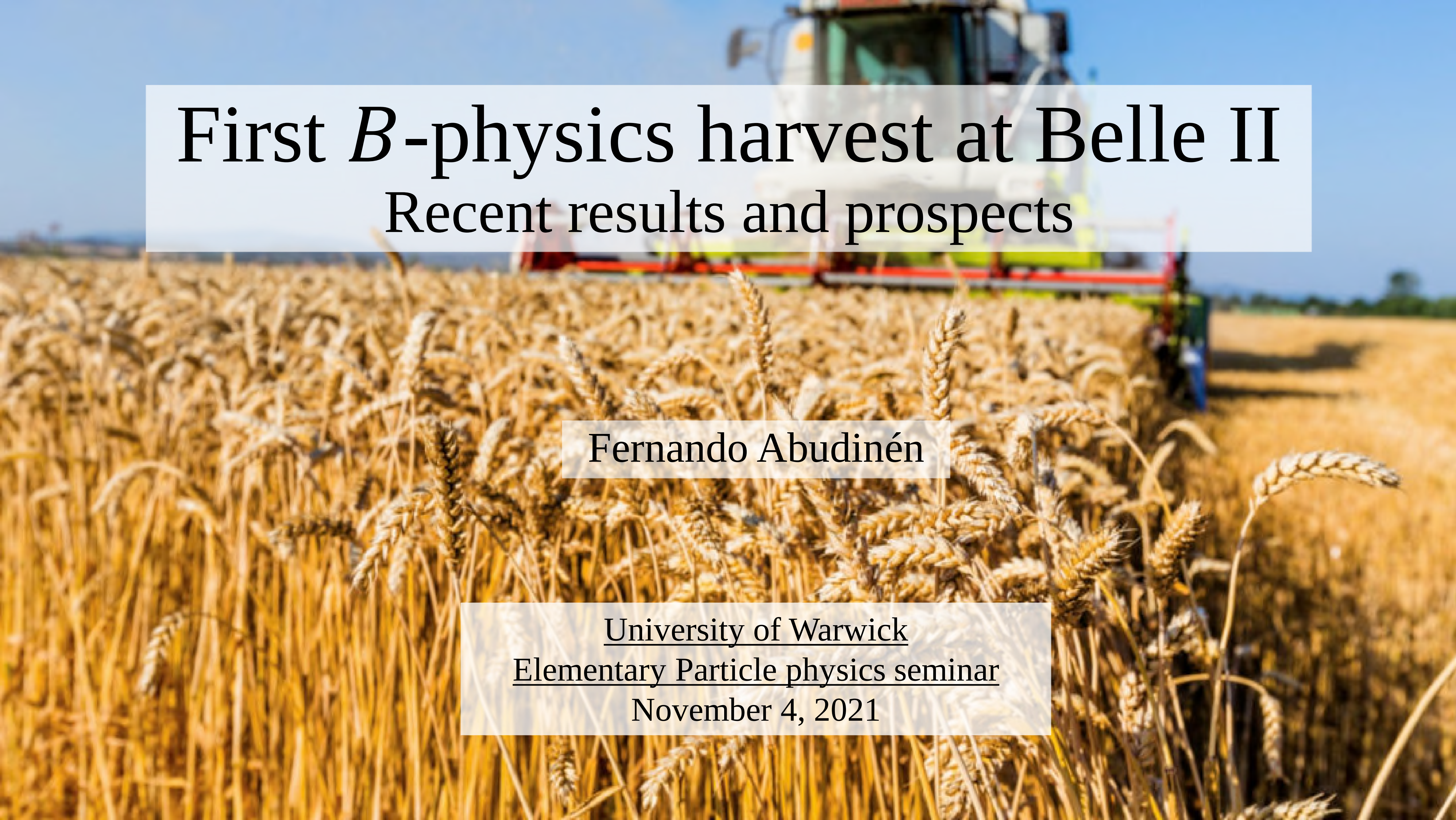


First B-physics harvest at Belle II

Recent results and prospects

Fernando Abudinén

University of Warwick
Elementary Particle physics seminar
November 4, 2021

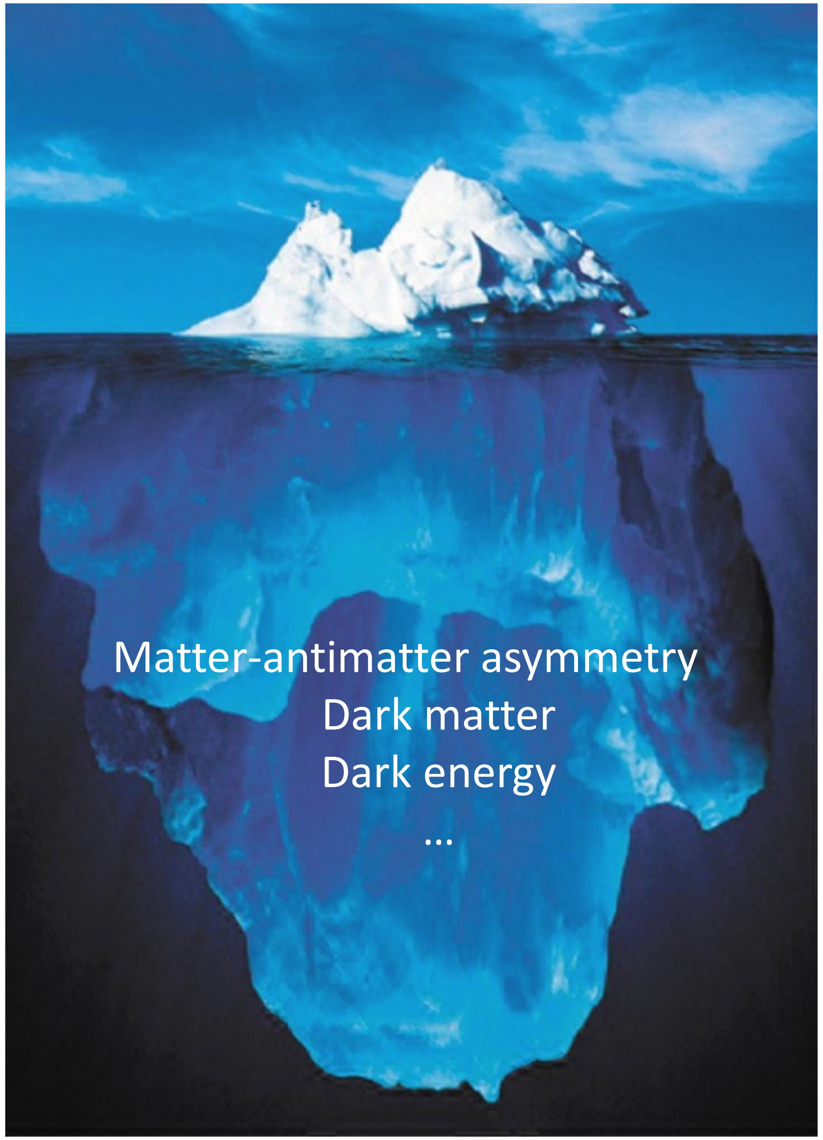
The Standard Model

- Describes three out of the four fundamental forces in nature predicting accurately thousands of measurements over many orders of magnitude in energy.

⇒ Most precisely experimentally probed theory ever but fails at providing a full-picture explanation for many cosmological observations and leaves several intrinsic questions open such as the particle hierarchy, etc.

⇒ Might be an effective theory of a universal one.

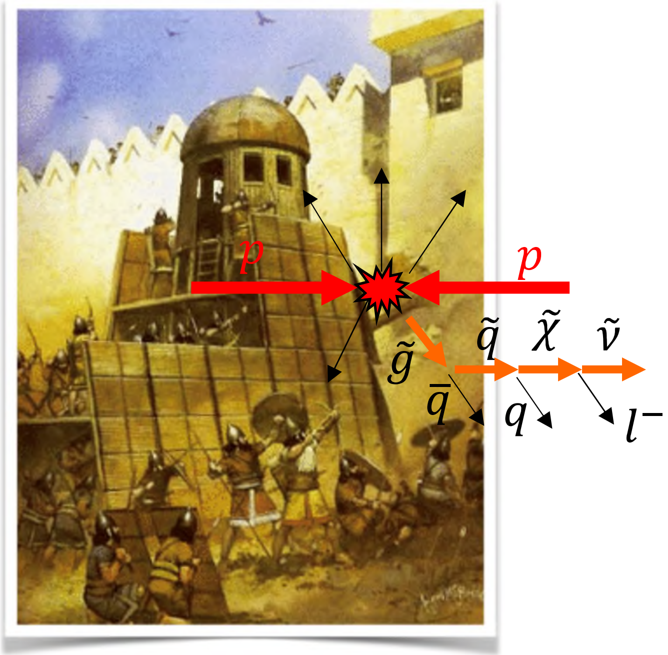
⇒ Holy grail of today's experimental particle physics is to find signatures of dynamics beyond the Standard Model.



Two ways out

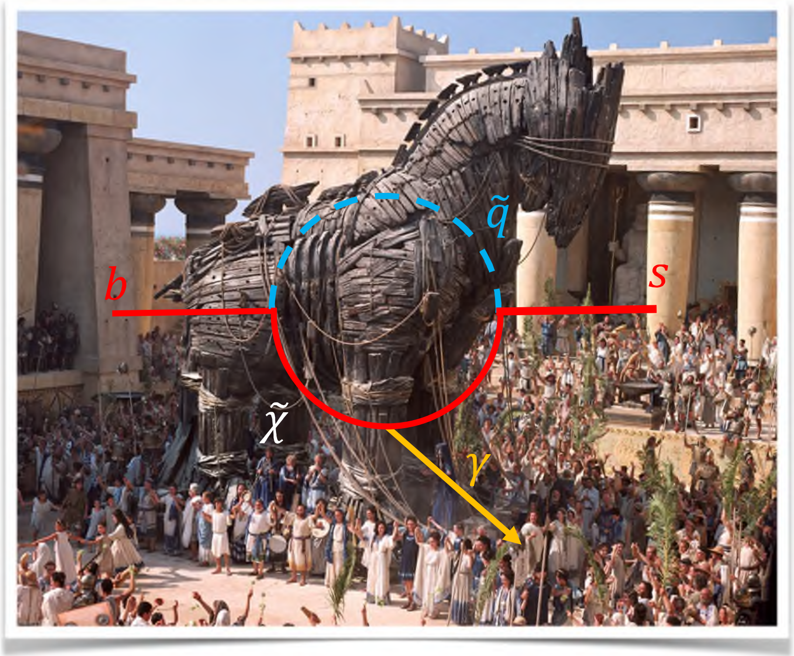
Energy frontier

Direct high-energy production of non-SM particles.



Intensity frontier

Indirect quantum probing of massive non-SM particles in known low-energy processes.



⇒ Currently no evidence for non-SM physics at the high-energy frontier

⇒ Intensity frontier offers indirect sensitivity to very high energy scales

⇒ Weak interactions of quarks offer rich opportunities for intensity frontier

Quark-flavor dynamics

- Described in the SM by CKM quark-flavor mixing matrix

$\Rightarrow$ Parametrized by 3 real and 1 imaginary phase

$\Rightarrow$ Im. phase: source of all charge-parity violation effects

$\Rightarrow$ $\mathcal{O}(100)$ accessible processes that are potential for probing non-SM dynamics

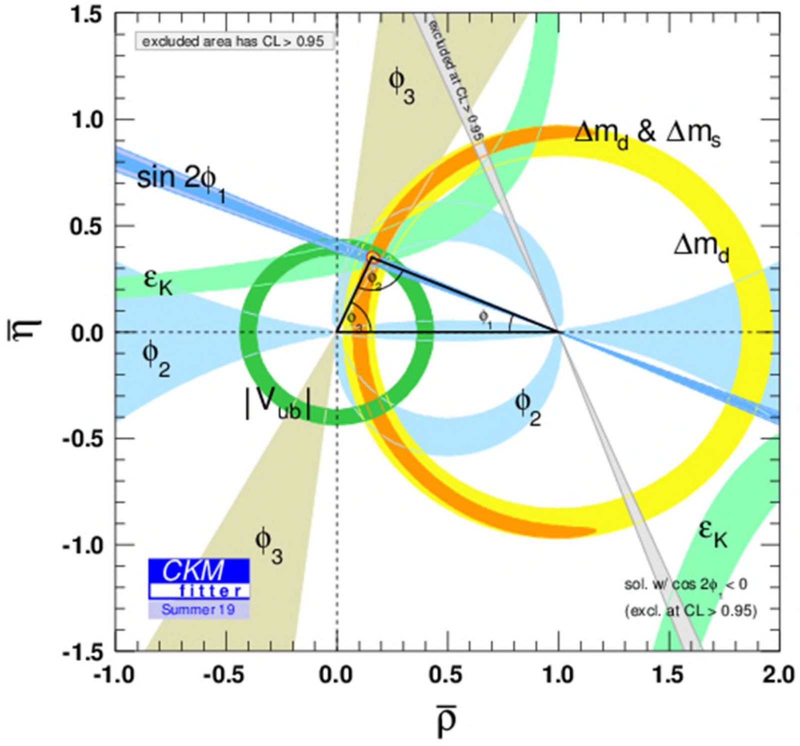
$\Rightarrow$ Plenty of opportunities to probe the SM in B dynamics

(Largest CP violation effects expected in B processes)

$\Rightarrow$ CKM description is successful, but still room for non-SM effects within current precision

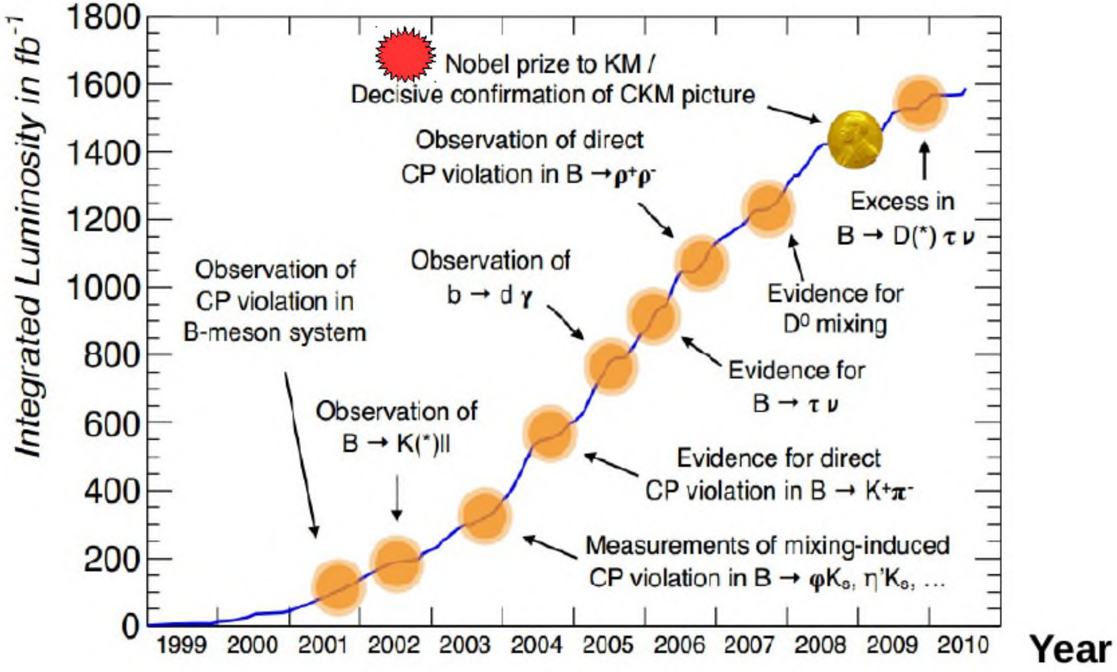
$\Rightarrow$ Motivates further precision measurements at intensity frontier

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{Weak eigenstates}} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{Mass eigenstates}}$$



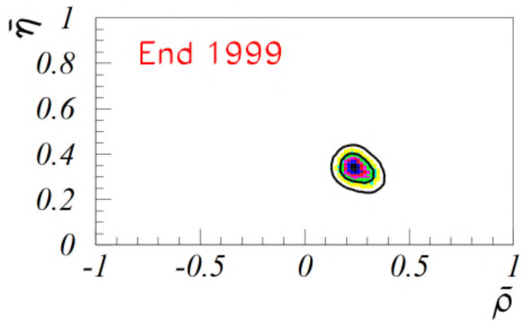
Progress comes with data

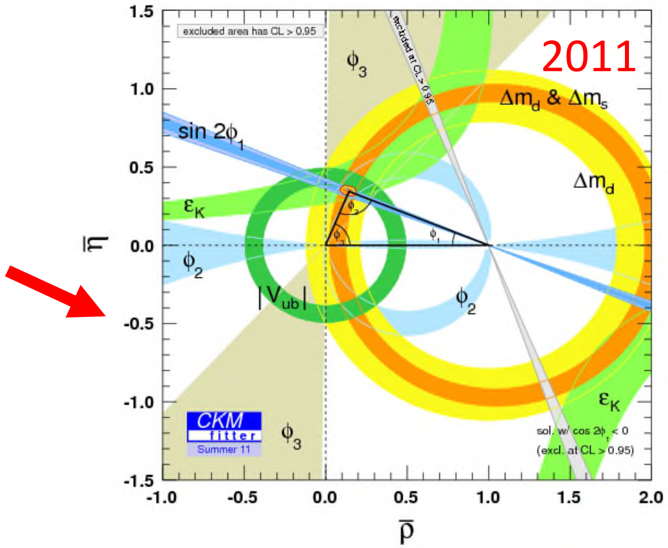
- The BaBar and Belle experiments collected $\sim 1.5\ \text{ab}^{-1}$ at the first generation B factories (PEP-II and KEKB)
- Impressive number of discoveries and observations of rare decays (not only in B physics, but also charm, τ, exotics particles and dark sector)



- Continuing along this path (and to compete with LHCb on a radically different experimental setup) needs major leap in luminosity

$\Rightarrow$ Strong motivation to upgrade to Belle II and SuperKEKB



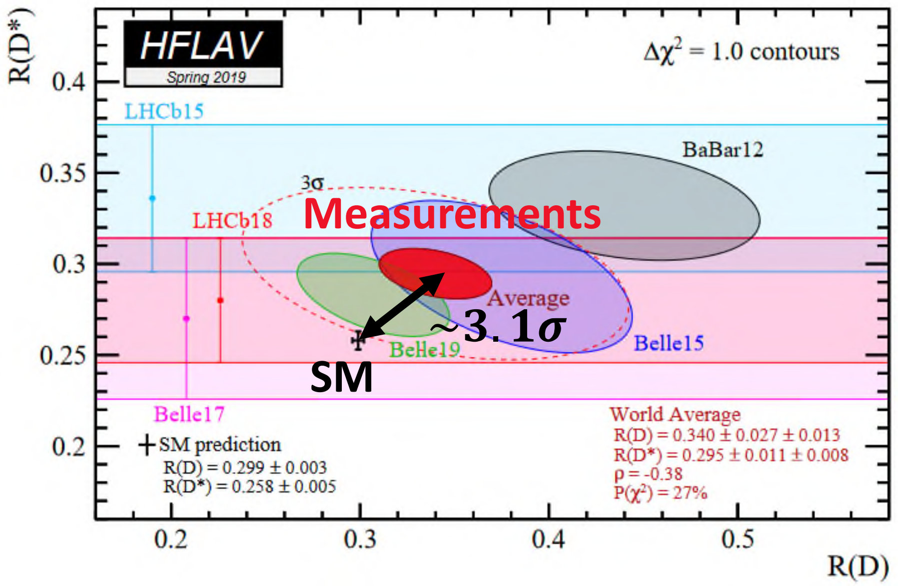


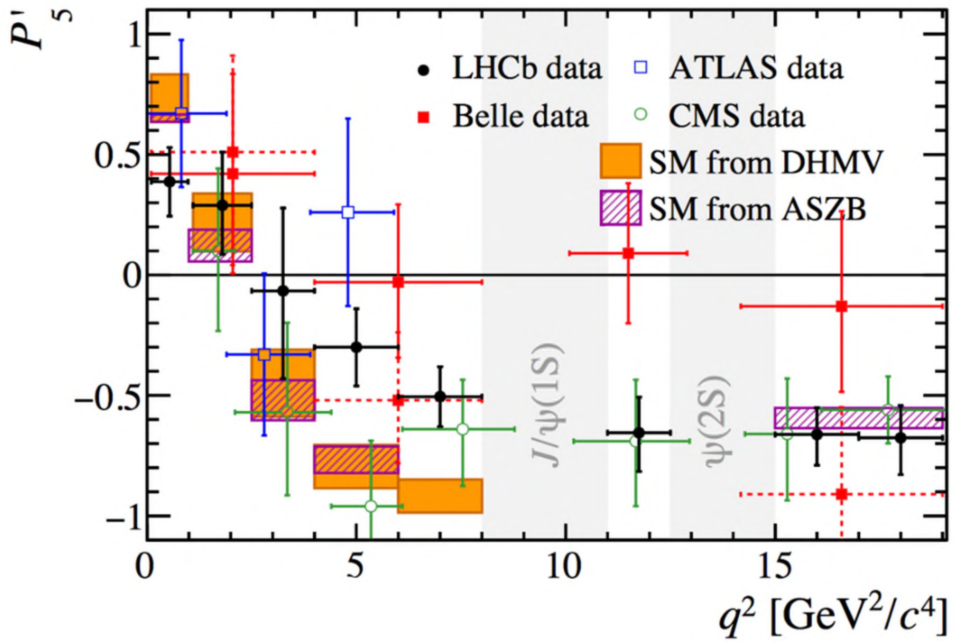
Emerging flavour anomalies

Some cracks in the big picture have been developing in the last few years:

- $B \rightarrow D^{(*)}\tau\,\nu$ - $R(D)$ and $R(D^*)$,
- Deviations from Lepton Flavor Universality, partial branching fractions, and angular distributions in $b \rightarrow s\,\ell^+\ell^-(\ell = e, \mu)$ transitions,
- $(g-2)_\mu$,
- $\Delta A_{\mathrm{FB}} = A^{\mu}_{\mathrm{FB}} - A^{e}_{\mathrm{FB}}$ in $b \rightarrow c\ell\nu$,
- …

$\Rightarrow$ These intriguing hints need independent confirmation, also on channels not yet observed (e.g. $b \rightarrow s\,\nu\bar{\nu}$, $b \rightarrow s\tau^+\tau^-$, …)

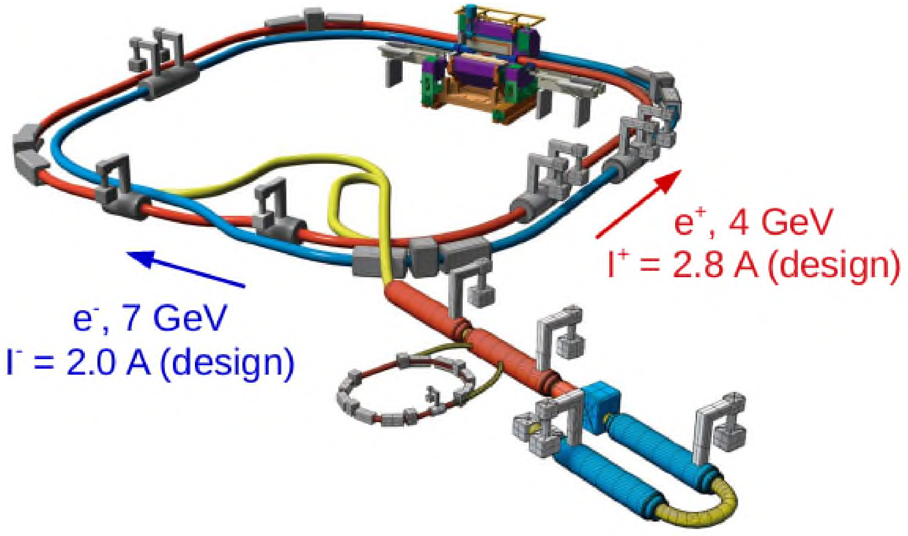




Outline

- The SuperKEKB collider
- The Belle II experiment
- Progress of data taking
- Experimental tools and performance
- Recent Belle II results and prospects
- Outlook

The SuperKEKB collider

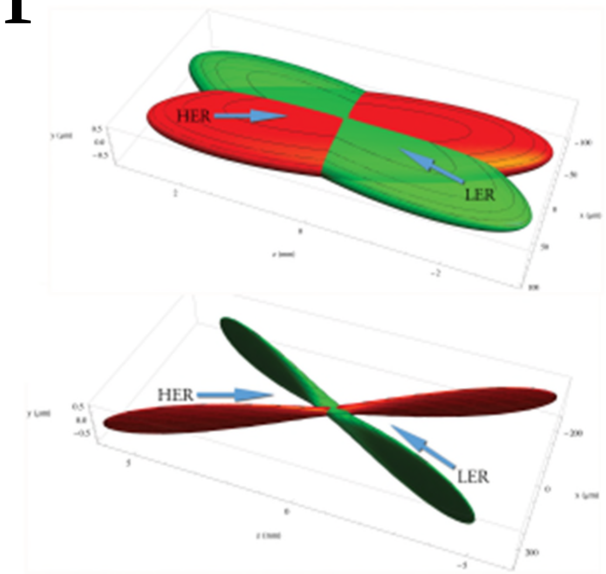


KEKB

↓

SuperKEKB

$$L \propto \frac{I_{e^+} \cdot I_{e^-}}{\sigma_x \cdot \sigma_y}$$



Design improvements over KEKB:

- $\times$ 20 by “nanobeam scheme”
- $\times$ 1.5 by increasing beam currents

Goals:

- Inst. lumi: $6 \cdot 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Integrated lumi: $50\ \mathrm{ab}^{-1}$

	$I_{e^+},\ I_{e^-}$	σ_y
Design:	2.8 A, 2.0 A	60 nm
Achieved:	0.7 A, 0.8 A	230 nm

Challenge: $\times \frac{2}{3}$ boost

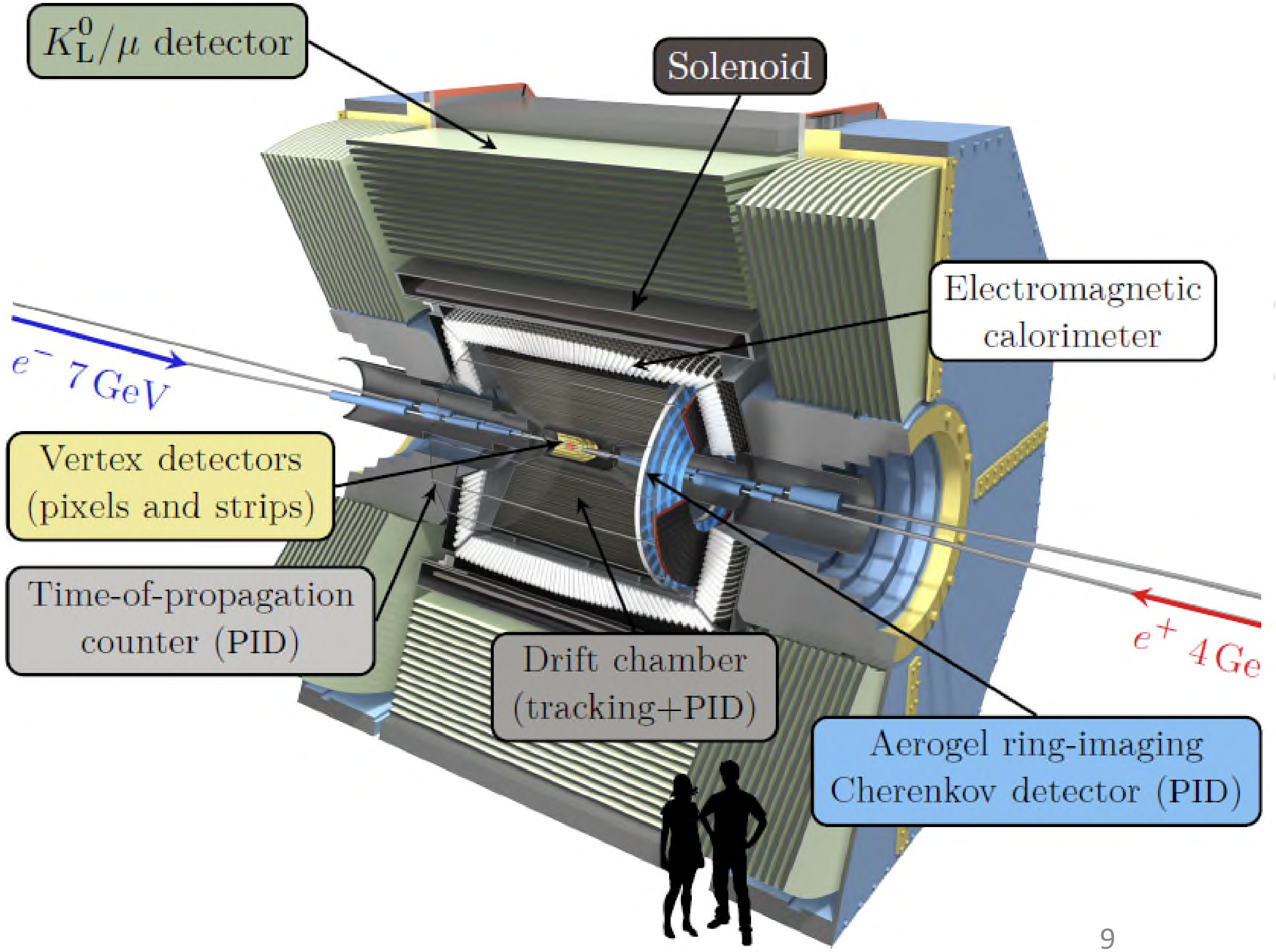
The Belle II detector

Looks like the Belle detector, but is practically brand new
(only structure, solenoid and calorimeter crystals are reutilized)

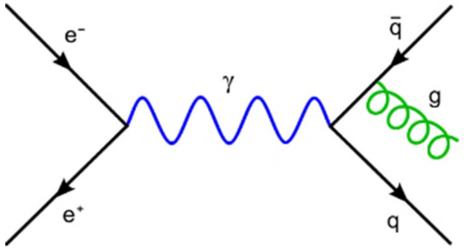
Upgrade highlights:

- Improved vertexing resolution
- Better p_t resolution (larger chamber)
- Slightly higher acceptance
- Improved PID detectors
- Better hermeticity due to lower boost
- More sophisticated trigger

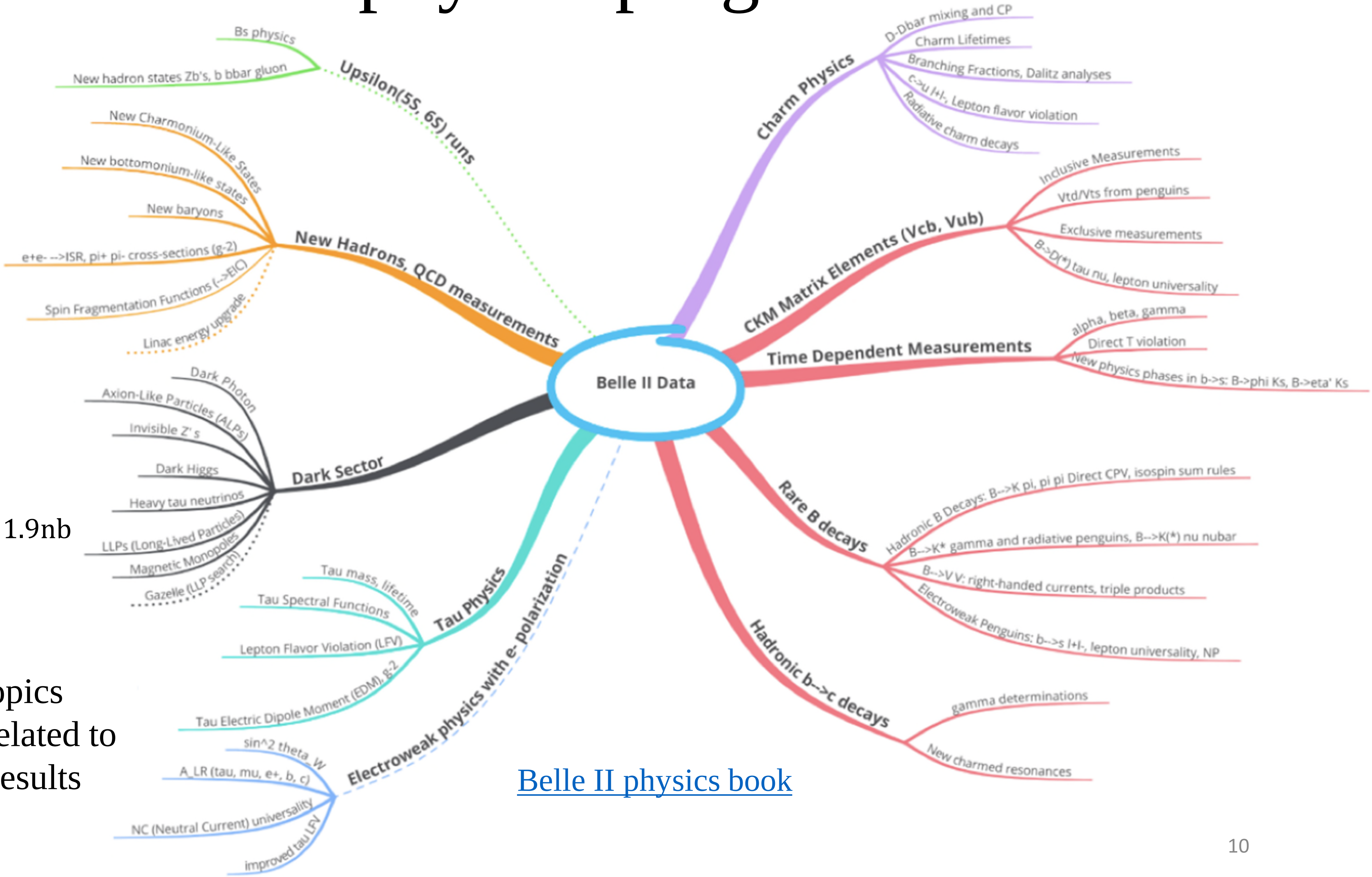
Challenges: increased backgrounds, higher trigger rates.



Belle II physics program



$e^+e^- \to B\,\bar{B}$: 1.05 nb
$e^+e^- \to \tau^+\tau^-$: 0.92 nb
$e^+e^- \to c\,\bar{c}$: 1.3 nb
$e^+e^- \to q\bar{q}\ (q = u, d, s)$: 1.9nb

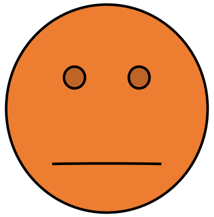


⇒ Large variety of topics
⇒ Will touch those related to recent B-physics results

Belle II physics book

Pros and cons of Belle II

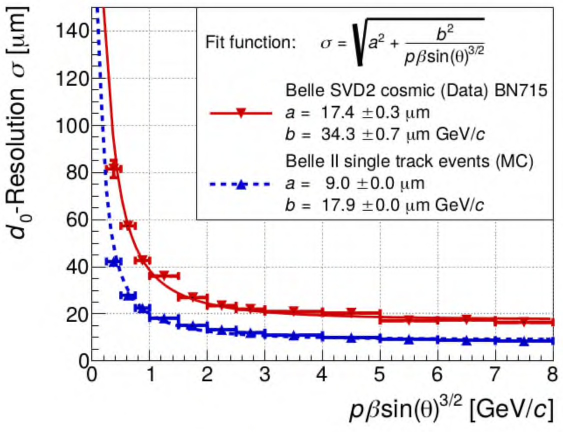
- The kinematics of the collision is known precisely,
- In $\Upsilon(4S) \to B\bar{B}$ events, no additional particles are produced (can use B-tagging),
- $B\bar{B}$ pairs produced in a quantum entangled state (flavor states orthogonal at decay time of first B),
- Low-multiplicity and τ-pair processes are easily accessible (can trigger on final states with a single visible particle),
- High efficiency and purity of neutrals (π^0, $\eta^{(\prime)}$, $K^0_{\mathrm{S,L}}$, …),

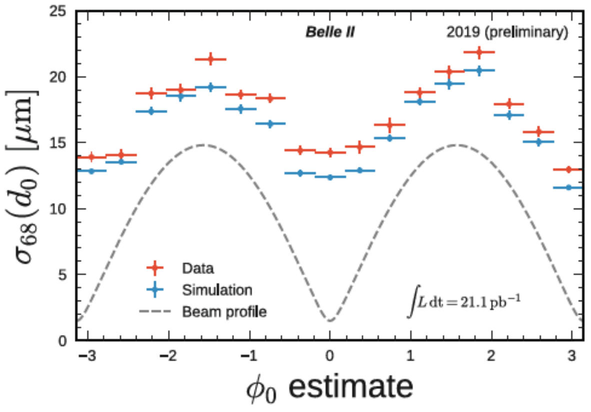


- "Manageable" backgrounds (but machine backgrounds will be a challenge for both detector, trigger, and analysis at high-lumi conditions),

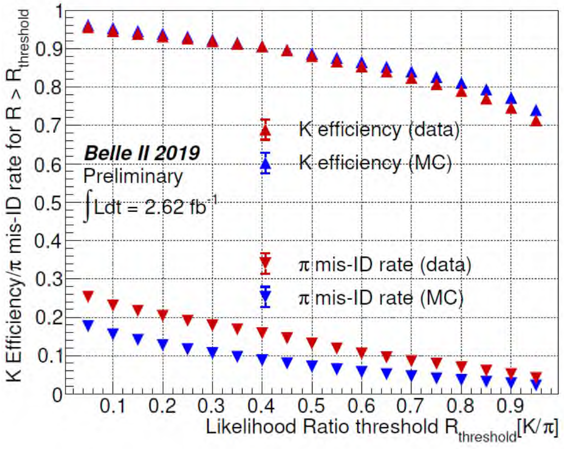
- Low cross-section (compared to hadron machines),
- Relatively low boost of B and D mesons, (time-dependent analyses of B_s^0 mesons is out of question),
- Cannot go much higher in energy than the mass of the $\Upsilon(4S)$.

Belle II early performance





Expected factor 2 improvement in track impact parameter resolution confirmed by data.

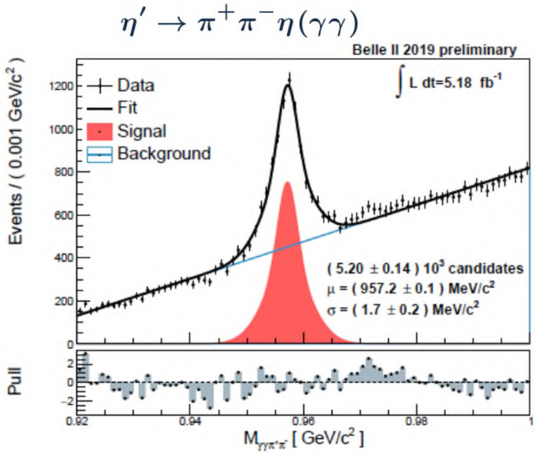


PID capabilities not yet fully exploited.

Currently working on improving understanding of new PID detectors.

	Data	MC
$\mu_{\Delta t}$ [ps]	-0.03 ± 0.06	-0.09 ± 0.02
$\sigma_{\Delta t}$ [ps]	0.56 ± 0.18	0.44 ± 0.09

Improvement in time resolution wrt. Belle ($\sigma_{\Delta t} \approx 92$ps) despite boost reduction.



Good performance in reconstruction of neutrals.

Currently working on improving the calibration of electromagnetic calorimeter.

Data taking, status and plans

Phase III (2019 -): start of physics run with full detector and ramp of lumi

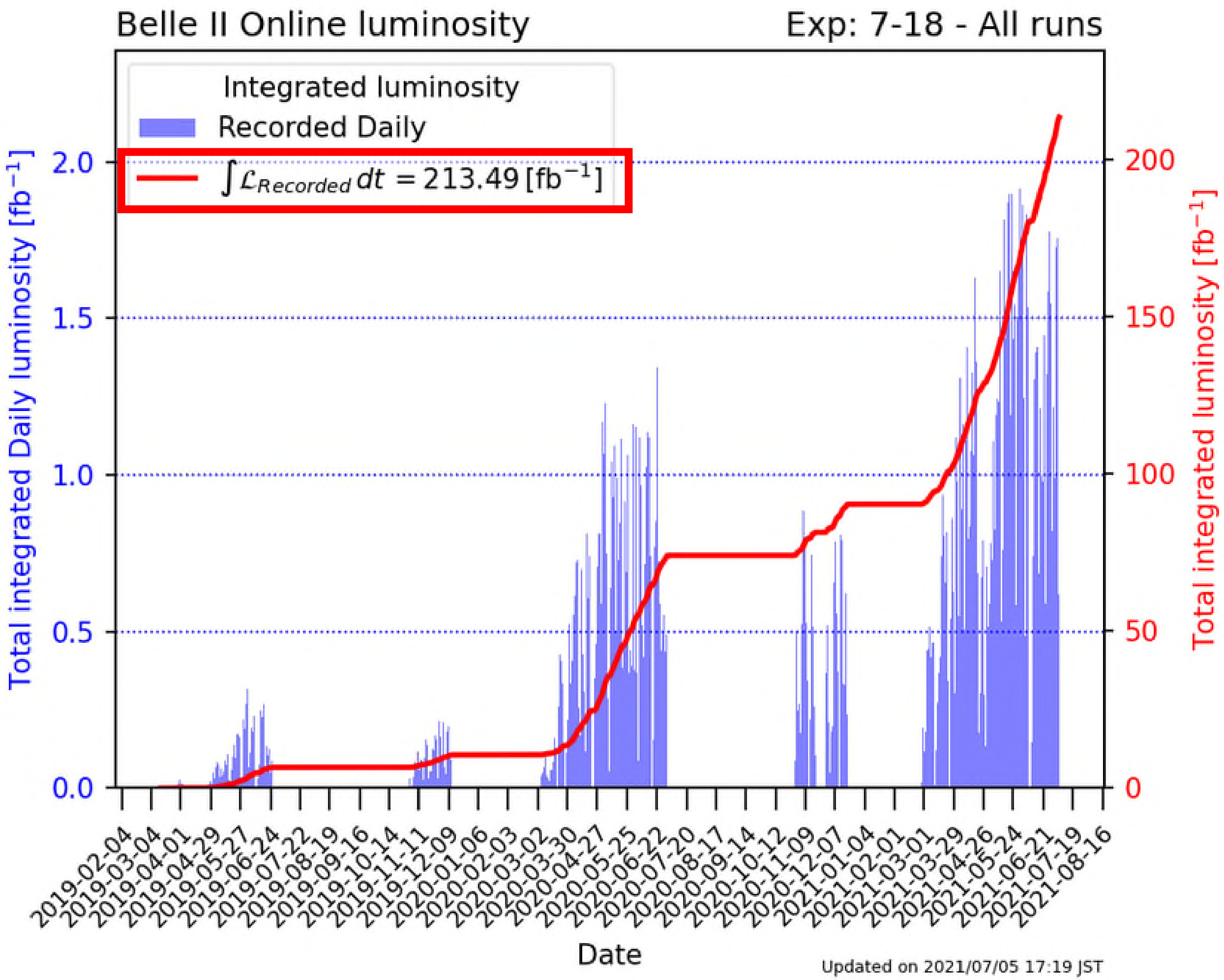
- Extraordinary effort from locally based people to keep the ball rolling during COVID19 times
- Data taking efficiency ~90%

⇒ Recorded lumi ~213 fb^{-1}

- KEKB world record inst. lumi broken in June 2020 running at ~2 × lower current

Records	Belle/KEKB	Belle II/SuperKEKB
Peak lumi $[10^{34} cm^{-2} s^{-1}]$	2.1	3.1
Recorded lumi/day $[fb^{-1}]$	1.48	1.96

- In 2023 will start a ~9 months shutdown to replace the yet incomplete pixel vertex detector



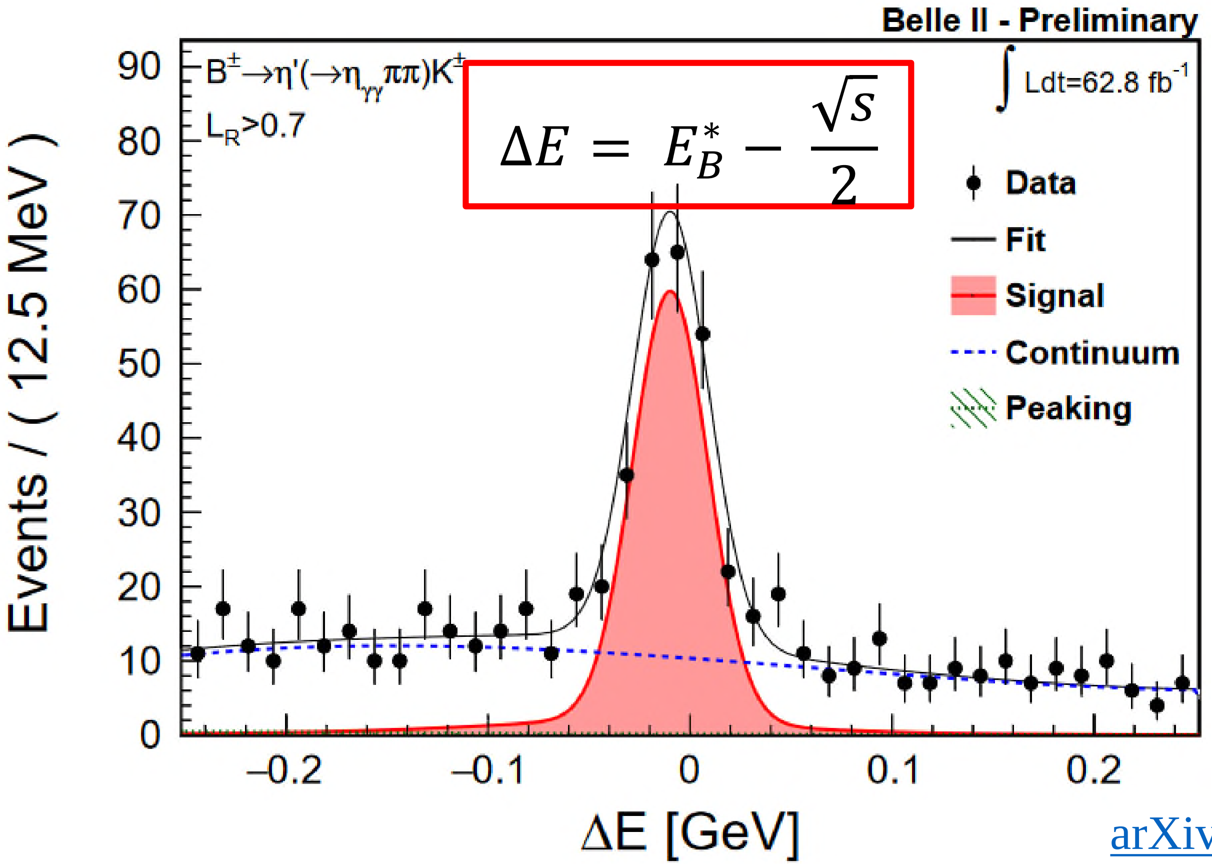
⇒ So far produced physics results using up to 128 fb^{-1}

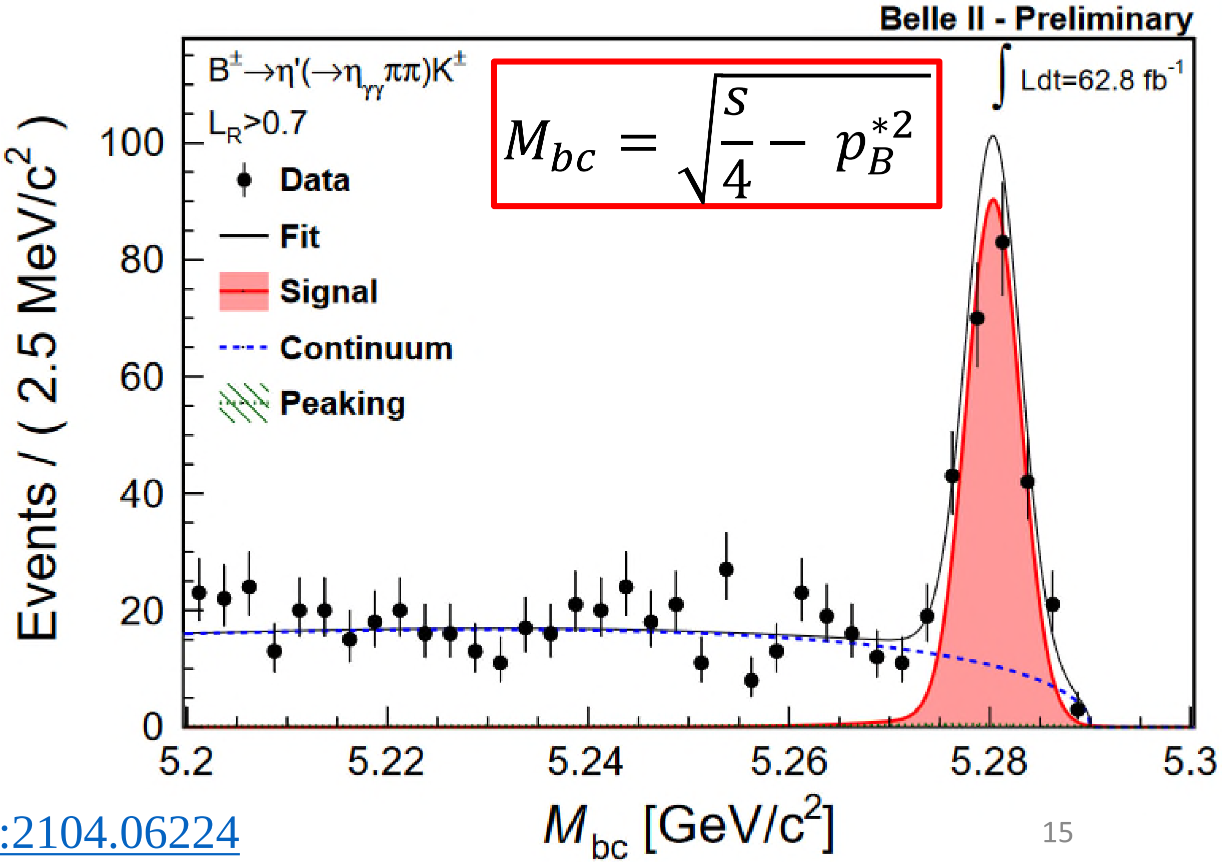
Experimental tools

B-factory observables

B-candidates reconstructed by combining tracks, neutral clusters, π^0, K_S^0, and intermediate candidates (D, $\eta^{(\prime)}$, …) through kinematic and decay-vertex fits of the considered decay chain.

Two key variables discriminate against background for fully reconstructed final states:



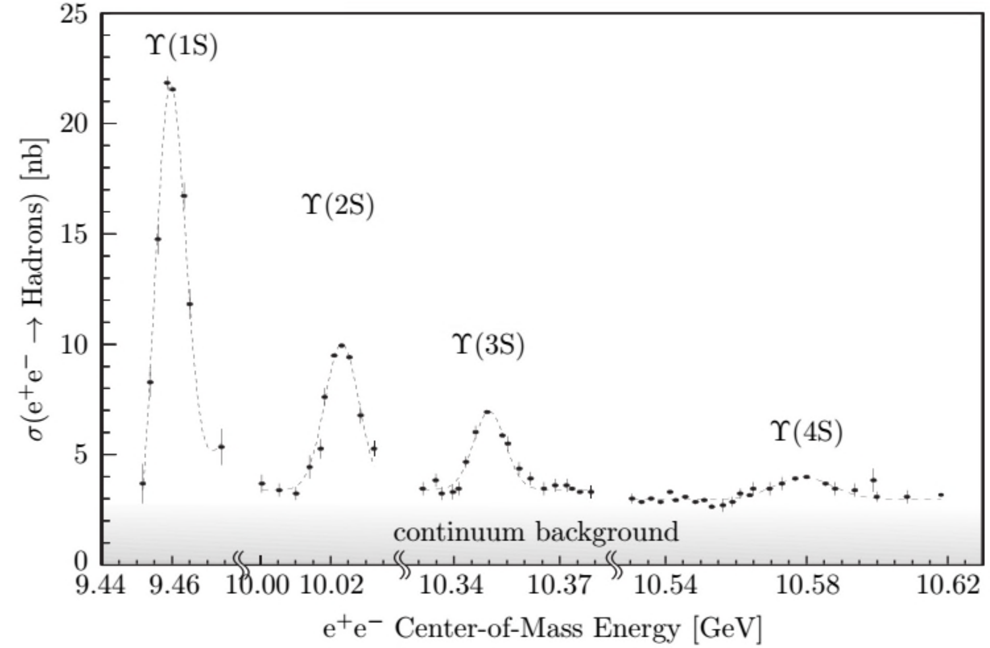


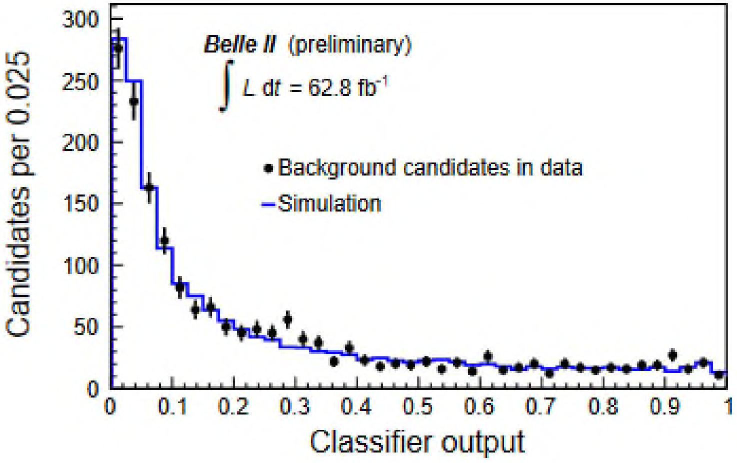
arXiv:2104.06224

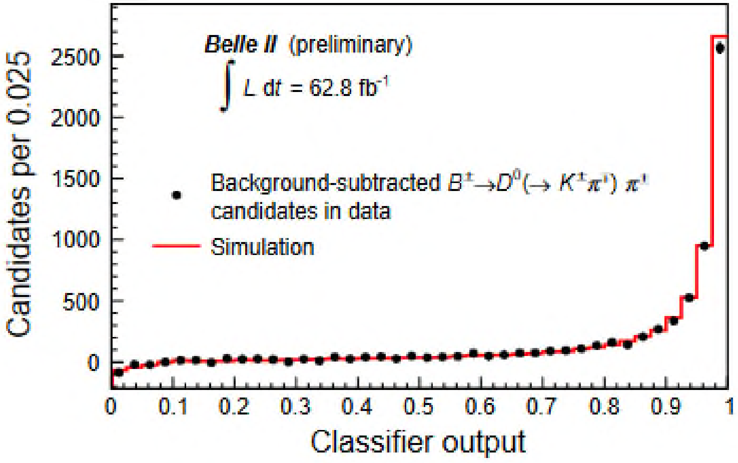
Suppression of continuum background

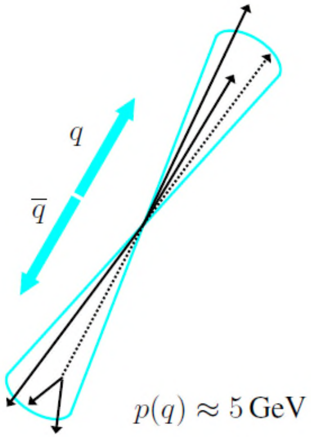
For many final states (especially charmless B decays), hadronic events with light $q\bar{q}$ pairs (continuum) are the dominant background source, which is suppressed by exploiting observables sensitive to topological differences between $q\bar{q}$ and $B\bar{B}$ events.

$\Rightarrow$ Usually through machine learning techniques

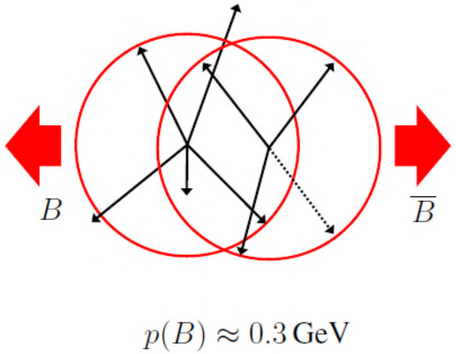








$e^+e^- \to q\bar{q}$ $(q \in \{u, d, s, c\})$

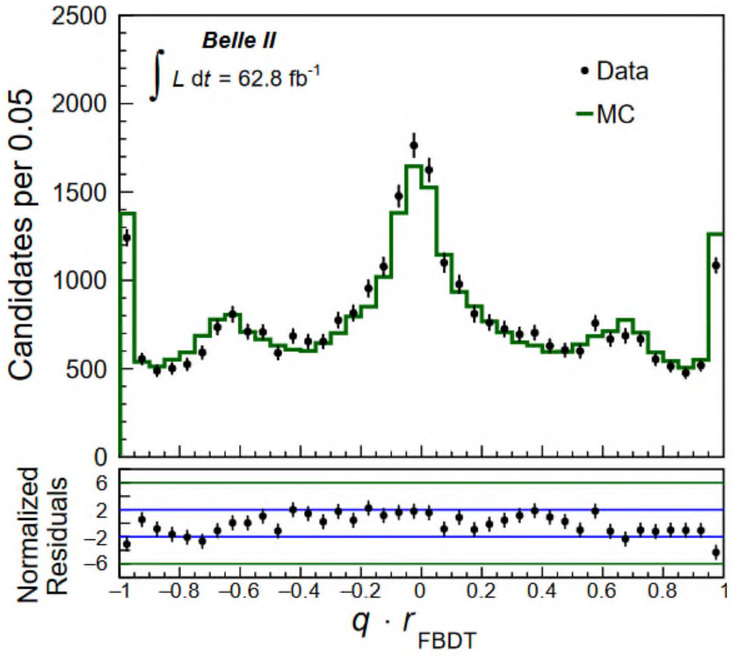


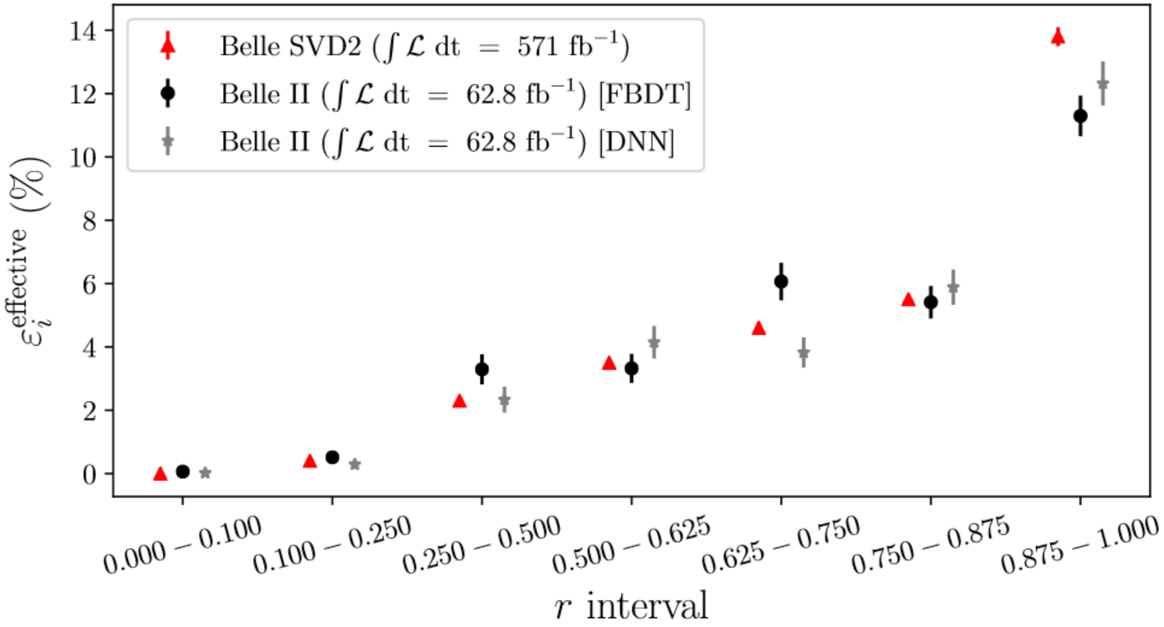
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

arxiv:2109.10807

B-flavor tagger

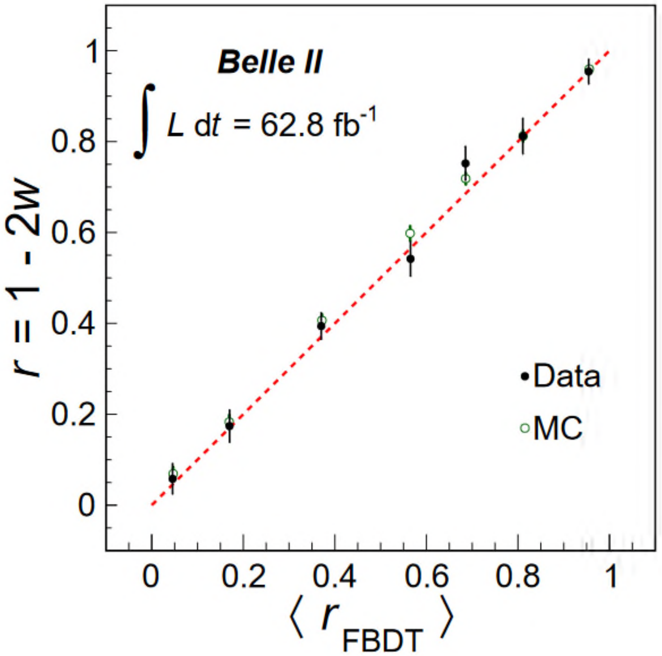
- B-flavor tagging is crucial for many $B^0 - \bar{B}^0$ mixing and CP-violation analyses
- One of the two B-mesons (signal side) is fully reconstructed (in a self-tagging or CP eigenstate)
- The flavor (B^0 or $\bar{B}^0$) of the accompanying B-meson is determined by multivariate algorithms combining info from tracks ($e^\pm$, $\mu^\pm$, $K^\pm$, $\pi^\pm$), and presence of K_S^0 and Λ^0.



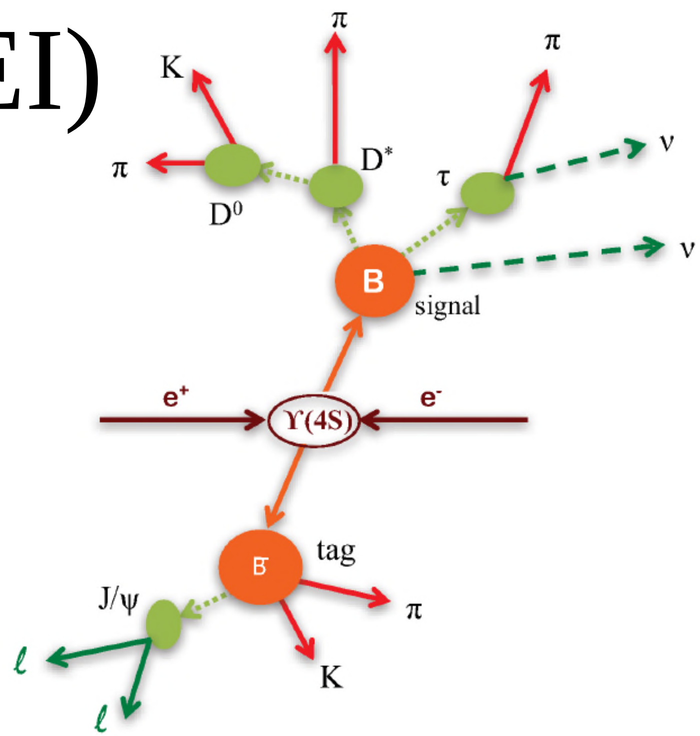


Eff. effcy.	$\varepsilon \cdot (1 - 2w)^2$
Belle	$(30.1 \pm 0.4)\%$
Belle II	$(30.0 \pm 1.3)\%$
Belle II (MC)	32.5%

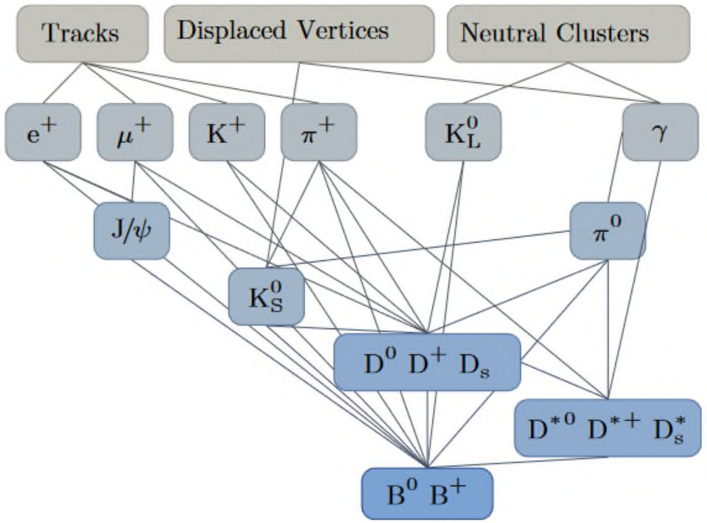
arXiv:2110.00790



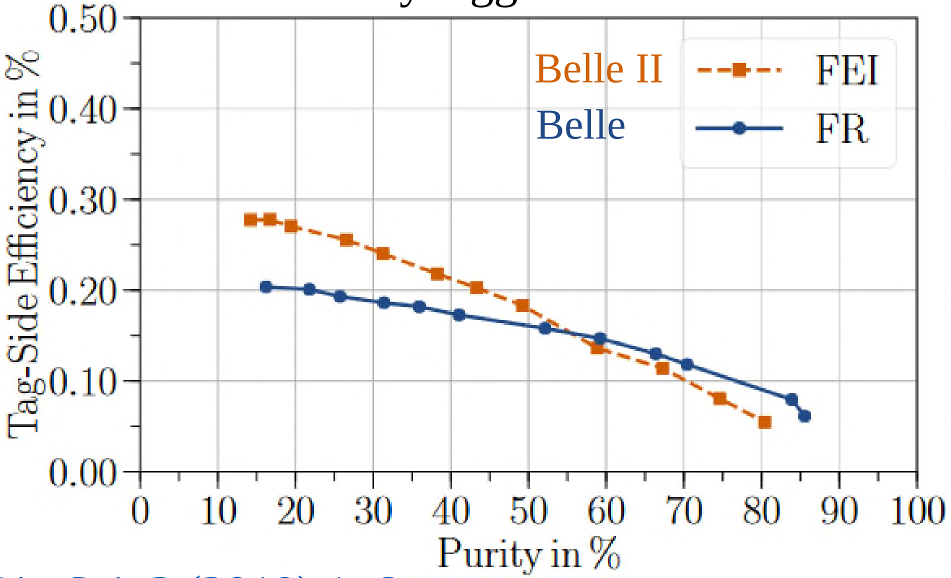
Full event interpretation (FEI)



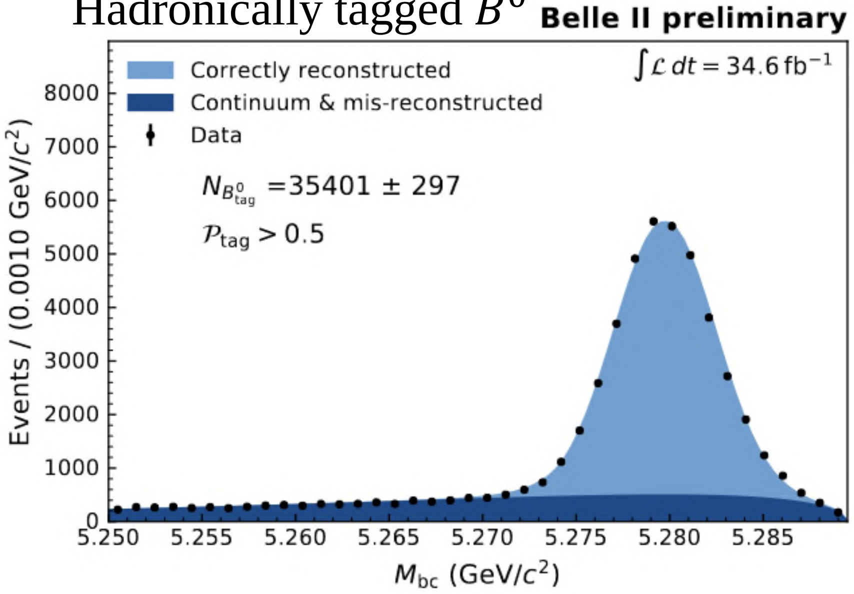
- Advanced tool to analyse final states with missing energy
- One of the two B-mesons in the event is reconstructed into a hadronic or semileptonic final state (about 10000 possible decay chains considered)
- Significant impact on the overall efficiency and dramatic increase in background control, especially in modes with neutrinos in the final state



Hadronically tagged B^0 in Belle data



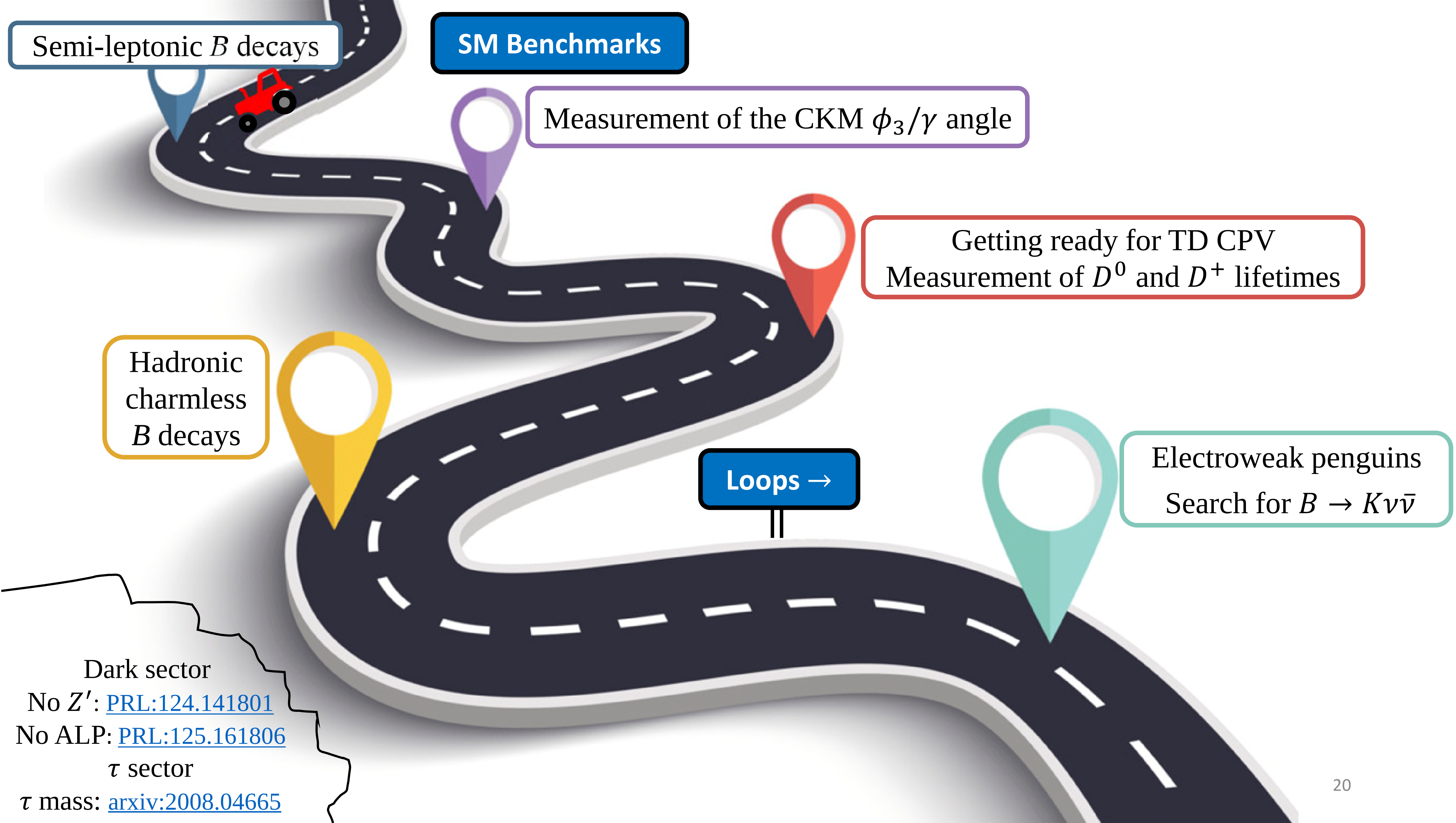
Hadronically tagged B^0



Comp. Soft. Big Sci. 3 (2019) 1, 6

arXiv:2008.06096

Recent Belle II physics results
On the way to the loops

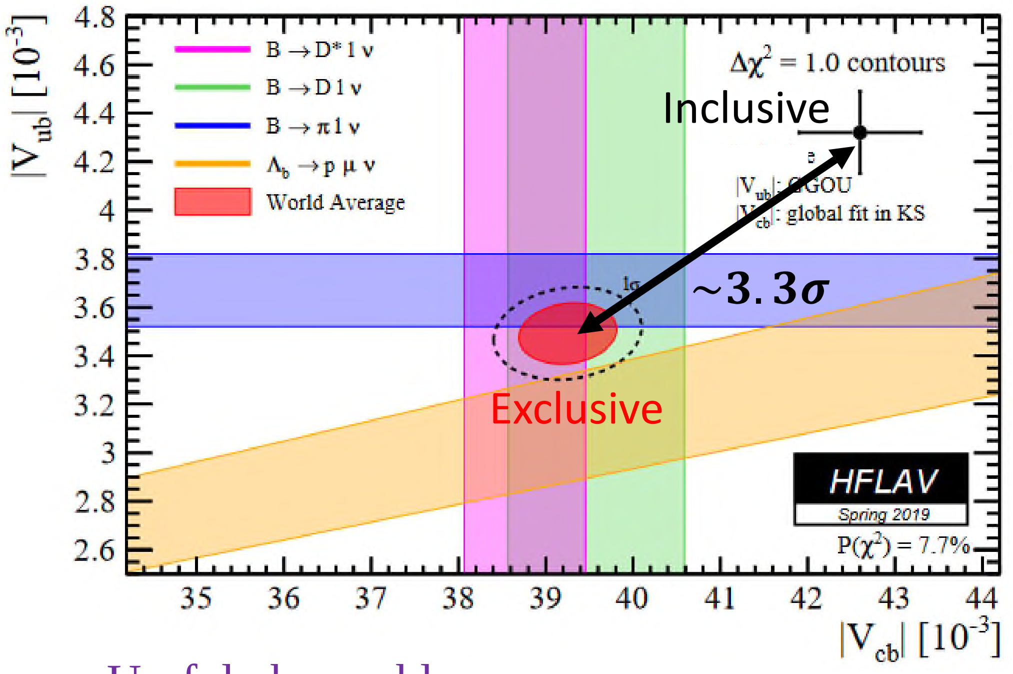

Semi-leptonic B decays
SM Benchmarks
Measurement of the CKM ϕ_3/γ angle
Getting ready for TD CPV
Measurement of D^0 and D^+ lifetimes
Hadronic charmless B decays
Loops →
Electroweak penguins
Search for $B \to K\nu\bar{\nu}$
Dark sector
No Z': PRL:124.141801
No ALP: PRL:125.161806
τ sector
τ mass: arxiv:2008.04665

Semileptonic B decays

- Long-standing tension between inclusive and exclusive determinations of $|V_{ub}|$ and $|V_{cb}|$
- Analysis of inclusive and exclusive semi-leptonic B decays performed using tagged and untagged approaches:

  $|V_{ub}|$: $B \to X_u \ell \nu$, $B \to \{\pi, \rho, \eta\} \ell \nu$ ($\ell = e, \mu$)

  $|V_{cb}|$: $B \to X_c \ell \nu$, $B \to D^{(*)} \ell \nu$ ($\ell = e, \mu$)



Tagged approach: reconstruct tag-side B meson using FEI and extract signal from composition fit of M^2_{miss} or M_X

$\Rightarrow$ Low efficiencies, but high purity

Untagged approach: reconstruct signal B meson and use $\cos\theta_{BY}$ to extract signal, or select lepton (exploiting topological info) and use p^*_l to extract signal.

$\Rightarrow$ Higher efficiencies, but low purity

Useful observables:

M^2_{miss}: missing mass squared

M_X: mass of X_u or X_c system

θ_{BY}: angle between momentum of B meson and of $D^{(*)}\,l$ system in $\Upsilon(4S)$ frame

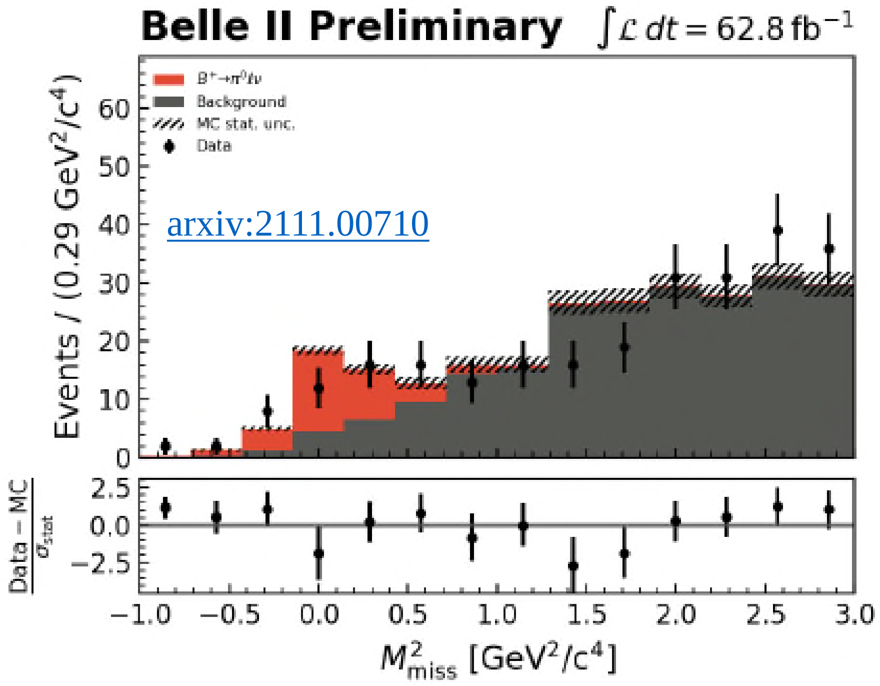
p^*_l: momentum of primary lepton in $\Upsilon(4S)$ frame

Results from tagged analyses

Using hadronically tagged $B\bar{B}$ events

Inclusive $B \rightarrow X_c \ell \nu$

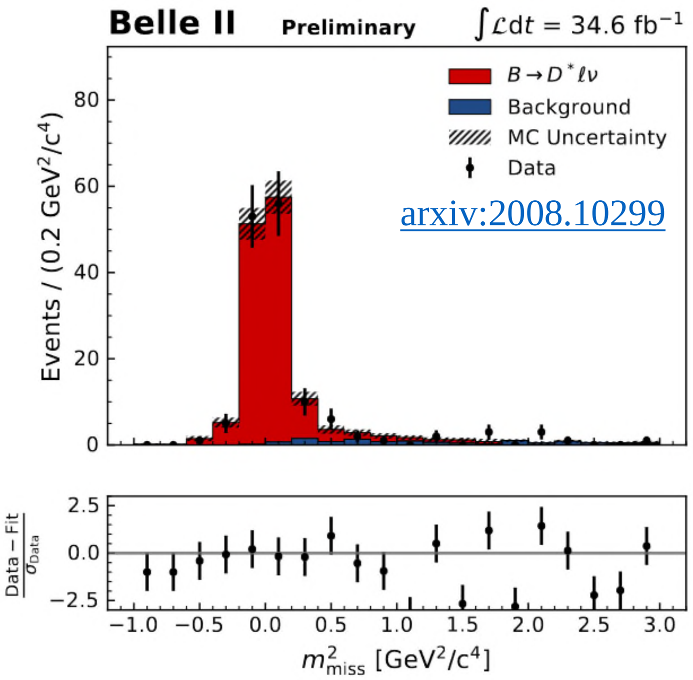
Exclusive $\bar{B}^0 \rightarrow \pi^0 \ell^- \bar{\nu}_\ell$



arxiv:2111.00710

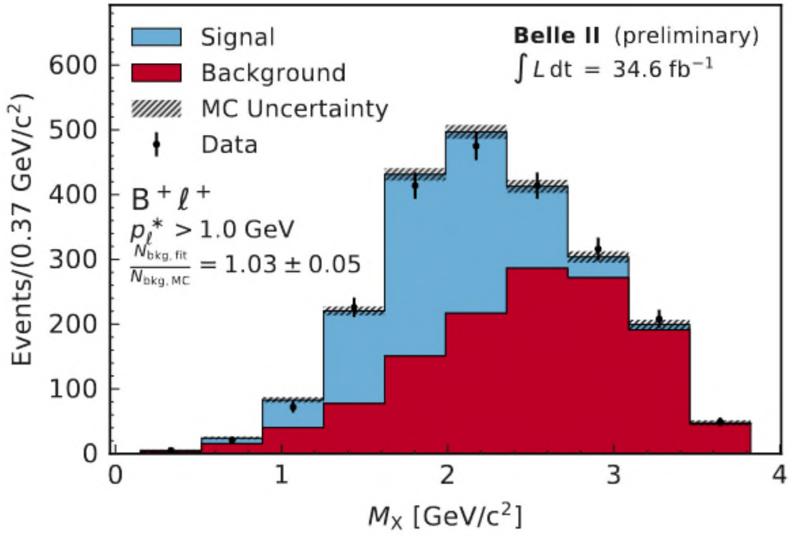
$\mathcal{B} = (8.29 \pm 1.99 \pm 0.046)\%$

Exclusive $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$

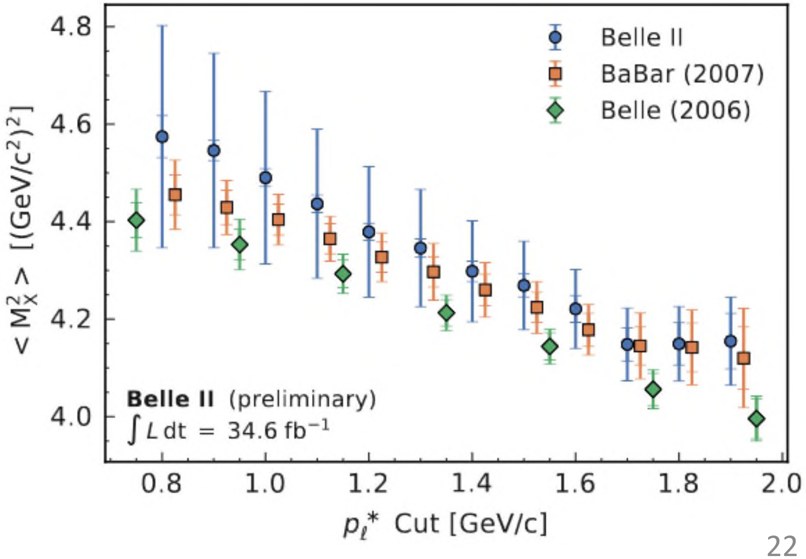


arxiv:2008.10299

$\mathcal{B} = \left(4.51 \pm 0.41 \pm 0.27 \pm 0.45_{\pi_s}\right)\%$



arxiv:2009.04493



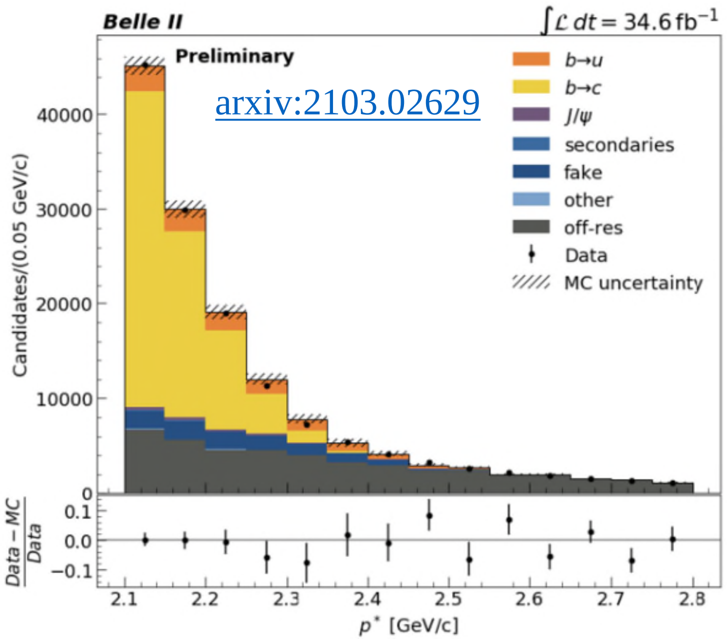
⟹ Measured $\mathcal{B}(B \rightarrow \pi^{+,0} \ell^- \bar{\nu}_\ell)$ with > 6σ and $\rho \ell^- \bar{\nu}_\ell$

⟹ Results in agreement with world averages

⟹ Hadronic mass moments will help constraining $|V_{cb}|$

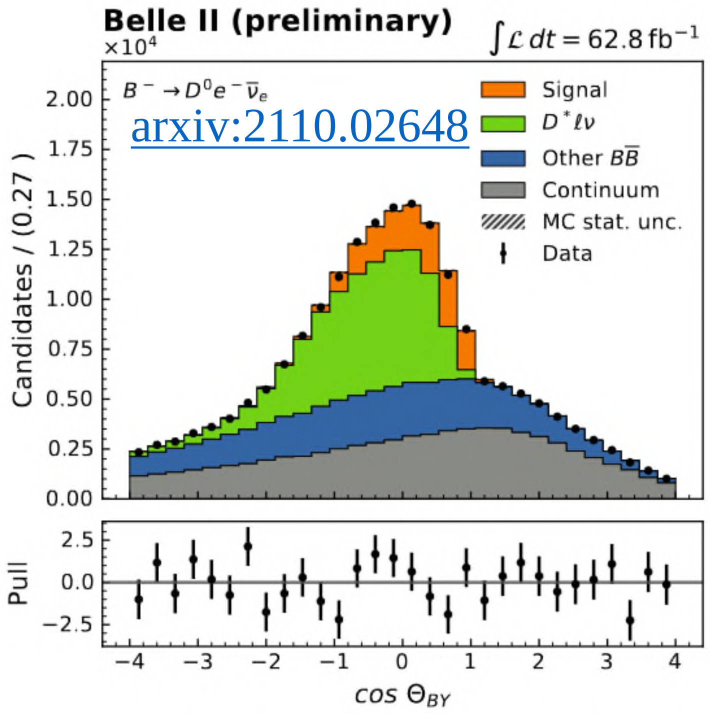
Results from untagged analyses

Inclusive $B \to X_u \ell \nu$



3σ significance for $b \to u \ell \nu$

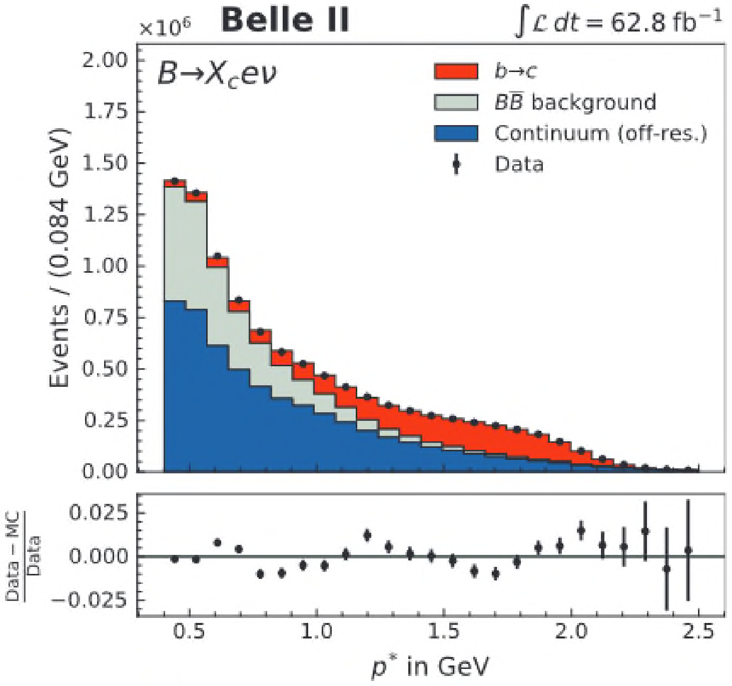
Exclusive $B^+ \to \bar{D}^0 \ell^+ \nu_\ell$



$\mathcal{B} = (2.29 \pm 0.05 \pm 0.08)$

$R(e/\mu) = 1.04 \pm 0.05 \pm 0.03$

Inclusive $B \to X_c \ell \nu$



$\mathcal{B} = (9.75 \pm 0.03 \pm 0.47)$

Dom. sys.: $B \to X_c \ell \nu$ composition

$\Rightarrow$ Dominant syst. uncertainties associated with tracking/PID will reduce in future

$\Rightarrow$ Results for branching fractions compatible and competitive with world averages

Prospects for $R(D)$ and $R(D^*)$

Belle II physics book

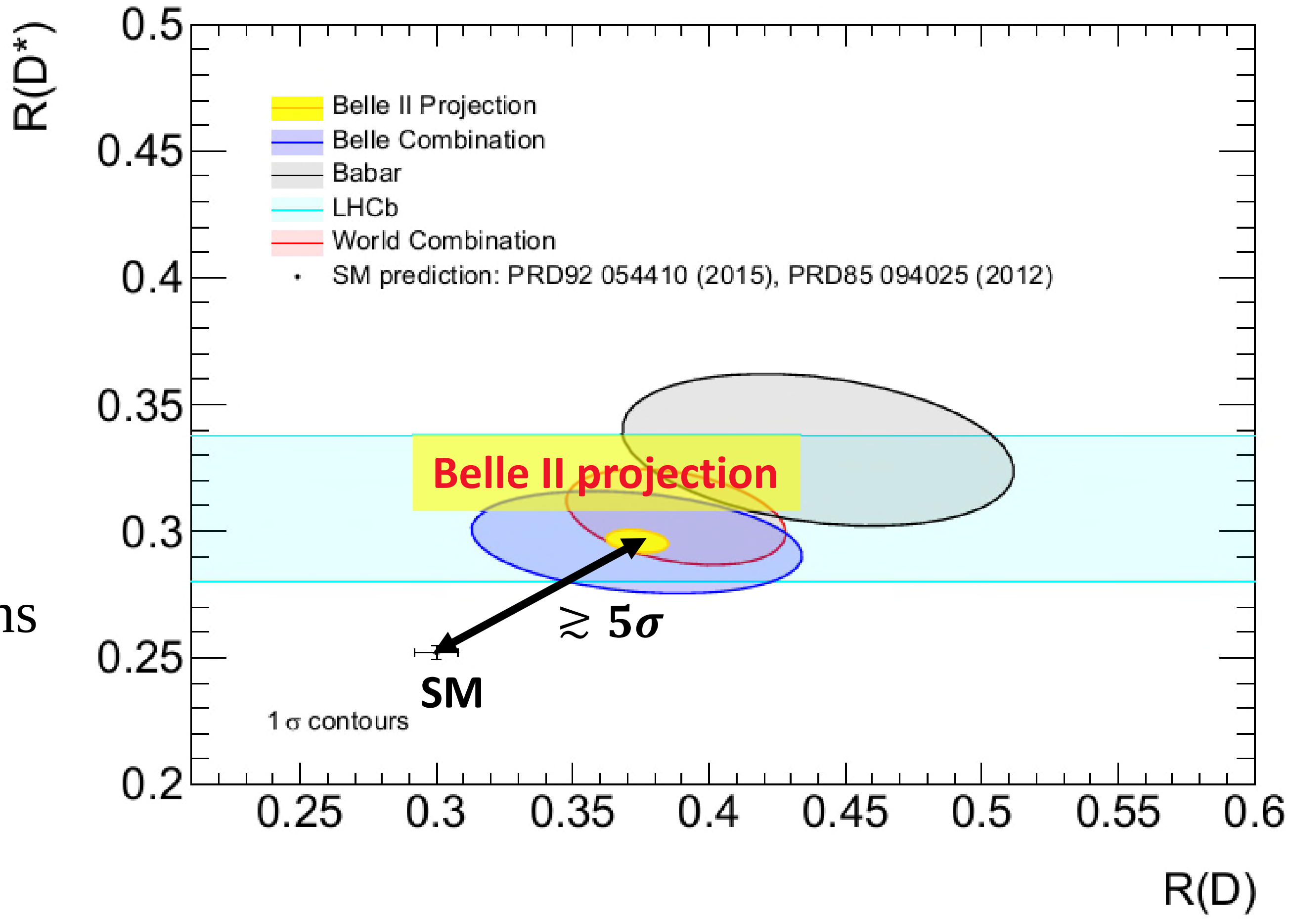
- Belle II can conduct multiple independent tagged and untagged measurements:

  Hadronically/SL tagged

  Untagged

  Hadronic and leptonic τ decays

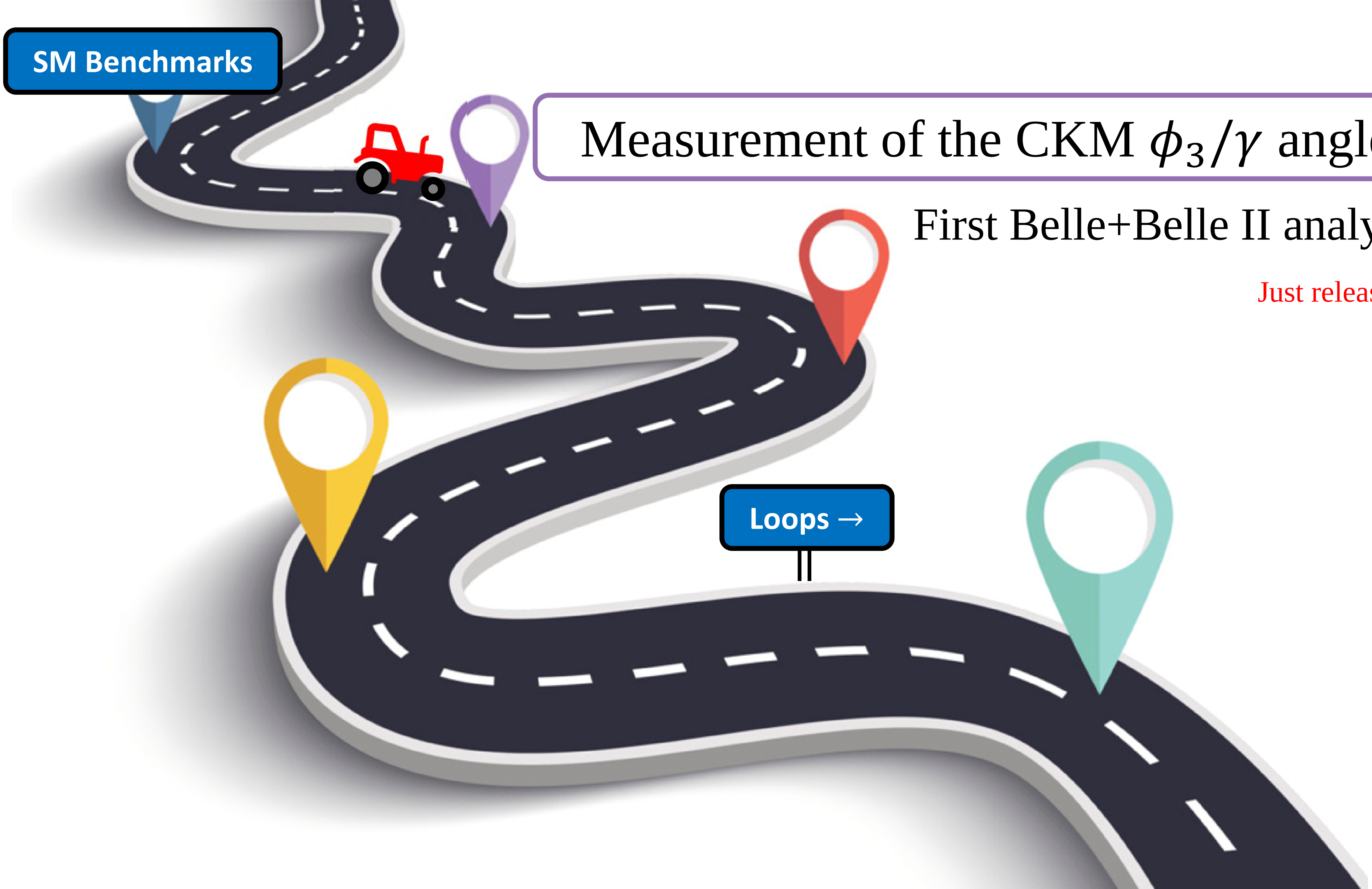
$\Rightarrow$ Belle II expected to make important contributions (provided enough data is collected)



Measurement of the CKM ϕ_3/γ angle

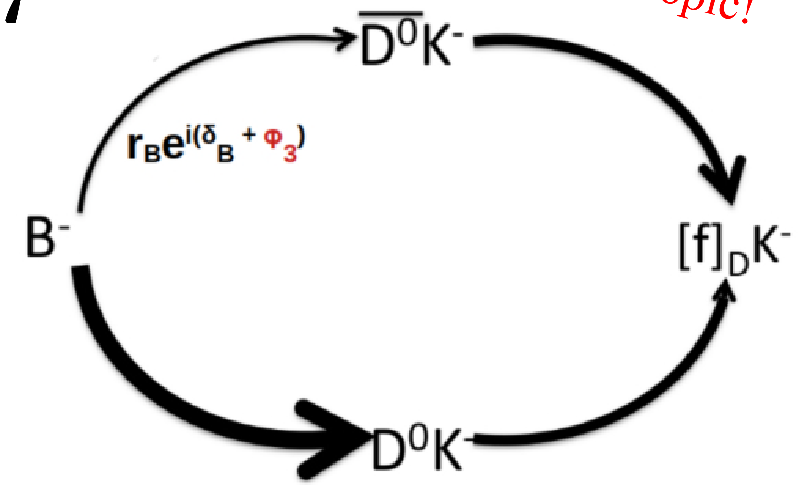
First Belle+Belle II analysis

Just released!



Measurement of ϕ_3/γ

Hot topic!



ϕ_3/γ is weak phase between $b \to u$ and $b \to c$ transition

$\Rightarrow$ Proceeding only through tree-level $B^- \to D^0K^-$ decays

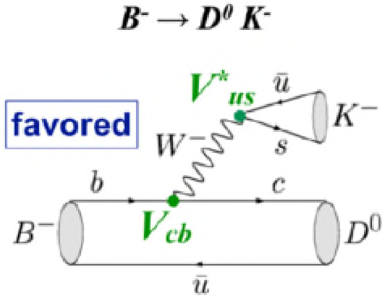
$\Rightarrow$ SM benchmark, no theory uncertainties [$\mathcal{O}(10^{-7})$]

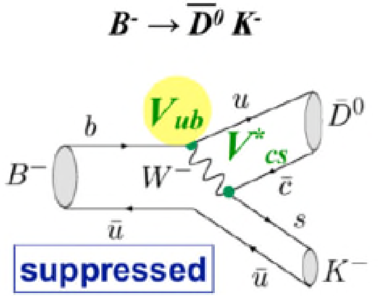
$\Rightarrow$ Common final state allows interference between two paths

$\Rightarrow$ Interference gives access to the phase

$\Rightarrow$ Level of interference depends on B and D physics

$\Rightarrow$ Experimentally challenging due to small branching fractions





BPGGSZ method: use self-conjugate $D(K^0_S h^- h^+)$ final states

$\Rightarrow$ Sensitive to ϕ_3 by comparing Dalitz distr. for B^+ and B^-

$\Rightarrow$ Magnitude and position of CP asymmetries driven by values of r_B, ϕ_3, δ_B and physics of D decay

$\Rightarrow$ Use binned model-independent approach (avoid model uncties.)

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

Measurement of ϕ_3/γ

Hot topic!

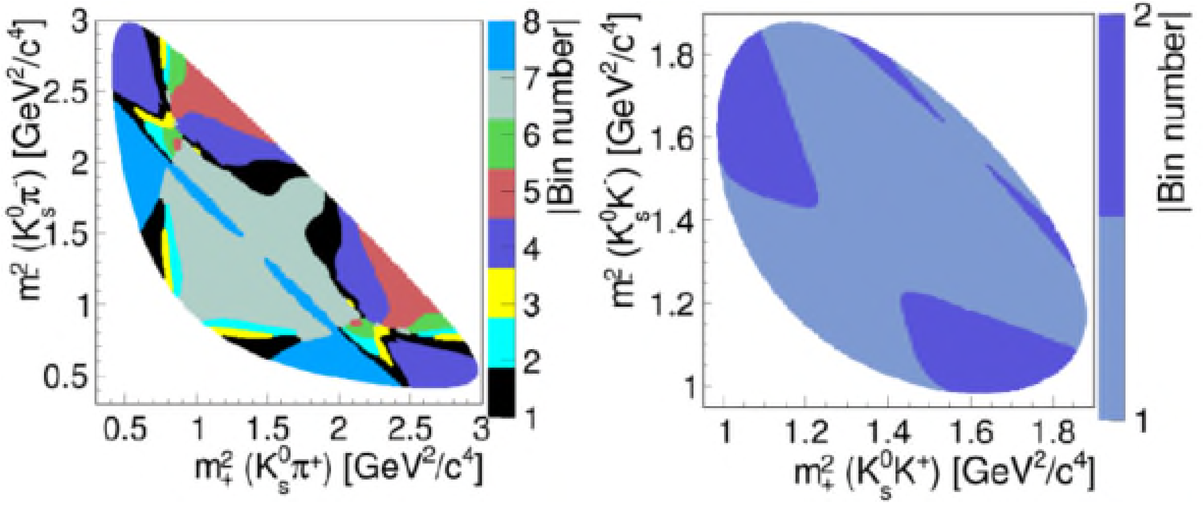
- Yields in each bin related to physics parameters and D^0 decay info:

$$N_i^{\pm} = h_{B^\pm}\left[F_i + r_B^2 \overline{F}_i + 2\sqrt{F_i \overline{F}_i}(c_i x_\pm + s_i y_\pm)\right].$$

$h_{B\pm}$: Normalization constant

$$(x_\pm, y_\pm) = r_B(\cos(\phi_3 + \delta_B), \sin(\phi_3 + \delta_B))$$

Maximum sensitivity binning



Amplitude averaged strong phase difference between D^0 and $\overline{D}^0$ obtained from CLEO and BESIII

Fraction of pure D^0 decay taking into account the reco and selection efficiency

Improvements wrt. previous Belle:

- Use of $D(K_S^0 K^- K^+)$ channel (+10% of data)
- Improved suppression of continuum background (more inputs and use of transformed discriminator output as fit observable)
- Fractions F_i obtained directly from simultaneous fit to $B \rightarrow Dh$ data (LHCb strategy)
- Simultaneous determination of PID effcy. and mis-ID rates through joint $B \rightarrow DK$ and $B \rightarrow D\pi$ fit

arxiv:2110.12125

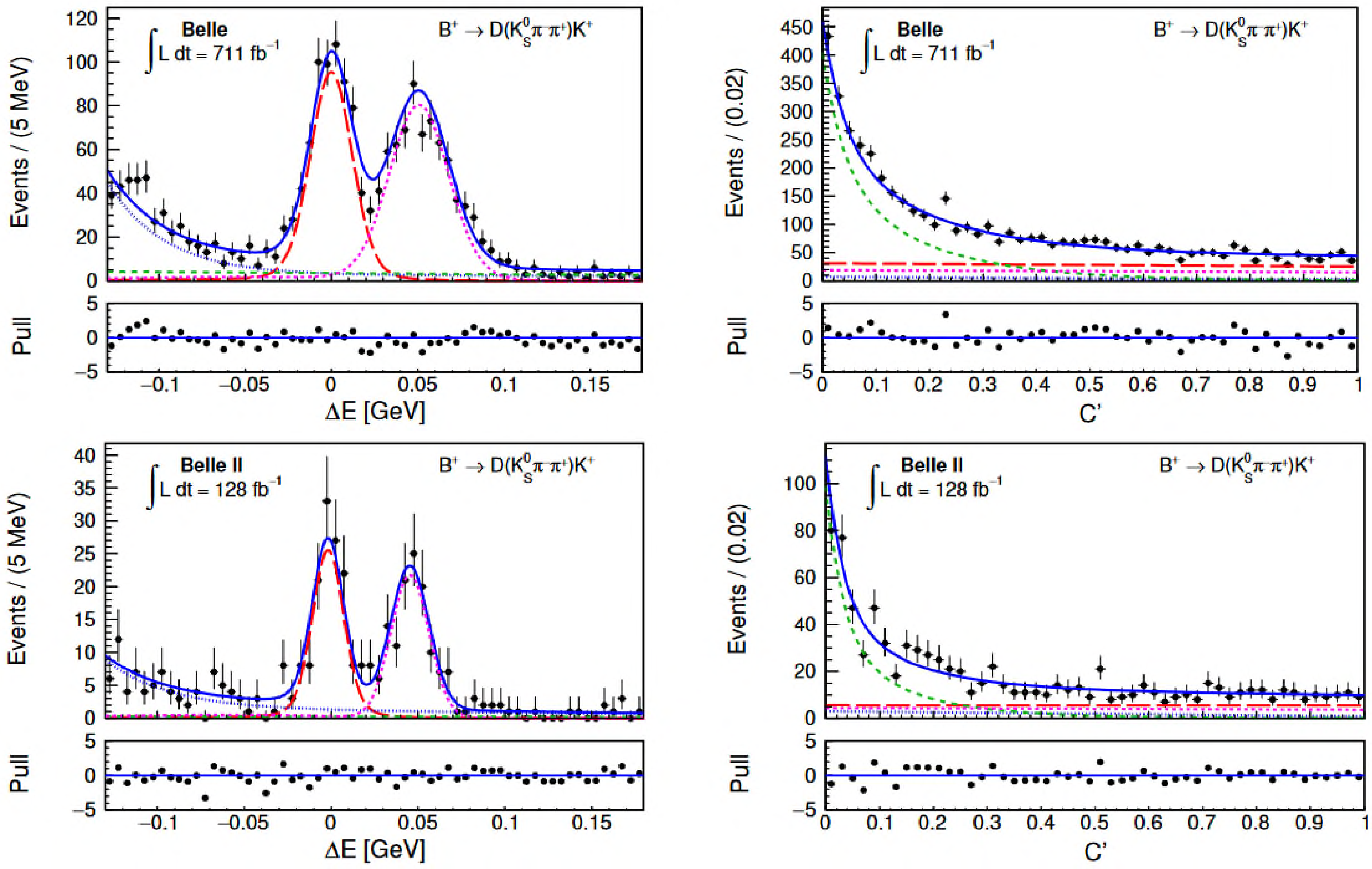
Measurement of ϕ_3/γ

Hot topic!

Belle data

⇒Analysed with Belle II software using B2BII package

Belle II data



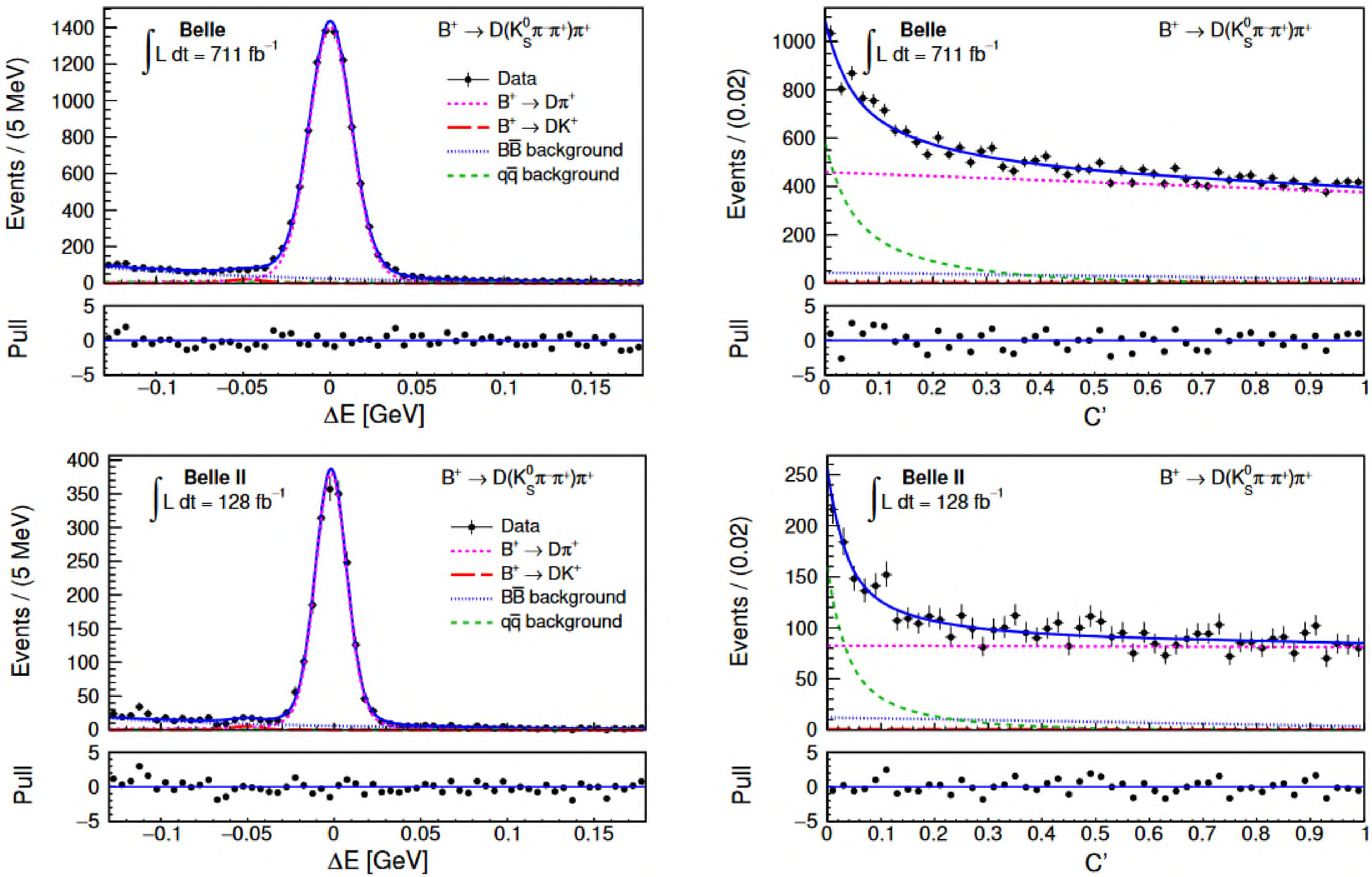
⇒ Fit performed simultaneously to Belle and Belle II data

Measurement of ϕ_3/γ

Hot topic!

Belle data

Belle II data



$\Rightarrow$ Fit performed simultaneously to $B \to DK$ and $B \to D\pi$ data

Measurement of ϕ_3/γ

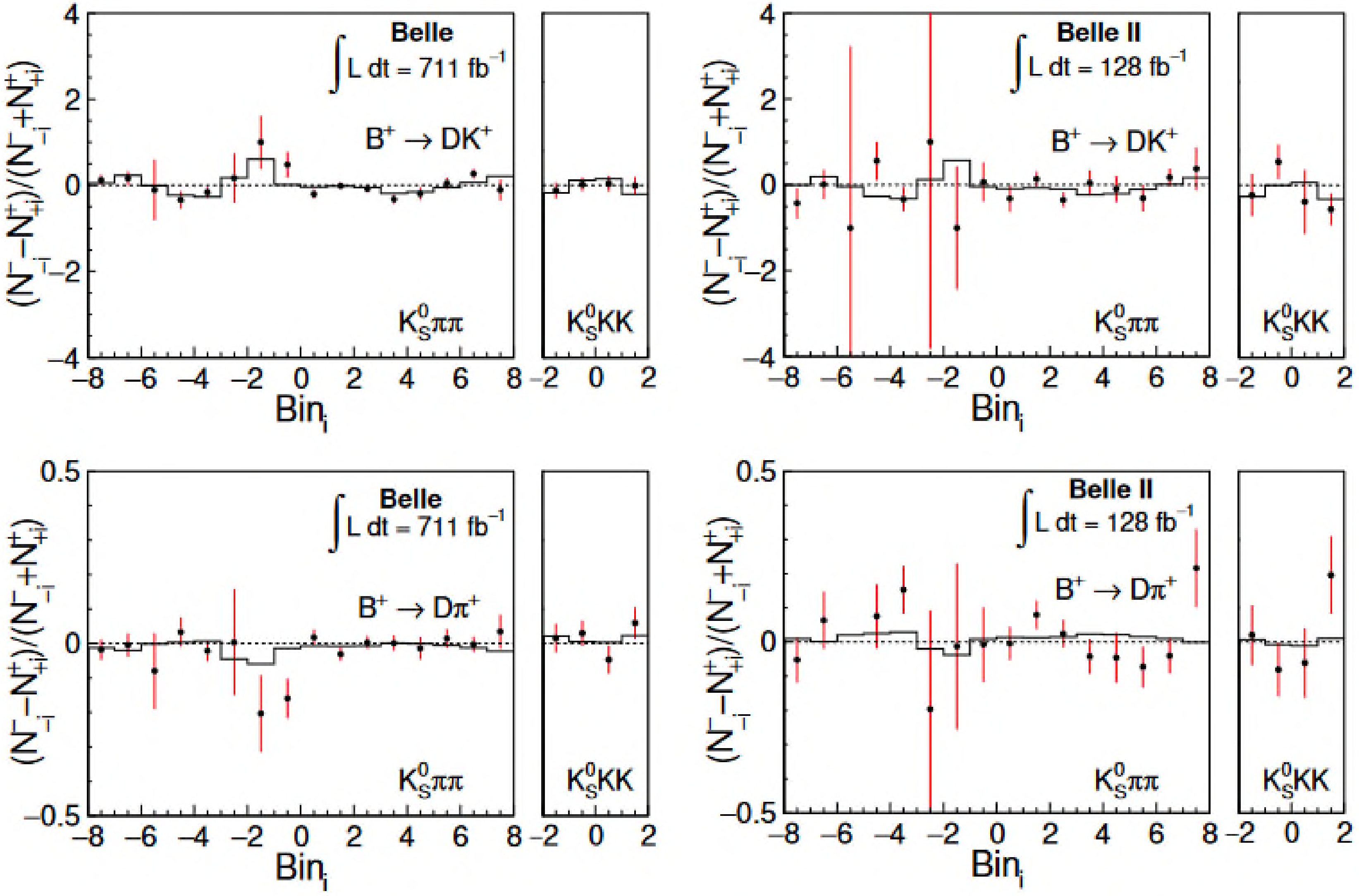
Hot topic!

Asymmetries per bin:

- Dots with error bars:
Fits with independent bin yields

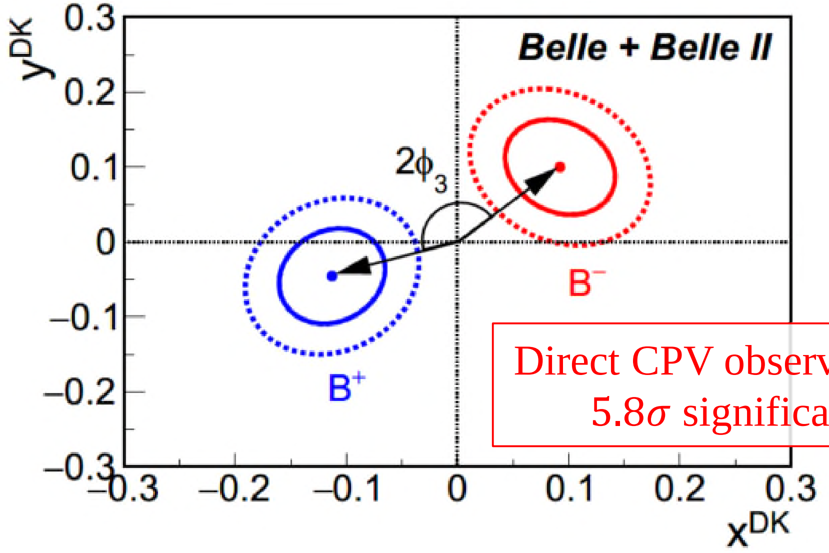
- Solid line:
Best combined fit values of $(x_\pm,\ y_\pm)$

- Dotted line:
Fit without allowed CPV
$(x_+, y_+) = (x_-, y_-)$



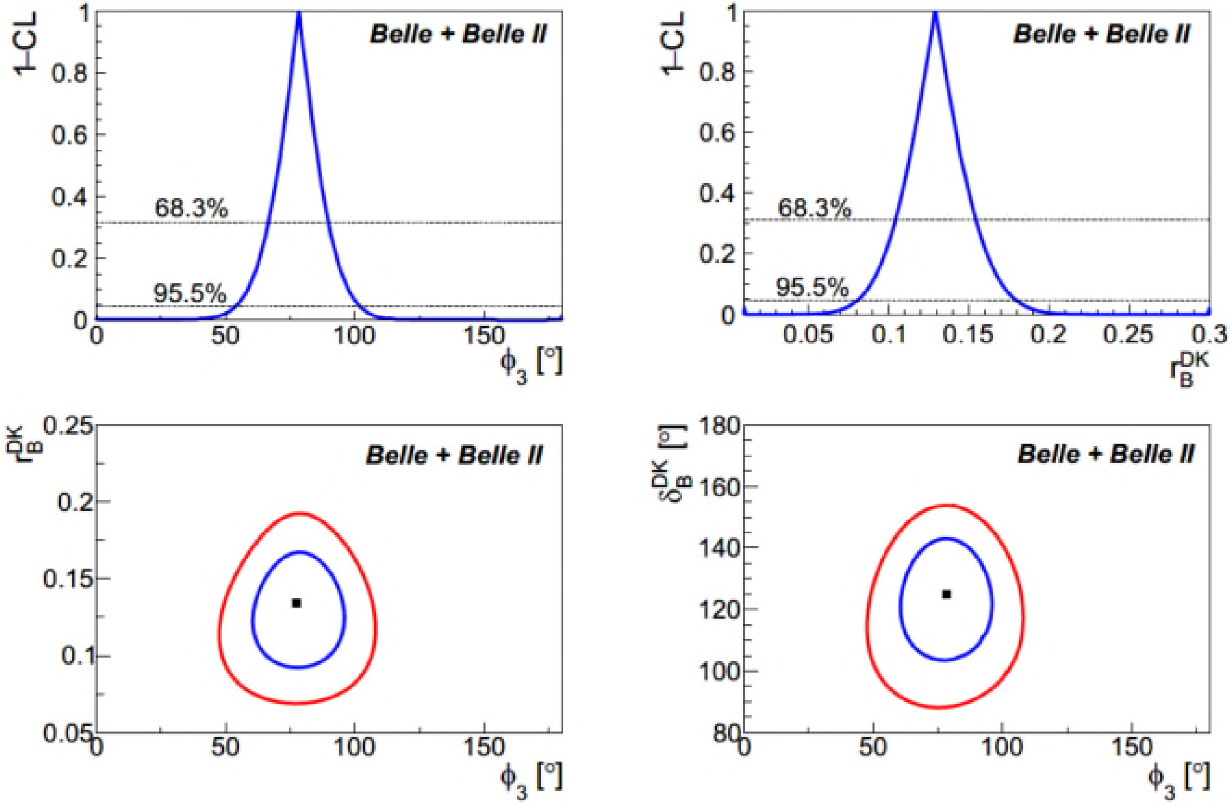
Measurement of ϕ_3/γ

Hot topic!



Direct CPV observed with 5.8σ significance

$\delta_B(°)$	124.8 ± 12.9 (stat.) ± 0.5 (syst.) ± 1.7 (ext. input)
r_B^{DK}	0.129 ± 0.024 (stat.) ± 0.001 (syst.) ± 0.002 (ext. input)
$\phi_3(°)$	78.4 ± 11.4 (stat.) ± 0.5 (syst.) ± 1.0 (ext. input)



- $\Rightarrow$ Reduced stat. uncty. 15° → 11°
- $\Rightarrow$ Reduced syst. uncty. 4° → 0.5°
- $\Rightarrow$ External input uncty. 4° → 1° (thanks to BESIII)

- $\Rightarrow$ In the future, Belle II will make important contributions in modes with neutrals in final state
- $\Rightarrow$ Expected ~4° combined precision with 10 ab^{-1}

arxiv:2110.12125
Submitted to JHEP

Getting ready for TD CPV

Measurement of
D^0 and D^+ lifetimes

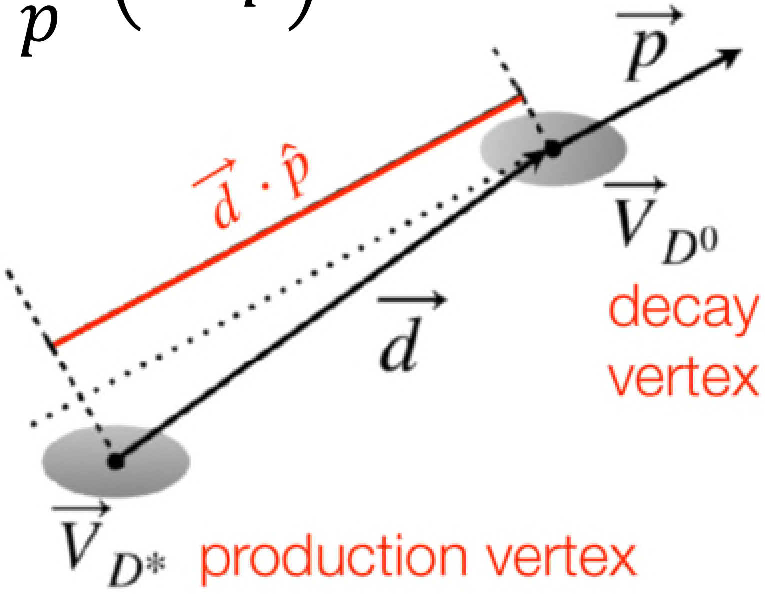
Just released!

Measurement of D^0 and D^+ lifetimes

Hot topic!

- Ideal benchmark to asses (vertex) detector performance, decay reconstruction and ability to control systematic uncertainties for time-dependent measurements.
- Select high-purity $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\,\pi^+$ and $D^{*+} \rightarrow D^+(\rightarrow K^-\pi^+\pi^+)\,\pi^0$ candidates
- Compute the decay time t and its uncertainty σ_t from the D production and decay vertices and its momentum $\vec{p}$
- Extract lifetime with a fit to the (t, σ_t) distribution (PDFs extracted from data without simulation input)

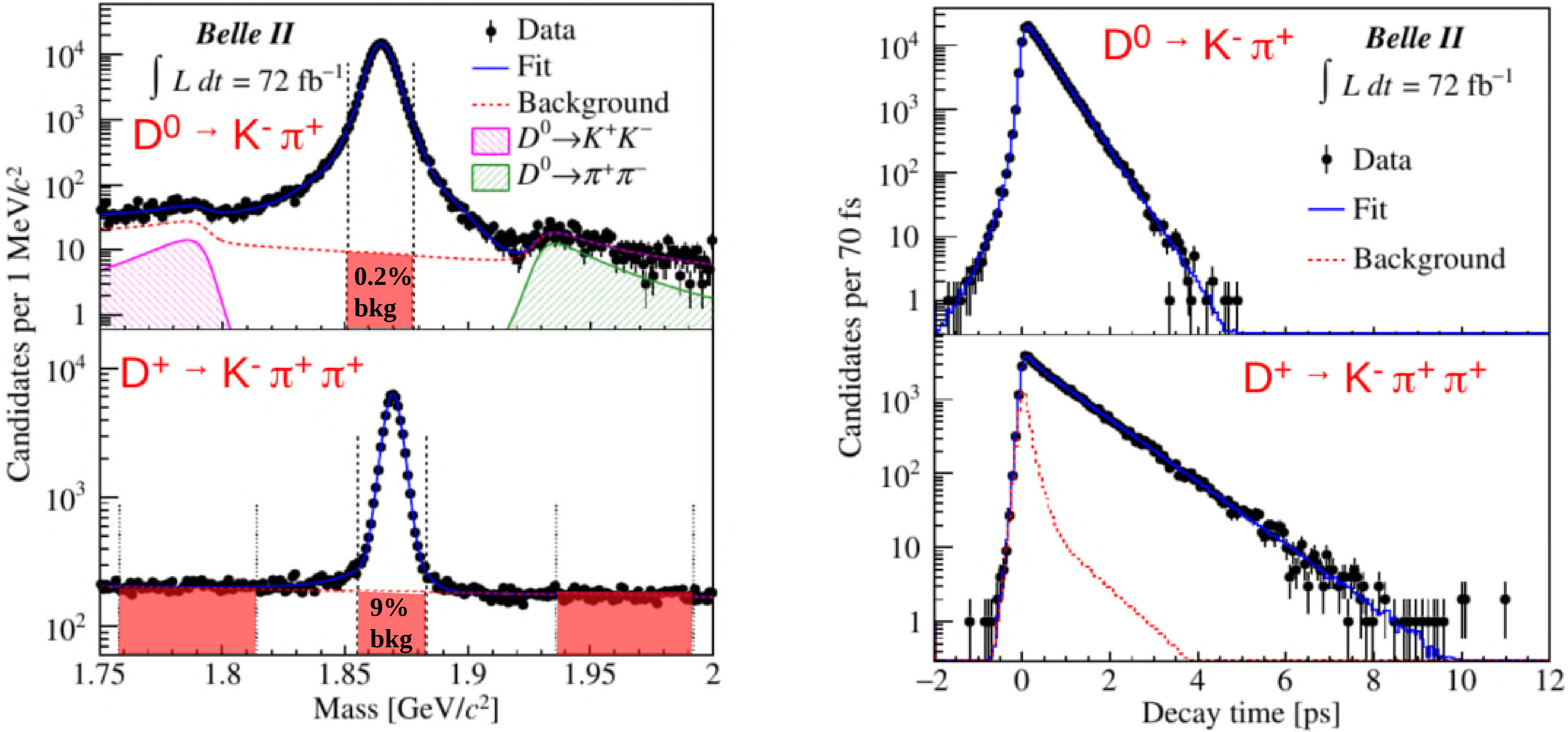
$$t = \frac{m_D}{p}\left(\vec{d} \cdot \hat{\vec{p}}\right)$$



Decay vertex displaced by $\sim 200/500$ μm for D^0/D^+

Measurement of D^0 and D^+ lifetimes

Hot topic!



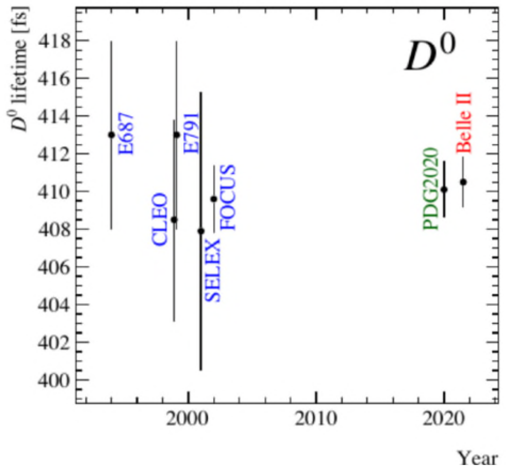
For D^0: Small background contamination ignored in the fit (considered within syst. uncertainties)

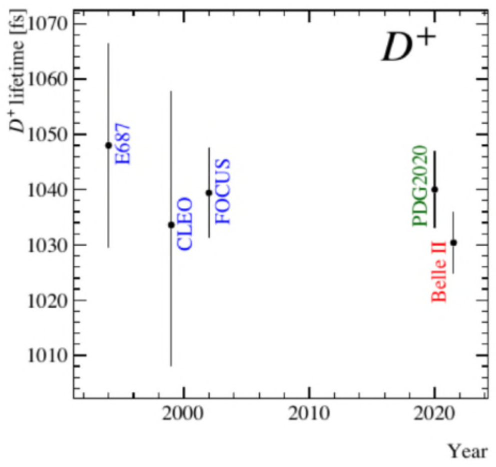
For D^+: Bkg. PDF extracted from sideband data (simultaneous fit for sideband and signal region)

Measurement of D^0 and D^+ lifetimes

Hot topic!

	Belle II	WA
$\tau(D^0) =$	$(410.5 \pm 1.1 \pm 0.8)$ fs	(410.1 ± 1.5) fs
$\tau(D^+) =$	$(1030.4 \pm 4.7 \pm 3.1)$ fs	(1040 ± 7) fs



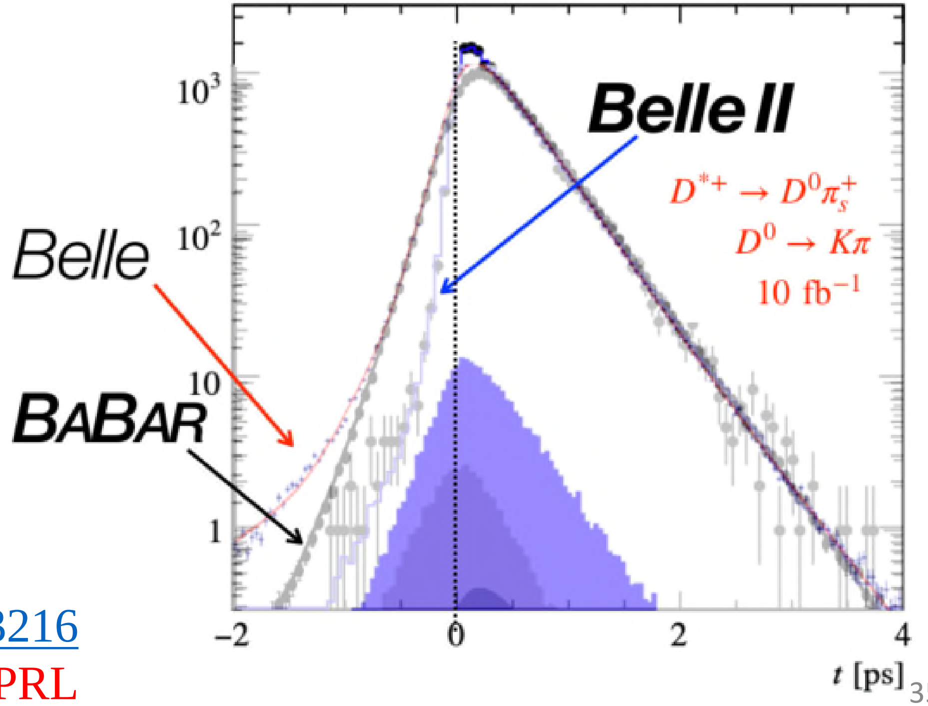


$\Rightarrow$ Results consistent with and more precise than world average

$\Rightarrow$ Still statistically limited, dominant syst. uncertainties come from detector alignment and modelling of background (for D^+)

$\Rightarrow$ First and most precise measurement in last 20 years

$\Rightarrow$ Spectacular demonstration of Belle II vertexing capabilities compared to its predecessors



arxiv:2108.03216

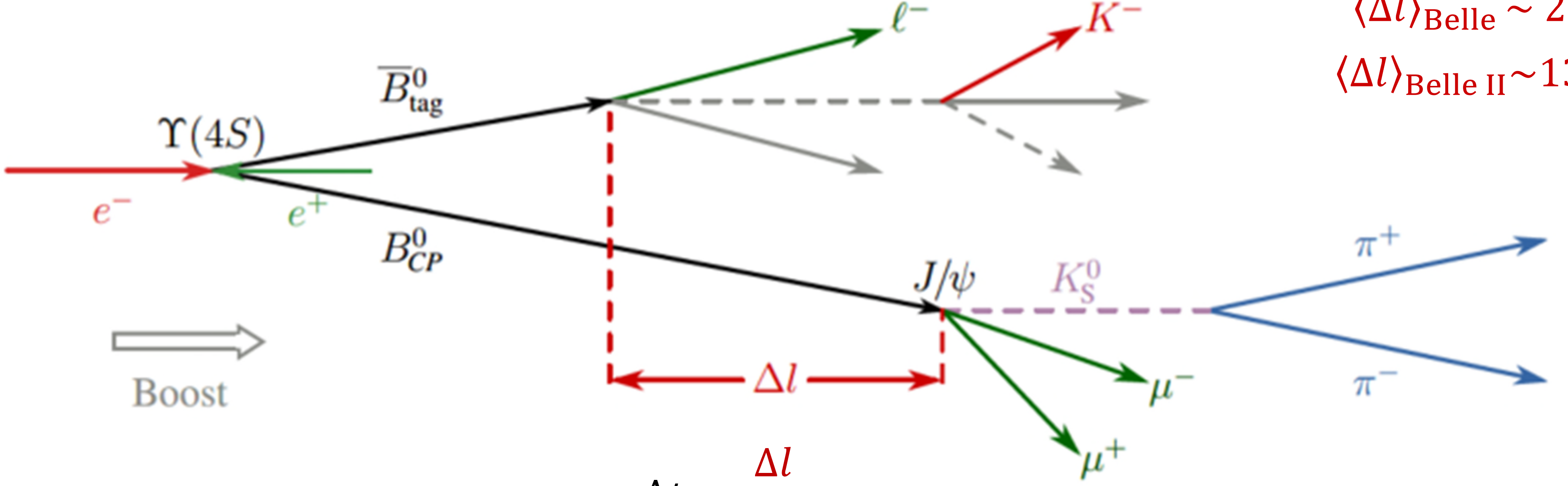
Accepted by PRL

Time-dependent CP violation in B decays

- Flagship measurement of B factories
- Requires vertex reco of signal and tag-side B, and tag-side B flavor q

$\langle \Delta l \rangle_{\text{Belle}} \sim 200\ \mu\text{m}$

$\langle \Delta l \rangle_{\text{Belle II}} \sim 130\ \mu\text{m}$



$$\Delta t = \frac{\Delta l}{\beta\gamma c}$$

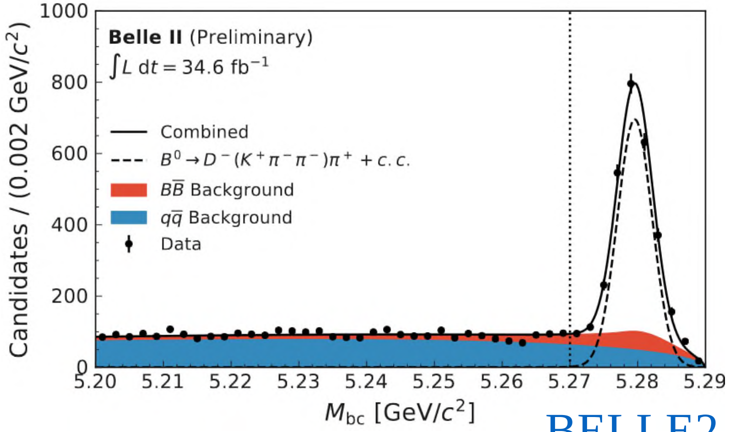
$$\mathcal{P}^{\text{Sig}} = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t)\right)\right] \qquad q_{B^0,\bar{B}^0} = 1, -1$$

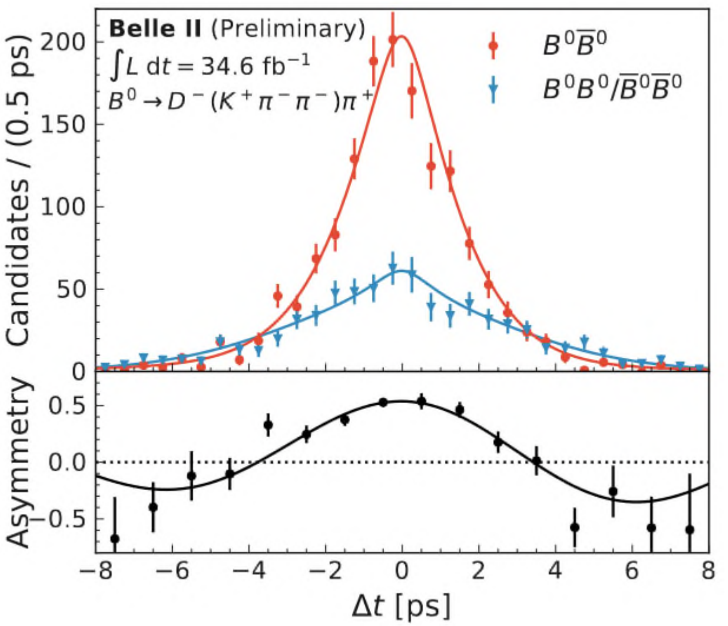
- Still very important at Belle II: φ_1/β (current precision ~0.7°) and φ_2/α (~5°) are fundamental inputs of the CKM fit.

$\Rightarrow$Expect to improve by a factor ~5

Getting ready for TD CPV in $B \to J/\psi K^0$

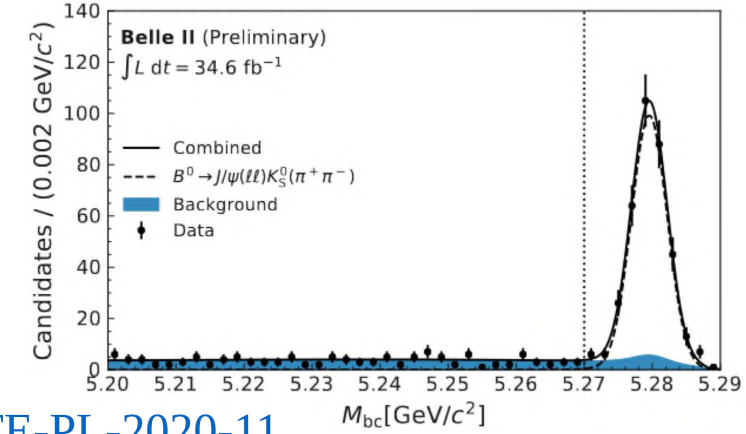
$B^0 - \bar{B}^0$ mixing in $B \to D\pi$



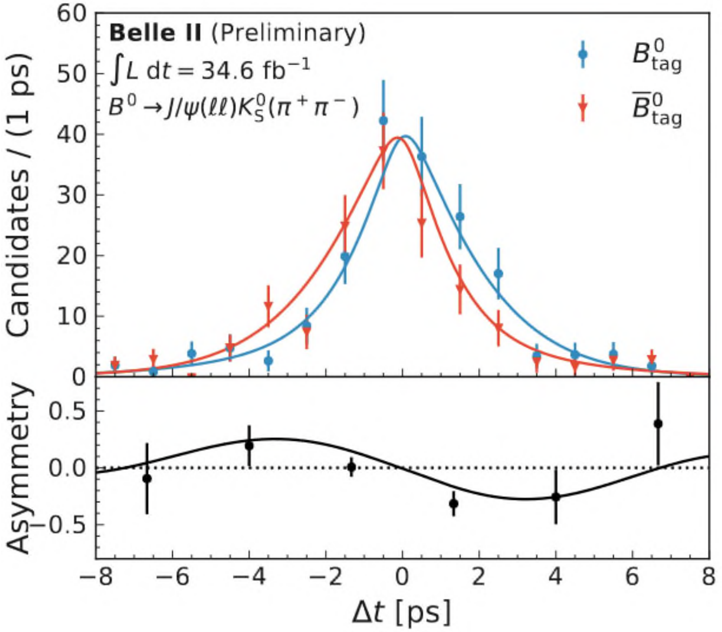


$\Delta m = (0.531 \pm 0.046 \pm 0.013)\ \text{ps}^{-1}$

CP-violation in $B \to J/\psi K_S^0$



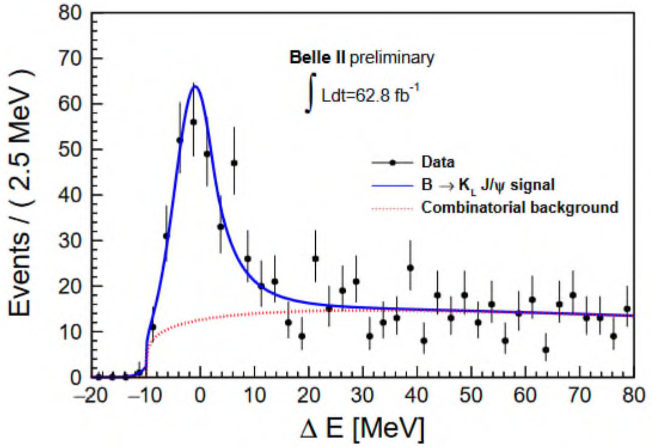
BELLE2-NOTE-PL-2020-11



$\mathcal{S}_{CP} = 0.55 \pm 0.21 \pm 0.04$

(significance $\sim 2.7\sigma$)

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



- ⇒ Reconstruction and MVA selection relies on neutral clusters in KLM (and ECL)
- ⇒ Reconstructed ~250 events for $J/\psi \to \mu\mu$ and ee
- ⇒ Important and complementary mode

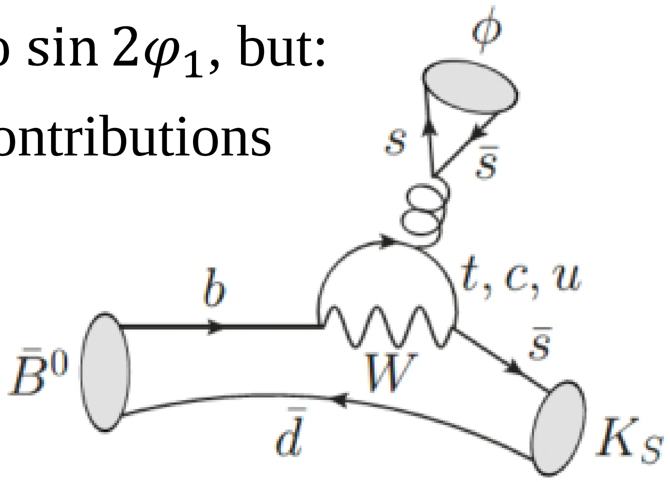
arxiv:2106.13547

Non-SM effects in penguin dominated modes?

- Measurements of TD CPV in $b \to q\bar{q}s$ transitions ($q = u, d, s$) sensitive to $\sin 2\varphi_1$, but:

$\Rightarrow$ Being mostly penguin dominated, potentially very sensitive to non-SM contributions

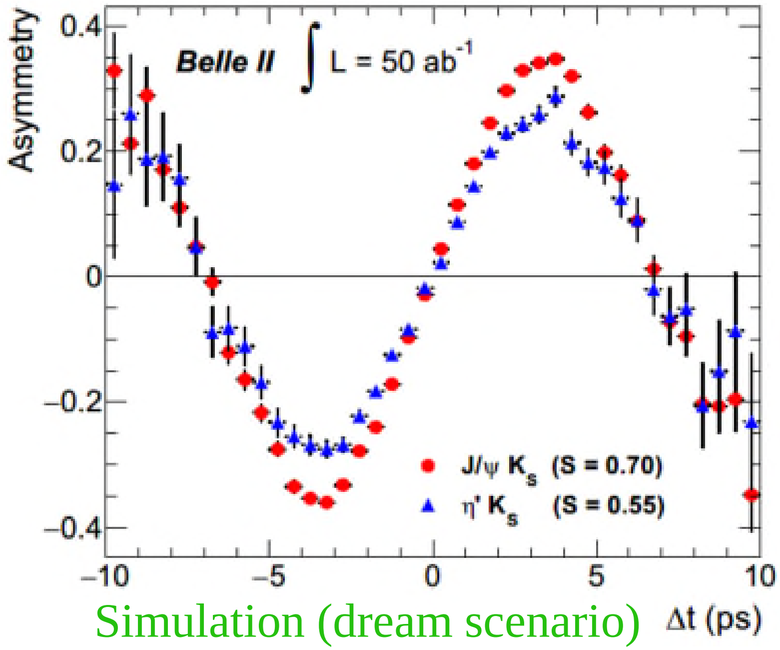
$\Rightarrow$ For some modes, theory can make precise predictions on $\Delta\mathcal{S}_f$



$\Delta\mathcal{S}_f$: difference in $\mathcal{S}_{CP}$ with respect to "golden mode" $J/\psi\ K^0$

Mode	QCDF [662]	QCDF (scan) [662]	$SU(3)$	Data
$\pi^0 K_S^0$	$0.07^{+0.05}_{-0.04}$	$[0.02, 0.15]$	$[-0.11, 0.12]$ [664]	$-0.11^{+0.17}_{-0.17}$
$\rho^0 K_S^0$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.02]$		$-0.14^{+0.18}_{-0.21}$
$\eta' K_S^0$	$0.01^{+0.01}_{-0.01}$	$[0.00, 0.03]$	$(0 \pm 0.36) \times 2\cos(\phi_1)\sin\gamma$ [665]	-0.05 ± 0.06
ηK_S^0	$0.10^{+0.11}_{-0.07}$	$[-1.67, 0.27]$		—
ϕK_S^0	$0.02^{+0.01}_{-0.01}$	$[0.01, 0.05]$	$(0 \pm 0.25) \times 2\cos(\phi_1)\sin\gamma$ [665]	$0.06^{+0.11}_{-0.13}$
ωK_S^0	$0.13^{+0.08}_{-0.08}$	$[0.01, 0.21]$		$0.03^{+0.21}_{-0.21}$

Belle II physics book



Simulation (dream scenario)

Reconstruction of $B \to \eta' K$

- Highly sensitive to non-SM contributions among penguin-dominated modes (most precise $\Delta\mathcal{S}_f$ prediction)
- Key challenge: suppression of continuum background

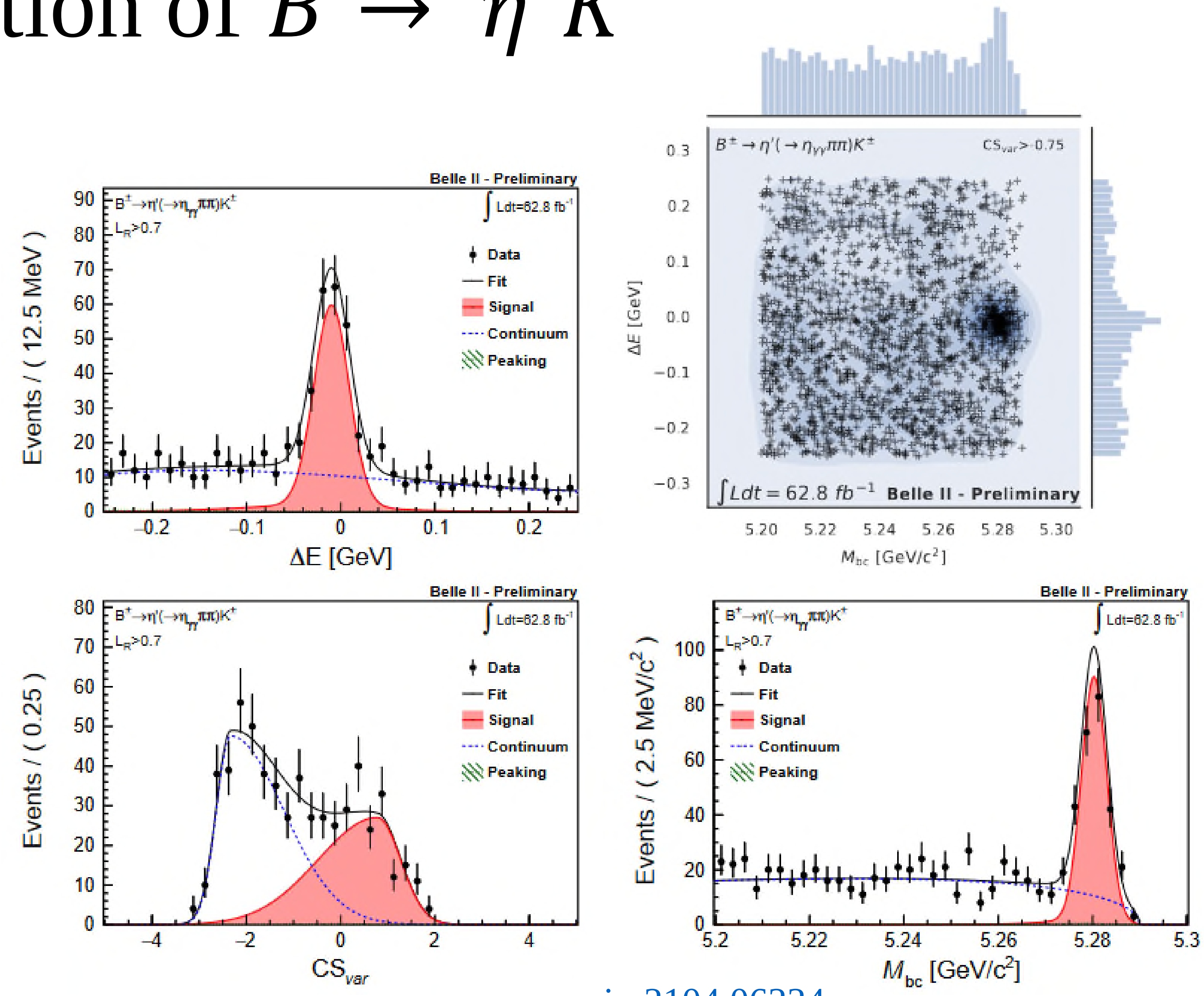
$\Rightarrow$ Use output of MVA discriminator as fit observable

$$\mathcal{B}\left(B^{\pm} \to \eta' K^{\pm}\right) = \left(63.4 \,^{+3.4}_{-3.3}\,(\mathrm{stat}) \pm 3.2\,(\mathrm{syst})\right) \times 10^{-6}$$

$$\mathcal{B}\left(B^{0} \to \eta' K^{0}\right) = \left(59.9 \,^{+5.8}_{-5.5}\,(\mathrm{stat}) \pm 2.9\,(\mathrm{syst})\right) \times 10^{-6}$$

$\Rightarrow$ Consistent with world average

$\Rightarrow$ $\sim 2 \times$ higher yield/lumi than Belle



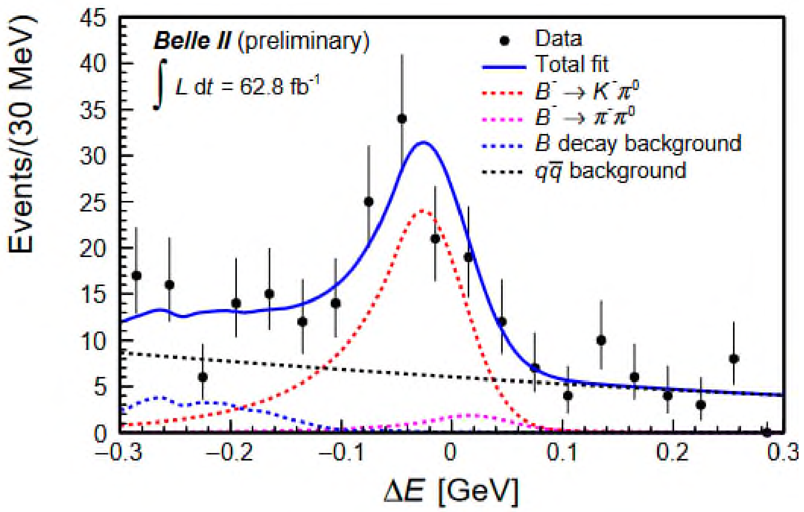
arxiv:2104.06224


SM Benchmarks
Hadronic charmless B decays
Loops →

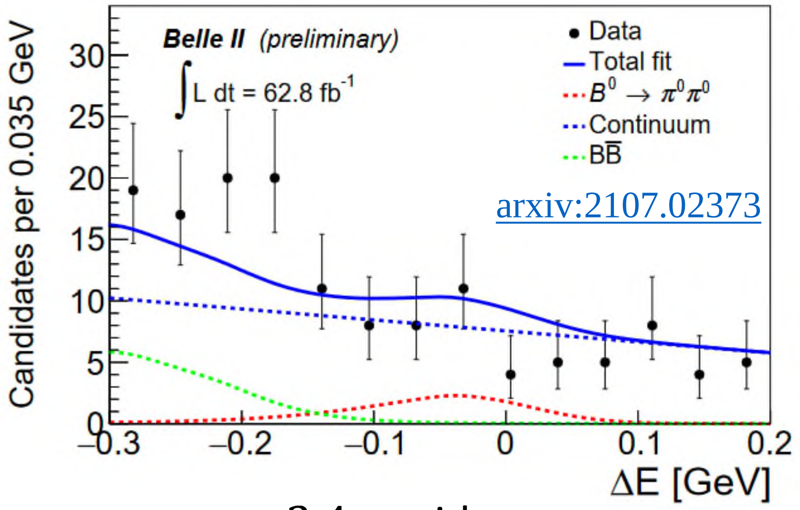
Hadronic charmless B decays

- Weak B decays not mediated by $b \to c$ transitions
- Only way to directly access the CKM angle ϕ_2/α
- Multiple tests of isospin and $SU(3)$ relations
- Exigent indicators of physics performance: challenge PID, neutrals reco and bkg. suppression

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

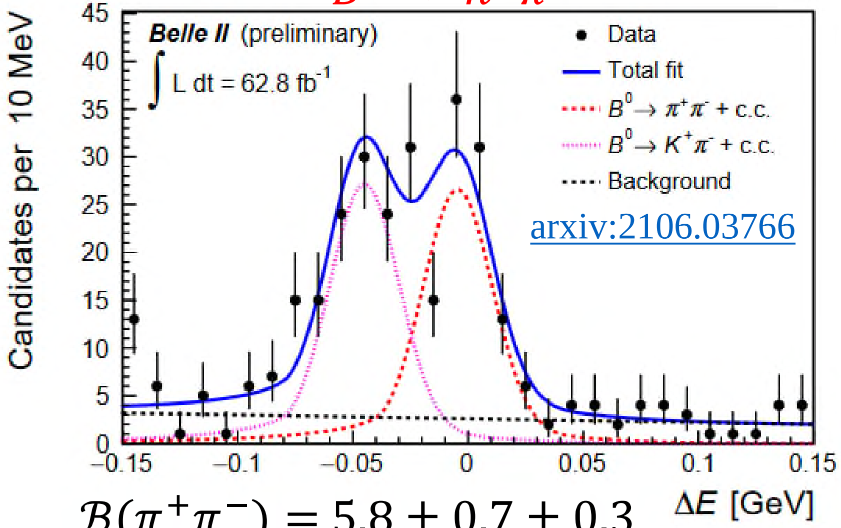


$B^0 \to \pi^0\pi^0$



3.4σ evidence

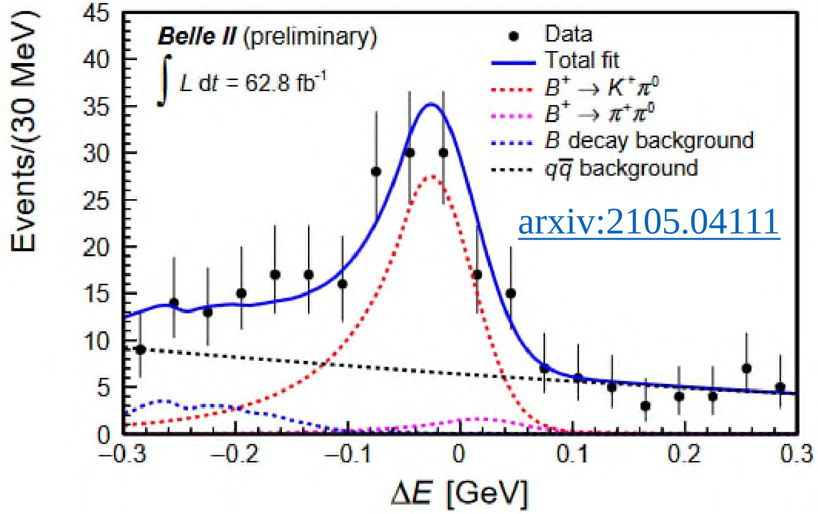
$B^0 \to h^+\pi^-$



$\mathcal{B}(\pi^+\pi^-) = 5.8 \pm 0.7 \pm 0.3$

$\mathcal{A}_{CP}(K^+\pi^-) = -0.16 \pm 0.05 \pm 0.01$

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



$\mathcal{A}_{CP}(K^+\pi^0) = -0.09 \pm 0.09 \pm 0.03$

$\Rightarrow$In agreement with world averages and performance comparable with Belle's

Towards BSM using isospin

A precise sum rule among four $B \to K\pi$ CP asymmetries [1]

Michael Gronau August 2005

A sum rule relation is proposed for direct CP asymmetries in $B \to K\pi$ decays. Leading terms are identical in the isospin symmetry limit, while subleading terms are equal in the flavor SU(3) and heavy quark limits. The sum rule predicts $A_{\rm CP}(B^0 \to K^0\pi^0) = -0.17 \pm 0.06$ using current asymmetry measurements for the other three $B \to K\pi$ decays. A violation of the sum rule would be evidence for New Physics in $b \to s\bar{q}q$ transitions.

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

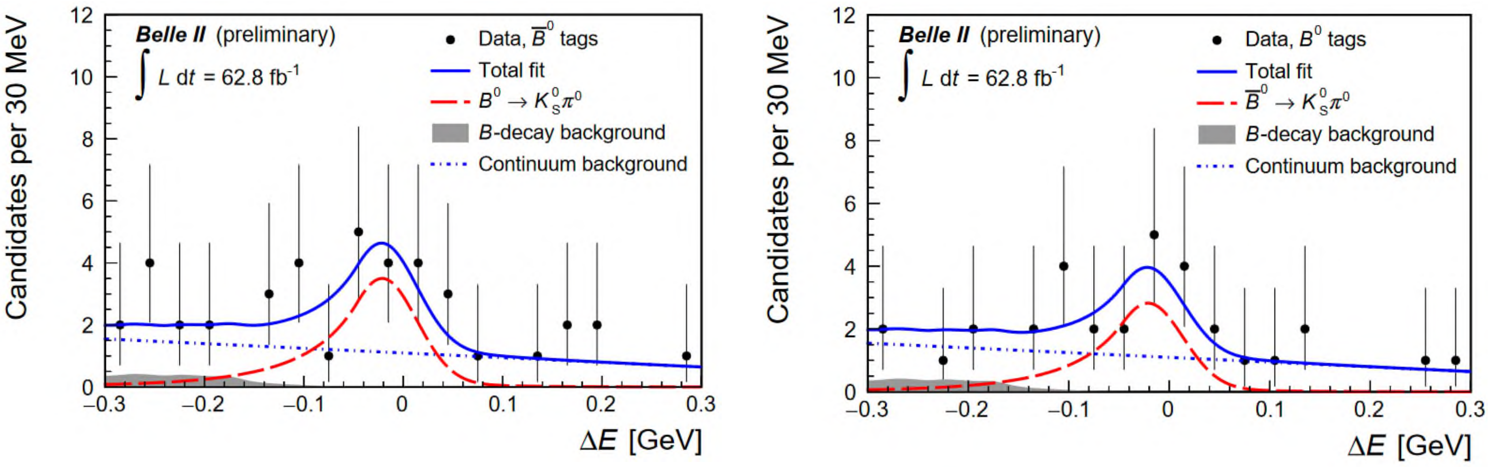
$\Rightarrow$ Measured all inputs

arxiv:2105.04111

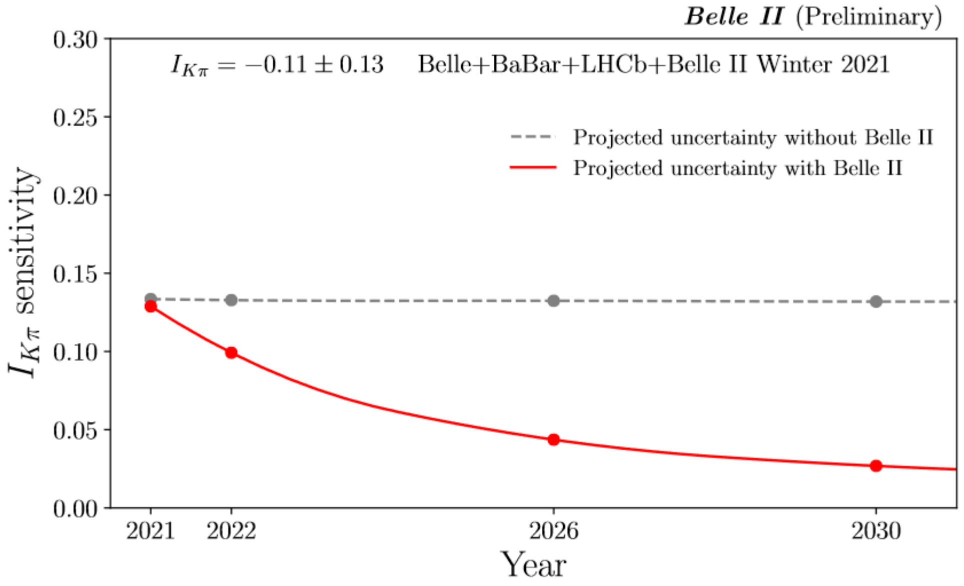
arxiv:2106.03766

arxiv:2104.14871

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



$\mathcal{A}_{CP}(K^0\pi^0) = -0.40 \pm 0.45 \pm 0.04$



$\Rightarrow$ Precision will be limited by $\mathcal{B}$ and $\mathcal{A}_{CP}$ of $K^0\pi^0$

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

- Isospin analysis of $B \to \rho\rho$ decays provides most precise constraint on ϕ_2/α
- Precision currently limited by $B \to \rho^+\rho^0$
- Needs measurement of long. pol. fraction f_L (CP-eigenvalue depends on the helicity state)

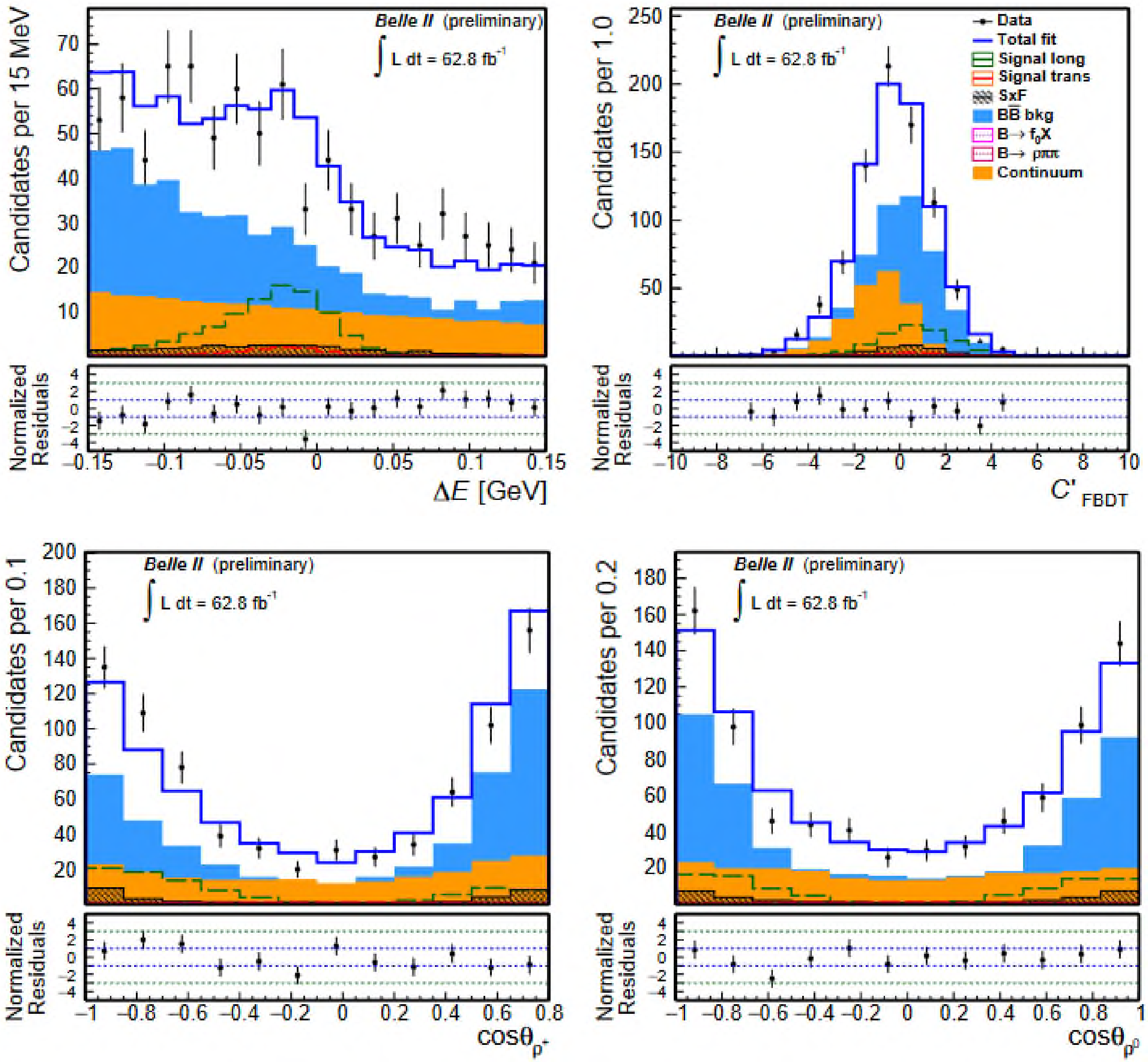
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(\mathrm{stat}) \pm 4.0(\mathrm{syst})] \times 10^{-6}$$

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

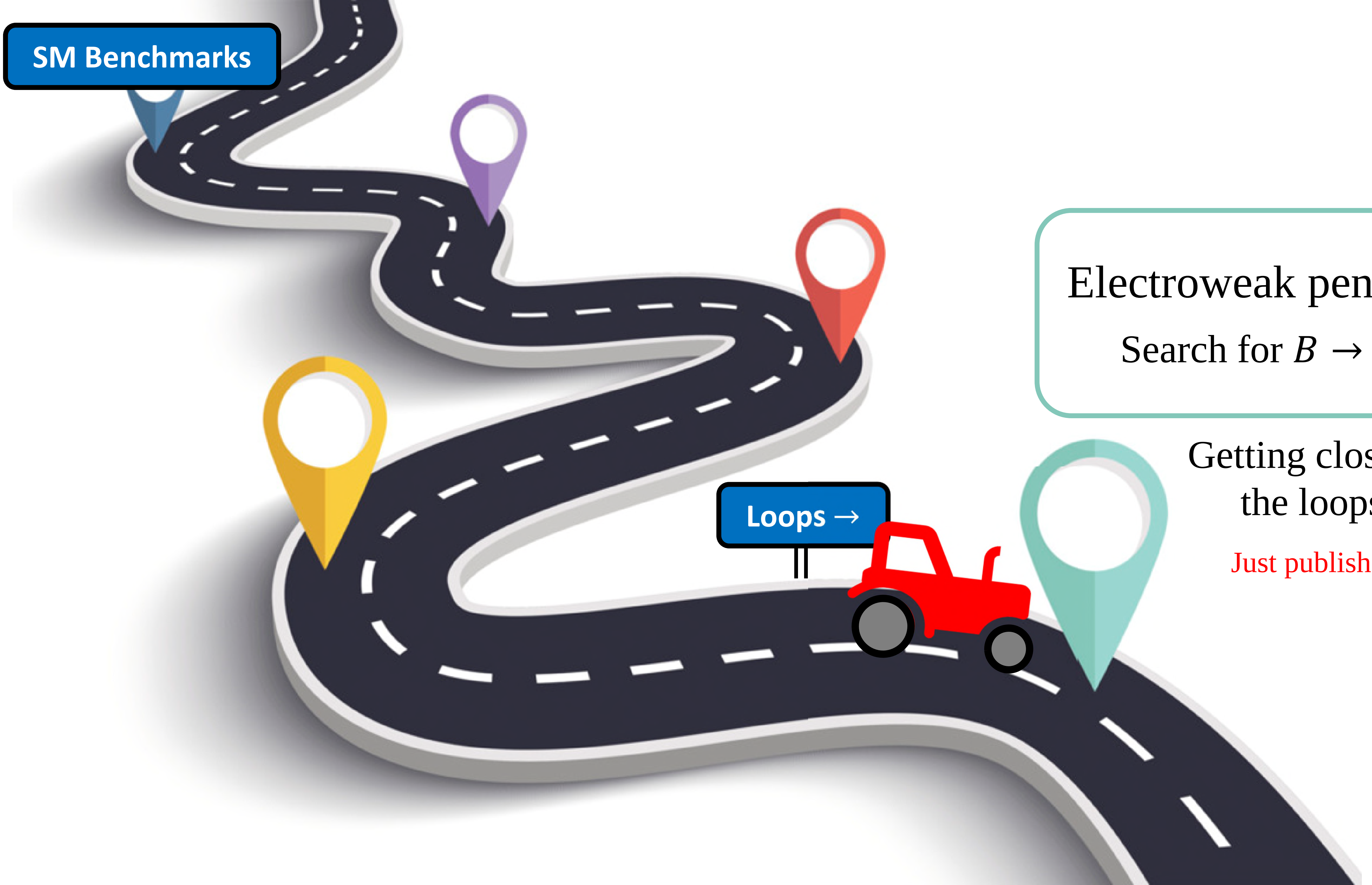
⇒ Compatible with world average

⇒ Improved performance by factor ~2 wrt. early Belle thanks to improved bkg. suppression and 6D ML fit

⇒ About to update Belle measurement using same method on Belle data (using B2BII)



arxiv:2109.11456



Electroweak penguins:

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

Getting closer to the loops!

Just published!

Electroweak penguins

- Radiative and electroweak penguin decays are flavor-changing neutral currents (FCNC) which proceed via loop diagrams in the standard model and thus suppressed

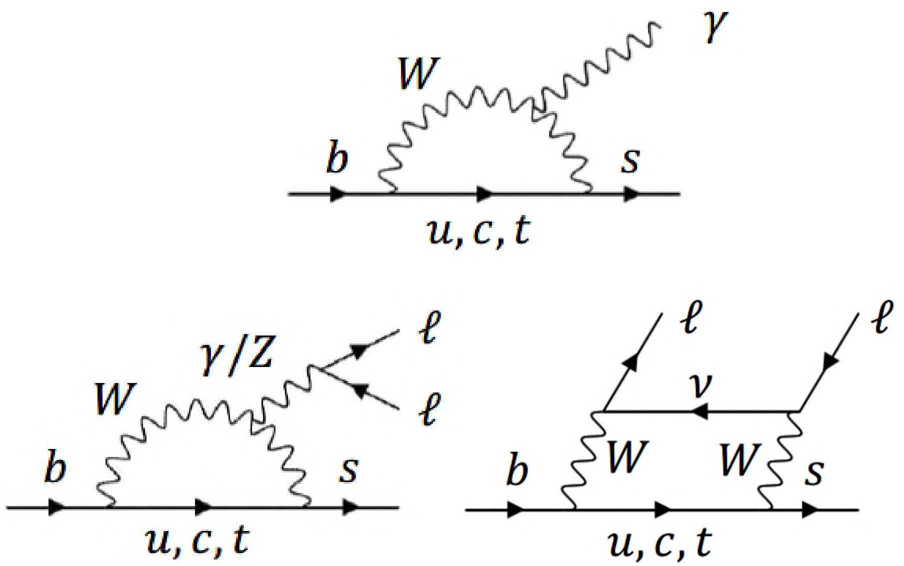
$\Rightarrow$ Sensitive to non-SM contributions in the loop

Highlights of recent Belle II results:

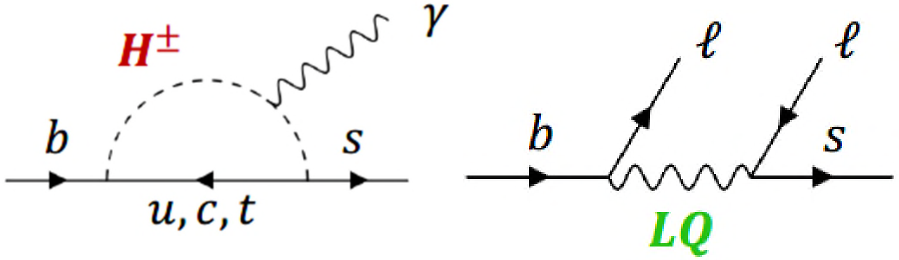
- Exclusive measurement of $\mathcal{B}(B \to K^*\gamma)$
- Observation of $B \to X_s\gamma$ with untagged method
- Search for $B^+ \to K^+\nu\bar{\nu}$ with inclusive tagging

Novel method producing first Belle II B-physics paper

Diagrams in SM



Possible non-SM contributions



Charged Higgs

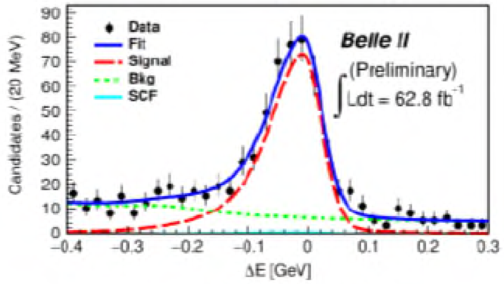
Leptoquark

Electroweak penguins

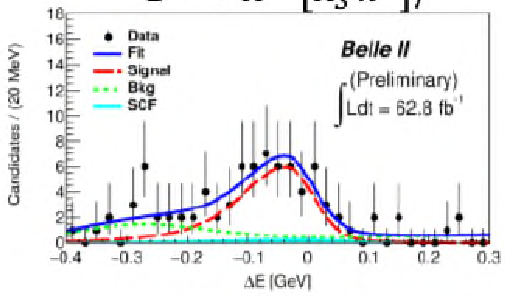
Exclusive $B \to K^*\gamma$

- B decays fully reconstructed with high-energy photons

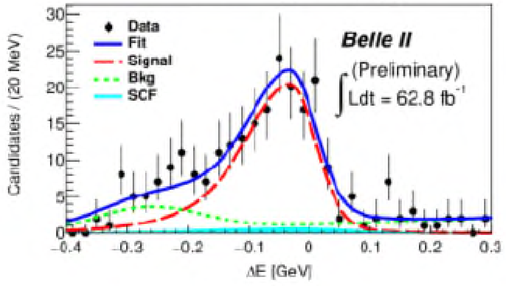
$B^0 \to K^{*0}[K^+\pi^-]\gamma$



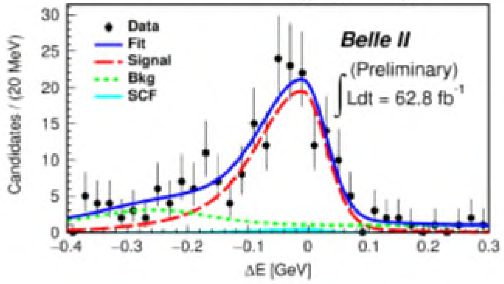
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$



$B^+ \to K^{*+}[K^+\pi^0]\gamma$



$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$



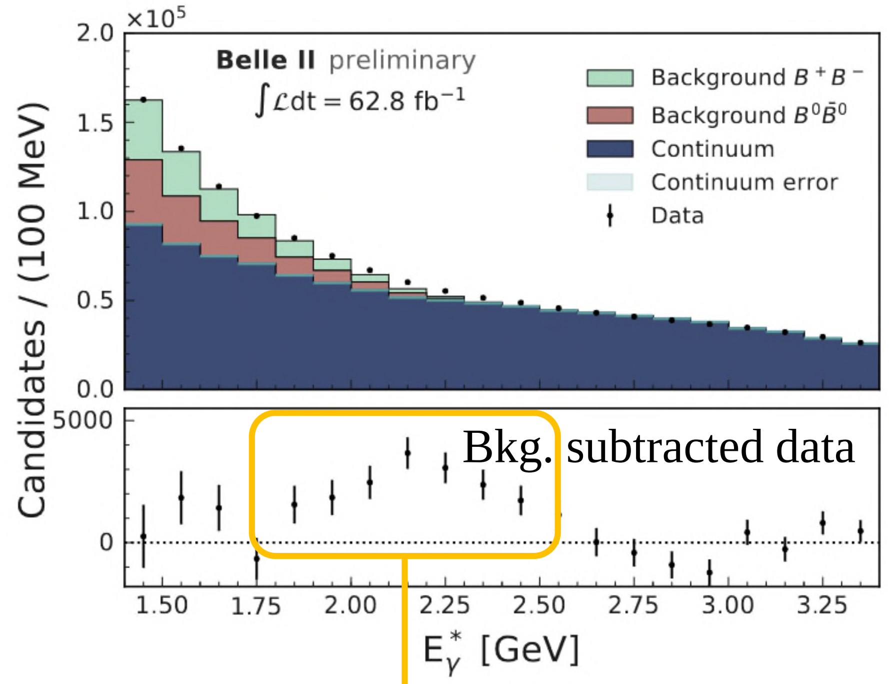
Mode	Br (fit) x10^{-5}	Br (PDG) x10^{-5}
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$4.5 \pm 0.3(\text{stat}) \pm 0.2(\text{syst})$	4.18 ± 0.25
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	$4.4 \pm 0.9(\text{stat}) \pm 0.6(\text{syst})$	
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$5.0 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$	3.92 ± 0.22
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	$5.4 \pm 0.6(\text{stat}) \pm 0.4(\text{syst})$	

$\Rightarrow$ All values consistent with world average

arxiv:2110.08219

Inclusive untagged $B \to X_s\gamma$

- Select single photon after background suppression and use energy spectrum to extract signal

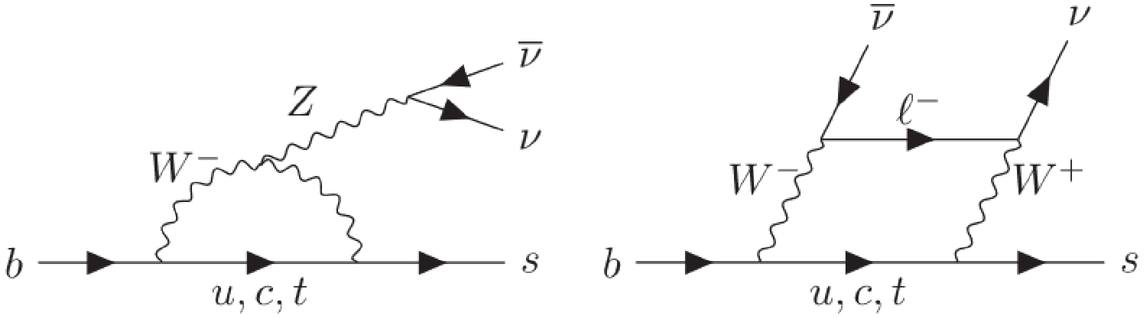


$\Rightarrow$ Excess at expected energy clearly visible.

BELLE2-NOTE-PL-2021-004

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

Hot topic!



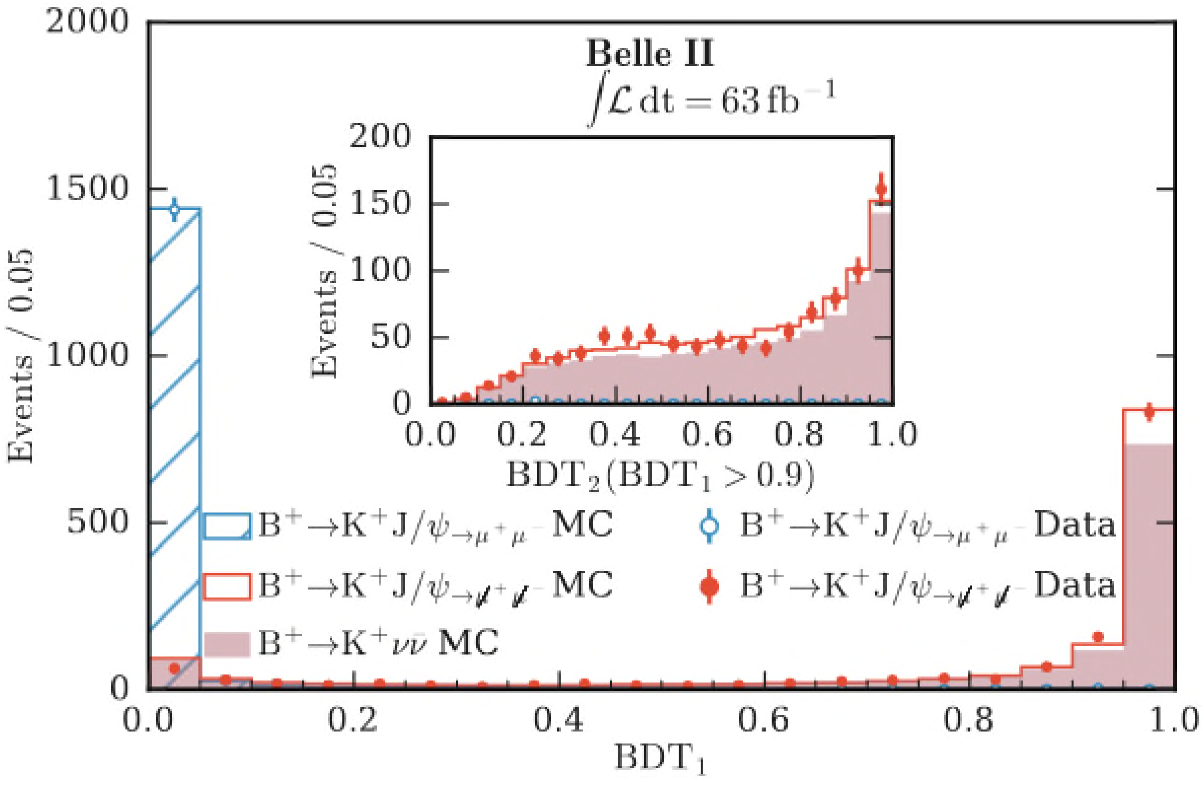
- Small theoretical uncertainty due to absence of charged leptons
- Select track with highest transverse momentum as signal Kaon and tag event using remaining objects
- Train MVA (BDT) to suppress backgrounds using vertex and topological info, missing energy, and ΔE of other B meson (remaining objects).

⇒ Two BDT-classifiers are trained BDT_1 and BDT_2

⇒ Select events with $\mathrm{BDT}_1 > 0.9$ and then train BDT_2

- Signal extracted from $(p_T(K^+), \mathrm{BDT}_2)$ hist. via binned ML fit

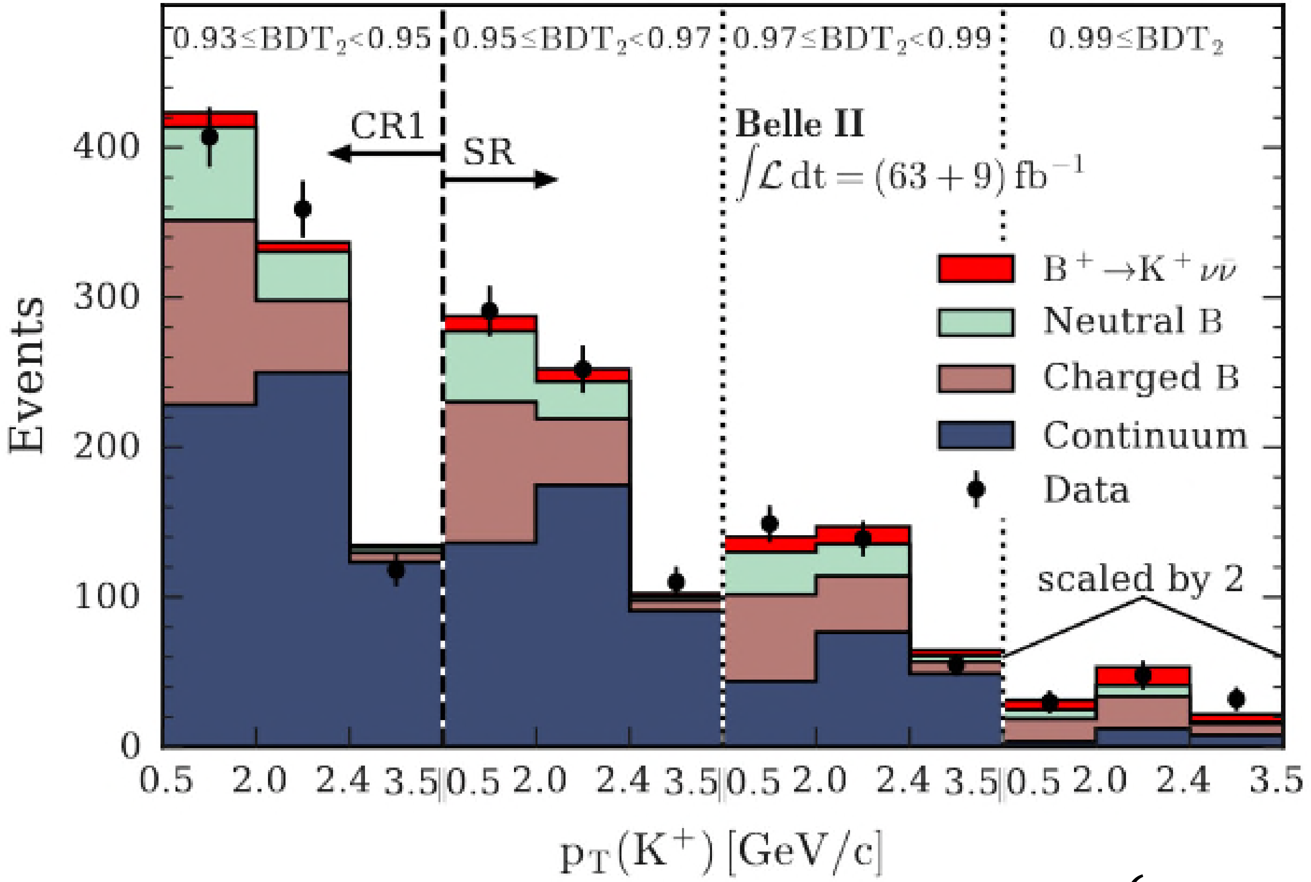
BDT validation with $B^+ \to J/\psi(\mu\mu)\, K^+$ data



PRL:127.181802

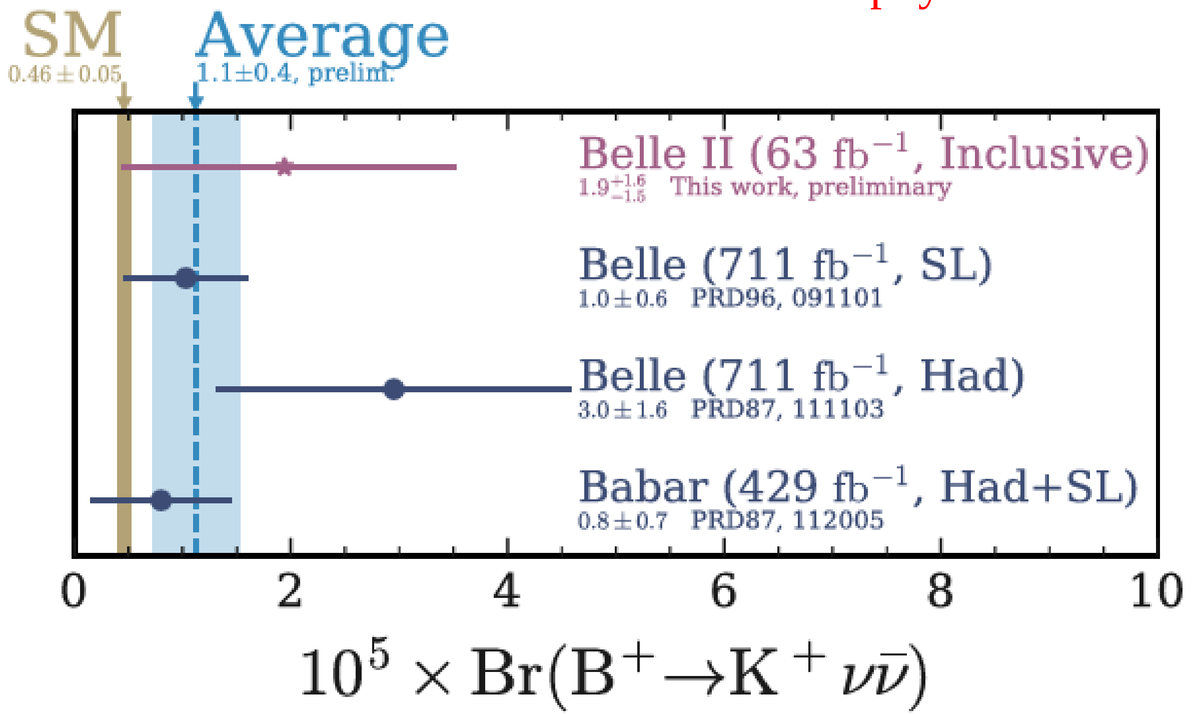
Search for $B^+ \to K^+\nu\bar{\nu}$

Hot topic!



PRL:127.181802

First Belle II B-physics PRL



$$\mathcal{B} = \left(1.9 \pm 1.3_{\text{stat}} \pm 0.8_{\text{syst}}\right)\%$$

$\Rightarrow$ No significant signal observed and upper limit set to $B < 4.1 \cdot 10^{-5}$(90% CL)

$\Rightarrow$ Already competitive with tagged Belle and BaBar analyses

Summary an outlook

- Good performance confirmed by benchmarking with well-known physics
- Overall good agreement between data and simulation proves good understanding of detector performance and tools
- Despite limited statistics overall Belle II physics performance comparable with or higher than Belle and BaBar.

$\Rightarrow$ Spectacular show off of vertexing capabilities with new D lifetime measurements

$\Rightarrow$ Inclusive measurements start becoming competitive thanks to novel MVA techniques

- Calibration-related systematics not currently an issue but will require more work for future precision measurements
- Restarted taking data this week (updates in progress!)

$\Rightarrow$ Belle II on track to probe non-SM physics in B dynamics

Thank you!
ありがとうございます！