Belle II flavor: where do we stand?

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on behalf of the Belle II collaboration

107º Congresso Nazionale SIF — Heavy Flavor Session
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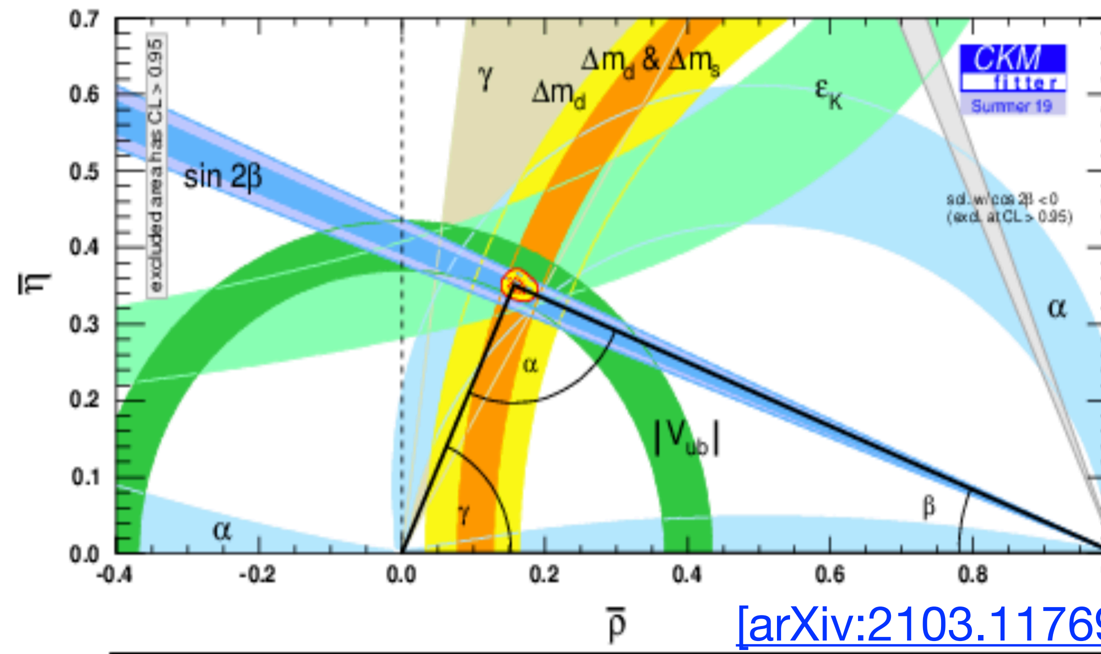
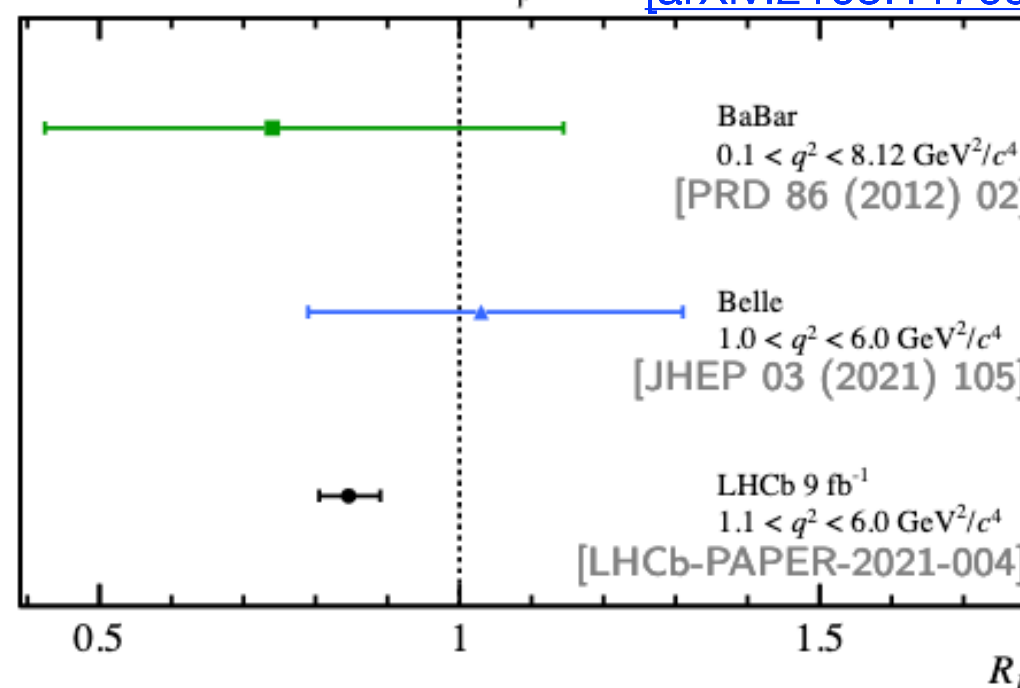
Big picture

Huge progress in flavor physics in the last two decades, testifying the success of the CKM paradigm up to ~10%.

Zero-in on BSM in the next decade.



[arXiv:2103.11769]



Not just CKM matrix.
Recently-emerged anomalies

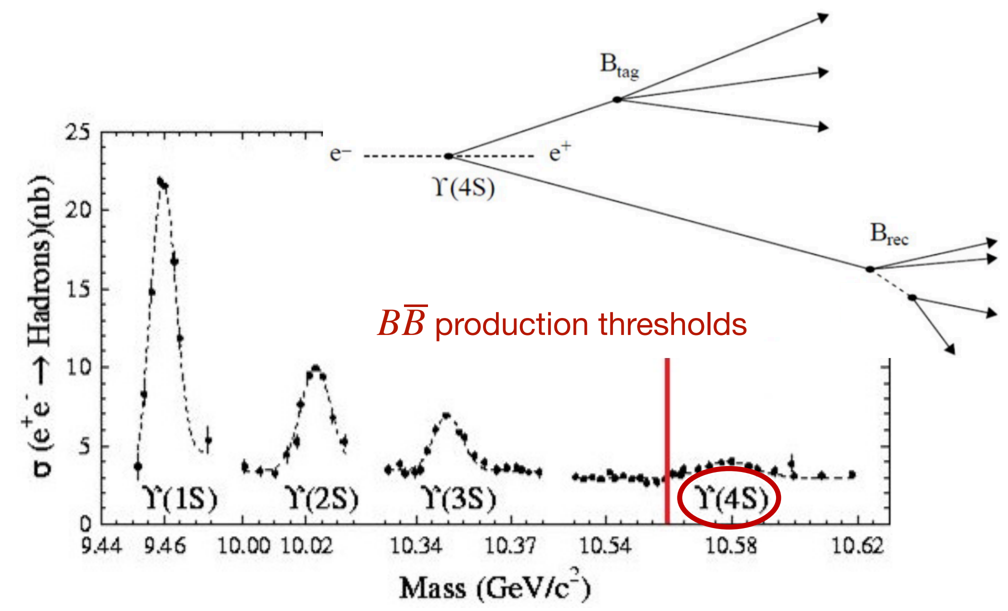
- R(D) and R(D*) — $B \to D^{(*)}\tau\nu$;
- LFU in $b \to s l^+ l^-$ $(l = e, \mu)$;

indicate that opportunities for non-SM physics are numerous.

Belle II aims at 5-10x precision improvement over first generation *B*-factories and explore rarer processes. Competitive with, and complementary to, LHCb.

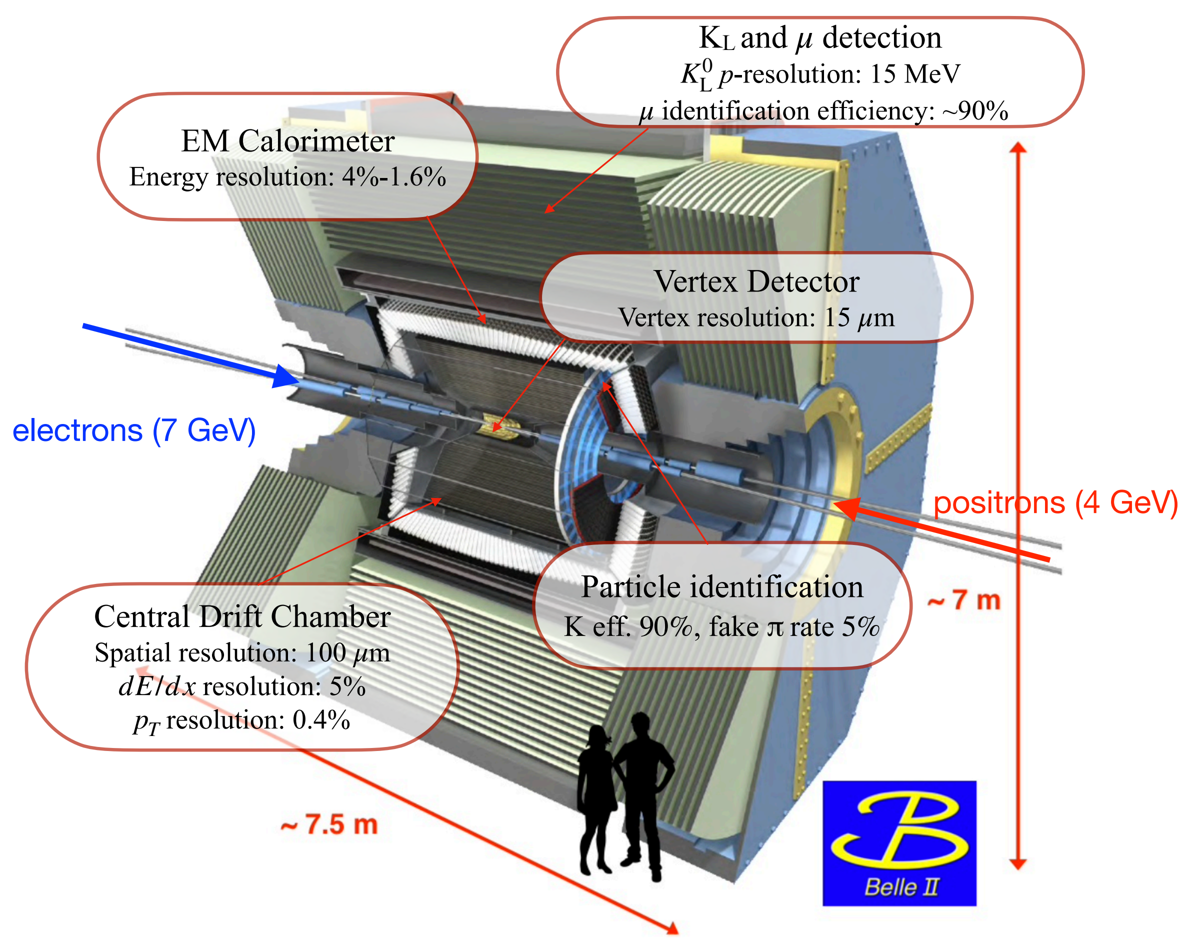
The instrument

Energy-asymmetric e^+e^- collisions at the $\Upsilon(4S)$. CM boosted with βɣ~0.28<0.5 (BaBar/Belle), compensate with improved vertex resolution and higher containment of $B\overline{B}$ decay products.



Final focus magnets to
- squeeze vertical size to ~50 nm;
- large crossing angle of ~83 mrad.

⇒ 30x intensity wrt previous *B*-factories.



~100% of $\Upsilon(4S)$ decay to $B\overline{B}$ pairs

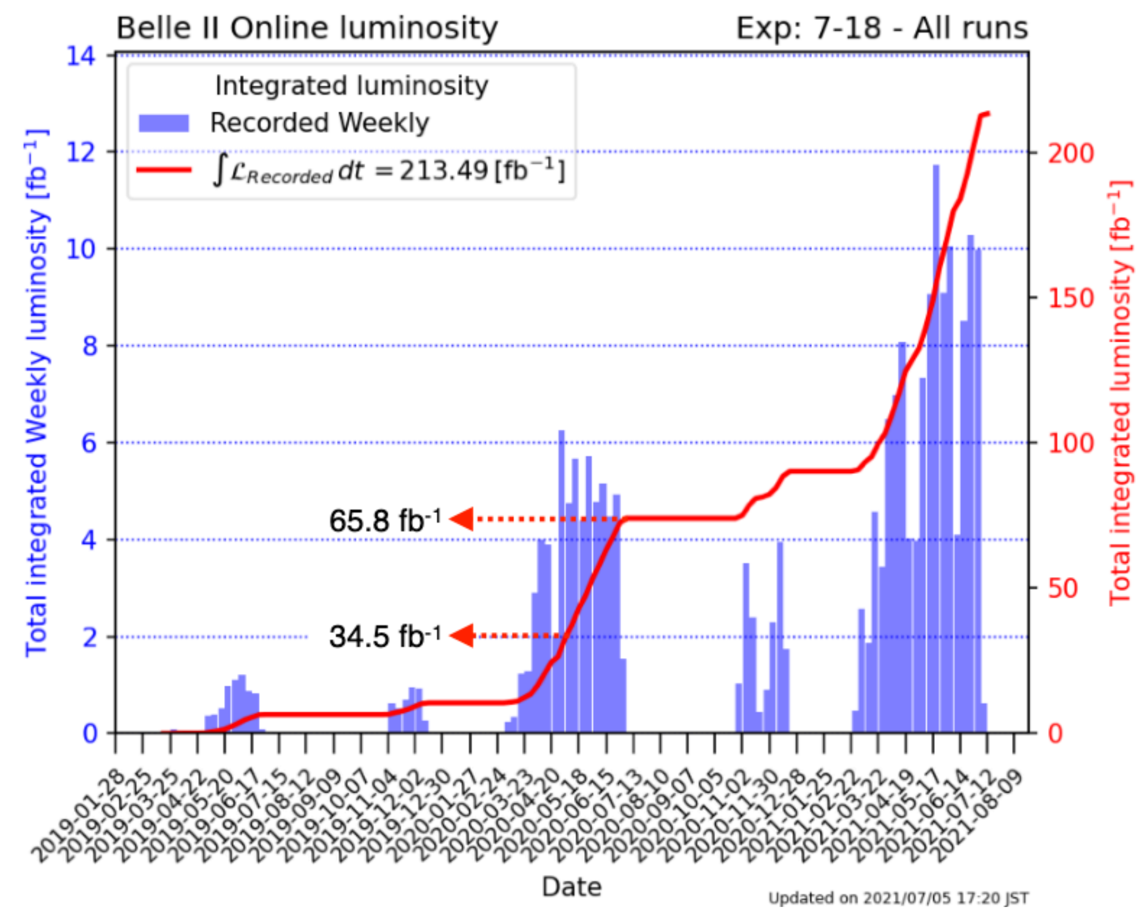
- No additional particles ⇒ low backgrounds;
- Known collision energy + hermetic detector ⇒ full event reconstruction;
- Coherent B and $\overline{B}$ evolution.

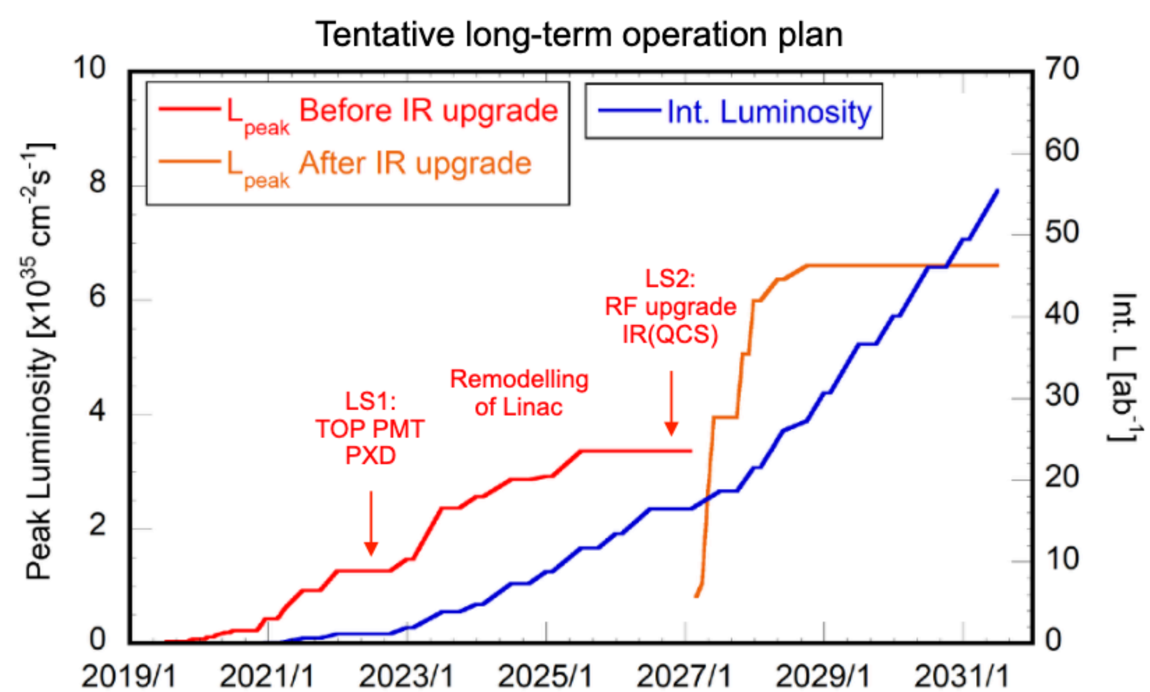
The data

Started in 2019, currently ~210 fb^{-1}.
◉ sample comparable to BaBar's and Belle's by summer 2022;
◉ 50 ab^{-1} in the next ~10 years.

Successful operations even during pandemic, 89.5% efficiency.
Super *B*-factory mode (records):
- intensity: **3.12 x 10^{34} $cm^{-2}s^{-1}$**;
- 1.96 fb^{-1} per day;
- 12 fb^{-1} per week;
- 40 fb^{-1} per month.

Tentative plan:
- shutdown in 2022 for vertex detector works and PMTs replacement;
- might have a long shutdown in ~2026 to improve interaction region.



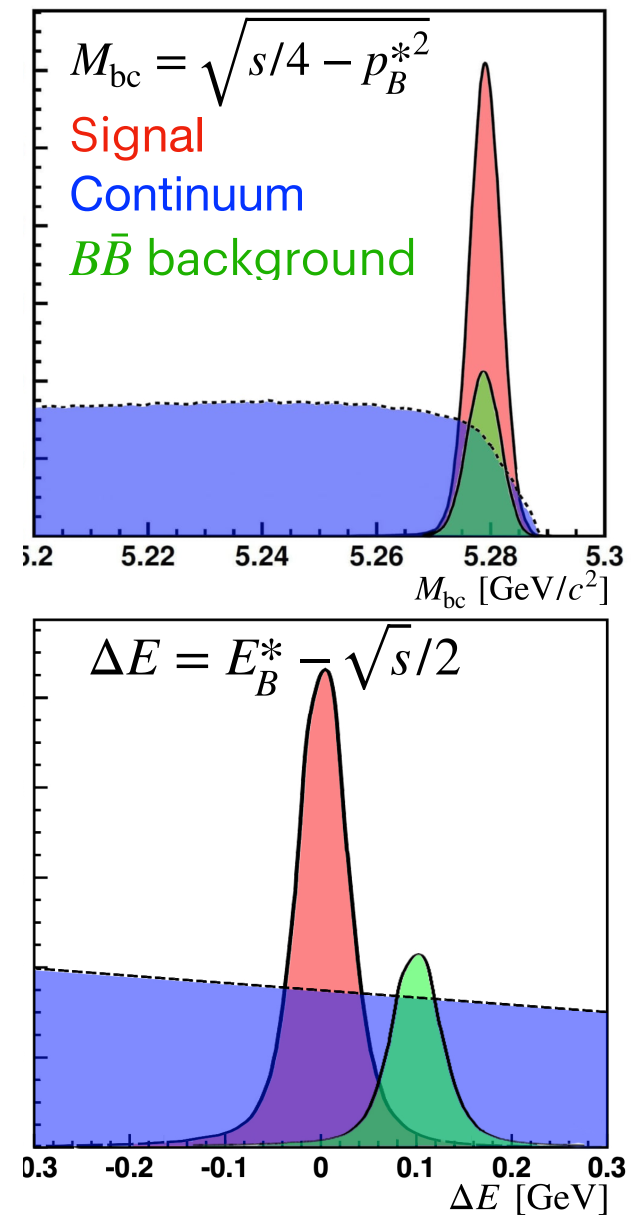


Flavor physics at Belle II

Neutral reconstruction, precise knowledge of $\sqrt{s}$, high flavor-tagging performance offer Belle II the best/unique reach on final states with multiple π^0, η, γ, ν, …
⇒ complementarity with existing flavor experiments.

- Improve on $|V_{ub}|$ and $|V_{cb}|$, *advantage on semileptonic decays, full suite of approaches*;
- γ down to ~1°, *systematics different from LHCb's*;
- Compare tree and penguin on β *exploiting unique final states*;
- *Reconstruct full sets of isospin-partner decays* to cancel hadronic uncertainties and systematics (α, *Kπ-puzzle*, …);
- BSM searches in decays with *(semi-)invisible final states*;
- Time-dependent CPV *exploiting efficient flavor tagging and neutral final states*;
- Charm CPV and rare decays.

Beyond flavor (not in this talk): dark sector, τ physics, spectroscopy…



Today: first sampler of competitive measurements and perspectives for near future.

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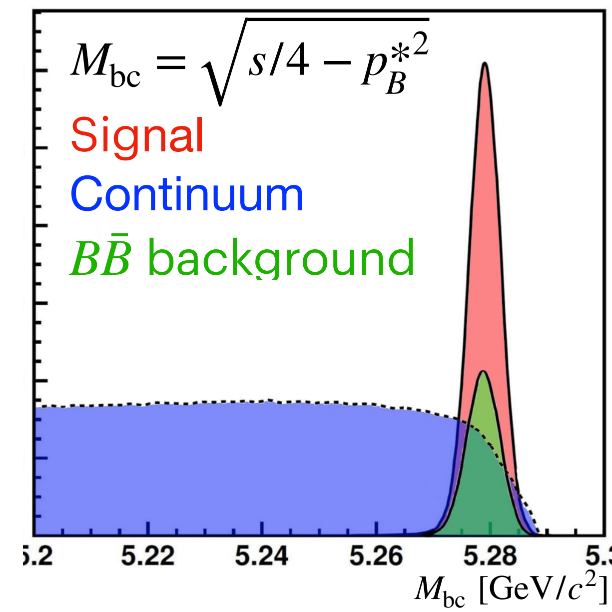
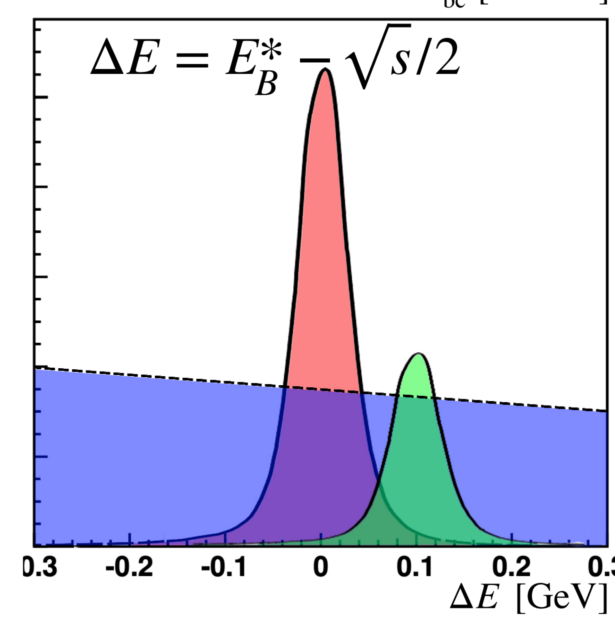




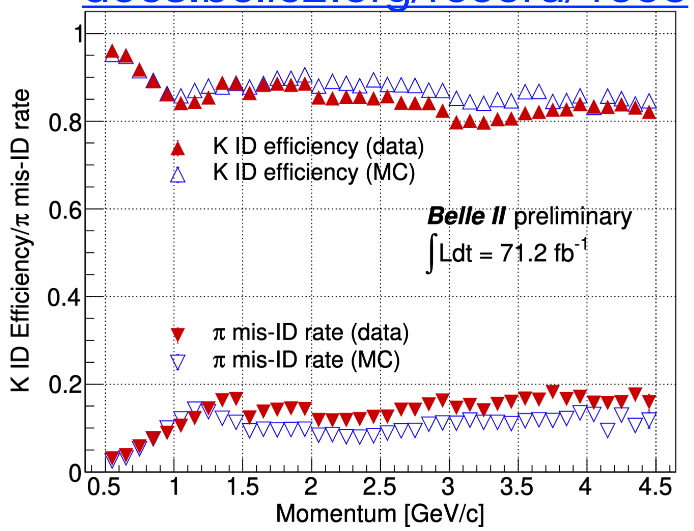
Beyond flavor (not in th
sector, τ physics, spec

- **L. Corona**: *Ricerca di nuova fisica nel settore oscuro in stati finali con fotoni ed energia mancante a Belle II: risultati e prospettive*
- **M. Laurenza**: *Z' and Dark Higgsstrahlung searches in events with muon pairs at Belle II*
- **S. Moneta**: *Tau-lepton lifetime measurement at Belle II*

Today: first sampler of competitive measurements and perspectives for near future.

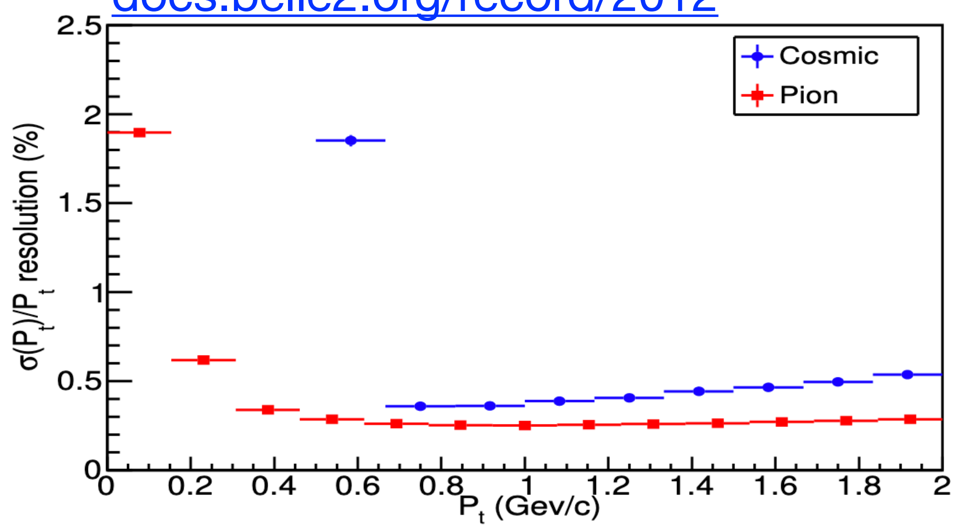
Performance overview

docs.belle2.org/record/1558



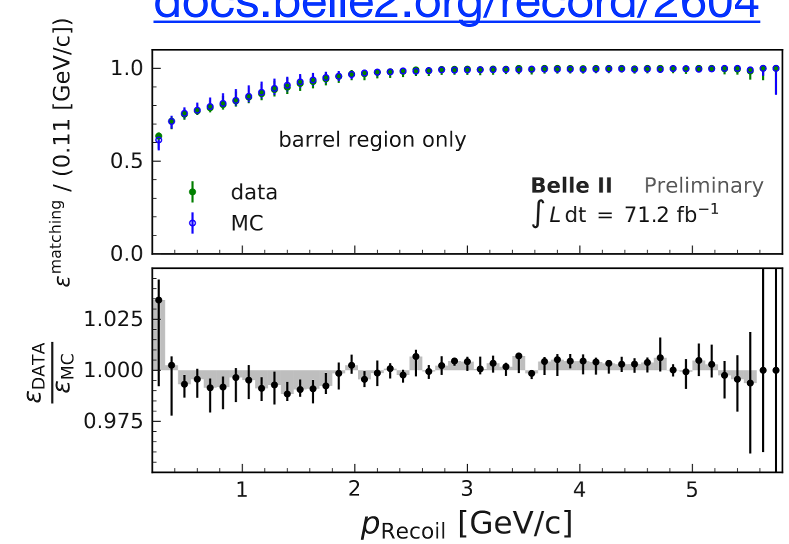
Strong charged particle identification.

docs.belle2.org/record/2012



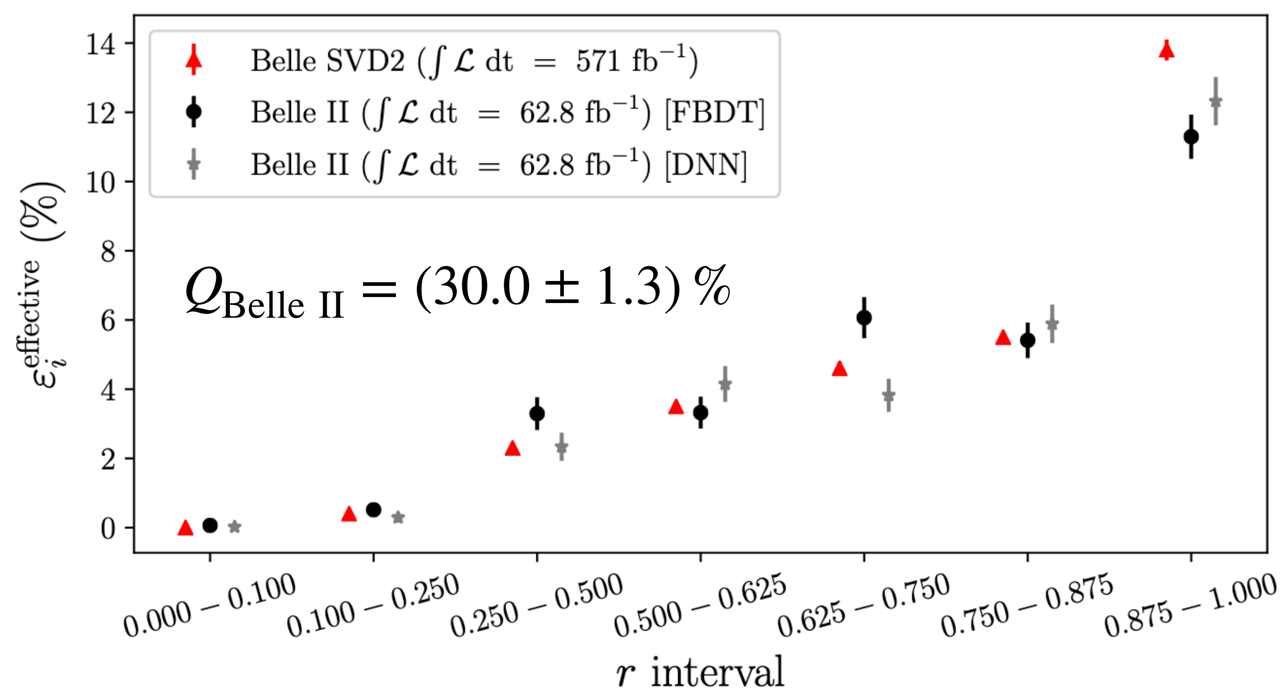
Good momentum resolution.

docs.belle2.org/record/2604



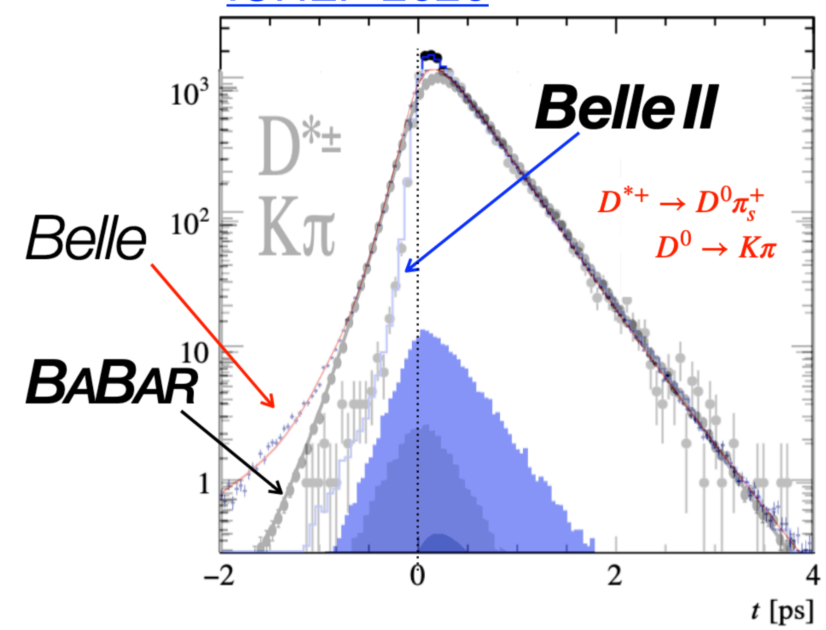
High ɣ efficiency.

To be submitted to EPJC



Flavor tagging efficiency comparable to Belle.

ICHEP 2020



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

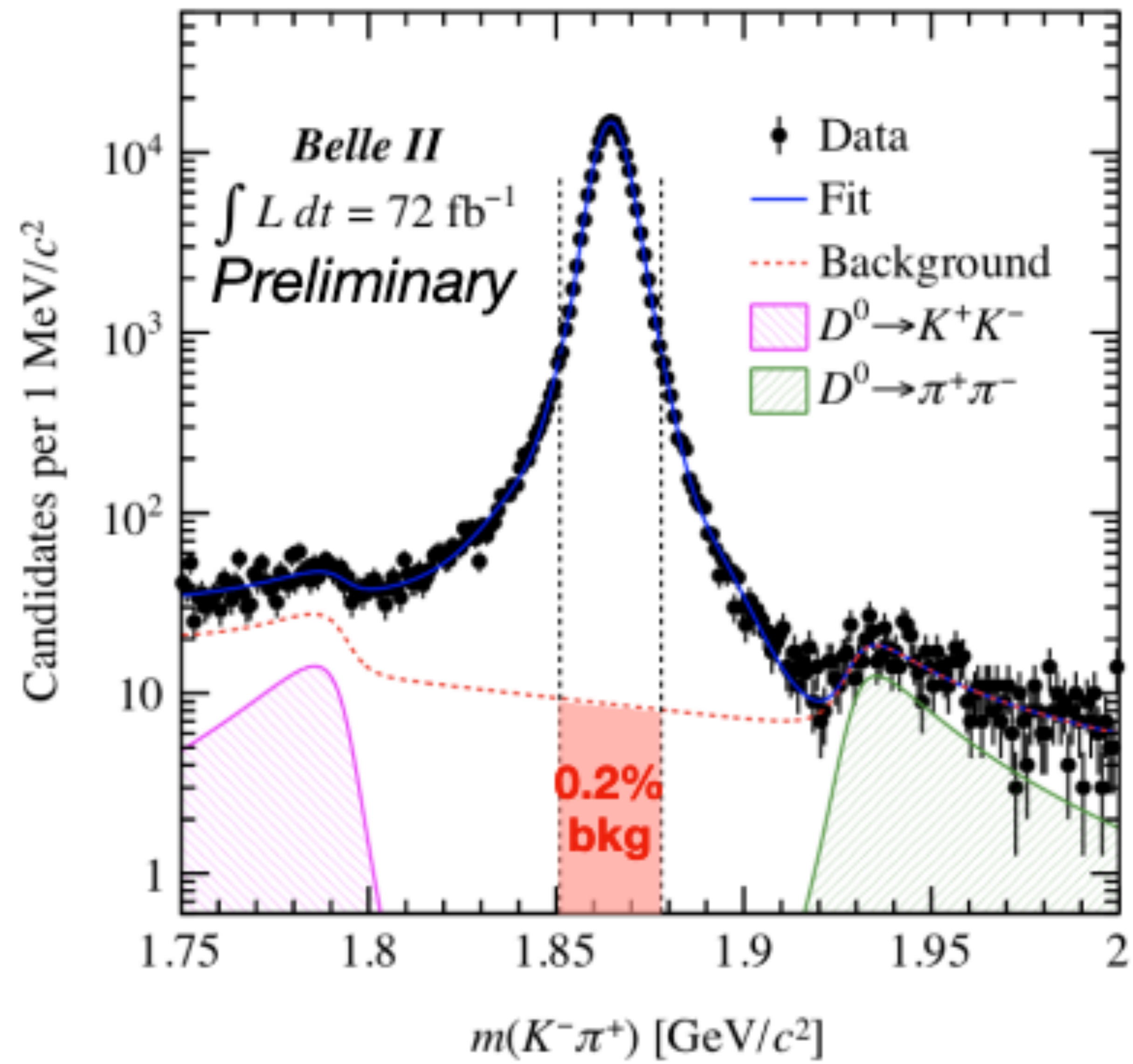
Precise D lifetimes

[arXiv:2108.03216]
Submitted to PRL

Stringent tests of effective models used for predictions.
Understanding of systematic effects for time-dependent CPV/mixing analyses.

Current best from FOCUS 2002, ~1% precision dominated by systematics.

High-purity D*-tagged
$D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$.
No lifetime-biasing cuts.

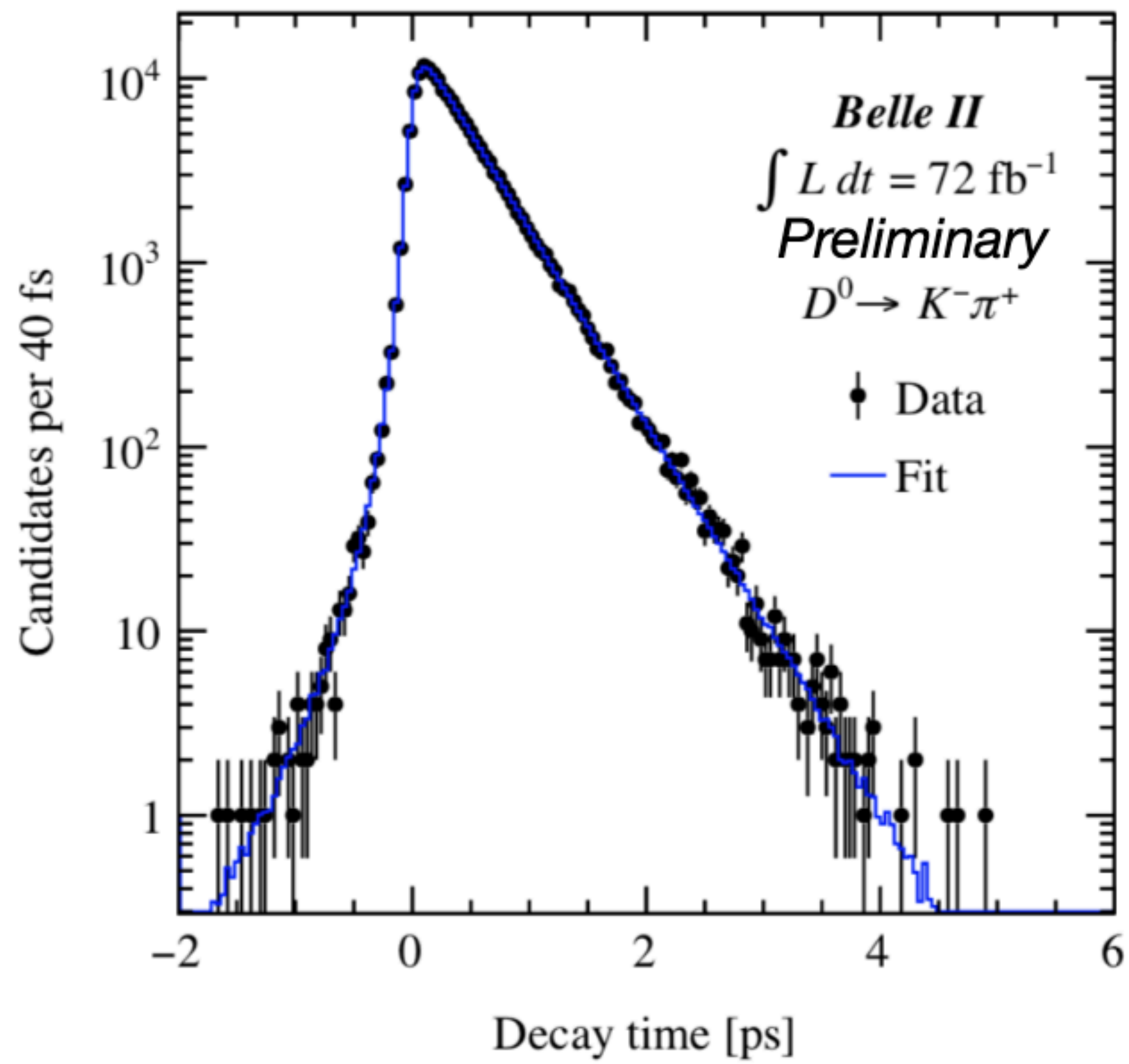


World-best

[arXiv:2108.03216]
Submitted to PRL

2D fit of decay-time and its uncertainty.
Resolution model from data.
Challenge: controlling the systematics.
Leading contribution from misalignment, calibrated periodically with control data.
Dominant bkg model syst. for D^+.

	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

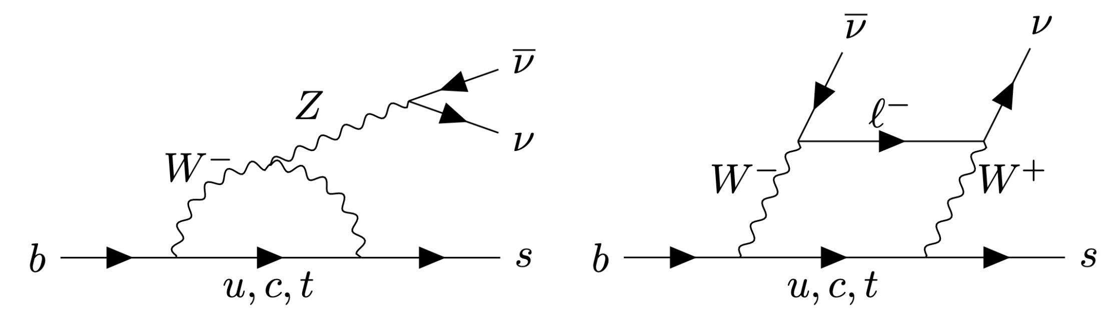


World's best. Dominated by sample size.

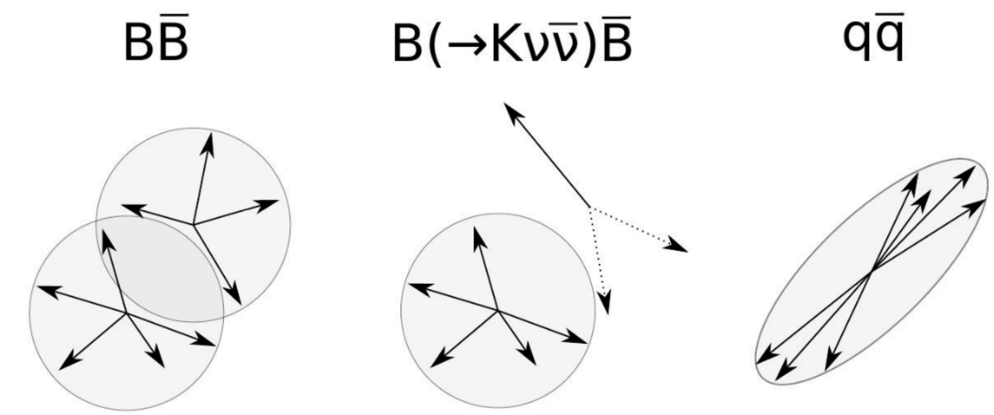
Excellent vertexing capabilities, key for time-dependent measurements.

Invisible final states

BSM search in $b \to s$ penguins;
$\mathbf{B^{\pm}} \to \mathbf{K^{\pm}}\nu\overline{\nu}$: unobserved, th. clean.
Unique Belle II reach.

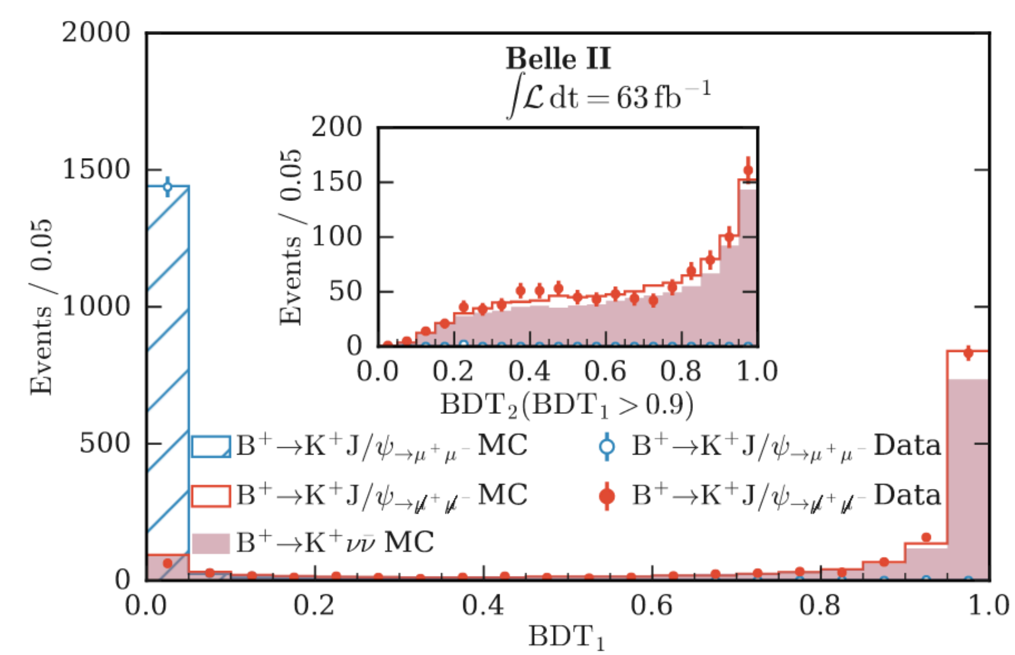


Key: keep signal efficiency high.
Wrt previous searches, inclusive tagging
⇒ much higher efficiency: ε~4.3 %
(O(10) better than Belle/BaBar).



Signal candidates from highest-p_T track.
Distinctive topology: train BDT_1 to discriminate signal and background.
Apply first selection, then re-train BDT_2
→ significant separation improvement.

Validate BDTs in data and simulation on $B^+ \to K^+ J/\psi_{(\to\mu^+\mu^-)}$, also removing muons and reweighting p(K^+) to mimic signal.



Novel approach yields great efficiency improvement.

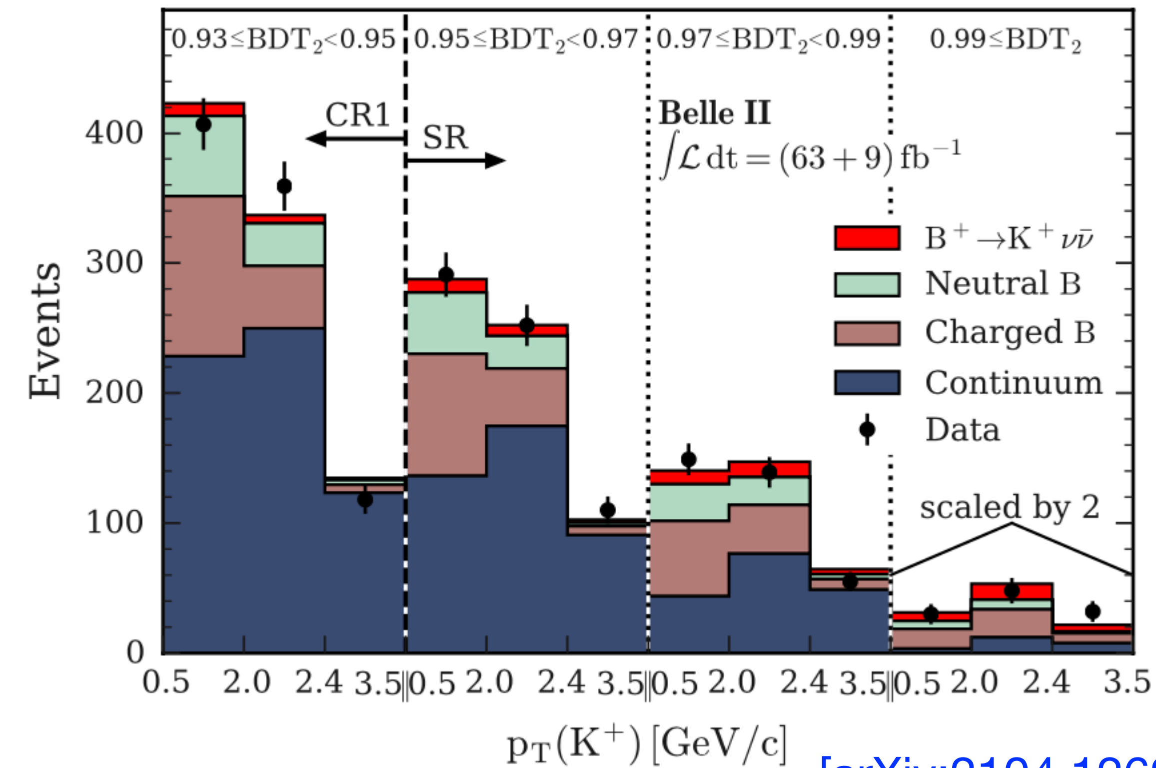
$B^{\pm} \to K^{\pm}\nu\bar{\nu}$ signal extraction

2x12 regions in the BDT_2 x $p_T(K^{\pm})$ space in on- and off-resonance data. Extract signal from binned fit.

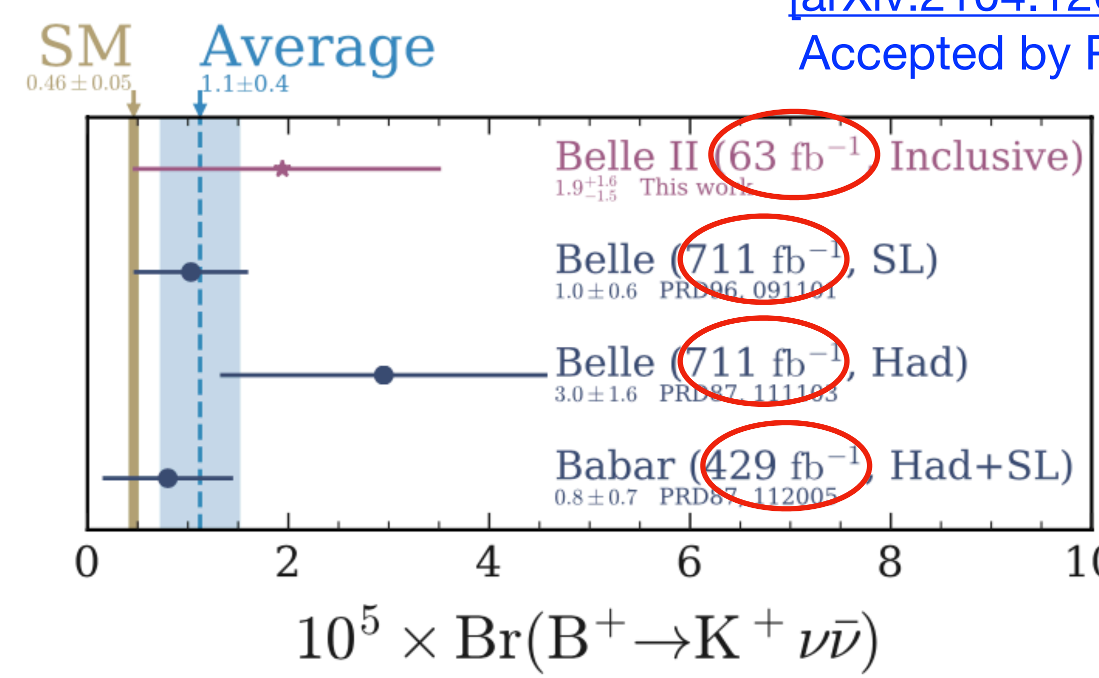
Templates from simulation, constrain continuum bkg by fitting jointly off-resonance data.

Leading systematics from background normalization of individual contributions.

Purity:
- 6% in signal region
- 22% in BDT_2>0.99 region



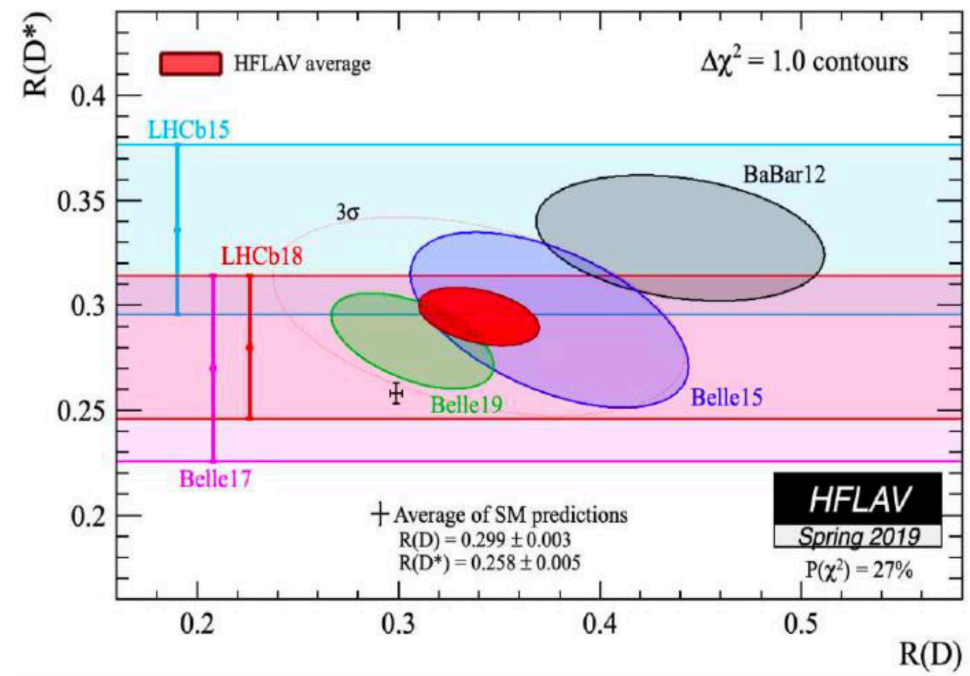
[arXiv:2104.12624]
Accepted by PRL



Precision already comparable to that of Belle/BaBar, despite 5-10x smaller sample size.

Prospects on anomalies

R(D(*)): measured in $B \to D^{(*)}\tau\nu$ decays. Currently addressing normalization modes $B \to D^{(*)}l\nu$. Belle and BaBar results show how impactful B-factories results are.

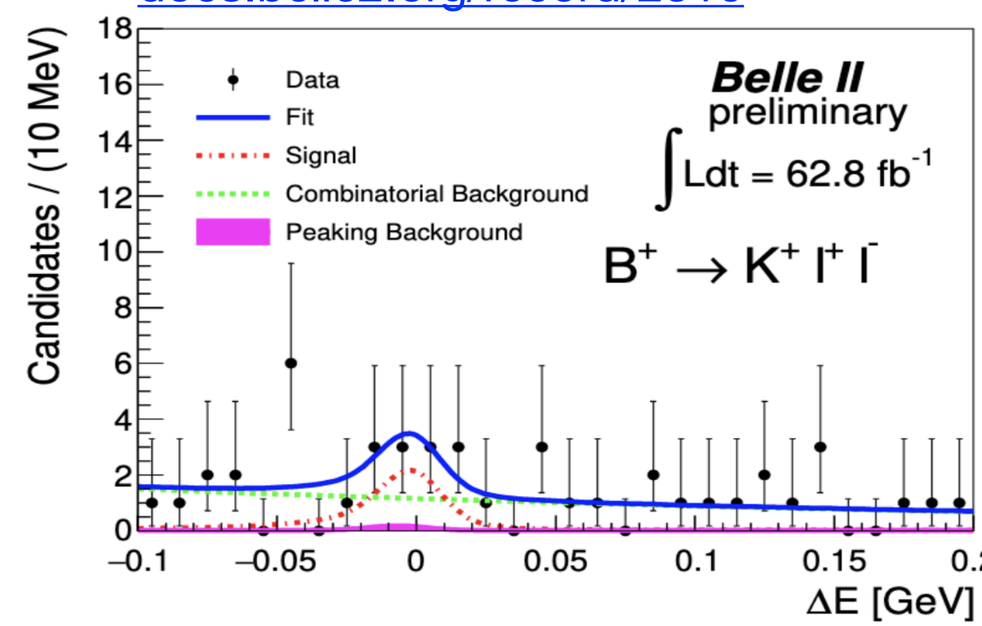


R(K(*)): first measurement of $B^{\pm} \to K^{\pm}l^{+}l^{-}$ decays. Signal yield from 2D ΔE-M_{bc} fit, main challenge is the low statistics.

$$N(B^{\pm} \to K^{\pm}l^{+}l^{-}) = 8.6^{+4.3}_{-3.9}(\text{stat}) \pm 0.4(\text{syst})$$

Projection to reach 5σ sensitivity at ~20 ab^{-1}. Hardly competitive with LHCb.

docs.belle2.org/record/2310



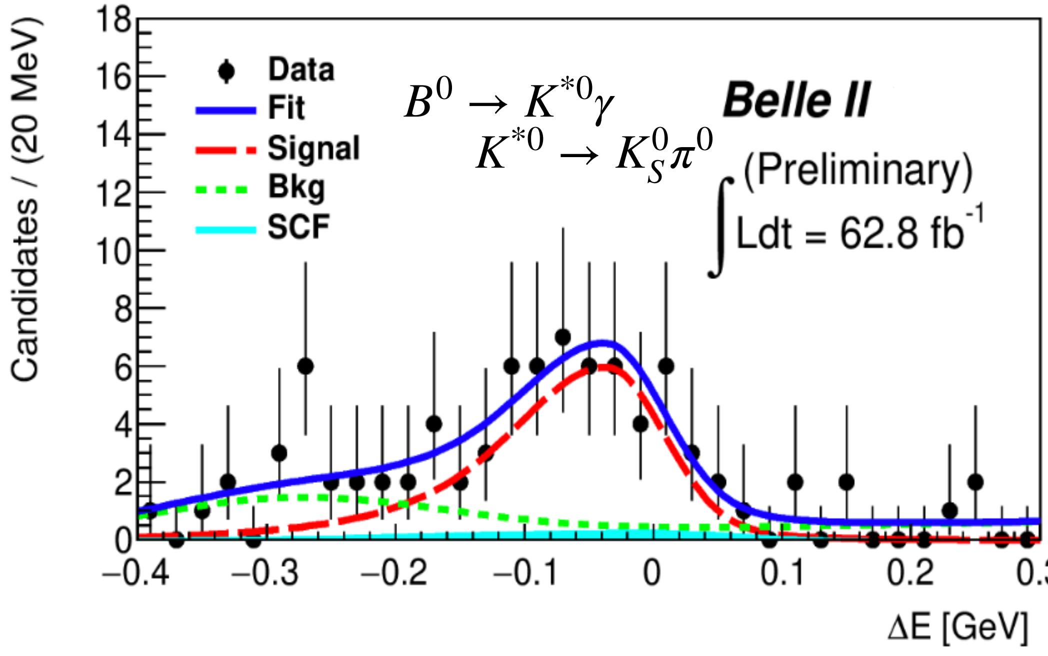
Searches for $b \to s\gamma$

Proceed dominantly via penguin loops
⇒ sensitive probes for non-SM physics.

Belle 2017: presence of isospin asymmetries [arXiv:1707.00394].

More promising in early data over $b \to s$ owing to higher rates and final states suited for Belle II.

First Belle II measurements.
Signal yields from fits of ΔE distributions, efficiencies from simulation.
Main challenge in the treatment of γ coming from π^0 or η decays.



Mode	B.F (Fit) $\times 10^{-5}$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$4.6 \pm 0.3 \pm 0.3$
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	$4.4 \pm 0.9 \pm 0.6$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$5.1 \pm 0.5 \pm 0.5$
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	$5.5 \pm 0.6 \pm 0.4$

Targeting β

β from penguins: $B^0 \to \phi K_S^0,\ \phi\eta'$.
Compared with tree ($B^0 \to J/\psi K_S^0$).

First reconstructions of $B \to \eta' K$:

- BDT against $e^+e^- \to q\bar{q}$ background;
- model misreco'd signal events from simulation;
- signal from 3D fit of ΔE-M_{bc}-BDT output.

$$\mathcal{B}(B^\pm \to \eta' K^\pm) = [63.4^{+3.4}_{-3.3}(\text{stat}) \pm 3.4(\text{syst})] \times 10^{-6}$$

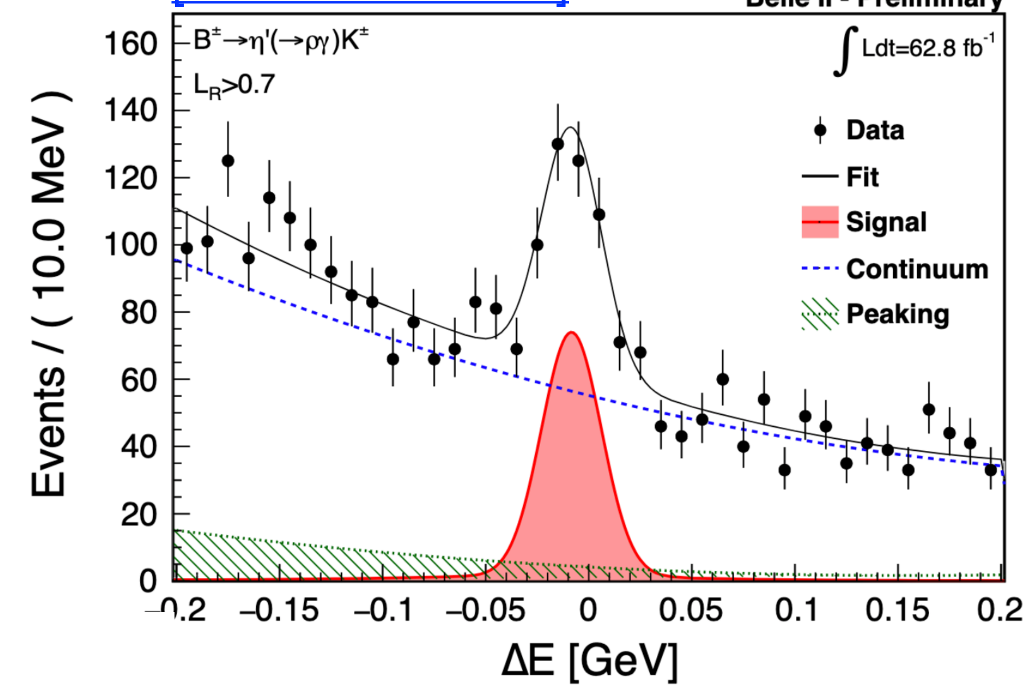
$$\mathcal{B}(B^0 \to \eta' K^0) = [59.9^{+5.8}_{-5.5}(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-6}$$

$B^0 \to J/\Psi K_L^0$: alternative approach to measure sin(2β), unique to Belle II. Key in K_L^0 reco, done with MVA algorithms. Signal from ΔE fit.

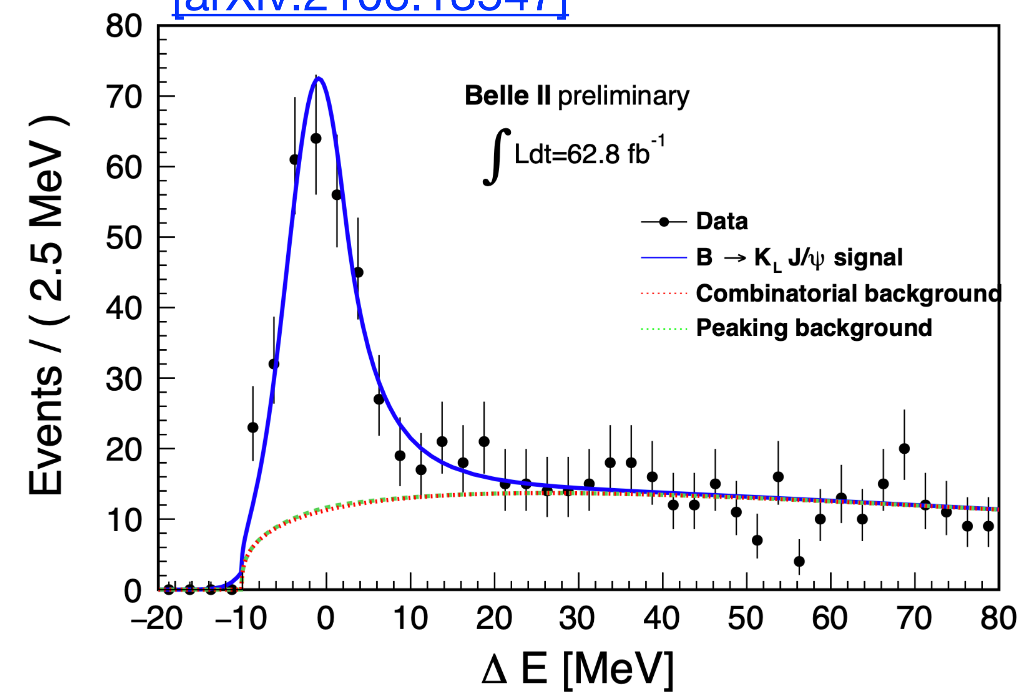
$$N(B^0 \to J/\Psi_{\to\mu^+\mu^-} K_L^0) = 267 \pm 21(\text{stat}) \pm 28(\text{peak})$$

$$N(B^0 \to J/\Psi_{\to e^+e^-} K_L^0) = 226 \pm 20(\text{stat}) \pm 31(\text{peak})$$

[arXiv:2104.06224]



[arXiv:2106.13547]



First steps in channels where Belle II will be competitive.

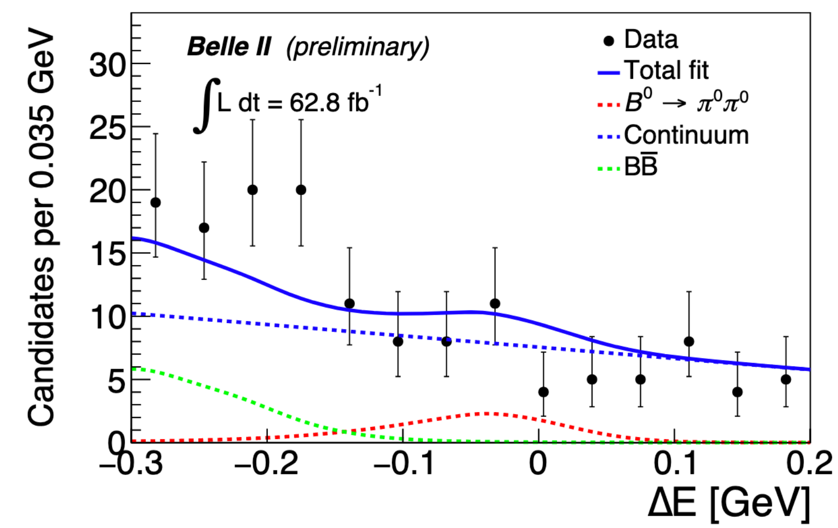
Towards α

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

$B^0 \to \pi^0\pi^0$: very challenging because four ɣ's.
Train BDT to suppress background photons.
Then 3D fit of ΔE-M_{bc}-continuum suppression BDT.
Unique Belle II reach.

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

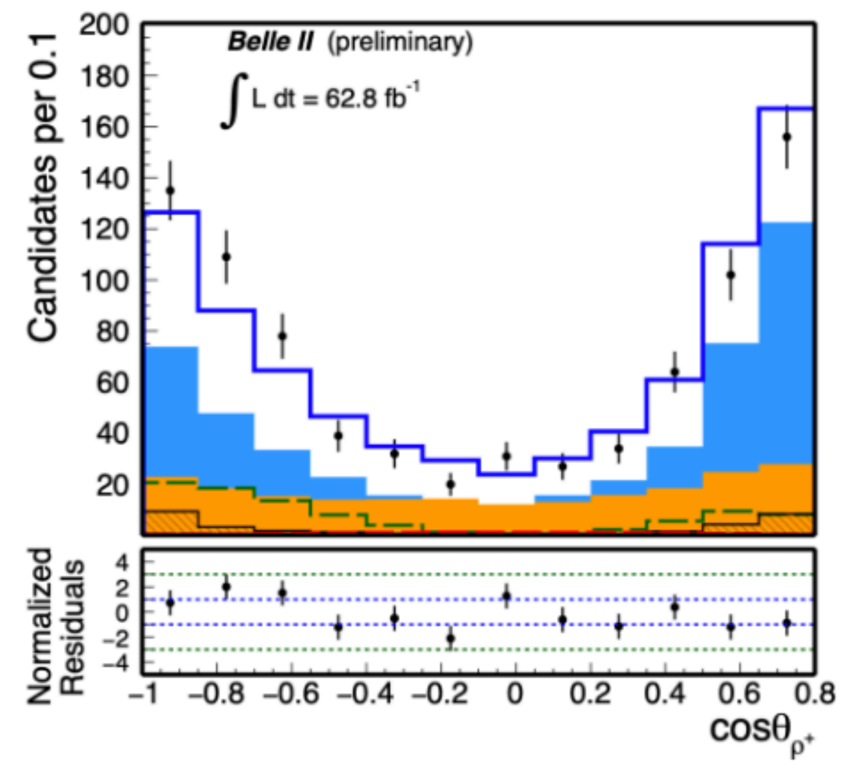
[arXiv:2107.02373]



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

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

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



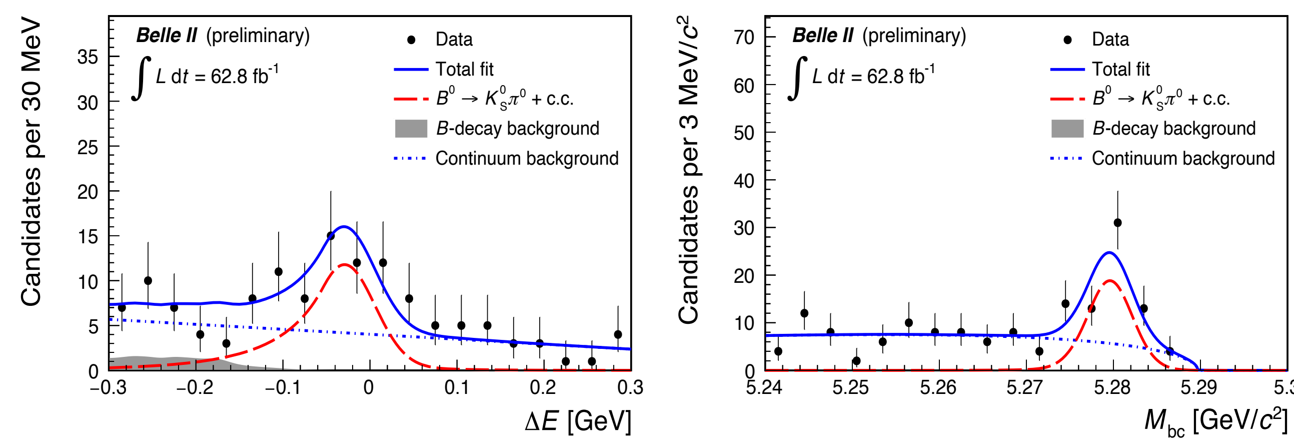
20% precision improvement wrt Belle on the same lumi!
Wrt BaBar's best (scaled): better on BF, same on f_L.

On track to measure the CKM angle *α* at Belle II.

Exploiting isospin relations

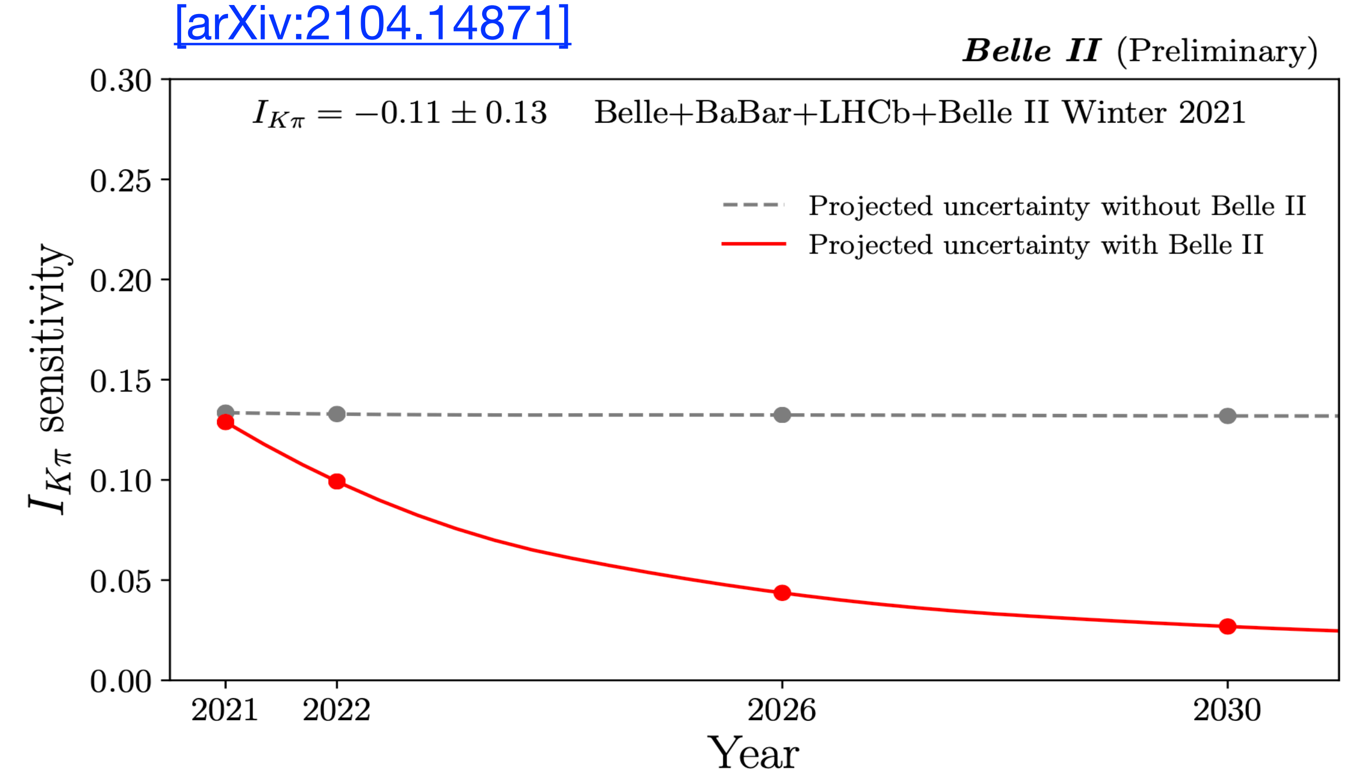
$$I_{K\pi} = A_{\rm CP}^{K^+\pi^-} + A_{\rm CP}^{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{\rm CP}^{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{\rm CP}^{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

Surprising differeces btw $A_{\rm CP}^{K^+\pi^-}$ and $A_{\rm CP}^{K^+\pi^0}$.
Accommodate all $B\to K\pi$ results in a reliable SU(3) “sum rule”: stringent SM test.



$B^0 \to K^0\pi^0$: simultaneous ΔE-M_{bc} fit of the two flavor-specific samples to determine BF and time-integrated A_{CP}.
Need flavor-tagging.

[arXiv:2104.14871]



$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst})$$

$$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$$

Belle II input fundamental to reduce uncertainty on Kπ-isospin sum-rule.

Standard Model references

Preparing for γ

$B^- \to D^{(*)0}K^-$ best probes of γ through interference btw $b \to c\bar{u}s$ and $b \to u\bar{c}s$ (golden channel with $D^0 \to K^0_S\pi^+\pi^-$).

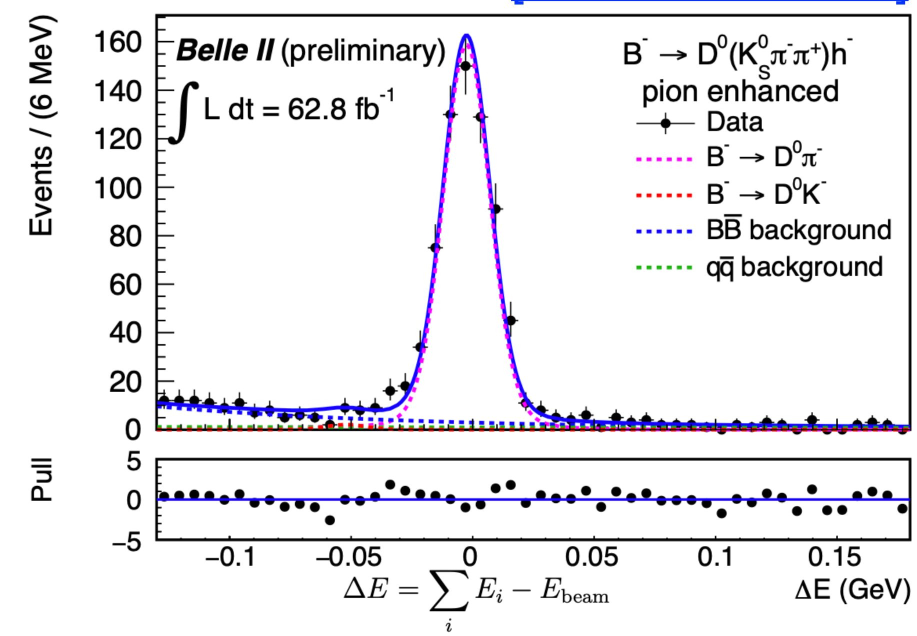
Ratios between decays suppress systematic uncertainties. Simultaneous fit of K/π-enriched samples.

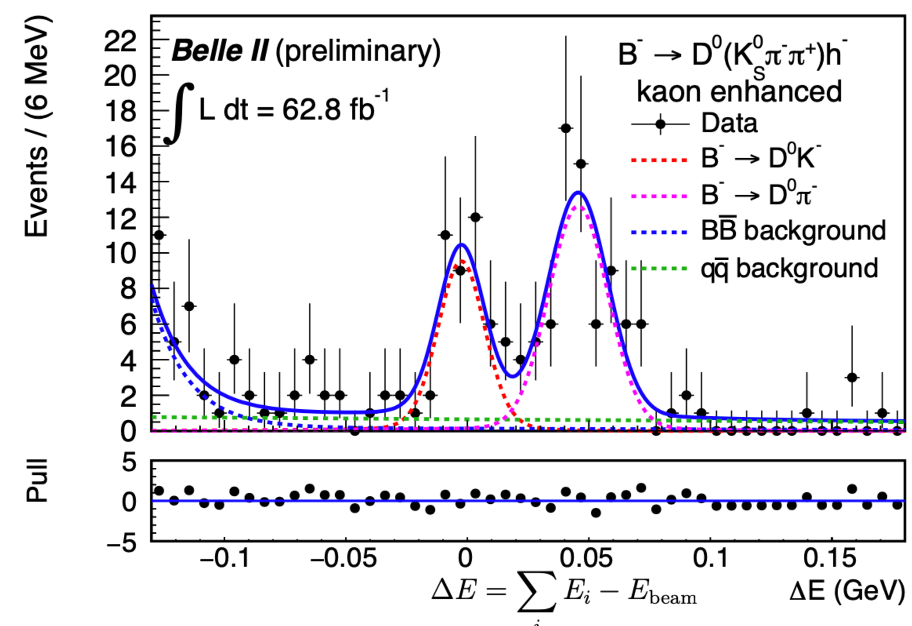
$$R^{(*)0} = \frac{\Gamma\left(B^- \to D^{(*)0}K^-\right)}{\Gamma\left(B^- \to D^{(*)0}\pi^-\right)} \qquad R^{(*)+} = \frac{\Gamma\left(\overline{B}^0 \to D^{(*)+}K^-\right)}{\Gamma\left(\overline{B}^0 \to D^{(*)+}\pi^-\right)}$$

	$B^- \to D^0(K^-\pi^+)h^-$	$B^- \to D^0(K^0_S\pi^+\pi^-)h^-$	$\bar{B}^0 \to D^+h^-$
Belle II $R^{+/0}$ ($\times 10^{-2}$)	$7.66 \pm 0.55\ ^{+0.11}_{-0.08}$	$6.32 \pm 0.81\ ^{+0.09}_{-0.11}$	$9.22 \pm 0.58 \pm 0.09$
LHCb $R^{+/0}$ ($\times 10^{-2}$)	$7.77 \pm 0.04 \pm 0.07$ [24]	$7.77 \pm 0.04 \pm 0.07$ [24]	$8.22 \pm 0.11 \pm 0.25$ [25]

Parallel re-optimization of measurement on Belle data is ongoing.

[arXiv:2104.03628]





Belle + Belle II combined measurement of γ soon.

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

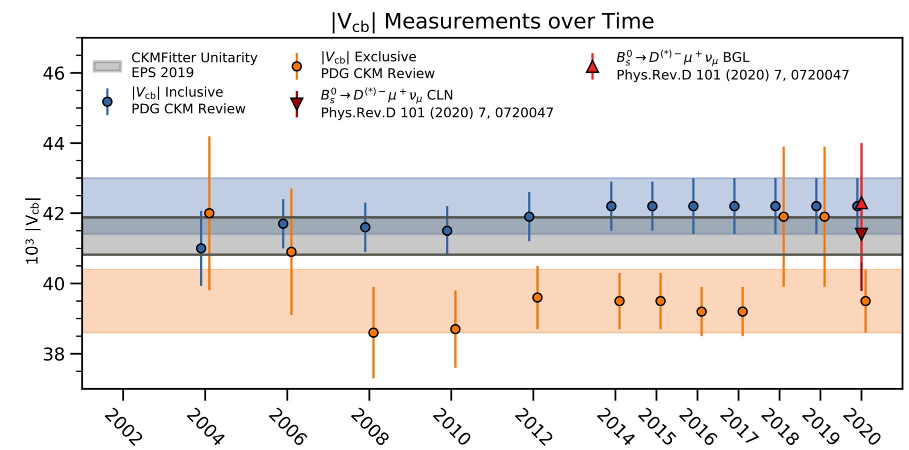
Semi-leptonic B decays free of BSM contributions → key roles for $|V_{cb}|$ and $|V_{ub}|$.

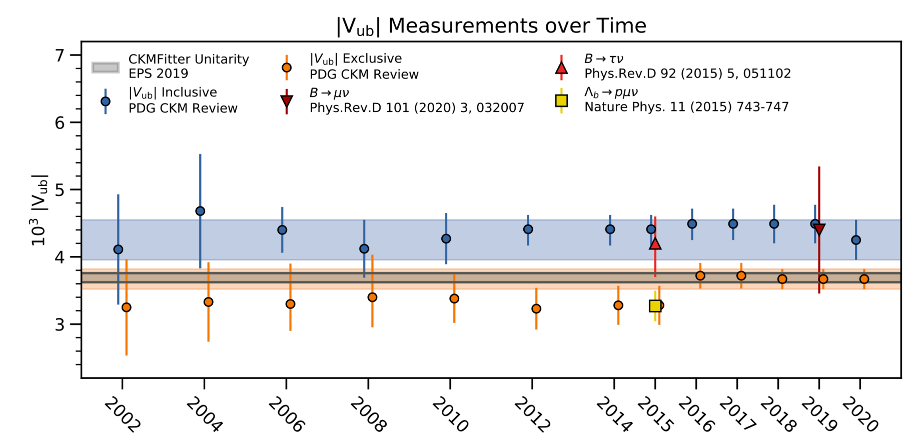
Inclusive and exclusive determinations offer independent and complementary results
⇒ long-standing discrepancies observed.

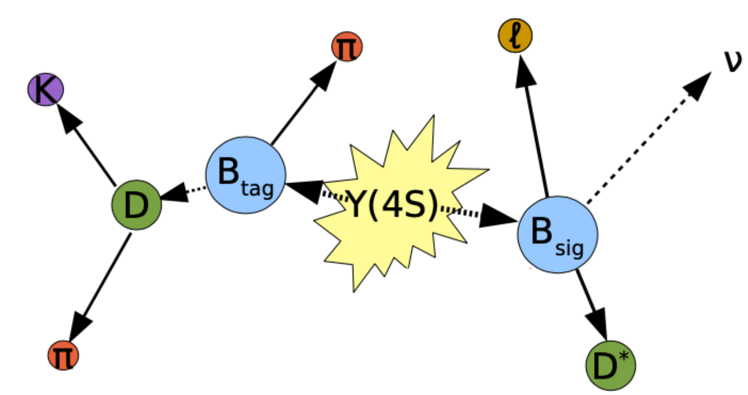
- $|V_{cb}|$ from $B \to X_c l\nu,\ B \to D^{(*)} l\nu \quad (l = e, \mu)$
- $|V_{cb}|$ from $B \to X_u l\nu,\ B \to \pi(\rho, \eta) l\nu \quad (l = e, \mu)$

exploiting Belle II unique features:

- partially reconstructed final states (ν);
- use missing energy as observable;
- reconstruction of tag-side to increase purity.

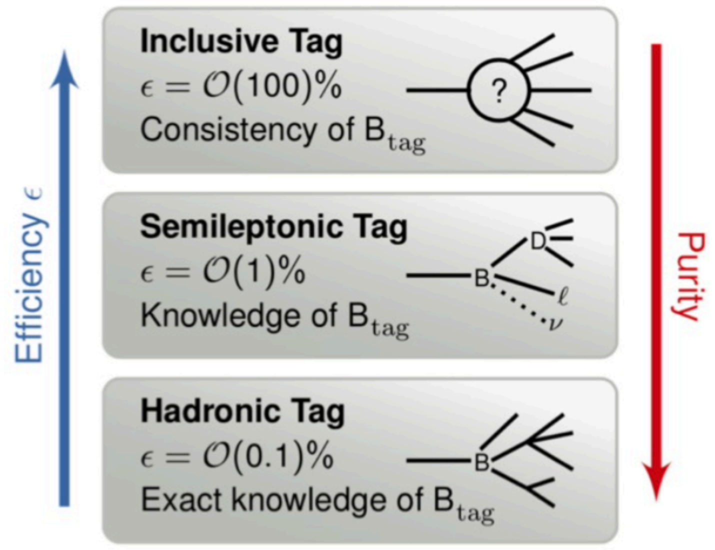


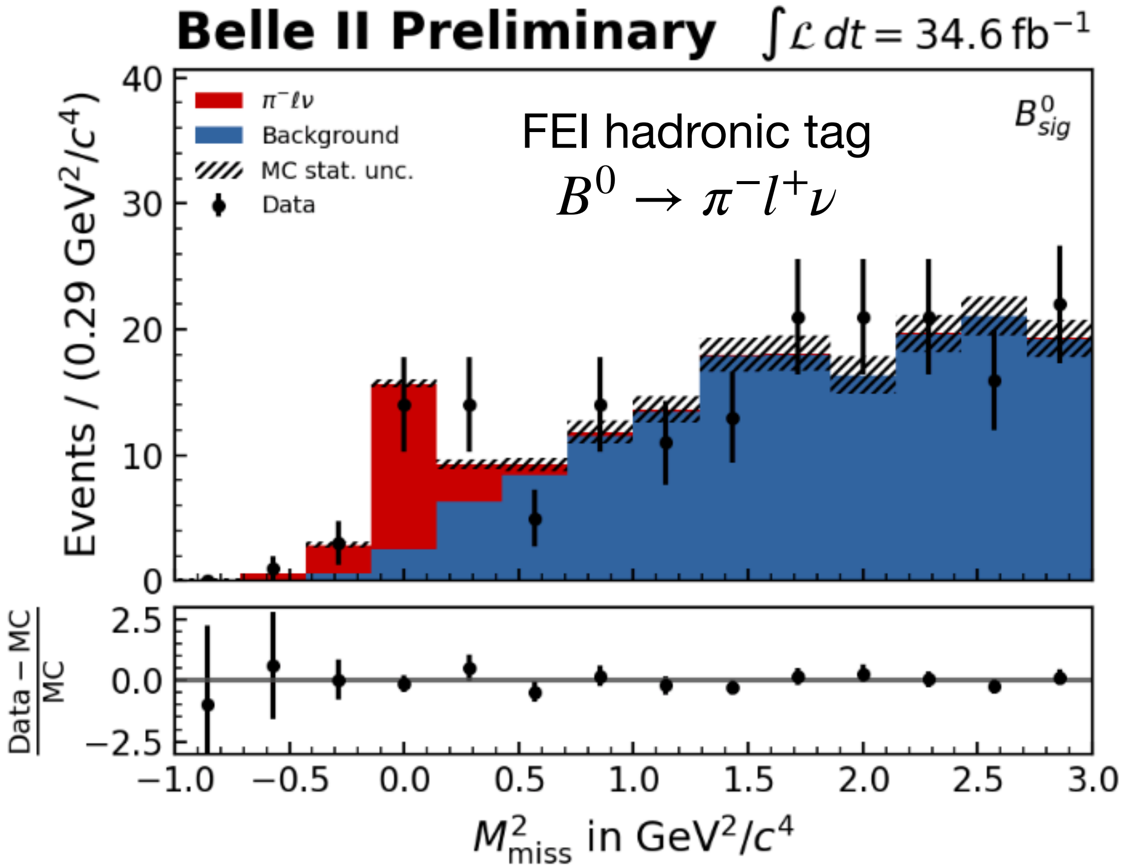




Inclusive-tagging

Belle II **F**ull **E**vent **I**nterpretation (**FEI**) exploits MVA in tagged approach to reconstruct $O(10^3)$ different tag-side decays.
Key is to have a reliable data-driven calibration.
Measured by fitting the M^2_{miss} distribution.





$$\mathscr{B}(B^0 \to \pi^- l^+ \nu_l) = [1.54 \pm 0.43(\text{stat}) \pm 0.07(\text{syst})] \times 10^{-4}$$

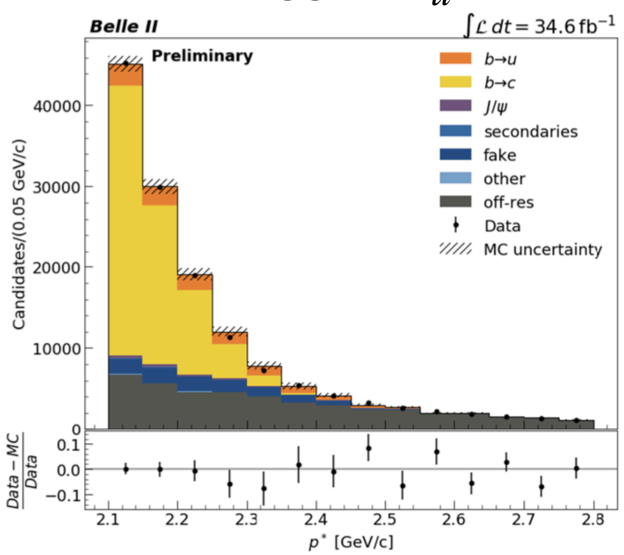
[arXiv:2008.08819]

Combine Belle II features and new analysis tools to improve $|V_{ub}|$ and $|V_{cb}|$ precision.

Inclusive and exclusive $b \to (c, u)l\nu$

Exploit large variety of different analyses to understand the remaining discrepancies.

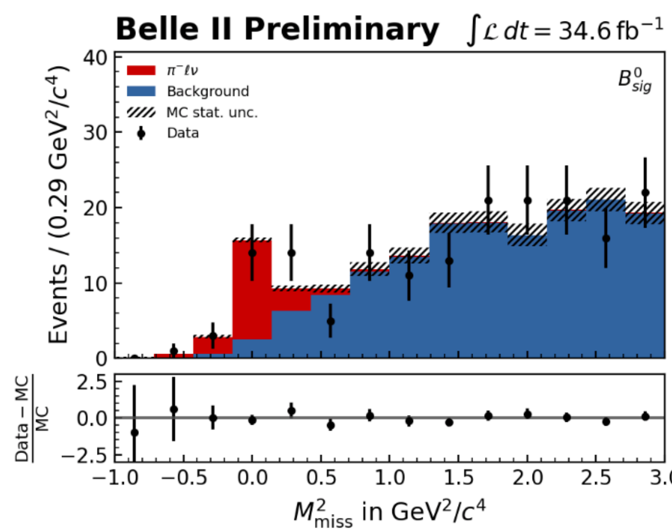
Untagged $X_u l\nu$



3σ significance for $b \to u$

[arXiv:2103.02629]

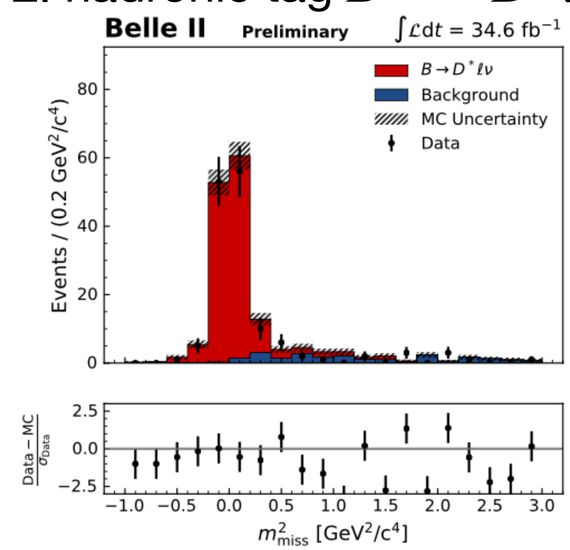
FEI hadronic tag $B^0 \to \pi^- l^+ \nu$



$\mathscr{B}(B^0 \to \pi^- l^+ \nu_l) = [1.54 \pm 0.43_{\text{stat}} \pm 0.07_{\text{syst}}] \times 10^{-4}$

[arXiv:2008.08819]

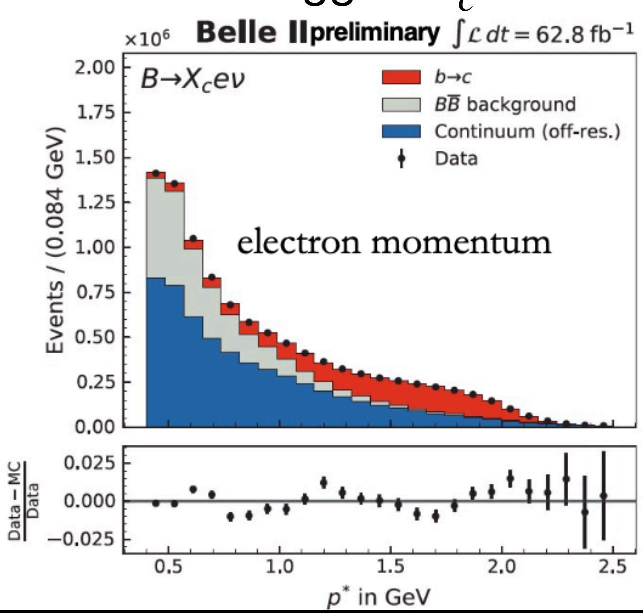
FEI hadronic tag $B^0 \to D^* l\nu$



$\mathscr{B}(\overline{B}^0 \to D^{*+} l^- \overline{\nu}_l) = [4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s}]\,\%$

[arXiv:2008.10299]

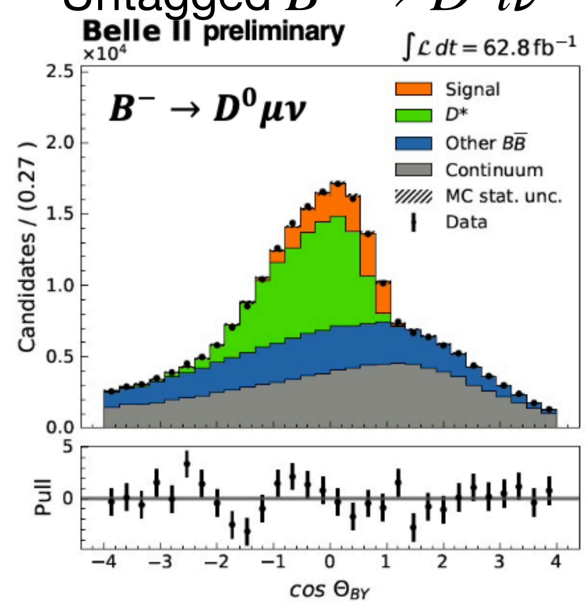
Untagged $X_c l\nu$



$\mathscr{B}(B \to X_c l\nu) = [9.75 \pm 0.03_{\text{stat}} \pm 0.47_{\text{syst}}]\,\%$

EPS 2021, to be submitted

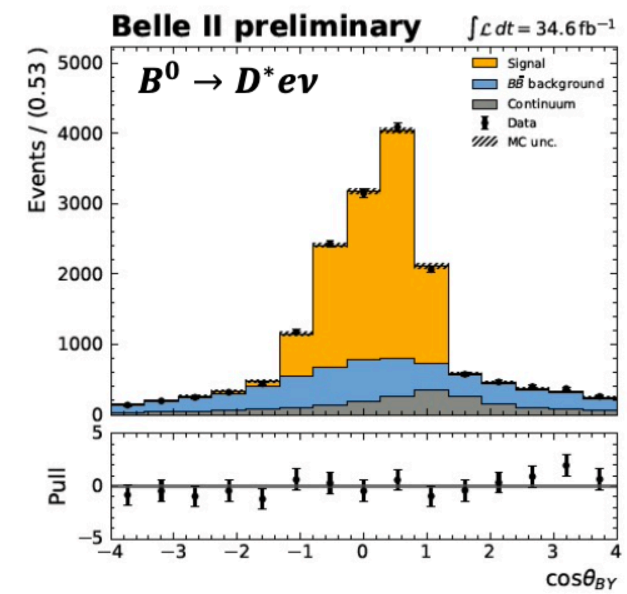
Untagged $B^0 \to D^0 l\nu$



$\mathscr{B}(\overline{B}^- \to D^0 l^- \overline{\nu}_l) = [2.293 \pm 0.41_{\text{stat}} \pm 0.053_{\text{syst}} \pm 0.084_{\pi_s}]\,\%$

EPS 2021, to be submitted

Untagged $B^0 \to D^* l\nu$



$\mathscr{B}(\overline{B}^0 \to D^{*+} l^- \overline{\nu}_l) = [4.60 \pm 0.05_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.45_{\pi_s}]\,\%$

[arXiv:2008.07198]

Summary

Belle II aims at probing uncharted non-SM territory and improving the precision on flavor-physics parameters.

First competitive measurements, even with reduced data sample.

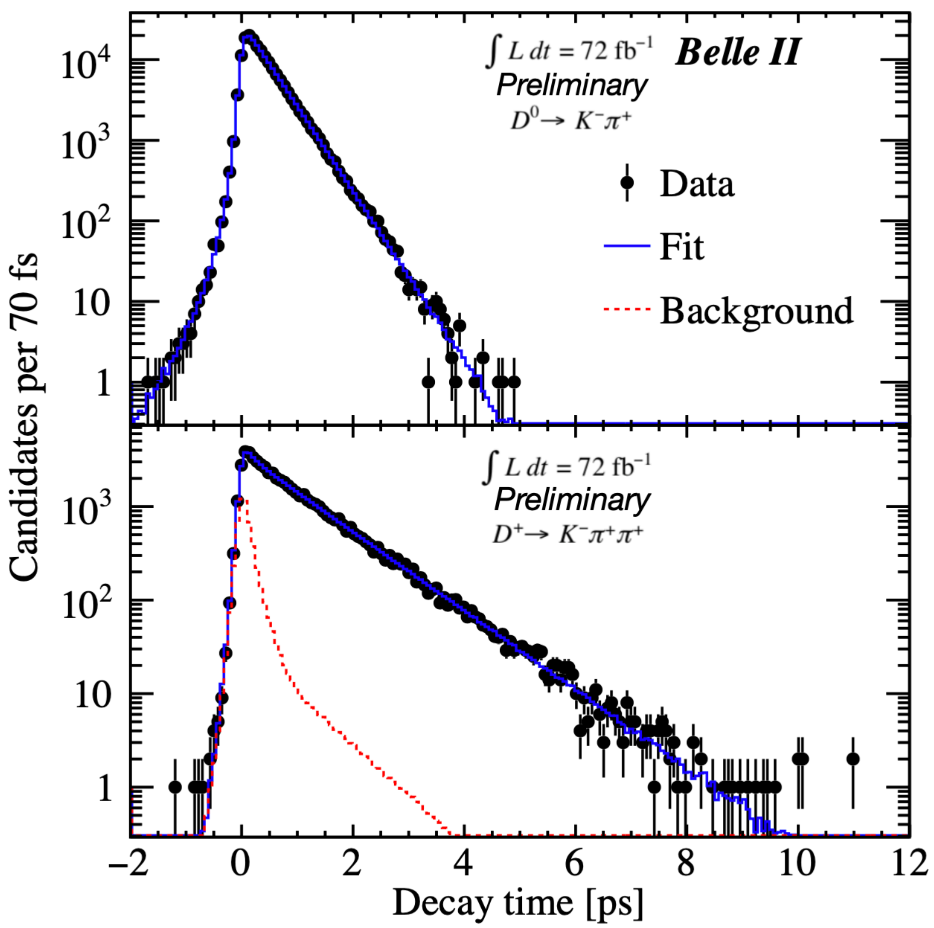
- D lifetimes [arXiv:2108.03216];
- $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ [arXiv:2104.12624];

Plethora of preliminary results shown, good understanding of all detector aspects.

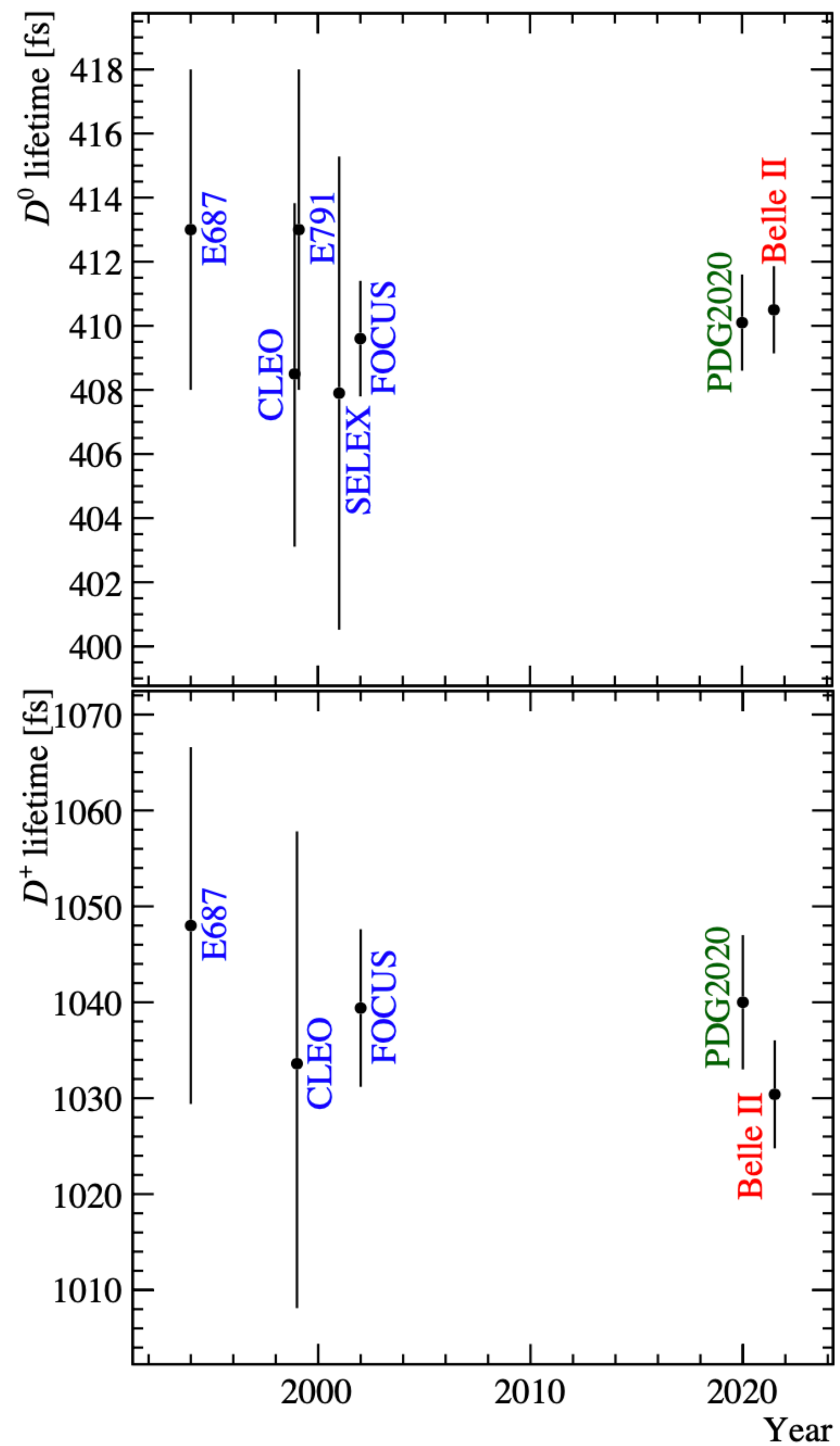
We are back.

backup

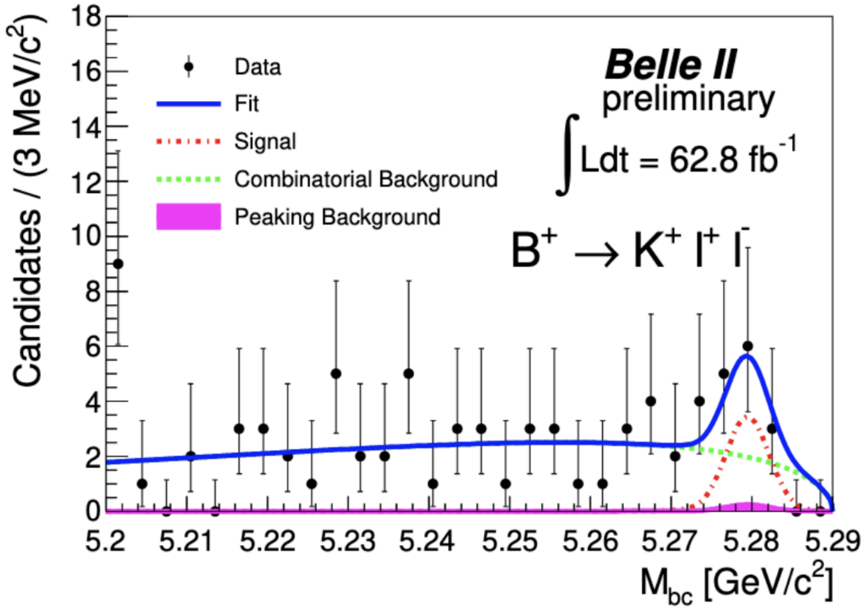
D^0 and D^+ lifetime measurements

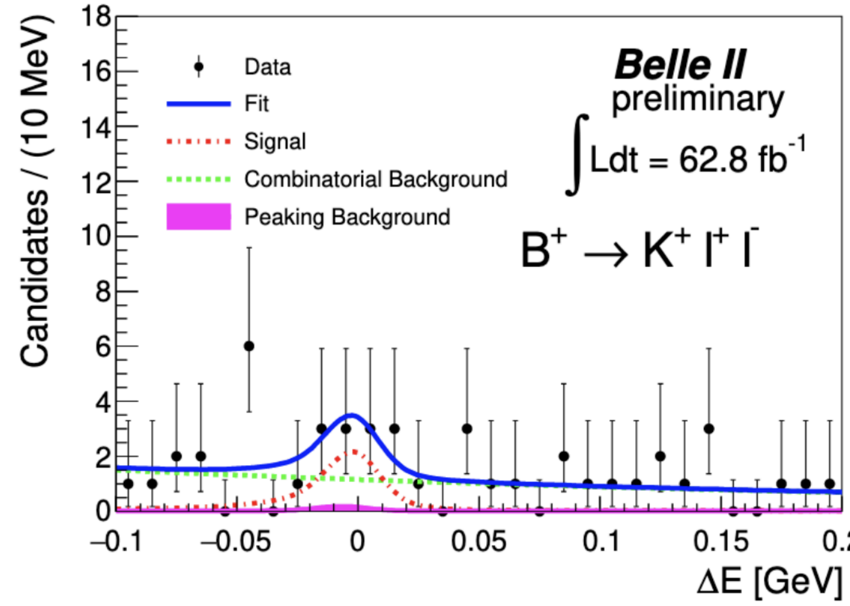


Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Statistical	1.1	4.7
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total systematic	0.8	3.1

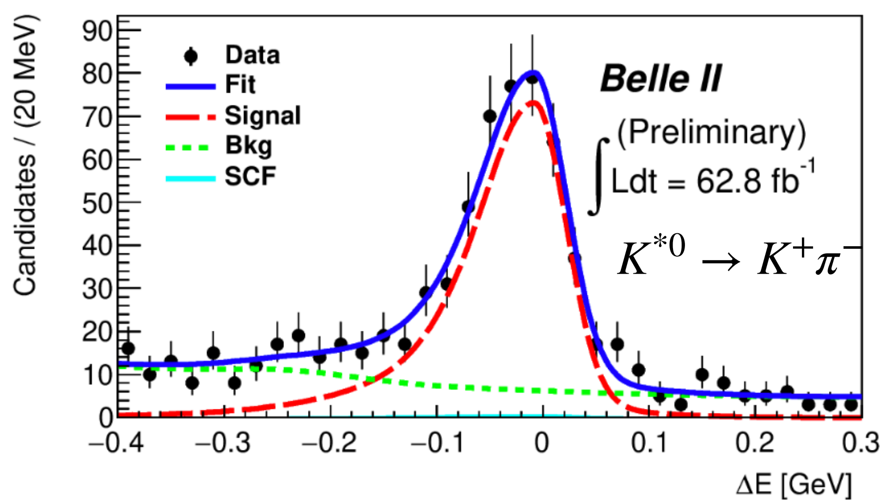


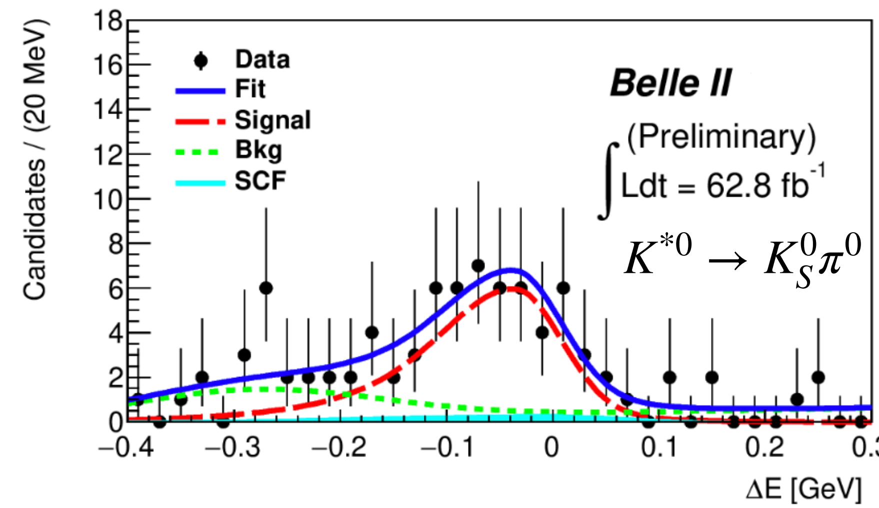
More $b \to s(\gamma)$ studies



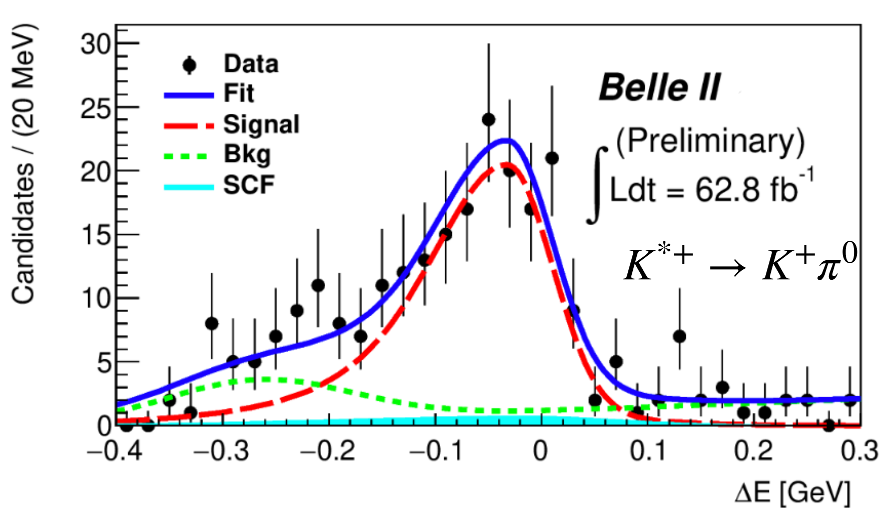


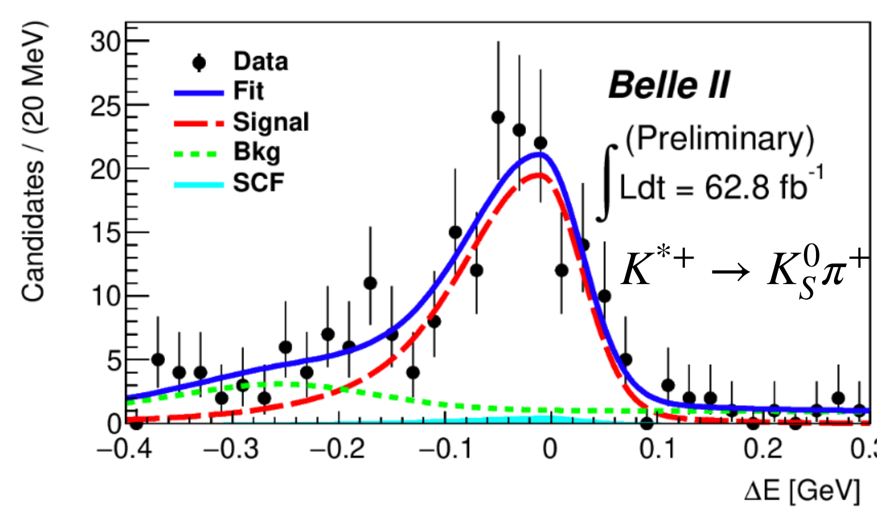
$B0 \to K^{*0}\gamma$



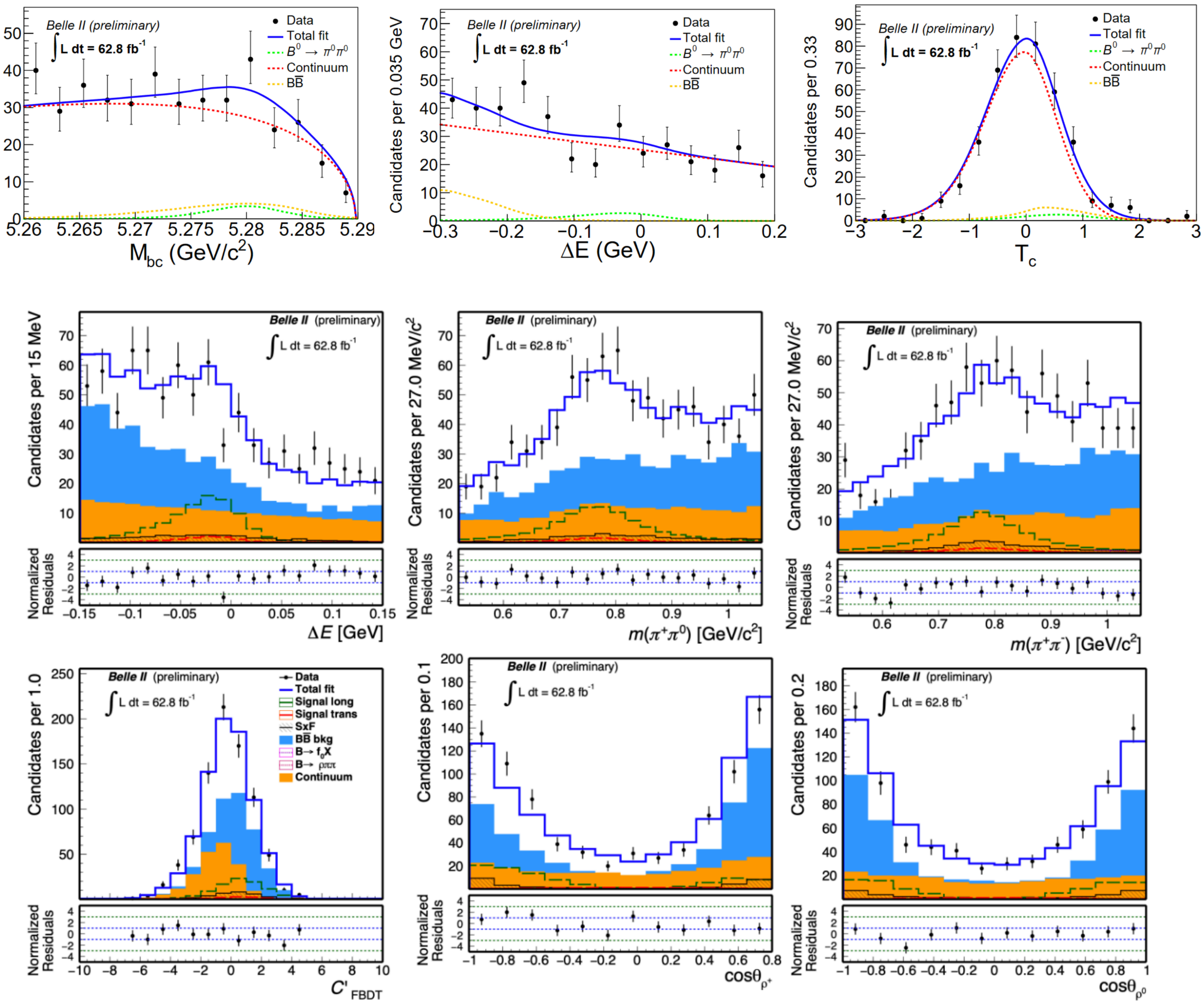


$B+ \to K^{*+}\gamma$

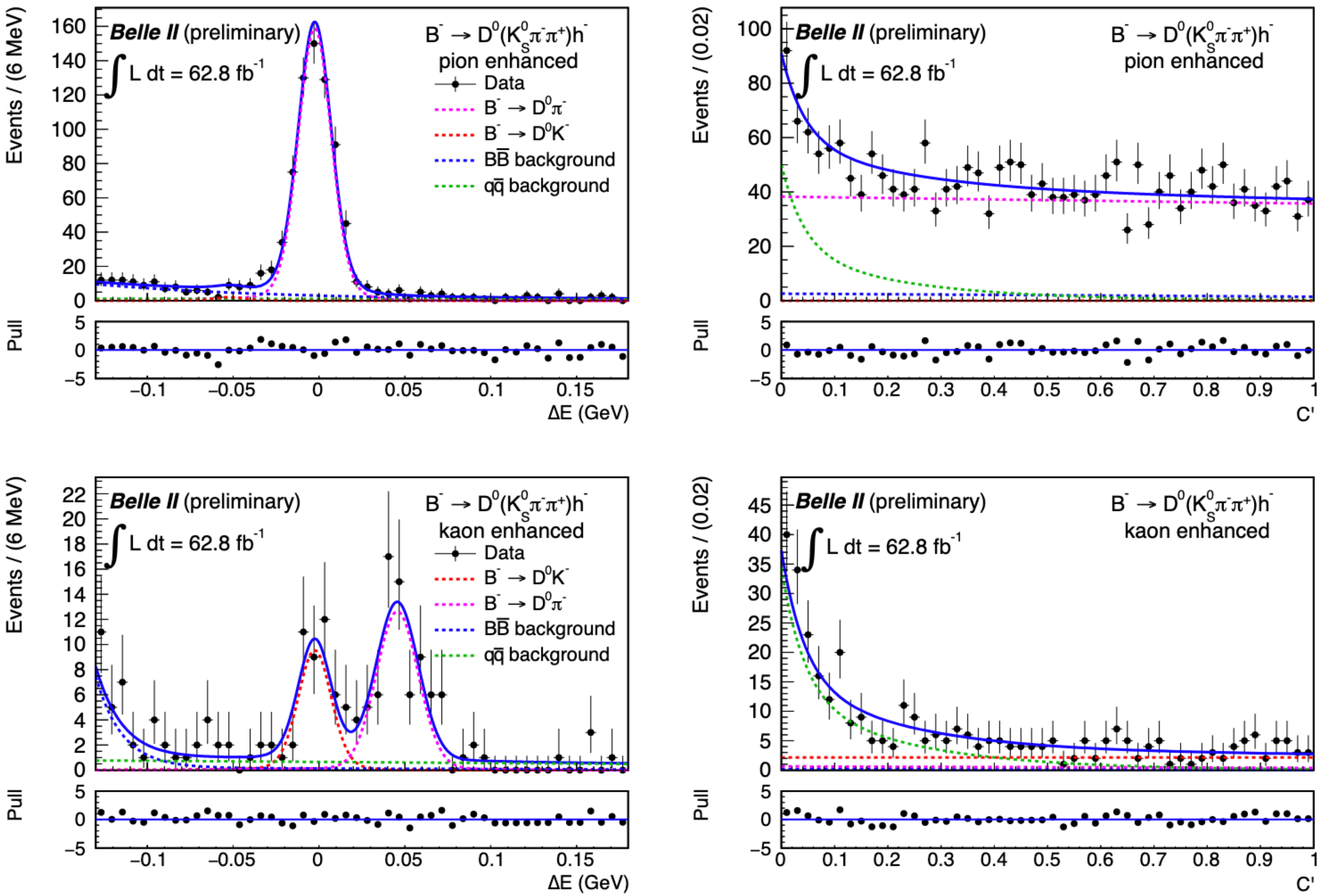




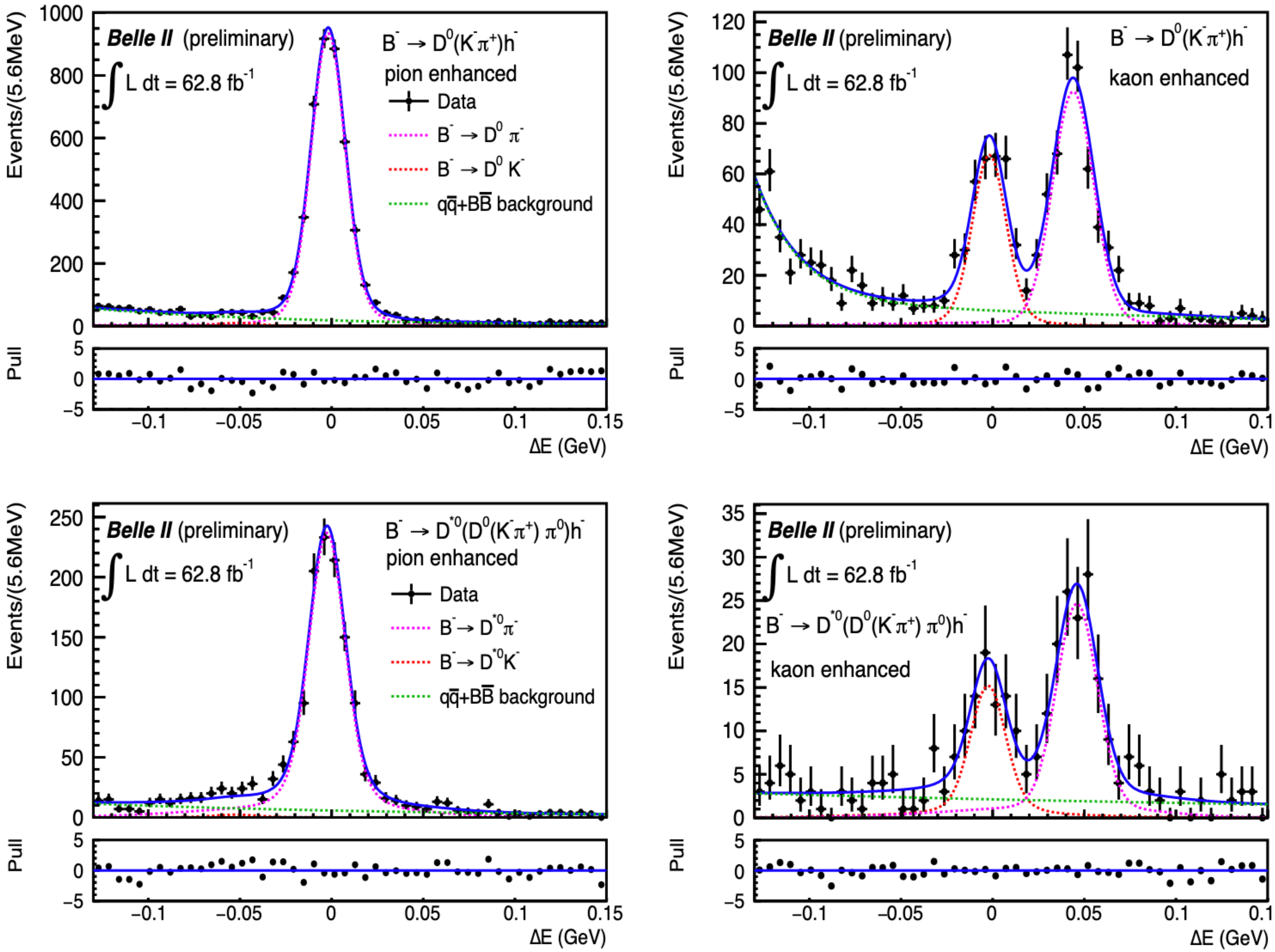
$B^0 \to \pi^0\pi^0, B^+ \to \rho^+\rho^0$



$$B^- \rightarrow D^0(\rightarrow K_S^0\pi^-\pi^+)h^-$$



$B^- \to D^{(*)0}h^-;\quad (D^0 \to K^-\pi^+)$



$\overline{B}^0 \to D^{(*)+} h^-$