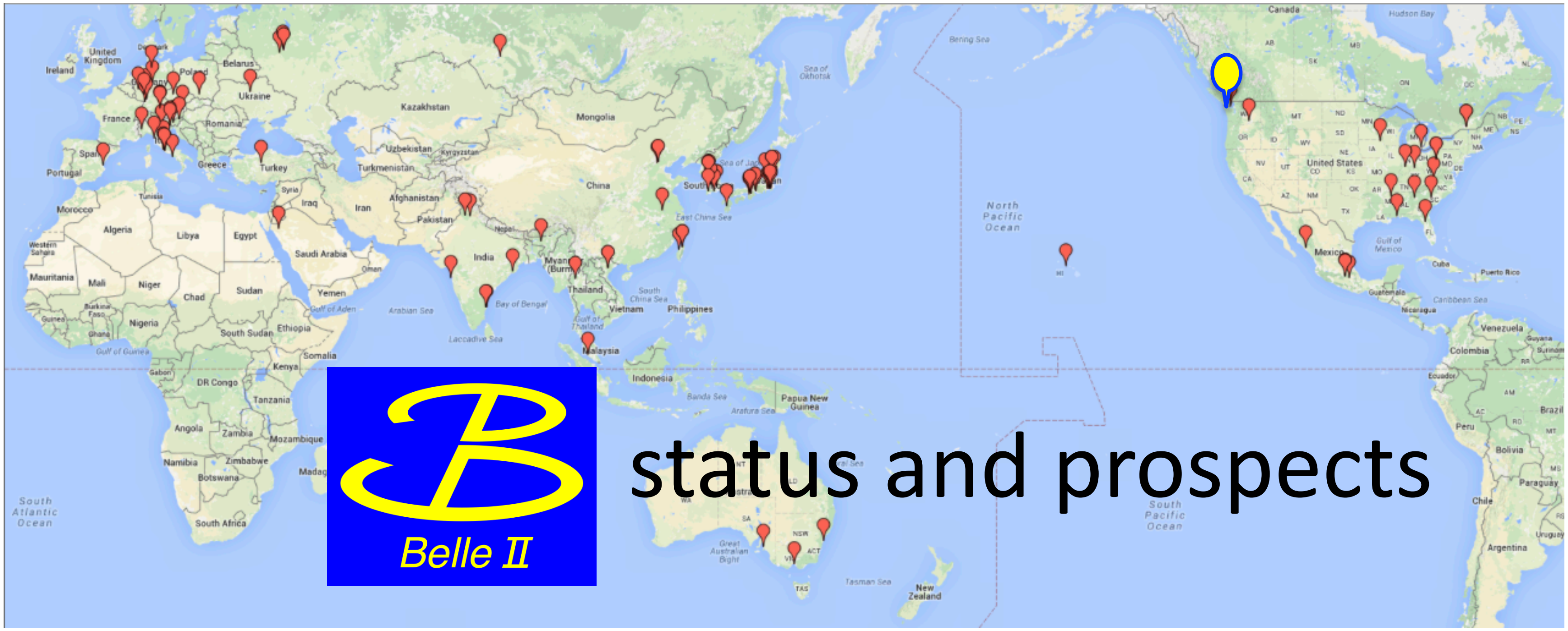
University of Victoria

INSTITUTE OF PARTICLE PHYSICS



Belle II status and prospects

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INFN-Bologna seminar

NSERC CRSNG

VISPA – Victoria Subatomic Physics and Accelerator Research Centre

Canada Foundation for Innovation
Fondation canadienne pour l'innovation

Outline

- The mystery of flavor
- Legacy of the e^+e^- B factories
  - Validation of CKM picture
  - unresolved questions
- Physics goals of Belle II
  - broad program: B, charm, tau, dark forces, EW
- SuperKEKB and Belle II status
  - Design and construction
  - Commissioning

Flavor – why?

Flavor and the Proliferation of Parameters

gauge sector

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

describes the gauge interactions of the quarks and leptons

parametrized by
3 gauge couplings
g_1, g_2, g_3

Higgs sector

$$+ |D_\mu \phi|^2 - V(\phi)$$

breaks electro-weak symmetry and gives mass to the $W^\pm$ and Z bosons

2 free parameters
Higgs mass
Higgs vev

flavor sector

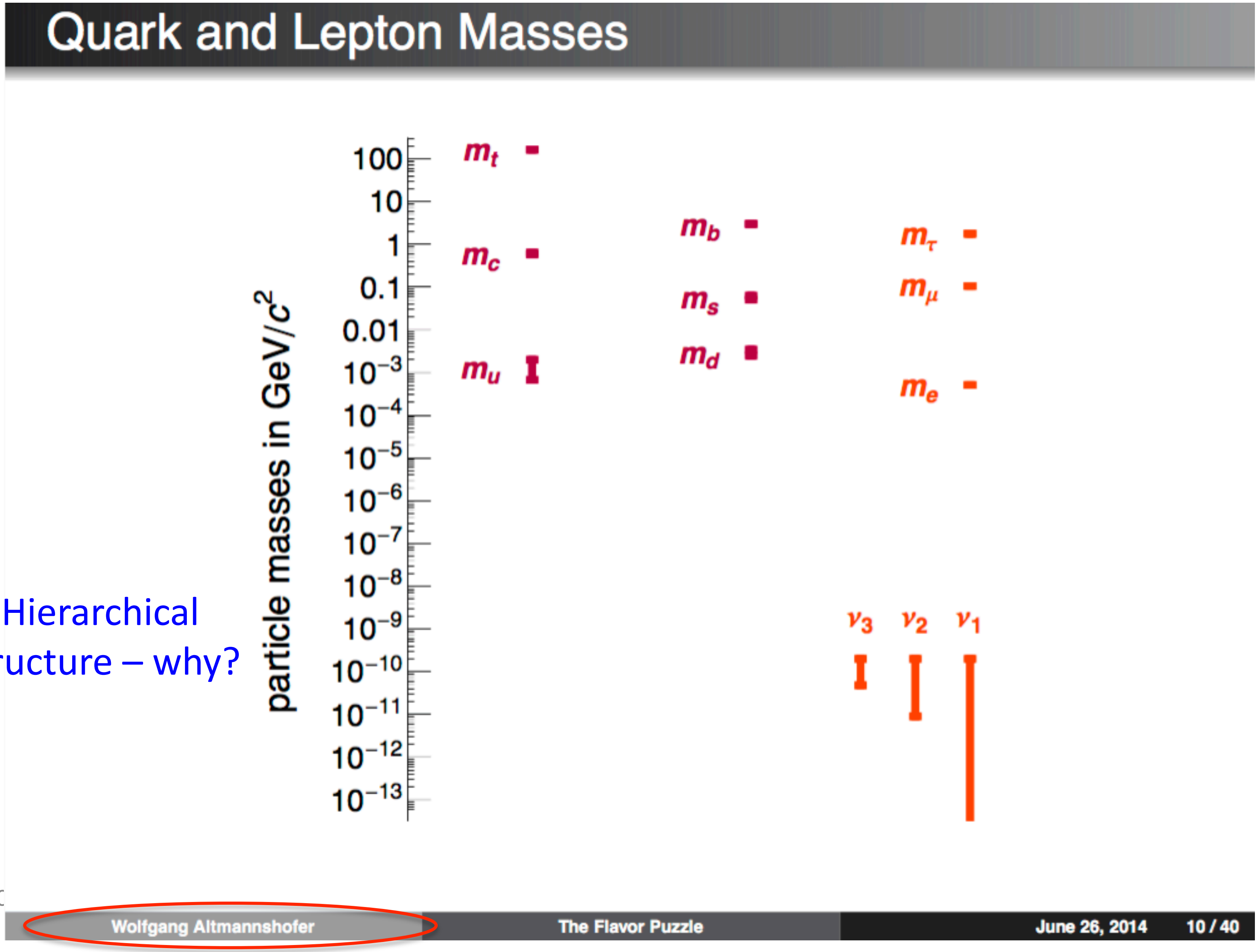
$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$

leads to masses and mixings of the quarks and leptons

22 free parameters
to describe the masses and mixings of the quarks and leptons

the flavor sector is the most puzzling part of the Standard Model

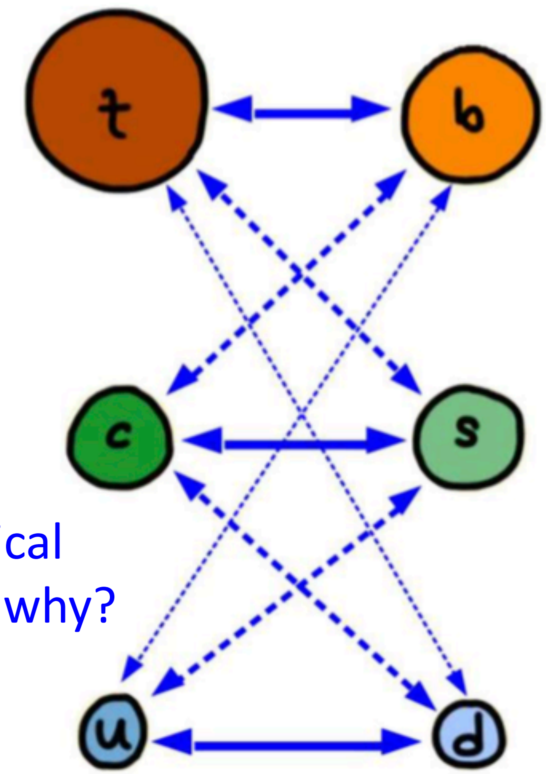
Flavor - patterns



Hierarchical structure – why?

Flavor - patterns

Distinct Decay Pattern of the Quarks in the SM



Hierarchical structure – why?

in the Standard Model there are no direct transitions within up-type or down-type quarks

→ GIM mechanism (Glashow, Iliopoulos, Maiani)

no flavor changing neutral currents (FCNCs) at tree level

transitions among the generations are mediated by the $W^{\pm}$ bosons and their relative strength is parametrized by the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

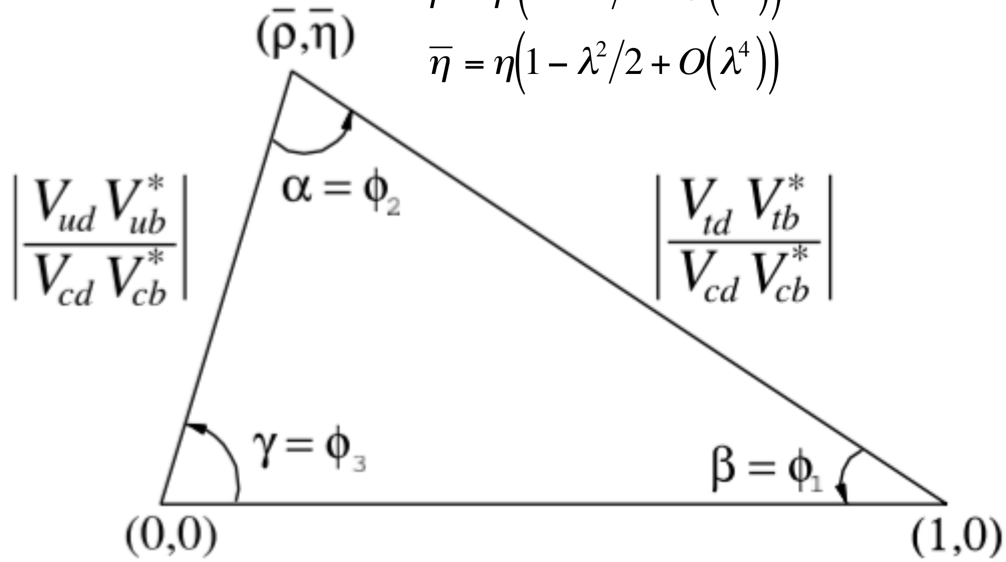
CKM picture

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Mis-alignment of weak and mass eigenstates; only known source of flavor-changing interaction
- Imaginary phase → only known source of CP (and T) violation
- Unitarity conditions correspond to triangles in complex plane

$$\bar{\rho} = \rho\left(1-\lambda^2/2 + O(\lambda^4)\right)$$
$$\bar{\eta} = \eta\left(1-\lambda^2/2 + O(\lambda^4)\right)$$



$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

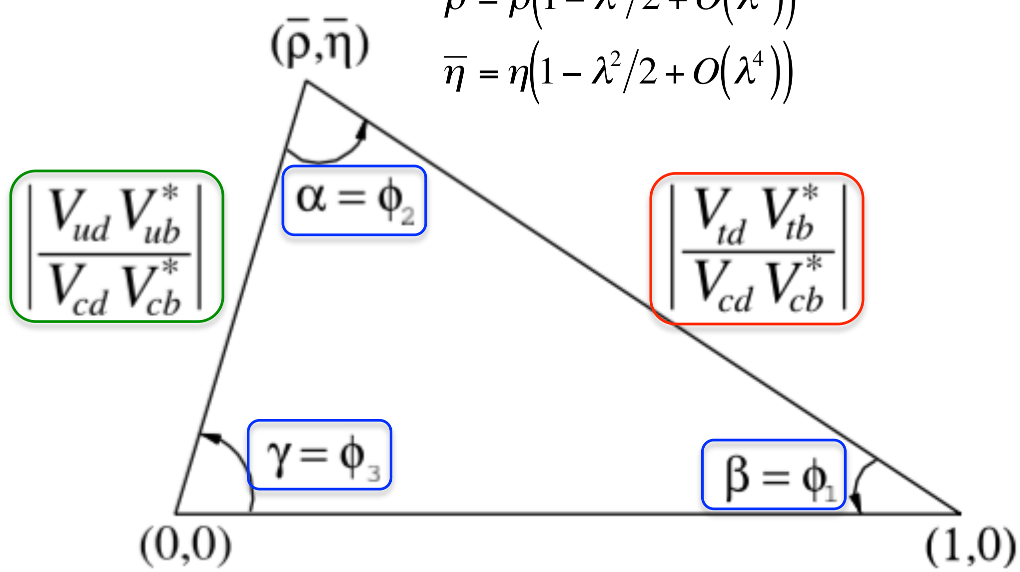
CKM picture

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- CP asymmetries measure the angles ϕ_1, ϕ_2, ϕ_3
- Tree-level decays measure $|V_{ub}/V_{cb}|$
- $B\bar{B}$ oscillations measure $|V_{td}/V_{ts}| \approx |V_{td}/V_{cb}|$

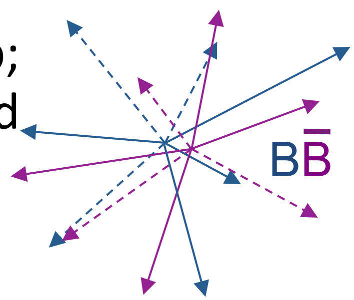
$$\bar{\rho} = \rho\left(1-\lambda^2/2 + O(\lambda^4)\right)$$
$$\bar{\eta} = \eta\left(1-\lambda^2/2 + O(\lambda^4)\right)$$

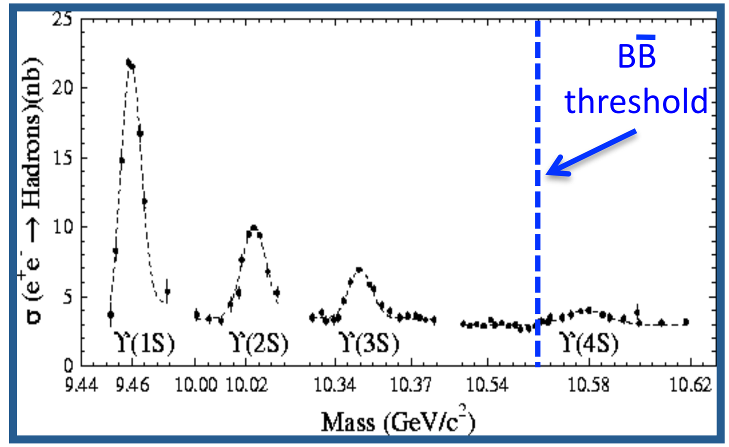


$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

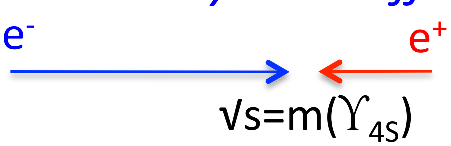
Asymmetric e^+e^- B factories

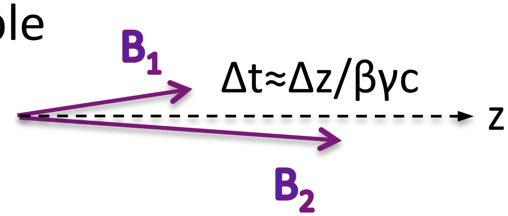
- Goal – measure time-dependent CP asymmetries in B decays
- $\sigma(e^+e^- \rightarrow \Upsilon_{4S} \rightarrow B\underline{B}) = 1.05$ nb; produces quantum-correlated $B\underline{B}$ pair with $p_B \approx 0.06\ m_B$





- Innovation of Pier Oddone – boost Υ_{4S} system along beam line to make *B meson decay time difference* measurable

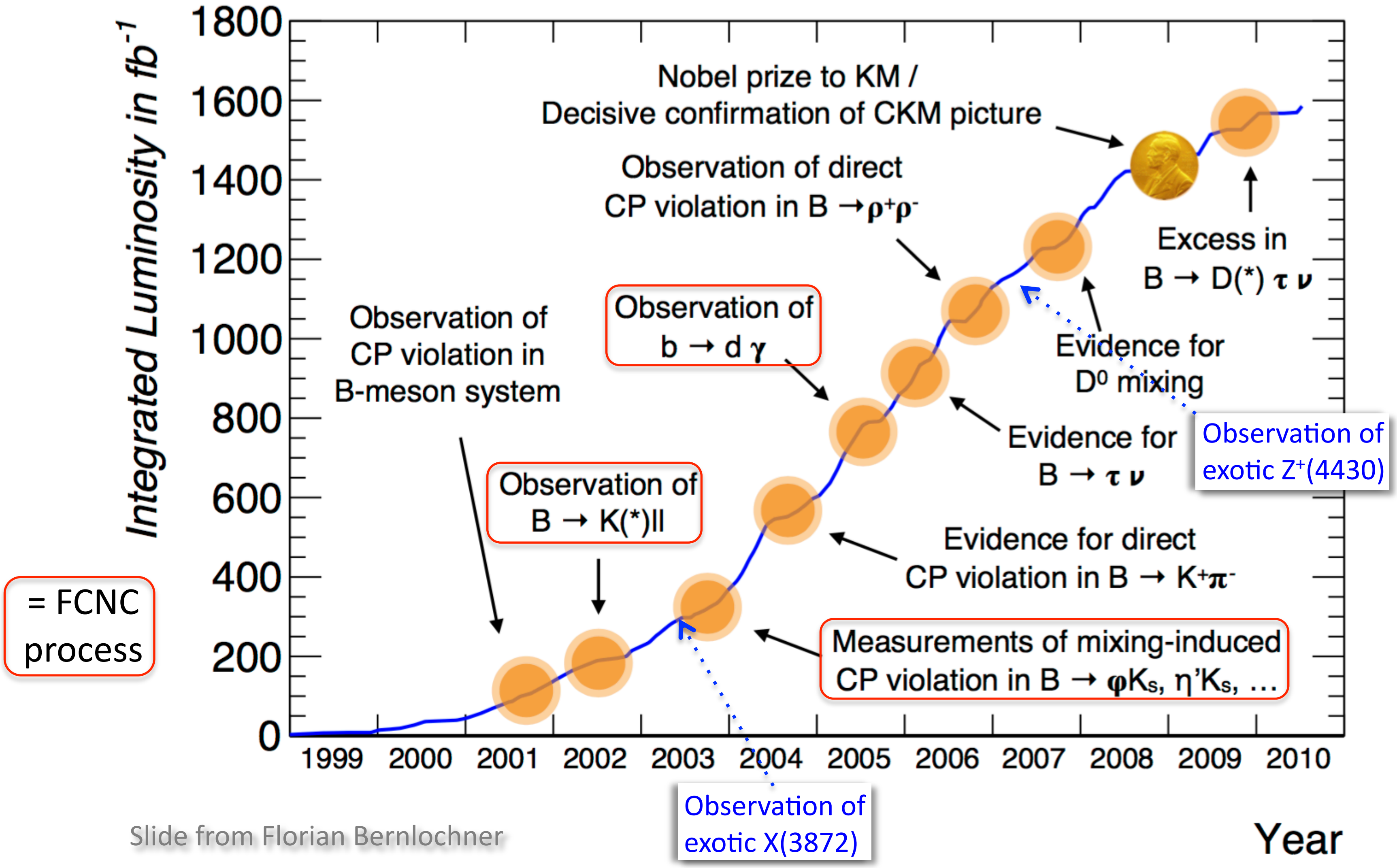




Choose beam energies to give $\beta\gamma \approx 0.5 \rightarrow \Delta z \approx 200\mu m$

- This, plus high luminosities ($>10^{34}/cm^2/s$), enabled a rich legacy of discovery

Selected highlights from BaBar and Belle



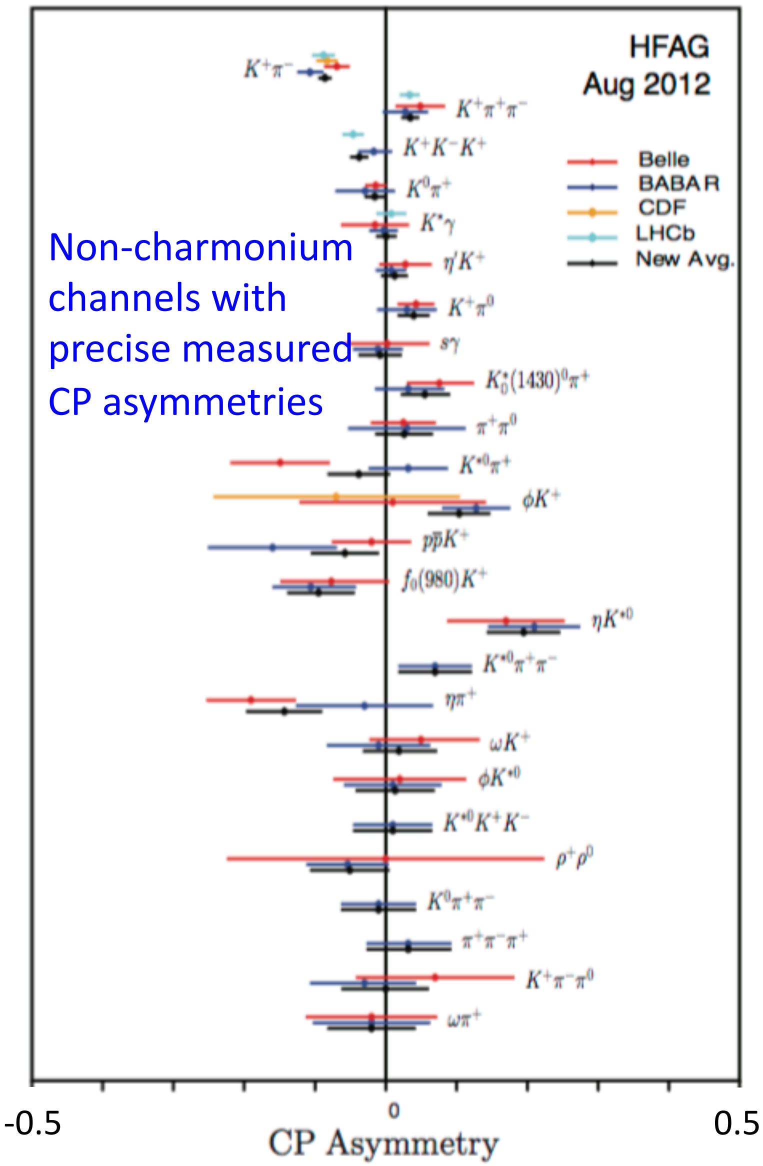
Slide from Florian Bernlochner

Impact of B factories and LHCb

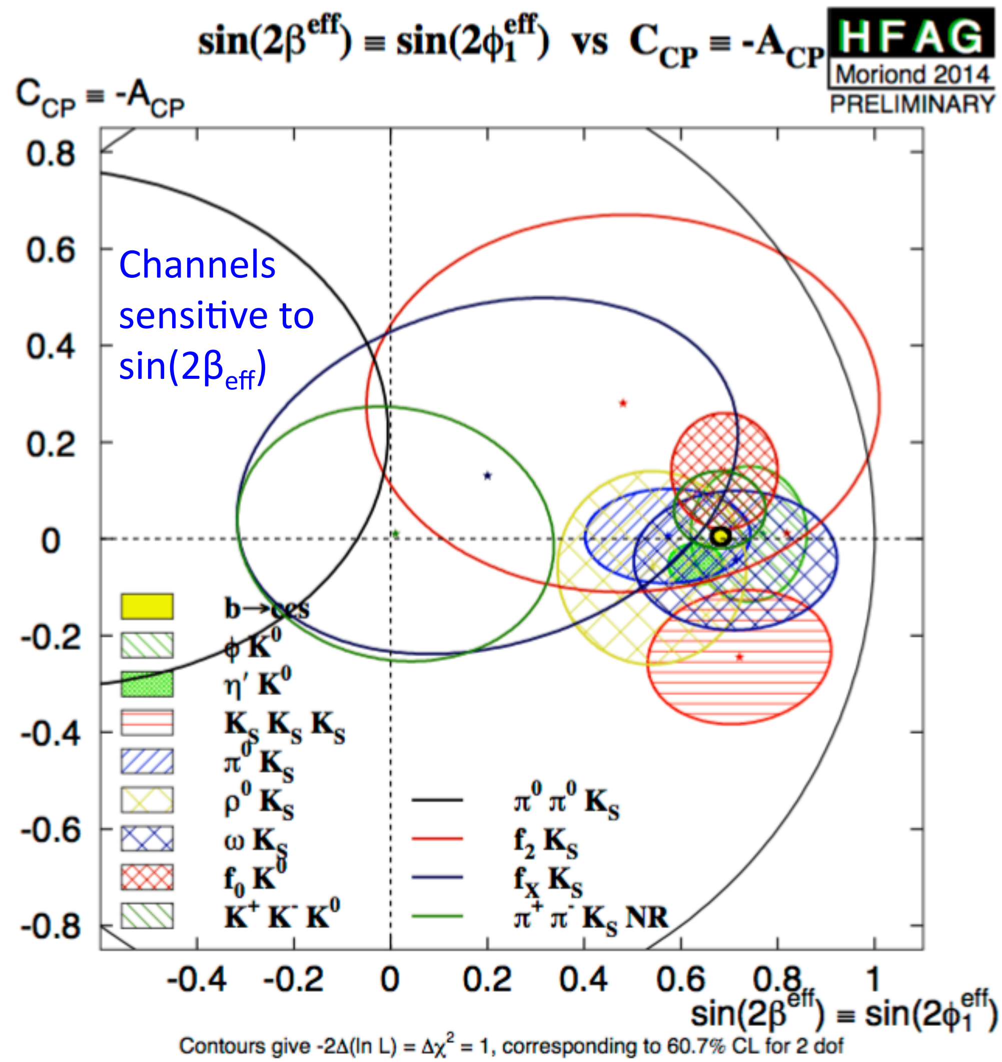
- Comprehensive measurements of CP asymmetries, $B\underline{B}$ oscillations and $|V_{ub}/V_{cb}|$ overconstrain the unitarity triangle
  - CP asymmetries sensitive to each angle in the Unitarity Triangle measured
  - **>60 pages** of CP asymmetry measurements in PDG listings

  → CKM picture firmly established
- Precision measurements are sensitive to New Physics
  - leptonic decays (e.g. $B_{d,s} \rightarrow \mu^+\mu^-$)
  - EW radiative decays ($b \rightarrow s/d\ \gamma$, $b \rightarrow s/d\ l^+l^-$, $b \rightarrow s/d\ \nu\underline{\nu}$)
- $D\underline{D}$ mixing and charm CP asymmetries probe NP
- New exotic hadron states established (confirmed and augmented with measurements at hadron colliders and BES-III)
- Decays to final states $D^{(*)}\tau\nu$ deviate from expectations

CP asymmetries from a few dozen selected channels



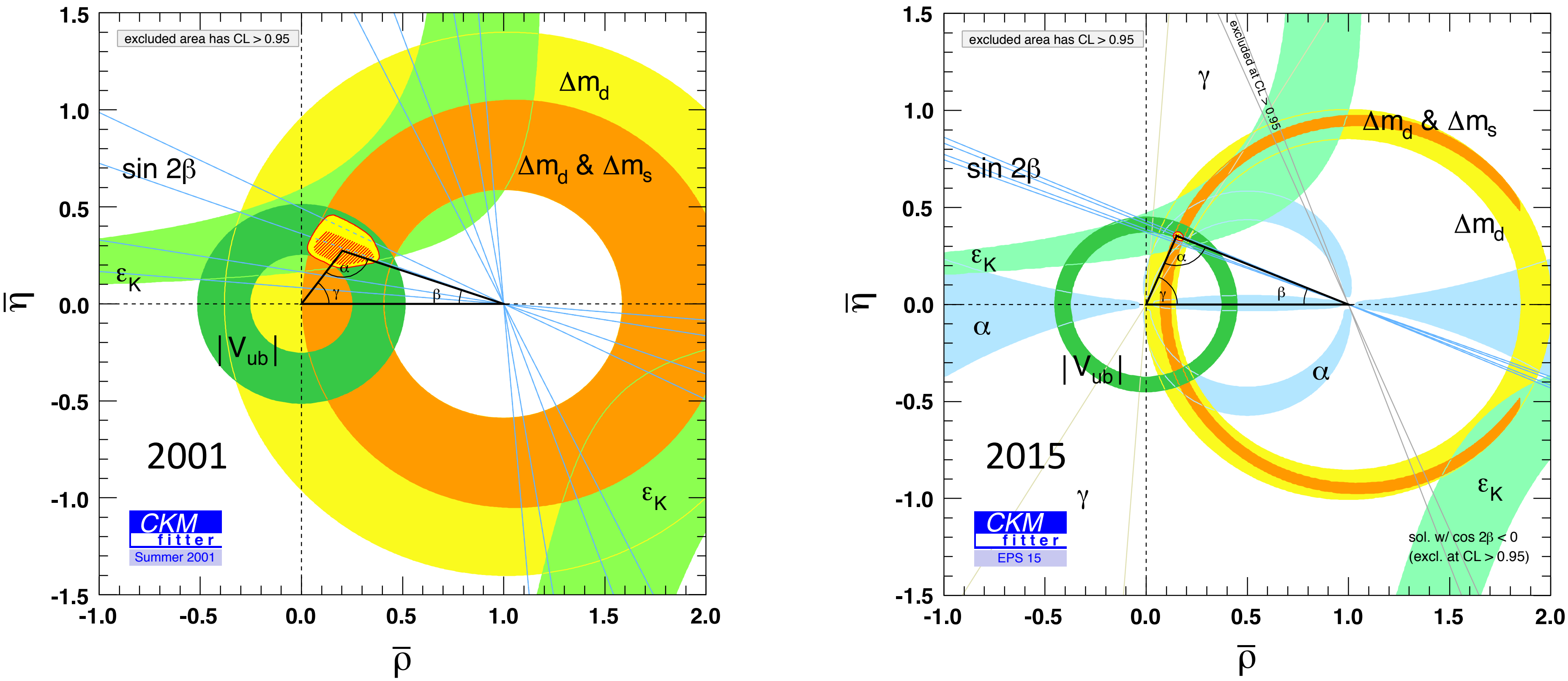
Non-charmonium channels with precise measured CP asymmetries



Channels sensitive to $\sin(2\beta_{eff})$

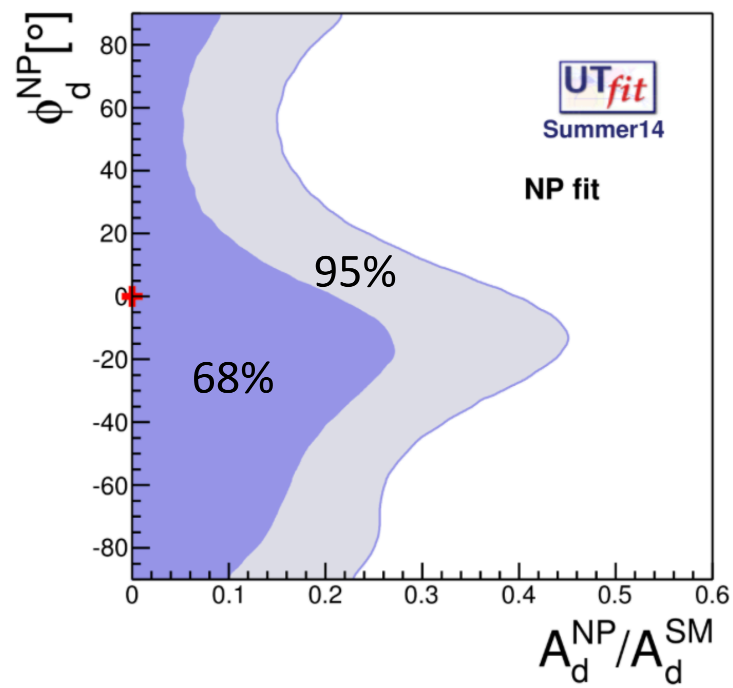
CKM unitarity – then and now

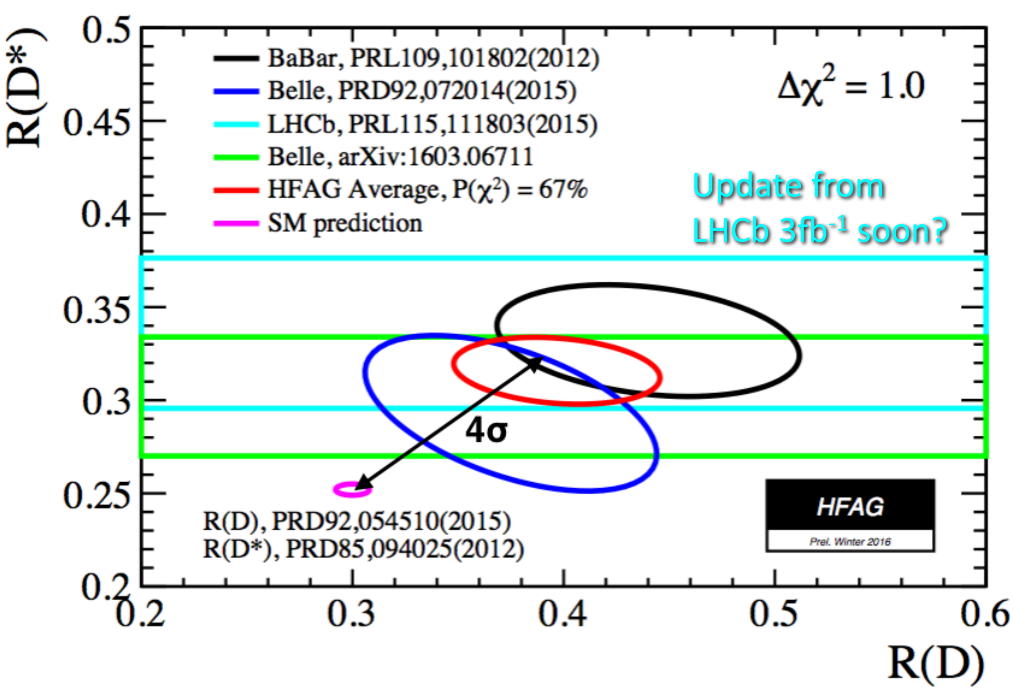
- Comprehensive measurements of CP asymmetries, oscillations and $|V_{ub}/V_{cb}|$ overconstrained unitarity triangle and established CKM picture
- Precision measurements are sensitive to deviations from BSM physics



(Some) Unresolved questions

- CKM picture established, but bounds on NP still weak: e.g., NP amplitude in |ΔB=2| transitions can be ~20% for arbitrary phases



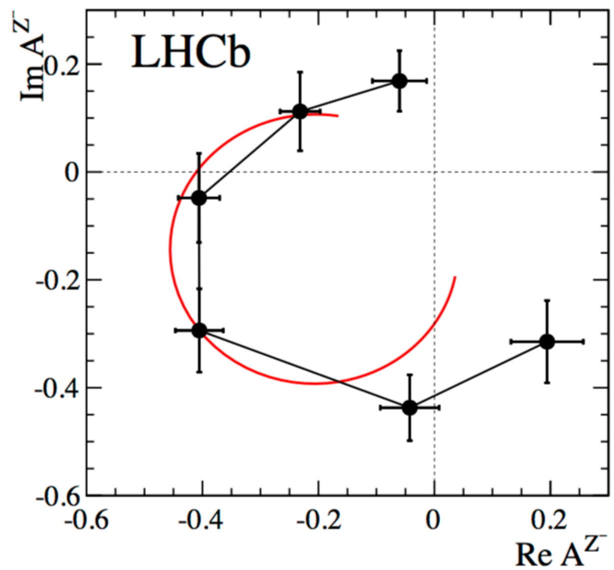


- BaBar, Belle and LHCb all see enhanced rates for decays into $D^{(*)}\tau\nu$ final states
- All measurements exceed SM

Exotic hadrons

- Belle discovered charmonium-like X(3872) → J/ψ $\pi^+\pi^-$ in 2003; first of many states that don't fit into qqq or $q\underline{q}$ spectrum
- $Z(4430)^-$ → ψ' π^- discovered by Belle in 2007; clearly exotic and, as LHCb shows, clearly resonant
- Pentaquark ($qqqq\underline{q}$) established in J/ψ p by LHCb in 2015
- Spurred lots of theoretical activity: n-quark states, meson molecules, etc.
- Nothing here breaks QCD, but it's fun to see that nature is not "confined" to the simplest structures

Argand diagram for $Z^-(4430)$: $m^2(\psi'\pi^-)$ increases counterclockwise

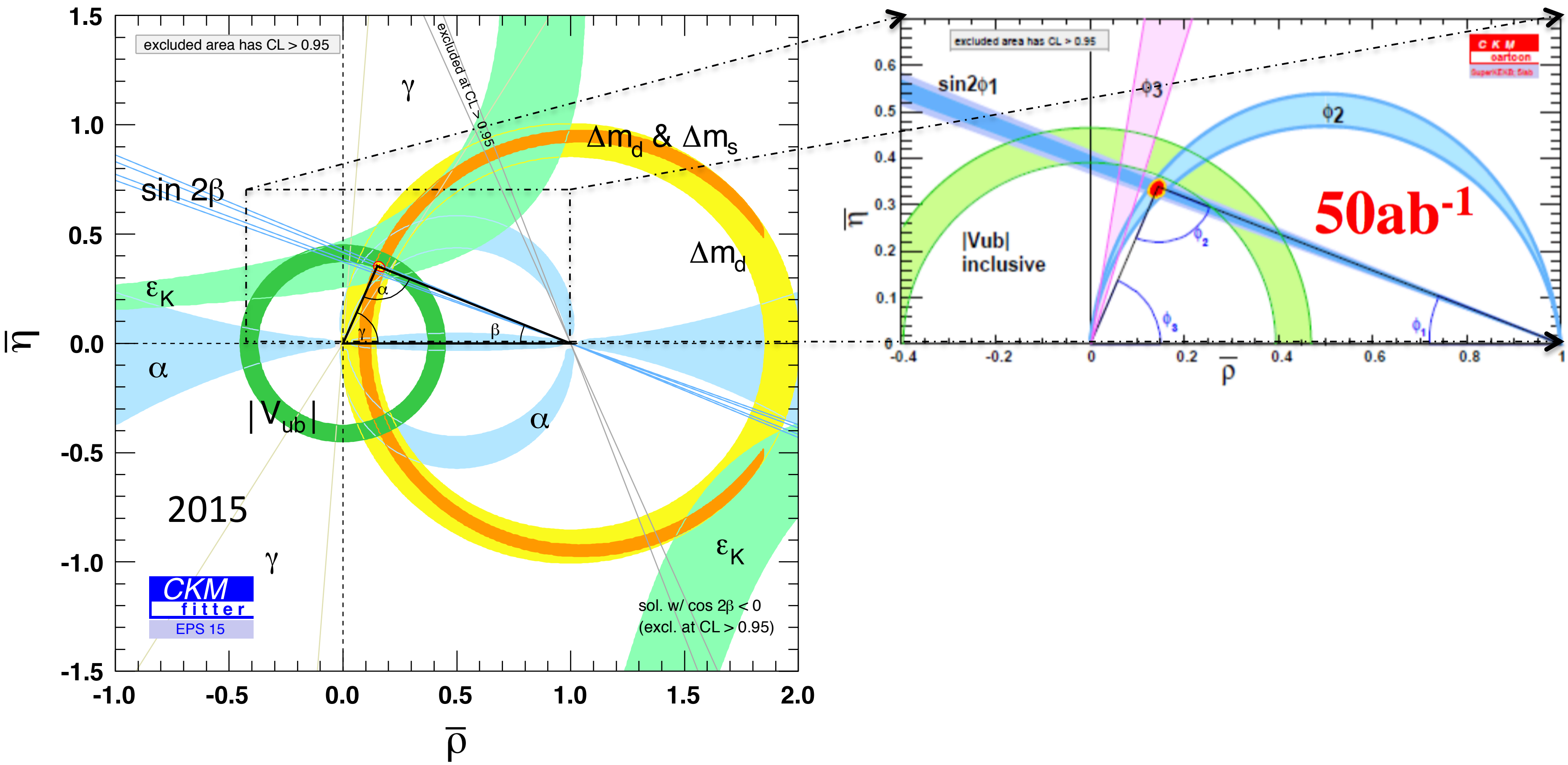


Physics goals for Belle II

- Belle II and LHCb are complementary: where they measure the same quantities, systematic uncertainties are different; each has unique capabilities
- In contrast to the initial B factories, where the motivation was to measure CPV in the $B_d\underline{B}_d$ meson system, the motivations for Belle II are more democratic:
  - CPV asymmetries, Unitarity Triangle constraints
  - B – FCNC decays ($b \to s/d\ l^+l^-$, $s/d\ \nu\underline{\nu}$)
  - B decays to 3rd-generation leptons (e.g. $D^{(*)}\tau\nu$)
  - τ – LFV in τ decays
  - DM – Dark forces
  - c – D mixing, CPV
  - EW – precision EW ($\sin^2\theta_W$)
  - …

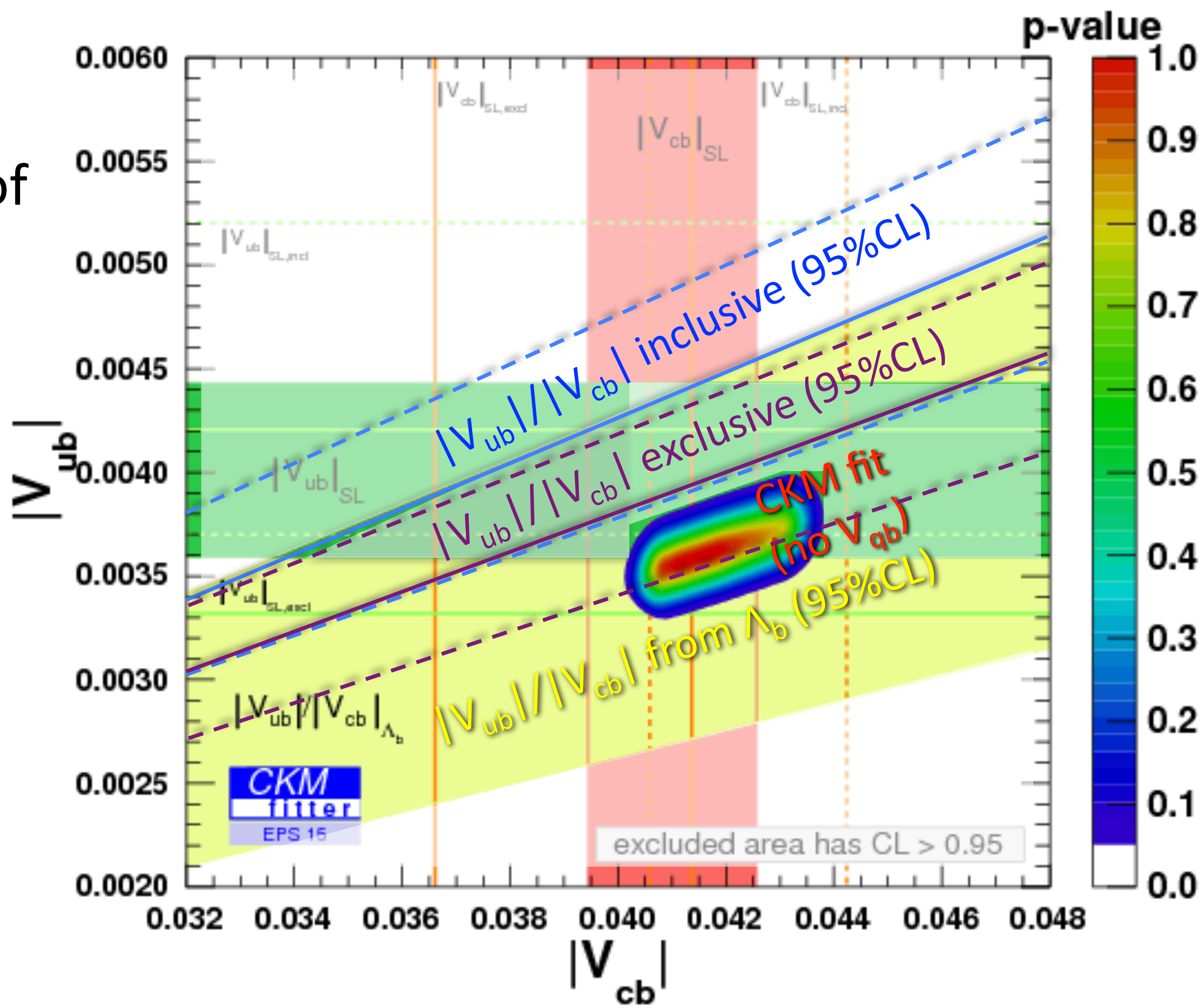
CKM unitarity – now and then

- Projected improvement in measurements of sides, angles



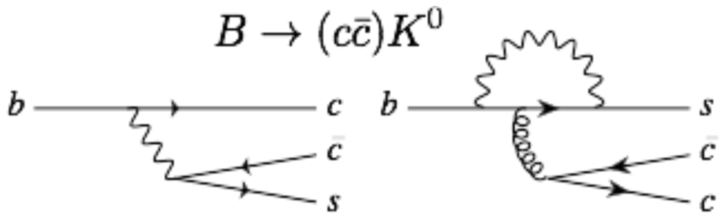
$|V_{qb}|$ – what gives?

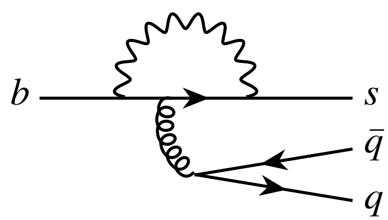
- Diagonal bands show $|V_{ub}/V_{cb}|$ from three sets of measurements:
  Incl: 0.107±0.006
  Excl: 0.095±0.005
  Λ_b: 0.083±0.006
- Ellipse is from CKM fit based on other inputs
- Needs to be sorted out



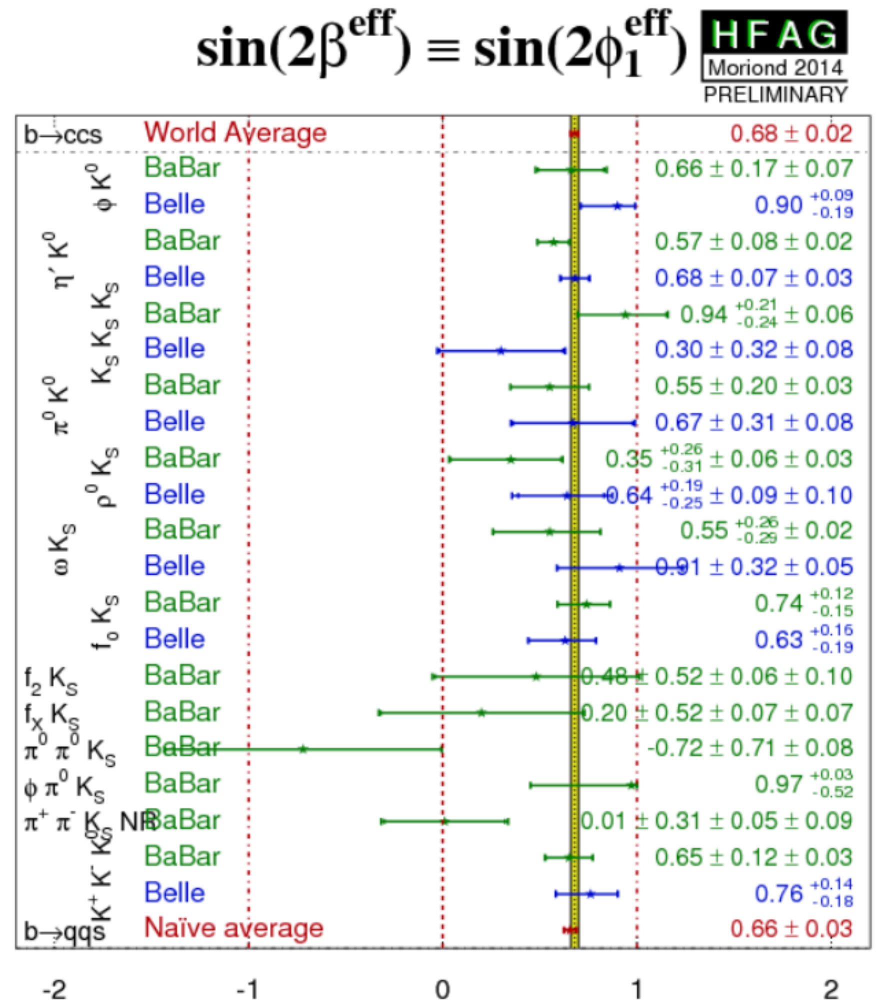
Compare CPV in tree and penguin modes

- CP asymmetry ~same for b→c$\underline{c}$s and b→s$\underline{s}$s in SM; not for NP



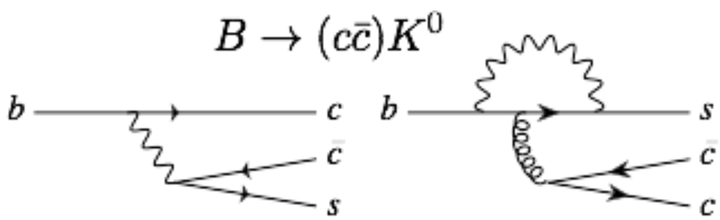


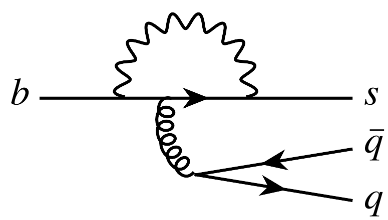
Belle and BaBar results →



Compare CPV in tree and penguin modes

- CP asymmetry ~same for b→ccs and b→sss in SM; not for NP





Belle II sensitivity on selected modes

$$B \to \eta' K^0$$

Error on sin(2β)	tot.
B-Factories	9.4%
Belle II 5/ab	4.2%
Belle II 50/ab	**1.6%**

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

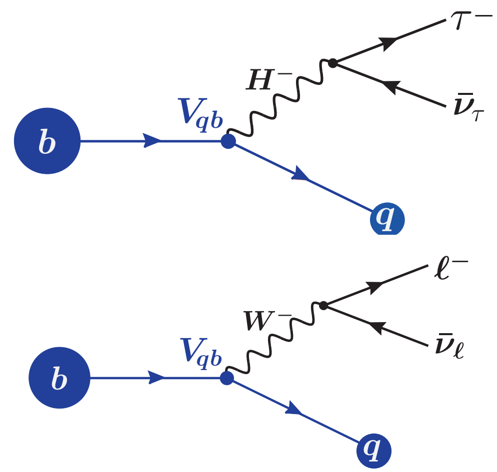
Error on sin(2β)	tot.
B-Factories	17.8%
Belle II 5/ab	7.9%
Belle II 50/ab	**2.7%**

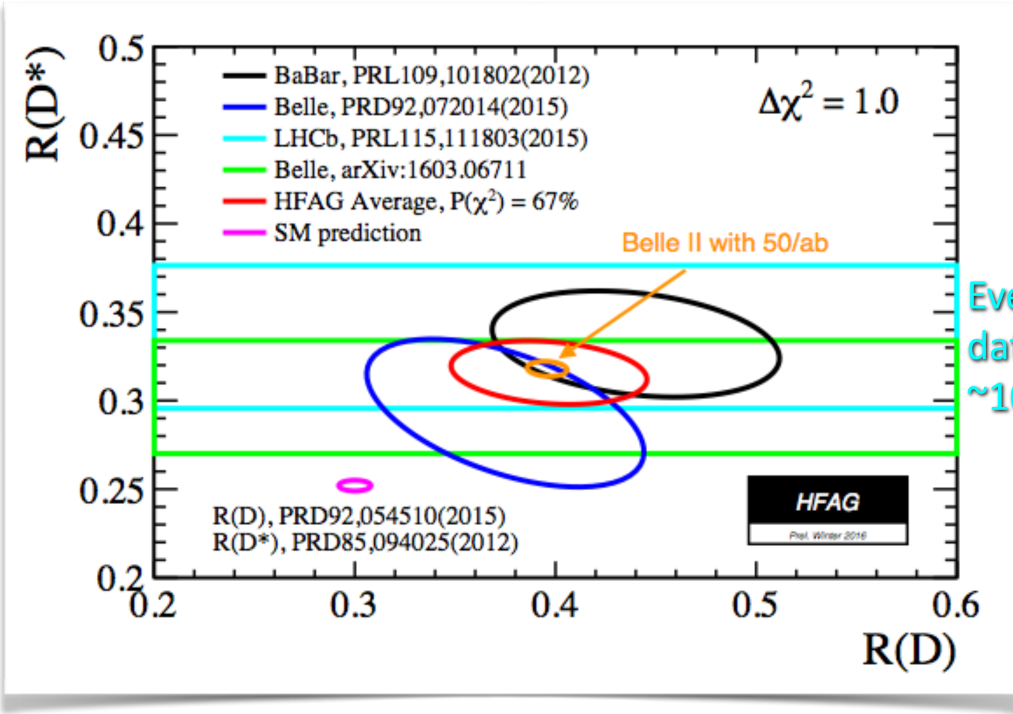
$$B \to K^0 K^0 K^0$$

Error on sin(2β)	tot.
B-Factories	33.9%
Belle II 5/ab	15.1%
Belle II 50/ab	**4.9%**

Decays to 3rd-generation leptons

- Semi-tauonic decays sensitive to, e.g., charged Higgs
- Ratio of SM decays $R(D^{(*)}) = \Gamma(B \to D^{(*)}\tau\nu)/\Gamma(B \to D^{(*)}l\nu)$ ($l=e,\mu$) well predicted (dependence on efficiencies, FFs largely cancel)
- Also measure $R(\pi)$, $R(D^{**})$…





Eventual LHCb dataset will be ~10x current

$R(D)$

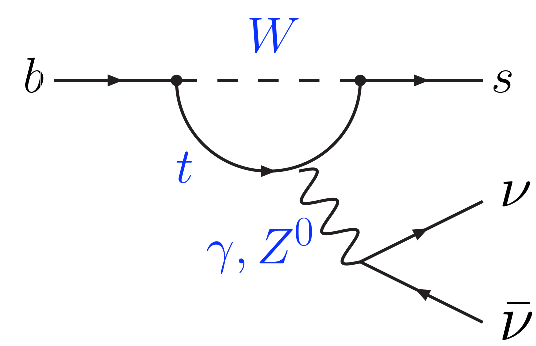
Error	stat.	tot.
B-Factories	13%	16.2%
Belle II 5/ab	3.8%	5.6%
Belle II 50/ab	1.2%	**3.4%**

$R(D^*)$

Error	stat.	tot.
B-Factories	7.1%	9.0%
Belle II 5/ab	2.1%	3.2%
Belle II 50/ab	0.7%	**2.1%**

Radiative decays $b \to s\nu\underline{\nu}$

- Theoretically clean – no FSI (unlike $b \to s l^+ l^-$)
- Sensitivity unique to e^+e^- environment



had. tagged

$B^0 \to K_S \nu\bar{\nu}$ SM ~ 2.2 x 10^{-6}

Error	stat.
B-Factories	590%
Belle II 5/ab	220%
Belle II 50/ab	**94%**

$B^0 \to K^{*0} \nu\bar{\nu}$ SM ~ 9.5 x 10^{-6}

Error	stat.
B-Factories	112%
Belle II 5/ab	42%
Belle II 50/ab	**22%**

$B^+ \to K^+ \nu\bar{\nu}$ SM ~ 4.7 x 10^{-6}

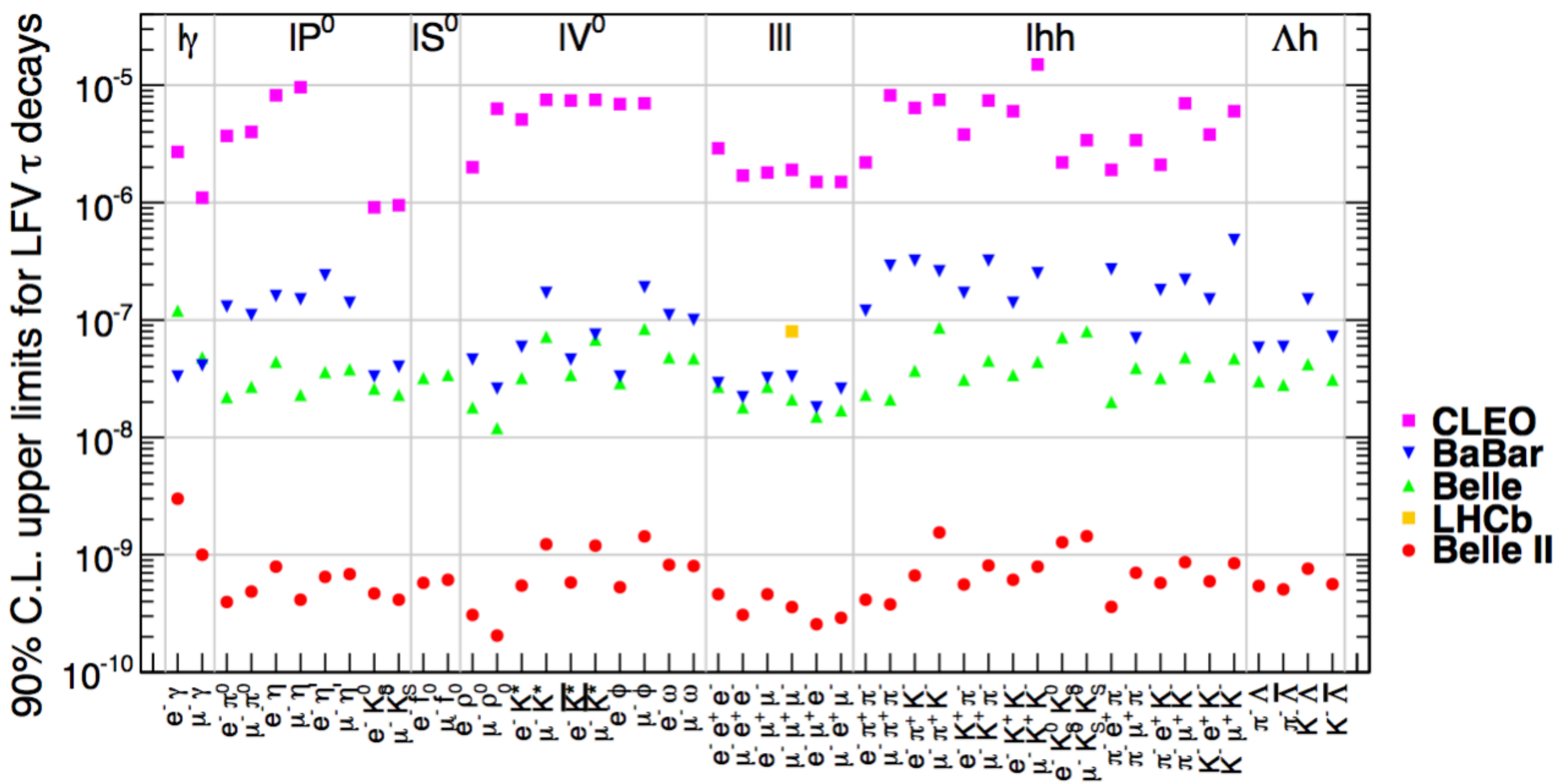
Error	stat.
B-Factories	130%
Belle II 5/ab	49%
Belle II 50/ab	**22%**

$B^+ \to K^{*+} \nu\bar{\nu}$ SM ~ 10.2 x 10^{-6}

Error	stat.
B-Factories	120%
Belle II 5/ab	45%
Belle II 50/ab	**22%**

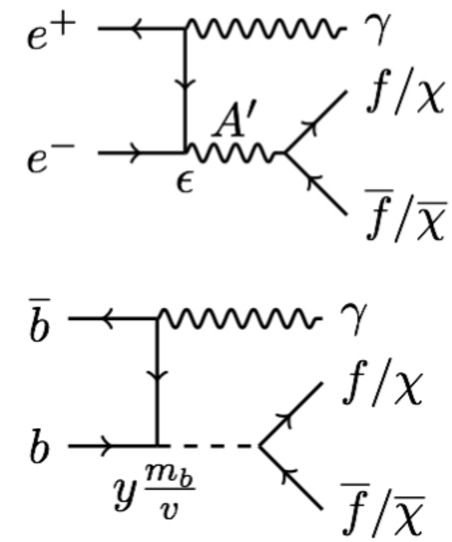
τ lepton flavour violation

- Excellent environment to search for LFV in a large range of final states
- Belle II sensitivity will probe NP models

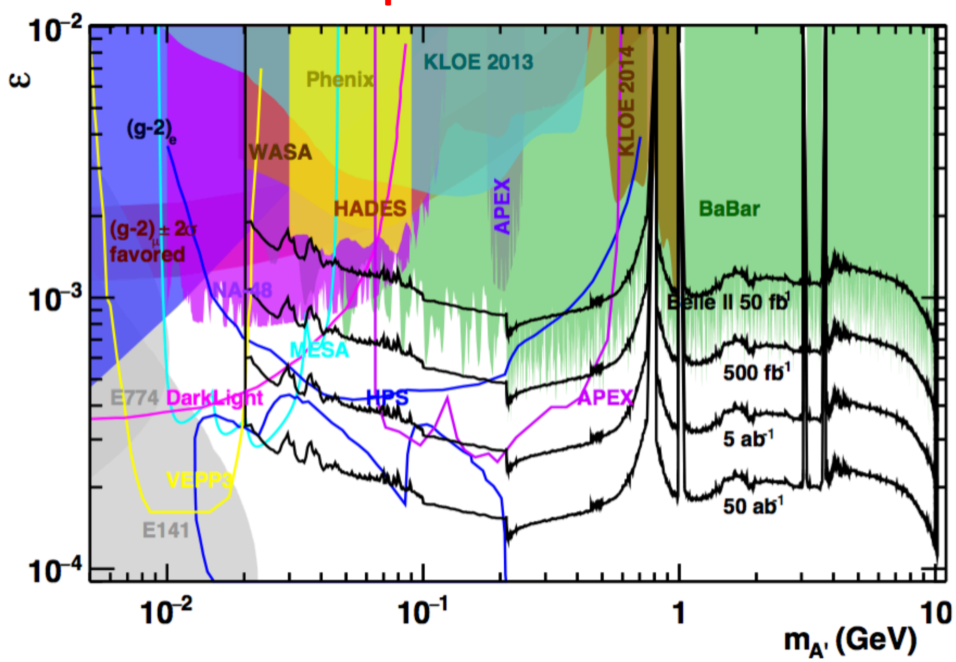


Dark forces

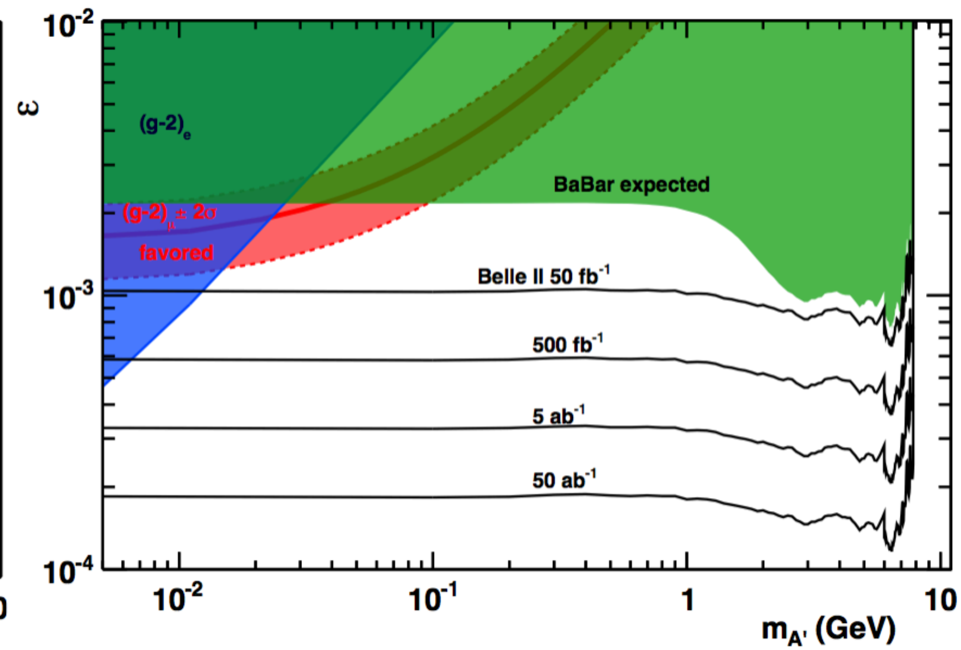
- Belle II has good sensitivity to new mediators with mass in the 0.01-10 GeV range in both dilepton and invisible final states via dedicated single photon trigger



Dilepton final state



invisible final state



The main improvement: luminosity

- The necessary step in sensitivity requires a large increase in luminosity: $2.1\times10^{34} \rightarrow 80\times10^{34}$
- Use nano-beams (idea borrowed from SuperB)

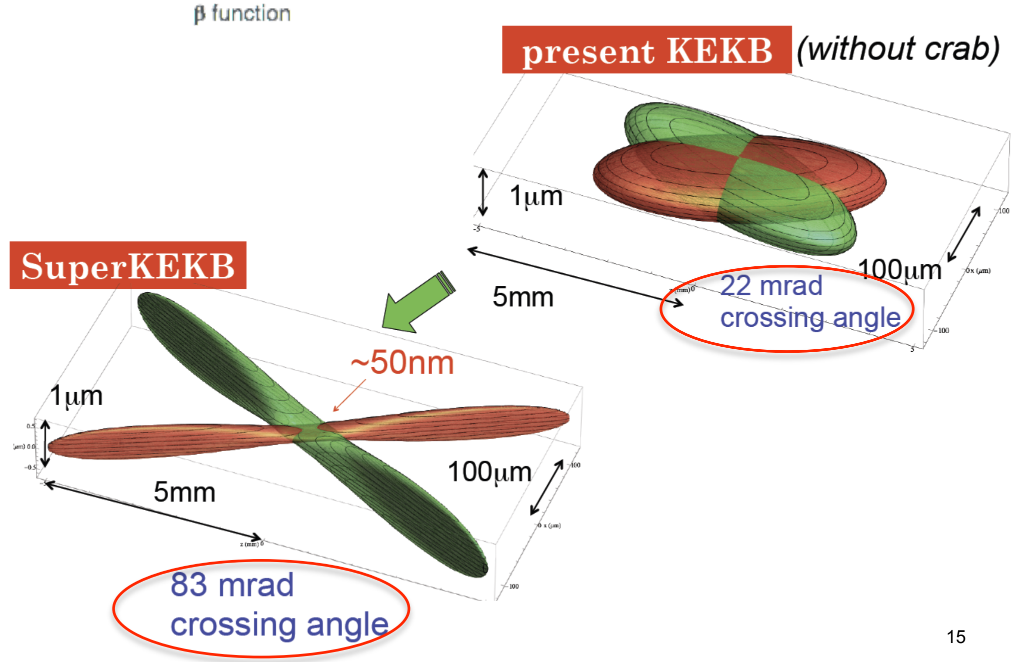
LER/HER	KEKB	SuperKEKB
Energy [GeV]	3.5/8	4.0/7.0
β_y^* [mm]	5.9/5.9	0.27/0.30
β_x^* [mm]	1200	32/35
I [A]	1.64/1.19	3.6/2.6
ε [nm]	18/24	3.2/4.6
# bunch	1584	2500
L [10^{34}cm^{-2}s^{-1}]	2.1	80

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \zeta_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Lorentz factor; beam current; beam-beam parameter; beam size aspect ratio; vertical β function; geometric factors

$$\zeta_{\pm y} \sim \sqrt{\beta^*/\epsilon}$$

emittance; β function



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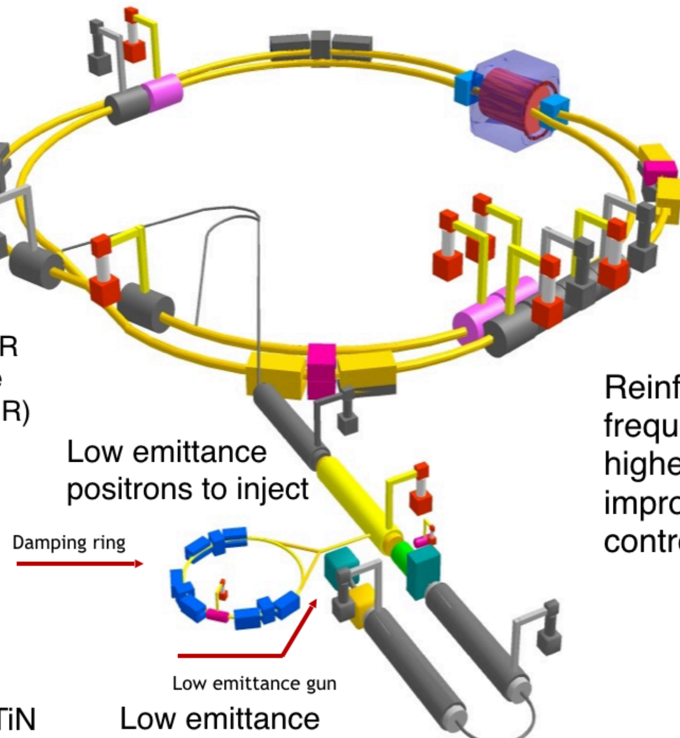
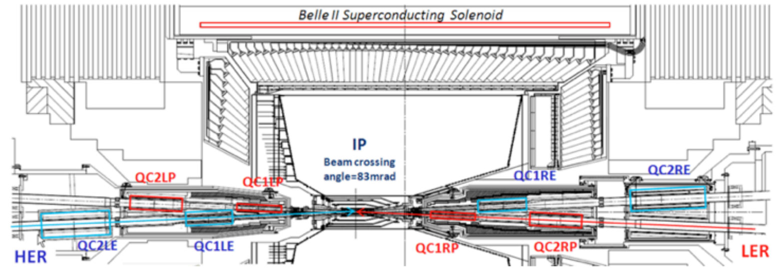
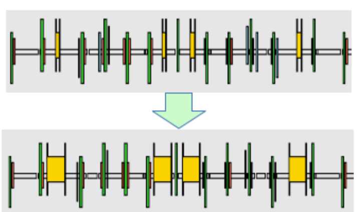
SuperKEKB accelerator

New superconducting final focusing magnets near the IP





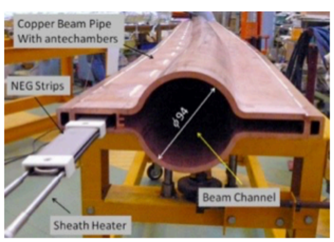
Redesign the lattices of HER & LER to squeeze the emittance. Replace short dipoles with longer ones (LER)



Low emittance positrons to inject

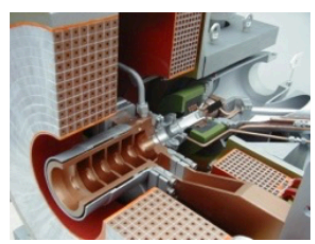
Reinforced RF (radio frequency) system for higher beam currents, improved monitoring & control system

Replaced old beam pipes with TiN coated beam pipes with antechambers



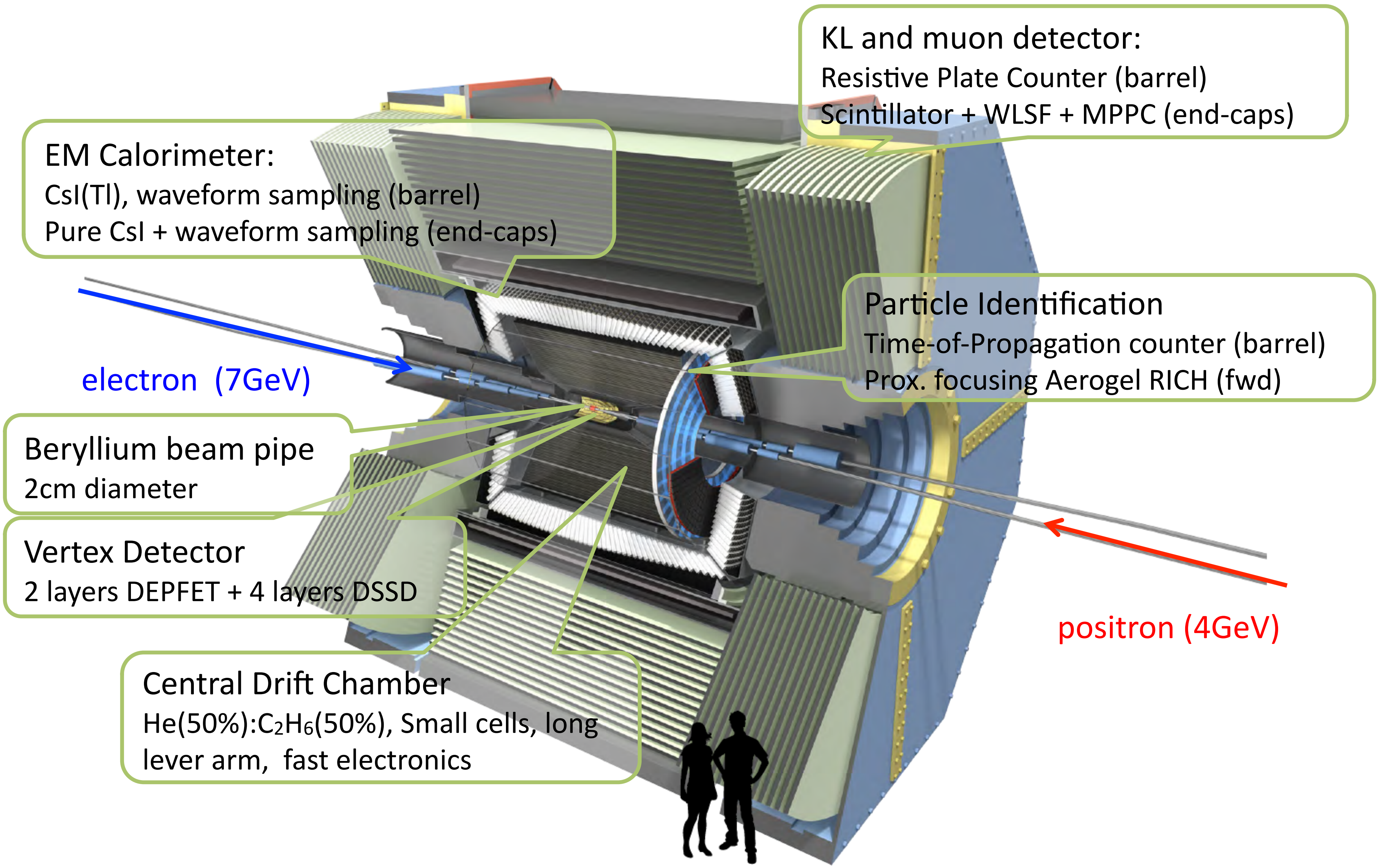
Low emittance electrons to inject

Upgrade positron capture section



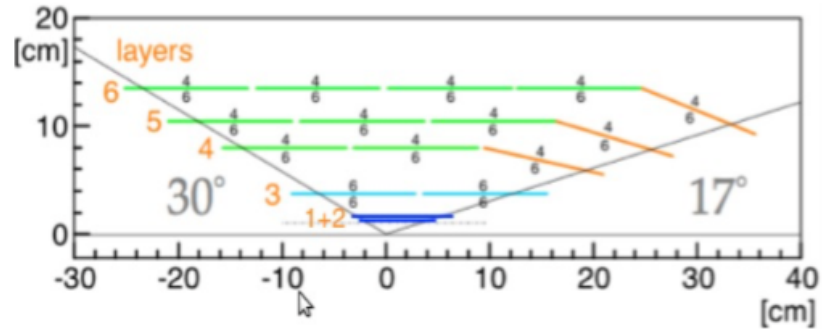
Slide from Florian Bernlochner

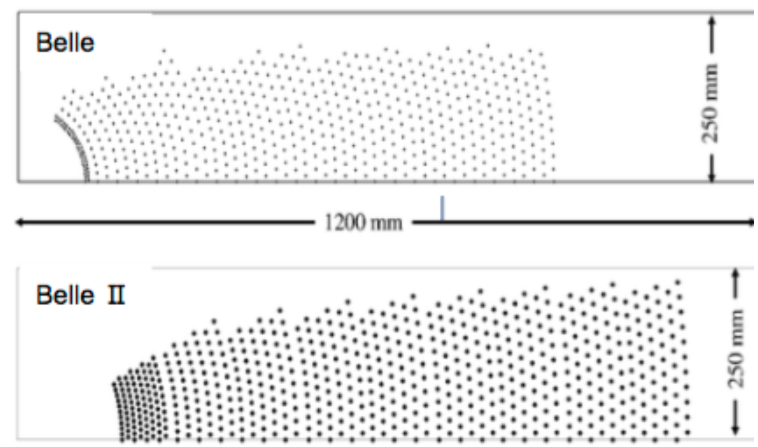
Belle II Detector Overview



Belle II enhancements

- Smaller beampipe,
  - Si pixel layer at 1.4cm; excellent z impact parameter resolution (20μm)
- Larger SVD and CDC
  - better Ks efficiency, impact parameter, flavor tagging
- TOP and ARICH
  - better K/π separation in both barrel and endcap
- ECL and KLM
  - Upgrades to deal with larger beam background, pileup
- Improved hermiticity, trigger, DAQ

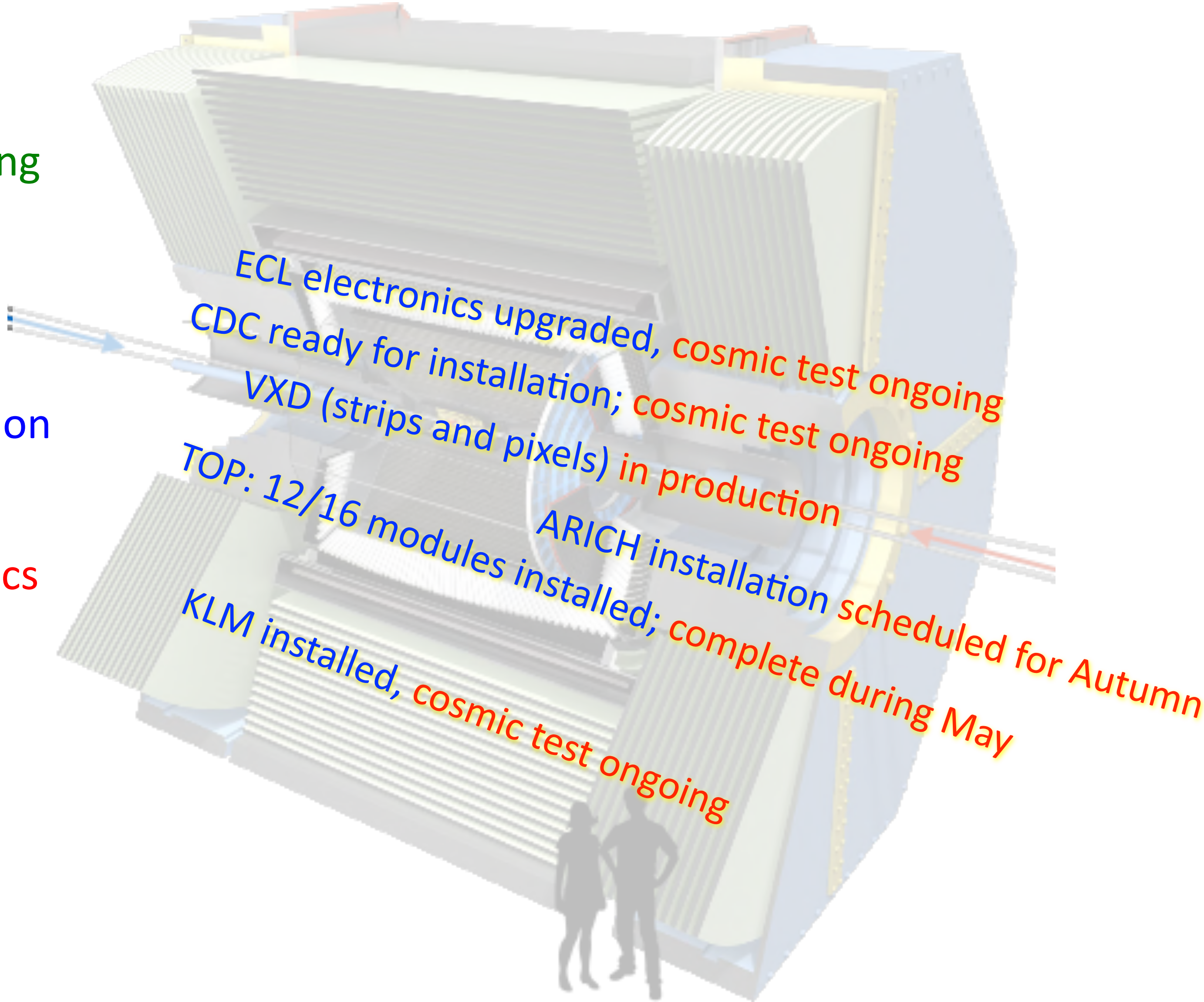




	Belle PID (%)	Belle II PID (%)
Ave. K efficiency	88	94
π fake rate	9	4

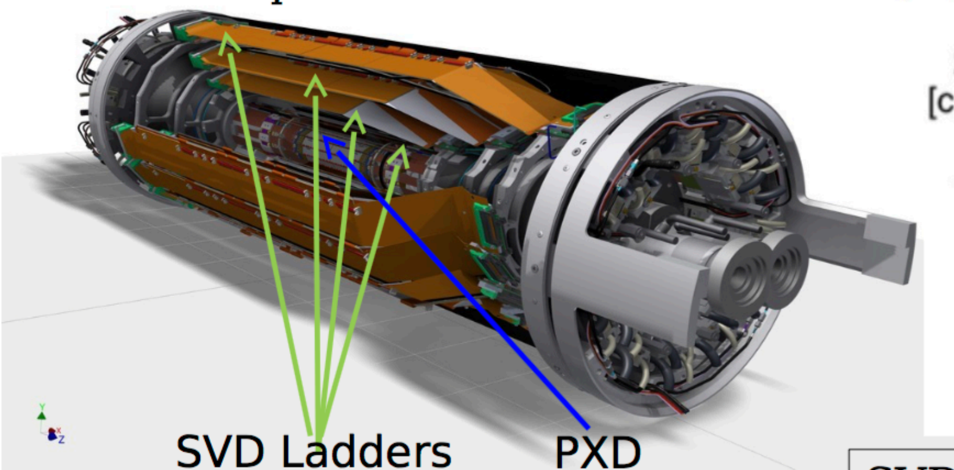
Belle II construction status

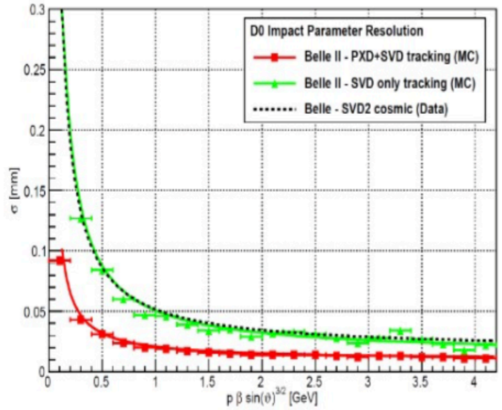
- On schedule
- Commissioning with beam in 2017 (except VXD)
- VXD installation in 2018
- Start of physics late 2018

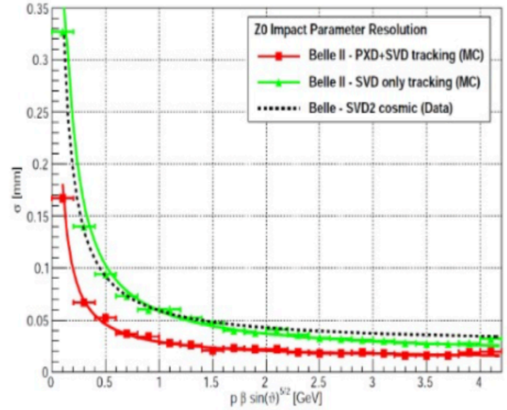


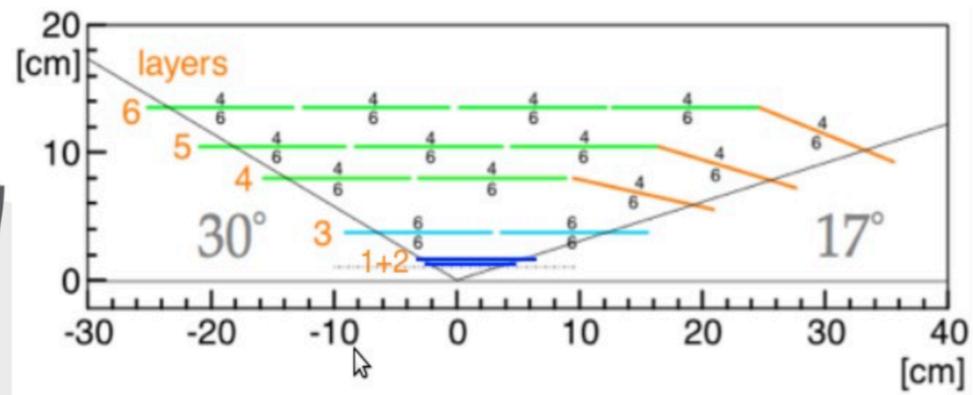
Belle II: Vertex detector (VXD)

- VXD = silicon vertex detector (SVD) + pixel detector (PXD)
- Provides precise measurement of the primary and secondary vertices of short-lived particles
- VXD under production









PXD:
- 2 layers of DEPFET pixels
- Inner most layer very close to IP (r = 1.4cm)
- Very low material budget
- Excellent spatial granularity (σ ≤15μm)

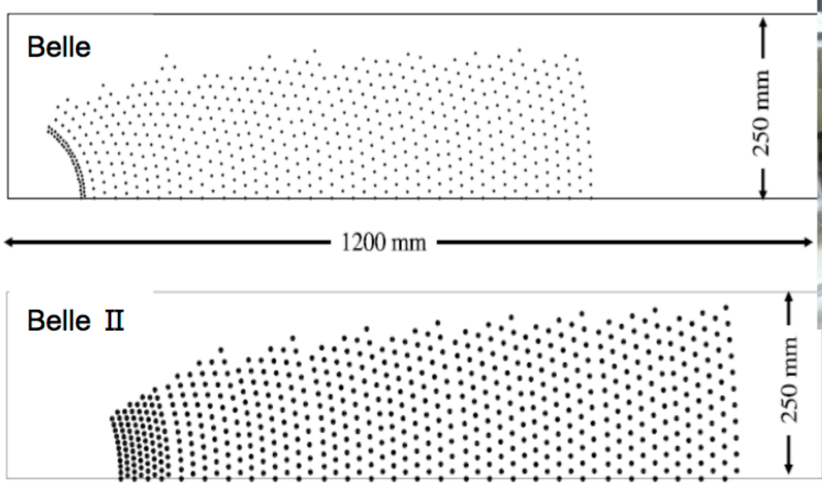
SVD:
- 4 layers of DSSD detectors
- Excellent timing resolution (σ ~ 2-3 ns)
- Low material budget
- Larger outer radius (6.05 cm → 14 cm)
- Inner radius: 3.8cm
- covers the full Belle II angular acceptance of 17° < θ < 150°

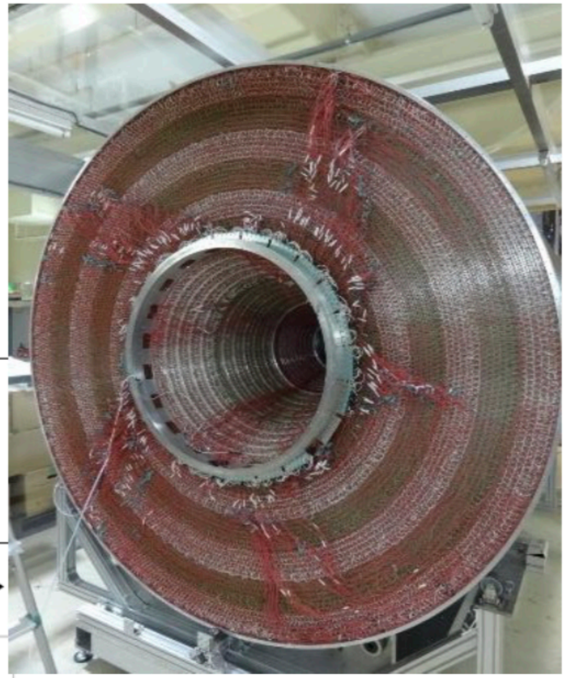
Belle II: CDC

- Belle II CDC is larger than Belle CDC
- Smaller drift cells with sense wires and more layers allow better charged track reconstruction and dE/dx measurement compared to Belle
- Faster readout electronics
- Ready for Installation
- Cosmic ray test ongoing

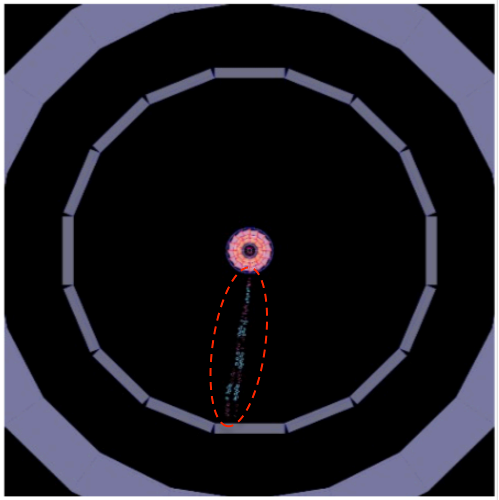
	Belle	Belle-II
Radius of inner boundary (mm)	88	168
Radius of outer boundary (mm)	863	1111
Number of layers	50	56
Number of total sense wires	8400	14336
Gas	He-C_2H_6	He-C_2H_6
Diameter of sense wire (mm)	30	30

Wire Configuration

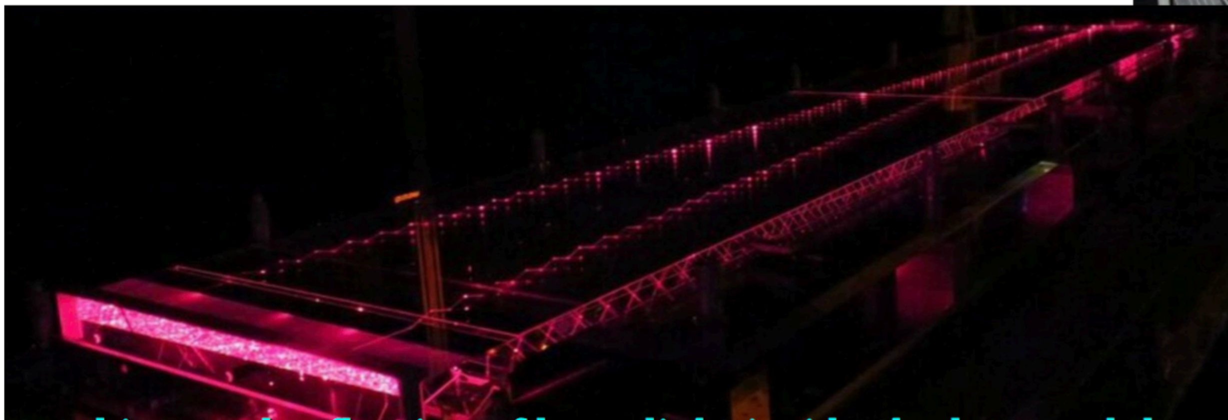




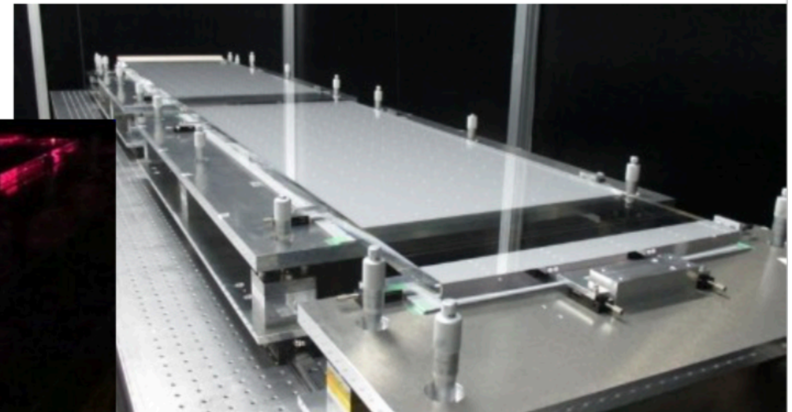
Event display



Particle ID: TOP (Barrel)



total internal reflection of laser light inside the last module



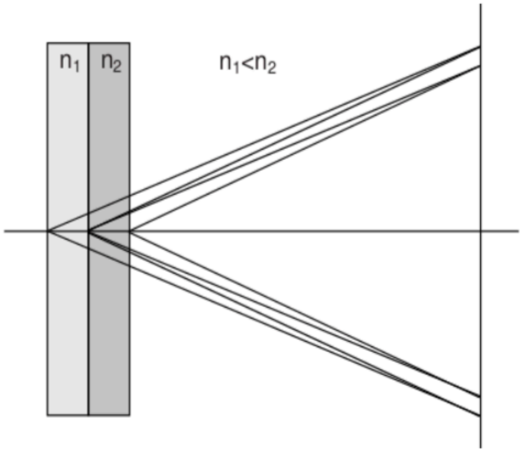
Modules of size: 20mm x 0.45 m x 2.7m

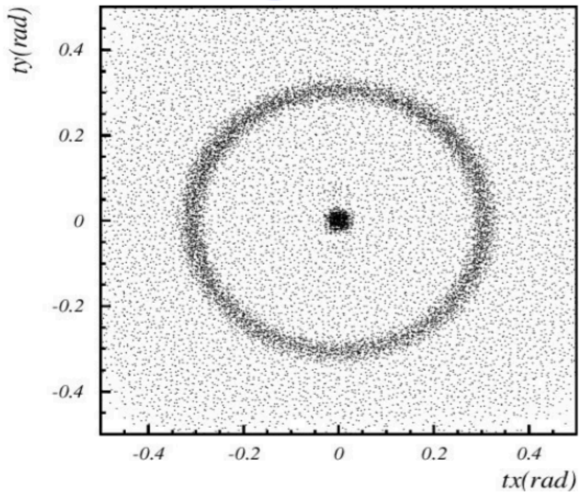
Comparison between Belle II PID (simulation) and Belle PID

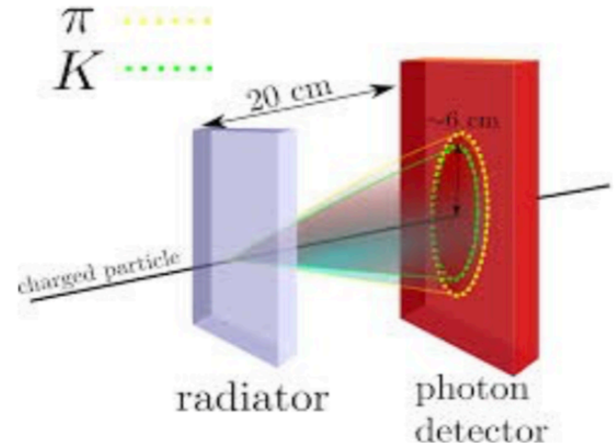
	Belle PID (%)	Belle II PID (%)
Ave. K efficiency	88	94
π fake rate	9	4

- TOP used for particle identification in Barrel region covering whole range of momentum.
- Cherenkov photons internally reflected inside the quartz radiator were measured as Cherenkov image reconstructed from the 3-D information (x, y, time) by pixelated MCP-PMTs (Micro-Channel Plate Photo-Multiplier Tubes) having excellent time resolution.
- Each module consists of two quartz bars, array of photo detectors, focussing mirror and prism.
- 12/16 have been Installed in barrel region. All modules are glued. Complete Installation in May.
- Commissioning of all 16 modules ongoing.

Particle ID: Aerogel RICH (Forward Endcap)

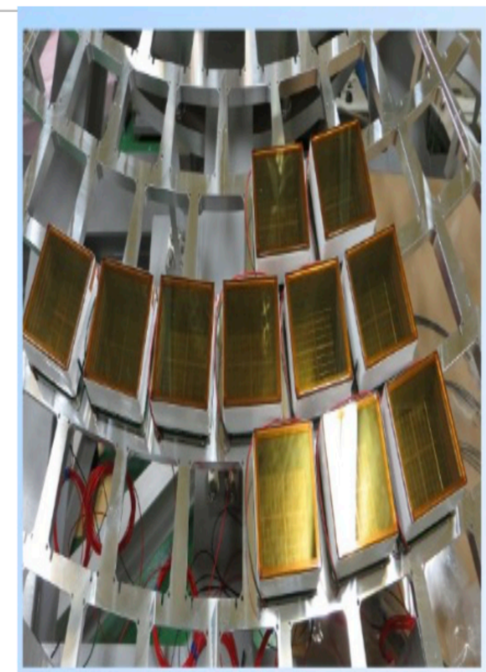






Two 2cm thick aerogel layers with $n_1 = 1.045$, $n_2 = 1.055$

- ARICH Identifies particle covering full momentum in the forward endcap.
- Two layers of aerogel lead to better photon yield without affecting resolution.
- 420 Hybrid Avalanche Photo Detectors (HAPD), 144 channels each.
- The beam test results and simulations show excellent KID efficiency at a low π misID.
- Successful magnetic field test. Installation in Autumn.



Belle II: ECL

Upgrade from Belle → Belle II to compensate larger background in Belle II

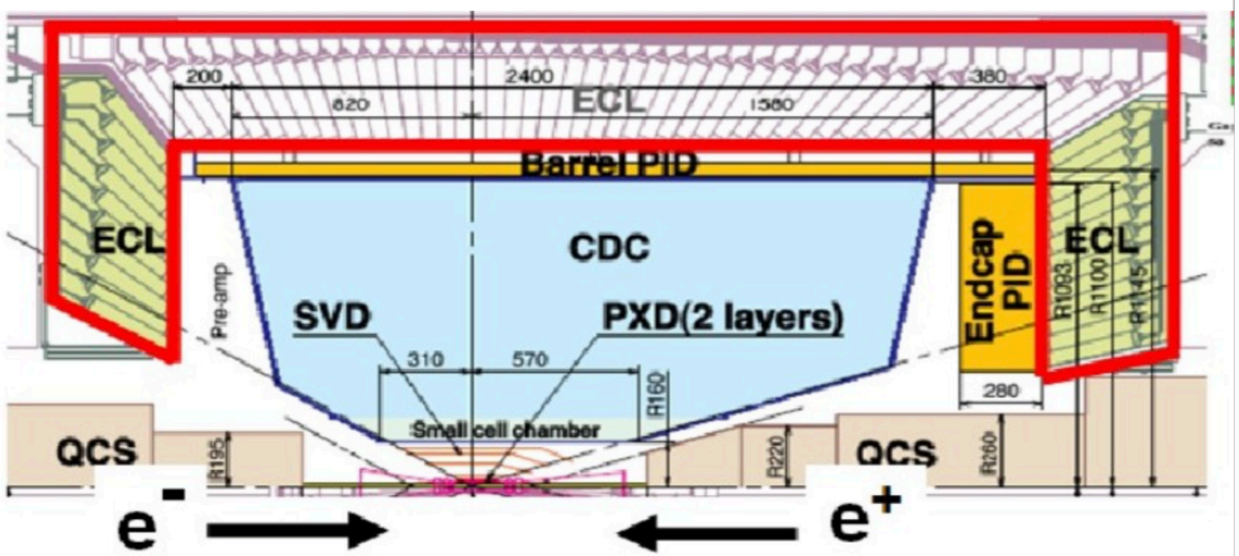
- Barrel and Endcap ECL: Reusage of Belle CSI (TI) crystal calorimeter with improved back-end readout electronics having better waveform sampling to compensate larger beam related background.
- Barrel ECL already installed.
- Cosmic test on going.

Belle II ECL trigger efficiency (simulation) compared to Belle ECL efficiency

Physics trigger: $E_{tot} > 1$ GeV

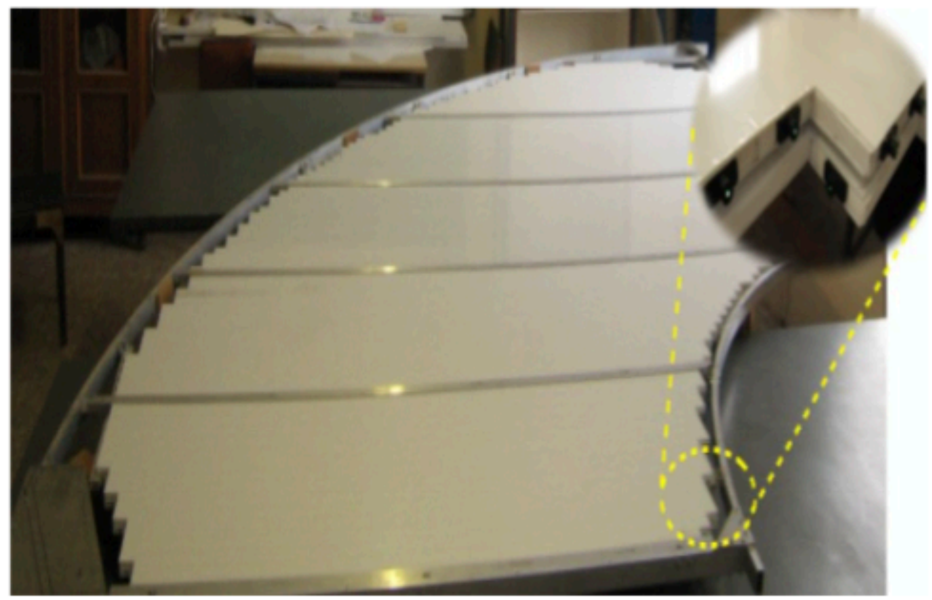
	ε_{phys} (total)	ε_{signal}	ε_{bkg}
Belle1	99.42%	88.70%	10.72%
Belle 2	99.90%	99.12%	0.78%

Statistic error ~ 0.06 %

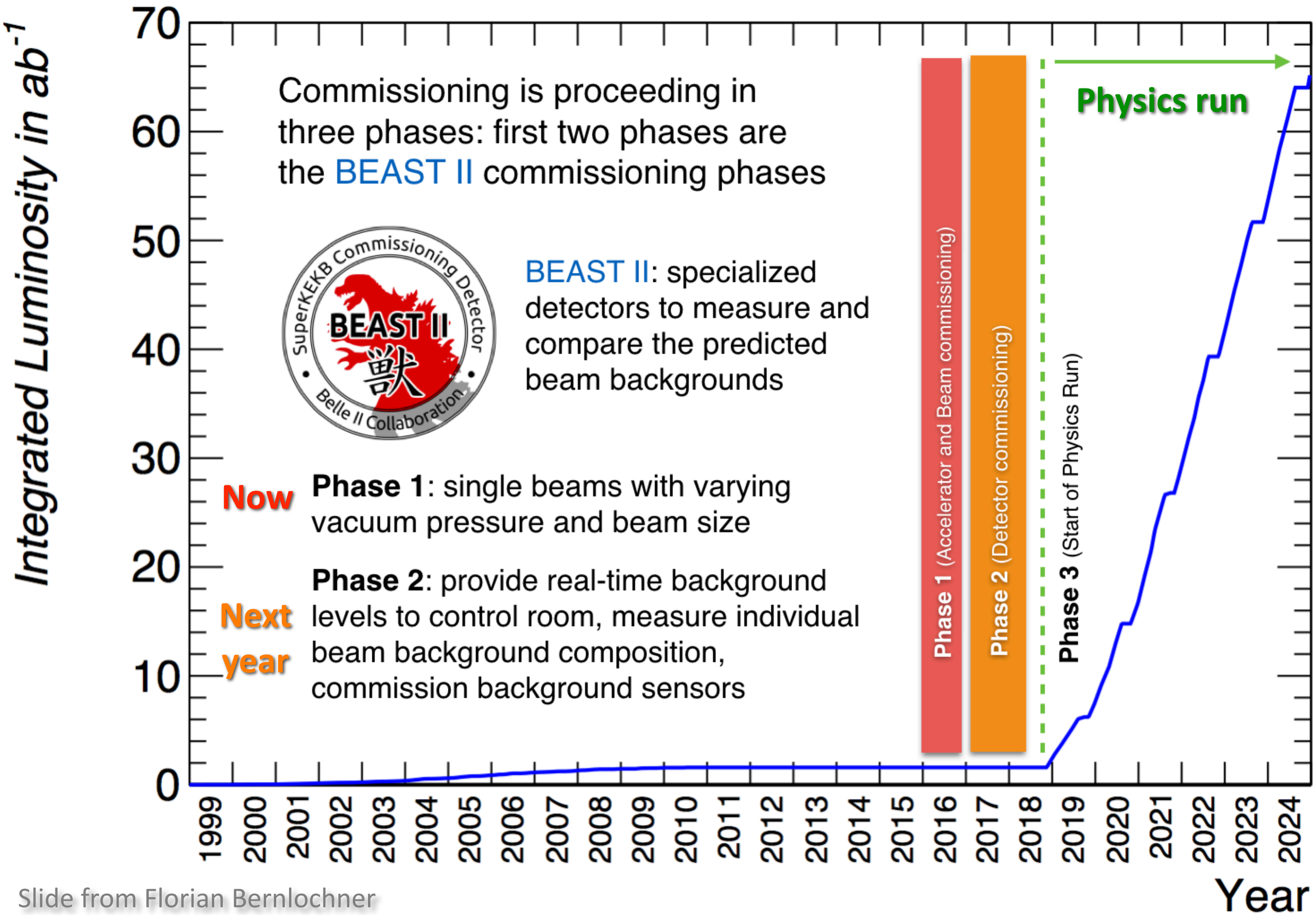


Belle II: KLM

- Due to expected high neutron background and to keep KLM efficiency, Endcaps and two innermost barrel RPC layers of Belle were replaced with scintillators
- Absorptive Iron plates, where KL can shower hadronically
- Installation completed in 2013 (barrel KLM) and 2014 (endcap KLM)
- Commissioning in progress with cosmic rays



Overall Belle-II schedule



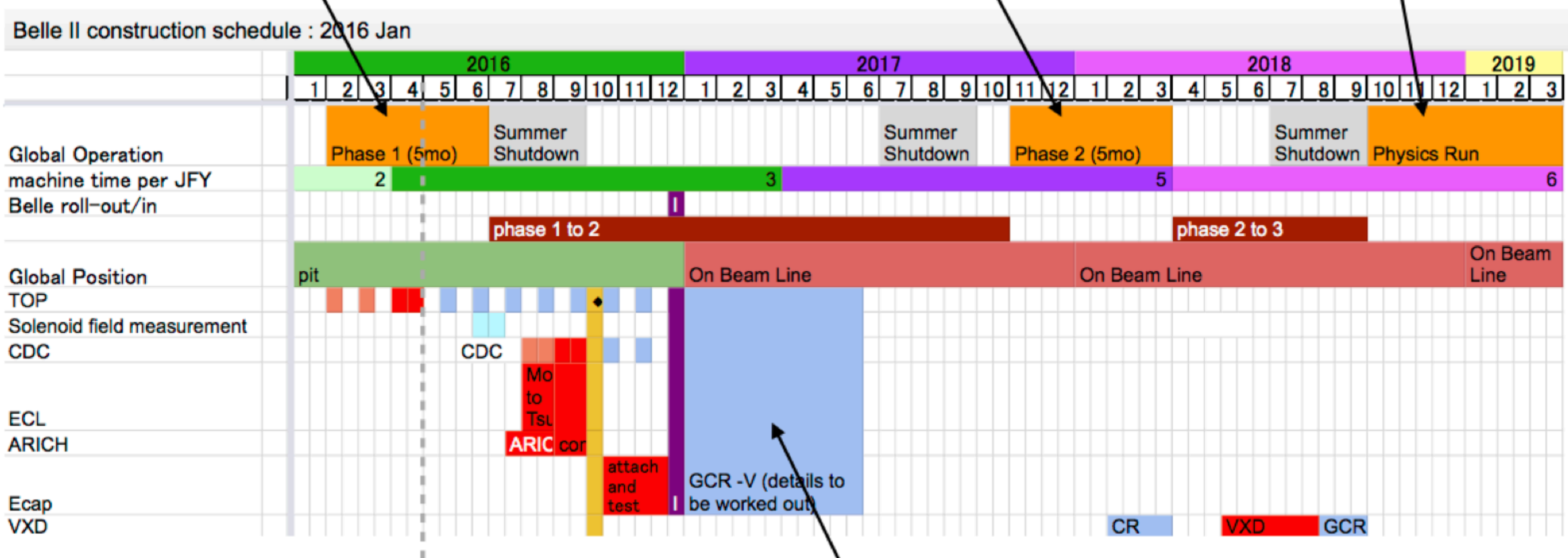
Slide from Florian Bernlochner

Schedule in more detail

Phase 1: single beams, commissioning detectors only (no Belle II)

Phase 2: colliding beams, Belle II except vertex detectors

Phase 3: physics, full detector



now

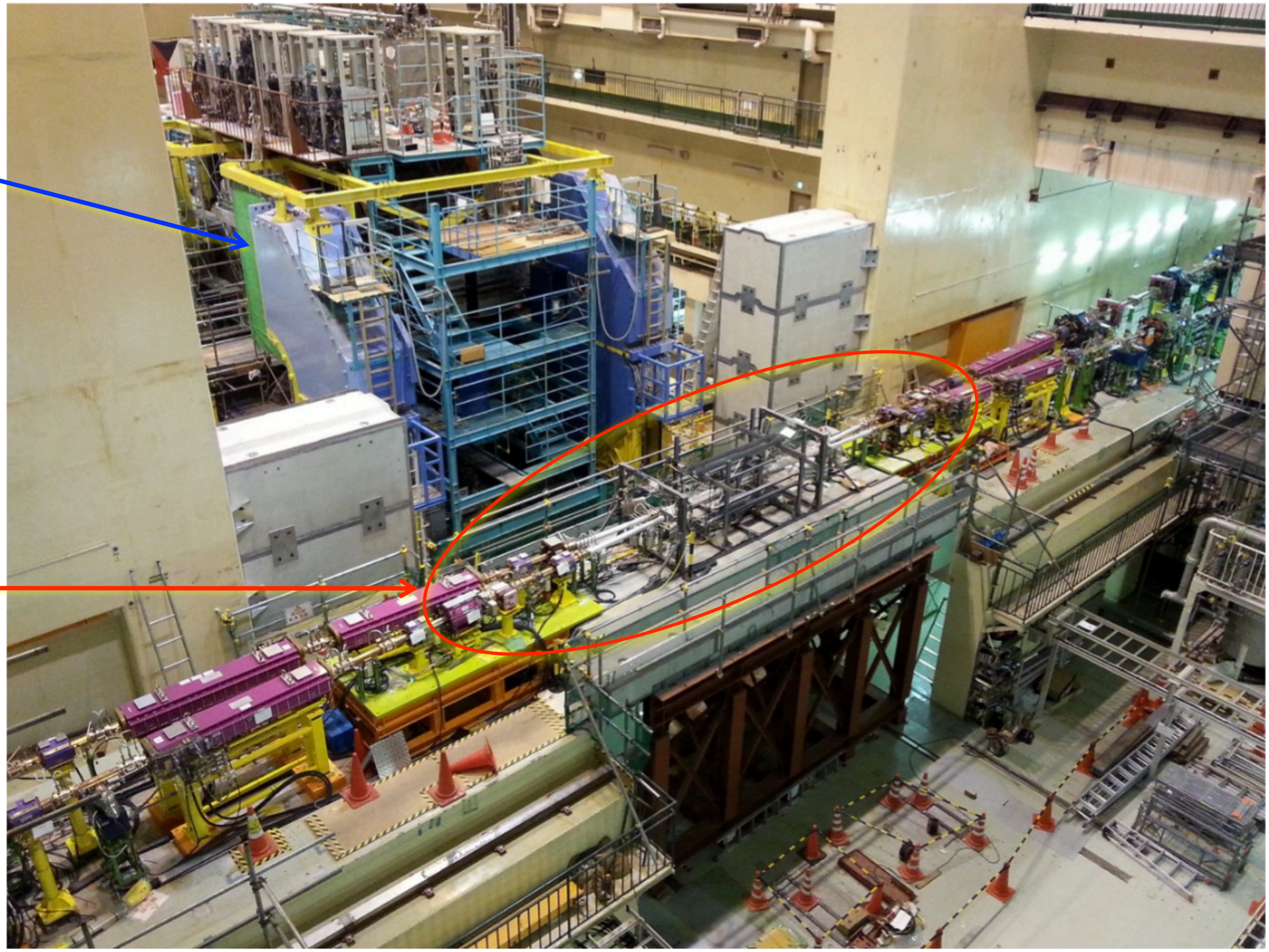
Global cosmic run (without vertex detectors)

- 0–20 fb^{-1} in Phase 2, 100–200 fb^{-1} in first physics run.

BEAST commissioning detector for Phase 1

Belle II – to be rolled into position for 2017

BEAST-II



Peter Kodys

BEAST II

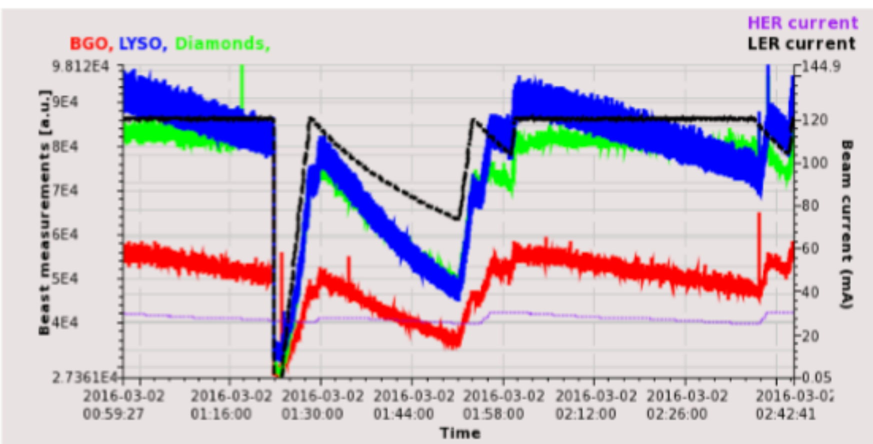
Beam **E**xorcism for a **S**table Experimen**T II**

- The higher luminosity comes with higher predicted backgrounds; BEAST II measures beam background to optimize shielding, validate simulation
- Background from Touschek (intra-beam) scattering, beam-gas, synchrotron radiation, radiative Bhabha, 2-photon processes
- Measurements underway (with both beams but no collisions)

BEAST II measurements

- Independent subdetectors provide comprehensive view of beam-related backgrounds
- UVic PhD student designed shielding for endcap EM Cal
- Current currents: LER 0.6A, HER 0.5A

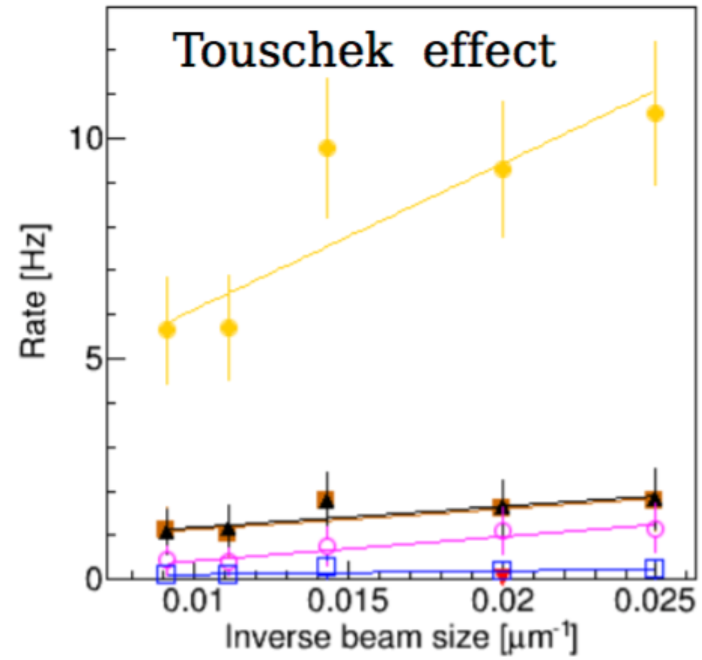
BEAST II Online monitor display

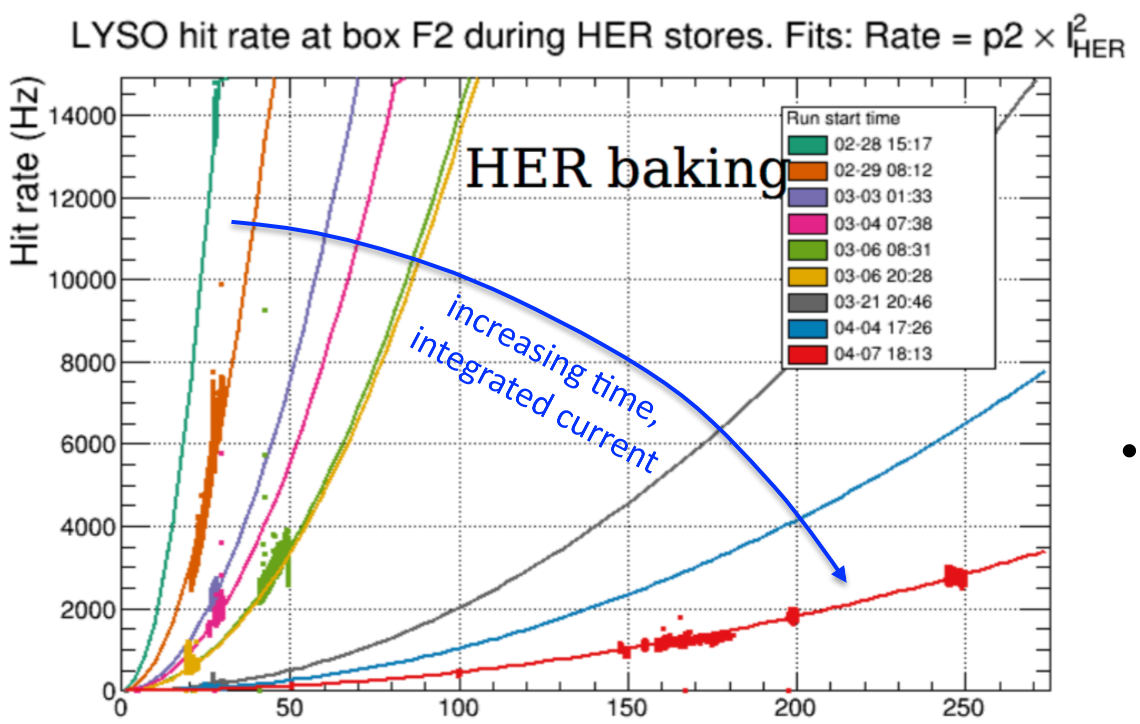


Systems	Number of Detectors Installed	Unique Measurement
"CLAWS" Scintillator	8	Injection backgrounds
Diamonds	4	ionizing radiation dose
PIN Diodes	64	Neutral vs charged radiation dose
BGO	8	luminosity
Crystals University of Victoria	6 CsI(Tl) 6 CsI 6 LYSO	EM energy spectrum
He-3 tubes University of Victoria	4	thermal neutron flux
Micro-TPCs	2	fast neutron flux

More BEAST II data

- Touschek (particle loss due to multiple Coulomb scattering within a bunch) grows with inverse beam size (density); lost particles hit beam pipe (reduces beam lifetime)





Hit rate vs current seen on various days

- Bake-out of vacuum chamber proceeding as expected

Summary

- Belle II can access a broad range of physics including B, charm, tau, precision EW and dark forces
- SuperKEKB is circulating e^+ and e^- beams; backgrounds are being measured by the dedicated BEAST II detectors
- Belle II construction is nearly complete; the detector rolls into position in 2017 (vertex detector to be installed in 2018)
- We're looking forward to probing new physics in friendly competition with LHCb