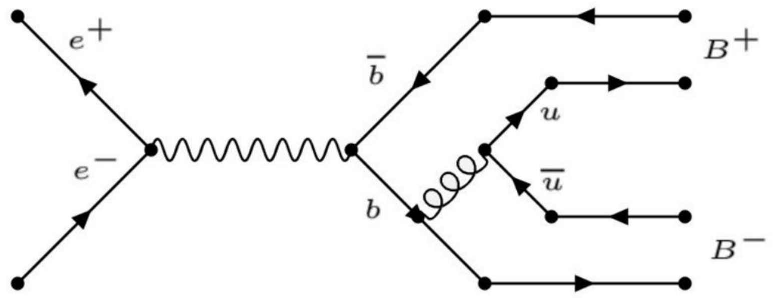
BELLE II

ON THE PRECISION FRONTIER

Caleb Miller

Queens Summer Institute 2022

SuperKEKB



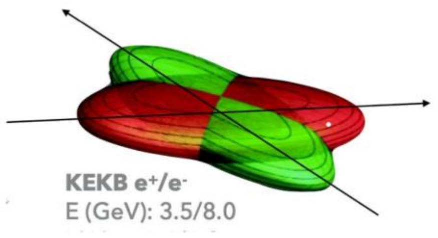
Collides electrons and positrons together at 10.58 GeV

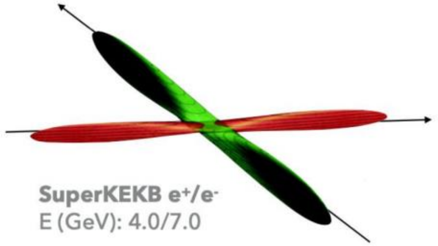
- "B-Factory" as 10.58 GeV is on resonance to produce free B mesons

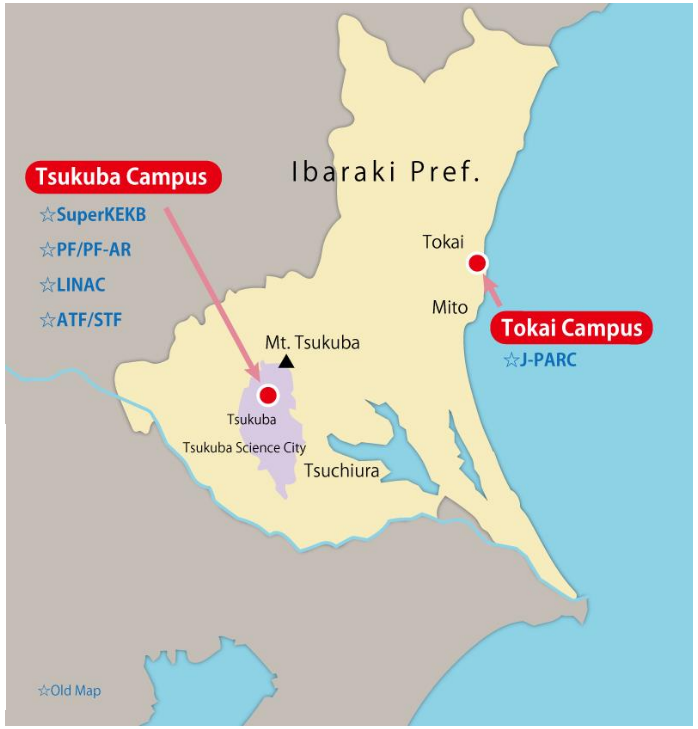
3 km loop

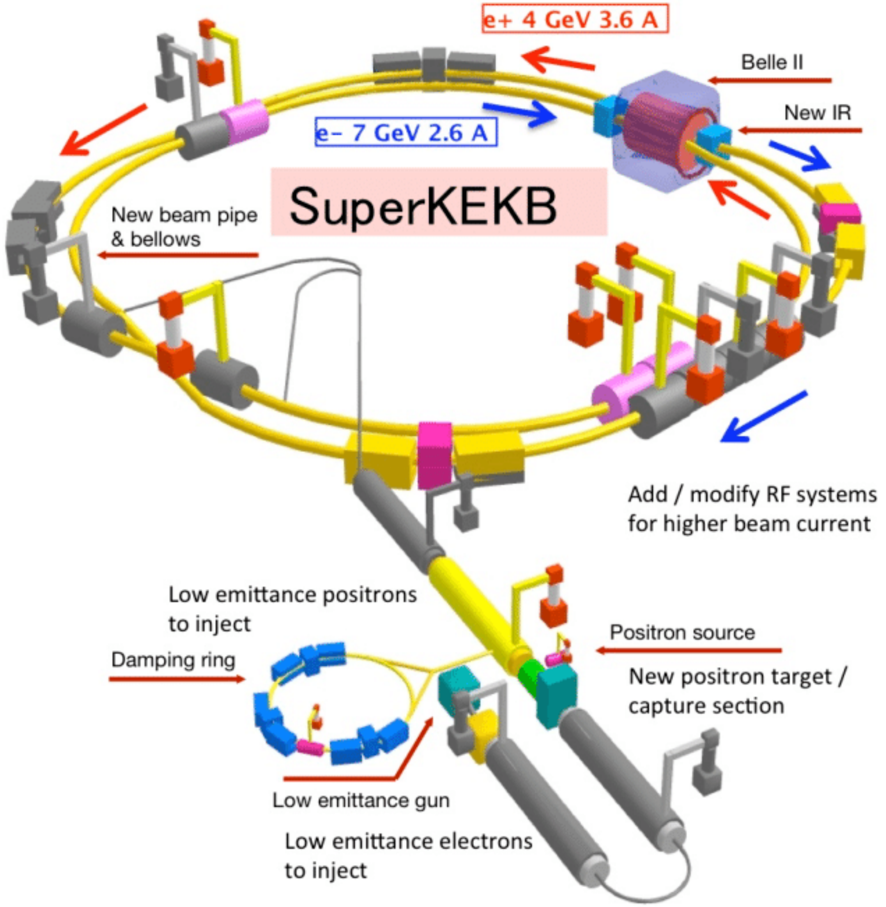
Located at KEK in Japan

Major improvement to data collection rate due to new beam squeezing technique









Belle II Detector

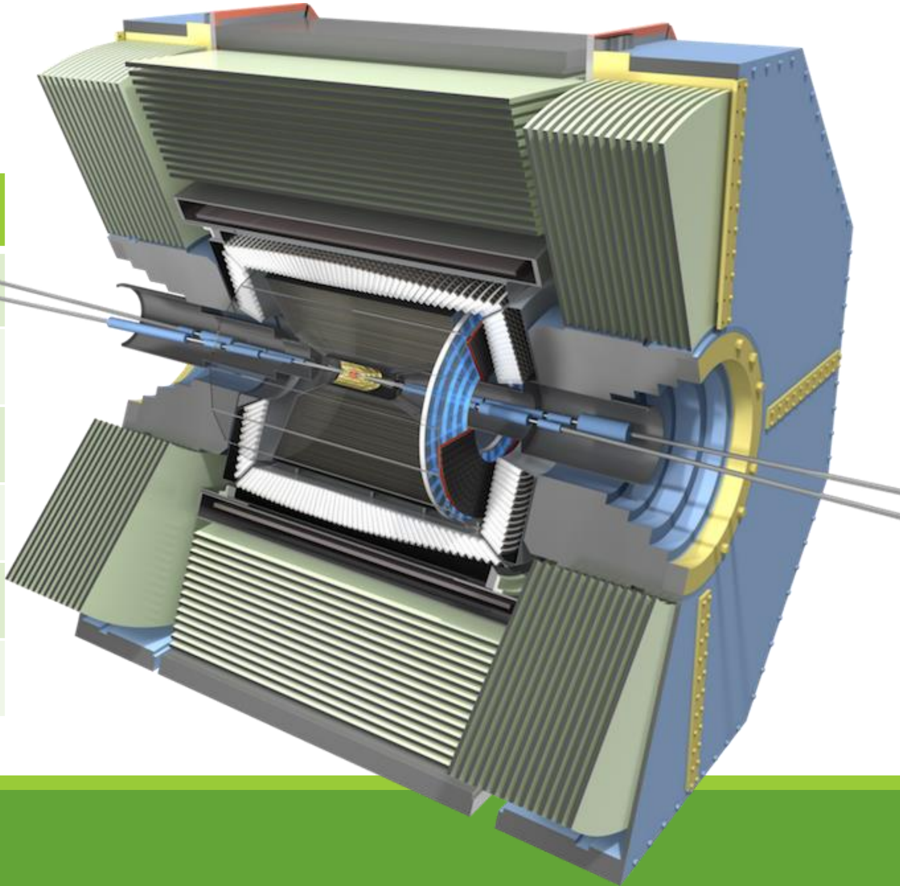
Belle II is considered a general purpose detector

Multiple sub-detectors work in tandem to build up the most complete picture of a collision possible

Collaboration was formed from the Belle and BaBar groups

- ~1000 active members, of which ~400 grad students

Sub-Detectors
PXD (Pixel Detector)
SVD (Silicon Vertex Detector)
CDC (Central Drift Chamber)
TOP/ARICH (Time-Of-Propagation / Aerogel Ring Cherenkov Detectors)
ECL (Electromagnetic Calorimeter)
KLM (Kaon-Long Muon Detector)

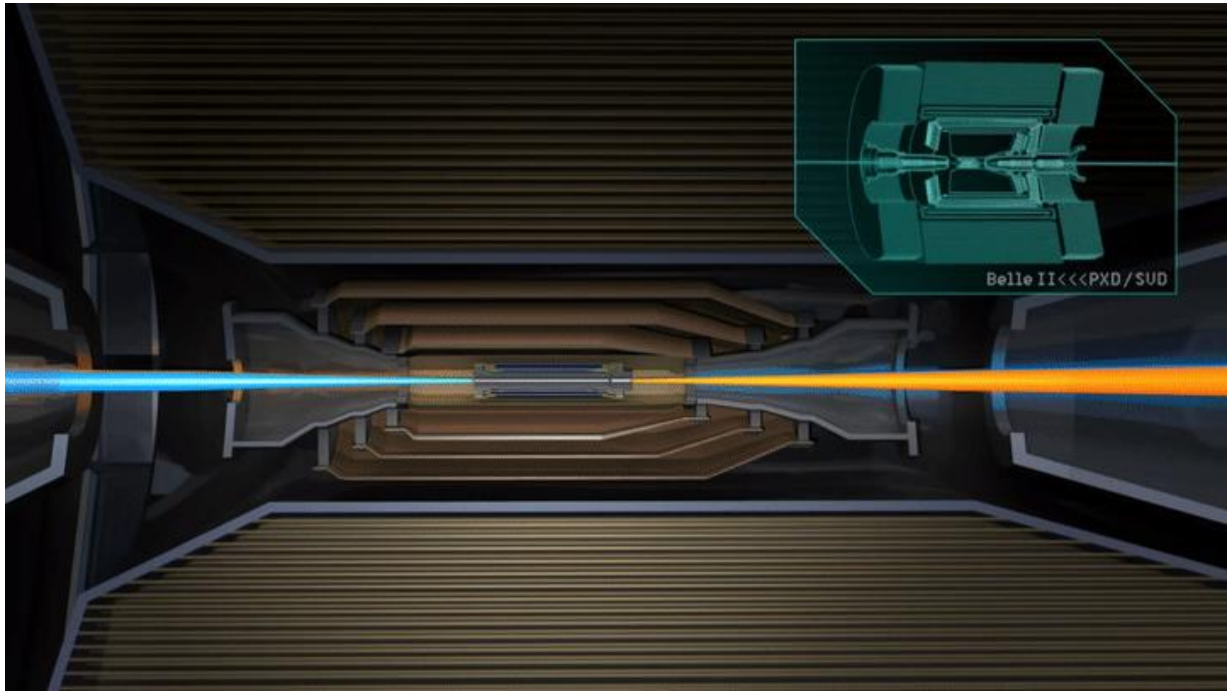


VXD (Vertex Detector)

The first two sub-detectors provide precise position reconstruction of the interaction point

PXD is made up of 50 micron squares of silicon in two layers around the beam pipe

SVD is long strips of silicon (12 cm) wrapped in a barrel-fashion around the beam pipe

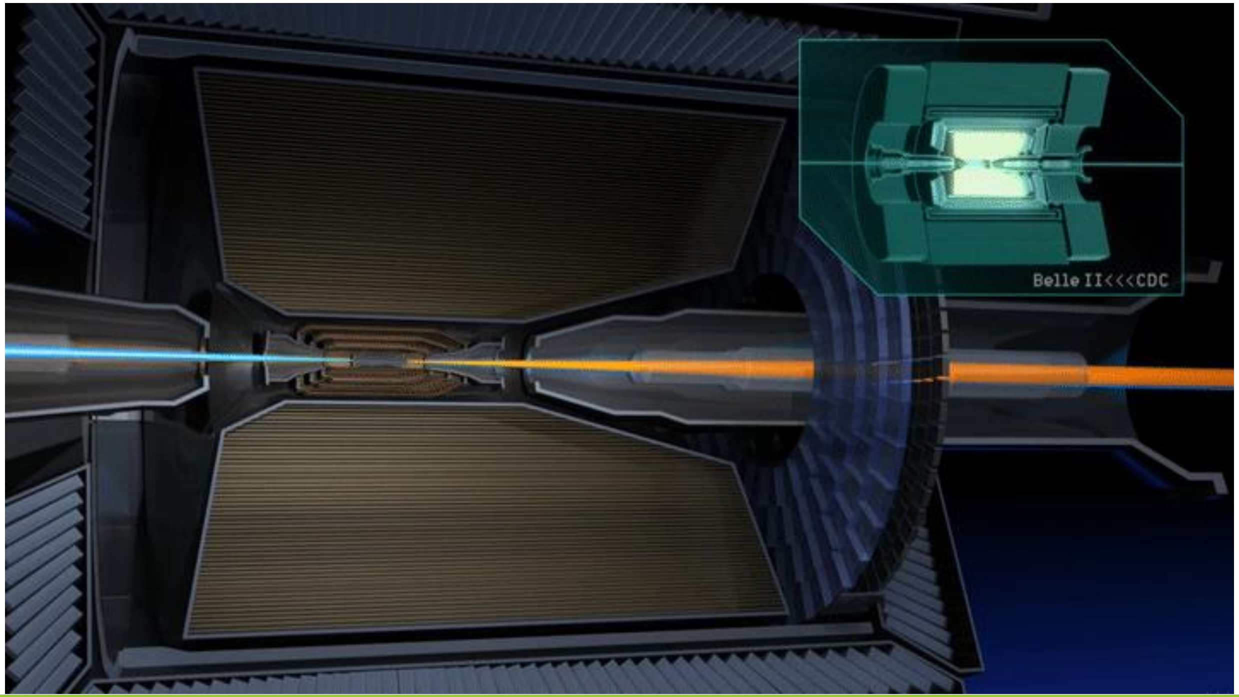


CDC (Central Drift Chamber)

The CDC tracks ionizing charged particles as they pass through ~1m of gas

14336 sense wires all within a 1.5 T magnetic field

Measures sign of electric charge, momentum, and dE/dx

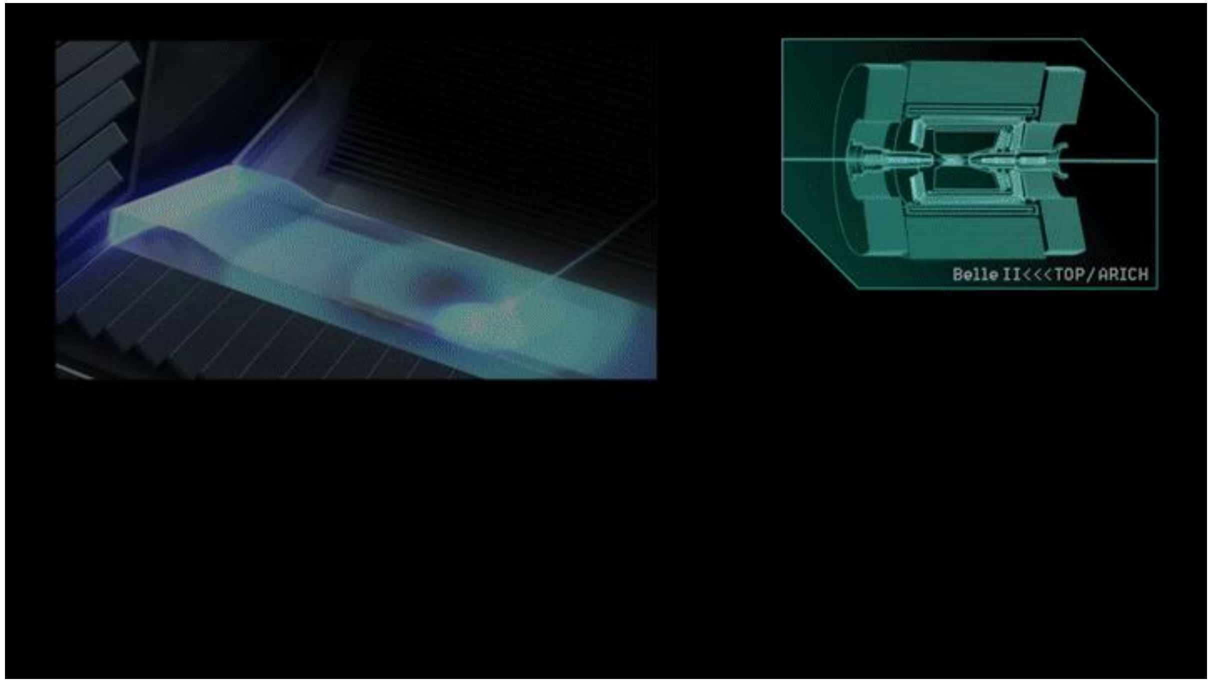


TOP/ARICH

Particles travelling faster than the speed of light in a medium emit Cherenkov radiation

Sonic boom of light with an opening angle dependent on the particle speed: $\cos\theta=(n\beta)^{-1}$

Knowing the speed and momentum of a particle allows us the extract the mass

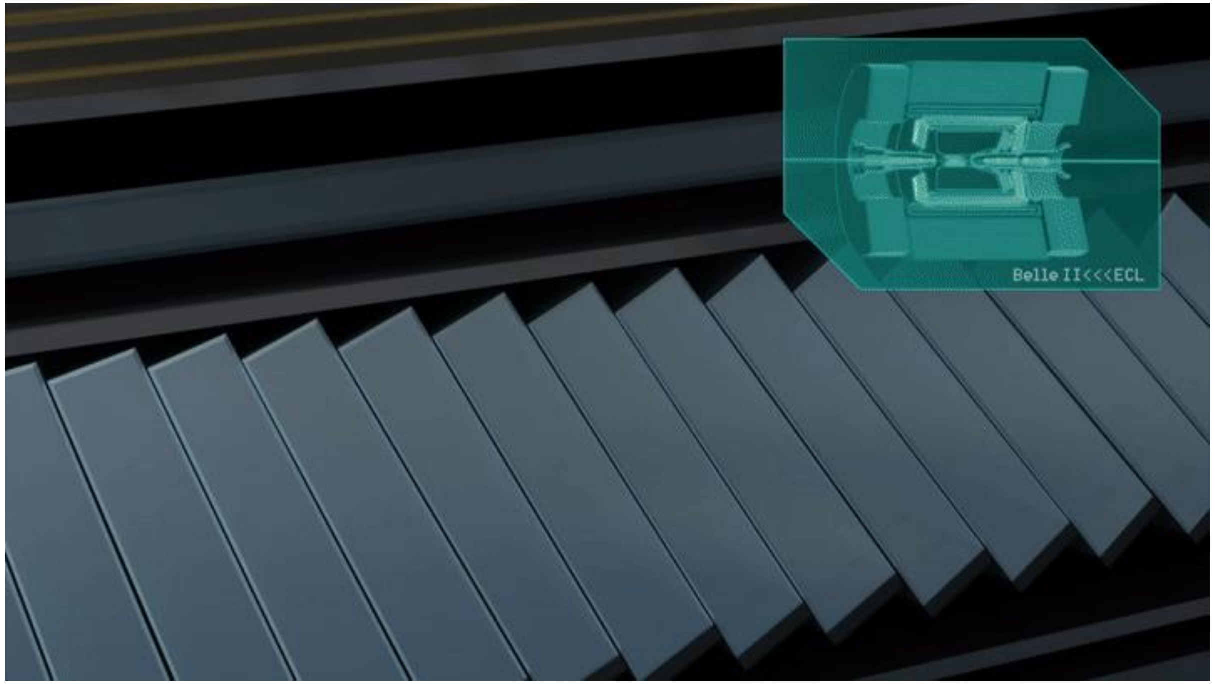


ECL (Electromagnetic Calorimeter)

Acts as a backstop for most particles due to the dense nature of the detector

~9000 salt (CsI(Tl)) crystals line the barrel and end caps of Belle II, and act as scintillators

Large Canadian contributions in Pulse Shaped Discrimination and timing calibrations

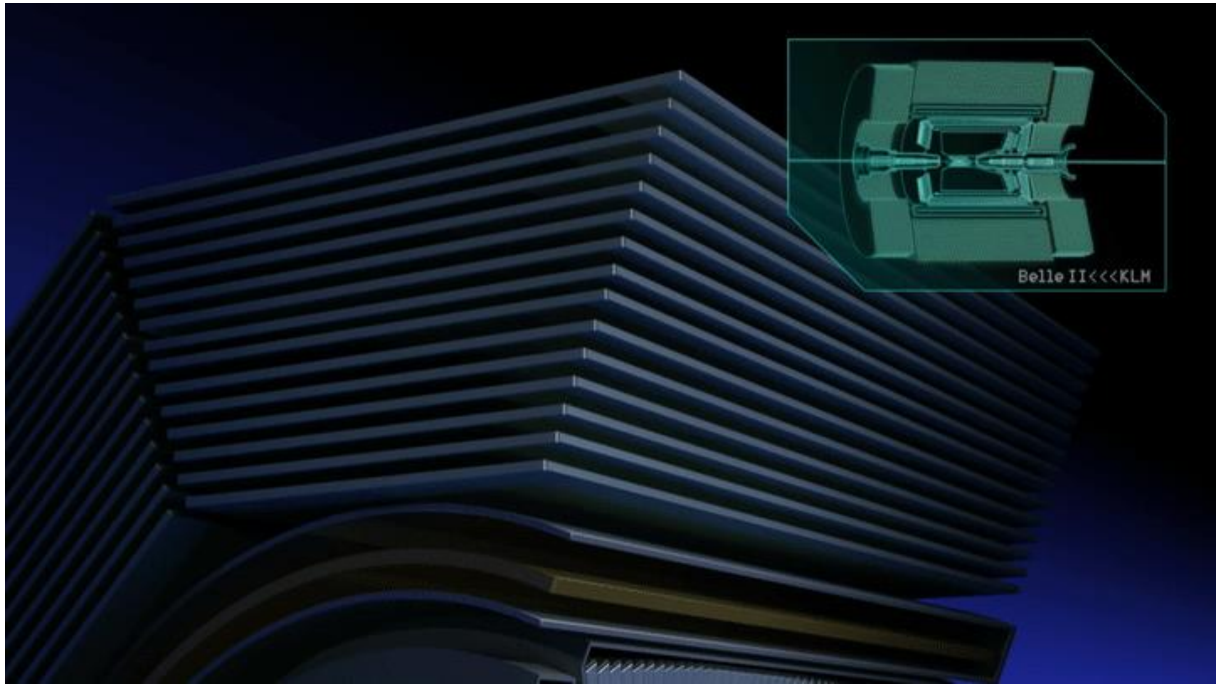


KLM (Kaon-Long and Muon Detector)

Some kaons (two quark meson (sđ)) and muons pass through the ECL

By instrumenting the magnet flux return we can detect the hadronic showers, and passing muons

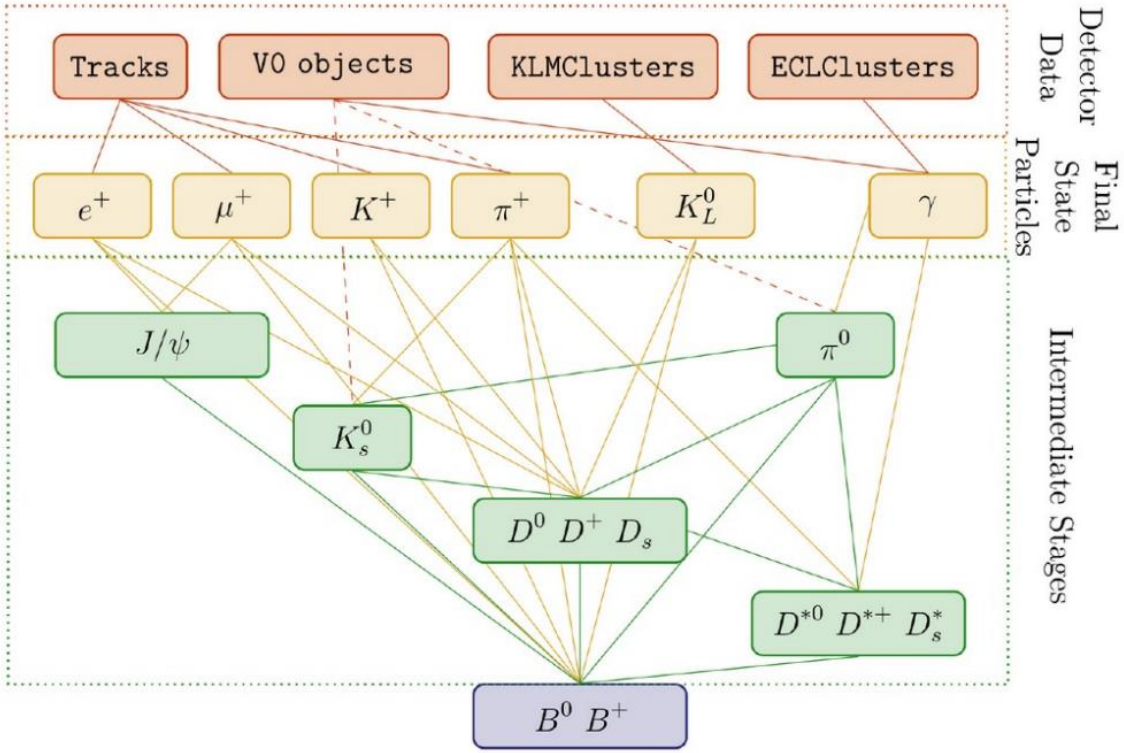
Consists of alternating plates of iron and scintillator paddles



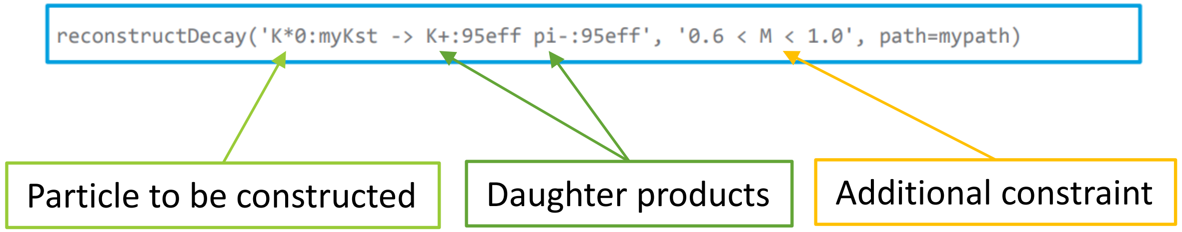
Belle II Event Reconstruction

From the raw detector data experts build lists of basic/final state particles

From the particle lists we can build up particles and events of interest



User friendly python package makes this easy for an analyst (open source basf2)



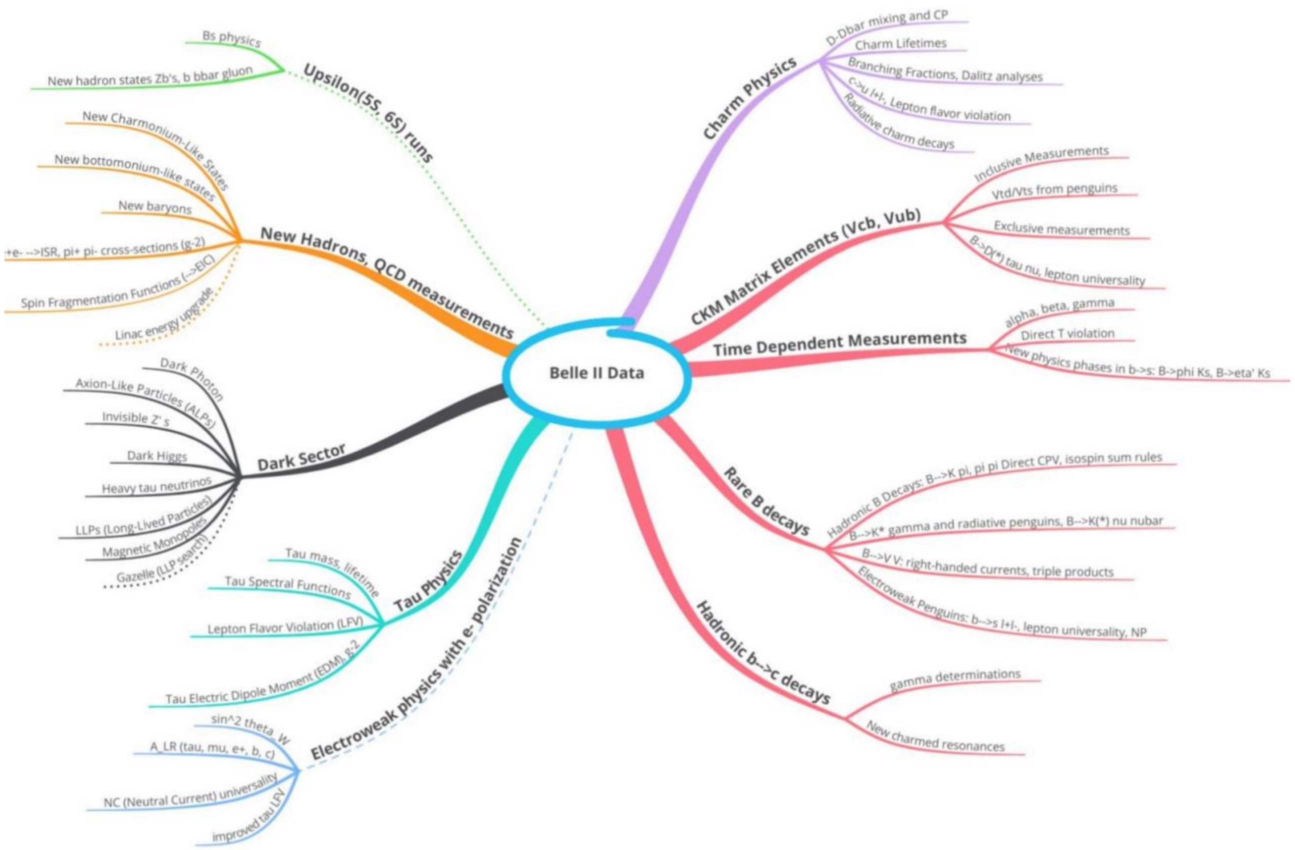
Once our particle chain is built we save all relevant variables (momentum, mass, charge, etc…) for fine tuning and plotting

Physics Results

The design of Belle II allows many different types of physics to be studied

Some examples:

- Lepton Flavour Violation
- Precision Tests of Standard Model
- Dark Higgsstrahlung

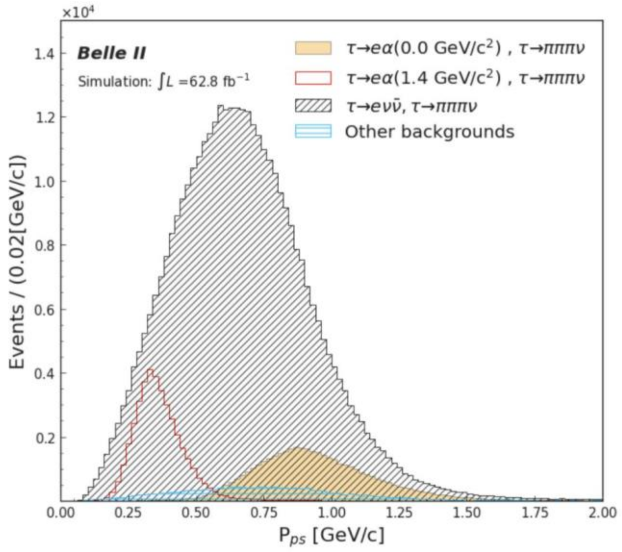


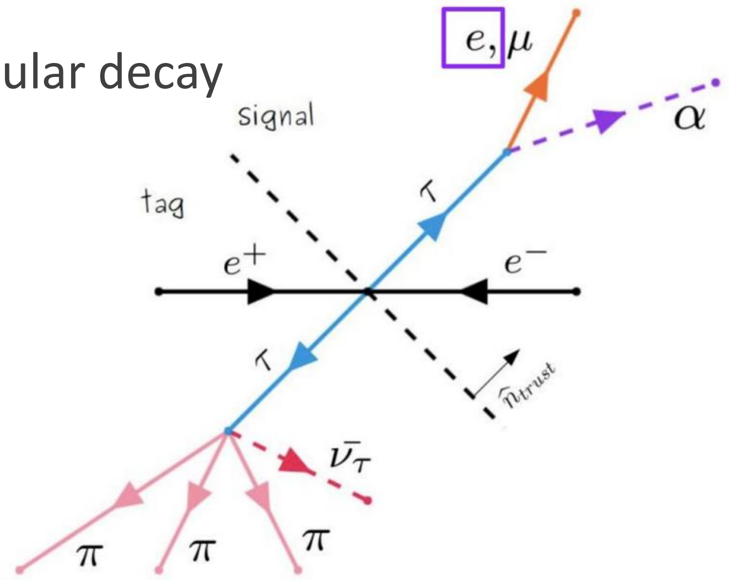
Lepton Flavour Violation in $\tau \to \ell\alpha$

Typically when a Tau particle decays into a electron or muon two neutrinos are emitted to preserve lepton flavour ($\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$)

The large mass of the τ allows the possibility for some new invisible particle, α, to be created in the decay and violate lepton flavour conservation

Need to find signal among irreducible background of the regular decay





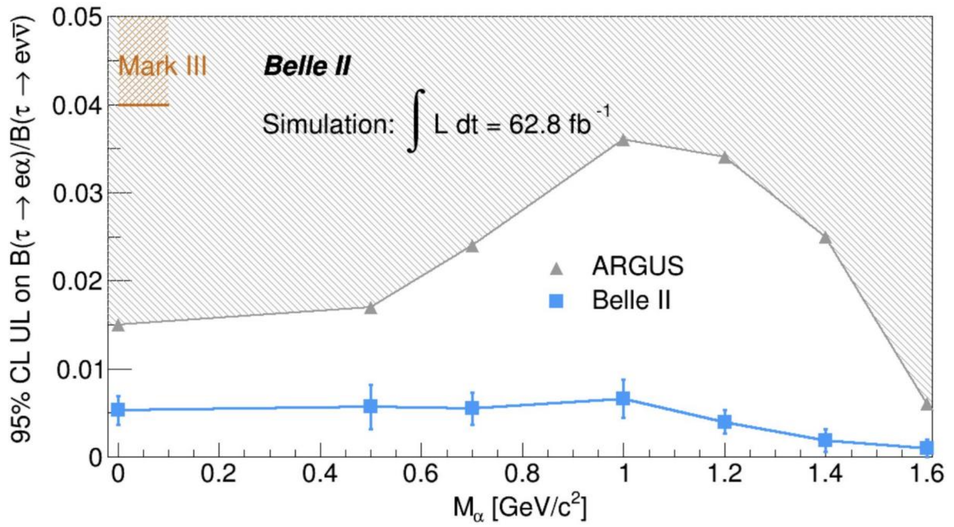
Lepton Flavour Violation in $\tau \rightarrow \ell\alpha$

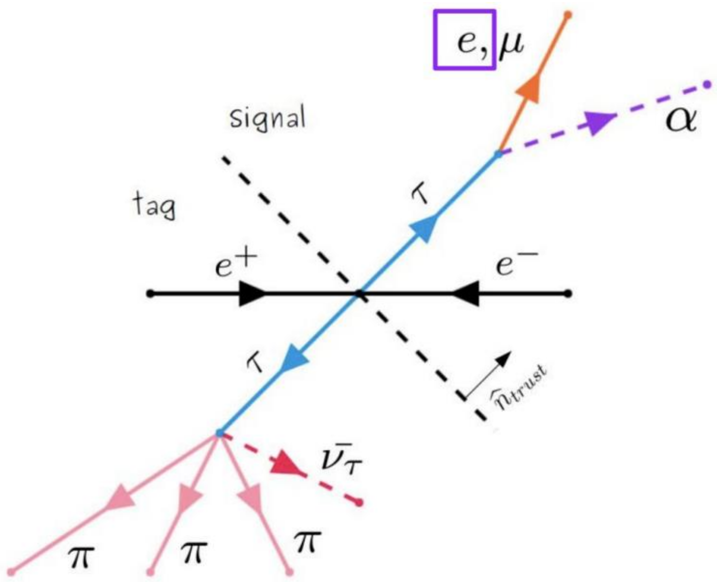
Analysis complicated by lack of knowledge of τ direction

Use the 3 pion momenta to approximate a “pseudo rest frame”

Shape analysis of electron momentum in rest frame gives best sensitivity

Data results expected this summer





Λ_c^+ Lifetime

The Λ_c^+ baryon is a "heavy proton" and contains a charm quark in place of an up quark

- Proton – uud, Λ_c^+ - udc

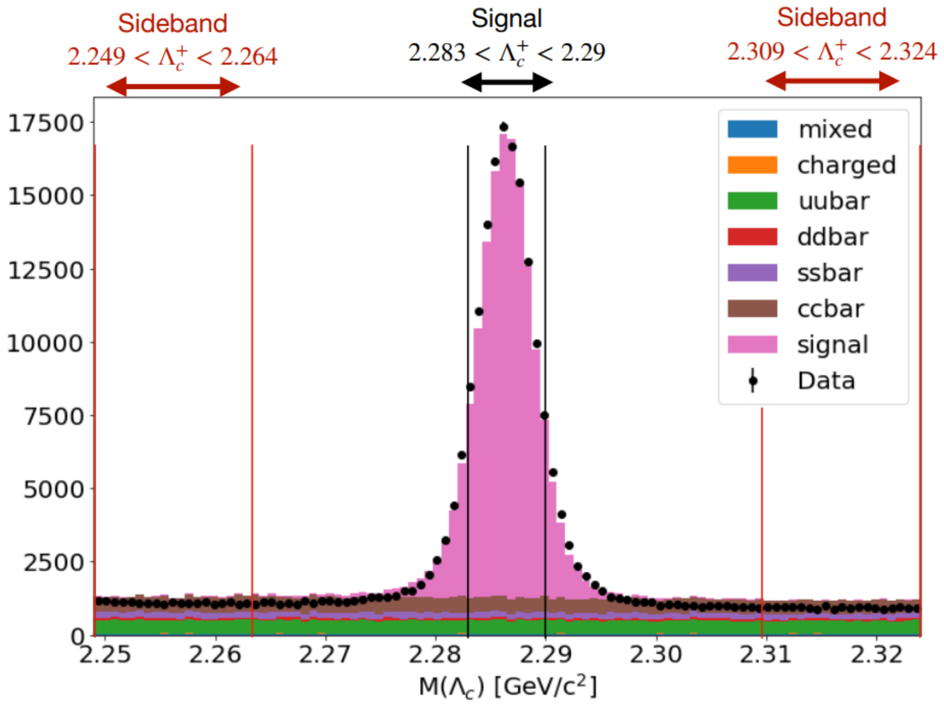
Precision measurement of the lifetime informs our understanding of the behaviour of heavy quarks

Improves theorist's ability to predict new physics

Measure lifetime from $\Lambda_c^+ \to pK^-\pi^+$ decay

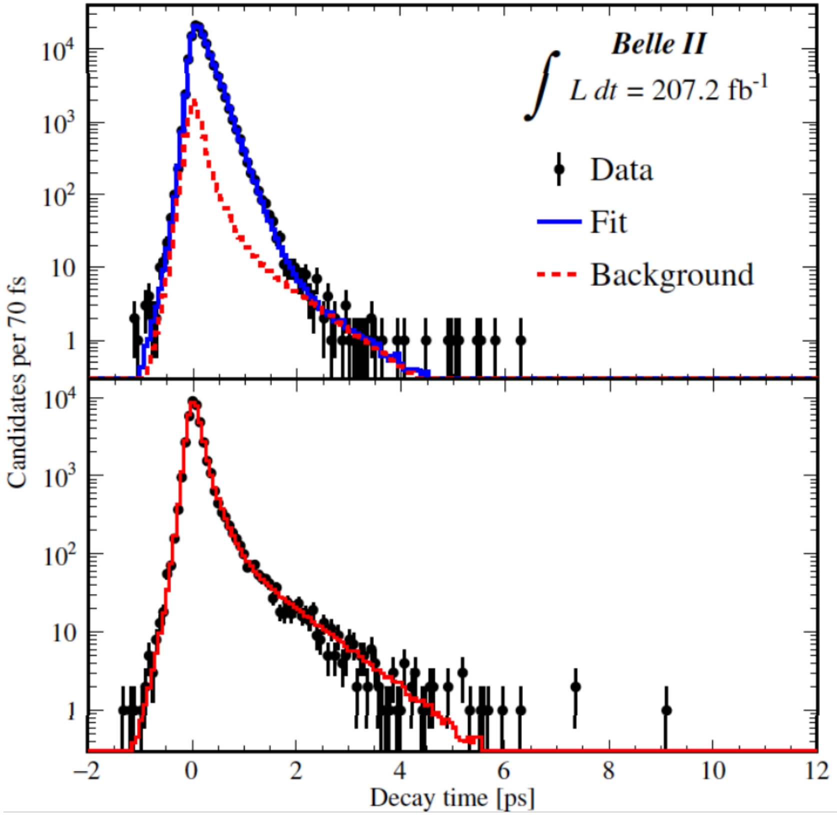
Lifetime is directly related to decay width

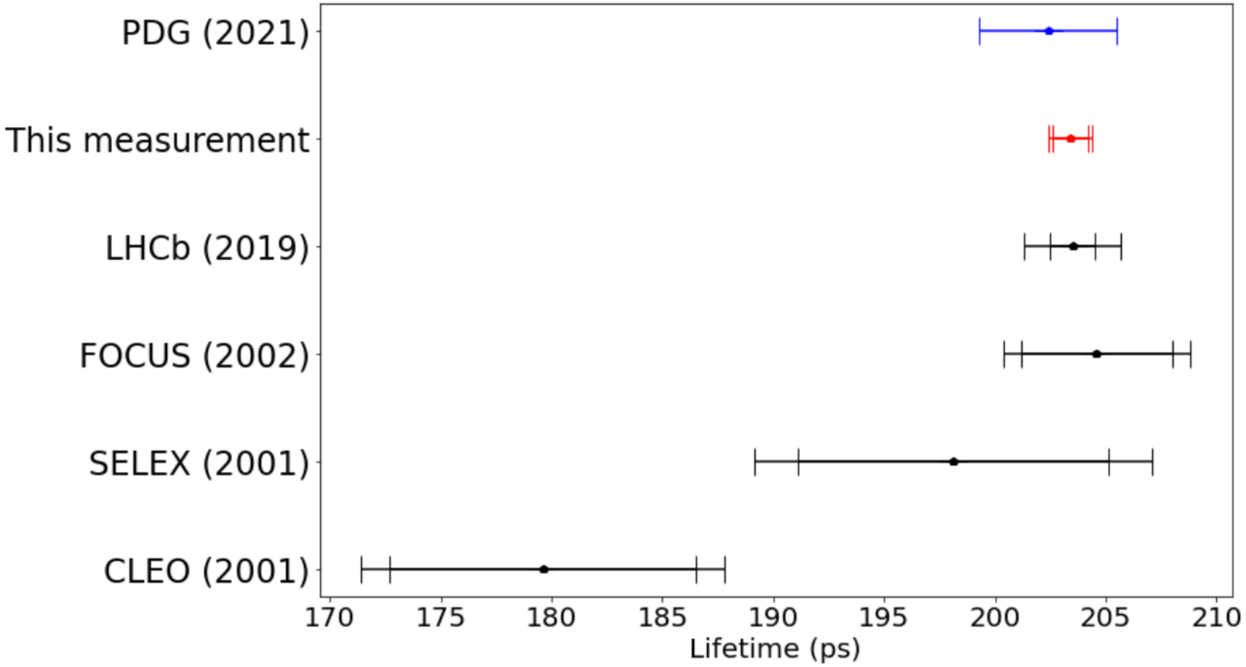
$$\tau = \frac{\hbar}{\Gamma}$$



Λ_c^+ Lifetime

New public result:





Lifetime = $203.4 \pm 0.8_{stat} \pm 1.0_{sys}$ fs

Dark Higgsstrahlung

Assuming dark matter exists and interacts with regular matter with more than just gravity it's reasonable to expect we might produce it in Belle II

One possibility with few previous constraints is a dark Higgs boson

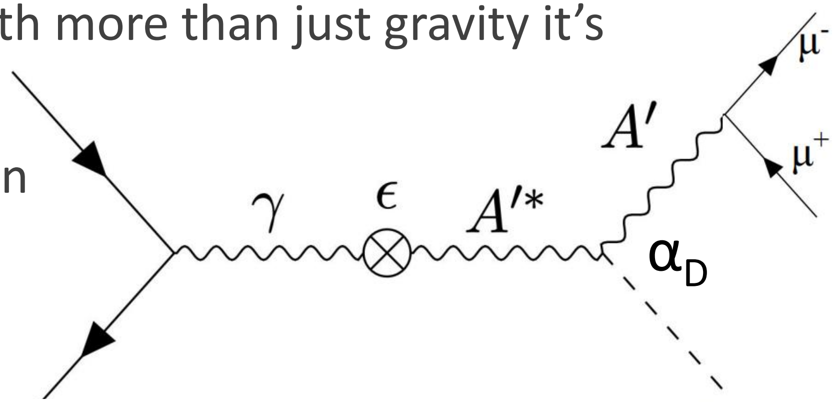
First produce a massive dark photon (A') through kinetic mixing

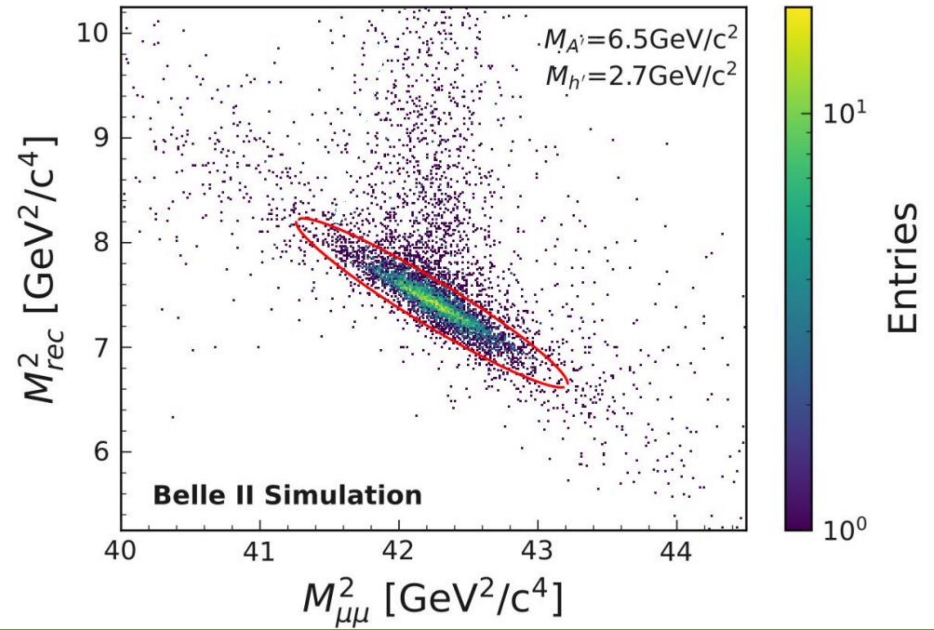
- $m_{h'} > m_{A'}$ regime probed by Belle and BaBar
- $m_{h'} < m_{A'}$ regime partially tested by KLOE

For the small dark Higgs mass the Higgs is long-lived

Look for A' decay in form of 2 muons

Signal appears as a peak in muon pair mass vs missing recoil mass

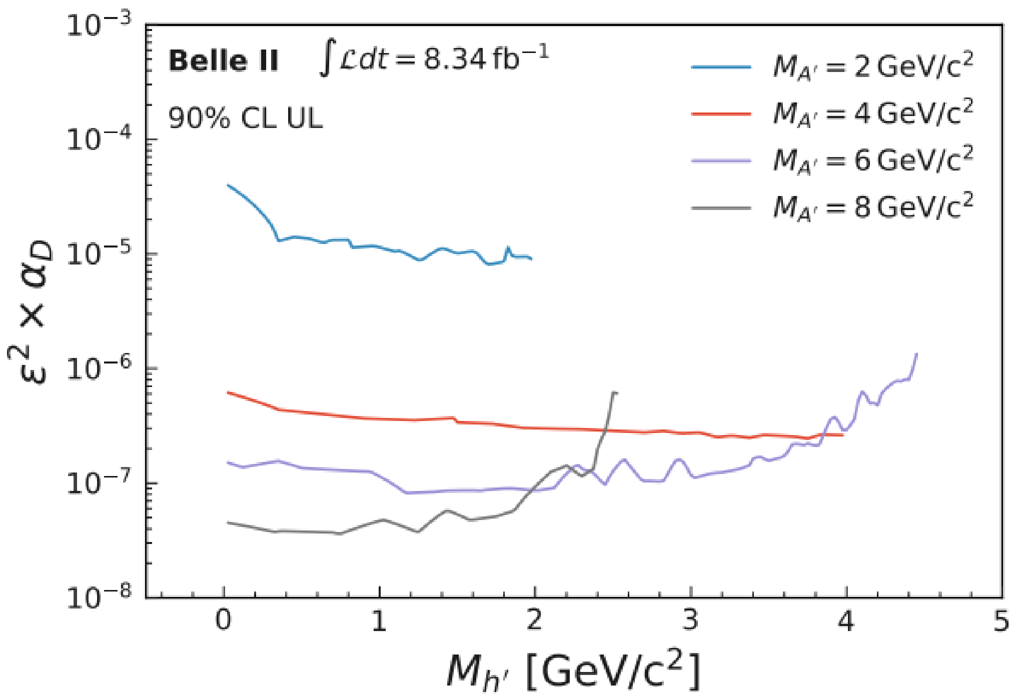


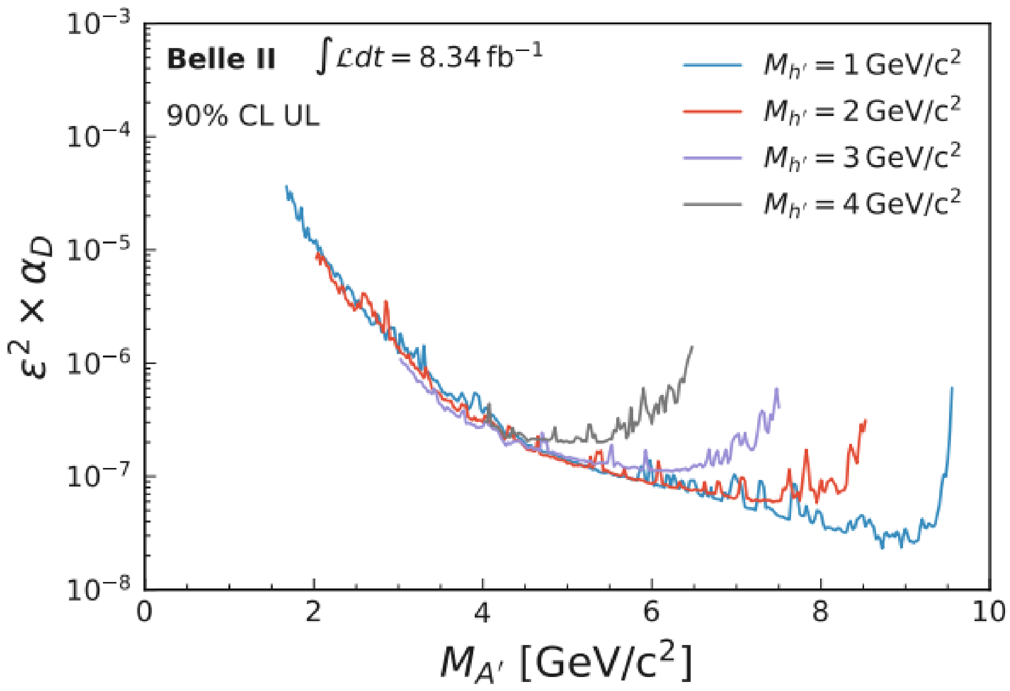


Dark Higgsstrahlung

New exclusion limits on mass of h’ and A’

Should be submitted to PRL soon





The Future

Belle II is quickly collecting data with world record integrated luminosities (measure of data rate)

Lots of new and exciting physics results being published or shown at conferences

Detector is performing well and results have significant improvement in systematic uncertainties compared to Belle and BaBar

Could we do better? (from Belle II Upgrade SNOWMASS paper)

- New layers for vertex detector
- New electronics for drift chamber
- New PMTs for TOP detector

Detector upgrades will improve detector performance but doesn’t enable any new physics analysis

However proposal to upgrade SuperKEKB with a polarized electron beam could enable a whole new physics program

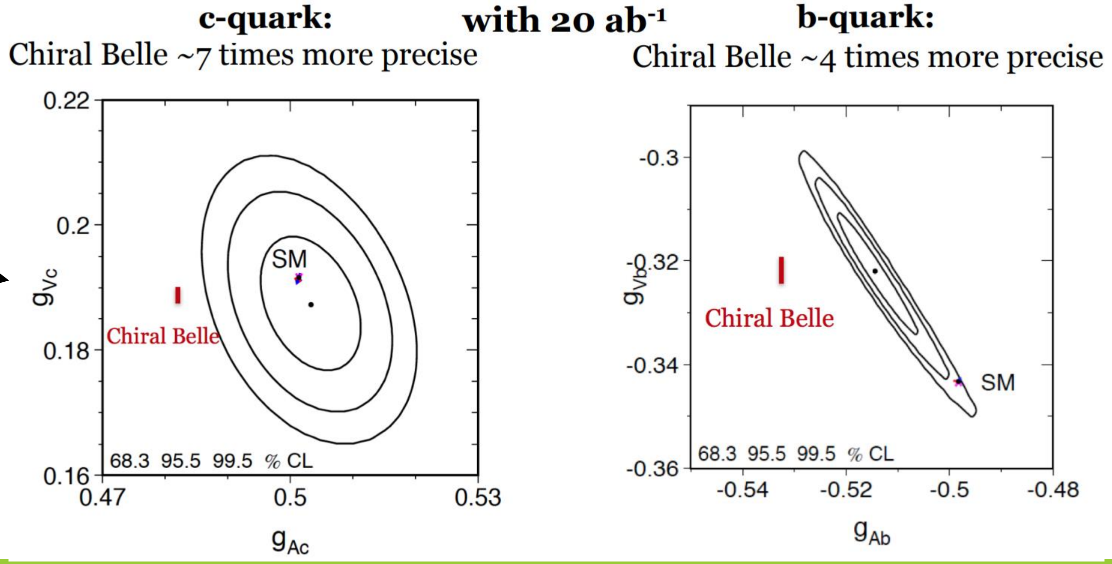
Beam Polarization Motivation

Beam polarization is being considered as a future upgrade to SuperKEKB

A polarized electron beam would allow Belle II to make many precise measurements of electroweak parameters. Including A_{LR} for e,μ,τ,c,b. For Born level s-channel process:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_f s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

Red bars show expected +/- 1 sigma uncertainty. Position arbitrary.



adapted from figure 7.4 of *Precision electroweak measurements on the Z resonance*, Physics Reports 427(5), 2006

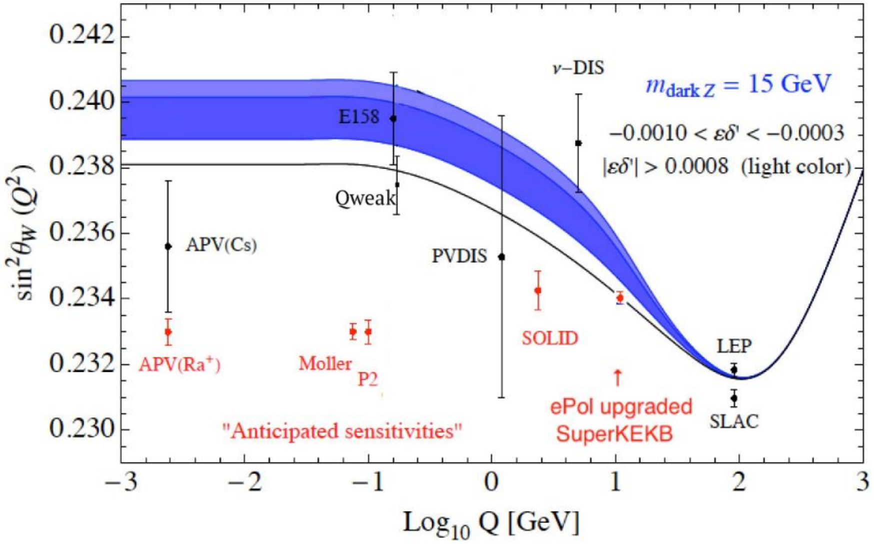
Beam Polarization Motivation

Beam polarization is being considered as a future upgrade to SuperKEKB

A polarized electron beam would allow Belle II to make many precise measurements of electroweak parameters. Including A_{LR} for e,μ,τ,c,b. For Born level s-channel process:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_f s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

Chiral Belle expects:
$\sigma(\sin^2\theta_W) \approx 0.0002$ (40 ab^{-1})



Red bars show expected sensitivity of future experiments. position arbitrary.

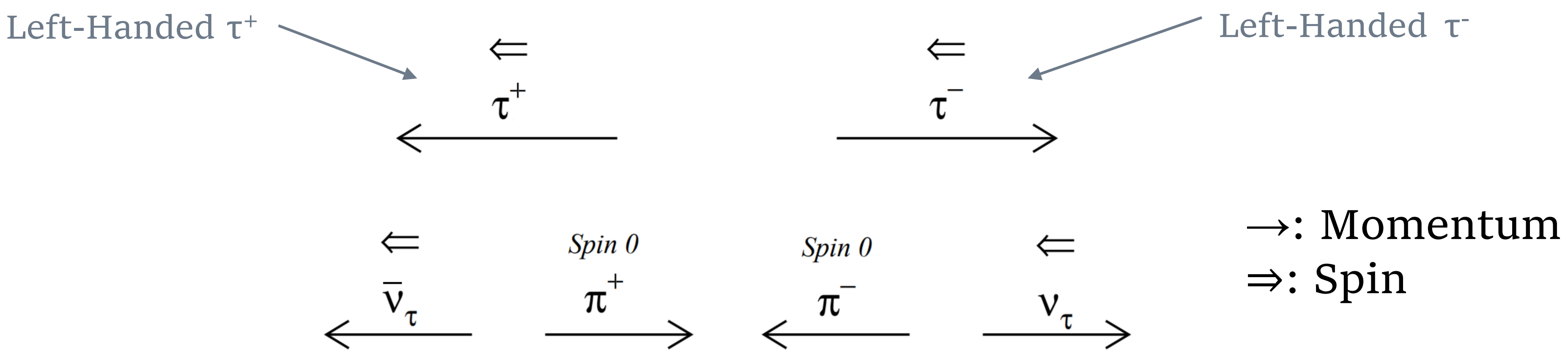
adapted from figure 3 of H. Davoudiasl, H.S. Lee and W.J. Marciano, Phys.Rev.D 92(5),2015

Tau Polarimetry

The polarization of tau's (P_τ) produced in e^+e^- collisions at 10.58 GeV is related to the electron beam polarization (P_e) through:

$$P_{\tau^-} = P_e \frac{\cos\theta}{1+\cos^2\theta} - \frac{8G_F s g_V^\tau}{4\sqrt{2}\pi\alpha}\left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right)$$

Tau polarization information can be extracted from the kinematics of the tau decay



Tau Polarimetry

Proof of concept completed at BaBar (predecessor to Belle II)

BaBar beam was unpolarized but can show precision achievable

Preliminary measurement is:

PRELIMINARY

$$\langle P \rangle = -0.0010 \pm 0.0036_{\text{stat}} \pm 0.0030_{\text{sys}}$$

Publication expected this summer

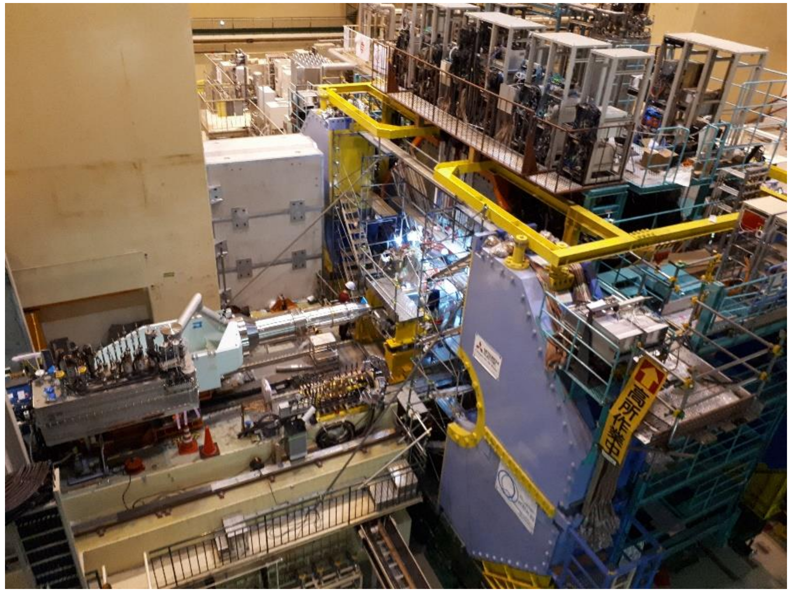
Implementation at Belle II expected soon

Conclusions

Belle II is demonstrating the ability to make world leading precision measurements

Expectation is our precision will improve further as we better understand the detector and implement upgrades

Many analysis, software, and hardware projects available for new grad students



Enjoy your summer

Thank you for listening