Flavor Physics

A short (and biased!) introduction

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Nuclear and Particle Physics Software group

Physics Department Summer Lectures 2025

June 23, 2025

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Flavor?

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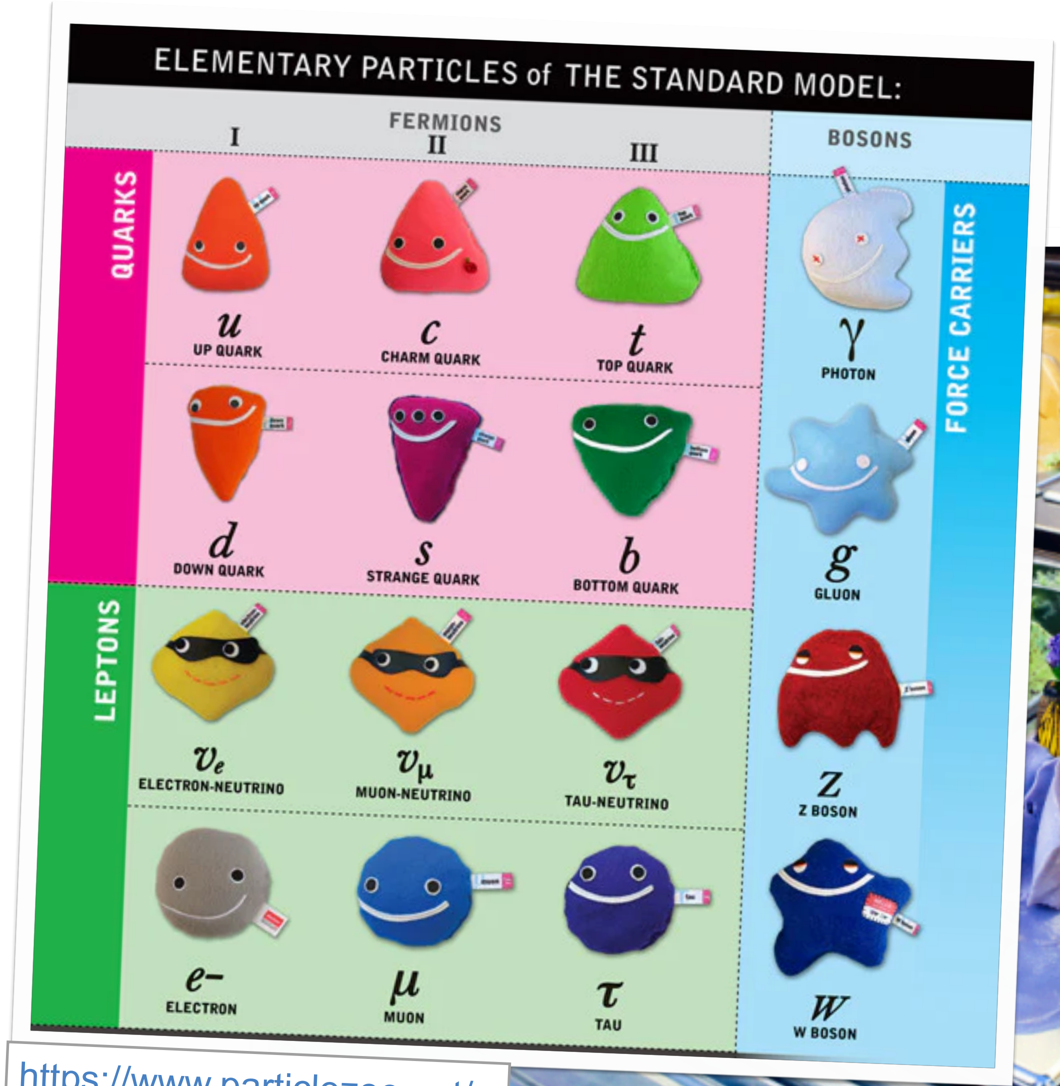
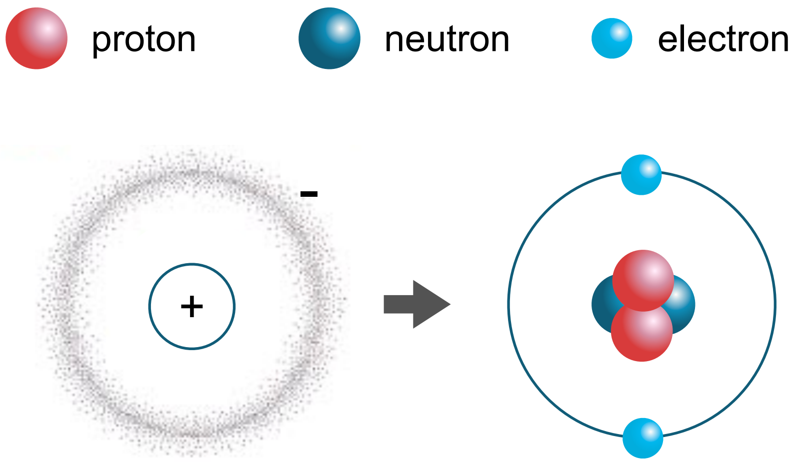
Flavor?



https://www.particlezoo.net/

The Quark Model

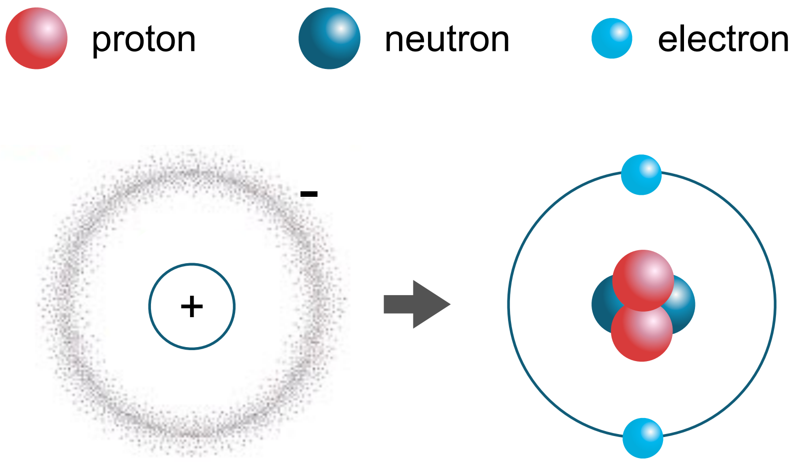
Subatomic Particles

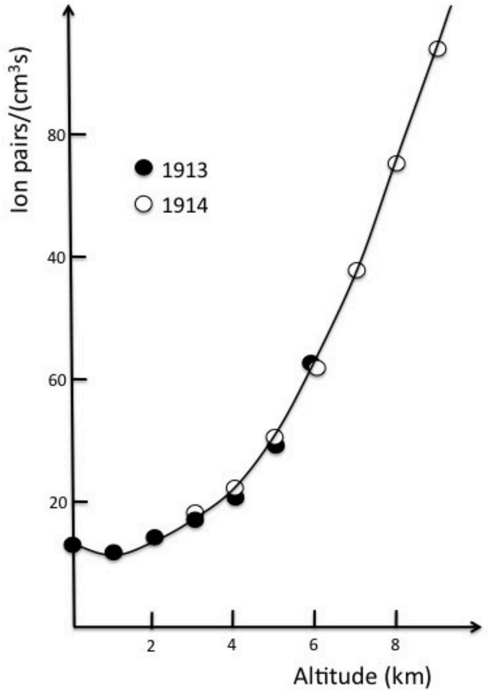


H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo		Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La		Ta	W		Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po		Rn
	Ra	Ac	Th		U												

Ce	Pr	Nd		Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

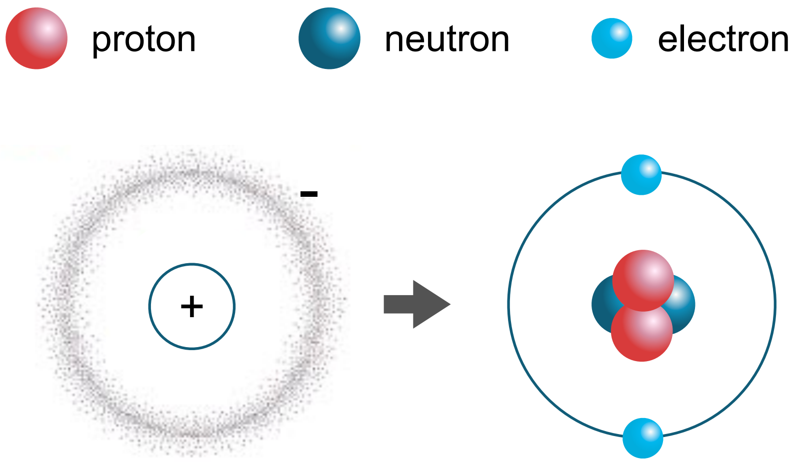
Subatomic Particles

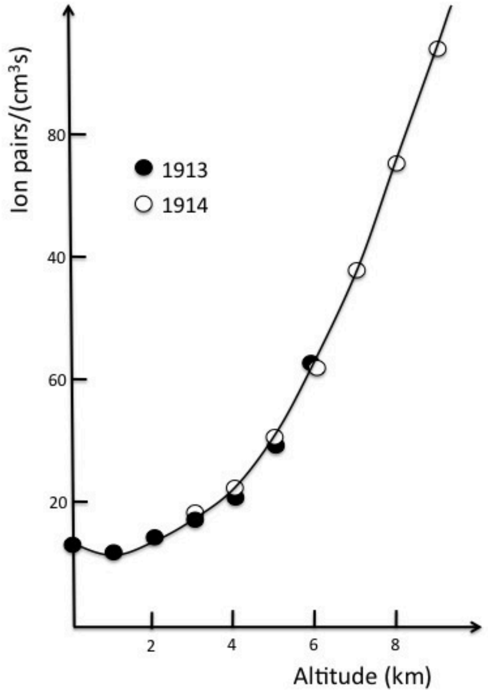




- Hess (1912) and Kohlhoster (1914)

Subatomic Particles





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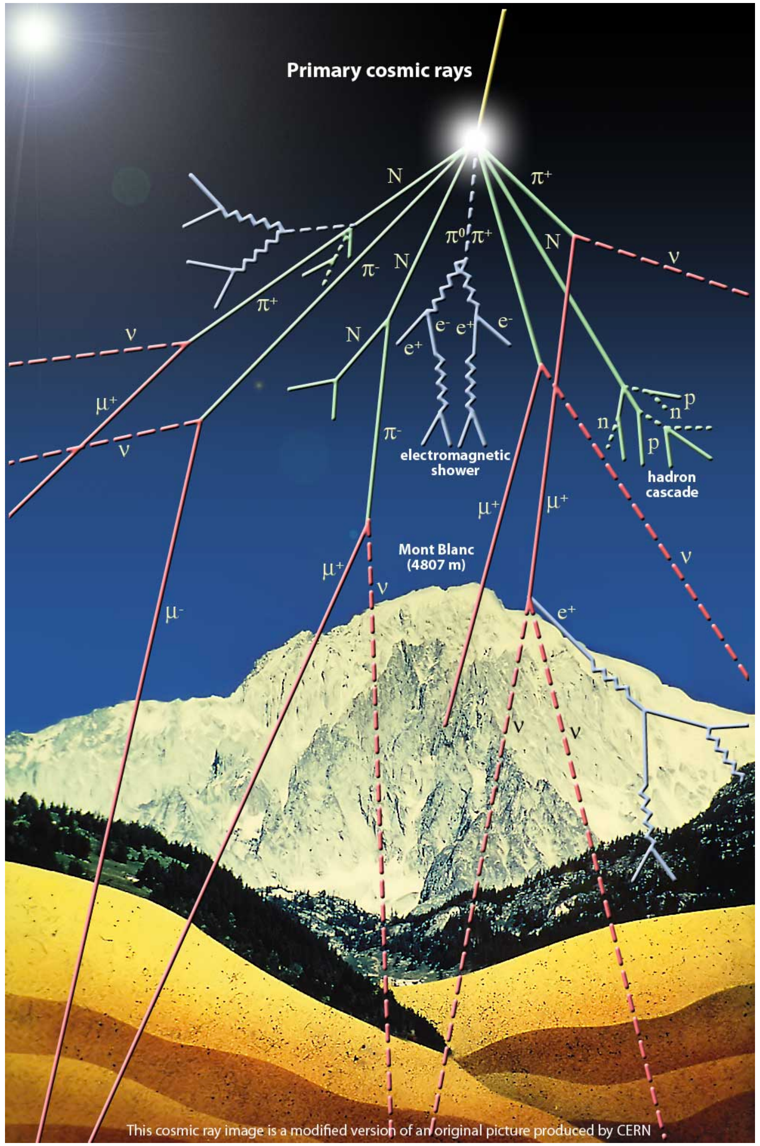
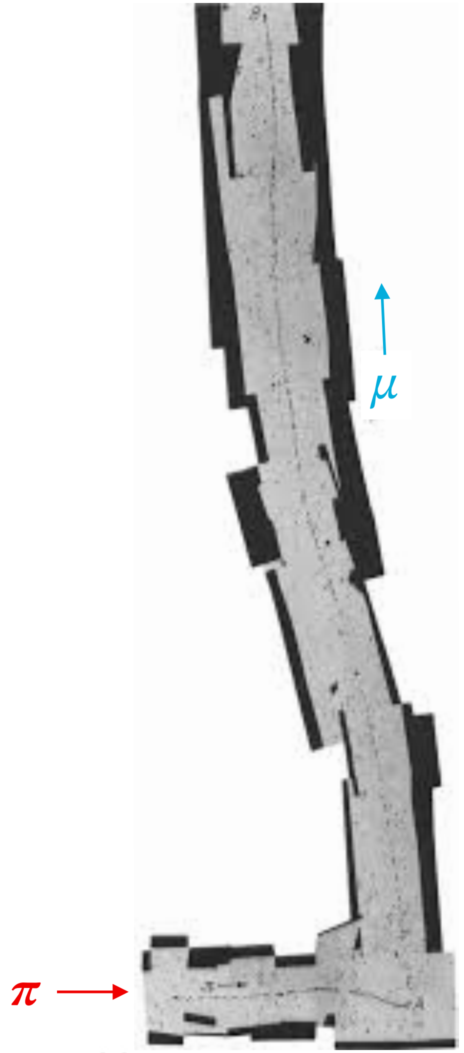


Muons and Pions



Powell et. al, 1947

Photo: Marietta_Kurz

- New particles discovered after studying cosmic rays with photographic emulsions
  - Anderson and Neddermeyer (1936) identified the **muon** as particles that curved differently from electrons passing a magnetic field
  - Powell et al (1947) identified two kinds of particles looking at the tracks: **pions** and **muons**

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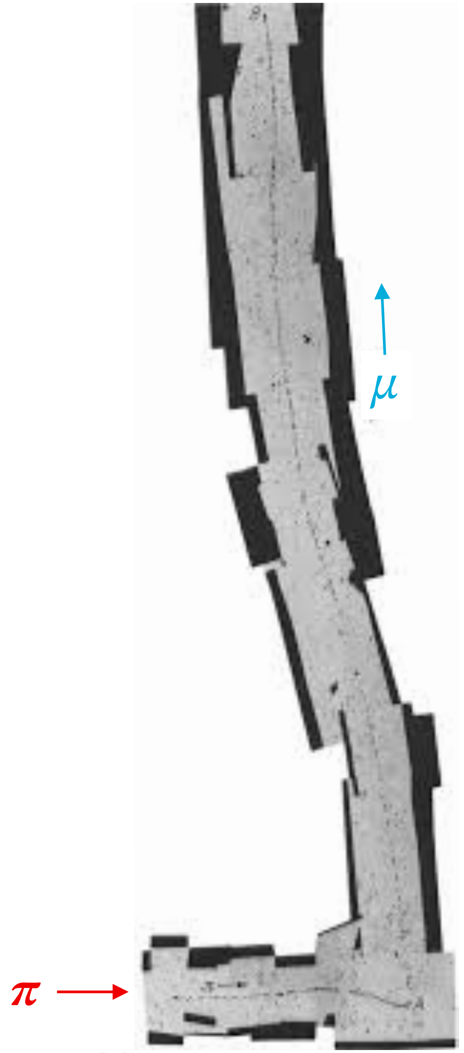
Muons and Pions



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Who ordered *that*?

I. Rabi

Strange Particles

- After the pion, several **mesons** (greek "mesos", meaning middle) were discovered with the years: $\rho, \eta, \omega, \ldots$
- Of particular interest was a decay observed in cosmic rays
  $K^0 \to \pi^+\pi^-$
- This was the first observation of an unusual long-lived meson. Very **strange** for that time!
- Some other “strange” particles started to appear. They are produced copiously but decay slowly (~10^{-10} s)
- Gell-Mann and Nishijima found a simple solution. They assigned to each particle a property called “strangeness”

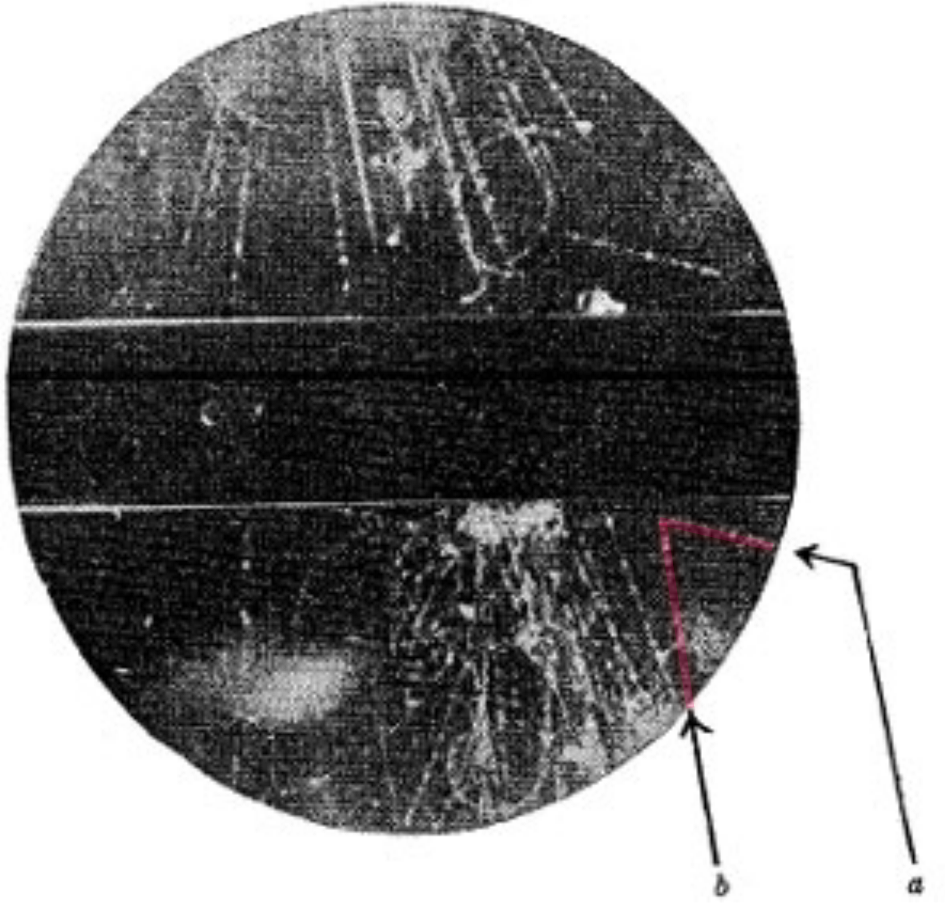

Figure: G. D. Rochester & C. C. Butler, Nature 160 (1947) 855-857

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Gell-mann octet for mesons

- For each meson, a **strangeness** is assigned, as shown in the diagram
- Processes witch not-conserve strangeness are called "**weak**", and they have long timescales (~10^{-10} s)
  - Strong and EM processes conserve strangeness with a short timescale (~10^{-23} s)
- Then, a decay of a Kaon into two pions is a weak process

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

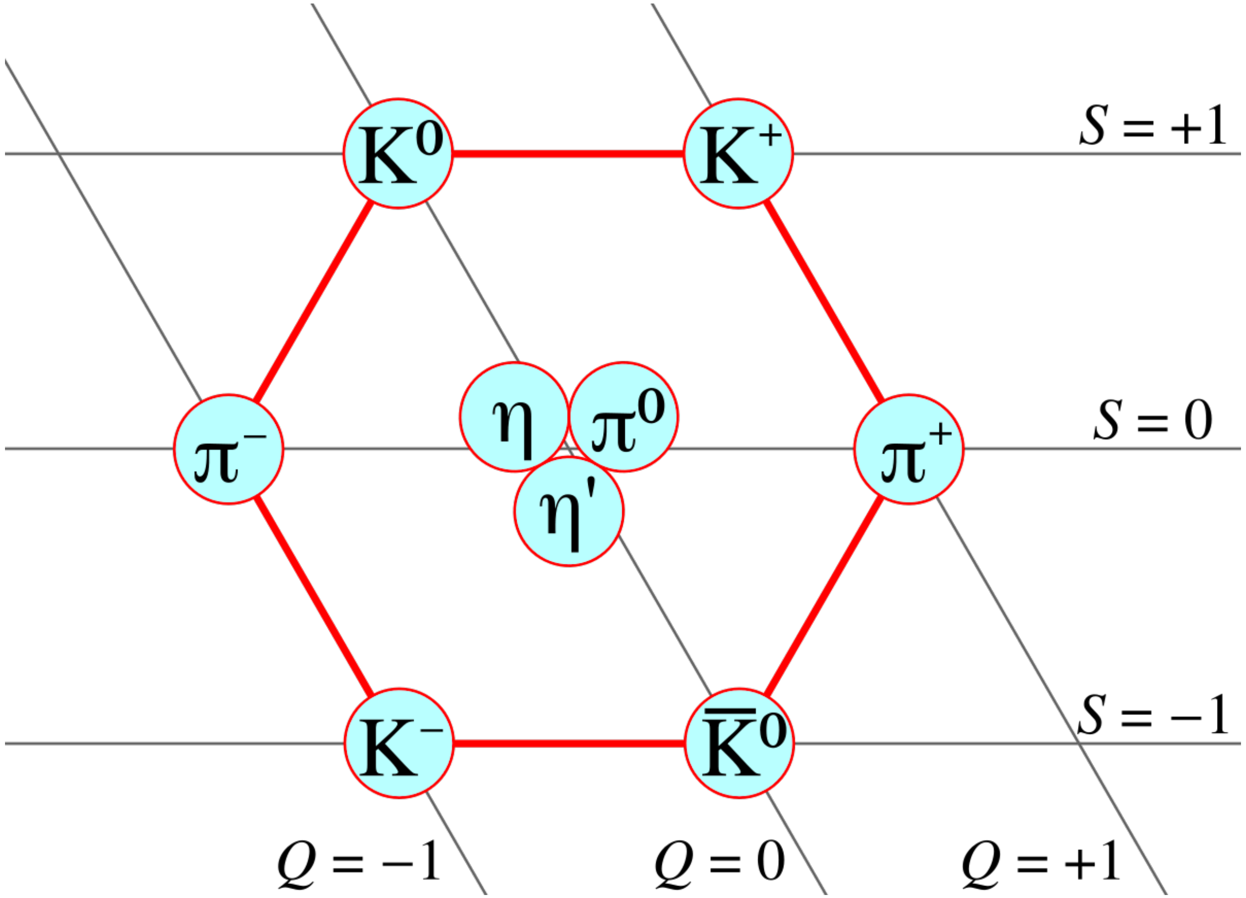

Figure: Wikimedia

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Gell-mann octet for baryons

- The **baryons** (greek word “barýs”, meaning "heavy") can also be arranged into an octet
- What is the nature of the following processes?
  - $\Lambda^0 \rightarrow p^+ \pi^-$
  - $\rho^0 \rightarrow \pi^+ \pi^-$

(with $S(\rho) = 0$)

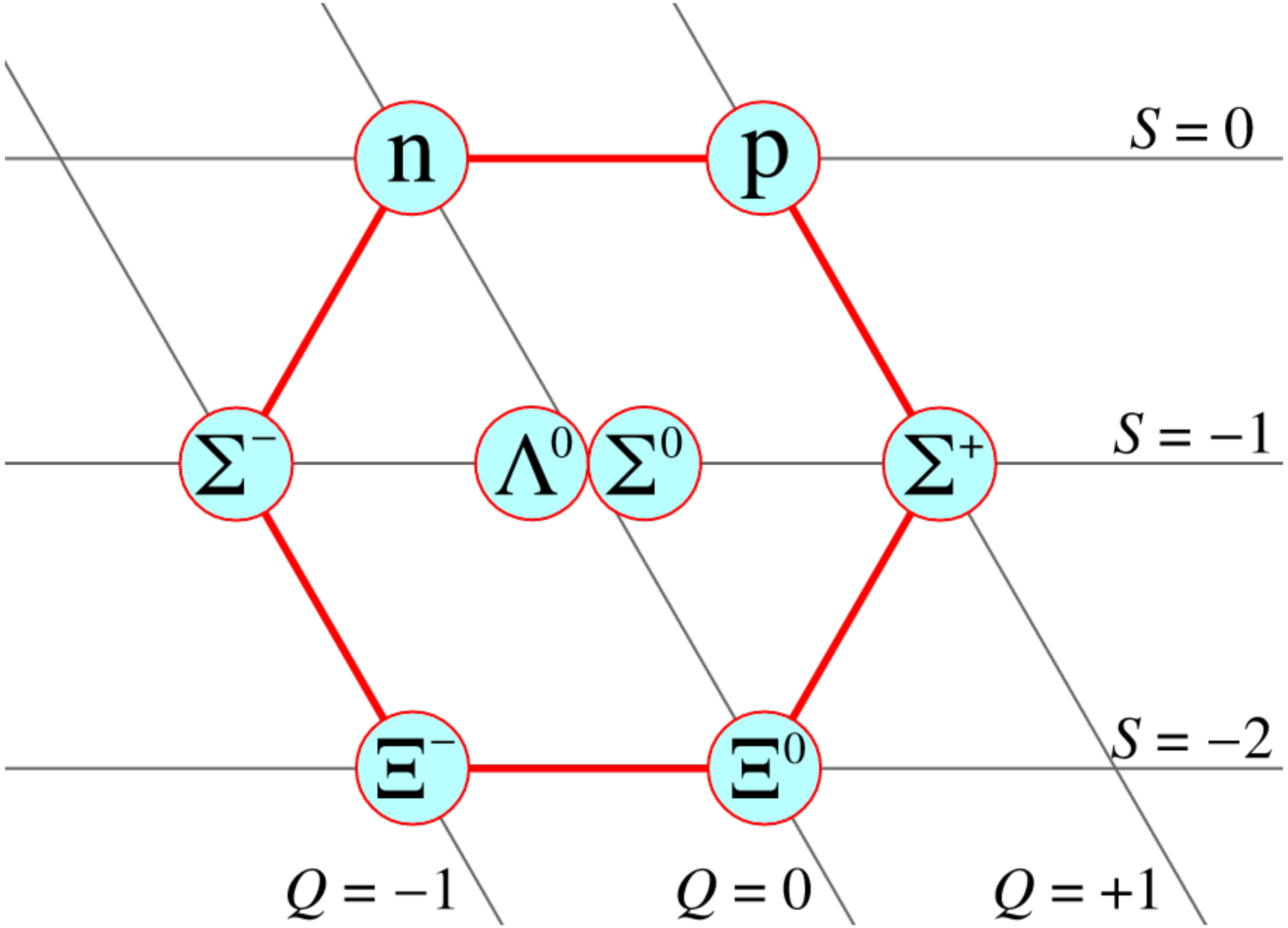

Figure: Wikimedia

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Gell-mann octet for baryons

- The **baryons** (greek word “barýs”, meaning "heavy") can also be arranged into an octet
- What is the nature of the following processes?
  - $\Lambda^0 \to p^+\pi^-$ Weak (10^{-10} s)
  - $\rho^0 \to \pi^+\pi^-$ Strong (10^{-24} s)

  (with $S(\rho) = 0$)

- The strangeness of the particles describes why some process are long-lived and some others are produced in a short time range

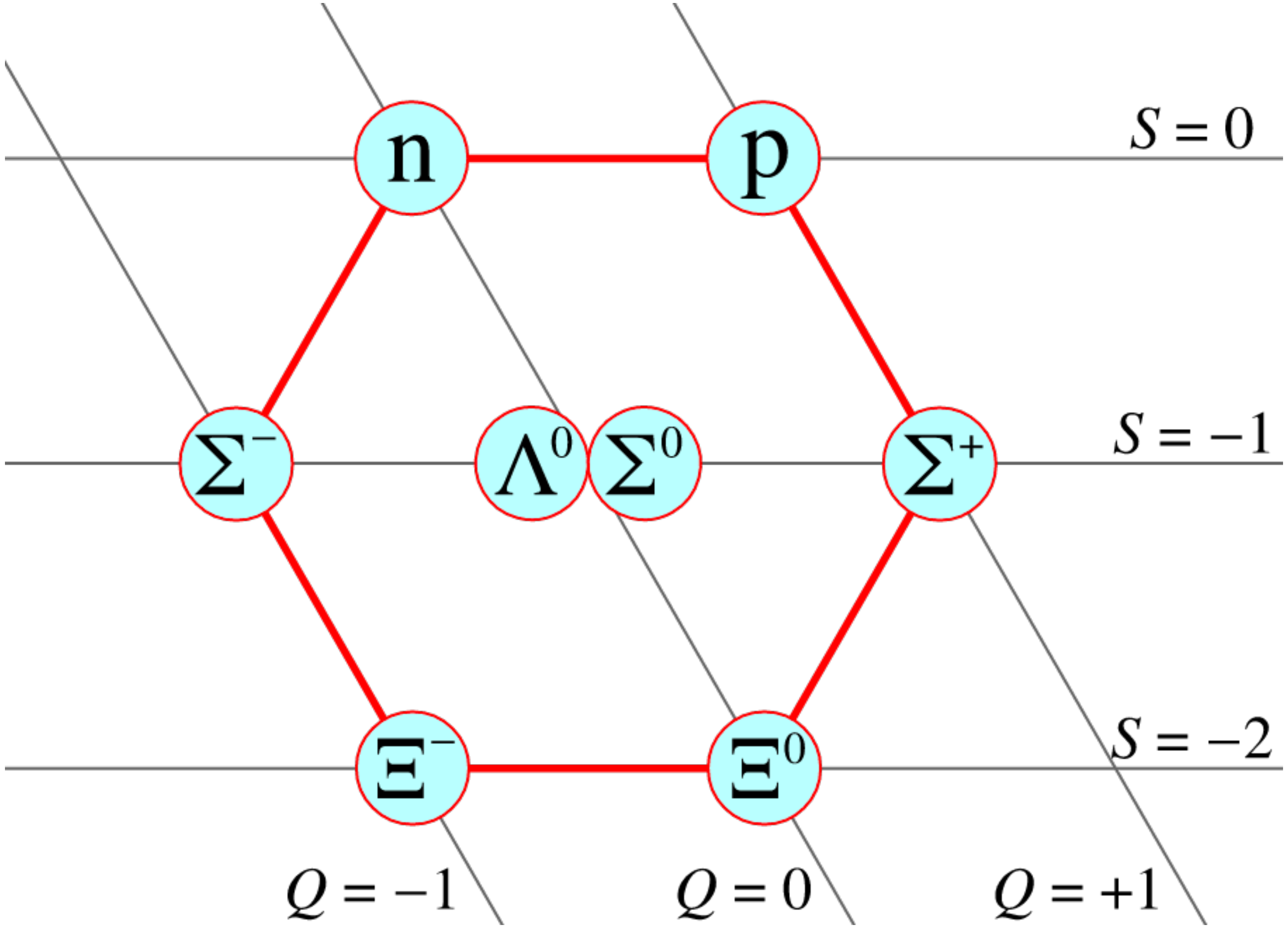

Figure: Wikimedia

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Decuplet of Baryons

- Now the question was, why these so many particles fit so well in these arrangements?
- Do you remember how 3 particles (p, n, e) explain the existence of all the elements in the periodic table?
- It seems something similar is happening here, right?

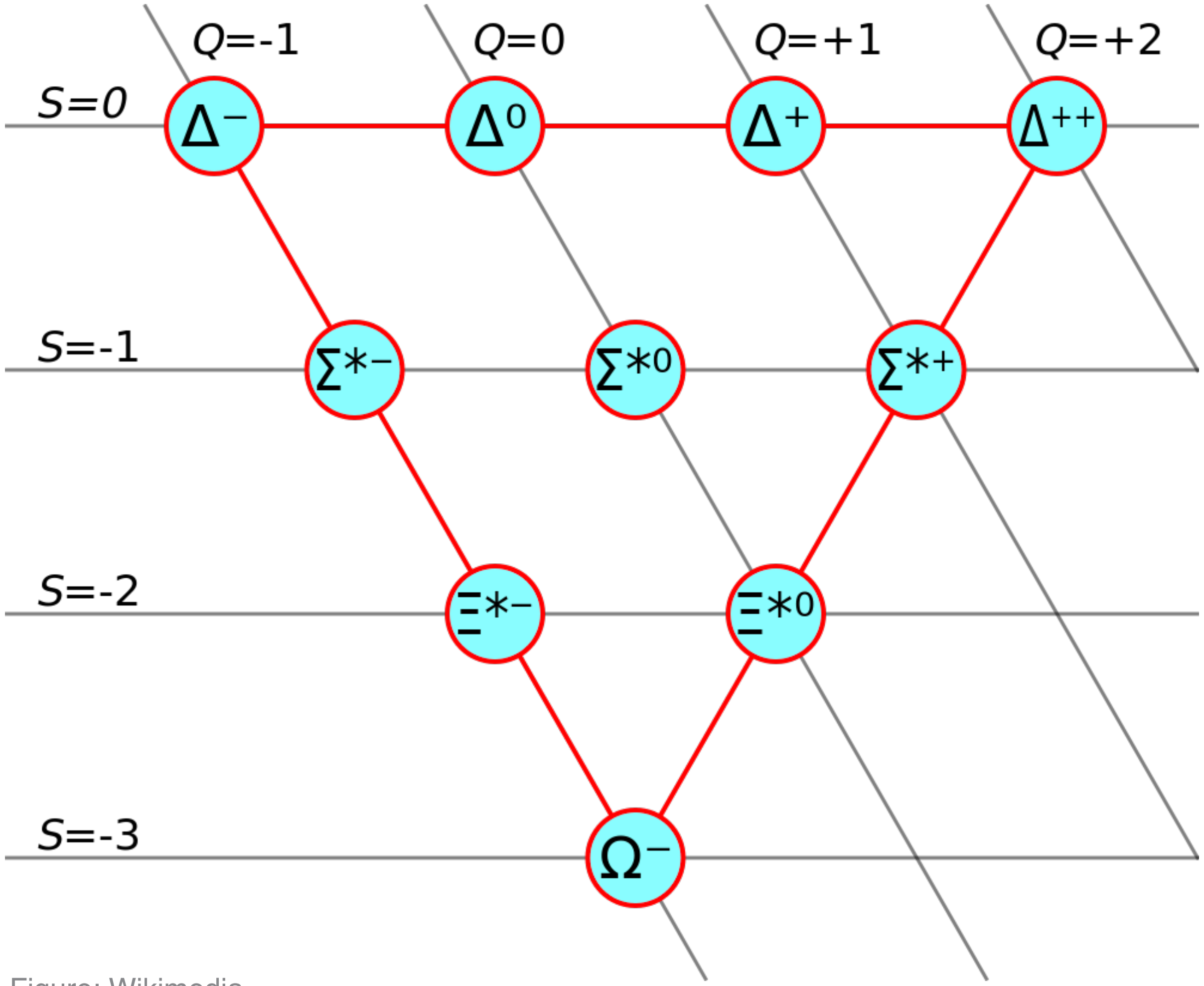

Figure: Wikimedia

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- Fun fact: this one (Ω-) was predicted by the Gell-Mann model **before** its discovery

  It was discovered here at the Brookhaven National Lab!

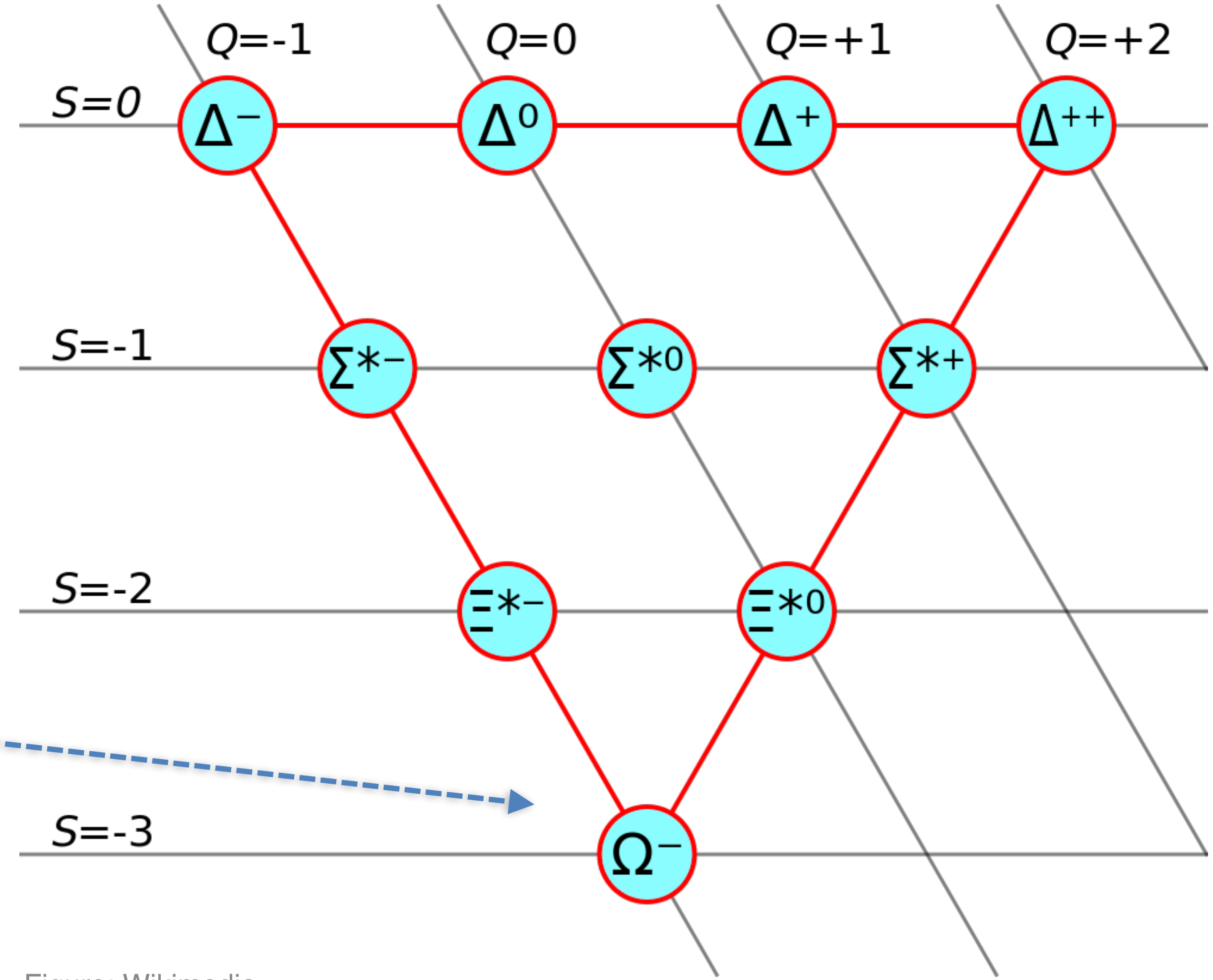

Figure: Wikimedia

The Quark Model

- Gell-Mann proposed that all the mesons and baryons are composed of quarks
- Three **"flavors"**: up (u), down (d), and strange (s)

Originated in 1971 with Murray Gell-Mann and Harald Fritzsch, who borrowed the term from ice cream flavors while brainstorming at a Baskin-Robbins

The Quark Model

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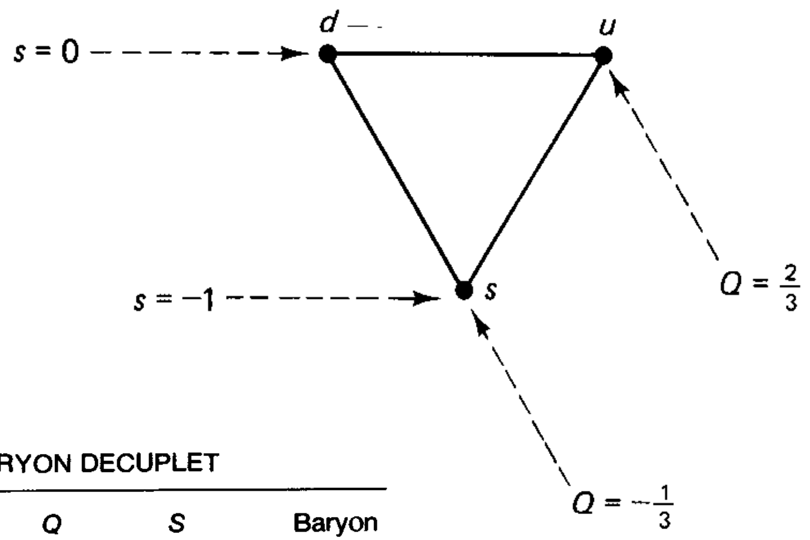
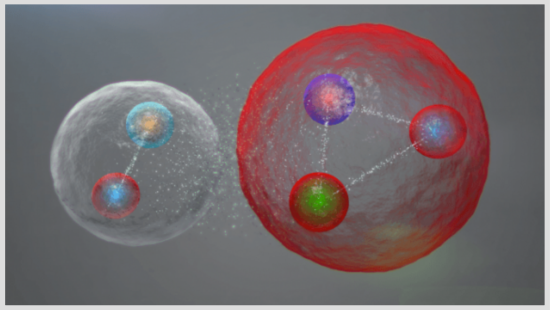
- Every baryon is made of three quarks, with the anti-baryons made of three antiquarks



The Quarks

THE BARYON DECUPLET

qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	−1	0	Δ^{-}
uus	1	−1	Σ^{*+}
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	Ω^{-}



Figures: Griffiths, Introduction to Particle Physics

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- Three **“flavors”**:
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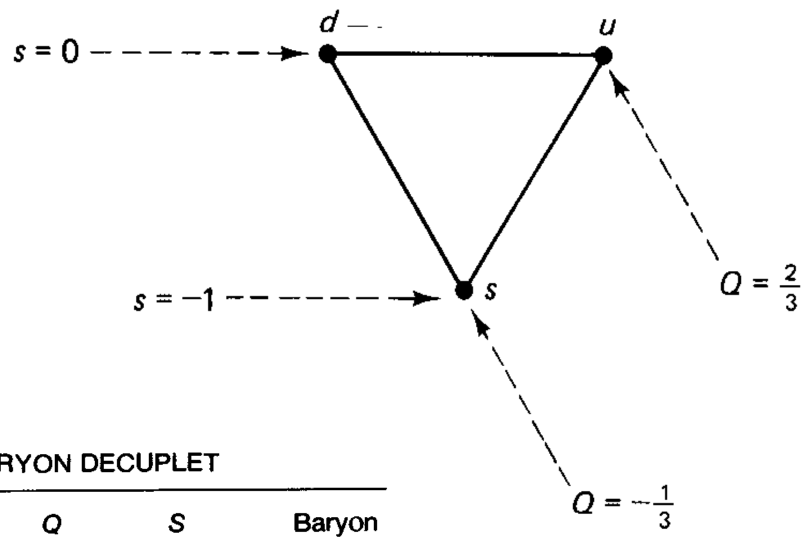
- Every baryon is made of three quarks, with the anti-baryons made of three antiquarks
- Every meson is made of a quark and antiquark



The Quarks

THE BARYON DECUPLET

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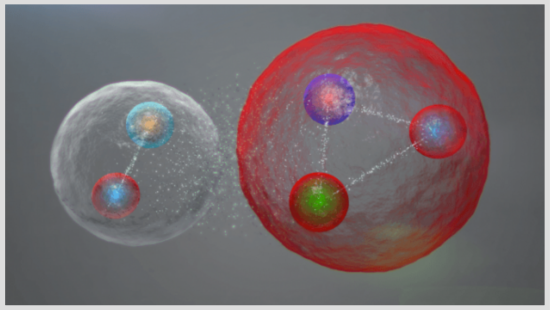
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	Ω^{-}

THE MESON NONET

$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	−1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	−1	−1	K^-
$s\bar{d}$	0	−1	$\bar{K}^0$
$s\bar{s}$	0	0	??

Figures: Griffiths, Introduction to Particle Physics



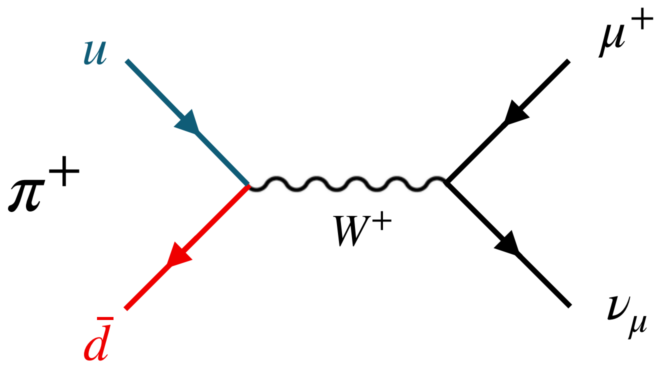
“Strangeness” is just the content of strange quarks!

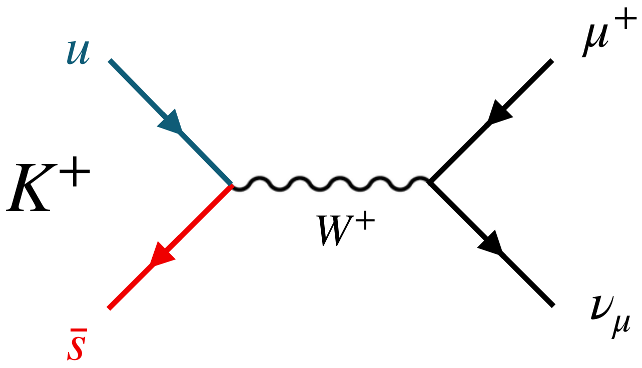
Quark Mixing

The Cabibbo Angle

$BR(K^- \to \mu^- \bar{\nu}_\mu) = 63.5\%$ $BR(\pi^- \to \mu^- \bar{\nu}_\mu) = 99.9\%$

Why?





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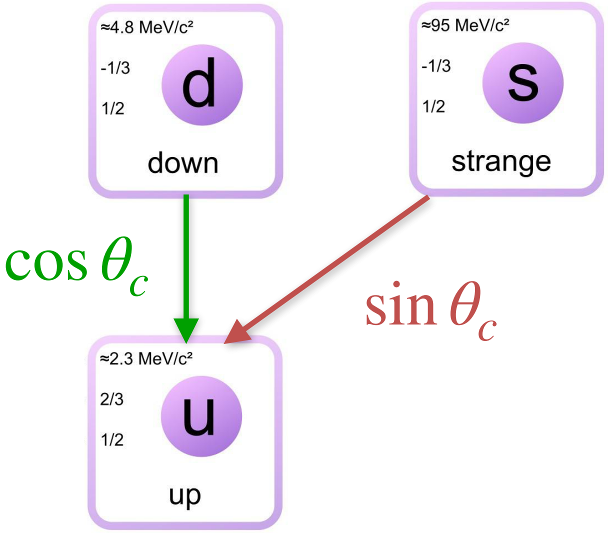
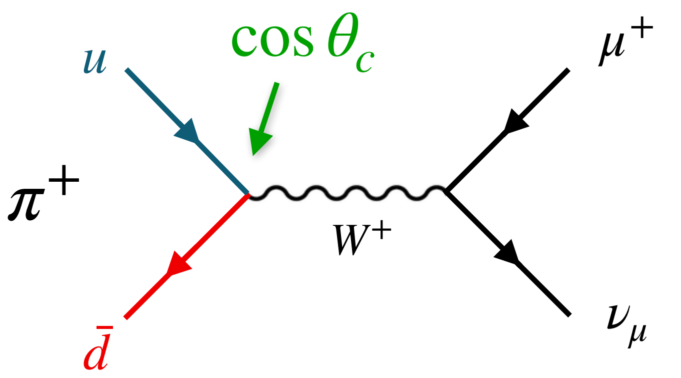
The Cabibbo Angle

$BR(K^- \to \mu^- \overline{\nu}_\mu) = 63.5\%$ $\qquad BR(\pi^- \to \mu^- \overline{\nu}_\mu) = 99.9\%$

- Flavor states of the quarks are combinations of physical states. That explains the mixing between them.
- The **Cabibbo angle** is related to the probability that down and strange quarks decay into up quarks.
- We can write such probabilities as $|V_{ud}|$ and $|V_{us}|$. The relation between the flavor and physical states is
  $d' = V_{ud} d + V_{us} s$
- Or, written as a mixing angle
  $d' = \cos\theta_c d + \sin\theta_c s$

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$





The Cabibbo Angle

$$BR(K^- \to \mu^- \bar{\nu}_\mu) = 63.5\% \qquad BR(\pi^- \to \mu^- \bar{\nu}_\mu) = 99.9\%$$

$$\frac{BR(K^+ \to \mu^+ \nu)}{BR(\pi^+ \to \mu^+ \nu)} \propto \frac{\sin^2 \theta_c}{\cos^2 \theta_c}$$

- Flavor states of the quarks are combinations of physical states. That explains the mixing between them.
- The **Cabibbo angle** is related to the probability that down and strange quarks decay into up quarks.
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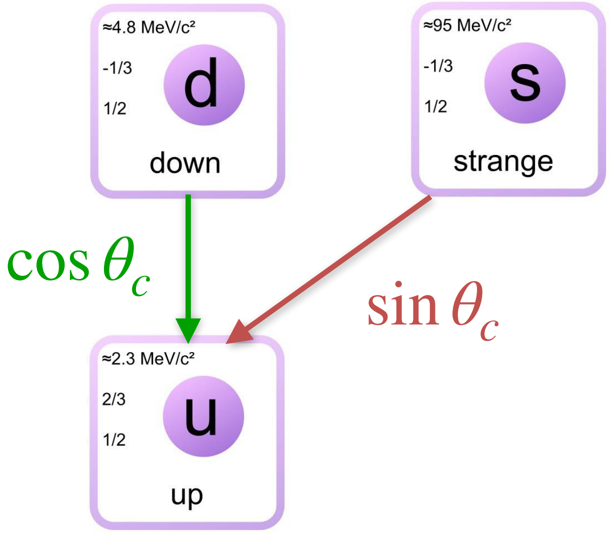
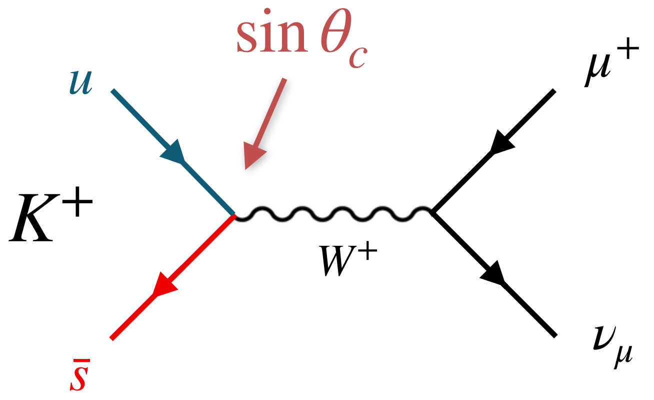
- Or, written as a mixing angle $d' = \cos\theta_c d + \sin\theta_c s$

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\tan\theta_c = \frac{|V_{us}|}{|V_{ud}|} = \frac{0.22534}{0.97427}$$

$$\Rightarrow \theta_c = \ 13.02^\circ$$

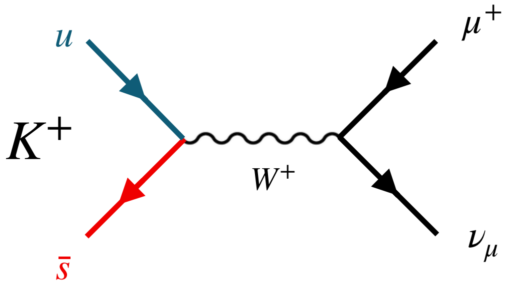


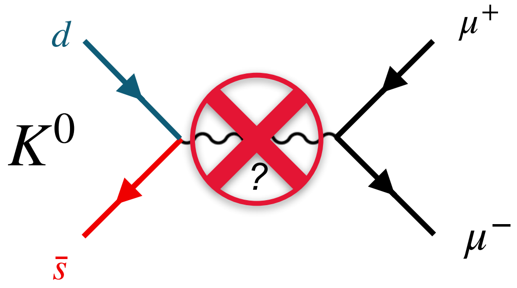


The GIM Mechanism

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

Why?!





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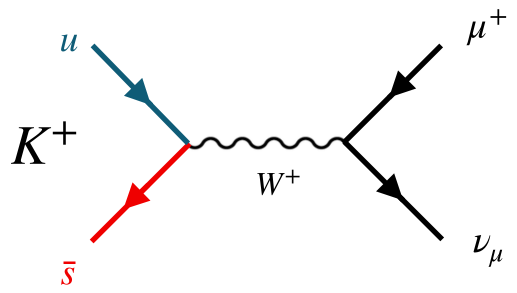
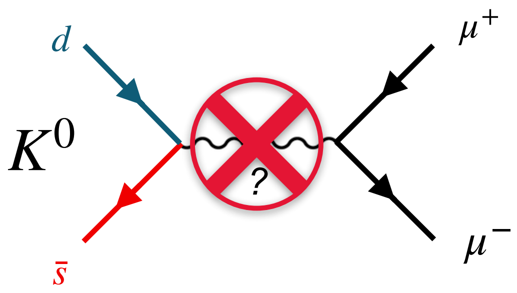


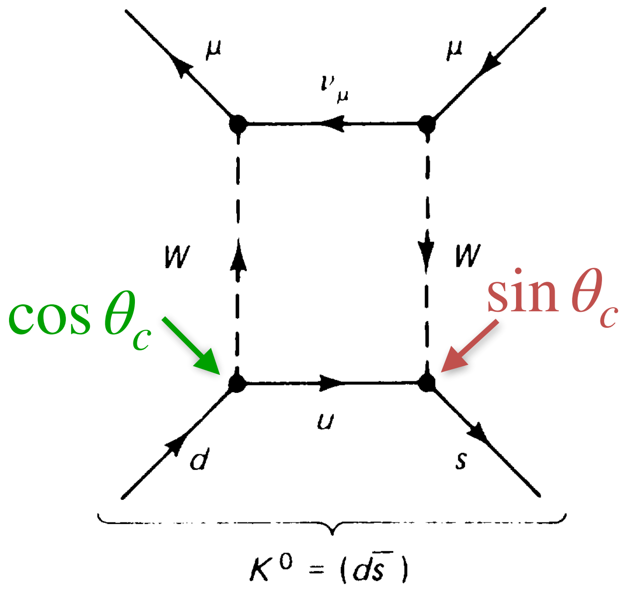


- In 1969-70 Glashow, Iliopoulos, and Maiani (GIM) proposed a solution to the to the rate puzzle:
- **The branching fraction for K^0 was expected to be small as the first order diagram is forbidden**

The 2nd order diagram ("box") was calculated and was found to give

$$BR(K^0 \to \mu^+\mu^-) \propto cos^2\theta_c \cdot sin^2\theta_c$$

still a rate higher than the experimental measurement!



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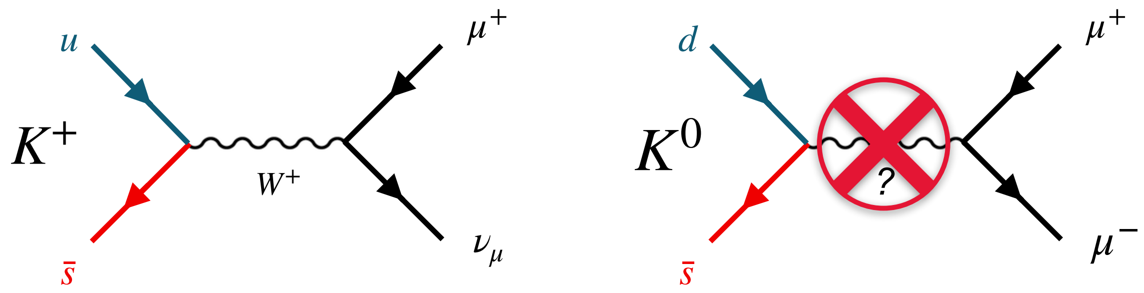
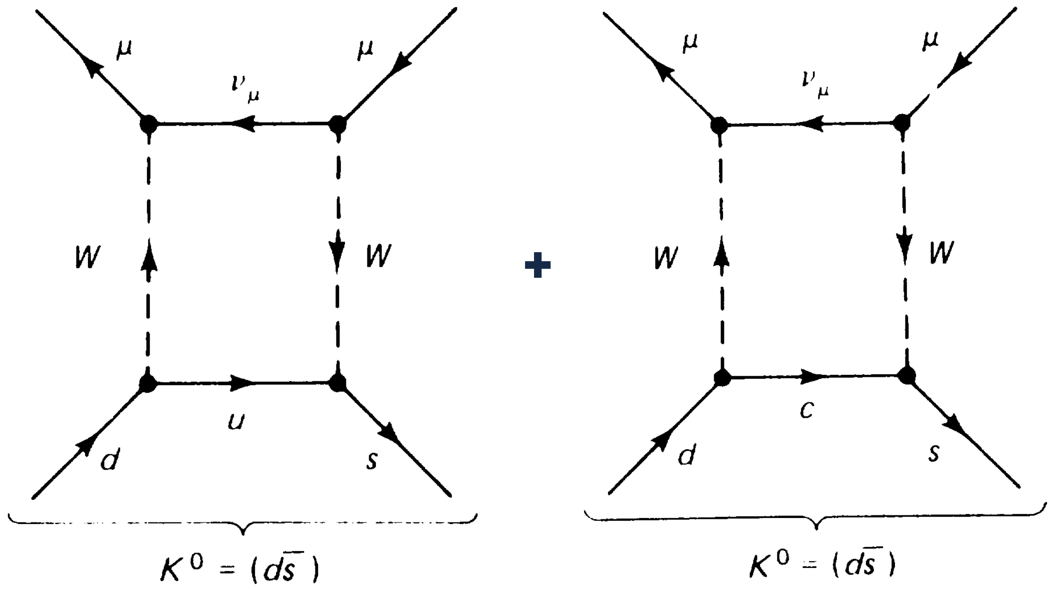


- **GIM proposed the existence of a fourth quark "charm"**
- The new quark produces a second box diagram, which interferes with the first one (consequence of the quantum nature of the particles)
- **In order to explain the ratio of the K^0 decays, the charm quark needs a mass of ~1.5 GeV**



The GIM Mechanism

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

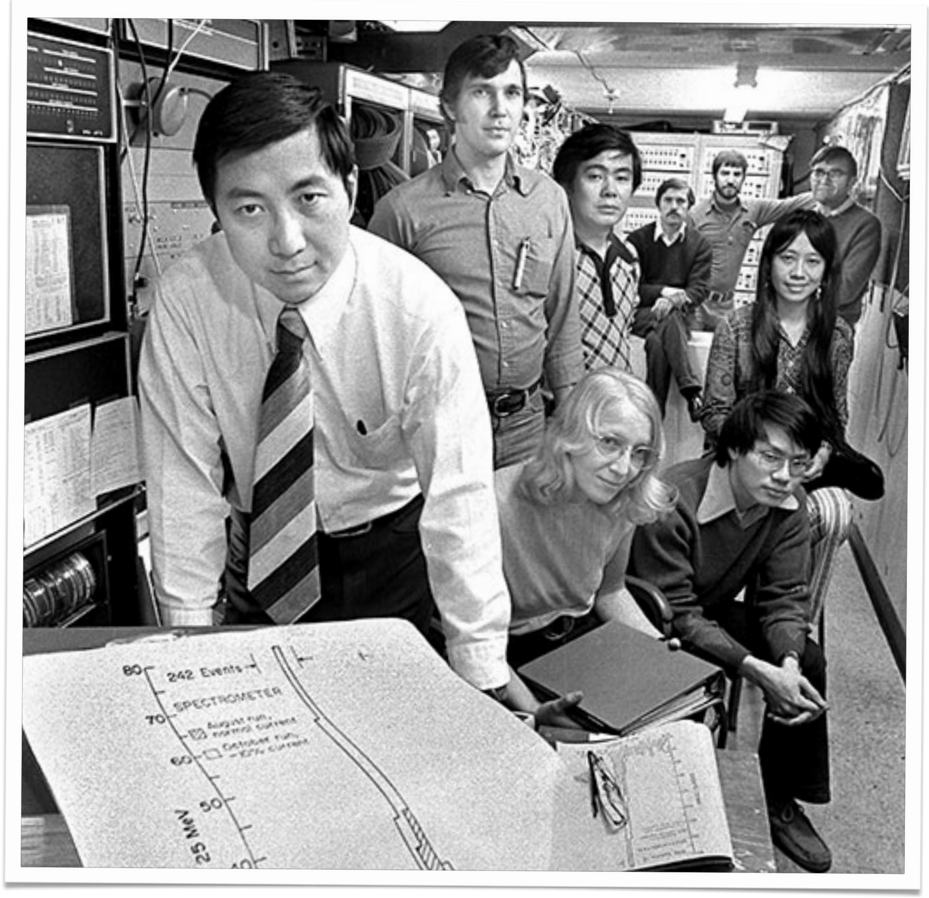
Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

The discovery of the J/ψ

- **The J meson was observed for the first time at BNL by Samuel Ting and his team in 1974**
- **It has a mass of ~3.1 GeV**
- This J was “stranger” than the strange particles
    - Too heavy - three times the mass of the proton
    - With a lifetime of 10^{-20} - typical hadron of that mass has a lifetime of 10^{-23}
- The discovery was kept under secret, while the team double-check their results
- Later that year, a second group in SLAC observed the same particle and they called ψ
- Both groups agreed to call it J/ψ



https://www.bnl.gov/bnlweb/history/nobel/1976.php

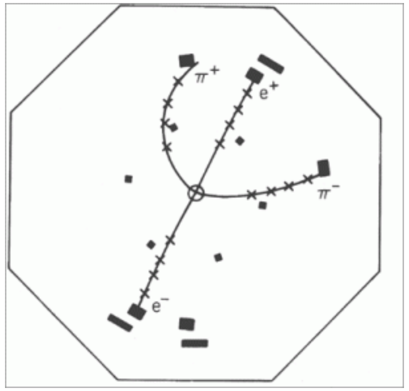


Figure: SLAC

1974

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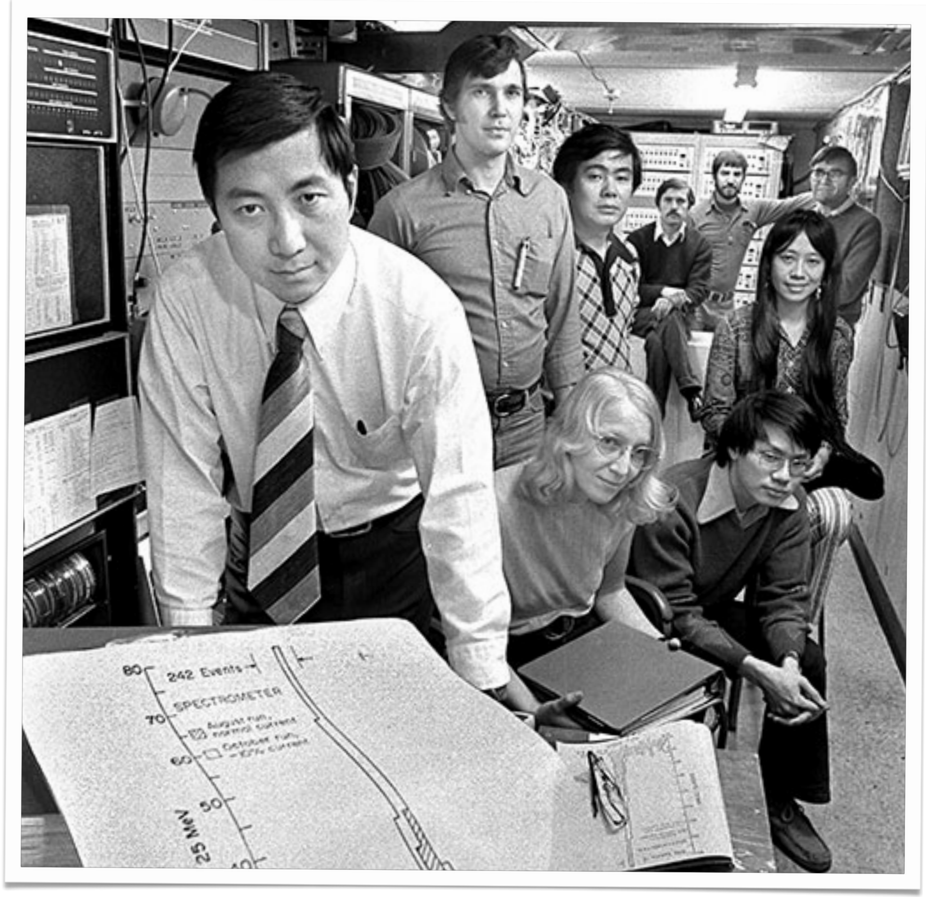
- Later that year, a second group in SLAC observed the same particle and they called ψ
- Both groups agreed to call it J/ψ
- **It was identified as a cc state, confirming the existence of the charm quark**



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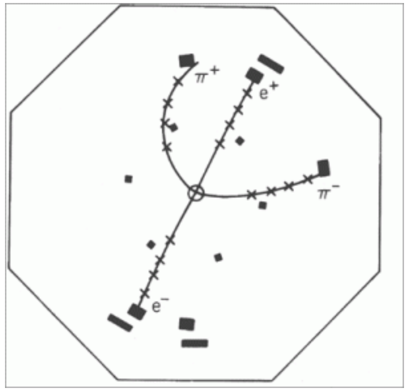

Figure: SLAC

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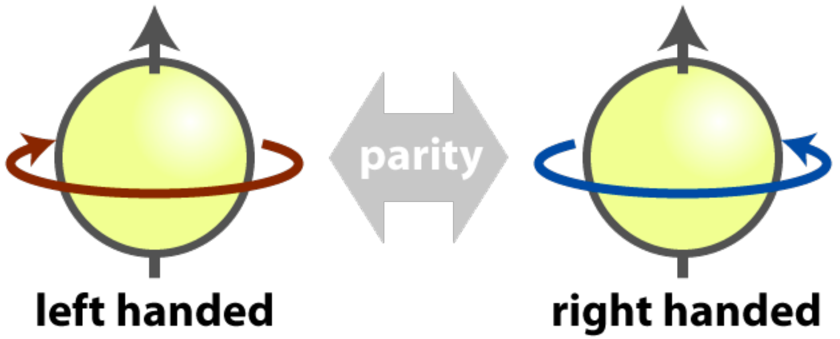
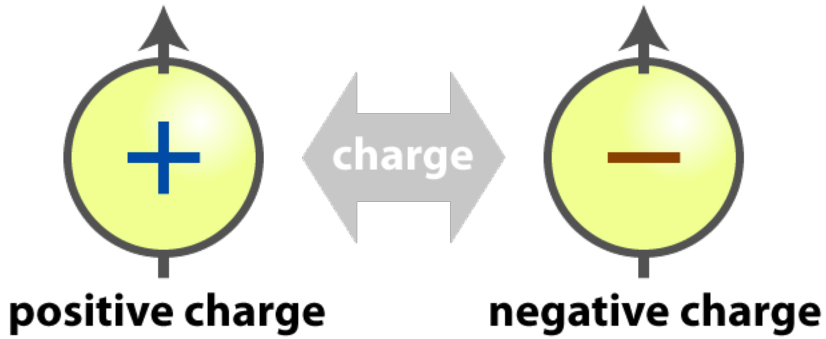
CP Violation

CP Symmetry

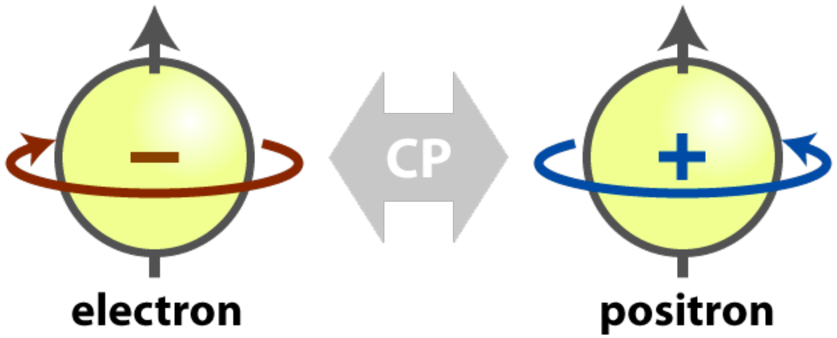




- C and P symmetries are conserved by electromagnetic and strong forces, **but maximally violated by weak forces**

https://www.bnl.gov/bnlweb/history/nobel/1957.php

The direction that the particle spins with respect to its direction of motion determines whether it is left-handed or right-handed



- CP symmetry are **almost** conserved.

Figures: Flip Tanedo, quantumdiaries.org

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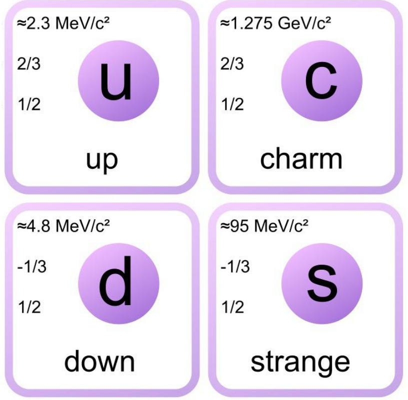
Mixing Parameters



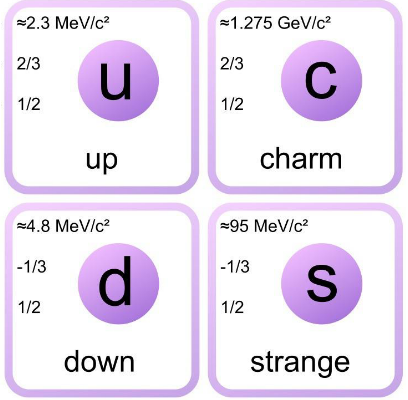
$$\begin{pmatrix} d_W \\ s_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \end{pmatrix}$$

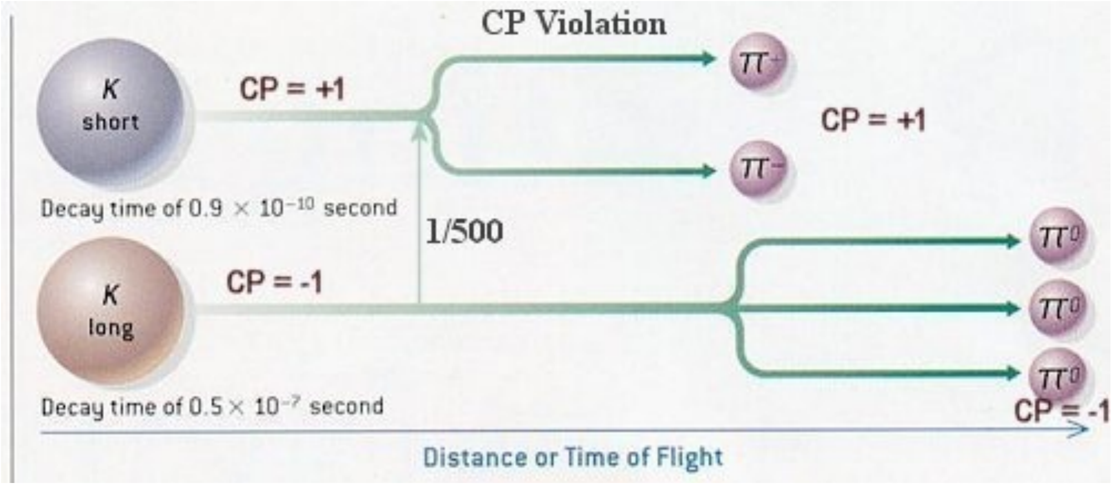
- 1 mixing angle
- No CPV phase
  (No CP violation)

1970

Figures: Wikimedia

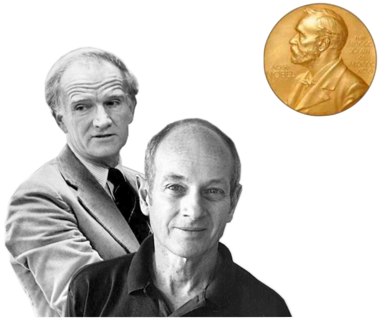
Mixing Parameters





https://www.bnl.gov/bnlweb/history/nobel/1980.php

CP Violation in Kaon system



Cronin & Fitch (1963)

$$\begin{pmatrix} d_W \\ s_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \end{pmatrix}$$

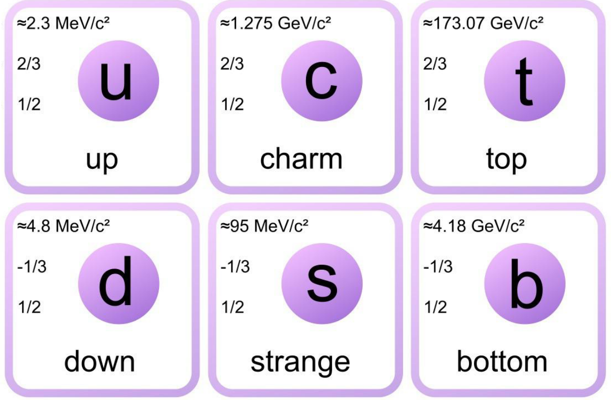
- 1 mixing angle
- No CPV phase
  (No CP violation)

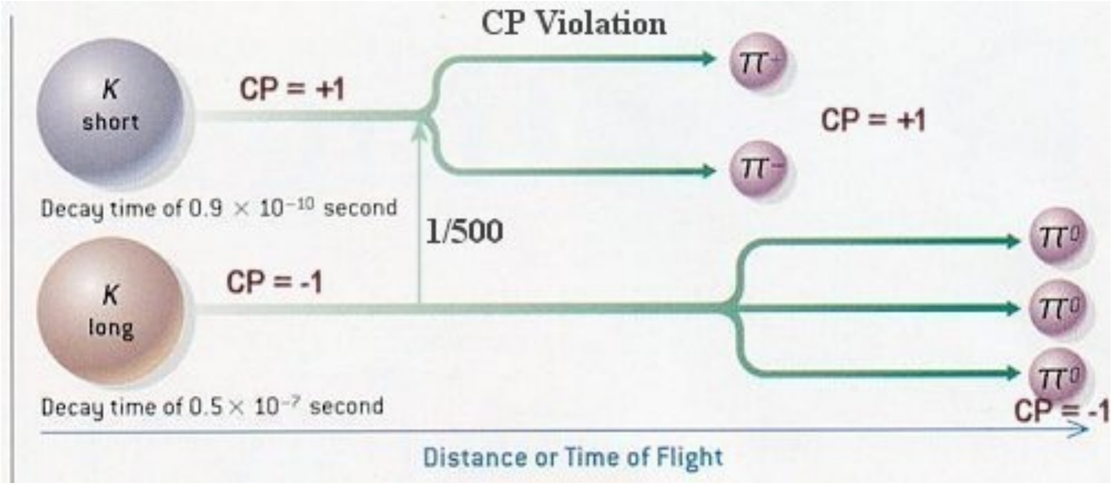
1970

Figures: Wikimedia

Brookhaven National Laboratory

Mixing Parameters





CP Violation in Kaon system

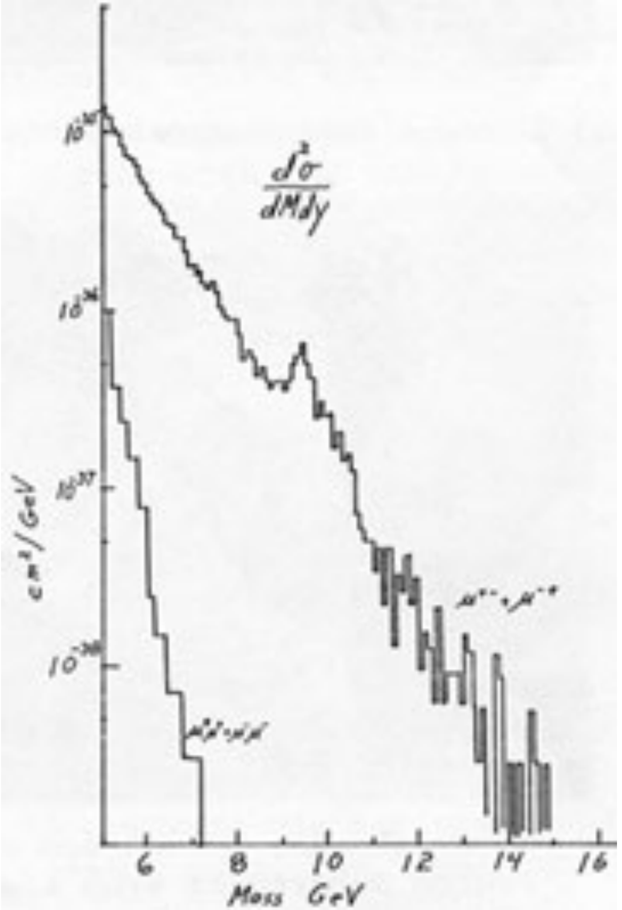
$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

- 3 mixing angles
- 1 CPV phase

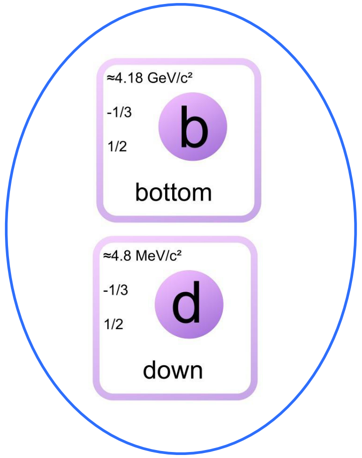
1973

Figures: Wikimedia

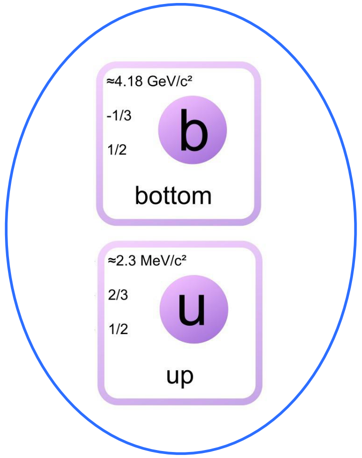
B Mesons



1977
Discovery of the quark bottom at Fermilab

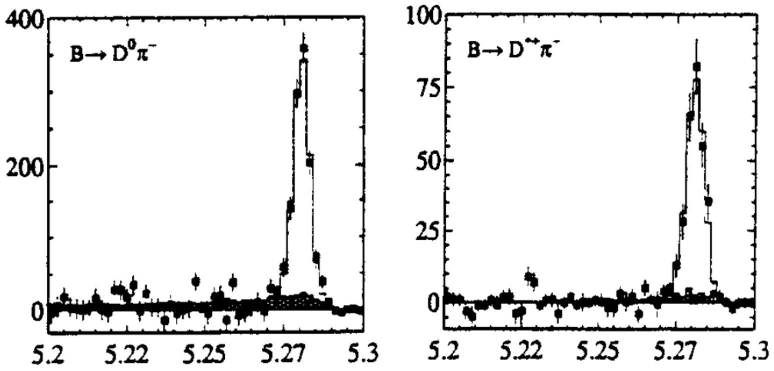


B^0, $\overline{B}^0$



B^+, B^-

1983
CLEO successfully reconstructed B mesons

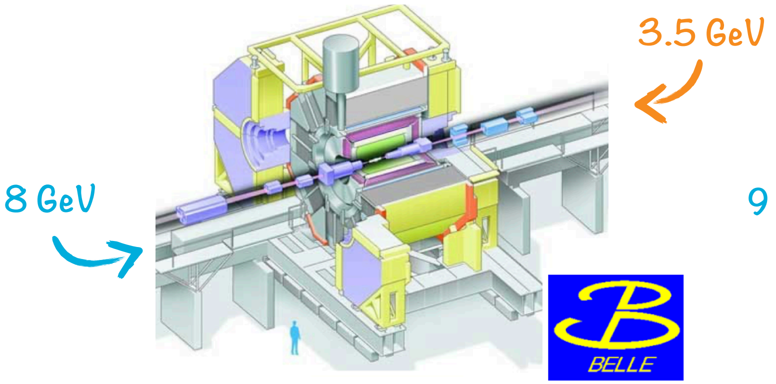


https://history.fnal.gov/historical/experiments/extra_upsilon.html

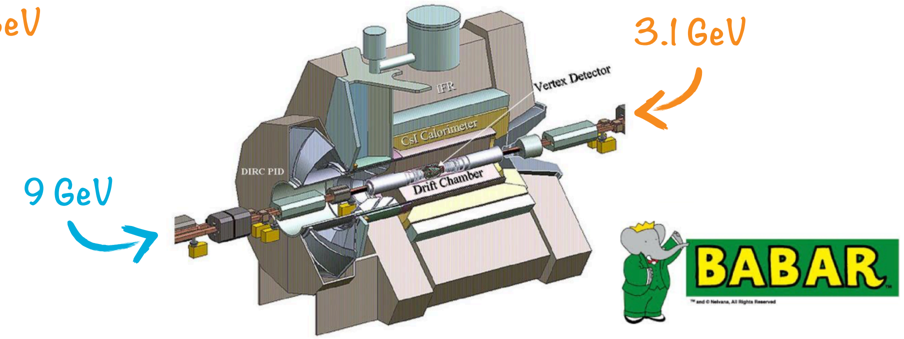
AIP Conf. Proc. 424, 75–84 (1998)

Brookhaven National Laboratory

B-Factories

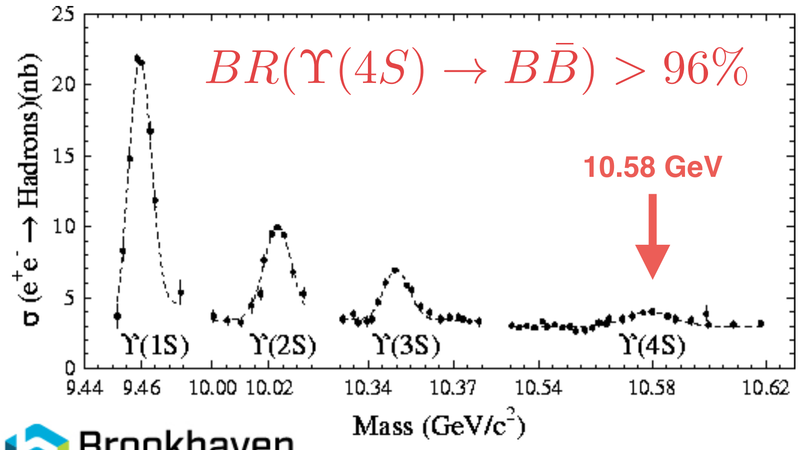


KEKB collider : 711 fb^{-1}@Y(4S)
[1999-2010]

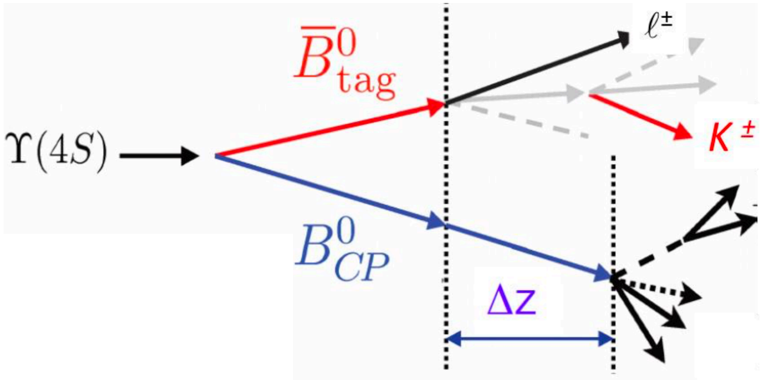


SLAC-PEP II collider : 462 fb^{-1}@Y(4S)
[1999-2008]

- Well-defined initial state
- High luminosity
- Asymmetric collisions



- Allows to make time dependent analysis of CP asymmetries



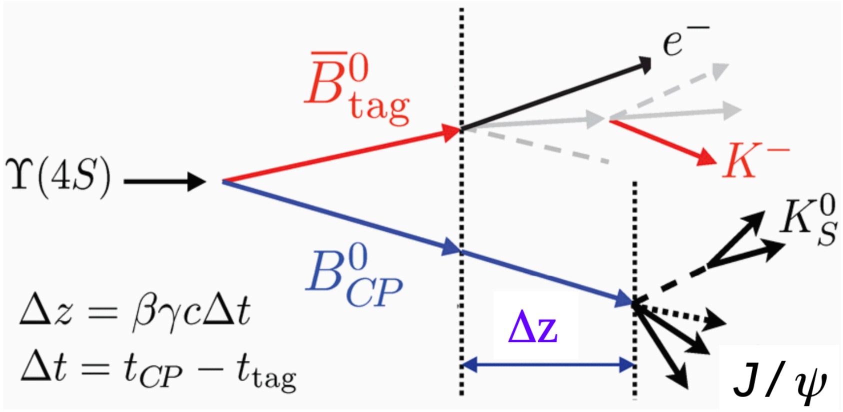
CP Violation in the B meson system

- The "golden channel" $B^0 \to J/\psi\, K_s^0$

$$A_{CP}^{B\to f}(\Delta t) \equiv \frac{\Gamma(B^0(\Delta t)\to f) - \Gamma(\bar{B}^0(\Delta t)\to f)}{\Gamma(B^0(\Delta t)\to f) + \Gamma(\bar{B}^0(\Delta t)\to f)}$$

$$= S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)$$

Mix-induced CPV — Direct CPV



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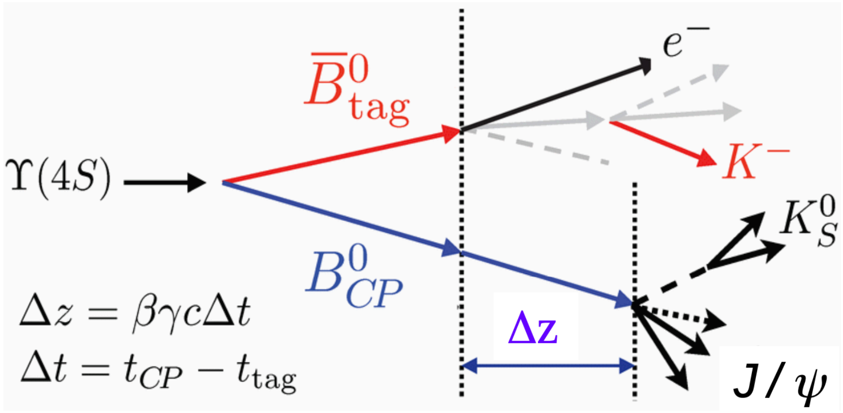
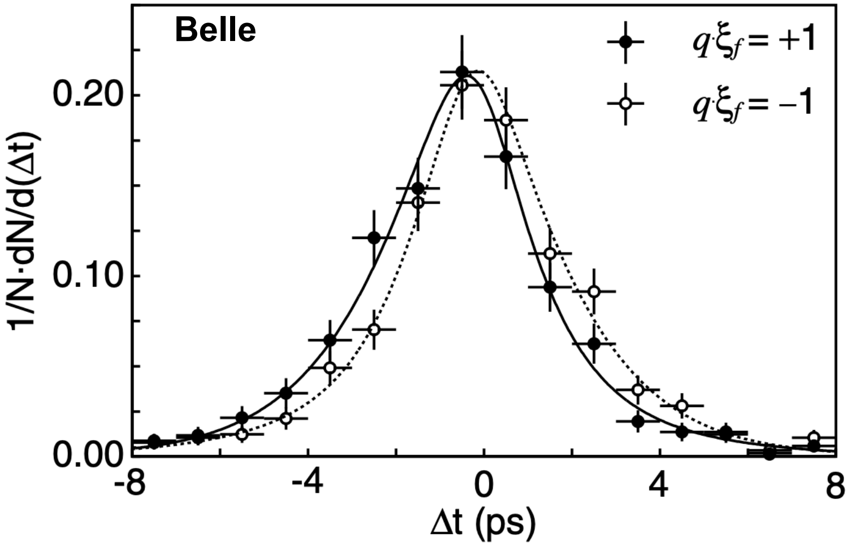
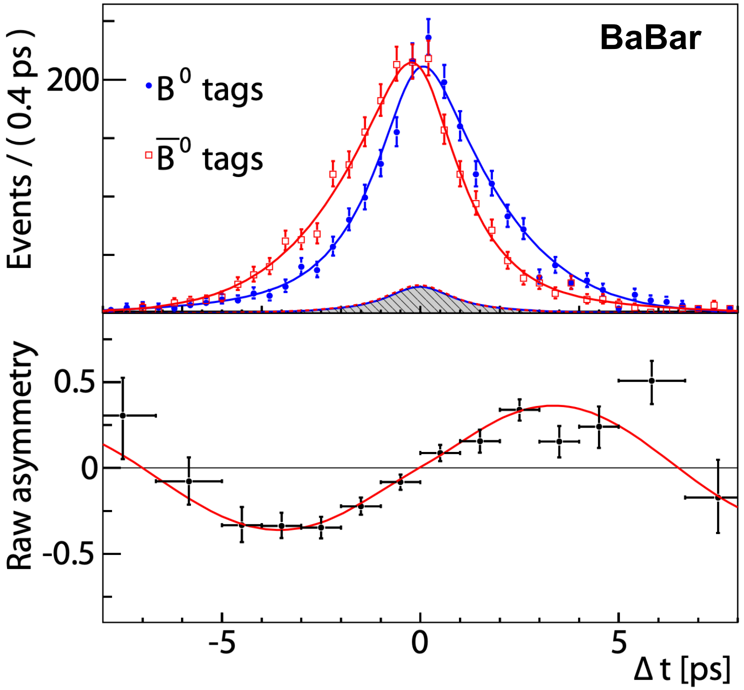
$$= S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)$$

Mix-induced CPV (S) Direct CPV (C)







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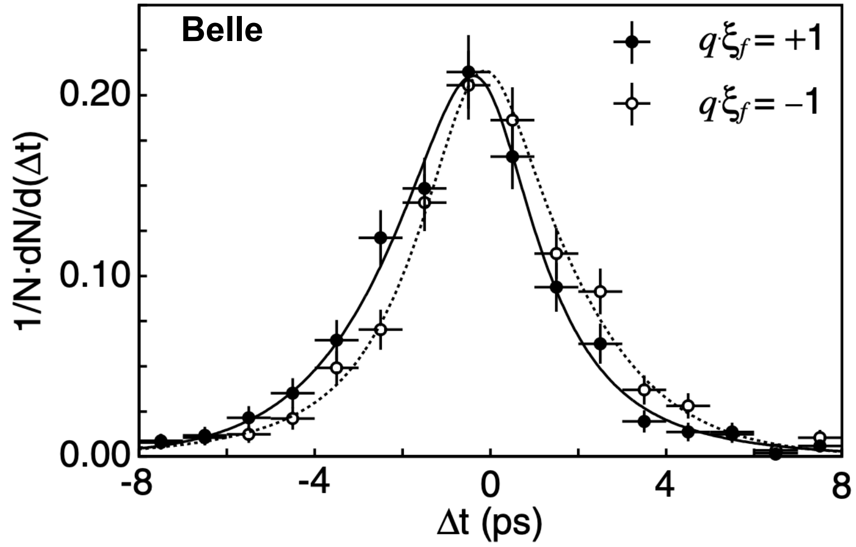
Mix-induced CPV Direct CPV

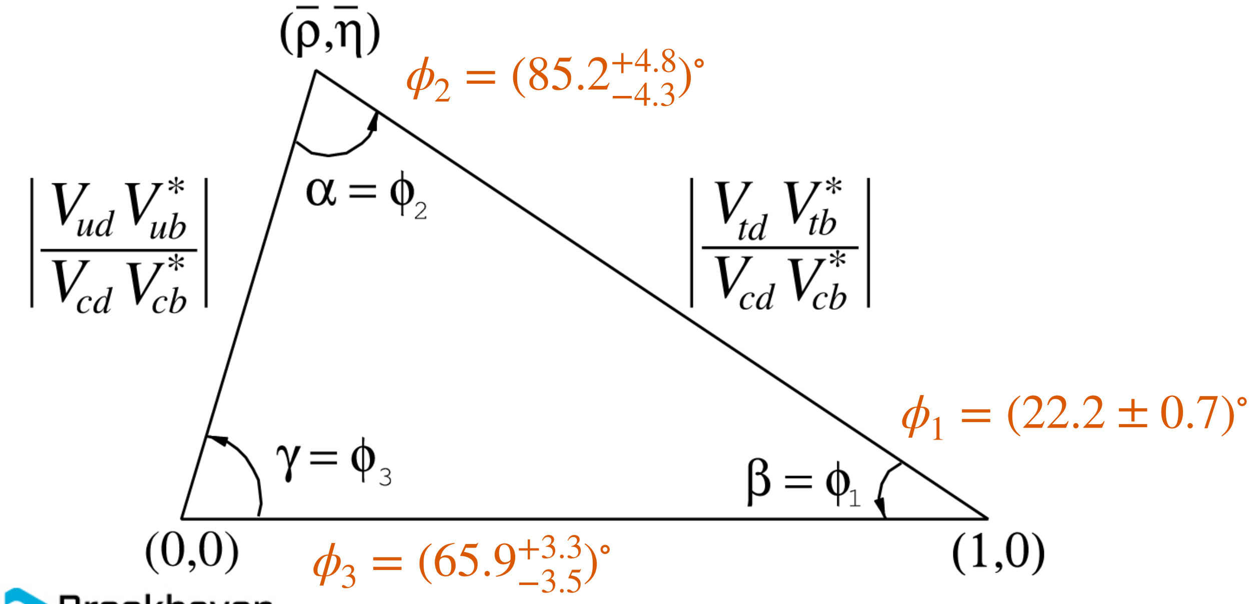


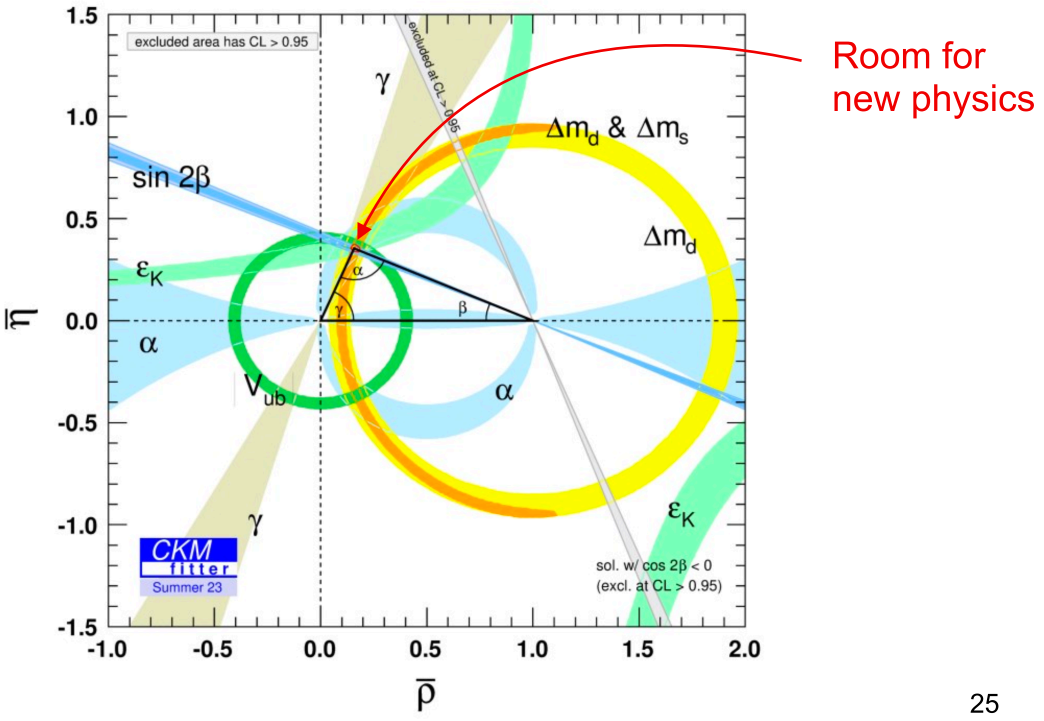
The CKM Matrix Unitarity

- Unitarity conditions can be represented as triangles
  - Three mixing angles and one CP violating phase

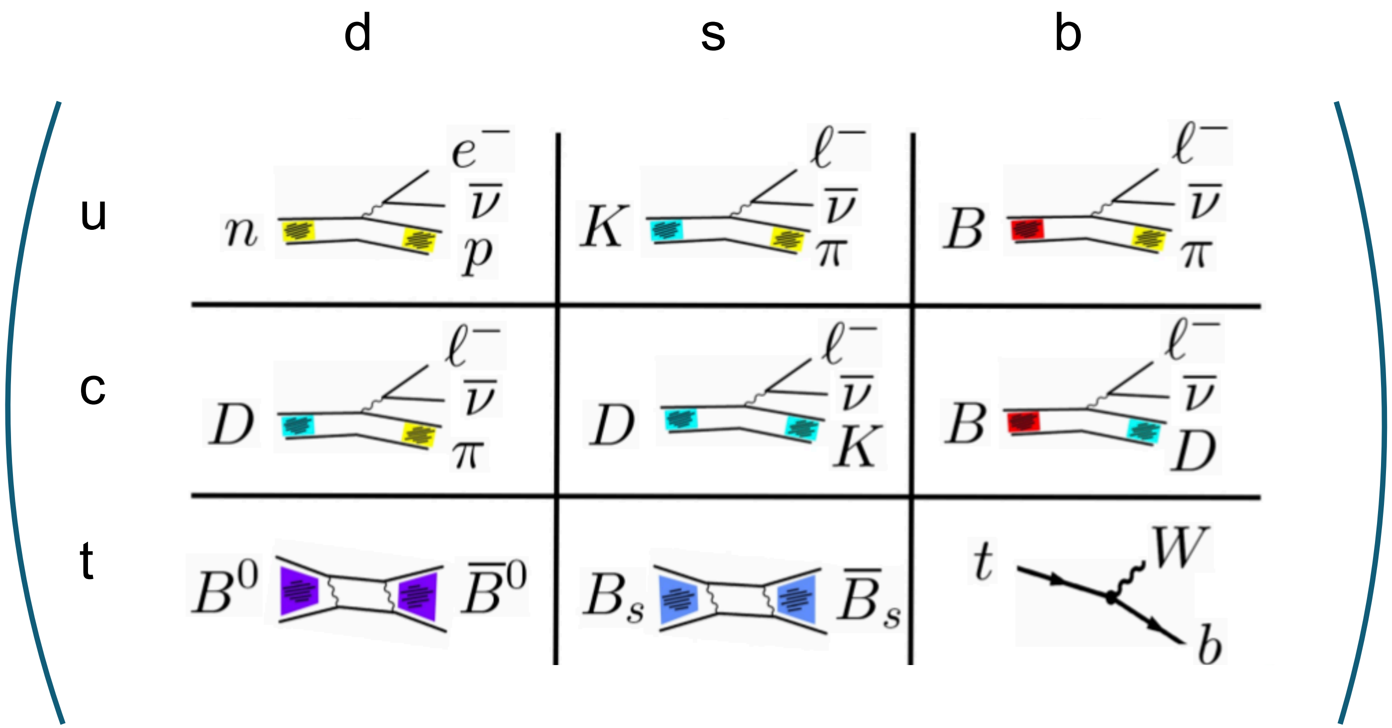
$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

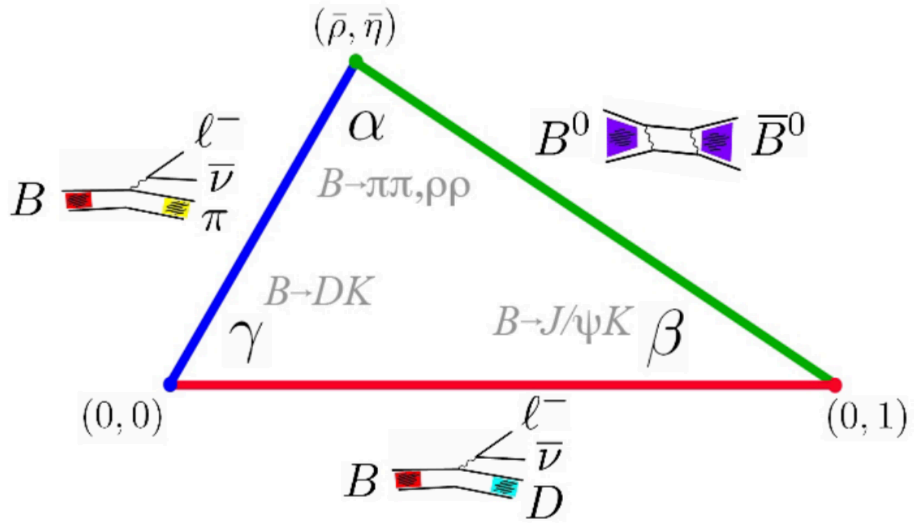
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$





Extracting CKM Parameters



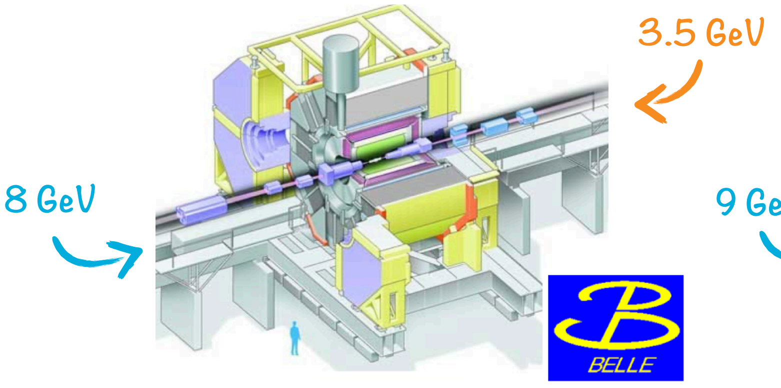


Figures: L. Silva, http://ckmfitter.in2p3.fr/www/docs/slides_ckmworkshop_2023.pdf

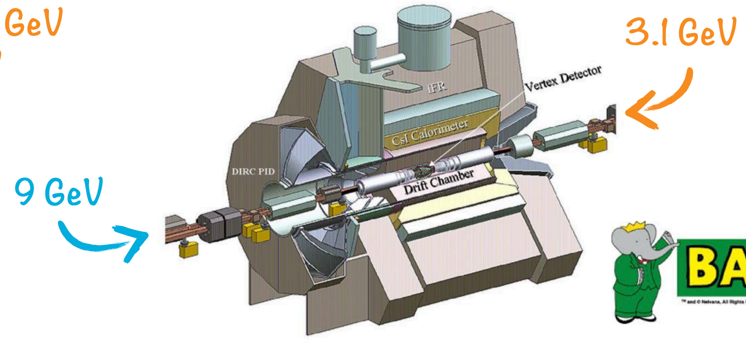
B-Factories

electron (7 GeV)

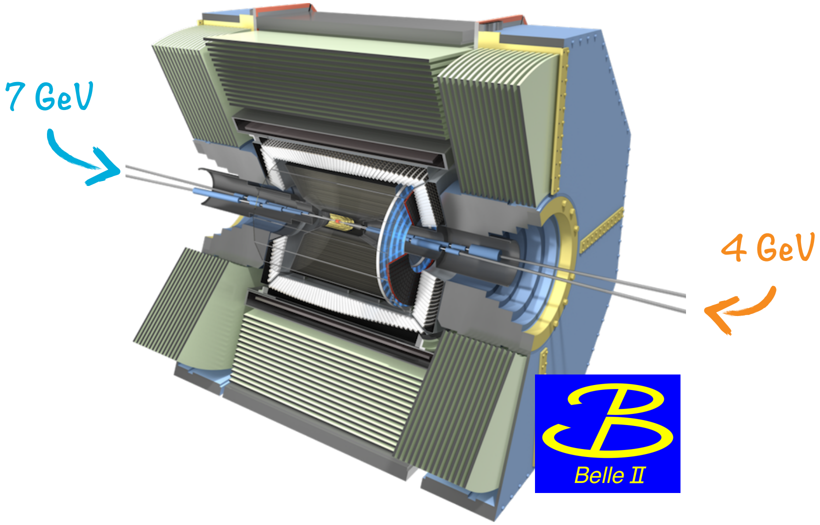
B-Factories



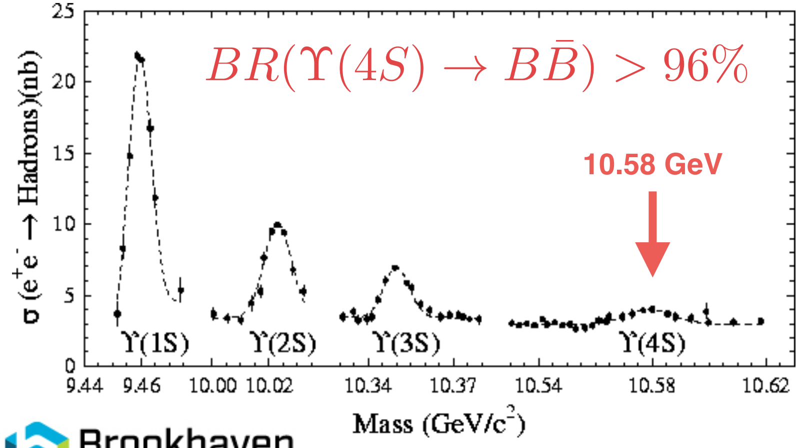
KEKB collider : 711 fb^{-1}@Υ(4S)
[1999-2010]



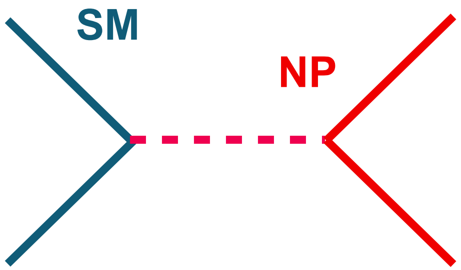
SLAC-PEP II collider : 462 fb^{-1}@Υ(4S)
[1999-2008]



SuperKEKB collider: 2018 - to date



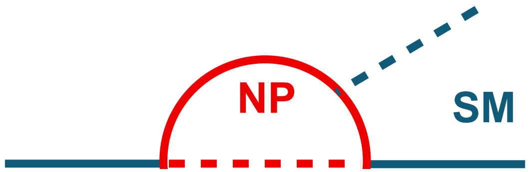
Energy frontier



Limited by beam energy

vs

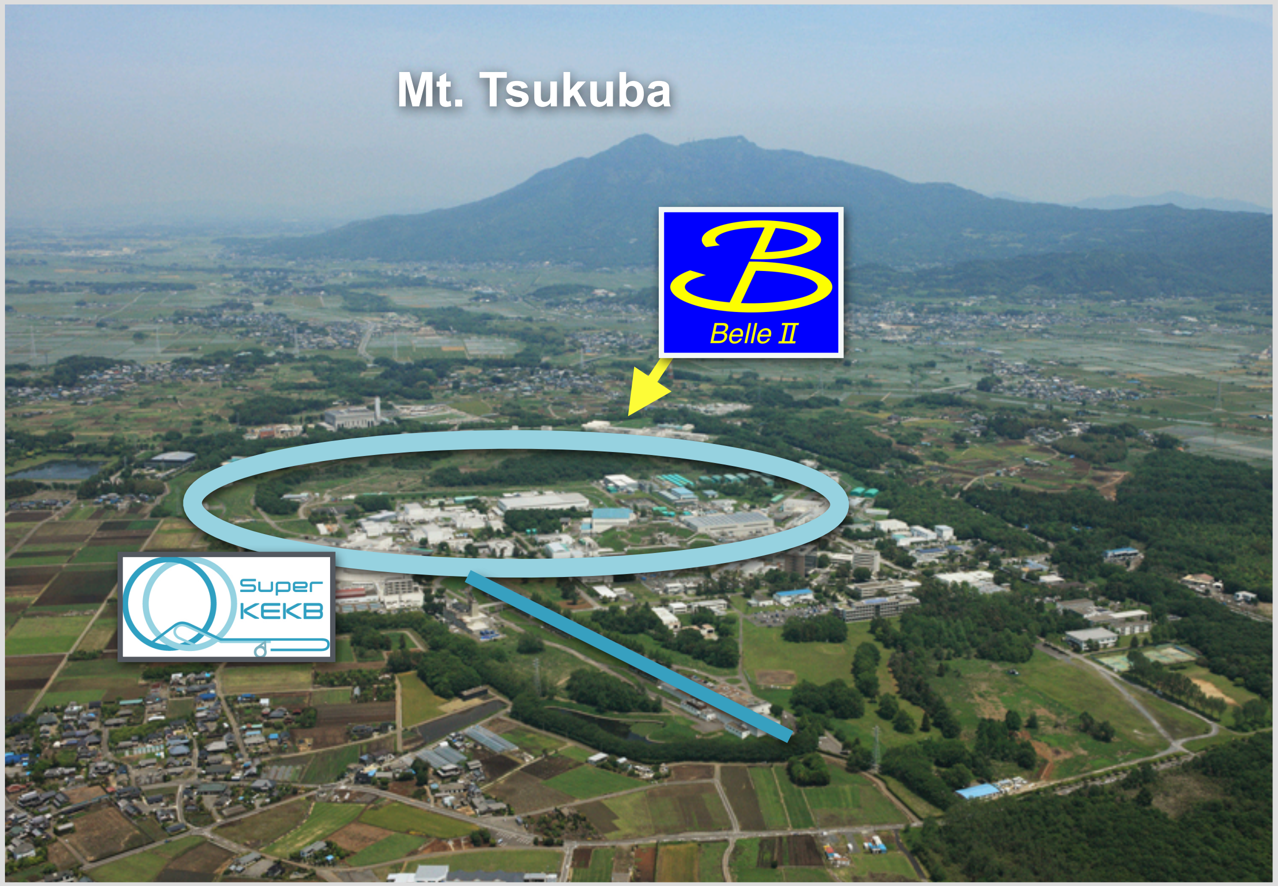
Intensity frontier

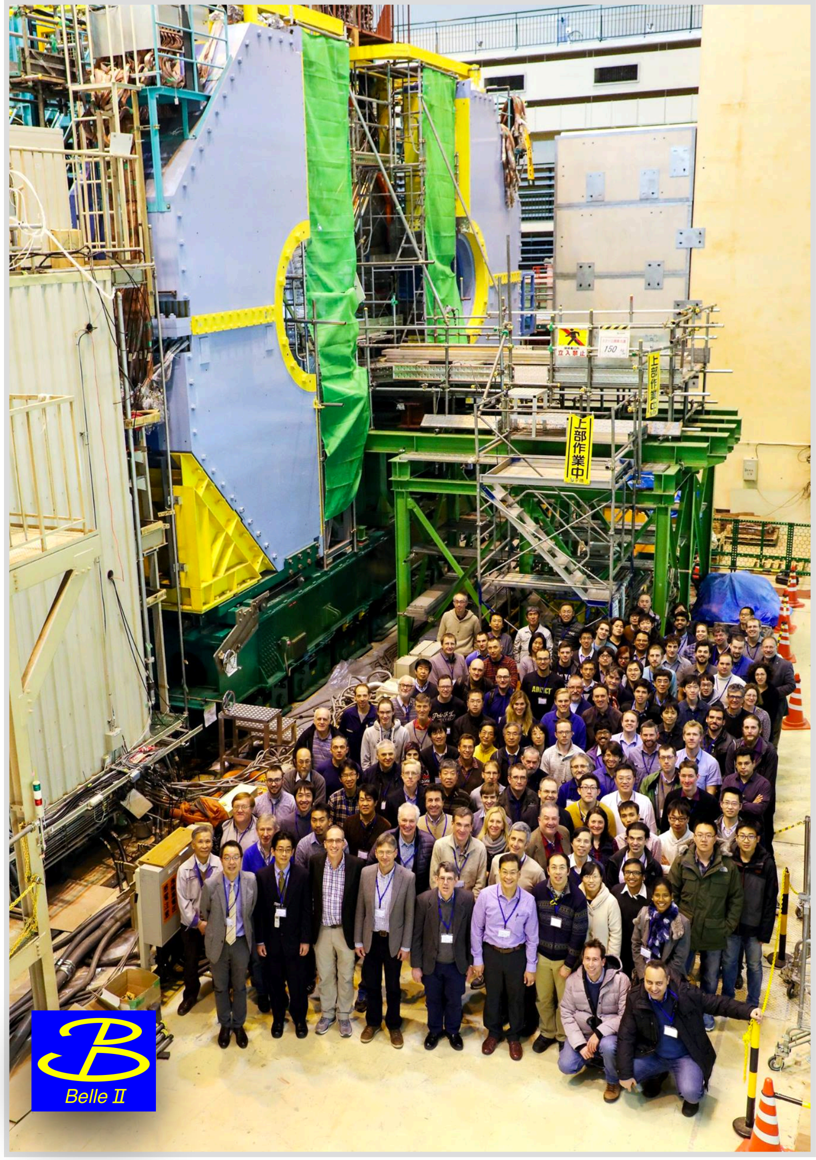


Limited by statistics

The Belle II Collaboration

1200 members, 125 institutions, 28 countries





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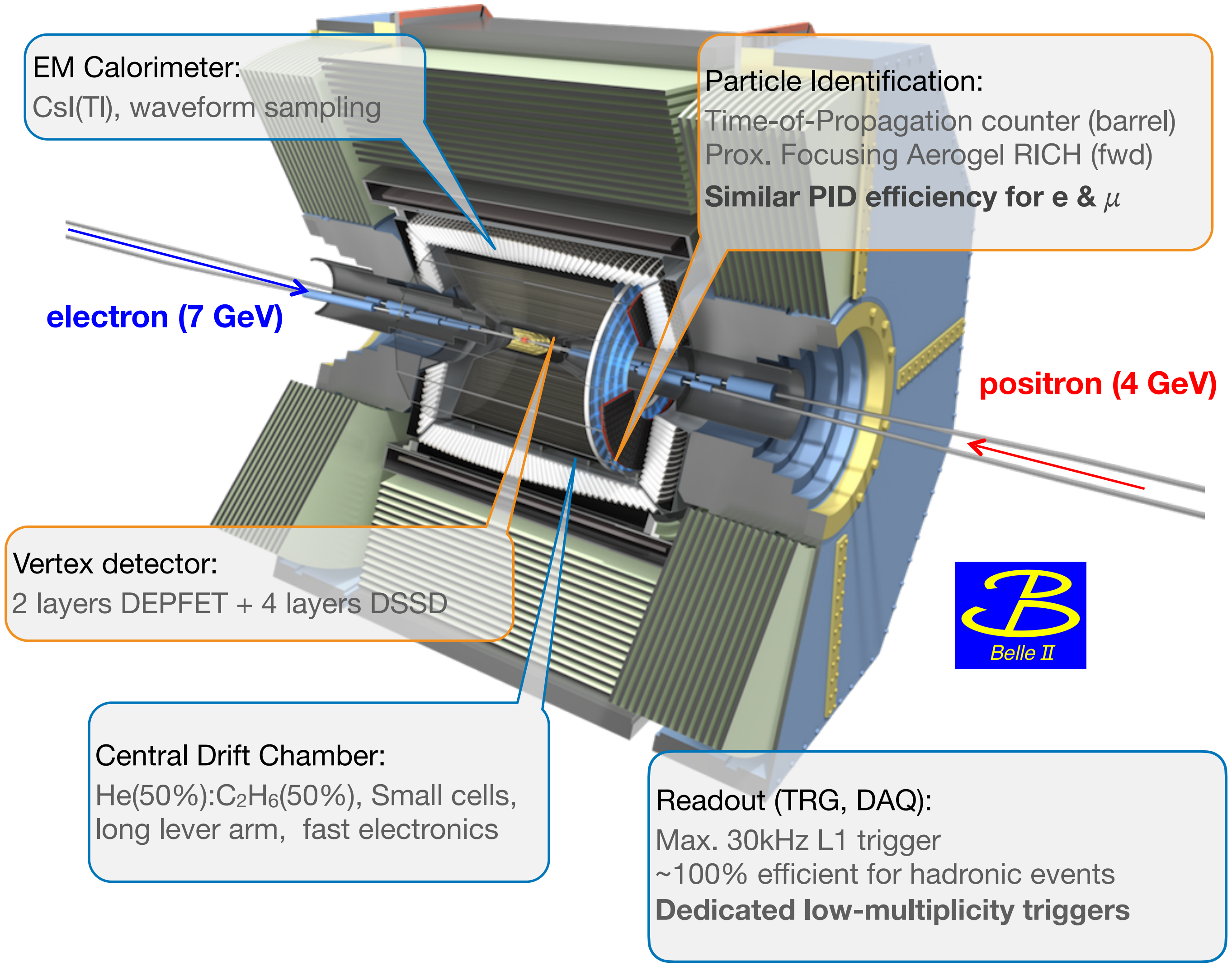
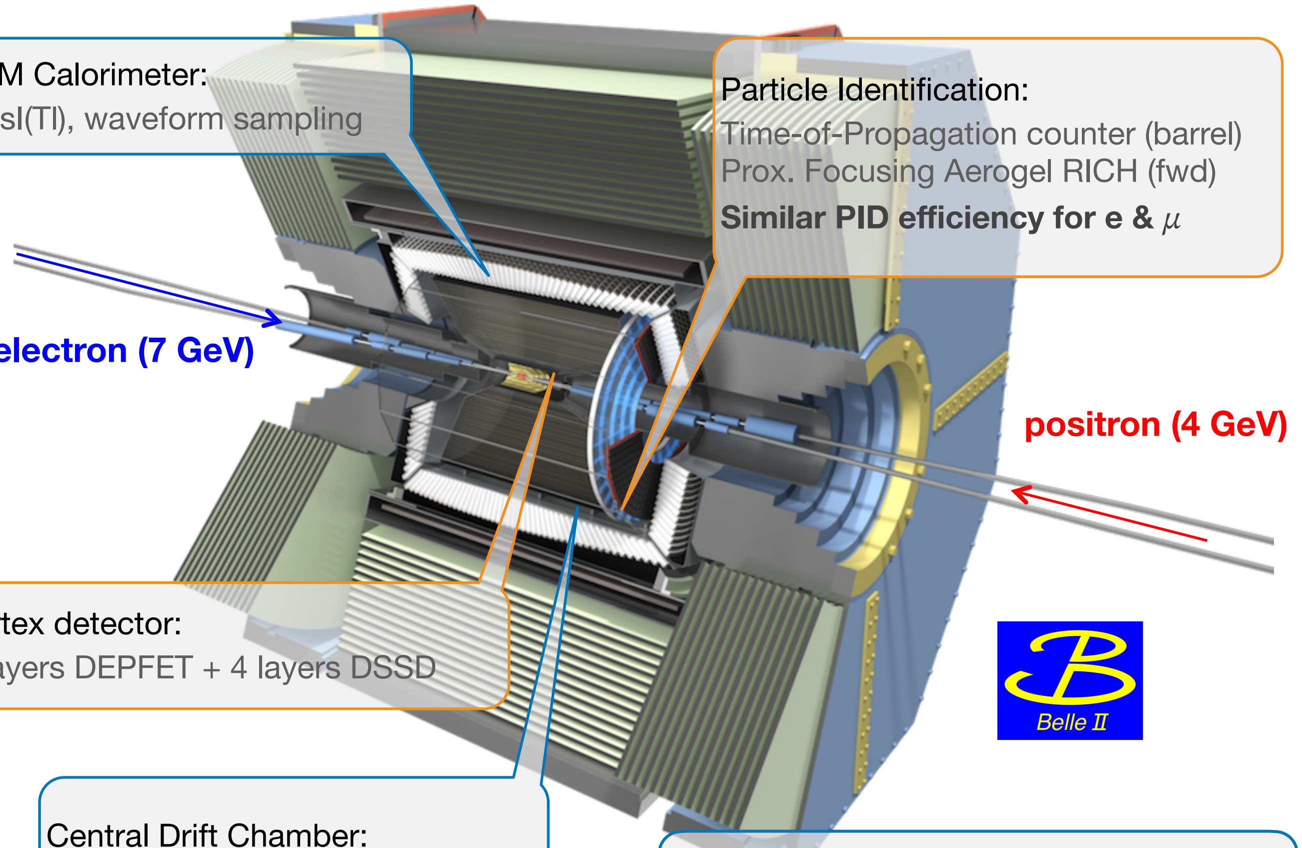
Belle II in a Nutshell



arXiv:1011.0352 [physics.ins-det]

Belle II in a Nutshell



EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. Focusing Aerogel RICH (fwd)
Similar PID efficiency for e & μ

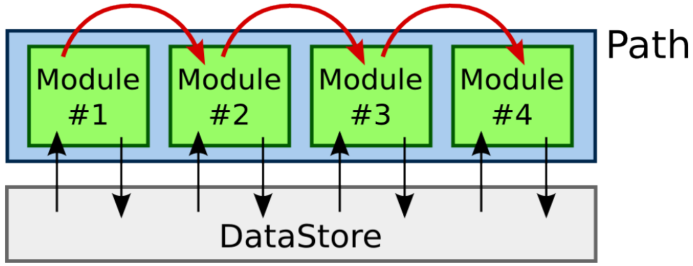
Vertex detector:
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber:
He(50%):C_2H_6(50%), Small cells,
long lever arm, fast electronics

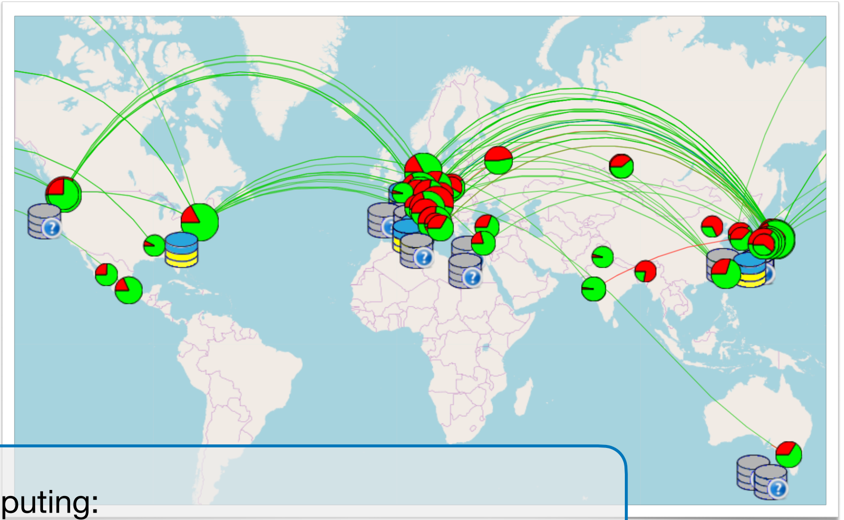
Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic events
Dedicated low-multiplicity triggers

arXiv:1011.0352 [physics.ins-det]

Software:
Open-source algorithms for simulation, reconstruction, visualization, and analysis



Comput. Softw. Big Sci. 3 1 (2019)

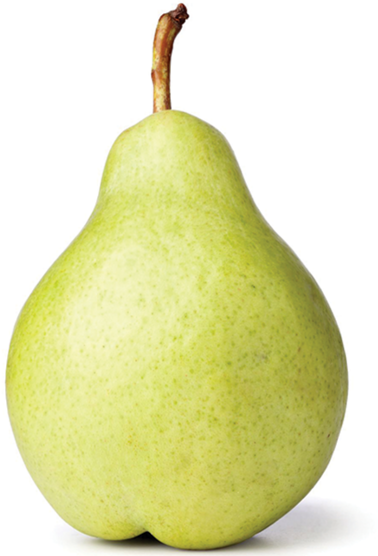


Computing:
Distributed over the world via grid

EPJ Web Conf., 245 (2020) 11007

B-Factories 101: Event Shape and Kinematics

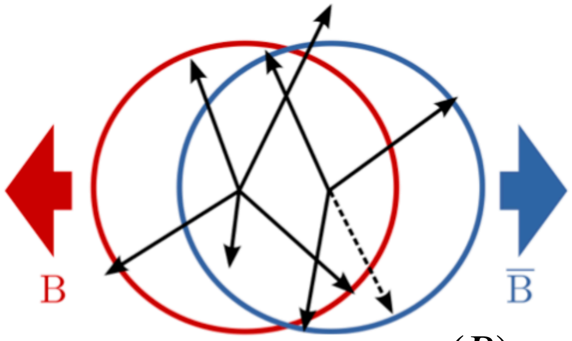
or



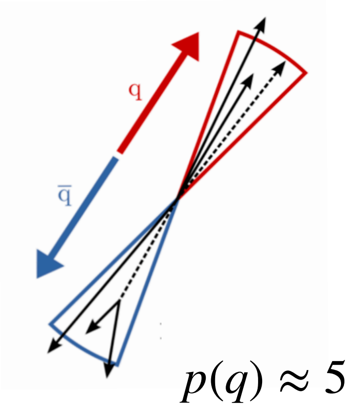
B-Factories 101: Event Shape and Kinematics

- $B\bar{B}$ events have a spherical shape, useful to discriminate them from $q\bar{q}$ events

$$\sqrt{s} = 10.58 \text{ GeV} \approx 2m_B$$



$p(B) \approx 0.3 \text{ GeV}/c$

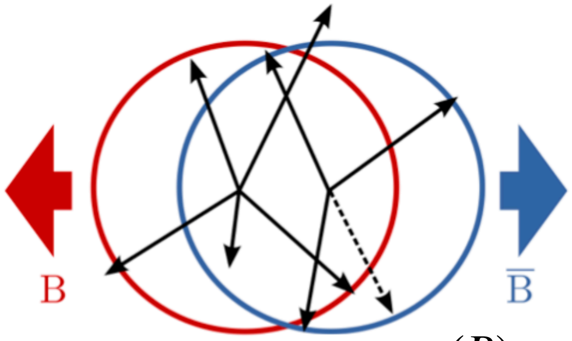


$p(q) \approx 5 \text{ GeV}/c$

B-Factories 101: Event Shape and Kinematics

- $B\bar{B}$ events have a spherical shape, useful to discriminate them from $q\bar{q}$ events

$$\sqrt{s} = 10.58 \text{ GeV} \approx 2m_B$$



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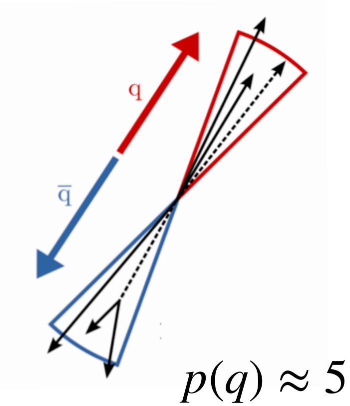
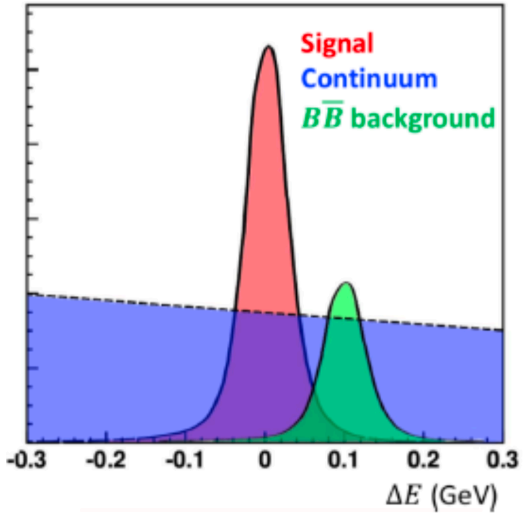


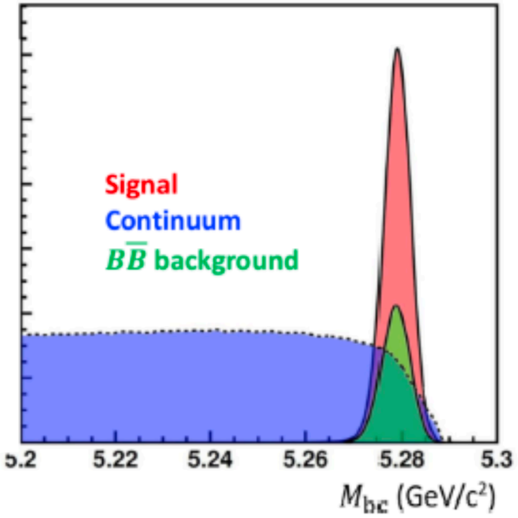
$p(q) \approx 5 \text{ GeV}/c$

- Kinematic constraints are used to separate signal from background and $q\bar{q}$ continuum

$$\Delta E = E_B - \sqrt{s}/2$$



$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{\,2}}$$



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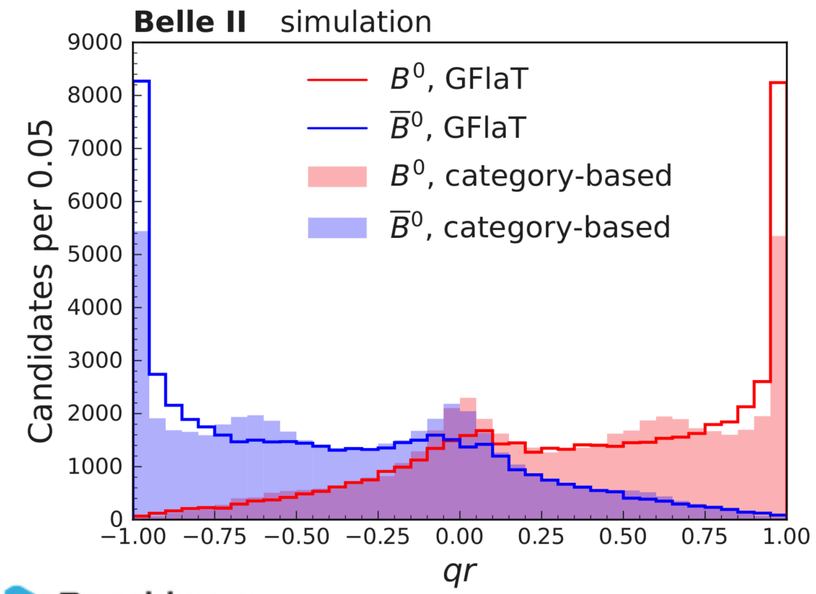
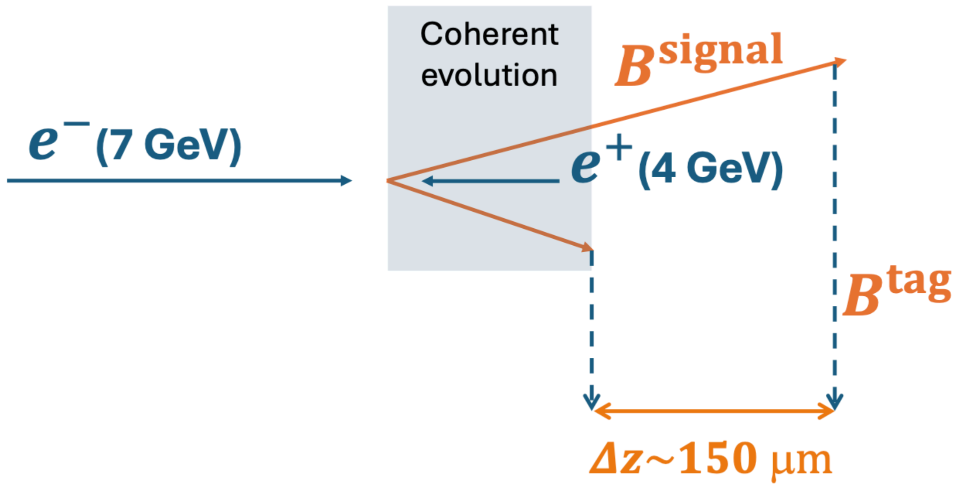
B-Factories 101: Flavor tagging and ϕ_1

- A novel technique in Belle II to tag flavors:
  Graph neural-network flavor tagging (GFlaT)
  - Accounts for relations between final-state particles
  - Calibrated using "self-tagging" B decays, like
    $B^0 \to D^{*-}\pi^+ \to \bar{D}\pi^-\pi^+ \to K^+\pi^-\pi^-\pi^+$





Analysis technique unique to B factories

Brookhaven National Laboratory

Phys. Rev. D 110, 012001 (2024)

B-Factories 101: Flavor tagging and ϕ_1

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  - Accounts for relations between final-state particles
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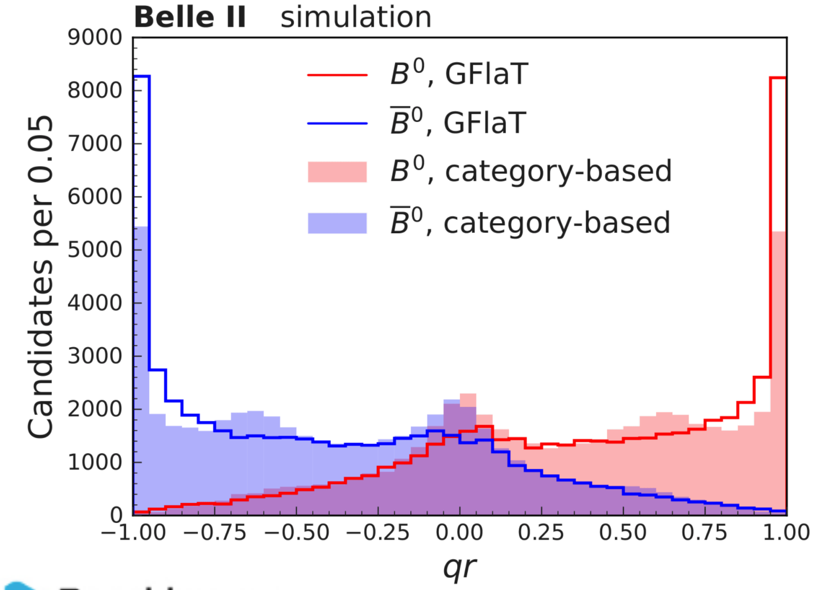


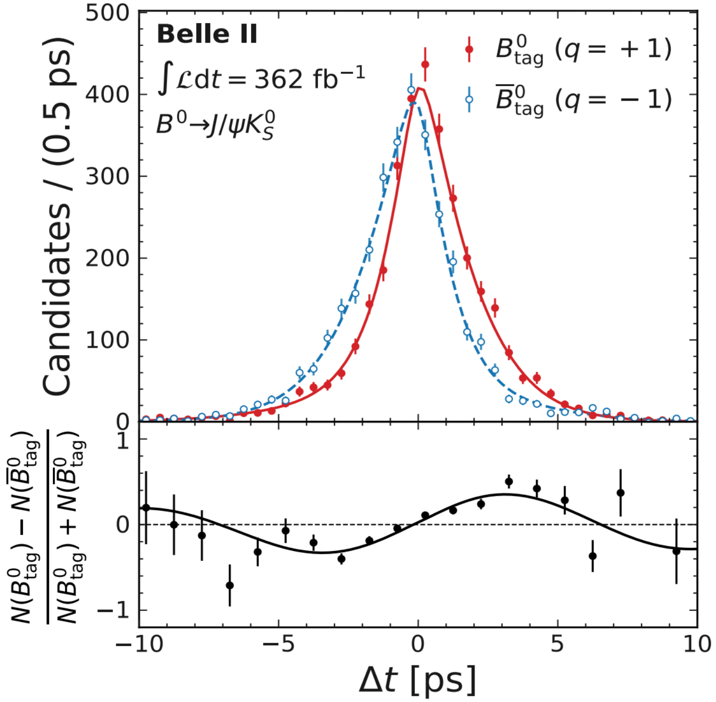
Improvement of 20% in effective tagging power vs previous algorithm

- Using as a benchmark the "golden channel" $B^0 \to J/\psi\, K_s^0$

$$A_{CP}^{B\to f}(\Delta t) \equiv \frac{\Gamma(B^0(\Delta t) \to f) - \Gamma(\bar{B}^0(\Delta t) \to f)}{\Gamma(B^0(\Delta t) \to f) + \Gamma(\bar{B}^0(\Delta t) \to f)}$$

$$= S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)$$

Mix-induced CPV — Direct CPV — $S = |\sin(2\phi_1)|$



$\phi_1 = (23.2 \pm 1.5 \pm 0.6)^\circ$

Brookhaven National Laboratory

Phys. Rev. D 110, 012001 (2024)

ϕ_2: $B^0 \to \pi^0\pi^0$

Phys. Rev. D 111, L071102 (2025)

$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = \frac{\Gamma(\overline{B}^0 \to \pi^0\pi^0) - \Gamma(B^0 \to \pi^0\pi^0)}{\Gamma(\overline{B}^0 \to \pi^0\pi^0) + \Gamma(B^0 \to \pi^0\pi^0)}$$

- Tree-level $b \to u\bar{u}d$ decays are sensitive to ϕ_2
  - loop $b \to d$ loop contributions add an extra phase $\Delta\phi_2$
- Determining ϕ_2 from $B \to \pi\pi$ decays, requires BRs and ACP of:

$$B^0 \to \pi^+\pi^-,\ B^+ \to \pi^+\pi^0,\ B^0 \to \pi^0\pi^0$$

[Phys. Rev. Lett. 65, 3381]

ϕ_2: $B^0 \to \pi^0\pi^0$

[Phys. Rev. D 111, L071102 (2025)]

$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = \frac{\Gamma(\overline{B}^0 \to \pi^0\pi^0) - \Gamma(B^0 \to \pi^0\pi^0)}{\Gamma(\overline{B}^0 \to \pi^0\pi^0) + \Gamma(B^0 \to \pi^0\pi^0)}$$

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$$B^0 \to \pi^+\pi^-,\ B^+ \to \pi^+\pi^0,\ B^0 \to \pi^0\pi^0$$

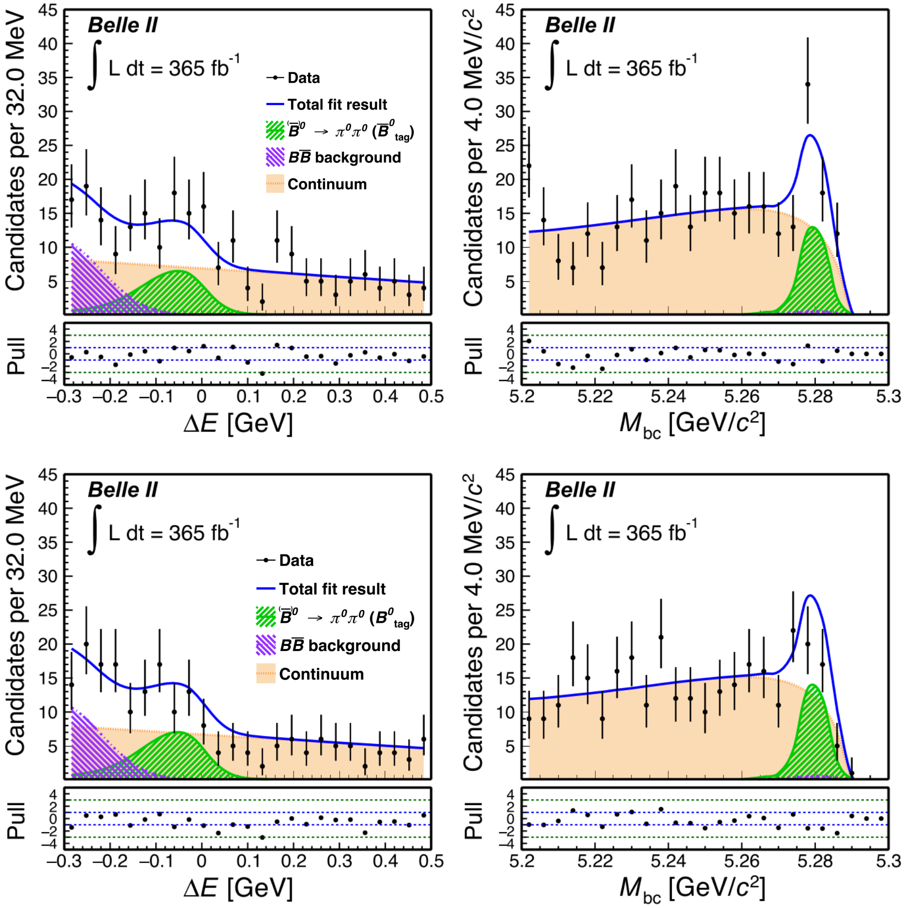
[Phys. Rev. Lett. 65, 3381]

- Updated measurement of $B^0 \to \pi^0\pi^0$at Belle II with full run 1 statistics
  - Experimentally challenging: 4 photons with no tracks
  - A BDT classifier to discriminate signal
  - Using the **graph flavor tagger** to determine signal flavor and measure CP asymmetry

$$\mathscr{B}(B \to \pi^0\pi^0) = (1.26 \pm 0.20 \pm 0.12) \times 10^{-6}$$

$$A_{CP}(B \to \pi^0\pi^0) = 0.06 \pm 0.30 \pm 0.05$$

World-best!



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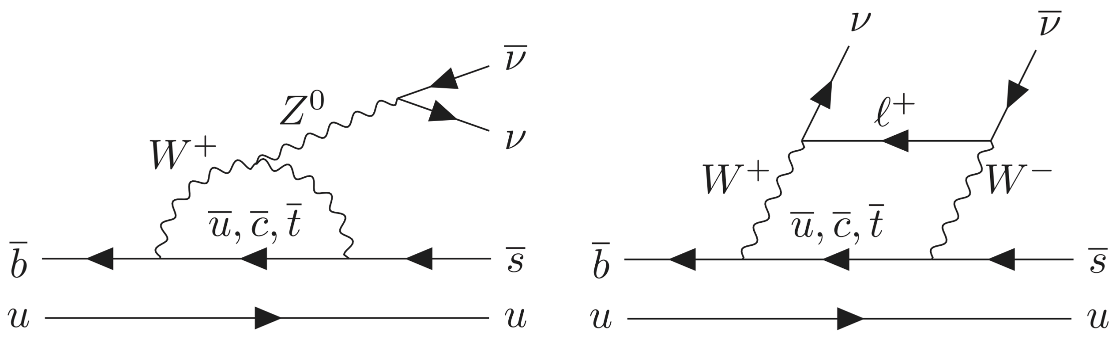
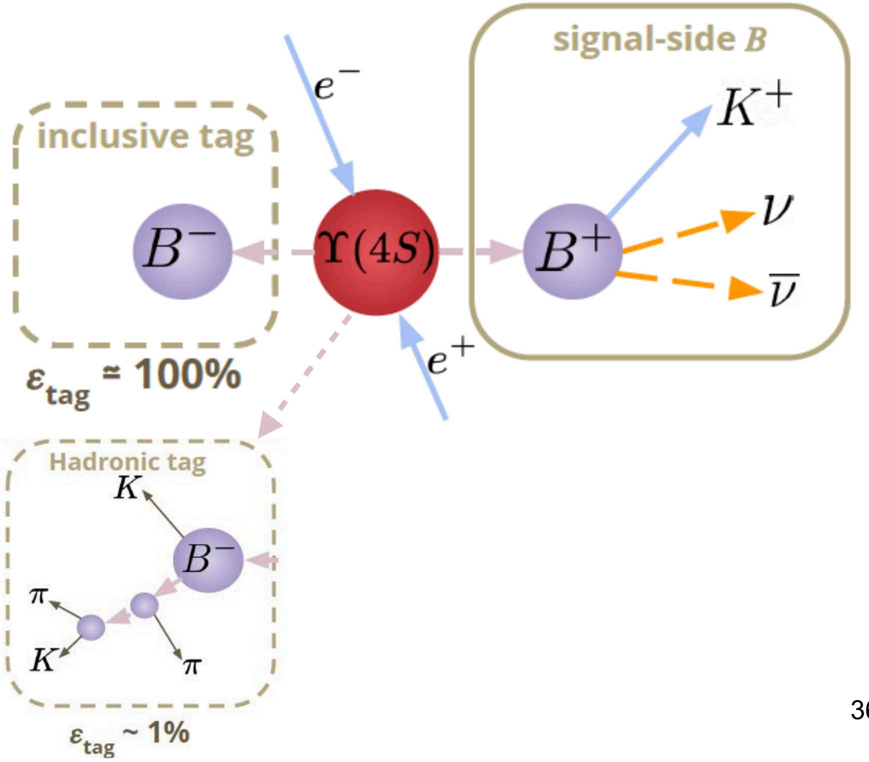
$B^+ \to K^+\nu\bar{\nu}$ decays

- Flavor-changing neutral current $b \to s\nu\bar{\nu}$ transitions suppressed in the SM due to the GIM mechanism
- Reliable prediction for the branching ratio in the SM

$$BR(B^+ \to K^+\nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$$ PRD 107, 014511 (2023)



- Can be modified by non-SM contributions
  - $B^+ \to K^+ +$ dark matter
  - Leptoquarks (hypothetical particles that would interact with quarks and leptons)
- New approach: inclusive + hadronic B-tagging & MVA classifier
  - **Inclusive tag** increase signal efficiency by 35% vs exclusive tag
  - **Hadronic tag** for consistency check and 10% increase in precision for final combination



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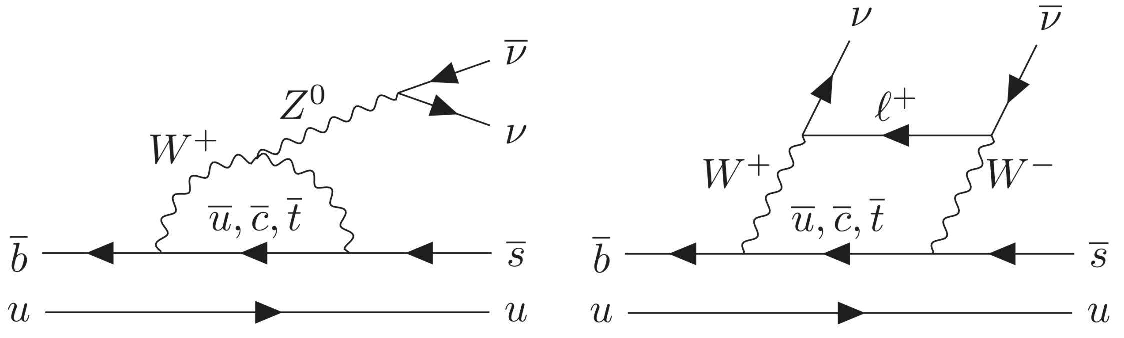
$B^+ \to K^+\nu\bar{\nu}$ decays

- Flavor-changing neutral current $b \to s\nu\bar{\nu}$ transitions suppressed in the SM due to the GIM mechanism
- Reliable prediction for the branching ratio in the SM

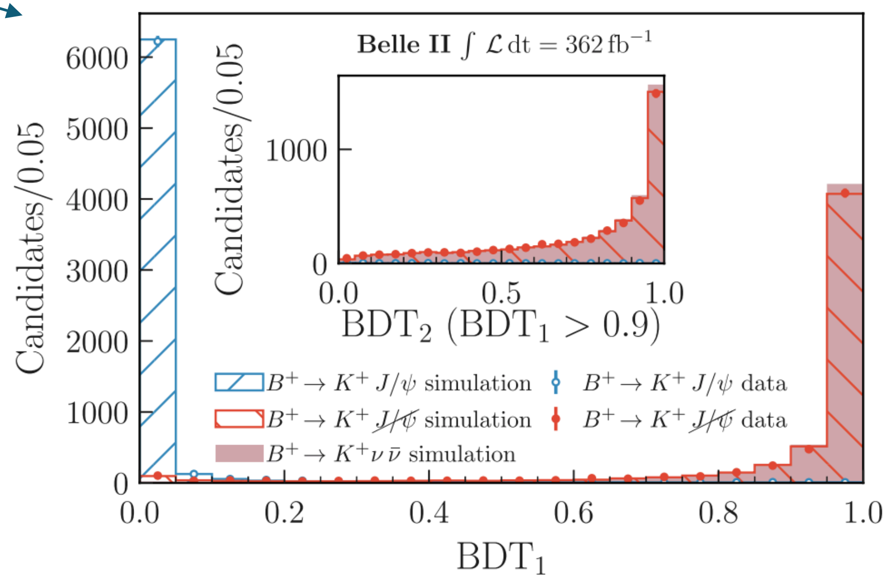
$$BR(B^+ \to K^+\nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$$ PRD 107, 014511 (2023)



- Can be modified by non-SM contributions
  - $B^+ \to K^+$ + dark matter
  - Leptoquarks

- New approach: inclusive + hadronic B-tagging & MVA classifier
  - **Inclusive tag** increase signal efficiency by 35% vs exclusive tag
  - **Hadronic tag** for consistency check and 10% increase in precision for final combination

- Validated with $B^+ \to K^+ + J/\psi$:



Evidence for $B^+ \to K^+ \nu\bar{\nu}$ decays

[Phys. Rev. D 109, 112006]

- Perform binned maximum likelihood fit

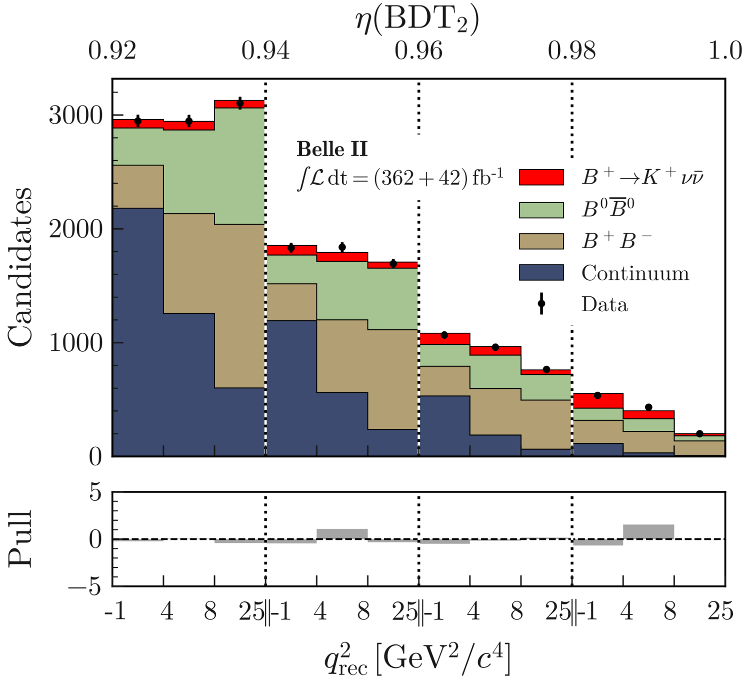
Inclusive tag: fit in bins of di-neutrino mass (q^2_{rec}) and classifier output:

ITA: $BR = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

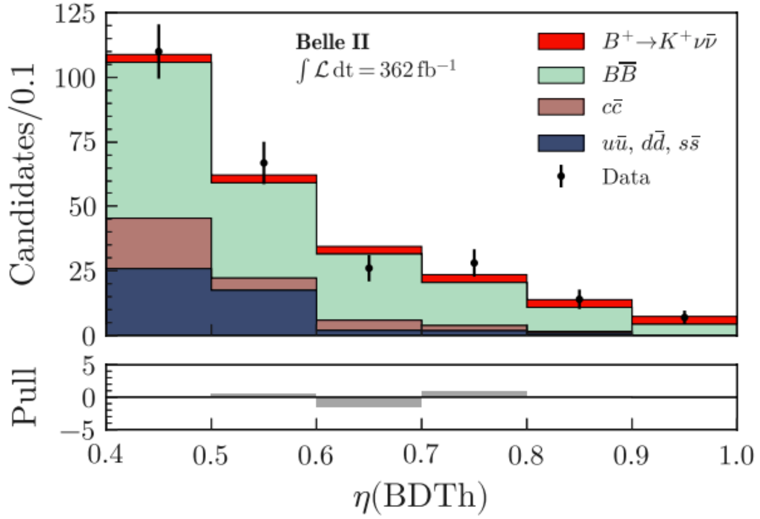
HTA: $BR = (1.1\ ^{+0.9}_{-0.8}\ ^{+0.8}_{-0.5}) \times 10^{-5}$

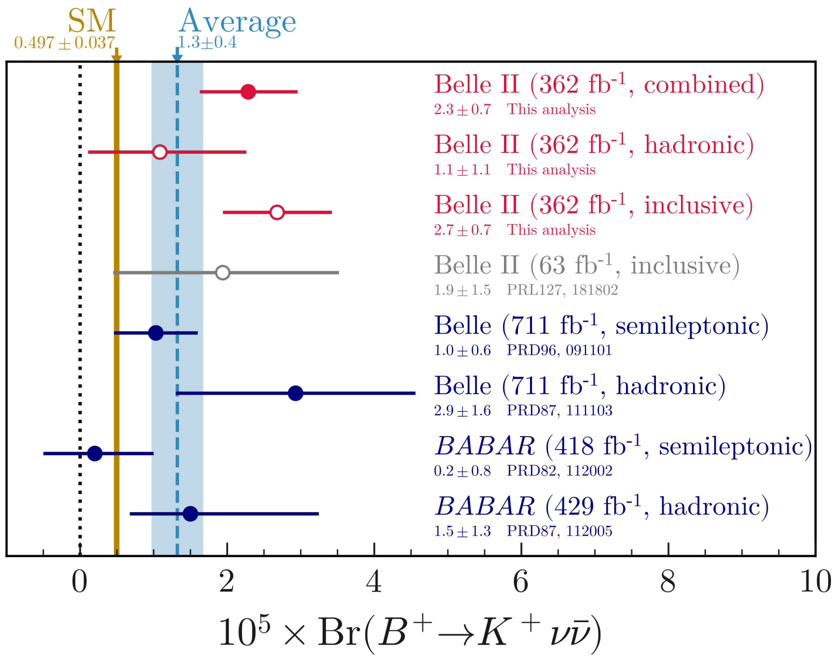
Combined: $BR = (2.3 \pm 0.5\ ^{+0.5}_{-0.4}) \times 10^{-5}$

Fit Result
- 3.5σ excess
- 2.7σ from SM



Hadronic tag: in bins of classifier output:





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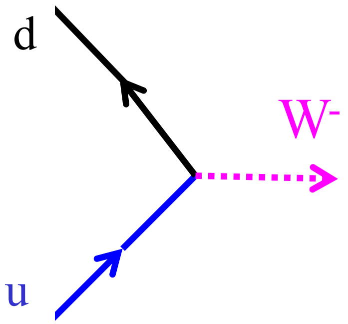
What about the leptons?

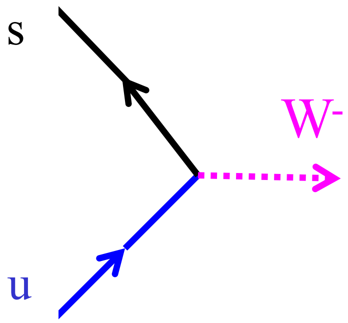
Weak Interactions in the SM

For quarks:

Allowed



Allowed

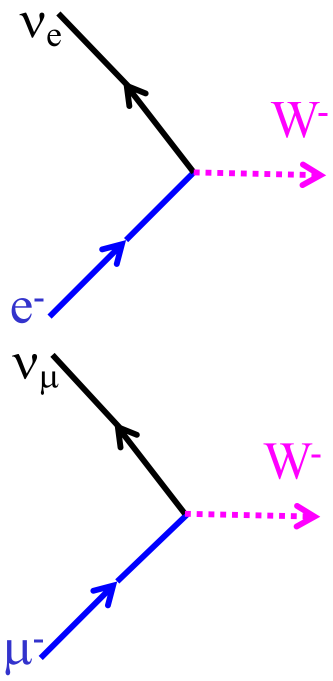


1) **Quarks allow mixing between flavors Leptons, don't**

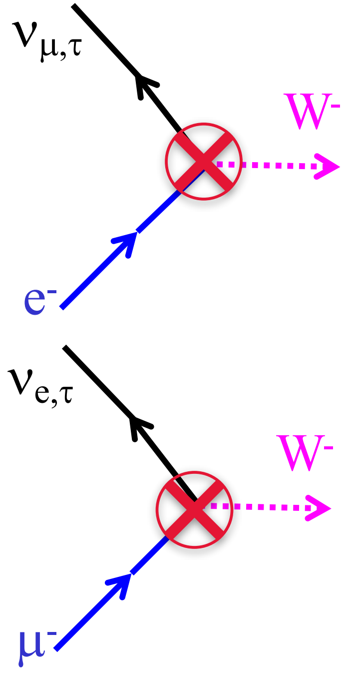
2) **All three charged leptons interact with the electroweak force in the same way**

For leptons:

Allowed



Forbidden



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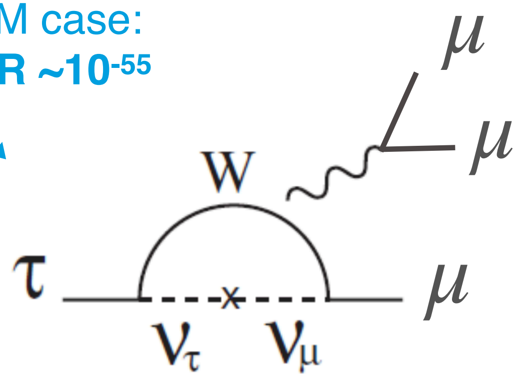
Lepton Flavor Violation?

- However, neutrinos change flavor!
  - Neutrino oscillation confirms mix between flavors in the lepton sector
  - But only in neutrinos!
- What about charged leptons?
  - Neutrinos with mass → CLFV
  - But extremely suppressed

SM case:
BR ~10^{-55}



[Eur. Phys. J. C 79, 84 (2019)]

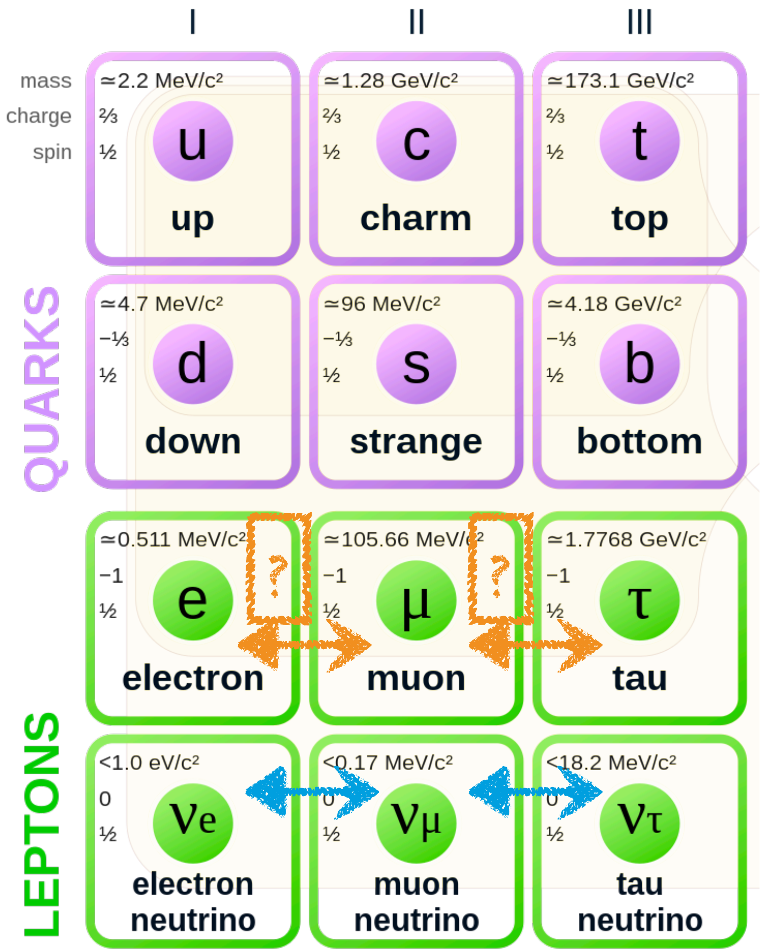


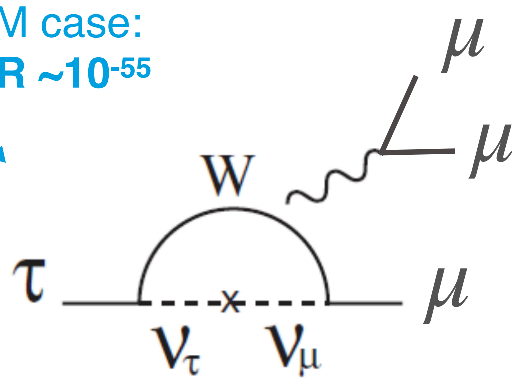
Figure: Wikipedia

Lepton Flavor Violation?

- However, neutrinos change flavor!
  - Neutrino oscillation confirms mix between flavors in the lepton sector
  - But only in neutrinos!
- What about charged leptons?
  - Neutrinos with mass → CLFV
  - But extremely suppressed

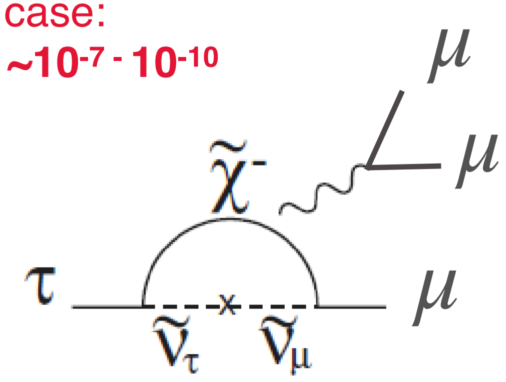
- **Observation of CLFV is a clear signature of New Physics!**

SM case:
BR ~10^{-55}



[Eur. Phys. J. C 79, 84 (2019)]

NP case:
BR ~10^{-7} - 10^{-10}



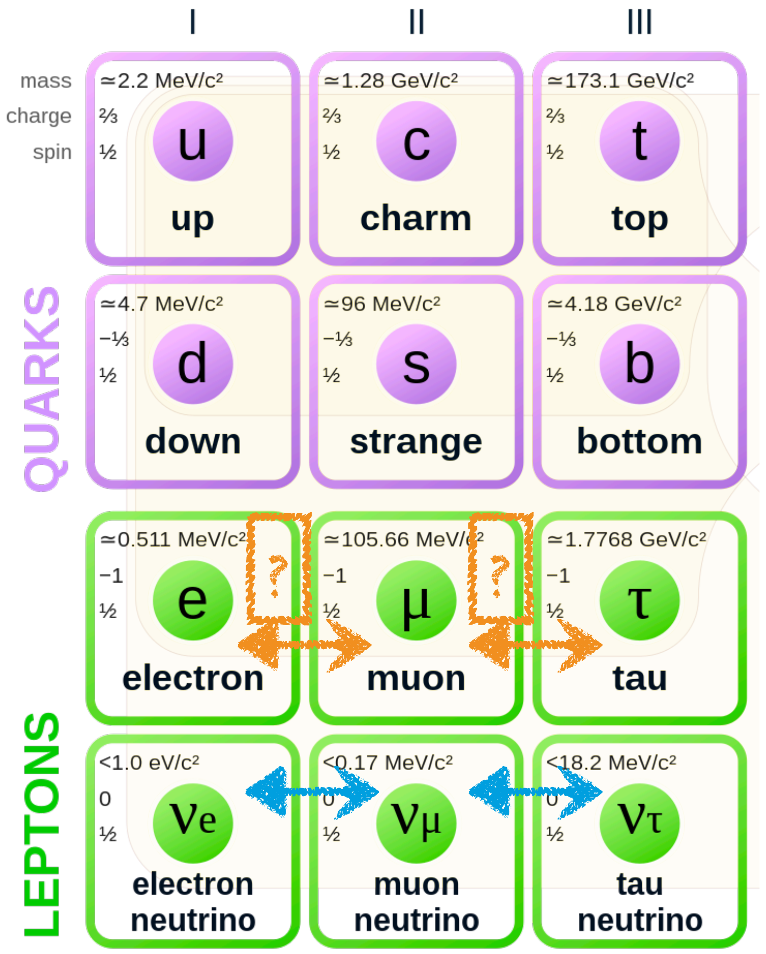


Figure: Wikipedia

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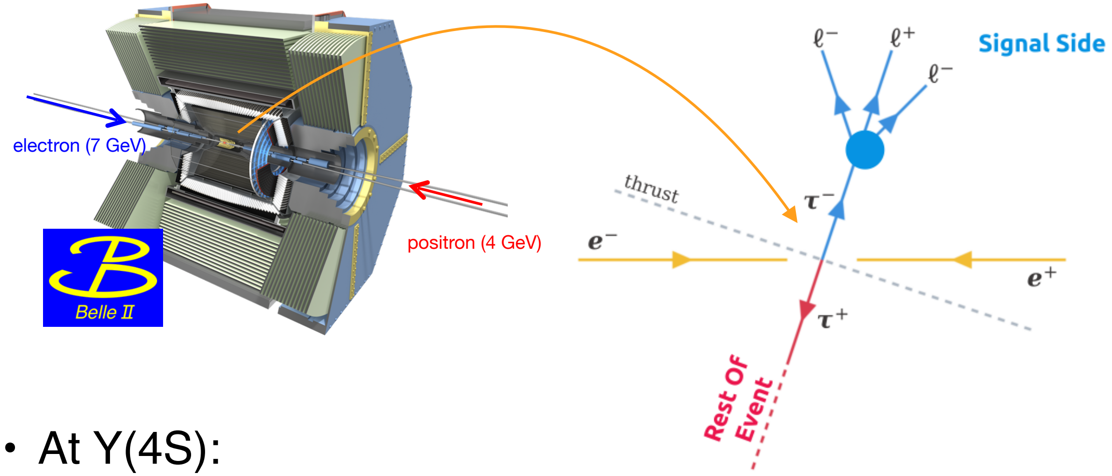
$\tau \to 3\mu$



- At Y(4S):

$$\sigma(e^+e^- \to B\bar{B}) = 1.05 \text{ nb}$$

$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92 \text{ nb}$$

Belle II is a τ Factory too

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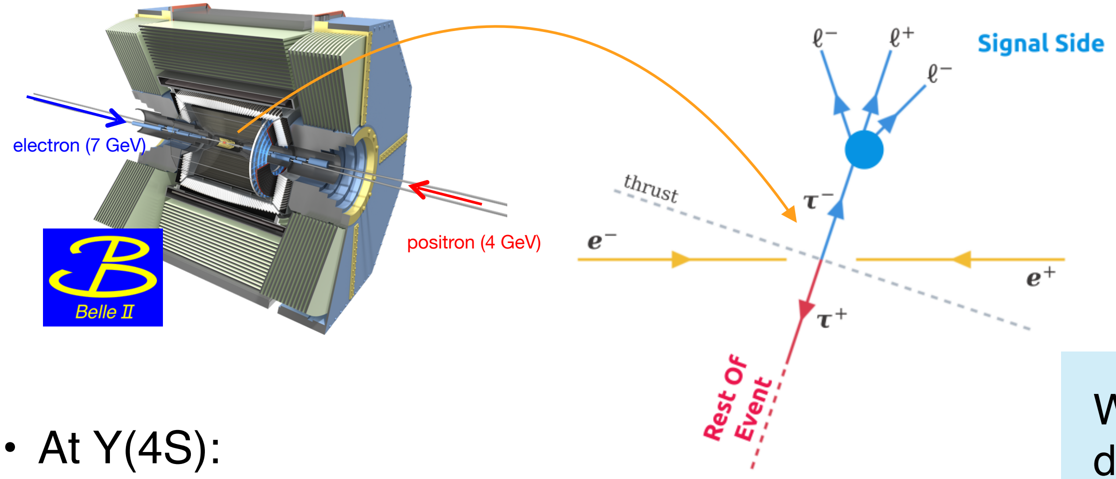
$\tau \to 3\mu$



- Inclusive tagging: only the signal τ is reconstructed from 3 muons
- Machine learning based selection with the rest of event
- Define a signal region in the $M_{3\mu}$, ΔE plane
  - One event after opening the box

- At Y(4S):

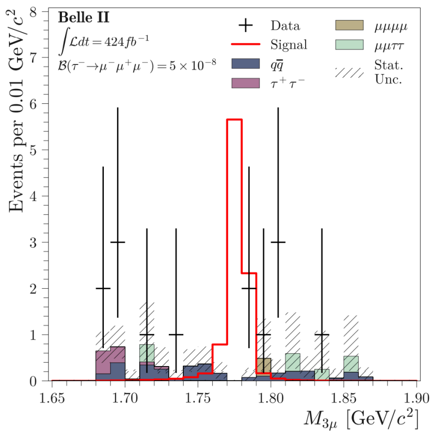
$$\sigma(e^+e^- \to B\bar{B}) = 1.05 \text{ nb}$$

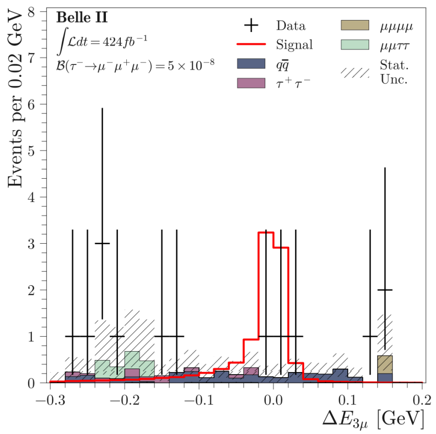
$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92 \text{ nb}$$

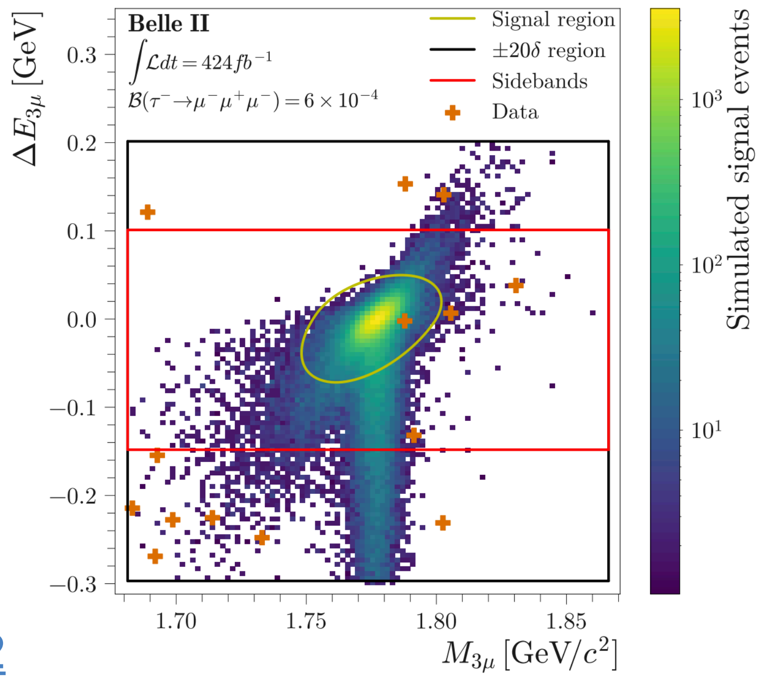
Belle II is a τ Factory too

World-best limit despite smaller data sample than Belle

$$\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^+) < 1.9 \times 10^{-8}$$







JHEP 09 (2024) 062

Expected upper limits on CLFV tau decays

- Neutrinoless 2-body or 3-body decays to 52 final states
- In some SM extensions, cLFV decays are expected at rates only one order of magnitude below present bounds

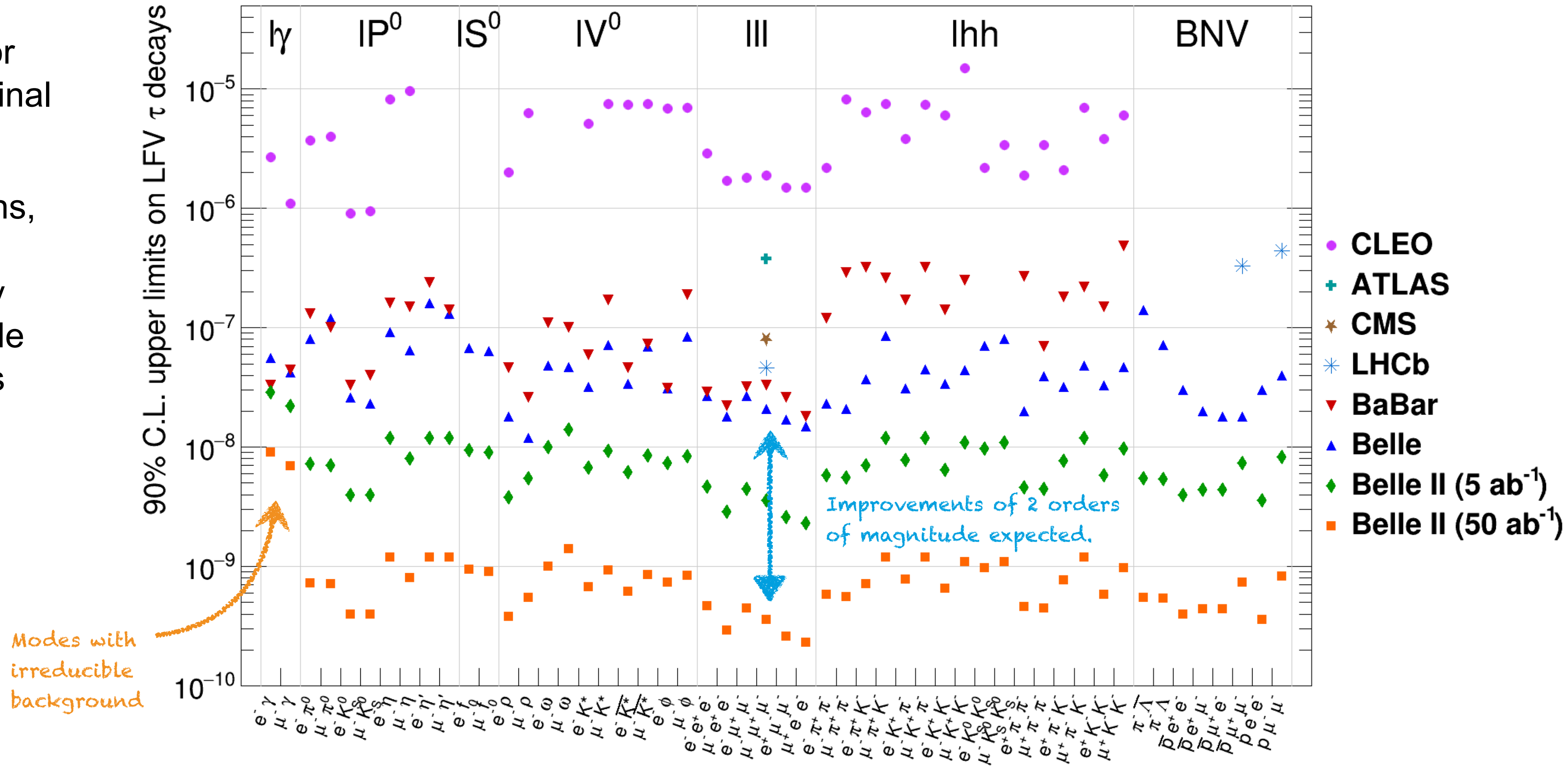
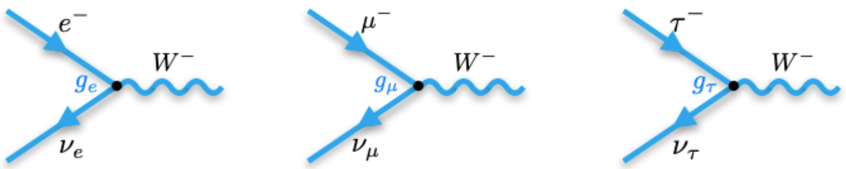


Figure: CLFV @ Snowmass 2021 arXiv:2203.14919 (2022)

Lepton Flavor Universality Test

$g_e = g_\mu = g_\tau$?



- The coupling of leptons to W bosons is flavor-independent in the SM
- τ decays enable a test of μ – e universality
- Experimental challenge: particle ID

$$\left(\frac{g_\mu}{g_e}\right)^2 \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \stackrel{\text{SM}}{=} 1$$

$$R_\mu = \frac{BR(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{BR(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \stackrel{\text{SM}}{=} 0.9726$$

Lepton Flavor Universality Test

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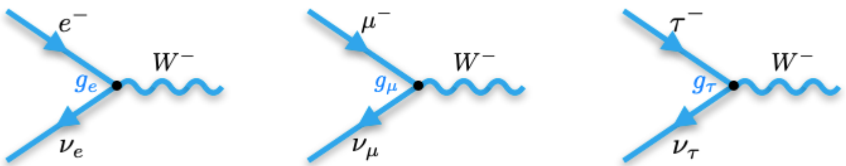

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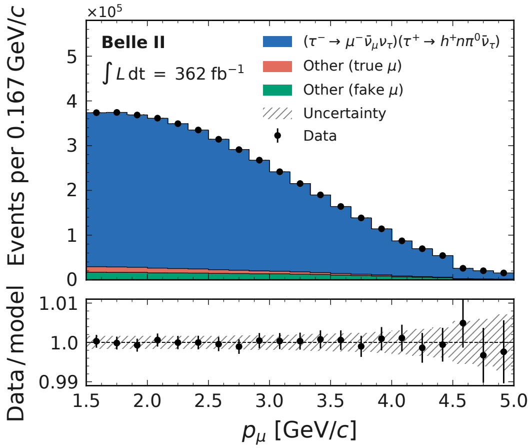
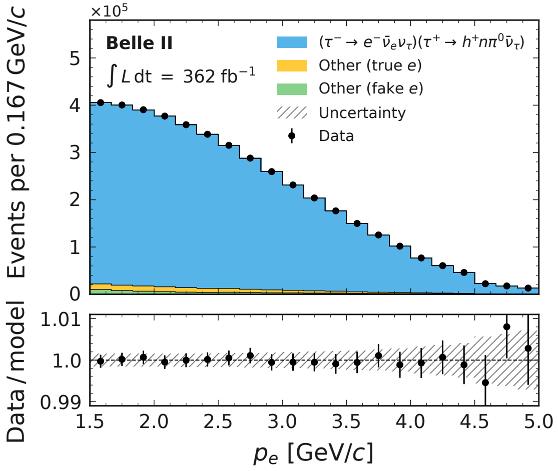
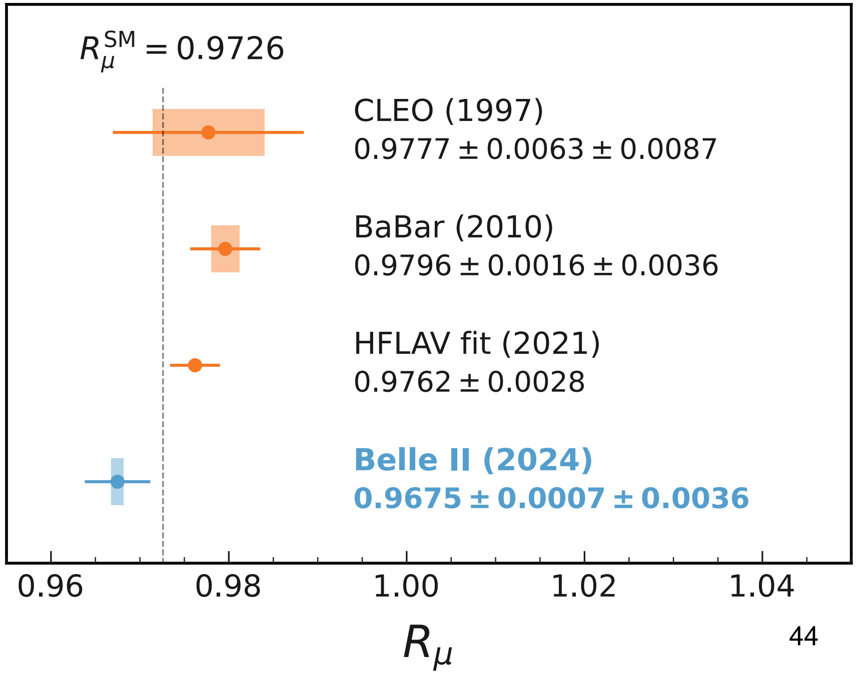
- Most precise test of universality in τ decays from a single measurement
- Consistent with the SM at 1.4σ







J. High Energ. Phys. 2024, 205 (2024)

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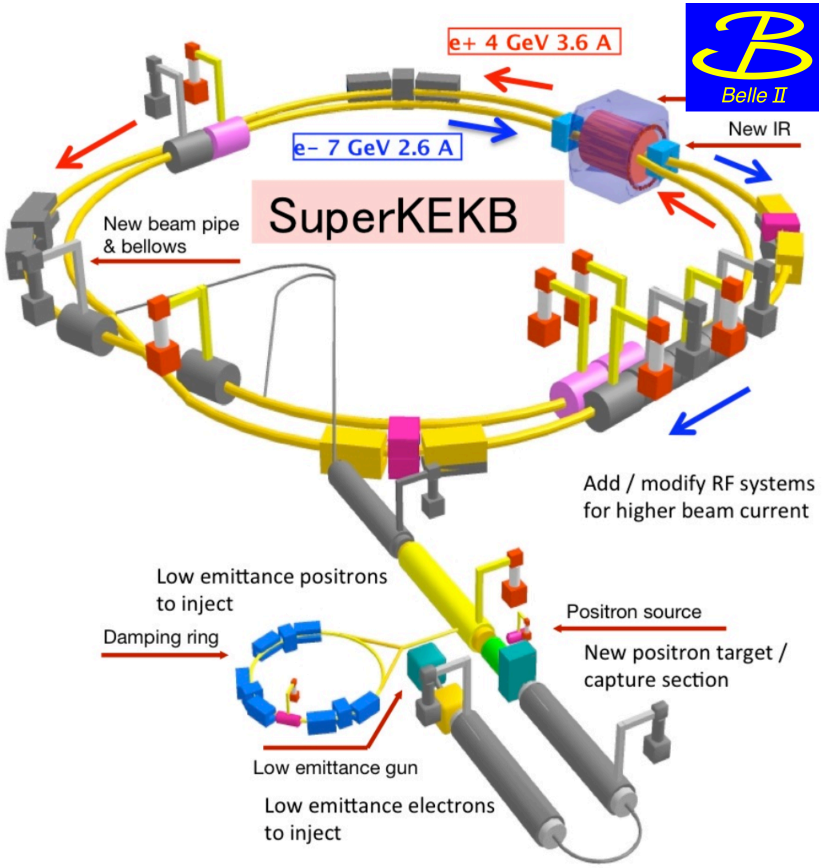
Summary

- Flavor physics study the flavor structure of the Standard Model, via
  - Precision measurements of observables sensitive to SM parameters
  - Searches of forbidden/highly suppressed modes
- Its a huge and diverse field, no time to cover everything!
- We don't understand yet why there are three generations of quarks and leptons, their hierarchical mass spectrum, or the origin of their mixing parameters
- Experiments around the world are working on more precise measurements that address these questions and potentially reveal a more complete picture of underling mechanisms
  - The next "big discovery" can be around the corner
- Stay tuned! Exciting times ahead

Image: @yukiRPM

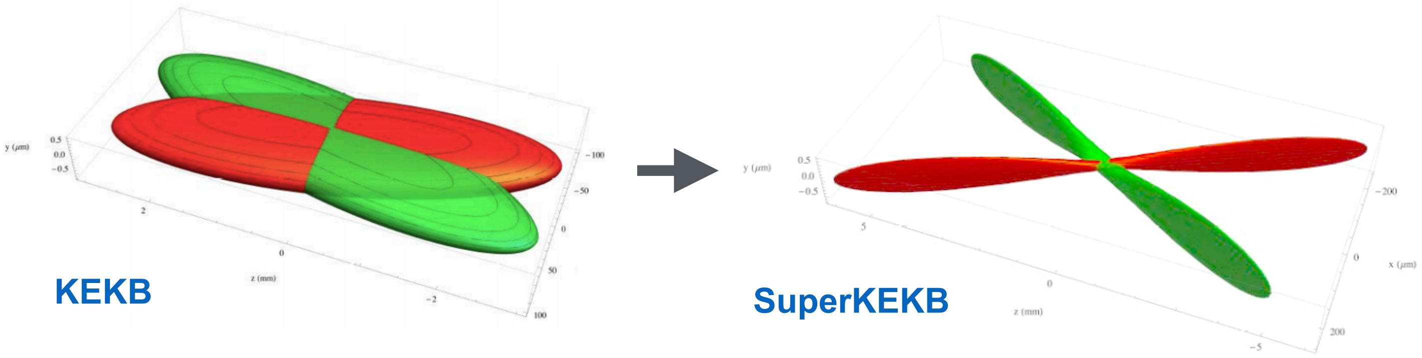
Backup

SuperKEKB



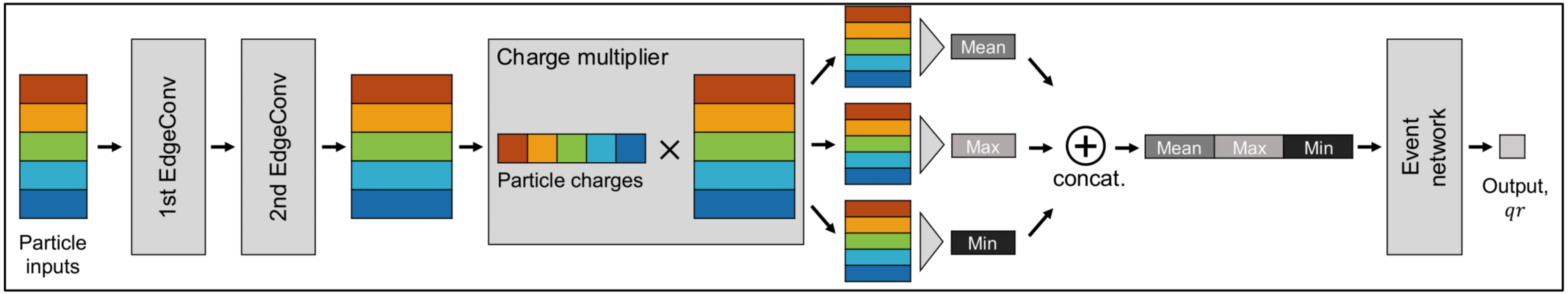
- Goal: deliver multi ab^{-1} data set
  O(10) more than previous B factories

- "Nano-beams": vertical beam size is 50 nm at the IP



- Challenges at $L=6.0x10^{35}$ cm^{-2} s^{-1}:
  - **Higher background** (Radiative Bhabha, Touschek, beam-gas scattering, etc.)
  - **Higher trigger rates** (High performance DAQ, computing)

Graph neural-network flavor tagger



Tagging Categories

Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	ℓ^-
Intermediate Kinetic Lepton	ℓ^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum p^*	ℓ^-, π^-
Fast-Slow-Correlated (FSC)	ℓ^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$\overline{B}^0 \to D^{*+}\ \bar{\nu}_\ell\ \ell^-$
$\quad \hookrightarrow D^0\ \pi^+$
$\quad\quad \hookrightarrow X\ K^-$

$\overline{B}^0 \to D^+\ \pi^-\ (K^-)$
$\quad \hookrightarrow \overline{K}^0\ \nu_\ell\ \ell^+$

$\overline{B}^0 \to \Lambda_c^+\ X^-$
$\quad \hookrightarrow \Lambda\ \pi^+$
$\quad\quad \hookrightarrow p\ \pi^-$

Input variables

Variables	Usage	Descriptions
QpTrack(categoryName) * charge	Input features	multiplication of the charge of each particle by the category-baed Flavor Tagger output for each of the 13 categories;
p_x, p_y, p_z (px, py, pz)		momentum of a charged particle
electronID_noSVD_noTOP, muonID, pionID, kaonID, protonID, deuteronID		particle identification probability calculated from a global likelihood ratio of sub-detectors
x, y, z (dx, dy, dz)	Input coordinates, and edge-features $\boldsymbol{x}_{i_j} - \boldsymbol{x}_i$	distance of POCA to the interaction point
charge	Charge multiplier block	charge of a charged particle

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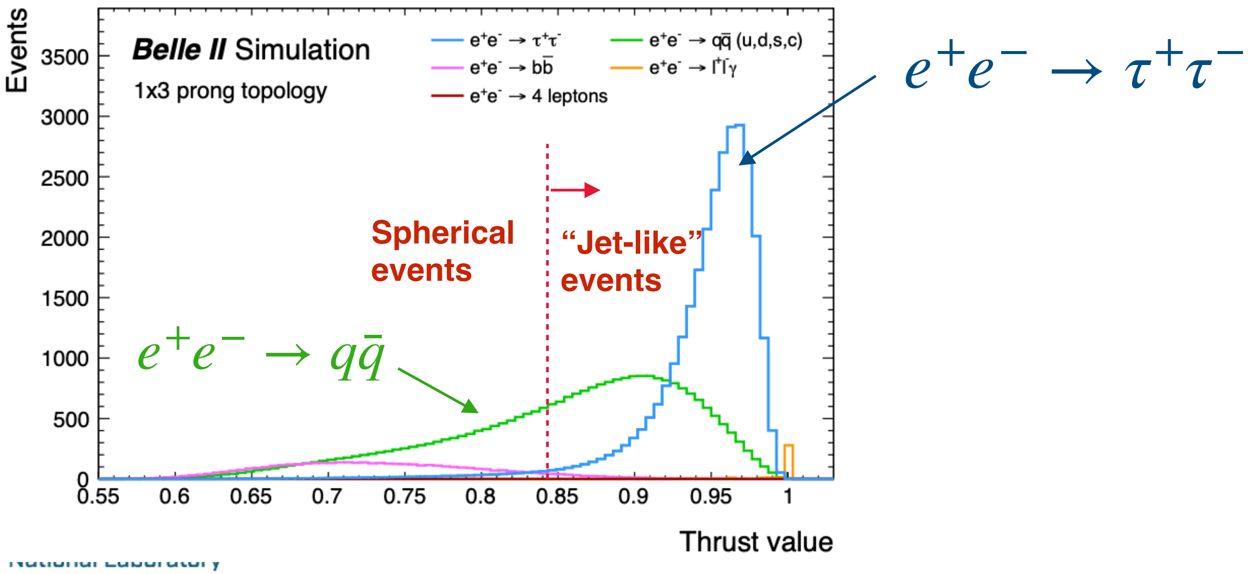
How do we reconstruct taus at Belle II?

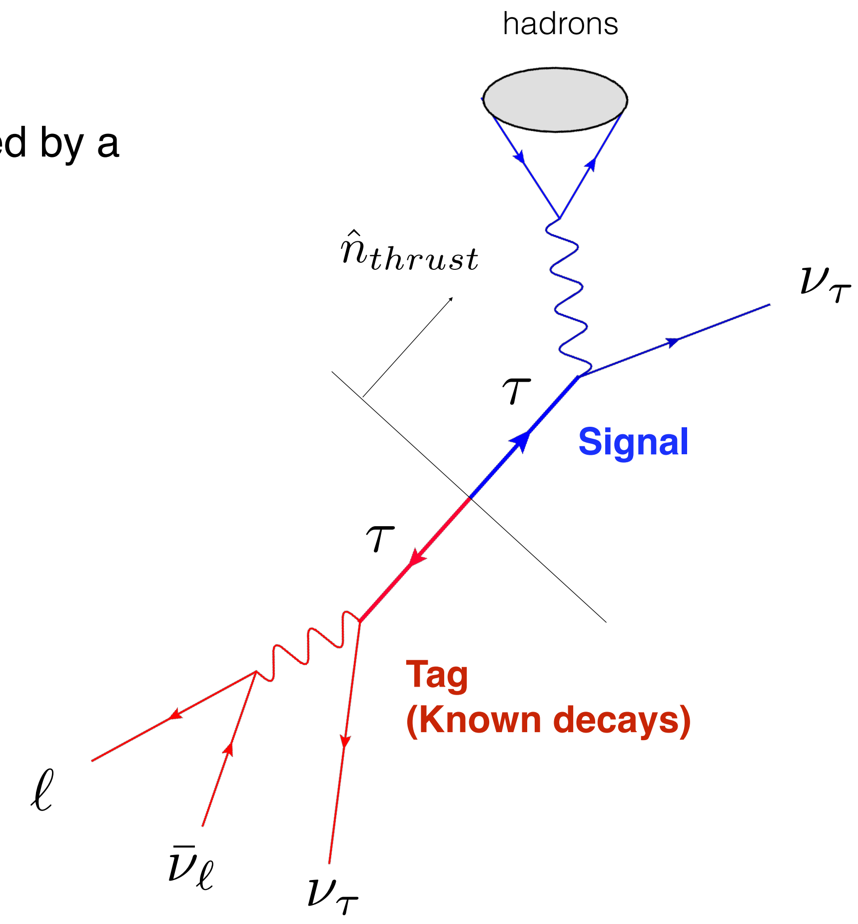
- A τ event is never reconstructed completely (we lose neutrinos), then we use features of the event to identify τ-pair candidates.

- Event is divided in two sides (signal and tag) using a plane defined by a **thrust axis**, build with all the final state particles:

- $$V_{thrust} = \frac{\sum_i |\vec{p}_i^{\,cm} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p}_i^{\,cm}|}$$

- Thrust axis: $\hat{n}_{thrust}$ such that V_{thrust} is maximum.



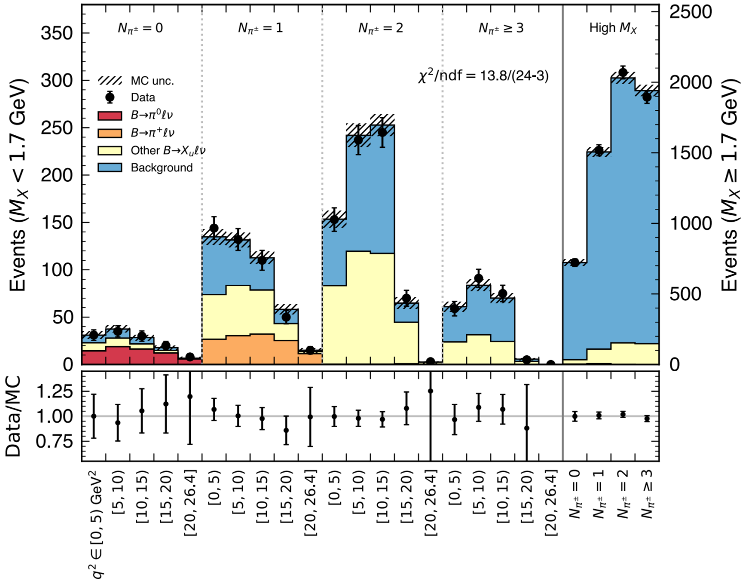


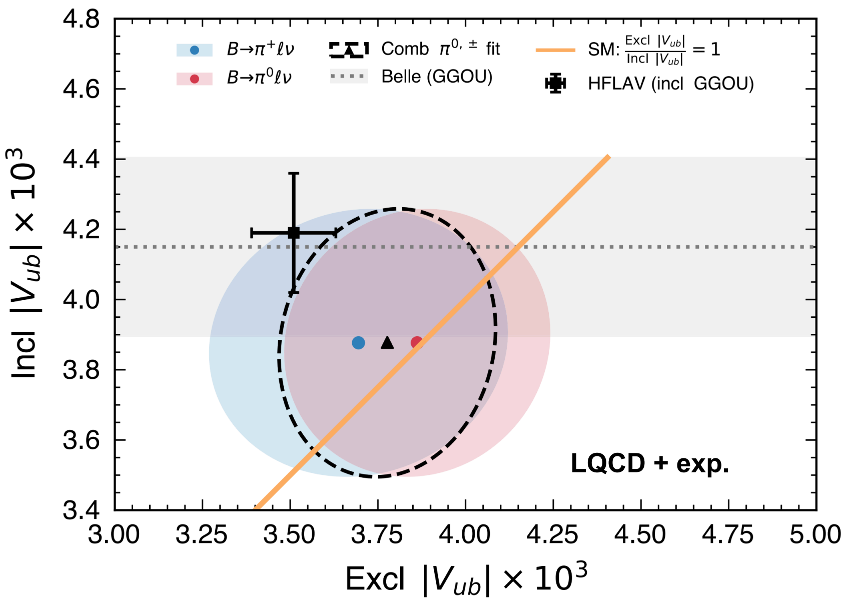
Simultaneous Determination of Exclusive & Inclusive $|V_{ub}|$

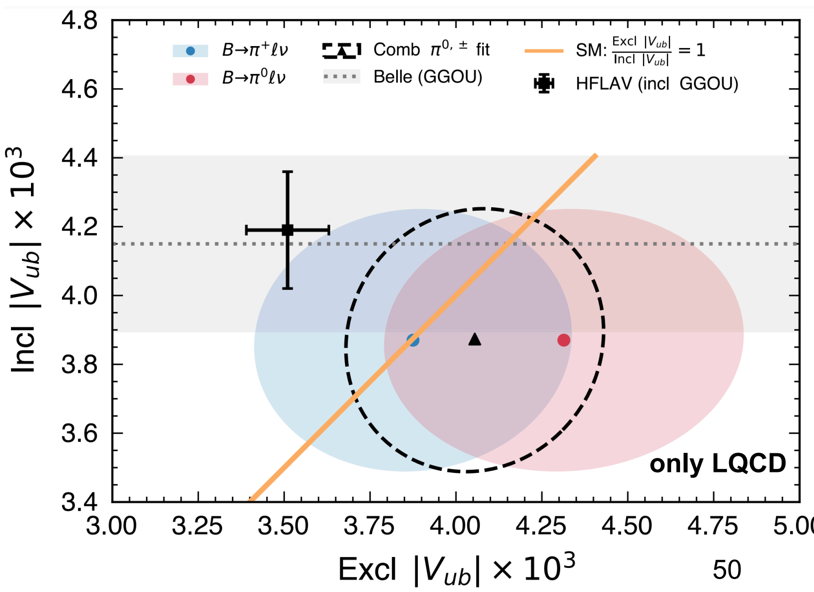
- Long standing 3σ discrepancy between **exclusive** and **inclusive** determination of $|V_{ub}|$
- New measurement using the full Belle dataset.
- Fitter corporates experimental observation of **$B \to \pi \ell \nu$** & other **$B \to X_u \ell \nu$** normalizations
- Various fit scenarios applied:
  - Combined or separate **$B^+ \to \pi^0 \ell \nu$ & $B^0 \to \pi^+ \ell \nu$**
  - Input form factor constraint: **Lattice QCD (LQCD) + exp.** or **only LQCD**

Phys. Rev. Lett. 131, 211801

- New result is
  - consistent between excl and incl analyses
  - In agreement with CKM expectation







|V$_{ub}$| from $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

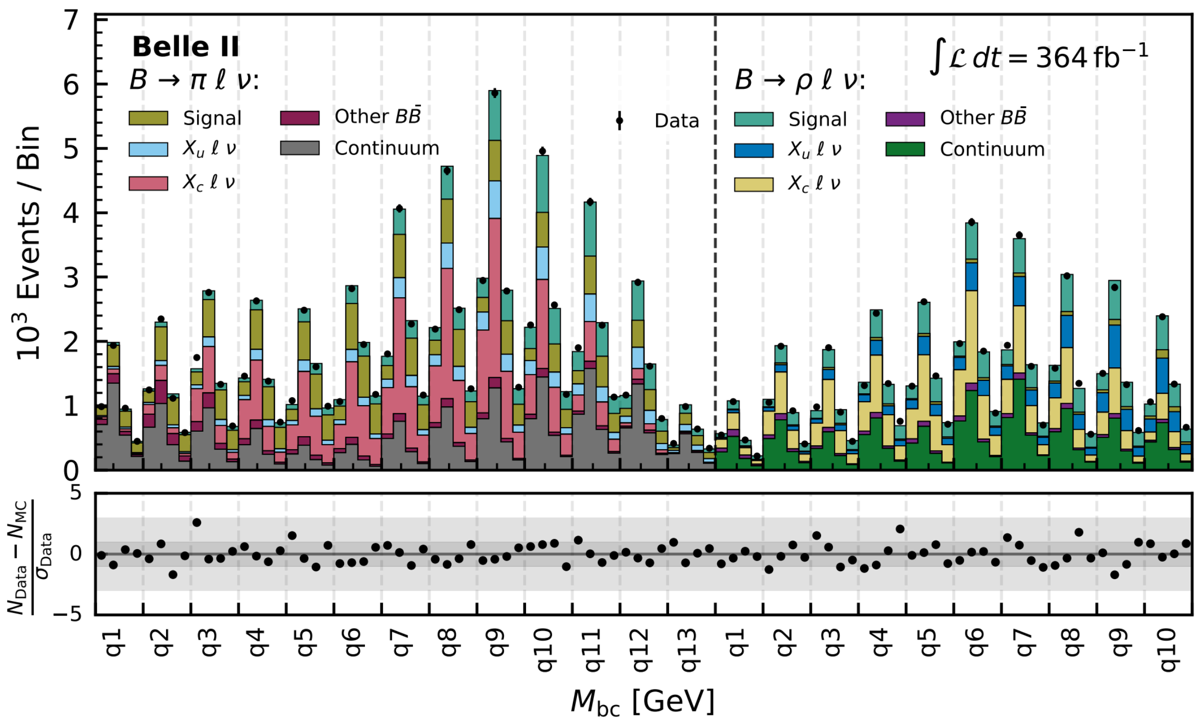
- The rate of $b \to u$ decays is proportional to $|V_{ub}|^2$; Determination by inclusive and exclusive methods differ by 2.5σ

[PDG 2023]

- Simultaneous study of the charmless semileptonic decays $B^0 \to \pi^- \ell^+ \nu$ & $B^+ \to \rho^0 \ell^+ \nu$
  - Extract signal yields from simultaneous fit to binned MC templates
- p_ν estimated from all reconstructed tracks and clusters
  - Then used to reconstruct M_{bc} & ΔE
- Background suppressed using BDTs

$$q^2 = (p_B - p_{\pi/\rho})^2$$

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$



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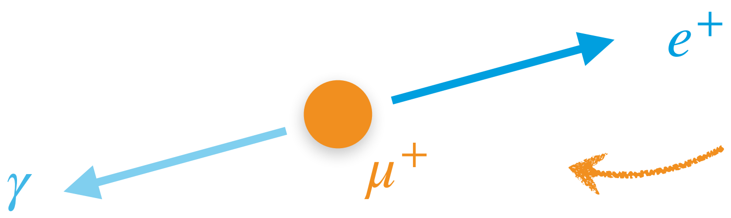
$\mu^+ \to e^+\gamma$

- In the CMS, the final state is a back-to-back, **monochromatic** (52.8 MeV) positron and photon.

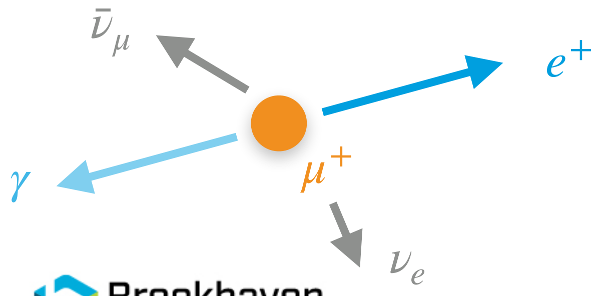


1) μ^+ cannot be captured in Nuclei.
2) The muon beam comes from proton-target interactions.

- Two sources of background:

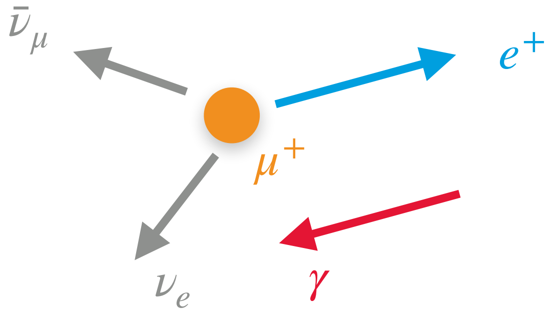
Irreducible background

$\mu^+ \to e^+\gamma\nu_e\bar{\nu}_\mu$



"Accidental" background

$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ + γ from elsewhere.



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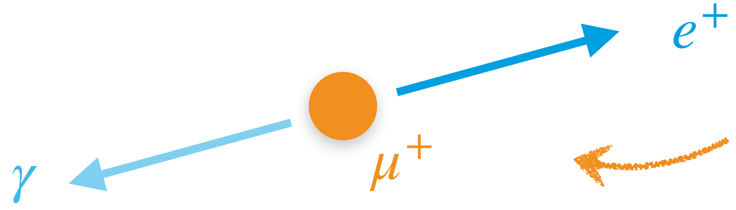

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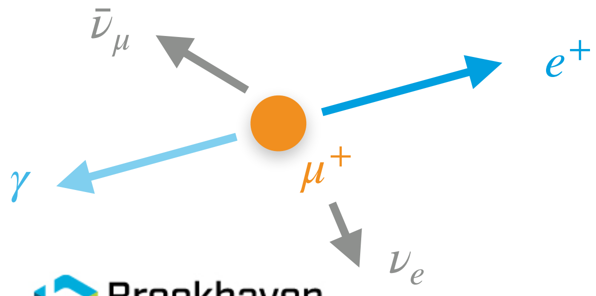
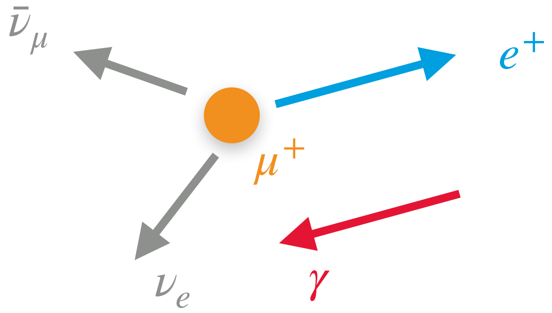


"Accidental" background

$\mu^+ \to e^+\nu_e\bar{\nu}_\mu + \gamma$ from elsewhere.



- First search of a CLFV mode (even before the neutrino was discovered):

Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. HINCKS AND B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
December 9, 1947

THE meson decay process which is identified by a mean life of 2.2 microseconds[1] has been usually thought of as consisting of the emission of an electron and a single neutrino, as suggested by the well-known Yukawa explanation of the ordinary beta-process in nuclei. However, the Yukawa theory is at variance with the results of the experiment of Conversi, Pancini, and Piccioni,[2] and since there remains no strong justification for the electron-neutrino hypothesis,[3] a direct experiment to test an alternative hypothesis—*that the decay process consists of the emission of an electron and a photon, each of about 50 Mev*—has been performed.

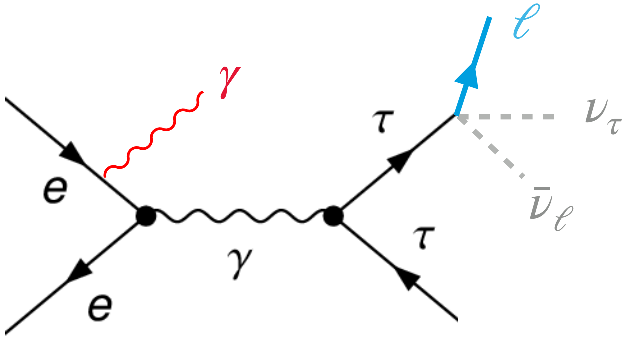
Phys.Rev. 73 (1948) 257-258

$\tau^+ \to \ell^+ \gamma$

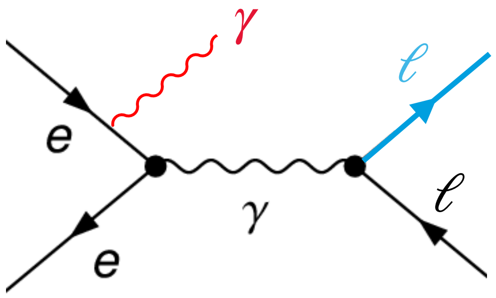
- Considered the golden modes for search of CLFV.
  - τ's rate production (10^{10}/yr) is much lower w.r.t. μ's (10^{11} /sec).
  - However, BSM branching ratios can be orders of magnitude larger than in associated muon decays.

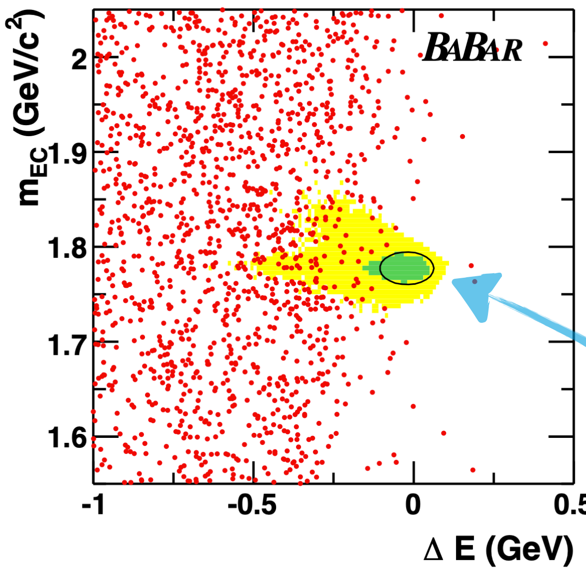
- Searching for signal events in a 2D region.
- Strong background contributions:

Irreducible background



Mis-id tagging





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- Strongest UL for $\tau^+ \to e^+\gamma$ from BaBar

BR($\tau^+ \to e^+\gamma$) < 3.3 x 10^{-8}

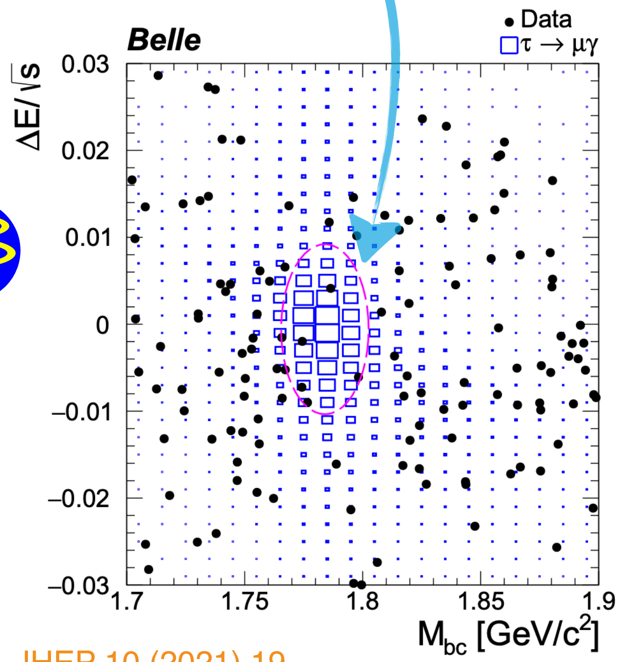
Signal region (2σ)

- Most recent result from Belle, setting the strongest UL for $\tau^+ \to \mu^+\gamma$

BR($\tau^+ \to \mu^+\gamma$) < 4.2 x 10^{-8}

$$M_{\rm bc} = \sqrt{(E^{\rm CM}_{\rm beam})^2 - |\vec{p}^{\,\rm CM}_{\ell\gamma}|^2},$$

$$\Delta E/\sqrt{s} = (E^{\rm CM}_{\ell\gamma} - \sqrt{s}/2)/\sqrt{s},$$



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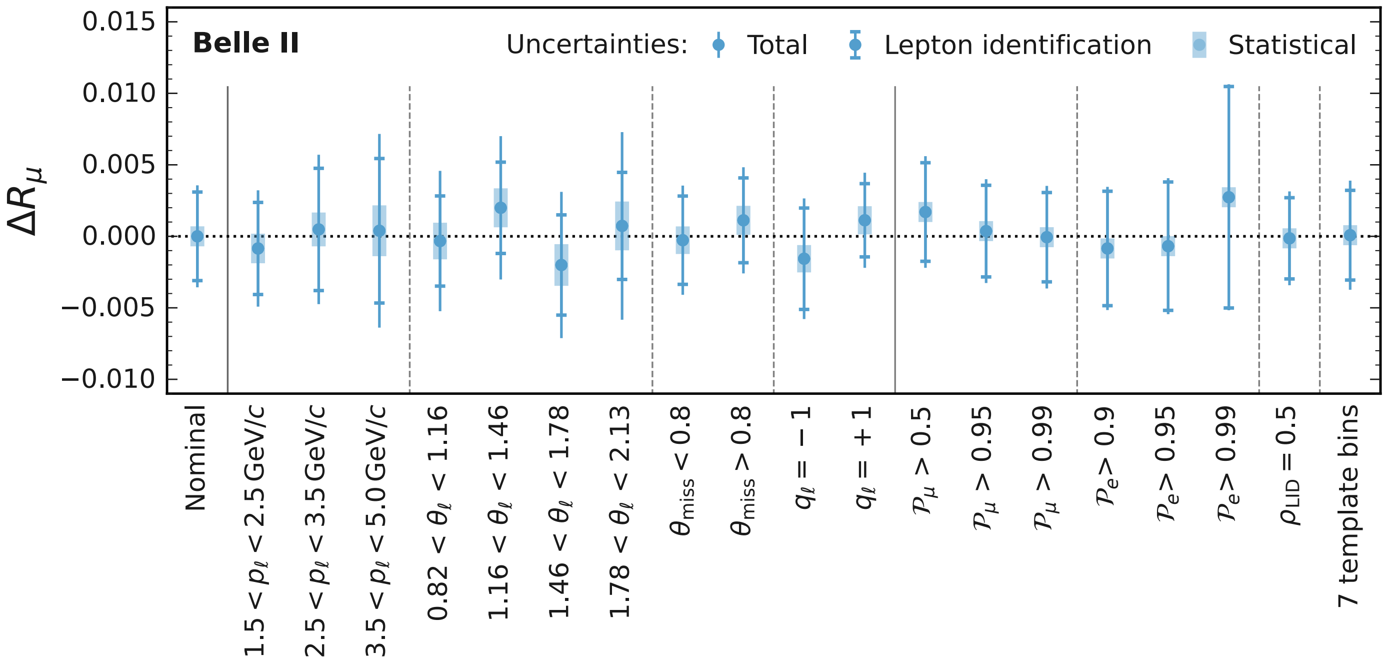
Tests of LFU at Belle II



Source	Uncertainty [%]
Charged-particle identification:	0.32
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Imperfections of the simulation:	0.14
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum distribution	0.06
Tag side modelling	0.05
π^0 efficiency	0.02
Particle decay-in-flight	0.02
Tracking efficiency	0.01
Modelling of ISR	0.01
Photon efficiency	< 0.01
Photon energy	< 0.01
Detector misalignment	< 0.01
Momentum correction	< 0.01
Trigger	0.10
Size of the simulated samples	0.06
Luminosity	0.01
Total	0.37

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