Physics Colloquium, UT Dallas, April 10, 2019

Beauty Past & Future: the Belle and Belle II experiments

Belle II

- What is flavor?
- Flavor and CP in Belle
- The Big Questions & flavor
- The future of flavor at Belle II

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Belle & Belle II

Belle: 50+ institutions, ~14 nations, ~400-600 collaborators

Belle II: 100+ institutions, ~25 nations, ~800 collaborators

Belle/Belle II: heavy flavor physics - What is flavor?

Standard Model: 12 fermion flavors (+antifermion)

- 3 generations(distinguished only by mass)x2 typesx2 ea (strong & EM couplings)

  "stable" (except for weak interaction)

- leptons: no strong interactions

Charged leptons	e^-	μ^-	τ^-
neutrinos	ν_e	ν_μ	ν_τ

- quarks: strong (hadronic) interactions

charge +2/3	u_{p}	c_{harm}	$t_{op/truth}$
charge –1/3	d_{own}	s_{trange}	$b_{ottom/beauty}$

What is significant about flavor?

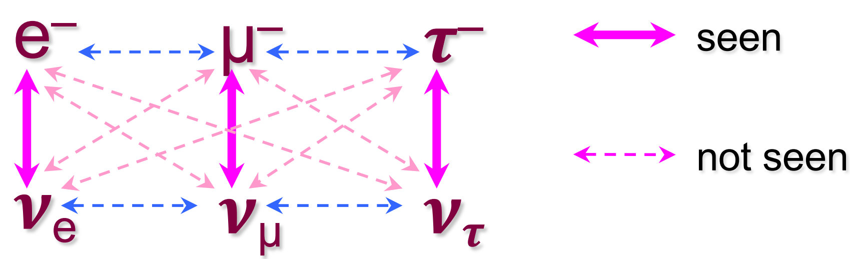
Standard Model: 12 fermion flavors (+antifermion)

Flavors interact only via the Weak force, mediated by $W^{\pm}$, Z^0

- leptons: ~universal weak coupling g_F, no generation x-ing

$W^{\pm}$ "charged current"

Elegant

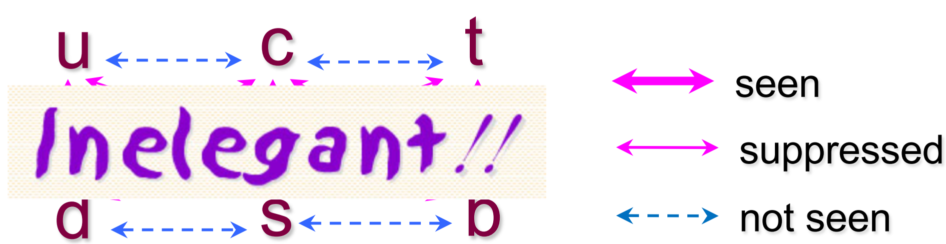


Z^0 "neutral current"

- quarks: neutral current – ≈universal, no generation x-ing

- quarks: charged current – all different, ≈ generation-conserving

$$g_F \times \begin{array}{c c} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$



9 complex couplings →18 free parameters

Elegance restored

GIM (Glashow-Iliopoulos-Maiani) picture:

"weak eigenstates" ≠ mass eigenstates d, s, b

-> matrix represents linear transformation between 2 bases:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathcal{M} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix

$\left.\begin{array}{r} \text{complex} \\ \text{preserves metric} \\ \text{" orthogonality} \end{array}\right\} \equiv$ unitary

Matrix is then

$$g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d' & s' & b' \end{array} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

universal, generation-conserving

Explains

- suppression of flavor-changing neutral currents
- multiplicity of charged current couplings
- AND …….

Irreducible complexity follows from unitarity for >2 generations
$\rightarrow$proposed as explanation of CP violation in K_L (observed 1963)

e.g. for 3 generations,
4 free parameters, including
1 irreducible **imaginary** part

(Kobayashi-Maskawa 1973)

explicit parametrization(Wolfenstein):

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

irreducibly complex

$\Rightarrow$ CP Violation

First 3rd- generation particle (τ) seen in 1975
CP-violation measured in B-decays 2002

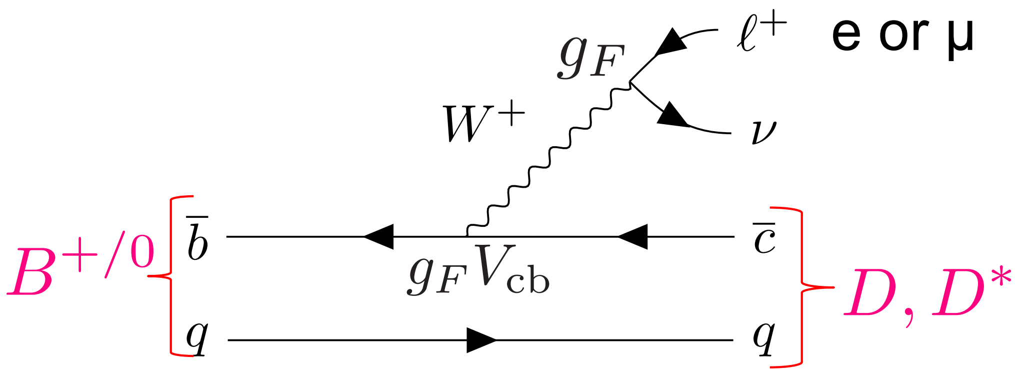
Measurement of CKM elements & CP

Decay rates ∝ |Amplitude|^2

$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{bmatrix}$$

"Tree" modes: single matrix element; rate is real, decay is exponential

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



$D^*\ell\bar{\nu}$ PRD 82, 112007 (2010)

$$|V_{\rm cb}| = (37.5 \pm 0.2 \pm 1.1 \pm 1.0) \times 10^{-3}$$

$D\ell\bar{\nu}$ PRD 93, 032006 (2016)

$$|V_{\rm cb}| = (39.9 \pm 1.3) \times 10^{-3}$$

Limited by theory uncertainties

Measurement of CKM elements & CP

Decay rates ∝ |Amplitude|^2

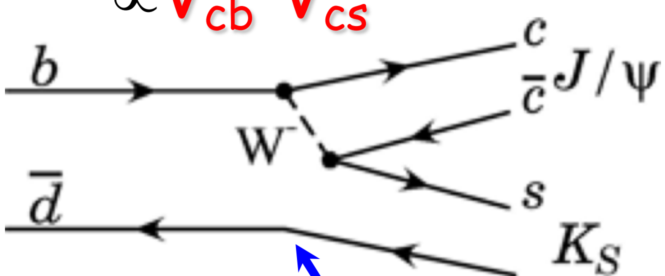
$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{bmatrix}$$

Modes with >1 path: interference; rate may be complex

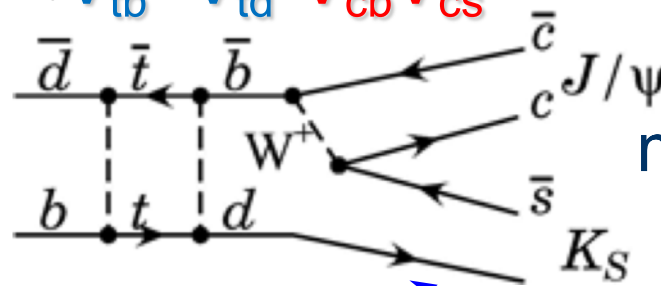
→ time oscillation on exponential decay, CP asymmetric

$$B^0 \to J/\psi K^0_S$$

$\propto V_{cb}^{*} V_{cs}$



$\propto V_{tb}^{*2} V_{td}^{2} V_{cb} V_{cs}^{*}$

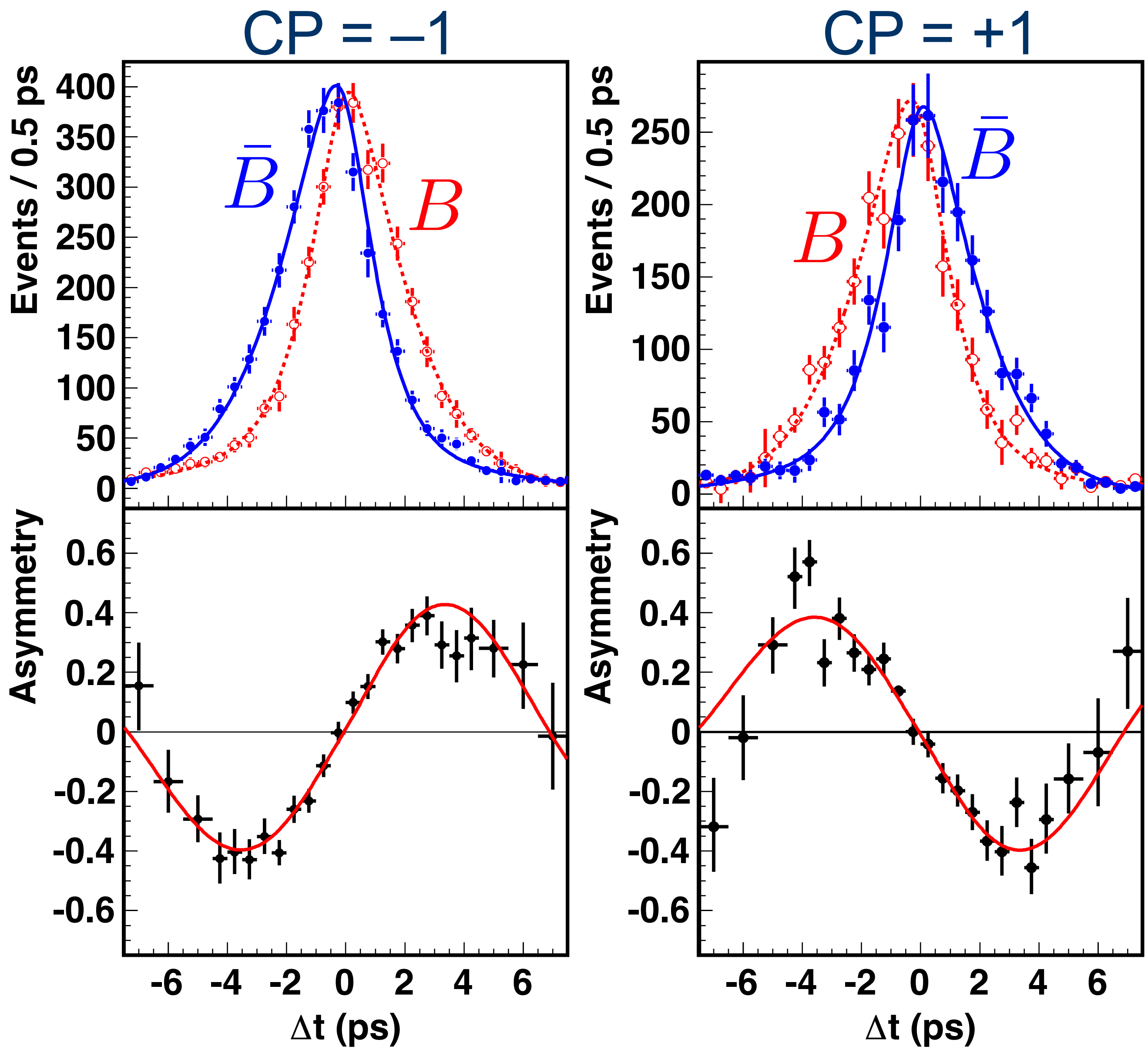


mixing+tree

identical hadronic processes → same |Amplitude|

CP Oscillations in B

PRL 108, 171802 (2012)



CP=+1,–1: Opposite sign oscillations, Amplitude is proportional to sin $2\varphi_1$

φ_1 is complex phase of $V_{tb}^{*}V_{td}$

Unitarity of CKM matrix

Decay rates ∝ |Amplitude|^2

$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{bmatrix}$$

Unitarity: $$\sum_k V_{ik} V^*_{jk} = \delta_{ij}$$

Explicitly for i=1, j=3:

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

$$= \lambda^3 A[\underbrace{(\rho + i\eta) - 1 + (1 - \rho - i\eta)}]$$

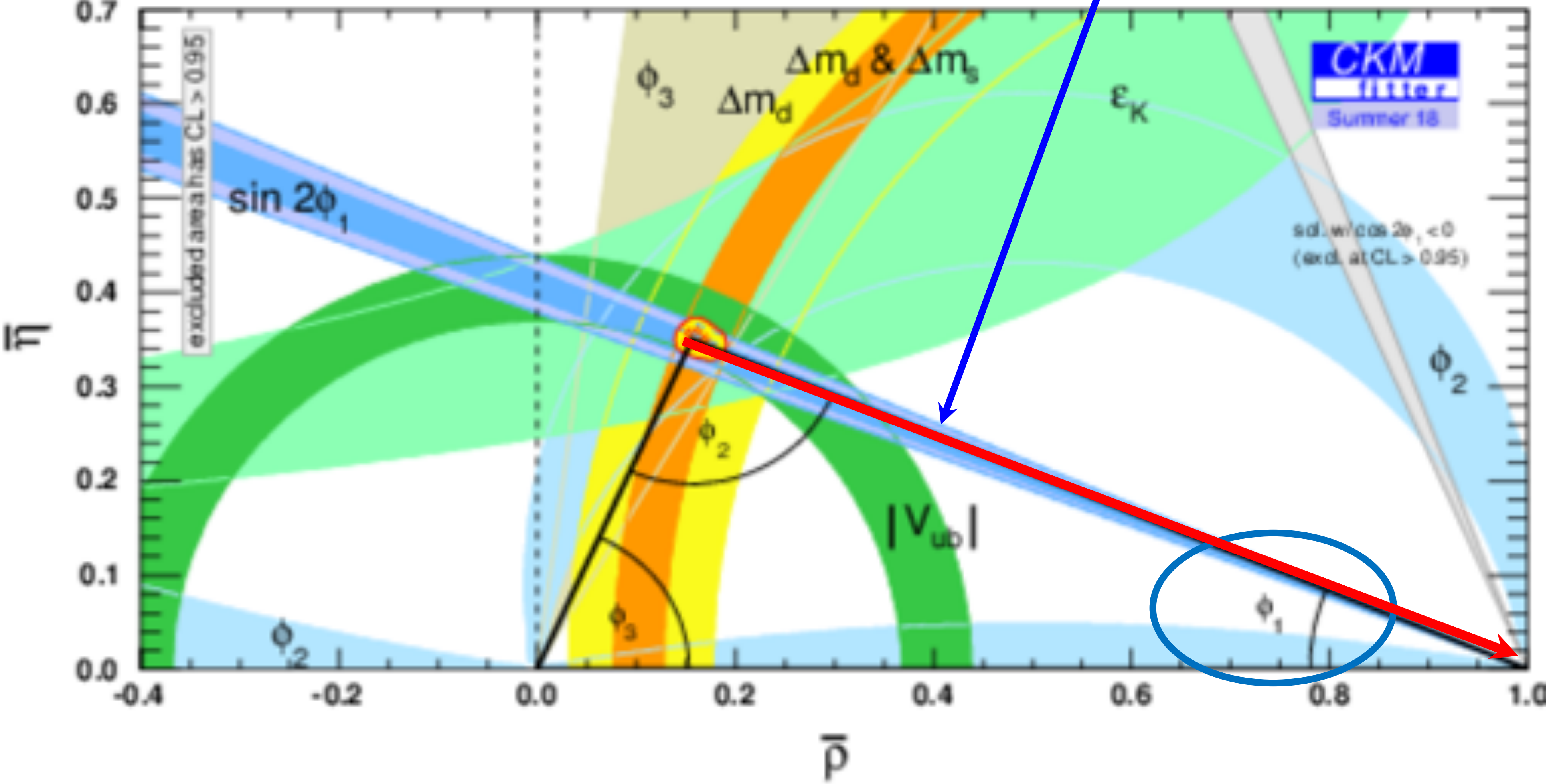
3 terms form “Unitarity triangle”

Unitarity triangle

$$(\rho + i\eta) - 1 + (1 - \rho - i\eta)$$

$$\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$$

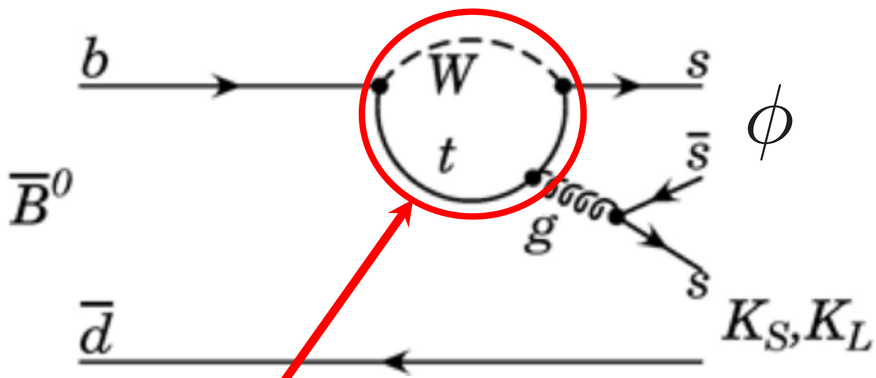
CKMfitter:
Composite all CKM measurements

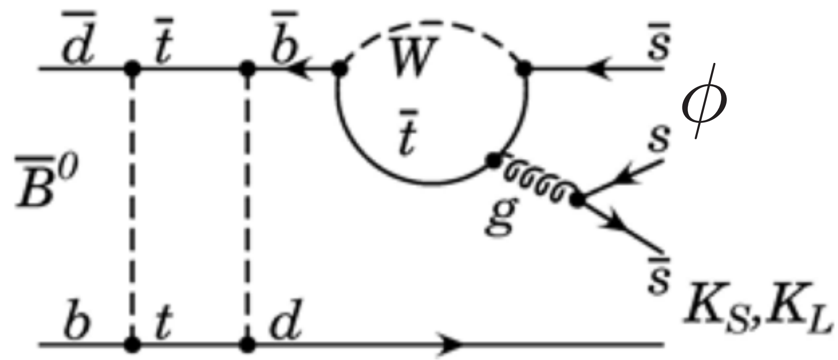


Similar (but different) paths to $\sin 2\varphi_1$

$$B^0 \to \phi K^0$$

"penguin" (real V_{ij}) $\propto V_{tb}^{*} V_{ts}$ mixing+penguin $\propto V_{tb}^{*2} V_{td}^{2} V_{tb} V_{ts}^{*}$





Same difference → Standard Model CP asymmetry ~ $\sin 2\varphi_1$

"New CP-violating Physics" can result in different "$\sin 2\varphi_1$"

heavy flavor (b) factories

Past

- B factories: KEKB/Belle & PEP-II/Babar
  - 1999-2010 e^+e^- @10.6 GeV (cms)
  - Combined 1.25×10^9 B pairs, ~same # of charm pairs
    - Collect ~100% of B's
    - Belle publications: 524 & counting
      - https://belle.kek.jp/bdocs/b_journal.html

Present

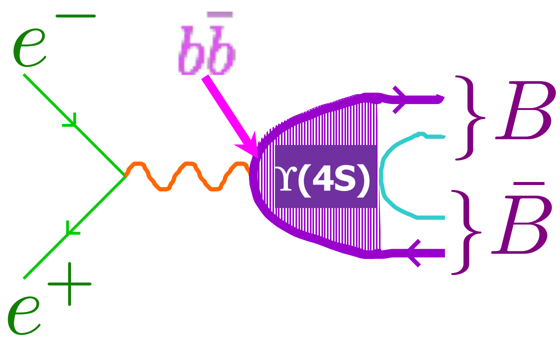
- LHCb at LHC
  - 2008- pp @ 7-13 TeV
  - ~9 fb^{-1} σ_b ~ 72-144 μb (O|10^{12}| b's); σ_c~ 2-3 mb (O|10^{13}| c's)
    - Low collection eff, biased toward final states with charged tracks

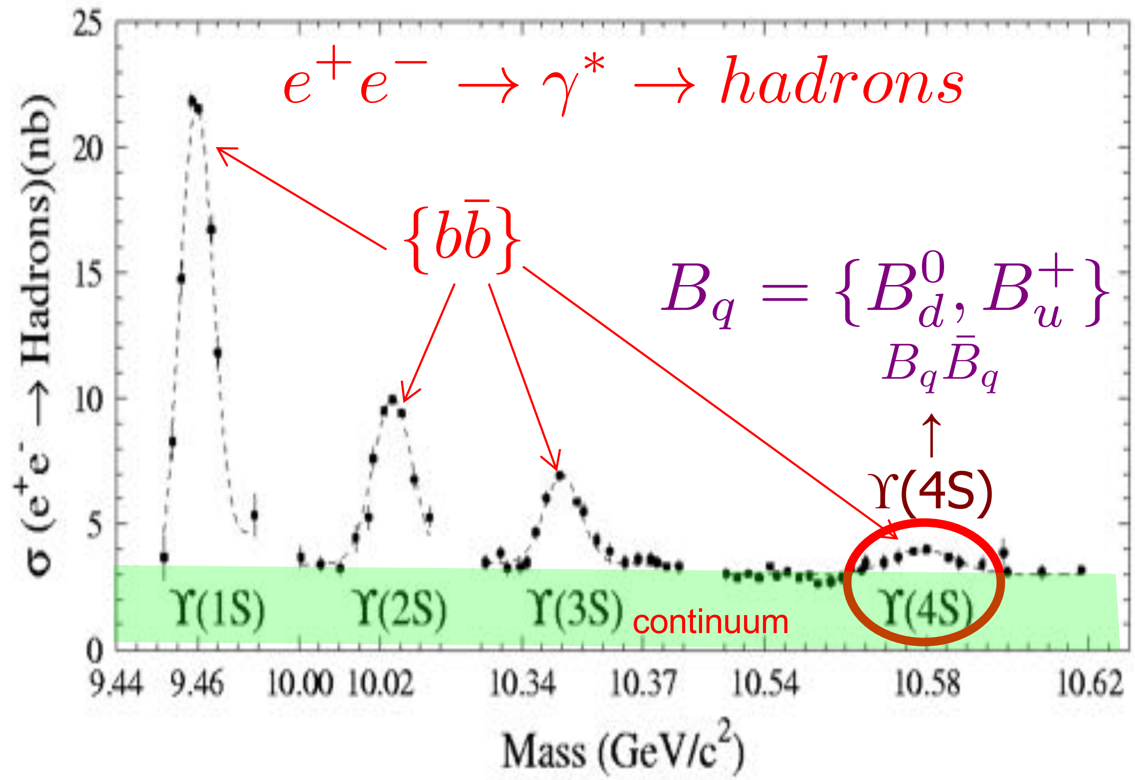
Future

- SuperKEKB/Belle II
  - 2019- e^+e^- @10.6 GeV (cms)
  - By 2027 ~50 ab^{-1} ~ 5×10^{10} B pairs, charm, etc.
    - measurements requiring clean decay times, neutrals, …

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

Upsilon region
~10 GeV





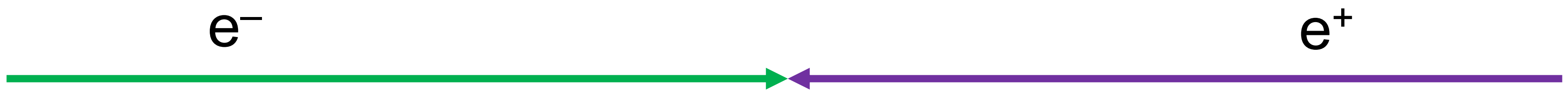
e⁺e⁻ vs pp collisions

- 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 @ ϒ(4S): exclusive B pair events – **clean**
- Full B reconstruction → sample of unreconstructed single B's

B full reconstruction tagging

In center-of-mass system

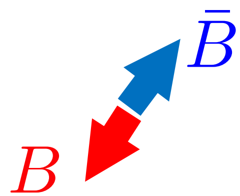
$$\sqrt{s} = 10.579\ \mathrm{GeV}$$



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

B full reconstruction tagging

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



pc~0.33 GeV

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

B full reconstruction tagging

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

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

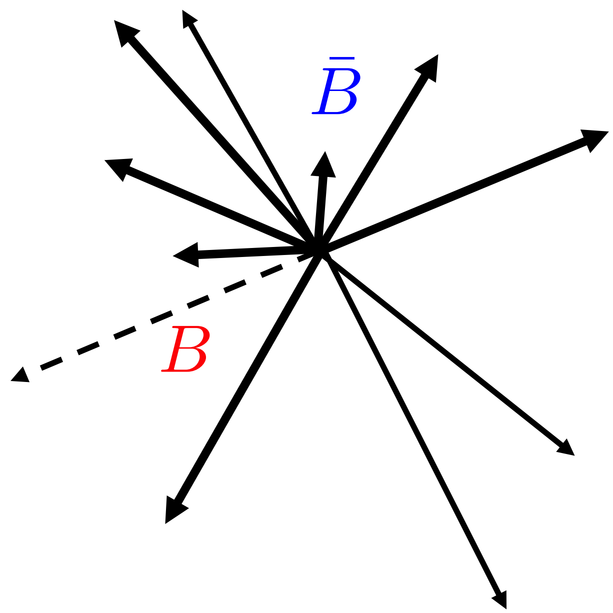
$\nu_\ell/\bar{\nu}_\ell$

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

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

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

etc



B full reconstruction tagging

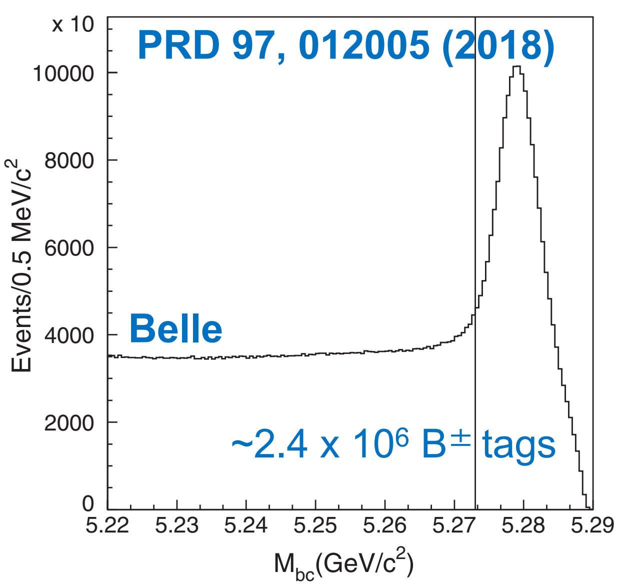
Full reconstruction tagging(>1000 modes)

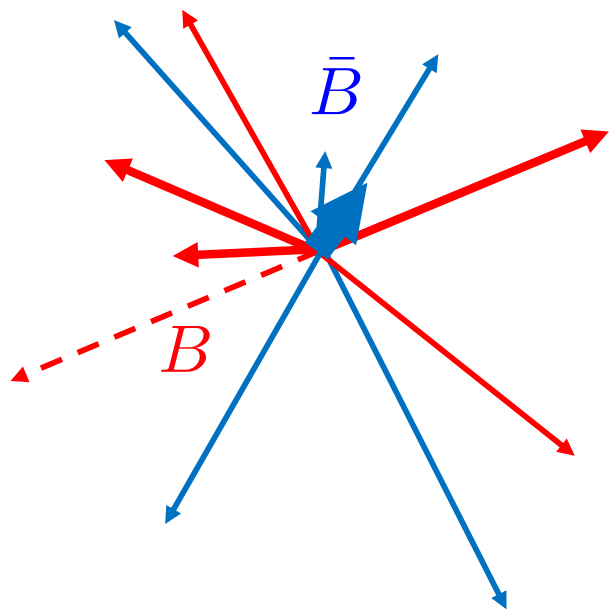
$$E_{\mathrm{tag}} = \sum_{i,\mathrm{tag}} E_i = E_{\mathrm{beam}}$$

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

→ Beam-constrained mass

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





Total efficiency ≈0.3%

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

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

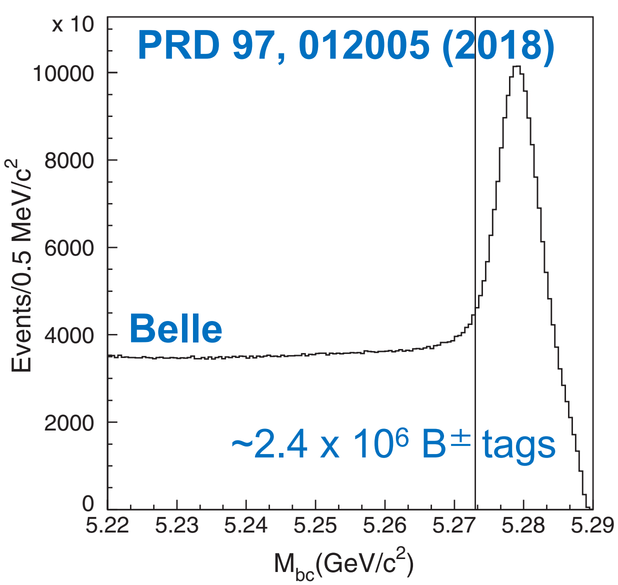
Full reconstruction tagging(>1000 modes)

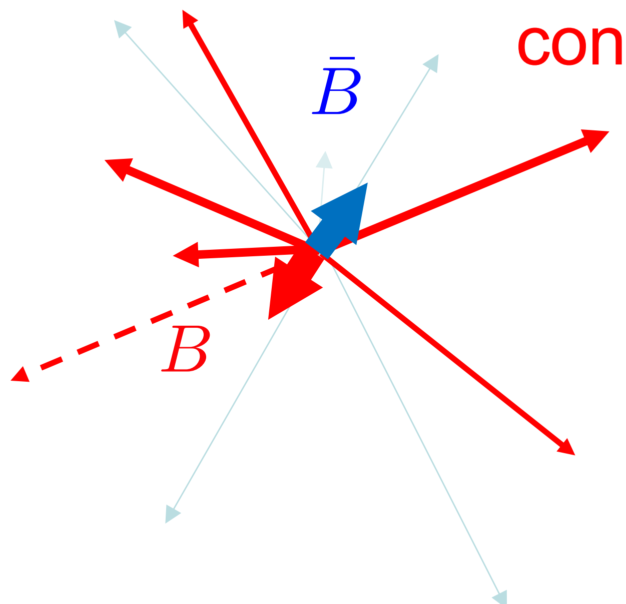
$$E_{\mathrm{tag}} = \sum_{i,\mathrm{tag}} E_i = E_{\mathrm{beam}}$$

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

→ Beam-constrained mass

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





All remaining particles (detected & undetected)

constitute the opposite B

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

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

→ absolute branching fractions

→ inclusive rates

→ Missing mass analysis

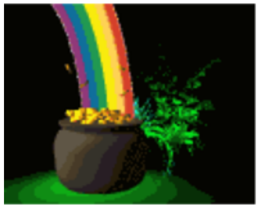
Neutrinos

Inefficiently reconstructed particles

Belle II physics goals

Big **Q**uestions
- Origin of generations & role of flavor
- CP violation and baryon asymmetry

Both necessarily involve 3 generations → heavy quarks

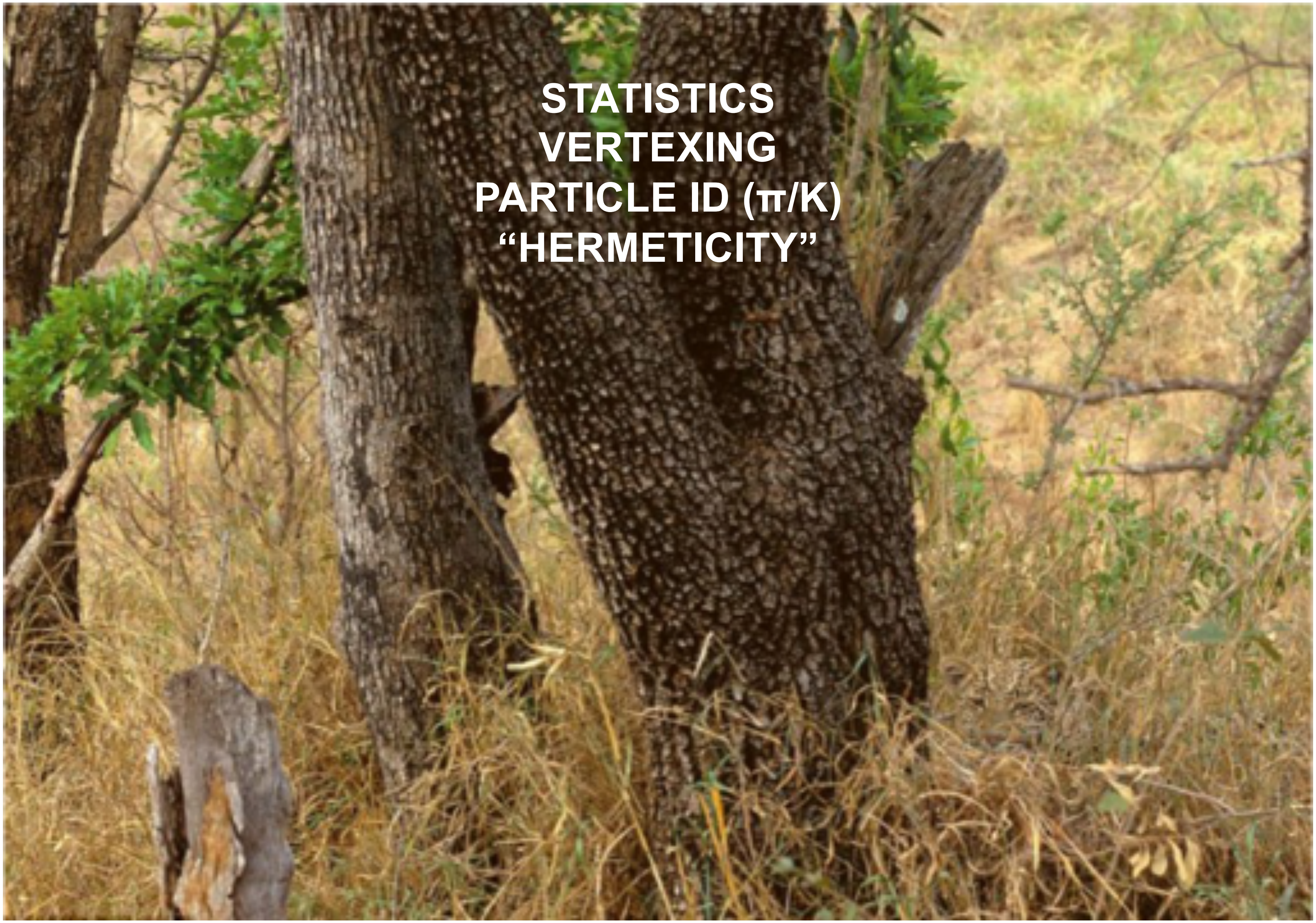


Upcoming generation of b experiments will address these at TeV scale
- Precision in Standard Model:
  - CKM matrix magnitudes & phases → CP asymmetry, rare decays
  - Multi-prong analysis of a rich zoo of particles & processes
- Hadronic infrastructure: required for precision CKM
  - HQ symmetries
  - Effective field theories
  - Flavor SU(3)
  - fragmentation
  - Spectroscopy
- Deviations from SM: “New Physics”

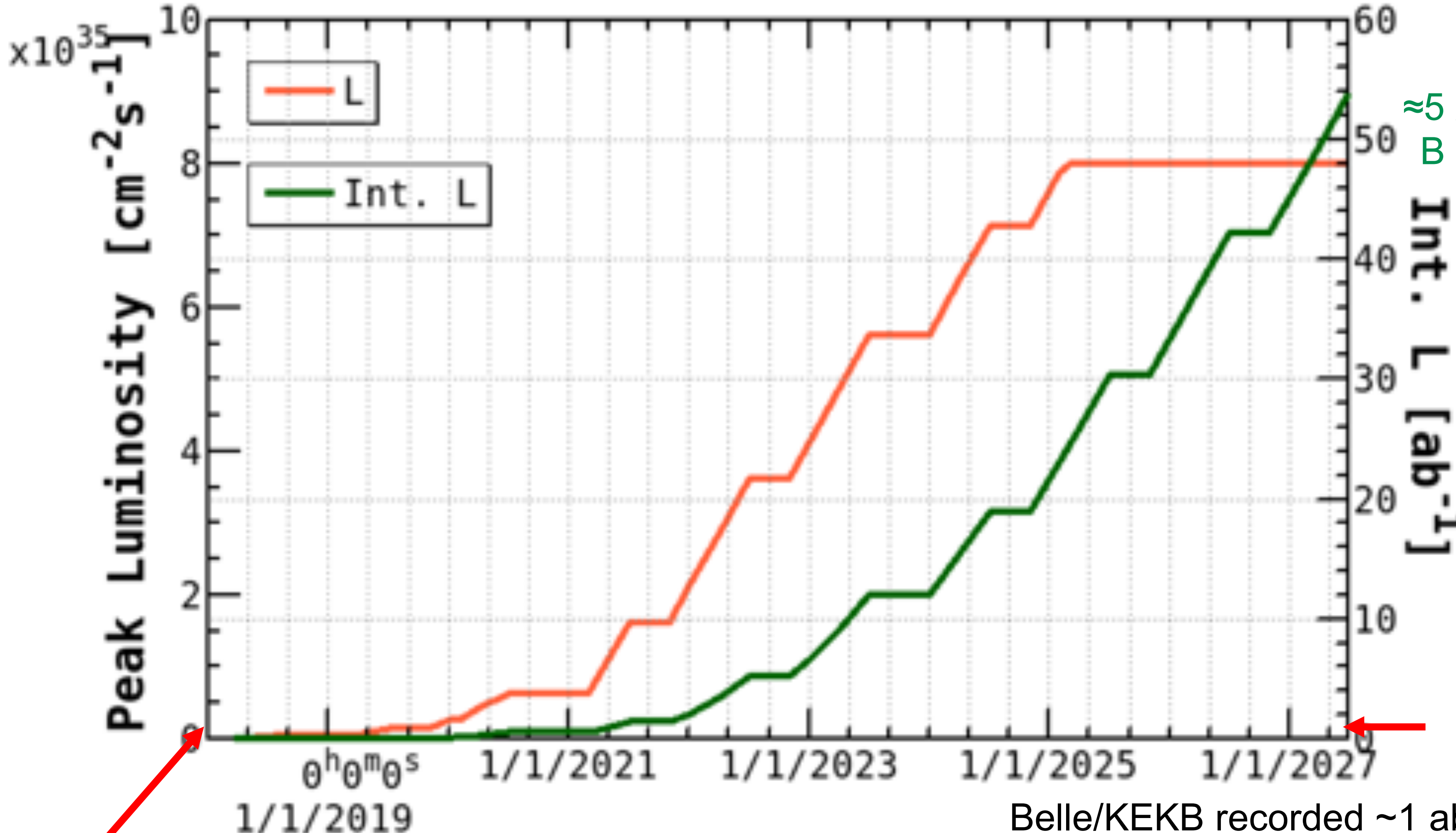
Belle II: seeking the New …

Belle II: seeking the New …

By improving precision on the Old



Statistics: projected SuperKEKB luminosity

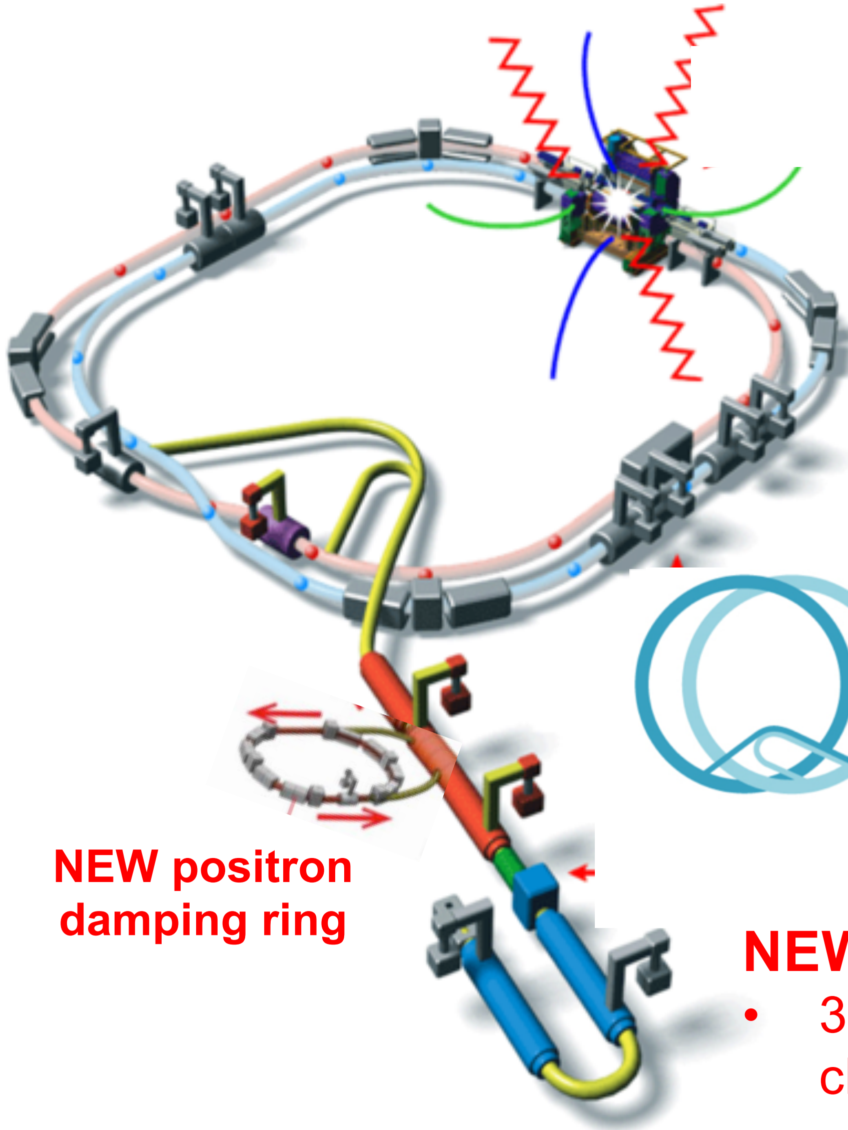


≈5 x 10^{10}
B pairs

KEKB achieved
2 x 10^{34} cm^{-2} s^{-1}
(world record in 2009)

Belle/KEKB recorded ~1 ab^{-1}
1999-2010

KEKB and SuperKEKB: asymmetric e^+e^- annihilation



NEW positron damping ring

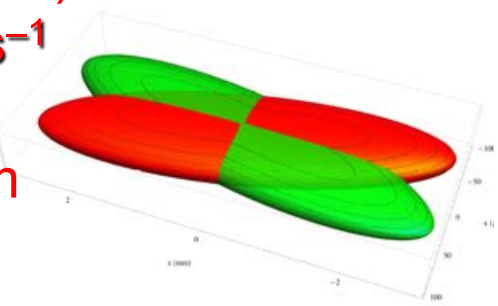
KEKB B-factory 1999-2010

3.5 + 8.0 GeV ($\beta\gamma$ = 0.425)

L_{max} = 2.11 X 10^{34} $cm^{-2}s^{-1}$

Beam size

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



"crab" RF cavities

4/07-

SuperKEKB

4.0 + 7.0 GeV ($\beta\gamma$ = 0.28)

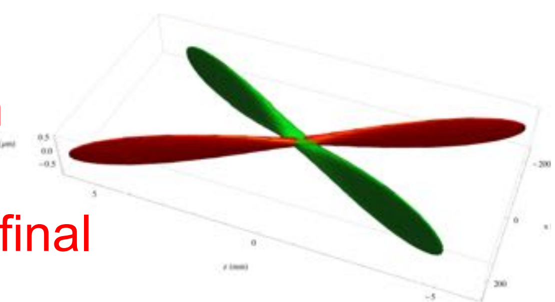
L_{max} = 5 X 10^{35} $cm^{-2}s^{-1}$

Nano-Beam

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

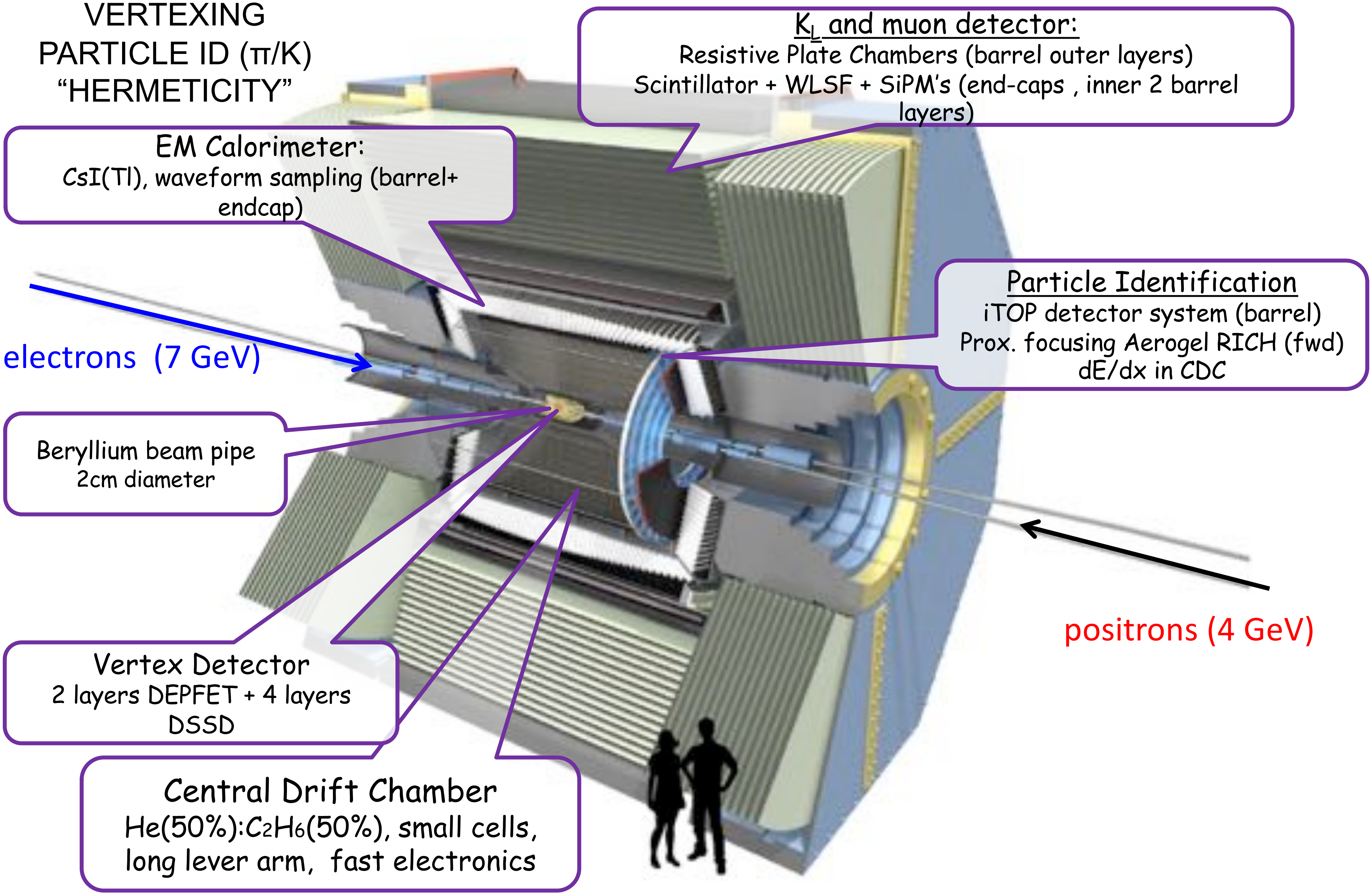
NEW

- 3 km positron ring vacuum chamber
- complex superconducting final focus
- positron damping ring



Belle II Detector

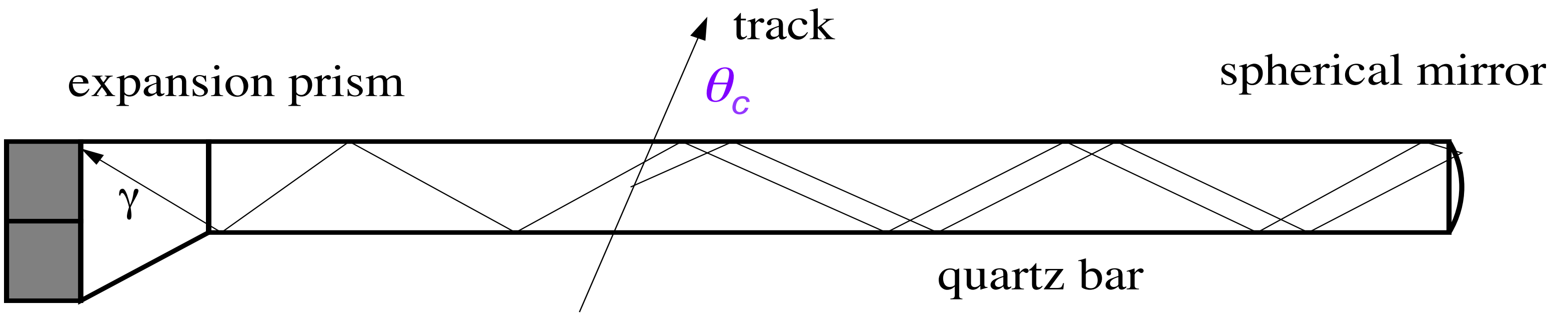
STATISTICS
VERTEXING
PARTICLE ID (π/K)
"HERMETICITY"



π vs K identification: iTOP (Japan/US/Slovenia/Italy)

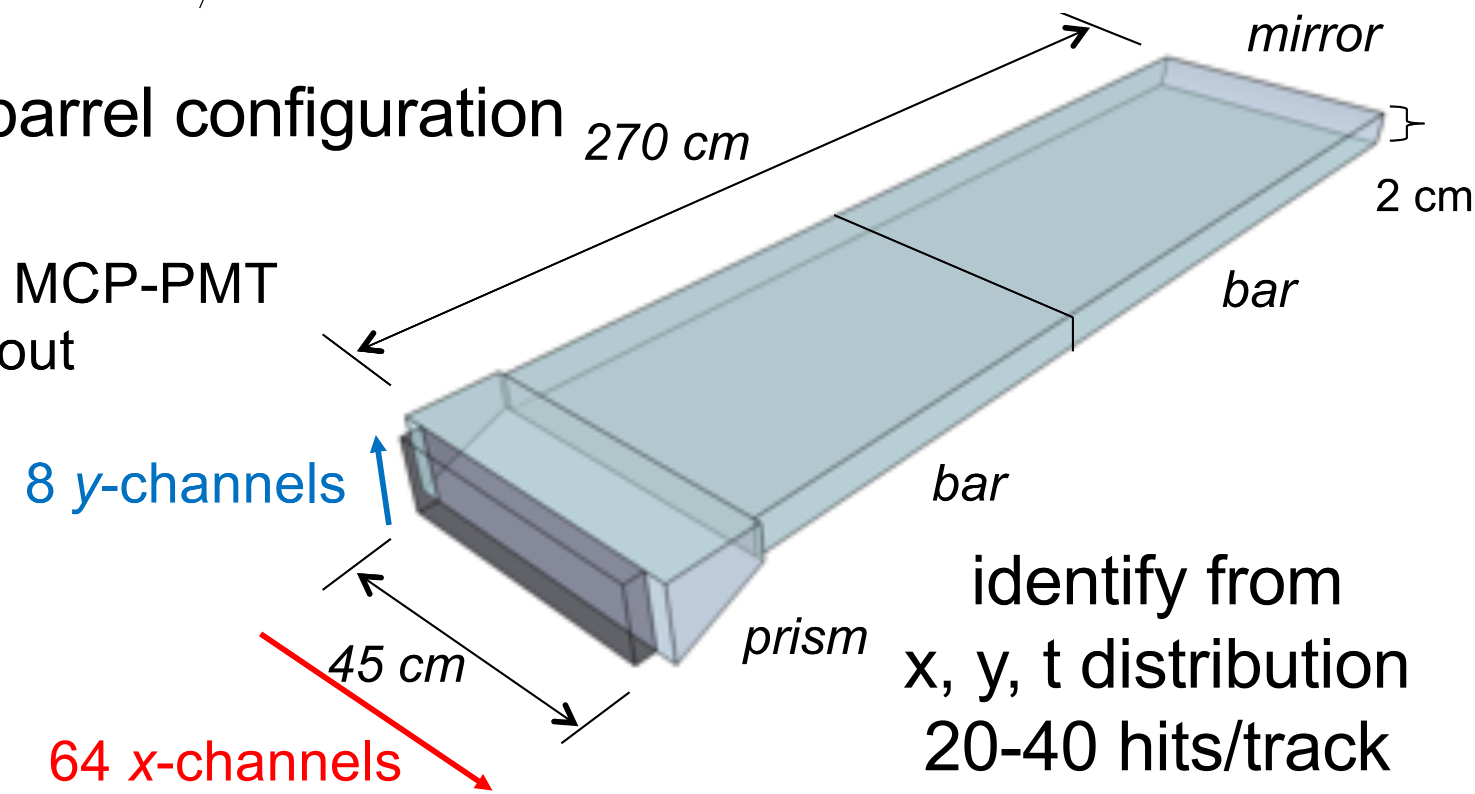
Flavor studies require good discrimination between π, K mesons: distinguished only by mass; challenging at relativistic speeds

Quartz Cerenkov radiator measures v/c



16 modules, barrel configuration

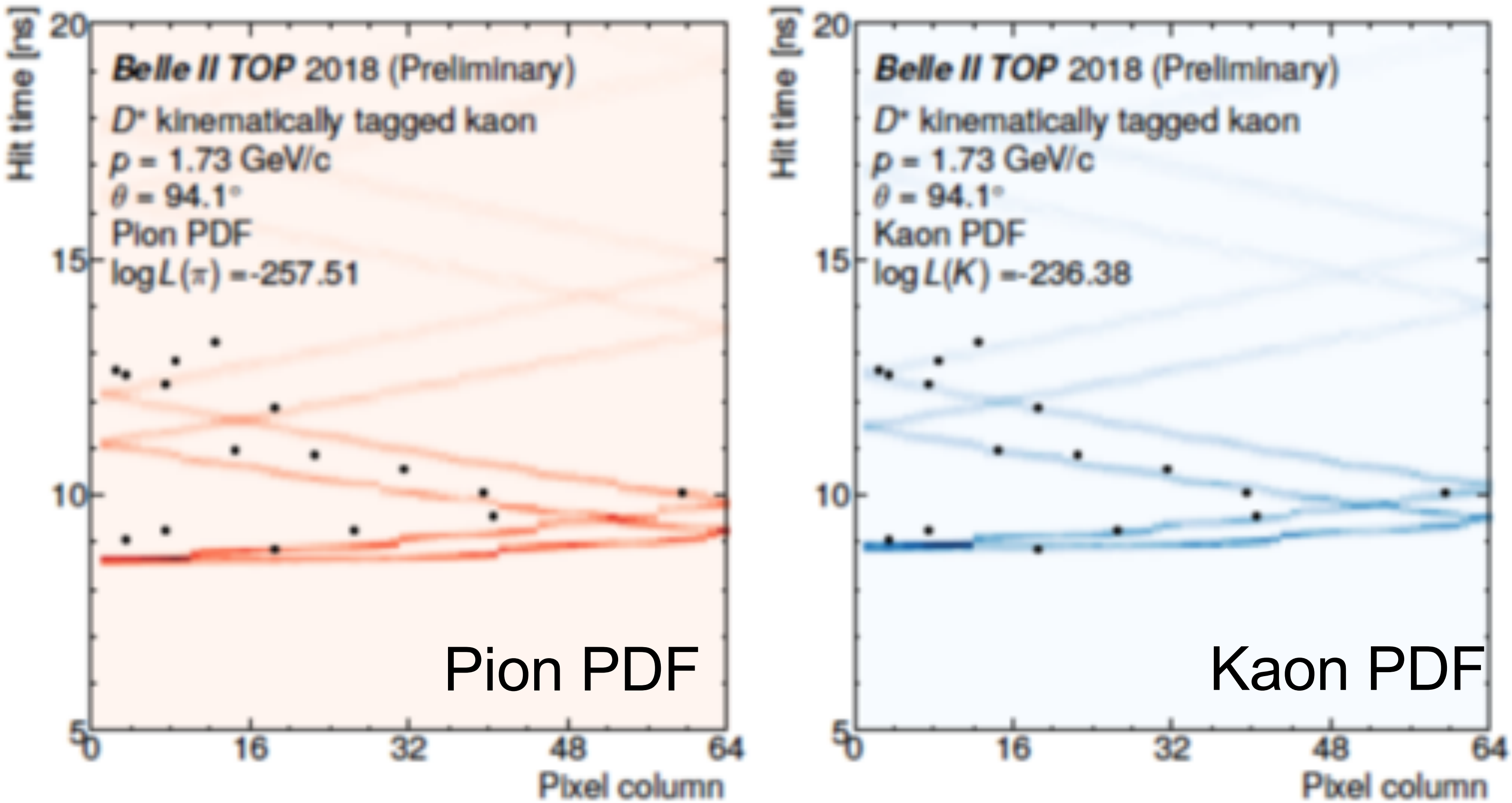
Multichannel MCP-PMT readout



identify from
x, y, t distribution
20-40 hits/track

Particle ID: iTOP

Kinematically identified kaon from a D^{*+}



t vs x

Probability Distribution Function (PDF)
depends on particle speed, entry point & angle

Belle II Physics

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 (689 pages) **arXiv:1808.10567**; to be *submitted to PTEP*

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
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ 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
$S(B \to K_S^0\pi^0\gamma)$	***	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

K. Kinoshita
UT Dallas, April 10, 2019

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

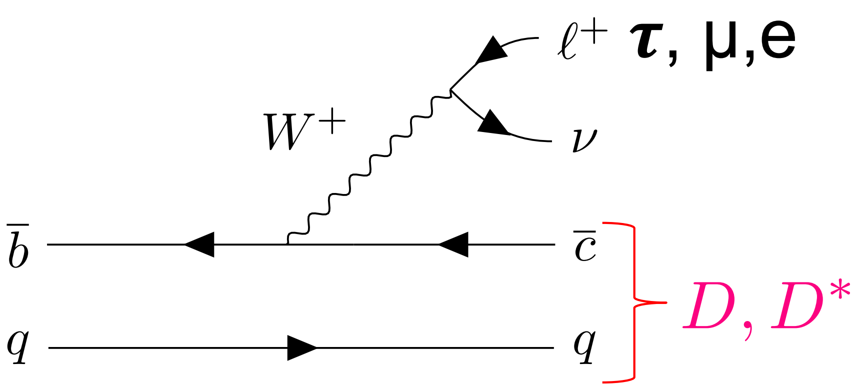
*** Belle
** Belle/LHCb
* LHCb
X unlikely
□ not studied

Many other tables!
Other B decays
tau
Charm

Tantalizing hints of beyond (SM) in existing results

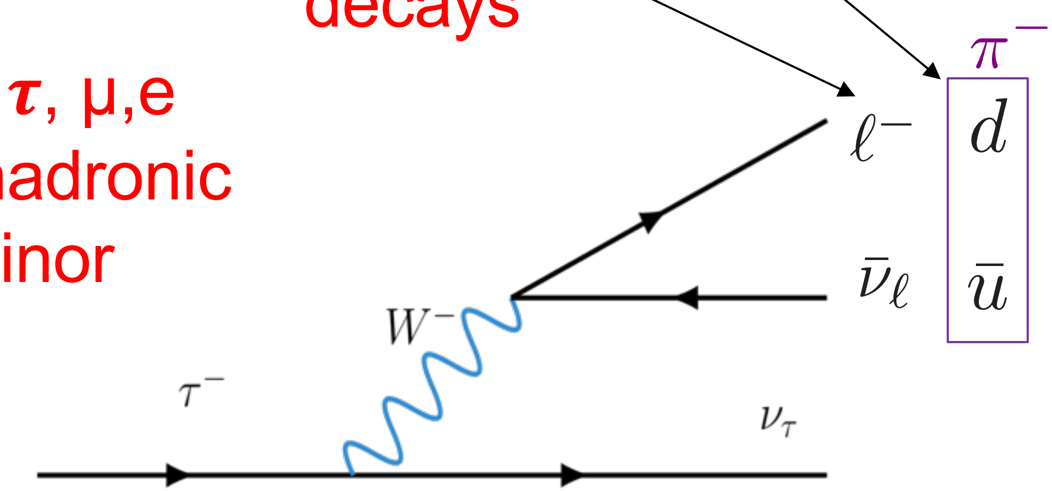
Lepton Universality

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



Experimental challenges

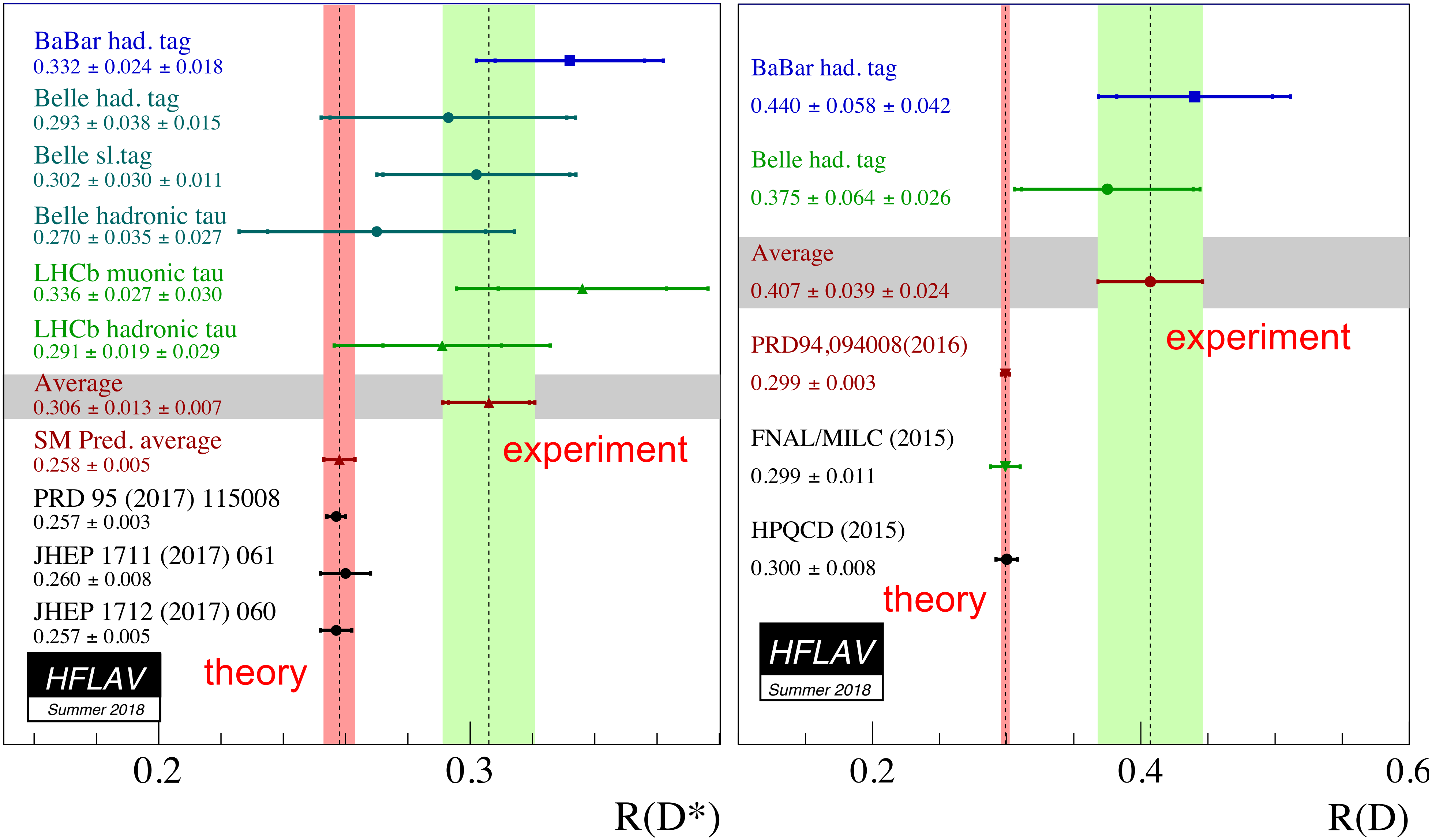
- Multiple neutrinos
  - Tagged analyses
    - Full B reconstruction
    - Partial B reconstruction
  - Leptonic & hadronic tau decays



- SM: single coupling for $\boldsymbol{\tau}$, μ,e
- Theoretically robust – hadronic uncertainties cancel (minor corrections)

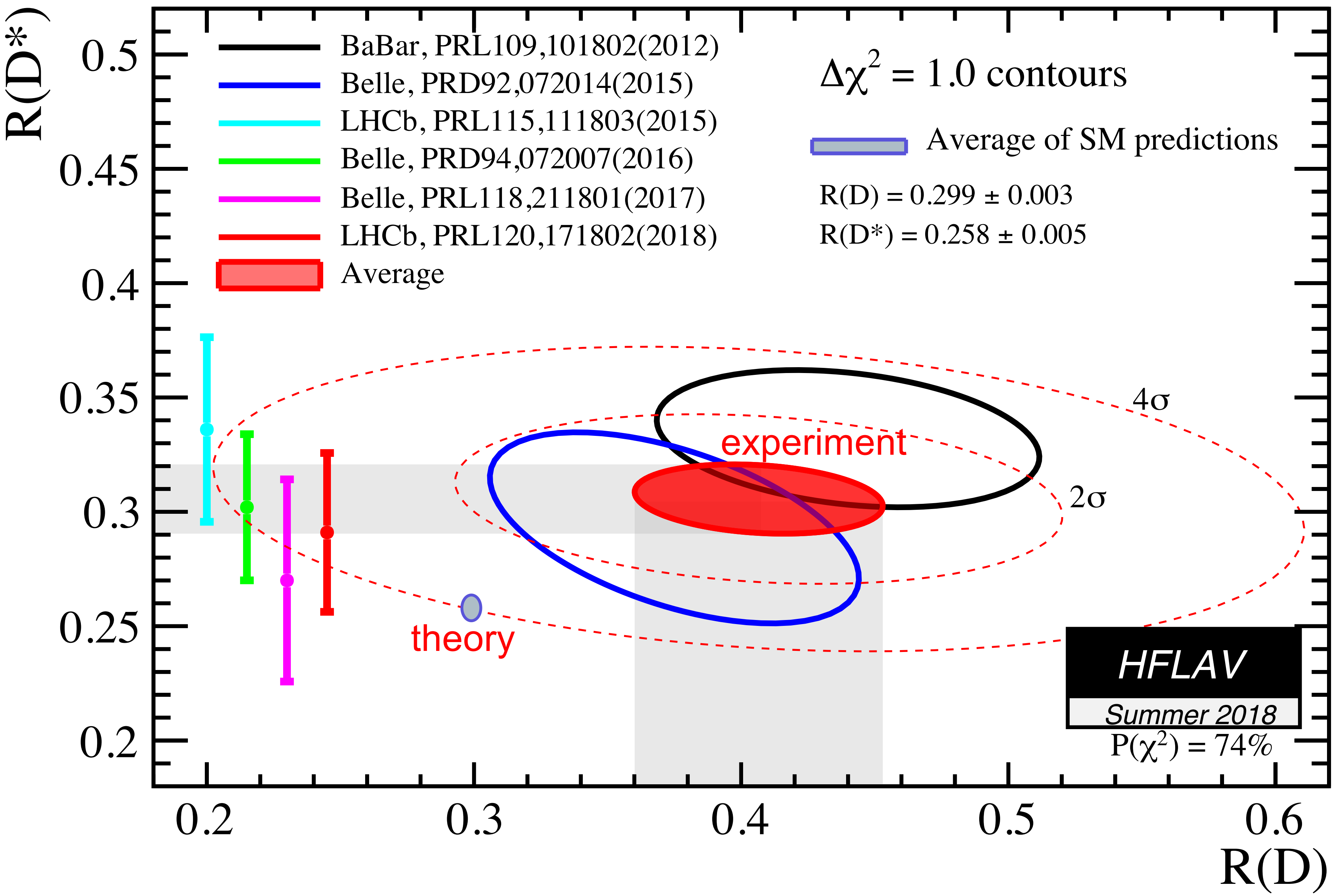
Lepton Universality

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



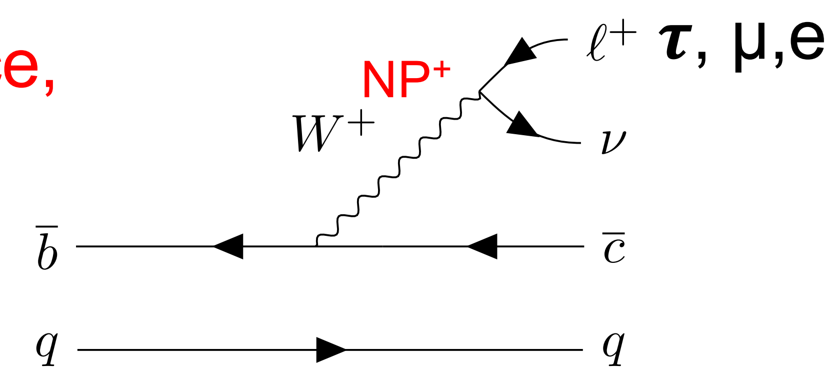
Lepton Universality

Combined: ≈3.9 σ from SM expectation



Lepton Universality

Handles on NP for $\mathcal{R}(D^{(*)})$:
Lepton polarization, q² dependence, angular distributions



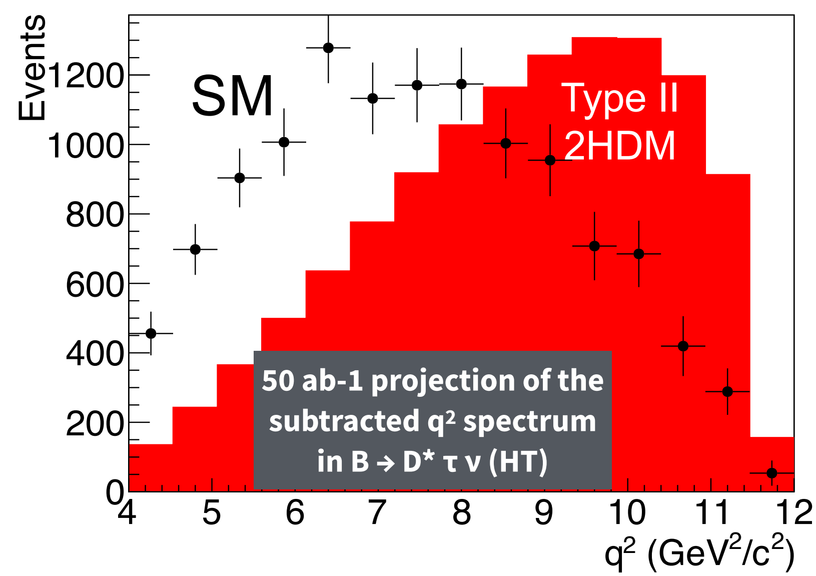
Belle: PRL 118, 211801

Tau polarization via hadronic decay

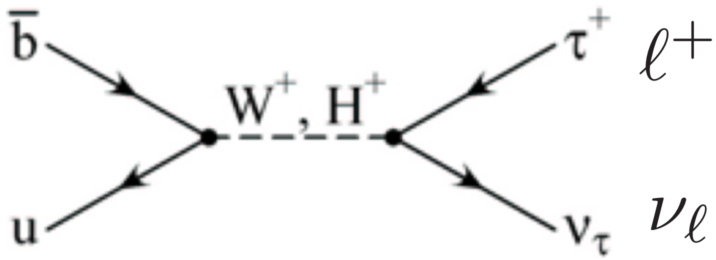
$$p_\tau(D^*) = -0.38 \pm 0.51(\mathrm{stat})^{+0.21}_{-0.16}(\mathrm{sys})$$

SM: – 0.497

Belle II: q² 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 →τν) = 7.5±1.x10^{-5}
  - B(B → μν) = (3.8±0.3)x10^{-7}
  - B(B → eν) ≈ 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

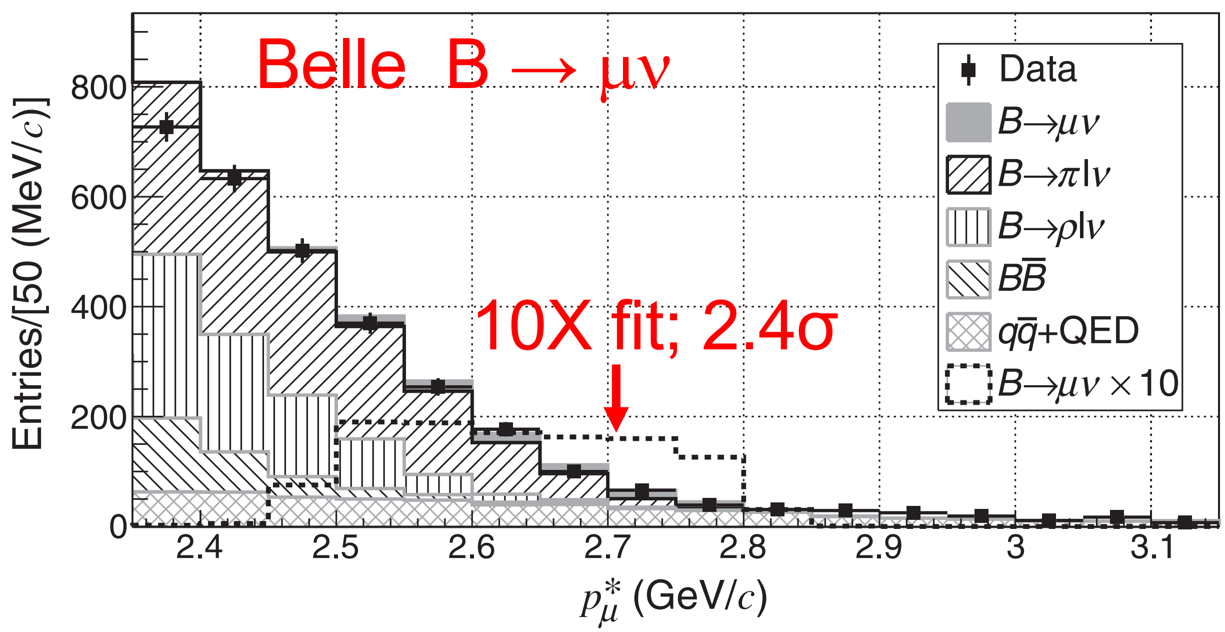
$B(B \to \tau\nu) = 7.5 \pm 1.x10^{-5}$

$B(B \to \mu\nu) = (3.8 \pm 0.3)x10^{-7}$

Experiment

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

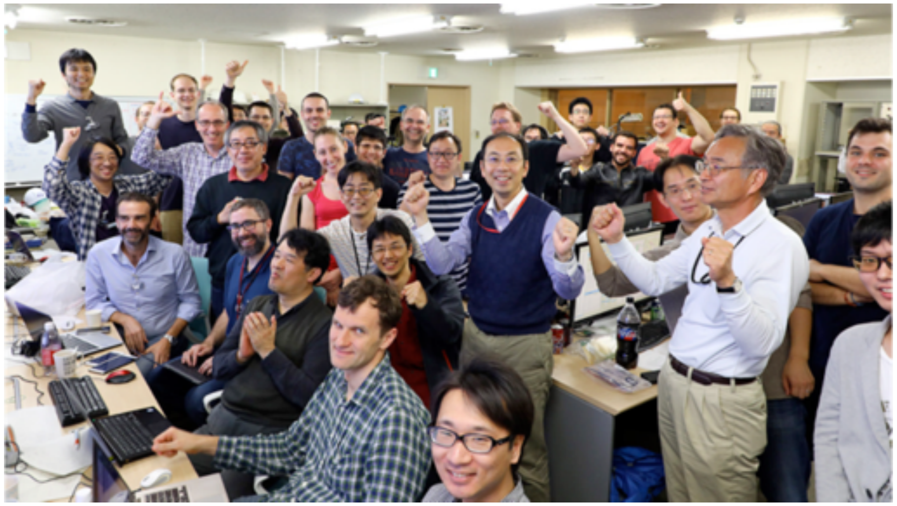
$B(B \to \mu\nu) = (6.4 \pm 2.2 \pm 1.6)x10^{-7}$ PRL 121, 031801 (2018)



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

Belle II commissioning

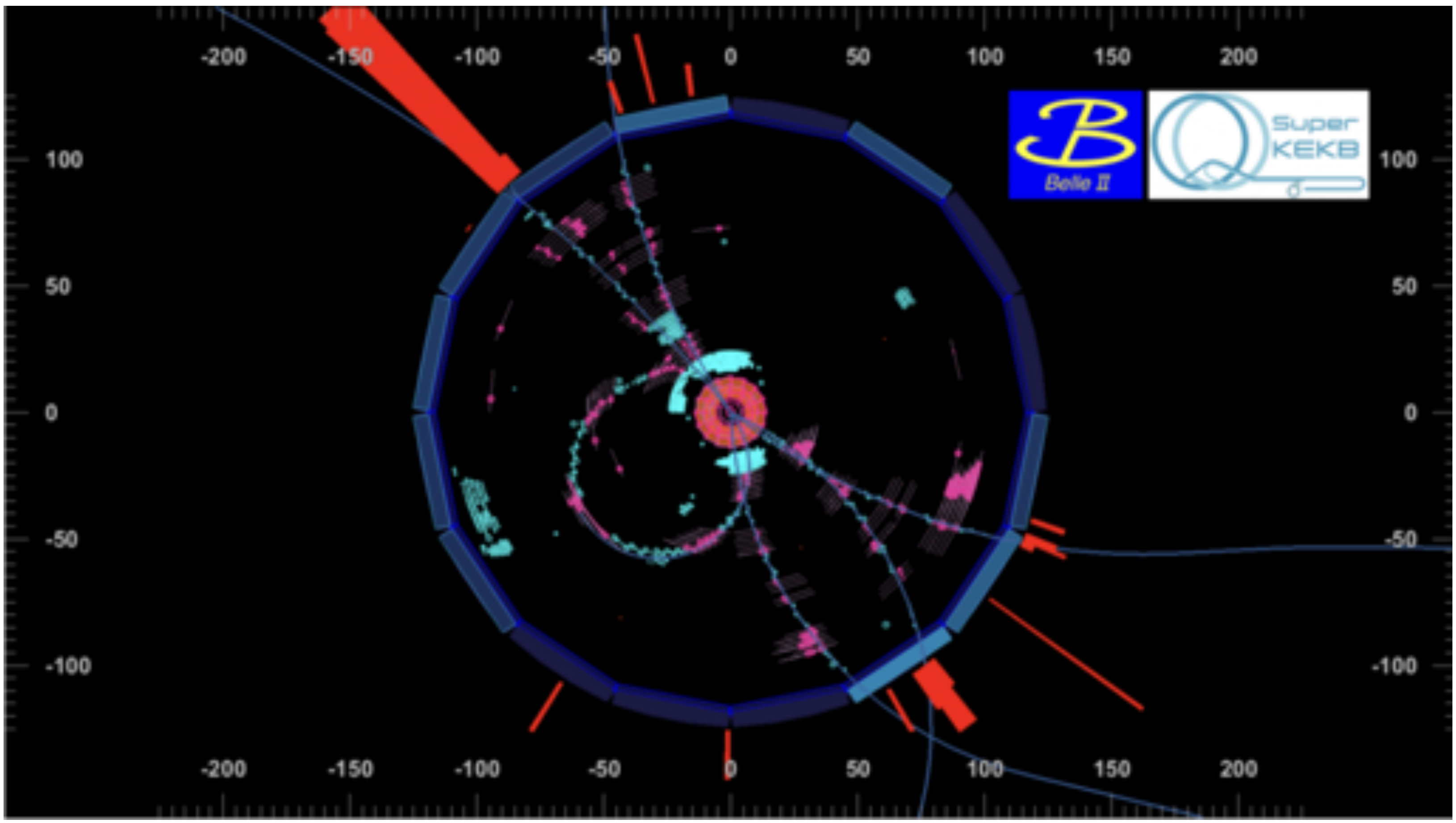
- 11/17 Cosmic rays
- 3-7/18 "Phase II" with beams $\int L\,dt \approx 0.5$ fb^{-1}
  - Luminosity improvements
  - Background studies/reduction
- 4/26/18 First collisions/ $L > 1 \times 10^{33}$ cm^{-2}s^{-1}



- 3/25/19 "Phase III" first physics run with beams

Belle II commissioning

- 3/25/19 “Phase III” first physics run with beams



Summary

Beauty and Flavor Physics

- CKM: the only Standard Model source of CP violation
  - Mismatch with matter-antimatter asymmetry of the universe
  - Origins of flavor
- Belle:
  - first measurement of CP asymmetry in B decay
  - Multiple precision CKM measurements
  - Hints of tension
- Belle II
  - Probe of TeV scale, CP study, complementary to Energy Frontier
  - Extensive theory/experiment studies (B2TIP)
  - 2018: commissioning run
  - 2019: Phase III run for physics
    - with full Si tracker system
    - Beam collisions as of 3/25
- An exciting new era in flavor physics

Belle II: seeking the New …

By improving precision on the Old … and looking VERY CAREFULLY