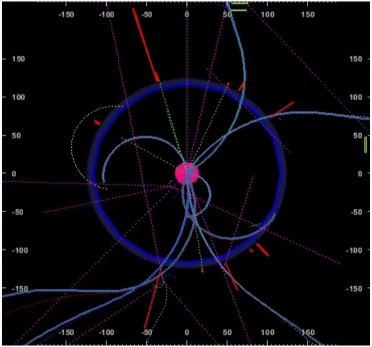
Physics at Belle II

Kevin Varvell

Sydney CPPC Meeting 27-Jun-2022

Particle Physics Group
The University of Sydney



What has particle physics given us so far?

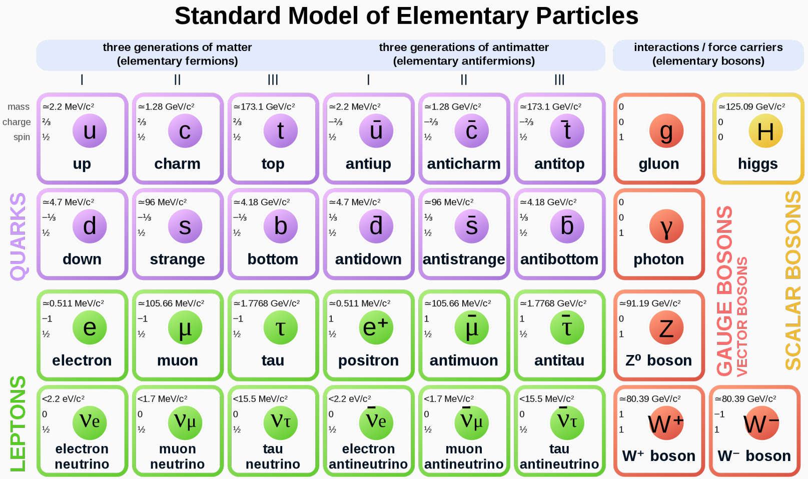


Image: Wikipedia: Particle Physics

What else would we like to know?
(Selections from a long list)

Why three generations?

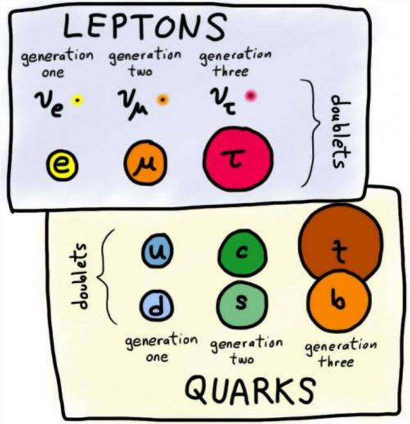


Image: Jim Pivarski, CERN

What else would we like to know?

What's with the masses?

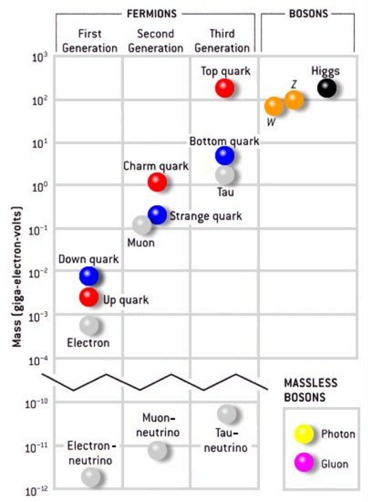
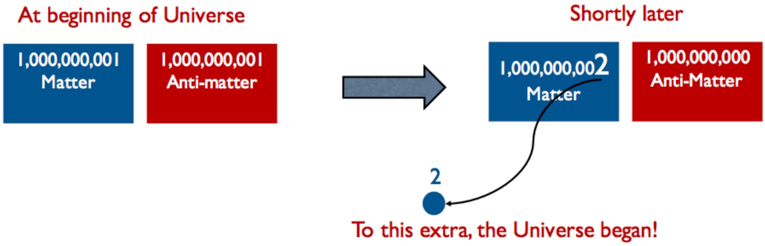


Image: http://universe-review.ca/F15-particle01.htm Figure 15-04a

Why is the Universe overwhelmingly matter?



$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Image: S. Cao VJSE 2016

What else would we like to know? (Selections from a long list)

What lurks in the dark?

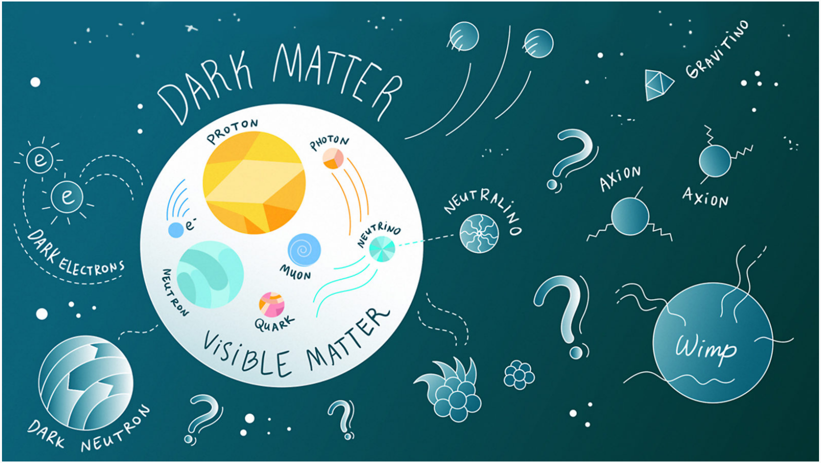


Image: Sandbox Studio, Chicago

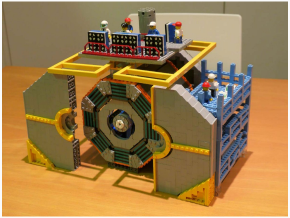
Today's lecture is brought to you by the letter B

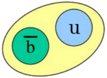
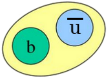
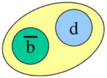
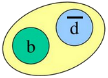
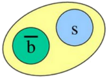
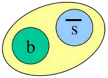
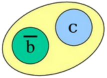
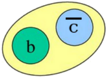
b is for *bottom*-quark

B is for B-Factory

B is for B-meson

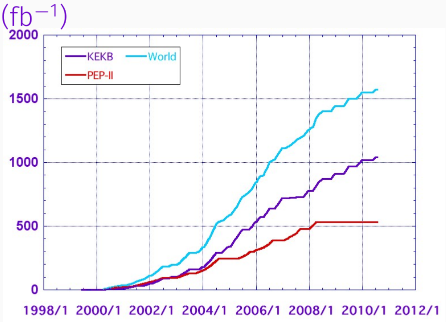
B is for Belle II



		Mass		
B^+		5.28 GeV		B^-
B^0		5.28 GeV		$\bar{B}^0$
B_s^0		5.37 GeV		$\bar{B}_s^0$
B_c^+		6.27 GeV		B_c^-

Only the top two rows will really concern us today

The first decade of this century was the "Age of the B-factories"

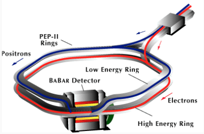


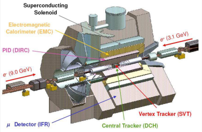
Designed to make lots of B mesons

BaBar: $\sim$ 470 million $B\bar{B}$ pairs

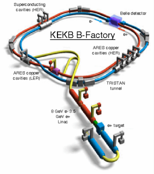
Belle: $\sim$ 770 million $B\bar{B}$ pairs

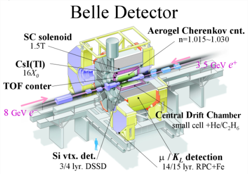
PEP-II/BABAR USA (1999-2008)





KEKB/Belle Japan (1999-2010)



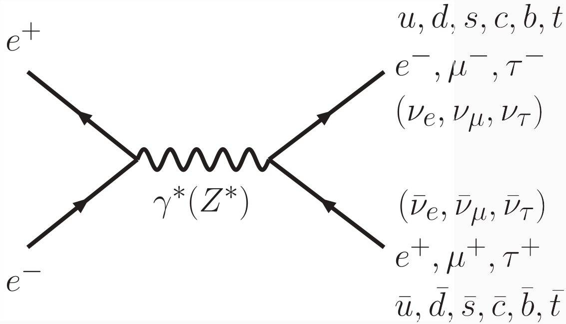


Electron-positron colliders

University of Sydney a part of Belle

What happens when electrons and positrons collide?

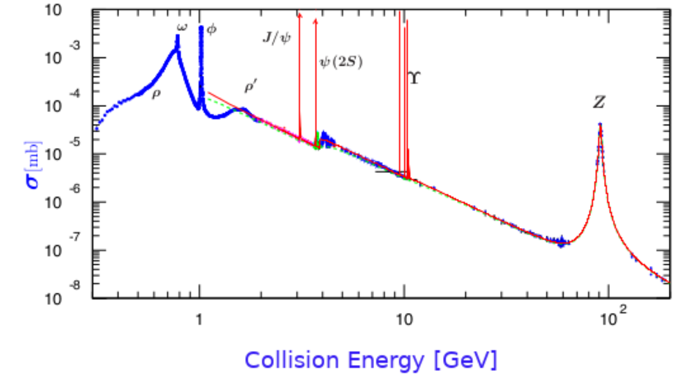
At lowest order



plus t-channel Bhabha scattering, annihilation to photons, etc.

Electron-positron colliders operate at a range of energies

Cross section for $e^+ + e^- \rightarrow hadrons$



Note the *resonances*

B-factories exploit the $\Upsilon(4S)$ resonance ($b\bar{b}$ bound state)

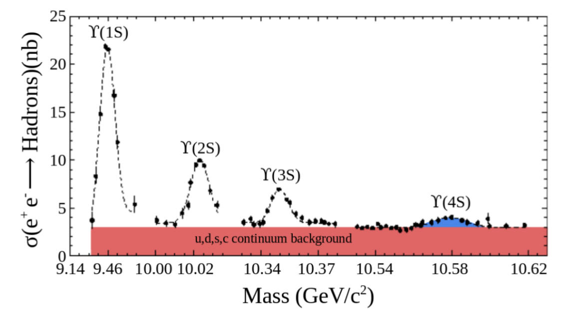
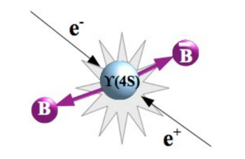


Image from arXiv:0901.1443 [hep-ex]

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



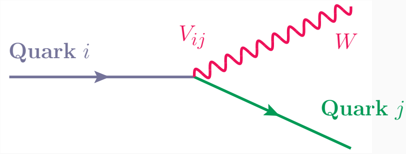
$$e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow B^0 + \overline{B}^0 \quad \sim \text{ half the time} \quad (B^0 : d\bar{b})$$

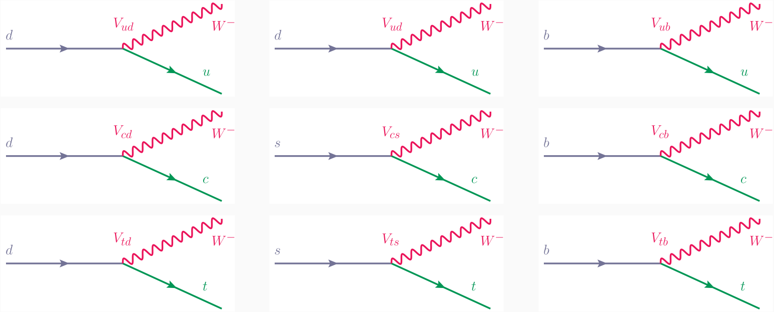
$$e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow B^+ + B^- \quad \sim \text{ half the time} \quad (B^+ : u\bar{b})$$

The mean lifetime of B^+, B^0 mesons is $\sim 1.5 \times 10^{-12}$ s

They decay in *thousands* of different decay modes

Weak couplings of quarks can cross generations





This is formally captured in the Cabibbo-Kobayashi-Maskawa (CKM) matrix

From the SM Lagrangian density ...

$$\mathcal{L}_{qW} = -\frac{e}{\sqrt{2}\sin\theta_W}\left(u_L^\dagger, c_L^\dagger, t_L^\dagger\right)\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} \tilde{\sigma}^\mu d_L \\ \tilde{\sigma}^\mu s_L \\ \tilde{\sigma}^\mu b_L \end{pmatrix} W_\mu^+ + \text{Hermitian conjugate}$$

The V_{ij} are parameters of the SM (measured in experiment).

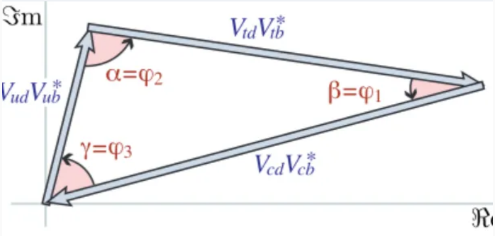
The CKM matrix is roughly diagonal, and the elements can in principle be complex.

The matrix should be unitary (gives 9 equations):

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix}\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The unitarity of the CKM matrix can be represented in the complex plane

The most well-know equation: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$



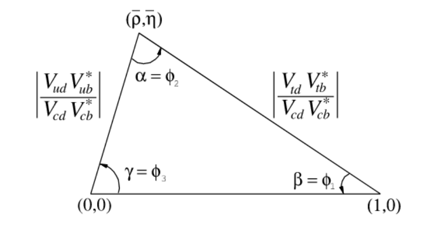
There are six triangles in total

A popular parametrization of V_{CKM} is Wolfenstein's

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

Four independent parameters A, λ, ρ, η. $\lambda = |V_{us}| \approx 0.22.$

Recast Unitarity Triangle as



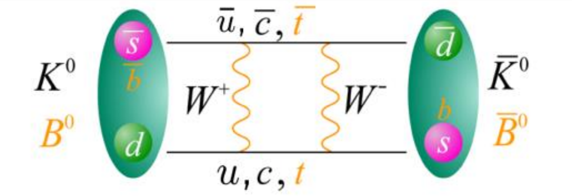
$\bar\rho + i\bar\eta = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$

Measure params experimentally

$\bar\eta \neq 0 \Rightarrow CP$ violation (CPV)

$\phi_1 + \phi_2 + \phi_3 \neq 180° \Rightarrow$ BSM

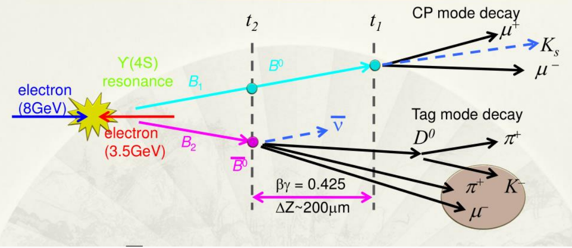
Matter can oscillate into antimatter via the weak interaction

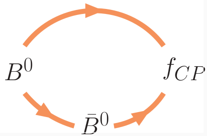


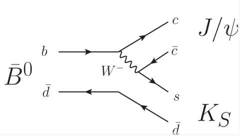
CPV with neutral kaons has been known since 1964.
Experiment of Christenson, Cronin, Fitch and Turlay. PRL **13** 138 (1964)

What about for *B* mesons?

Belle PRL **87** 091802 (2001) and BaBar PRL **87** 091801 (2001) both got result

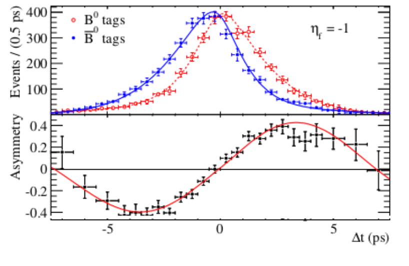




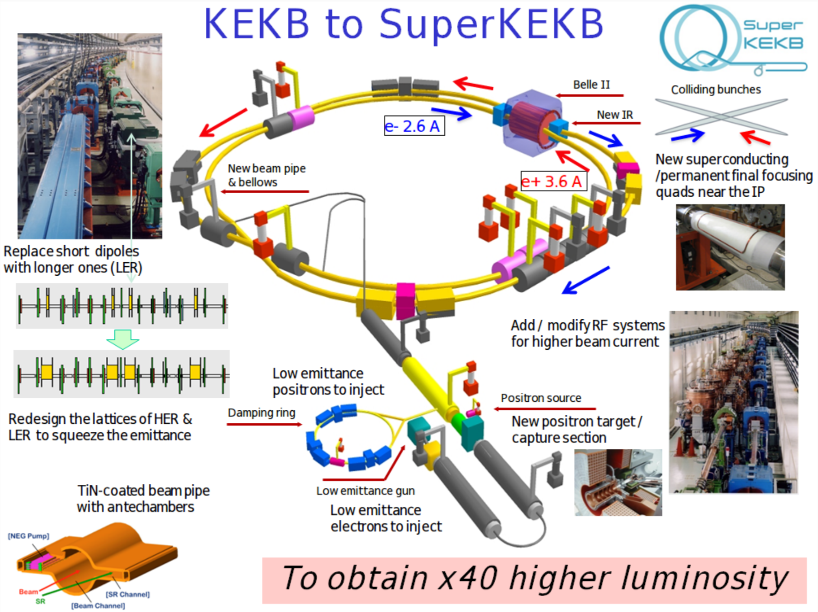


Belle result at right

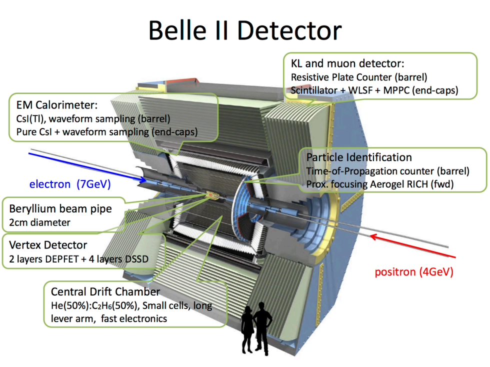
The fact that the red and blue curves do not lie on top of each other is evidence for *CP* violation



In operation since 2019 - SuperKEKB and Belle II



Belle II is an improved version of Belle, largely to handle higher collision rates



Aiming for 50 $\mathrm{ab}^{-1} = 50000\ \mathrm{fb}^{-1} \approx 50 \times$ Belle data

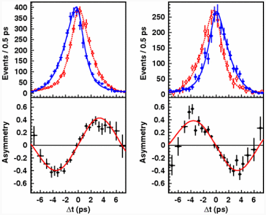
This is around 50 billion $B\bar{B}$ pairs of mesons

Around 420 million so far ...

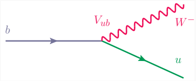
Belle II has many physics aims relating to “Flavour Physics”

Here are three:

- *CP* violation in *B* decays (continue the Belle legacy)

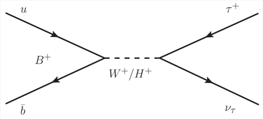


- Explore the CKM matrix governing weak transitions e.g. $B^0 \to \pi^- \ell^+ \nu_\ell$



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

- Search for deviations from the Standard Model via rare *B* decays e.g. $B^+ \to \ell^+ \nu_\ell$, e.g. $B \to D^{(*)} \tau^+ \nu_\tau$



Rare decays have their pros and cons

The cons:

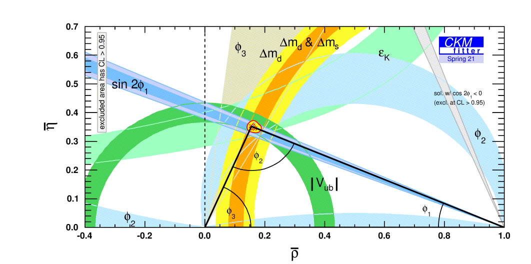
- Less signal decays to look for $\Rightarrow$ Need lots of data
- Harder to see signal above backgrounds which mimic the signal

The pros:

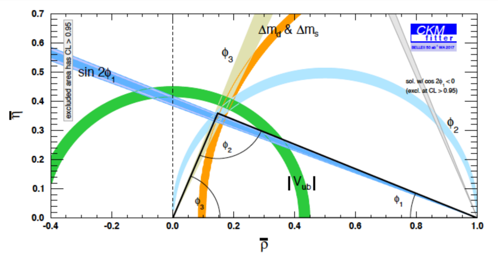
- Rare in the Standard Model means easier to tell if there is a deviation from the Standard Model prediction

We would like to test unitarity of CKM matrix more precisely

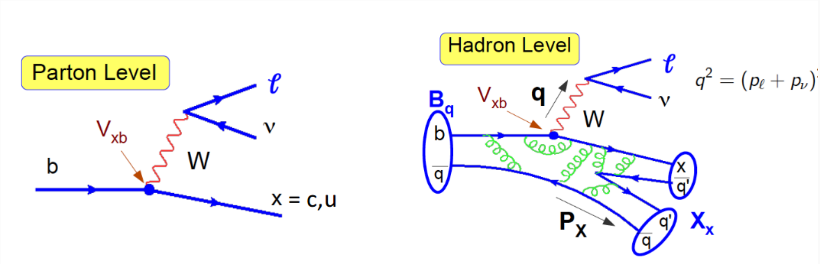
Currently



Belle II 50 ab^{-1}
(projection)

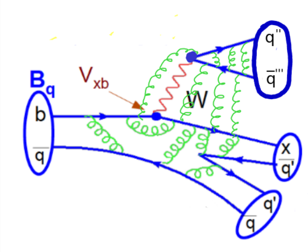


The strong interaction can make life complicated when studying the weak



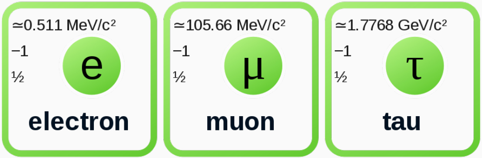
From J. Dingfelder, FPCP 2018 talk

More complicated form factors
$\Rightarrow$ rely on Lattice, theory input



Have cracks started appearing in the Standard Model?

In the Standard Model, electrons, muons and taus behave exactly the same apart from effects due to having different masses



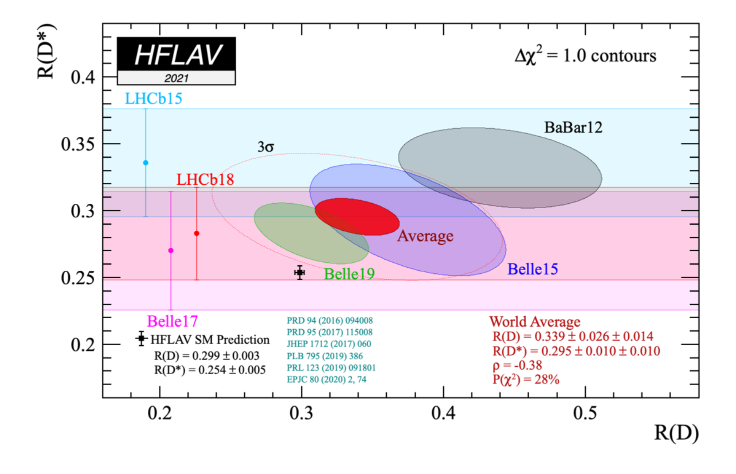
Known as Lepton Flavour Universality

In the last few years, observation of "Flavour Anomalies" have started to challenge this

Deviations from the SM in rare decays?

Here is one example of a flavour anomaly: $R(D^{(*)})$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \quad \text{where} \quad \ell = e, \mu$$



Potential explanations for $R(D^{(*)})$ involve "new physics"

blue: Standard Model particle red: new particle

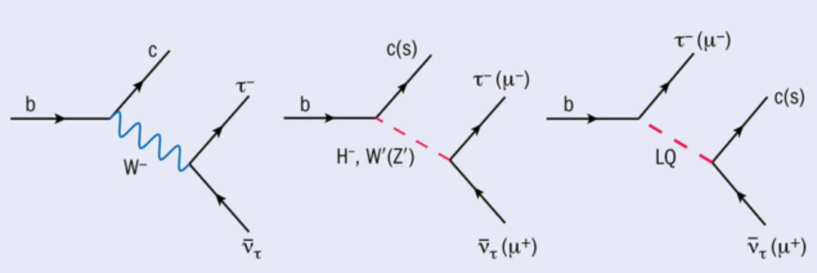


Image: CERN Courier May/June 2019

H^- is a charged Higgs boson

W', Z' are heavier versions of W and Z bosons

LQ is a "lepto-quark"

all predicted by various new theories beyond the Standard Model

Here is a second example of a flavour anomaly

$$R(K^*) = \frac{\mathcal{B}(B \to K^* \mu^+ \mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)}$$

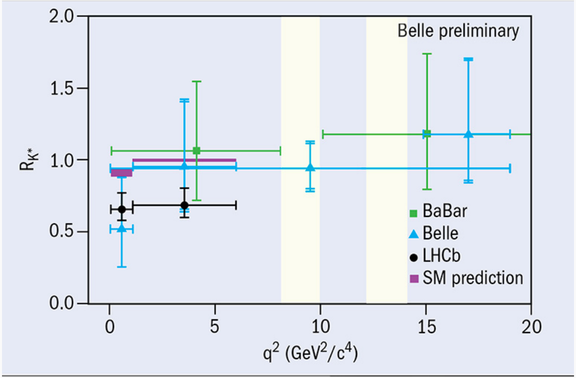


Image: CERN Courier May/June 2019

q^2 is related to the energy/momentum carried by the pair of charged leptons

Again, potential explanations for $R(K^*)$ involve "new physics"

blue: Standard Model particle red: new particle

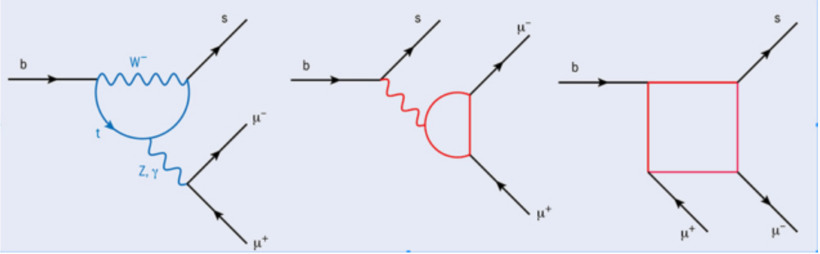
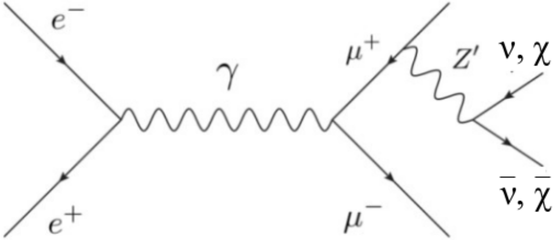


Image: CERN Courier May/June 2019

Further reading if interested

https://cerncourier.com/a/the-flavour-of-new-physics/

Invisibly decaying Z' in $e^+e^- \to \mu^+\mu^- Z'$ $L_\mu - L_\tau$ models

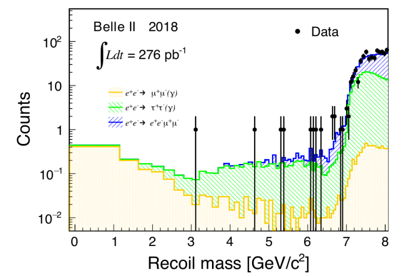


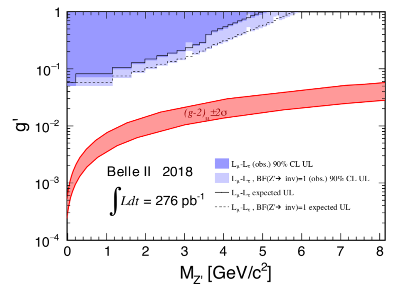
B. Shuve and I. Yavin, Phys. Rev. D 89, 113004 (2014).
W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, JHEP 12, 106 (2016).

Invisibly decaying Z' in $e^+e^- \to \mu^+\mu^- Z'$

Belle II first physics paper

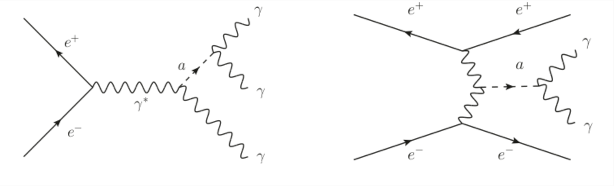
Phys. Rev. Lett. 124, 141801 (2020)



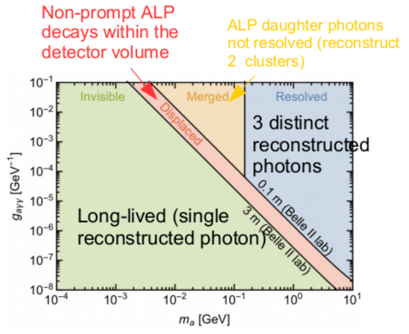


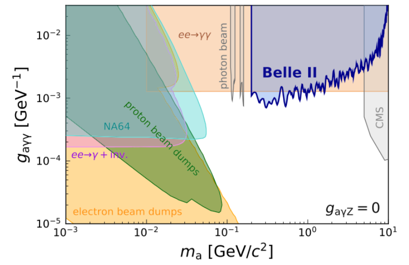
Also search for $e^+e^- \to e^\pm\mu^\mp Z'$

ALP = Axion-Like-Particle: pseudoscalar particle coupling to bosons



$$\tau \sim 1/(m_a^3 g_{a\gamma\gamma}^2)$$

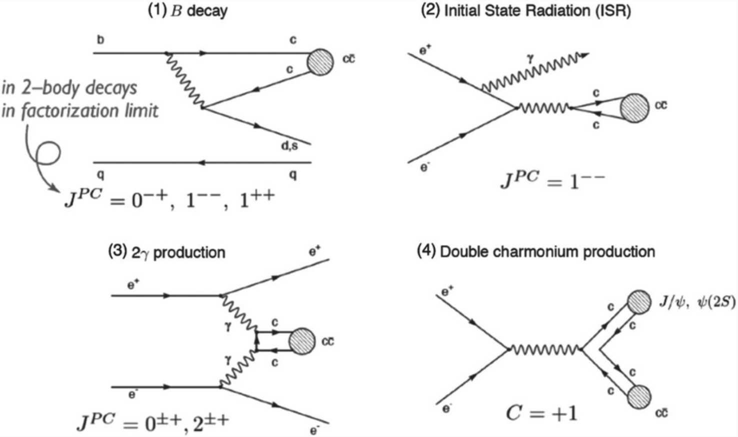




PRL 125 161806 (2020)

What else can Belle II do? Search for new strongly bound states

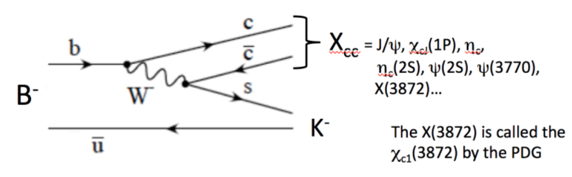
Here are four ways to produce charmonium-like states

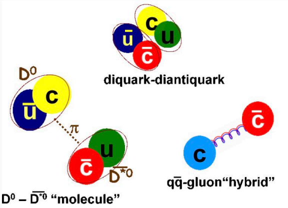


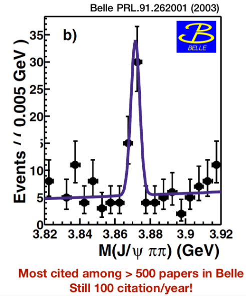
https://arxiv.org/abs/1603.09229v1

A classic example is the $X(3872)$

Discovered by Belle in 2003

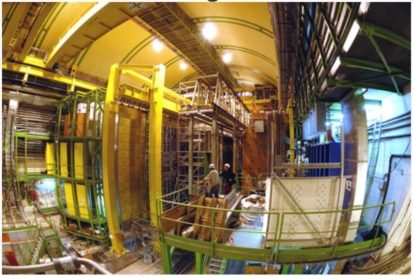






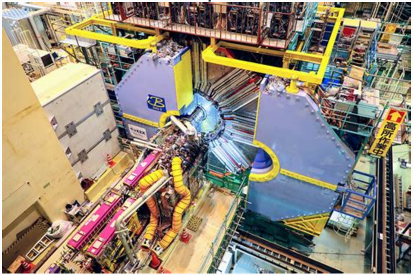
Belle II has competition

LHCb at CERN’s Large Hadron Collider



LHCb: Many more *B* mesons

Belle II at KEK in Japan



Belle II: Better with decays with missing energy

It’s still early days but much to look forward to ...

- Belle has published over 600 papers (and counting)

- Belle II has published only 6 papers to date (but plenty in pipeline)

- Belle II will run into the 2030s