Belle II

Beauty physics at Belle II

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On behalf of the Belle II collaboration

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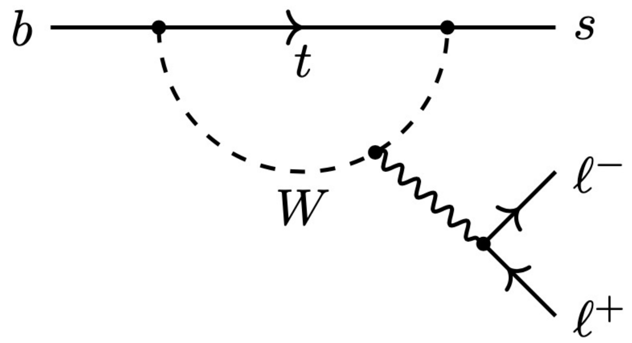
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

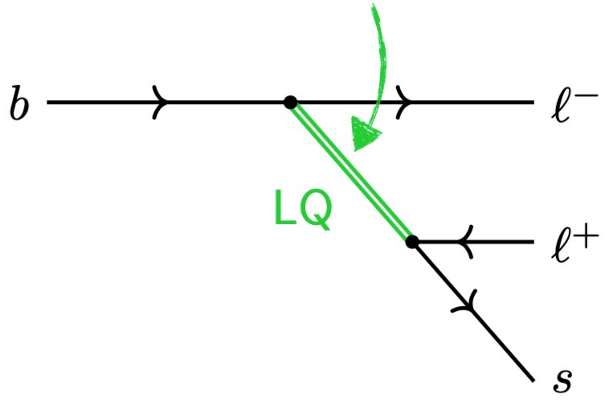
The beauty of B physics

- The power of indirect searches
  - GIM mechanism (1970): charm presence invoked from the suppression of $K^0 \rightarrow \mu\mu$ before the discovery of J/ψ (1974)
  - Kobayashi-Maskawa (1973): 3 generation quark mixing needed to explain CP violation in neutral kaon decays
  - Top mass limit >50 GeV infered from B^0-$\overline{B}^0$ mixing (1987) before actual top discovery top (1995)
- Because of the large b-quark mass, loop and rare B decays offer a rich potential for indirect searches of New Physics (NP)

$b \rightarrow s\ell^+\ell^-$ are FCNC processes that can only occur via loop in the SM



observables are altered by new (virtual) particles



SuperKEKB and Belle II

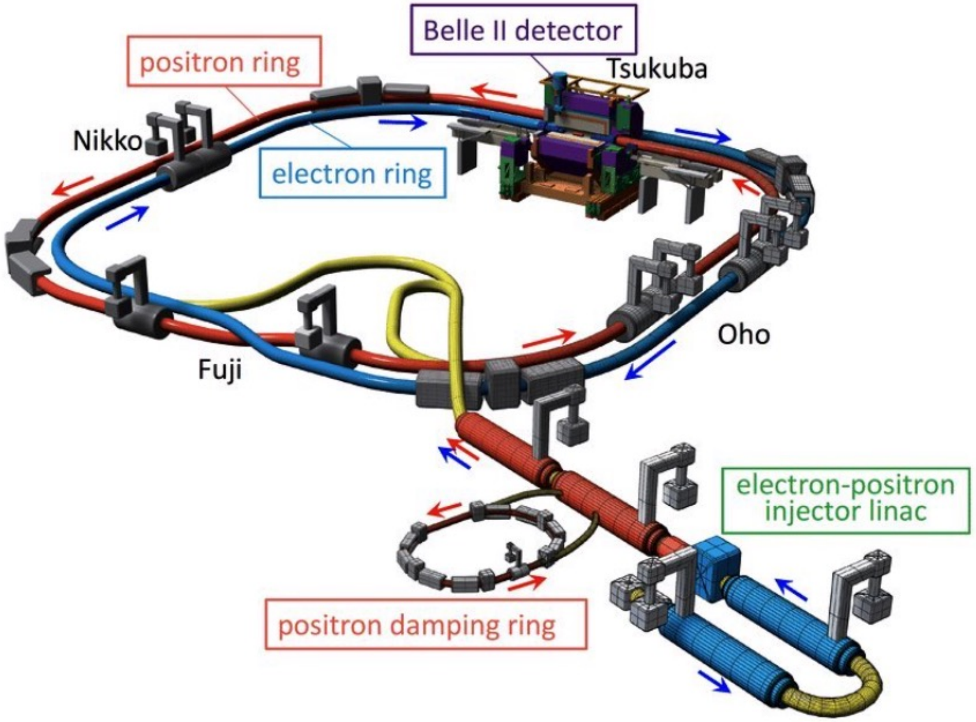
The SuperKEKB machine

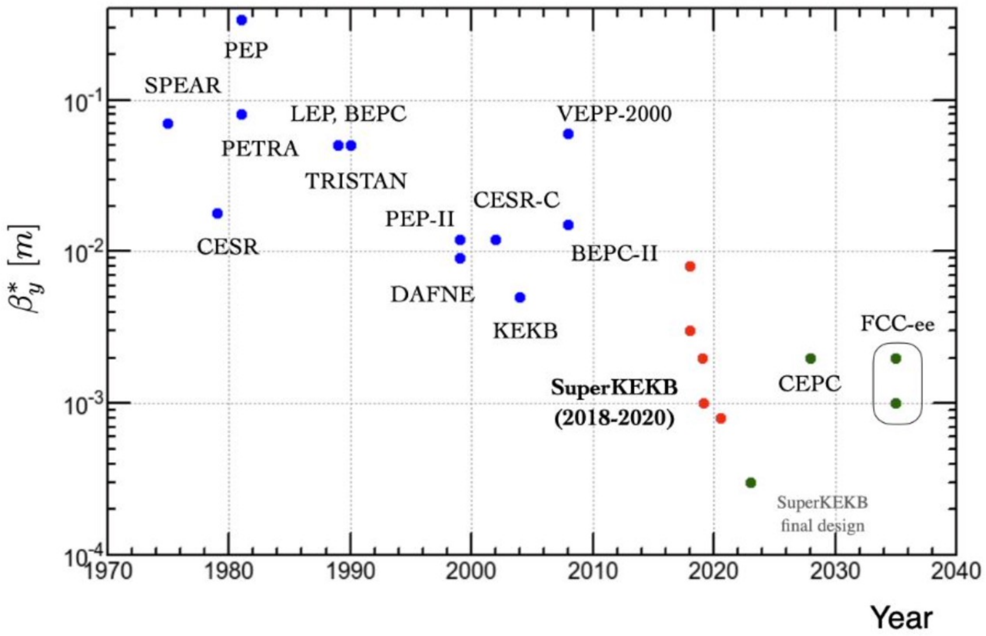
- Asymmetric e^+e^- collider optimized for luminosity
    - On-threshold production of $B\overline{B}$ (10.58 GeV)
    - Aims at an integrated luminosity of 50/ab (about 50 times the B factory data samples)
    - This is achieved by a x20 times smaller β_y^* (nano-beam scheme) and x1.5 times higher beam currents compared to KEKB

beam current

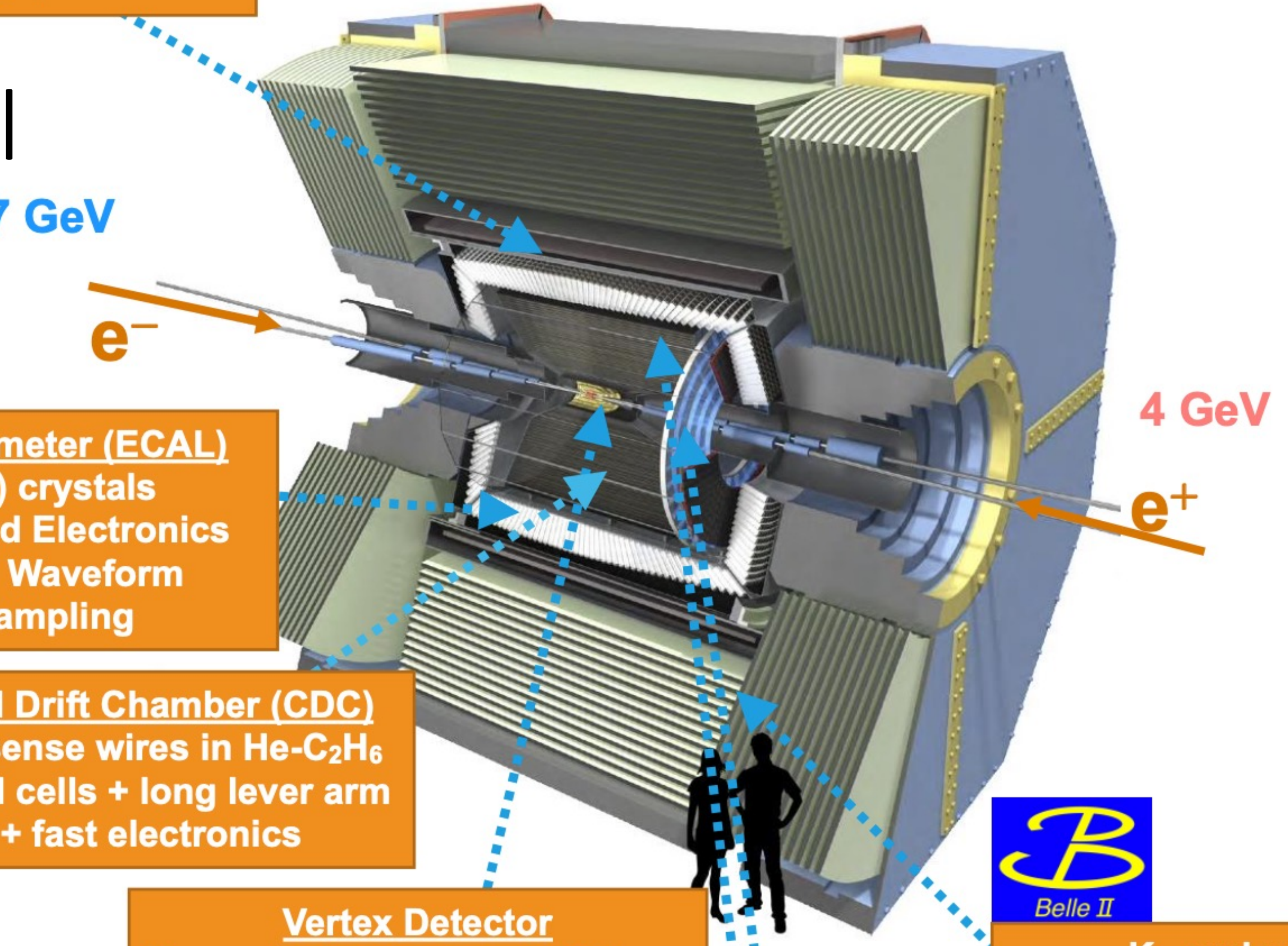
$$L = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

vertical beta function at IP



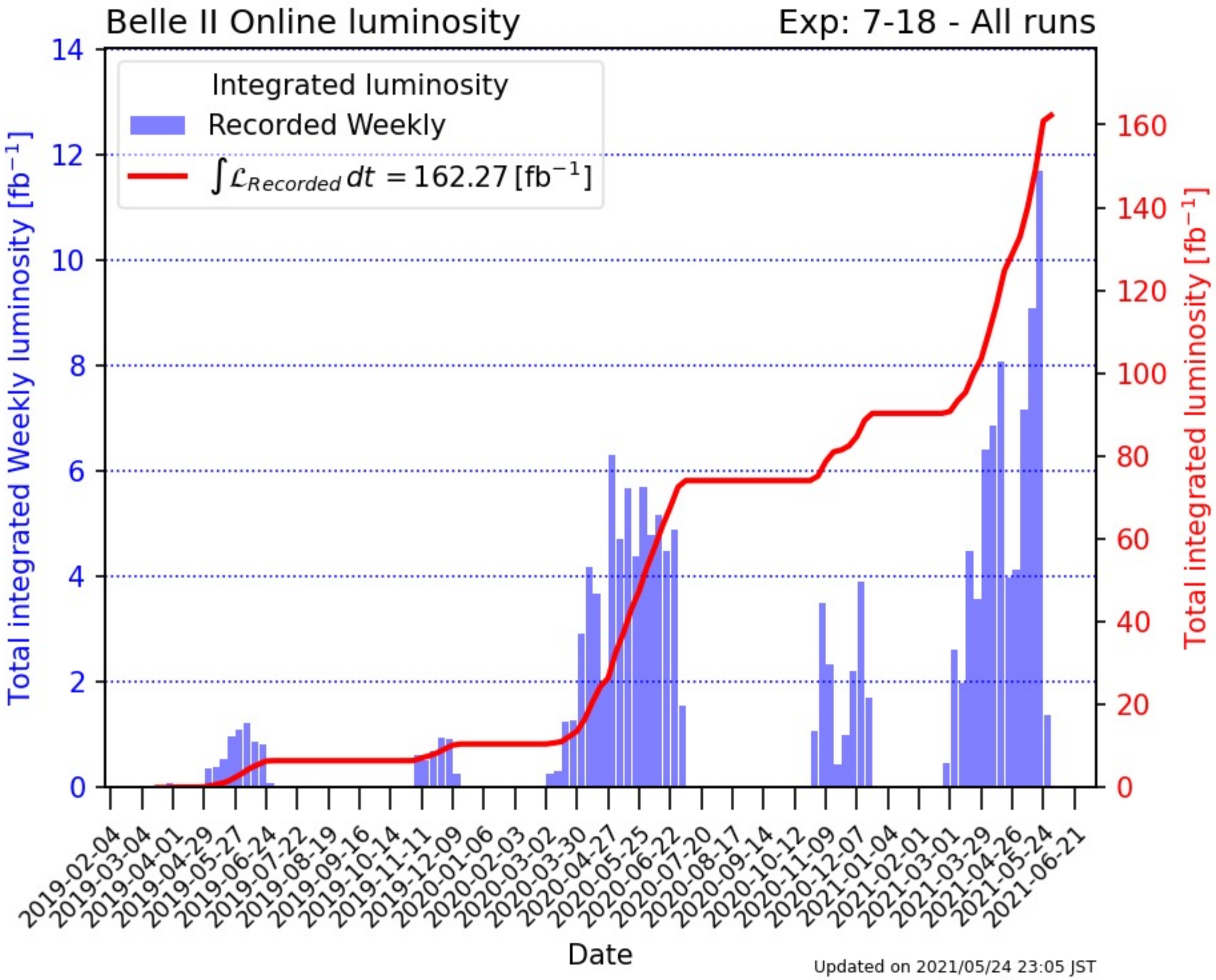


The Belle II detector



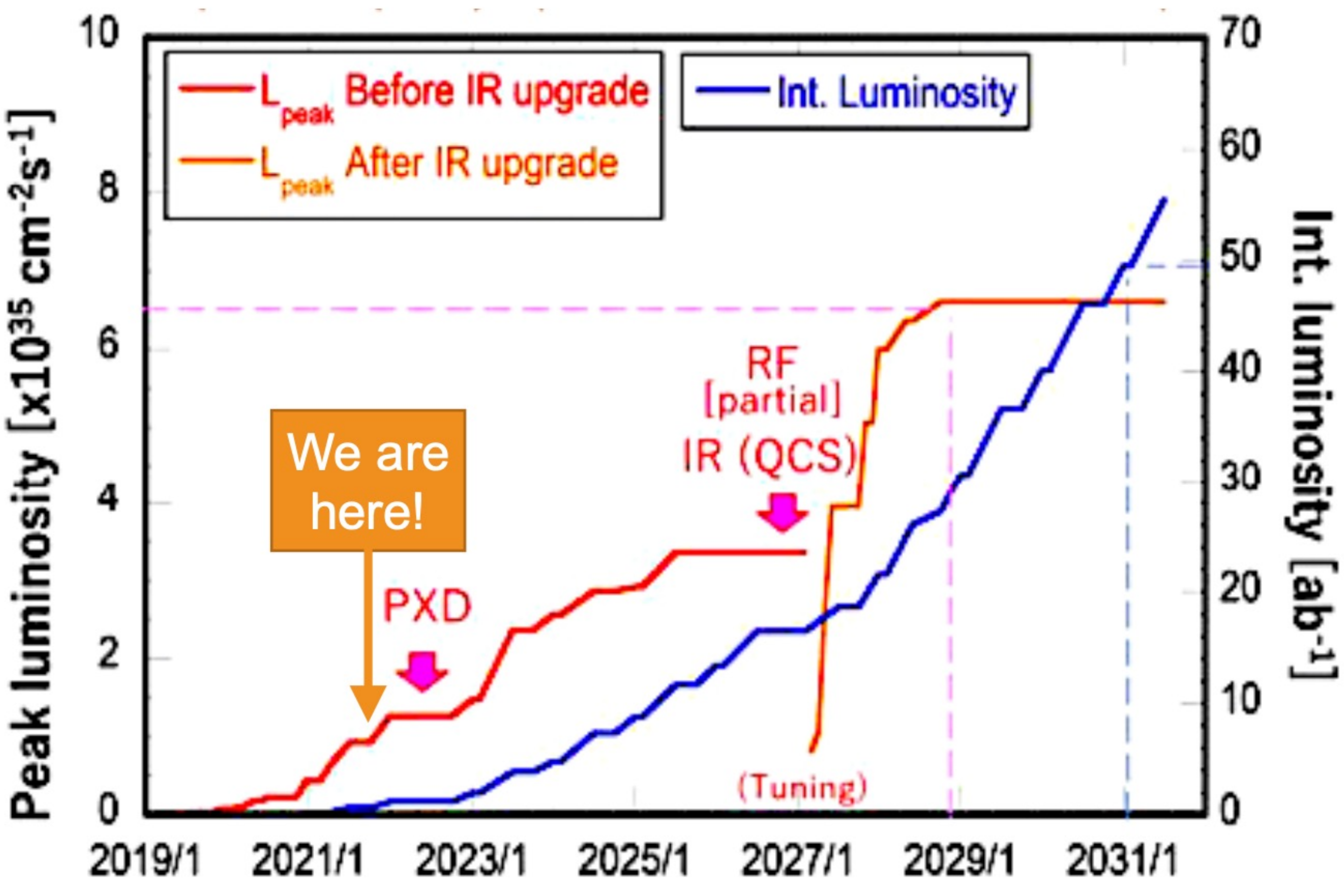
Belle II luminosity status

- SuperKEKB/Belle II have been operating since 2019 including the COVID-19 pandemic period
- Instantenous luminosity record: 2.957×10^{34}/cm2/s (May 18, 2021)
- Total recorded: 162.27/fb (May 24, 2021)



Luminosity prospects

- Long shutdown from Summer 2022
  - For PXD layer 2 installation and TOP PMT replacement
  - Belle II luminosity will reach to about the Belle data sample (711/fb)
- Long shutdown 2026
  - For IR upgrade (QCS final focussing magnets upgrade)
  - About 15/ab recorded by 2026
- Ultimate luminosity goal is 50/ab by ~2030



Belle II physics covered in this talk

- $B^+ \to K^+ \nu\bar{\nu}$ with inclusive tagging
  - $\to$ Cyrille Praz "Search for rare electroweak decay B^+ -> $K^+\nu\bar{\nu}$ in early Belle II dataset" (DM VI, May 26)

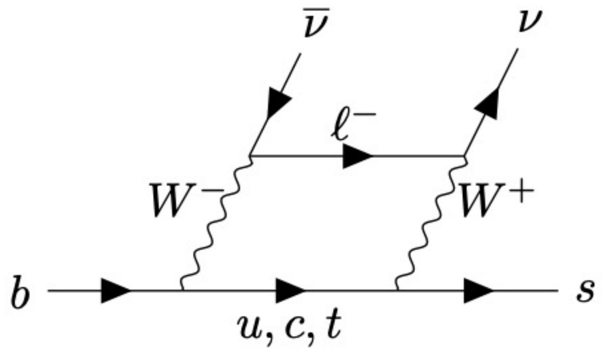
- Towards R(K) in Belle II
  - $\to$ Soumen Halder "Results and Prospects of Radiative and Electroweak Penguin Decays at Belle (II)" (Higgs III, May 26)

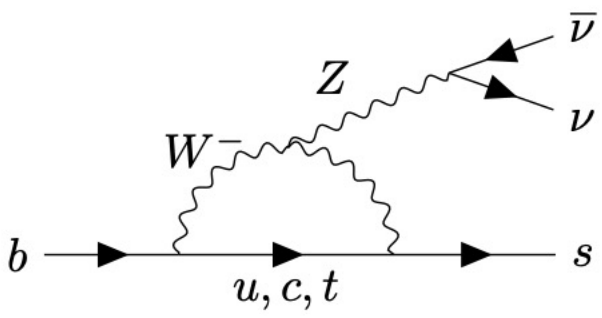
- Measurements of the CKM angles
  - $\to$ Chiara La Licata "The re-discovery of the decays for the CP violation measurements at Belle II" (Flavor II, May 24)
  - $\to$ Sebastiano Raiz "Charmless B decays at Belle II" (Flavor I, May 24)

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

Theory $B^+ \to K^+\nu\nu$bar

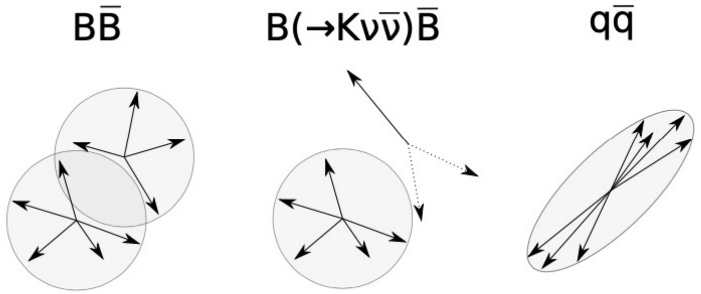
- Electroweak penguin and box diagram contributions
- SM branching fraction: (4.6 +/- 0.5) x 10^{-6} (arXiv:1409.4557)
- Not observed yet, best upper limit (BaBar) <1.6 x 10^{-5}

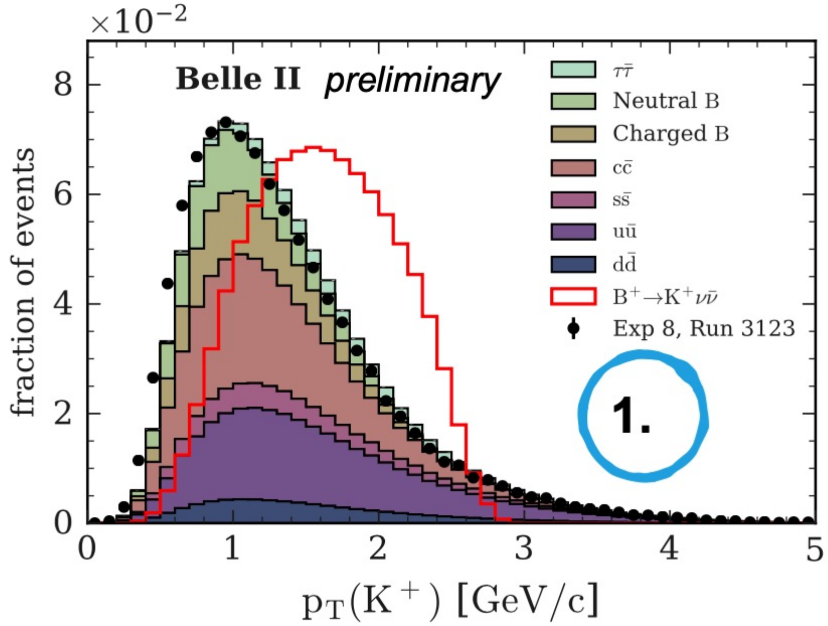




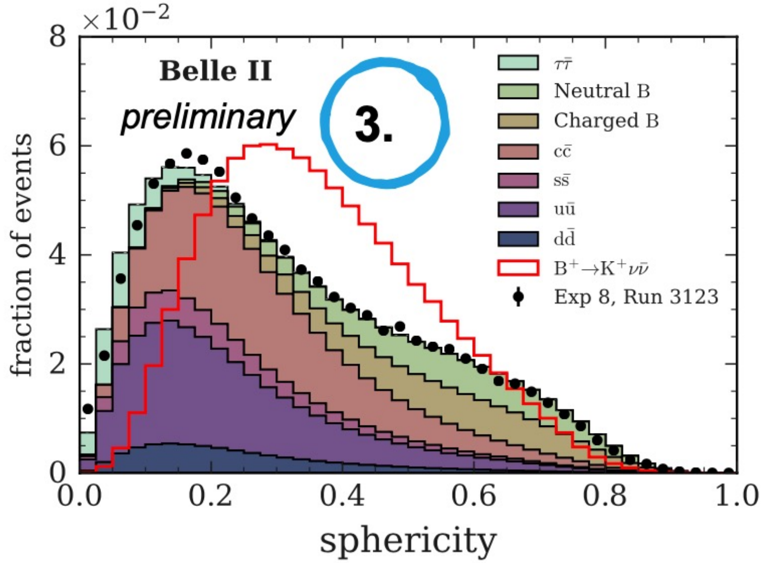
Belle II inclusive tag

1. Reconstruct signal = the highest p_T track with at least 1 PXD hit (~80% ϵ_{sig})
2. All other tracks and clusters reconstructed as rest-of-event (ROE) object
3. Discriminating variables are identified and used later as an input to Boosted Decision Trees (BDTs)
   - Event-shape, ROE dynamics, Kinematics of signal B, Vertexing variables





In comparison with tagged approaches this inclusive tag approach leads to **higher signal efficiency but also larger background contributions** from *B*-decays (Neutral/Charged *B*) and continuum production ($e^+e^- \rightarrow c\bar{c}, s\bar{s}, u\bar{u}, d\bar{d}$, τ pair)



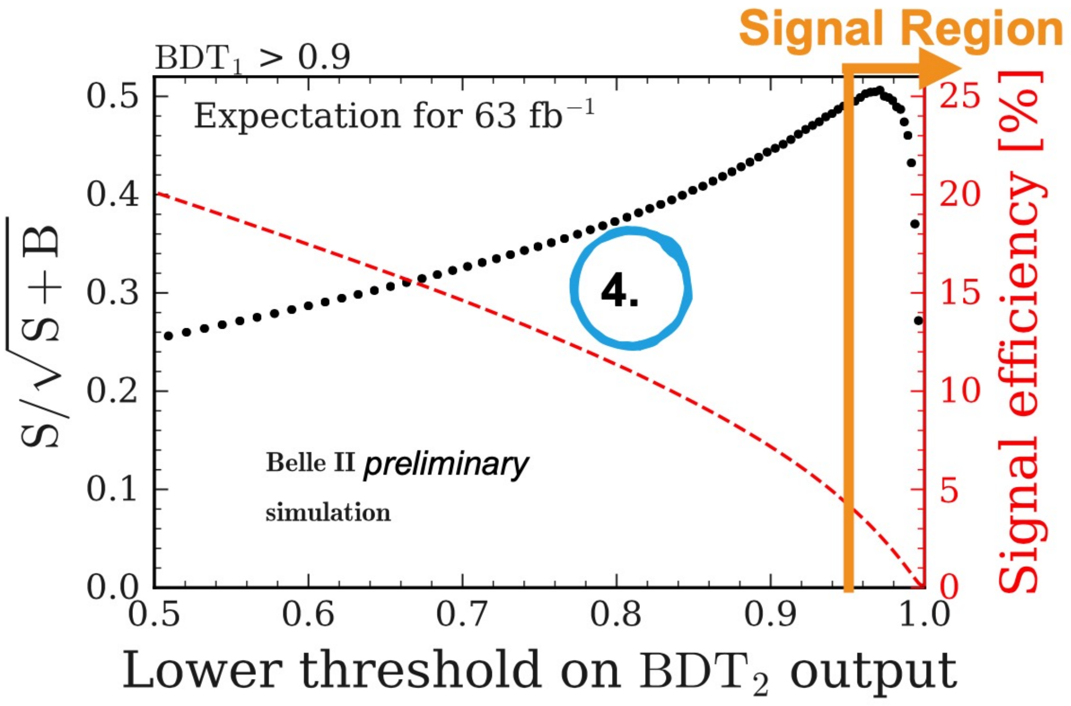
Belle II inclusive tag (2)

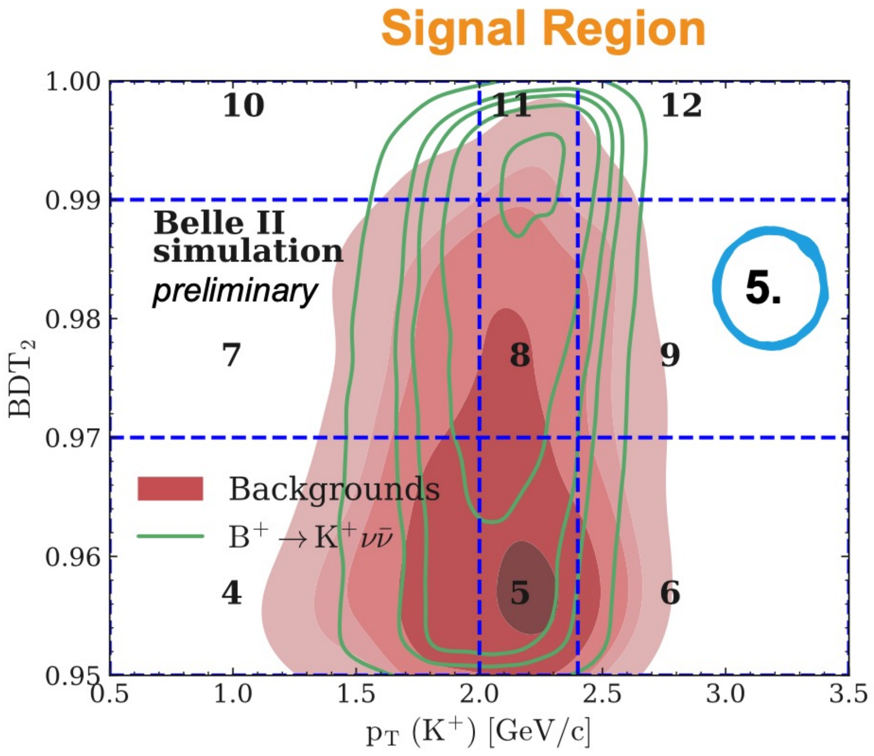
MVA Selection and Measurement Region Definition:

4. Two consecutive BDTs are trained and applied to suppress the backgrounds

(signal: $\mathbf{B}^+ \rightarrow \mathbf{K}^+\nu\bar{\nu}$, background: generic B decays + continuum)

5. Identify **signal region (SR)** with BDT_2 output and bin further in 2D: BDT_2 x $p_T(K^+)$ to maximise sensitivity

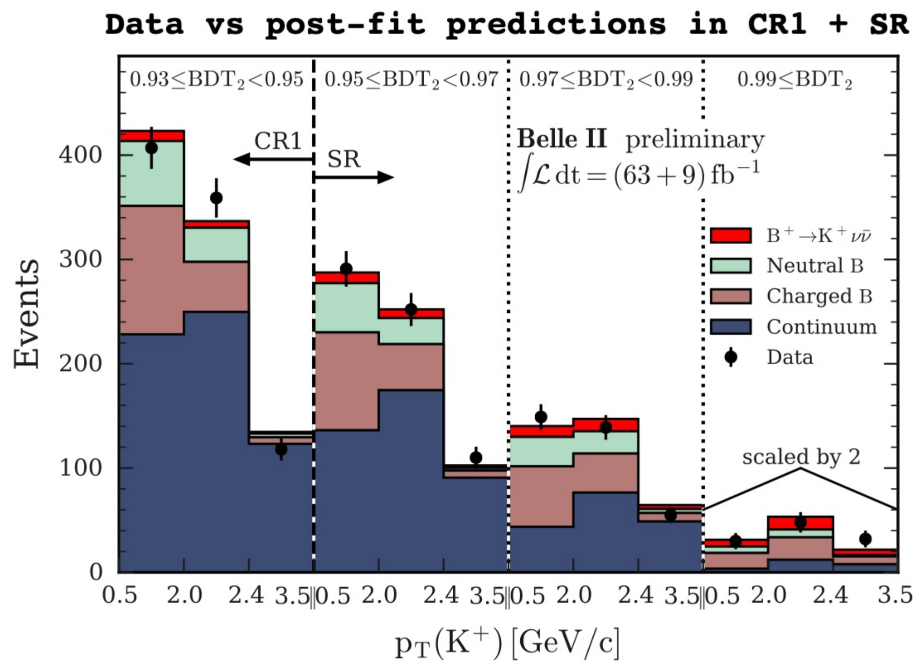


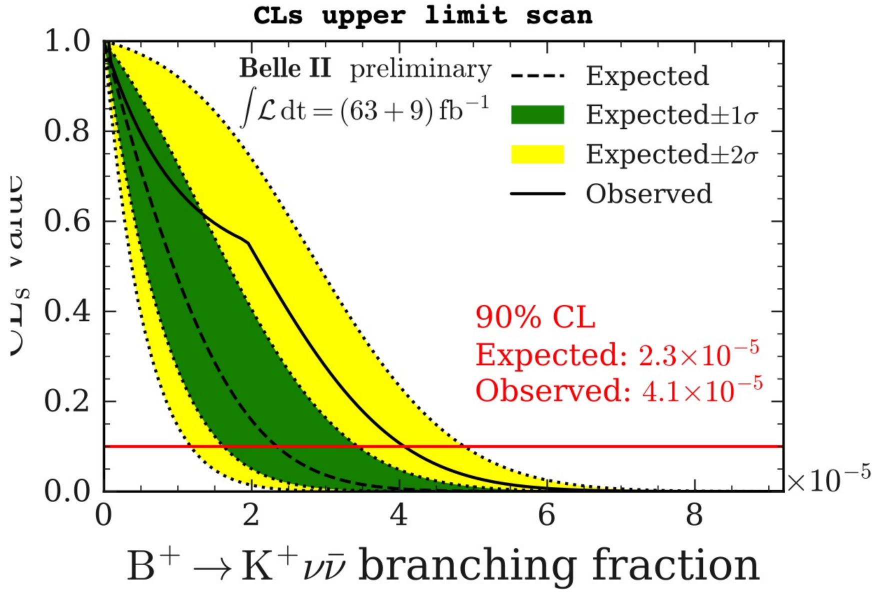


Moriond 2021:63 fb^{-1}

Belle II preliminary result

- Signal extracted using a binned ML fit to on- and off-resonance data with 175 nuisance parameters
- Preliminary 90% CL upper limit: 4.1 x 10^{-5}
- Submitted to Phys. Rev. Lett. (arXiv:2104.12624)





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

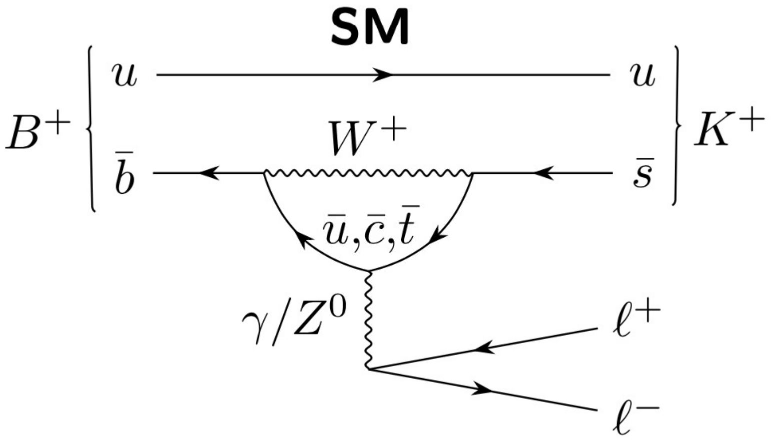
R(K) and R(K*)

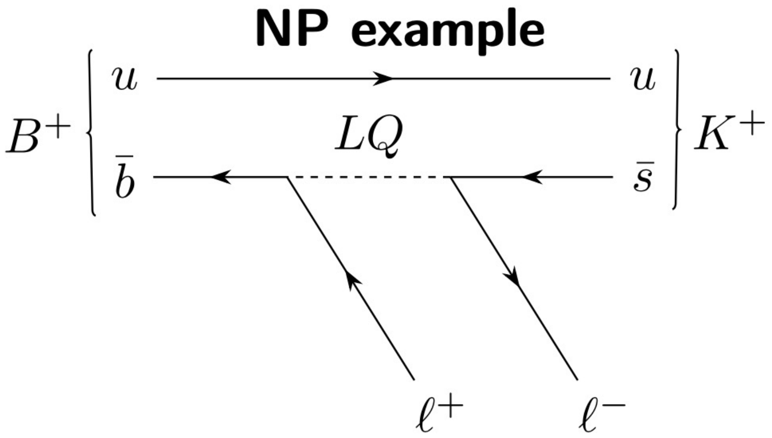
Searching for New Physics in b → sl$^+$l$^-$

1. **Branching Fractions**
   $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$

2. **Angular analyses**
   $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$

3. **Lepton Flavour Universality involving μ/e ratios**
   $B^0 \to K^{*0}\ell^+\ell^-$, $B^+ \to K^+\ell^+\ell^-$





R(K) and R(K*) – testing lepton universality

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour
  $\rightarrow$ Branching fractions differ only by phase space and helicity-suppressed contributions

- Ratios of the form:

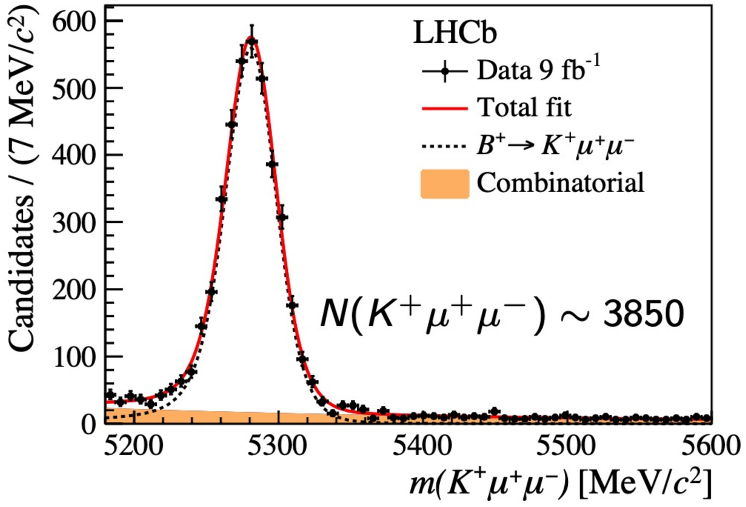
$$R_{K^{(*)}} := \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \rightarrow K^{(*)}e^+e^-)} \overset{\mathrm{SM}}{\cong} 1$$

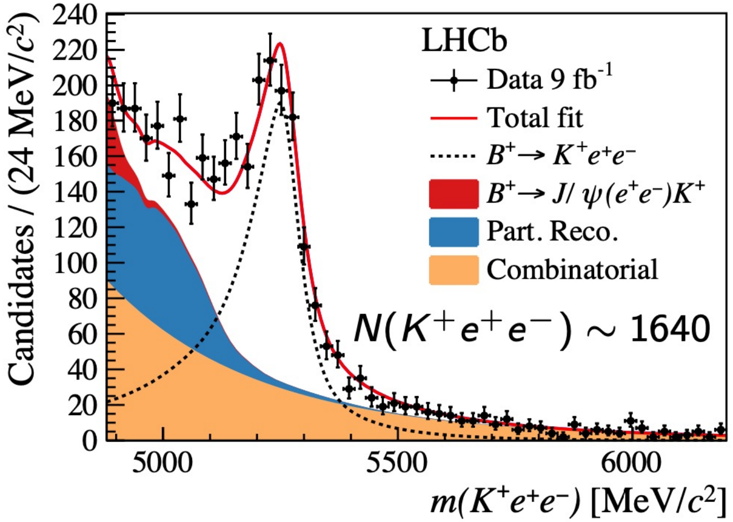
- In SM free from QCD uncertainties affecting other observables
  $\rightarrow \mathcal{O}(10^{-4})$ uncertainty [JHEP07(2007)040]
- Up to $\mathcal{O}(1\%)$ QED corrections [EPJC76(2016)8,440]

$\rightarrow$ **Any significant deviation is a smoking gun for New Physics.**

LHCb measurement of R_K

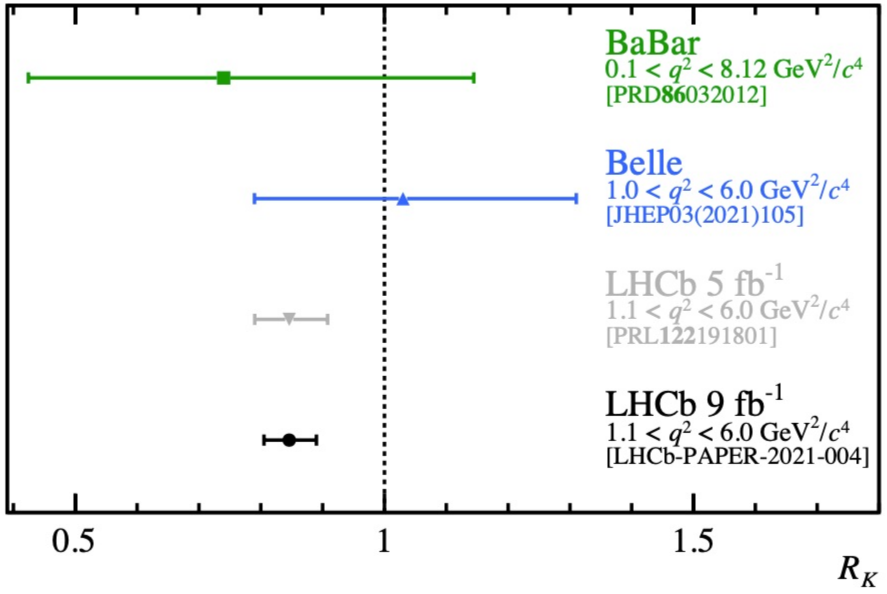
[LHCb-PAPER-2021-004]





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

$\rightarrow$ Evidence of LFU violation at 3.1σ



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

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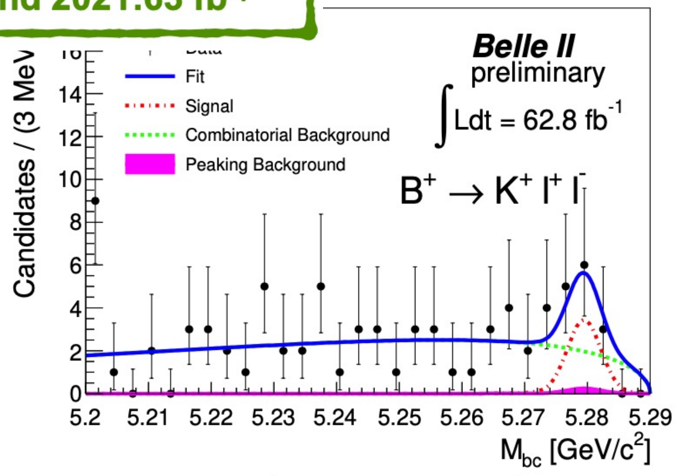
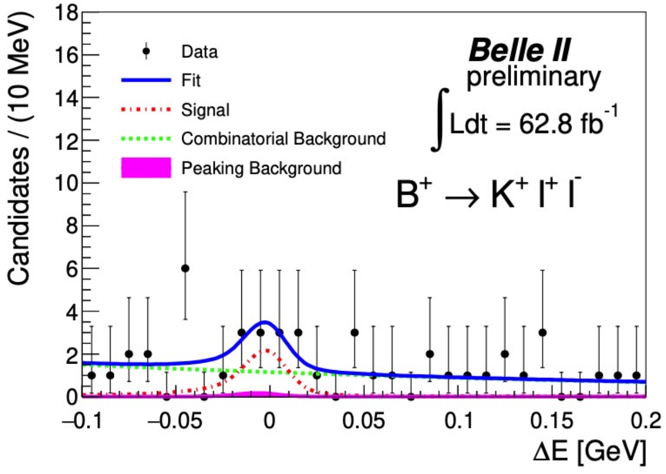


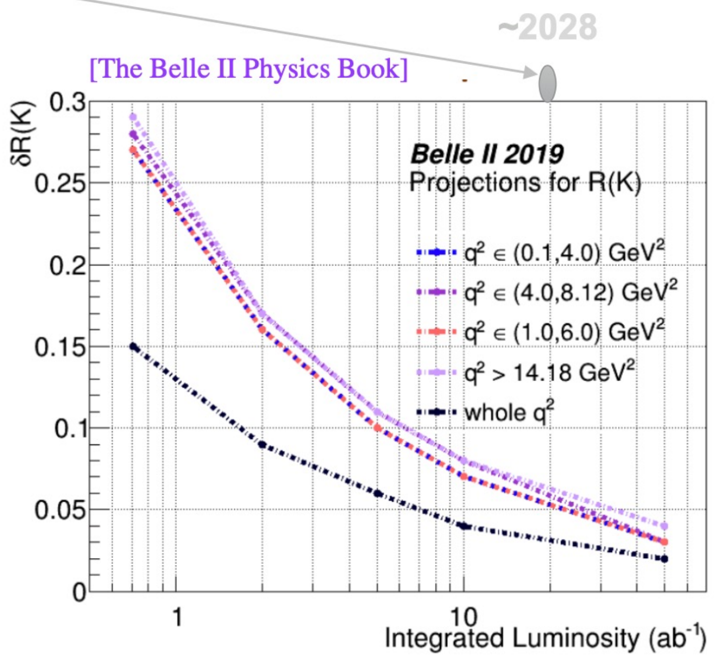
$$M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{p_B}|^2}$$



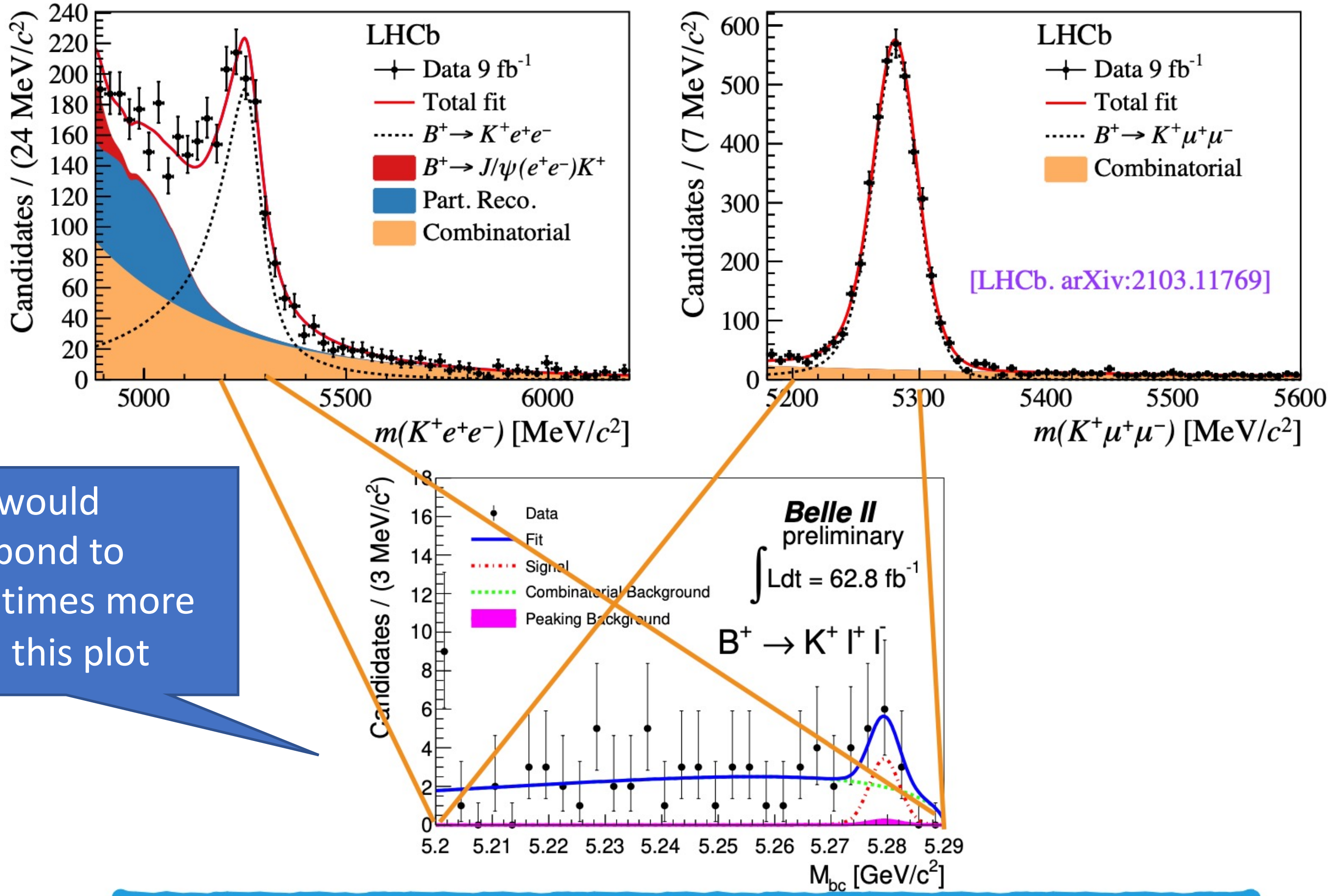
$$\Delta E = E_B - E_{beam}$$

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}



R(K) Belle II vs. LHCb



50/ab would correspond to ~1000 times more data in this plot

In comparison to LHCb, 3 different aspects to consider: efficiency, statistics and resolution

	Belle II	LHCb
Signal	K^+, K_S	K^+
Same K e e Statistics	1 ab^{-1}	1 fb^{-1}
B->K mu mu Efficiency	30 %	~5 %
B->K e e Efficiency	30 %	<5% Lower due to tracking and trigger
B->K e e Resolution	Better thanks to M_{bc}	Worse because of Brems
High q^2 bin	Accessible	Hard

Electrons (and muons) in Belle II have better resolution thanks to M_{bc}

Angular analysis B → K*μμ

longitudinal K* polarization

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\,d\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

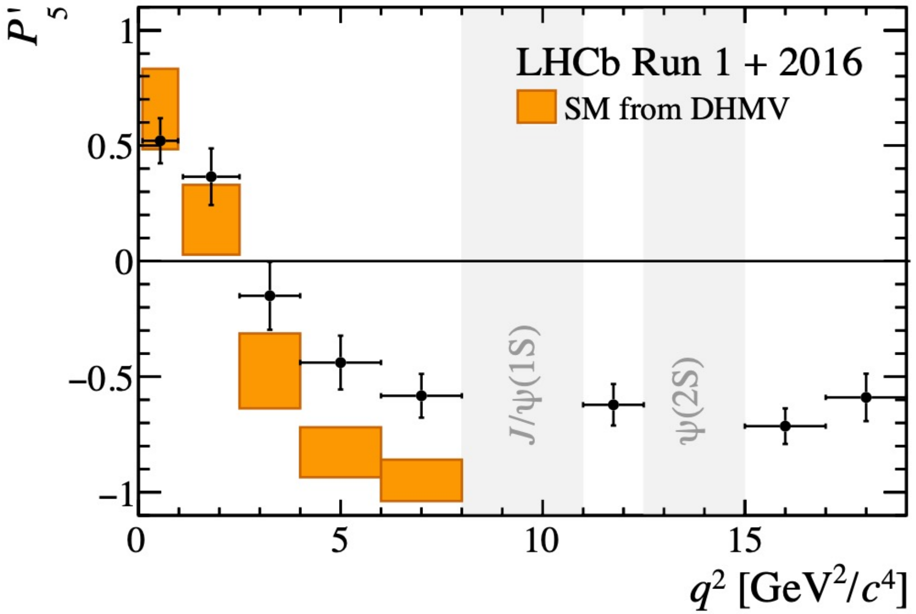
CP-averaged rate

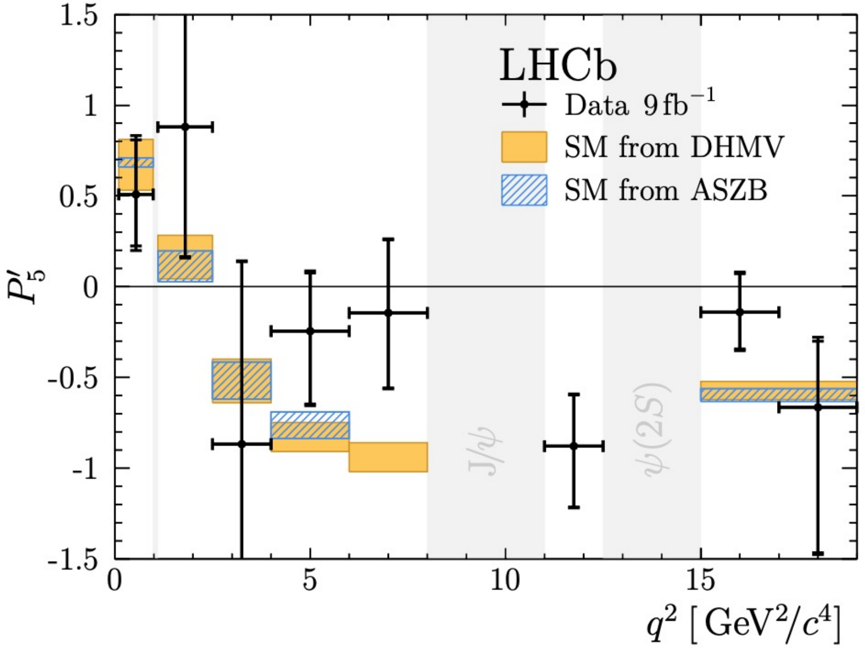
$$P_5' = S_5/\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}$$

Angular analysis of $B \to K^*\mu^+\mu^-$

- Orthogonal experimental systematics and more precise theory predictions

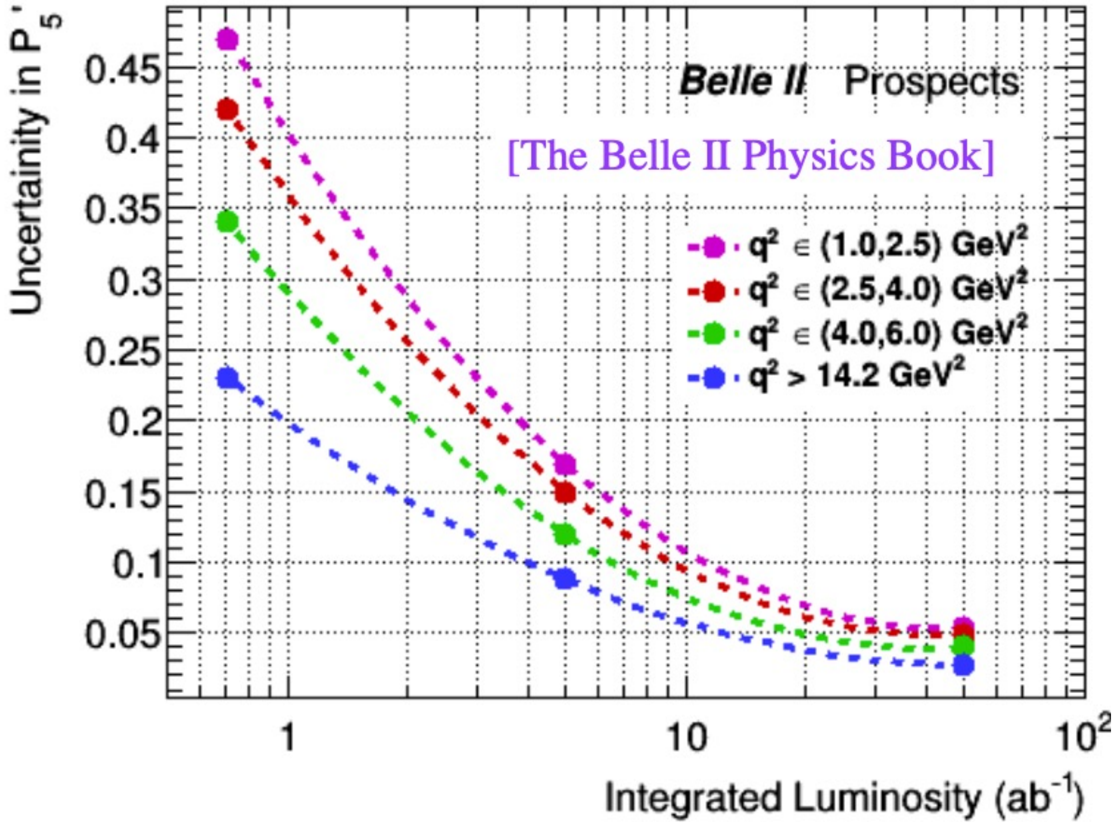
Left: $B^0 \to K^{*0}\mu^+\mu^-$ [PRL125011802(2020)], Right: $B^+ \to K^{*+}\mu^+\mu^-$ [arXiv:2012.13241]





- Combination of all angular observables suggests $\sim 3\sigma$ tension with SM predictions in each channel

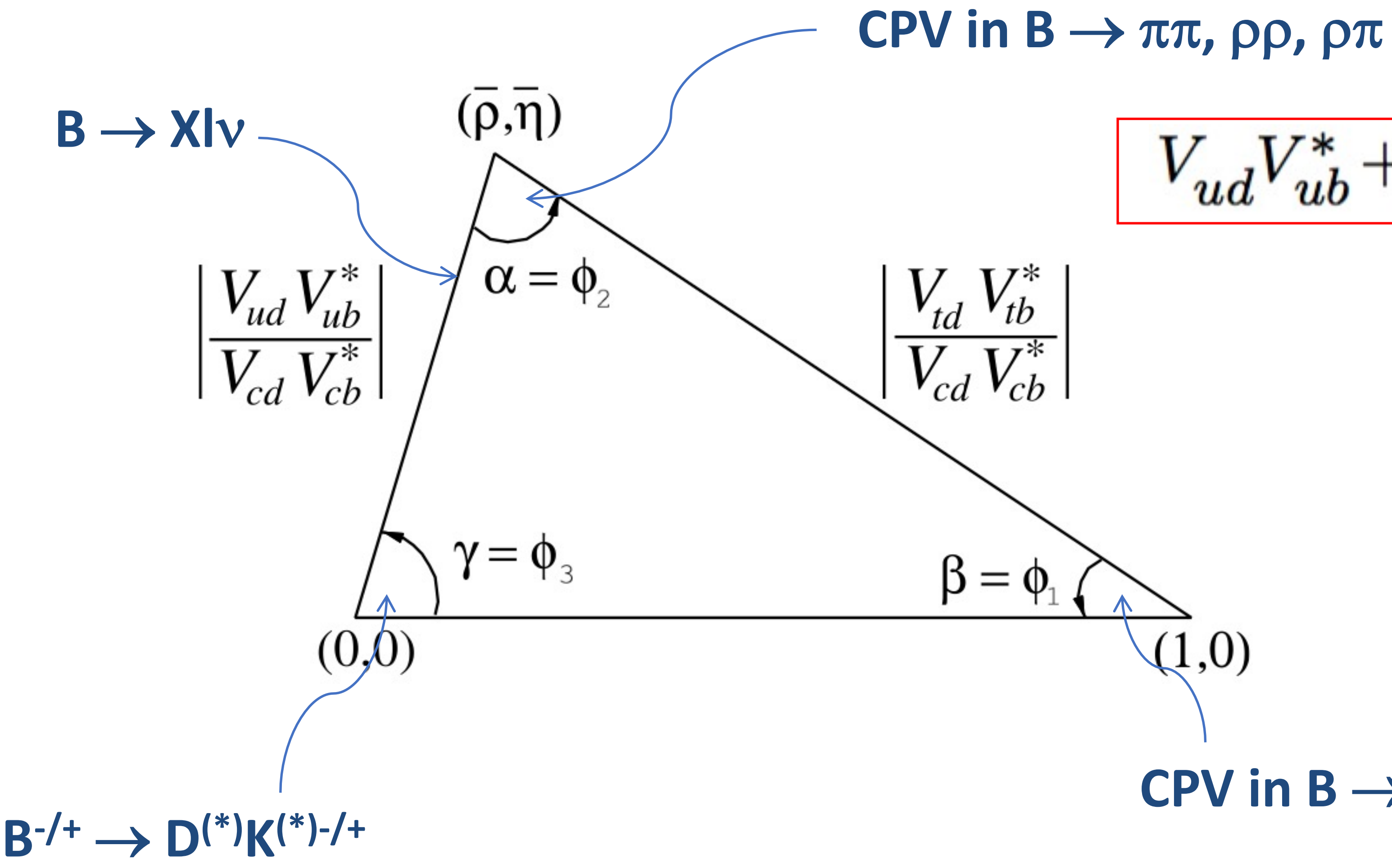
Belle II prospects for the angular analysis



- LHCb sees the largest tension in the muon channel (e channel is SM-like)
- At 2.8/ab the Belle II uncertainty in P'5 (both e & mu) will be comparable to LHCb 3/fb (mu only)

CKM angles

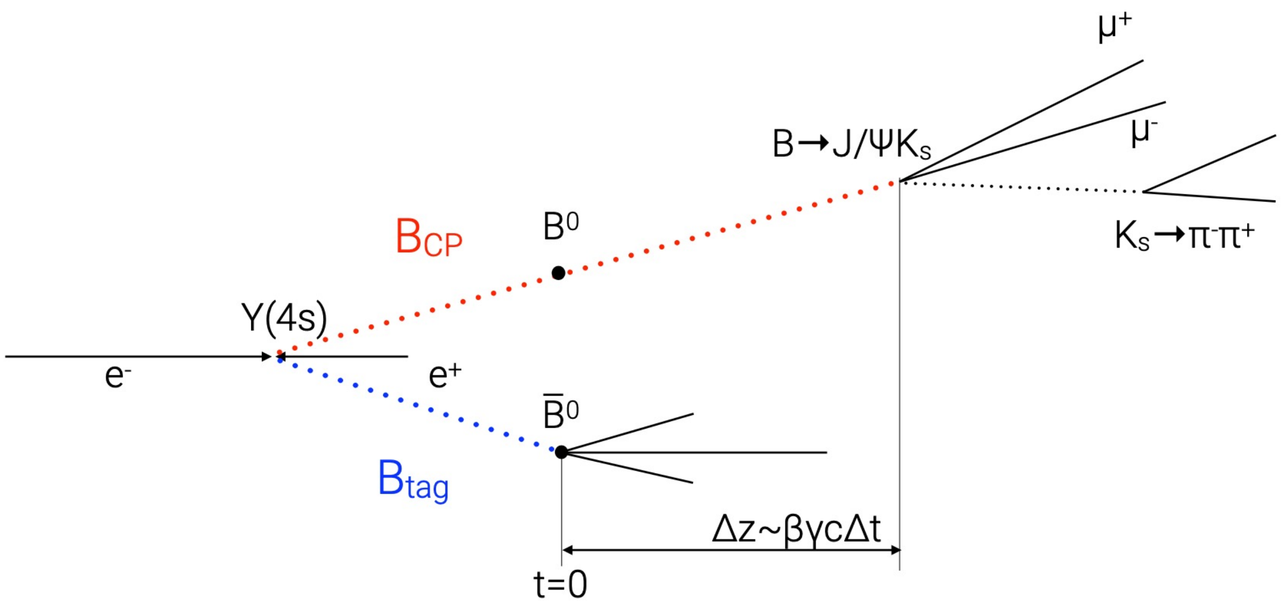
Probing the CKM unitarity triangle



$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Time-dependent CPV in $B \to J/\psi\ K_s$

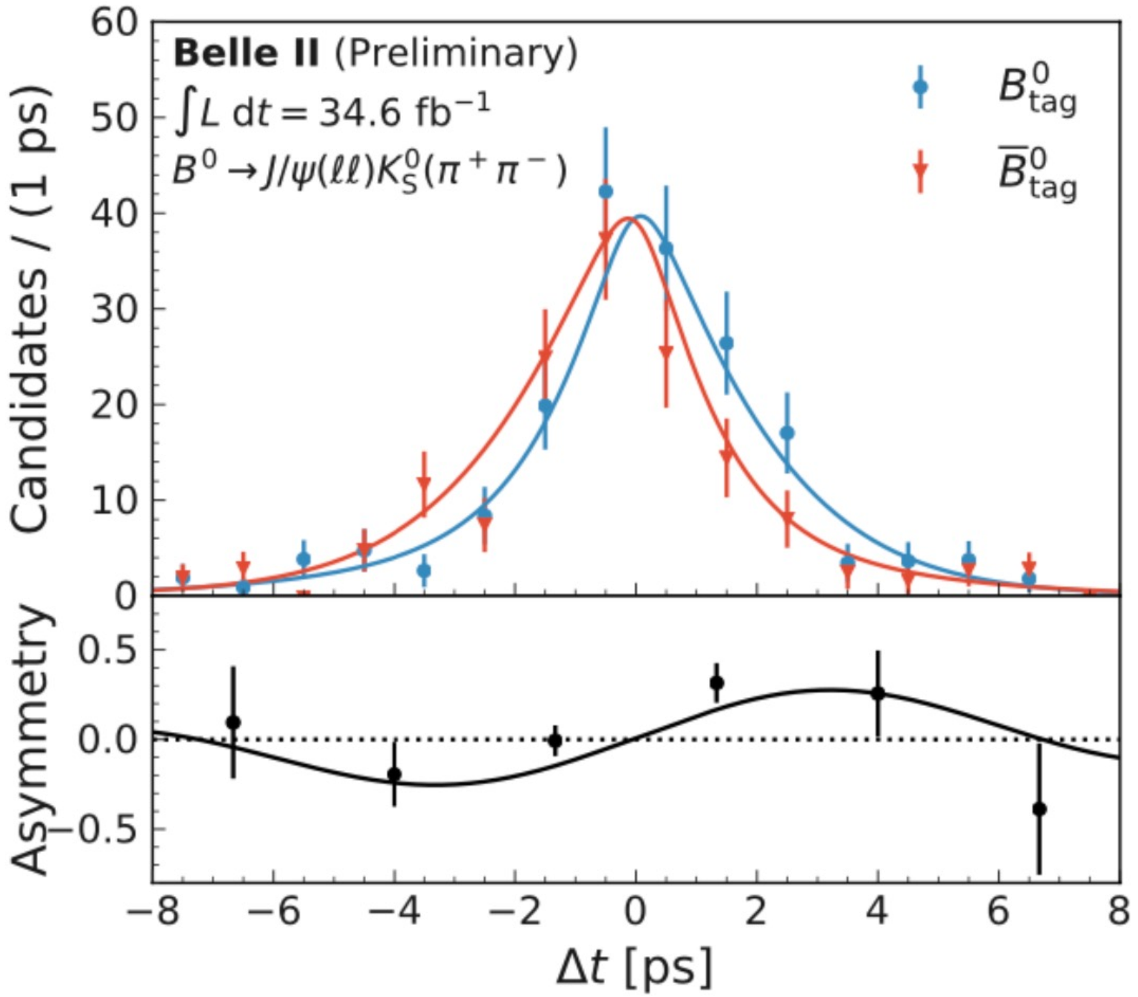
$$A_{CP}^{raw} = \frac{\Gamma(\bar{B}^0_{t=0} \to J/\Psi K_S) - \Gamma(B^0_{t=0} \to J/\Psi K_S)}{\Gamma(\bar{B}^0_{t=0} \to J/\Psi K_S) + \Gamma(B^0_{t=0} \to J/\Psi K_S)} = sin(\Delta m_d \Delta t) sin(2\phi_1)$$

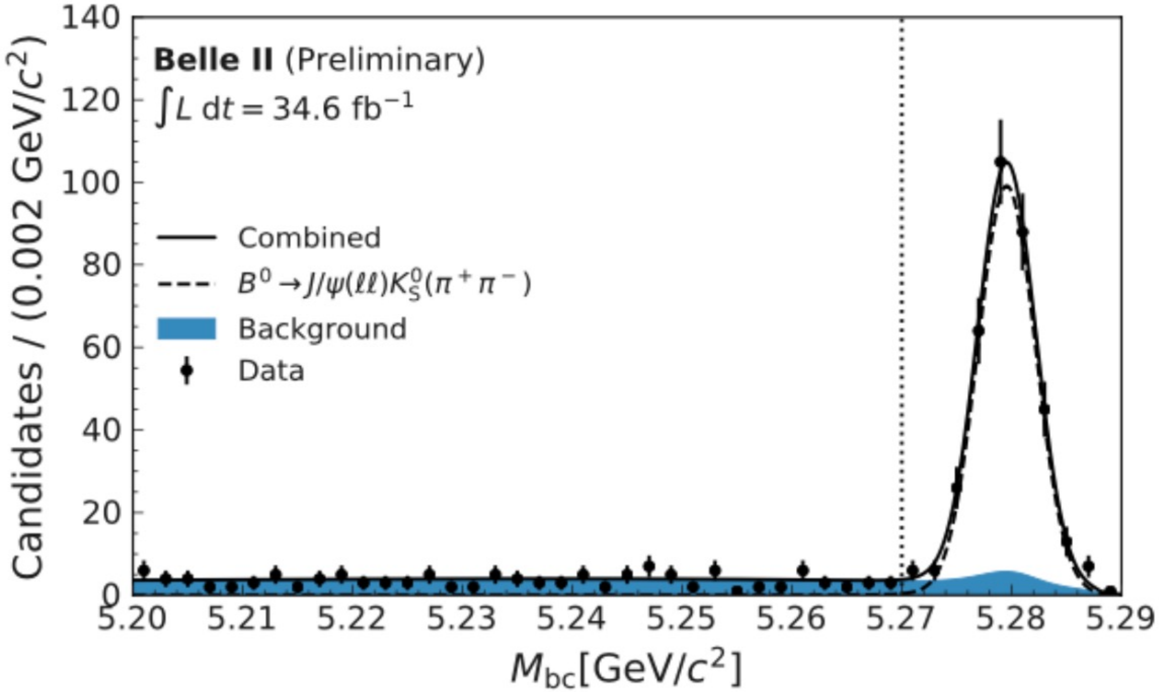


- Three "ingredients"
  - Reconstructed decay
  - Time measurement Δt
  - Flavour tag
- Challenge
  - Reduced boost of SuperKEKB leads to Δz 200 μm $\to$ 130 μm

First Belle II sin $2\phi_1$ measurement

ICHEP 2020: 35 fb^{-1}





$\sin 2\phi_1 = (0.55 \pm 0.21\ (\text{stat}) \pm 0.04\ (\text{syst}))\ \text{ps}^{-1}$

significance ~2.7σ

First measurement of $B \to J/\psi\, K_L$

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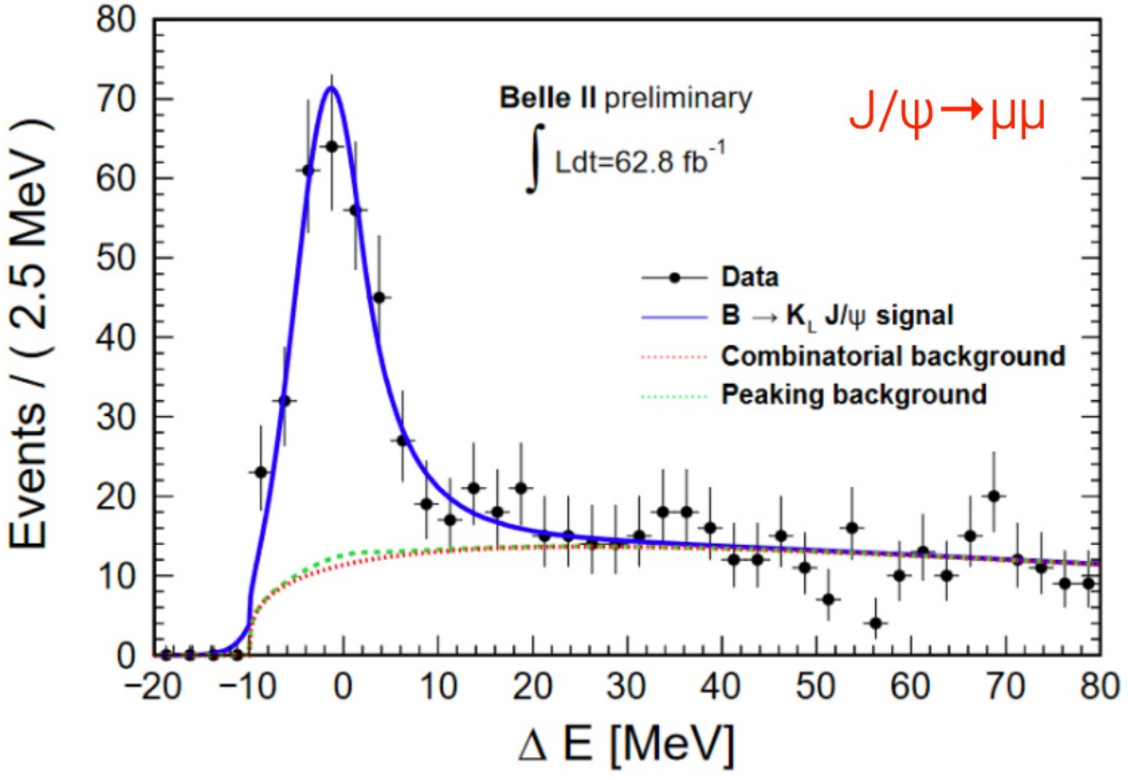
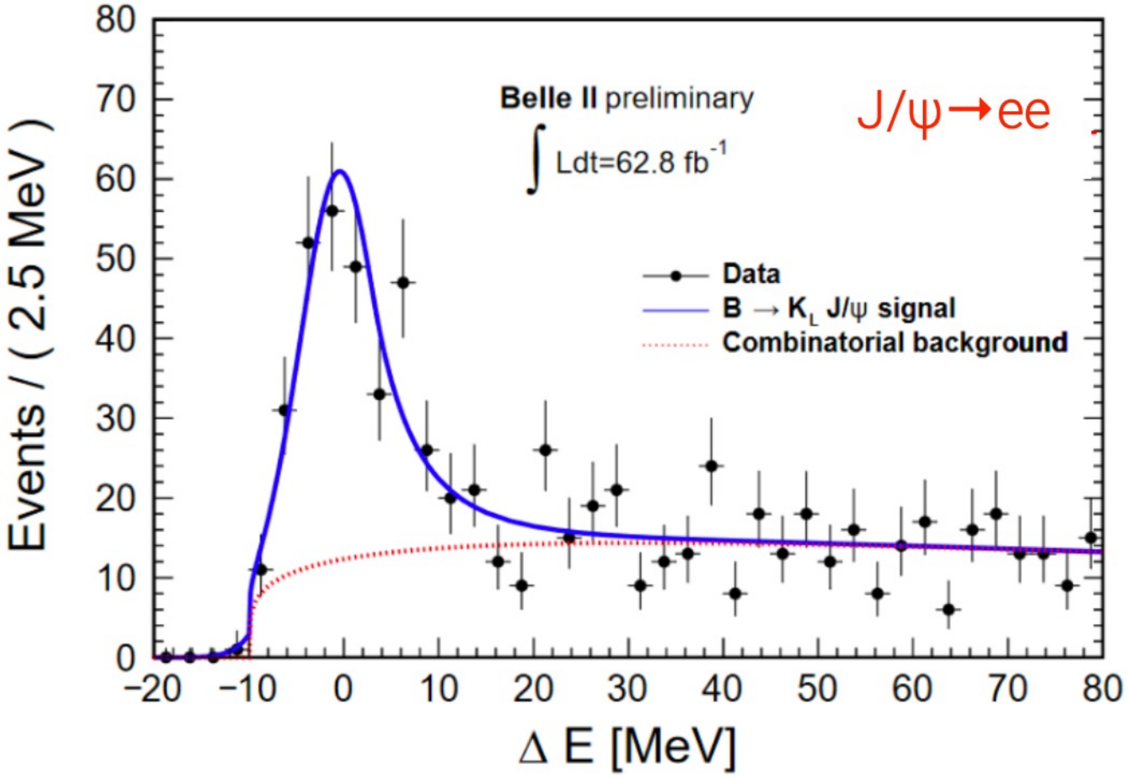




BELLE2-CONF-PH-2021-009

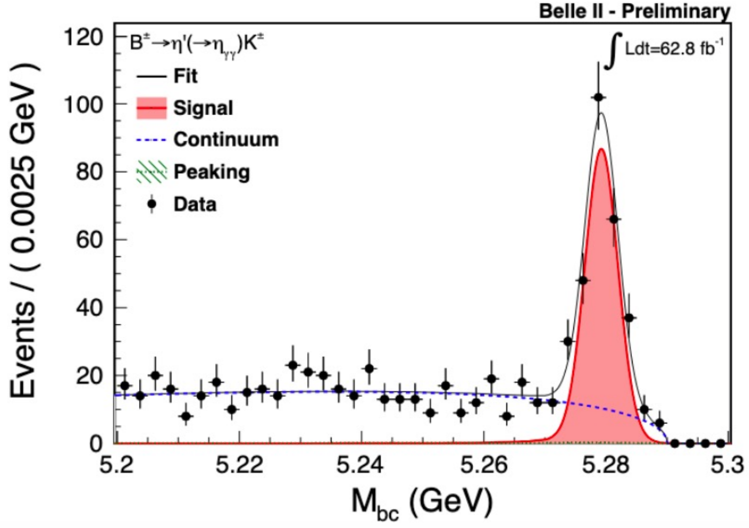
The event yield of $(7.3\pm0.4)/fb^{-1}$, consistent with Belle

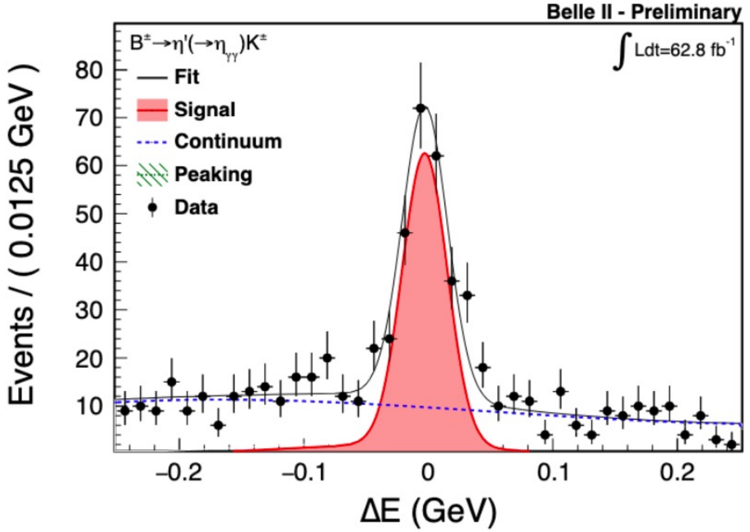
Rediscovery of B → η’K

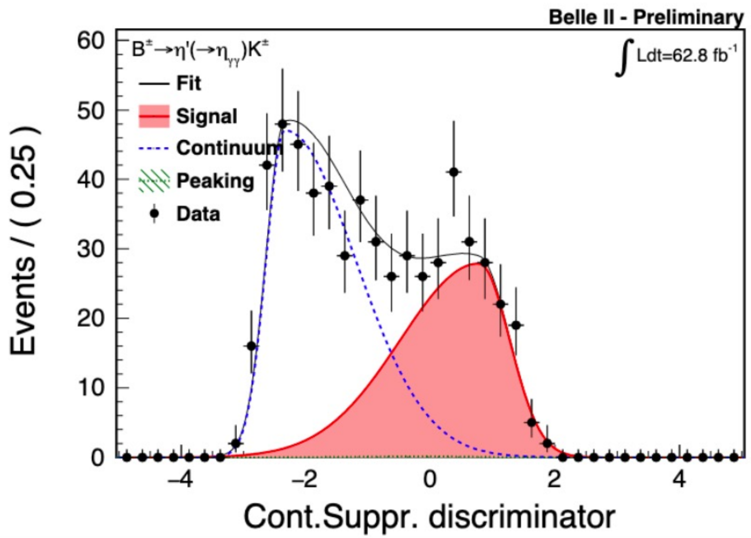
Moriond 2021:63 fb-1

BELLE2-CONF-PH-2021-009
arXiv:2104.06224 [hep-ex]

$B^{\pm} \to \eta' K^{\pm}$ with $\eta' \to \eta\pi^+\pi^-$







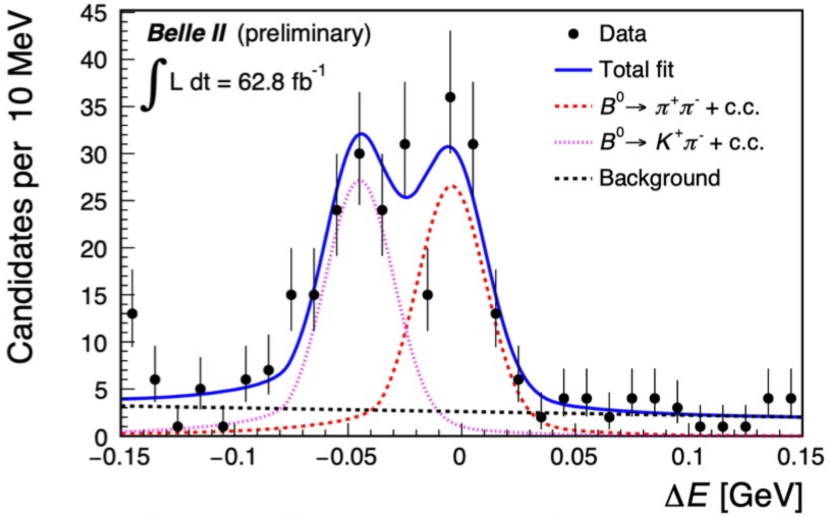
Mode	$\mathcal{B}(10^{-6})$
$B^{\pm} \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^{\pm}$	$63.9^{+4.6}_{-4.4} \pm 4.0$
$B^{\pm} \to \eta'(\to \eta(\to \pi^+\pi^-)\gamma)K^{\pm}$	$62.9^{+4.8}_{-4.8} \pm 5.5$
$B^{0} \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^{0}_{S}$	$61.6^{+8.6}_{-8.0} \pm 3.9$
$B^{0} \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^{0}_{S}$	$58.5^{+7.9}_{-7.4} \pm 4.4$

- Penguin-dominated mode
- Time-dependent CPV is expected to be sensitive to NP in the penguin loop

Towards α/ϕ_1

Moriond 2021:63 fb^{-1}

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

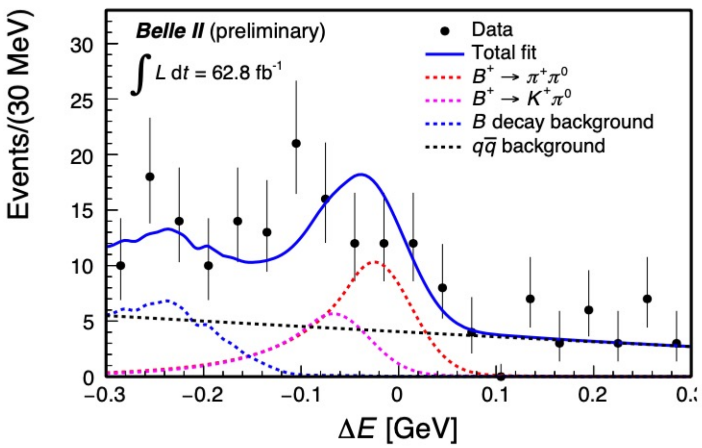


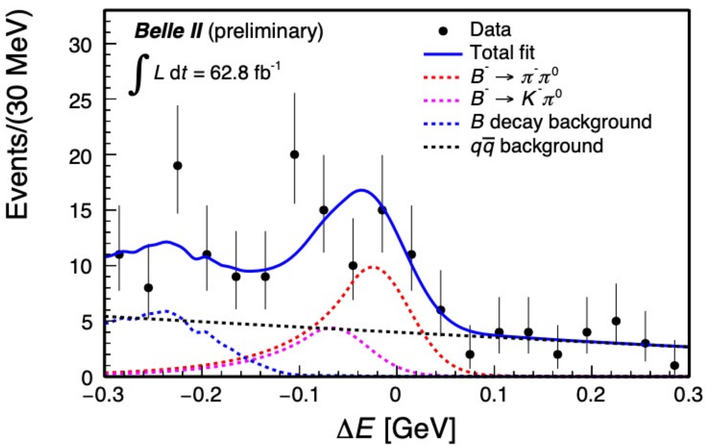
Benchmarks PID and ΔE resolution.

$\mathcal{B}(B^0 \to \pi^+\pi^-) = [5.8 \pm 0.7(\text{stat}) \pm 0.3(\text{syst})] \times 1$

BELLE2-CONF-PH-2021-007

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





Probes π^0 reconstruction and PID.

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

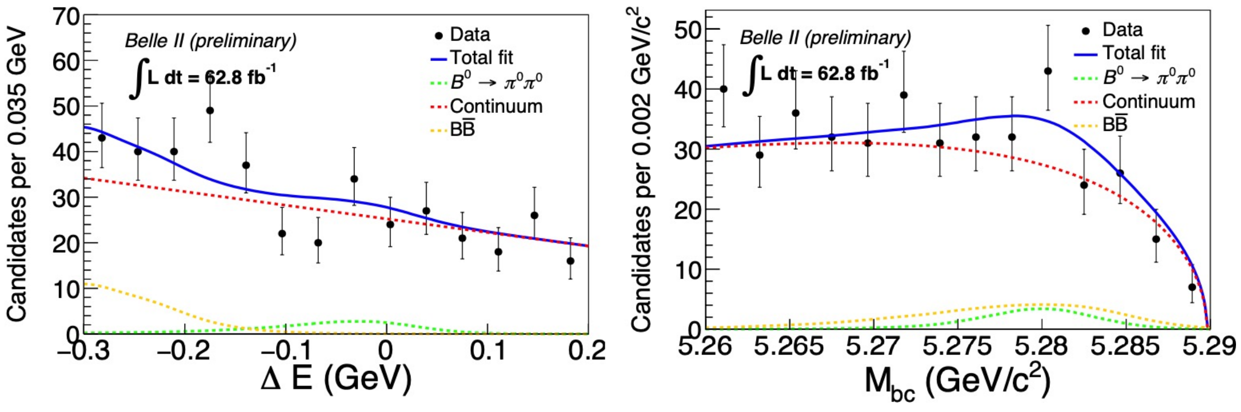
$A_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$

BELLE2-CONF-PH-2021-006

arXiv:2105.04111 [hep-ex]

Towards α/ϕ_1 (2)

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



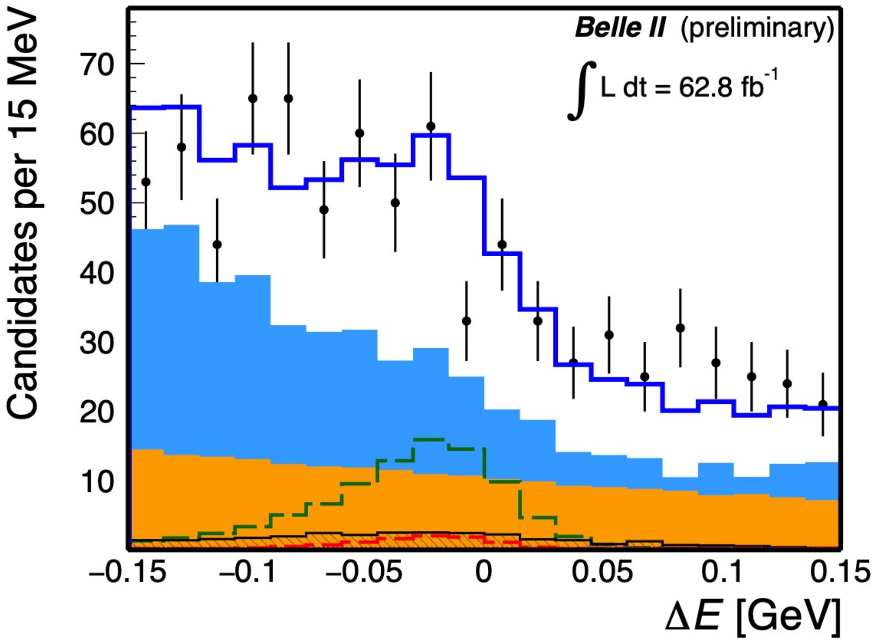
First reconstruction in Belle II data!

N($B^0 \to \pi^0\pi^0$): $14\ ^{+6.8}_{-5.6}$

$\mathcal{B}(B^0 \to \pi^0\pi^0) = [1.09^{+0.50}_{-0.41}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}$

BELLE2-CONF-PH-2021-010

$B^+ \to \rho^+\rho^0$



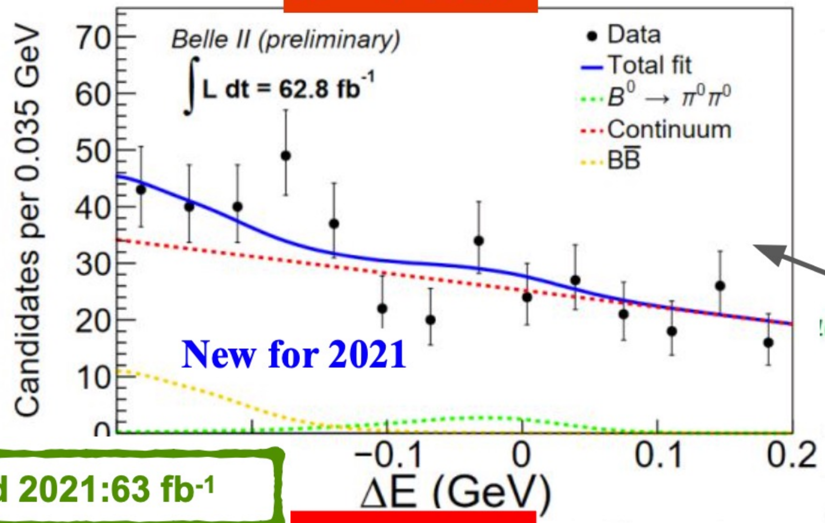
$\text{N} = 104 \pm 16$

$\mathcal{B} = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$

BELLE2-CONF-PH-2021-003

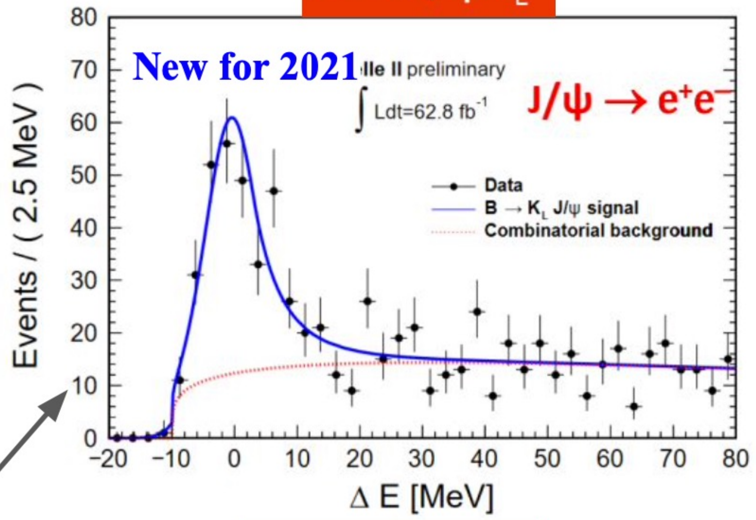
Moriond 2021:63 fb^{-1}

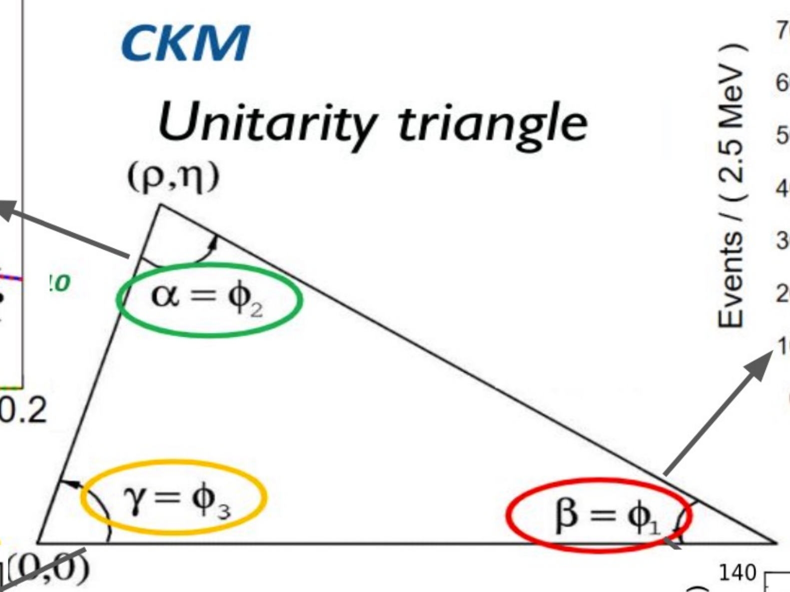
$B^0 \to \pi^0\pi^0$



Moriond 2021:63 fb^{-1}

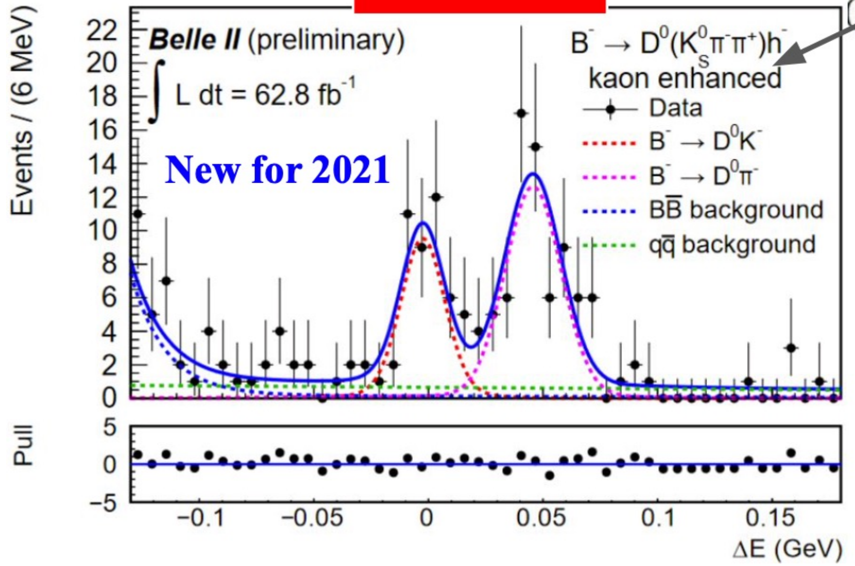
$B^0 \to J/\psi K_L^0$



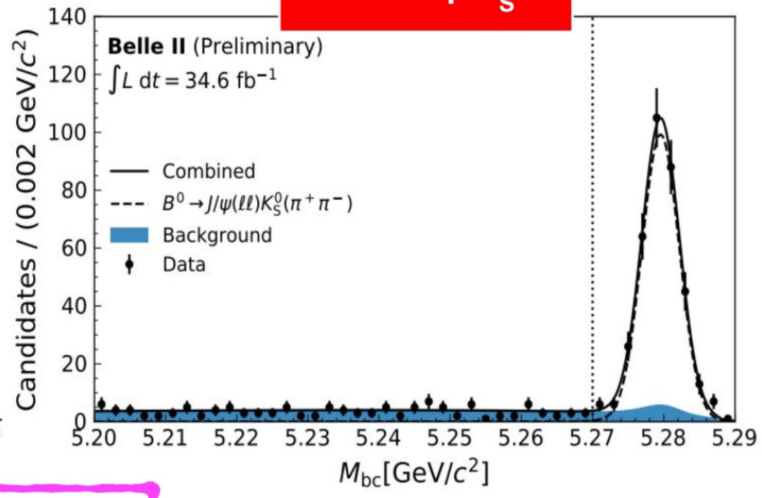


Moriond 2021:63 fb^{-1}

$B^0 \to D^0 h^-$



$B^0 \to J/\psi K_s^0$



$$\Delta E = E_B^* - E_{\text{beam}}^*$$

$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^{*\,2} - p_B^{*2}}$$

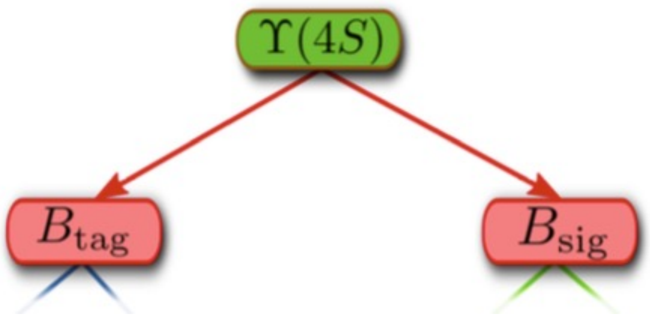
ICHEP 2020: 35 fb^{-1}

Summary

- The SuperKEKB machine and the Belle II detector have successfully started data taking in 2019
  - Peak luminosity: 2.957 x 10^{34}/cm2/s, Integrated: 162.27/fb (May 24, 2021)
  - Operation continues despite the COVID-19 pandemic
- Early Belle II physics
  - While the first publications are dominated by dark matter physics, competitive B physics results start to emerge
  - 90% C.L. upper limit on $B^+ \to K^+ \nu\bar{\nu}$ at 4.1 x 10^{-5} (submitted to PRL)
  - Belle II can also confirm the LHCb anomalies in R(K) and P'_5 but more integrated luminosity will be needed
  - Preparing for another round of tests of CKM unitarity
- Stay tuned
  - When reaching the Belle I luminosity by about summer 2022 Belle II will be even more competitive in the field of B, charm and tau physics

backup

Tagging techniques for Y(4S) events



- Tagging provides:
  - Background suppression
  - Information on B_{sig} (4-momentum)

PURITY →

← EFFICIENCY

Untagged
- No requirement on B_{tag}
- High efficiency, low purity

Semileptonic tag
- $B_{tag} \rightarrow D^* l \nu$
- Efficiency ~O(0.2%)

Hadronic tag
- $B_{tag} \rightarrow$ hadrons
- Efficiency ~O(0.1%)