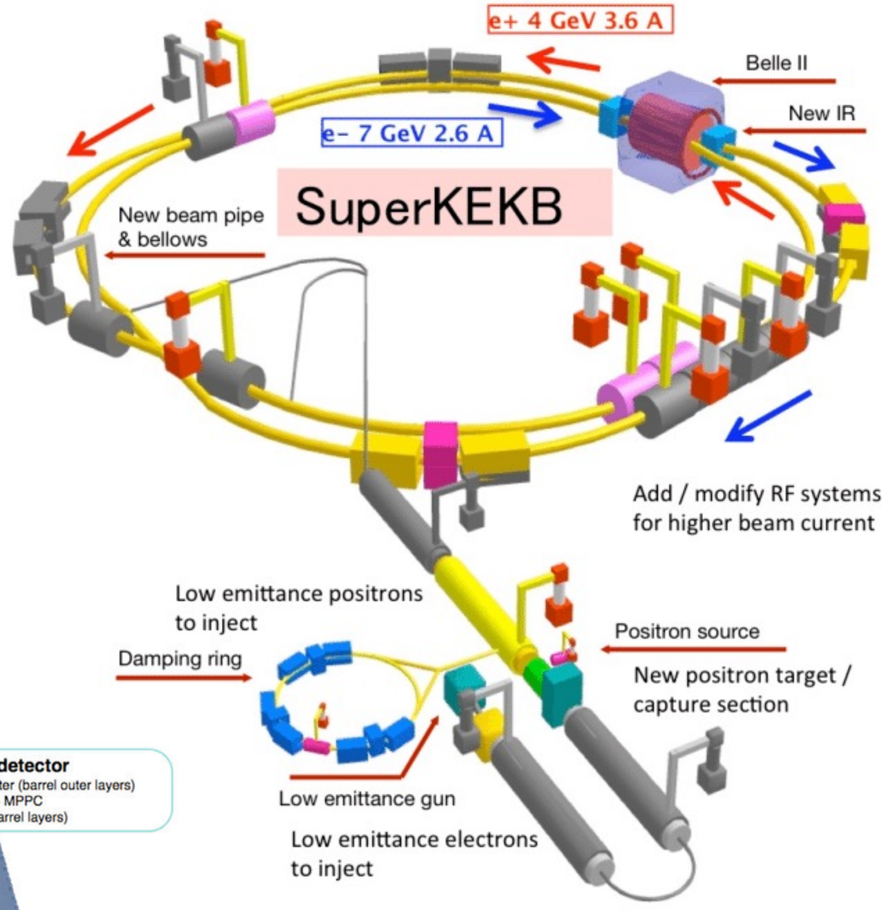
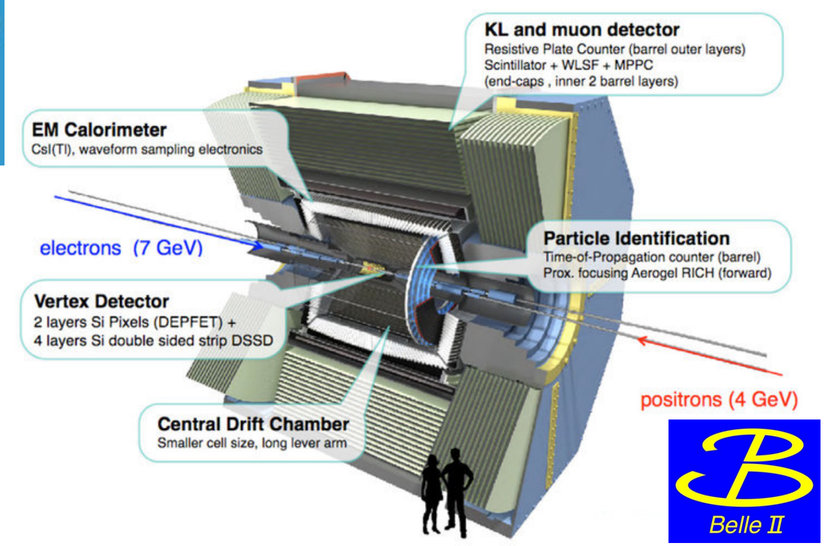
Gagan Mohanty
tifr

How can Belle II help?

Gagan Mohanty
tifr

Enter Belle II





☞ Mega exp. collaboration ≈1100 researchers, 123 institutions, 26 nations

Broad physics program

Null tests of the standard model (SM)

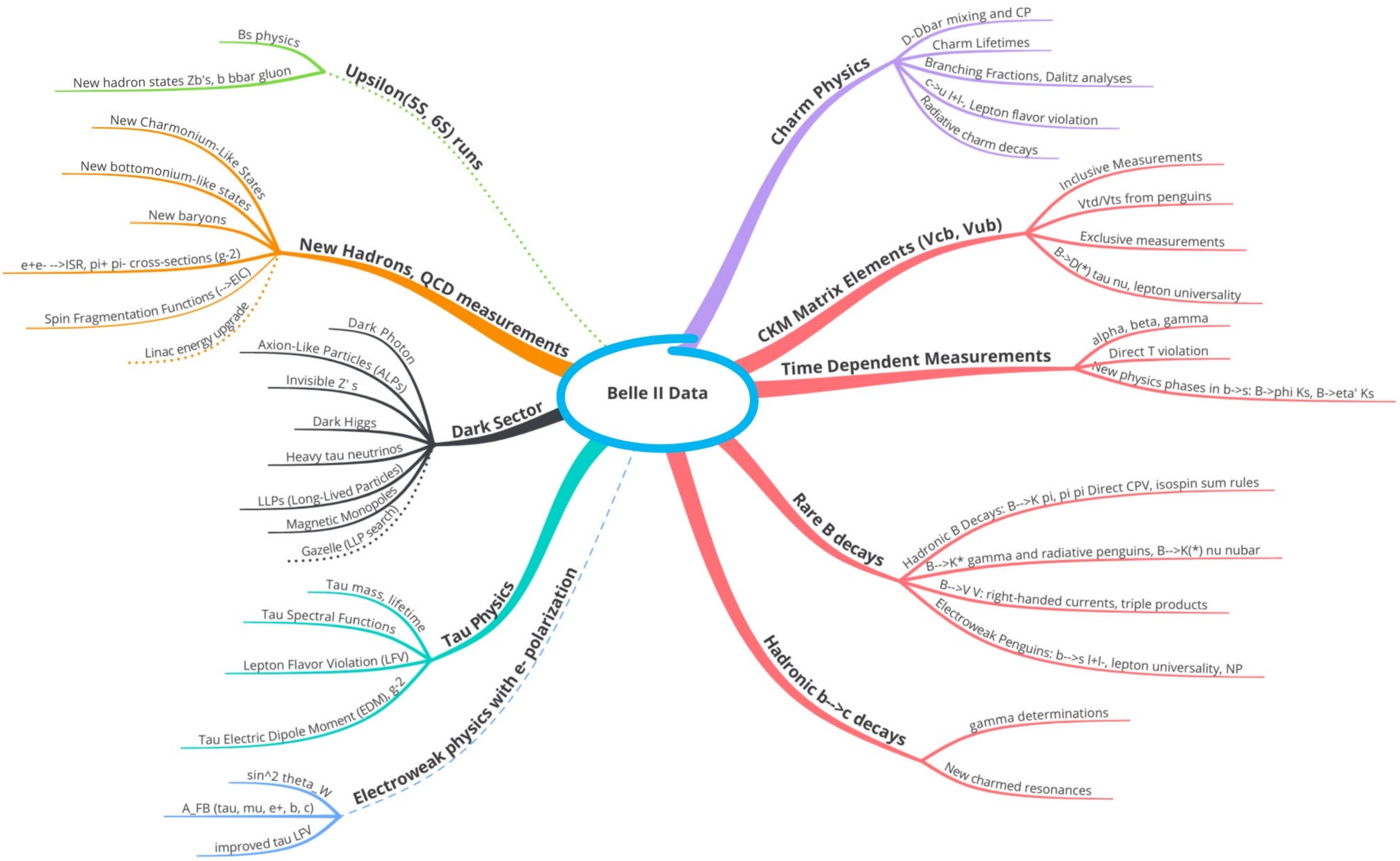
SM suppressed and forbidden decays

- Direct searches at Energy Frontier ⇒ no signal of new physics ⇒ stringent limits at few TeVs
- Indirect probe at Intensity Frontier ⇒ precision measurement of flavor observables, suppressed decays in the beauty, charm and tau sector etc.
- Belle II is unique and complementary to LHCb

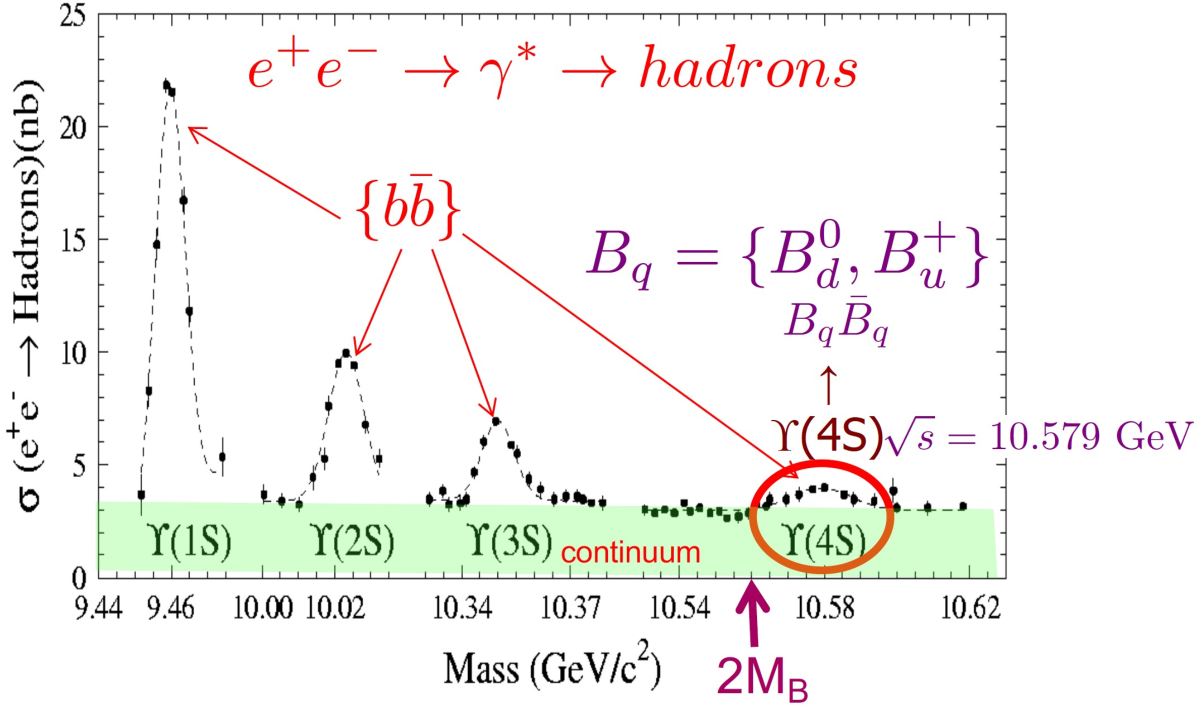
Test lepton flavor universality and search for LFV

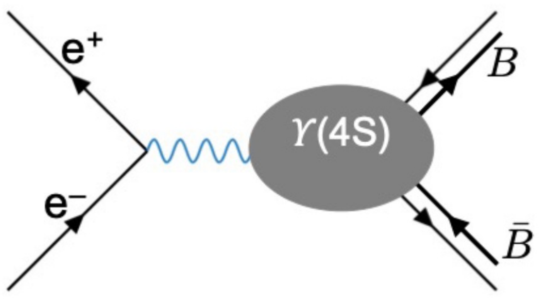
Hidden and dark sectors at GeV scale

Belle II mind map



Collision environment

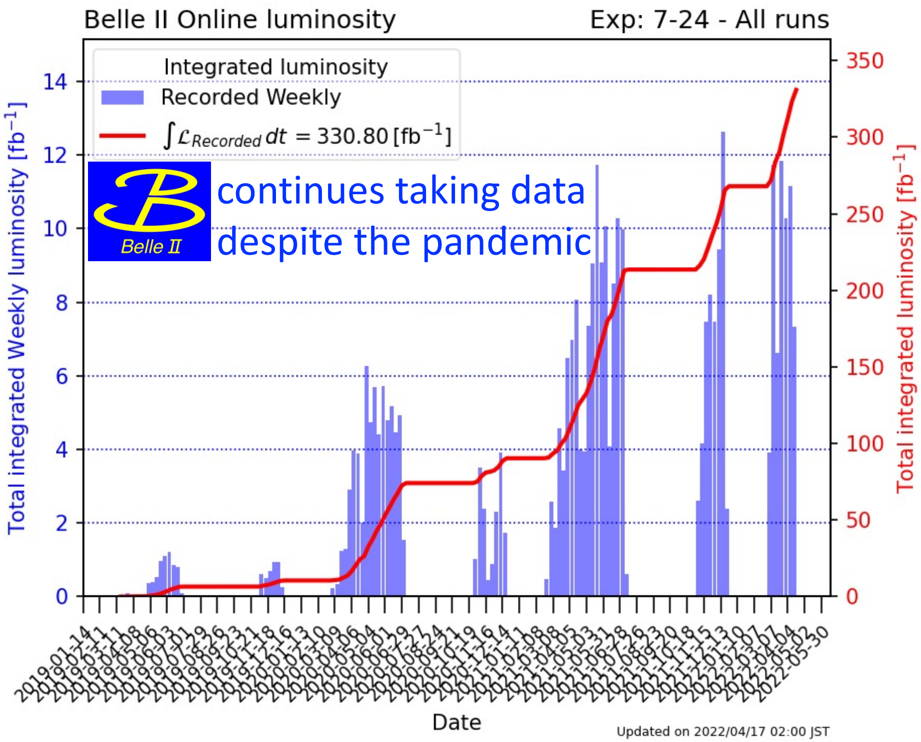




- e^+e^- annihilation at a center-of-mass energy ($\sqrt{s}$) near the $\Upsilon(4S)^\dagger$ resonance ⇒ the production of coherent B-meson (B^0 or B^+) pairs
- Data recorded below the peak ("off-resonance") used to model the $e^+e^- \rightarrow q\bar{q}$ continuum background
- Hermetic detector enables the capture of almost all detectable particles; great for the reconstruction of neutrals (γ, π^0, K_L^0 …)
- Average particle (charged + neutral) multiplicity: 15–20

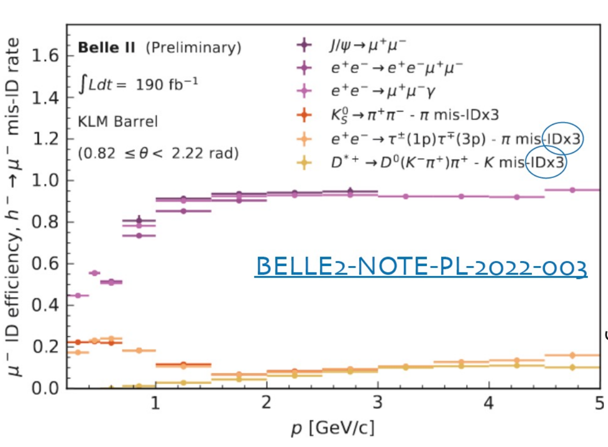
†Data taken above the $\Upsilon(4S)$, e.g., that at $\Upsilon(5S)$ can be used for B_s^0 meson studies

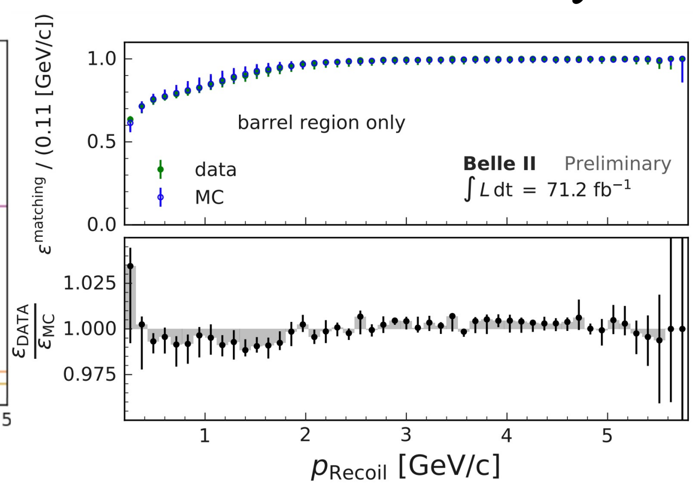
Dataset and performance

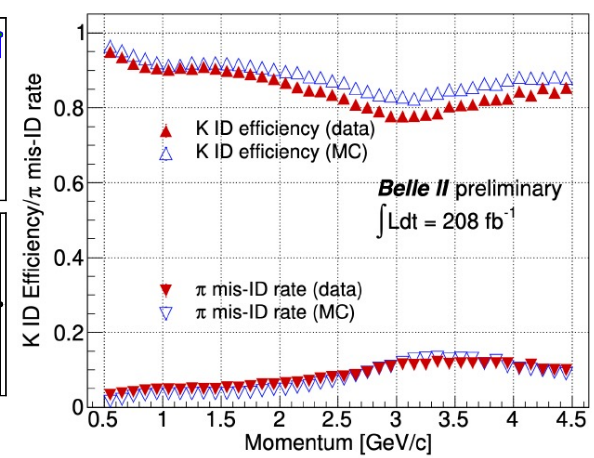


- ❑ Peak luminosity: $3.8\times10^{34}\mathrm{cm^{-2}s^{-1}}$ (world record)
- ❑ Path to reach $2.0\times10^{35}\mathrm{cm^{-2}s^{-1}}$ has been defined
- ❑ Still large factors to arrive at target peak luminosity ($6.0\times10^{35}\mathrm{cm^{-2}s^{-1}}$)
- ❑ Data recorded: 330 fb^{-1} of which a maximum of 190 fb^{-1} used in the studies presented

➢ A glance at performances relevant to the analyses shown in the talk







Key analysis steps

- Exploit the clean e^+e^- environment and well-defined kinematics (beam energy known to a few MeV precision) to reconstruct signal-side B candidates

$$M_{\mathrm{bc}} \equiv \sqrt{E_{\mathrm{beam}}^{*2} - \vec{p}_B^{\,*2}}$$

$$\Delta E \equiv E_{\mathrm{beam}}^{*} - E_B^{*}$$

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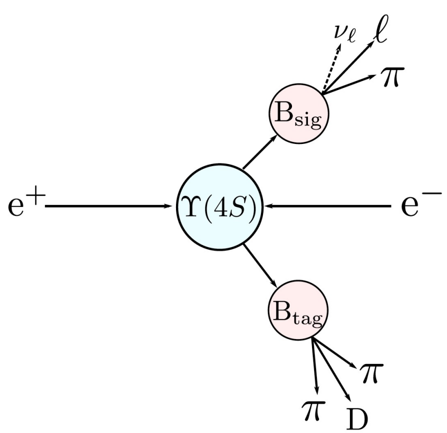
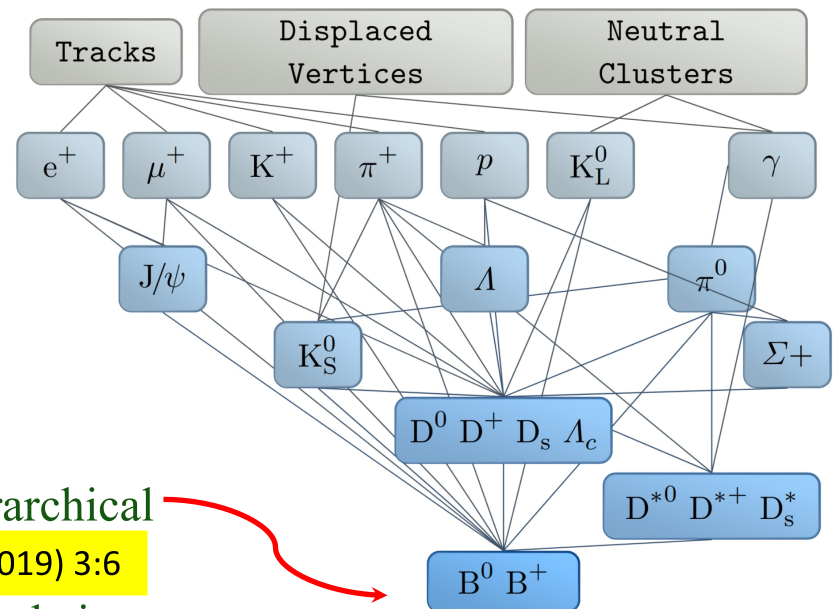
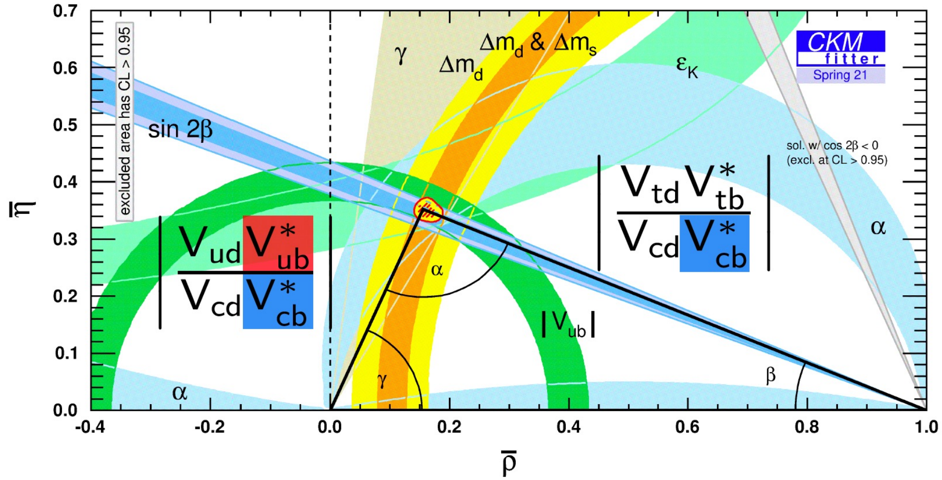
- If the signal B candidate has ≥ 1 invisible decay product, utilize properties of the recoiling ('tag') B candidate

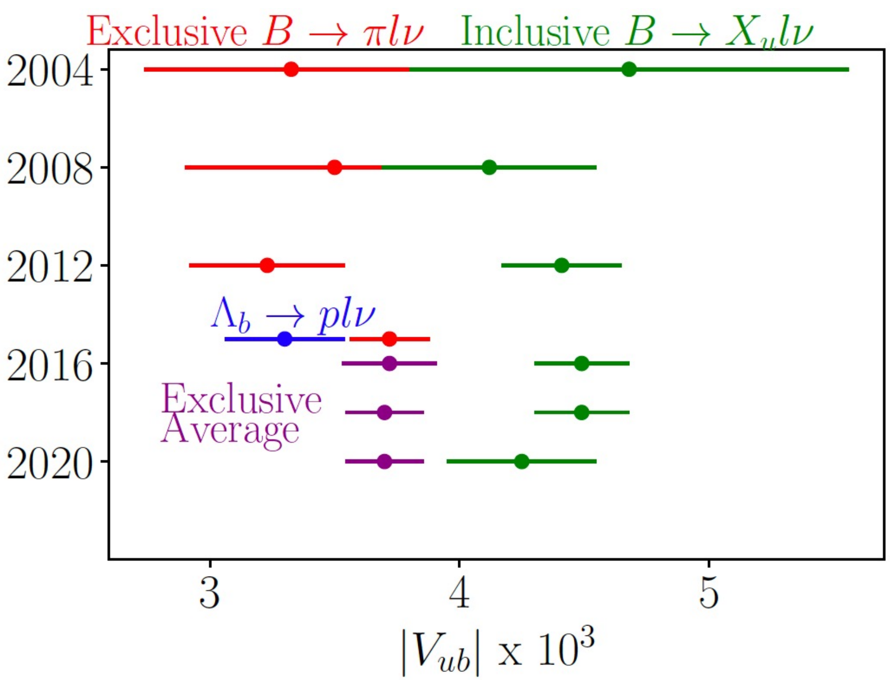


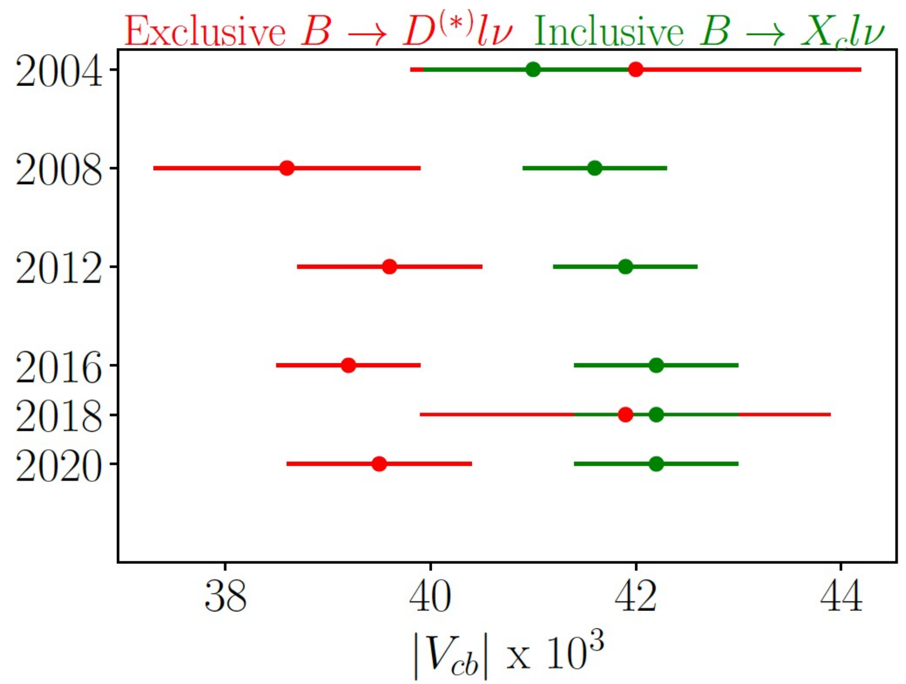


- MVA based tagging algorithm using a hierarchical approach ('FEI') Comp. Softw. Big Sci. (2019) 3:6
- Reconstruct close to 10,000 distinct decay chains
- About 30–40% improvement in efficiency for the same purity compared to Belle

Start with a longstanding puzzle

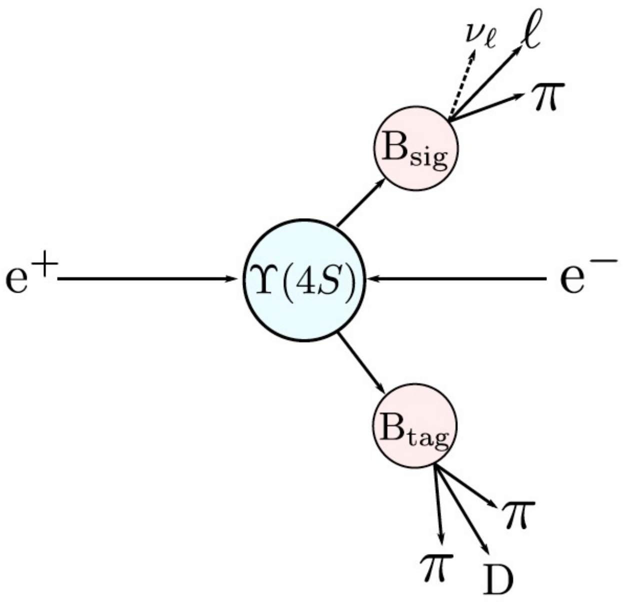






- Discrepancy between exclusive and inclusive determinations of $|V_{ub}|$ and $|V_{cb}|$

Measuring CKM matrix element $|V_{ub}|$



- Reconstruct $B \to \pi e^+ \nu_e (\pi = \pi^+ \text{or } \pi^0)$ decays
- Key challenges: statistics and π^0 reconstruction

- Perform a likelihood fit to missing mass squared distribution in three $q^2 = \left(p_e + p_{\nu_e}\right)^2$ bins:

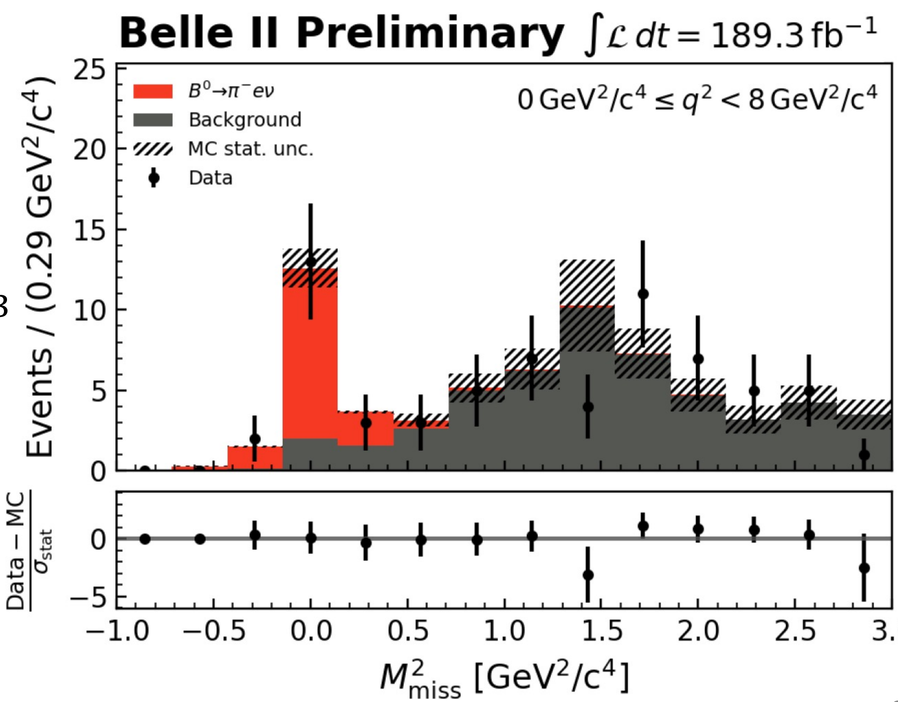
$$M^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_e - p_\pi\right)^2$$

- Observed significance: 3.8 – 5.4σ

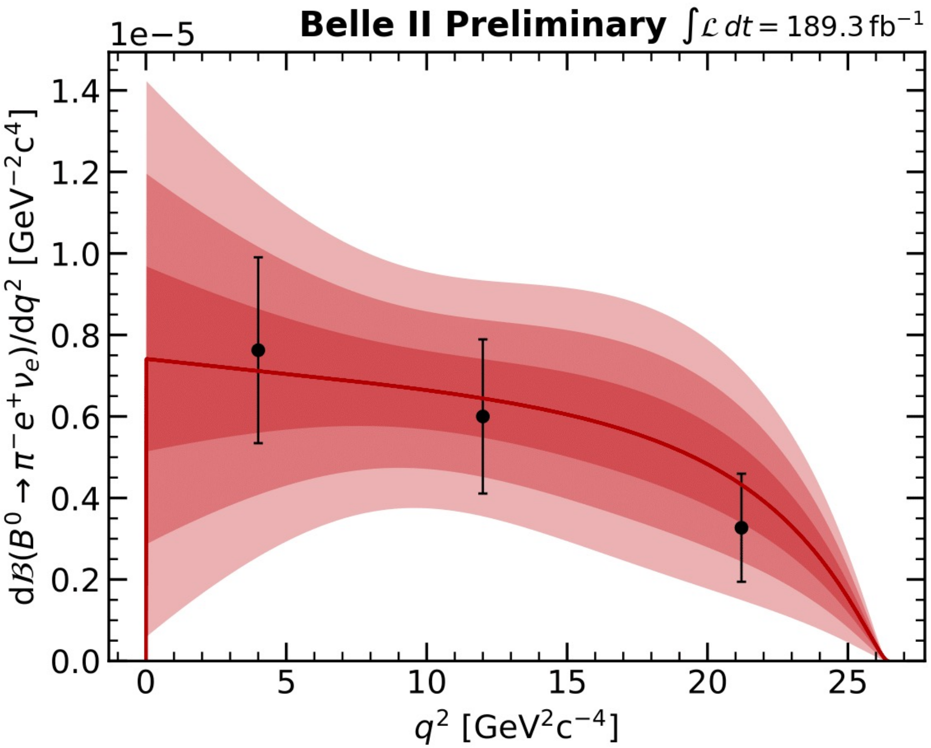
$$\mathcal{B}(B^0 \to \pi^- e^+ \nu_e) = (1.43 \pm 0.27 \pm 0.07) \times 10^{-3}$$

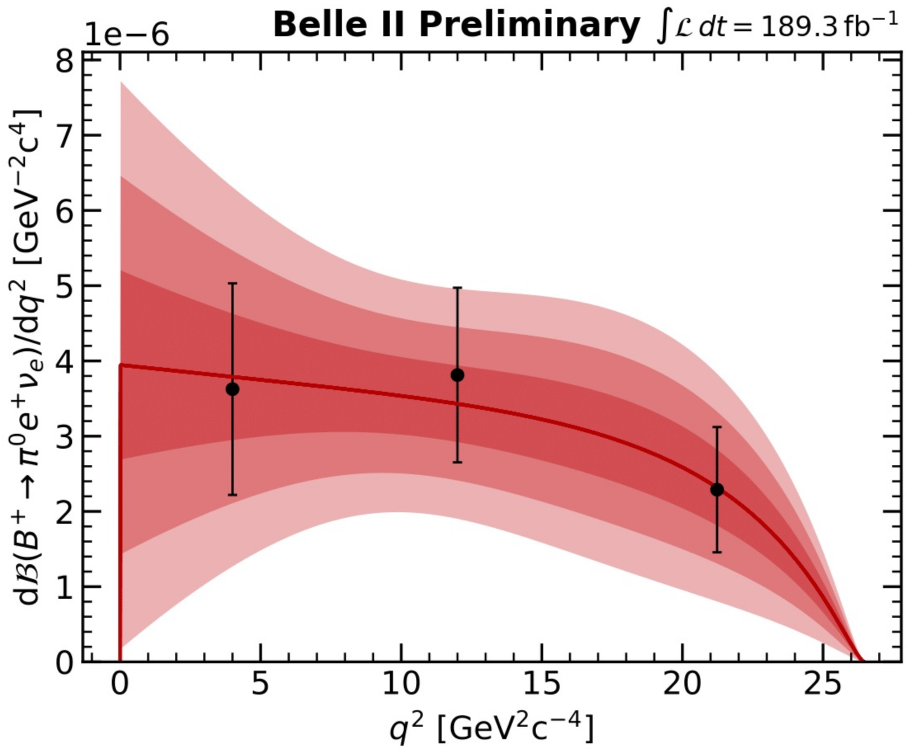
$$\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e) = (8.33 \pm 1.67 \pm 0.55) \times 10^{-3}$$

- Quoted uncertainties are statistical and systematic, respectively
- Within uncertainties, results agree with their world averages



Results on $|V_{ub}|$





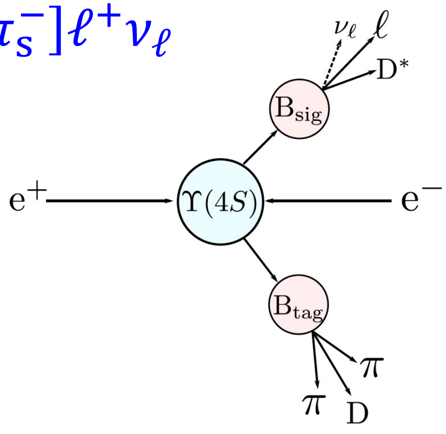
- Translate the unfolded q^2 spectrum into differential branching fraction $d\mathcal{B}/dq^2$
- Do a χ^2 fit of $d\mathcal{B}/dq^2 \propto f_+^2(q^2)|V_{ub}^2|$ using BCL form factor parameterization and lattice QCD constraints (Fermilab Lattice + MILC Collaborations)

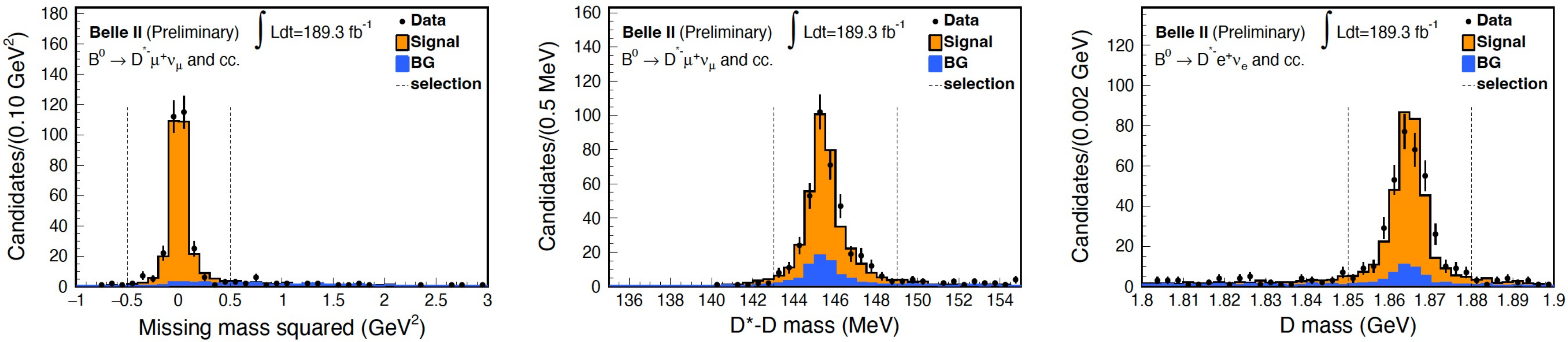
PRD 92, 014024 (2015)

Decay mode	Fitted $\lvert V_{ub}\rvert$
$B^0 \to \pi^- e^+ \nu_e$	$(3.71 \pm 0.55) \times 10^{-3}$
$B^+ \to \pi^0 e^+ \nu_e$	$(4.21 \pm 0.63) \times 10^{-3}$
Combined fit	$(3.88 \pm 0.45) \times 10^{-3}$

Measuring CKM matrix element $|V_{cb}|$

- Reconstruct the decay chain $B^0 \to D^{*-}[\to \overline{D}^0(\to K^+\pi^-)\pi_s^-]\ell^+\nu_\ell$
- Candidate selection relies on
  a) $m^2_{\rm miss} \equiv \left(p_{e^+e^-} - p_{\rm B_{tag}} - p_\ell - p_{D^*}\right)^2$
  b) difference between D^* and D mass $\equiv \Delta m$
  c) mass of D candidate $\equiv m_{\rm D}$
- Key challenge: detection of the π_s emanating from D^*





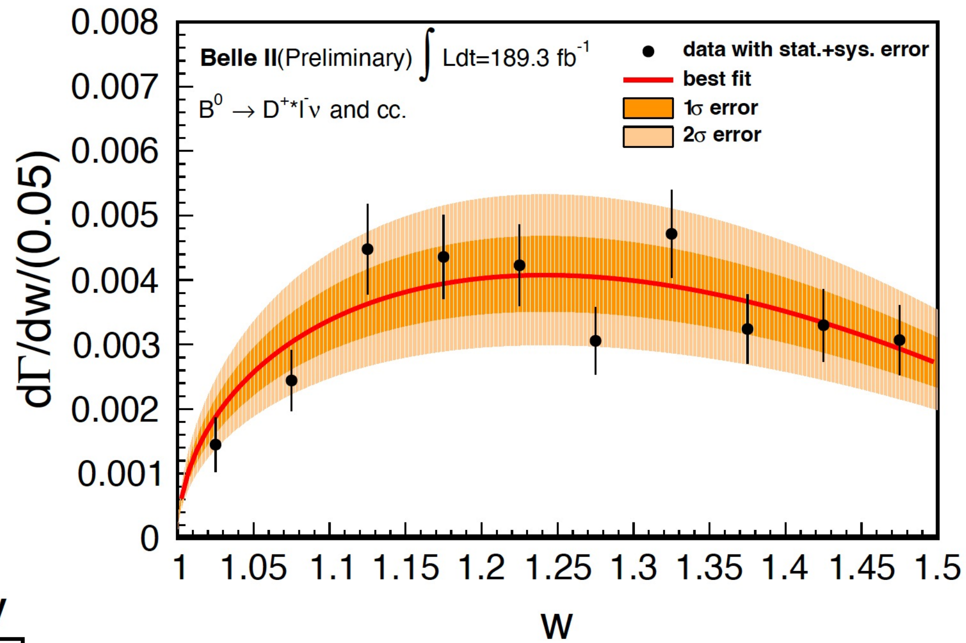
- Measured branching fraction is consistent with the world-average

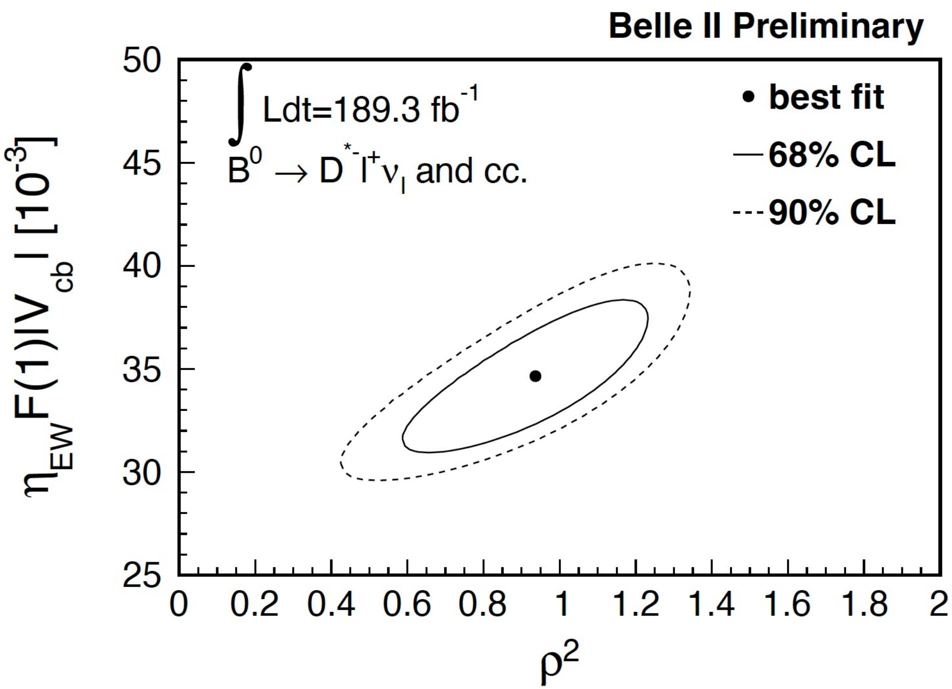
$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = [5.27 \pm 0.22 \pm 0.38]\% \ vs.\ \text{PDG: } (5.66 \pm 0.22)\%$$

➢ Dominant systematic sources: π_s detection and FEI efficiencies

Results on $|V_{cb}|$

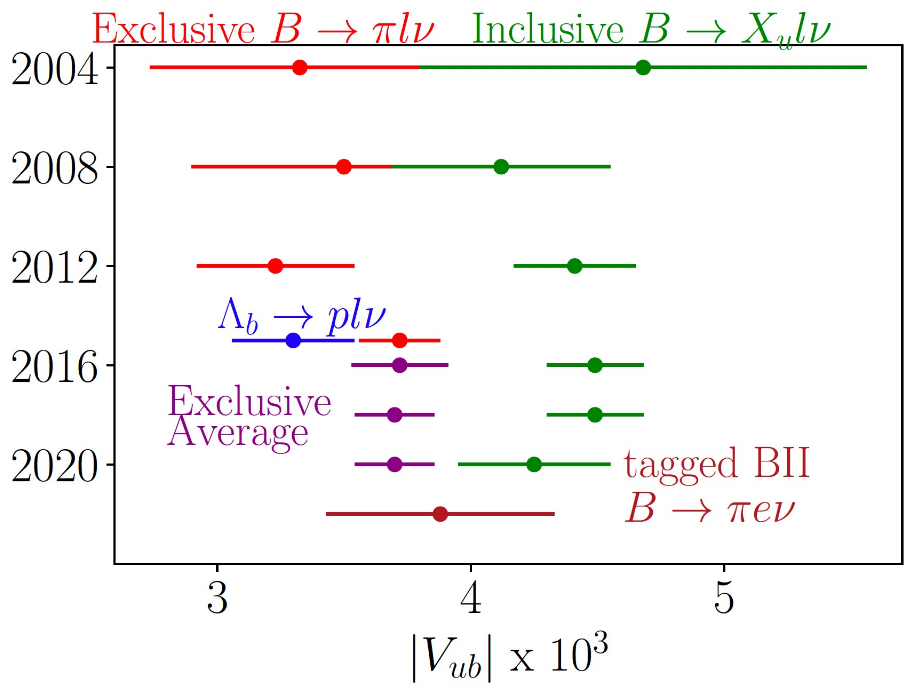
- Fit $\frac{d\Gamma}{dw} \propto \mathcal{F}^2(w)|V_{cb}|^2\eta_{\text{EW}}^2$ using the CLN form factor parameterization
  NP B530, 153 (1998)
  with $R_1(1)$ and $R_2(1)$ constrained to their HFLAV averages
- w is the product of velocities of the initial and final mesons:
  $w = (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*})$

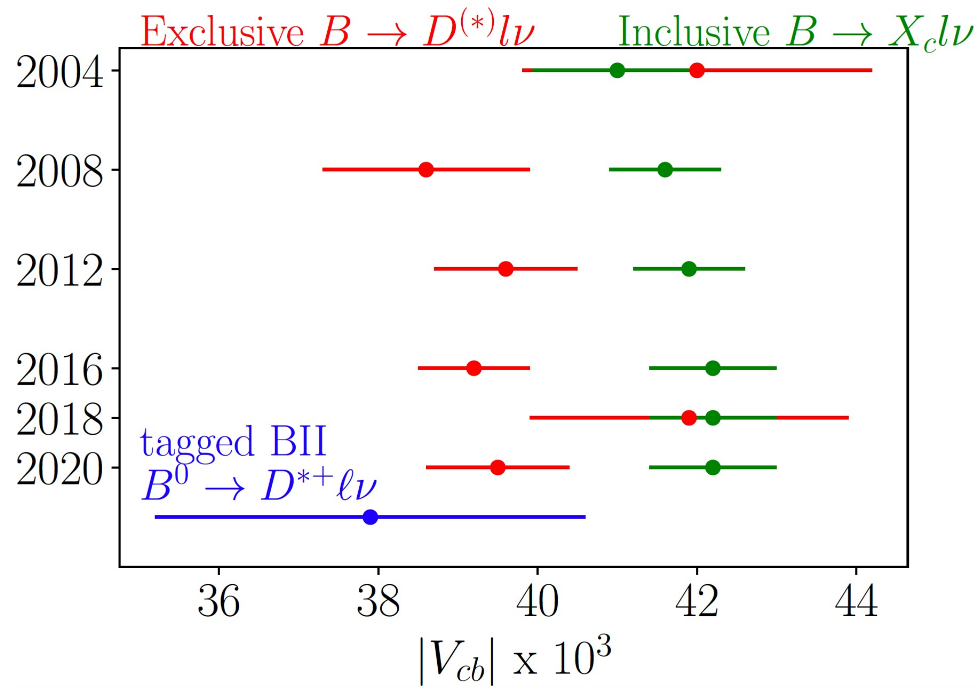




- We obtain:
  - $\eta_{\text{EW}} F(1)|V_{cb}| = (35.3 \pm 0.4) \times 10^{-3}$
  - $\rho^2 = 0.94 \pm 0.21$
- Subsequently derive:
  $|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$

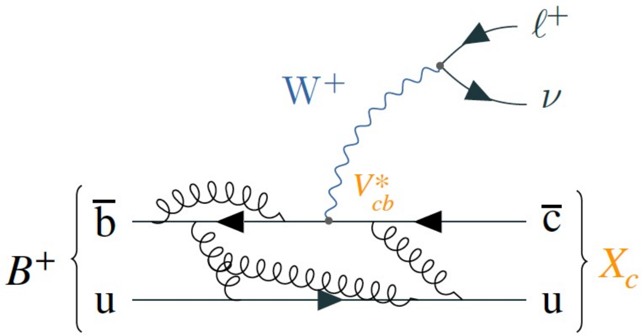
Putting them together

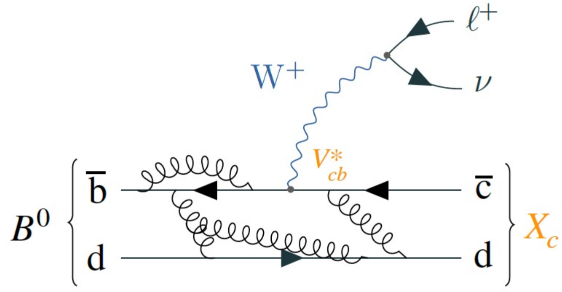


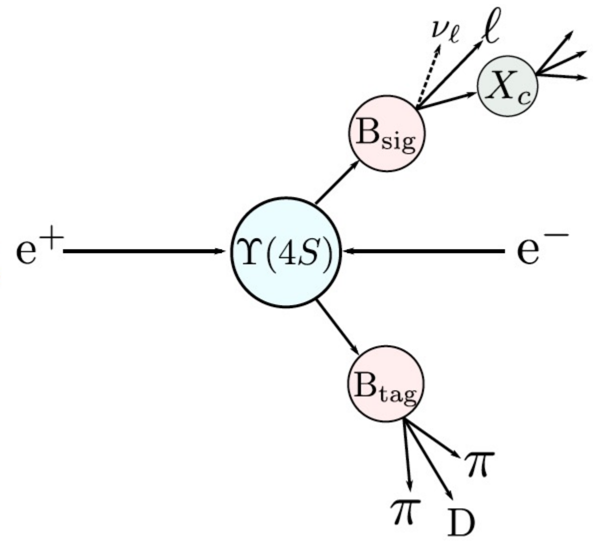


- These first tagged determinations of $|V_{ub}|$ and $|V_{cb}|$ from Belle II are statistically limited
- We expect a higher precision with untagged measurement as the corresponding efficiency is 20–30%

How about inclusive decays?





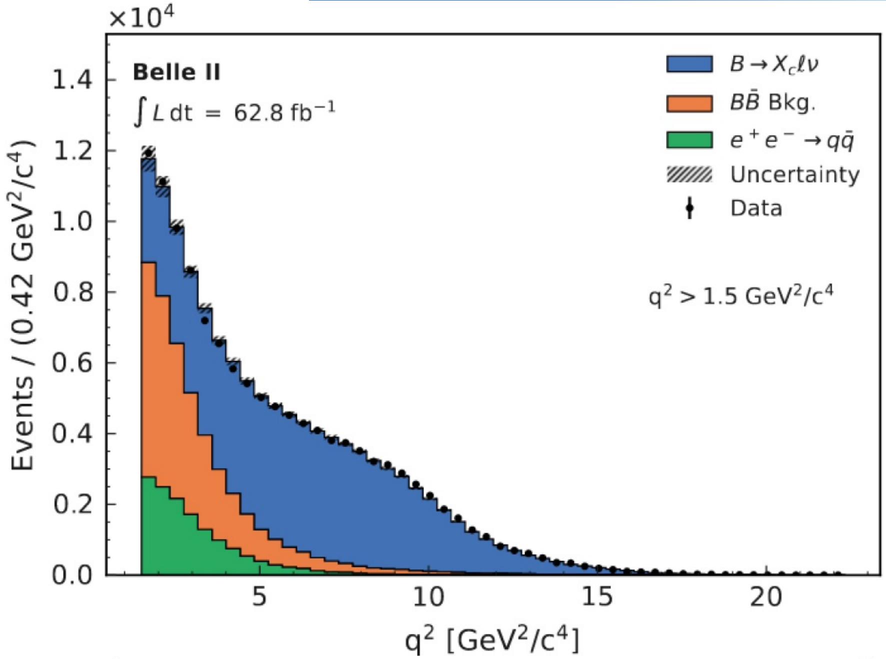


- Using operator product expansion (OPE), the decay width can be given as:

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2\left(1 + \frac{c_5(\mu)O_5(\mu)}{m_b^2} + \frac{c_6(\mu)O_6(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$$

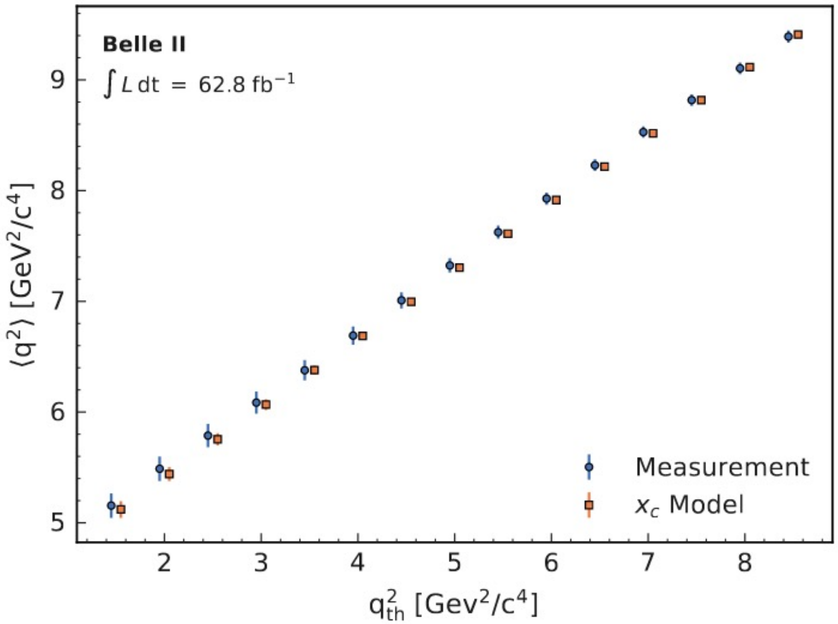
  where O_i hadronic matrix elements and c_i corresponding Wilson coefficients
- Moments of E_ℓ^* and M_X can be expressed with the same OPE formulation
  ⇒ need to measure moments for constraining the expansion parameters
- Novel idea: use $q^2 = m_{\ell\nu}^2$ moments due to less HQE parameters JHEP 02 (2019) 177
- Reparameterization invariance: 13 → 8 HQE parameters at $\mathcal{O}(1/m_b^4)$
- Performed a new measurement of $\langle (q^2)^n \rangle$ for $n = 1\text{–}4$

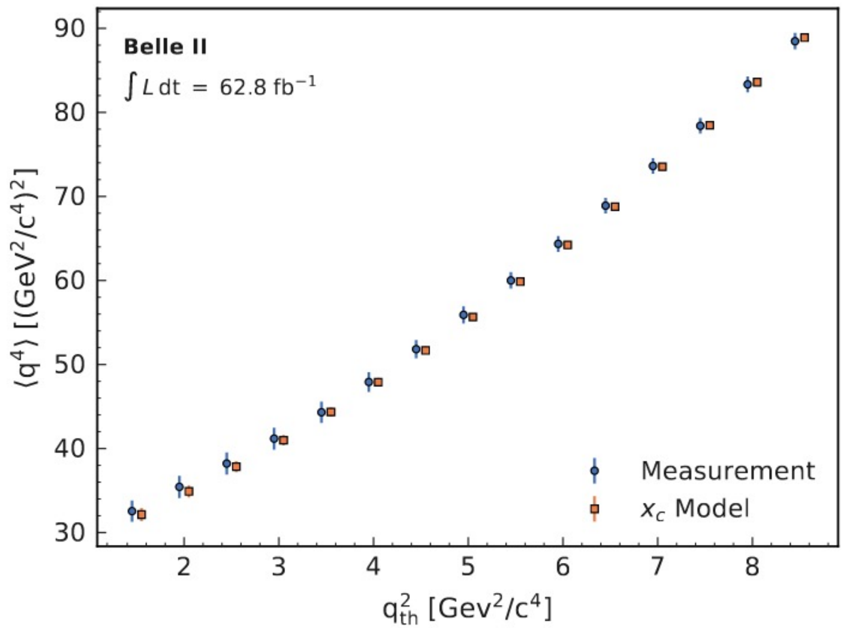
Getting q^2 moments in $B \to X_c \ell \nu$



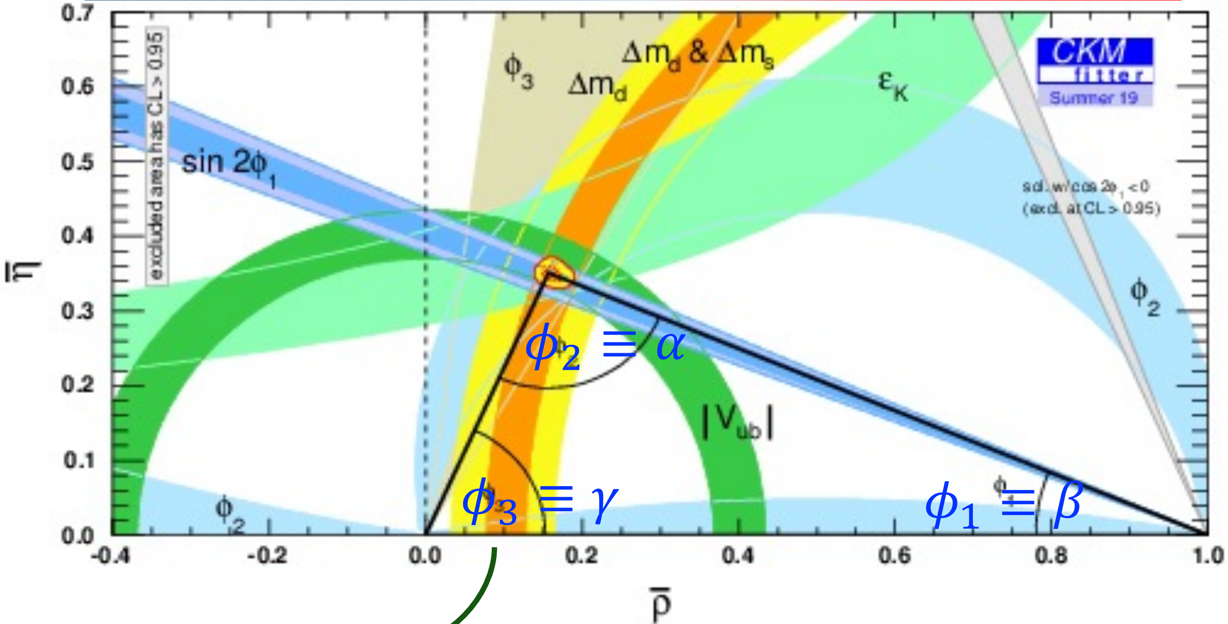
- Left plot is the data-MC comparison of the q^2 spectrum with background yields obtained from a likelihood fit to M_X
- Lower plots show $n = 1, 2$ moments of q^2 as a function of its lower threshold

➢ Expect the global fit for inclusive $|V_{cb}|$ using these moments in near future





Checking an SM candle: ϕ_3/γ



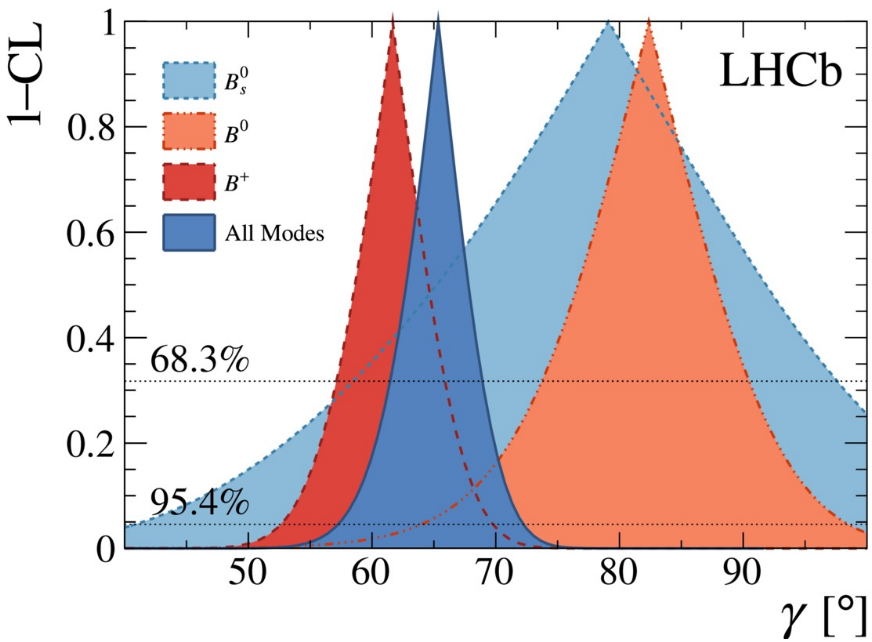
- Theoretically clean: $\mathcal{O}(10^{-7})$

JHEP 01 (2014) 051

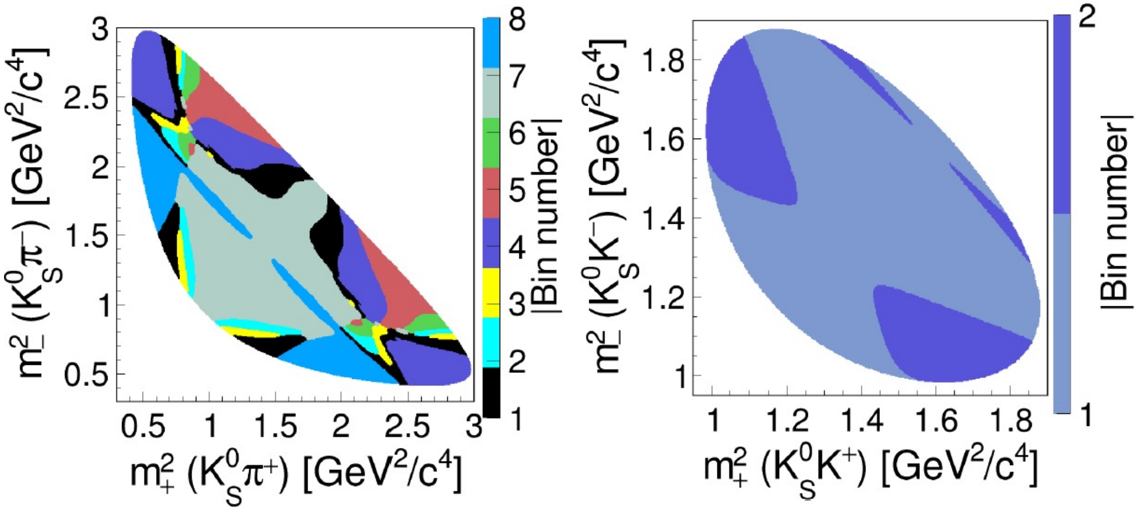
- Single most precise value is from LHCb:

$$\gamma = \left(65.4^{+3.8}_{-4.2}\right)^{\circ}$$

JHEP 12 (2021) 141

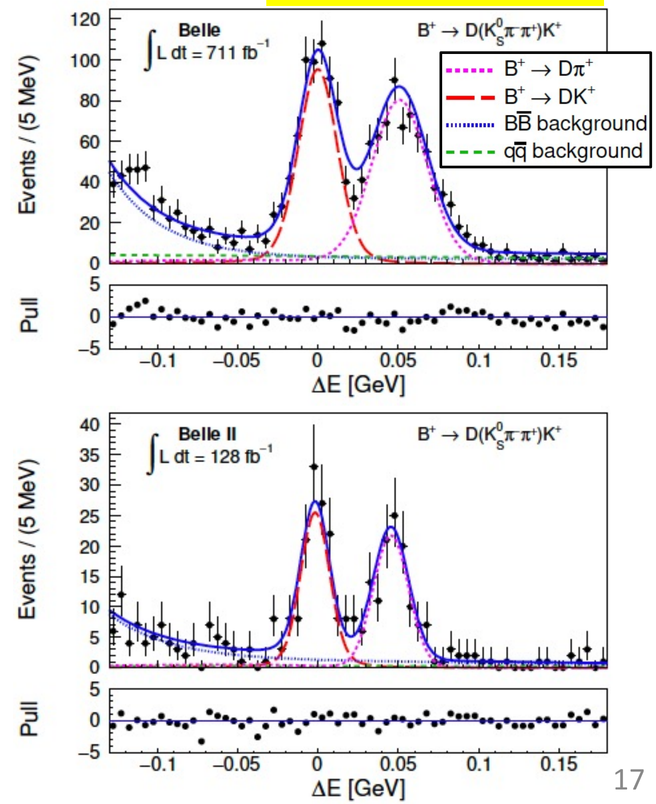


First measurement with Belle+Belle II data



- A model-independent Dalitz plot analysis of $B^+ \to D(K_S^0 h^+ h^-)h^+$ $(h = K, \pi)$ decays
- Simultaneous fit of two channels

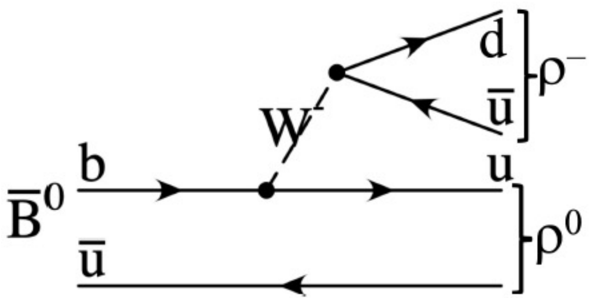
JHEP 02 (2022) 063



	Sample	Pion-enhanced		Kaon-enhanced	
D decay	Component	Belle	Belle II	Belle	Belle II
$D \to K_S^0\pi^+\pi^-$	$B^+ \to D\pi^+$	21325 ± 162	4193 ± 70	1764 ± 64	308 ± 23
	$B^+ \to DK^+$	140 ± 29	62 ± 11	1467 ± 53	280 ± 21
	$B\bar{B}$ background	5040 ± 155	1223 ± 68	1309 ± 85	387 ± 42
	$q\bar{q}$ background	9022 ± 172	1657 ± 69	6295 ± 122	1021 ± 47
$D \to K_S^0K^+K^-$	$B^+ \to D\pi^+$	2740 ± 56	519 ± 21	211 ± 18	50 ± 10
	$B^+ \to DK^+$	17 ± 4	2.1 ± 0.2	194 ± 17	34 ± 7
	$B\bar{B}$ background	333 ± 31	77 ± 12	110 ± 18	22 ± 7
	$q\bar{q}$ background	409 ± 37	124 ± 14	309 ± 28	92 ± 11

- We obtain $\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$
- Statistically limited ⇒ expect an LHCb-like precision in 10 ab^{-1}data

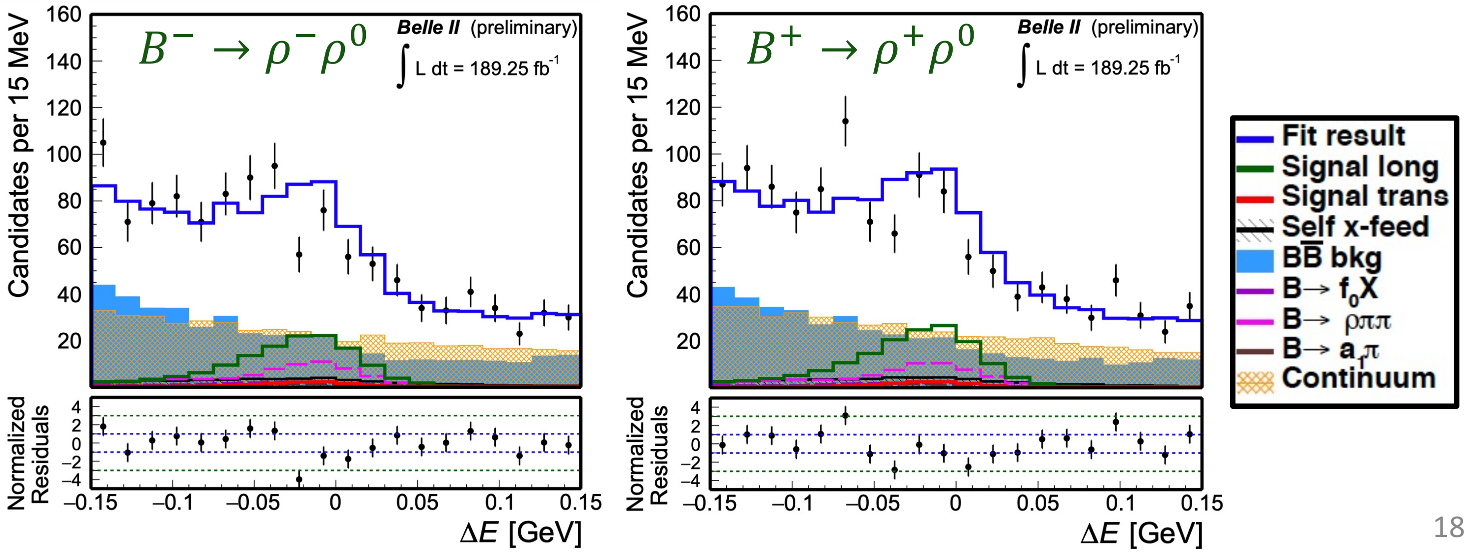
Towards the CKM angle ϕ_2/α



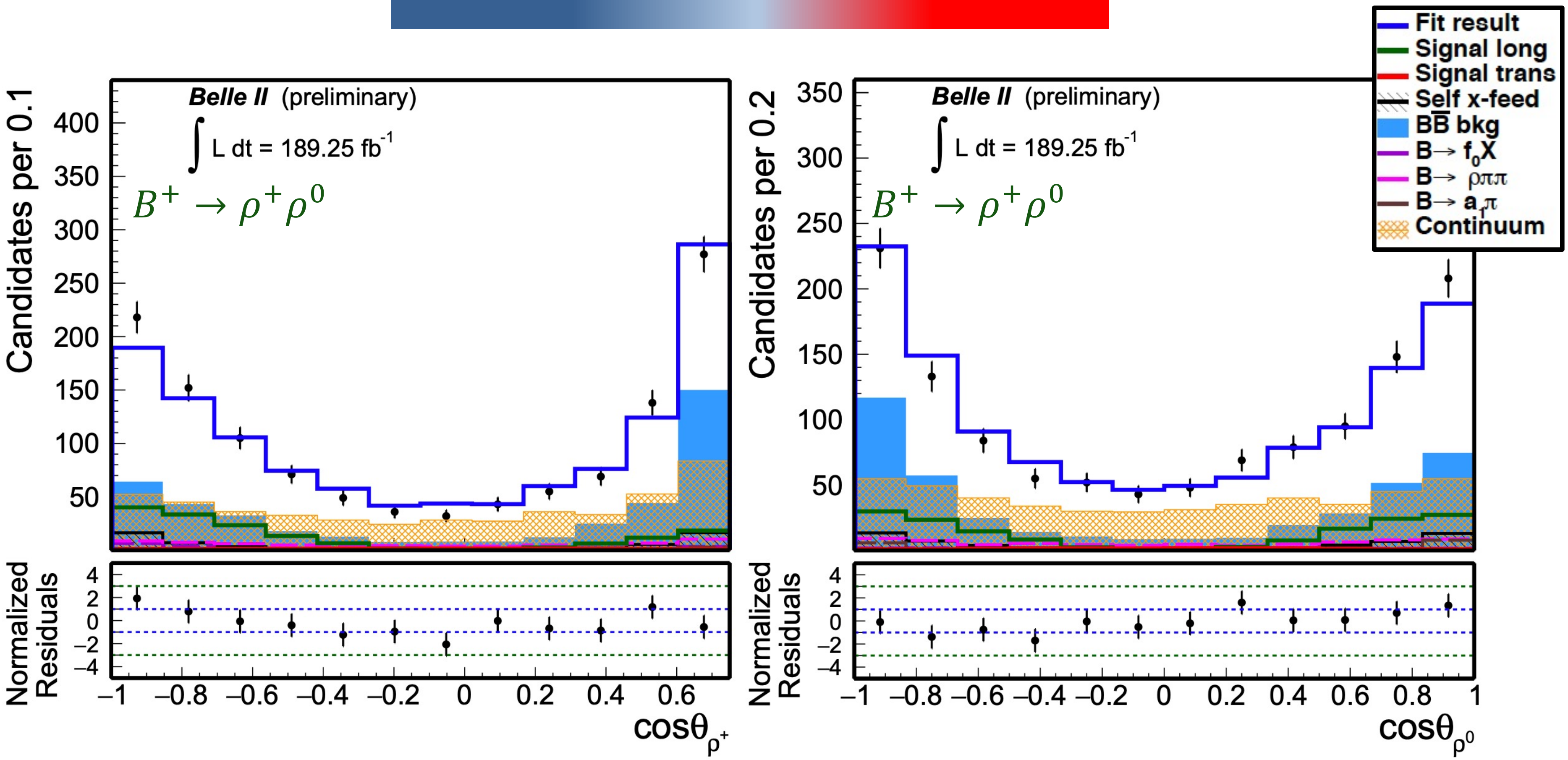
- Can extract α using info from three isospin-related decays $B^+ \to \rho^+\rho^0$, $B^0 \to \rho^+\rho^-$, and $B^0 \to \rho^0\rho^0$ PRL 65 (1990) 3381
- Belle II is unique having access to all of them

- Need to measure direct CP asymmetry in $B^+ \to \rho^+\rho^0$ where both ρ^+ and ρ^0 are longitudinally polarized
  a) Rate asymmetry of $B^+ \to \rho^+\rho^0$ and $B^- \to \rho^-\rho^0$ ⇒ arising due to potential interference between $b \to u$ tree and $b \to d$ penguin diagrams
  b) Longitudinal polarization fraction ⇒ sensitive to helicity angle distributions

- 6D template fit including correlations



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

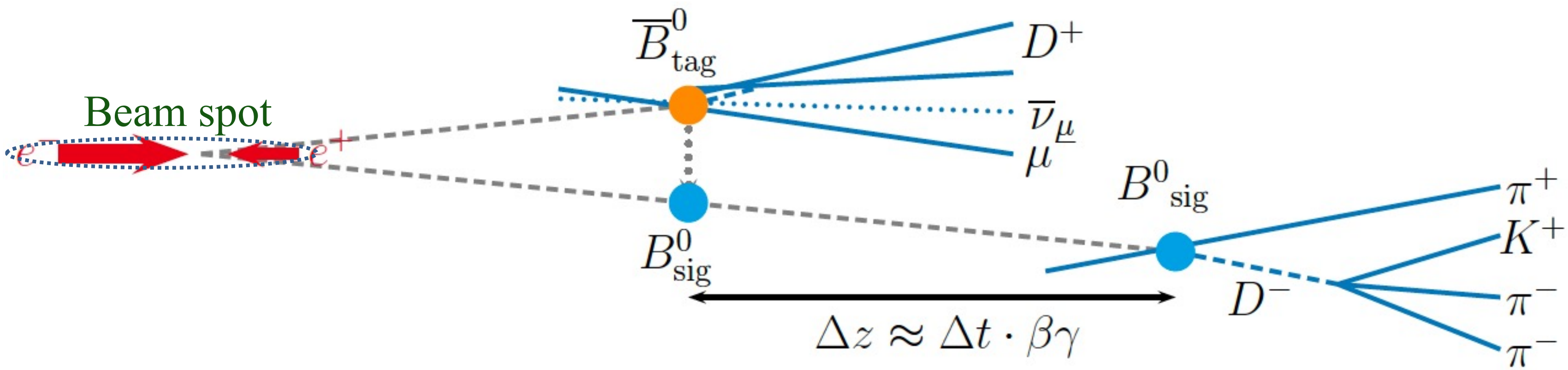


$$A_{CP} = -0.069 \pm 0.068\ (\text{stat.}) \pm 0.060\ (\text{syst.})$$
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.2^{+2.2}_{-2.1}\ (\text{stat.}) \pm 2.7\ (\text{syst.})) \times 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033}\ (\text{stat.}) \pm 0.027\ (\text{syst.})$$

- Results compatible with previous measurements, driven by BABAR

PRL 102 (2009) 141802

Study of time-dependent CP violation



- Crucial parameters for time-dependent studies
  a) Vertex resolution
  b) Tagging efficiency

Belle II: $\varepsilon_{tag} = (30.0 \pm 1.3)\%$
Belle : $\varepsilon_{tag} = (30.1 \pm 0.4)\%$

EPJ C (2022) 82:283

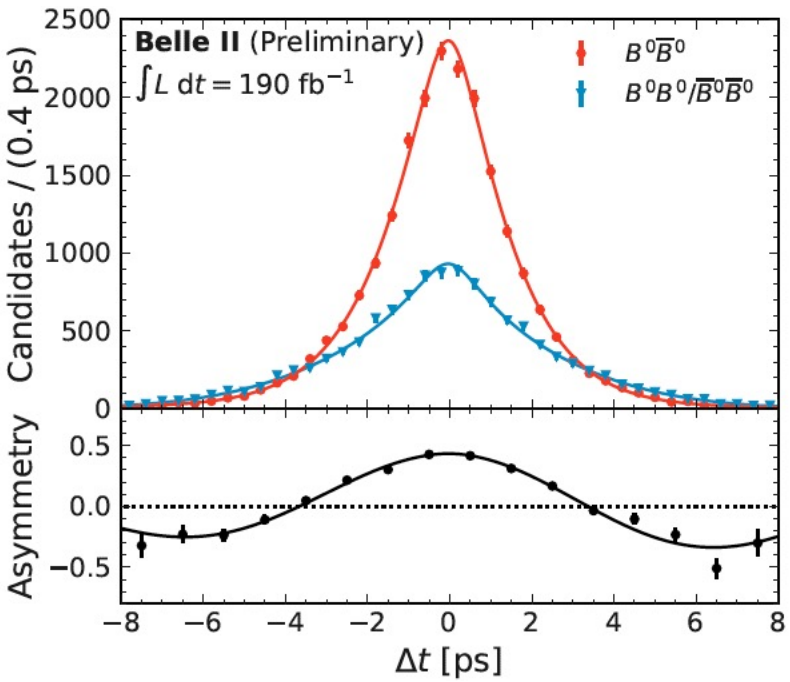
- Modified beam-energy scheme means a reduced boost with respect to Belle: $\beta\gamma = 0.43 \rightarrow 0.29 \Rightarrow \Delta z \approx 200 \rightarrow 130\ \mu\text{m}$
- Recover the precision on Δt ($\approx \Delta z/\beta\gamma c$) by having the first layer of the vertex detector just around the beam-pipe
- New (nano) beam scheme means a smaller beam spot that can also be used as a stronger constraint to improve the precision on vertex fit

A step in that direction: mixing and lifetime

Use about 40k decays reconstructed from hadronic $B^0 \to D^{(*)-}\pi^+/K^+$ channels

$$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat.}) \pm 0.008\,(\text{syst.})\ \text{ps}$$
$$\Delta m_d = 0.516 \pm 0.008\,(\text{stat.}) \pm 0.005\,(\text{syst.})\ \text{ps}^{-1}$$

- ❑ Results compatible with current world averages



Compared to best measurements of Belle and BABAR

- ➢ Slightly worse statistical uncertainty which can be improved with the inclusion of $B^0 \to D^{(*)-}\ell^+\nu$ channels
- ➢ Better alignment and background systematics
- ➢ Comparable resolution modeling systematics
- ✓ Key milestone in the Belle II program: now ready for time-dependent CP violation studies

In fact, we have already started...

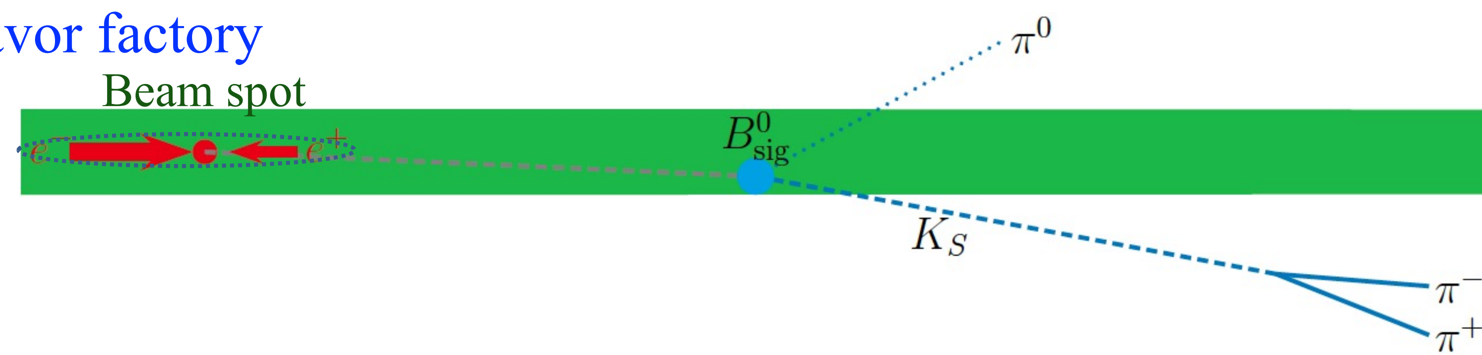
- Perform a time-dependent study to measure the branching fraction and direct CP asymmetry for $B^0 \to K^0\pi^0$ decays

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q\{\mathcal{A}_{CP}\cos(\Delta m_d \Delta t) + \mathcal{S}_{CP}\sin(\Delta m_d \Delta t)\}]$$

- In the SM, $\mathcal{A}_{CP} \approx 0$ and $\mathcal{S}_{CP} \approx \sin 2\beta$
- Further, branching fraction and $\mathcal{A}_{CP}$ are inputs to an isospin sum rule proposed in PLB 627, 82 (2005) $\Rightarrow$ null test for new physics

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

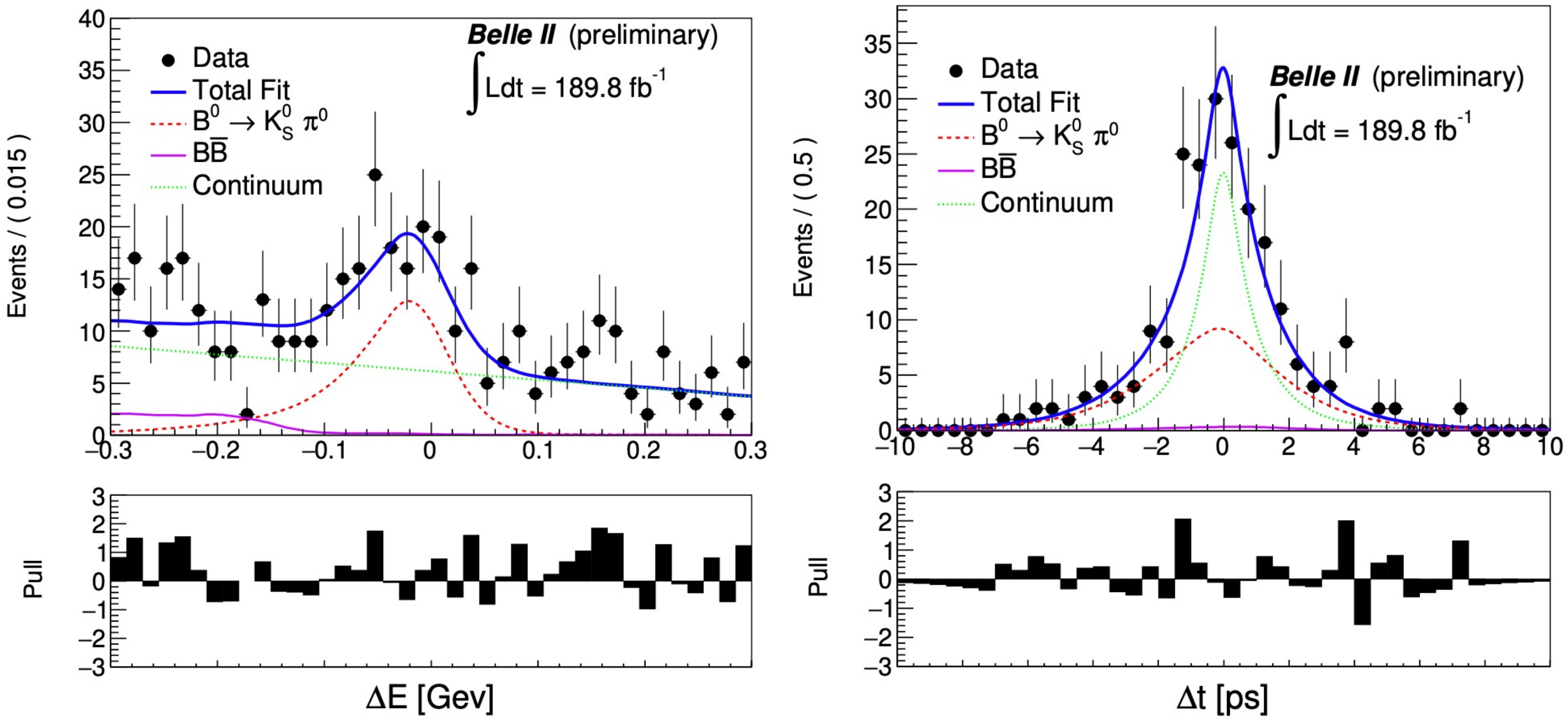
- Time-dependent study in a decay without any primary charged particle coming from B_{sig} is challenging and likely the sole preserve of an e^+e^- flavor factory



✓ Need good performance with neutrals and beam-spot constraint

Results on $\mathcal{B}$ and $\mathcal{A}_{CP}$ for $B^0 \to K^0\pi^0$

- 4D fit comprising M_{bc}, ΔE, continuum suppression output, and Δt
- Use $B^0 \to J/\psi(\mu^+\mu^-)K_S^0$ to calibrate the signal Δt shape
- Fix the $\mathcal{S}_{CP}$ value to current world average in order to maximize the precision on $\mathcal{A}_{CP}$



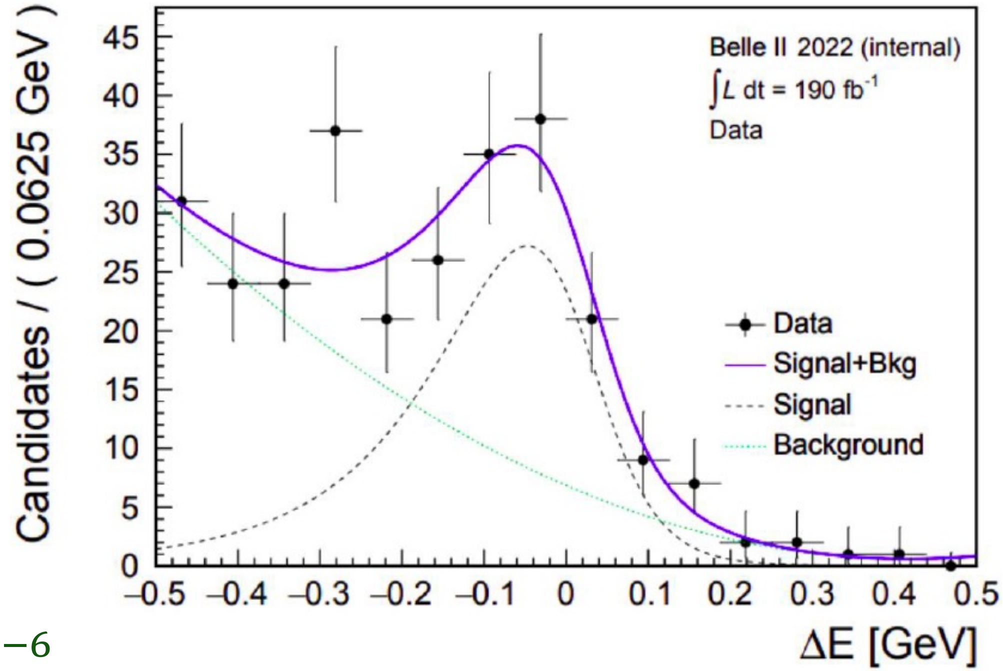
$$\mathcal{A}_{CP} = -0.41^{+0.30}_{-0.32}(\text{stat}) \pm 0.09(\text{syst})$$

$$\mathcal{B} = [11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst})]\times10^{-6}$$

Branching fraction for $B^0 \to K_S^0 \pi^0 \gamma$

- In the SM, photon is (right-) left-handed in $(B^0)\bar{B}^0 \to K_S^0\pi^0\gamma$ ⇒ we do not expect any time-dependent CP asymmetry in $B^0 \to K_S^0\pi^0\gamma$ decays
- Potential new physics can give rise to different chirality structure

  PRL 79 (1997) 185   JHEP 12 (2013) 102
- Belle II provides a unique setup for testing this possibility



In preparation for time-dependent analysis, measured the branching fraction:

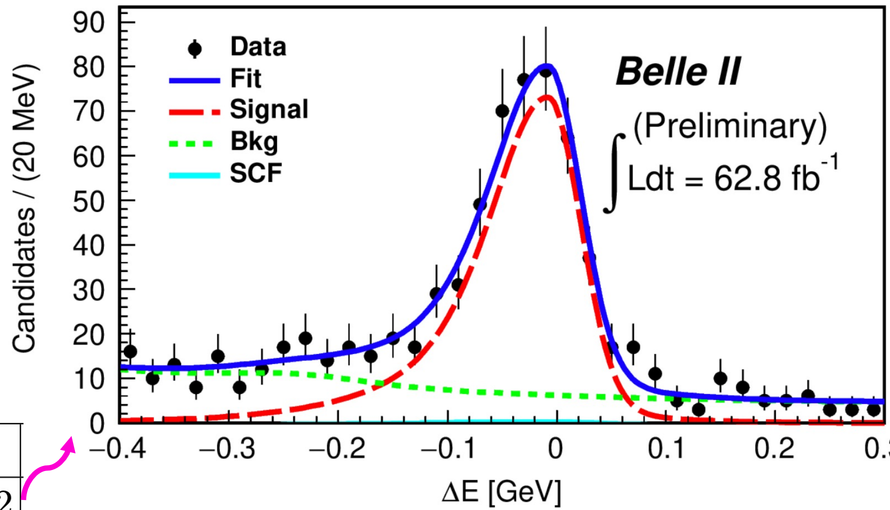
$\mathcal{B} = [7.3 \pm 1.8(\text{stat}) \pm 1.0(\text{syst})]\times 10^{-6}$

✓ Compatible with world average $(7.0 \pm 0.4)\times 10^{-6}$

Moving to related radiative decays

Branching fractions for $B \to K^*\gamma$ with $K^* \to K^+\pi^-$, $K_S^0\pi^0$, $K^+\pi^0$ and $K_S^0\pi^0$

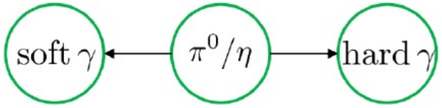
- Extract the signal yield from an unbinned maximum-likelihood fit to the ΔE distribution
- Branching fractions are in fair agreement with world averages



Mode	Signal yield	Efficiency (%)	$\mathcal{B}_{\text{meas}}$ $[10^{-5}]$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	454 ± 28	15.22 ± 0.03	$4.5 \pm 0.3 \pm 0.2$
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	50 ± 10	1.73 ± 0.01	$4.4 \pm 0.9 \pm 0.6$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	169 ± 18	4.84 ± 0.02	$5.0 \pm 0.5 \pm 0.4$
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	160 ± 17	4.23 ± 0.02	$5.4 \pm 0.6 \pm 0.4$

arXiv:2110.08219

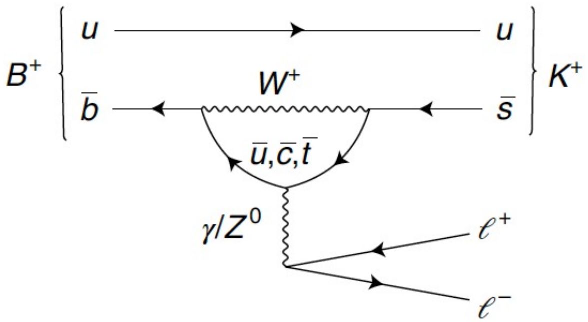
- Major systematic sources: fit model, mis-modeling of π^0/η veto, and selection variables in simulation (depending on the channel)

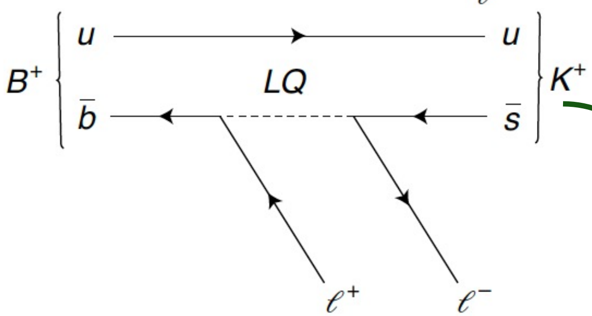


(hard photon from asymmetric π^0/η faking signal γ)

✓ Update with full available dataset is ongoing to measure the branching fraction, CP violation and isospin asymmetry; may be noted that Belle has observed 3.1σ evidence for isospin violation PRL 119 (2017) 191802

Talk of the town





- If one keeps mass terms aside, the SM does not distinguish between leptons of different flavor
- The ratio:

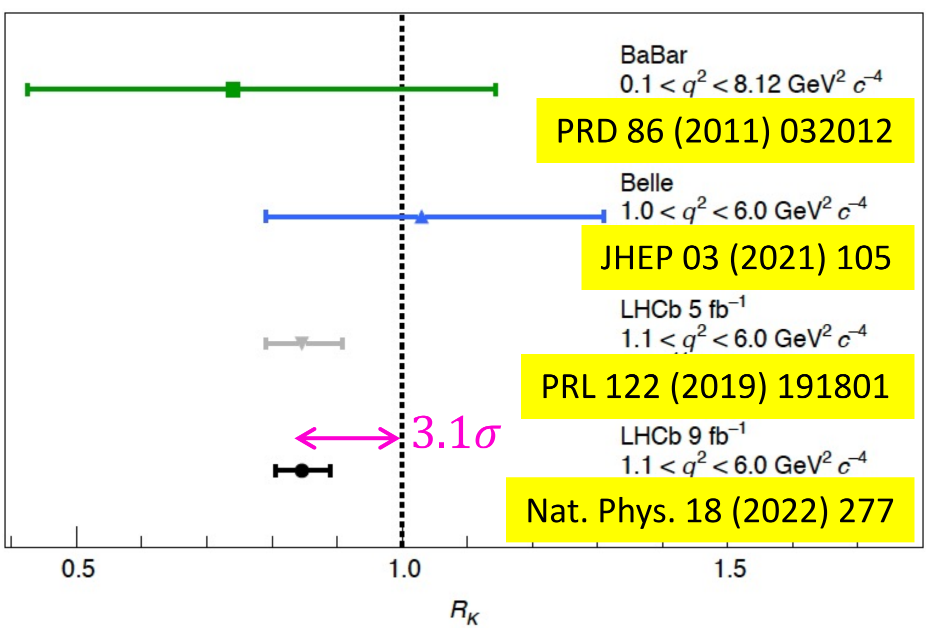
$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

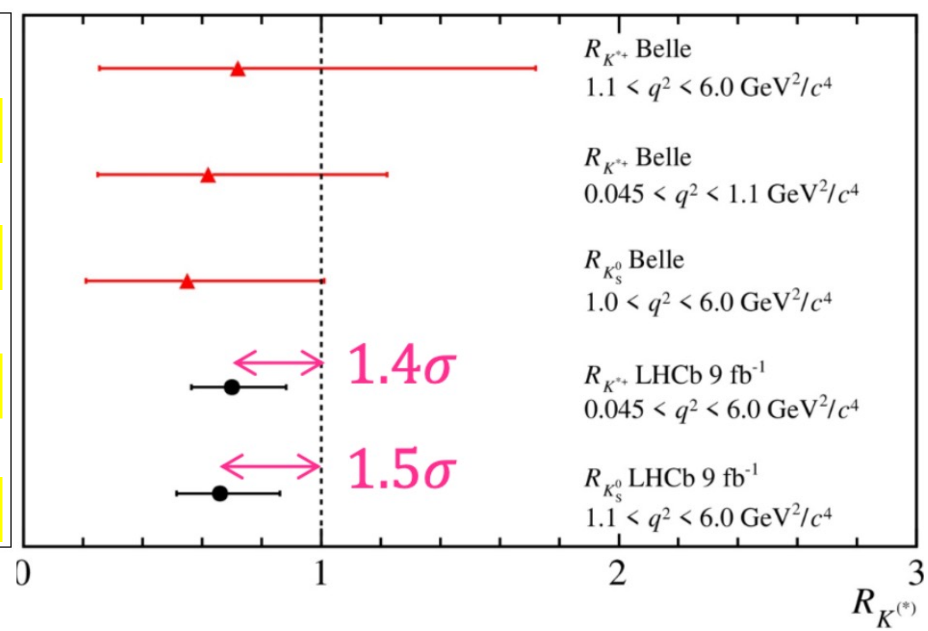
is expected to be one to an accuracy of $\mathcal{O}(10^{-2})$

⇒ lepton flavor universality (LFU)

- New physics can affect these observables

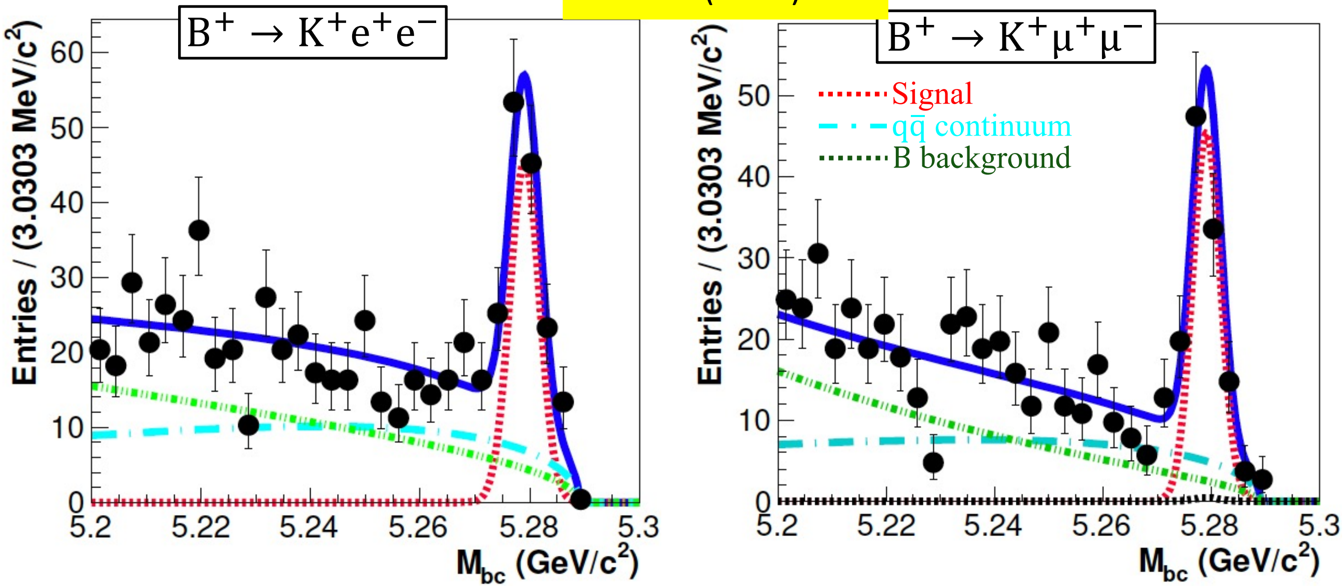
✓ LHCb finds evidence for LFU violation





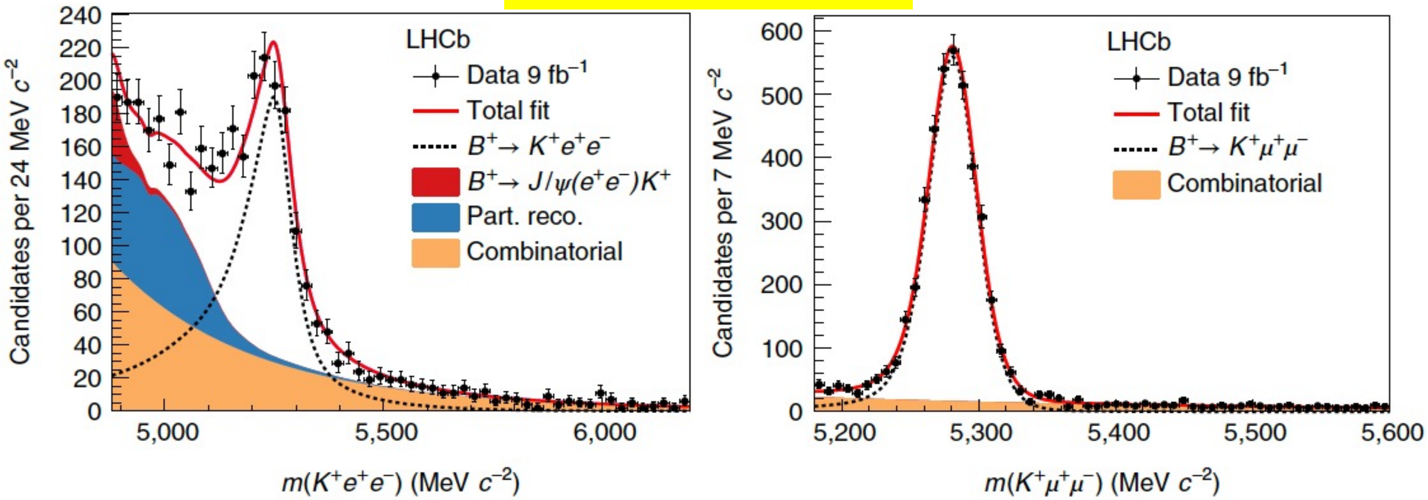
Something to keep in mind

JHEP03 (2021) 105



- Belle (II) has got similar sensitivity both for electron and muon modes
- Electron mode is not as clean as the muon for LHCb (lower two plots)

Nat. Phys. 18 (2022) 277



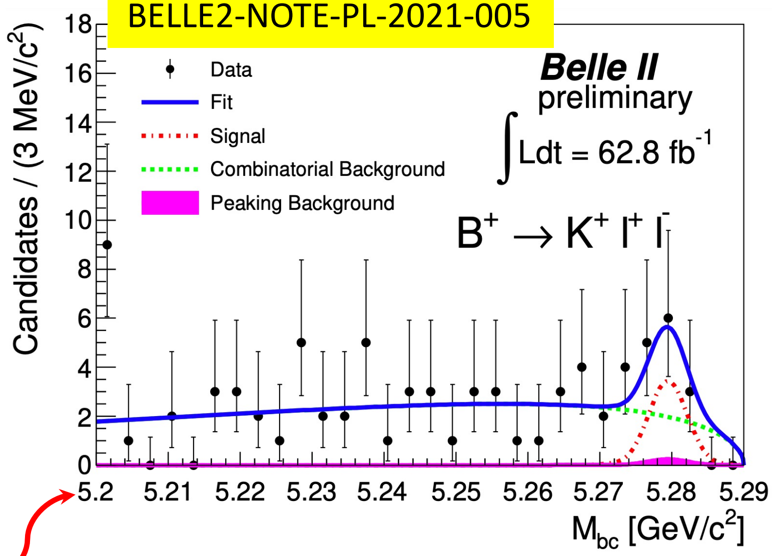
Where do we stand?

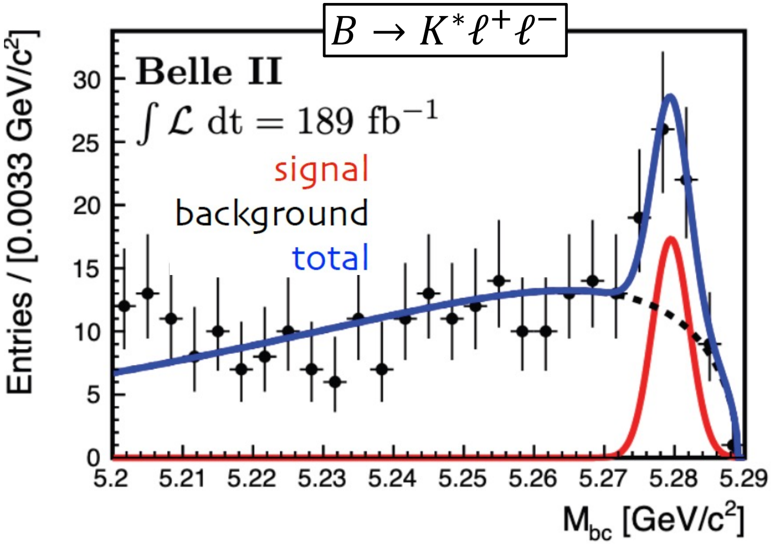
USP: Belle II can

a) provide essential independent checks of $R(K^{(*)})$ anomalies with few ab^{-1} data
b) measure $R(X_s)$ for inclusive B decays
c) provide independent measurements of absolute branching fractions for e and μ modes

❑ 2021 prelim results for $B^+ \to K^+\ell^+\ell^-$ with only 63 fb^{-1}: 2.7σ significance for signal

BELLE2-NOTE-PL-2021-005





	PDG $\mathcal{B} \times 10^6$
$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$	0.94±0.05
$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$	1.03±.19
$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$	0.99±0.12

❑ Limited by the sample size

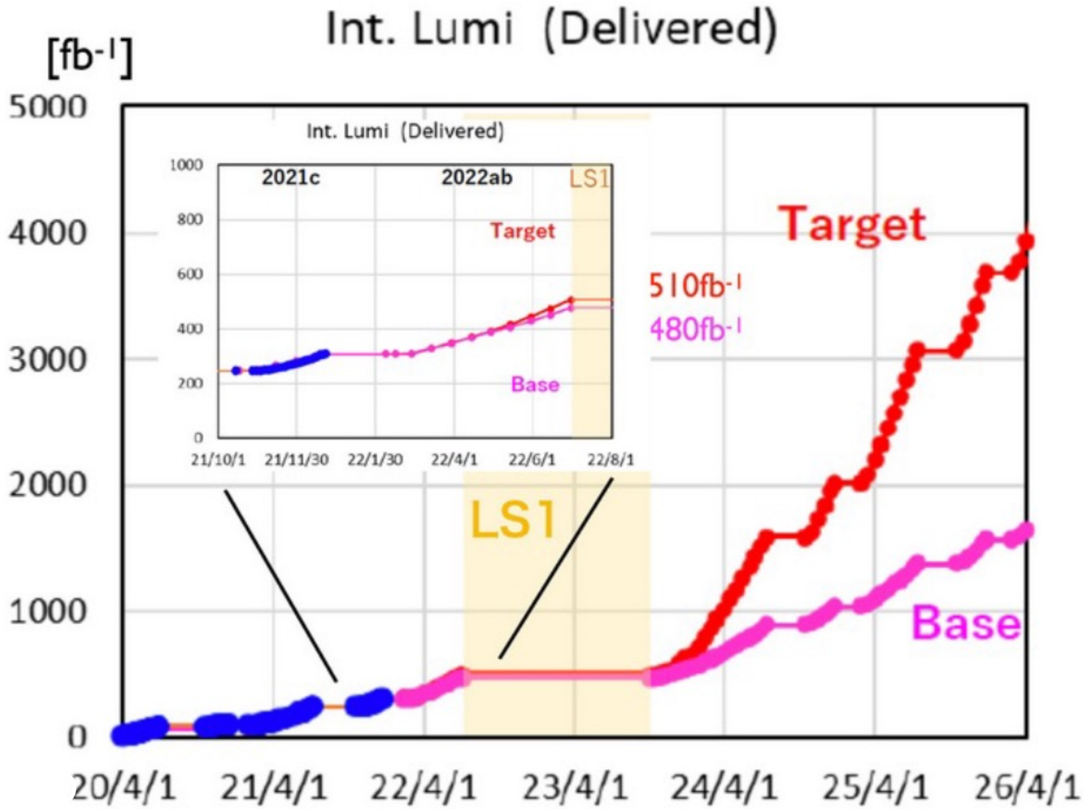
❑ Precision of both electron and muon modes in the same ballpark

❑ Electron mode is off by 2.5σ wrt PDG; we expect it to be competitive with 1 ab^{-1}

What does future hold?

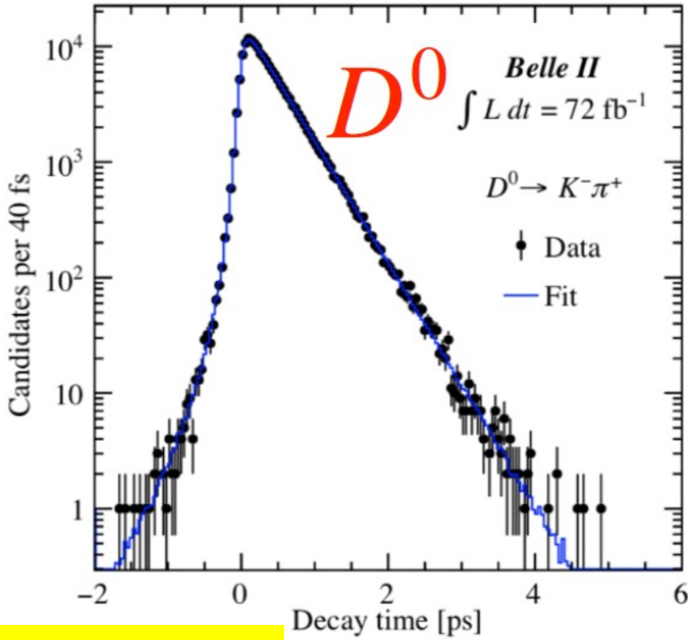
PTEP 2019 (2019) 12, 123C01

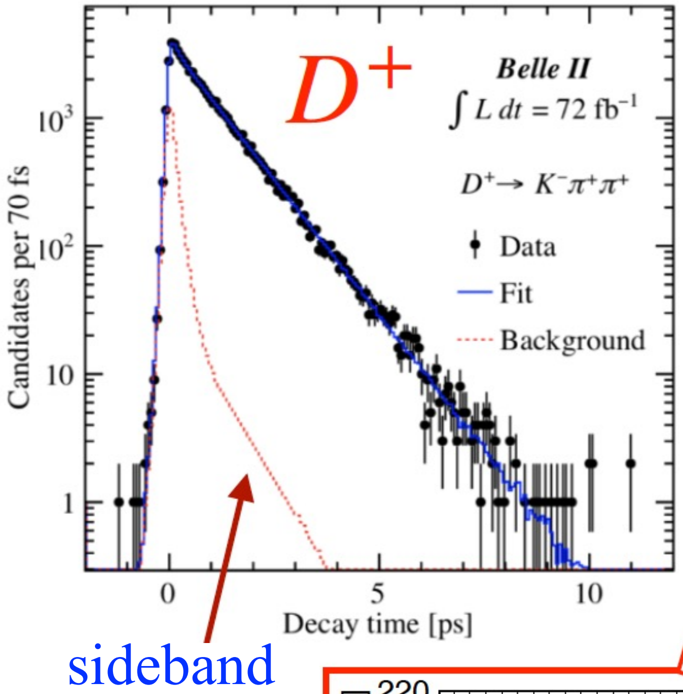
Observables	Belle $0.71\,\text{ab}^{-1}$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (>14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (>14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (>14.4 GeV^2)	28%	11%	3.4%



- Need to wait till 2026 to have 5 ab^{-1} of data that would allow us to probe LFU to $\mathcal{O}(10\%)$

Precise measurement of charm lifetimes

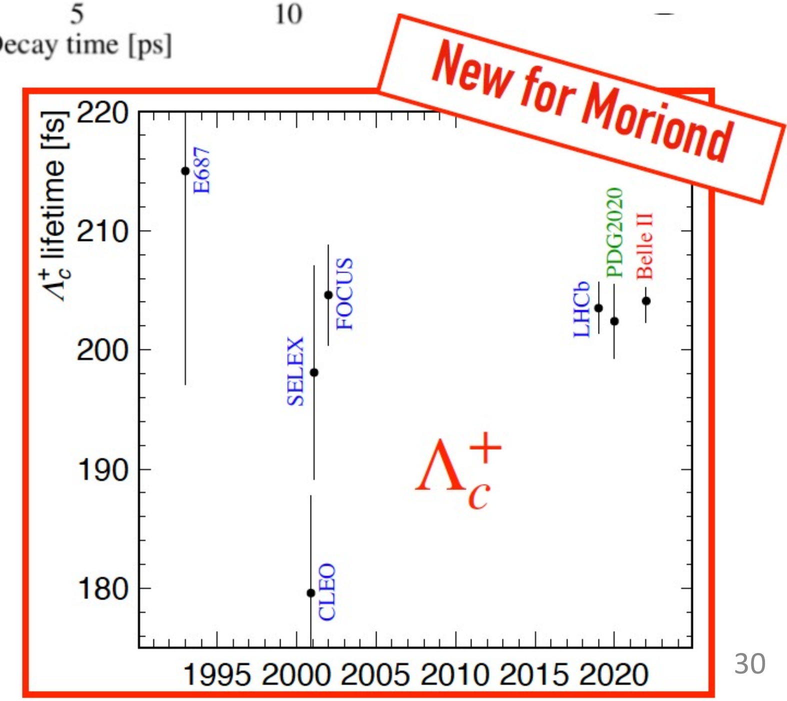




PRL 127 (2021) 211801

	Belle II	World average
$\tau(D^0)$ =	**(410.5 ± 1.1 ± 0.8) fs**	(410.1 ± 1.5) fs
$\tau(D^+)$ =	**(1030.4 ± 4.7 ± 3.1) fs**	(1040 ± 7) fs
$\tau(\Lambda_c^+)$ =	**(204.1 ± 0.8 ± 0.7 - 1.4) fs**	(202.4 ± 3.1) fs

☞ Power of instrumentation ⇒ vertex detector

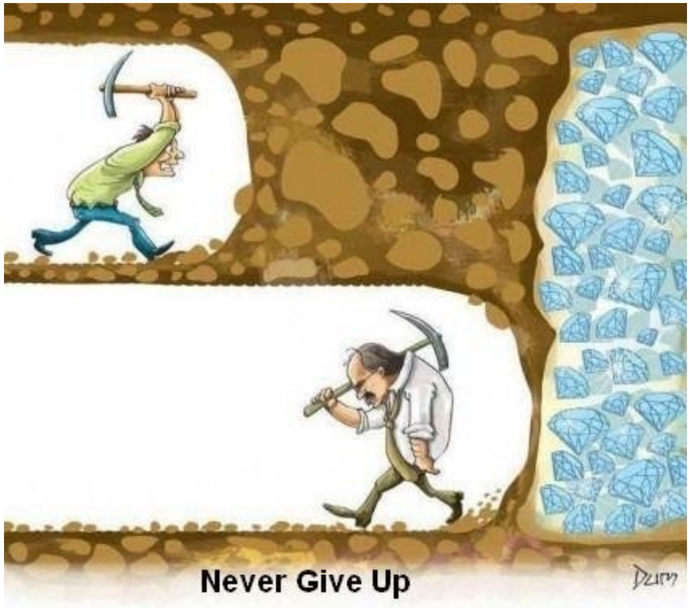


Summary

- Focus on some of the recent analyses from Belle II that are mostly sensitive to new physics
- A number of interesting studies that I have been unable to cover in this talk can be accessed from the Belle II publication page: https://confluence.desy.de/pages/viewpage.action?pageId=138001973

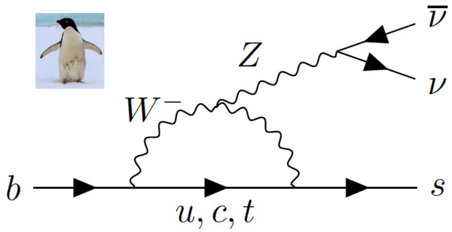
- Much more to come from this exciting experiment at the Intensity Frontier

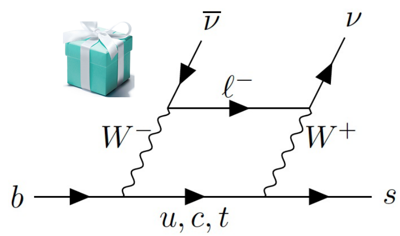
- Stay tuned …



Additional information

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

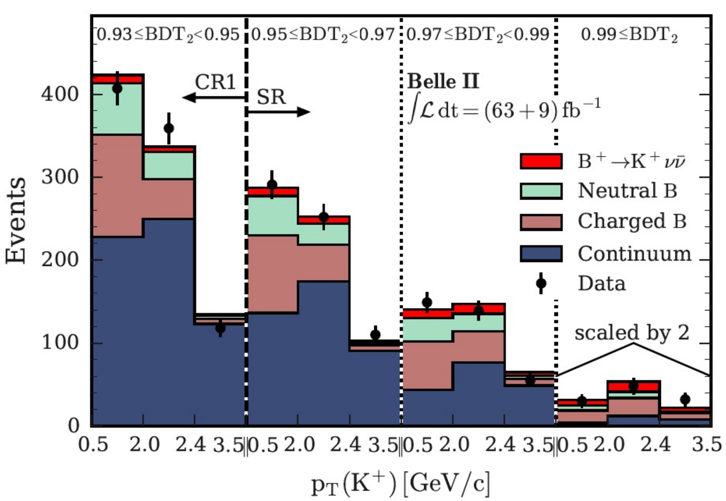




- ❑ This suppressed FCNC decay offers a complementary probe of NP scenarios proposed to explain flavor anomalies

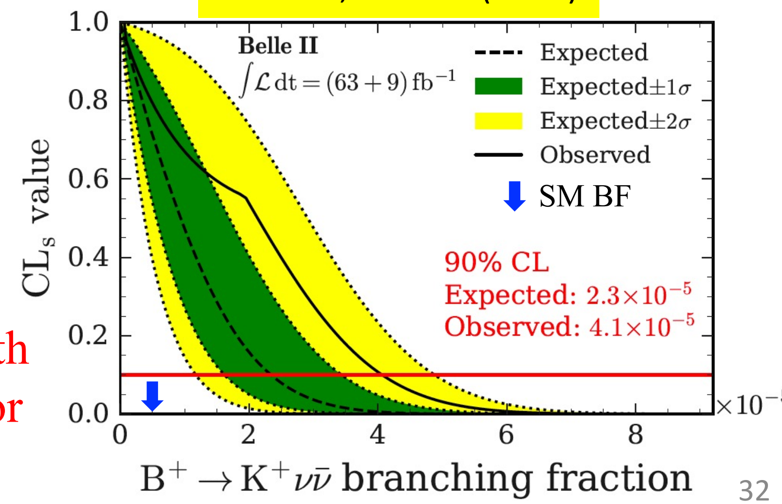
PRD 98, 055003 (2018); 102, 015023 (2020); 101, 095006 (2020)

- ❑ It could help constrain models with leptoquarks, axions, or DM particles
- ❑ Experimentally very challenging with two (escaping) neutrinos
- ❑ Belle II deployed a novel inclusive tagging method
  - ➢ Substantially larger signal efficiency of $\sim 4\%$ compared to $\ll 1\%$ of the earlier approaches at the cost of higher background levels
- ❑ Two boosted decision tree classifiers, of which the 2^{nd} one is nested, to fight against various backgrounds



☞ Competitive with earlier results for similar data

PRL 127, 181802 (2021)



Systematic uncertainty for $B^0 \to D^{*-} \ell^+ \nu_\ell$

Systematic sources	Relative uncertainty (%)
FEI efficiency	3.9
Low momentum π efficiency	4.1
Tracking efficiency	0.9
Lepton particle identification	2.0
Background	1.2
$N_{B\bar{B}}$	2.9
f_{+0}	1.2
$\mathcal{B}\left(D^{*-} \to \pi^- \bar{D}^0\right)$	0.7
$\mathcal{B}\left(\bar{D}^0 \to K^+ \pi^-\right)$	0.8
ECL energy	1.0
Form factor	0.1
MC statistics	1.8
Total	7.3

- Most dominant source is low-momentum pion (π_s) efficiency followed by FEI efficiency