Flavor Physics at Belle II

Pablo Goldenzweig

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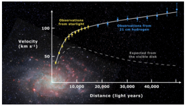
Karlsruhe Institute of Technology

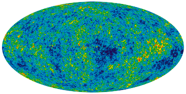
Belle II

Flavor Physics Beyond the Standard Model

Strong evidence that physics beyond the SM exists:

- Temperature fluctuations of cosmic background radiation and rotation curves from spiral galaxies indicate existence of Dark Matter.



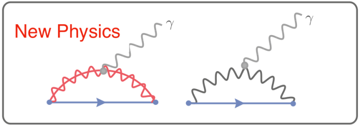


SM not a theory of everything: Quantum mechanics and gravity do not bond.

Perhaps both are a limit of a more fundamental theory?

Intensity Frontier Experiments:

Indirect search of New Physics through quantum effects.

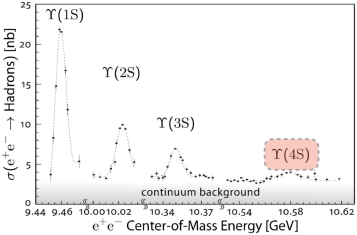


Belle II produces large quantities of b quarks for such searches.

For $e^+e^- \to \tau^+\tau^-$, e.g., F. Tenchini @Flavor2019

Physics of an e^+e^- B Factory

- Collide e^+ and e^- at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.



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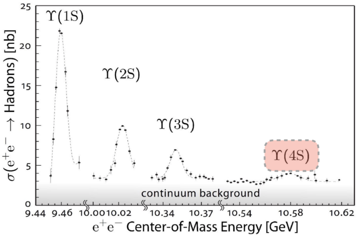
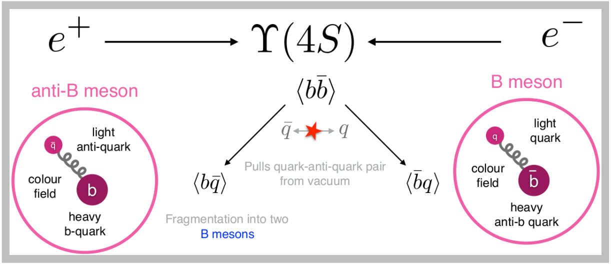
- $\Upsilon(4S)$ decays to B^+B^- and $B^0\bar{B}^0$ 96% of the time.





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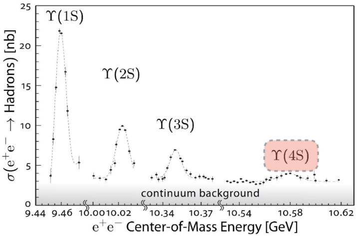
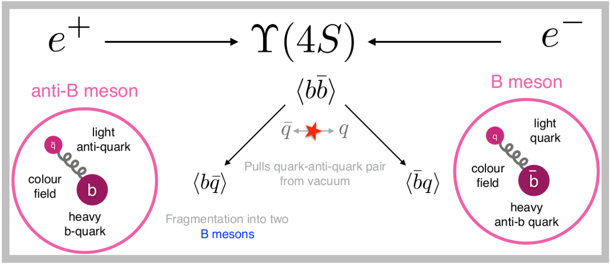
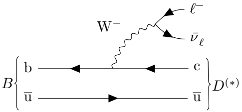
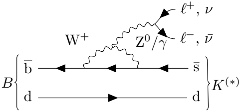
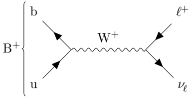
- $\Upsilon(4S)$ decays to B^+B^- and $B^0\bar{B}^0$ 96% of the time.
- Reconstruct B meson from final state particles in detector.





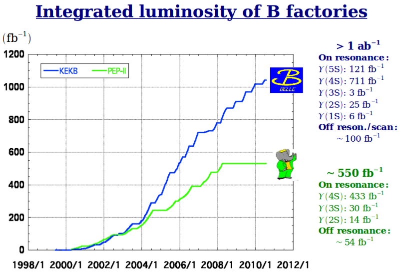






Success of the B Factories (1999-2010)

- Spectacular accelerator and detector performance.
- Discovery of CP violation in B decays.
- Confirmation of the CKM picture of flavor physics.
- Discovery of several new particles.
- Limits on New Physics scenarios.



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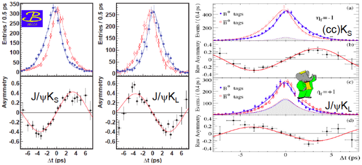
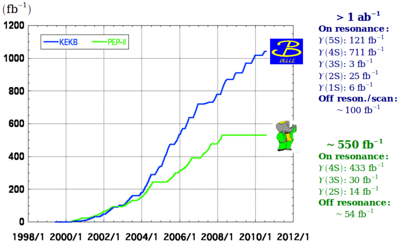


Integrated luminosity of B factories



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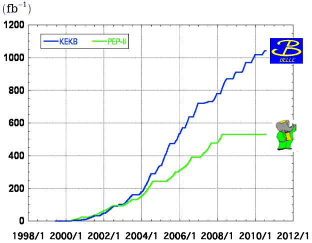
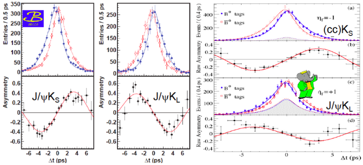
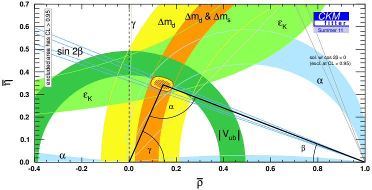


> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}





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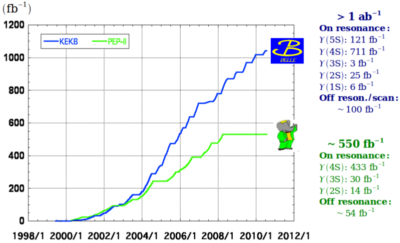

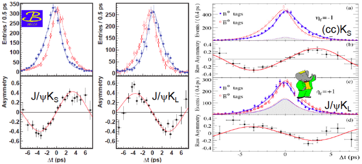

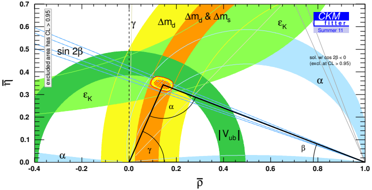

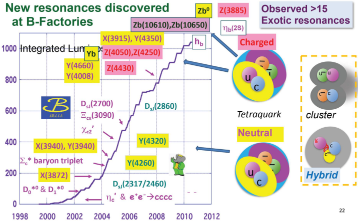

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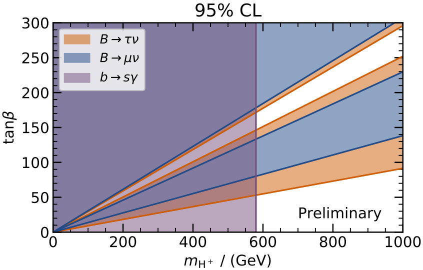
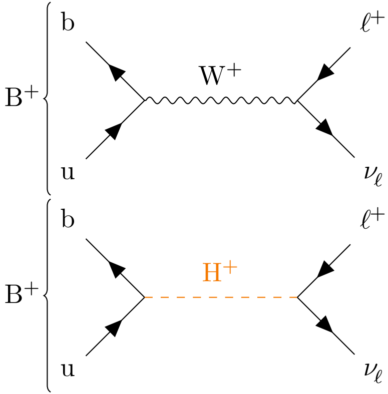
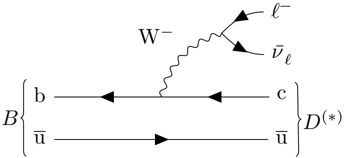
Moriond EW 2019



E.g., 2 Higgs Doublet Model (Type II)

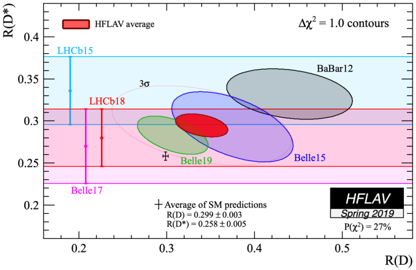


$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell) = \mathcal{B}^{\mathrm{SM}} \times \left| 1 - \frac{m_{\mathrm{B}}^2 \tan^2 \beta}{m_{\mathrm{H}^+}^2} \right|^2$$

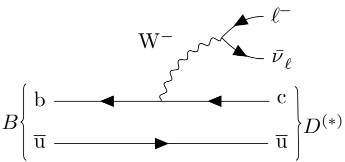


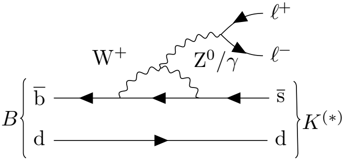
$$\mathcal{R}\left(D^{(*)}\right) = \frac{\mathcal{B}\left(\overline{B}\to D^{(*)}\tau\nu\right)}{\mathcal{B}\left(\overline{B}\to D^{(*)}\ell\nu\right)}$$

Belle 19 1904.08794



⇒ Tensions with the SM





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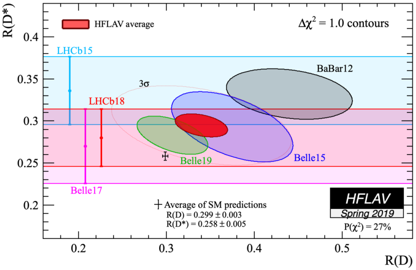

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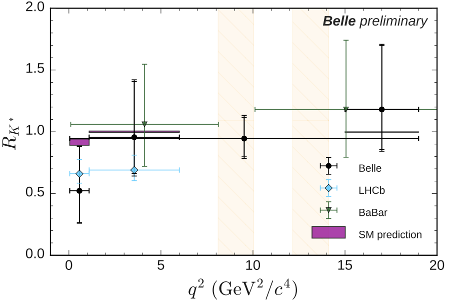
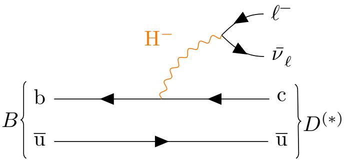
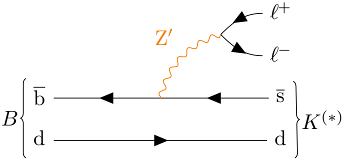


⇒ Tensions with the SM ⇒ $H^{\pm}$, Z', LQ ?





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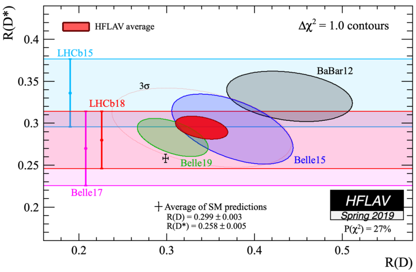

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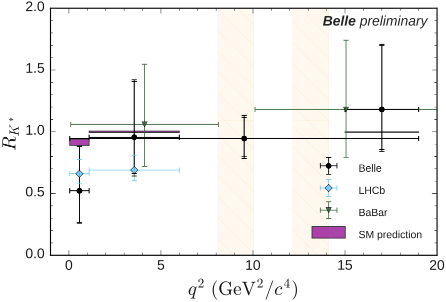


Belle II Physics

Broad program to search for New Physics in B, D and τ decays

- **New CP violating phases?**
  $\Rightarrow$ *CPV in B and D decays.*
- **Signatures of charged Higgs bosons or leptoquarks?**
  $\Rightarrow$ $B^+ \to \ell^+\nu$ *and* $D^{(*)}\tau\nu$ *decays.*
- **Right-handed currents from new physics?**
  $\Rightarrow$ *Photon polarization in radiative decays.*
- **New physics in flavor changing neutral current transitions?**
  $\Rightarrow$ *Electroweak penguin decays* $b \to s\ell^+\ell^-, s\nu\overline{\nu}$.
- **Exotic tetraquark, pentaquark and hybrid QCD states?**
- **Hidden dark sector accessible from B decays?**

The Belle 2 Physics Book (1808.10567)

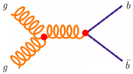
Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

& Quarkonium... Dark Sector...

Belle II Physics

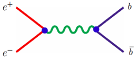
Complementarity with LHCb

LHCb



- Large cross section.
- Decays to all charged particle final states.
- Fast mixing.

Belle II



- Clean experimental environment.
- Holistic interpretation of events with missing energy (ν).
- Decays with multiple photons.
- Inclusive decays ($B \to X_{s,d}\gamma$).
- Long-lived particles (K_S and K_L).

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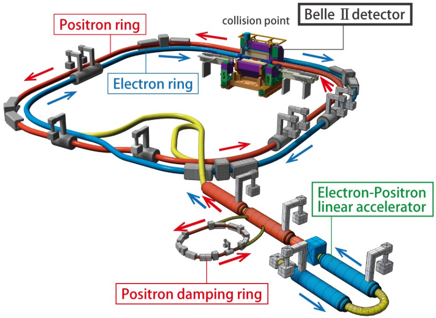
& Quarkonium... Dark Sector...

SuperKEKB Accelerator

Upgrade to achieve 40x peak $\mathcal{L}$ under 20x bkgd

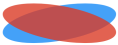
$$\mathcal{L} = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_{\mathcal{L}}}{R_{\xi_y}}\right)$$



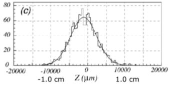
Doubling the beam currents.

Reduction in the beam size by 1/20 at the IP.

Ordinary collision KEKB



Z vertex distribution

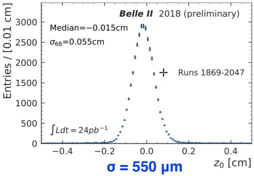


σ = 4.5 mm

Nano-Beam (SuperKEKB)

Z vertex distribution

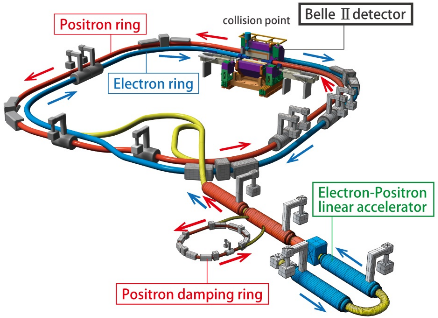
Belle II case 2018 data



σ = 550 μm

Upgrade to achieve 40x peak $\mathcal{L}$ under 20x bkgd

$$\mathcal{L} = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_{\mathcal{L}}}{R_{\xi_y}}\right)$$



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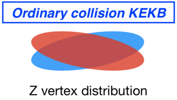
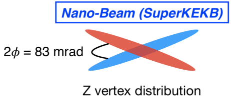
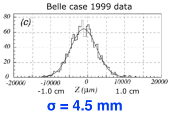
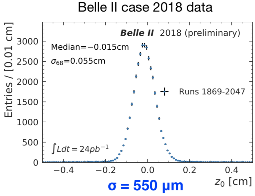
Reduction in the beam size by 1/20 at the IP.





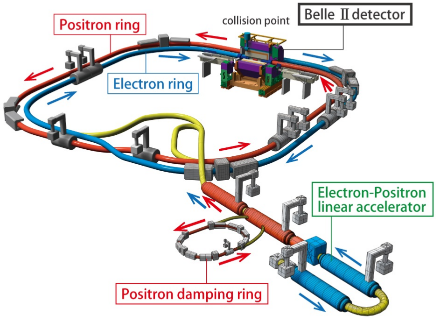




SuperKEKB Accelerator

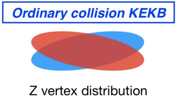
Upgrade to achieve 40x peak $\mathcal{L}$ under 20x bkgd

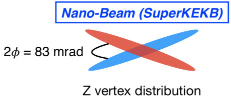
$$\mathcal{L} = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_{\mathcal{L}}}{R_{\xi_y}}\right)$$

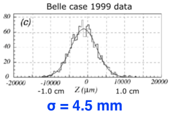


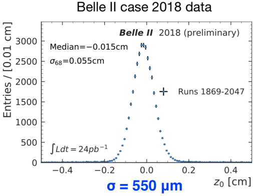
Doubling the beam currents.

Reduction in the beam size by 1/20 at the IP.

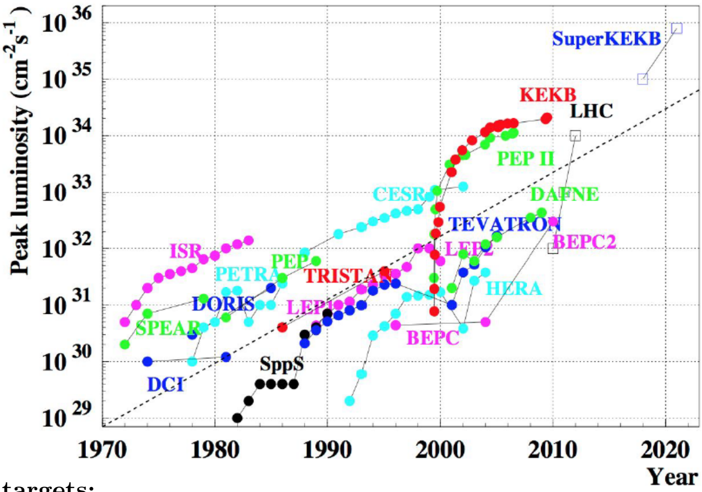








SuperKEKB ⇒ *The Intensity Frontier*

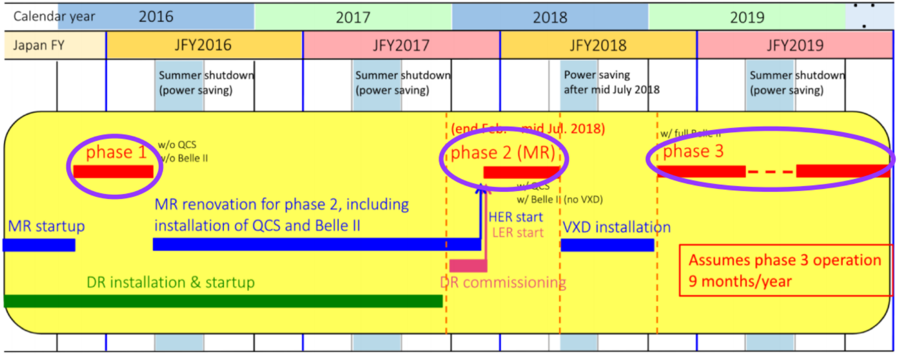


Belle II targets:

$\mathcal{L}_{\textbf{Instantaneous}} = 8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$

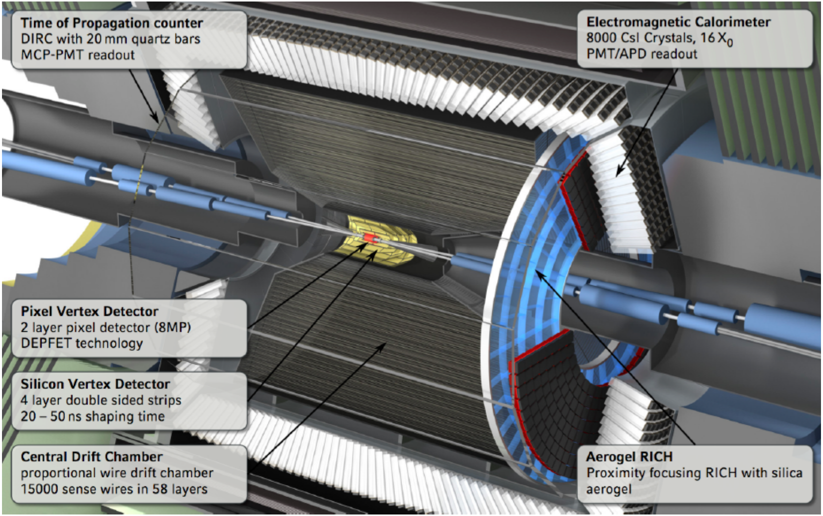
$\mathcal{L}_{\textbf{Integrated}} = 50\text{ab}^{-1}$ **by 2024** **(50× Belle dataset)**

Global Schedule



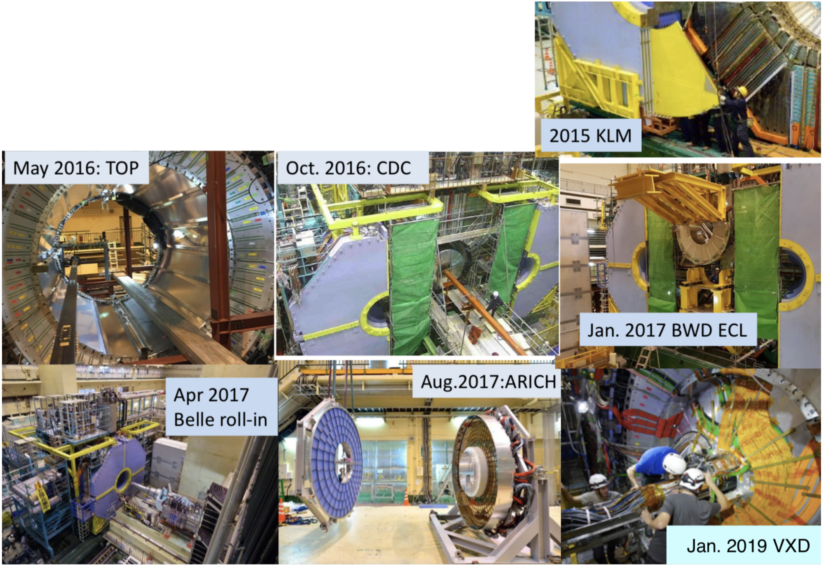
- **Phase 1:** SuperKEKB commissioning without final focusing and without Belle II detector [1-6/2016].
- **Phase 2:** Collision data taking with final focusing. Belle II with no final vertex detector [4-7/2018]. Recorded 0.5 fb^{-1}. Results shown today.
- **Phase 3:** Collision data taking with full Belle II detector [3/2019].

The Belle II Detector

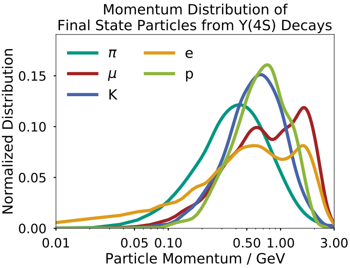


Targeted improvements: *Increase K_S^0 efficiency; Improve IP and secondary vertex resolution, K/π separation, and π^0 efficiency; Particle and μ ID in endcaps.*

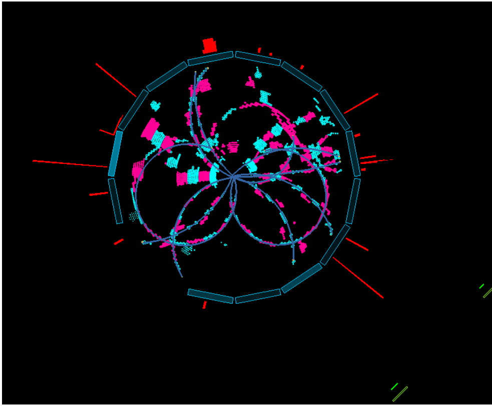
Sub-detector Installation



- Few tracks and clusters.
- Nothing produced in addition to the $\Upsilon(4S)$.
- *High reconstruction efficiency*.
- *Very good particle identification*.



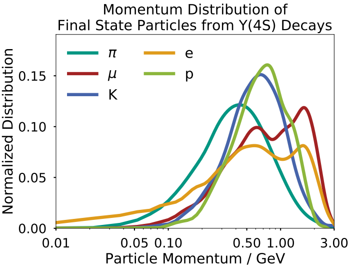
Spring 2018 pilot run



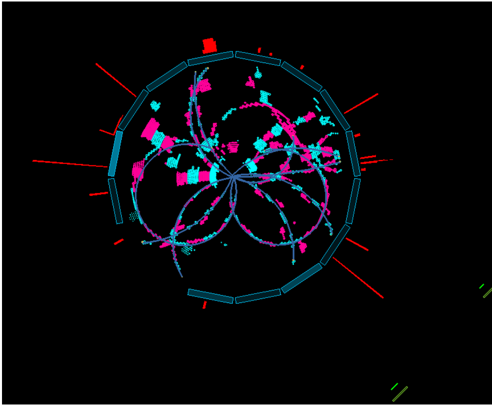
Belle II Hadronic Event

- Few tracks and clusters.
- Nothing produced in addition to the $\Upsilon(4S)$.

- *High reconstruction efficiency.*
- *Very good particle identification.*



Spring 2018 pilot run



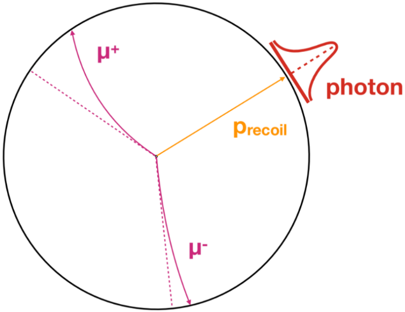
→ *Large beam-induced backgrounds.*

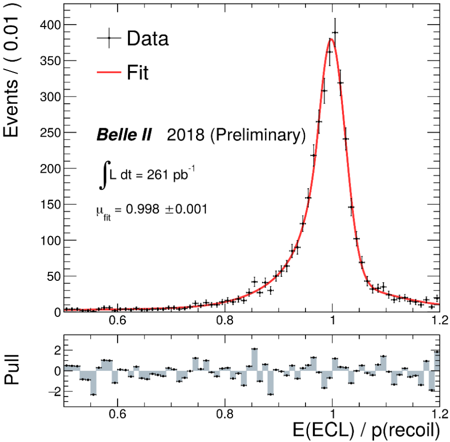
→ *Low p_T tracks.*

Neutral Reconstruction: *Key Belle II Strength*

Radiative dimuon events in first data

$$e^+e^- \to \mu^+\mu^-\gamma$$





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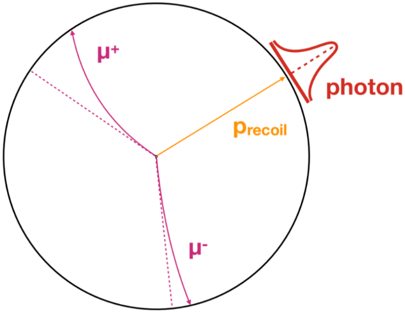
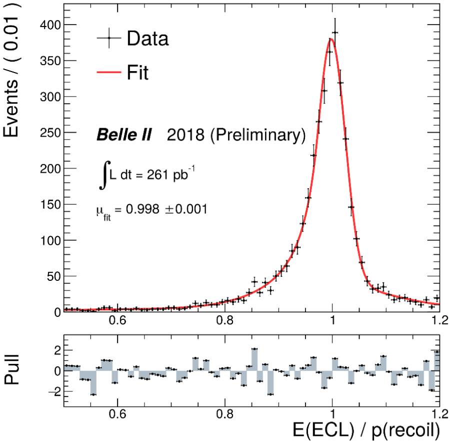
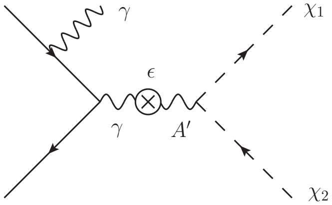




⇒ ***Ready for dark matter searches with NEW single & triple photon triggers***

Dark Photon

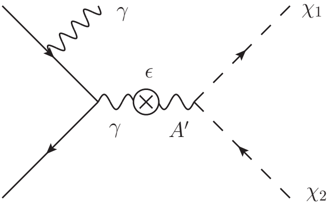


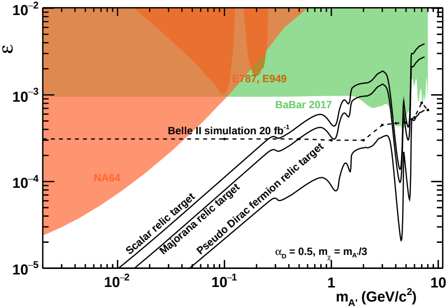
- Massive vector particle A' mixes with the SM γ.
- Can decay to experimentally invisible $A' \to \chi_1\chi_2$ final state.

$\Rightarrow$ Require ISR γ:

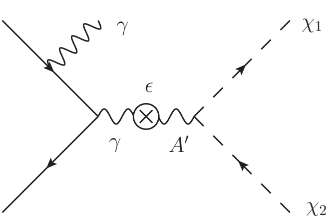
$$E_{\gamma ISR} = \frac{s - m^2_{A'}}{2\sqrt{s}}$$

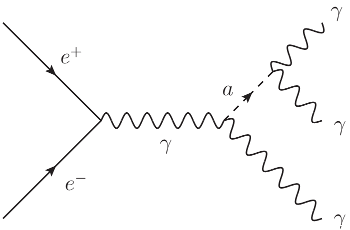
Dark Photon

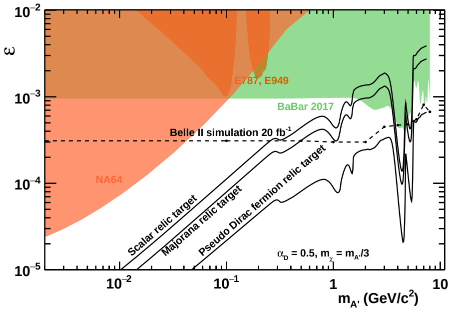




1808.10567



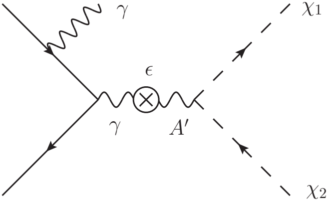


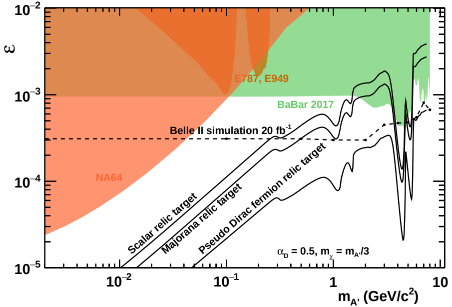


1808.10567

- ALP-strahlung experimentally easier than γ-fusion.
- Three photons within tracking acceptance:
  $\Rightarrow$ Add up to beam energy.
  - Zero tracks.
  - Bump in di-γ mass.

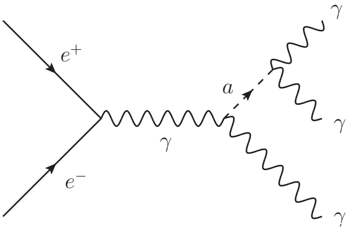
Dark Photon

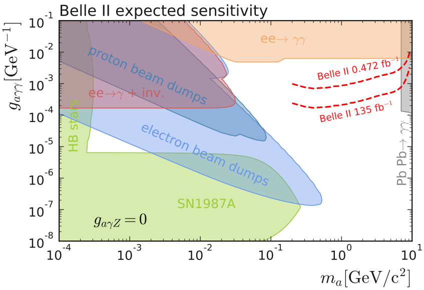




1808.10567

ALPs



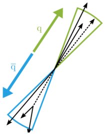


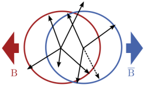
No systematics. 1709.00009

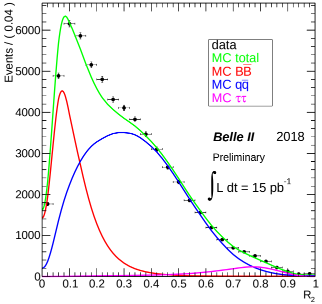
Only dominant $e^+e^- \to \gamma\gamma\gamma$ background included.

135fb^{-1} assumes no $\gamma\gamma$ trigger veto in the barrel.

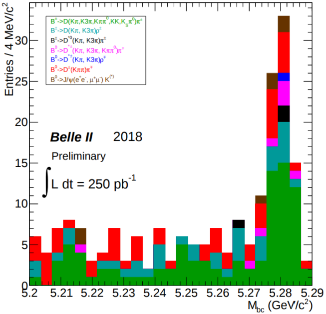
Topological variables used to suppress light-quark-jet $e^+e^- \to q\bar{q}$ continuum background.







$$R_2 = \frac{H_2}{H_0}, \quad H_l = \sum_{i,j} \frac{|p_i||p_j|}{E_{\mathrm{vis}}^2} P_l\left(\cos\theta_{i,j}\right)$$



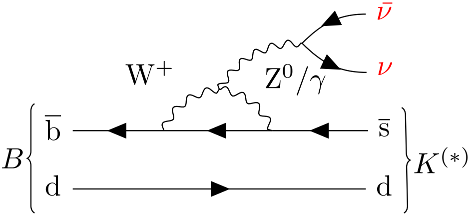
$$M_{bc} \equiv \sqrt{E_{beam}^2 - p_B^2}$$

Rediscovery of several B meson decays.

Missing Energy Decays

Several key B decay channels contain neutrinos in the final state: $\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$, $B^+ \to \ell^+\nu_\ell$, $B^+ \to \ell^+\nu_\ell\gamma$, $B \to \pi\ell\nu_\ell$,

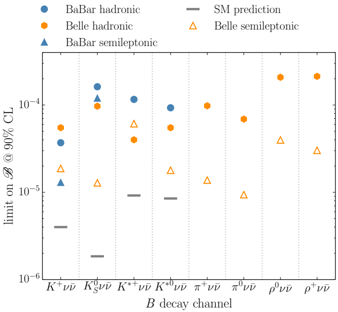
$B \to h^{(*)}\nu\bar{\nu}$



Cannot be directly reconstructed

Several key B decay channels contain neutrinos in the final state: $\overline{B} \to D^{(*)} \ell \overline{\nu}_\ell$, $B^+ \to \ell^+ \nu_\ell$, $B^+ \to \ell^+ \nu_\ell \gamma$, $B \to \pi \ell \nu_\ell$,

$B \to h^{(*)} \nu \overline{\nu}$



– Observed limits leave room for NP contributions.
  1702.03224
– Axion/ALP are prime NP candidates.
  1612.05492
  1612.08040

Missing Energy Decays

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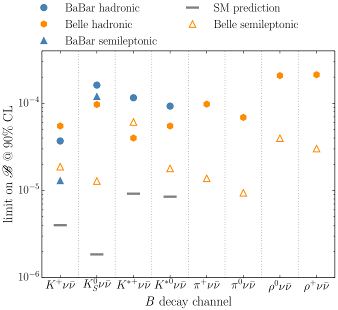


– Observed limits leave room for NP contributions. 1702.03224

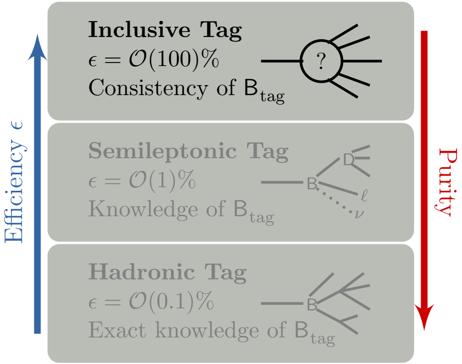
– Axion/ALP are prime NP candidates. 1612.05492 1612.08040

Take advantage of experimental setup of B-factories:

- **$B\bar{B}$ pairs are produced without any additional particles;**
- **Detectors enclose the interaction region almost hermetically;**
- **Collision energy (initial state) is precisely known:**

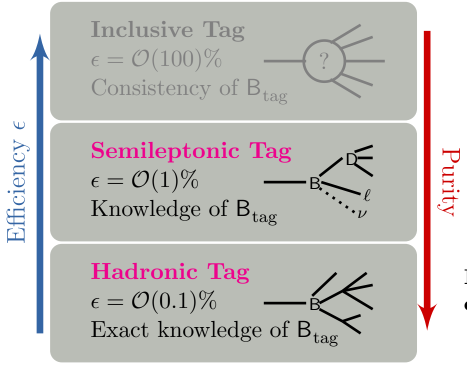
$$p_{e^+} + p_{e^-} = p_B + p_{\bar{B}}.$$

B Tagging



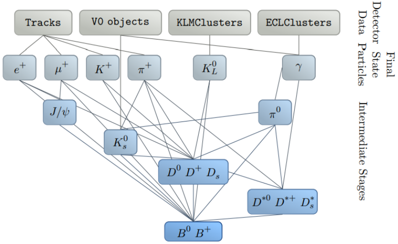
Inclusive Tag
$\epsilon = \mathcal{O}(100)\%$
Consistency of B_{tag}
?
Semileptonic Tag
$\epsilon = \mathcal{O}(1)\%$
Knowledge of B_{tag}
B
D
ℓ
ν
Hadronic Tag
$\epsilon = \mathcal{O}(0.1)\%$
Exact knowledge of B_{tag}
B
Efficiency ϵ
Purity

B Tagging



T. Keck *et al.*, Comput Softw Big Sci (2019) 3: 6

Exclusive Tagging:
The Full Event Interpretation (FEI)

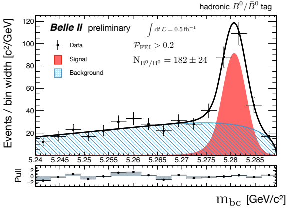


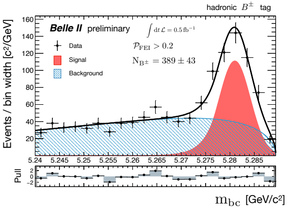
Hierarchical tag-side B-meson recombination algorithm for Belle II.

- Utilizes $\mathcal{O}(200)$ decay channels with BDTs trained for each decay.
- Reconstructs $\mathcal{O}(10\text{k})$ unique decay chains in 6 stages.
- 3x higher MC reconstruction efficiencey than predecessor algorithm.

2018 Belle II Data $\mathcal{L} = 0.5\ \text{fb}^{-1}$

Observe $\sim$ 571 fully reconstructed B mesons.





Exclusive Tagging:
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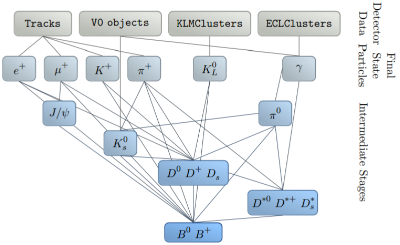


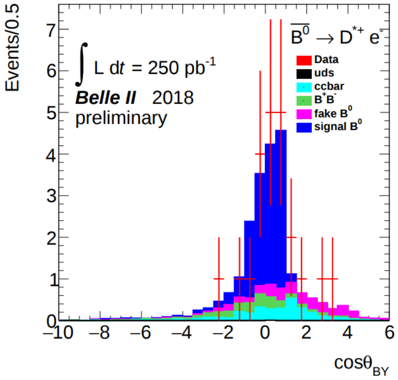
Hierarchical tag-side B-meson re-combination algorithm for Belle II.

- Utilizes $\mathcal{O}(200)$ decay channels with BDTs trained for each decay.
- Reconstructs $\mathcal{O}(10k)$ unique decay chains in 6 stages.
- 3x higher MC reconstruction efficiencey than predecessor algorithm.

First look at $\overline{B}^0 \to D^{*+} e^- \overline{\nu}_e$ decays

Observed 22 events in untagged sample:

- 15 events in the signal window of $\cos\theta_{BY} \in (-1, 1)$.
- 13 expected from simulation.



$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*}$$

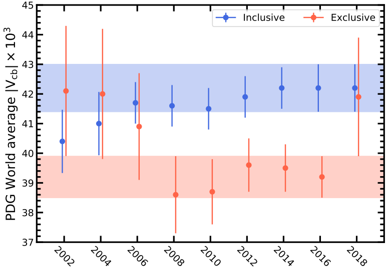
Y = visible final state system $\left(D^* e\right)$

First look at $\overline{B}^0 \to D^{*+} e^- \overline{\nu}_e$ decays

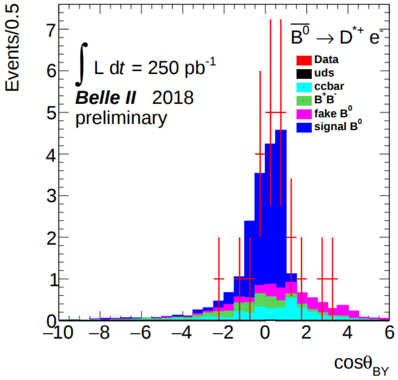
Observed 22 events in untagged sample:

- 15 events in the signal window of $\cos\theta_{BY} \in (-1, 1)$.
- 13 expected from simulation.

Branching fraction of $\overline{B}^0 \to D^{*+} e^- \overline{\nu}_e$ decays is a key ingredient in resolving the 3.5σ tension in exclusive vs. inclusive measurements of $|V_{cb}|$.



2018 exclusive avg. includes unpublished Belle 1702.01521



$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*}$$

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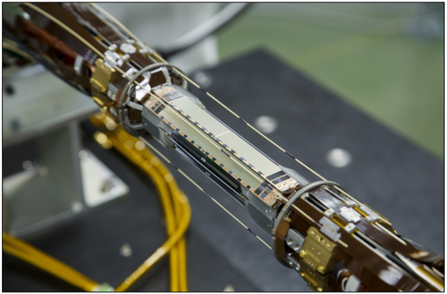
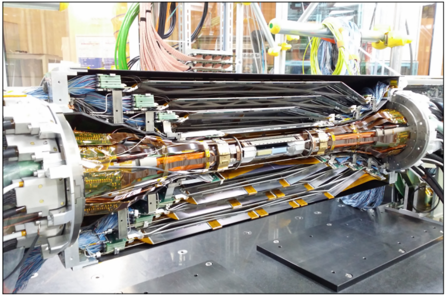
Preparation for Phase 3



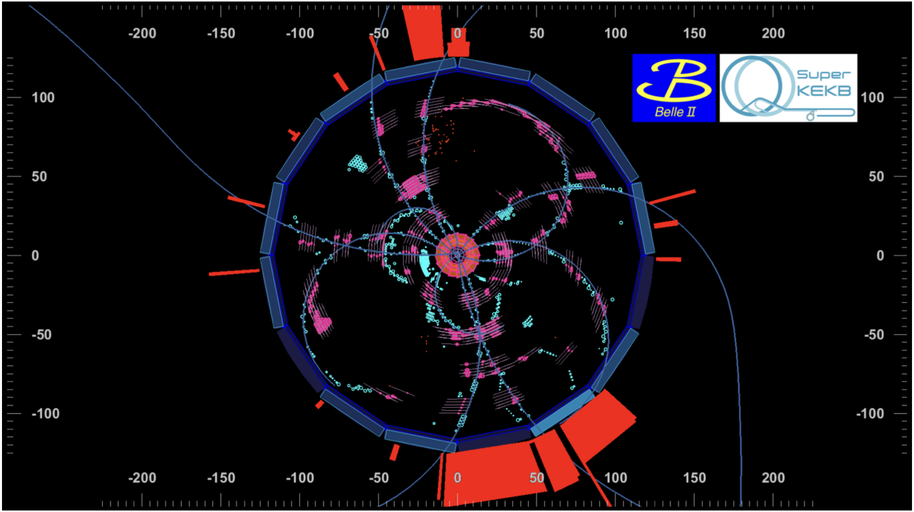
PXD mounted on beam pipe



PXD combined with one half of SVD

⇒ *Full PXD operation (with 2 layers) scheduled for 2020.*

First $B\overline{B}$ Event in Phase 3

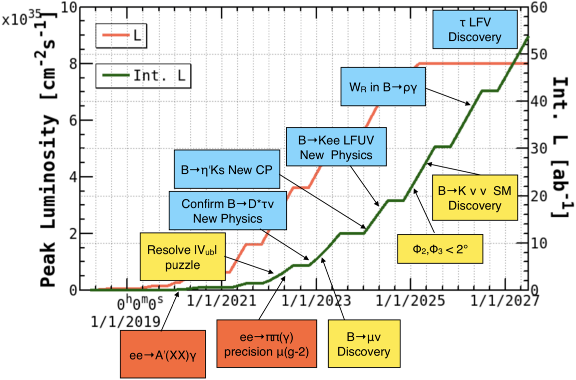


Summary

Belle II poised to usher in a new era of precision flavor physics with 50 ab^{-1} of data collected at the SuperKEKB accelerator.

– Commissioning phase has concluded and data taking with the full detector commenced in 3/2019.

– Potential for exciting results in the first years of data taking.



Thank you!

Planck 2019

Extra material

Si pixel (2 layers) and strip (4 layers):

- 1^{st} pixel layer at $r = 14mm$ to IP

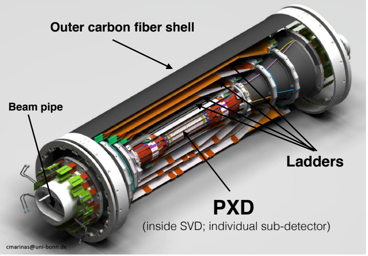
  [Belle at $r = 20mm$]

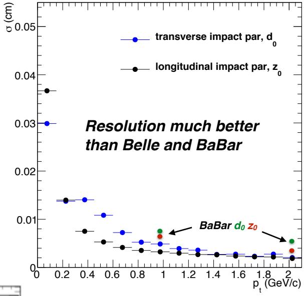
  Improves vertex resolution along z-axis

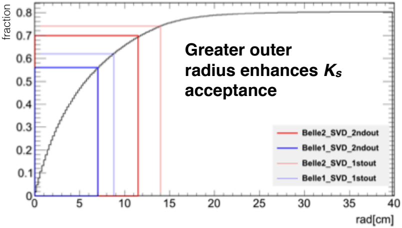
- Larger SVD w/outer layer at $r = 135mm$.

  [Belle at $r = 88mm$]

  Higher fraction of K_S' with vertex hits improves vertex resolution

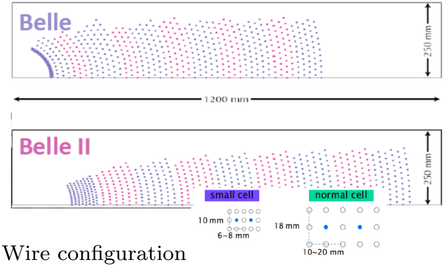






Central Drift Chamber:

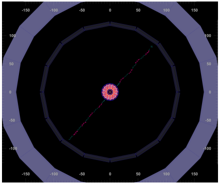
- $He(50\%)$ $C_2H_6(50\%)$.
- Larger outer radius of 1111mm (Belle 863mm) allows for improved p resolution.
- Smaller cells with lower occupancy and capacity for higher hit rate.



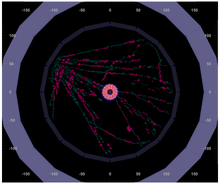
Wire configuration

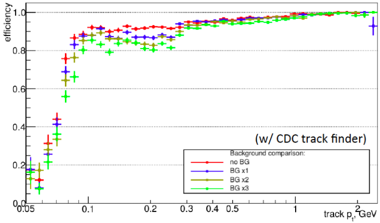
Full readout of the CDC

Single track



Showering event





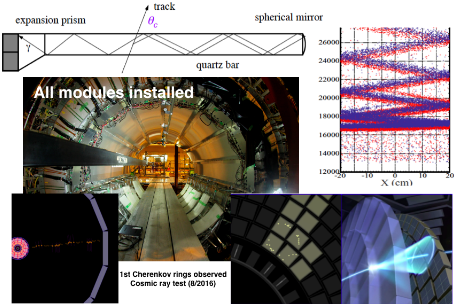
Simulated track reconstruction efficiency

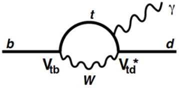
Stable performance for up to 3x predicted beam BG

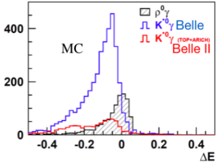
Particle Identification

Two RICH systems covering full momentum range

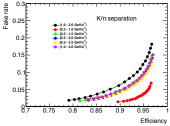
- Barrel: Time of Propagation (TOP) counter (16 modules).
  - ⇒ *Measure x-y position of Cherenkov γ's and their arrival time.*
- Forward Endcap: Aerogel Ring Imaging Cherenkov detector (ARICH)
  - ⇒ *Proximity focusing with silica aerogel (4σ separation at $1 - 3.5$ GeV/c)*

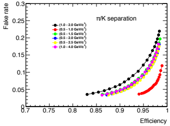






Average ϵ_K vs. π fake rate improved: Fake rate decreases by ≈ 3 for the same ε w.r.t. Belle

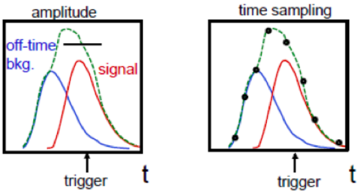


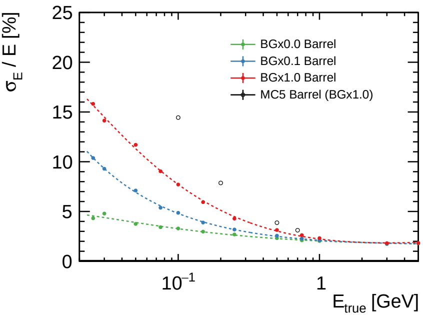


The background $B \to K^*\gamma$ (Belle/Belle II) $\approx 30x$ more abundant than $B \to \rho\gamma$.

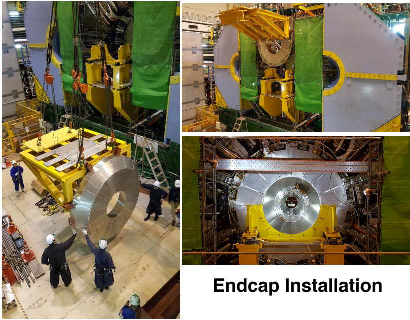
Re-usage of Belle's CsI(TI) crystal calorimeter, but with new electronics with 2MHz wave form sampling to compensate for the larger beam-related backgrounds and the long decay time of CsI(TI) signals.

⇒ *Resolution much better at Belle II*





Peak energy resolution in the ECL barrel as a function of true photon energy

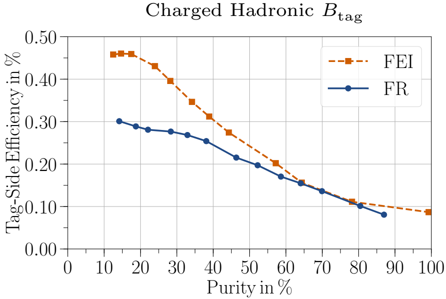


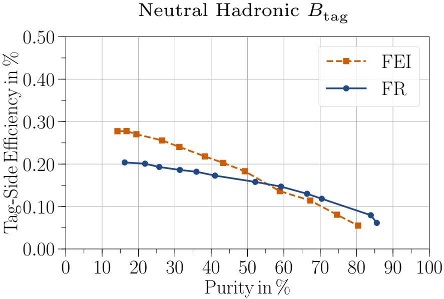
Endcap Installation

Performance on Belle Data

Applicable in Belle *and* Belle II analyses within the Belle II analysis software framework:

Allows one to make a benchmark comparison of the tag-side efficiency with the predecessor Belle Full Reconstruction (FR) algorithm.

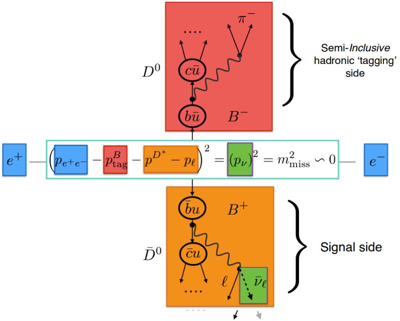


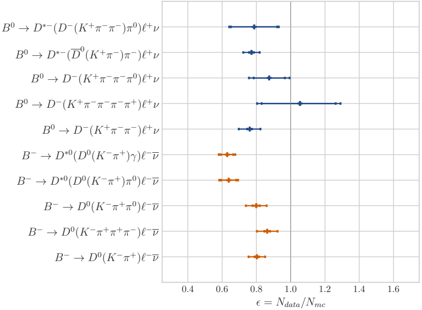


* Perform physics analysis on Belle data with increased statistics (from the same 711 fb^{-1}), *while we await a large Belle II dataset.*

Use the FEI on Belle data to reconstruct several well known semileptonic decays.

$\epsilon = N_{DATA}/N_{MC}$

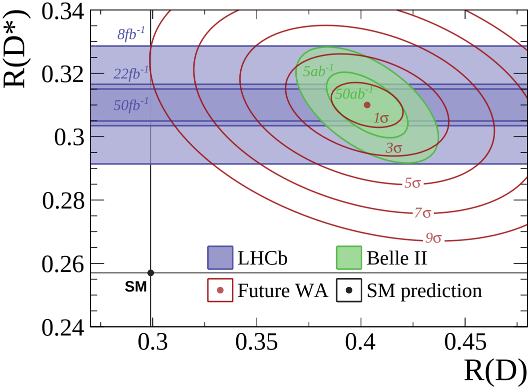




$\epsilon_{\text{charged}} = 0.74 \pm 0.05$ $\quad$ $\epsilon_{\text{neutral}} = 0.86 \pm 0.07$

$\overline{B} \to D^{(*)}\tau\overline{\nu}$ with Belle II & LHCb arXiv:1709.10308

Measurement	SM prediction	Current World Average	Current Uncertainty	Projected Uncertainty[1]				
				Belle II		LHCb		
				5ab^{-1} 2020	50ab^{-1} 2024	8fb^{-1} 2019	22fb^{-1} 2024	50fb^{-1} 2030
$R(D)$	(0.299 ± 0.003)	$(0.403 \pm 0.040 \pm 0.024)$	11.6%	5.6%	3.2%	-	-	-
$R(D^*)$	(0.257 ± 0.003)	$(0.310 \pm 0.015 \pm 0.008)$	5.5%	3.2%	2.2%	3.6%	2.1%	1.6%

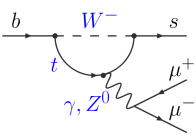


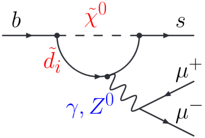
Currently re-analyzing the Belle hadronic-tag measurement *with the Belle 2 Full Event Interpretation (improved tag-side recombination algorithm).*

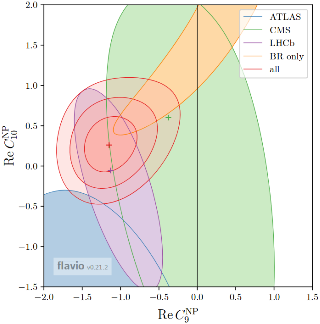
[1] *Projected uncertainties not including improvements in detectors and algorithms.*

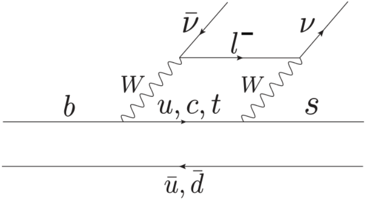
Flavor Anomalies

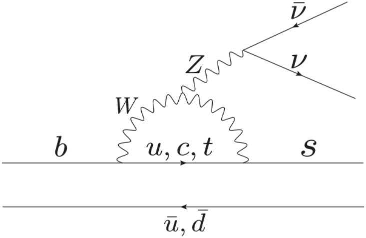
$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$





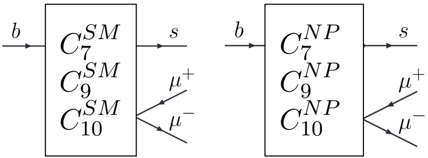


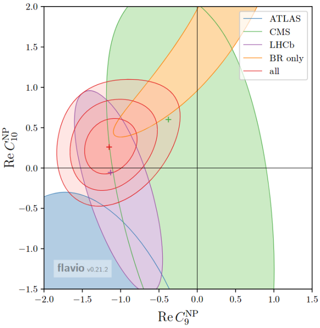


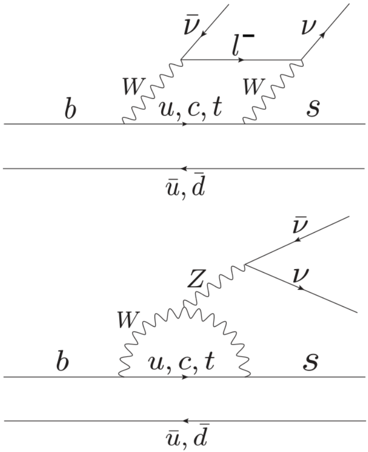


Flavor Anomalies

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

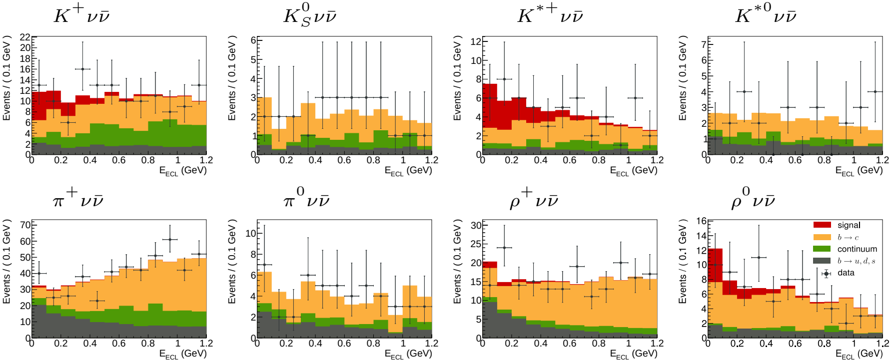






Belle $B \to h^{(*)}\nu\bar{\nu}$ Semileptonic Tag Result

PRD **96**, 091101(R) (2017)



- Histogram templates to model signal and bkgds from charm B decay, charmless B decay, and continuum.
- Relative fractions of the background components fixed to MC expectations.
- Signal and overall background yield allowed to vary.

Channel	Observed N_{sig}	Significance
$K^+\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	$1.9\,\sigma$
$K_S^0\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	$0.0\,\sigma$
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	$2.3\,\sigma$
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	$0.0\,\sigma$
$\pi^+\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	$0.0\,\sigma$
$\pi^0\nu\bar{\nu}$	$0.2 \pm 5.6 \pm 1.6$	$0.0\,\sigma$
$\rho^+\nu\bar{\nu}$	$6.2 \pm 12.3 \pm 2.4$	$0.3\,\sigma$
$\rho^0\nu\bar{\nu}$	$11.9 \pm 9.0 \pm 3.6$	$1.2\,\sigma$

$B \to h^{(*)}\nu\bar{\nu}$: Upper Limits

- **Expected (exp.) and observed upper limits at the 90% confidence level** (including systematic uncertainties)

Channel	Efficiency	Expected Limit	Measured Limit
$K^+\nu\bar{\nu}$	2.16×10^{-3}	0.8×10^{-5}	1.9×10^{-5}
$K^0_S\,\nu\bar{\nu}$	0.91×10^{-3}	1.2×10^{-5}	1.3×10^{-5}
$K^{*+}\nu\bar{\nu}$	0.57×10^{-3}	2.4×10^{-5}	6.1×10^{-5}
$K^{*0}\nu\bar{\nu}$	0.51×10^{-3}	2.4×10^{-5}	1.8×10^{-5}
$\pi^+\nu\bar{\nu}$	2.92×10^{-3}	1.3×10^{-5}	1.4×10^{-5}
$\pi^0\nu\bar{\nu}$	1.42×10^{-3}	1.0×10^{-5}	0.9×10^{-5}
$\rho^+\nu\bar{\nu}$	1.11×10^{-3}	2.5×10^{-5}	3.0×10^{-5}
$\rho^0\nu\bar{\nu}$	0.82×10^{-3}	2.2×10^{-5}	4.0×10^{-5}

Combine charged and neutral modes:

- The systematic uncertainties are evaluated on independent MC and data control samples for charged and neutral modes.
  $\Rightarrow$ *Can be considered uncorrelated.*
- Add the -$\mathcal{L}$ and scale the $\mathcal{B}$ of the neutral modes by τ_B^+/τ_B^0 and repeat the calculation of the limit:

$$\mathcal{B}(B \to K\nu\bar{\nu}) < 1.6 \times 10^{-5}$$

$$\mathcal{B}(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}$$

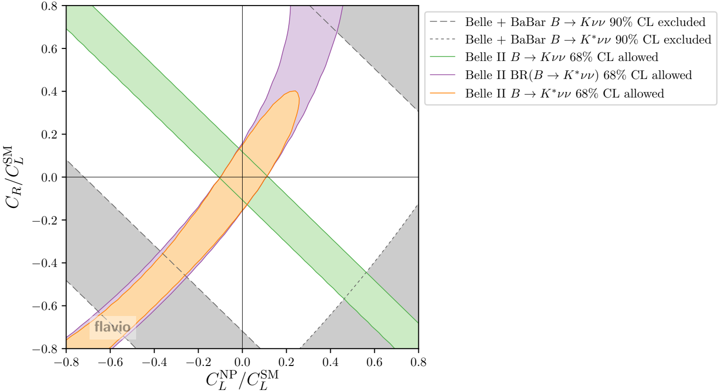
$$\mathcal{B}(B \to \pi\nu\bar{\nu}) < 0.8 \times 10^{-5}$$

$$\mathcal{B}(B \to \rho\nu\bar{\nu}) < 2.8 \times 10^{-5}$$

NP in $B \to K^{(*)}\nu\bar{\nu}$ @ Belle II

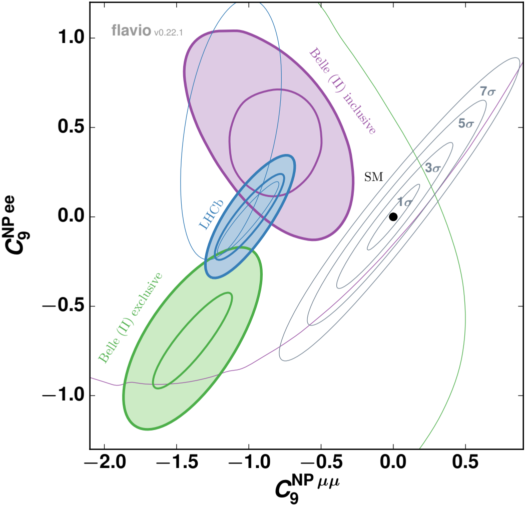
Constraints on NP contributions to C_L^{NP} & C_R^{NP} (norm. to the SM value of C_L)

- Gray areas show the 90% CL excluded regions from Belle & BaBar.
- Allowed region (@68% CL) of $B \to K^+\nu\bar{\nu}$ with 50ab^{-1} (assuming sensitivities in prev. slide)
- Constraints from $B \to K^*\nu\bar{\nu}$ using $\mathcal{B}$ only.
- Constraints from $B \to K^*\nu\bar{\nu}$ using $\mathcal{B}$ and f_L.



Hints of NP in C_9?

- Scan of the semileptonic coefficient C_9 comprise the inclusive $B\bar{B} \to X_s l^+ l^-$ $B \to K^{(*)} e^+ e^-$ and $B \to K^{(*)} \mu^+ \mu^-$
- Current mesurements hint at a deviation of $C_9^{\mathrm{NP}\,\mu\mu}$ from the SM (driven by LHCb).

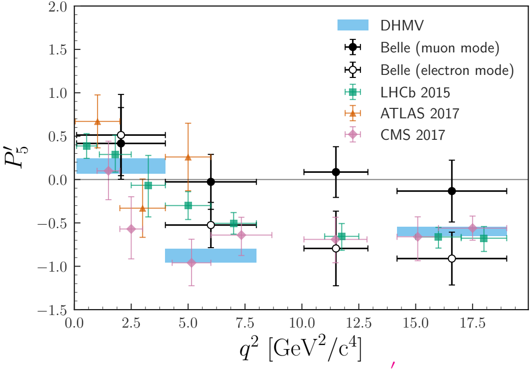


P_5' Anomaly: Full Angular Analysis of $B \to K^* \ell^+ \ell^-$

- The angular observable $P_5' = S_5/\sqrt{f_L(1-f_L)}$ is considered to be largely free from form-factor uncertainties.
  JHEP 05 (2013) 137
- Largest deviation of 2.6σ from the SM for the muon channel for $4 < q^2 < 8$ GeV$^4/c^2$.
- Electron channel deviation of 1.1σ.

- Belle II and LHCb will be comparable for this process.
- Belle II will be able to perform an isospin comparison of K^{*+} and K^{*0}, or the ground states K.

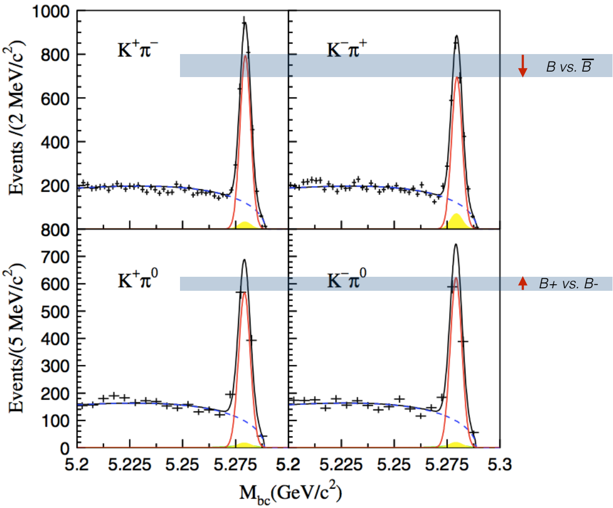
2017 ATLAS & CMS results, and
LF-dependent analysis by Belle
Belle: PRL 118, 111801 (2017) Plot: S. Wehle



Belle II sensitivity of P_5'

q^2 (GeV^2)	Belle	Belle II (50ab^{-1})
0.10 - 4.00	0.416	0.059
4.00 - 8.00	0.277	0.040
10.09 - 12.00	0.344	0.049
14.18 - 19.00	0.248	0.033

Measurements of $DCPV$ in $B^+ \to K^+\pi^0$ found to be different than $B^0 \to K^+\pi^-$

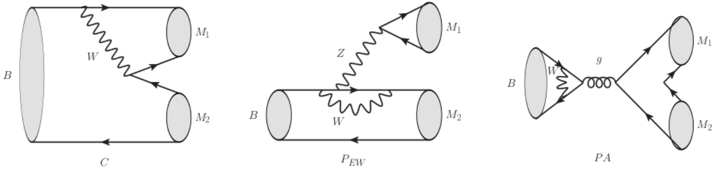


$$\mathcal{A}_{K^+\pi^0} - \mathcal{A}_{K^+\pi^-} = 0.112 \pm 0.027 \pm 0.007 \quad (4\sigma)$$

Additional SM Diagrams or New Physics?

The difference could be due to:

- Neglected diagrams contributing to B decays (theoretical uncertainty is still large).
  $K^+\pi^- : T + P + P_{EW}^C$
  $K^+\pi^0 : T + P + C + P_{EW} + P_{EW}^C + PA$



- Some unknown NP effect that violates Isospin.

⇒ **In combination with other $K\pi$ measurements** *and with the larger Belle II dataset, strong interaction effects can be controlled and the validitiy of the SM can be tested in a model-independent way.*

$B \to K\pi$: Test-of-sum Rule

Asymmetry (test-of-sum) rule for NP nearly free of theoretical uncertainties, where the SM can be tested by measuring all observables: [PLB 627, 82(2005), PRD 58, 036005(1998)]

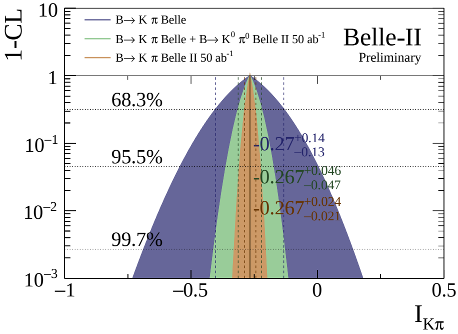
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+} \frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0} \frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0} \frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

$\left(I_{K\pi} = -0.0088^{+0.0016+0.0131}_{-0.0017-0.0091}\right)$ [@NNLO] PLB 750(2015)348-355

$$\boldsymbol{I_{K\pi} = -0.270 \pm 0.132 \pm 0.060} \text{ [Belle]}$$

- Most demanding measurement is $K^0\pi^0$ final state: $\mathcal{A}_{K^0\pi^0} = 0.14 \pm 0.13 \pm 0.06$.
  Belle, PRD 81, 011101(R) (2010)
- With Belle II, the uncertainty on $\mathcal{A}_{K^0\pi^0}$ from time-dep. analysis is expected to reach $\sim 4\%$.

  $\Rightarrow$ *Sufficient for NP studies*



Modified P_{EW} Sector

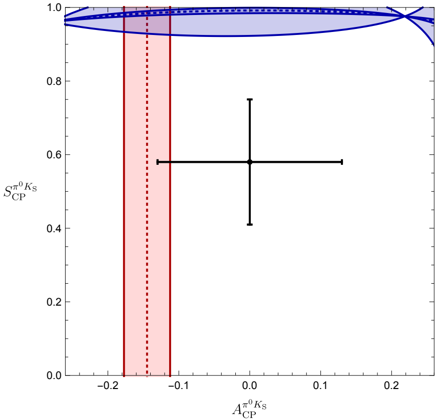
R. Fleischer *et al.*, arXiv:1712.02323, Moriond QCD

- Data point is the WA for $\mathcal{A}_{K^0\pi^0}$ and $\mathcal{S}_{K^0\pi^0}$.
- The $\mathcal{A}_{K^0\pi^0}$ value obtained from the sum rule with WA inputs for all other $\mathcal{A}_{K\pi}$ and $\mathcal{B}(K\pi)$ values.
- Isospin relation involving tighter constraints from CKM angle γ:

$$\sqrt{2}\mathcal{A}_{K^0\pi^0} + \mathcal{A}_{K^+\pi^0} = -\left(\hat{T}+\hat{C}\right)\left(e^{i\gamma} - qe^{i\phi}e^{i\omega}\right).$$

EW penguin effects described by

$$qe^{i\phi}e^{i\omega} \equiv -\left(\hat{P}_{EW} + \hat{P}^{C}_{EW}\right) / \left(\hat{T}+\hat{C}\right).$$



- Discrepancy can be resolved if: CP asymmetries move by $\approx 1\sigma$; $\mathcal{B}(K^0\pi^0)$ moves by $\approx 2.5\sigma$.
- **Or NP from EW Z penguins that couple to quarks:** ***Includes models with extra Z' bosons, which can be used to resolve anomalies in $B \to K^{(*)}\ell\ell$ measurements.***

Reducible vs. Irreducible Errors

Reducible

- The systematic uncertainties of the PDF parameters.
- Particle identification requirements.
- The possible CP violation effect in the accompanying B meson decays.
- Vertex resolution.
- Δt resolution function parametrization.
- Tag-side interference.

Irreducible

- Uncertainties in the interaction-point profile.
- Dependence on the vertex selection-criteria.
- The effect of detector misalignment.
- Possible bias in the ΔZ determination.
- $K^{\pm}$ $\pi^{\pm}$, π^{0} detection efficiency.
- Uncertainty in branching fraction measurements.
- Asymmetry of charged particle detection efficiency (in A measurements).
- Vertex reconstruction uncertainty originating from the SVD mis-alignment (in S measurements)