CKM Physics in e^+e^- Colliders

Shohei Nishida

KEK

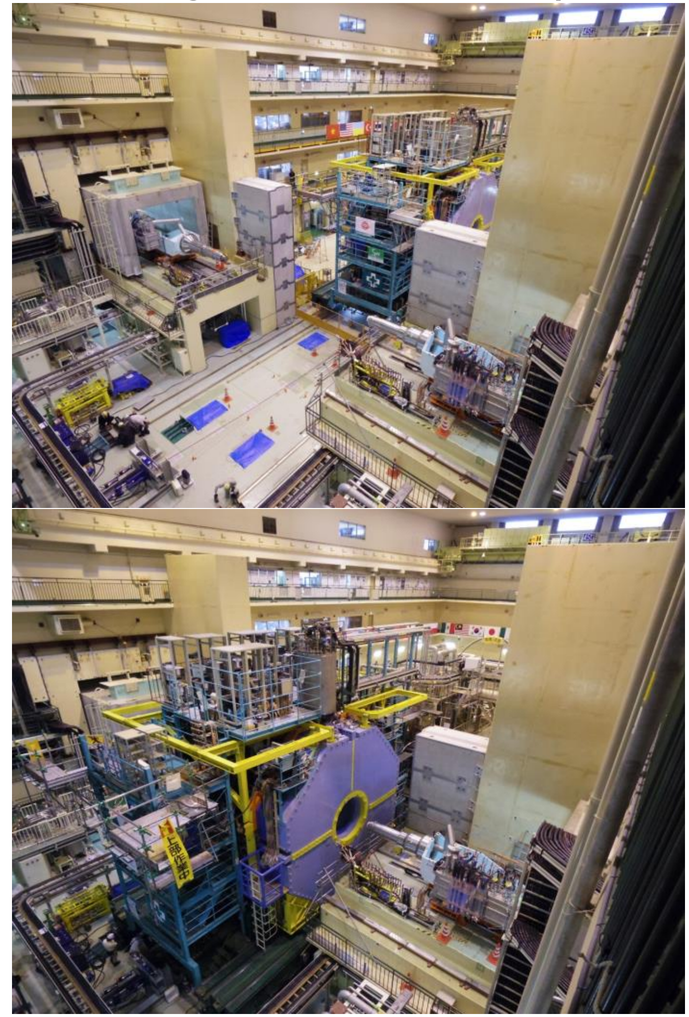
CKM 2018 @ Heidelberg

Sep. 17, 2018

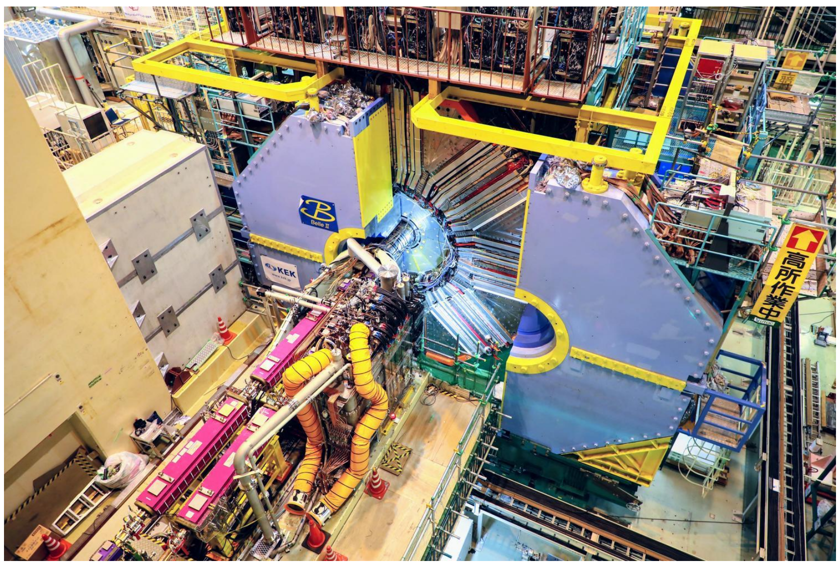
Contents

- Status of Belle II experiment.
- Results from BaBar and Belle.

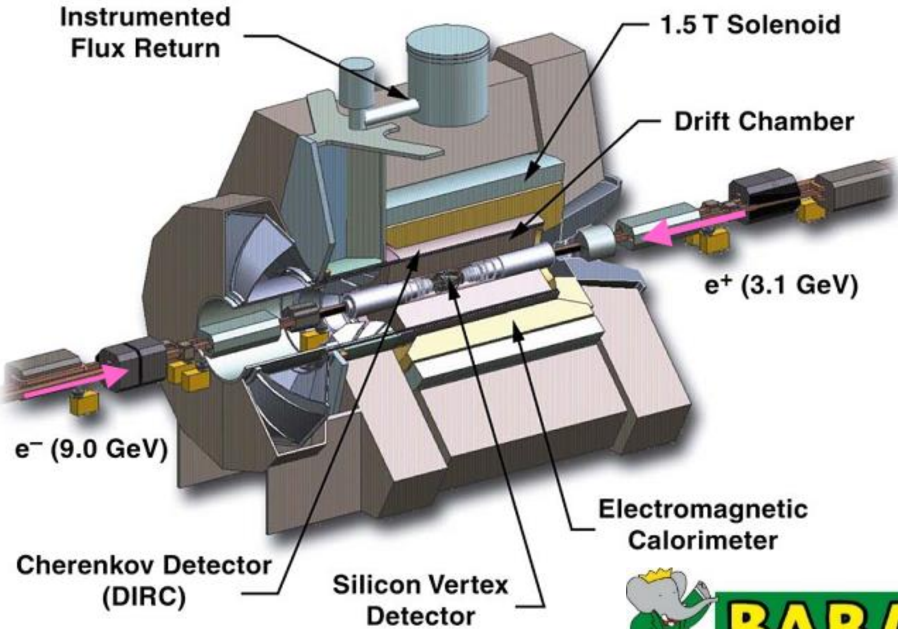
Belle II go to beamline (2017/4/11)

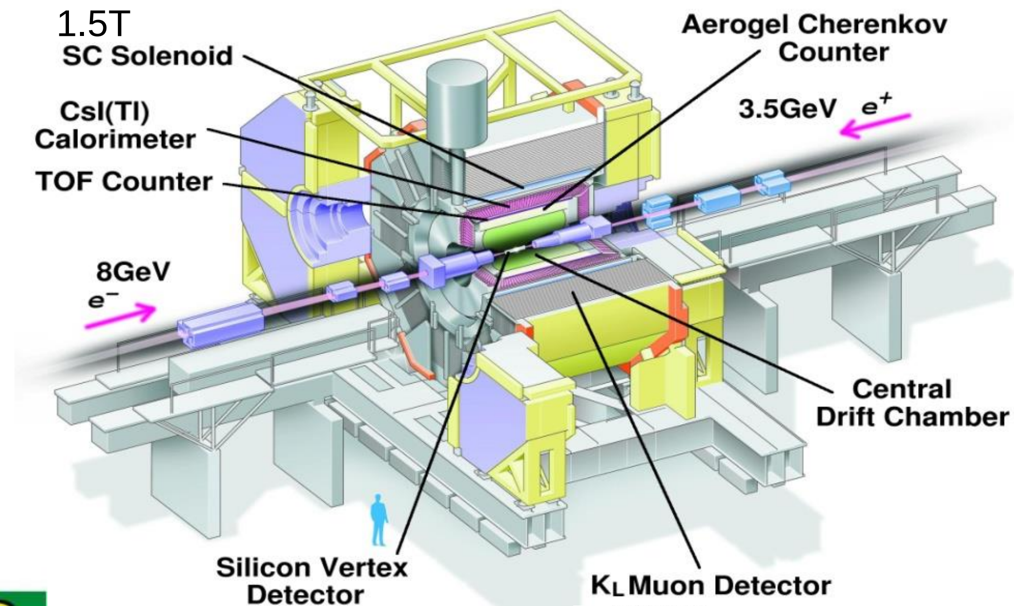


Belle II before Phase 2 (2018 Mar)



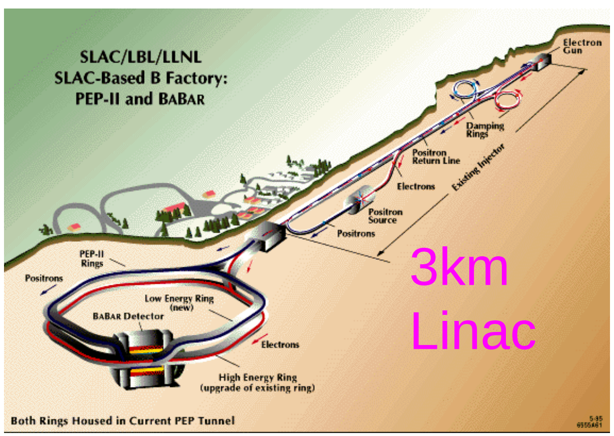
Two B Factories





BaBar @ PEP-II

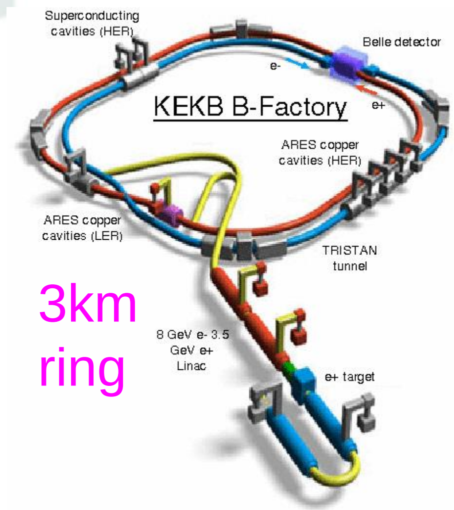
Belle @ KEKB



3km Linac

9 GeV e⁻ +
3.1 GeV e⁺

8 GeV e⁻ +
3.5 GeV e⁺

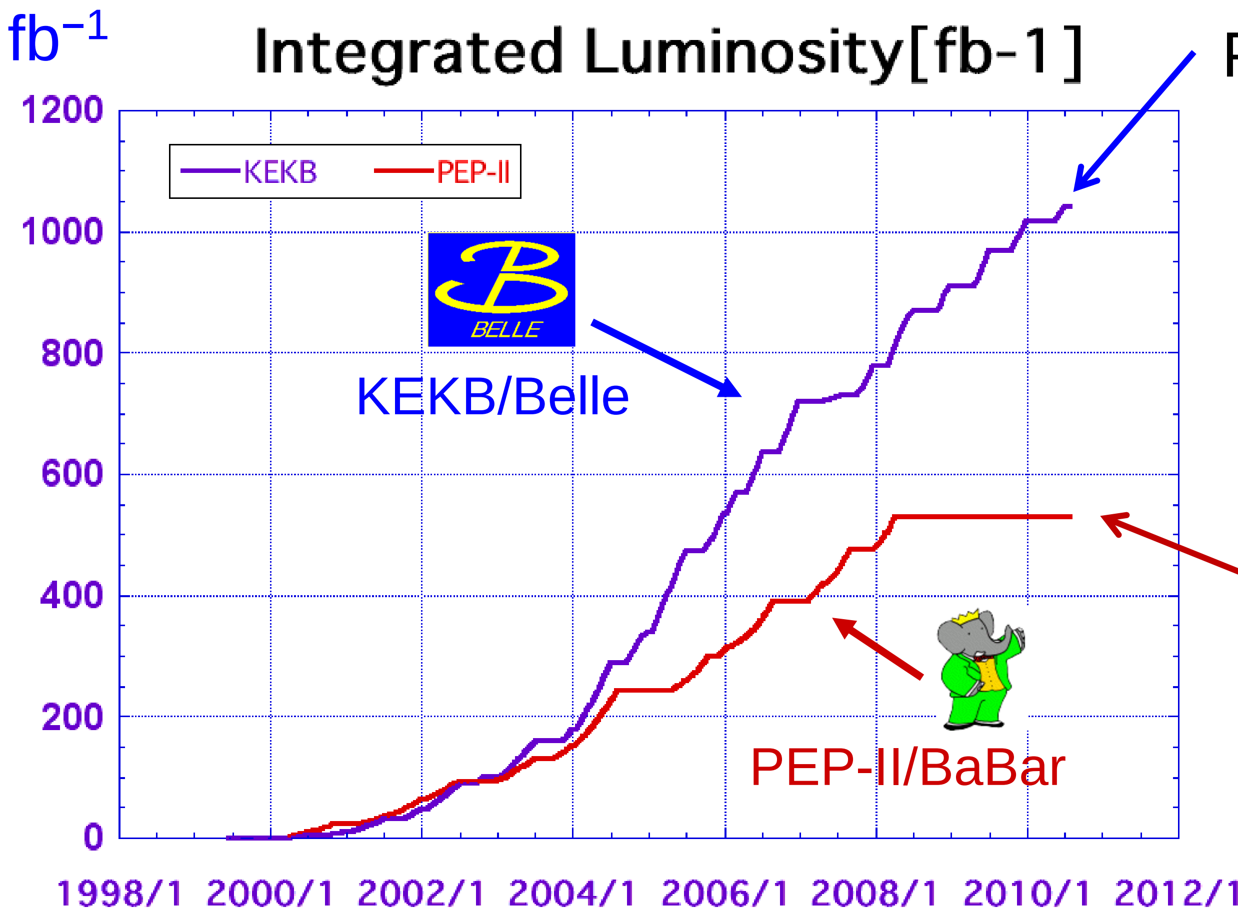


3km ring

Luminosity

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ (σ=1.1nb)

$1\ fb^{-1} \sim 10^6\ B\bar{B}$ @ $\Upsilon(4S)$



Total ~1040 fb^{-1}
Peak 2.11×10^{34} cm^{-2} s^{-1}

On resonance:
- $\Upsilon(5S)$: 121 fb^{-1} ← B_s
- $\Upsilon(4S)$: 711 fb^{-1}
- $\Upsilon(3S)$: 3 fb^{-1}
- $\Upsilon(2S)$: 24 fb^{-1}
- $\Upsilon(1S)$: 6 fb^{-1}

Off resonance, scan:
~ 100 fb^{-1}

Total 550 fb^{-1}
Peak 1.21×10^{34} cm^{-2} s^{-1}

On resonance:
- $\Upsilon(4S)$: 433 fb^{-1}
- $\Upsilon(3S)$: 30 fb^{-1}
- $\Upsilon(2S)$: 14 fb^{-1}

Off resonance:
~ 54 fb^{-1}

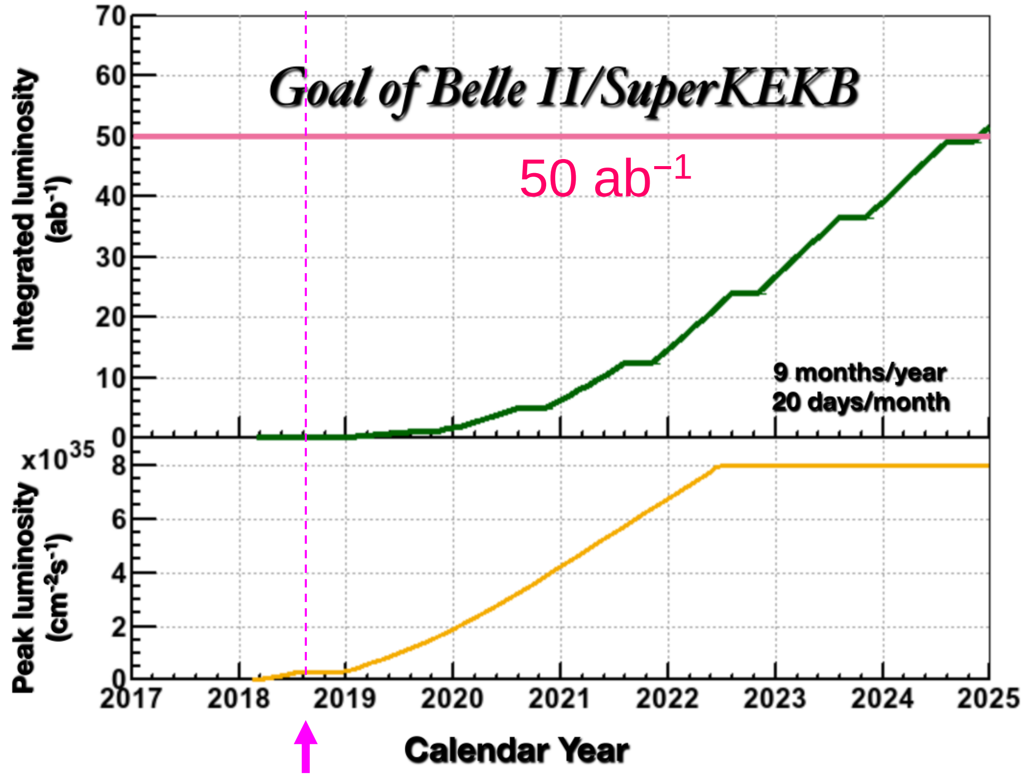
These data are taken till 2010.

Belle II Experiment

Belle II experiment with SuperKEKB started!

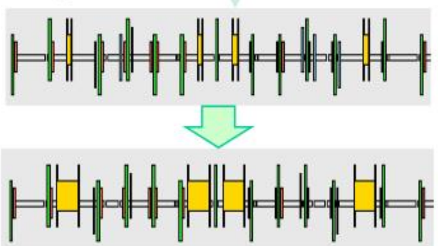
- SuperKEKB targeting $8 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$ ($\times$40 of Belle)
  - ✓ "Nano beam scheme":
    $\times$1/20 beam size (~50nm)
    $\times$2 beam current (2-3 A)
- Belle II spectrometer.
  - ✓ New type of vertex and PID detector.
- Phase 2 Operation in 2018.

Phase 1 (2016)	without Belle II
Phase 2 (2018)	with Belle II (no VXD)
Phase 3 (2019-)	with full Belle II



SuperKEKB

Replace short dipoles with longer ones (LER)

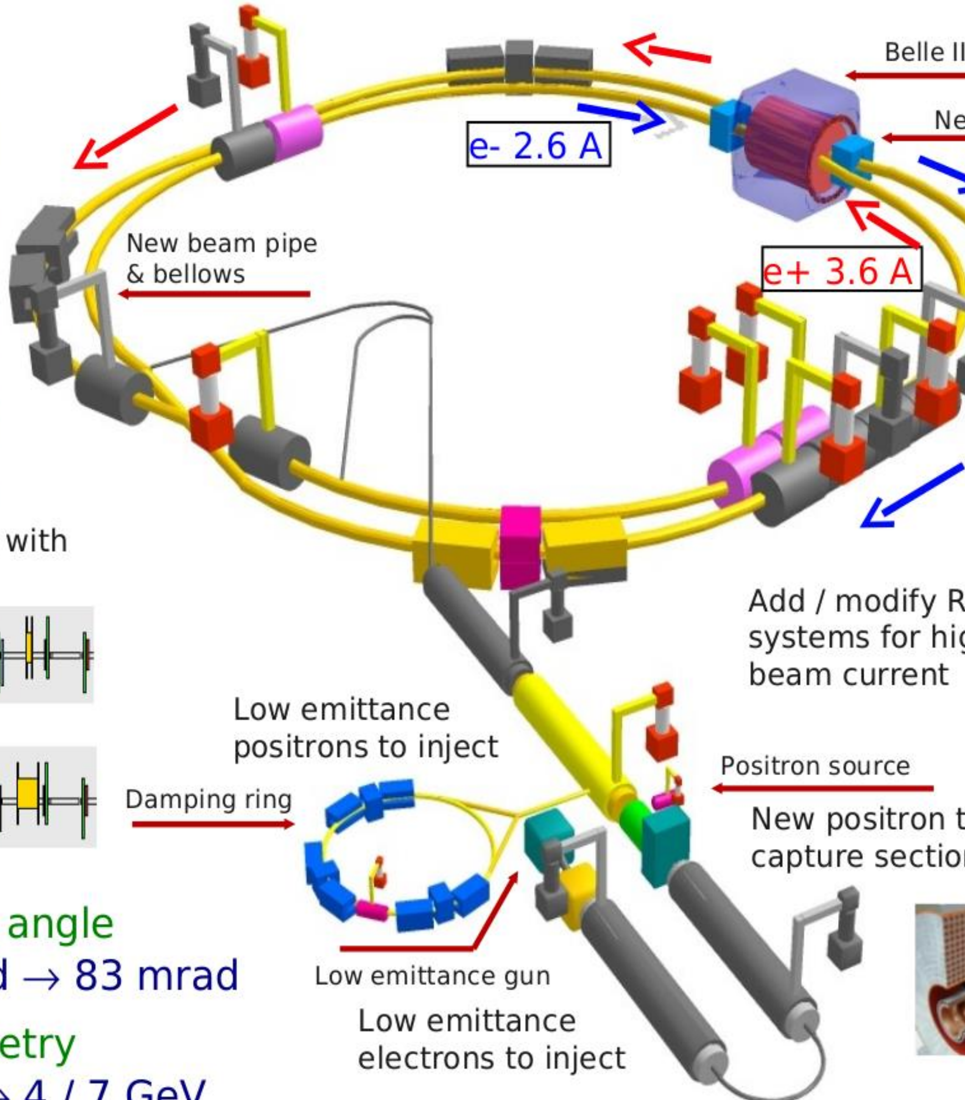


Larger crossing angle

2ϕ = 22 mrad → 83 mrad

Smaller asymmetry

3.5 / 8 GeV → 4 / 7 GeV

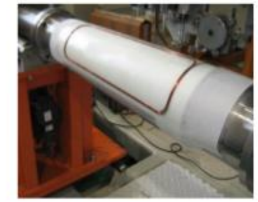


Low emittance positrons to inject

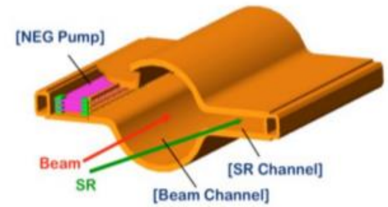
Low emittance electrons to inject

Add / modify RF systems for higher beam current

New superconducting /permanent final focusing quads near the IP

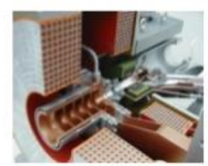


TiN-coated beam pipe with antechambers

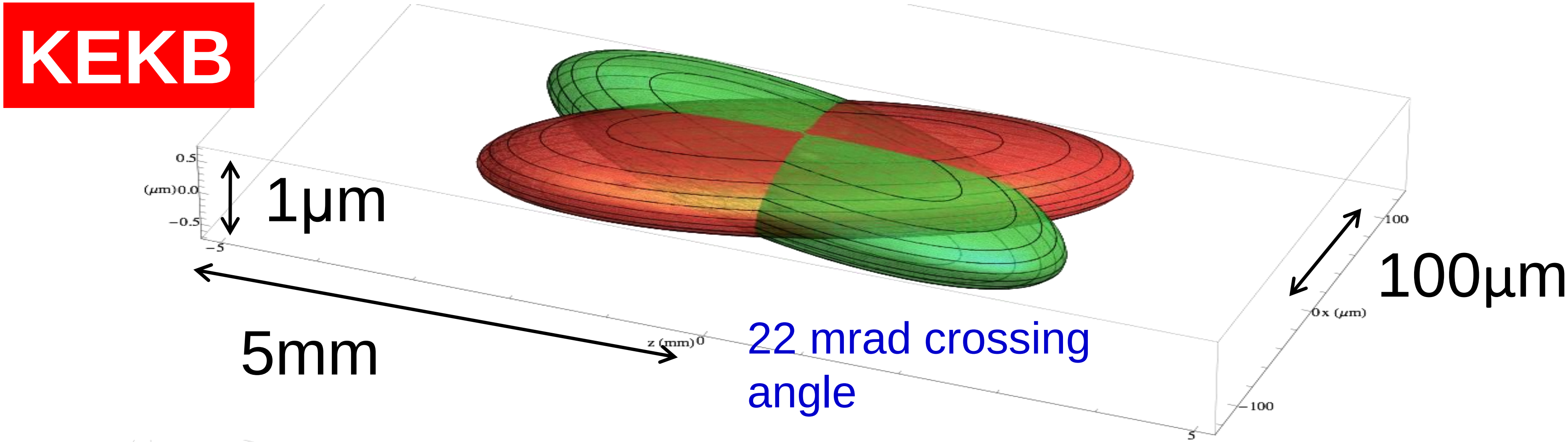


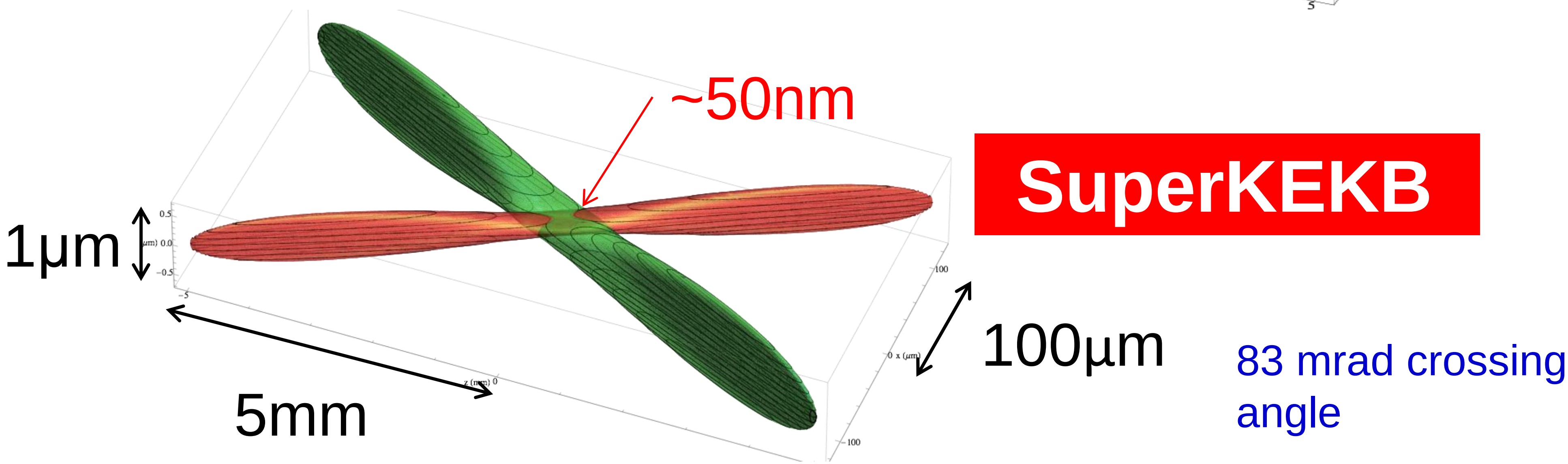
Redesign the lattices of HER & LER to squeeze the emittance

New positron target / capture section

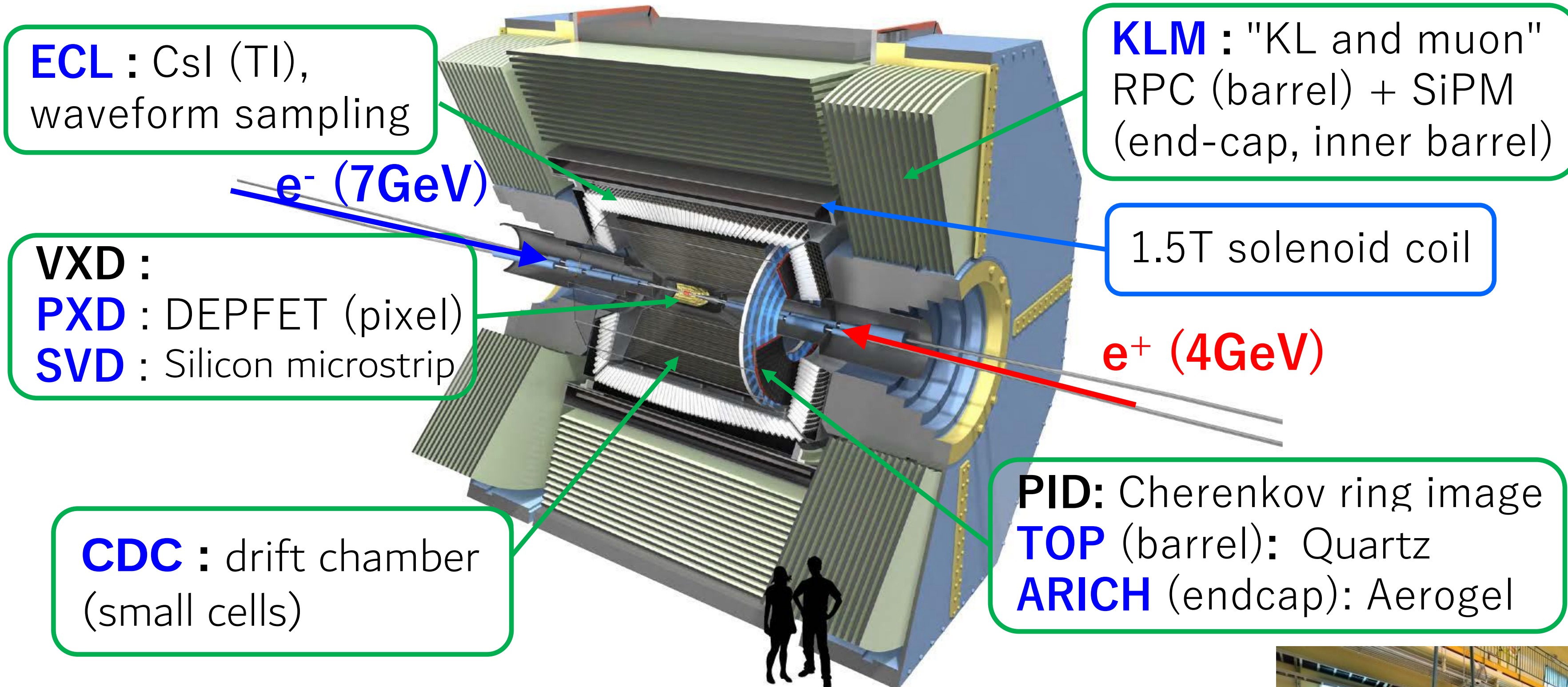


SuperKEKB


KEKB
1μm
5mm
100μm
22 mrad crossing angle


~50nm
SuperKEKB
1μm
5mm
100μm
83 mrad crossing angle

Belle II Spectrometer

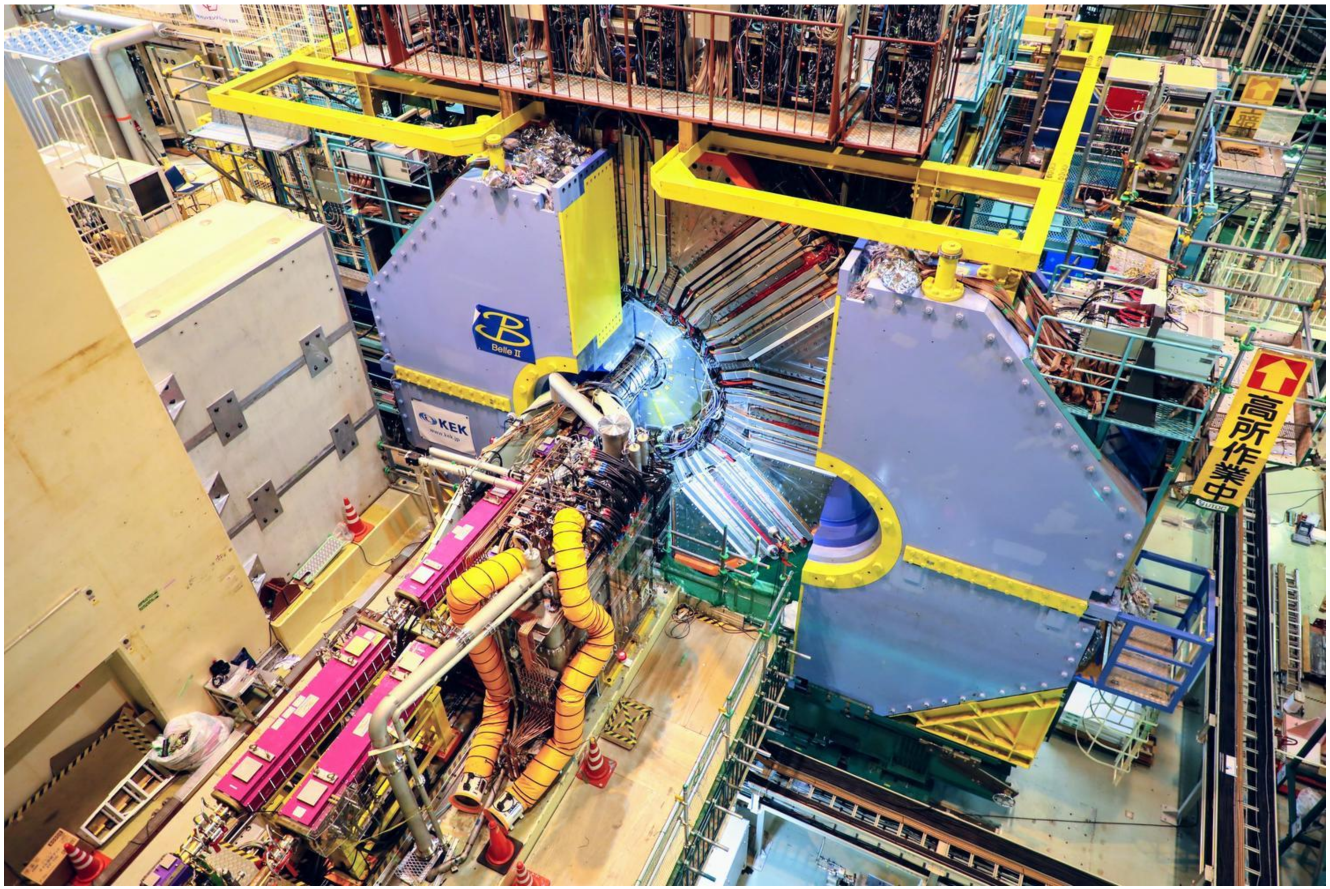


- Operation at higher luminosity (background)
- New type of Vertex and PID detector.

ARICH (during construction)

Phase II Operation

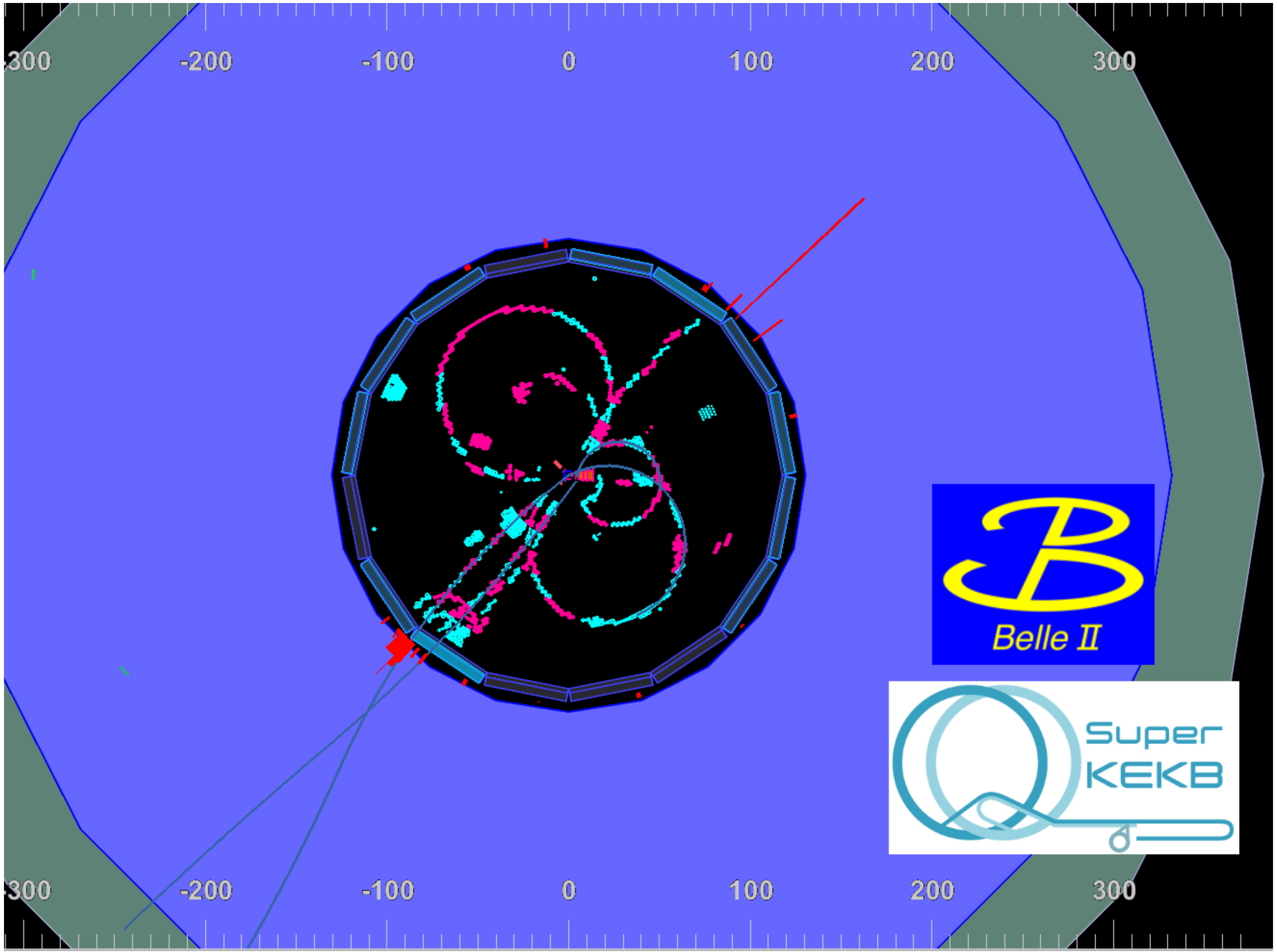
- The construction of SuperKEKB was completed.
- Belle II detector without vertex detectors.
- Phase II operation: Mar-Jul, 2018.

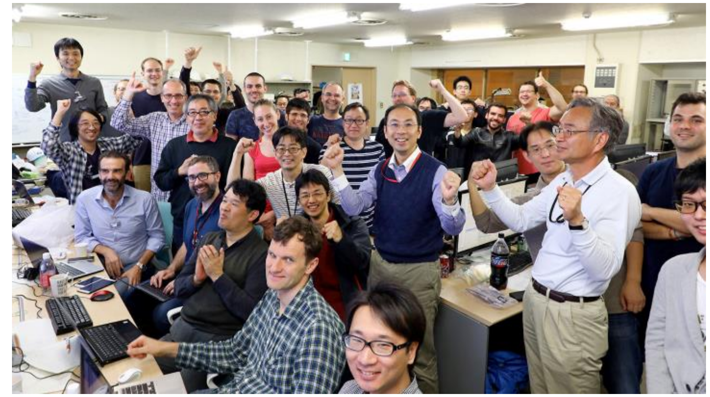


(Mar. 2018)

Belle II First Collision

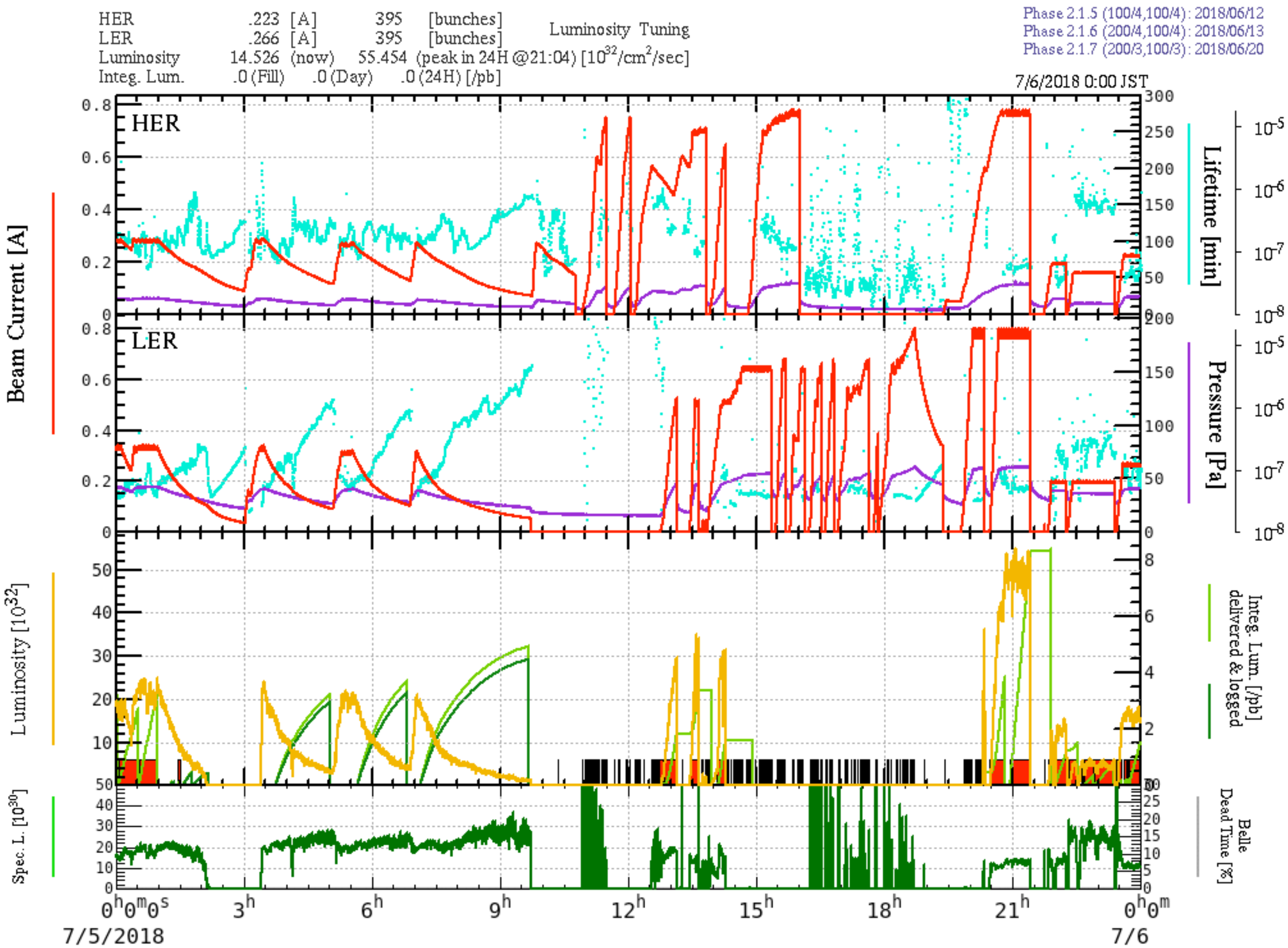
Belle II first collision at 0:46 on Apr. 26, 2018





Phase 2 Operation

One day history of SuperKEKB (Jul 5, 2018)



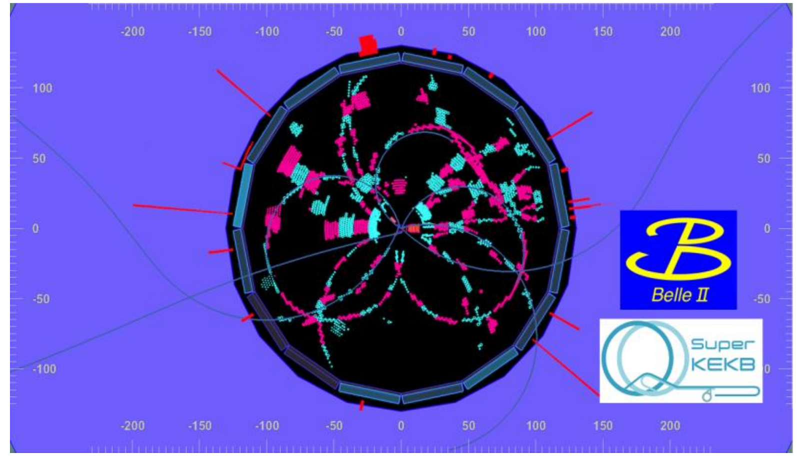
- Mostly accelerator tuning.
- Physics run (in the midnight).

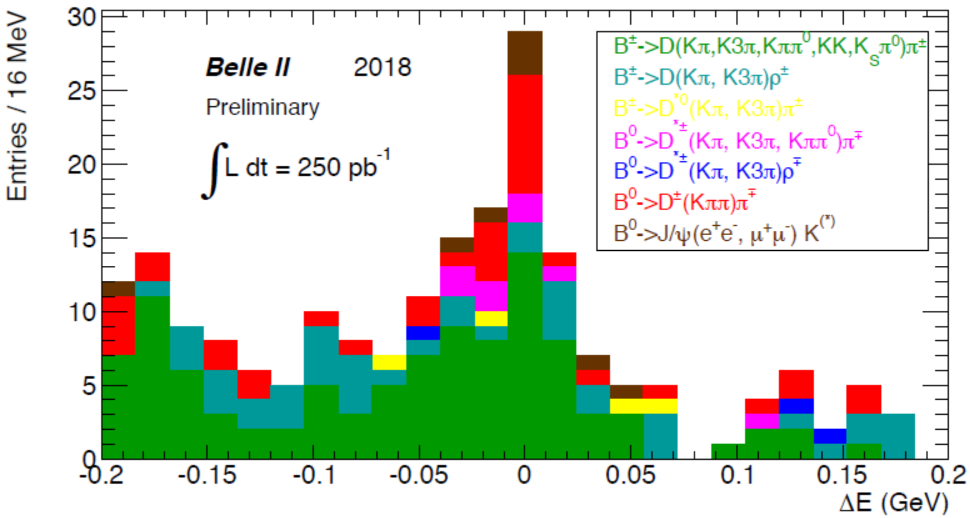
- Maximum luminosity 5.5×10^{33} cm^{-2}s^{-1} (during accelerator study).
  - ✓ 1-2 $\times 10^{33}$ cm^{-2}s^{-1} during physics run

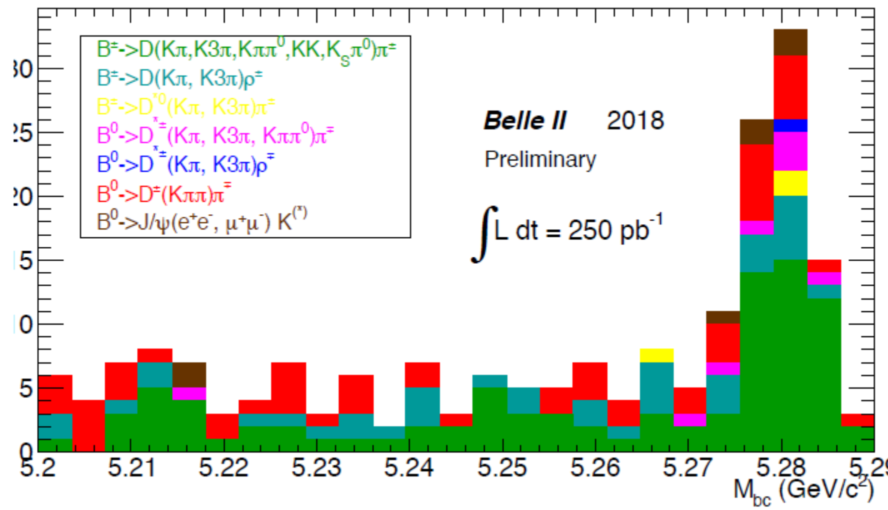
Phase 2 Operation

- The main purpose of Phase II operation was the accelerator tuning and the study of nano beam scheme.
- Physics data were also taken: total data size 0.5 fb^{-1}
  - ✓ Understanding of the detector.
  - ✓ B mesons are reconstructed.

potential $B\overline{B}$ candidate

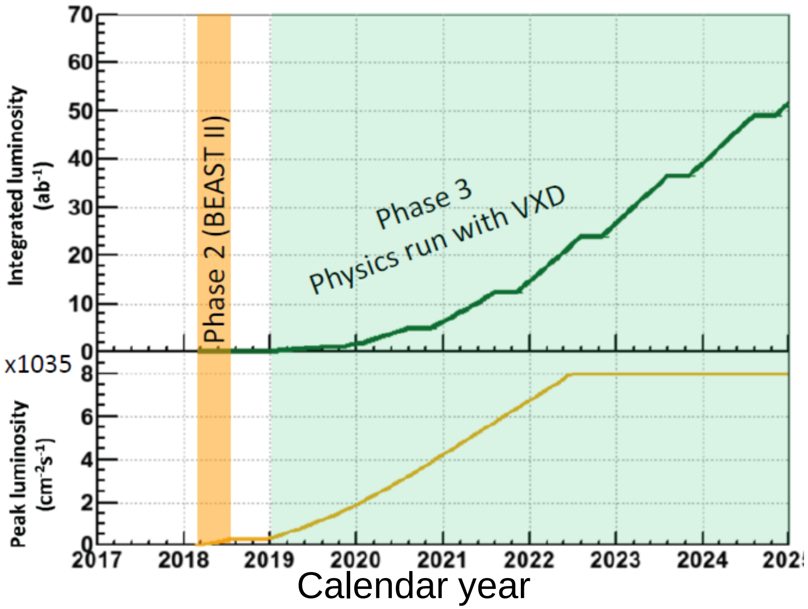


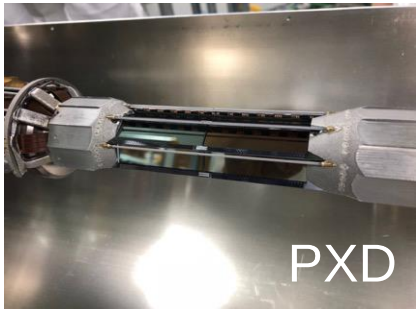


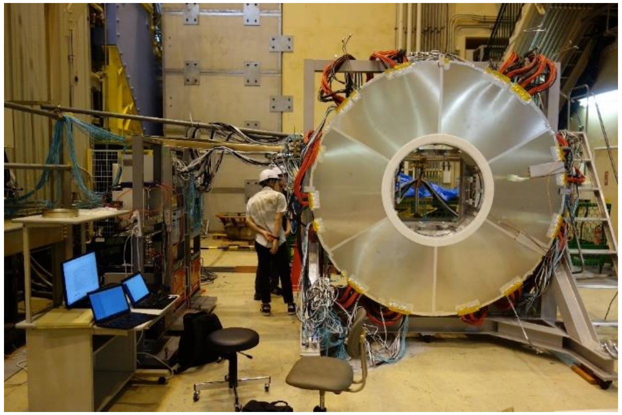


Toward Phase 3

- The construction of SVD (inner vertex detector) is finished. Under commissioning outside Belle II.
- Will be installed to Belle II together with PXD (innermost pixel detector) towards the end of this year.
- Other maintenance, repair work is going on.







Phase III operation (physics run) starts in early 2019.

Let's go back to BaBar and Belle

- Data were taken till 2008/2010.
- But the analysis is still active, and we have new results.

B Tagging Technique

- Reconstruction of B decay modes with one or more neutrinos in the final states.
- B mesons are produced in pair → Reconstruct or tag the other B.
  - ✓ Full reconstruction: reconstruct the other B with hadronic modes.
  - ✓ Semi-leptonic tag: tag the other B with semi-leptonic decays.
  - ✓ Inclusive: reconstruct signal B and check if the rests are consistent with B.
  - ✓ Untagged: do not tag the other B (applicable in case of one neutrino)
- In general, a method with high purity has low efficiency. Typical full reconstruction efficiency is O(0.1%).
- Effort to improve the performance, which directly affects the analysis sensitivity.

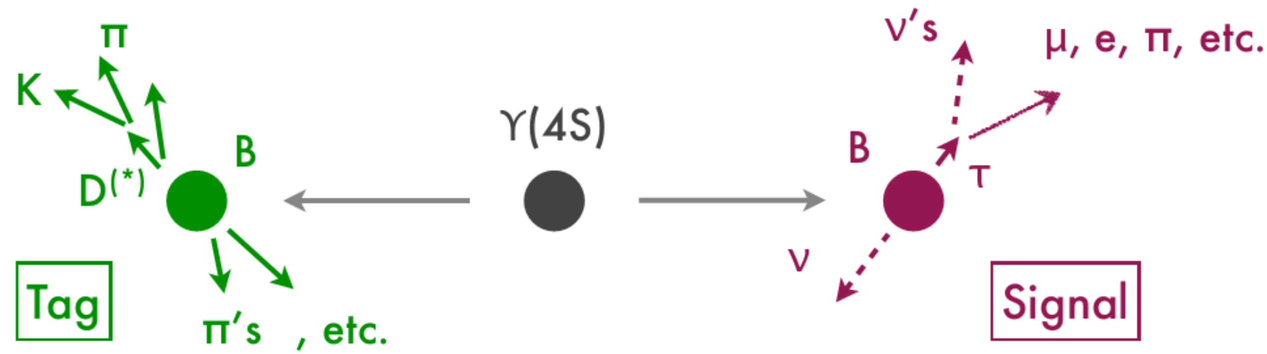
⇨ FEI (Full Event Interpretation) [arXiv:1807.08680]

Talk by R. Van Tonder (WG1)

New Result

$B \to \ell\nu\gamma$ by Belle (first result w/ FEI)

Talk by M. Gelb (WG2)



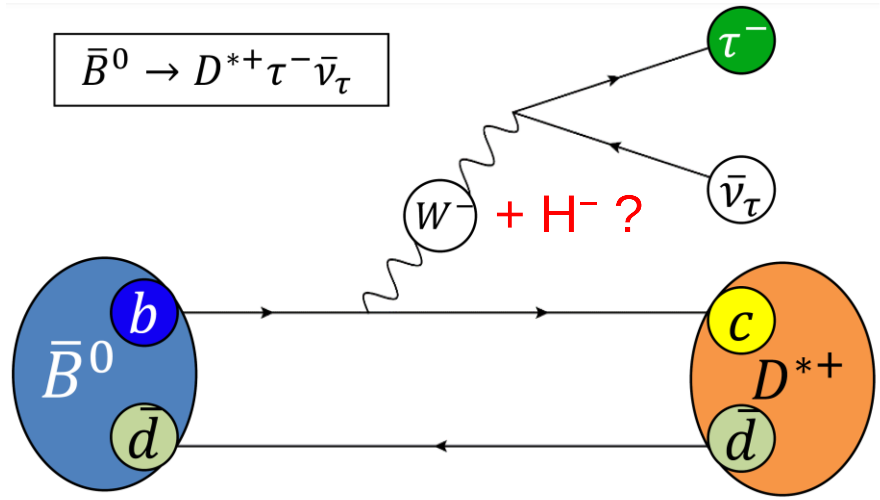
$B \to D^{(*)}\tau\nu$

- NP contribution is tree diagram?
  - ✓ Sensitive to charged Higgs.
- Measure the branching ratio

$$R(D^{(*)}) = \frac{BF(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{BF(\bar{B} \to D^{(*)}l^-\bar{\nu}_l)}$$

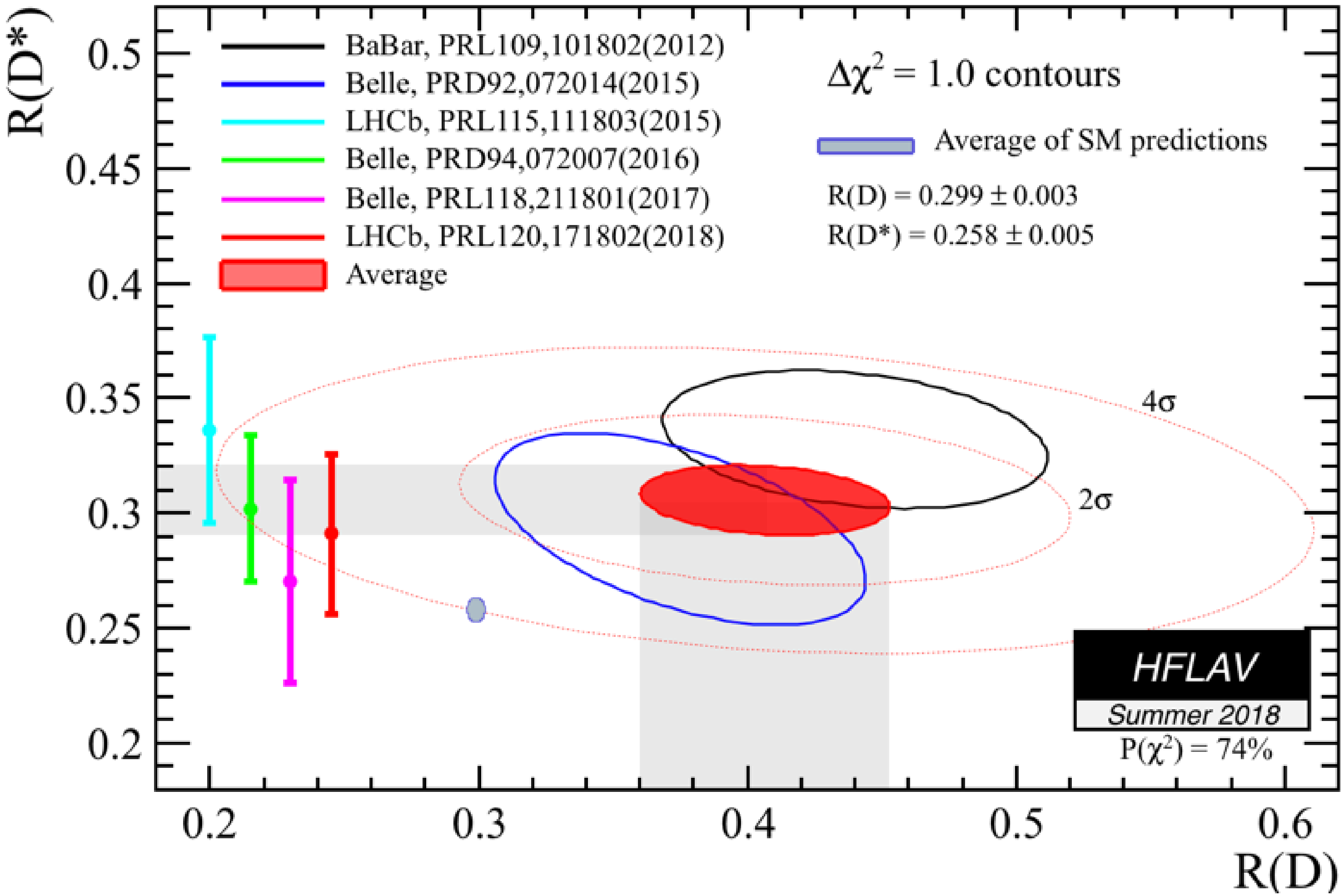
$(l^- = e^-, \mu^-)$

  - ✓ Cancel form factors.
  - ✓ Cancel experimental systematics



- Several measurements from Belle and BaBar
  - ✓ With different B tagging method → Independent sample

$B \to D^{(*)}\tau\nu$



- 3.8 σ deviation from the SM
- 2.3 σ in R(D)
- 3.0 σ in R(D*)

⇩

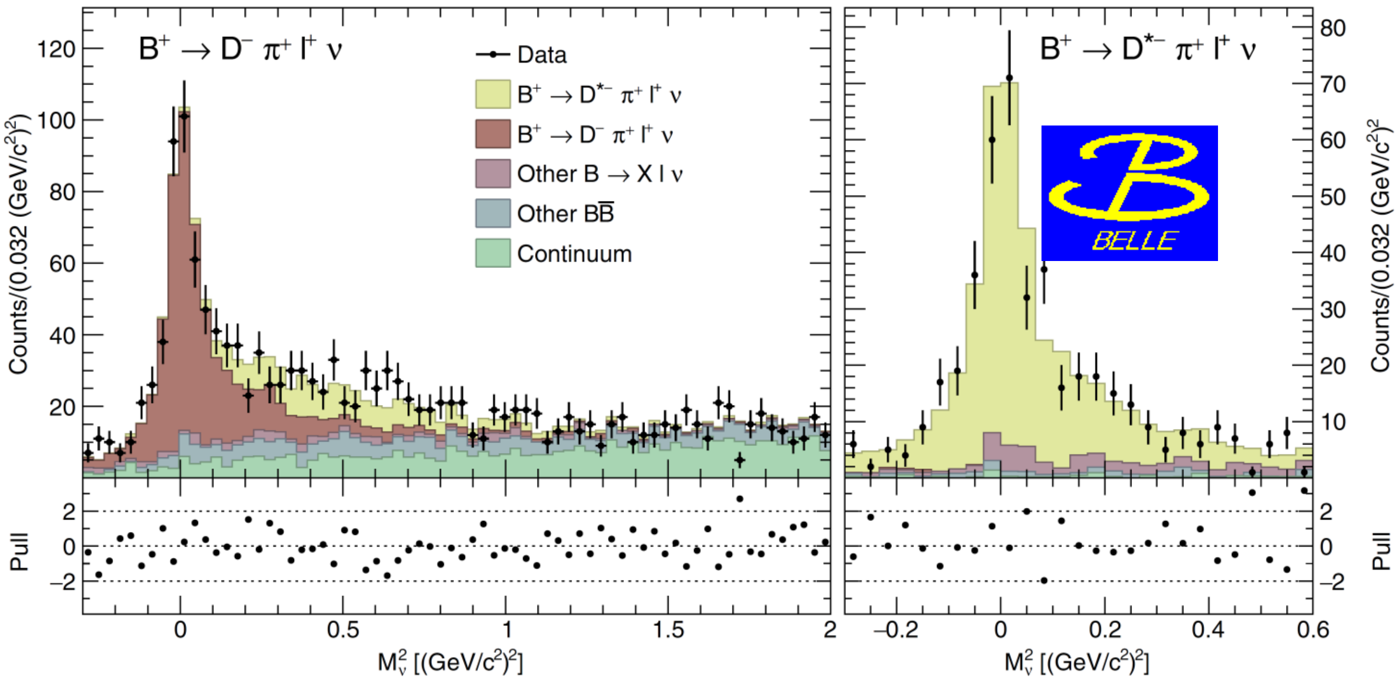
- More precise
- Other observables (polarization)

$B \to D^{(*)}\tau\nu$

For more precise measurement of $B \to D^{(*)}\tau\nu$

- More statistics → Belle II
- Better understanding of the systematics
  - ✓ Dominant systematic error : the uncertainty of $B \to D^{**}\ell\nu$ ($D^{**}\tau\nu$).

Measurement of $B \to D^{(*)}\pi\ell\nu$ at Belle



[PRD98, 012005 (2018)]

- Hadronic tag.
- Simultaneous fit on $B \to D\pi\ell\nu$ and $B \to D^*\pi\ell\nu$.

$B \to D^{(*)}\pi\ell\nu$

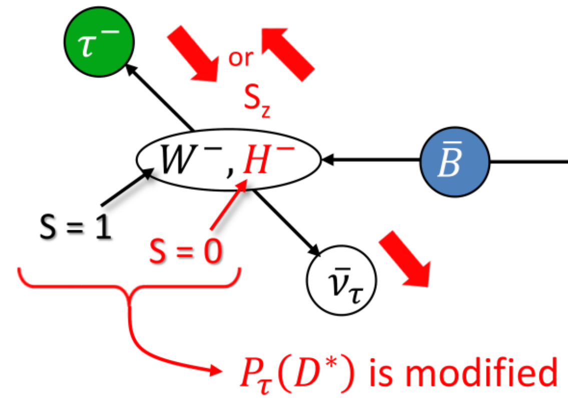
	Results	HFLAV2016
$B^+ \to D^-\pi^+\ell^+\nu$	$(4.55 \pm 0.27 \pm 0.39) \times 10^{-3}$	$(4.1 \pm 0.5) \times 10^{-3}$
$B^0 \to D^0\pi^-\ell^+\nu$	$(4.05 \pm 0.36 \pm 0.41) \times 10^{-3}$	$(4.2 \pm 0.6) \times 10^{-3}$
$B^+ \to D^{*-}\pi^+\ell^+\nu$	$(6.03 \pm 0.43 \pm 0.38) \times 10^{-3}$	$(6.0 \pm 0.6) \times 10^{-3}$
$B^0 \to D^0\pi^-\ell^+\nu$	$(6.46 \pm 0.53 \pm 0.52) \times 10^{-3}$	$(4.7 \pm 0.8) \times 10^{-3}$

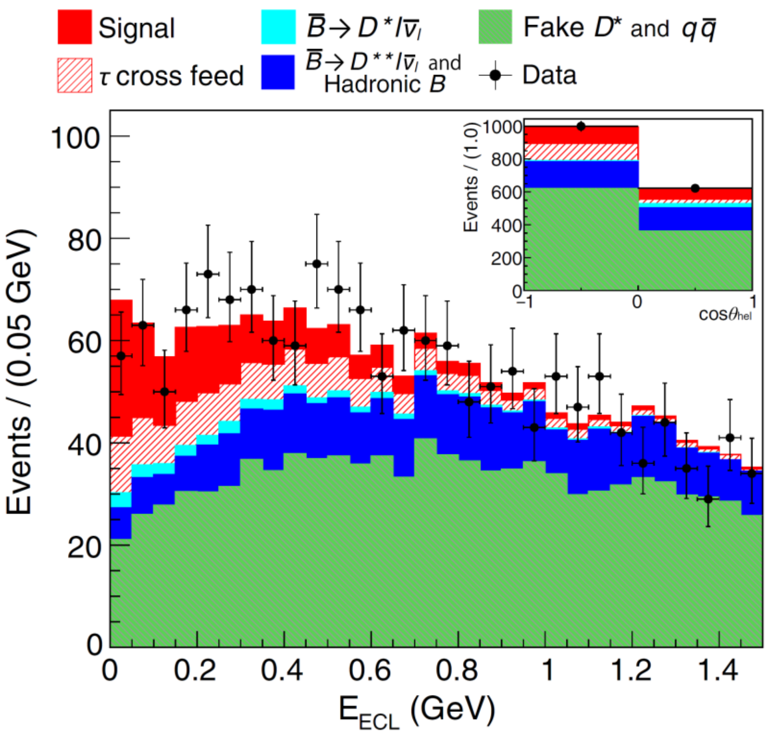
- Consistent with HFLAV.
- Precision is similar or slightly better compared to HFLAV2016.
- Main source of systematic errors are tag efficiency for charged modes, and PID, tracking efficiency for neutral modes.
  - ✓ Can be improved with luminosity (but not an easy work).

τ Polarization in $B \to D^*\tau\nu$

- Effect of the NP can appear in the polarization.
- Belle measured τ polarization in $B \to D^*\tau\nu$
  - ✓ Hadronic tag (full reconstruction)
  - ✓ Hadronic τ decays.
  - ✓ 2 bins of $\cos(\theta_{hel})$

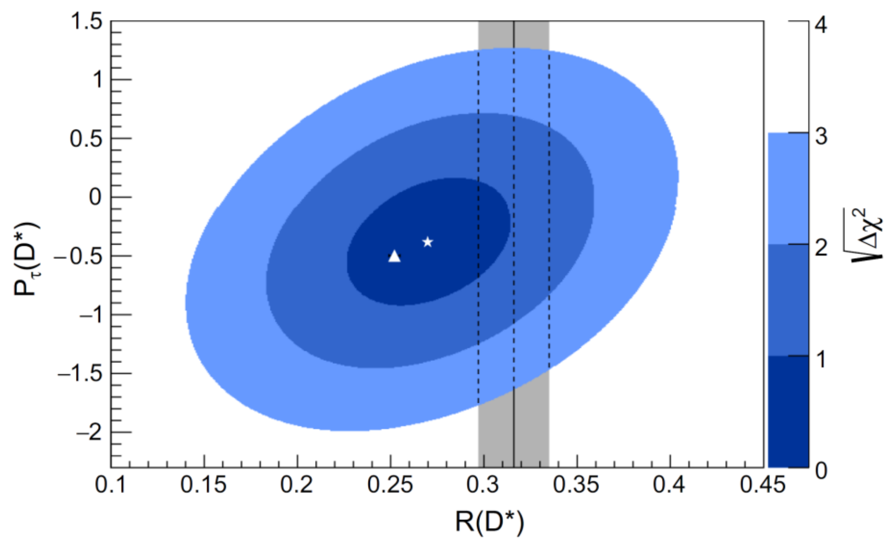
[PRL 119, 211801 (2017); PRD 97, 012004 (2017)]





$$P_\tau(D^*) = -0.38 \pm 0.51(stat.)^{+0.21}_{-0.16}(syst.)$$

SM : $P_\tau(D^*) = -0.497 \pm 0.013$

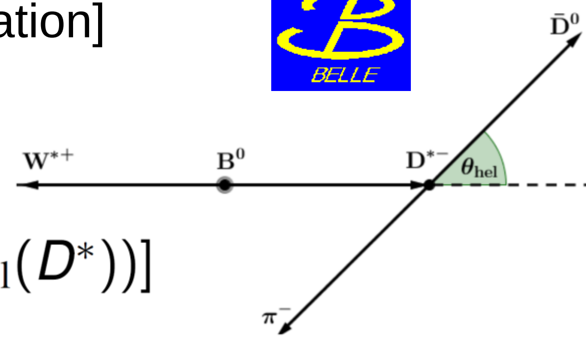


Consistent with the SM at 0.6σ

D* Polarization in $B \to D^*\tau\nu$

New Result

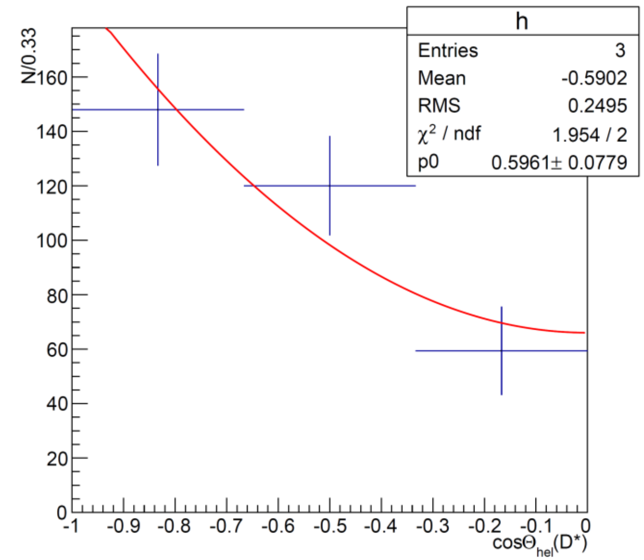
[BELLE-CONF-1805 in preparation]

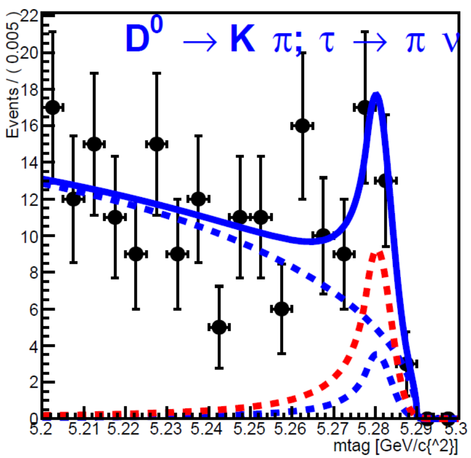


D* polarization in $B \to D^*\tau\nu$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}(D^*)} = \frac{3}{4}[2F_L^{D^*}\cos^2(\theta_{\rm hel}(D^*)) + (1-F_L^{D^*})\sin^2(\theta_{\rm hel}(D^*))]$$

- Inclusive reconstruction
- All τ decays can be used.
- Efficiency highly depends on $\cos\theta_{hel}(D^*)$.
- 3 bins of $\cos\theta_{hel}(D^*)$.





$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.03$

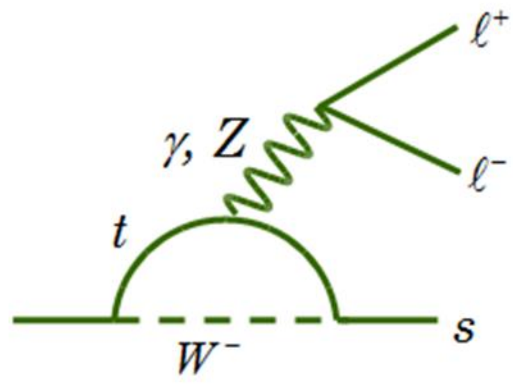
Consistent with SM (~0.45) within 2σ

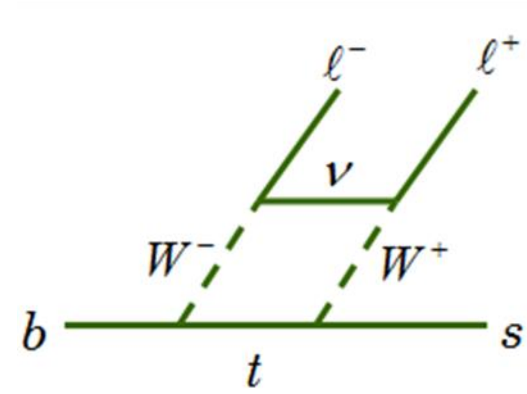
M(tag) for one mode with $-0.67 < \cos\theta_{hel}(D^*) < 0.33$.

Talk by K. Adamczyk (WG2)

EW Penguin B Decays

- $b \to s\ell^+\ell^-$: Electroweak penguin (or box) diagram.
  - ✓ Sensitive to C_7, C_9, C_{10} .
- "Anomalies" seen:
  - ✓ Lepton Flavour Universality.
  - ✓ Angular variable





$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)}$$

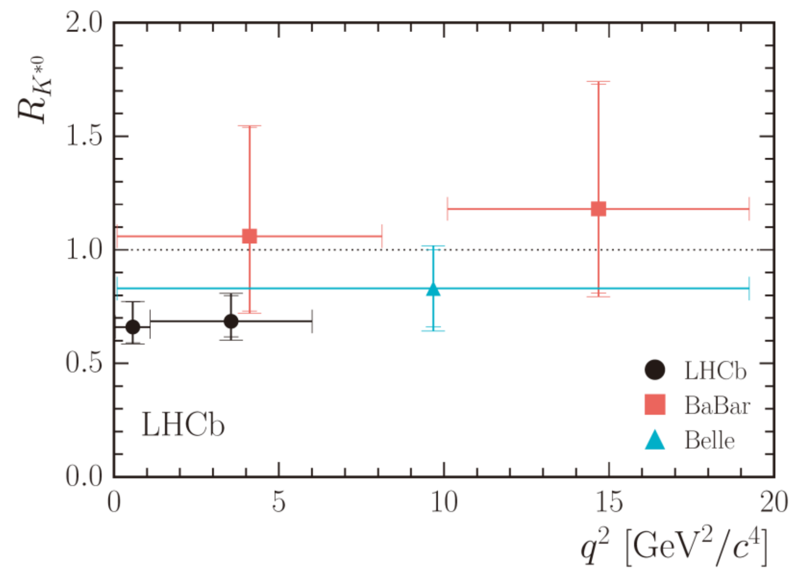
LHCb result

$R_K = 0.745\,^{+0.090}_{-0.074} \pm 0.036$ (2.6σ from SM)

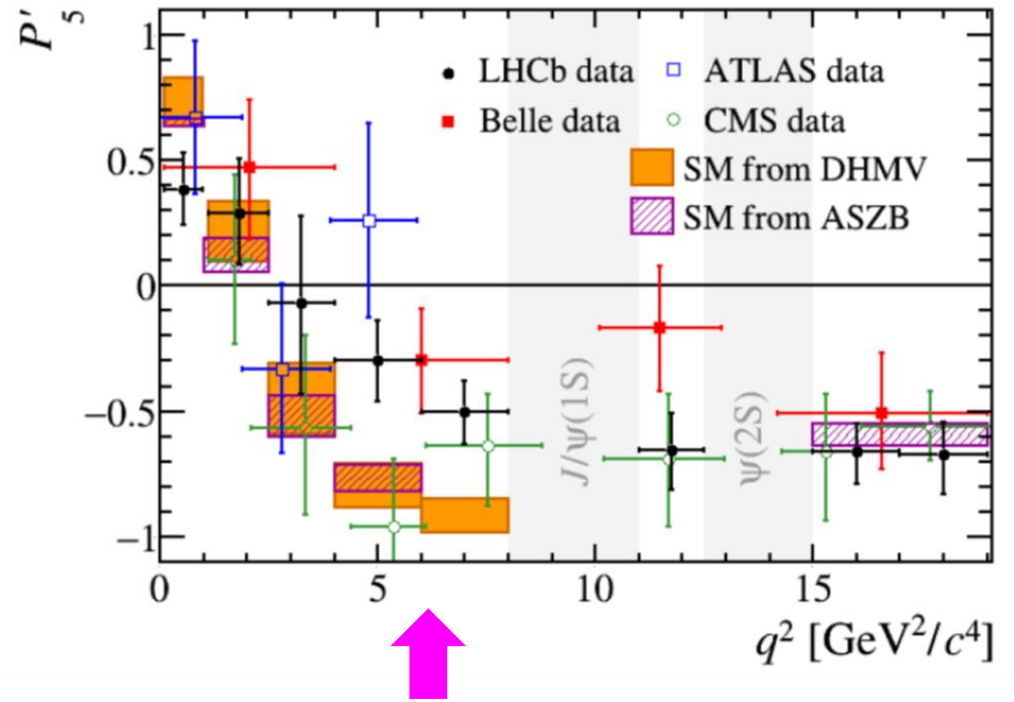
[PRL 113 (2014) 151601]

R_{K^*} : 2.1-2.4σ deviation from SM.

LHCb, JHEP08(2017)055

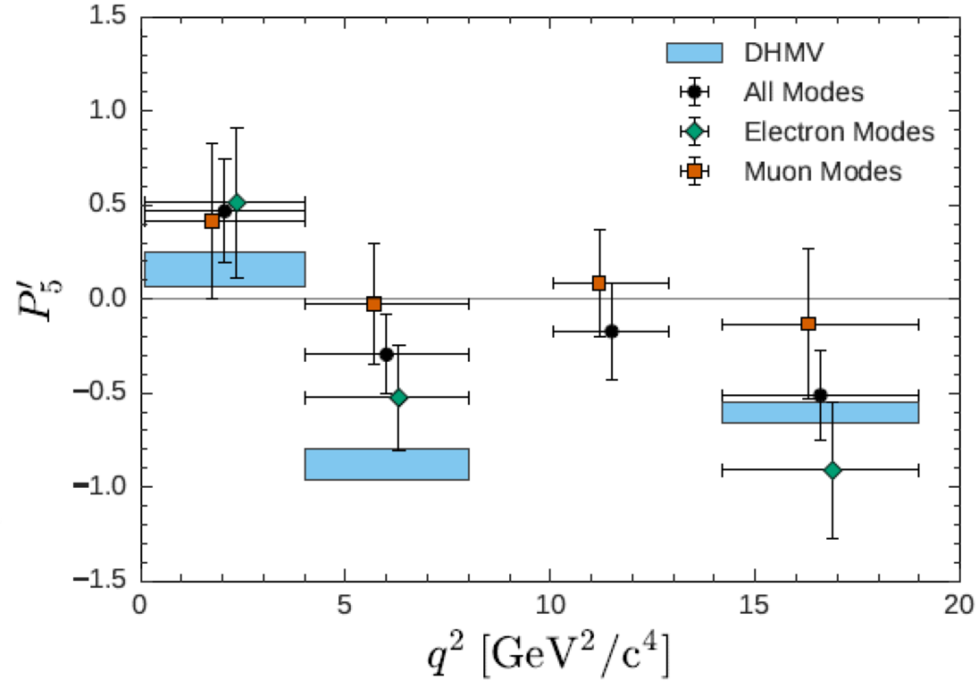


EW Penguin B Decays



- ~3σ deviation
- LHCb/ATLAS/CMS results from muon modes.

Belle measured P_5' separately for muon and electron modes.



- 2.6σ deviation in the muon mode.
- 1.1σ in the electron mode.

[PRL 118, 11801 (2017)]

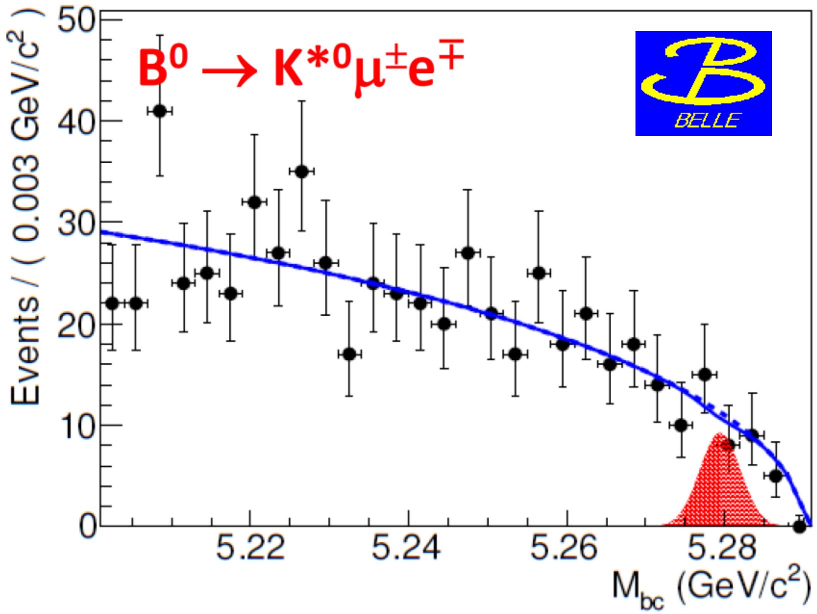
EW Penguin B Decays

New results in a few more related modes.

Talk by T.Gershon (WG3)

$B^0 \to K^{*0}\mu^\pm e^\mp$

- Deviation in R(K), R(K*) by LHCb.
- LFU violation $\to$ LFV

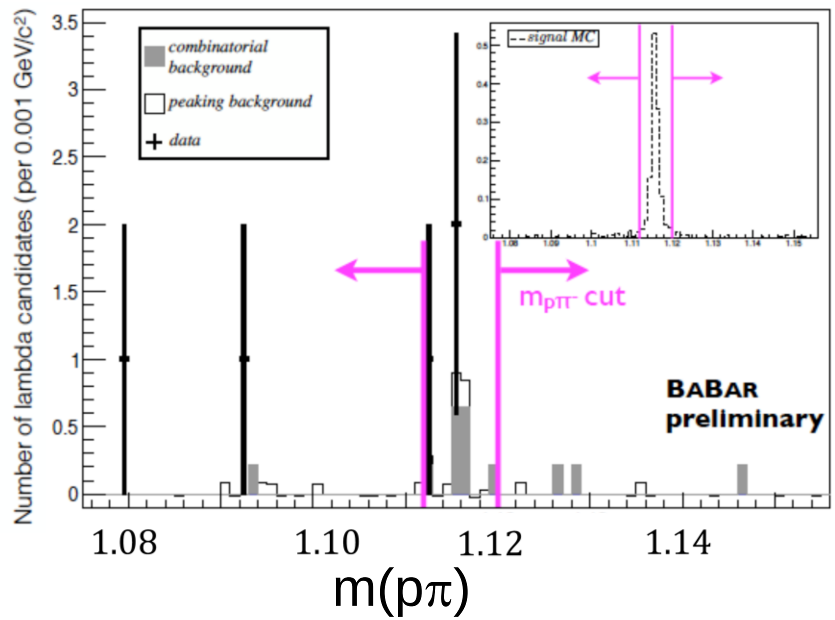


$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 1.8 \times 10^{-7}$

[arXiv:1807.03267, submitted to PRD]

$B^- \to \Lambda\bar{p}\nu\bar{\nu}$

- $b \to s\nu\bar{\nu}$: FCNC process
- SM : $\mathcal{B} = (7.9 \pm 1.9) \times 10^{-7}$
- Hadronic B tag

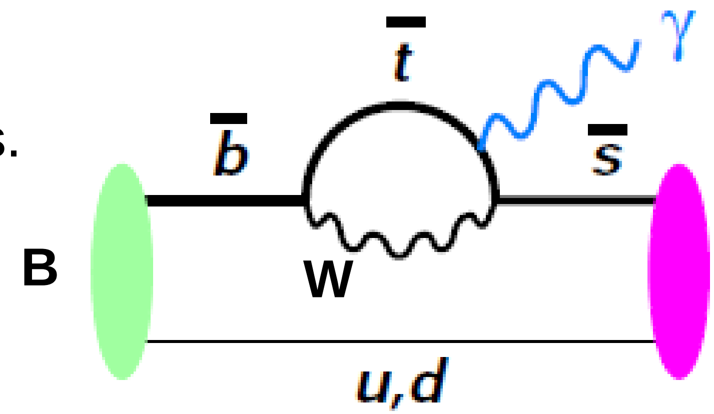


$\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu}) < 3.0 \times 10^{-5}$

$B \to X_s \gamma$

Radiative B Decay ($b \to s\gamma$)

- Penguin diagram (FCNC process).
- Good agreement between theory and experiments.
  - ✓ Strong constraint to New Physics



$B(B \to X_s\gamma;\ E_\gamma > 1.6\text{GeV})$
$= (3.32 \pm 0.15) \times 10^{-4}$ [HFLAV2018]
$= (3.36 \pm 0.23) \times 10^{-4}$ [Misiak 2015]†

† Misiak et al, PRL 114, 221801, (2015)

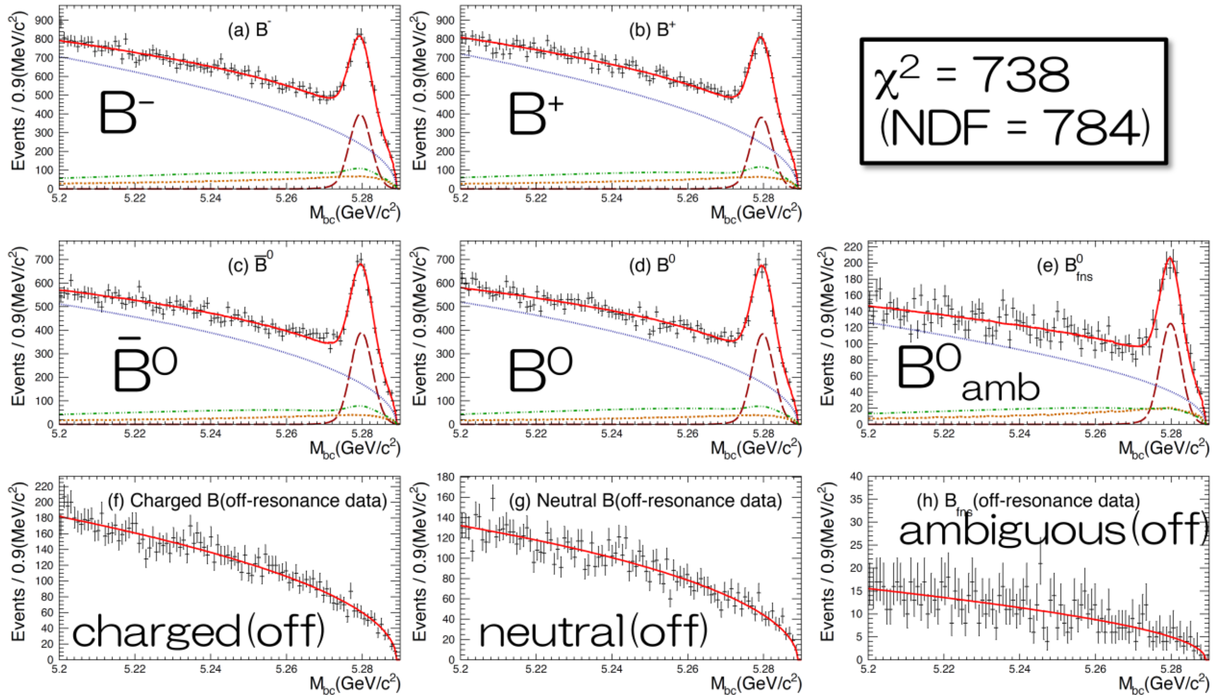
- A_{CP} of $B \to X_s\gamma$ is an interesting probe for NP, but has small (~2%) theoretical uncertainty.
- ΔA_{CP} (difference of A_{CP} between charged and neutral B) is a cleaner probe.

$$\Delta A_{CP}(B \to X_s\gamma) \equiv A_{CP}(B^+ \to X_s^+\gamma) - A_{CP}(B^0 \to X_s^0\gamma)$$

$B \to X_s \gamma$

[BELLE-CONF-1801, arXiv:1807.04236]

- Sum of 38 X_s modes with $M(X_s) < 2.8$ GeV.
  - ✓ 11 of them are flavour non specific modes.
- 8 M_{bc} distributions (including 3 from off-resonance) are simultaneously fitted.



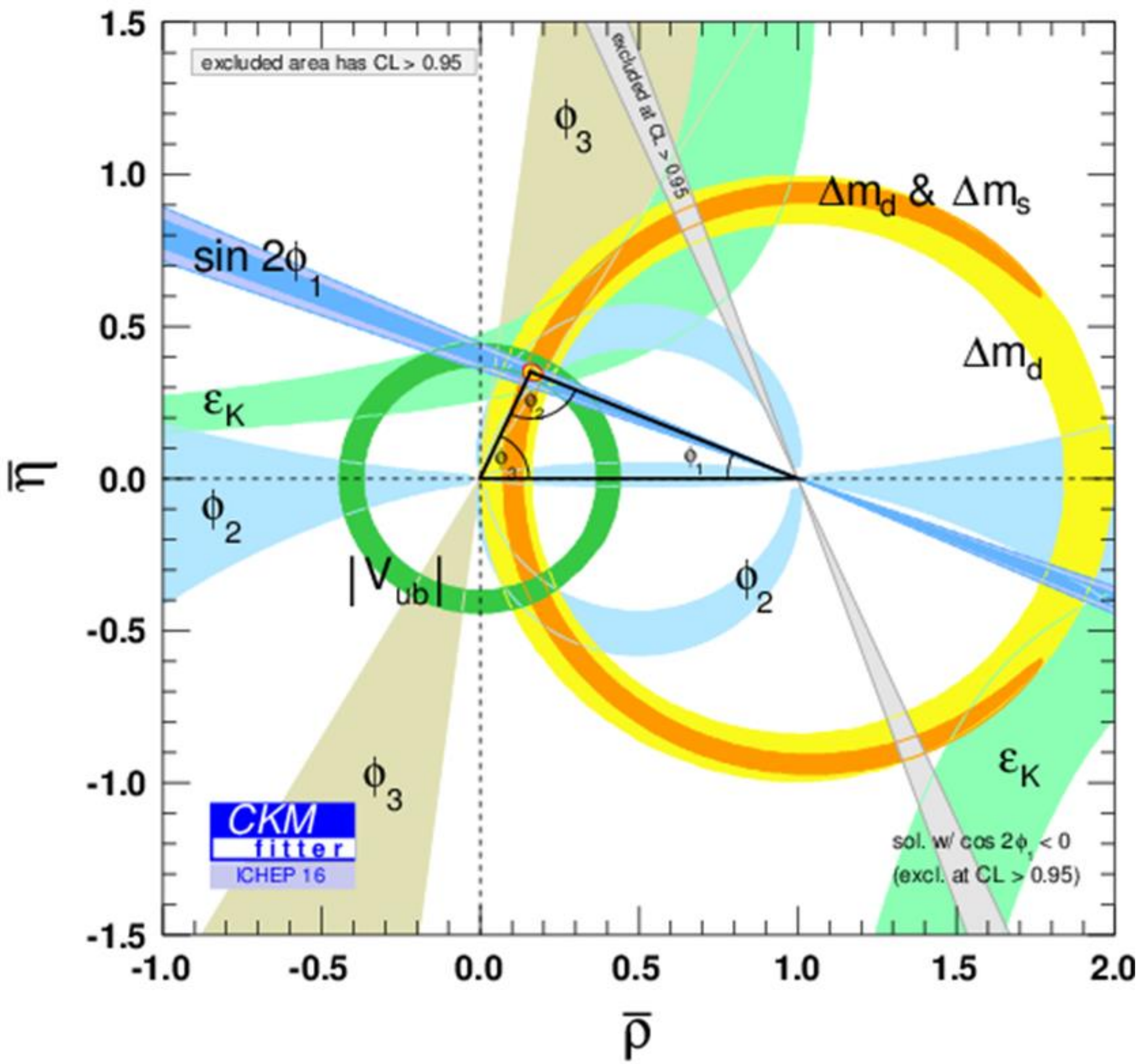
$\chi^2 = 738$
(NDF = 784)

$\Delta_{0-} = (+1.70 \pm 1.39 \pm 0.87 \pm 1.15)\%$ → reduce uncertainty for B.F.

$\Delta A_{CP} = (+1.26 \pm 2.40 \pm 0.67)\%$

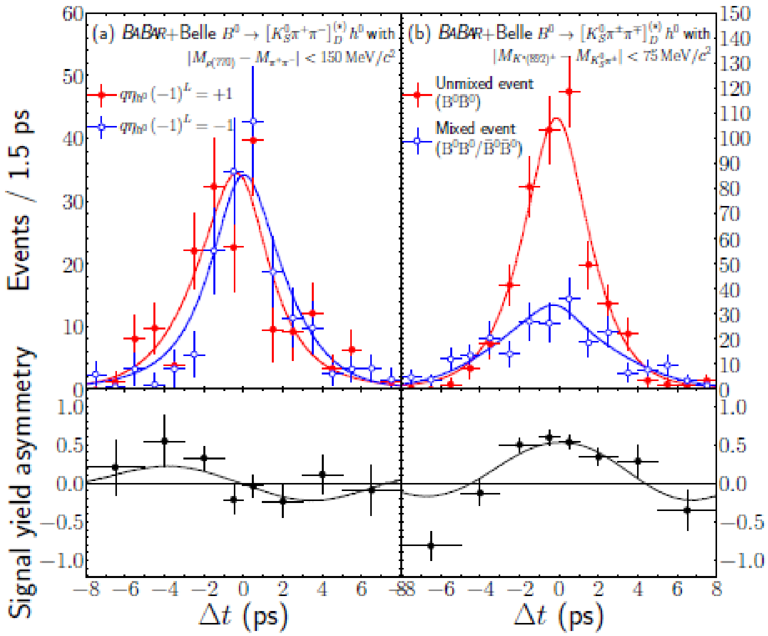
Constraint NP : $\Delta A_{CP} \approx 4\pi^2 \alpha_s \frac{\tilde{\Lambda}_{78}}{m_b} Im\left(\frac{C_8}{C_7}\right)$

Unitarity Triangle



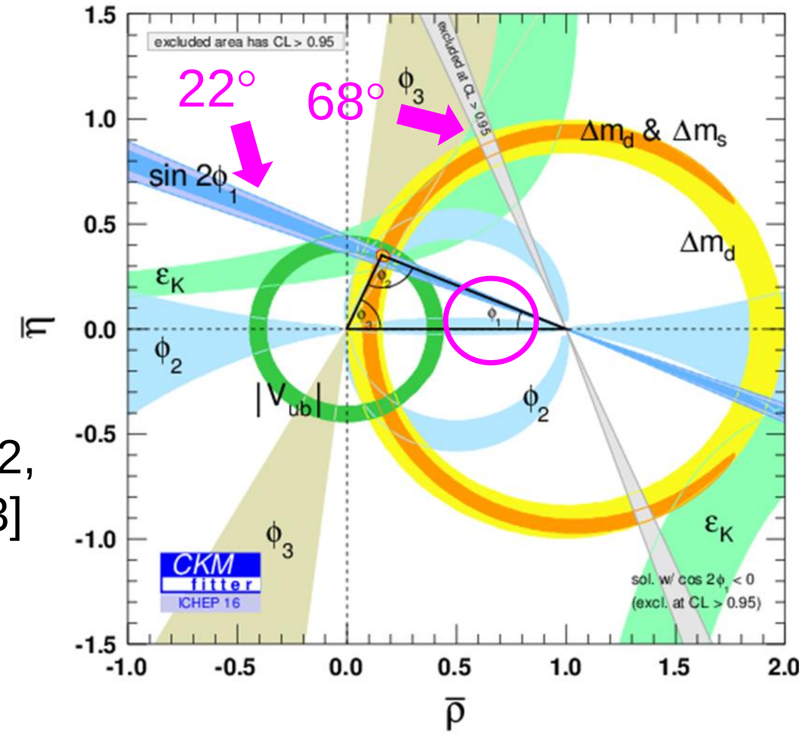
cos(2β) in B → D$^{(*)}$h^0

- sin2β is precisely measured, but trigonometric ambiguity exists for β.
- Time-dependent Dalitz analysis of B → D$^{(*)}$h^0, D → K$_S\pi^+\pi^-$ (h = π^0, η, ω) can resolve it.
- Joint Babar + Belle analysis.
  - ✓ 471 + 772 M B$\overline{\text{B}}$



(two different region in Dalitz plane)

[arXiv:1804.06152, arXiv:1804.06153]



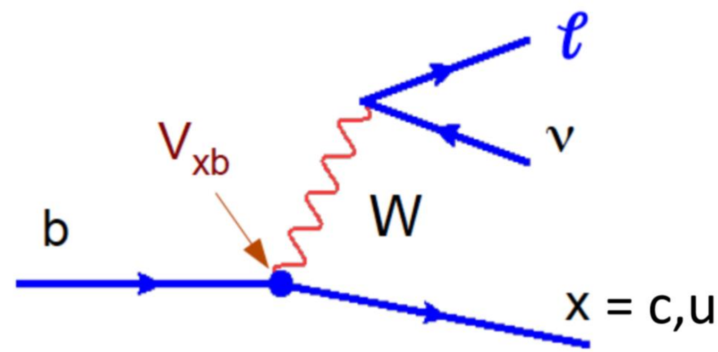
$$\sin(2\beta) = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$$
$$\cos(2\beta) = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$
$$\beta = \left(22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model})\right)^0$$

- First evidence of cos2β > 0.

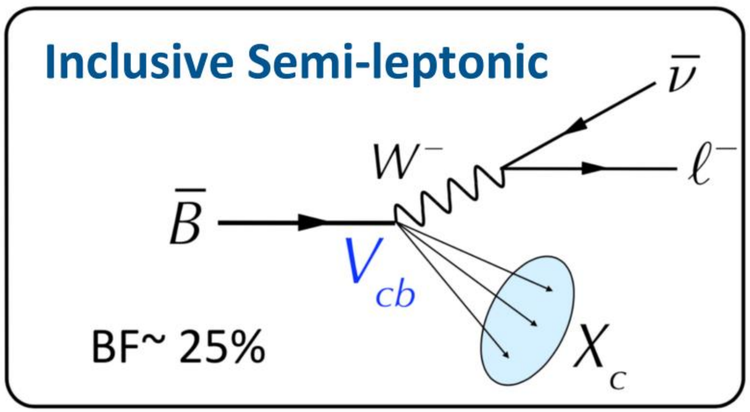
Talk by B.Pal (WG4)

$|V_{ub}|$ and $|V_{cb}|$

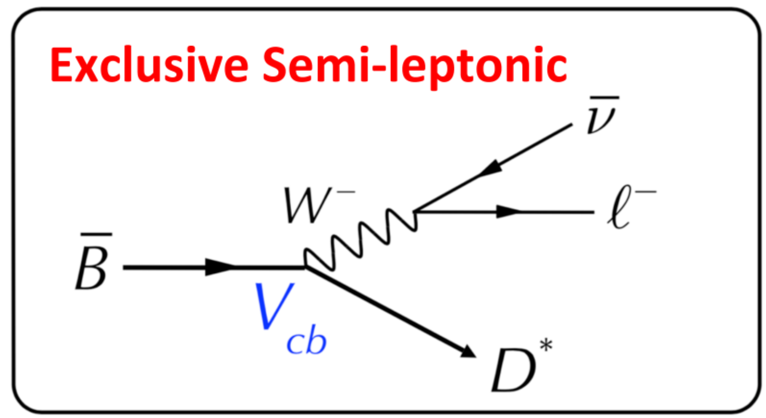
- $|V_{ub}|$ and $|V_{cb}|$ measurements are done using semi-leptonic decays $b \to u\ell\nu$, $c\ell\nu$.



- Two approaches: inclusive and exclusive



do not specify hadron state



specify hadrons (experimentally clean)

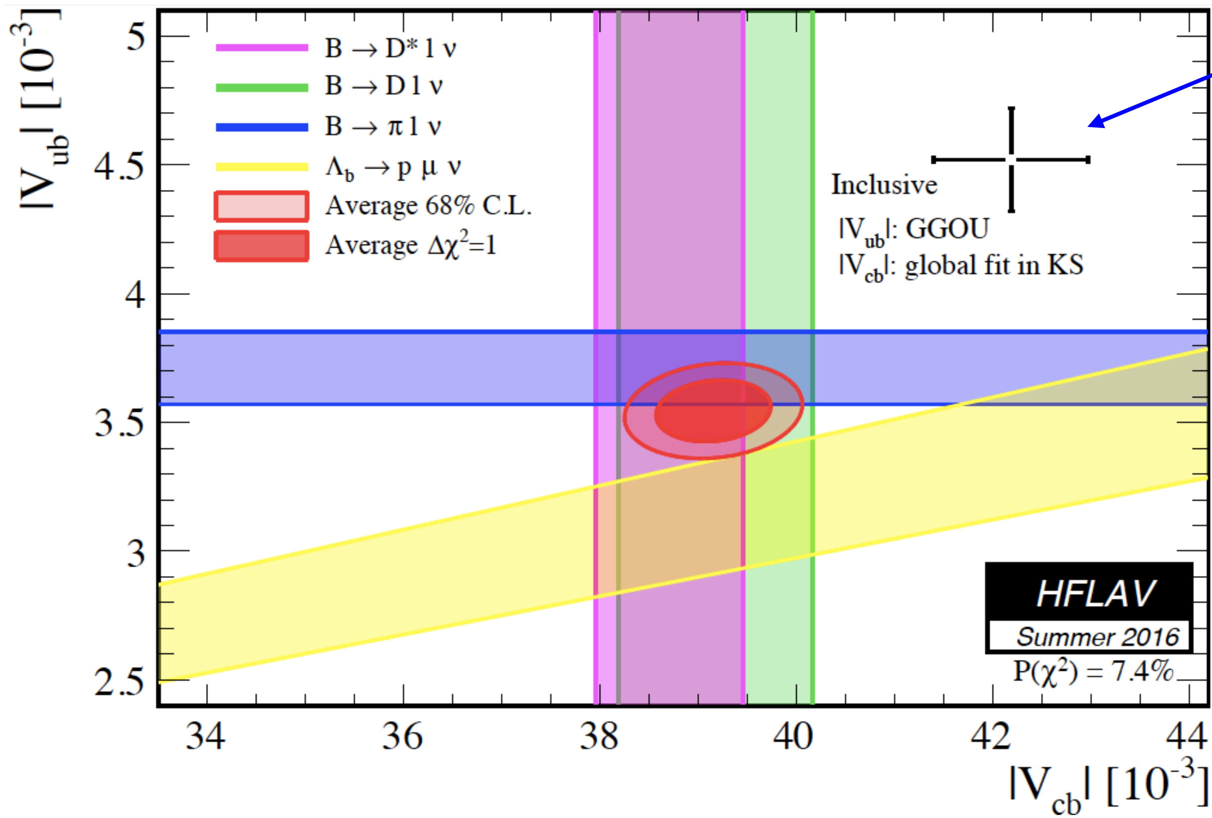
- QCD corrections to parton level decay rate
- Operator Product Expansion (OPE) in α_S and Λ/m_b

- QCD contributions parametrized in form factors
- Lattice QCD (high q^2) or LCSR (low q^2)

$|V_{ub}|$ and $|V_{cb}|$

Discrepancy between inclusive and exclusive

exclusive measurements



average for inclusive

$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ (inclusive)

$|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3}$ (exclusive)

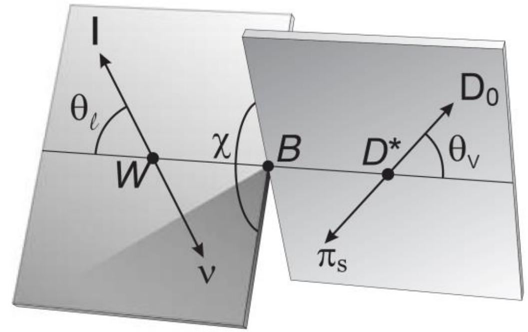
$|V_{ub}| = (4.49 \pm 0.16\ ^{+0.16}_{-0.18}) \times 10^{-3}$ (inclusive)

$|V_{ub}| = (3.72 \pm 0.19) \times 10^{-3}$ (exclusive)

Untagged $B \to D^*\ell\nu$

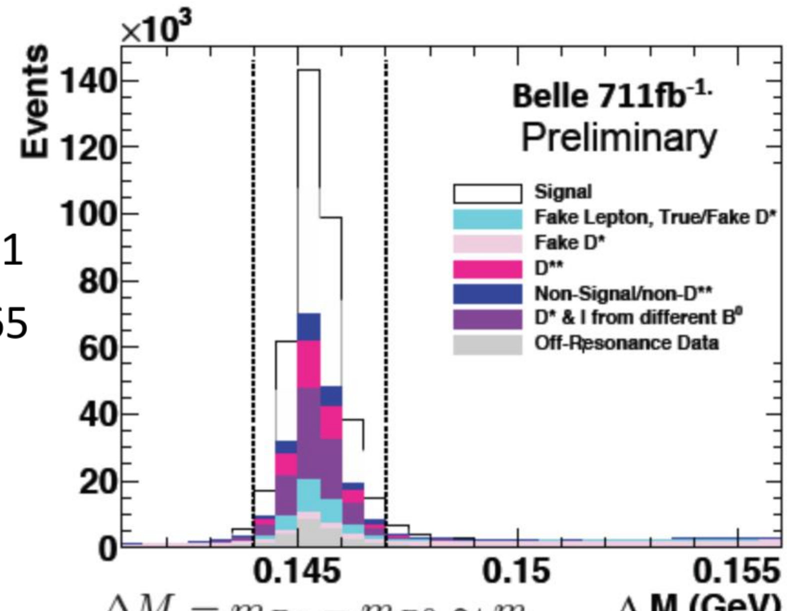
[BELLE-CONF-1803, arXiv:1809.03290]

- New result of untagged analysis of $B \to D^*\ell\nu$ was presented at ICHEP.
- Simultaneous fit to $\cos\theta_\ell$, $\cos\theta_V$, χ, w (hadronic recoil) to extract form factors and $F(1)\,|V_{cb}|$.
- Two form factor parametrization, CLN [NPB530, 153 (1998)] and BGL [PRL74, 463 (1995)] are used.
  - ✓ CLN was mainly used in previous measurements.



$N(B \to D^* e\nu) = 91381$

$N(B \to D^* \mu\nu) = 89965$



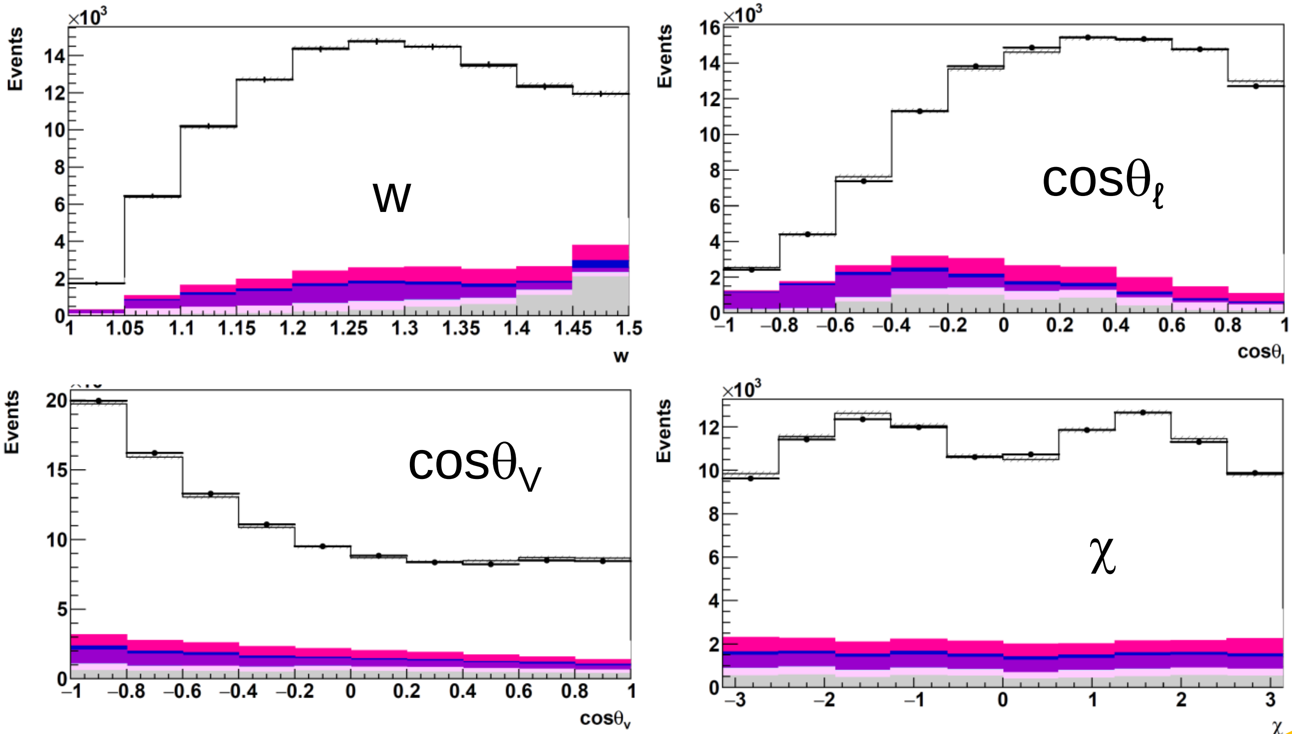
$\Delta M = m_{D^*} - m_{D^0} \sim m_{\pi_{slow}}$

Bonus: Lepton Flavor Universality test

$$\frac{\mathcal{B}(B^0 \to D^{*-} e^+ \nu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu)} = 1.01 \pm 0.01 \pm 0.03$$

Untagged B → D*ℓν

Fit for BGL parametrizations for B → D*μν



Talk by K. Lieret (WG2) and C. Schwanda (WG2)

world average

$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ (inclusive)

$|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3}$ (exclusive)

CLN: $|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$

BGL: $|V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$

consistent with previous (exclusive) results

consistent with inclusive result

some hint of inclusive/exclusive discrepancy?

More Results, Talks

- $B \to \mu\nu$ (untagged) [PRL 121, 031801 (2018)] — Talk by A. Sibidanov (WG2)
- $B \to \ell\nu\gamma$ (hadronic tag with Full Event Interpretation) — **New Result** — Talk by M. Gelb (WG2)
- CPV of $B \to J/\psi\pi^0$, $B \to K_S\pi^0\pi^0$ — Talk by B.Pal (WG4)
- Inclusive $B \to X_u\ell\nu$ (electron energy endpoint) [PRD 95, 072001 (2017)]
- Charmless B decays, $\gamma(=\phi_3)$, …..

and

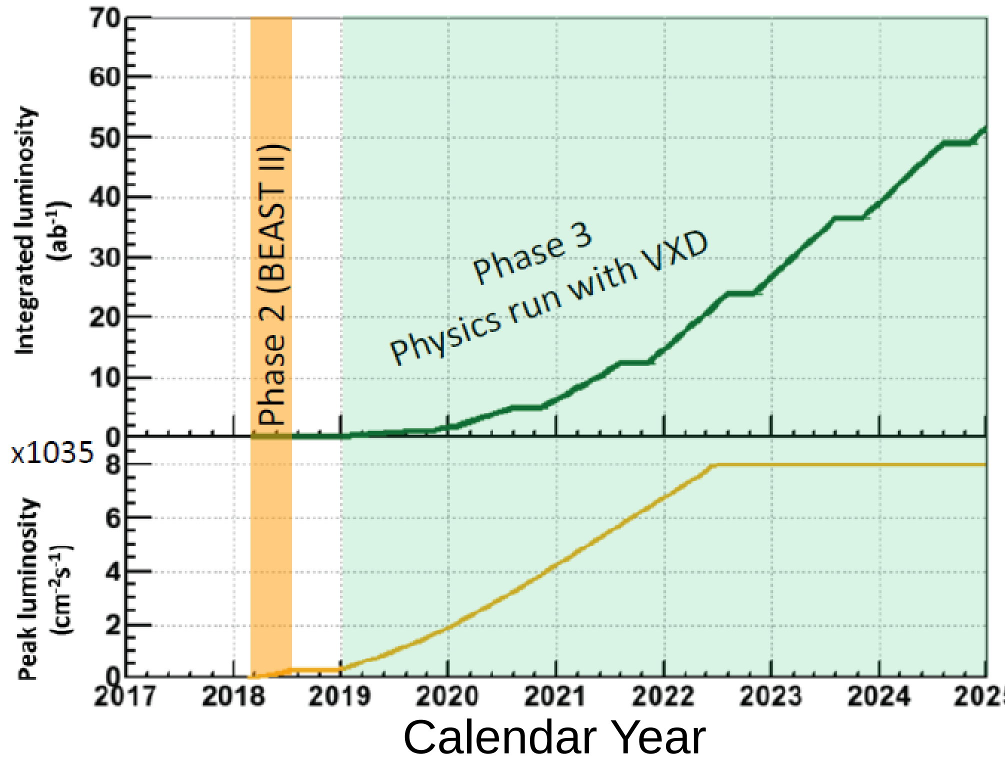
- Prospects for Belle II

Summary

- Belle II started. Phase 2 operation completed this year.
  - ✓ First collision.
  - ✓ Accelerator study, but some physics data are taken.
  - ✓ B mesons are reconstructed.

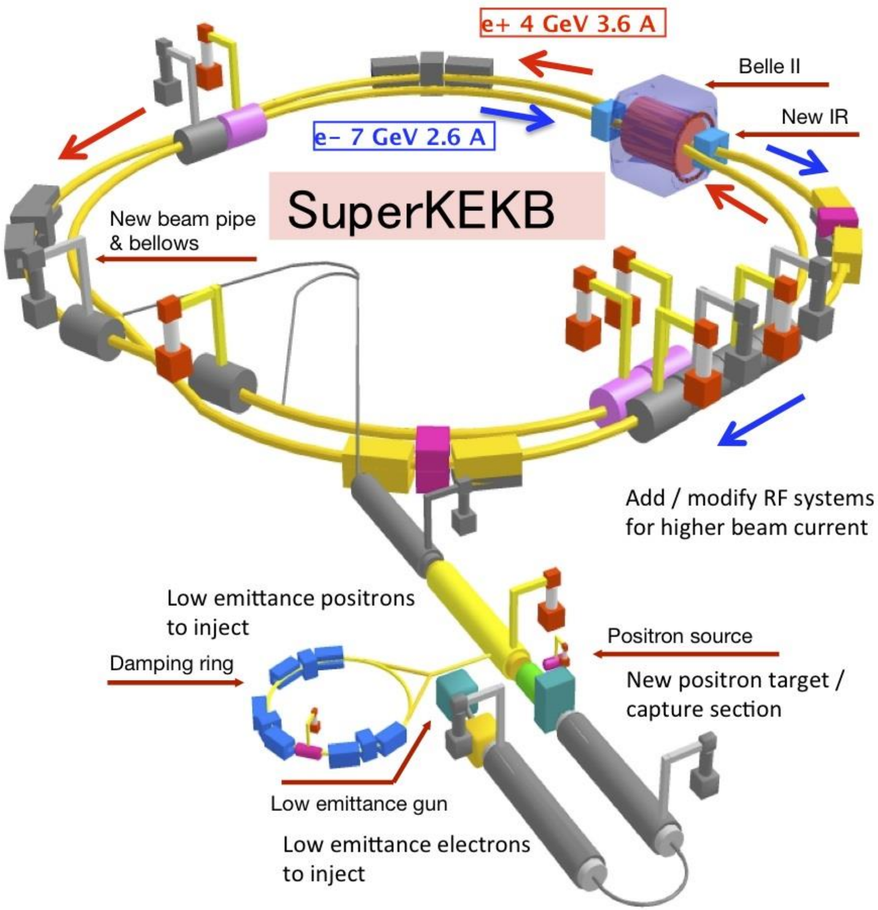
- New results from BaBar and Belle.
  - ✓ D* polarization in $B \rightarrow D^{*}\tau\nu$.
  - ✓ $\cos(2\beta)$ in $B \rightarrow D^{(*)}h^{0}$
  - ✓ $|V_{cb}|$ from $B \rightarrow D^{*}\ell\nu$
  - ✓ ….

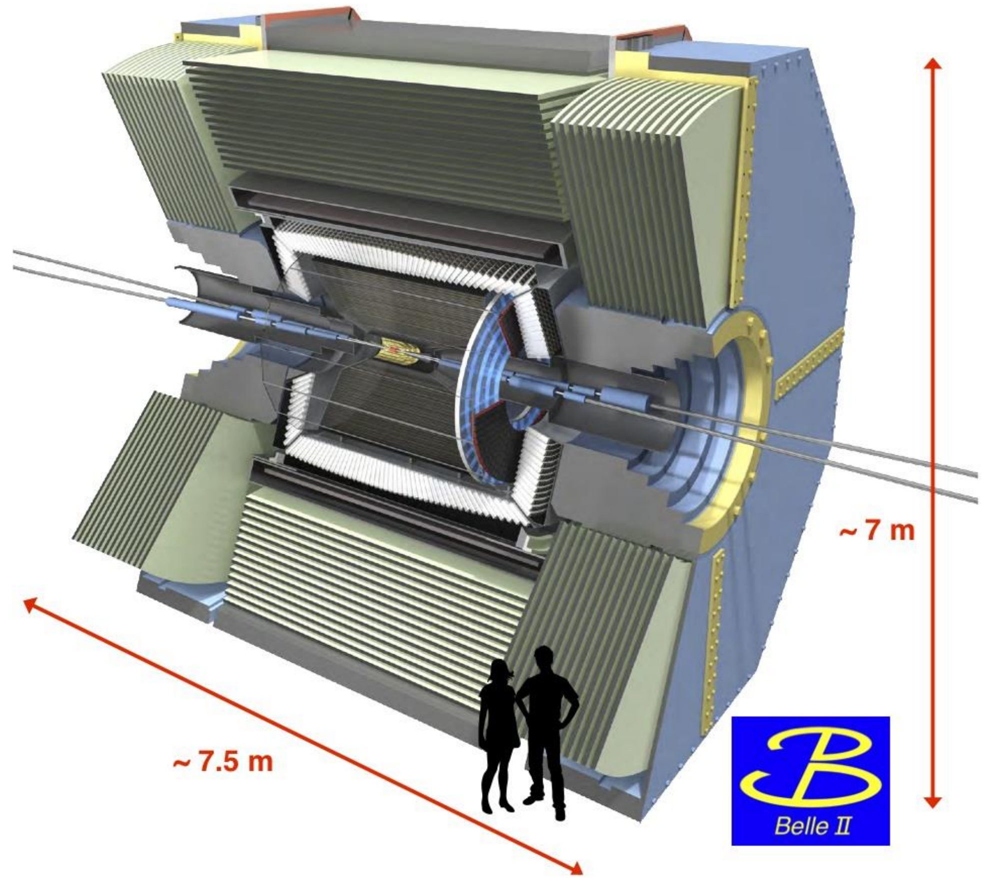
- Belle II Phase 3 (physics run) starts next year, and we expect first physics results soon. Stay tuned.



Backup

SuperKEKB and Belle II





SuperKEKB Parameter

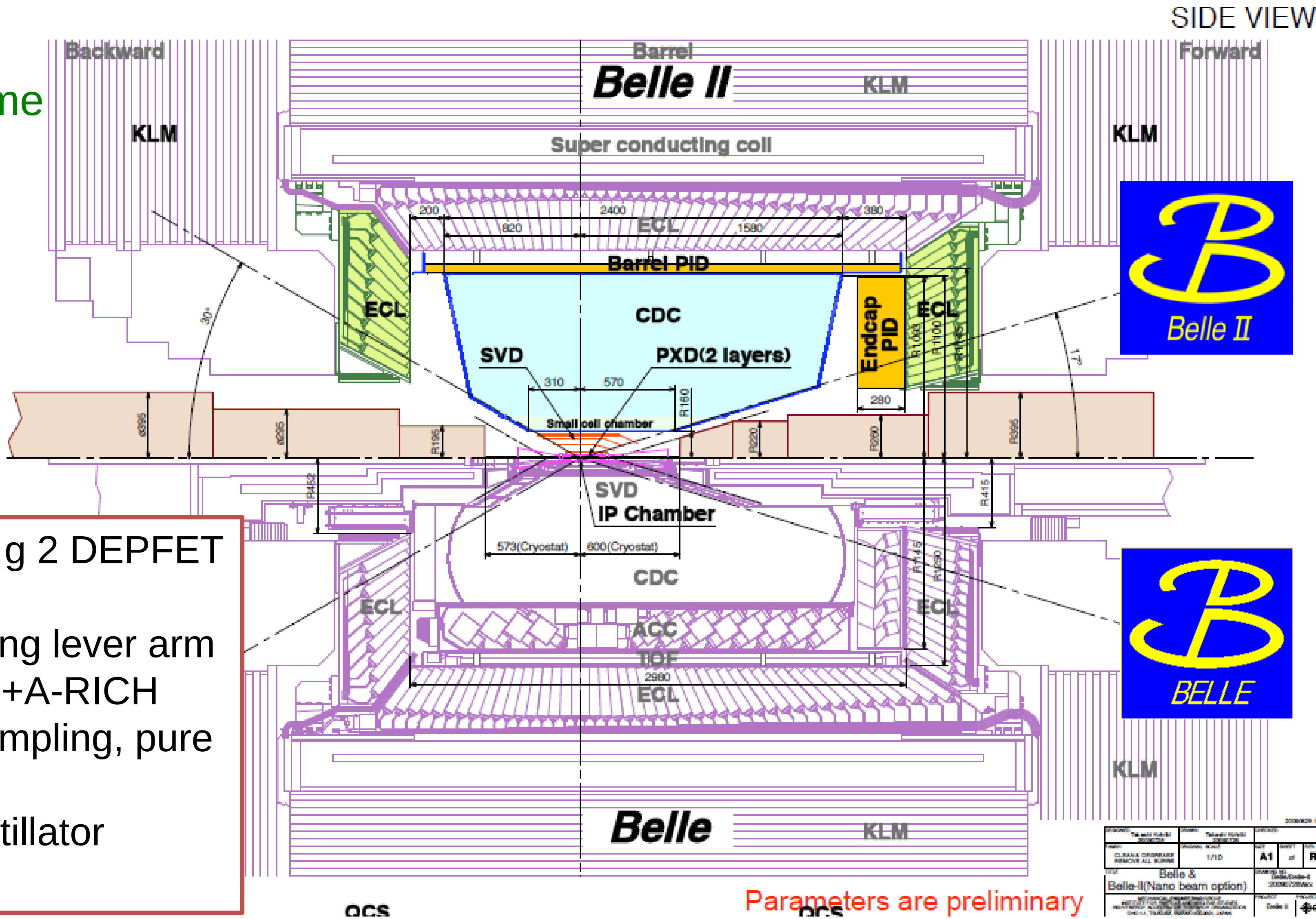
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	5.0	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.31	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0886	0.0830	
Luminosity	**L**	**2.1×10^{34}**		**8×10^{35}**		**$cm^{-2}s^{-1}$**

- **Small beam size & high current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of LER short lifetime

From Belle to Belle 2

Belle II

- At least, the same performance as Belle in higher luminosity.
- Better performance if important for physics



SVD: 4 DSSD lyrs g 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

Parameters are preliminary

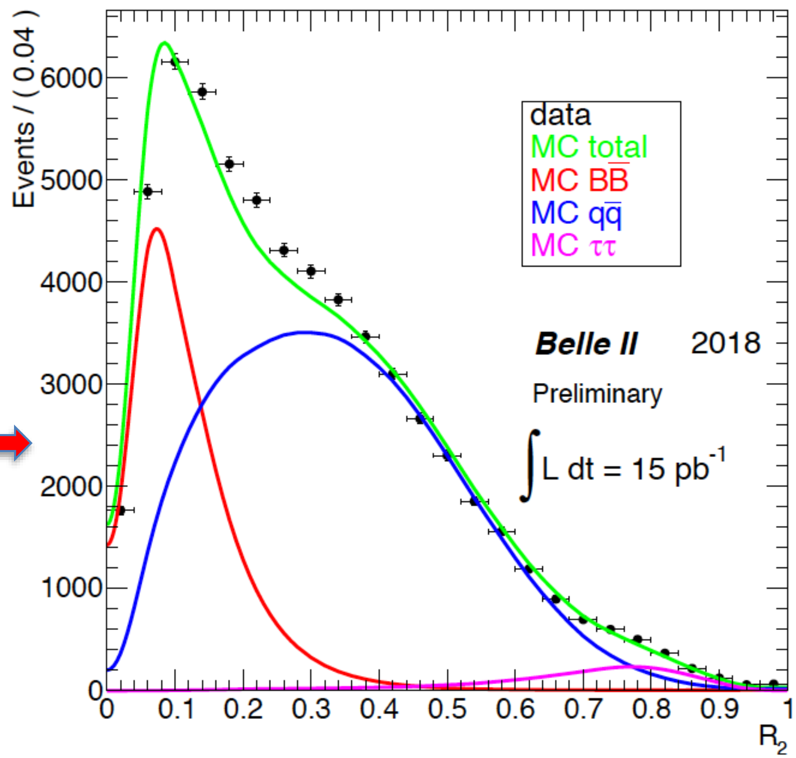
The Geography of the International Belle II collaboration

Belle II now has grown to ~800 researchers from 25 countries

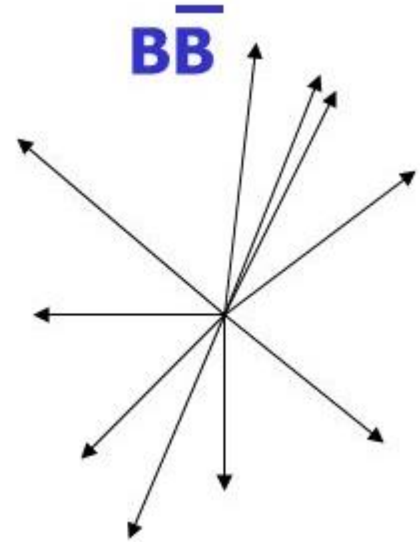
This is <u>rather unique</u> in Japan and Asia. The only comparable example is the T2K experiment at JPARC, which is also an <u>international collaboration</u>

Youth and potential: There are ~267 graduate students in the collaboration

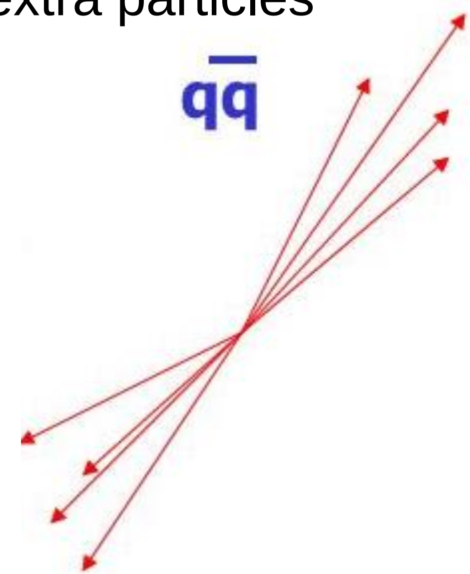
Event Topology tells us we are seeing B's



Spherical R_2 Jet-like

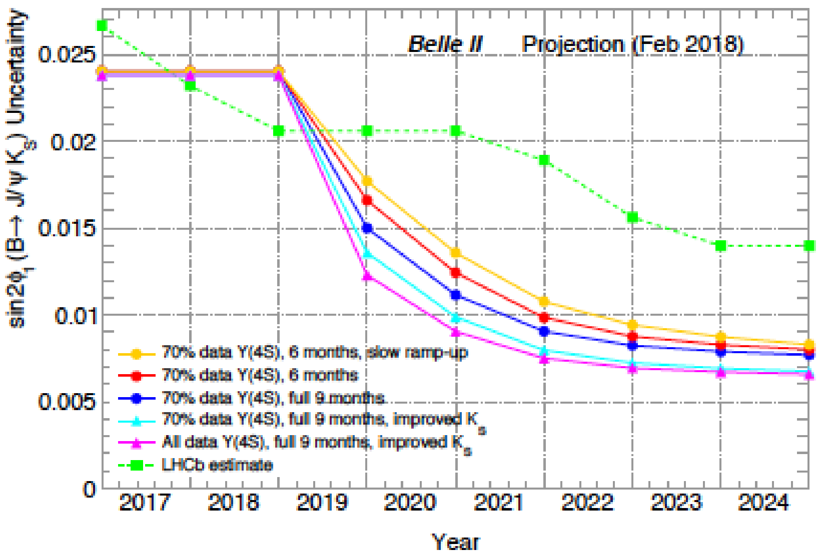


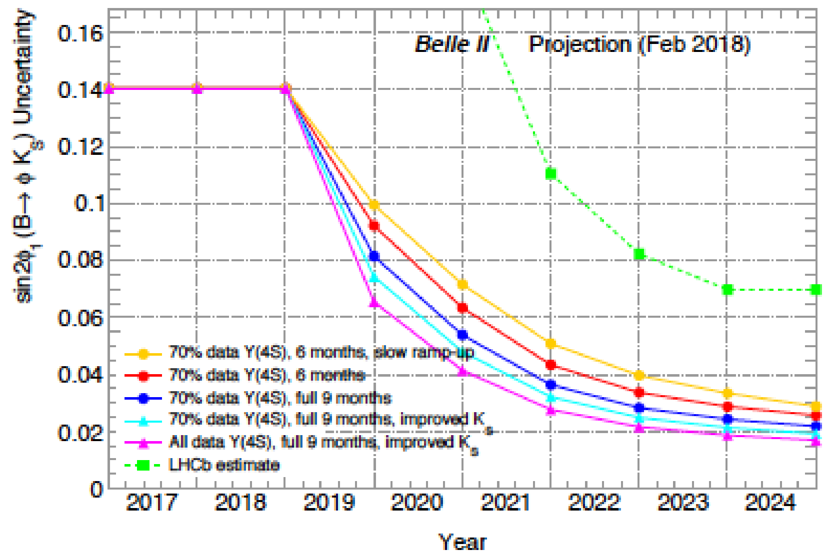
B pairs produced at rest in the CM with no extra particles

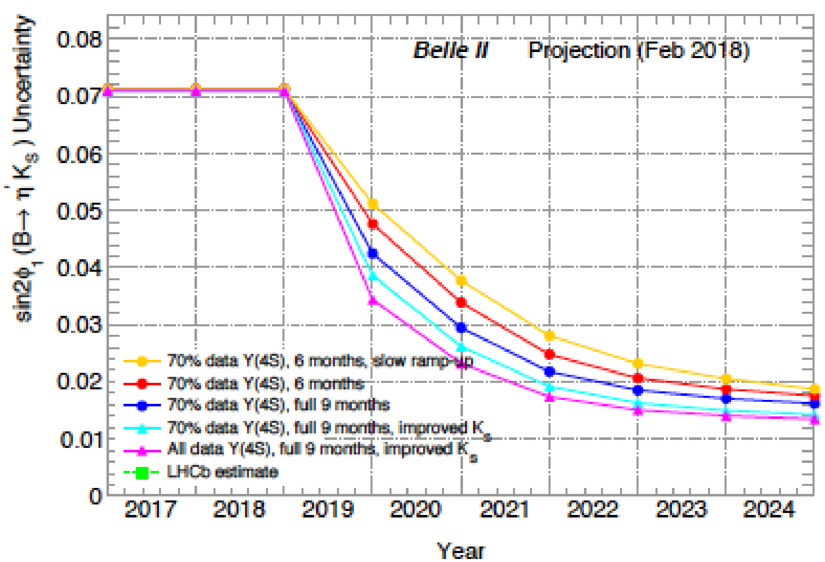


We are on the Y(4S) resonance and recording B anti-B pairs with ~99% efficiency.

Examples of Physics Competition and Complementarity







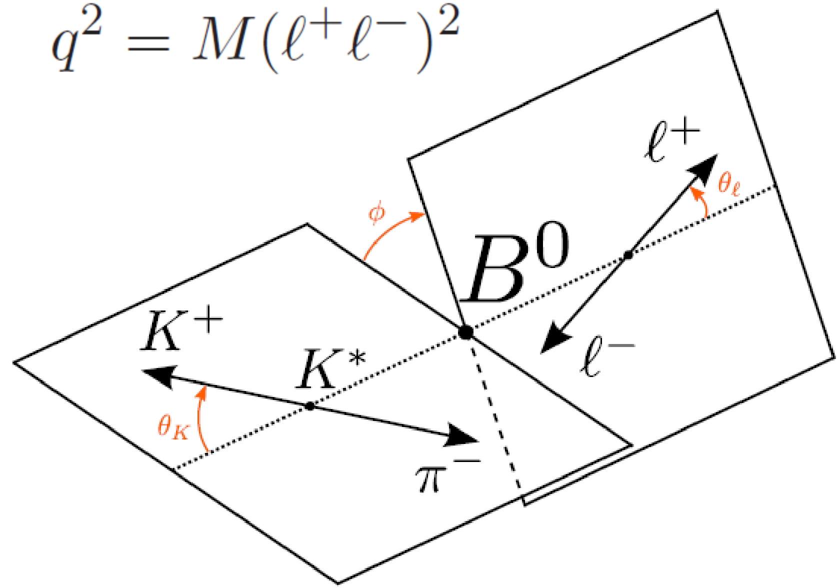
Use publicly available LHCb projections.

Angular Analysis of $B \to K^*\ell^+\ell^-$

Angular distribution in $B \to K^*\ell^+\ell^-$ ($K^* \to K\pi$)

$$q^2 = M(\ell^+\ell^-)^2$$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2}$$
$$= \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



- 8 variables : F_L (longitudinal polarization of K*) and S_j (j=3,4,5,6,7,8,9)
  - ✓ function of q^2

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$