The Belle II Experiment: status and physics prospects

Steven Robertson
Institute of Particle Physics
& McGill University

On Behalf of the Belle II Collaboration

Kruger2018
December 3 - 7, 2018

INSTITUTE OF PARTICLE PHYSICS

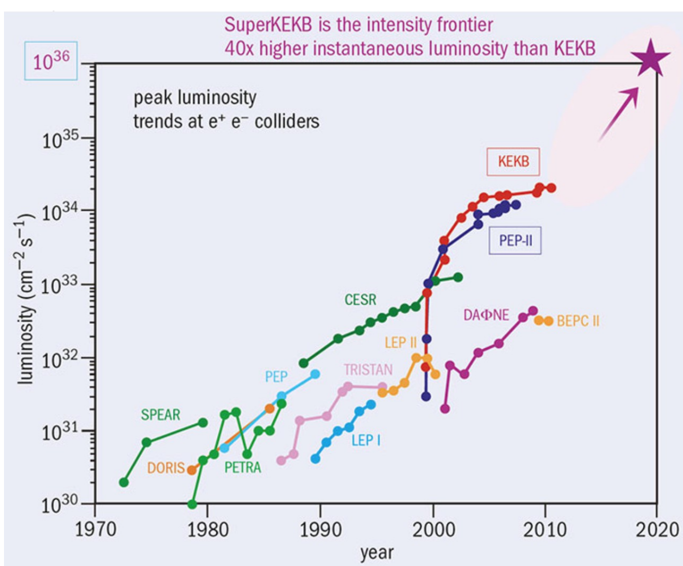
McGill

Belle II

Belle II is the successor of the Belle experiment at the KEK laboratory in Tsukuba, Japan

- Intensity frontier "Super B Factory" flavour physics experiment
- Target data set of ~30x the combined integrated luminosity of *BABAR* + Belle
- ~800 collaborators from 26 countries, including over 260 graduate students

First collisions achieved in 2018 during "Phase 2" accelerator commissioning run!



Outline:

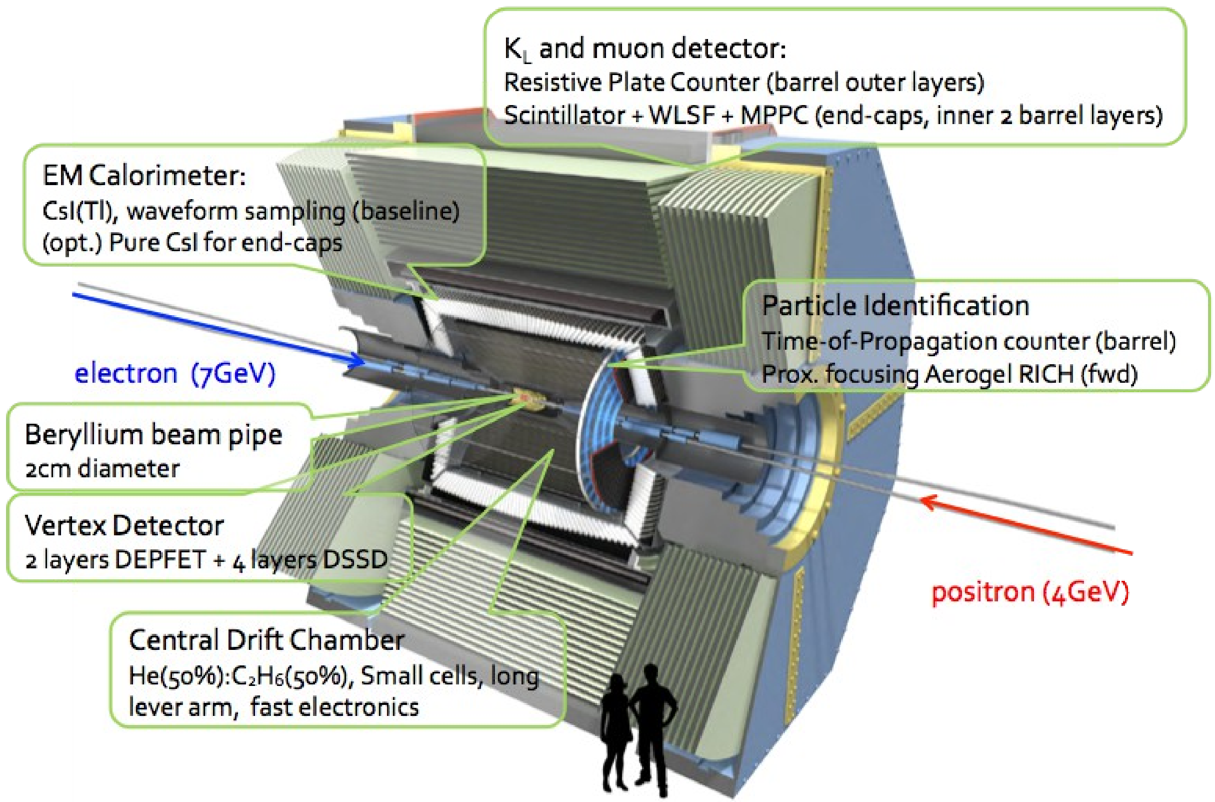
- SuperKEKB and Belle II
- Physics program
- Phase 2 commissioning results
- Future prospects

Belle II Detector

Anticipate ~40x increased instantaneous luminosity, and greatly increased beam background rates

Very substantial "upgrades" to the original Belle detector:

- Replacement of beam pipe and redesign of entire inner detector (including vertex detectors and drift chamber)
- New quartz-bar Time-of-Propagation PID in barrel region
- Retain existing CsI(TI) calorimeter crystals, but front-end electronics, feature extraction and reconstruction software entirely new
- Entirely new software framework and distributed computing environment

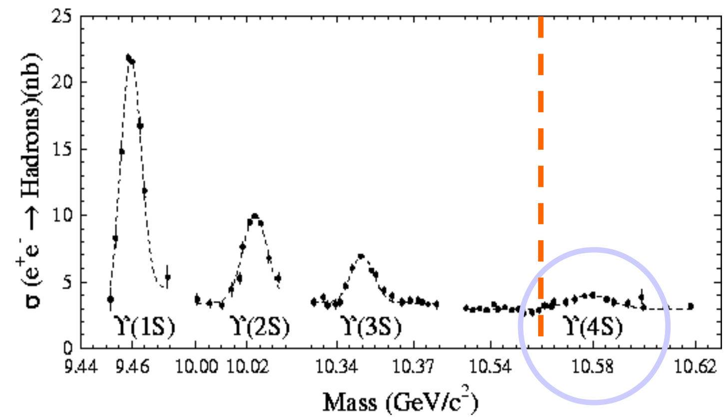


What's so "Super"?

e^+e^- collisions provide a very rich data set and a clean analysis environment

"Inclusive" hadronic and low multiplicity datasets are key features:

- Target data sample has a cross section of ~ 5 – 10 nb



8 x10^{35} $cm^{-2}s^{-1}$ luminosity yields ~5 kHz of "interesting" physics events

- O(1 kHz) of $B\bar{B}$ events
- ~30 kHz Bhabhas within detector acceptance
  - Level 1 trigger rejection essential!
  - Probability of multiple collisions per bunch crossing (aka "pileup"): <0.02%

Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

50 ab^{-1} integrated luminosity implies ~55 billion $B\bar{B}$ pairs in target data sample

- Analysis sensitivity in B, τ and charm to O(10^{-9}) branching fractions

Belle II Physics Program

Objective of the BABAR and Belle experiments was to validate the Kobayashi-Maskawa mechanism for CP violation within the SM

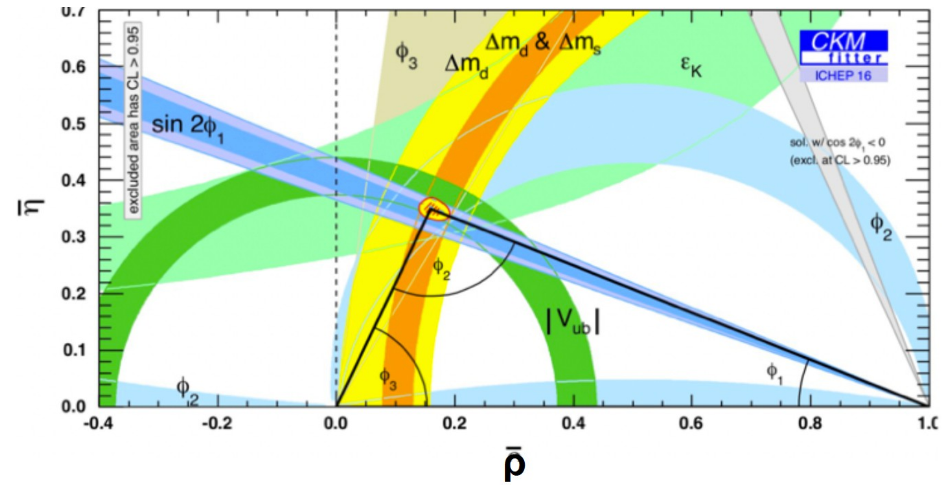
- i.e. demonstrated that measurements were consistent with CKM "Unitarity Triangle" expectations

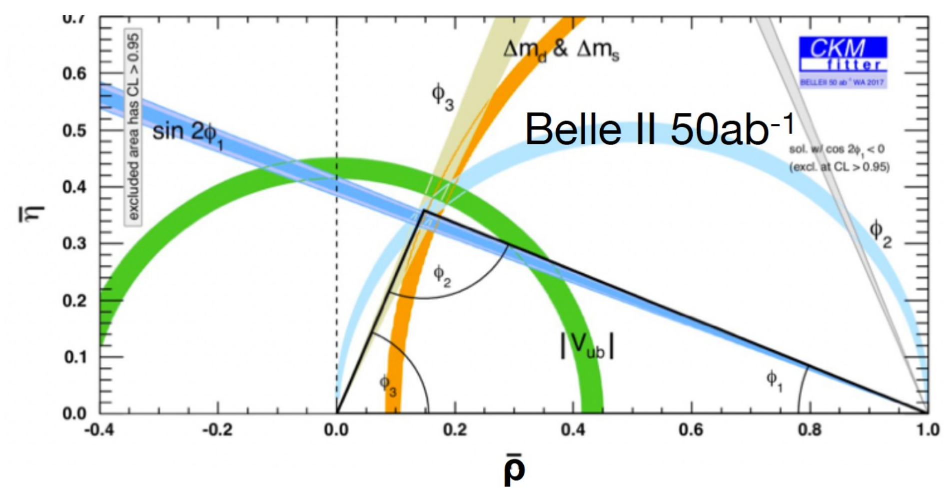
Belle II will look for deviations from this picture to provide evidence of beyond SM physics

- Compare precise measurements with (equally precise) theoretical predictions

$$V_{\mathrm{CKM}} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\,e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\,e^{-i\beta} & -|V_{ts}|\,e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

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

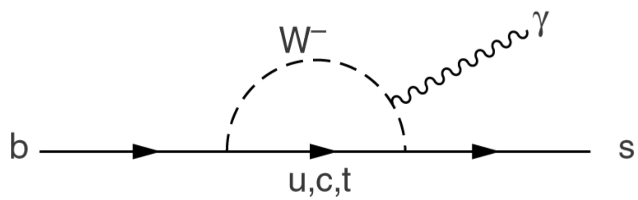




Very broad program of research spanning B, charm and τ physics, but also QED/QCD, quarkonium, light new physics direct searches etc.

Electroweak FCNCs

$B \rightarrow X_{s/d}\,\gamma$



C_7 (Photon penguin)

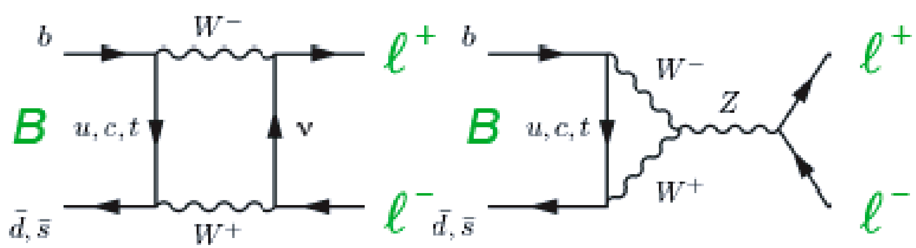
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)$$

Products of field operators (non-perturbative hadronic matrix elements; Heavy quark expansion in inverse powers of m_b)

Wilson coefficients (calculated perturbatively; encode short-distance physics)

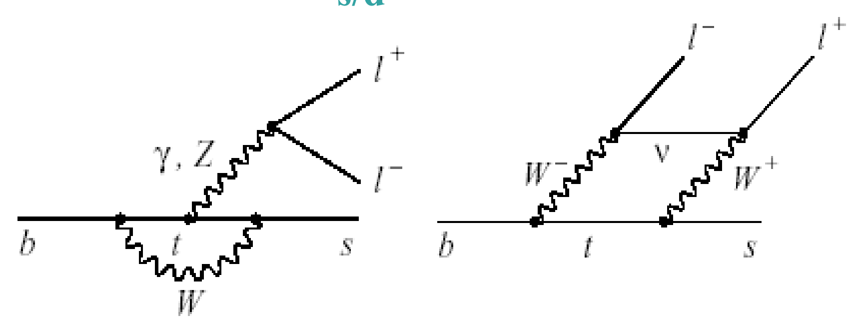
New physics could result in a distinctive pattern of deviations in observables across a variety of related FCNC modes

$B^0_{s/d} \rightarrow \ell^+\ell^-$



C_{10} (Axial vector EW)

$B \rightarrow X_{s/d}\,\ell^+\ell^-$



C_7 ,C_9 (Vector EW) and C_{10}

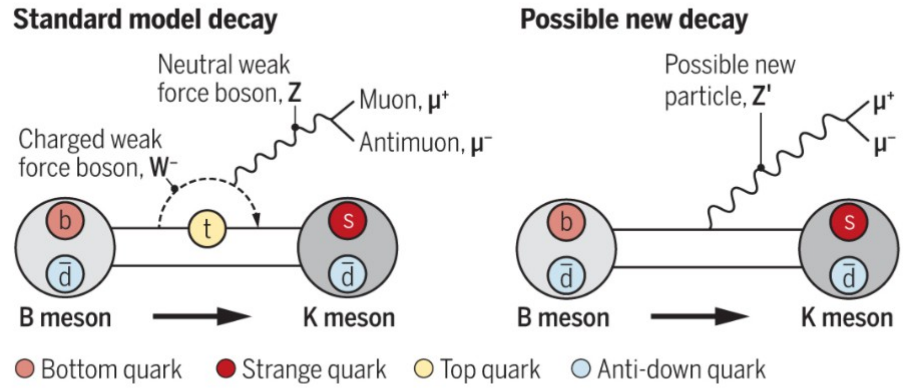
Potentially many observables:

- Branching fractions, CP asymmetries, kinematic distributions, angular distributions and asymmetries

$B \rightarrow K^{(*)}\ell^+\ell^-$ and $R_{K(*)}$

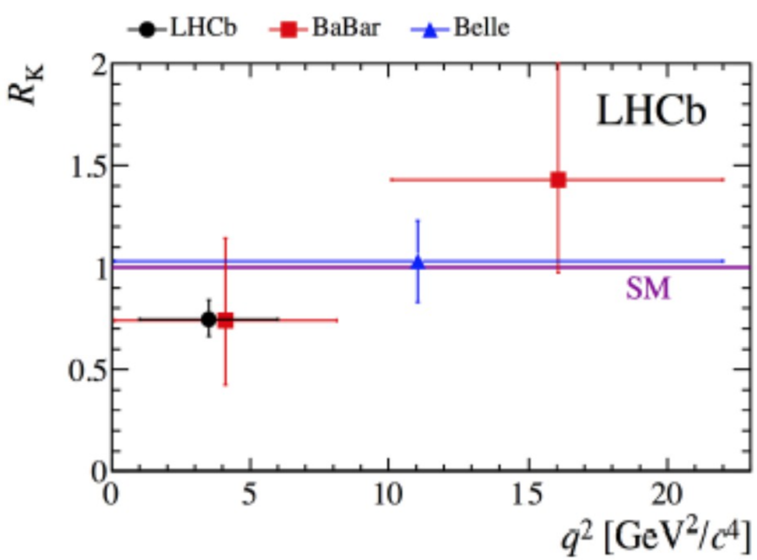
$B \rightarrow K^{(*)}\mu^+\mu^-$

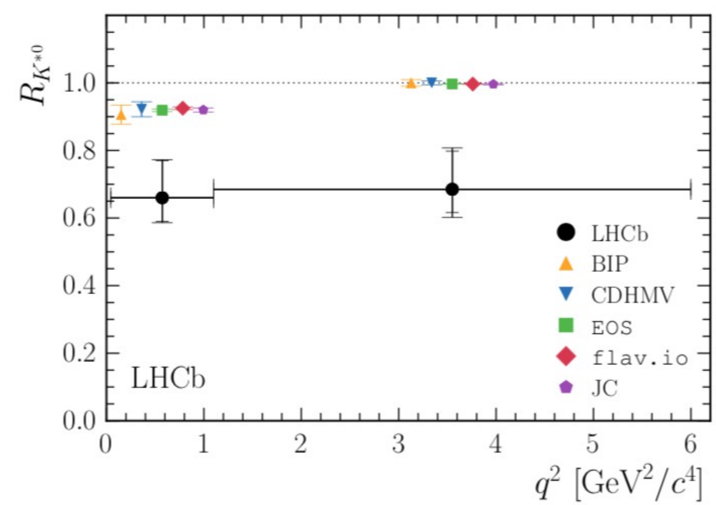
$B \rightarrow K^{(*)}e^+e^-$



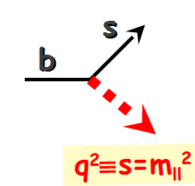
LHCb measurements in tension with SM expectations for ratio of muon and electronic final states:

$$R_{K^{(*)}}(q^2) = \frac{BF(B \rightarrow K^{(*)}\mu^+\mu^-)}{BF(B \rightarrow K^{(*)}e^+e^-)}$$





$R_{K^{*0}}$ vs q^2 for Run 1, LHCb Collaboration



$B \rightarrow K^{(*)} l^+ l^-$ and $R_{K(*)}$

$B \rightarrow K^{(*)} \mu^+ \mu^-$

$B \rightarrow K^{(*)} e^+ e^-$

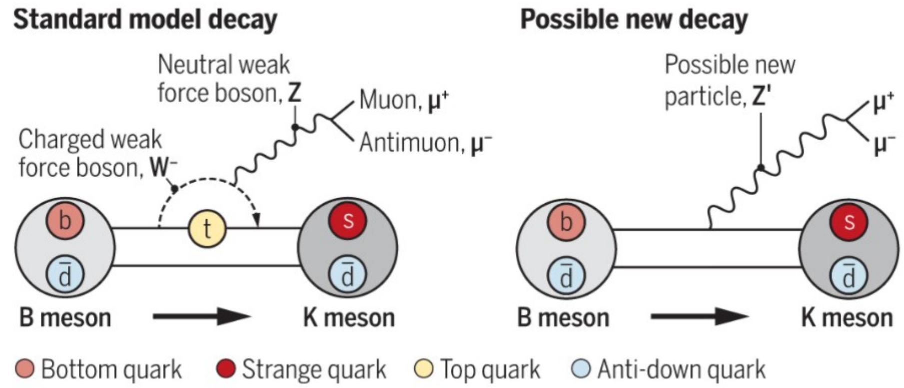
$B^0 \rightarrow K^{(*)0} l^+ l^-$

$B^+ \rightarrow K^{(*)+} l^+ l^-$

$B \rightarrow \pi\, l^+ l^-$

$B \rightarrow X_{s/d}\, l^+ l^-$

Belle II can measure absolute branching fractions, and has symmetric e/μ PID performance



... but there are also two distinct B charge/flavour states

...and two different final-state quark flavours (s,d)

... and also "inclusive" $X_{s/d}$ hadronic systems vs exclusive π,K, K* reconstruction

$B \to K^{(*)} l^+ l^-$ and $R_{K(*)}$

$B \to K^{(*)}\mu^+\mu^-$

$B \to K^{(*)}e^+e^-$

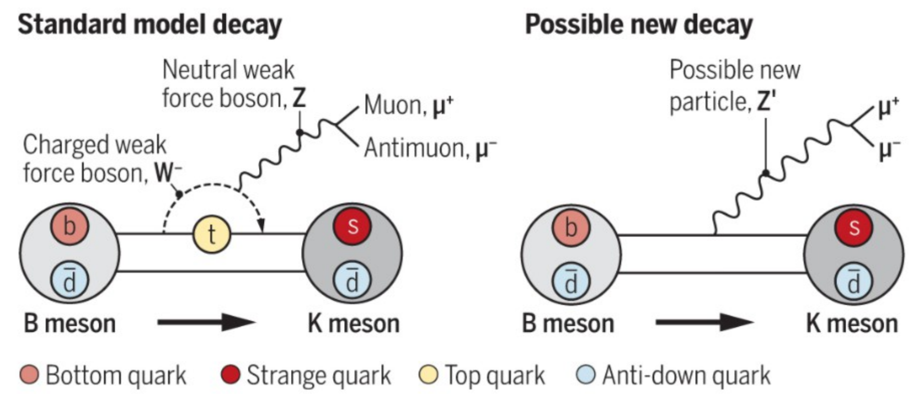
$B^0 \to K^{(*)0} l^+ l^-$

$B^+ \to K^{(*)+} l^+ l^-$

$B \to \pi\, l^+ l^-$

$B \to X_{s/d}\, l^+ l^-$

Belle II can measure absolute branching fractions, and has symmetric e/μ PID performance



... but there are also two distinct B charge/flavour states

...and two different final-state quark flavours (s,d)

... and also "inclusive" $X_{s/d}$ hadronic systems vs exclusive π, K, K* reconstruction

$B \to K^{(*)}l^+l^-$ and $R_{K^{(*)}}$

$B \to K^{(*)}\mu^+\mu^-$

$B \to K^{(*)}e^+e^-$

$B^0 \to K^{(*)0}l^+l^-$

$B^+ \to K^{(*)+}l^+l^-$

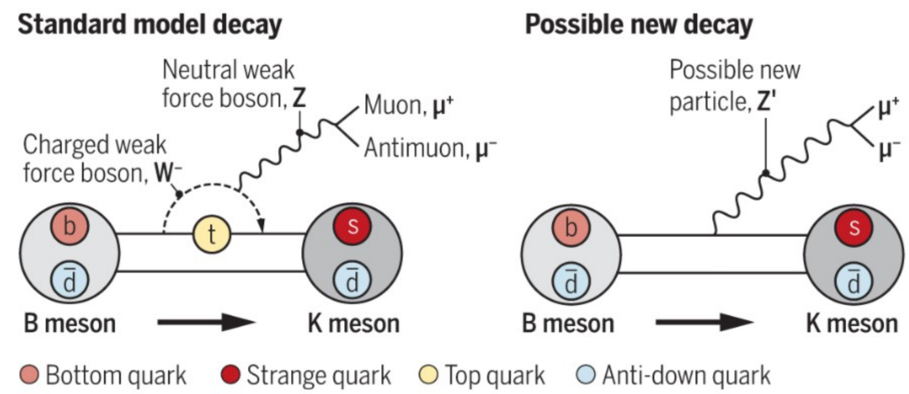
$B \to \pi\, l^+l^-$

$B \to X_{s/d}\, l^+l^-$

$B \to K^{(*)}\tau^+\tau^-$

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

$B \to K^{(*)}\tau^+l^-$



...also two additional lepton species (τ,ν) which can be studied

...and of course lepton flavour violating modes.

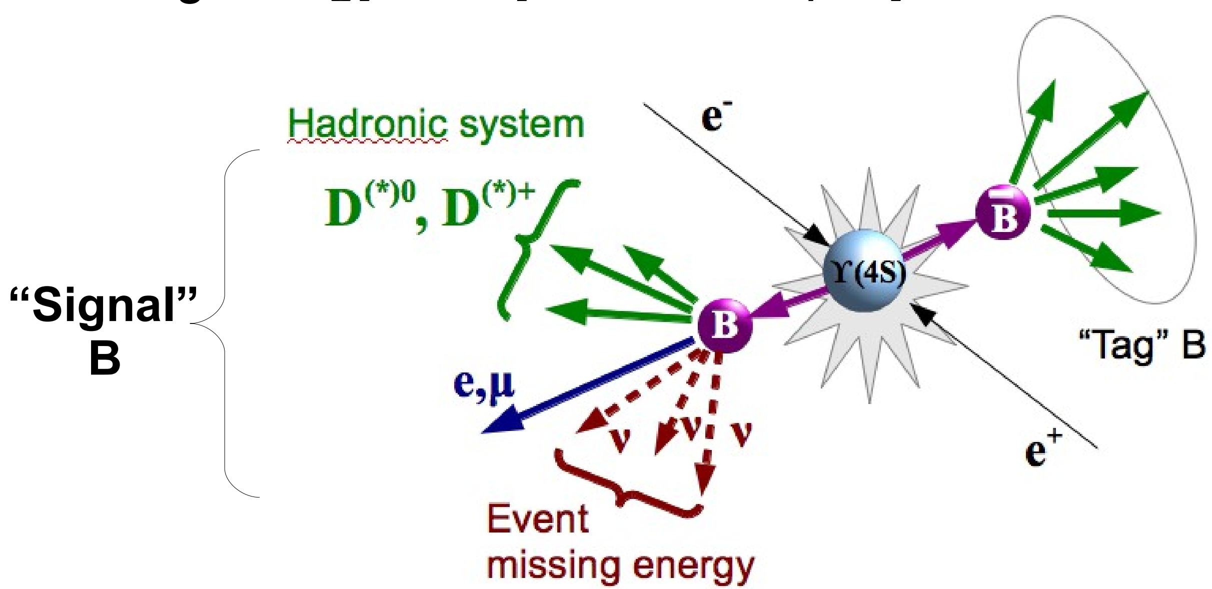
All with distinct experimental sensitivities and systematics, and theoretical sensitivities to various new physics scenarios

Missing energy decays

Unique capability to study B decay modes with missing energy:

- FCNC modes such as $B \to K^{(*)}\nu\bar{\nu}$, $B^0 \to \nu\bar{\nu}$, $B \to K^{(*)}\tau^+\tau^-$ etc.
- Semileptonic B decays such as $B \to D^{(*)}\tau^+\nu$, $B^+ \to \mu^+\nu$, and $B^+ \to \tau^+\nu$

Precisely known CM energy, combined with exclusive hadronic reconstruction of the accompanying B, permit the decay daughters of missing energy decays to be uniquely identified:

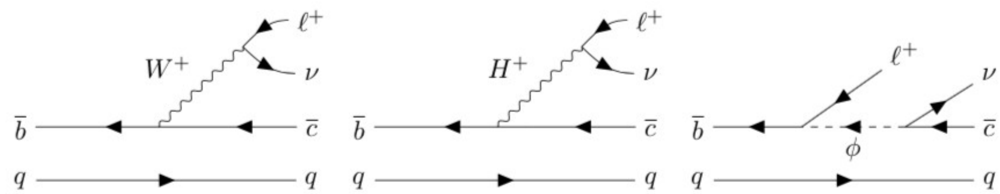


$$m_{BC} \equiv \sqrt{E^{*2}_{\rm beam} - p^{*2}_B}$$
$$\Delta E^* \equiv E^*_B - E^*_{\rm beam}$$

Similar methodology exists for reconstructing semileptonic B tags

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

$B \to D\tau\nu$ and $B \to D^*\tau\nu$ are tree-level SM decays containing 3rd generation quarks and leptons

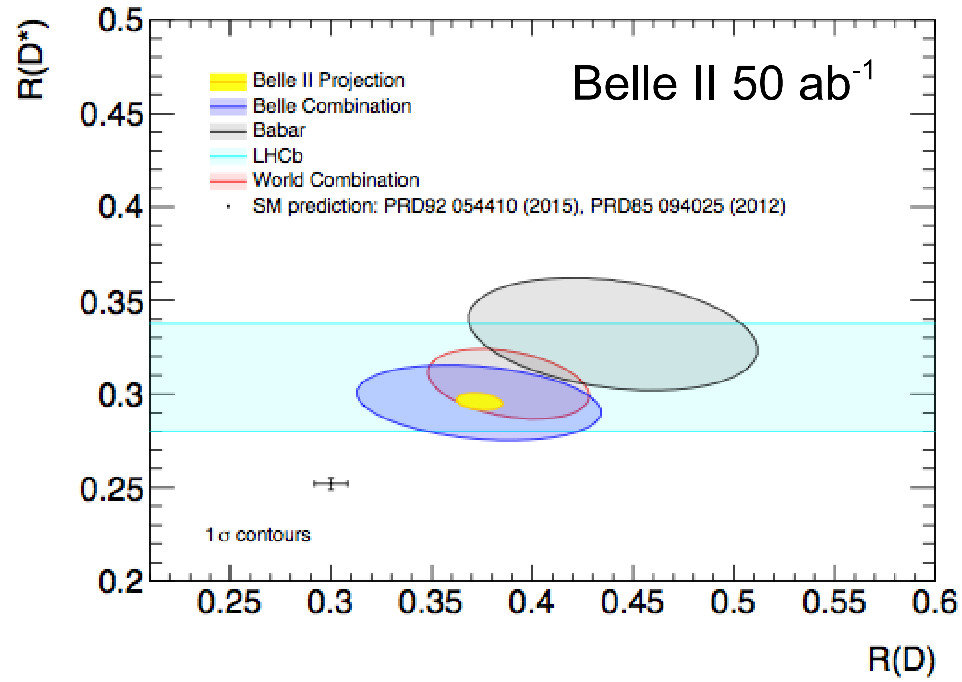


- Ratio of heavy-to-light lepton modes provides robust theoretical prediction

$$R = \frac{\mathcal{B}(b \to q\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(b \to q\,\ell\,\bar{\nu}_\ell)}$$

$$\ell = e, \mu$$

- Measurements from BABAR, Belle and LHCb all independently deviate from SM (combined ~4σ)



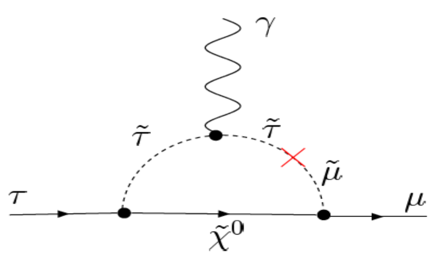
Belle II can precisely measure R(D) and R(D*) to constrain or identify BSM physics

- Both charged and neutral B and various final states

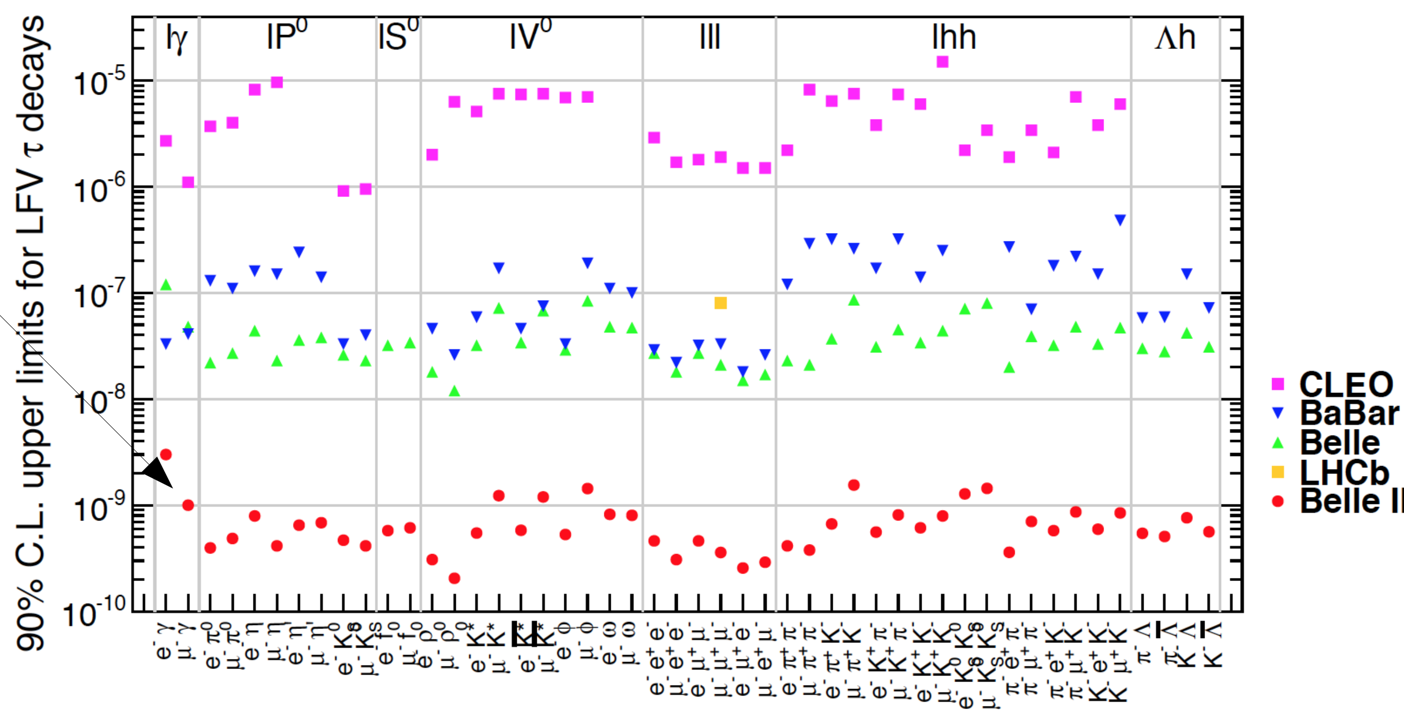
Rare and forbidden decays

Processes that are suppressed or forbidden within the SM can potentially be dramatically enhanced by new physics contributions

- e.g. Lepton flavour violation in τ decays:
  - "forbidden" in SM, but many new physics models saturate existing limits



Expected Belle II sensitivity with full data sample



Very clean searches at B factories and unambiguous signal of new physics

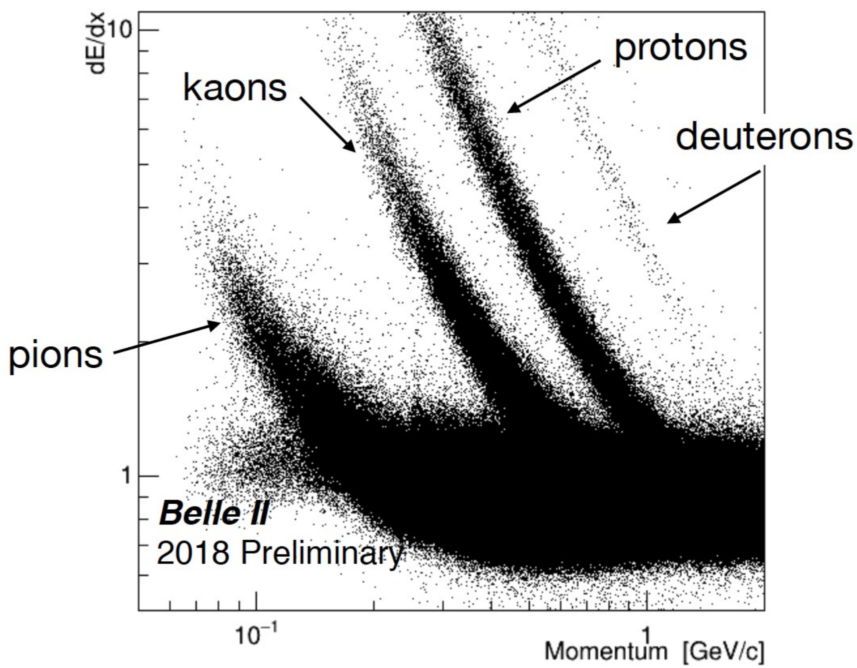
Phase 2 performance

2018 running provided opportunity to validate detector performance

- Achieved instantaneous luminosity of 5.5 x 10^{33} cm^{-2} s^{-1}
- Recorded 472 pb^{-1} integrated luminosity (~1 million B mesons)

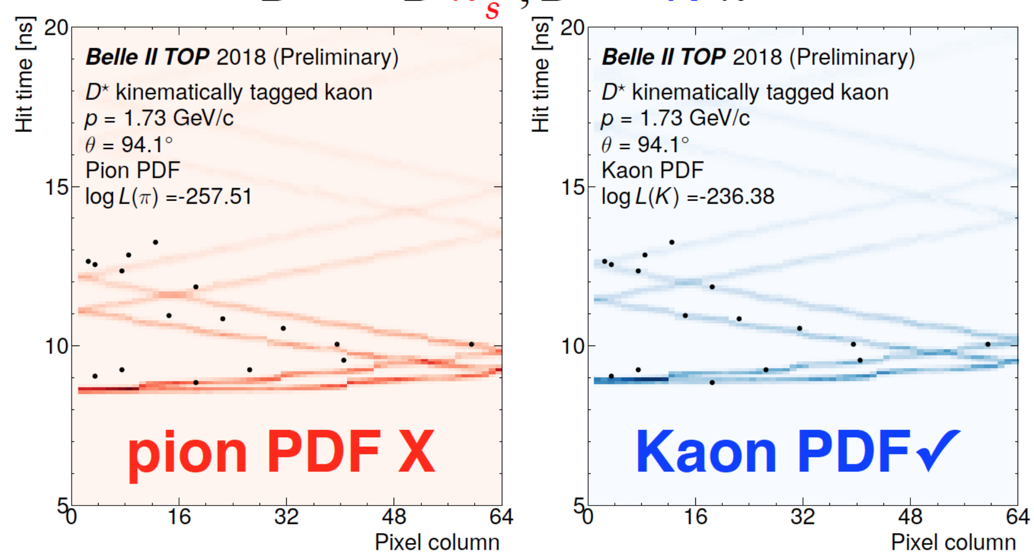
Particle identification:

Drift chamber (CDC)



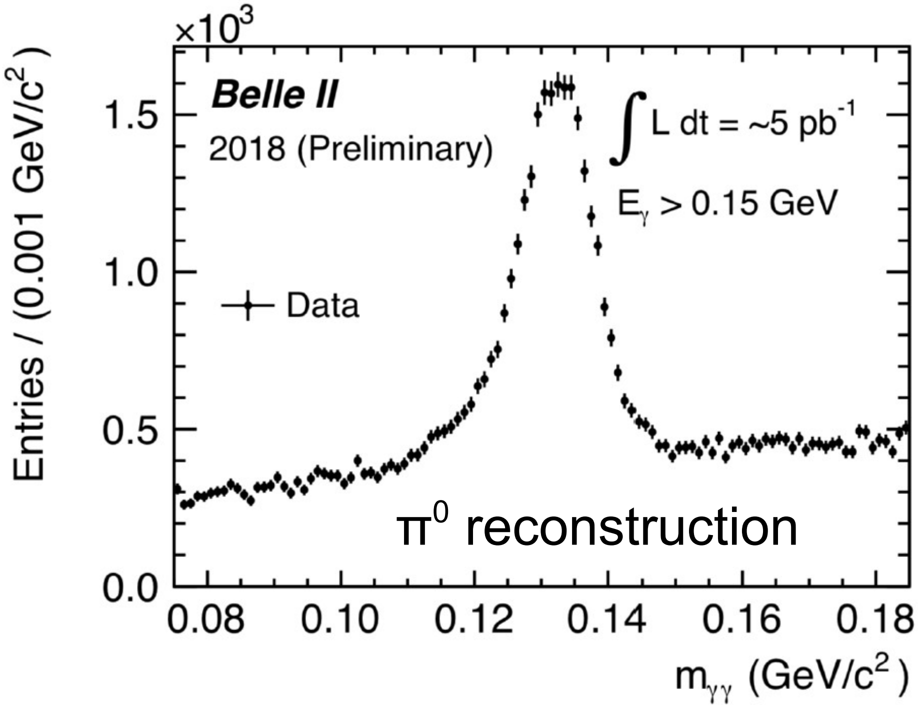
Time of Propagation (TOP) detector

$$D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$$

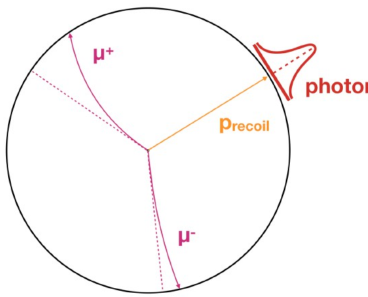


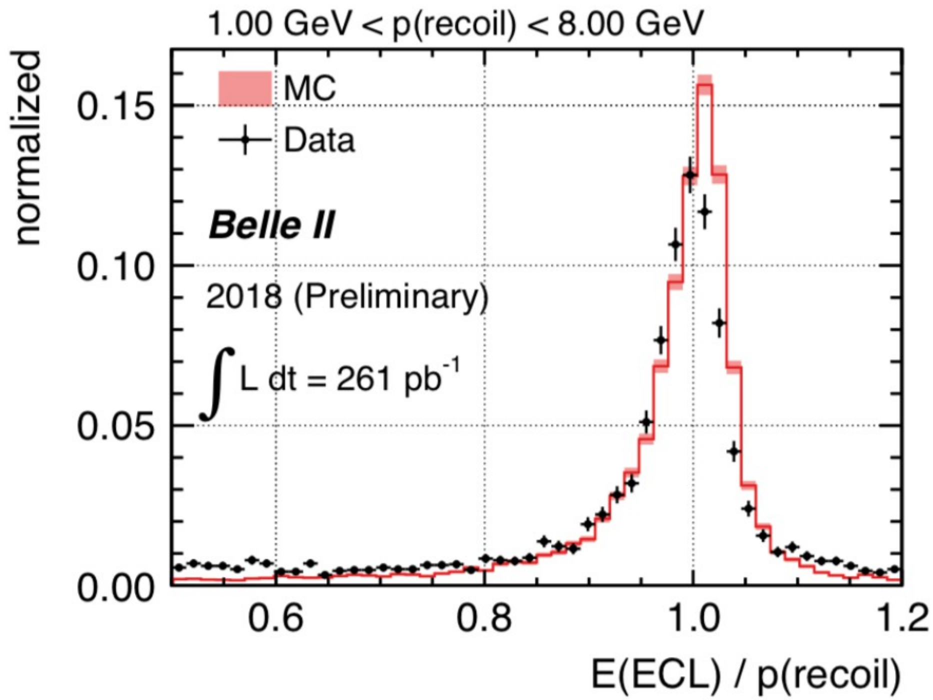
Phase 2 performance

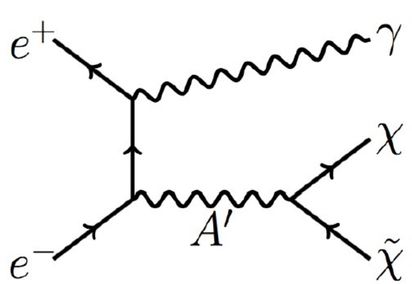
Calorimeter performance:



Single photon reconstruction based on $\mu^+\mu^-\gamma$ events







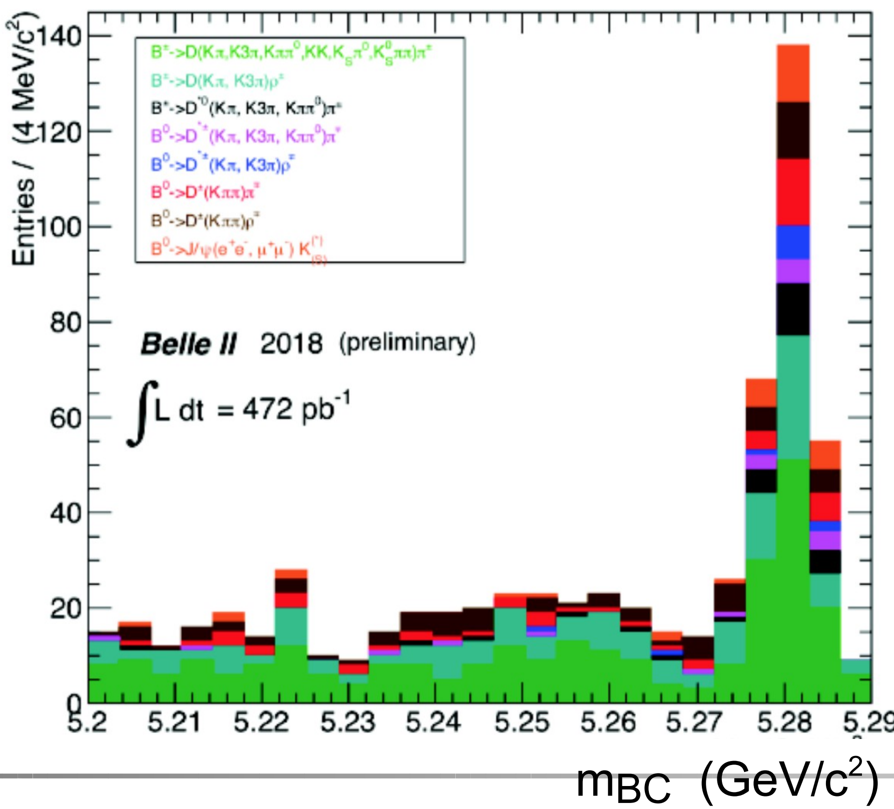
Single-photon trigger available for dark sector searches (early phase 3 physics!)

B mesons!

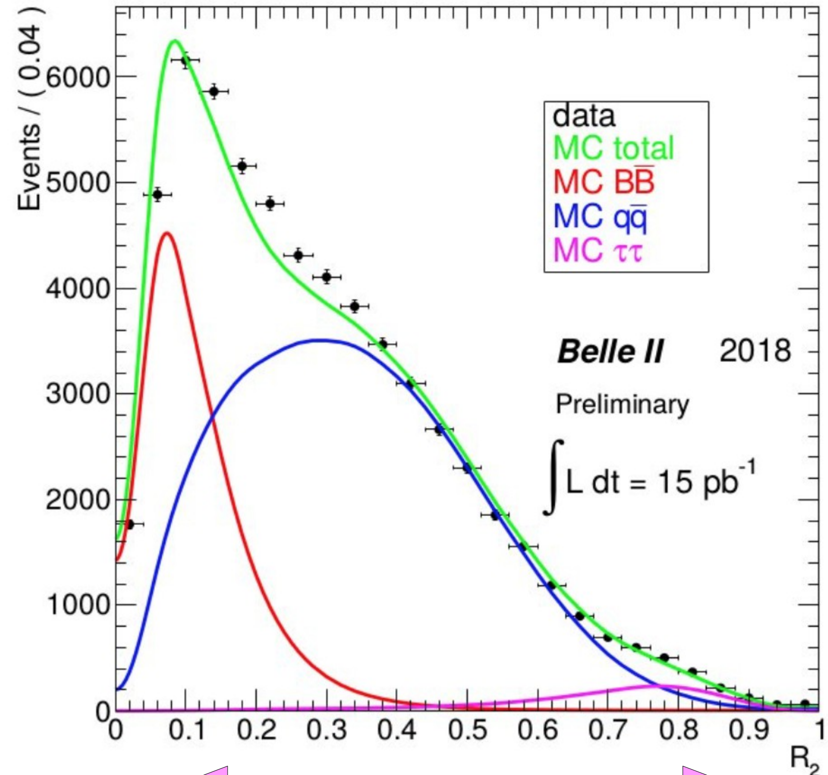
Clear evidence of B mesons in the Phase 2 dataset

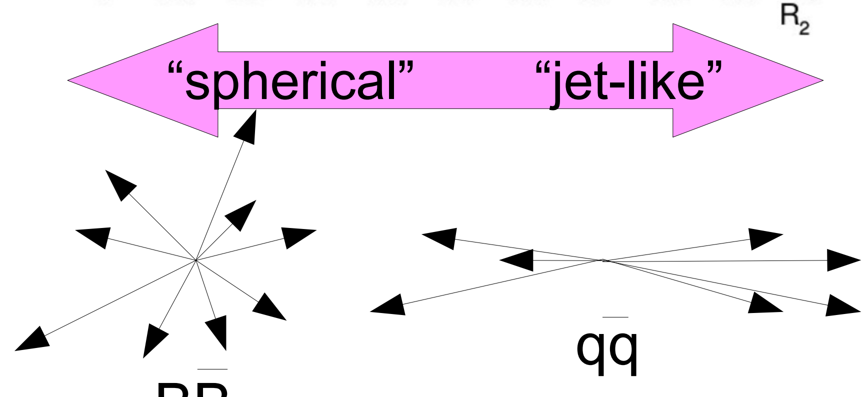
- Indicates that SuperKEKB was on the Υ(4S) resonance peak

Exclusively reconstructed B decays:



Event shapes:

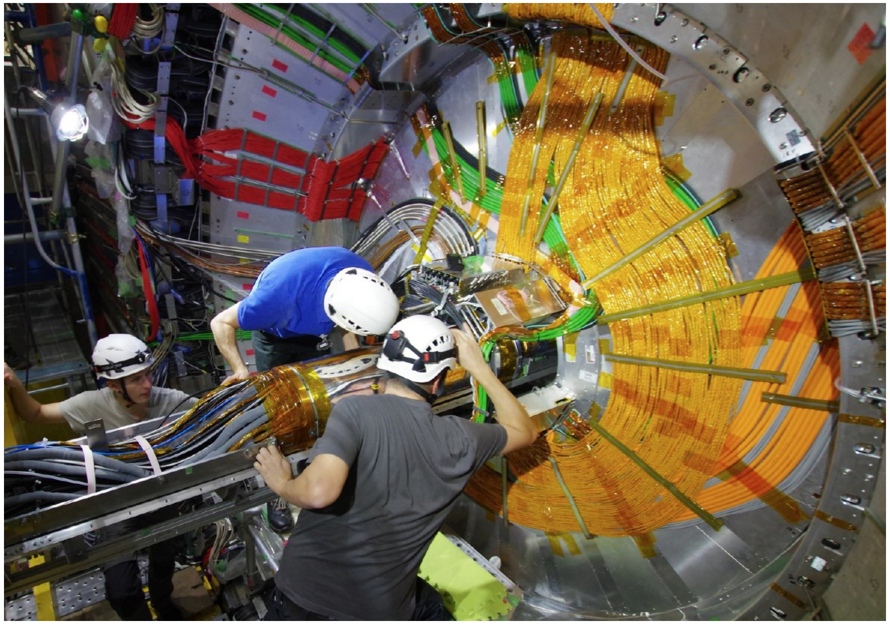


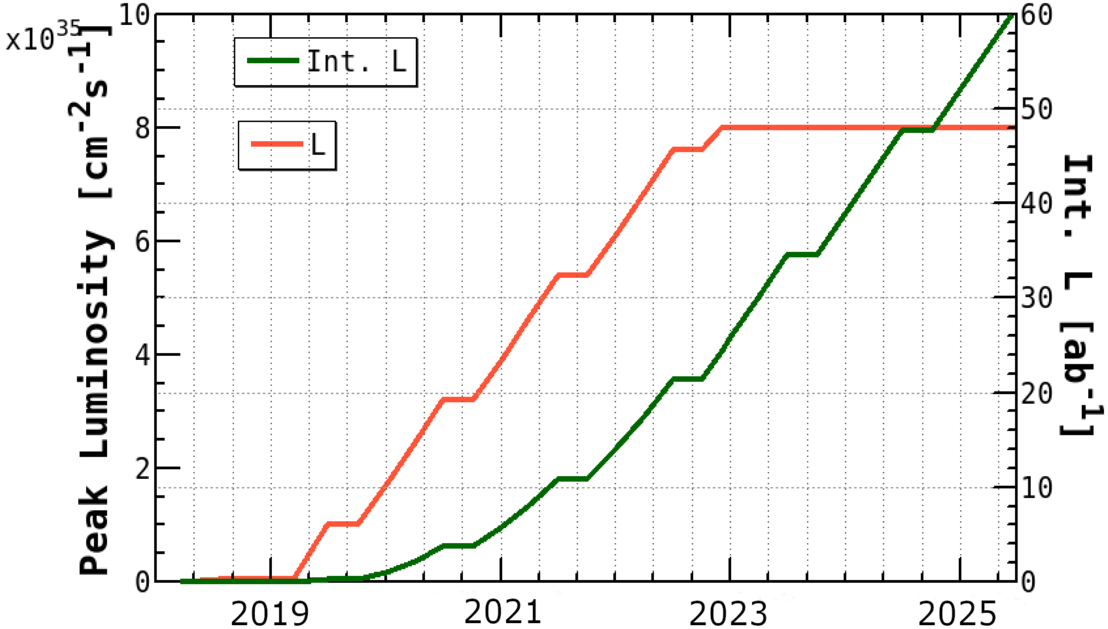


Prospects: Phase 3

Currently preparing for “factory mode” data taking

- Vertex detector has been installed
- Phase 3 run beginning March 2019; ~8 months of operation in 2019





- Exceed existing world $e^+e^- \to \Upsilon(4S)$ dataset by 2021
- Target of 50 ab^{-1} recorded by 2025

Conclusion

Belle II recorded its first data in 2018 during Phase 2 accelerator commissioning run

- Peak luminosity of 5.5×10^{33} $cm^{-2}s^{-1}$ and 472 pb^{-1} integrated
- "Modest" data sample permits validation of detector performance, exercising of physics tools
- Background rates are manageable; vertex detector has been installed for Phase 3

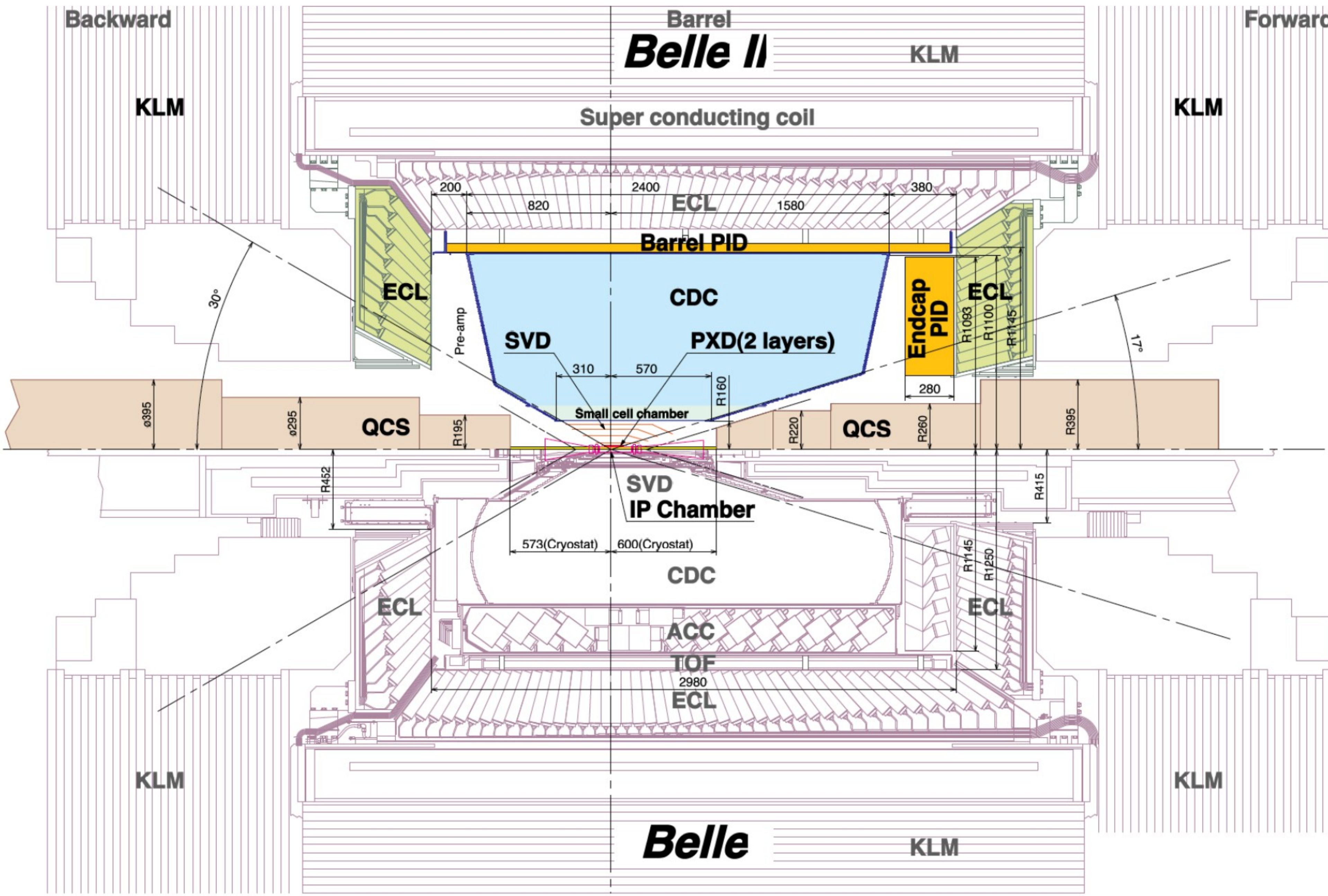
Physics data taking beginning in March 2019 with full detector capability

- "Early" physics prospects include exotic/dark photon searches which can be performed with modest data statistics
- Aim to supersede existing B factory data sets by ~2021

More information about the expected physics performance of Belle II can be found in arXiv:1808.10567[hep-ex]

Backup Slides

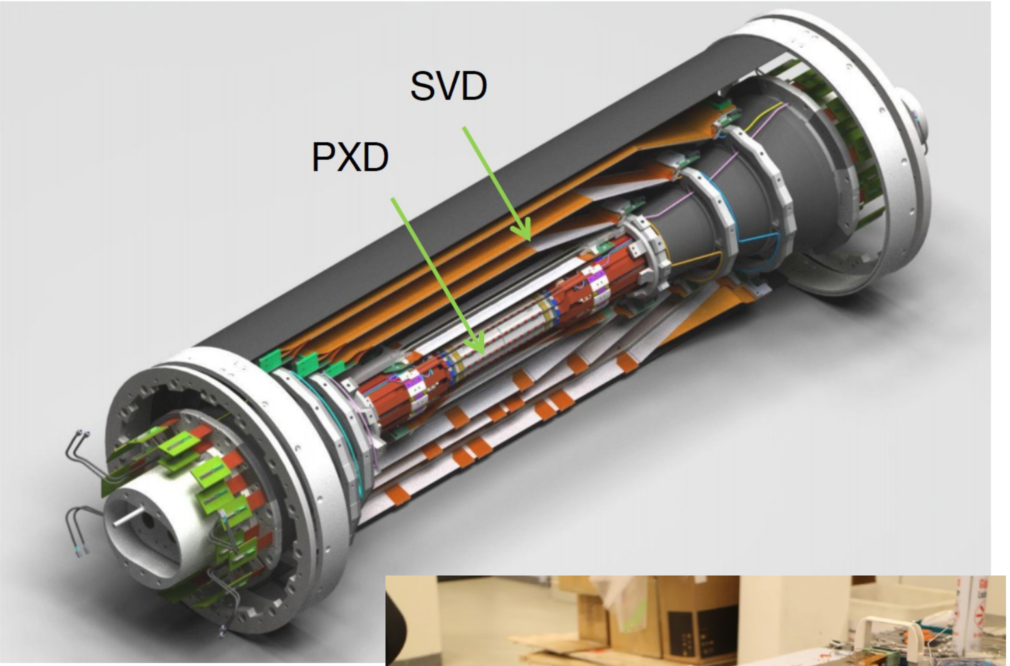
Belle II vs Belle



Vertex detectors

Belle II vertex detector has been installed for Phase 3 data taking

- Two distinct detectors:

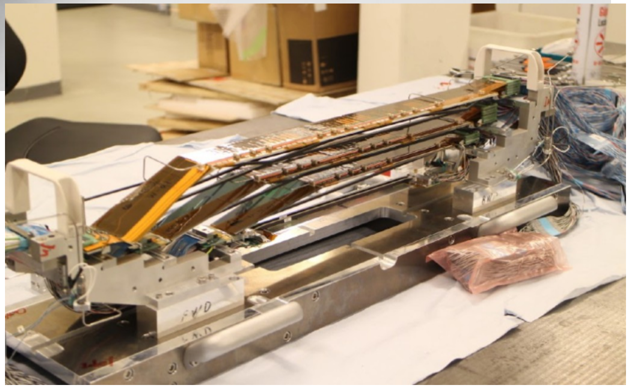


Pixel Detector (PXD)

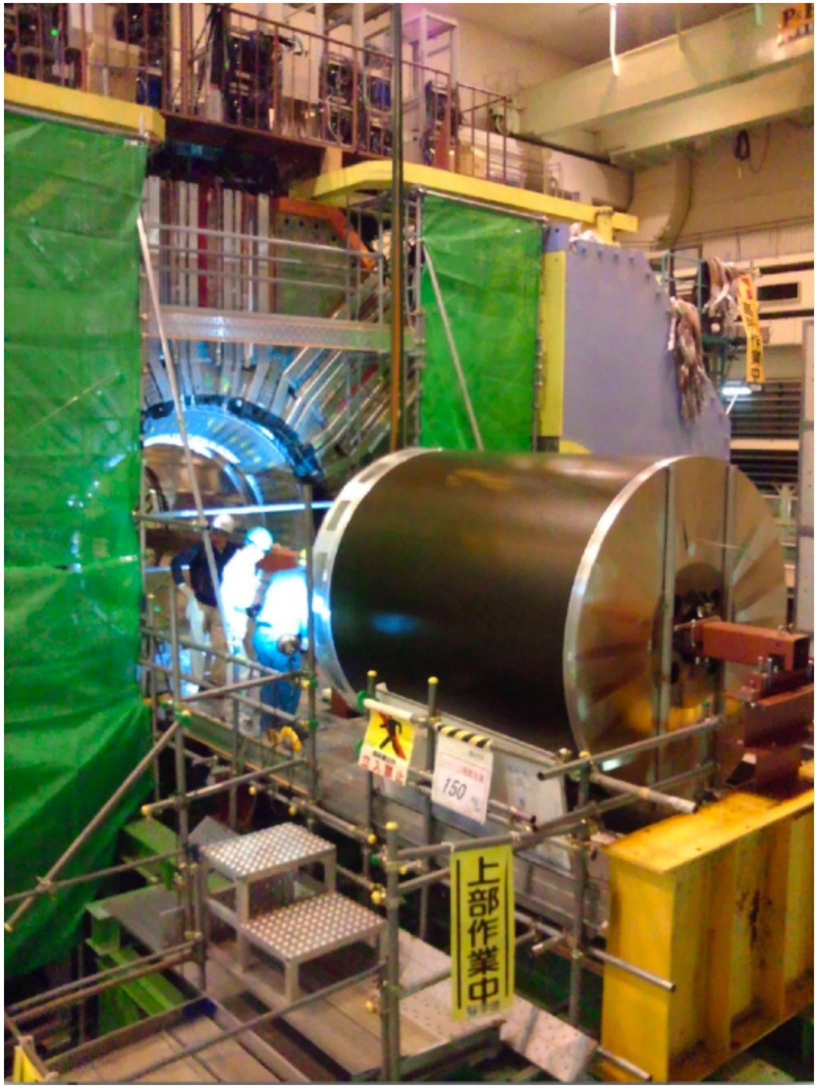
- 2 layers DEPFET modules
- Pixel size: 50 x 55-85 μm.
- Thickness: 75 μm,
  0.21% X_0 per layer

Silicon Vertex Detector(SVD)

- 4 layers of double-sided silicon strip detectors
- Slant in FWD region.
- material budget: 0.7% X_0 per layer



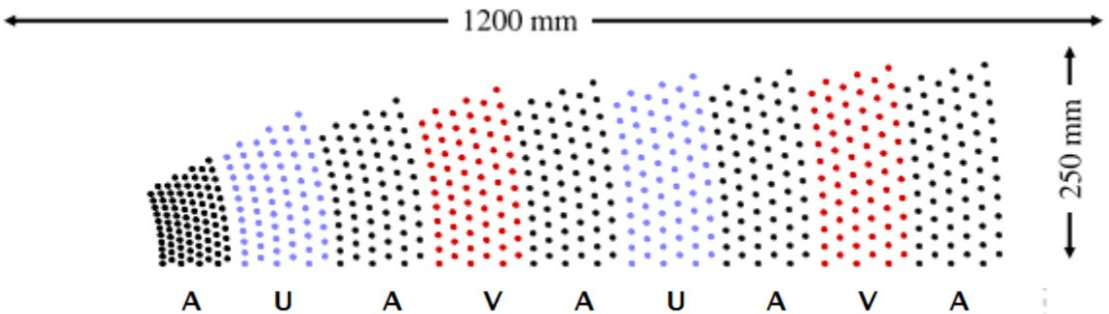
CDC



56 layer large-volume drift chamber

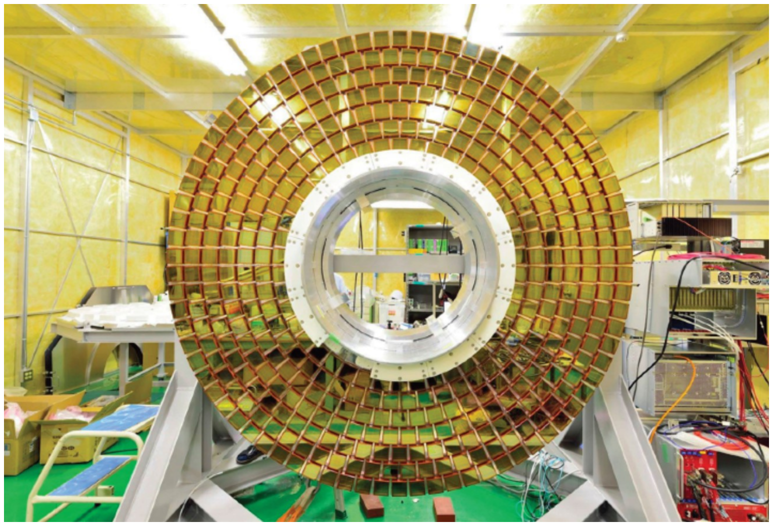
$He:C_2H_6$ 1:1 gas mixture
Total of 14336 sense wires

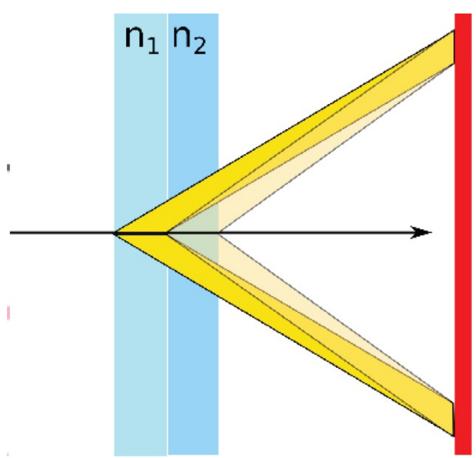
Smaller azimuthal cell sizes relative to Belle CDC



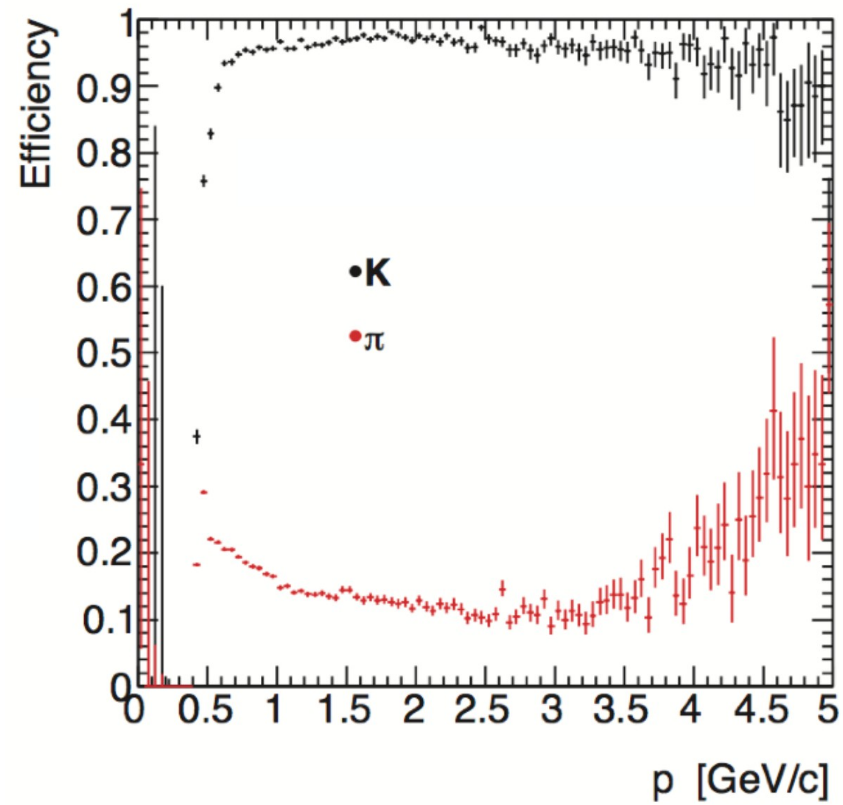
A: Axial layer
U: stereo layer, stereo angle > 0
V: stereo layer, stereo angle < 0

ARICH





Proximity focusing aerogel RICH
n = 1.045-1.055

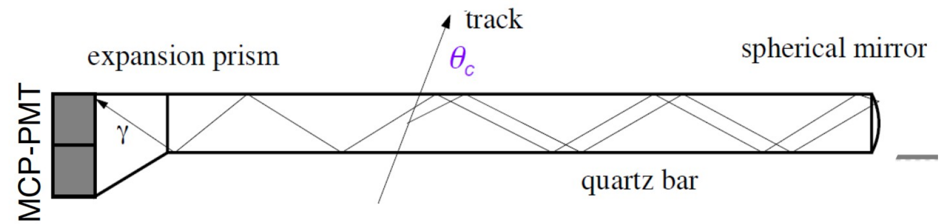


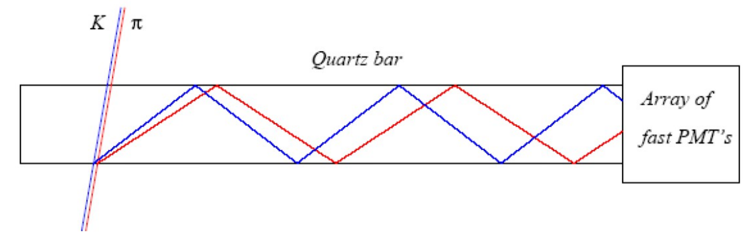
- Hybrid Avalanche Photo Detectors
- 420 units, 144 channels each

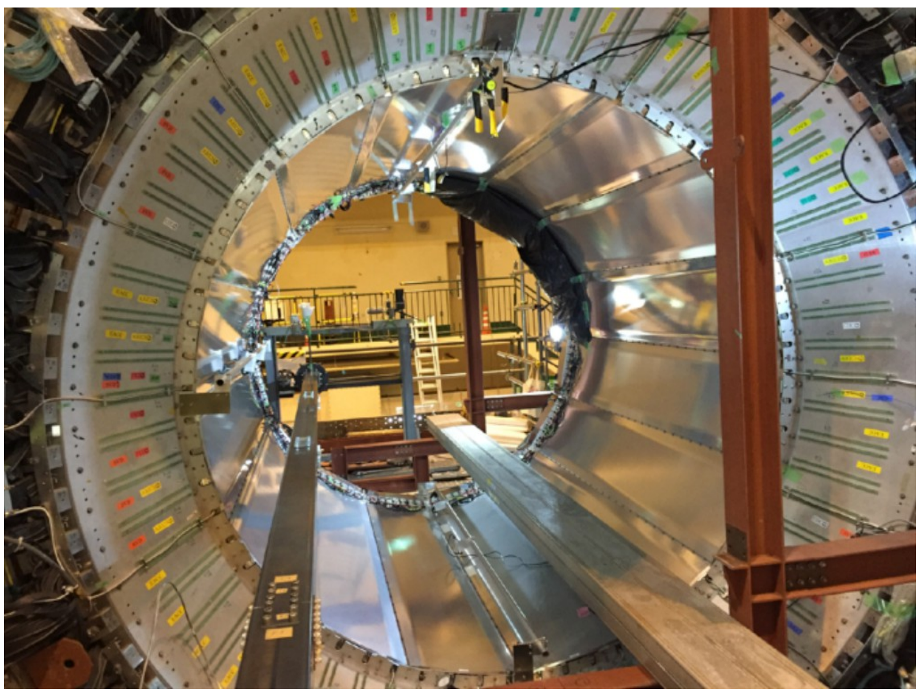
iTOP

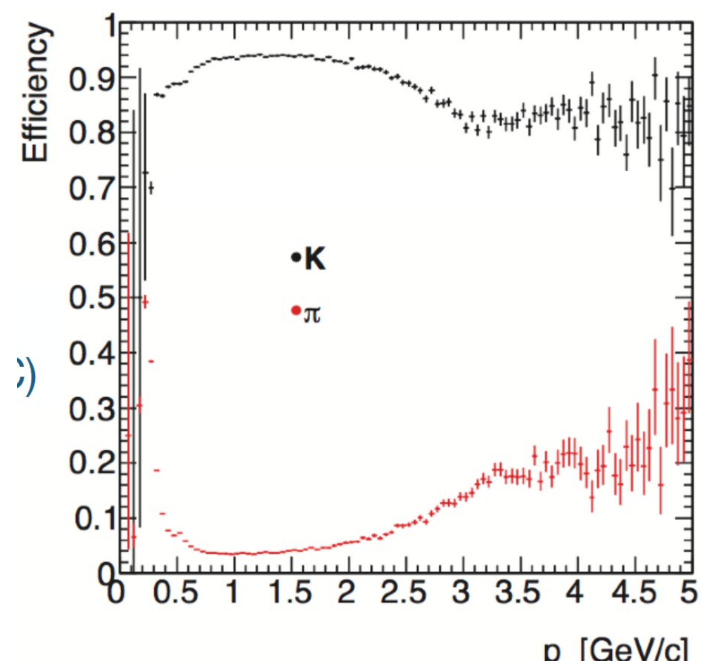
Barrel particle identification based on Cherenkov radiation in quartz bars

- Exploit propagation time of Cherenkov photons to infer Cherenkov angle









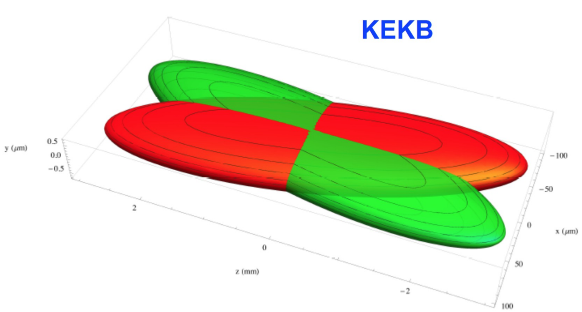
- 16 quartz bars: 2x1.25 m x 0.45 m x 2 cm
- 32 Micro-channel plate PMTs Hamamatsu SL-10 MCP PMT

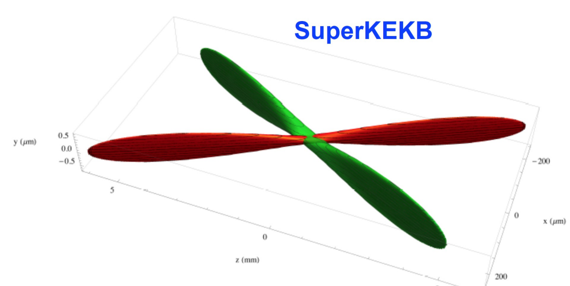
SuperKEKB

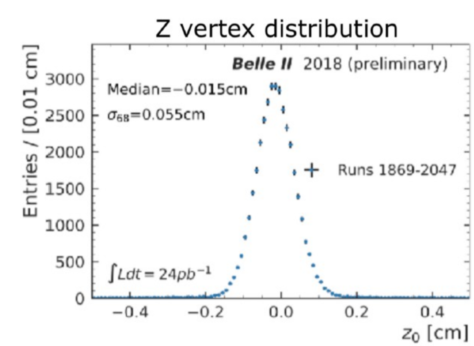
	KEKB Achieved LER	KEKB Achieved HER	SuperKEKB LER	SuperKEKB HER
RF frequency f [MHz]	508.9			
# of Bunches N	1584		2500	
Horizontal emittance εx [nm]	18	24	3.2	4.6
Beta at IP $\beta x^*/\beta y^*$ [mm]	1200/5.9		32/0.27	25/0.30
beam-beam param. ξy	0.129	0.090	0.088	0.081
Bunch Length Sz [mm]	6.0	6.0	6.0	5.0
Horizontal Beam Size sx^* [μm]	150	150	10	11
Vertical Beam Size sy^* [nm]	0.94		48	62
Half crossing angle φ [mrad]	11		41.5	
Beam energy Eb [GeV]	3.5	8	4	7.007
Beam currents Ib [A]	1.64	1.19	3.6	2.6
Lifetime t [min]	133	200	6	6
Luminosity L [$cm^{-2}s^{-1}$]	**2.1×10^{34}**		**8×10^{35}**	

Substantial upgrade of KEKB collider to provide e^+e^- collisions at $8\times10^{35} cm^{-2}s^{-1}$ luminosity for Belle II

- Low-emittance “nanobeam” scheme exploiting ILC and light-source technologies
- 4 GeV (e^+) on 7 GeV (e^-)
- New positron damping ring and positron beam vacuum chamber
- New final focus region





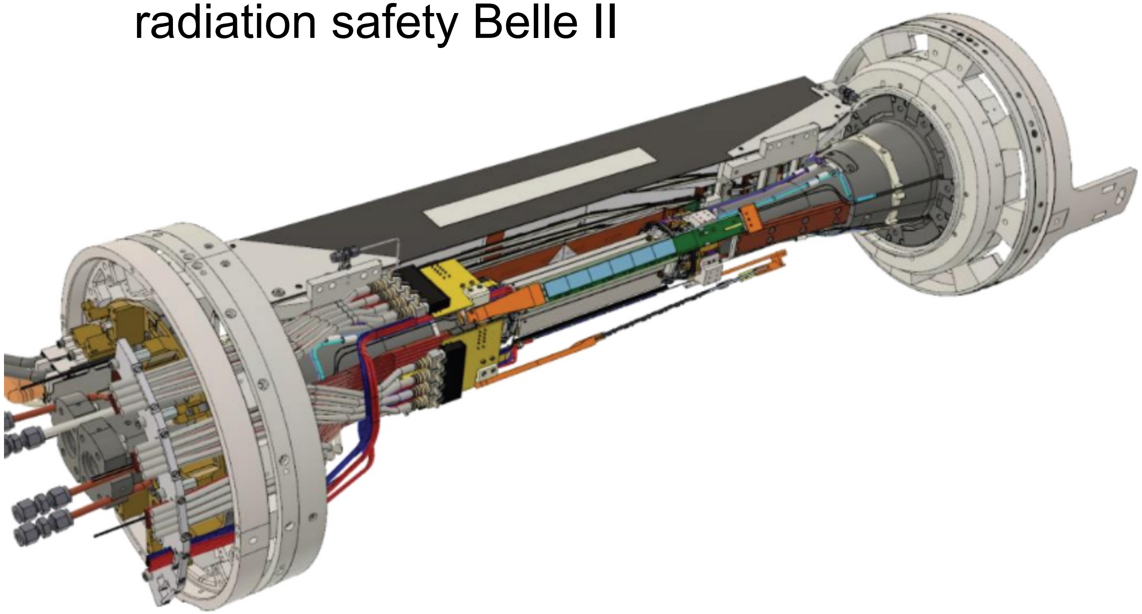


σ = 55μm

BEAST – phase 2

Belle II detector in position at IP, but without vertex detectors

- Dedicated background monitoring detectors positioned close to the IP to ensure radiation safety Belle II



2 PXD and 4 SVD layers in sector where the highest backgrounds are expected.

FANGS - FE-I4 based hybrid pixel to study Synchrotron Radiation background

CLAWS - scintillators with SiPM to study trickle injection background

PLUME - double-sided high granularity MIMOSA pixels

Also "permanent" background monitors installed along beam line outside of nominal Belle II angular acceptance:

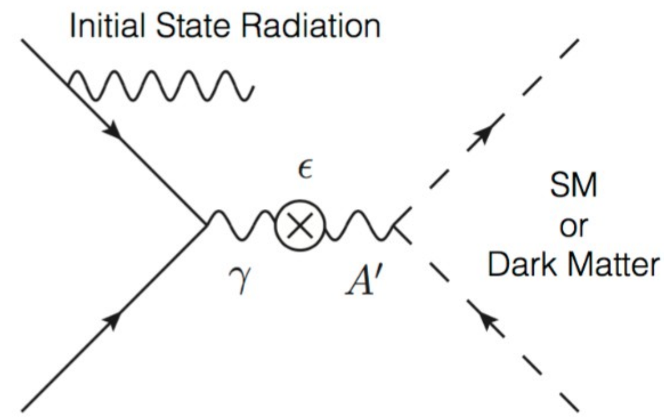
- PIN diodes
- Scintillator/MPPC (trickle injection backgrounds)
- He3 tubes (neutrons)

} Signals relayed to Belle II and SuperKEKB control rooms for beam tuning

Dark Forces

- Search for decay of $e^+e^- \to \gamma A'$ via $A' \to \chi\bar{\chi}$ or into SM particles
  - "visible" $A' \to l^+l^-$, or
  - "Invisible" A' decays, with A' mass determined from photon energy

$$E_\gamma^* = \frac{s - M_X^2}{2\sqrt{s}}$$



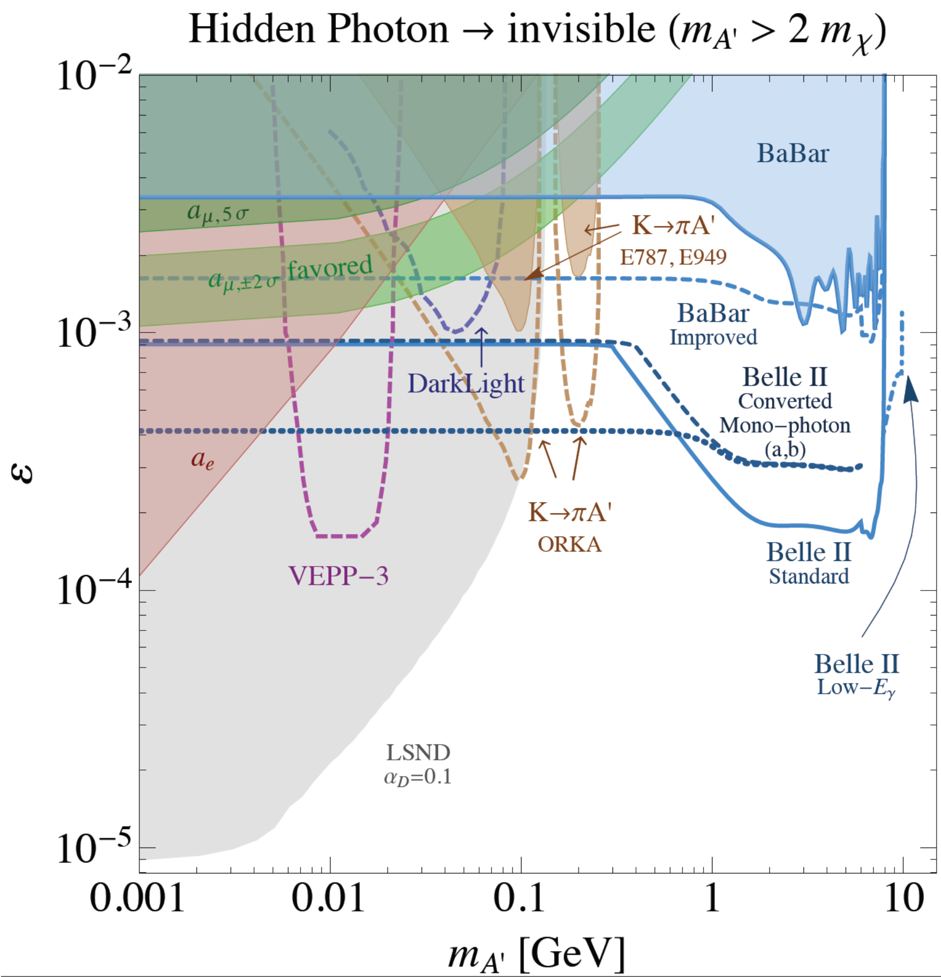
.... however, dark sector could be much more extensive, with one or more Abelian or non-Abelian interactions, fermions and Higgs bosons

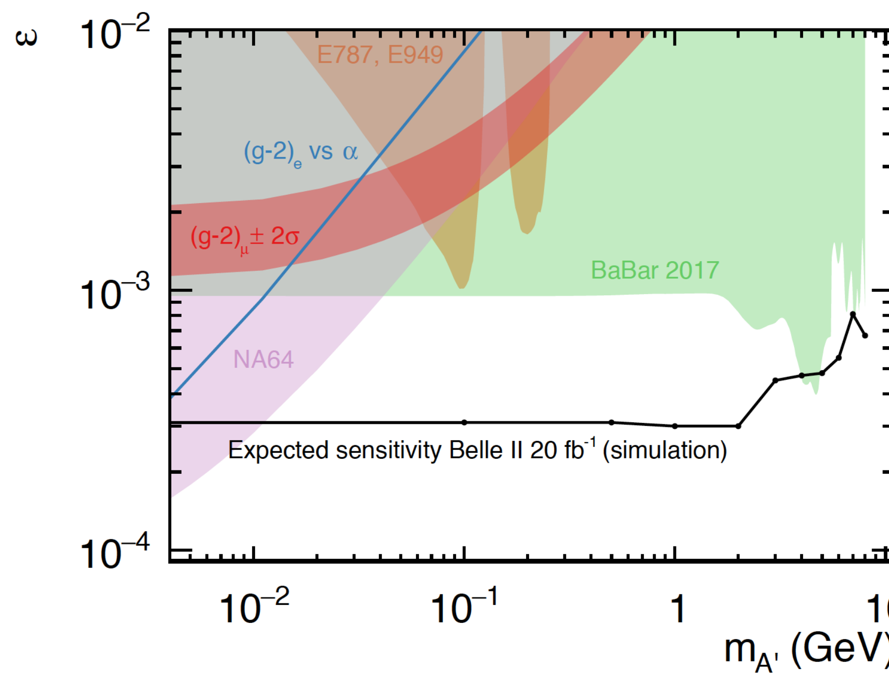
Can potentially be detected via one of a number of "portals" coupling the Dark Sector to the SM

Vector Portal → *Dark Photon*
Scalar Portal → *Higgs/Dark Scalars*
Pseudoscalar Portal → *Axion-like Particles*
Neutrino Portal → *Sterile Neutrinos*

- Sensitivity studies performed in the context of "Belle II physics book" (B2TiP), to be published in near future
- ALP sensitivity studies: arxiv: 1709.00009

Typically, these are narrow resonance ("bump hunt") searches in low multiplicity data samples


Hidden Photon → invisible ($m_{A'} > 2\, m_\chi$)
BaBar
$a_{\mu,5\sigma}$
$a_{\mu,\pm2\sigma}$ favored
K→πA'
E787, E949
BaBar
Improved
DarkLight
Belle II
Converted
Mono−photon
(a,b)
a_e
K→πA'
ORKA
Belle II
Standard
VEPP−3
Belle II
Low−E_γ
LSND
α_D=0.1
ε
$m_{A'}$ [GeV]
0.001
0.01
0.1
1
10
10^{-2}
10^{-3}
10^{-4}
10^{-5}


E787, E949
$(g-2)_e$ vs α
$(g-2)_\mu \pm 2\sigma$
BaBar 2017
NA64
Expected sensitivity Belle II 20 fb^{-1} (simulation)
ε
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
1
10
$m_{A'}$ (GeV)

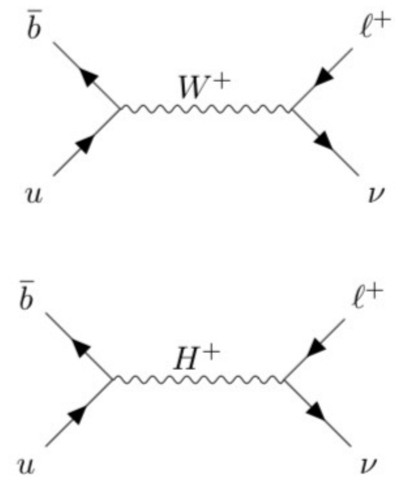
$B^+ \to l^+\nu$

Purely leptonic decays, $B^+ \to l^+\nu$ are helicity suppressed in the SM, with substantial potential for enhancement by new physics

- Theoretical uncertainties only from $|V_{ub}|$ and decay constant f_B

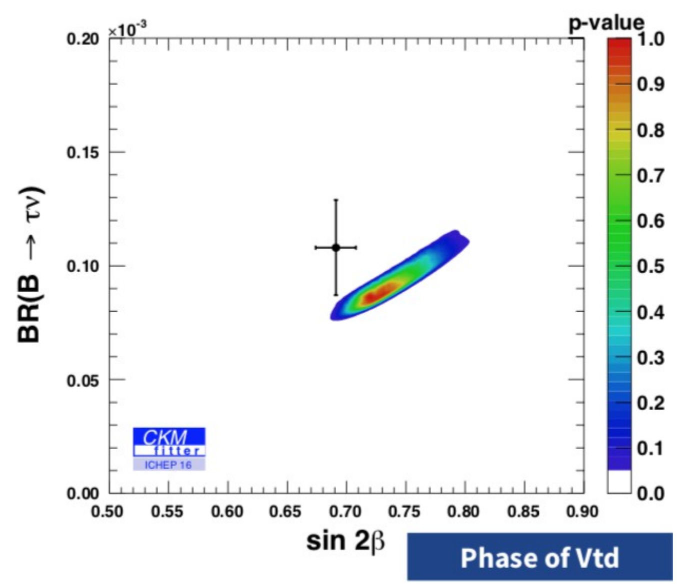
$$\mathcal{B}r(B^+ \to \ell^+\nu_\ell) = \frac{G_f^2}{8\pi}|V_{ub}|^2 f_B^2 m_B m_\ell^2 \tau_B \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2$$

$$r_{H+} = [\ 1 - \tan^2\beta\ (m^2_B/m^2_{H+})\ ]^2$$



- Experimental measurements of $B^+ \to \tau^+\nu$ are in tension wrt UT fit, but these results are not currently very precise
- Current limits on $B^+ \to \mu^+\nu$ from BABAR & Belle data close to SM

Lots of potential for discovery even with modest Belle II data set (2021?)

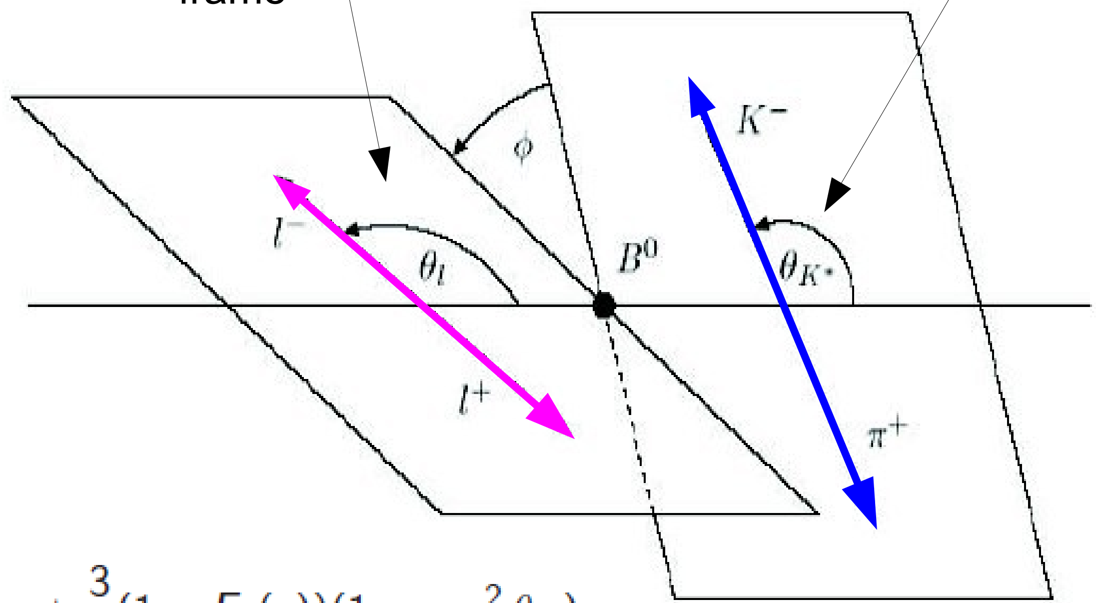


$B \to K^{(*)} \ell^+ \ell^-$

Fit angular distributions of $K^{(*)}$ and dilepton system to extract two observables:

Angle between $\ell^+[\ell^-]$ and B[B] in $\ell^+\ell^-$ rest frame

K angle in K* rest frame (K* polarization)



- K* longitudinal polarization fraction F_L

$$\frac{1}{\Gamma(s)} \frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2} F_L(s) \cos^2\theta_K + \frac{3}{4}(1 - F_L(s))(1 - \cos^2\theta_K)$$

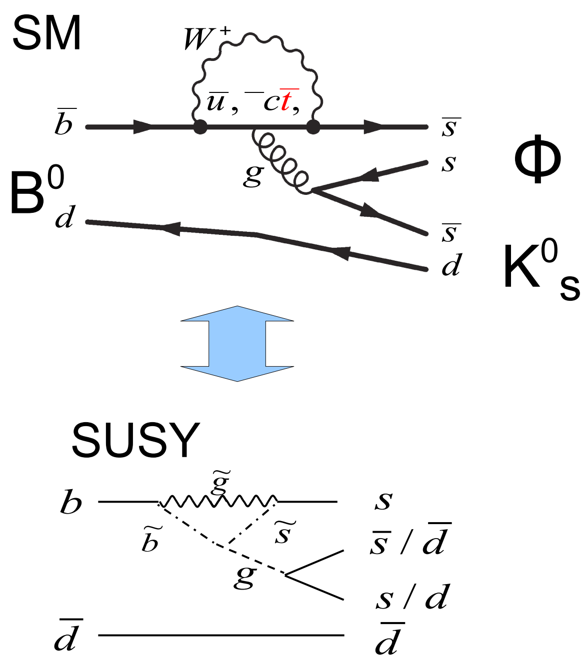
- $\ell^+\ell^-$ forward-backward asymmetry A_{FB}

$$\frac{1}{\Gamma(s)} \frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4} F_L(s)(1 - \cos^2\theta_\ell) + \frac{3}{8}(1 - F_L(s))(1 + \cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$

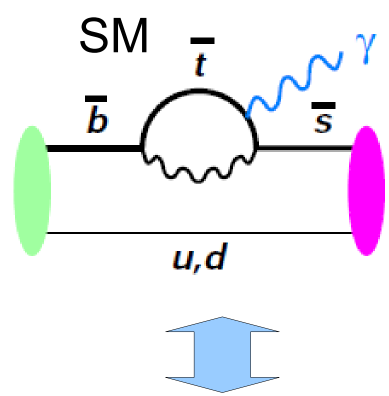
FCNC decays

Many decay modes with potential sensitivity to new physics contributions:

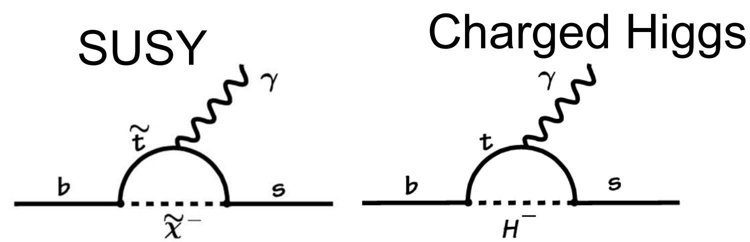
Hadronic decays:



Electroweak FCNCs:



Precision measurements of one-loop processes probe new physics mass scales which can far exceed direct searches



Many observables:

- Branching fractions, CP asymmetries, kinematic distributions, angular observables and asymmetries

Other topics

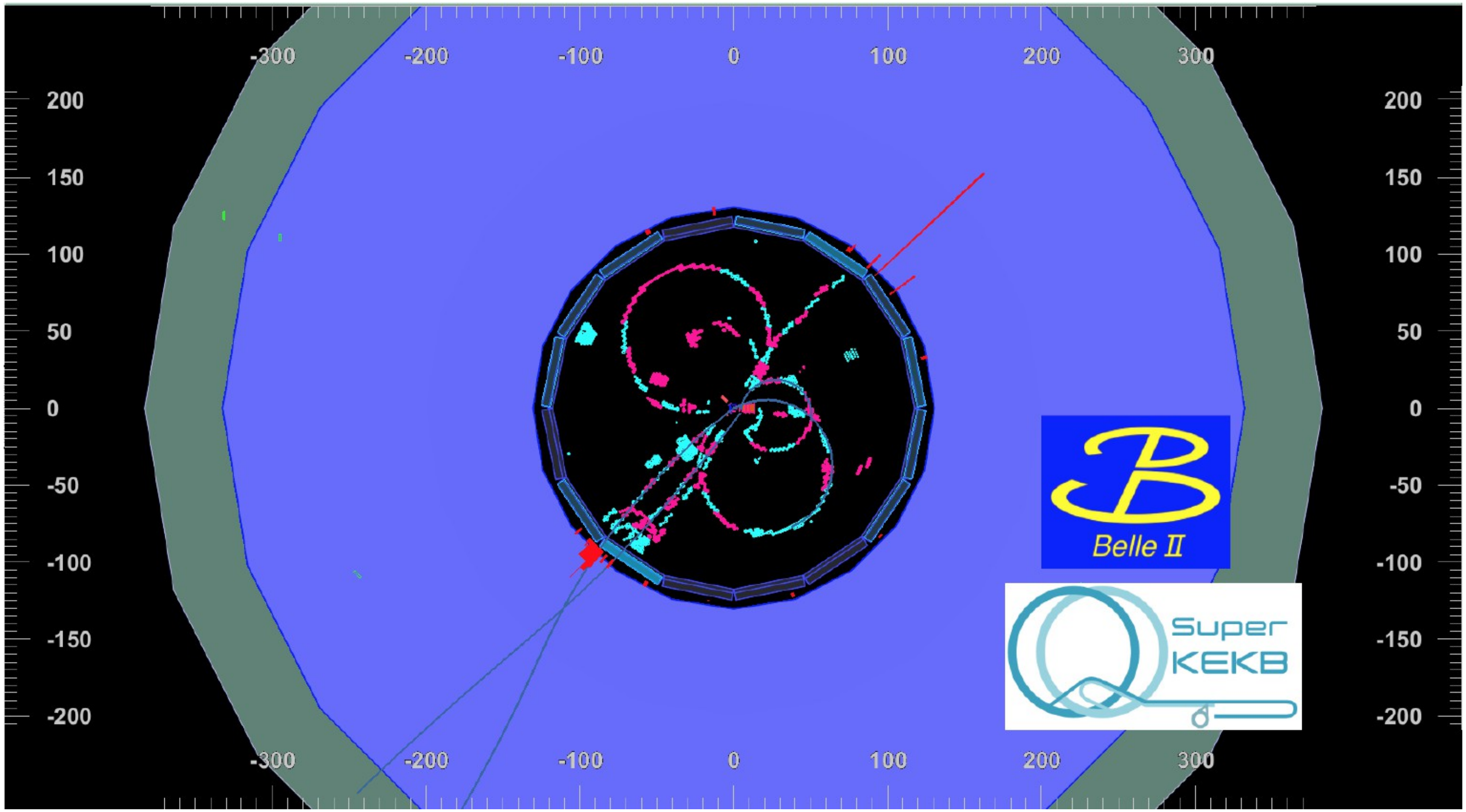
Many potential analysis topics beyond the usual "flavour" of B factories:

- Quarkonium and new states
- QED and continuum production cross sections
- Direct searches for light new particles
  - dark matter candidates, "dark sector", light Higgs, ALP searches etc.

Dark Forces:

Various models exist in which dark matter arises as part of a "dark sector" containing its own gauge interactions and particles

- Simplest scenario is to add a new U(1) gauge symmetry, with associated charge carried by dark-sector fermions
  - Spin-1 gauge boson "dark photon" A' can mix with SM photon, providing a "portal" to the dark sector. Mixing strength characterized by ε


-300 -200 -100 0 100 200 300
200 150 100 50 0 -50 -100 -150 -200
Belle II
Super KEKB

Flavour and New Physics

Effective flavour-violating couplings

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_{k=1} \left(\sum_i C_i^k \, Q_i^{(k+4)} \right) / \Lambda^k$$

New Physics scale

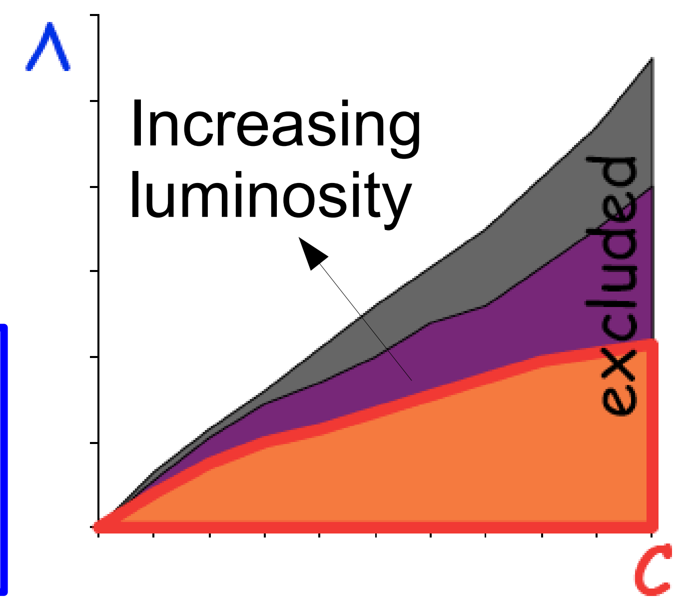
In explicit models:

- Λ ~ mass of virtual particles

  (e.g. Fermi theory: m_W)

- C ~ (loop coupling) x (flavour coupling)

  (e.g. SM/MFV: α_w x CKM)



Precision flavour measurements provide bounds on ratio C / Λ i.e. constrain coupling strengths at any given mass scale