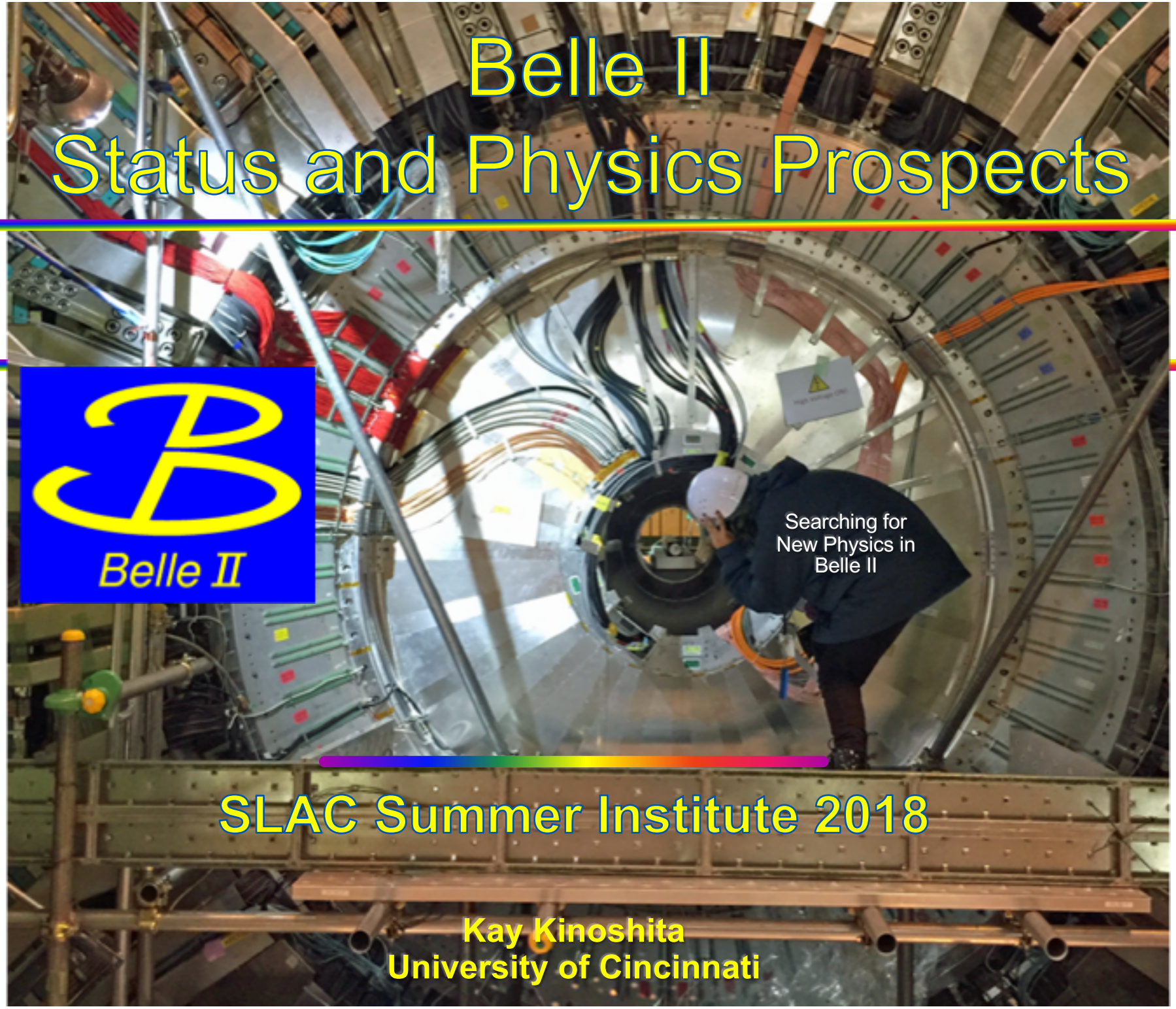
Belle II
Status and Physics Prospects



SLAC Summer Institute 2018

Kay Kinoshita
University of Cincinnati

Motivation

Big **Q**uestions

- Origin of generations & role of flavor
- CP violation and baryon asymmetry

Both necessarily involve 3 generations → heavy quarks

Upcoming generation of b experiments will address these at TeV scale

- Precision in Standard Model:
  - CKM matrix magnitudes & phases → CP asymmetry, rare decays
  - Multi-prong analysis of a rich zoo of particles & processes
- Hadronic infrastructure: required for precision CKM
  - HQ symmetries
  - Effective field theories
  - Flavor SU(3)
  - fragmentation
  - Spectroscopy

heavy flavor (b) factories

2008 Nobel Prize
Kobayashi & Maskawa

CURRENT/RECENT

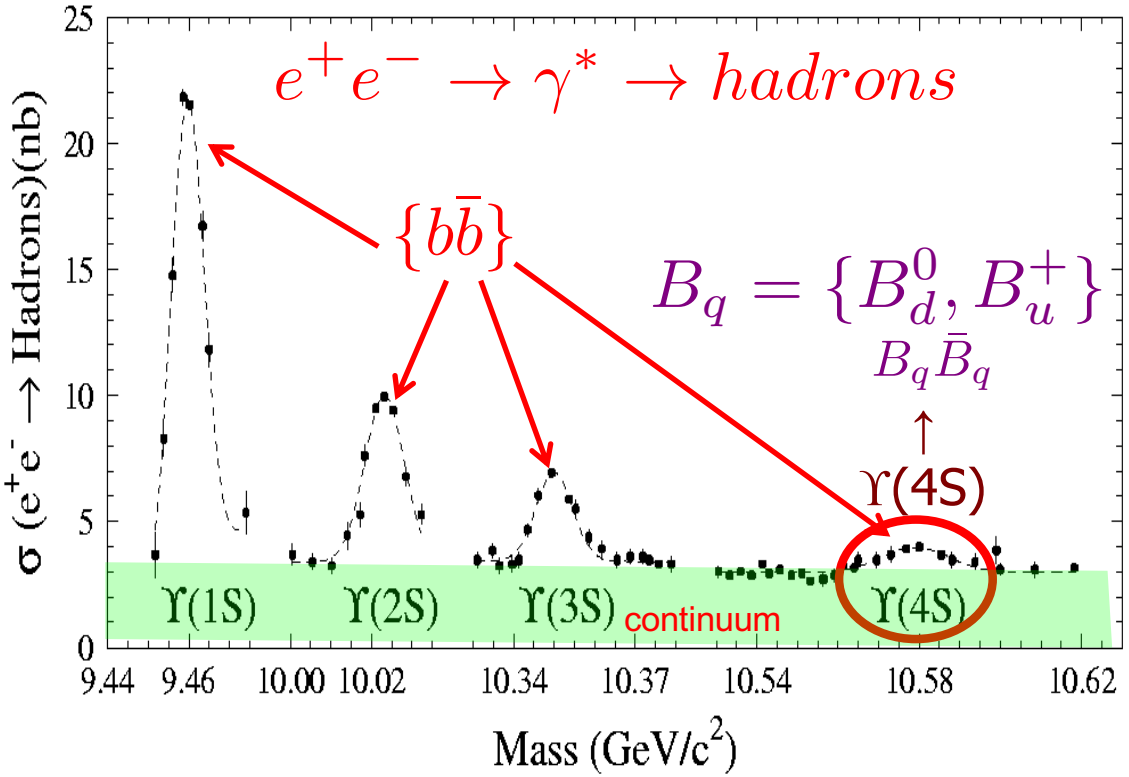
- B factories: KEKB/Belle, PEP-II/Babar
  - 1999-2010 e^+e^- @10.6 GeV (cms)
  - Combined 1.25 x 10^9 B pairs, ~same # of charm pairs
    - Collect ~100%, reconstruction efficiencies ~10-80%
- LHCb
  - 2008- pp @ 7-13 TeV
  - ~8 fb^{-1} σ_b ~ 72-144 μb (O|10^{12}| b's); σ_c~ 2-3 mb (O|10^{13}| c's)
    - Low collection eff, detection/reconstruction of neutrals

UPCOMING

- SuperKEKB/Belle II
  - 2018 - e^+e^- @10.6 GeV (cms)
  - By 2024 ~50 ab^{-1} ~ 5 x 10^{10} B pairs, charm, etc.
    - measurements requiring clean decay times, neutrals, …

SuperKEKB: $e^+e^- \rightarrow \Upsilon(4S)$ (primarily)

Upsilon region ~10 GeV



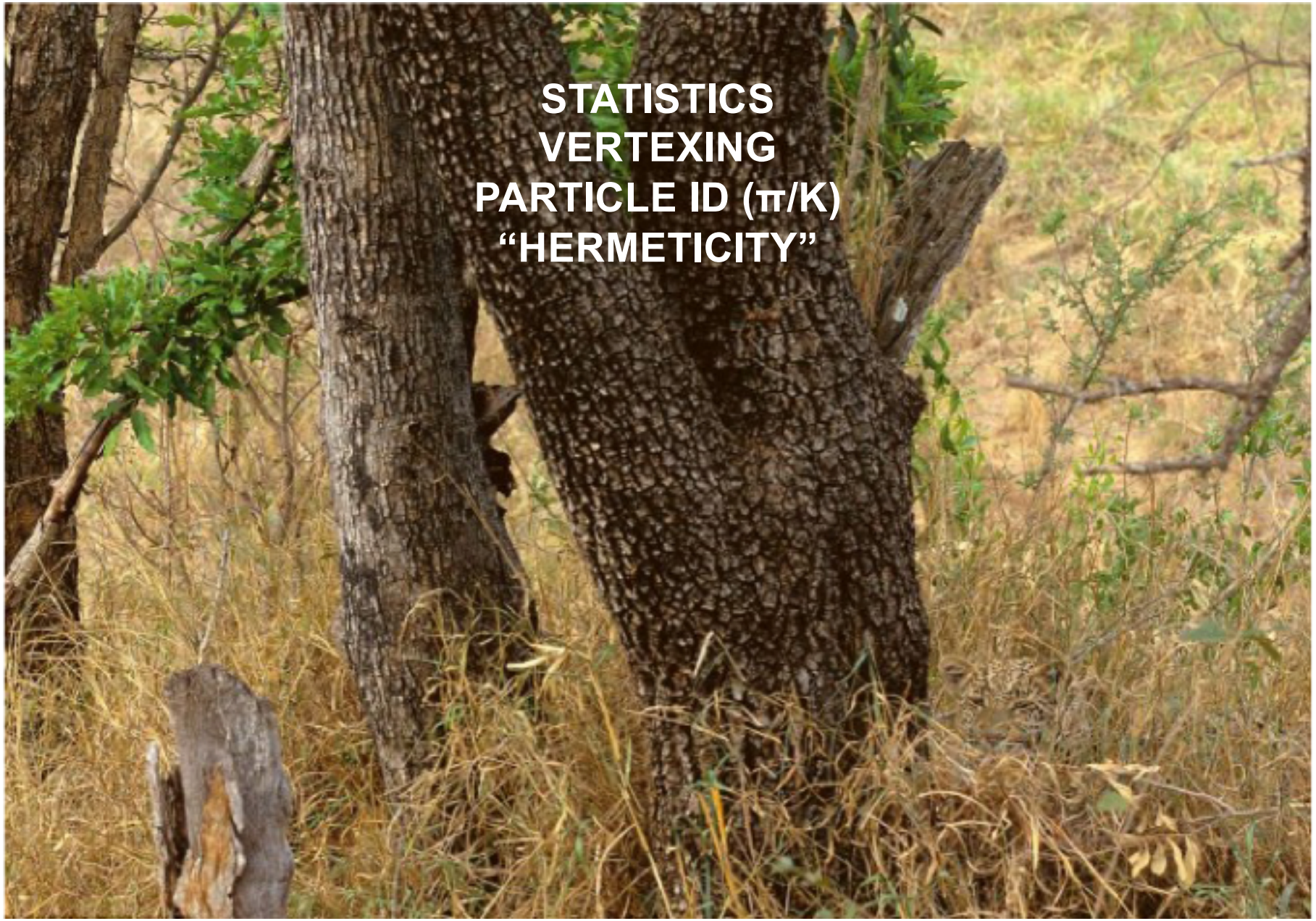
e^+e^- vs pp collisions

- Complete annihilation ⇒Event CMS = e^+e^- CMS
- "Hermetic" detector measures nearly all final particles
  => "neutrals reconstruction" {K_L, n, ν, dark matter}
- Average multiplicity (chg+neutral) ~15-20 (vs hundreds in pp)
- Near-threshold @ $\Upsilon(4S)$: exclusive B pair events – **clean**

Belle II approach: seek the New …

Belle II approach: seek the New …

By improving precision on the Old

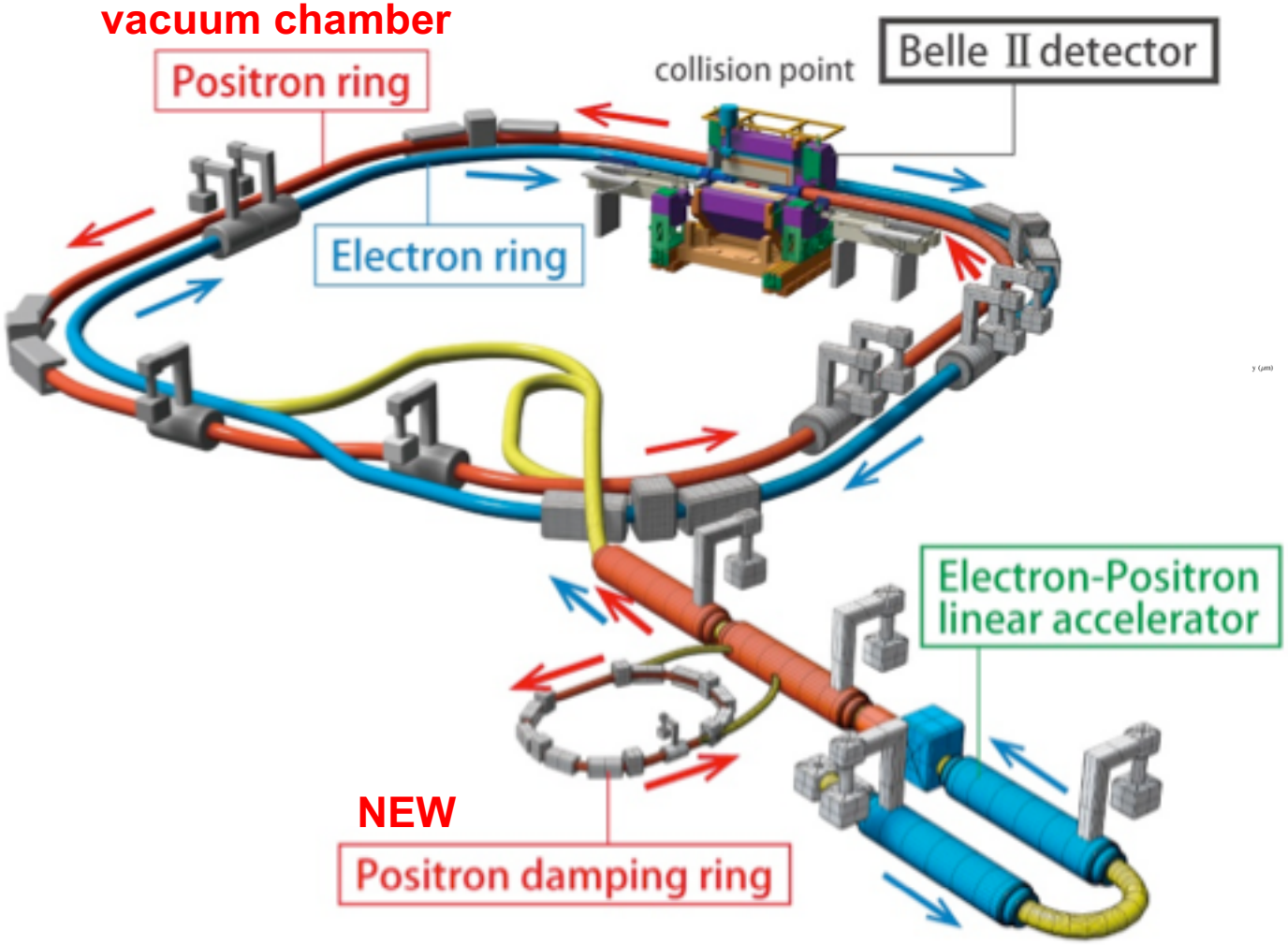


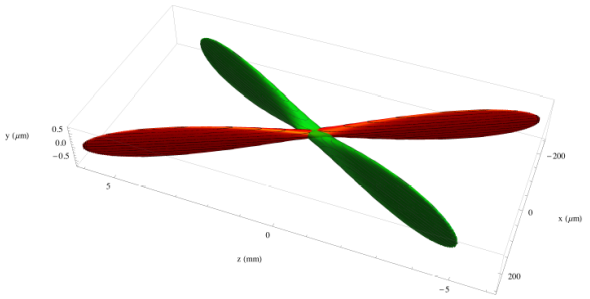
SuperKEKB

Belle II

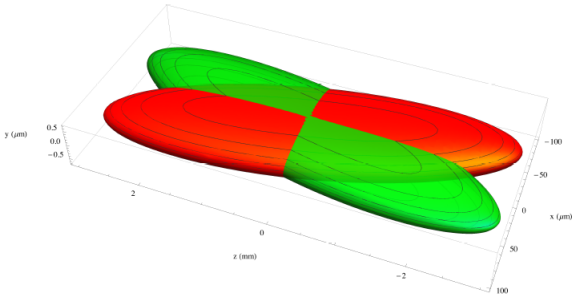
NEW complex superconducting final focus

NEW 3 km positron ring vacuum chamber



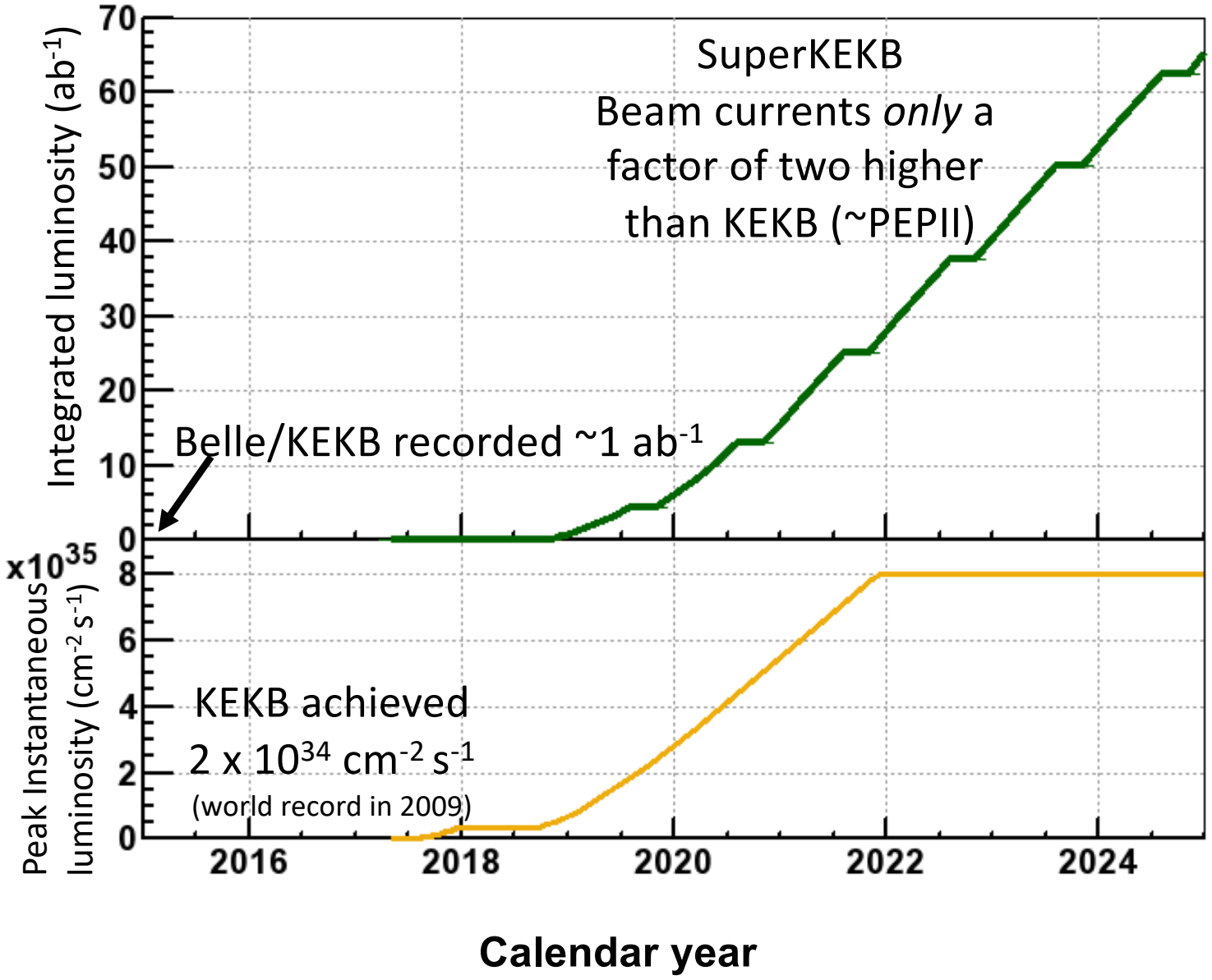


SuperKEKB nano-beam
50 nm x 10μm x 0.5 mm
41 mr crossing angle



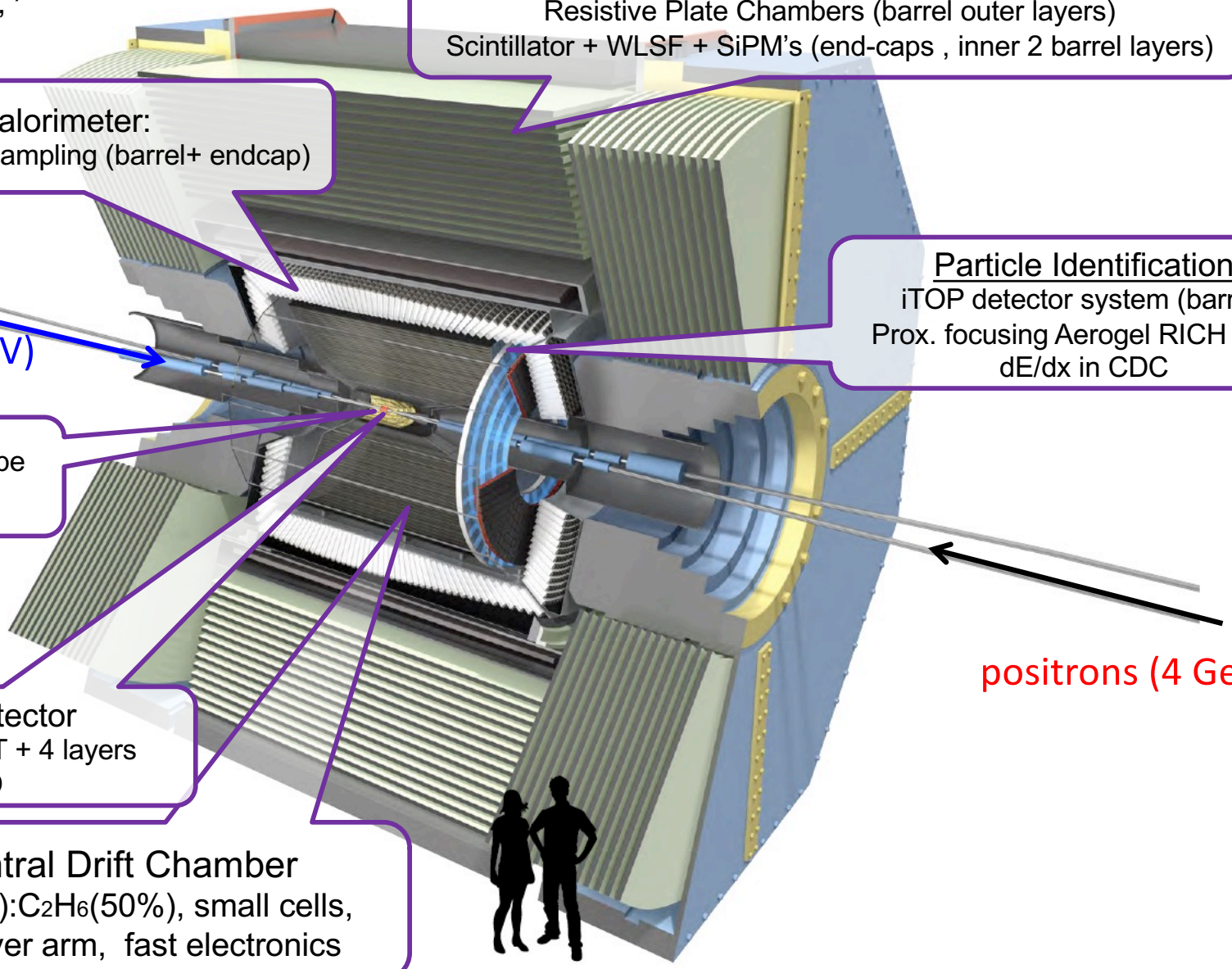
KEKB
2μm x 77μm x 12 mm
22 mr crossing angle

SuperKEKB/Belle II Luminosity Profile



Belle II Detector

STATISTICS
VERTEXING
PARTICLE ID (π/K)
"HERMETICITY"



K_L and muon detector:
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel+ endcap)

Particle Identification
iTOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd)
dE/dx in CDC

electrons (7 GeV)

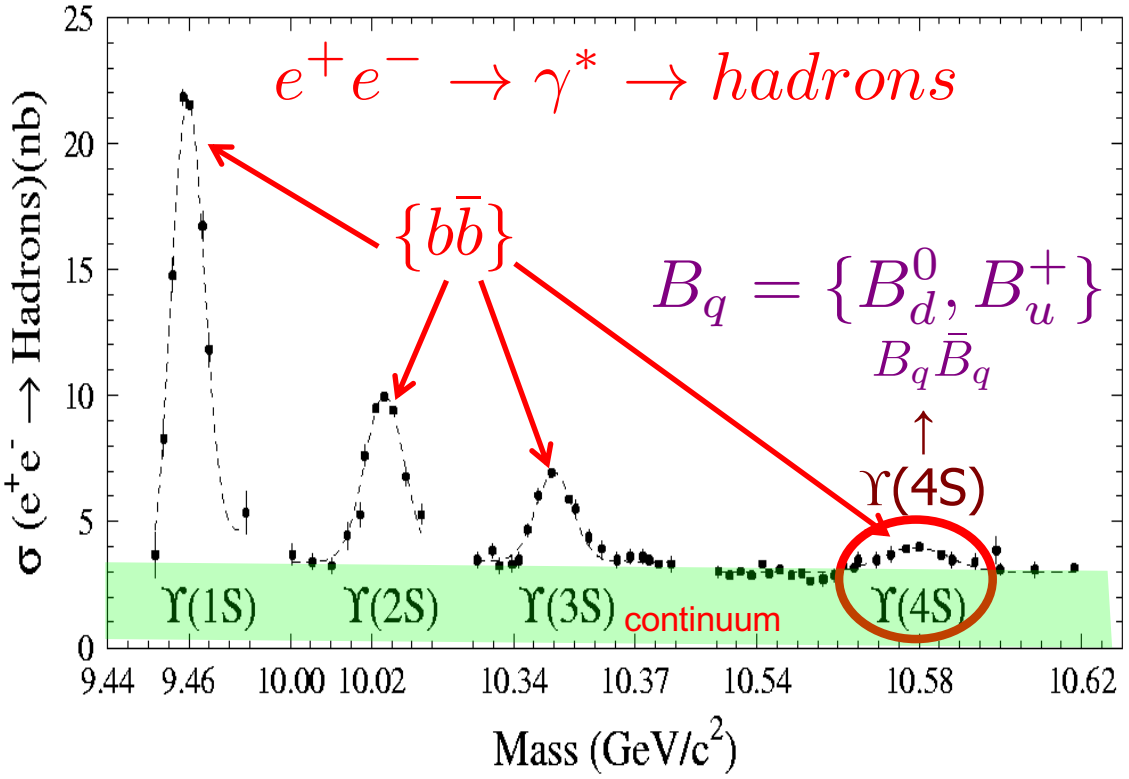
Beryllium beam pipe
2cm diameter

positrons (4 GeV)

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%), small cells,
long lever arm, fast electronics

B full reconstruction tagging

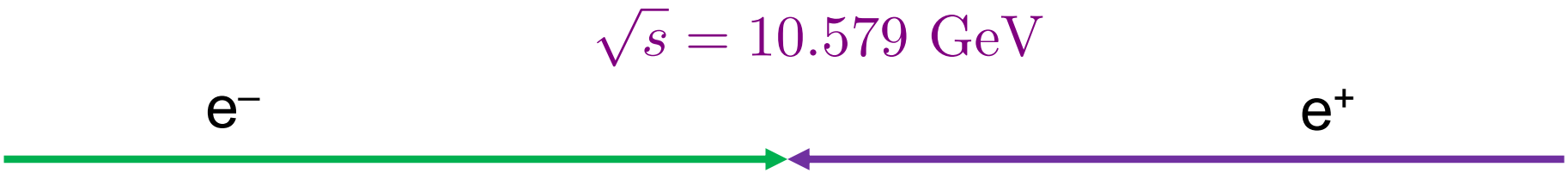


- A powerful feature of Υ(4S) for B physics
  - Event consists of B pair + *no additional particles*
  - E_{cms} is well defined by beams = $2E_{beam,\ cms}$
  - ⇒ Each B has cms energy: $E_B = E_{beam,\ cms}$

→ Full Reconstruction tagging

B full reconstruction tagging

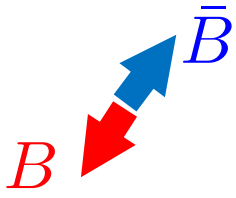
In center-of-mass system



SuperKEKB beams are asymmetric (7 Gev e^-/4 GeV e^+):
Each reconstructed particle 4-momentum is boosted to CMS

B full reconstruction tagging

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



pc~0.33 GeV

In lab frame each B travels $\beta\gamma c\tau$≈130 μm in direction of CMS

B full reconstruction tagging

$$e^+e^- \to \Upsilon(4S) \to B\bar{B} \to \pi^\pm/K^\pm/p/\bar{p}$$

$$K_L^0/n/\bar{n}$$

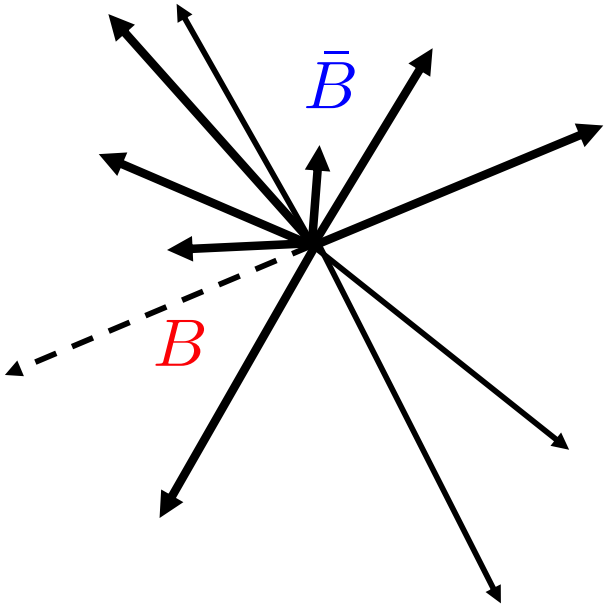
$$e^\pm/\mu^\pm$$

$$\nu_\ell/\bar{\nu}_\ell$$

$$K_S^0 \to \pi^+\pi^-$$

$$\pi^0 \to \gamma\gamma$$

etc



B full reconstruction tagging

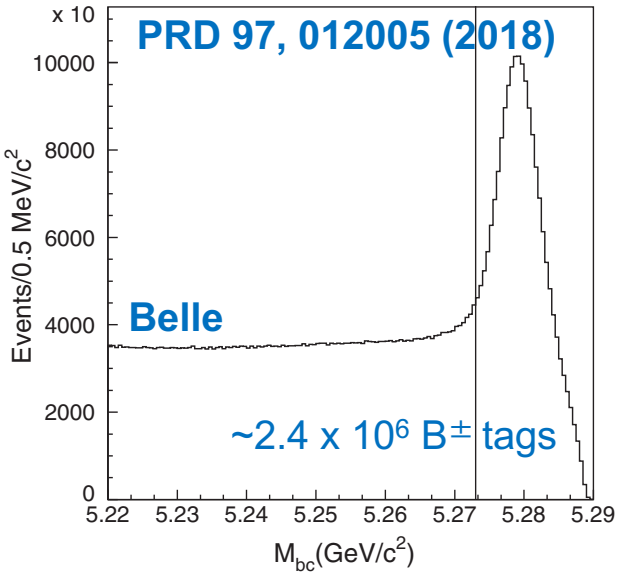
Full reconstruction tagging(>1000 modes)

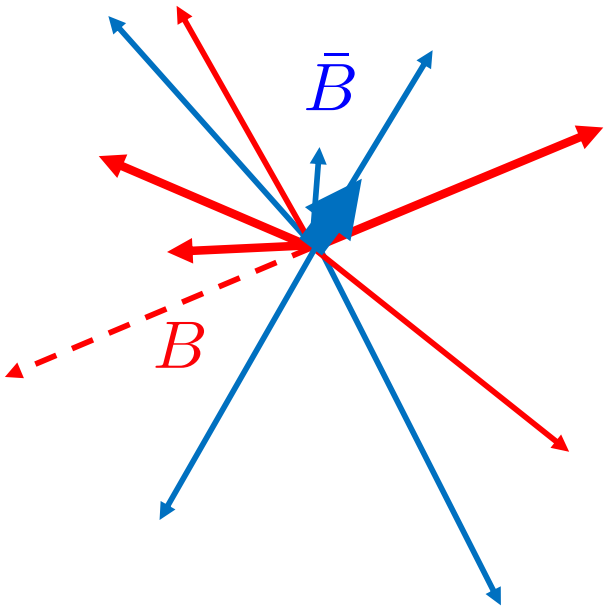
$$E_{\rm tag} = \sum_{i,{\rm tag}} E_i = E_{\rm beam}$$

$$\vec{p}_{\rm tag} = \sum_{i,{\rm tag}} \vec{p}_i$$

→ Beam-constrained mass

$$M_{\rm bc} = \sqrt{E^2_{\rm beam} - \vec{p}^{\,2}_{\rm tag}}$$





Total efficiency ≈0.3%

B^+ modes	B^0 modes
$B^+ \to \bar{D}^0\pi^+$	$B^0 \to D^-\pi^+$
$B^+ \to \bar{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+D^-$
$B^+ \to D_s^+\bar{D}^0$	$B^0 \to D^{*-}\pi^+$
$B^+ \to \bar{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+}D^-$
$B^+ \to D_s^{*+}\bar{D}^0$	$B^0 \to D_s^+D^{*-}$
$B^+ \to D_s^+\bar{D}^{*0}$	$B^0 \to D_s^{*+}D^{*-}$
$B^+ \to \bar{D}^0K^+$	$B^0 \to J/\psi K_S^0$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$
$B^+ \to J/\psi K^+\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^0$	

D^+, D^{*+}, D_s^+ modes	D^0,D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$D_s^+ \to K^+K^-\pi^+\pi^0$	
$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$D_s^+ \to \pi^+\pi^+\pi^-$	
$D_s^{*+} \to D_s^+\pi^0$	

B full reconstruction tagging

Full reconstruction tagging(>1000 modes)

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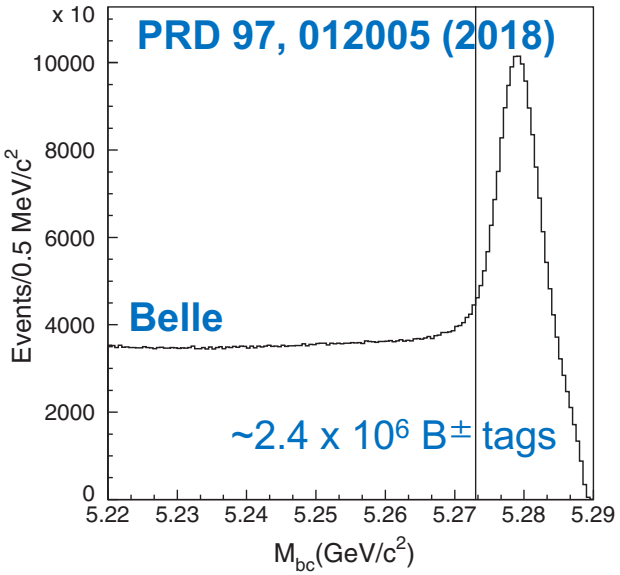
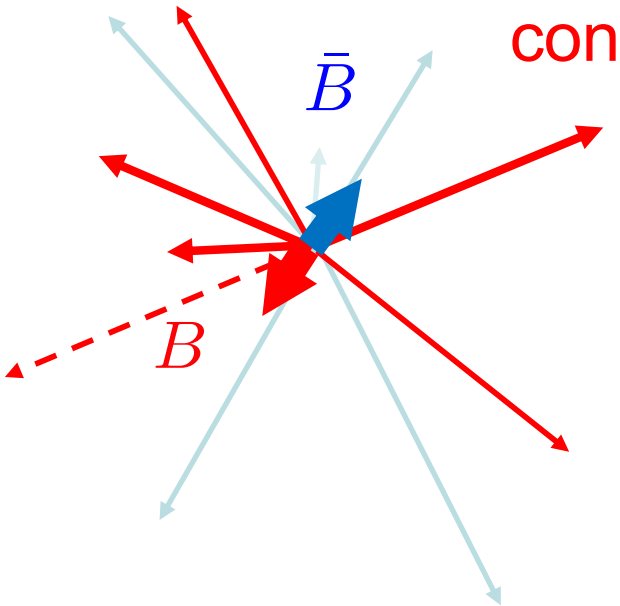
→ Beam-constrained mass

$$M_{\rm bc} = \sqrt{E^2_{\rm beam} - \vec{p}^{\,2}_{\rm tag}}$$





All remaining particles
(detected & undetected)
constitute the opposite B

$$E_{\rm opp} = E_{\rm beam}$$

$$\vec{p}_{\rm opp} = -\vec{p}_{\rm tag}$$

→ absolute branching fractions
→ inclusive rates
→ Missing mass analysis
  Neutrinos
  Inefficiently reconstructed particles

Belle II collaboration

≈800 researchers
from ≈25 countries,
>100 institutions

Belle II collaboration

Physics Plan

Belle II Theory Interface Platform (B2TIP) Workshop series, 2015-2018:

WG1
Semileptonic & Leptonic B decays

WG2
Radiative & Electroweak Penguins

WG3
α/φ_2 β/φ_1

WG4
γ/φ_3

WG5
Charmless Hadronic B Decay

WG6
Charm

WG7
Quarkonium(like)

WG8
Tau, low multiplicity

WG9
New Physics

Report (≈680 pages) to be submitted to PTEP in 2018

B2TIP: CKM "Golden" B measurements, competitiveness

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
CPV			
$S(B \to \phi K^0)$	***	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
$S(B \to K^0_S\pi^0\gamma)$	***	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

B2TIP: New Physics potential

Observables	Experimental Sensitivity	Multi-Higgs Models (§17.2)	generic SUSY	MFV (§17.3)	Z' models (§17.6.1)	gauged flavour (§17.6.2)	3-3-1 (§17.6.3)	left-right (§17.6.4)	leptoquarks (§18.2.1)	compositeness (§17.7)	dark sector (§16.1)	Sum
Semileptonic $b \to s$ Penguin Decays:												
$B \to K^{(*)}\ell\ell$ angular	⋆⋆	×	×	⋆⋆	⋆⋆	×	⋆⋆	×	⋆⋆⋆	⋆⋆	×	13
$R(K^*)$, $R(K)$	⋆⋆	×	×	×	⋆⋆	×	⋆⋆	×	⋆⋆⋆	⋆⋆	×	11
$\mathcal{B}(B \to X_s\ell\ell)$	⋆⋆⋆	×	×	⋆⋆⋆	⋆⋆	×	⋆⋆	×	⋆⋆⋆	⋆⋆	×	15
$R(X_s)$	⋆⋆⋆	×	×	×	⋆⋆	×	⋆⋆	×	⋆⋆⋆	⋆⋆	×	12
$\mathcal{B}(B \to K^{(*)}\tau\tau)$	⋆⋆⋆	⋆⋆⋆	×	⋆	⋆	×	⋆	×	⋆⋆⋆	⋆	×	13
$\mathcal{B}(B \to X_s\tau\tau)$	□	⋆⋆⋆	×	⋆	⋆	×	⋆	×	⋆⋆⋆	⋆	×	10
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	⋆⋆⋆	×	×	⋆	⋆	×	⋆	×	⋆⋆⋆	⋆	×	10
$\mathcal{B}(B \to X_s\nu\nu)$	□	×	×	⋆	⋆	×	⋆	×	⋆⋆⋆	⋆	×	7
Dark Sector (boson A', fermion χ):												
$e^+e^- \to A' \to$ invisible	⋆⋆⋆	×	×	□	×	×	×	×	×	×	⋆⋆⋆	6
$e^+e^- \to A' \to \ell\ell$	⋆⋆⋆	⋆	×	□	⋆	×	⋆	×	×	×	⋆⋆⋆	9
$e^+e^- \to A'\gamma$	⋆⋆⋆	⋆	×	□	⋆	×	⋆	×	×	×	⋆⋆⋆	9
$B \to$ invisible	⋆⋆⋆	×	×	□	⋆	×	⋆	×	⋆⋆⋆	×	⋆⋆⋆	11
$B \to KA'$	⋆⋆⋆	×	×	□	×	×	×	×	×	×	⋆⋆⋆	6
$B \to \pi A'$	⋆⋆⋆	×	×	□	×	×	×	×	×	×	⋆⋆⋆	6
$B^+ \to \mu^+\chi$	⋆⋆⋆	×	×	□	×	×	×	×	×	×	⋆⋆⋆	6
$B^+ \to \mu^+\nu A'$	⋆⋆⋆	×	×	□	×	×	×	×	×	×	⋆⋆⋆	6
$\Upsilon(3S) \to \gamma A'$	⋆⋆⋆	×	×	□	×	×	×	×	×	×	⋆⋆⋆	6

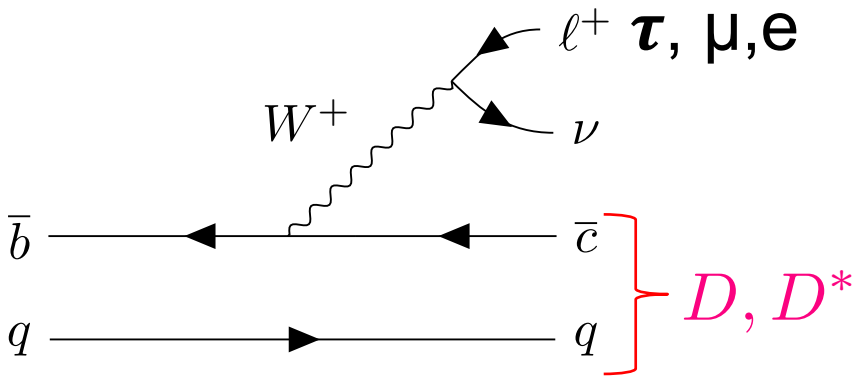
*** Belle
** Belle/LHCb
* LHCb
X unlikely
□ not studied

Many other tables!
Other B decays
tau
Charm

Tantalizing hints of beyond (SM) in existing results

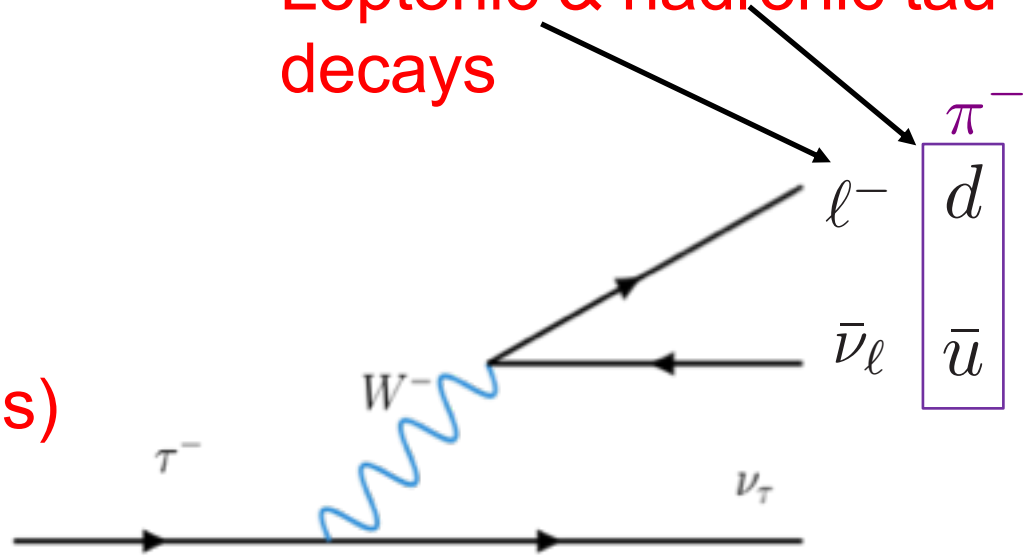
Lepton Universality

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$



Experiment

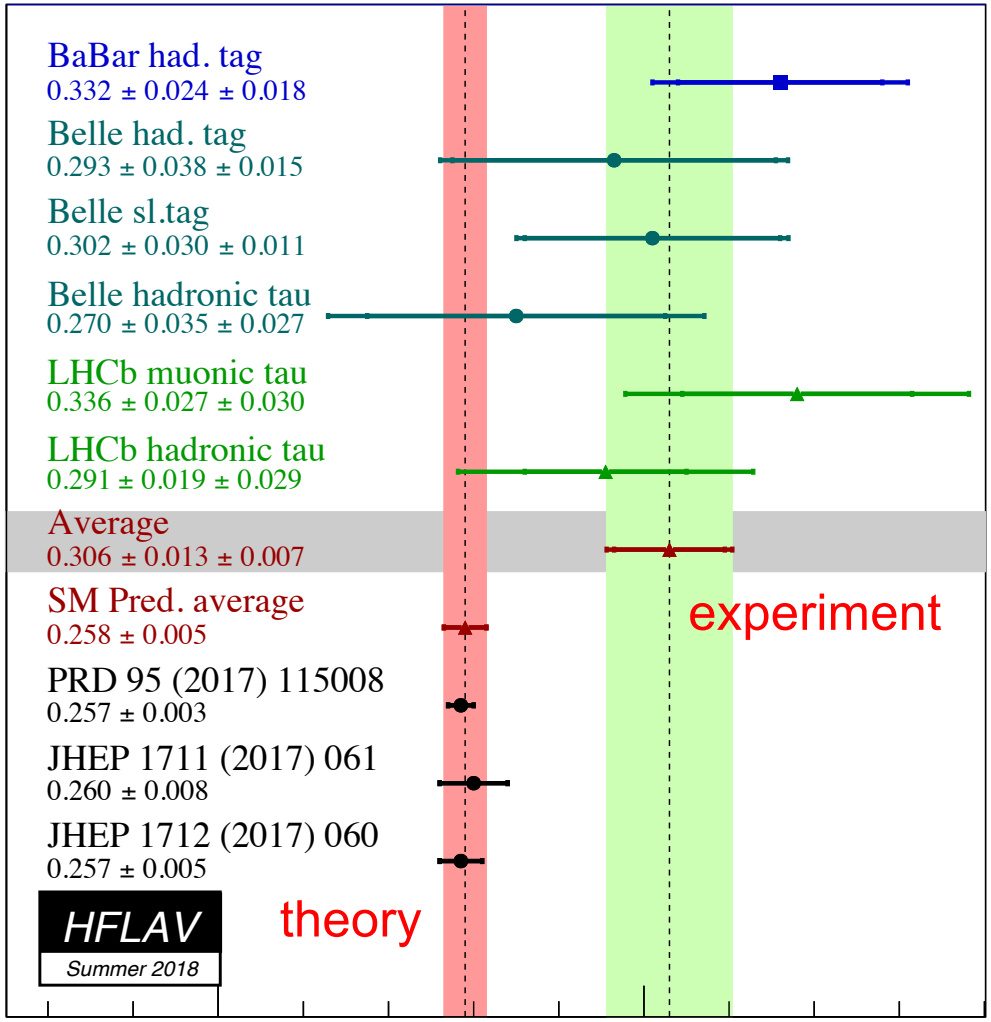
- Multiple neutrinos
  - Tagged analyses
    - Full B reconstruction
    - Partial B reconstruction
  - Leptonic & hadronic tau decays

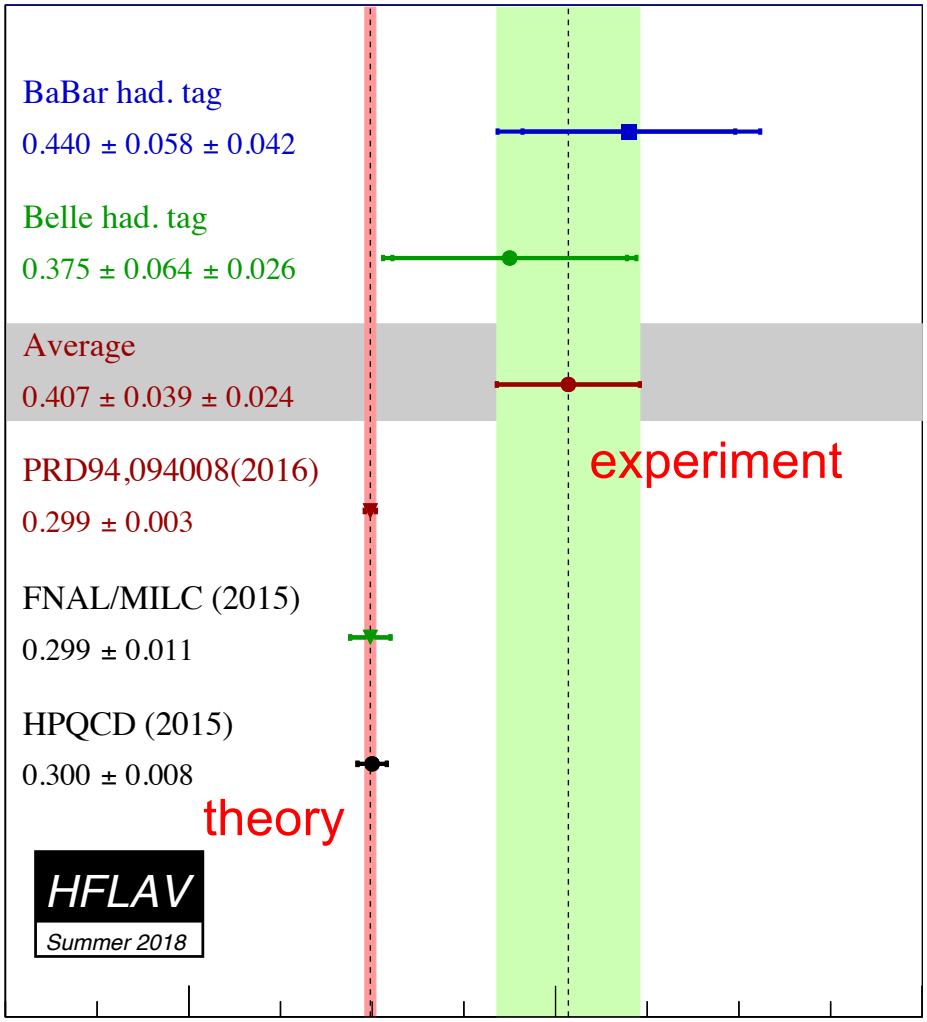


- SM: Lepton universality
- Theoretically robust – hadronic uncertainties cancel (minor corrections)

Lepton Universality

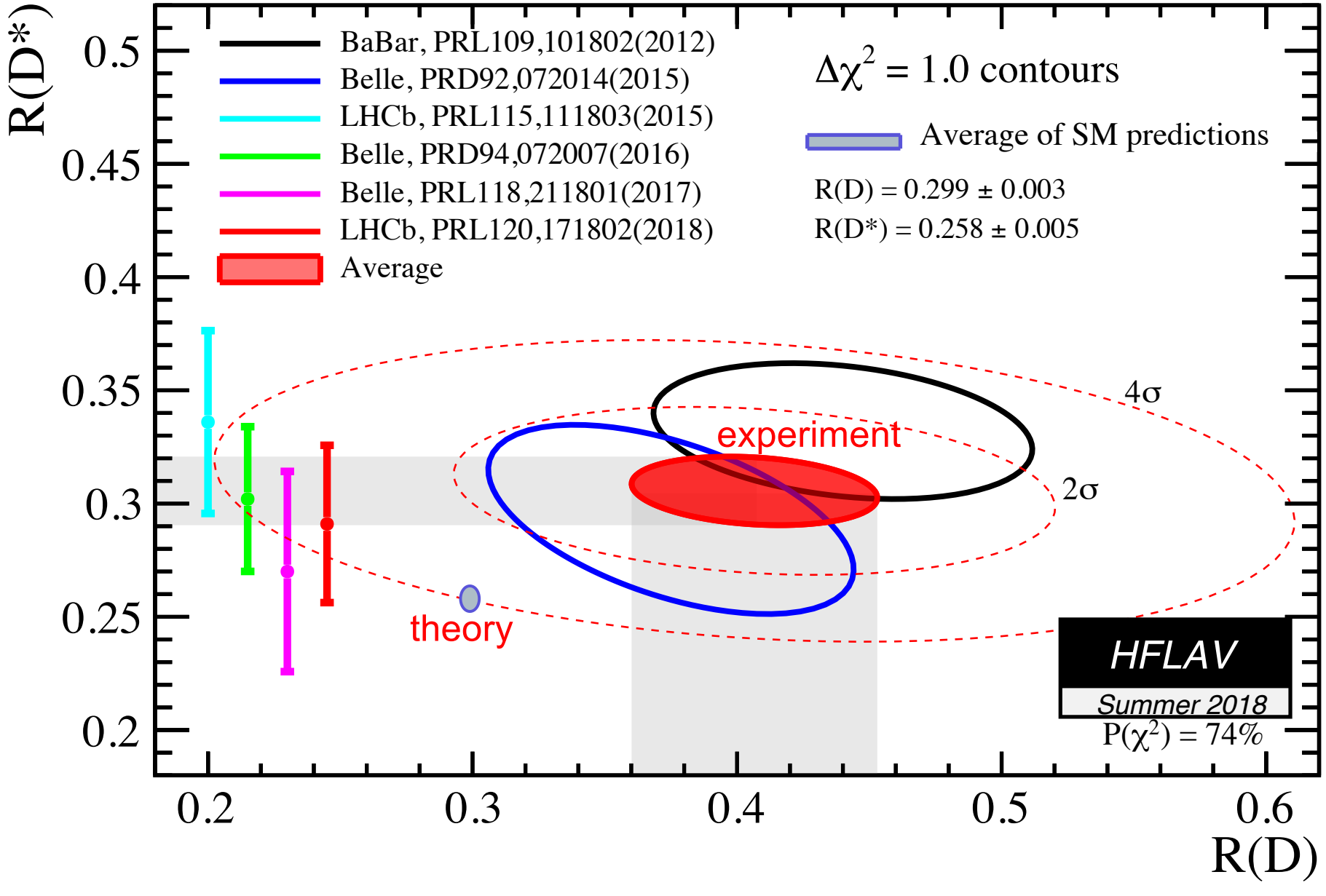
$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$





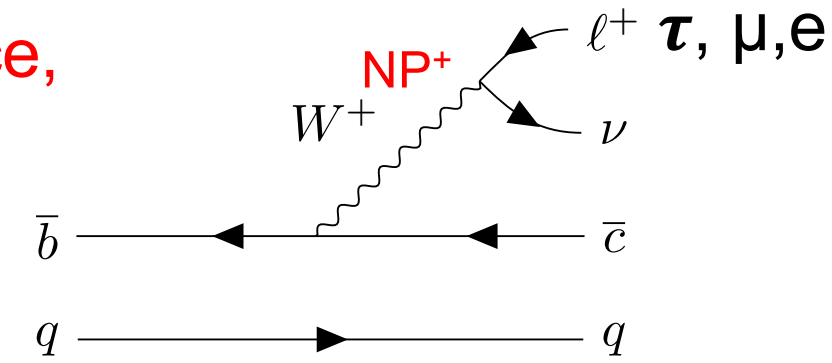
Lepton Universality

Combined: ≈3.9 σ from SM expectation



Lepton Universality

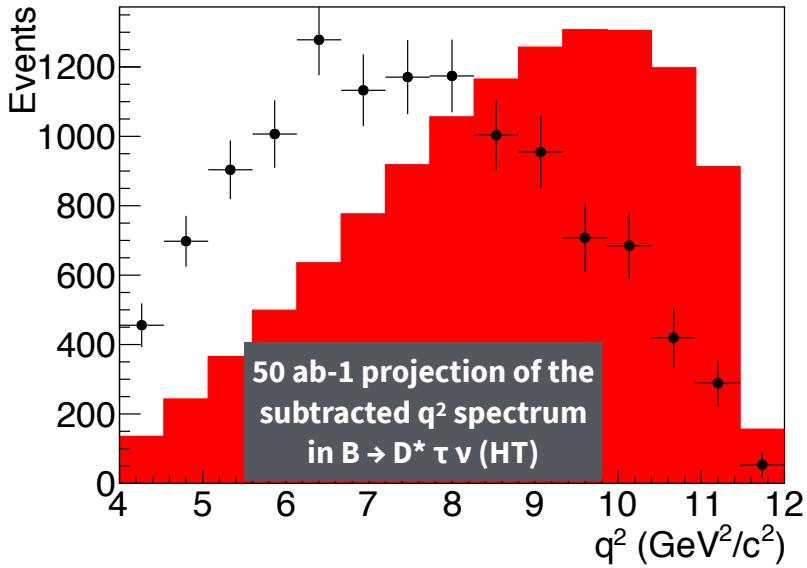
Handles on NP for $\mathcal{R}(D^{(*)})$:
Lepton polarization, q^2 dependence, angular distributions



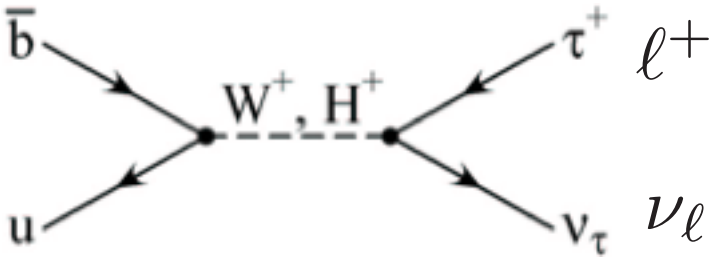
Belle: PRL 118, 211801
Tau polarization via hadronic decay
SM: – 0.497

$$p_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{sys})$$

Belle II: q^2 distribution



Leptonic decays



$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

- Clean |Vub| [f_b via lattice]
- SM
  - B(B $\to\tau\nu$) = 7.5$\pm$1.x10^{-5}
  - B(B $\to \mu\nu$) = (3.8$\pm$0.3)x10^{-7}
  - B(B $\to$ eν) $\approx 10^{-11}$
- Lepton universality

$$\mathcal{R}(\tau\bar{\nu}) \equiv \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)}$$

systematics cancel in ratio
→ strong test of universality

Leptonic decays

SM

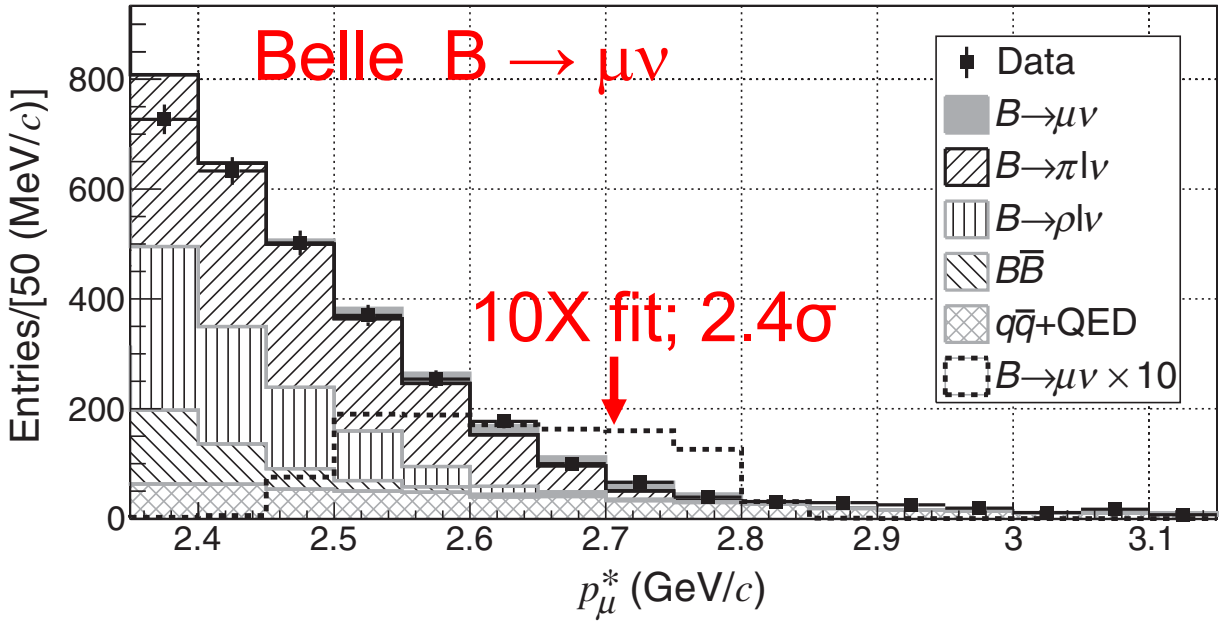
$B(B \to \tau\nu) = 7.5 \pm 1. \times 10^{-5}$

$B(B \to \mu\nu) = (3.8 \pm 0.3) \times 10^{-7}$

Experiment

$B(B \to \tau\nu) = (1.09 \pm 0.24) \times 10^{-4}$ PDG 2017

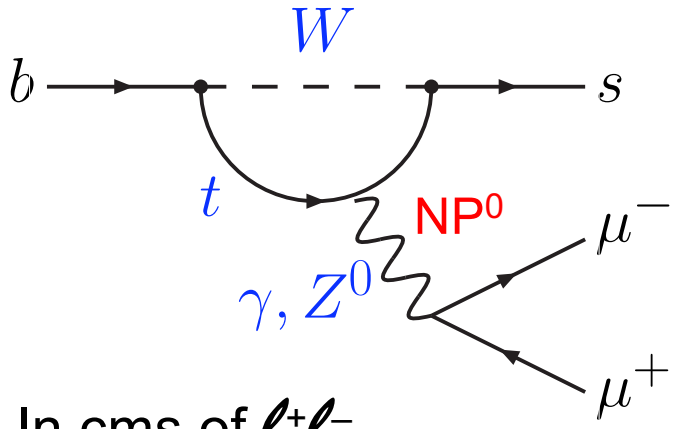
$B(B \to \mu\nu) = (6.4 \pm 2.2 \pm 1.6) \times 10^{-7}$ PRL 121, 031801 (2018)



Belle II expects to reach 5σ threshold with ≈5 ab^{-1}

Semileptonic penguin

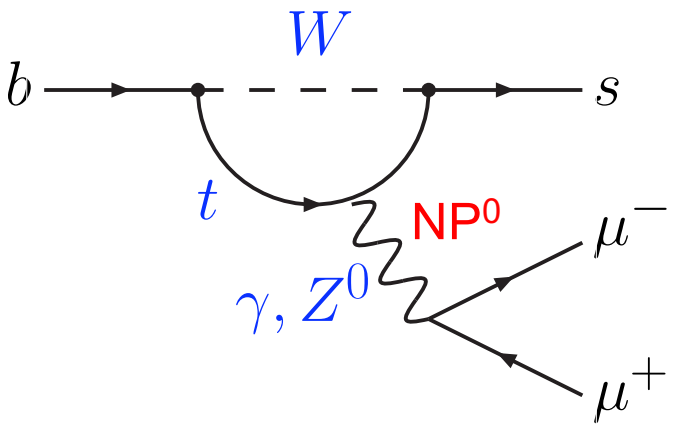
$B \to X_s \ell^+ \ell^-$



In cms of $\ell^+\ell^-$

- SM: rare (B≈10^{-6})
- Theory: hadronic uncertainty
  - Inclusive {b→s(all)$\ell^+\ell^-$} is more robust
  - Exclusive modes {e.g., B → $K^*\ell^+\ell^-$} – angular distributions & correlations
- Experiment: no neutrinos!
  - Inclusive: more challenging

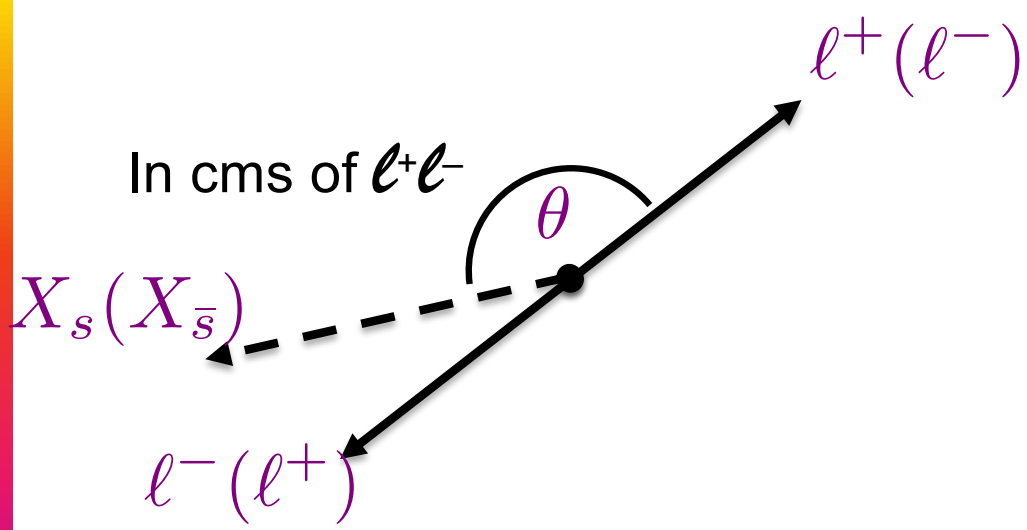
semi-inclusive forward/backward angular asymmetry

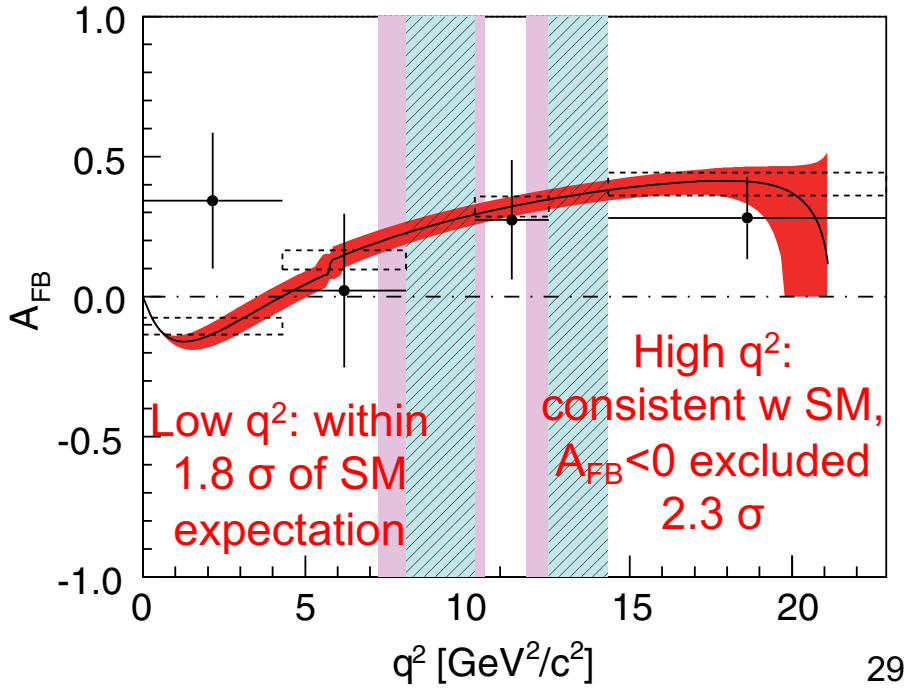


$$B \to X_s \ell^+ \ell^-$$

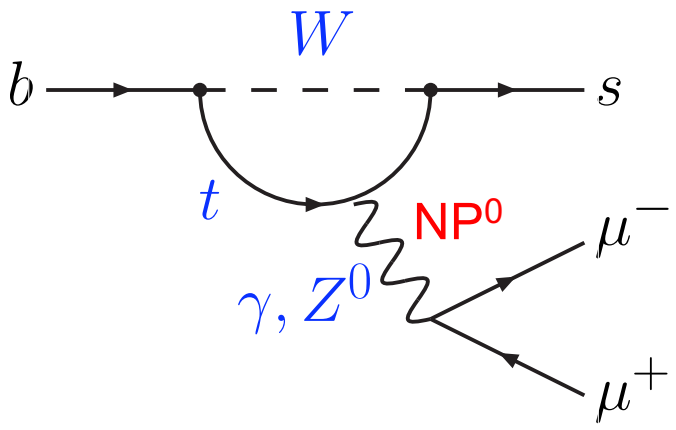
≈60% of all modes
Belle PRD 93, 032008 (2016)

$$\mathcal{A}_{\rm FB} \equiv \frac{\Gamma(b \to s\ell^+\ell^-; \cos\theta > 0) - \Gamma(b \to s\ell^+\ell^-; \cos\theta < 0)}{\Gamma(b \to s\ell^+\ell^-; \cos\theta > 0) + \Gamma(b \to s\ell^+\ell^-; \cos\theta < 0)}$$





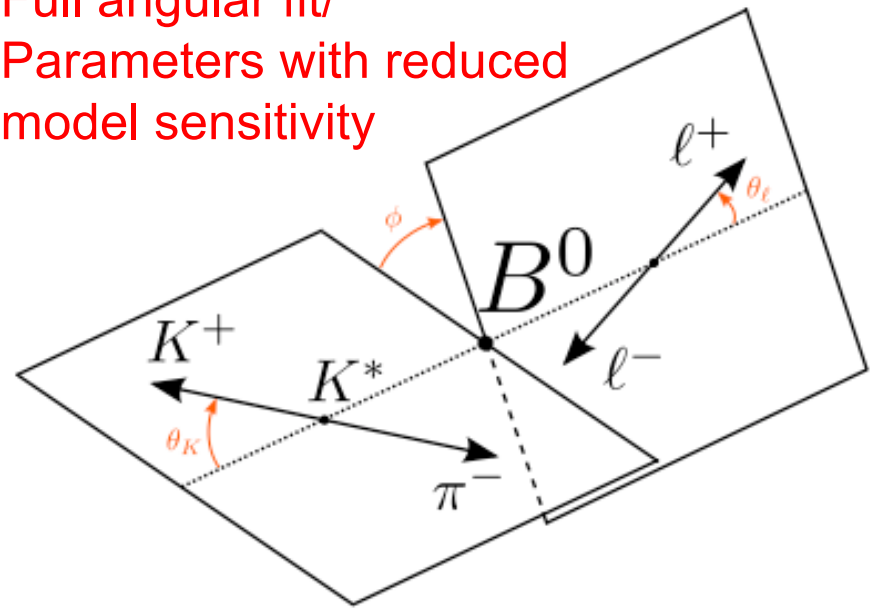
Exclusive $B \to K^{*0}\ell^+\ell^-$



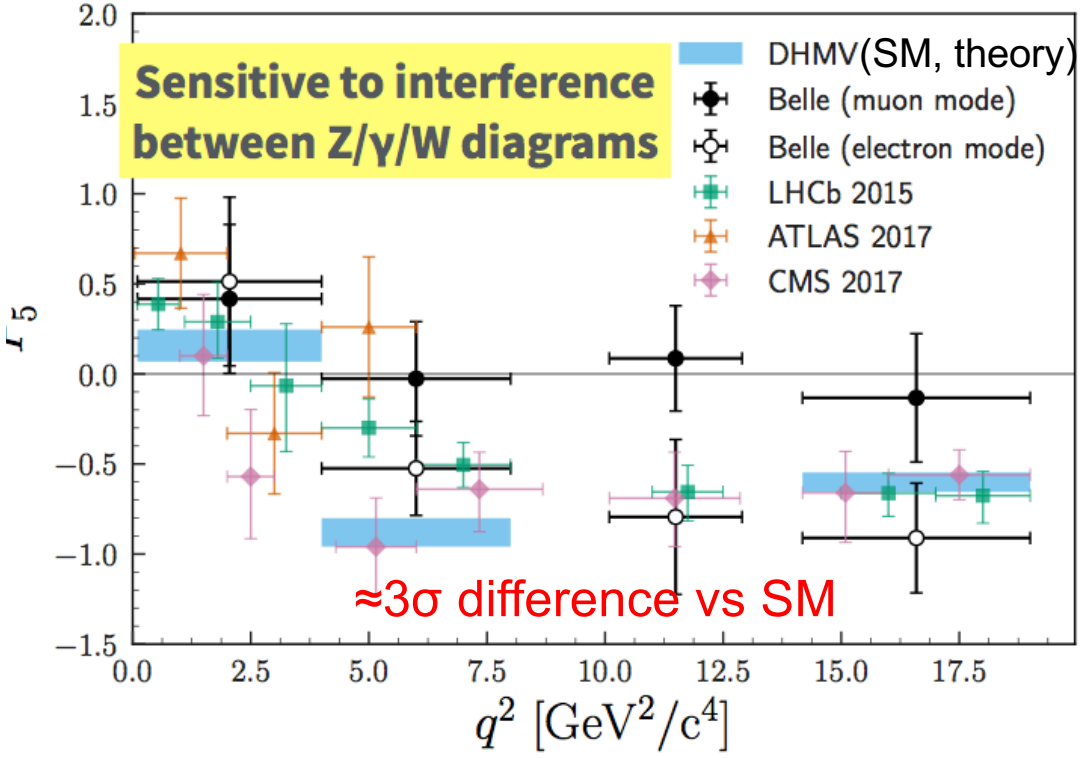
Angular analysis

LHCb JHEP 02, 104 (2016); 11, 047 (2016);
04, 142 (2017)
Belle PRL 118, 111801 (2017)
Babar PRD 93, 052015 (2016)
CMS PLB 753, 424 (2016); 781, 517 (2018)

Full angular fit/
Parameters with reduced
model sensitivity



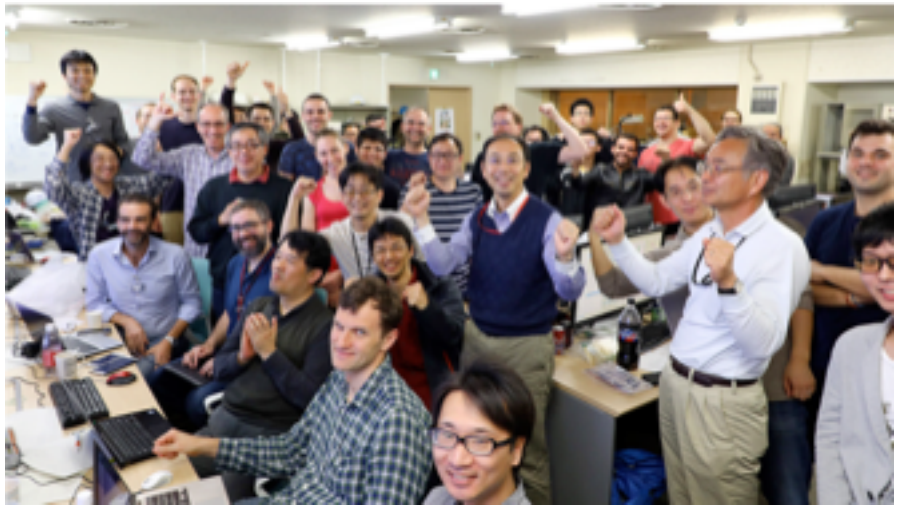
The decay is completely described by:
θ_ℓ, θ_K, ϕ and $q^2 = M^2_{\ell^+\ell^-}$



K. Kinoshita

Belle II commissioning

- 11/17 Cosmic rays
- 3/18 “Phase II” with beams
  - Increasing bunch numbers
  - Specific luminosity
  - Background studies/reduction
- 4/26/18 First collisions/ $L > 1 \times 10^{33}$ cm^{-2}s^{-1}



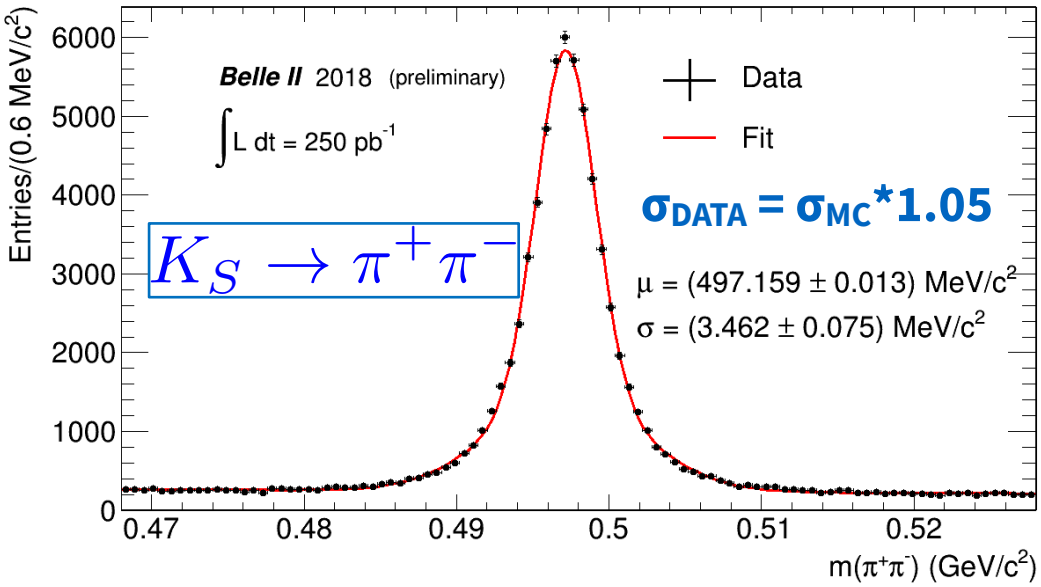
- 7/17/18 end Phase II: $L > 5.5 \times 10^{33}$ cm^{-2}s^{-1}
  - $\int L\, dt \approx 0.5$ fb^{-1}

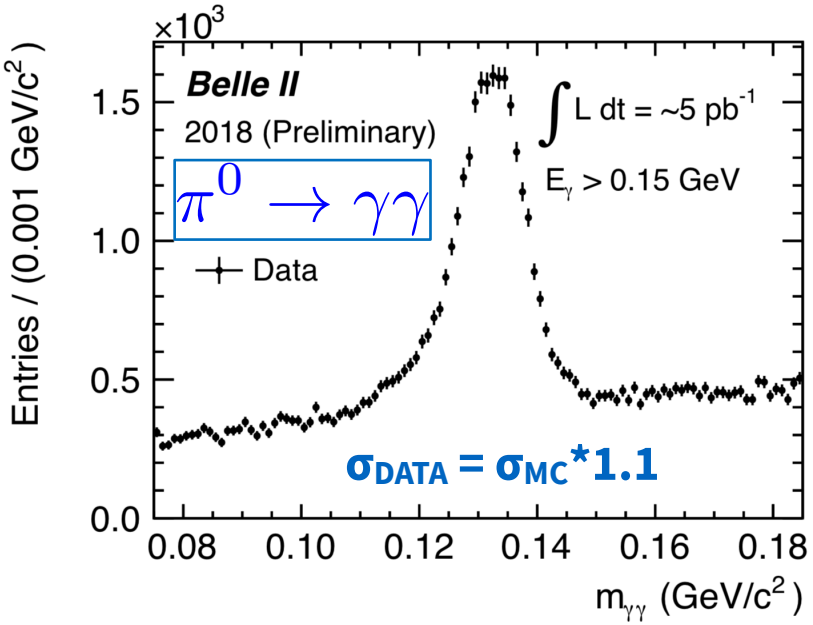
K. Kinoshita

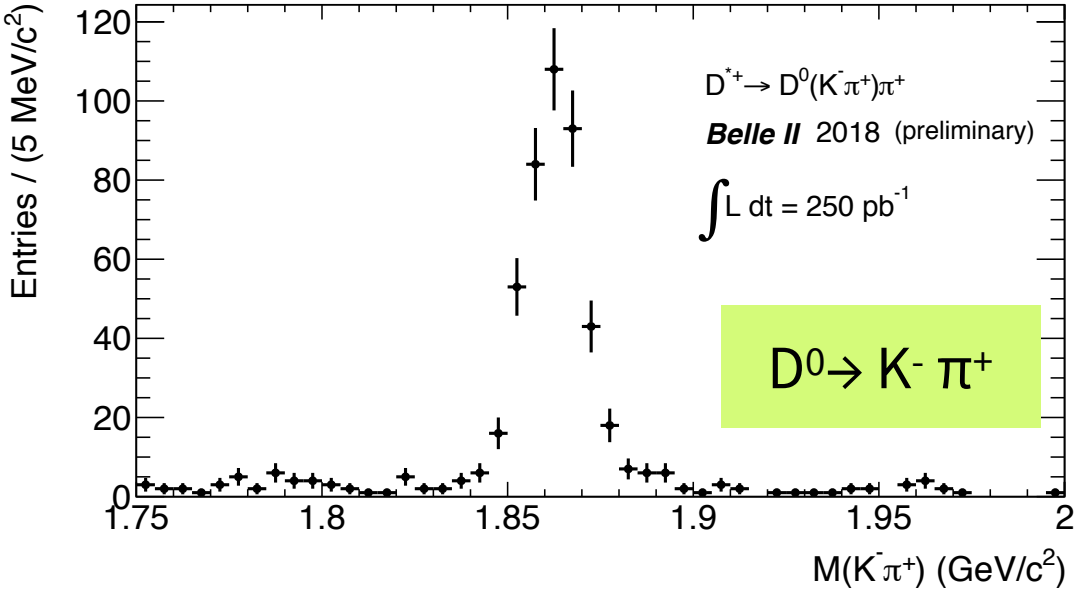
Belle II commissioning

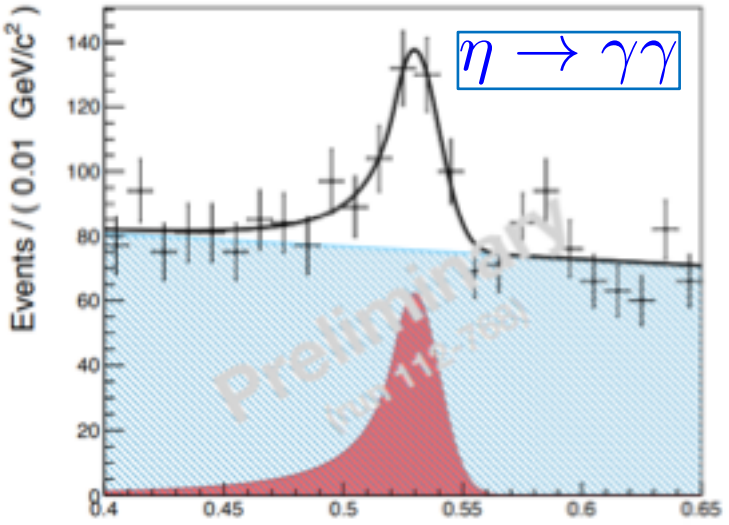
- **Phase II data – confirm/develop**
  - ❑DAQ
  - ❑Calibrations
  - ❑Offline analysis
  - ❑Tracking
  - ❑Calorimetry
  - ❑Particle ID
  - ❑Beam energy & collisions

tracking, calorimetry



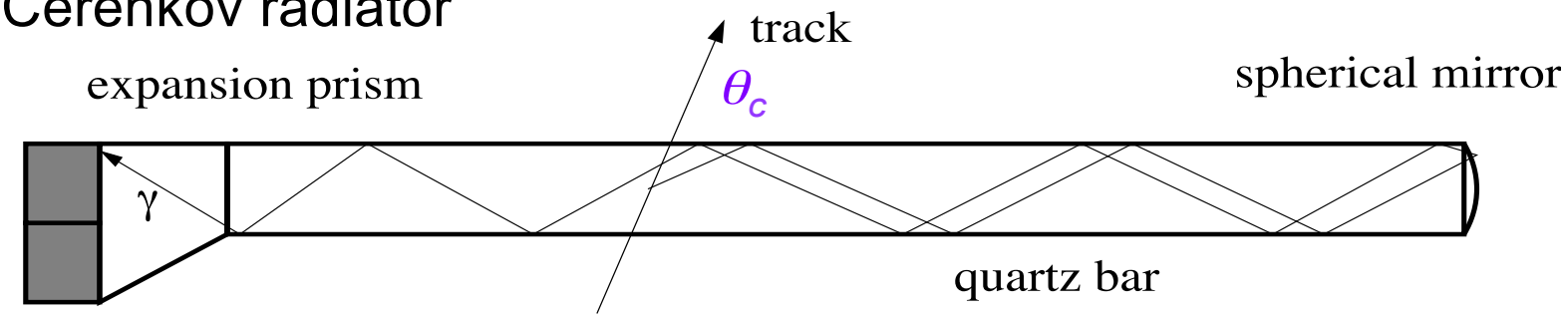




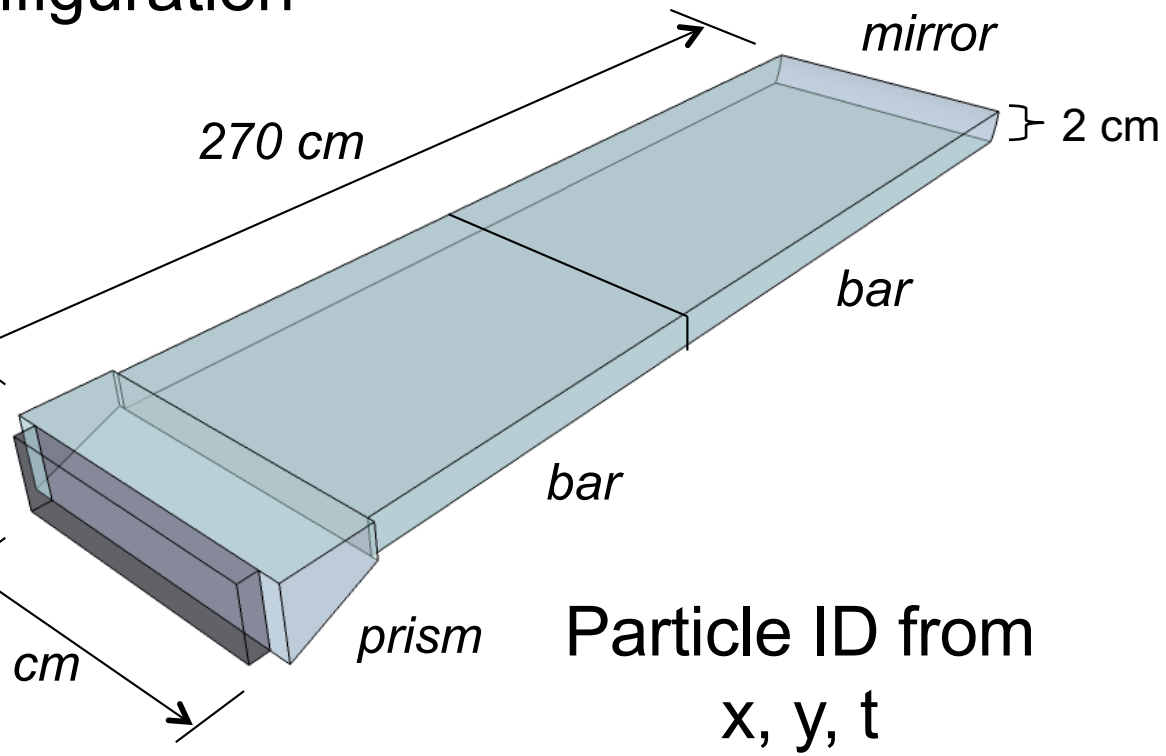


Particle ID: iTOP (Japan/US/Slovenia/Italy)

Quartz Cerenkov radiator



16 modules, barrel configuration



Multichannel MCP-PMT readout

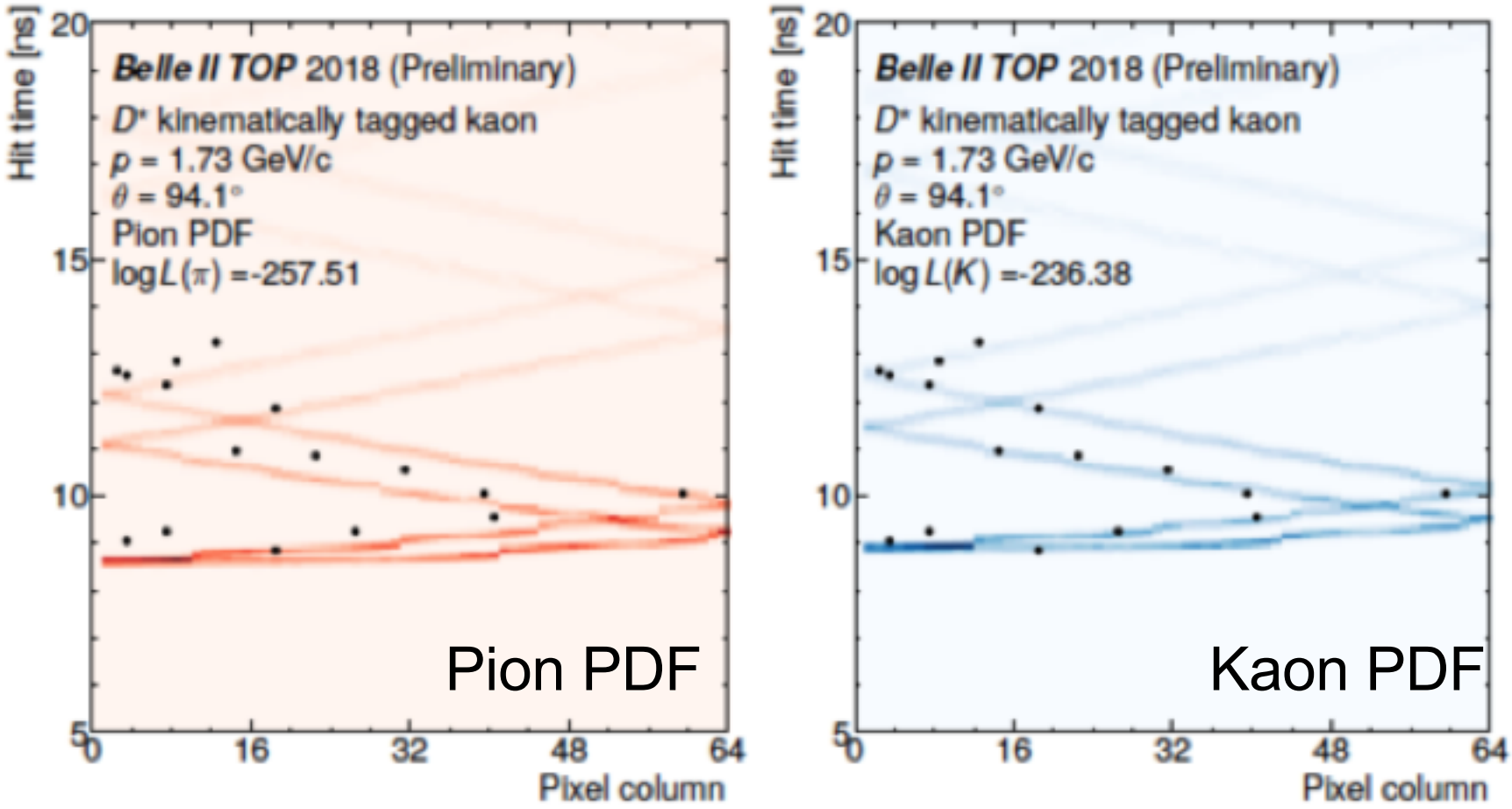
8 *y*-channels

64 *x*-channels

Particle ID from
x, y, t
20-40 hits/track

Particle ID: iTOP

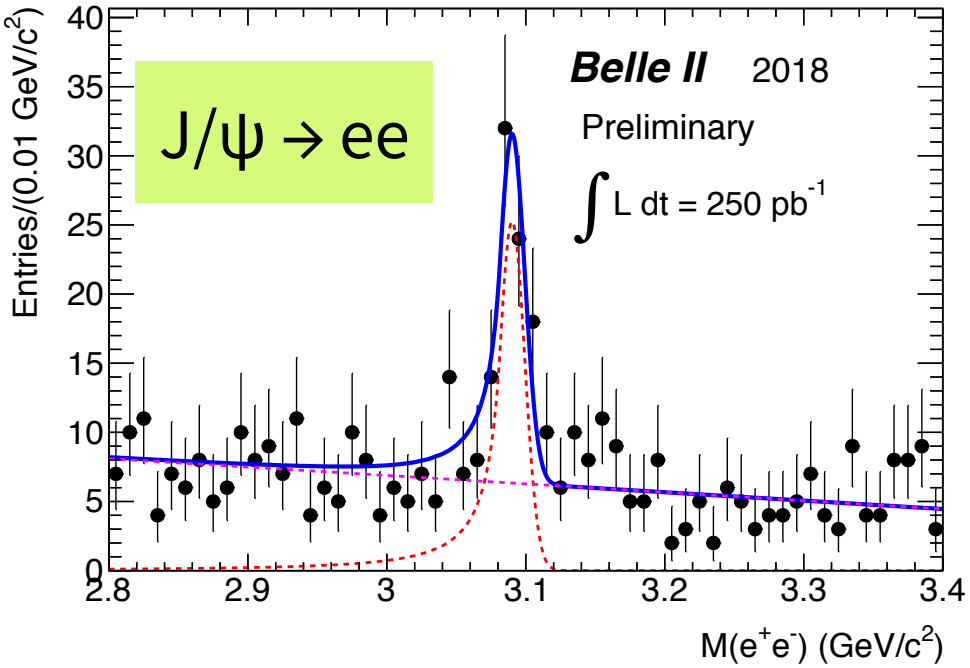
Kinematically identified kaon from a D^{*+}

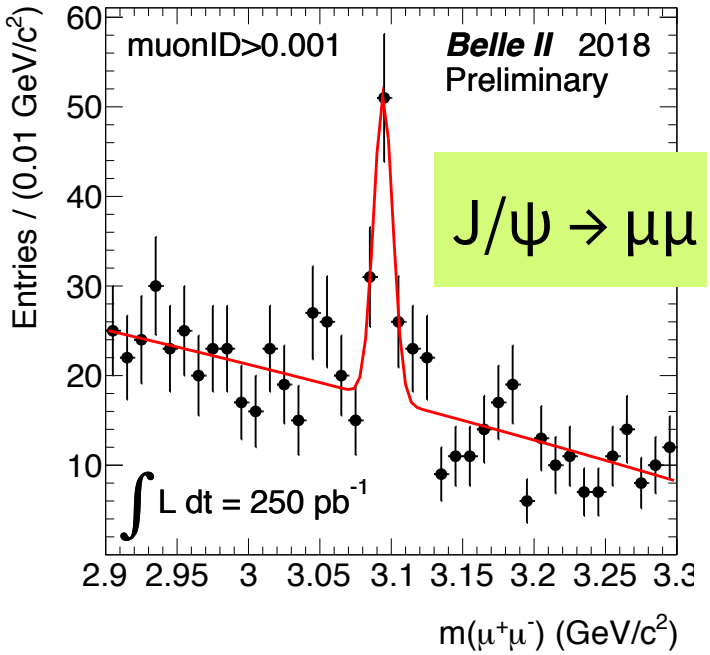


t vs x

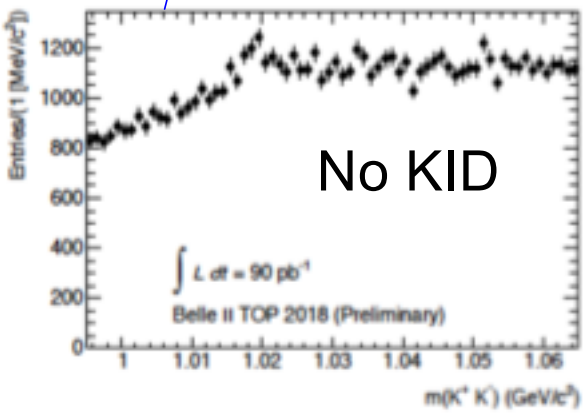
PDF depends on particle speed, entry point & angle

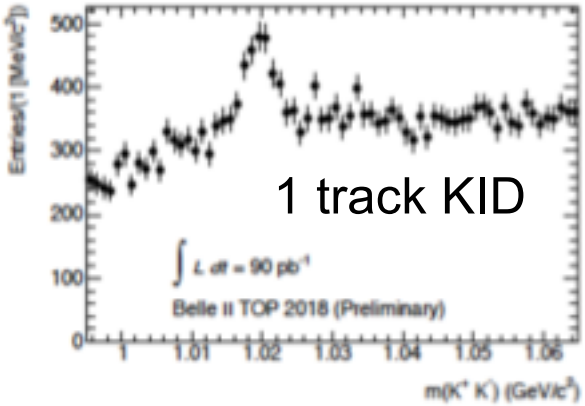
Particle ID

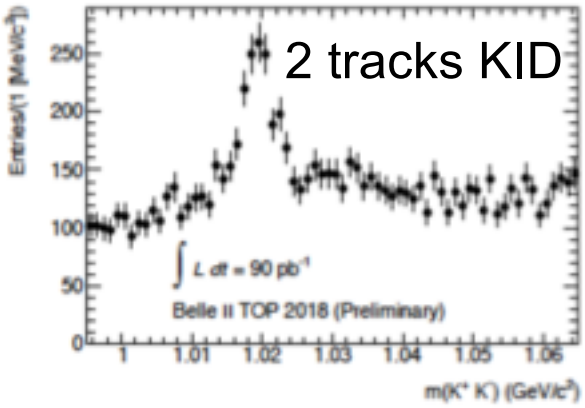




$\phi \to K^+K^-$

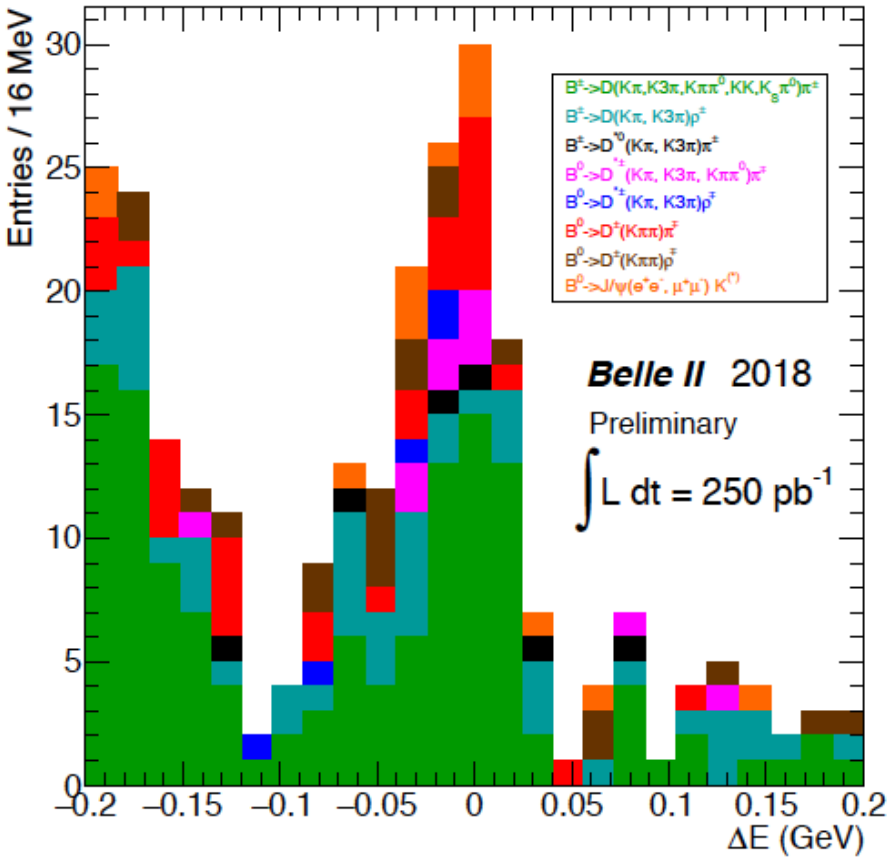


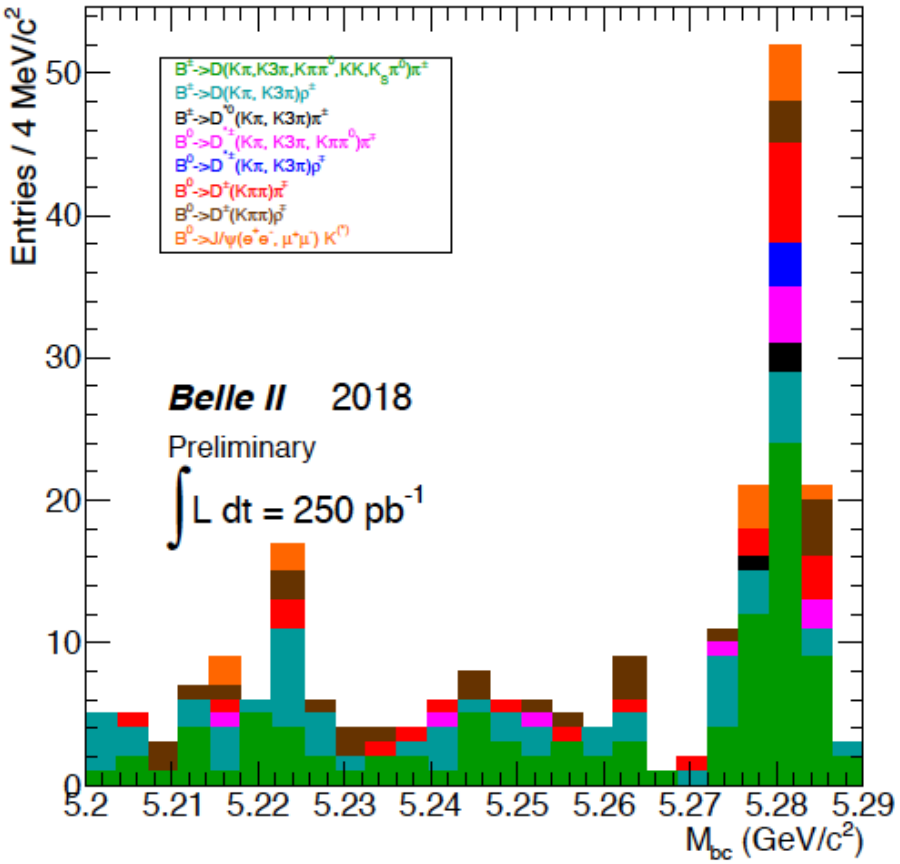




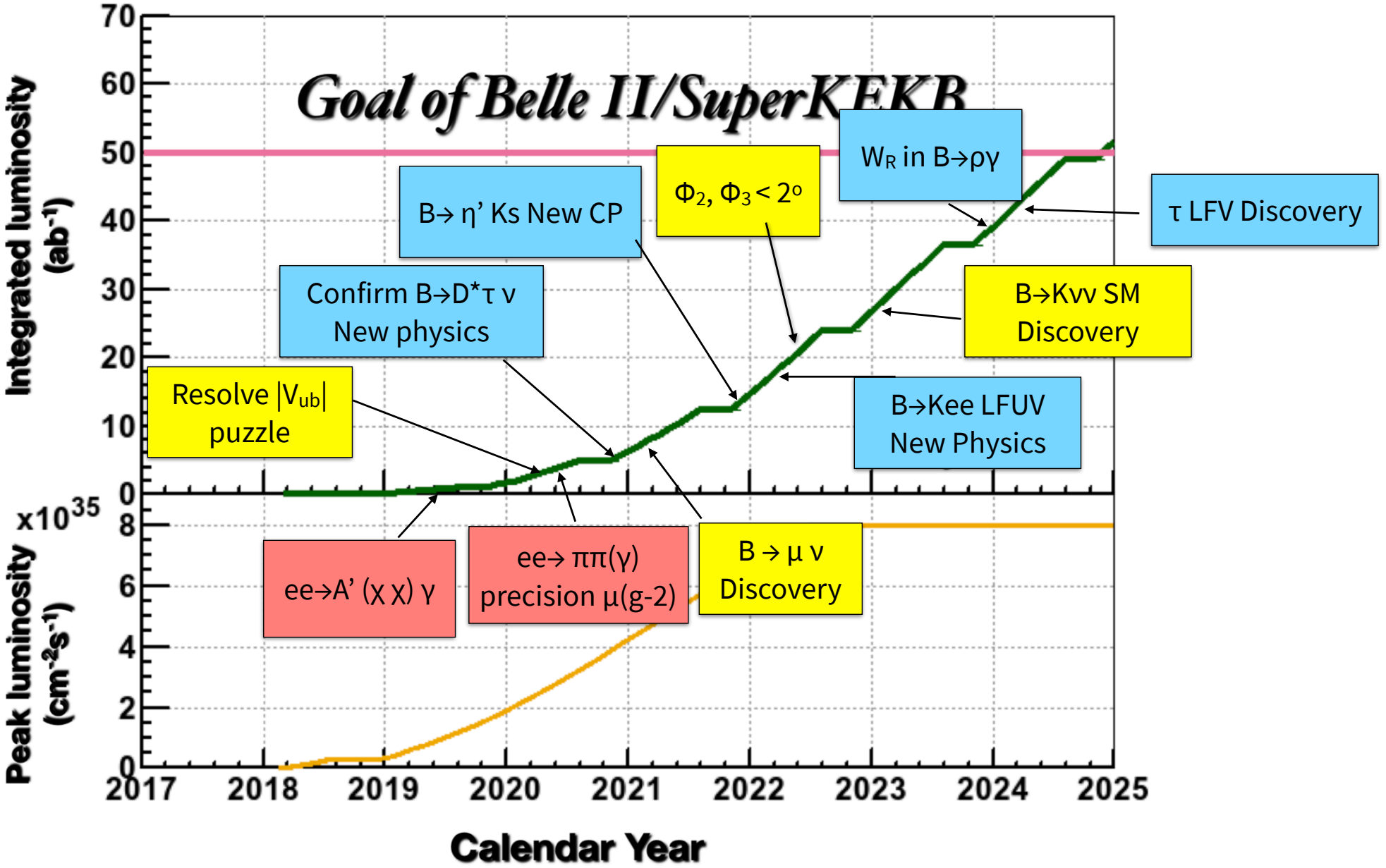
beam energy

Fully reconstructed B's





$$M_{\rm bc} = \sqrt{E^2_{\rm beam} - \vec{p}^{\,2}_{\rm tag}}$$


Goal of Belle II/SuperKEKB
Integrated luminosity (ab⁻¹)
Peak luminosity (cm⁻²s⁻¹)
x10³⁵
Calendar Year
2017
2018
2019
2020
2021
2022
2023
2024
2025
W_R in B→ργ
Φ2, Φ3 < 2°
B→ η' Ks New CP
τ LFV Discovery
Confirm B→D*τ ν New physics
B→Kνν SM Discovery
Resolve |Vub| puzzle
B→Kee LFUV New Physics
ee→A' (χ χ) γ
ee→ ππ(γ) precision μ(g-2)
B → μ ν Discovery

Summary

Belle II

- Probe of TeV scale, complementary to Energy Frontier
  - Clean events, "hermetic" detector (vs LHCb)
    - Tagging, "inclusive" studies
    - Modes that include γ, π^0, K_L, ν
- Precision in CKM → sensitivity to NP
- Extensive theory/experiment studies (B2TIP)
  - Many measurements accessible only by Belle
- Detector in commissioning
  - Phase II (March-July 2018) w partial Si trackers
  - First collisions 4/26, ≈0.5 fb^{-1} collected
  - Confirm operations: DAQ, tracking, calorimetry, particle ID
- Phase III to start February 2019
  - with full Si tracker system

Belle II approach: seek the New …

By improving precision on the Old … and looking VERY CAREFULLY