Recent results from Belle II

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for the Belle II Collaboration

Les Rencontres de Physique de la Vallée d’Aoste - March 8th, 2023

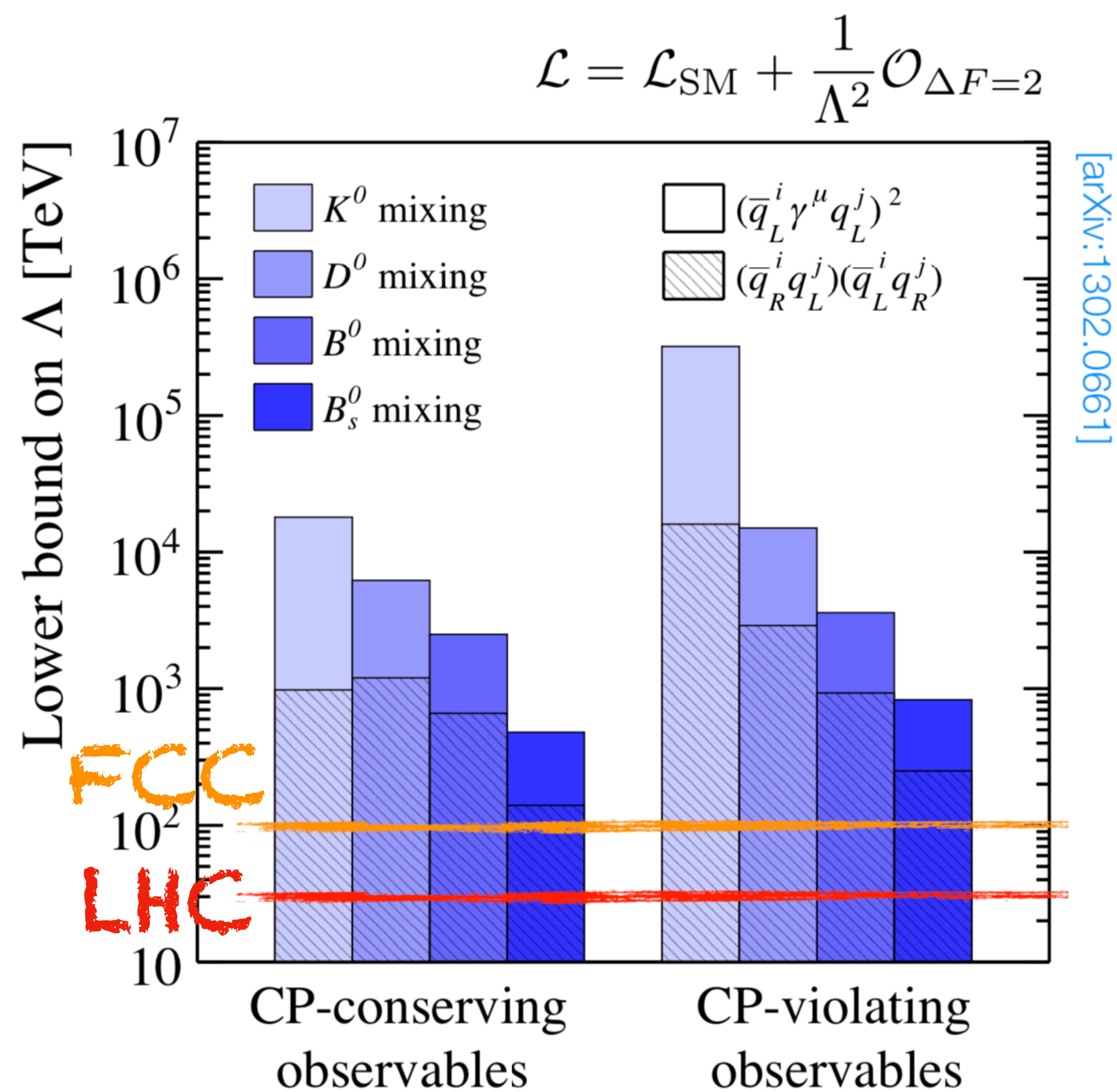
Probing the next scale

Flavor physics to access higher scales than those directly reachable at current or futures colliders.

Systematic approach to probe many redundant observables and look for emerging patterns that signal unexpected physics.

CKM paradigm remarkably successful so far, but deviations still allowed in most of the suppressed processes.

Name of the game is precision



Boosting the reach

Energy-asymmetric e^+e^- collisions at the $Y(4S)$ from SuperKEKB.

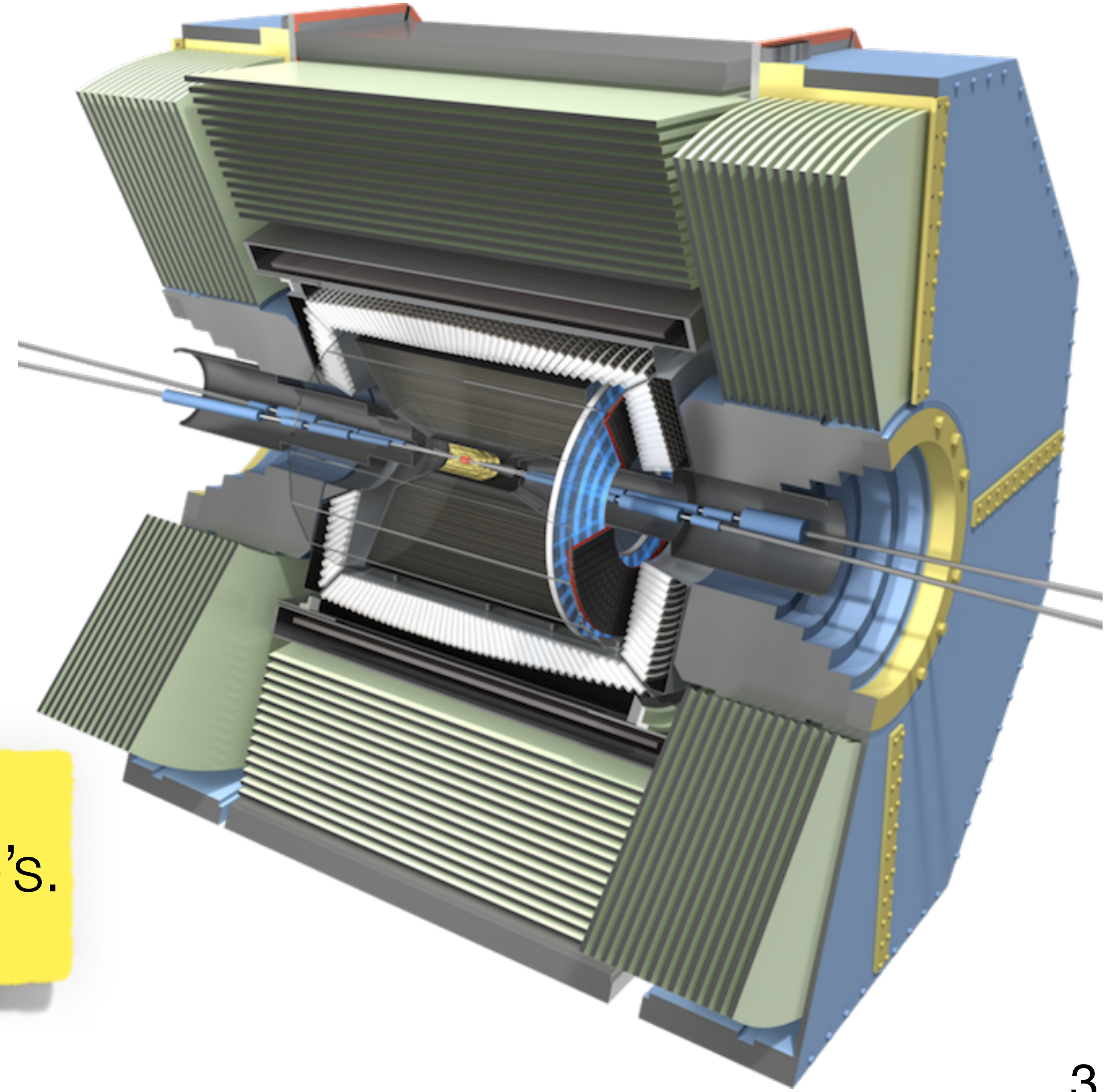
Unprecedented luminosity, $4.7\text{x}10^{34}$ cm^{-2} s^{-1} world record.

Belle II

Belle II looks like "old" Belle, but effectively a brand new instrument.

Excellent vertexing and tracking.
Good PID and neutrals.

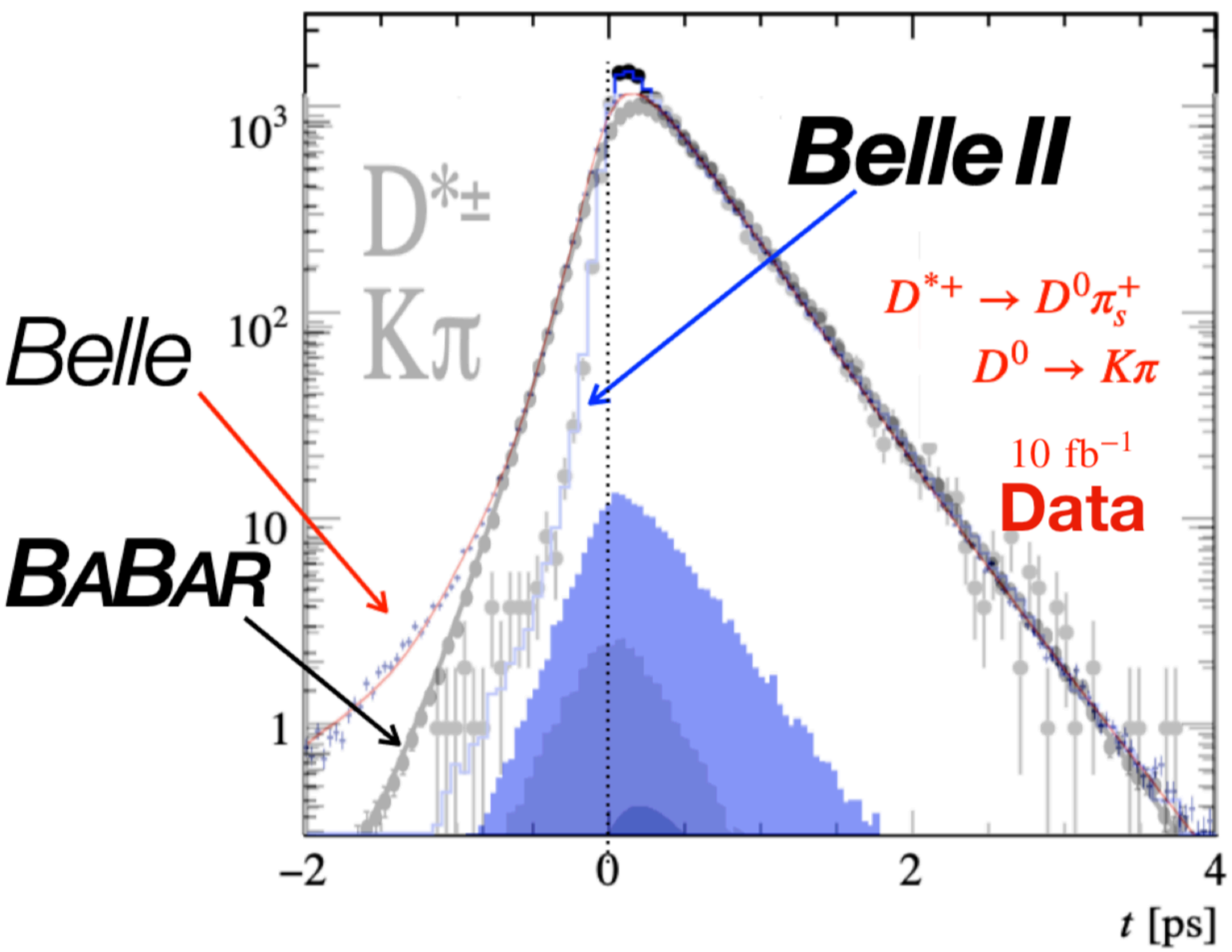
Performance pretty uniform over any final state and kinematic regime. Efficiency for reconstructing tracks, π^0, K_S are similar across the board.



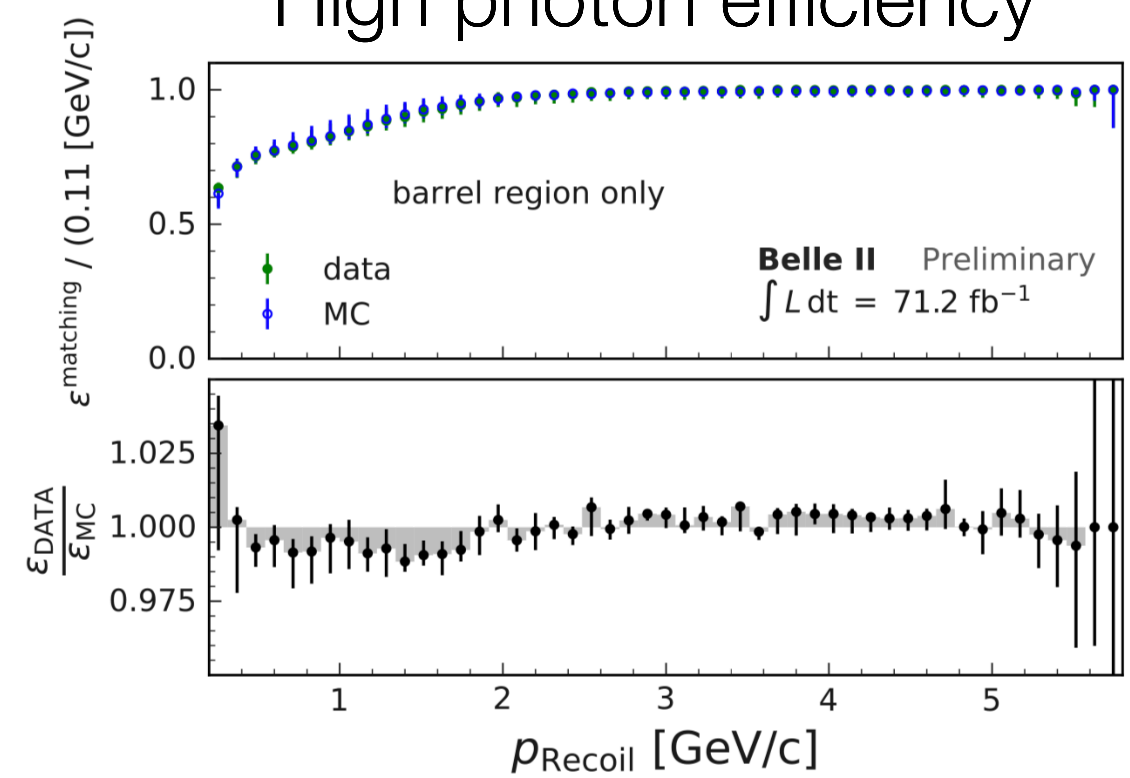
424 fb^{-1} of data on tape.
Comparable to Babar's. Half of Belle's.
Partly unique (energy scan)

Performance

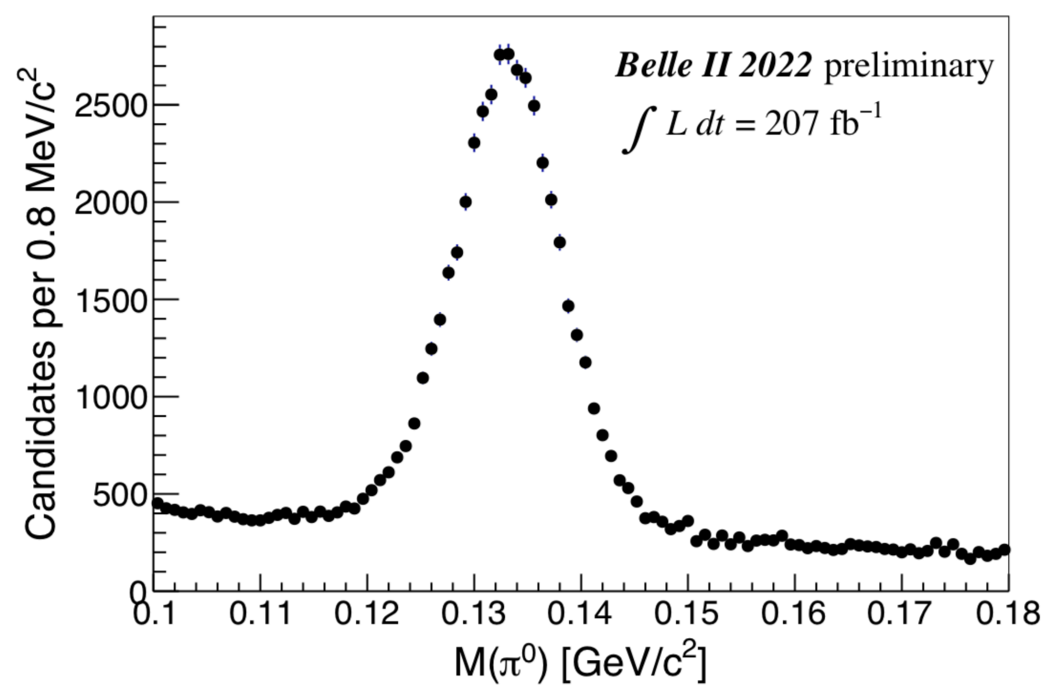
Net effect of better vertexing (PXD) and greatly-reduced size of the SuperKEKB interaction region (nano-beam scheme).



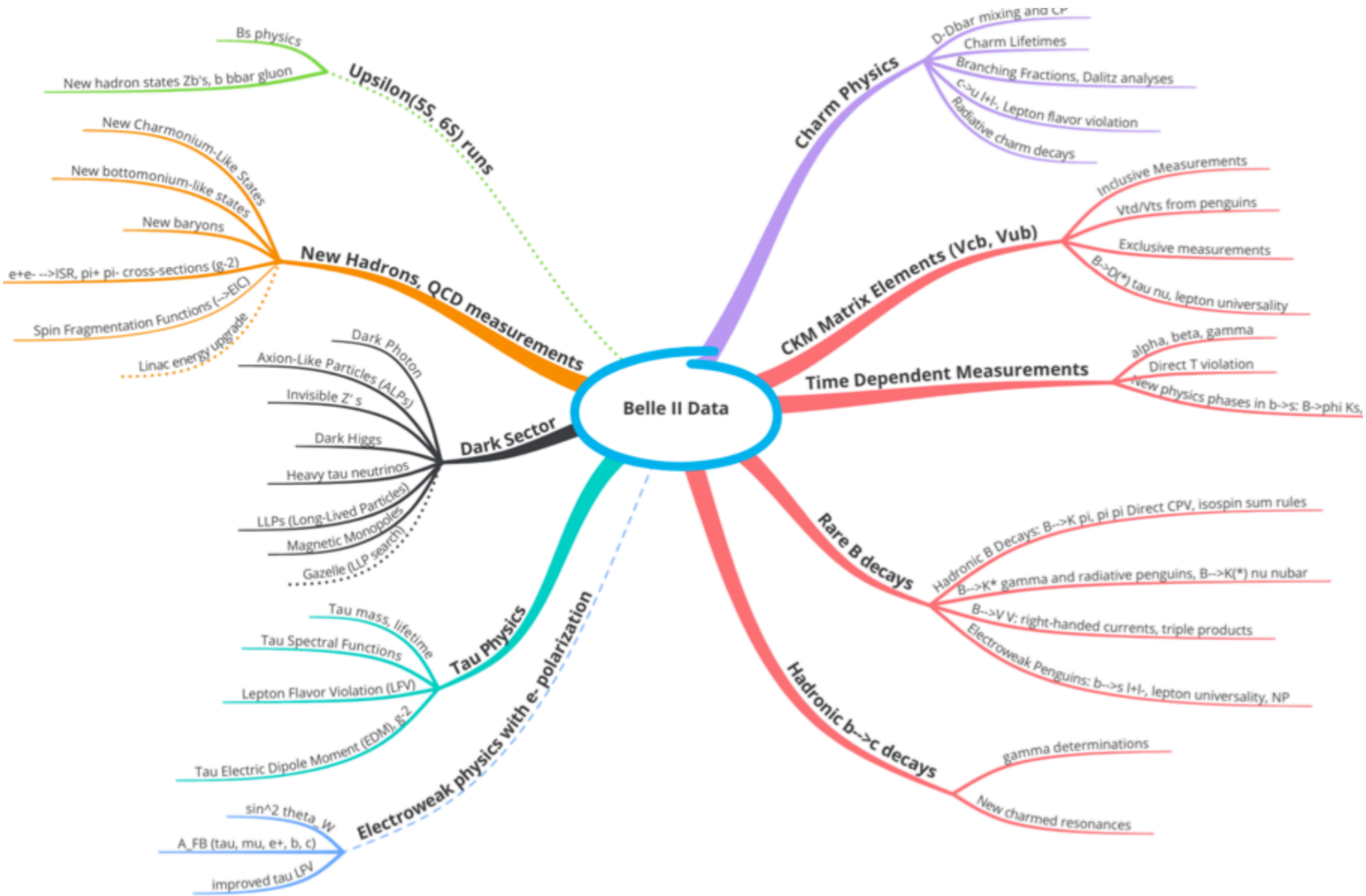
High photon efficiency



Good neutral reconstruction



A diversified physics program

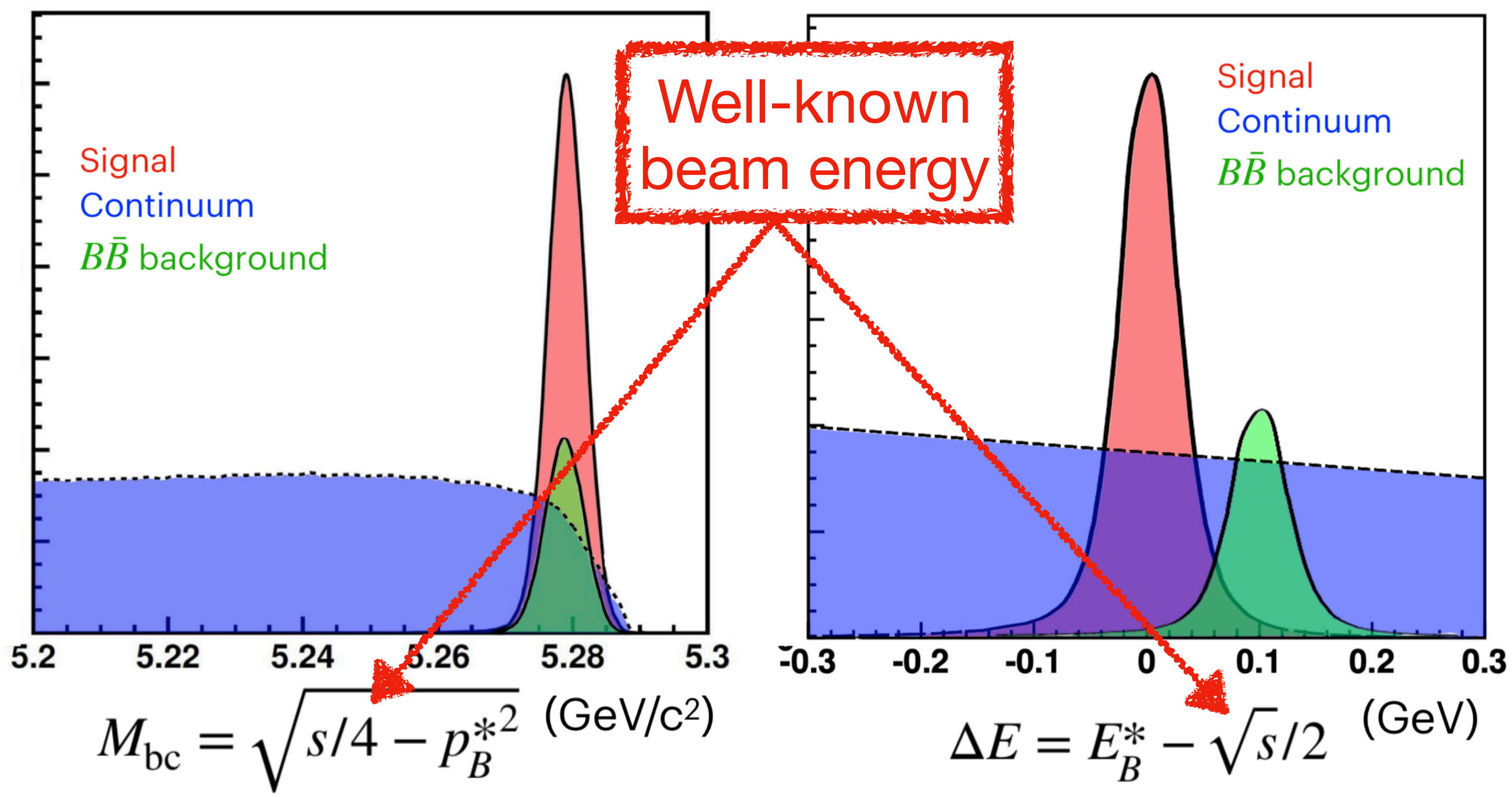


[Snowmass white paper]

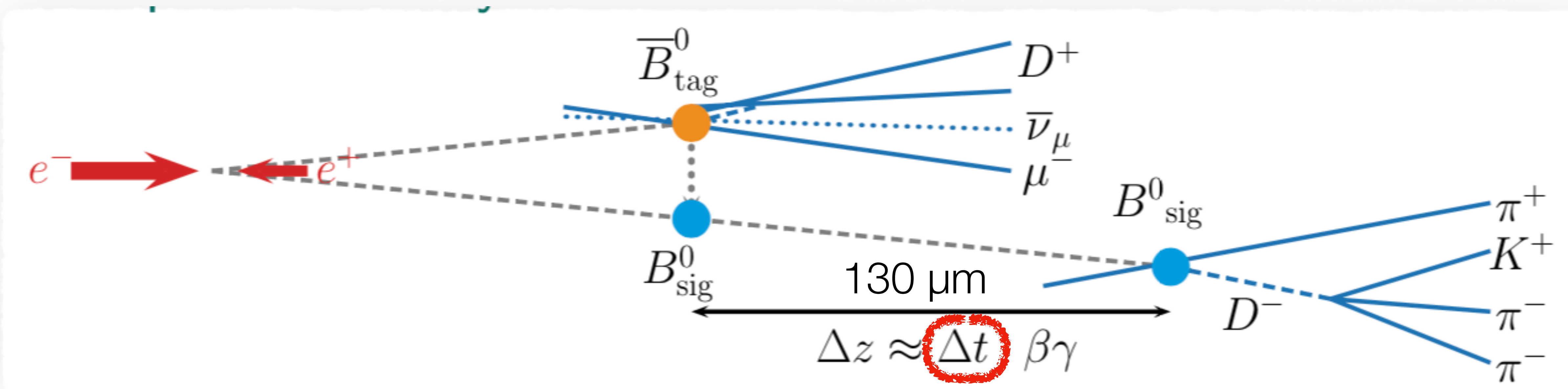
(Some) B-factory basics

Low-background production of 30 (now)—600 (design) $B\bar{B}$ per second.

Threshold B production from point-like colliding particles, $e^+e^- \to Y(4S) \to B\bar{B}$. Kinematic well constrained.



The asymmetric collision gives the boost to measure the displacement and tag the flavour



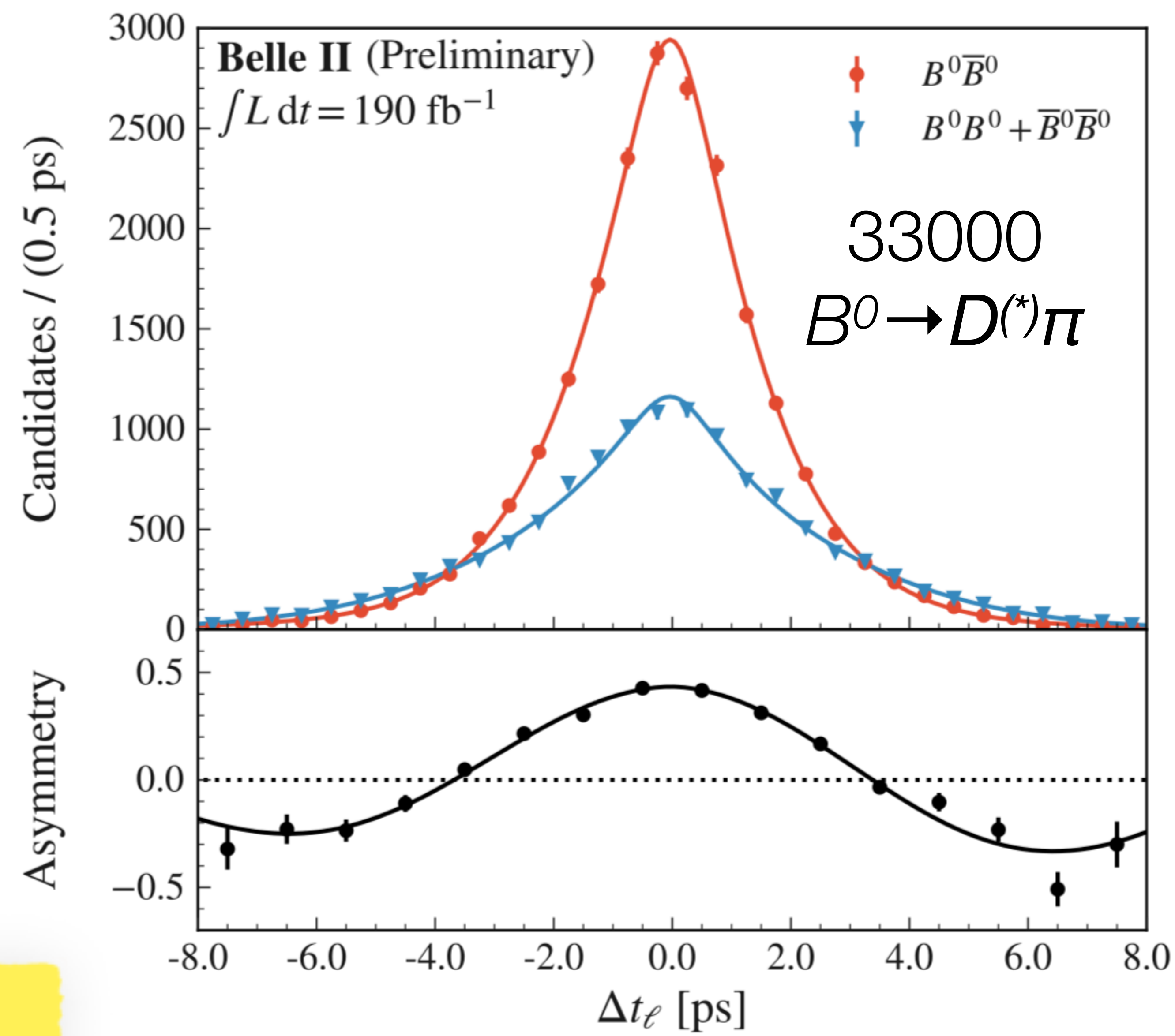
Courtesy of T. Humair

$B^0\overline{B^0}$ mixing benchmark

Reduced boost at Belle II:
B mesons flight only 130 µm on average (200 µm at Belle).
PXD to recover decay-time resolution.

Measurements of B^0 lifetime and $B^0\overline{B^0}$ mixing frequency to gear up for decay-time dependent CPV.

Deep understanding of decay-time resolution.
Testbed for flavour tagging: 30% effective efficiency on-par with best Belle performance.



33000 $B^0 \to D^{(*)}\pi$

$$\tau_{B^0} = (1.499 \pm 0.013 \pm 0.008)\ \mathrm{ps}$$

$$\Delta m_d = (0.516 \pm 0.008 \pm 0.005)\ \mathrm{ps}^{-1}$$

[arXiv:2302.12791]

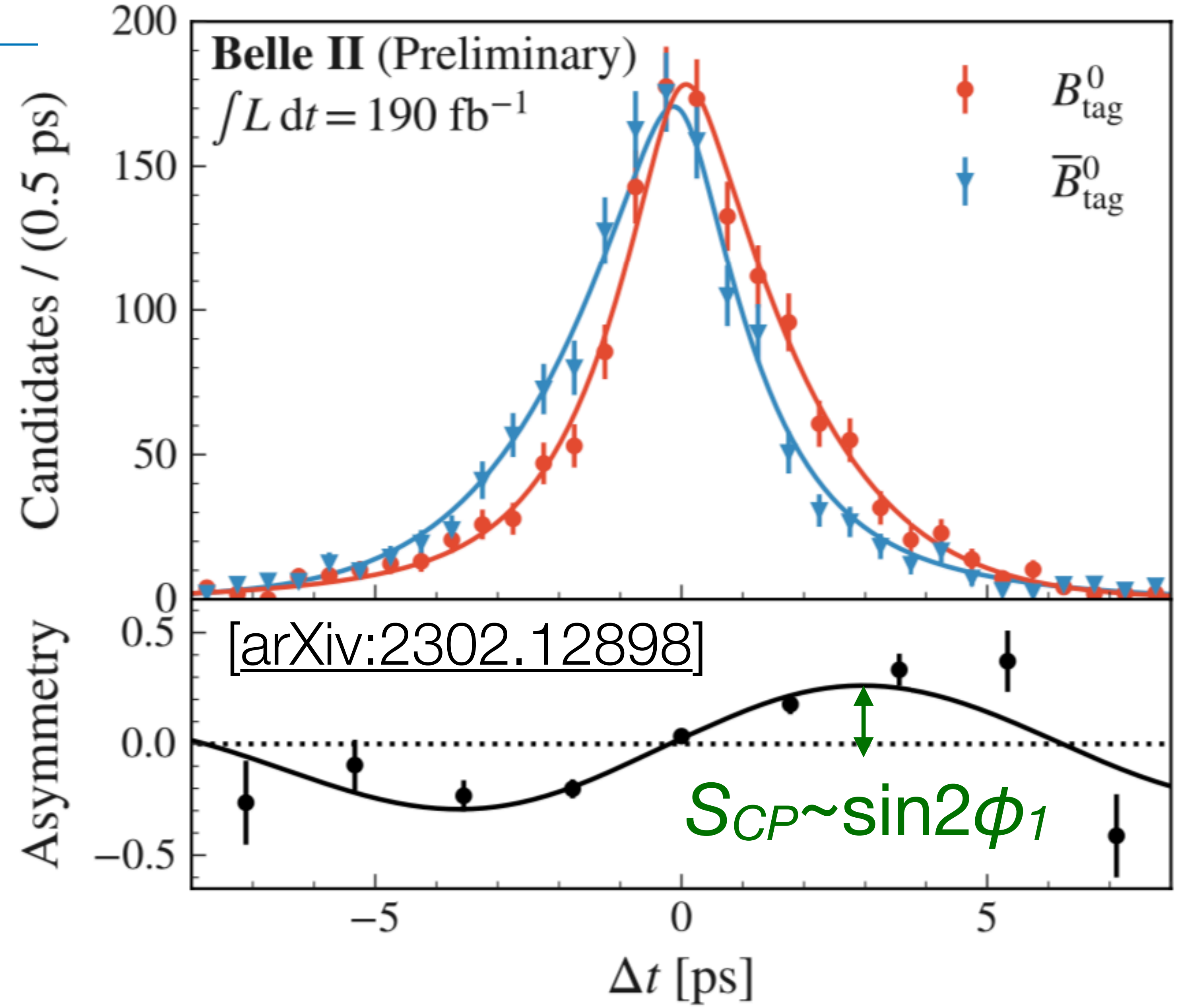
B-factory classic

ϕ_1/β best-known angle of the UT with 0.7 degree precision. Provide reference for non-SM searches in gluonic penguin decays.

Build upon the $B^0\overline{B}^0$ mixing analysis. Most sensitive mode $B^0 \to J/\psi K_S$. Measure decay-time dependent *CP* asymmetries

$$\mathcal{A}^{raw}(\Delta t) = \frac{N(\bar{B}^0 \to f_{CP}) - N(B^0 \to f_{CP})}{N(\bar{B}^0 \to f_{CP}) + N(B^0 \to f_{CP})}(\Delta t)$$
$$= A_{CP}\cos(\Delta m_d \Delta t) + S_{CP}\sin(\Delta m_d \Delta t)$$

2.8K $B^0 \to J/\psi K_S$



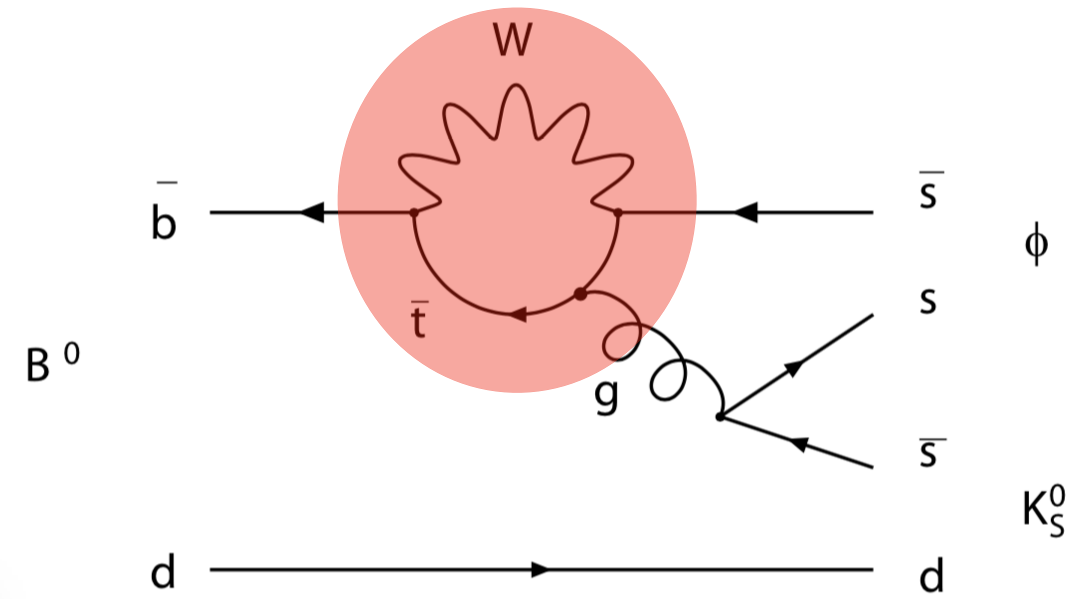
S_{CP} = 0.720 ± 0.062 (stat.) ± 0.016 (syst.)

A_{CP} = 0.094 ± 0.044 (stat.) $^{+0.042}_{-0.017}$ (syst.)

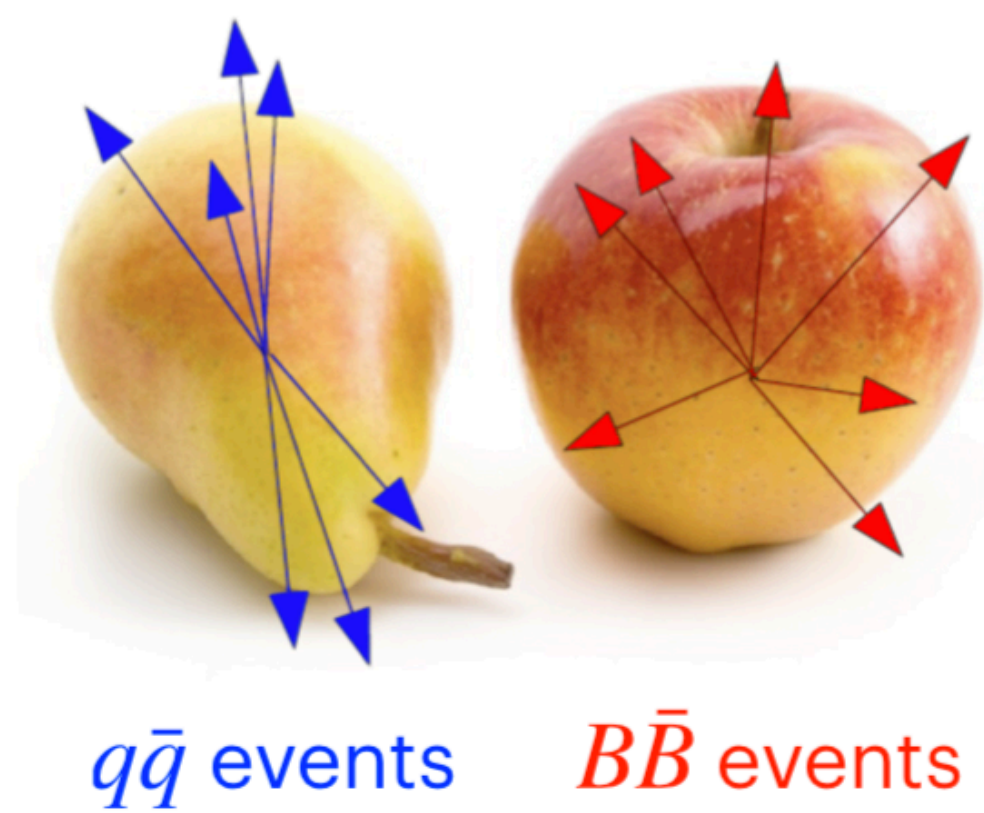
Not yet competitive with world best, but crucial testbed

β^{eff} from suppressed decays

Gluonic-penguin mode suppressed in the SM, BR ~ 10^{-5}-10^{-6}.
Important comparison of sin2β^{eff} with the reference favored channels to probe new amplitudes in loops.



Experimentally challenging.
Fully-hadronic final state with (many) neutrals. Need to fight against "continuum" light-quark production.
Background O(10^6) larger than signal.



Exploit discriminating event topology: continuum features a jet-like structure, while *B* decays isotropically at rest.
Boost event-classification with machine learning algorithms (BDT, NNet).

$B^0 \to \phi K_S$

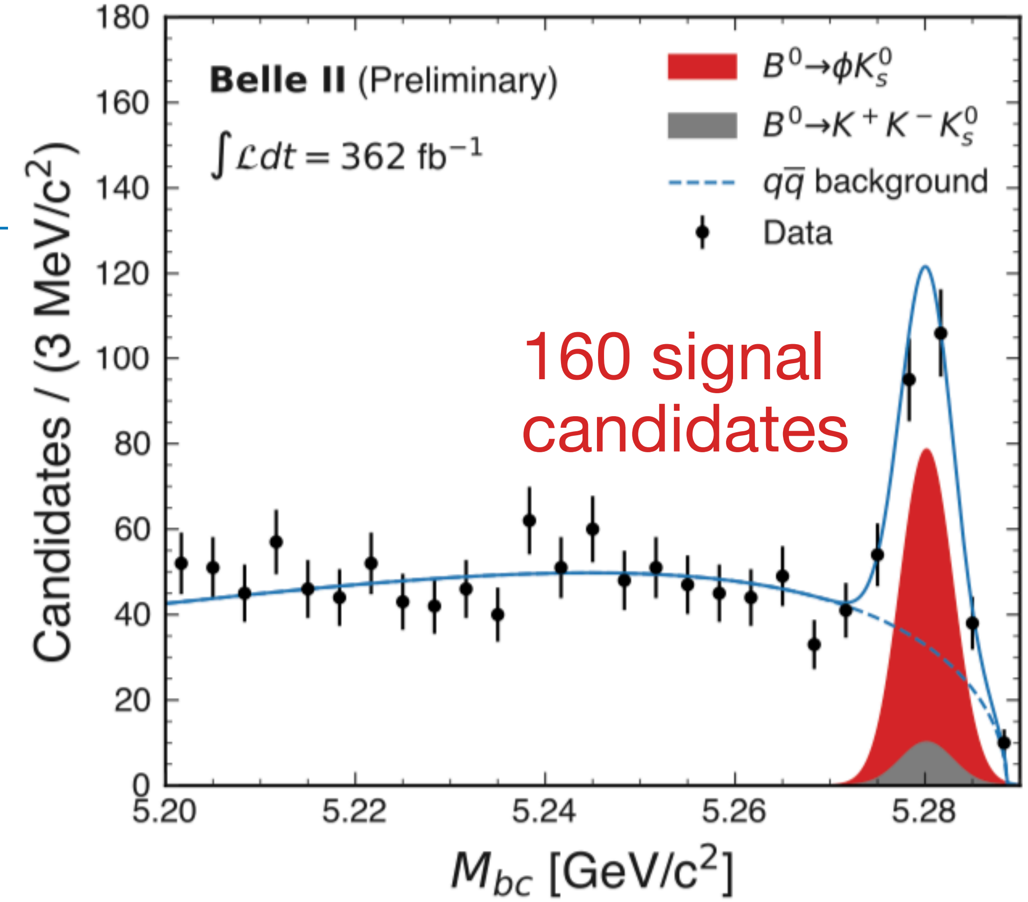
New for La Thuile!

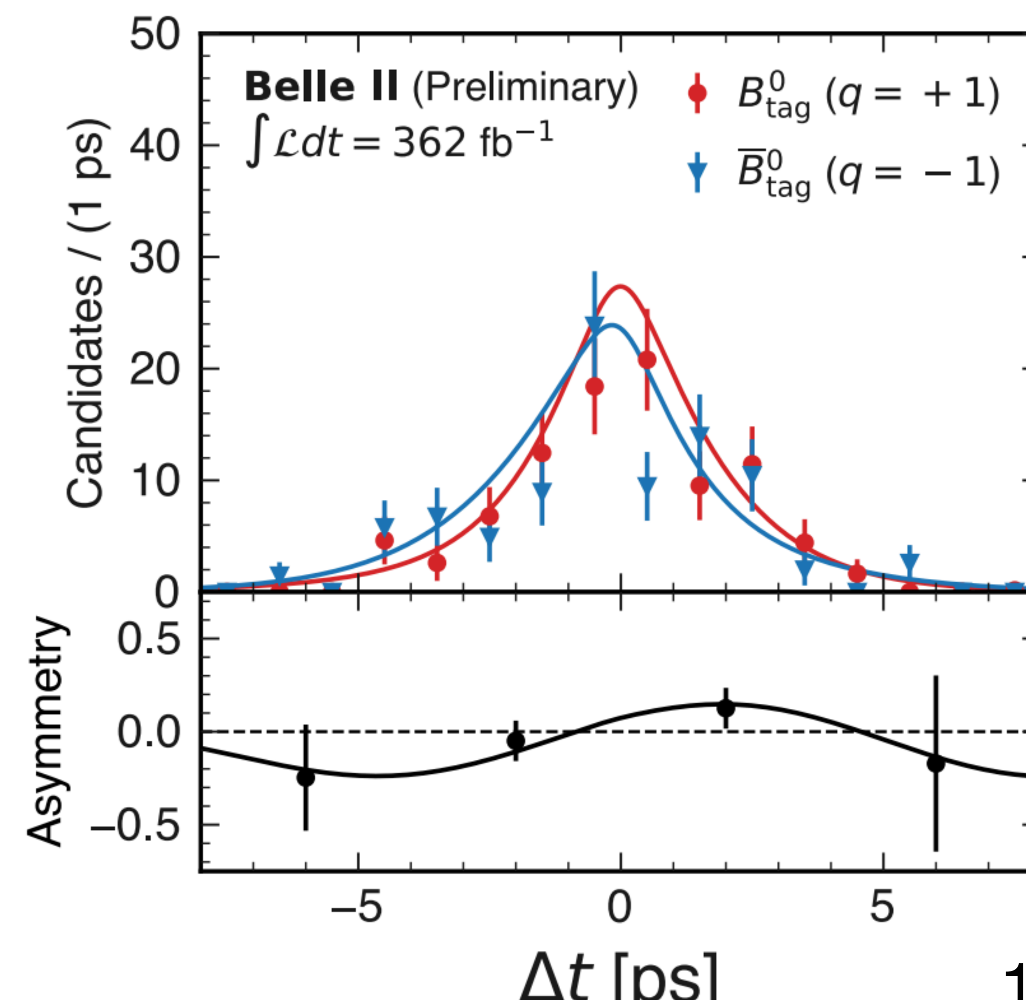
4D fit to mass, decay-time, continuum-suppression discriminator, helicity angle, to discriminate between signal and background and extract the asymmetry.

Validate the decay-time resolution on $B^+ \to \phi K^+$ control data.

$$A_{CP} = 0.31 \pm 0.20\,^{+0.05}_{-0.06}$$
$$S_{CP} = 0.54 \pm 0.26\,^{+0.06}_{-0.08}$$

Consistent with previous determinations.
Paving the way for $B^0 \to \eta^{(\prime)} K_S$.





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

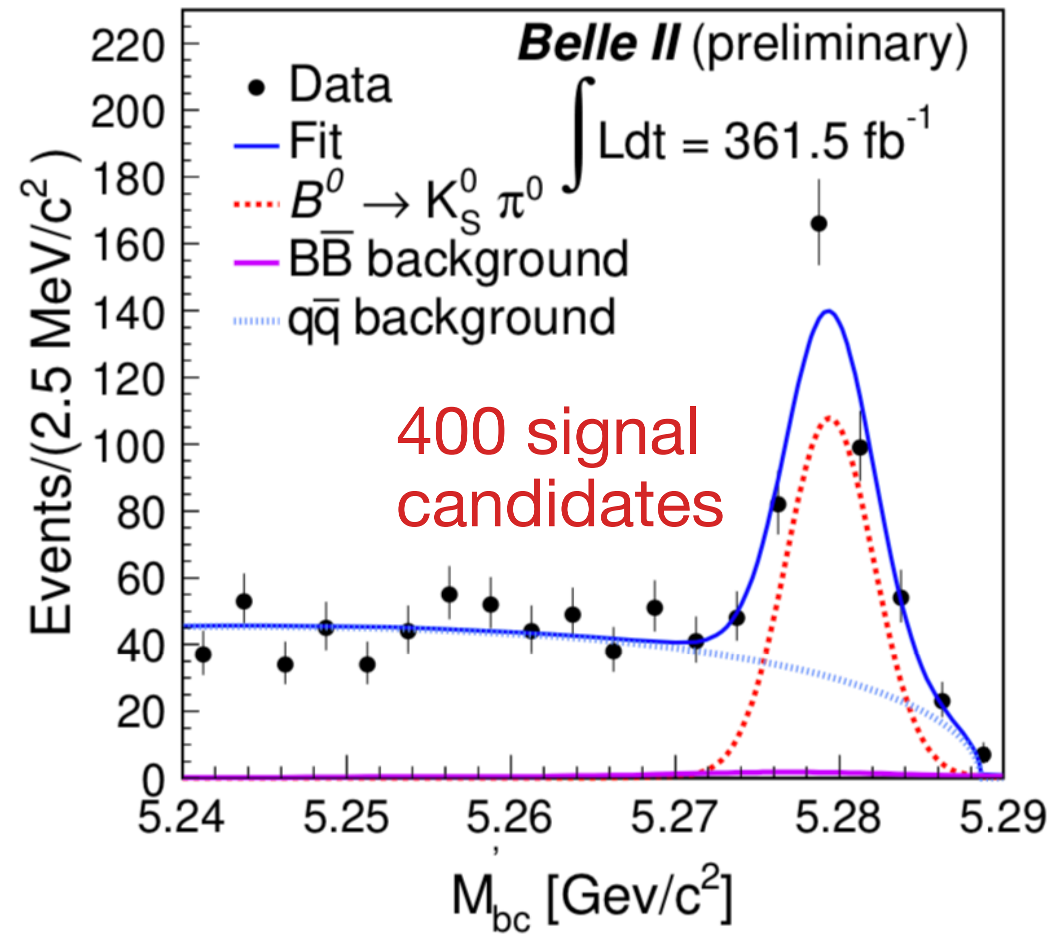
New for La Thuile!

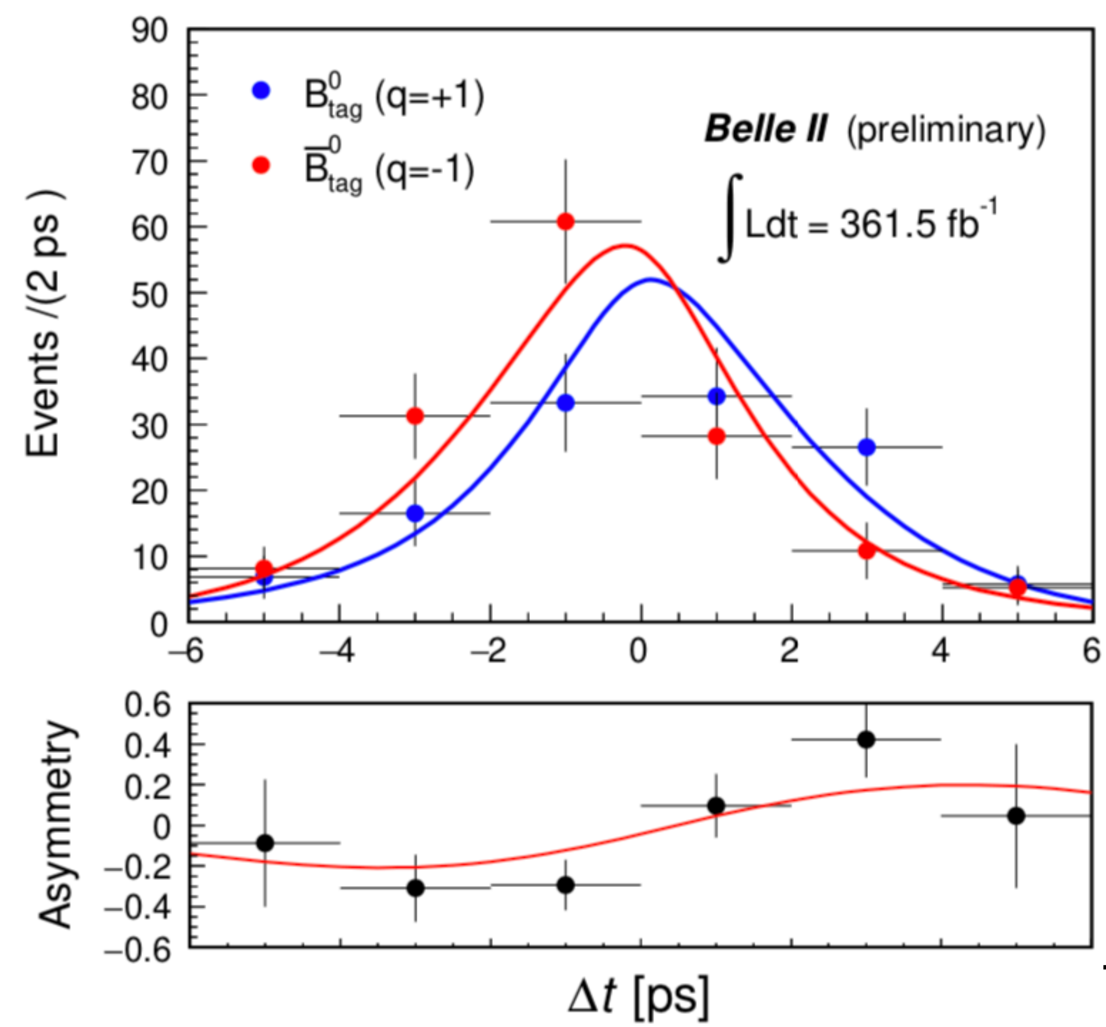
K_S flights 10 cm on average, decays after first silicon layers: challenging B vertex reconstruction, degraded decay-time resolution. Validate on $B^0 \to J/\psi K_S$ with K_S-only vertexing. Categorise the events according to decay-time uncertainty to measure TD asymmetries

$$A_{CP} = 0.04^{+0.15}_{-0.14} \pm 0.04$$

$$S_{CP} = 0.74^{+0.20}_{-0.23} \pm 0.04$$

Improved π^0 reconstruction and enhanced continuum-suppression yield precision competitive with world best results.





$K\pi$ isospin sum-rule

New for La Thuile!

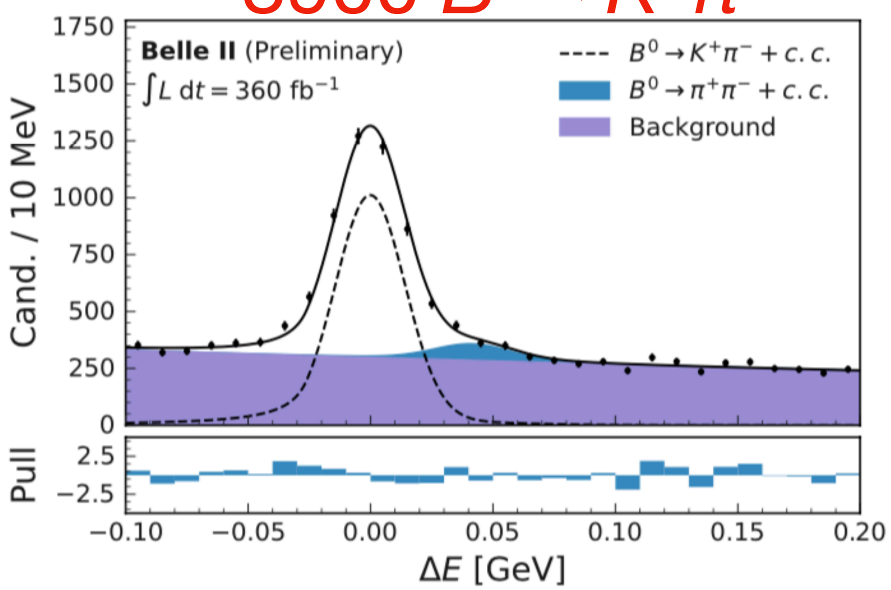
Appropriate combinations of $B \to K\pi$ channels greatly reduces hadronic unknown offering stringent SM null-test with O(1%) theoretical uncertainty

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

Experimentally consistent with zero with 10% precision limited by $K_S\pi^0$.

Belle II unique possibility to access all final states

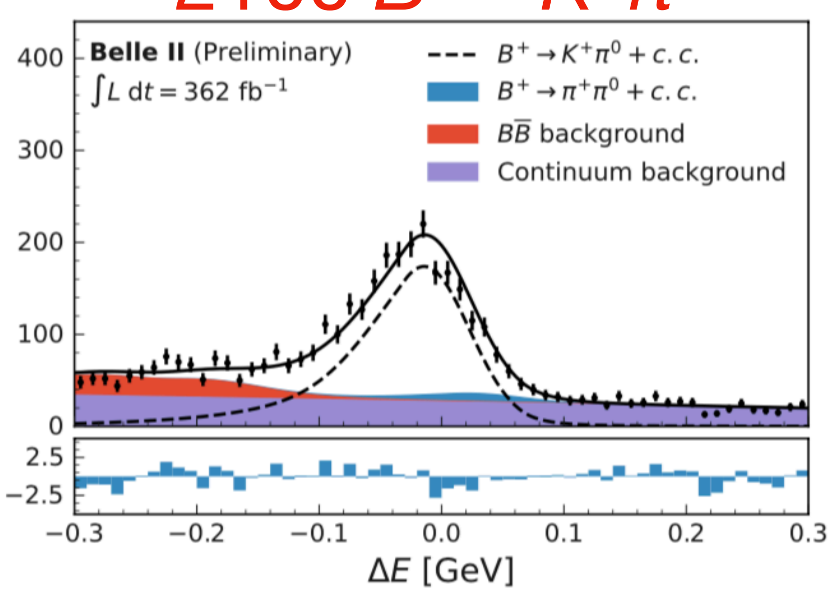
~3900 $B^0 \to K^+\pi^-$



$\mathscr{B} = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$

$A_{CP} = (-7.2 \pm 1.9 \pm 0.7)\,\%$

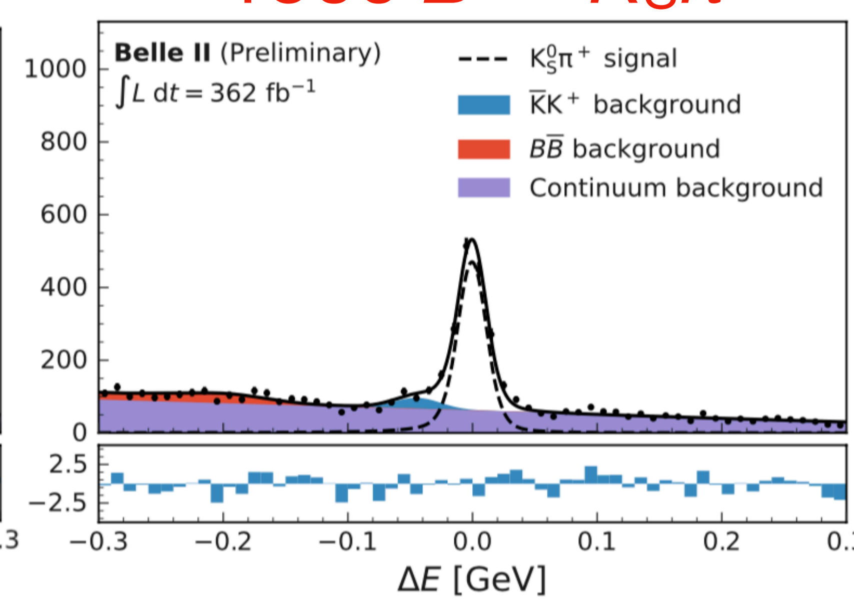
~2100 $B^+ \to K^+\pi^0$



$\mathscr{B} = (14.21 \pm 0.38 \pm 0.85) \times 10^{-6}$

$A_{CP} = (1.3 \pm 2.7 \pm 0.5)\,\%$

~1500 $B^+ \to K_S\pi^+$



$\mathscr{B} = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$

$A_{CP} = (4.6 \pm 2.9 \pm 0.7)\,\%$

$K\pi$ isospin sum-rule

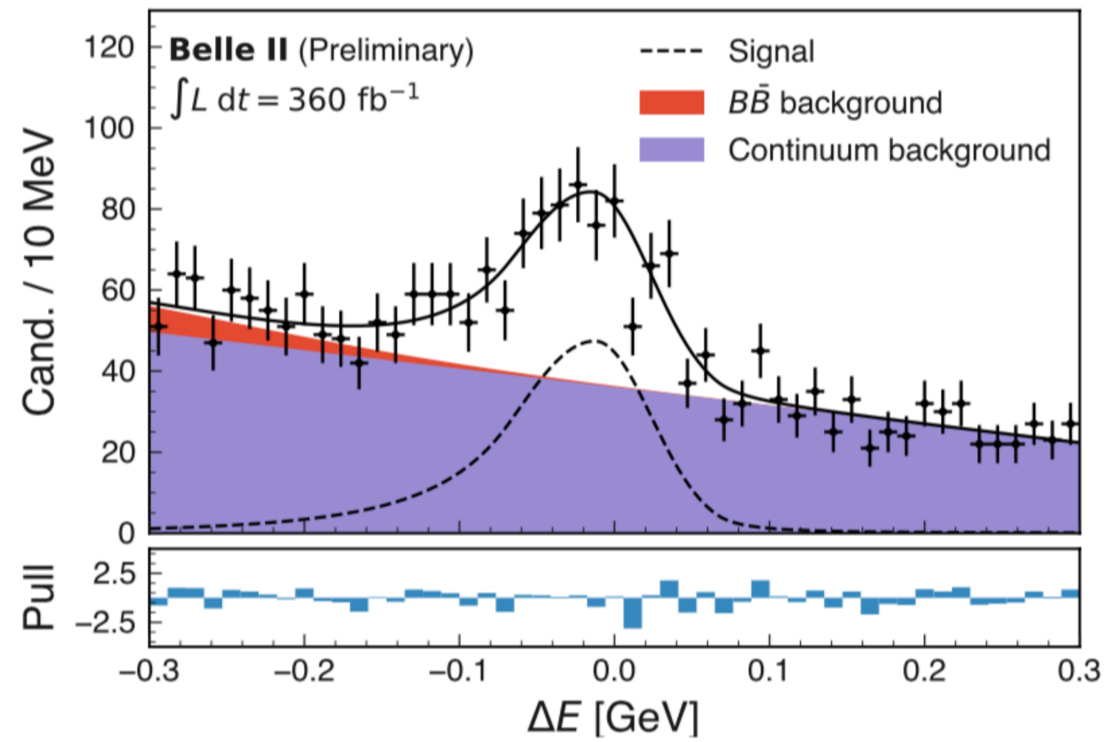
New for La Thuile!

$B^0 \to K_S\pi^0$: independent decay-time integrated analysis to measure BR and A_{CP}. Combining with time-dependent analysis to enhance sensitivity:

$$\mathcal{B} = (10.50 \pm 0.62 \pm 0.67) \times 10^{-6}$$

$$A_{CP} = (-1 \pm 12 \pm 5)\,\%$$

~500 $B^0 \to K_S\pi^0$



Putting all together, we obtain a Belle II isospin test:

$$I_{K\pi} = (-3 \pm 13 \pm 5)\,\%$$

Modes	Ratio
$\mathcal{B}_{K^0\pi^+}/\mathcal{B}_{K^+\pi^-}$	$1.180 \pm 0.040 \pm 0.027$
$\mathcal{B}_{K^+\pi^0}/\mathcal{B}_{K^+\pi^-}$	$0.687 \pm 0.022 \pm 0.040$
$\mathcal{B}_{K^0\pi^0}/\mathcal{B}_{K^+\pi^-}$	$0.508 \pm 0.031 \pm 0.030$

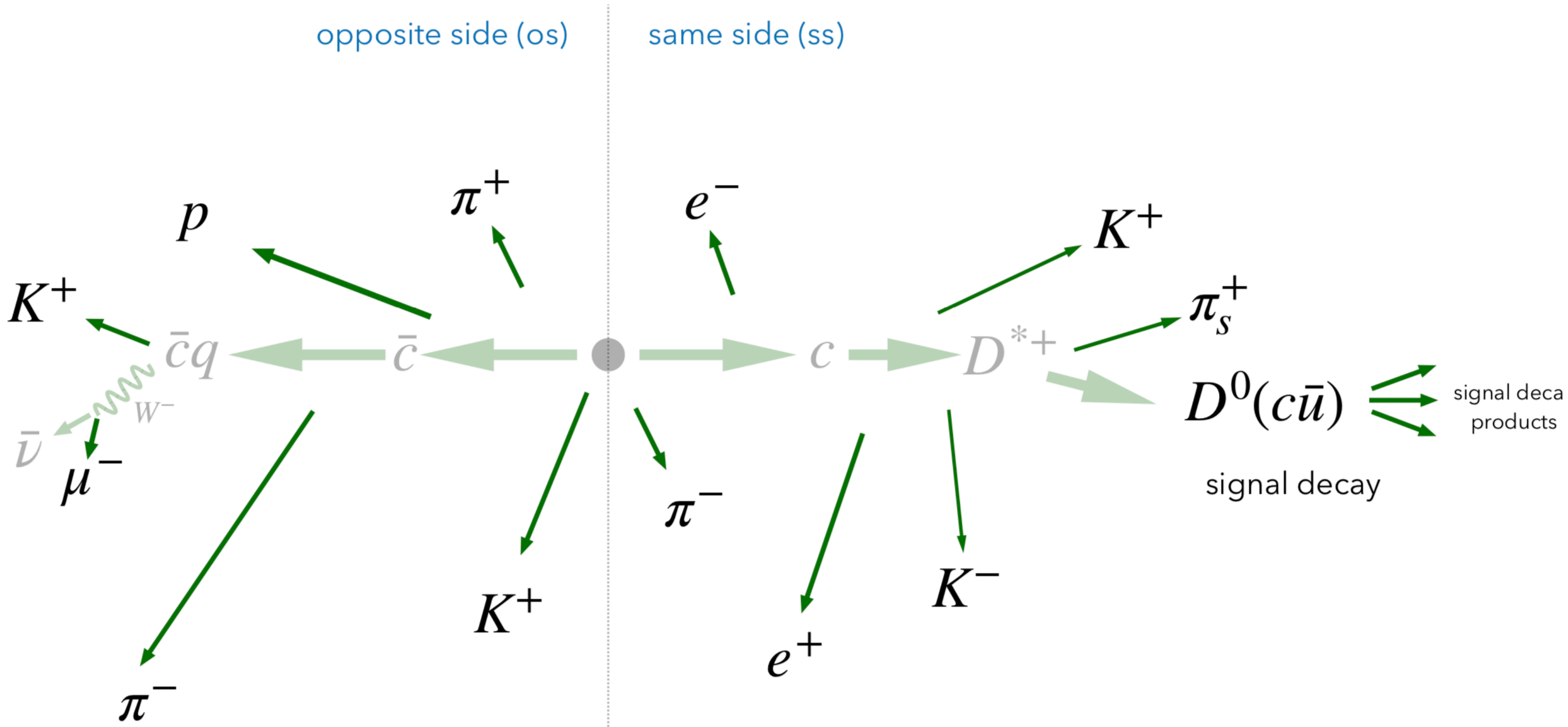
Agree with SM. Competitive with world average (-13 ± 11)%

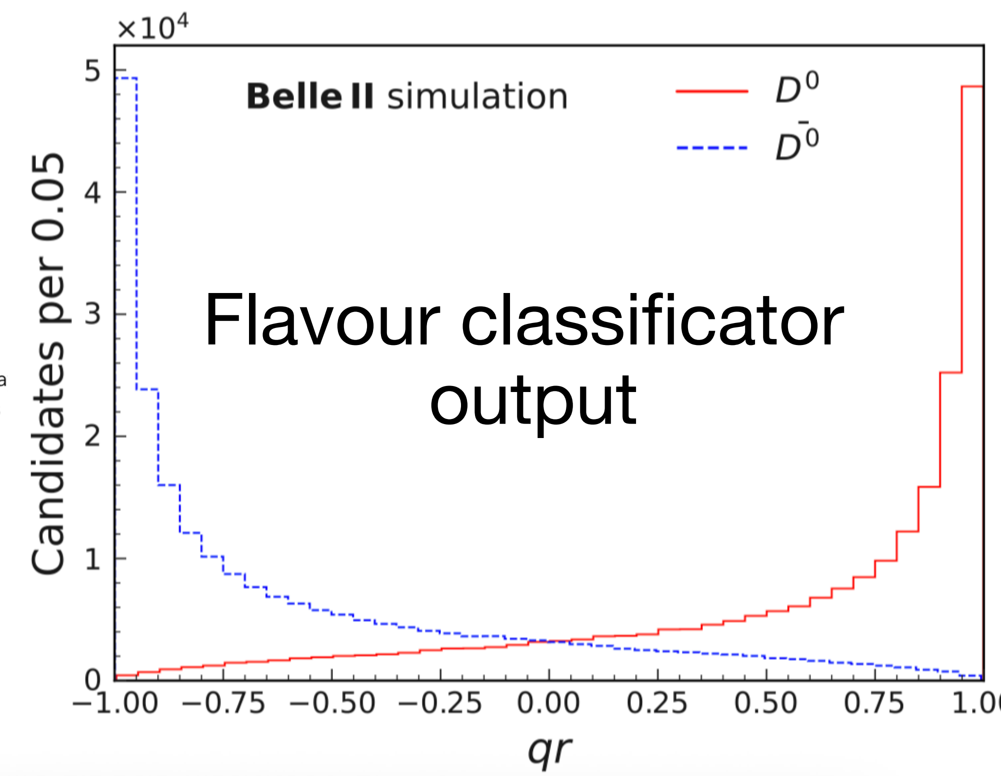
Enhancing charm reach

New for La Thuile!

Rich program of charm physics with neutrals ($\pi^0\pi^0, \pi^+\pi^0, K_S\pi^0, K_SK_S$, …) to complement LHCb CPV observations in $D^0 \to h^+h^-$.

New flavour-tagging algorithm to recover D^0 candidates not tagged by $D^{*+} \to D^0\pi^+$ strong decays. Exploit $c\bar{c}$ pair production and charge correlation between signal D flavour and the tracks in the rest of the events.





Calibrated with flavour-specific decays, 48% effective efficiency. Roughly doubling sample of tagged D^0 candidates.

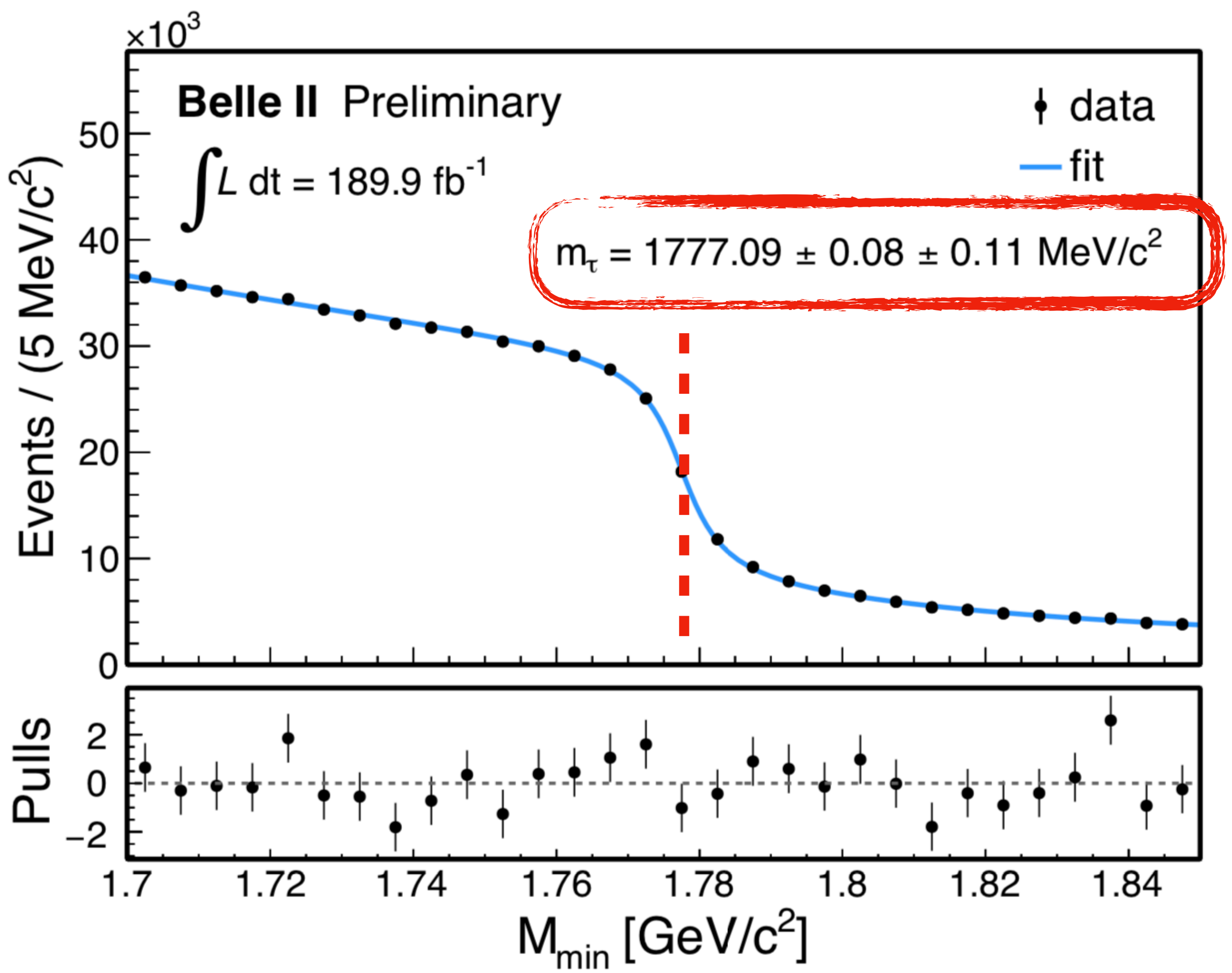
Precision τ physics

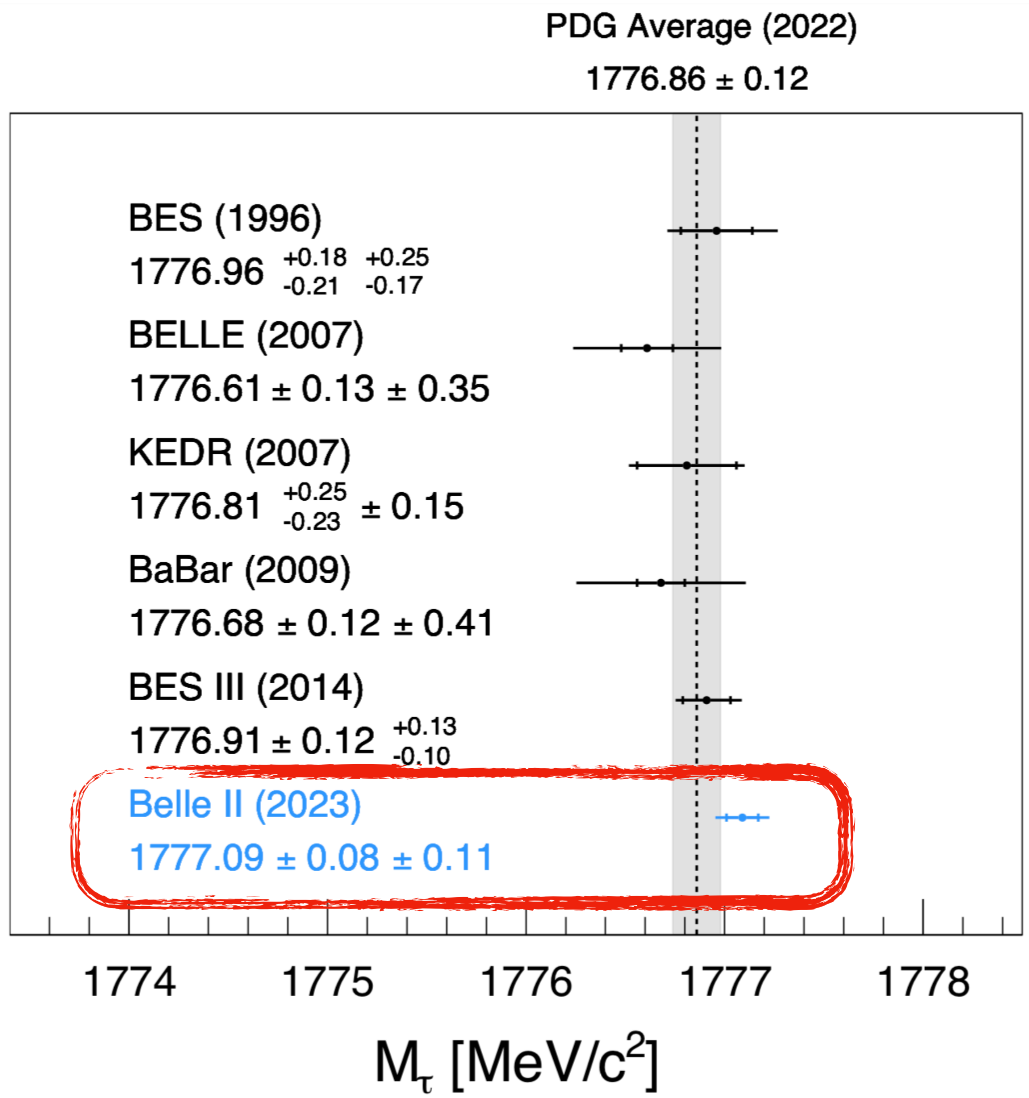
New for La Thuile!

High production of $e^+e^-\to\tau^+\tau^-$ events allow high-precision measurements of τ properties (mass, lifetime, edm…) and search for LFV decays.

Obtain world best τ mass measurement using $\tau^+\to\pi^+\pi^-\pi^+\nu$ decays.
Crucial knowledge of beam-energy and its resolution.

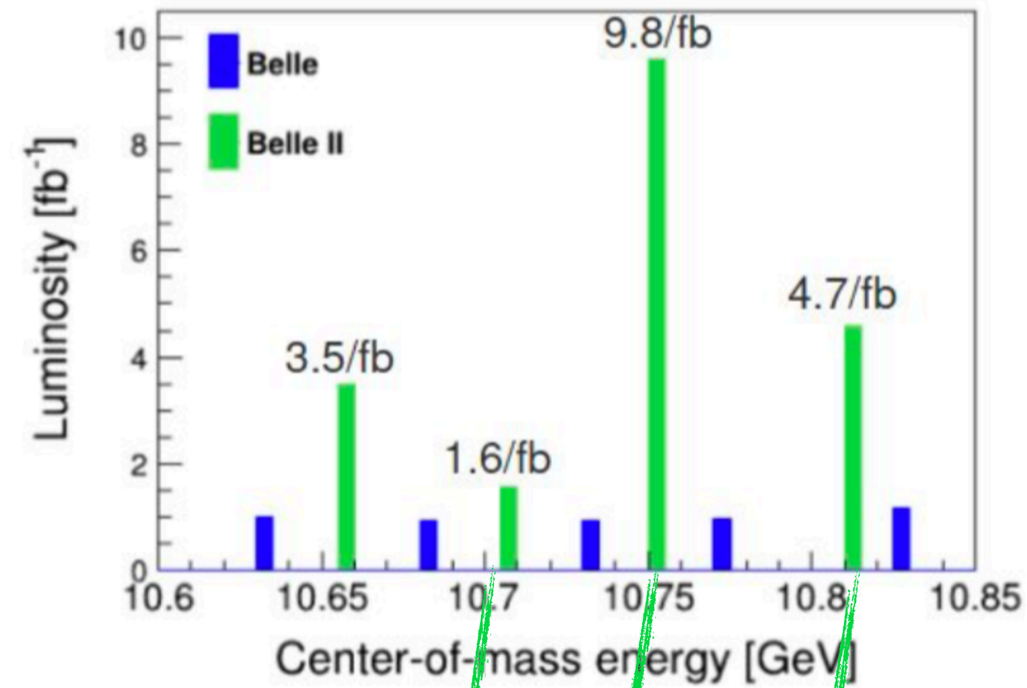
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau.$$



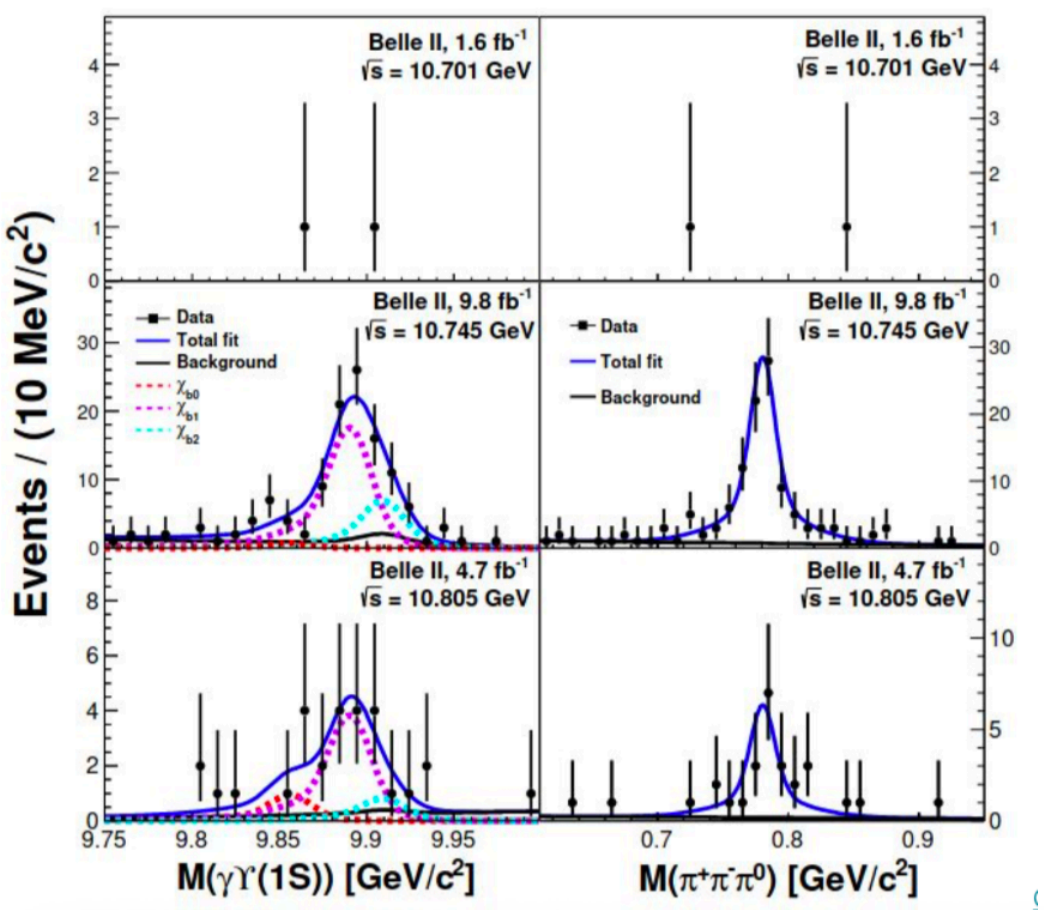


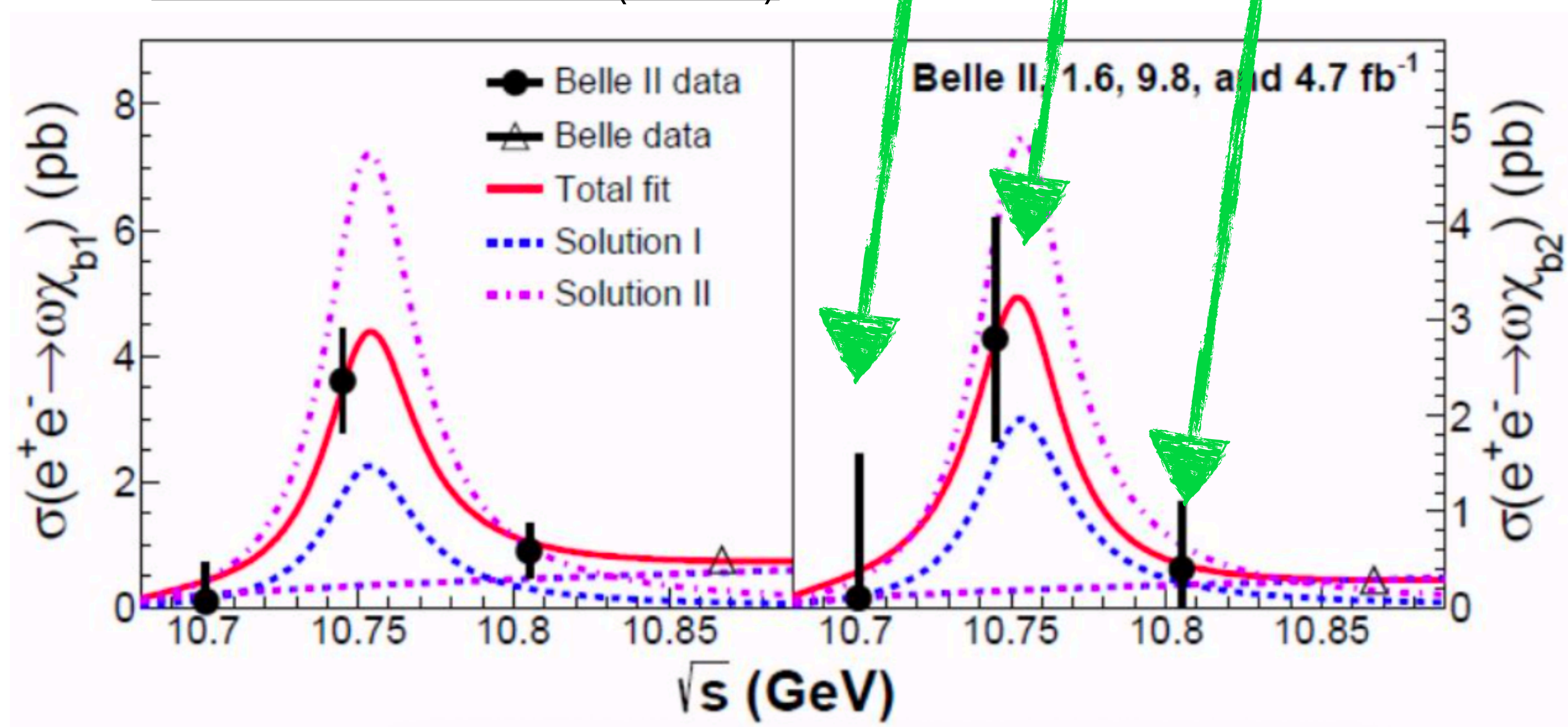
Unique sample

In 2021, collected data at four different E_{CM} to investigate uncharted regions of $b\bar{b}$ exotic states.
Expand on earlier studies from Belle.



PRL130 091902 (2023)

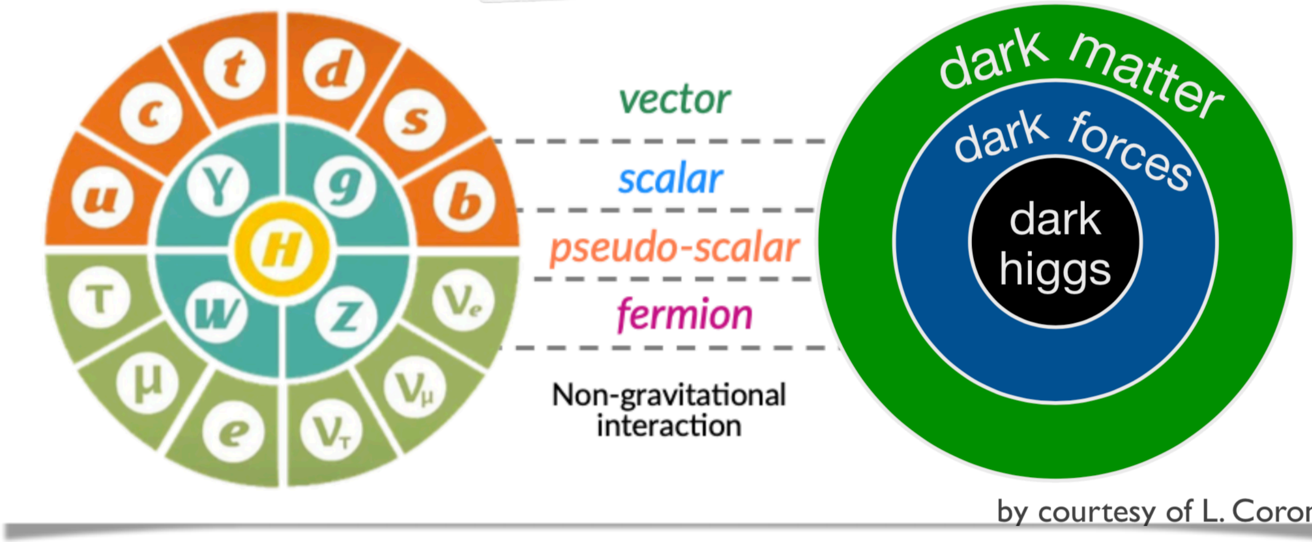




Observation of
$\Upsilon(10753)\to\omega\,\chi_{b1,2}(1P)$

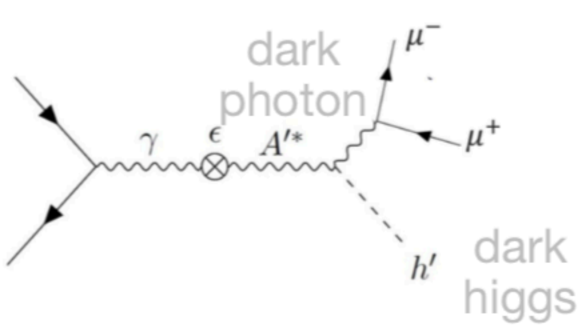
Measurement of x-section, peaks at $\Upsilon(10753)$

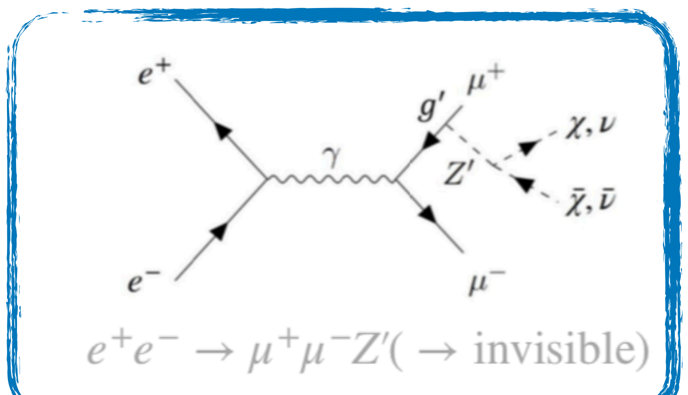
Not only flavor

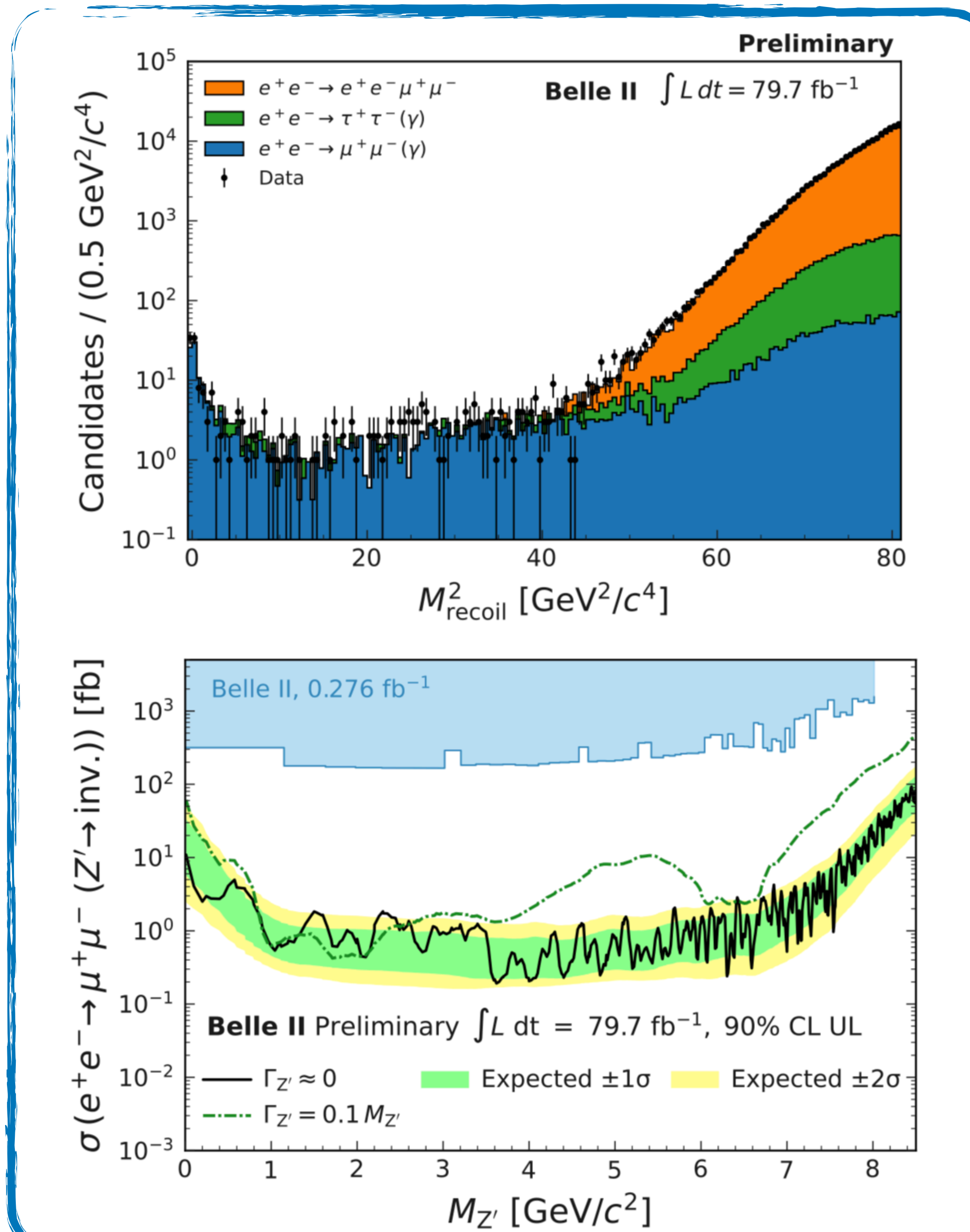


Dark matter is likely to exist, and WIMP searches are empty handed.
Dark sectors solve expt/pheno puzzles (e.g. strong CP). Only a few options of DS-SM couplings do not violate SM symmetries, making systematic exploration possible.

Belle II enjoys sensitivity in the light part of the spectrum (MeV-GeV masses).
A main challenges is to suppress the large SM background. Need dedicated low-multiplicity triggers.





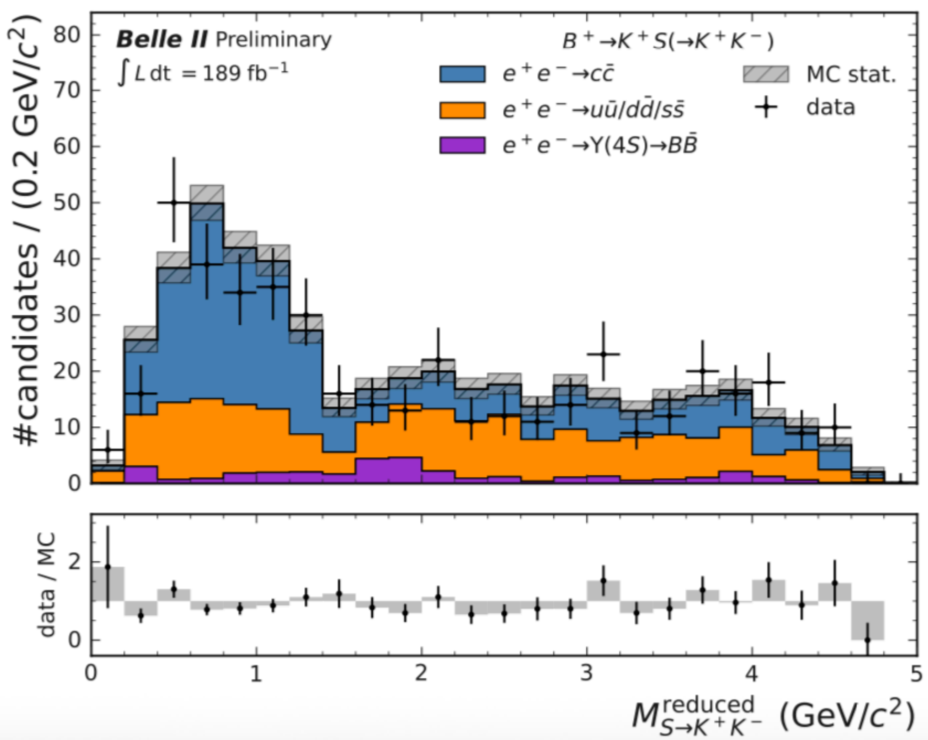


[arXiv.org:2212.03066]

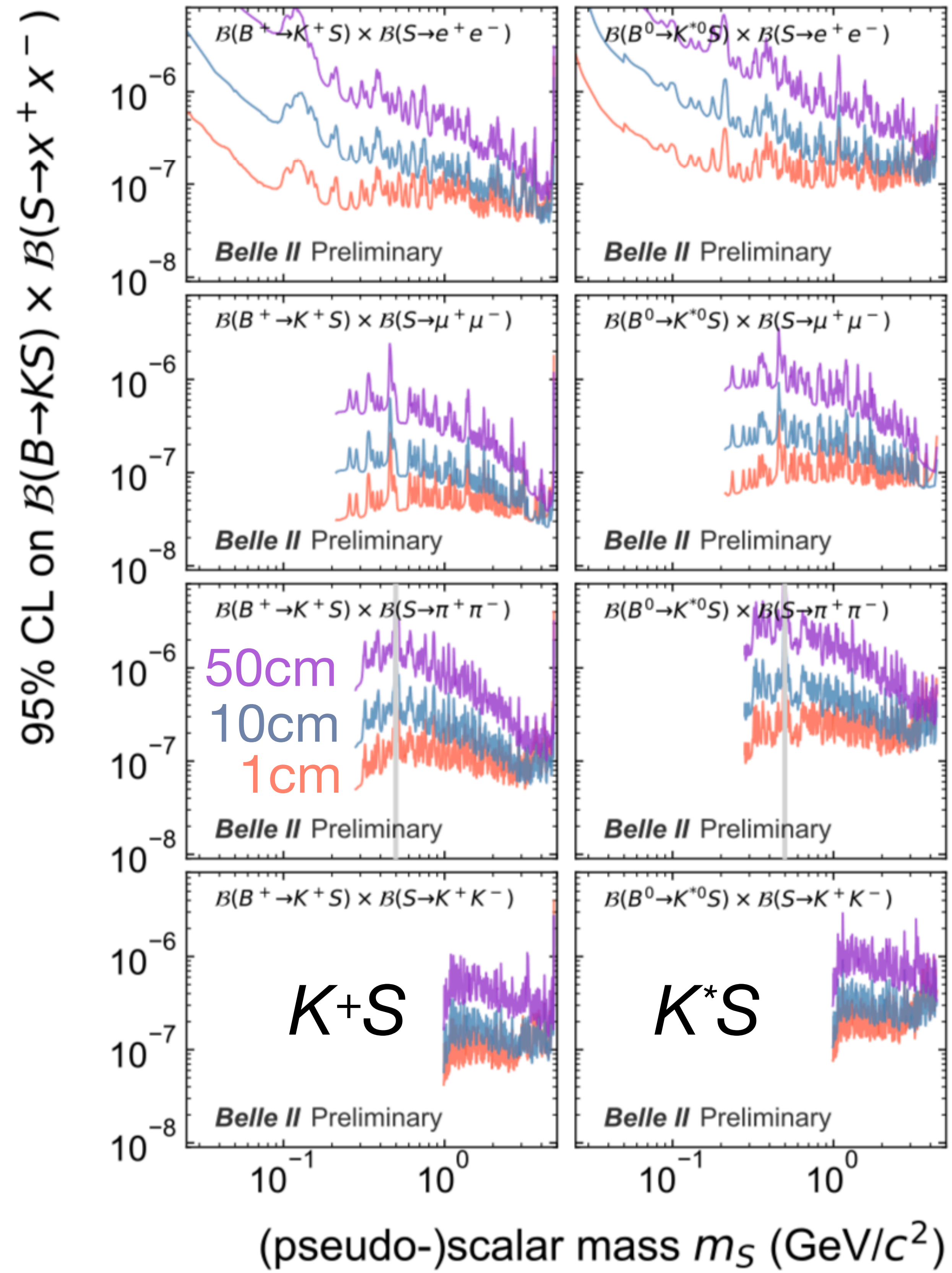
Long-lived particle in $b \to s$

New for La Thuile!

Long-lived particle (LLP) could be a mediator to a dark sector.
Search for a LLP scalar in decays $B \to K^{(*)}S(\to \pi^+\pi^-, K^+K^-, \mu^+\mu^-, e^+e^-)$.
Look for two-tracks making a displaced vertex, O(cm) away from the B meson.
Scan the 2-particle invariant mass.



No excess found in each channel, model-independent upper limits on total BR derived as a function of the LLP mass.

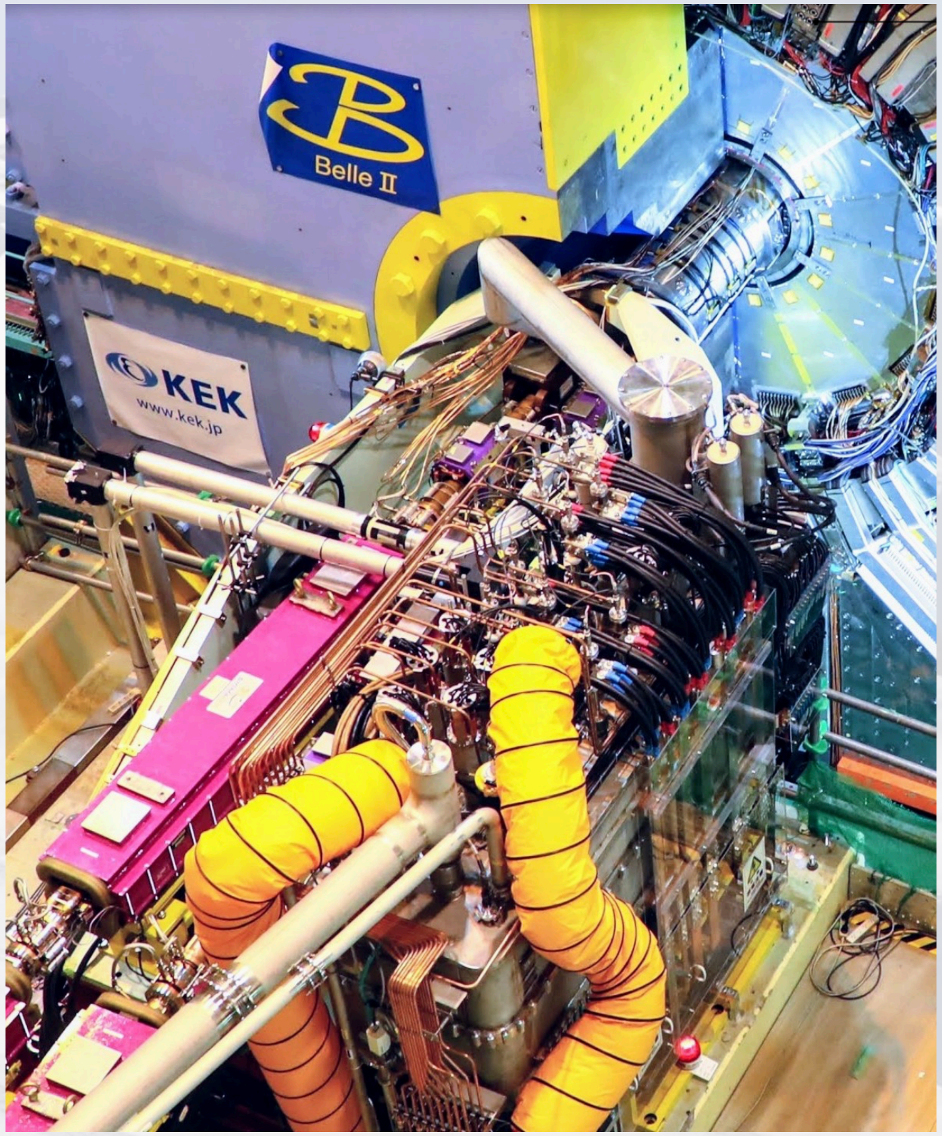


Summary

Belle II has now on tape a sample equivalent to that of BaBar, half of Belle.

Better detector, refined analyses:
kick in with competitive results, some already better than earlier measurements, some are unique to us. We keep refining our tools to further boost the reach.
Only a selection shown today.

Will resume data-taking next Winter. Currently preparing the detector and the machine to ramp-up at full speed.



Backup

Long-shutdown activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown for
- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- complete transition to new DAQ boards (PCIe40)
- replacing of ageing components
- additional shielding and increased resilience against beam background

Currently working on pixel detector installation:
- shipping to KEK in mid March
- final test in KEK scheduled in April

On track to resume data taking next Winter with new pixel detector.

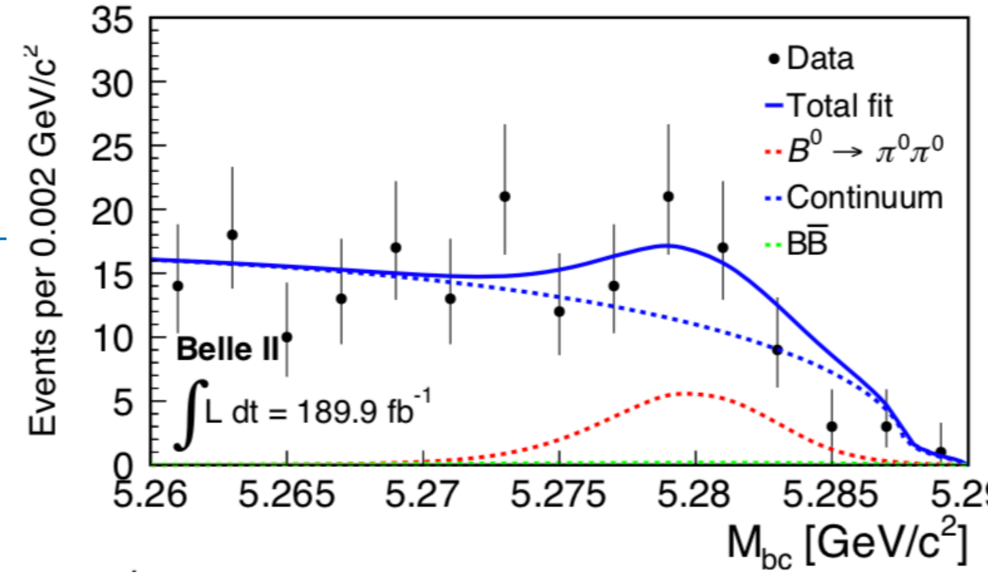
Neutrals, Belle II delight

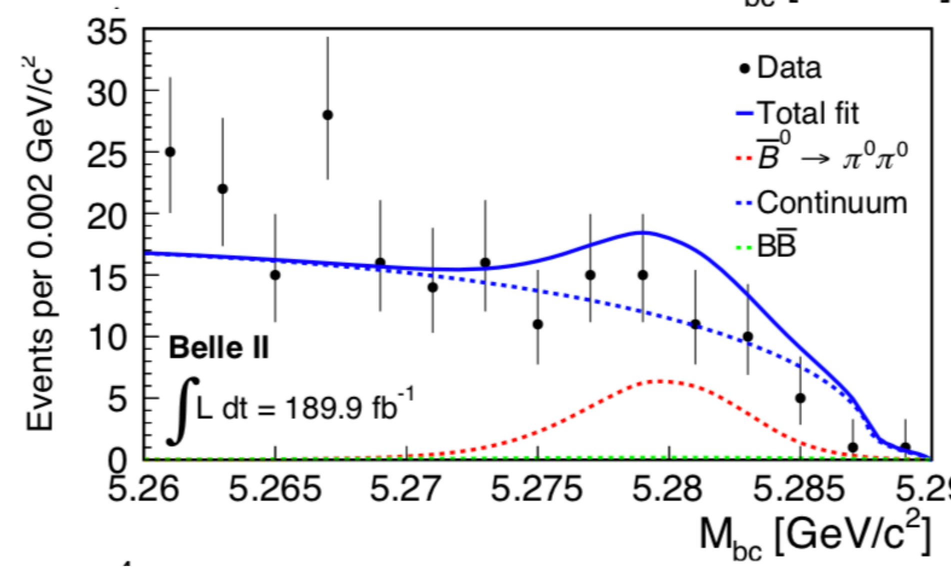
B⁰→π⁰π⁰, only photons in the final state

$$\mathcal{B} = (1.27 \pm 0.25 \pm 0.17) \times 10^{-6}$$

$$A_{CP} = 0.24 \pm 0.46 \pm 0.07$$

Belle II achieves Belle precision using 1/3 of data





B⁰→K

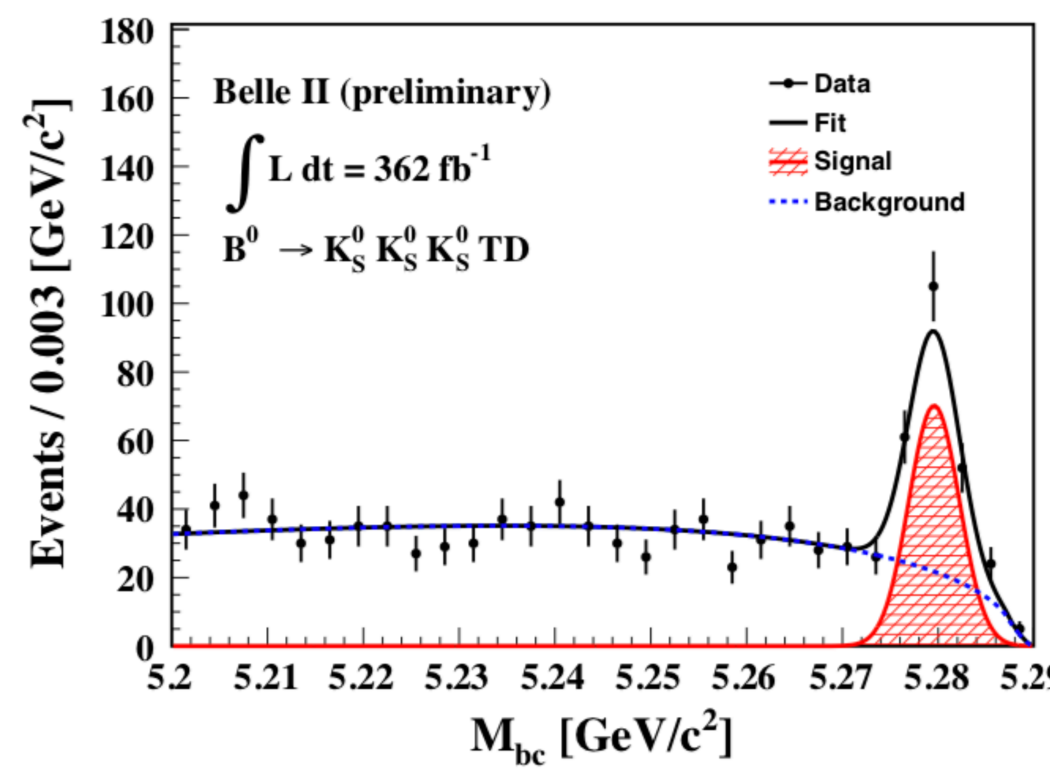
$B^0 \to K_S K_S K_S$, complex vertexing yet time-dependent analysis proved feasible.

New for La Thuile!

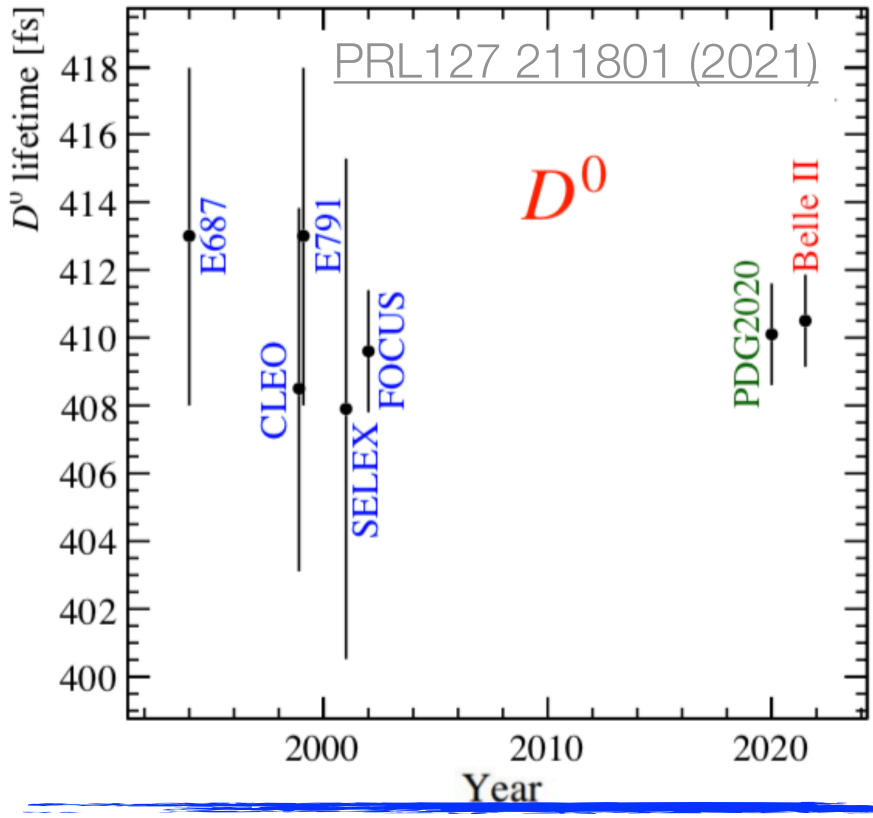
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

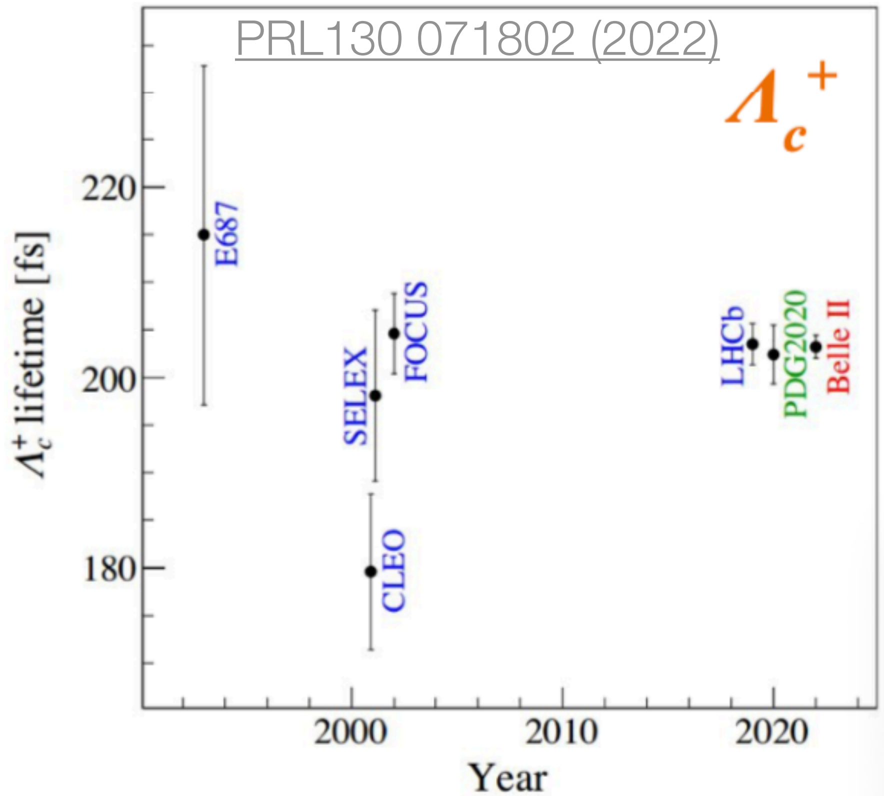
$$A_{CP} = 0.07^{+0.15}_{-0.20} \pm 0.02$$

Reached similar precision as wolrd's best results



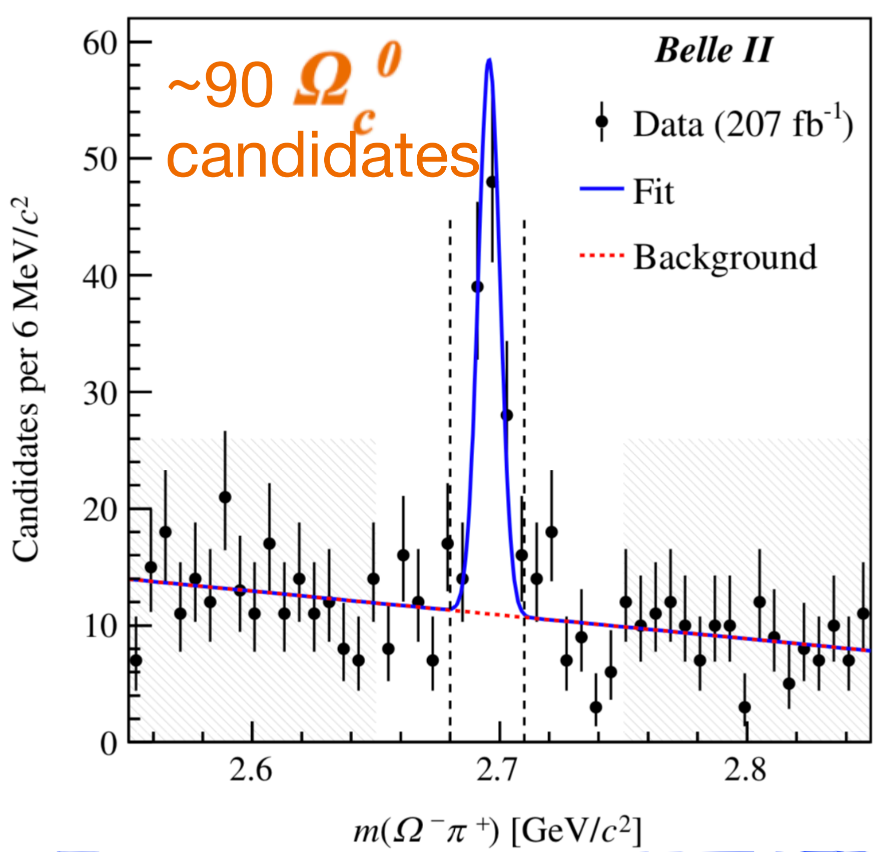
Charm lifetimes benchmark

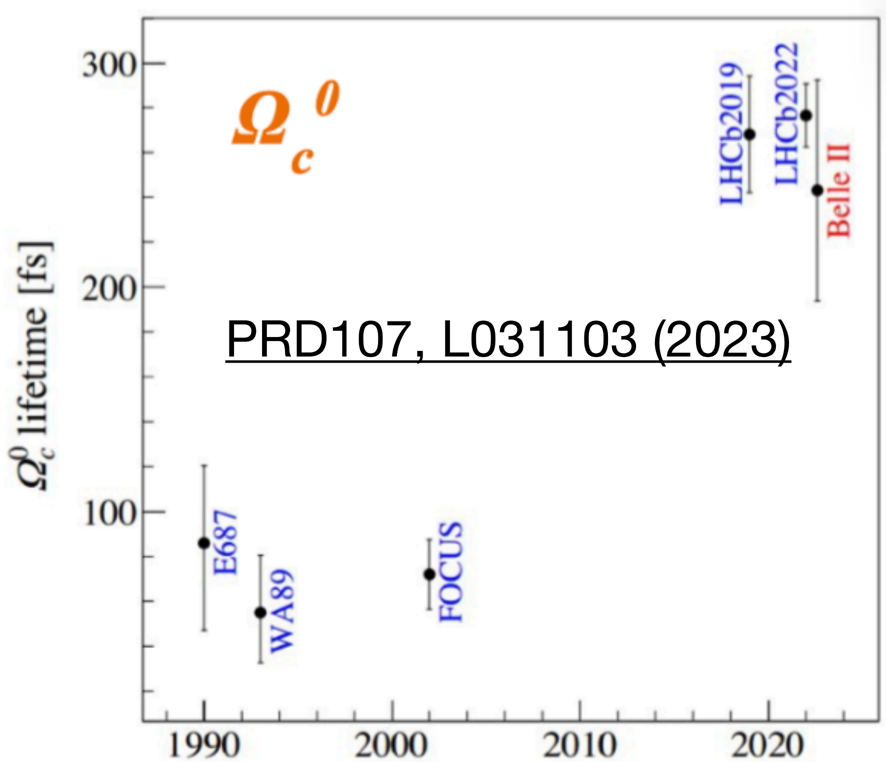




World's best measurements of D and Λ_c lifetimes, pushing the limit to few per-mill accuracy.

Excellent performance and alignment of our vertex detector established.



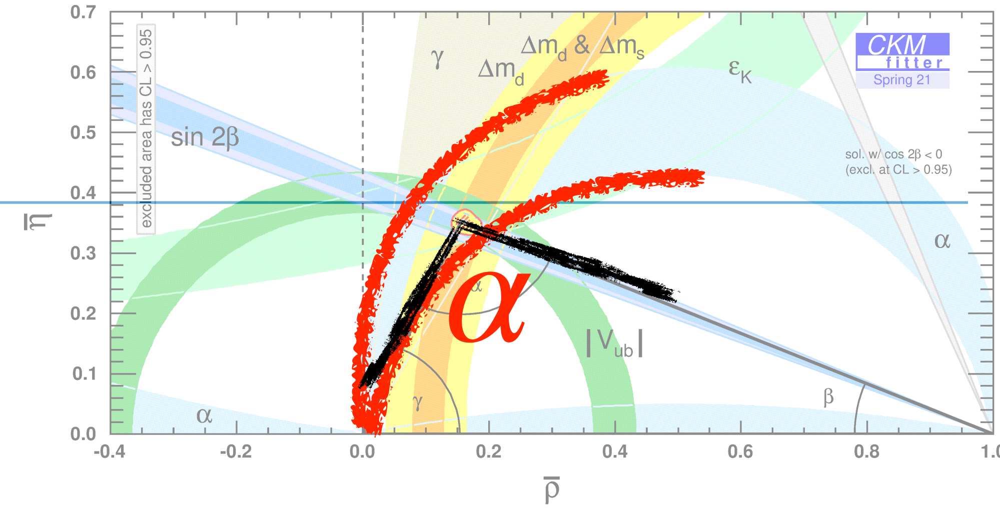


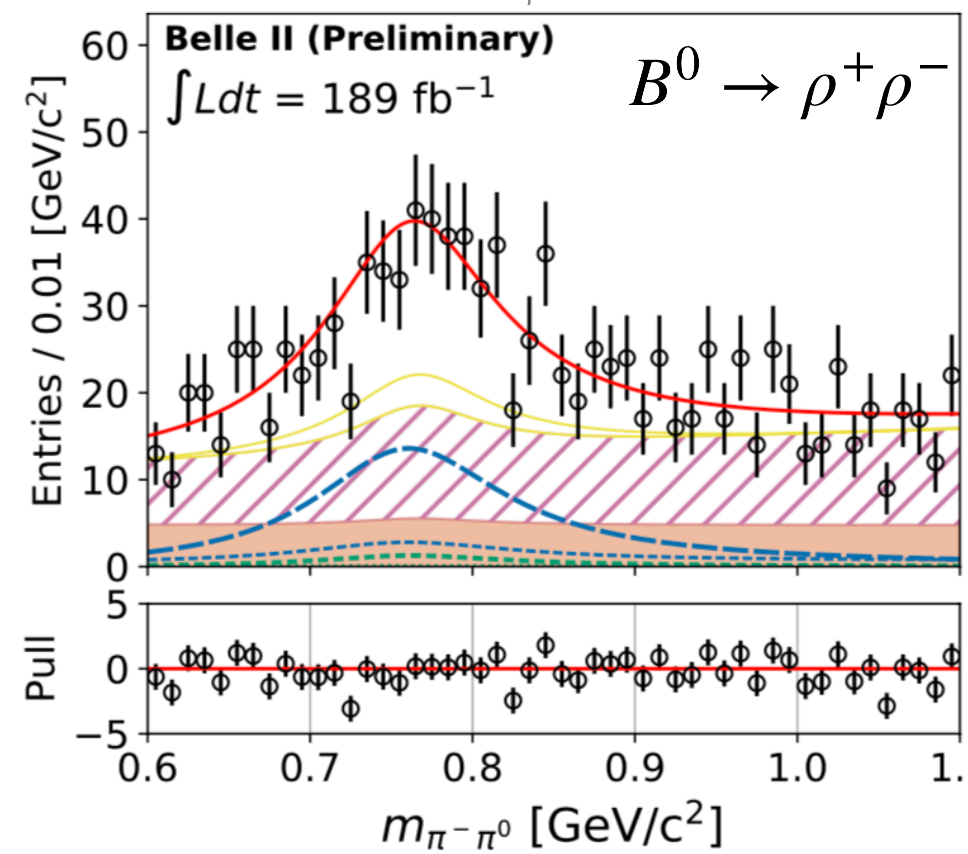
Confirmed LHCb Ω_c lifetime that challenged earlier determinations and HQE expectations.

Isospin for ϕ_2/α

ϕ_2/α least known angle of the UT.
Assessed by a combined analyses of *BR* and A_{CP} of $B \to \rho\rho$ and $B \to \pi\pi$ isospin family to suppress hadronic unknowns.

Belle II unique access to all inputs, but complex angular analysis to determine decay polarisation.
On par with Belle/Babar best performance.





$B^+ \to \rho^+\rho^0$ [arXiv:2206.12362]

$$\mathscr{B} = (23.2^{+2.2}_{-2.1} \pm 2.7) \times 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$

$$A_{CP} = -0.069 \pm 0.069 \pm 0.060$$

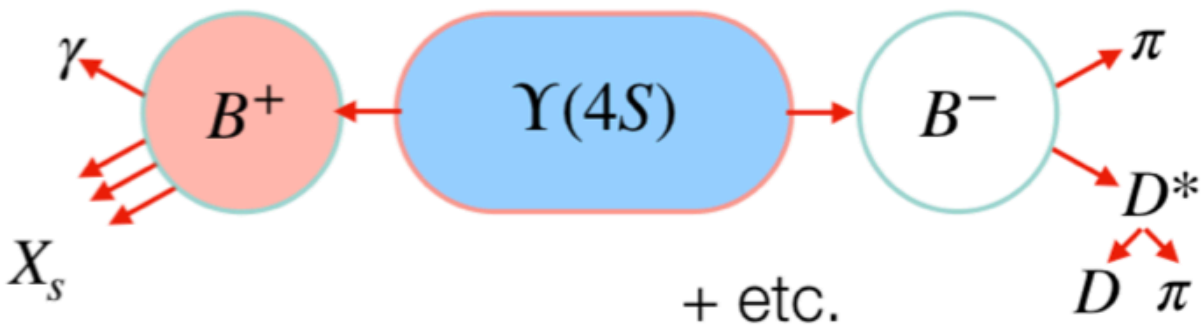
$B^0 \to \rho^+\rho^-$ [arXiv:2208.03554]

$$\mathscr{B} = (26.7 \pm 2.8 \pm 2.8) \times 10^{-6}$$

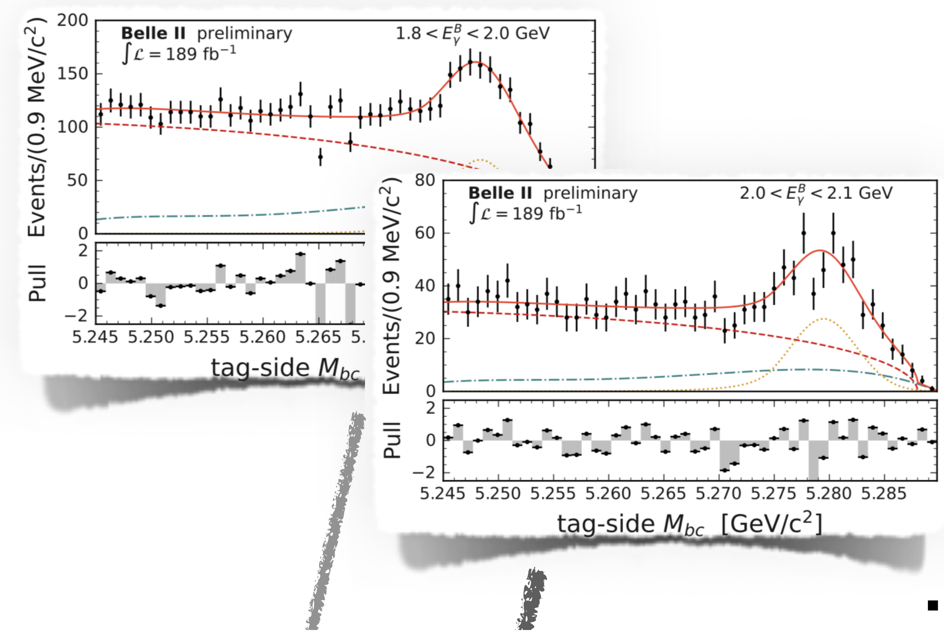
$$f_L = 0.956 \pm 0.035 \pm 0.033$$

Radiative decays

$B \to X_s\gamma$ probe of non-SM in electro-weak penguin decays complementary to $b \to s\, l^+l^-$ decays (remember anomalies?)



E_γ^B - photon energy in the B_{sig} rest frame



[arXiv.org.2210.10220]

E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ $[10^{-4}]$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)
2.1	2.49 ± 0.46 (stat.) ± 0.35 (syst.)

Results consistent with SM and previous determinations