $\delta^* = 1 - \frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{MC}}}$

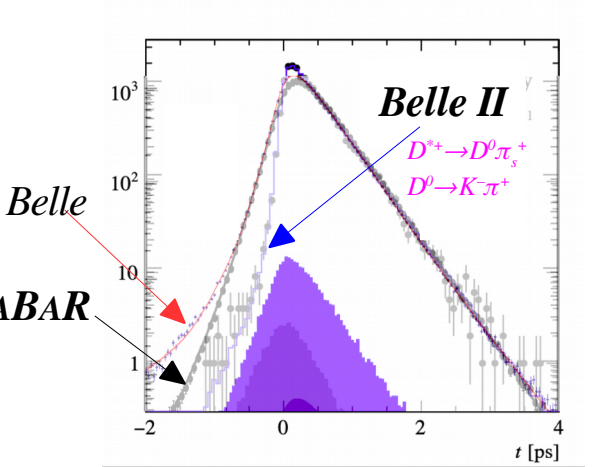
- Data/MC tracking efficiency mismatch compatible with zero
- Fake rate/track is in sub-percent level

Vertexing performances

D^0 lifetime:

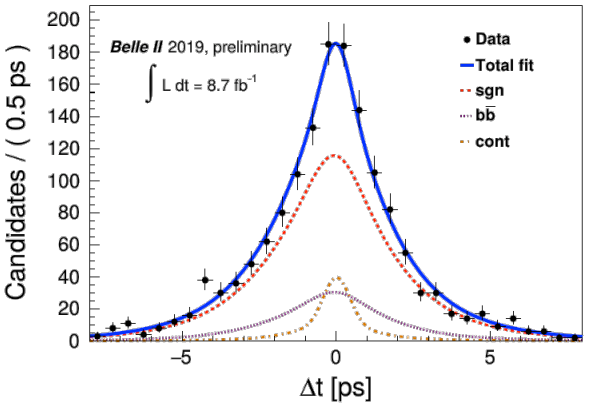
- D^0 identified using $D^{*+} \to D^0 \pi^+$
- Estimated vertex resolution ~ 40 μm
- Factor 2 improved t resolution @ Belle II (thanks to the pixel detector)
- L_{int} ~ 9.6 fb^{-1}: $\tau(D^0) = (412.3 \pm 2.0)$ fs, WA = (410.1±1.5) ps





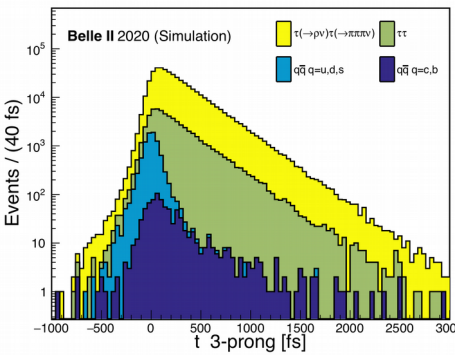
B^0 lifetime:

- Average distance between B vertices 200μm → 130 μm
- Estimated resolutions
  - Time: Δt ~ 1 ps ↔ Δt ~ 80 μm
  - Dominated by "tag"-side
- L_{int} ~ 8.7 fb^{-1}: $\tau(B^0) = (1.48 \pm 0.28_{stat} \pm 0.06_{syst})$ ps, WA = (1.519±0.004) ps



τ^- lifetime:

- 2x better proper decay time resolution than Belle
- Expect competitive results soon with only ~150 fb^{-1}



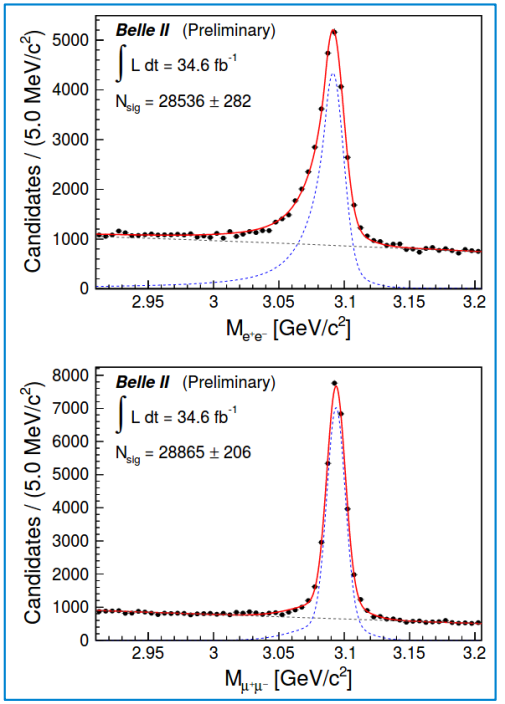
Particle identification: leptons

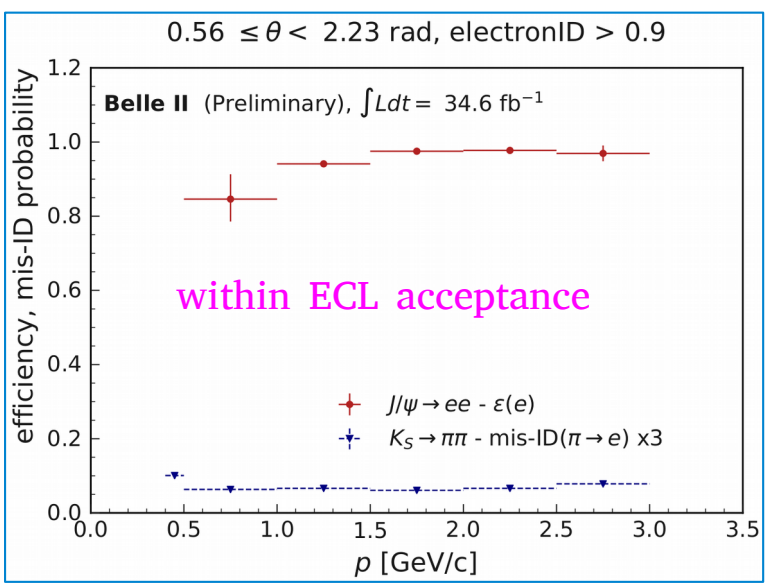
Using fully reconstructed events: J/ψ→ee, μμ

- Important for precision measurements of leptonic and semi-leptonic physics processes
- Identification mostly driven by K_L-μ detector, EM calorimeter, dE/dx (central drift chamber, vertex detector)
- Similar reconstruction efficiency
- Extracted for various lepton-ID and angular acceptances

$$\ell\text{ID} = \frac{\mathcal{L}_\ell}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}$$

Average identification efficiency ~94% (e-), ~90% (μ-), for a π mis-id rate of 2%(e-), 4% (μ-).



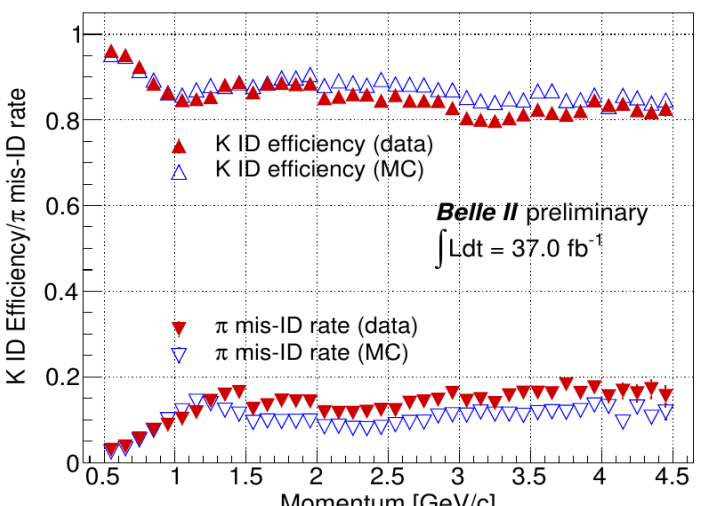


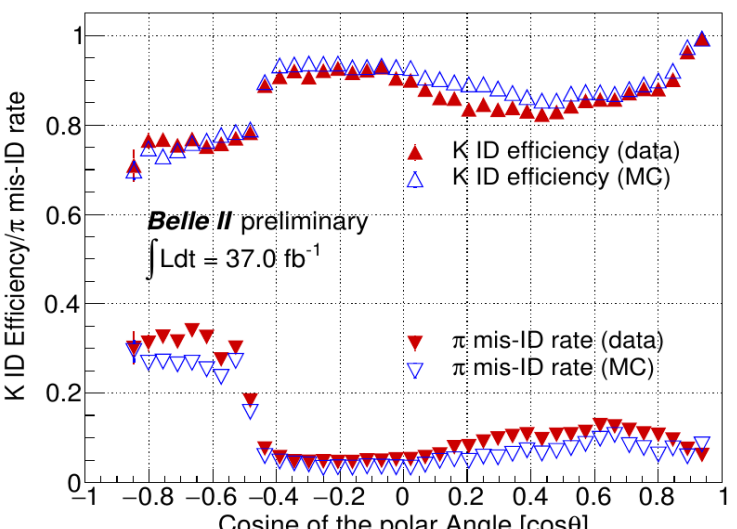
Particle identification: hadrons

$$K/\pi\text{–ID} = \frac{\mathcal{L}_{K/\pi}}{\mathcal{L}_K + \mathcal{L}_\pi}$$

Using fully reconstructed event: $D^{*+} \to D^0[K^-\pi^+]\pi^+$

- Better K/π separation necessary for precision measurement of hadronic and semi-leptonic physics parameters
- Identification driven by PID detectors, dE/dx (central drift chamber, vertex detector)
- $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$



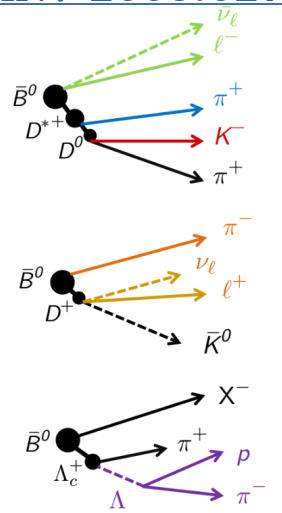


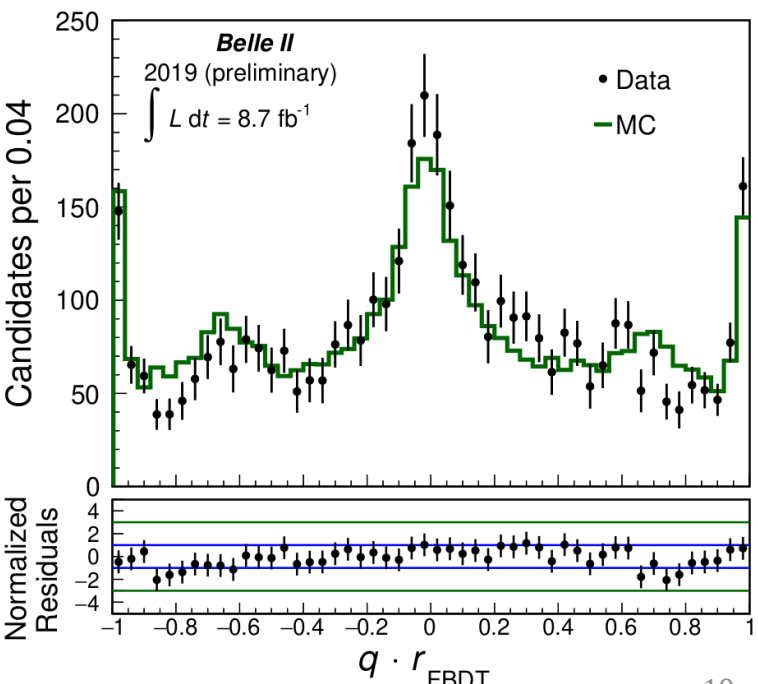
- Belle (KID>0.6): *85% efficiency, 7% fake rate*
- Belle II (KID>0.6): *83% efficiency, 10% fake rate*

Flavor tagging performance

arXiv: 2008.02707

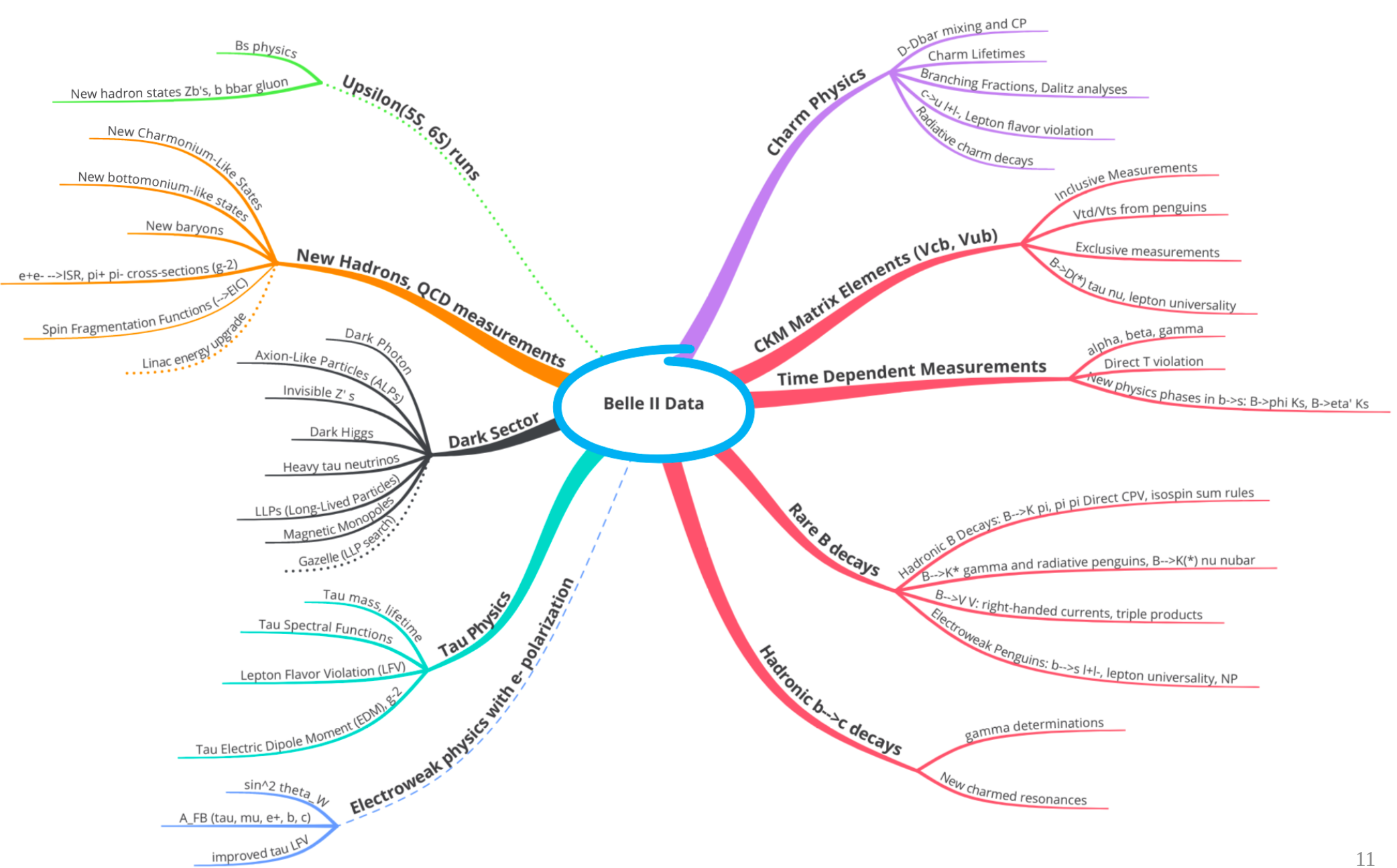
- Crucial tool for time-dependent CP violation analyses
- Complex MVA algorithm that combines informations such as charge and momentum of e, μ, π, K, Λ not associated with signal and returns flavour (q).dilution factor (r)
- Measured effective flavour tagging efficiency of neutral B: ε_{eff} = 33.8 ± 3.6(stat) ± 1.6(syst)%
- Belle: 30.1 ± 0.4 %
- Expectation: $\varepsilon_{eff} \approx$ 37 % based on MC.





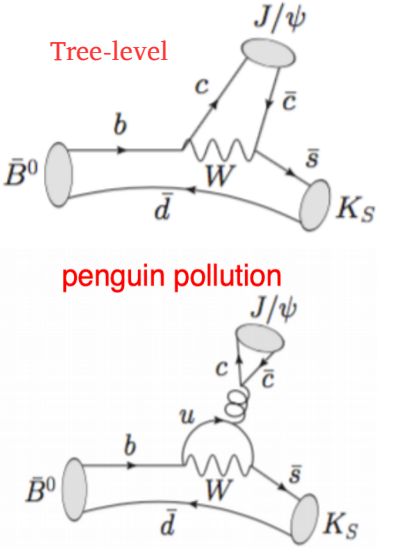
$$\varepsilon_{\text{eff}} = \sum_i \varepsilon_{\text{eff},i} = \sum_i \varepsilon_i \cdot (1 - 2w_i)^2$$

w: wrong tagging fraction


Belle II Data
Upsilon(5S, 6S) runs
Bs physics
New hadron states Zb's, b bbar gluon
New Hadrons, QCD measurements
New Charmonium-Like States
New bottomonium-like states
New baryons
e+e- -->ISR, pi+ pi- cross-sections (g-2)
Spin Fragmentation Functions (-->EIC)
Linac energy upgrade
Dark Sector
Dark Photon
Axion-Like Particles (ALPs)
Invisible Z' s
Dark Higgs
Heavy tau neutrinos
LLPs (Long-Lived Particles)
Magnetic Monopoles
Gazelle (LLP search)
Tau Physics
Tau mass, lifetime
Tau Spectral Functions
Lepton Flavor Violation (LFV)
Tau Electric Dipole Moment (EDM), g-2
Electroweak physics with e- polarization
sin^2 theta_W
A_FB (tau, mu, e+, b, c)
improved tau LFV
Charm Physics
D-Dbar mixing and CP
Charm Lifetimes
Branching Fractions, Dalitz analyses
c->u l+l-, Lepton flavor violation
Radiative charm decays
CKM Matrix Elements (Vcb, Vub)
Inclusive Measurements
Vtd/Vts from penguins
Exclusive measurements
B->D(*) tau nu, lepton universality
Time Dependent Measurements
alpha, beta, gamma
Direct T violation
New physics phases in b->s: B->phi Ks, B->eta' Ks
Rare B decays
Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
B-->K* gamma and radiative penguins, B-->K(*) nu nubar
B-->V V: right-handed currents, triple products
Electroweak Penguins: b-->s l+l-, lepton universality, NP
Hadronic b-->c decays
gamma determinations
New charmed resonances

A few recent Belle II physics results

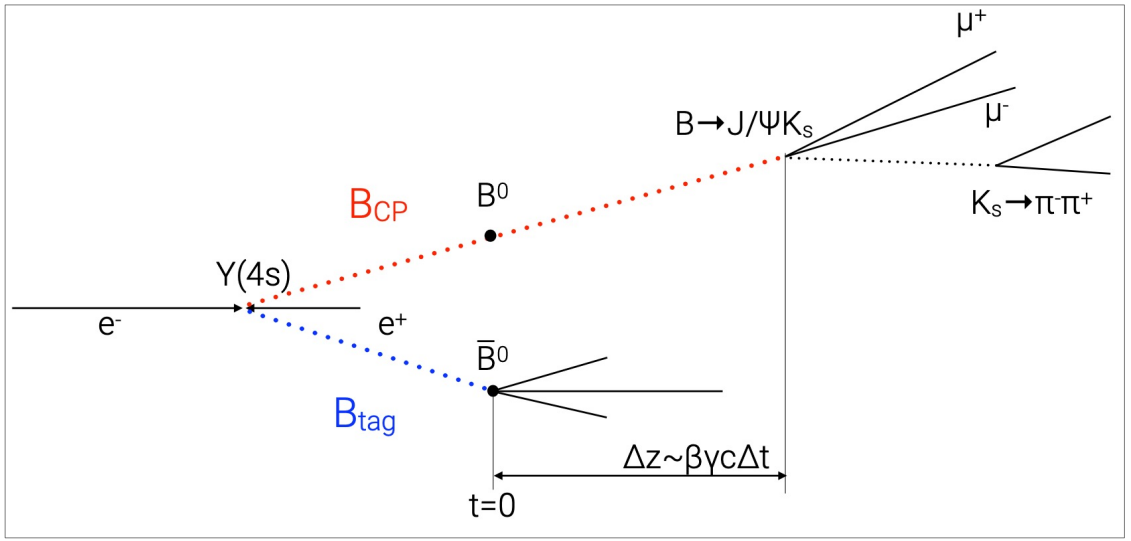
TDCPV ($B \to J/\psi K_S^0$)



- CPV in the interference between $B \to J/\Psi K_S$ and $B \to \bar{B}^0 \to J/\Psi K_S$ can be measured through the raw asymmetry

$$A_{CP} = A_{CP}^{raw} \cdot (1-2w) \otimes R(\Delta t) =$$

$$sin(\Delta m_d \Delta t) sin(2\phi_1) \cdot (1-2w) \otimes R(\Delta t)$$



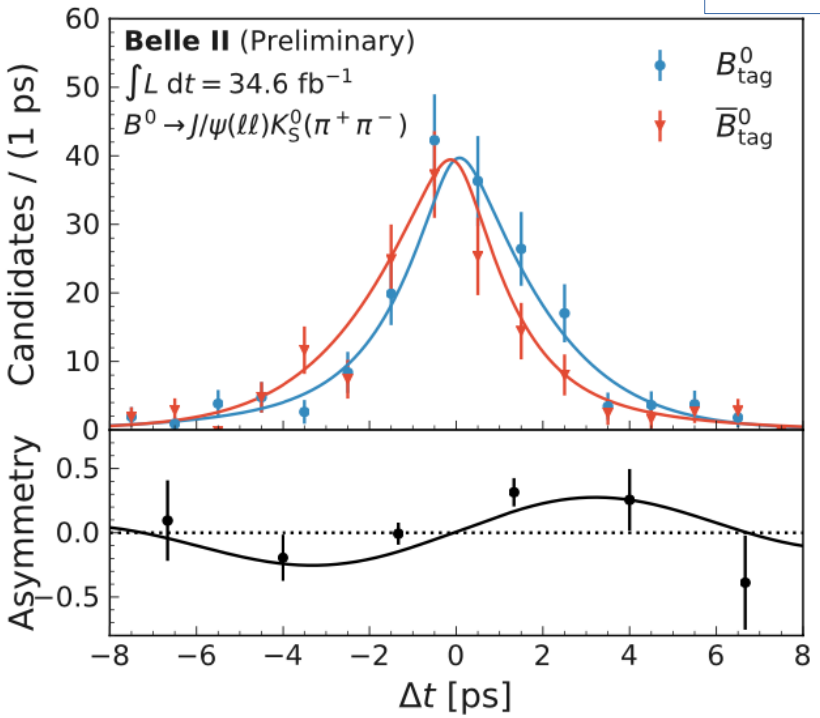
Measurement Ingredients

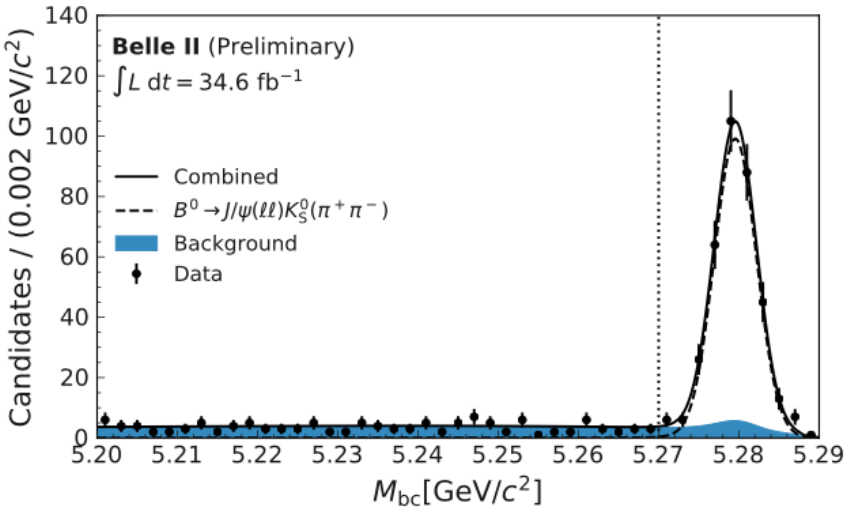
- Raw asymmetry: A_{CP}^{raw}
- Δt from the distance Δz between B_{CP} and B_{tag} ⇨ $\Delta t \sim \Delta z/\beta\gamma c$
- Wrong tag fraction (w) using flavor tagger
- mixing frequency: Δm_d

Belle II measurement of $\sin 2\Phi_1/\sin 2\beta$

- First time-dependent CP violation measurement at Belle II
- Decay mode: $B^0 \to J/\psi K_S$ with $J/\psi \to \mu\mu$, ee
- Belle II data set: 34.6 fb^{-1}

$$A_{CP}^{raw} = \frac{\Gamma(\bar{B}^0_{t=0} \to J/\Psi K_S) - \Gamma(B^0_{t=0} \to J/\Psi K_S)}{\Gamma(\bar{B}^0_{t=0} \to J/\Psi K_S) + \Gamma(B^0_{t=0} \to J/\Psi K_S)} = sin(\Delta m_d \Delta t) sin(2\phi_1)$$





$\text{Sin}2\varphi_1 \approx S_f = (0.55 \pm 0.21\ (\text{stat}) \pm 0.04\ (\text{syst}))\ ps^{-1}$

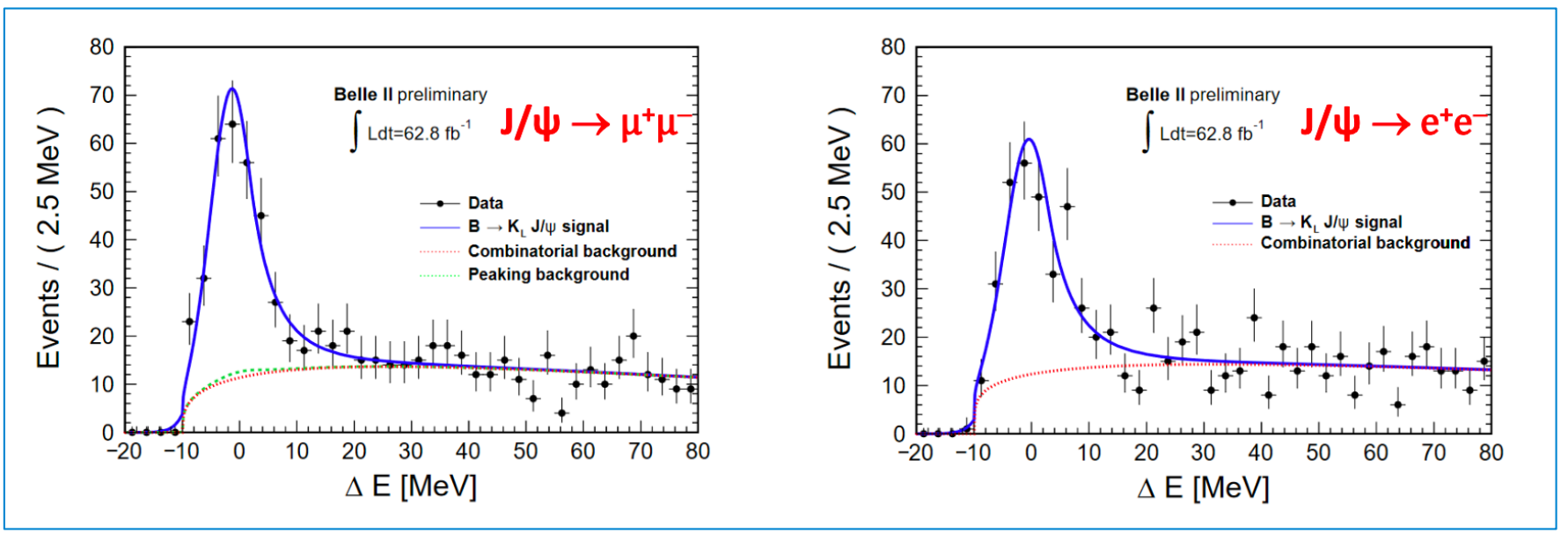
2.71σ away from 0 (accounting for the stat uncertainty only)

BELLE2-NOTE-PL-2020-11

WA: 0.685 ± 0.019

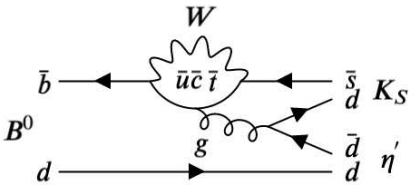
First measurement of $B^0 \to J/\psi K_L$ at Belle II

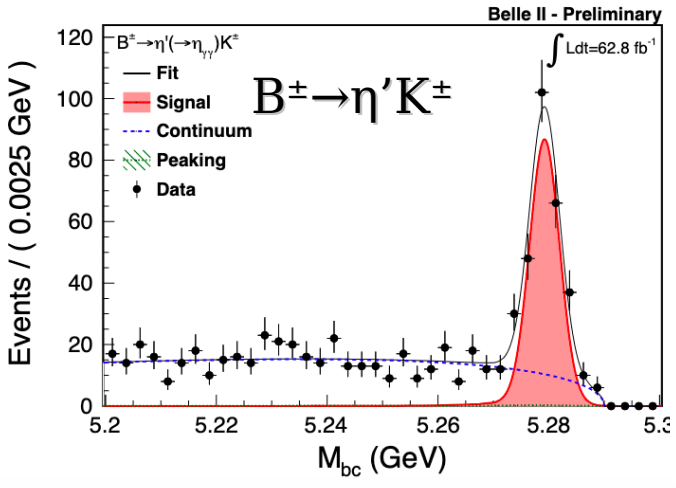
- An additional channel to provide measurement of $\sin(2\Phi_1)$
- $\eta_{CP}(K_L) = -\eta_{CP}(K_S)$
- Signal yield of $(7.3 \pm 0.4)/fb^{-1}$, consistent with Belle
- Next: time-dependent analysis for CPV measurement

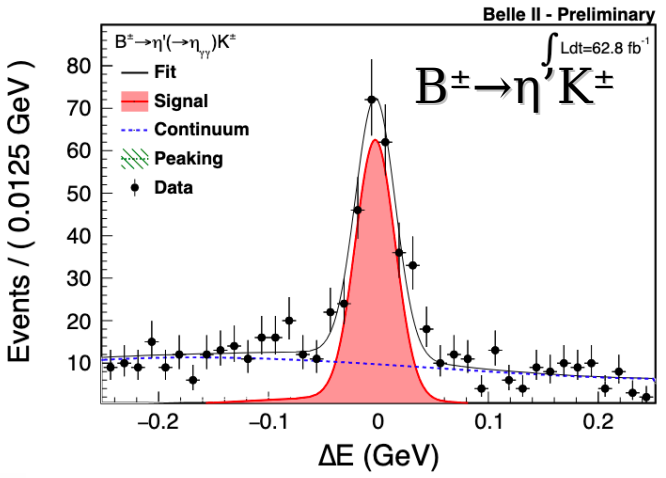


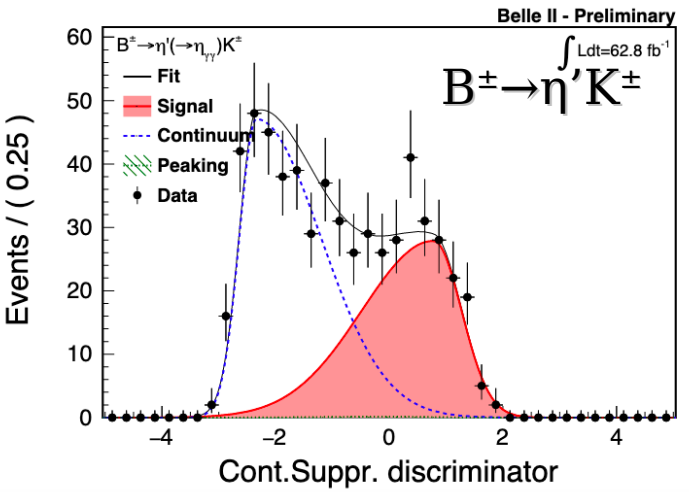
First measurement of B→ η'K_S at Belle II

Also covered by Radek Žlebčík









Channel	This analysis $\mathcal{B}$ $(\times 10^6)$	World average
$B^{\pm} \to \eta' K$	$63.4\ ^{+3.4}_{-3.3}(\text{stat}) \pm 3.4(\text{syst})$	70.4 ± 2.5
$B^{0} \to \eta' K^{0}$	$59.9\ ^{+5.8}_{-5.5}(\text{stat}) \pm 2.7(\text{syst})$	66 ± 4

- Penguin dominated mode
- Hence TDCPV is expected to be sensitive to NP

BELLE2-CONF-PH-2021-007 arXiv:2104.06224

Prospects for $\sin 2\Phi_1/\sin 2\beta$ measurements

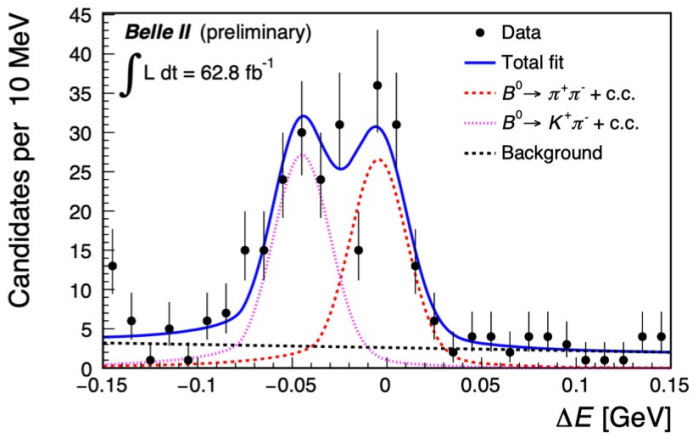
PTEP 2019, 123C01

	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK^0_S	0.21	0.14	0.08	0.06	0.024	0.020
$K^0_S \pi^0 \gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K^0_S \pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

Belle II measurement towards Φ_2/α

Detail covered by Ching-Hua Li

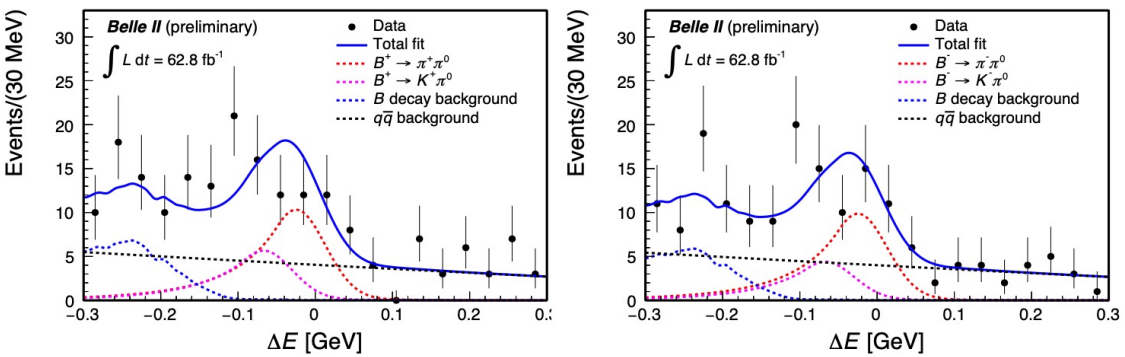
$B^0 \to \pi^+\pi^-$



Benchmarks PID and ΔE resolution.

$\mathcal{B}(B^0 \to \pi^+\pi^-) = [5.8 \pm 0.7(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-6}$

$B^+ \to \pi^+\pi^0$



Probes π^0 reconstruction and PID.

$\mathcal{B}(B^+ \to \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-6}$

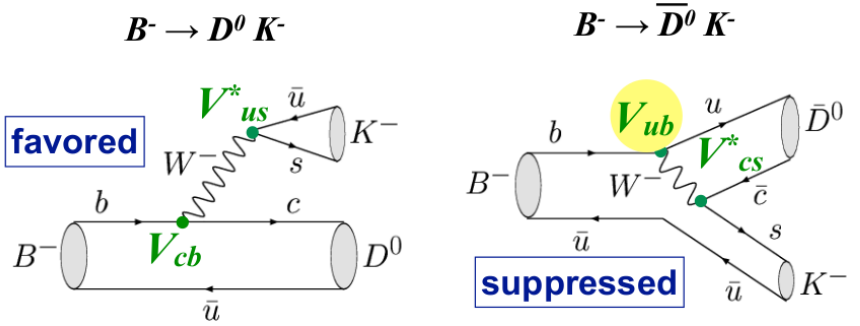
$A_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$

arXiv:2105.04111

Belle II measurement towards Φ_3/γ

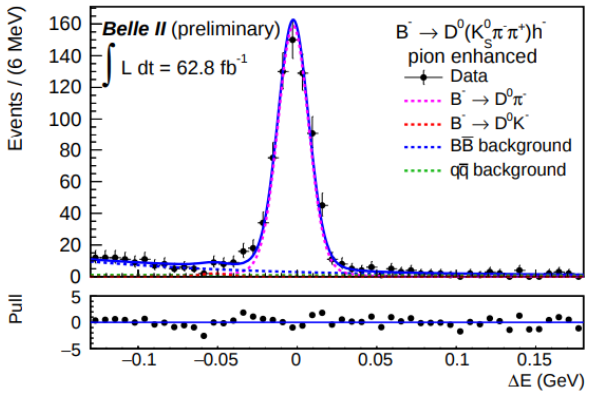
arXiv:2104.03628

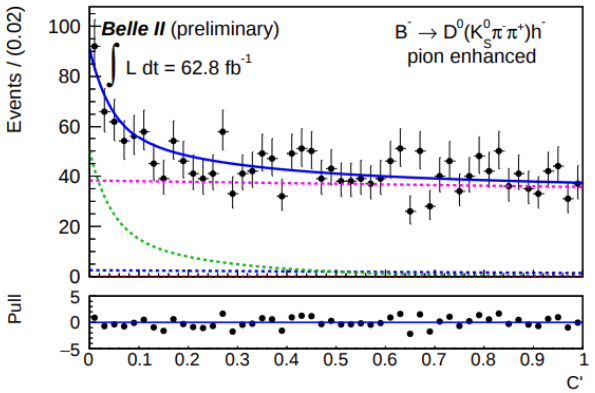
- Measured via the interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$ with various D^0 final states:
  - CP modes: K^-K^+, $\pi^-\pi^+$, $K_S^0\pi^0$
  - DCS modes: $K^+\pi^-$, $K^+\pi^-\pi^0$
  - Self-conjugate modes: $K_S^0\pi^-\pi^+$, $K_S^0K^-K^+$, $K_S^0\pi^-\pi^+\pi^0$
- $B^- \to D(K_S^0\pi^+\pi^-)K^-$ is the most sensitive channel to determine Φ_3

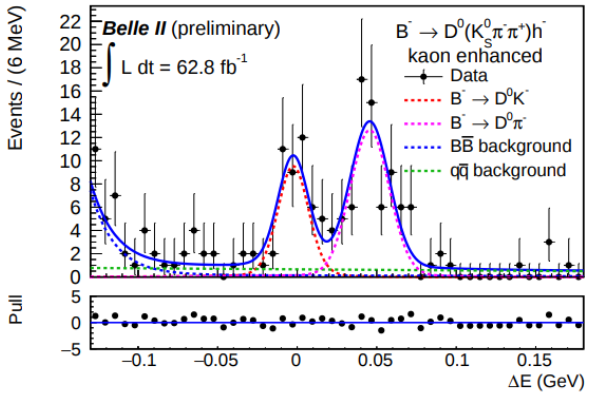


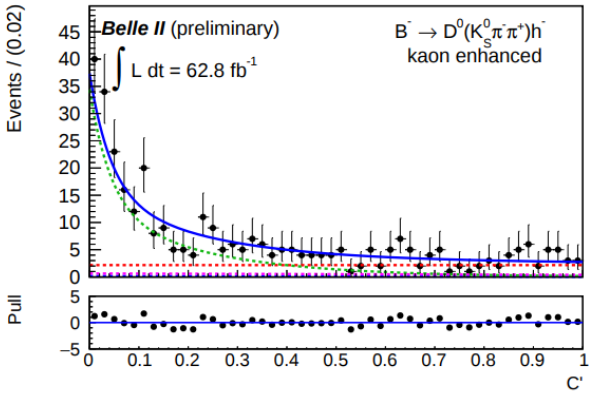
$$\frac{\mathcal{A}^{\text{suppr.}}(B^- \to \overline{D^0} K^-)}{\mathcal{A}^{\text{favor.}}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \phi_3)}$$

Results of $B \to D^{(*)}h$ using 62.8 fb^{-1} of Belle II data









- Simultaneous fit for B→ Dh (h = π/K)
- Improved ΔE resolution - better DK/Dπ separation than Belle
- Expected precision: $\delta\Phi_3 < 1.5^o$ predominantly from GGSZ $D \to K_S^0\pi^+\pi^-$

	$B^- \to D^0(K^-\pi^+)h^-$	$B^- \to D^0(K^0_S\pi^+\pi^-)h^-$	$\bar{B}^0 \to D^+h^-$	$B^- \to D^{*0}h^-$	$\bar{B}^0 \to D^{*+}h^-$
$R^{(*)+/0}$ $(\times 10^{-2})$	$7.66 \pm 0.55\ ^{+0.11}_{-0.08}$	$6.32 \pm 0.81\ ^{+0.09}_{-0.11}$	$9.22 \pm 0.58 \pm 0.09$	$6.80 \pm 1.01 \pm 0.07$	$5.99 \pm 0.82\ ^{+0.17}_{-0.08}$

$\Gamma(B \to DK)/\Gamma(B \to D\pi)$

Results are compatible with the world-average values arXiv:2104.03628

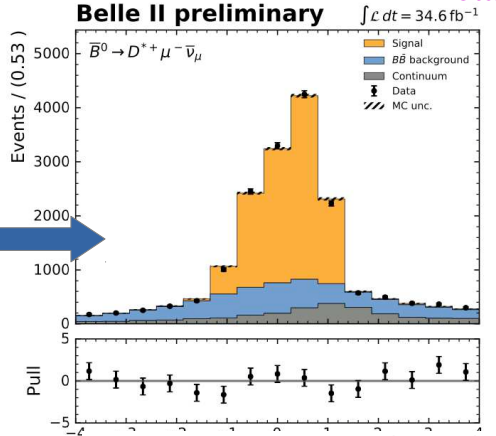
Semileptonic and leptonic B decays: Belle II Status

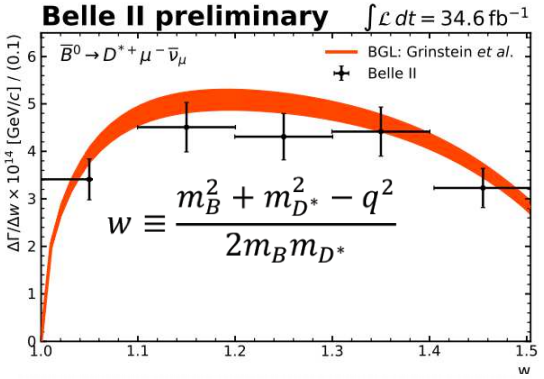
Detail covered by Qi-Dong ZHOU

|Vcb| from B→D*lν (untag)

- Signal extracted using $\cos\theta_{BY}$ distribution
- $B(B^0 \to D^{*-} l^+ \nu) = (4.60 \pm 0.05(\text{stat}) \pm 0.17(\text{sys}) \pm 0.45(\pi_s))\%$ (consistent with PDG)

arXiv:2008.07198

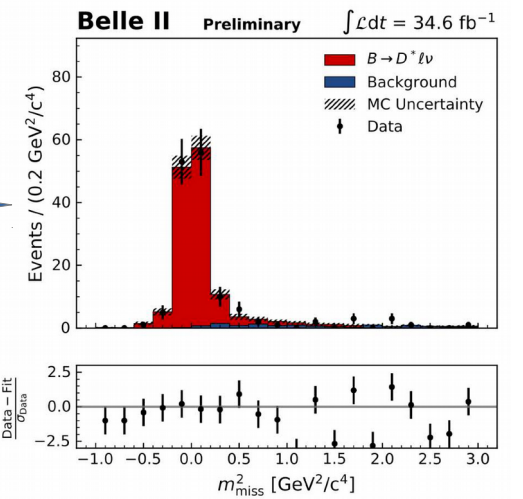




|Vcb| from B→D*lν (tagged)

- Signal extracted using m^2_{miss} distribution
- Hadronic tag using full event interpretation (FEI) algorithm
- $B(B^0 \to D^{*-} l^+ \nu) = (4.51 \pm 0.41(\text{stat}) \pm 0.27(\text{sys}) \pm 0.45(\pi_s))\%$ (consistent with PDG)

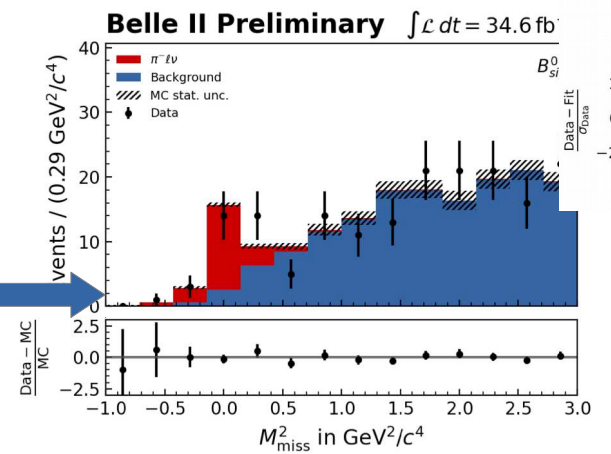
arXiv:2008.10299



|Vub| from B→πlν (tagged)

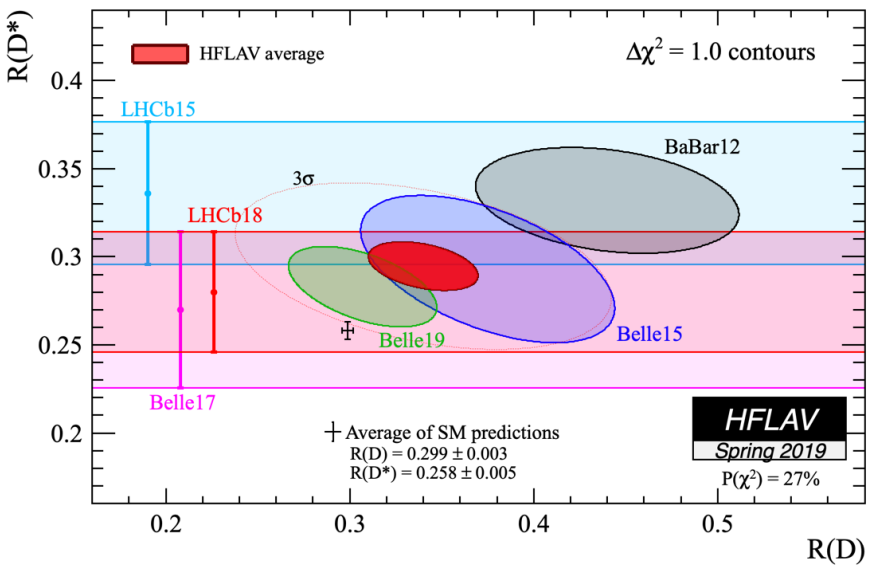
- Signal extracted using m^2_{miss} distribution
- Hadronic tag using FEI algorithm
- $B(B^0 \to \pi^- l^+ \nu) = (\ 1.58 \pm 0.43(\text{stat}) \pm 0.07\ (\text{sys})) \times 10^{-4}$ (consistent with PDG)

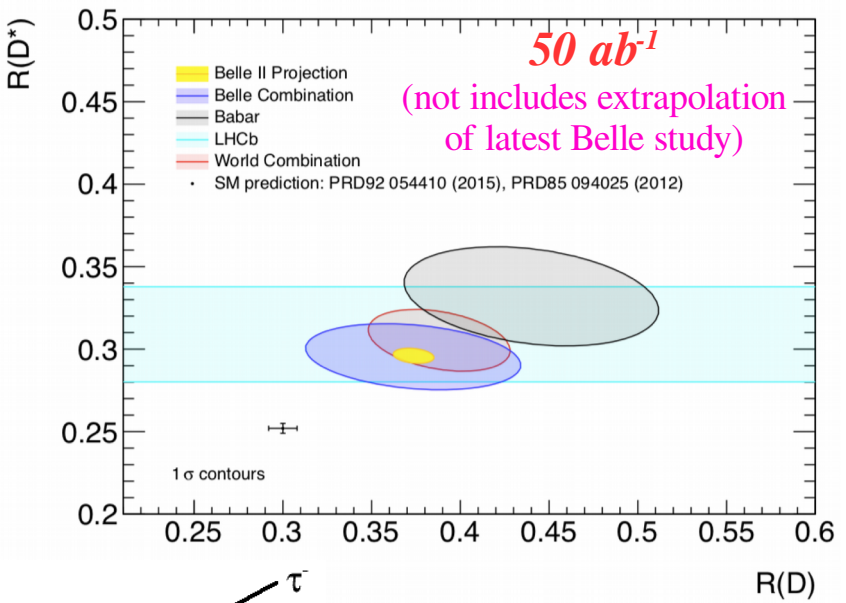
arXiv:2008.08819



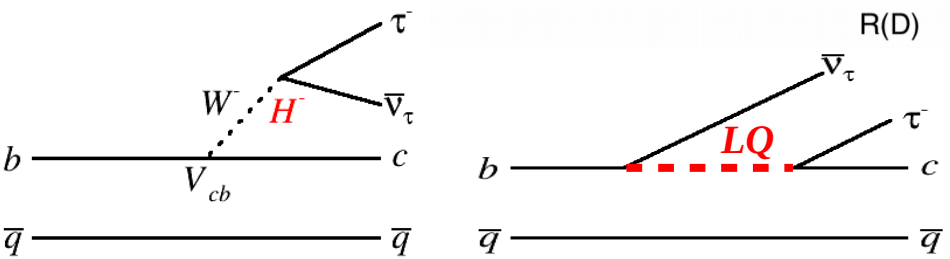
One of the hot topic of Belle II:

$B \to D^{*} \tau \nu$ a powerful probe for new physics





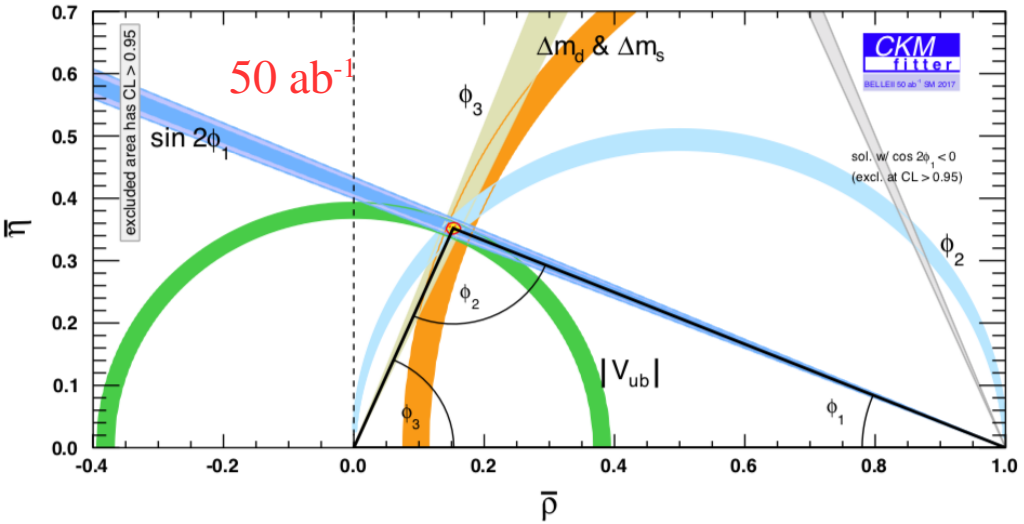
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}l\nu)} \quad (l = e, \mu)$$



- 3.1σ discripancy
- Sensitive to new physics models through charged Higgs and leptoquarks at tree level diagram
- Belle II will validate the excess with better sensitivity

Semileptonic and leptonic B decays: Belle II Target

- Precise measurements of the CKM matrix element are crucial for pinning down the allowed level of *CP* violation in the SM
- Anomalies in $|V_{ub}|$, $|V_{cb}|$, $B \to D^{*}\tau\upsilon$ needs to be understood
- Purely leptonic modes are Belle II focus for luminosity > 1 ab^{-1}



Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\|V_{cb}\|$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	–
$\|V_{cb}\|$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\text{ex.}} \pm 1.4\%_{\text{th.}})$	1.8%	1.4%
$\|V_{ub}\|$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$	3.4%	3.0%
$\|V_{ub}\|$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\text{ex.}} \pm 3.0\%_{\text{th.}})$	2.4%	1.2%
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$91 \cdot (1 \pm 24\%)$	9%	4%
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	20%	7%
$R(B \to D\tau\nu)$ (Had. tag)	$0.374 \cdot (1 \pm 16.5\%)$	6%	3%
$R(B \to D^{*}\tau\nu)$ (Had. tag)	$0.296 \cdot (1 \pm 7.4\%)$	3%	2%

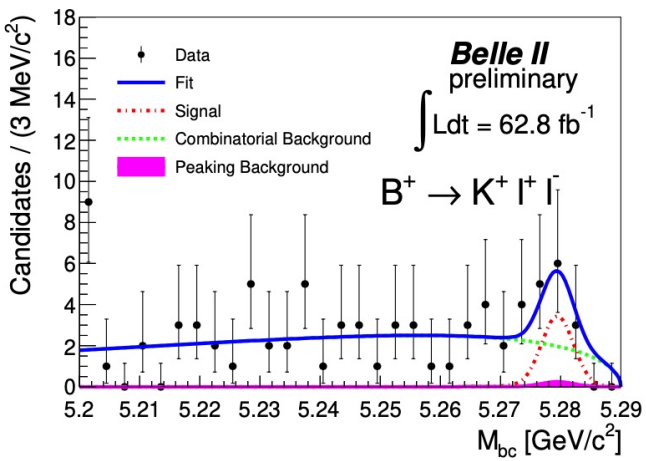
The Belle II Physics Book, PTEP 2019, 123C01

R(K) prospects at Belle II

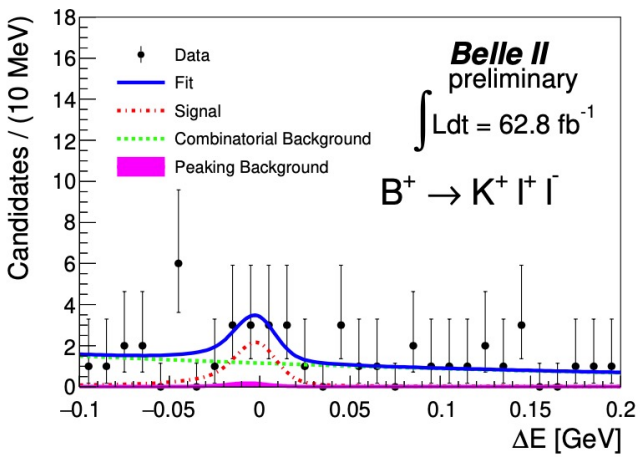
First Belle II measurement of $B^+ \to K^+ l^+ l^-$

- Signal yield extracted with 2D ML

  fit to M_{bc} and ΔE: $8.6^{+4.3}_{-3.9}(\text{stat}) \pm 0.4(\text{syst})$
- Significance: 2.7 sigma
- Peaking background from $B^+ \to K^+ \pi^+ \pi^-$



$$M_{bc} = \sqrt{E^2_{beam} - |\overrightarrow{p_B}|^2}$$



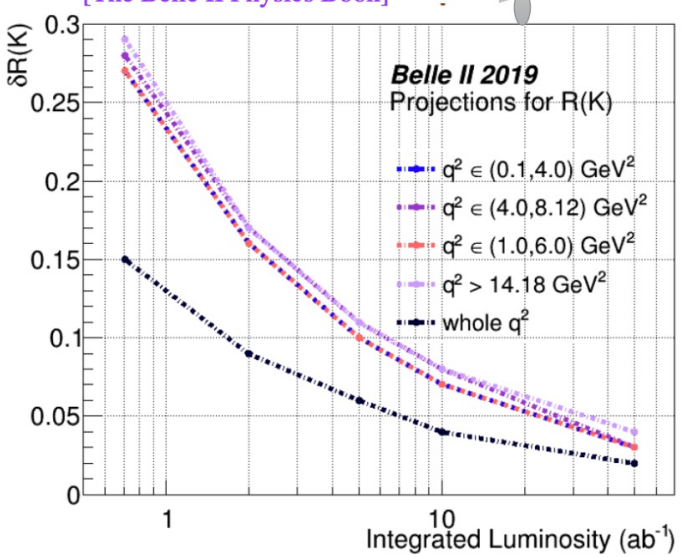
$$\Delta E = E_B - E_{beam}$$

Prospects for R(K)

- Measurement is going to be statistically limited for foreseeable future with leading systematics due to lepton ID~0.4%
- In order to confirm LHCb's R(K) anomaly (5 sigma) need at least 20 ab^{-1}

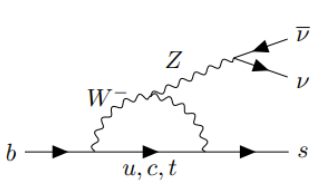
~2028

[The Belle II Physics Book]

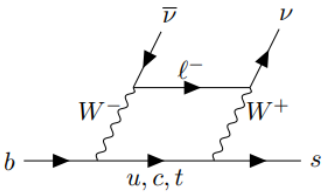


Search for $B^+ \to K^+ \nu\nu$ decays using an inclusive tagging method at Belle II

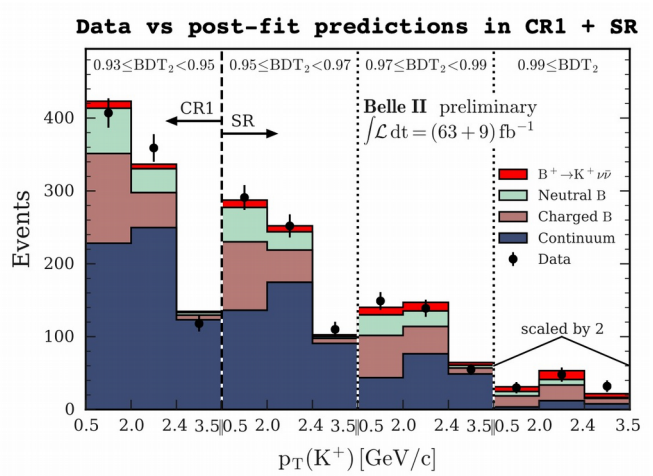
- SM branching fraction of $B^+ \to K^+ \nu\nu$: $(4.6 \pm 0.5) \times 10^{-6}$ (arXiv:1409.4557)
- Best upper limit by BaBar
- Belle II inclusive tag
  - New method
  - Signal track with highest p_T
  - Inclusive tagging method ⇒ 4 x higher signal efficiency than before
  - Analysis validated in $B \to J/\psi\, K$ decays with J/ψ excluded from reconstruction
- Signal extracted using a binned ML fit to on- and off-resonance data with 175 nuisance parameters
- 90% CL upper limit: 4.1×10^{-5}
- Submitted to Phys. Rev. Lett (arXiv:2104.12624)



(a) Penguin diagram



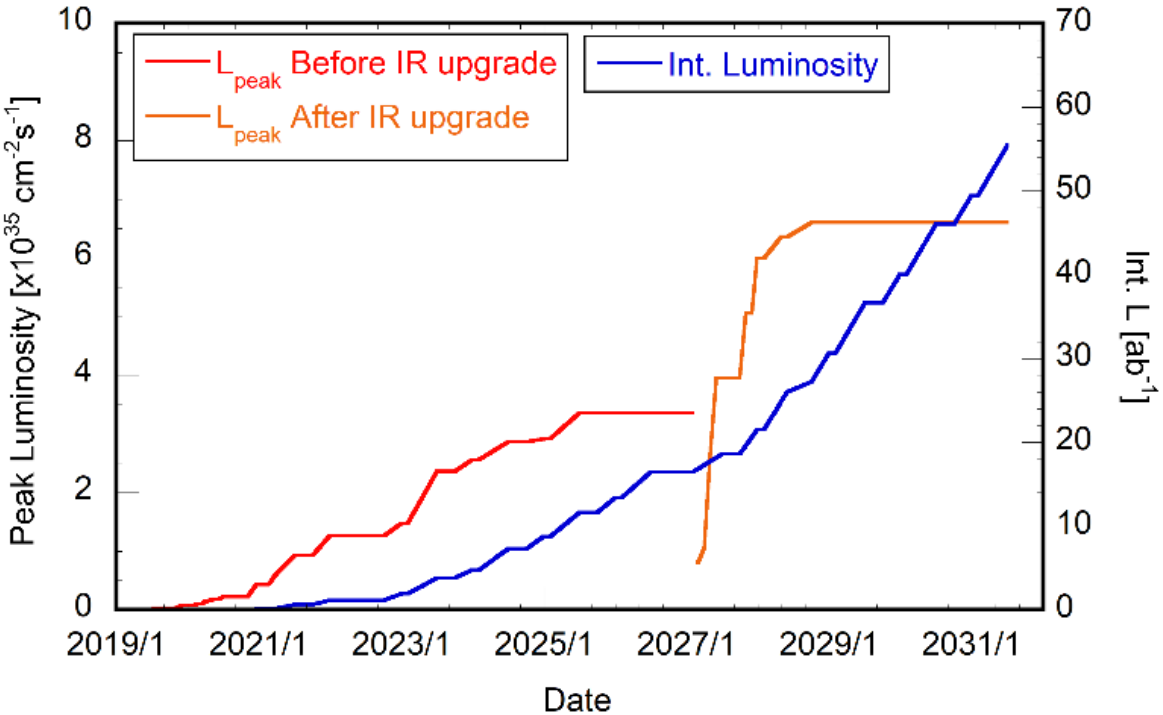
(b) Box diagram



Experiment	Year	Observed limit on $BR(B^+ \to K^+ \nu\bar{\nu})$	Approach	Data $[fb^{-1}]$
BABAR	**2013**	$< 1.6 \times 10^{-5}$ [Phys.Rev.D87,112005]	**SL + Had tag**	429
Belle	**2013**	$< 5.5 \times 10^{-5}$ [Phys.Rev.D87,111103(R)]	**Had tag**	711
Belle	**2017**	$< 1.9 \times 10^{-5}$ [Phys.Rev.D96,091101(R)]	**SL tag**	711
Belle II *preliminary*	**2021**	$< 4.1 \times 10^{-5}$	**Inclusive tag**	63

Luminosity Prospects:

- Goal: 50 ab^{-1} by next decade
- Short-term plan:
  - By summer 2022: 720 fb-1 (~ Belle dataset)
  - Summer 2022-spring 2023: full new pixel detector installation → important to maintain good vertex resolution at high luminosity
- Long term plan:
  - By 2026: ~15 ab -1 (~ 20 x Belle dataset)
  - 2026: QCS/IR modification necessary to reach design luminosity



Big Picture

- The SM is very successful but leaves unanswered questions
- The Belle II experiment at SuperKEKB aims to probe new physics beyond the SM with ultimate precision measurement of heavy flavor decays by taking the performance to a new level:
  - **50 times integrated luminosity wrt. previous record**
  - **21st - century detector technology**
  - **Probing new physics with unprecedented precision**
- Early results demonstrate the full operation/processing/physics chain
- Look forward to new physics results from Belle II !

More results not covered

- Radiative and electroweak Penguin B decays
  - Study of B $\rightarrow$K*γ decays at Belle II ➡ BELLE2-NOTE-PL-2019-021
- Dark sector (See talk by Laura Zani)
  - Search for an Invisibly Decaying Z′ at Belle II ➡ Phys. Rev. Lett. 124, 141801 (2020)
  - Search for Axion-Like Particles at Belle II ➡ Phys. Rev. Lett. 125, 161806 (2020)
- Tau physics ➡ Covered by Robert KARL "Tau mass measurement and tau physics prospects at Belle II"

THANK YOU!