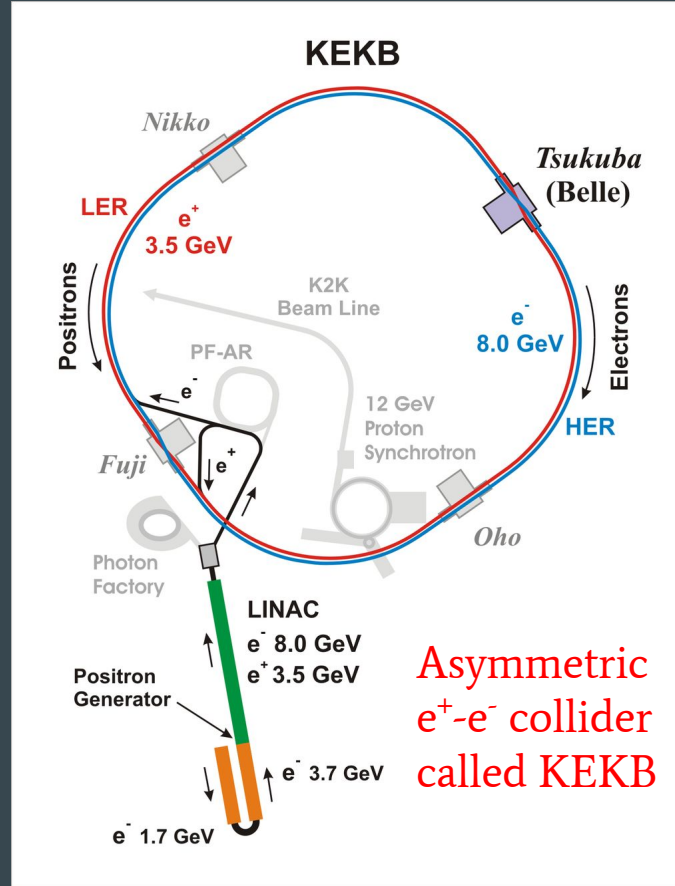
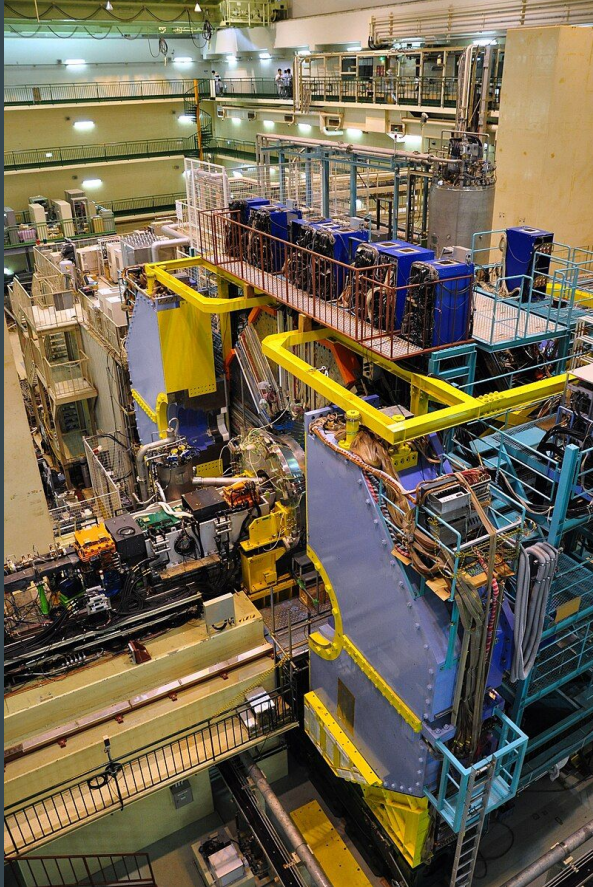


Flavour lectures



Accompanying slides

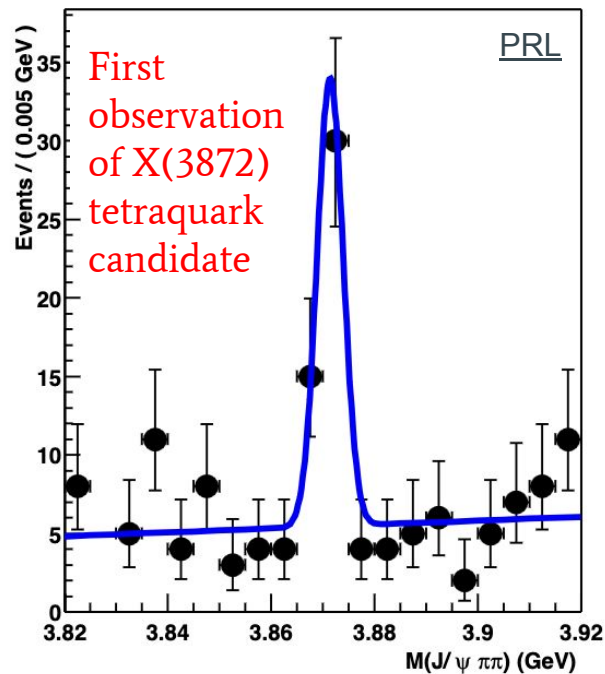
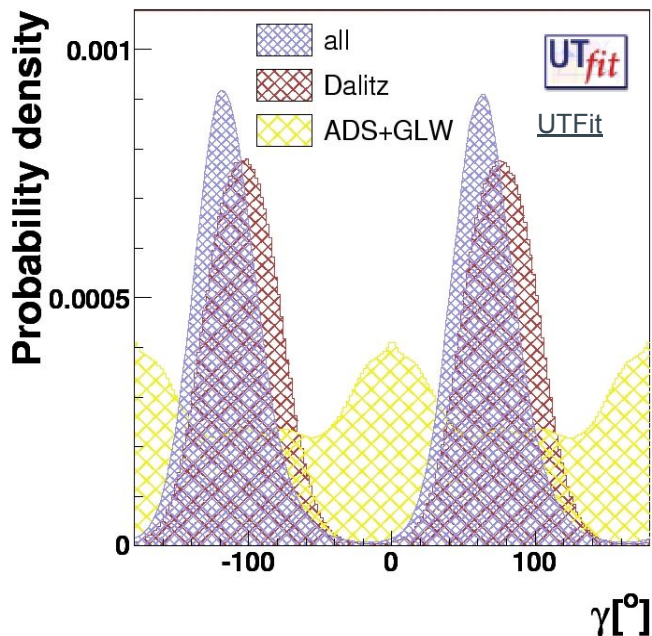
Flavour physics experiments - Belle



- 1999-2010 (11 yrs)
- Data collected at $\Upsilon(4S)$ ($b\bar{b}$) @ 10.58 GeV
- 771M $B\bar{B}$ pairs (+/-, 0) produced approx. at rest
- Some data collected at $\Upsilon(5S)$ for B_s studies

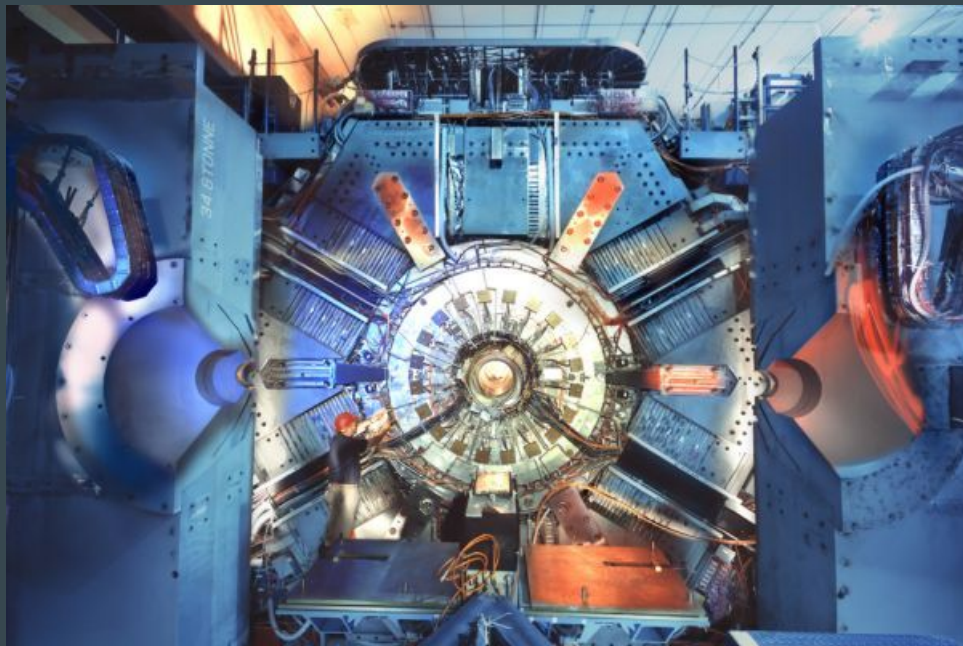
Flavour physics experiments - Belle

Determination of gamma from Belle only

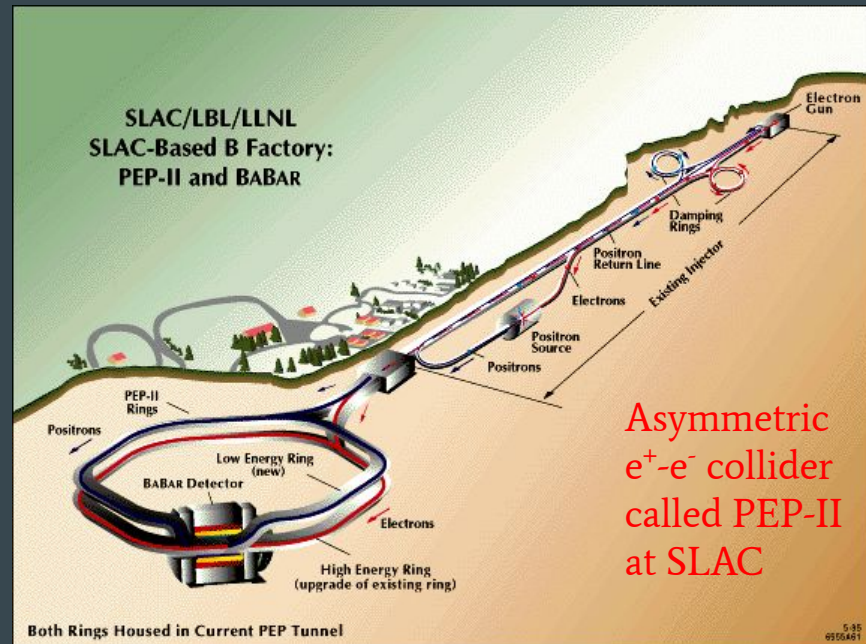


Nature of tetraquark remains unknown : $D^0 - \bar{D}^{0*}$ molecule?

Flavour physics experiments - BaBar

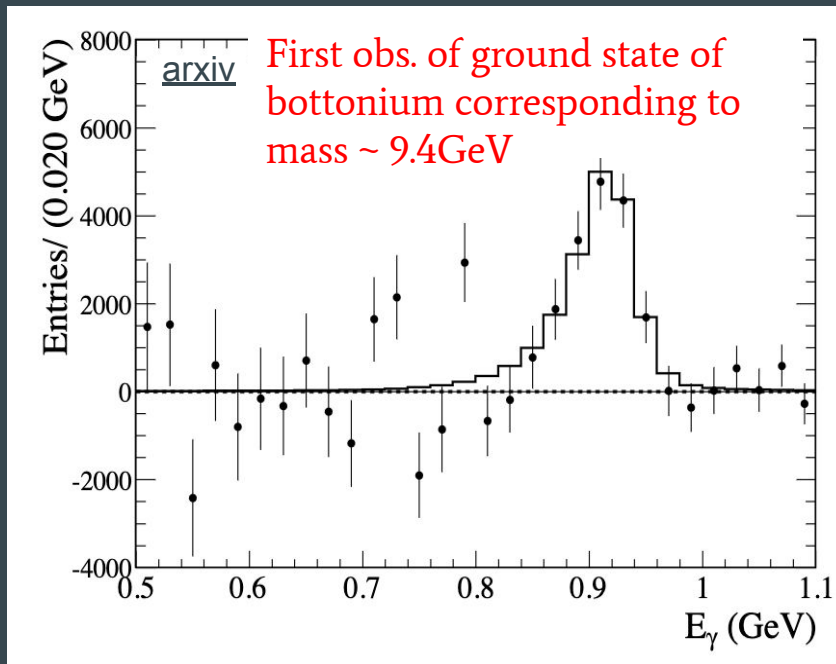
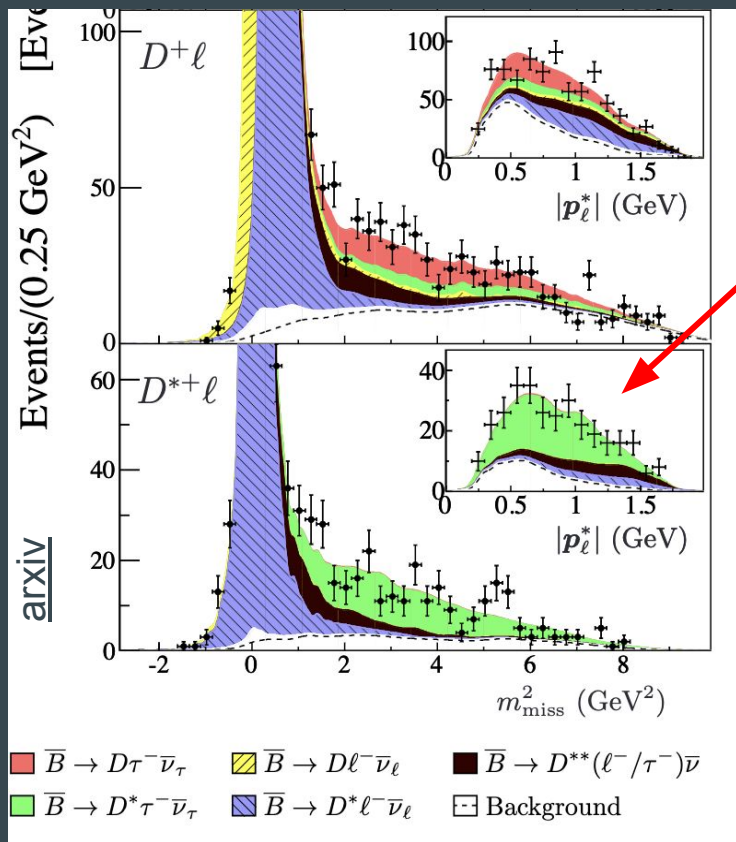


- 1999-2008 (9 yrs)
- Data collected at $\Upsilon(4S) \Rightarrow 384\text{M } B\bar{B}$ pairs

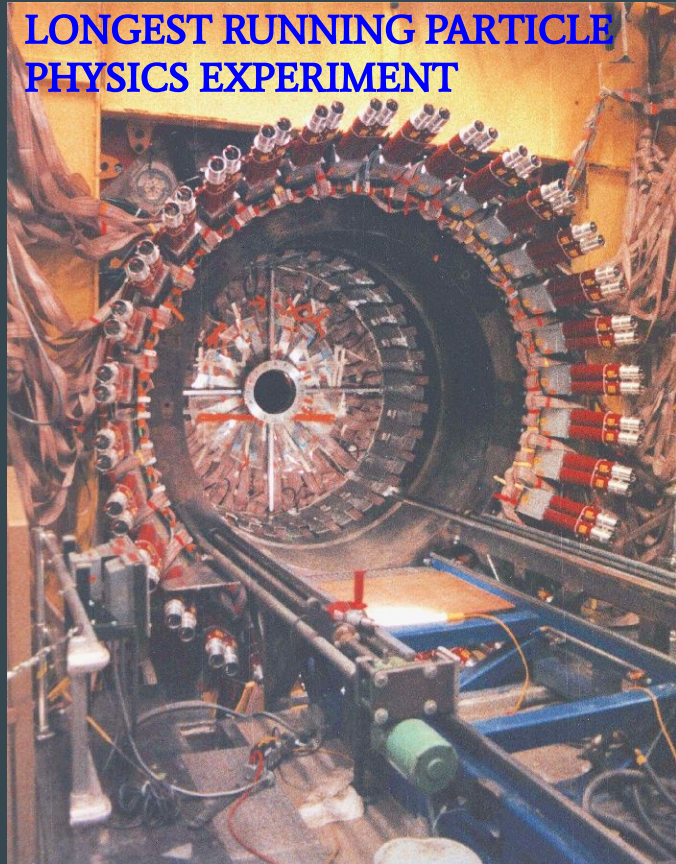


Flavour physics experiments - BaBar

Excess of tauonic
semi-leptonic B decays
over $l = e/\mu$, $R(D^{(*)})$



Flavour physics experiments - CLEO(-c)



A Personal History of **CESR** and **CLEO**

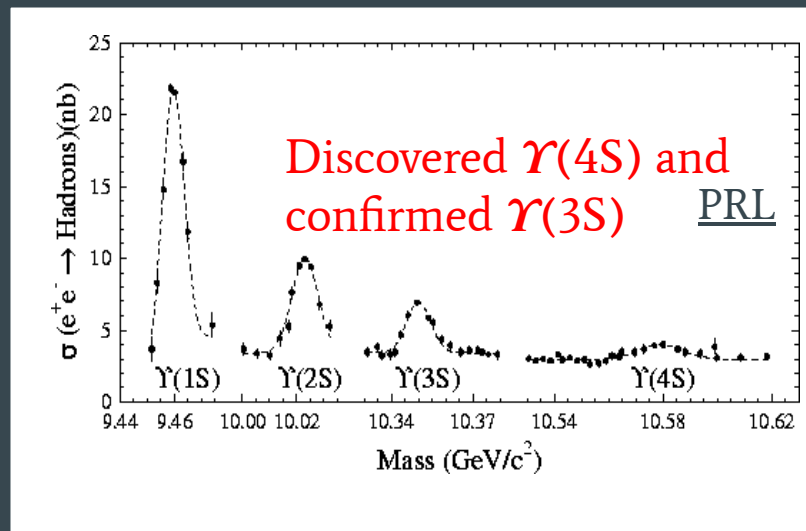
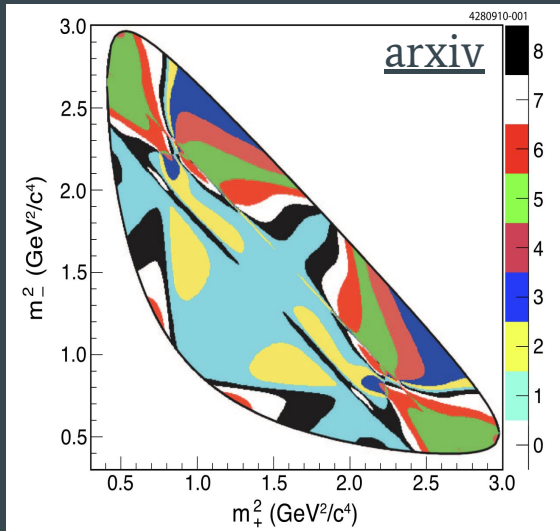
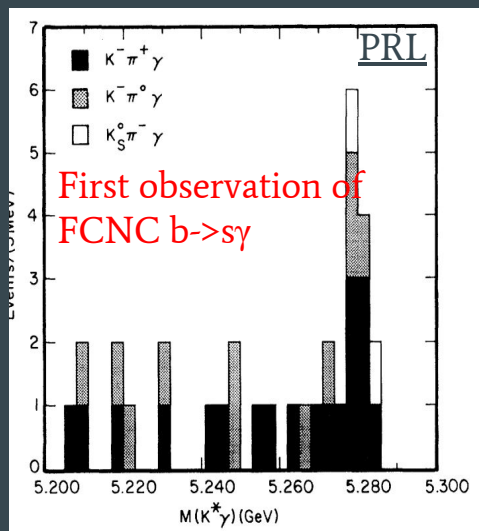
The Cornell Electron Storage Ring and
Its Main Particle Detector Facility

Karl Berkelman



- 1979-2008 (29 yrs)
- Symmetric e^+e^- collider called CESR at Cornell University
- Collisions at 3.5-12GeV for b - and c - physics (CLEO-c)

Flavour physics experiments - CLEO(-c)



Discovered 13 new Charm baryons

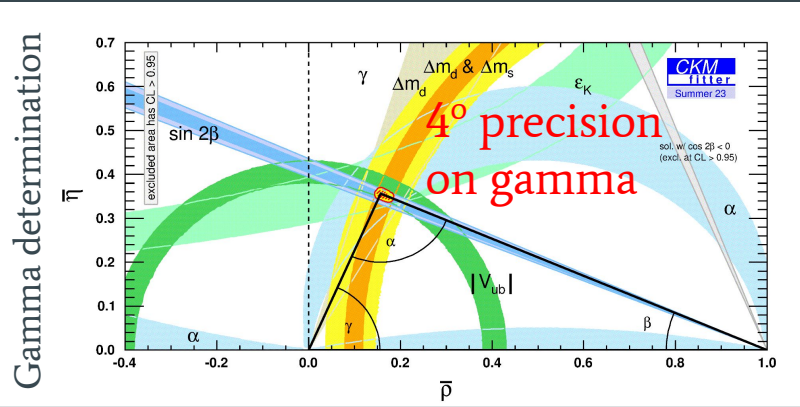
Flavour physics experiments - LHCb (UO)



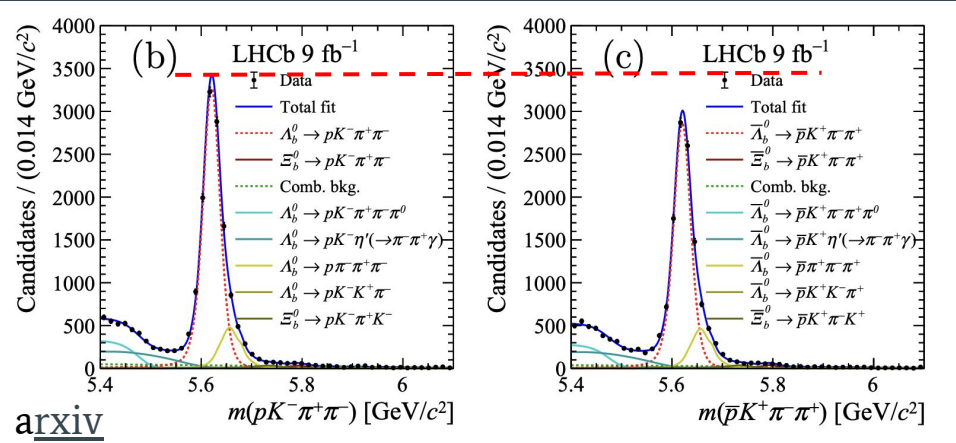
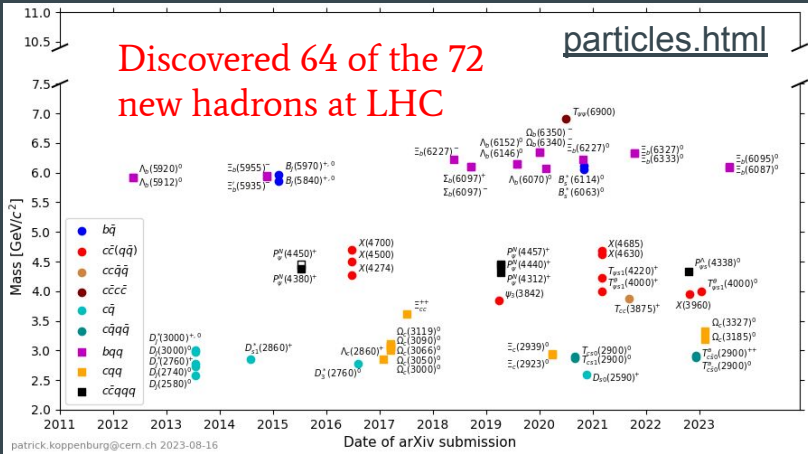
- 2011-2018 (7 yrs)
- Collisions from symmetric p-p collider called LHC
- Collisions at 7-13.6 TeV



Flavour physics experiments - LHCb



First observation of CPV in Charm mesons and later in baryons



6 sigma CPV in $\pi\pi\pi$ resonant region

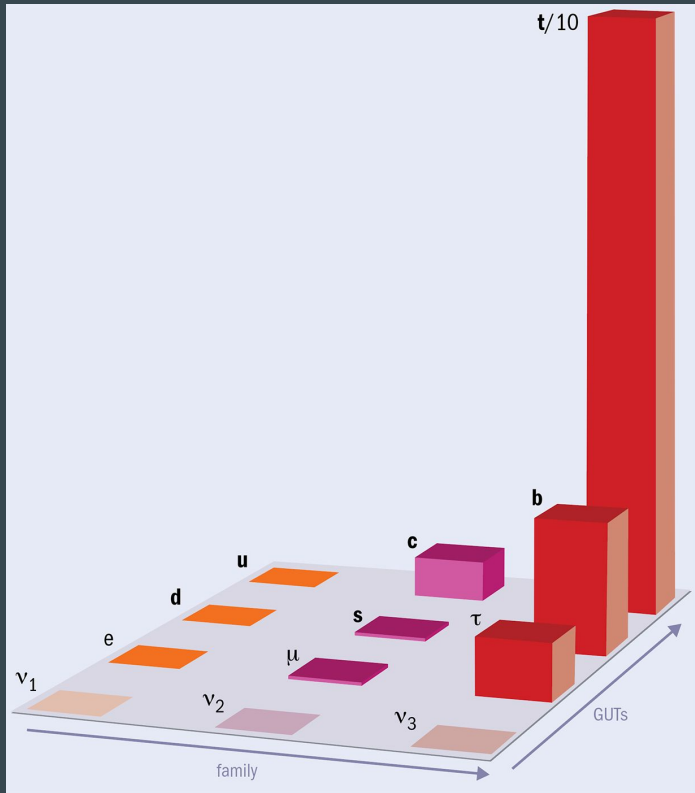
CPT

Quantity	Notation	P	C	T
Position	\vec{r}	-1	+1	+1
Momentum (Vector)	\vec{p}	-1	+1	-1
Spin (Axial Vector)	$\vec{\sigma} = \vec{r} \times \vec{p}$	+1	+1	-1
Helicity	$\vec{\sigma} \cdot \vec{p}$	-1	+1	+1
Electric Field	\vec{E}	-1	-1	+1
Magnetic Field	\vec{B}	+1	-1	-1
Magnetic Dipole Moment	$\vec{\sigma} \cdot \vec{B}$	+1	-1	+1
Electric Dipole Moment	$\vec{\sigma} \cdot \vec{E}$	-1	-1	-1
Transverse Polarization	$\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$	+1	+1	-1

Table 2 Discrete symmetries and fermionic currents. Here ψ and χ represent fermion fields.

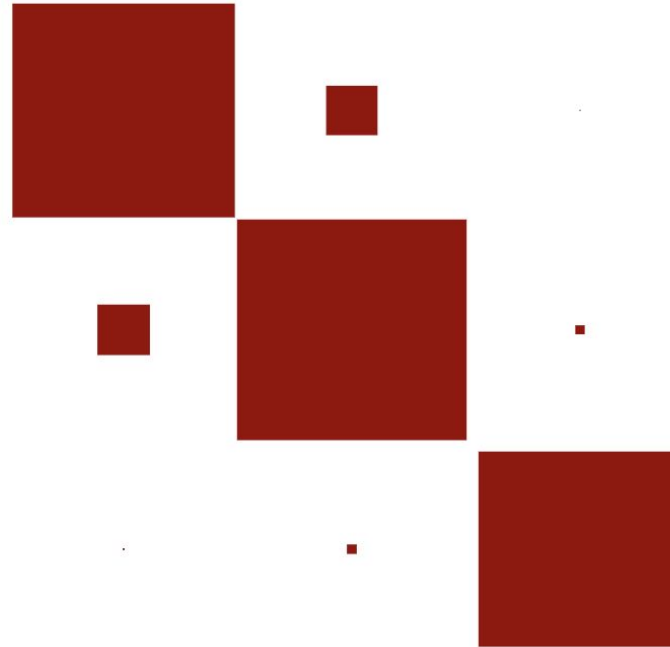
Current	P	T	C	CP	CPT
$\bar{\psi}\chi$	$\bar{\psi}\chi$	$\bar{\psi}\chi$	$\bar{\chi}\psi$	$\bar{\chi}\psi$	$\bar{\chi}\psi$
$\bar{\psi}\gamma_5\chi$	$-\bar{\psi}\gamma_5\chi$	$\bar{\psi}\gamma_5\chi$	$\bar{\chi}\gamma_5\psi$	$-\bar{\chi}\gamma_5\psi$	$-\bar{\chi}\gamma_5\psi$
$\bar{\psi}\gamma_\mu\chi$	$\bar{\psi}\gamma_\mu\chi$	$\bar{\psi}\gamma_\mu\chi$	$-\bar{\chi}\gamma_\mu\psi$	$-\bar{\chi}\gamma_\mu\psi$	$-\bar{\chi}\gamma_\mu\psi$
$\bar{\psi}\gamma_\mu\gamma_5\chi$	$-\bar{\psi}\gamma_\mu\gamma_5\chi$	$\bar{\psi}\gamma_\mu\gamma_5\chi$	$\bar{\chi}\gamma_\mu\gamma_5\psi$	$-\bar{\chi}\gamma_\mu\gamma_5\psi$	$-\bar{\chi}\gamma_\mu\gamma_5\psi$
$\bar{\psi}\sigma_{\mu\nu}\chi$	$\bar{\psi}\sigma_{\mu\nu}\chi$	$-\bar{\psi}\sigma_{\mu\nu}\chi$	$-\bar{\chi}\sigma_{\mu\nu}\psi$	$-\bar{\chi}\sigma_{\mu\nu}\psi$	$\bar{\chi}\sigma_{\mu\nu}\psi$

SM puzzles

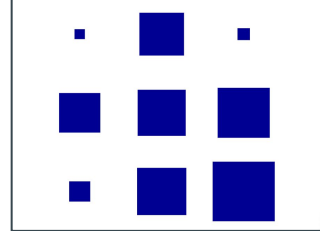


Quark and lepton masses span 12 orders of magnitude

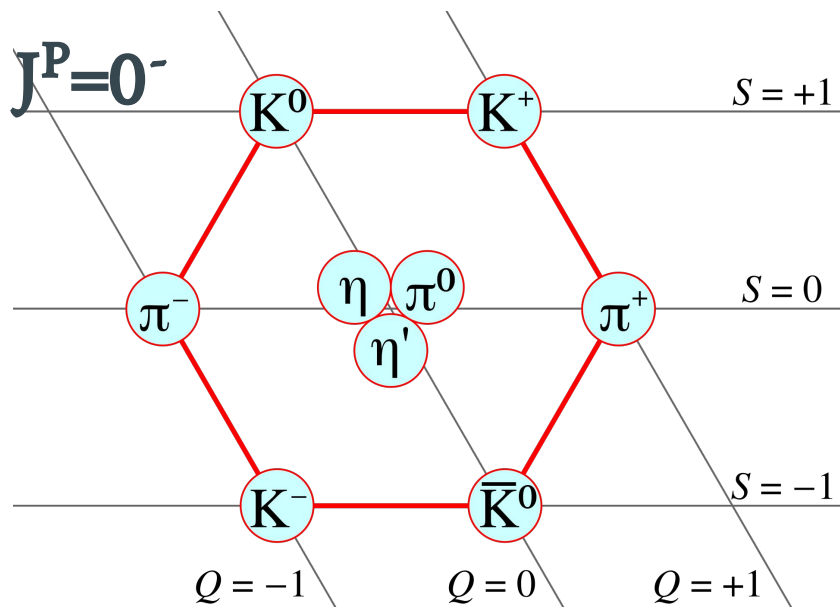
CKM matrix for the quark sector



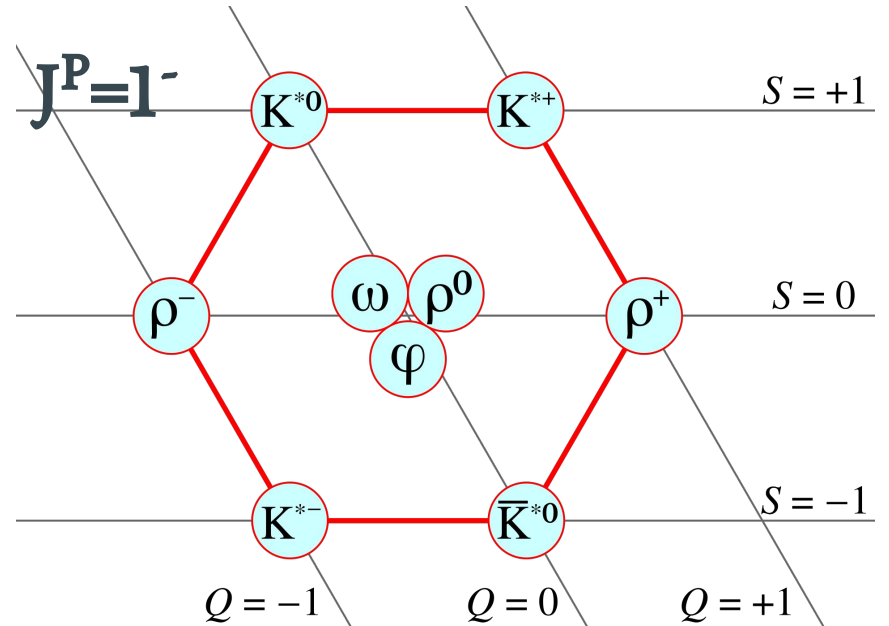
PMNS matrix for the neutrino sector



Flavour multiplets - SU(3) mesons

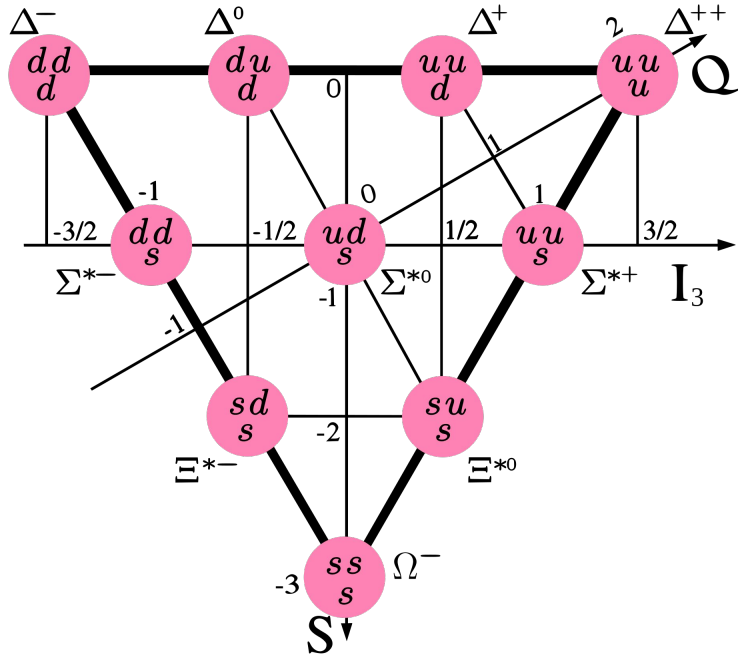


Pseudoscalar mesons of spin-0 form a nonet

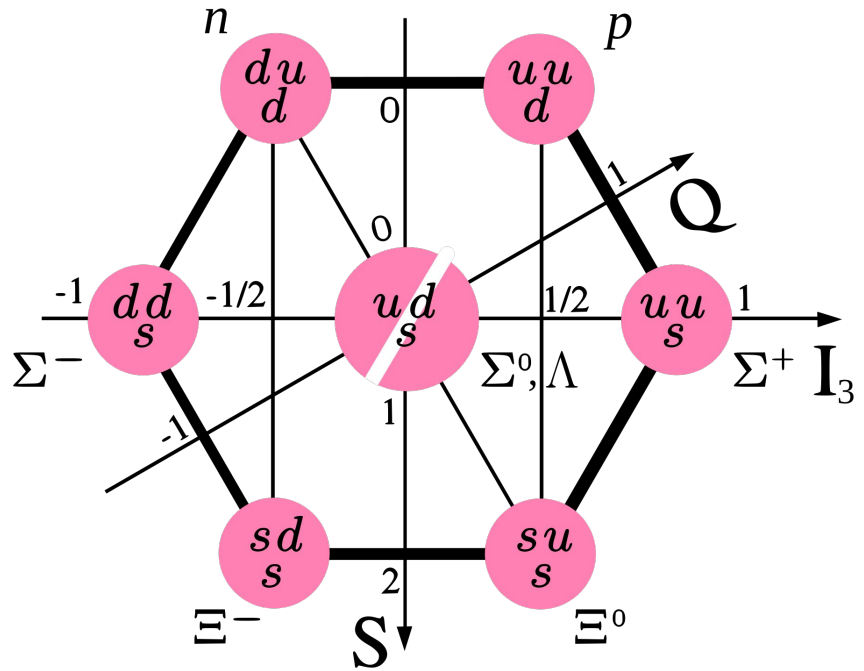


Vector mesons of spin-1 form a nonet

Flavour multiplets - SU(3) baryons



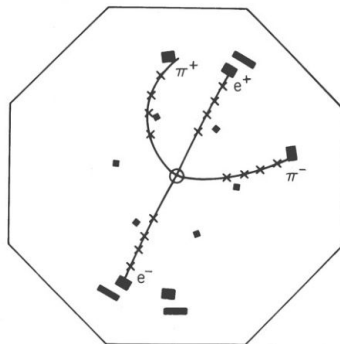
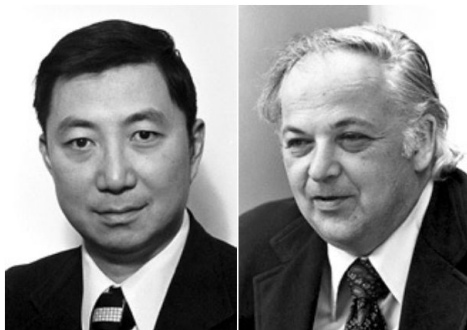
Combinations of three **u**, **d** or **s** quarks with a spin-3/2 form the *uds* baryon decuplet



Combinations of three **u**, **d** or **s** quarks with a spin-1/2 form the *uds* baryon octet

Charm discovery

- ▶ Experimental evidence for the charm quark came in 1974
- ▶ Discovery of charmonium (J) at Brookhaven in $p\text{Be} \rightarrow e^+e^-X$
- ▶ Discovery of charmonium (ψ) at SLAC in $e^+e^- \rightarrow (\text{hadrons}), e^+e^-, \mu^+\mu^-$



EW LETTERS

2 DECEMBER 1974

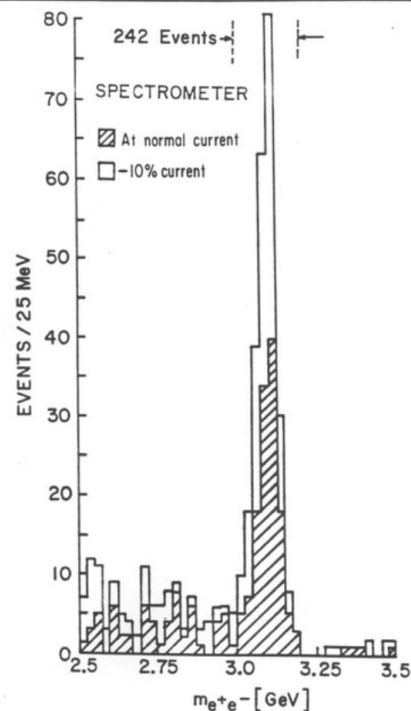
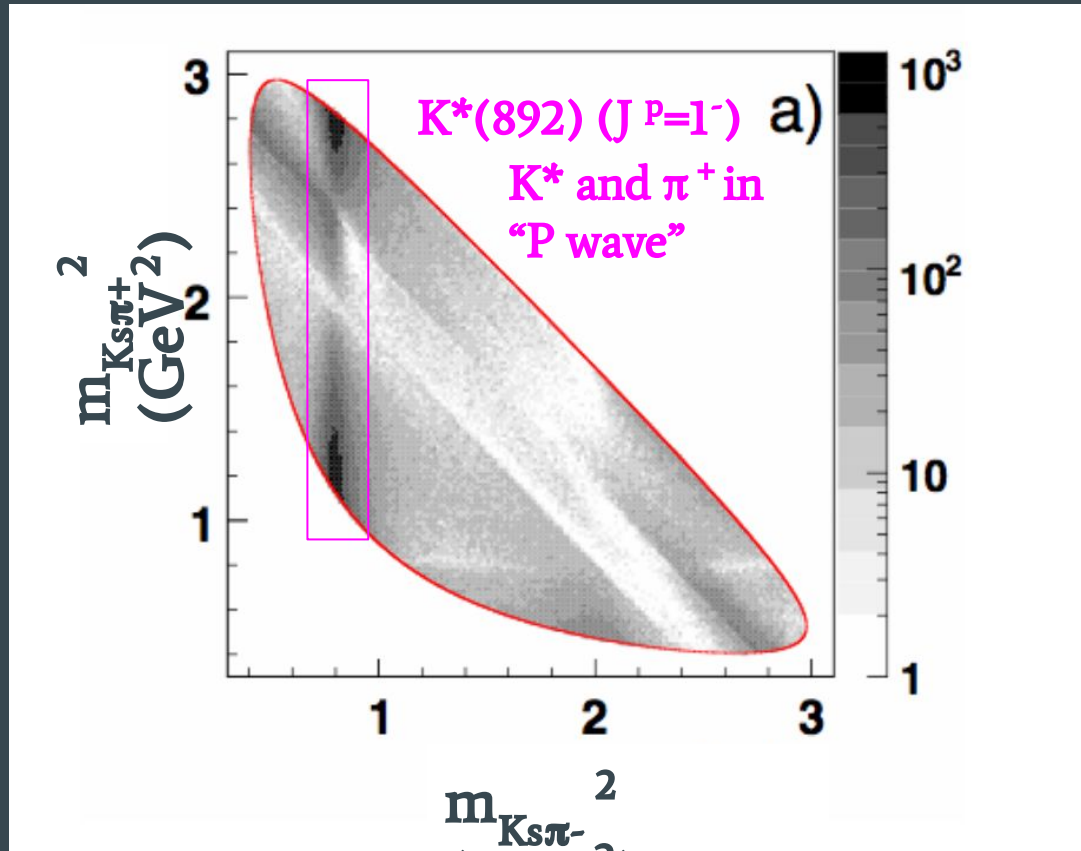


FIG. 2. Mass spectrum showing the existence of J . Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

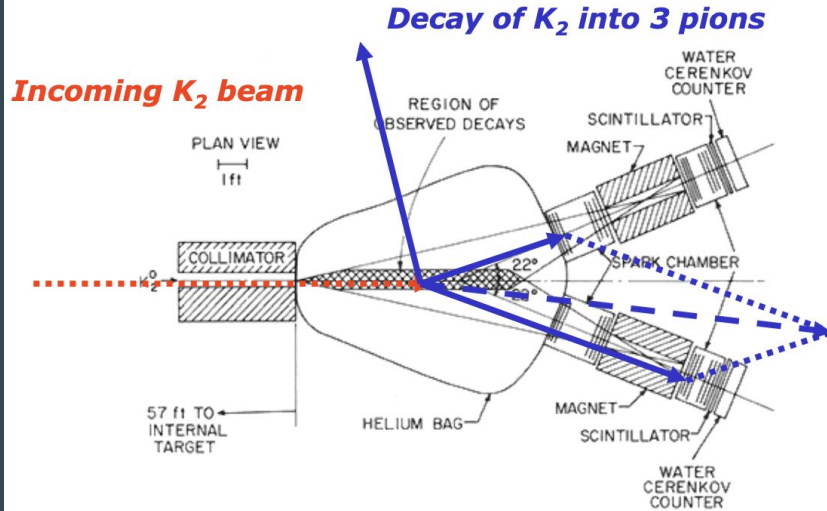
Dalitz plots



Cronin and Fitch experiment - CPV in Kaons

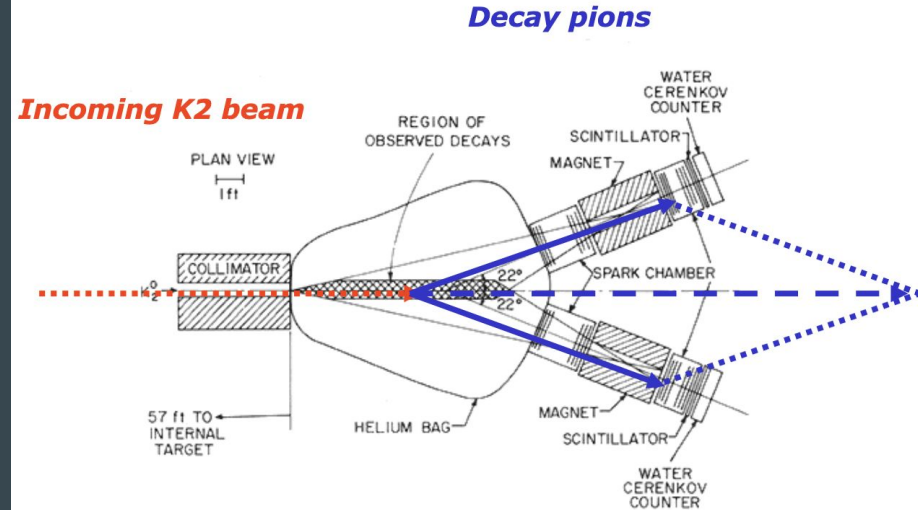
$$K_2 = K$$

Essential idea: Look for (CP violating)
 $K_2 \rightarrow \pi\pi$ decays 20 meters away from
 K^0 production point



If you detect two of the three pions of a $K_2 \rightarrow \pi\pi\pi$ decay they will generally not point along the beam line

Essential idea: Look for $K_2 \rightarrow \pi\pi$ decays
20 meters away from K^0 production point

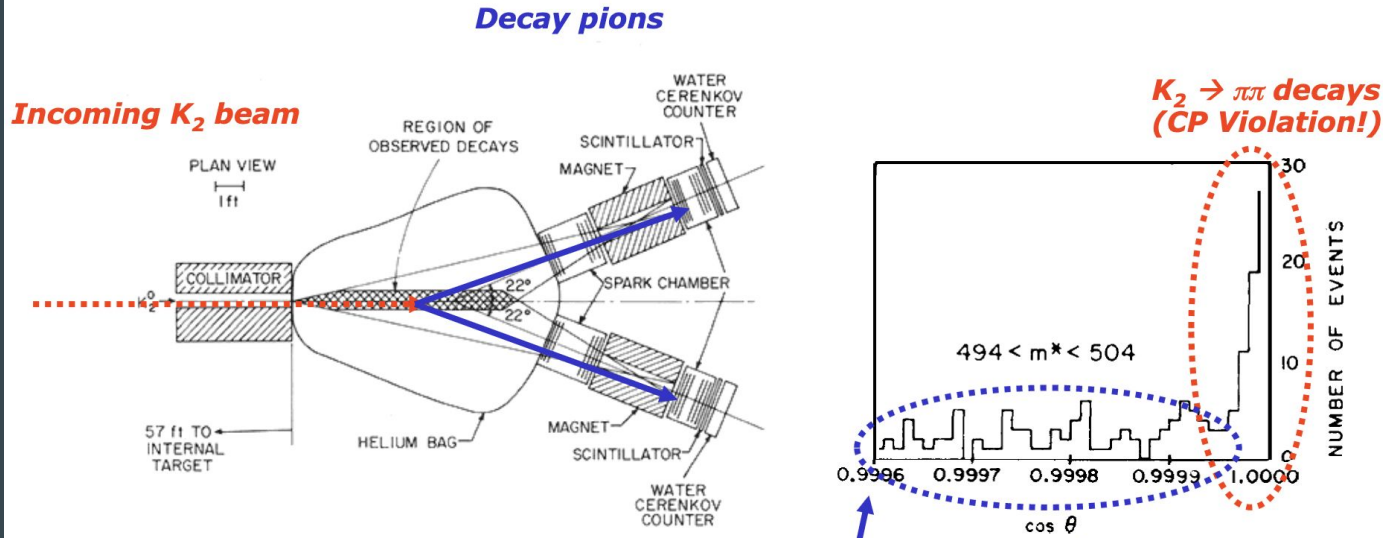


If K_2 decays into two pions instead of three both the reconstructed direction should be exactly along the beamline (conservation of momentum in $K_2 \rightarrow \pi\pi$ decay)

Cronin and Fitch experiment - CPV in Kaons

$$K_2 = K$$

Essential idea: Look for $K_2 \rightarrow \pi\pi$ decays
20 meters away from K^0 production point



Result: an excess of events at $\theta=0$ degrees!

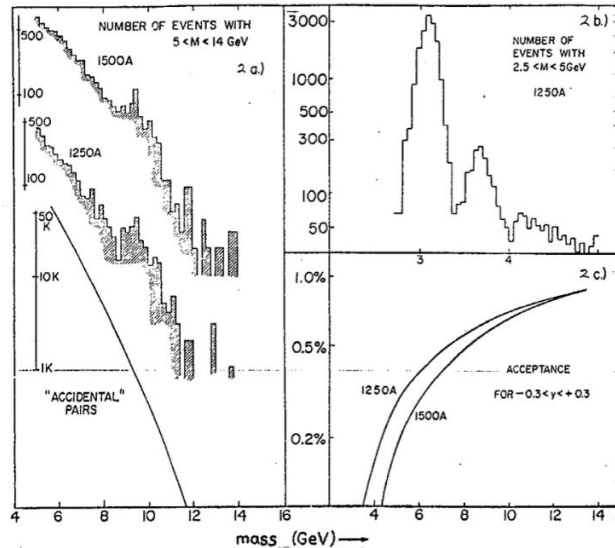
- CP violation, because K_2 (CP=-1) changed into K_1 (CP=+1)

Note scale: 99.99% of $K \rightarrow \pi\pi\pi$ decays are left of plot boundary

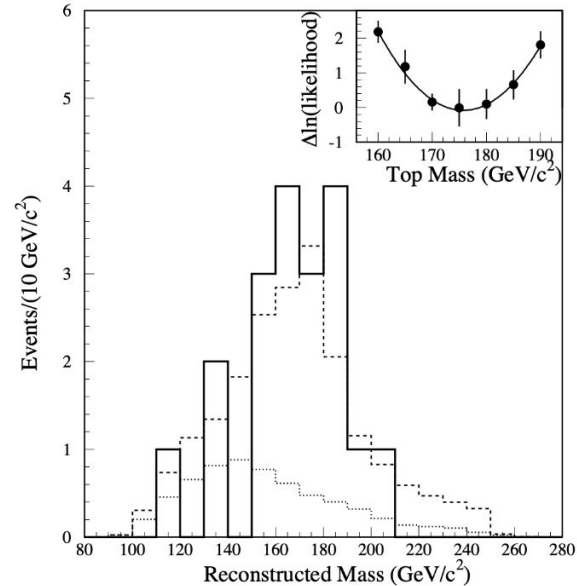
Beauty and Top observation

- ▶ Kobayashi and Maskawa's matrix and mechanism for CP violation predicted the existence of a third generation
- ▶ The Υ ($b\bar{b}$) resonance was discovered at Fermilab in 1977
- ▶ The top wasn't discovered until 1995 at the CDF and D0 experiments

Υ discovery at E288



Top discovery at CDF



CKM higher orders

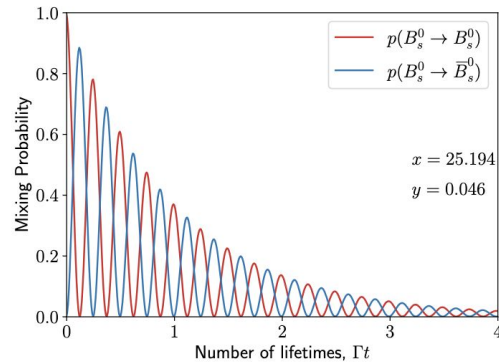
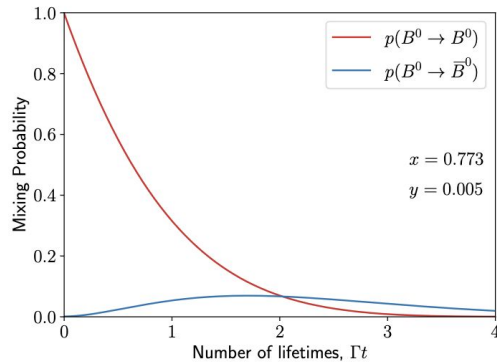
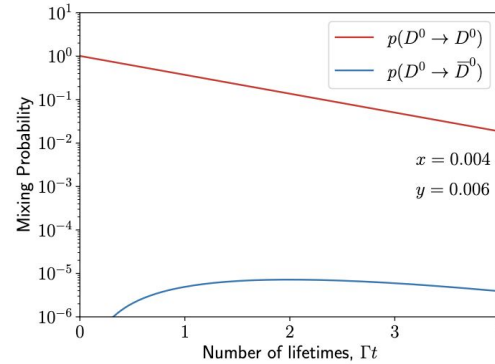
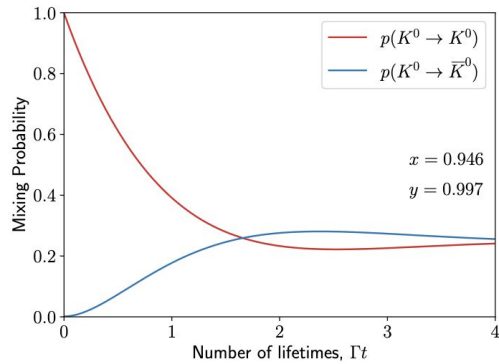
$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

$$\delta V = \begin{pmatrix} -\frac{1}{8}\lambda^4 & 0 & 0 \\ \frac{1}{2}A^2\lambda^5(1 - 2(\rho + i\eta)) & -\frac{1}{8}\lambda^4(1 + 4A^2) & 0 \\ \frac{1}{2}A\lambda^5(\rho + i\eta) & \frac{1}{2}A\lambda^4(1 - 2(\rho + i\eta)) & -\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

- Phase in $|V_{ts}|$ is only apparent at $\mathcal{O}(\lambda^4)$

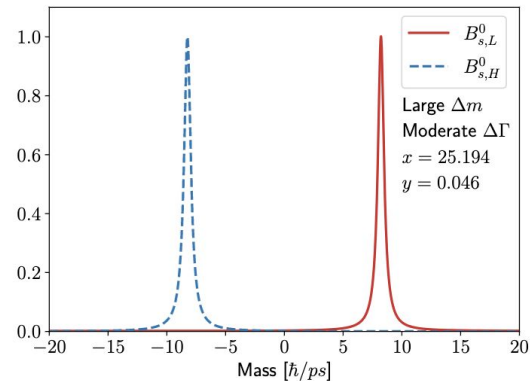
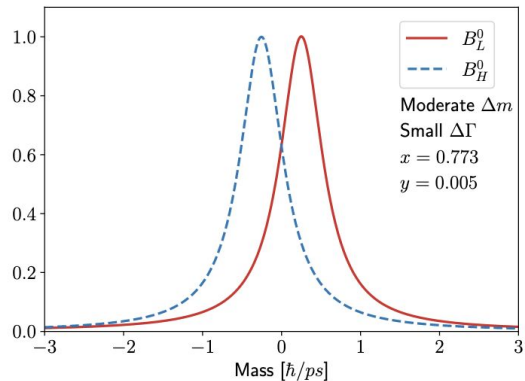
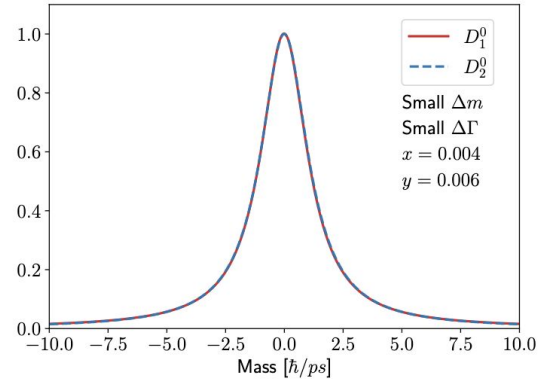
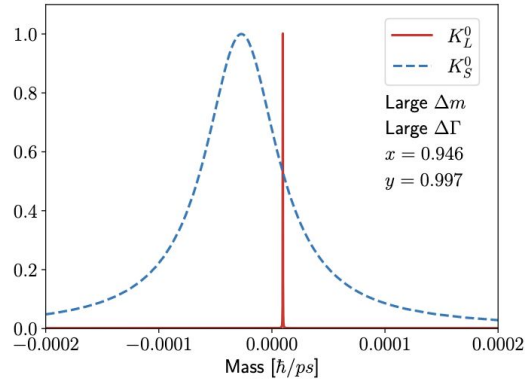
Neutral meson oscillation

$$|g_{\pm}(t)|^2 = \frac{e^{-\Gamma t}}{2} \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) \pm \cos(\Delta m t) \right]$$



Neutral meson oscillation

► Mass and width differences of the neutral meson mixing systems



Master equations

The “master equations” for neutral meson decays

$$\Gamma_{X^0 \rightarrow f}(t) = |A_f|^2 (1 + |\lambda_f|^2) \frac{e^{-\Gamma t}}{2} \left[\cosh\left(\frac{1}{2}\Delta\Gamma t\right) + C_f \cos(\Delta m t) + D_f \sinh\left(\frac{1}{2}\Delta\Gamma t\right) - S_f \sin(\Delta m t) \right] \quad (39)$$

$$\Gamma_{\bar{X}^0 \rightarrow f}(t) = |A_f|^2 \left| \frac{p}{q} \right|^2 (1 + |\lambda_f|^2) \frac{e^{-\Gamma t}}{2} \left[\cosh\left(\frac{1}{2}\Delta\Gamma t\right) - C_f \cos(\Delta m t) + D_f \sinh\left(\frac{1}{2}\Delta\Gamma t\right) + S_f \sin(\Delta m t) \right] \quad (40)$$

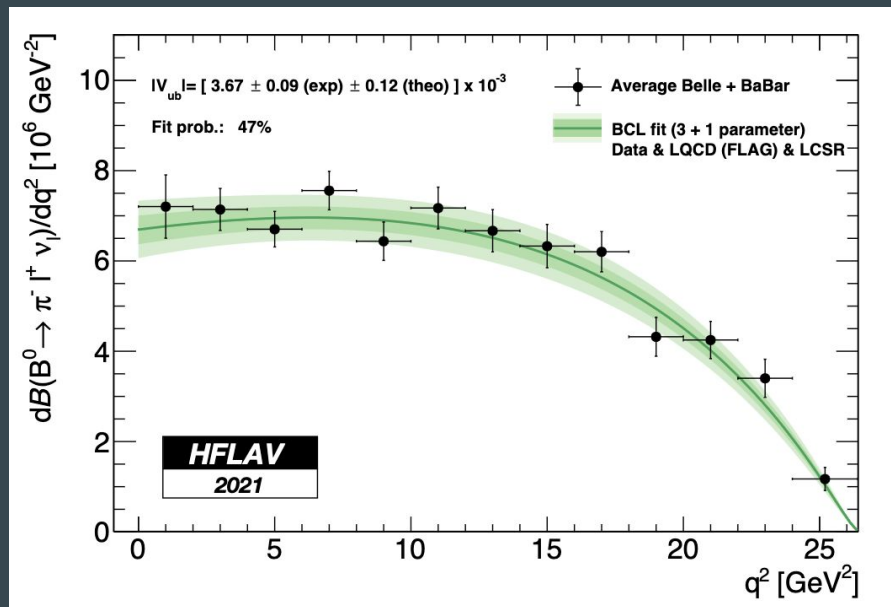
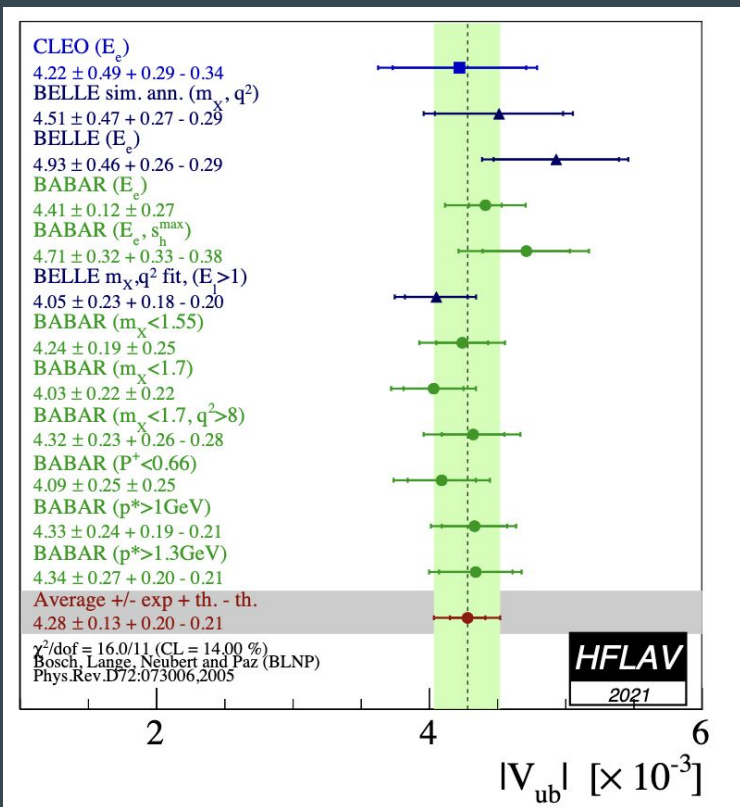
$$\Gamma_{X^0 \rightarrow \bar{f}}(t) = |\bar{A}_{\bar{f}}|^2 \left| \frac{q}{p} \right|^2 (1 + |\bar{\lambda}_{\bar{f}}|^2) \frac{e^{-\Gamma t}}{2} \left[\cosh\left(\frac{1}{2}\Delta\Gamma t\right) - C_{\bar{f}} \cos(\Delta m t) + D_{\bar{f}} \sinh\left(\frac{1}{2}\Delta\Gamma t\right) + S_{\bar{f}} \sin(\Delta m t) \right] \quad (41)$$

$$\Gamma_{\bar{X}^0 \rightarrow \bar{f}}(t) = |\bar{A}_{\bar{f}}|^2 (1 + |\bar{\lambda}_{\bar{f}}|^2) \frac{e^{-\Gamma t}}{2} \left[\cosh\left(\frac{1}{2}\Delta\Gamma t\right) + C_{\bar{f}} \cos(\Delta m t) + D_{\bar{f}} \sinh\left(\frac{1}{2}\Delta\Gamma t\right) - S_{\bar{f}} \sin(\Delta m t) \right] \quad (42)$$

where

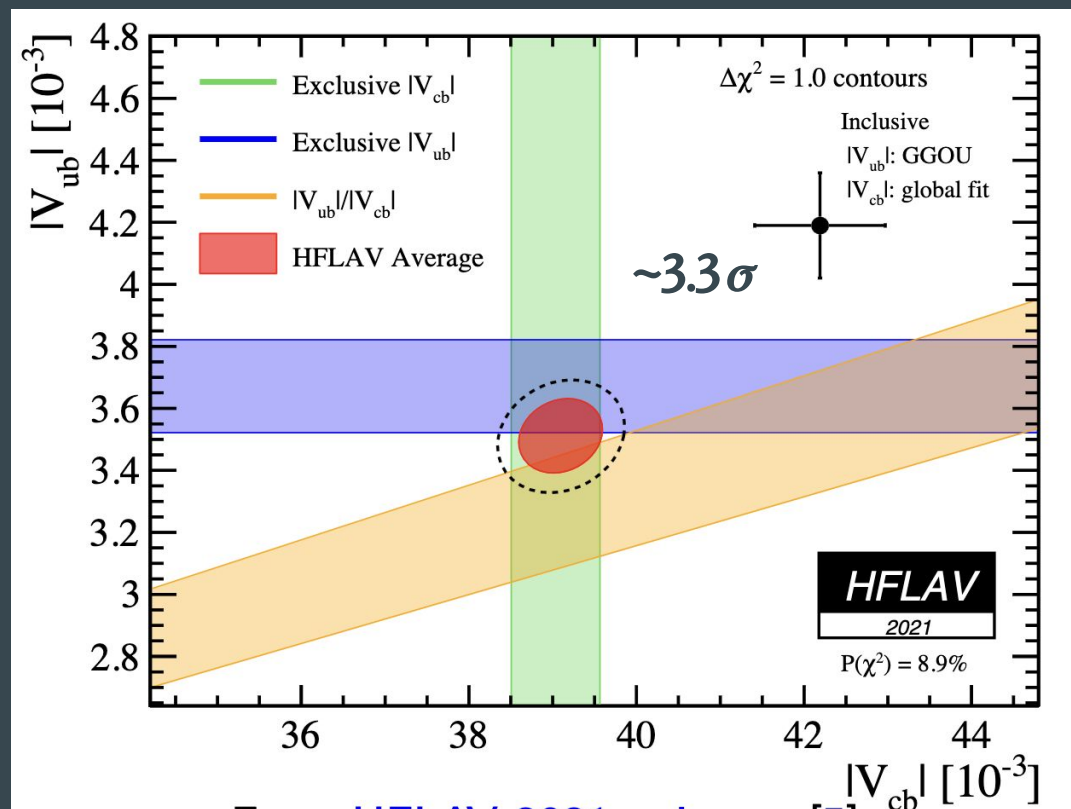
$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad D_f = \frac{2\mathcal{R}e(\lambda_f)}{1 + |\lambda_f|^2}, \quad S_f = \frac{2\mathcal{I}m(\lambda_f)}{1 + |\lambda_f|^2} \quad (43)$$

Vub measurements



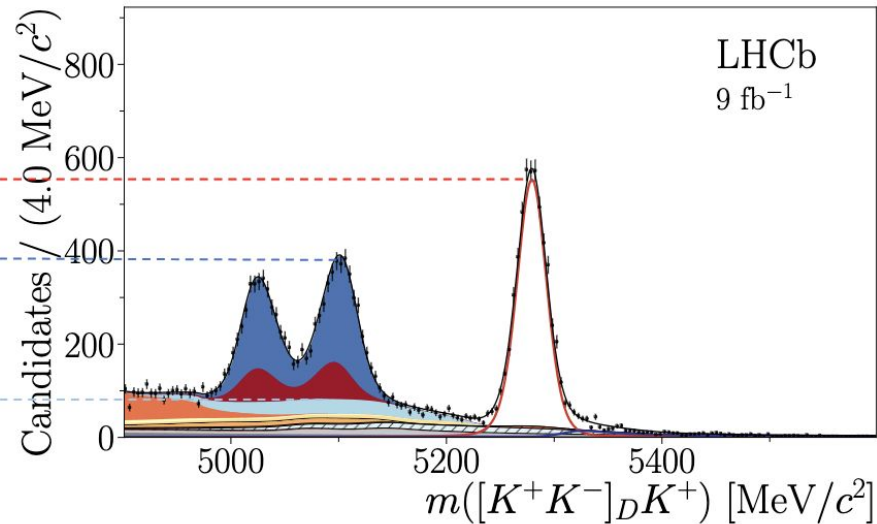
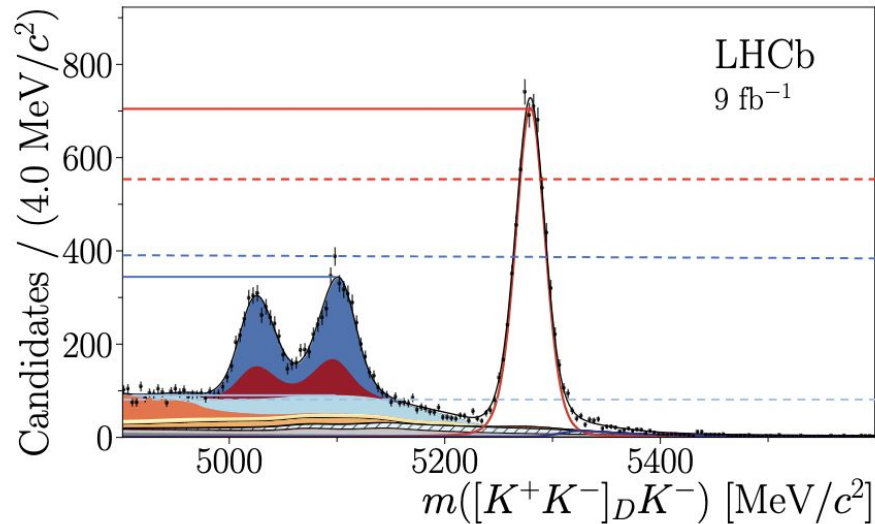
Vub measurements

HFLAV

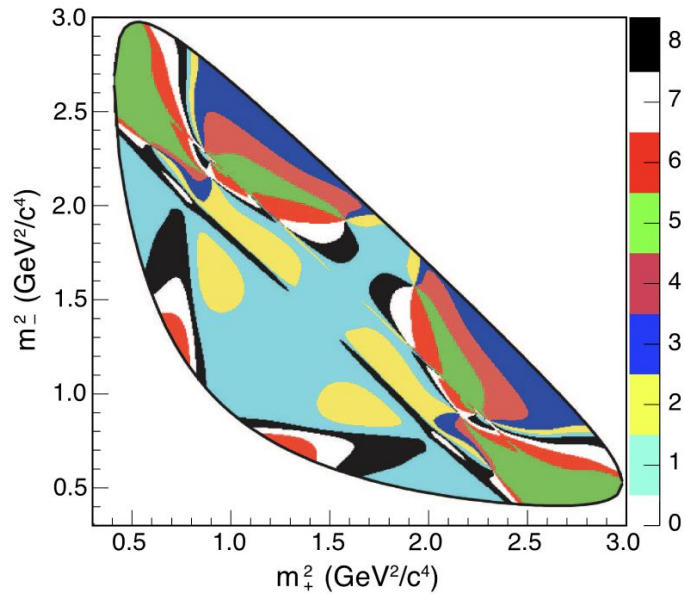


LHCb GLW measurements

[arxiv](#)



BPGGSZ method



Expected number of B^+ (B^-) events in bin i

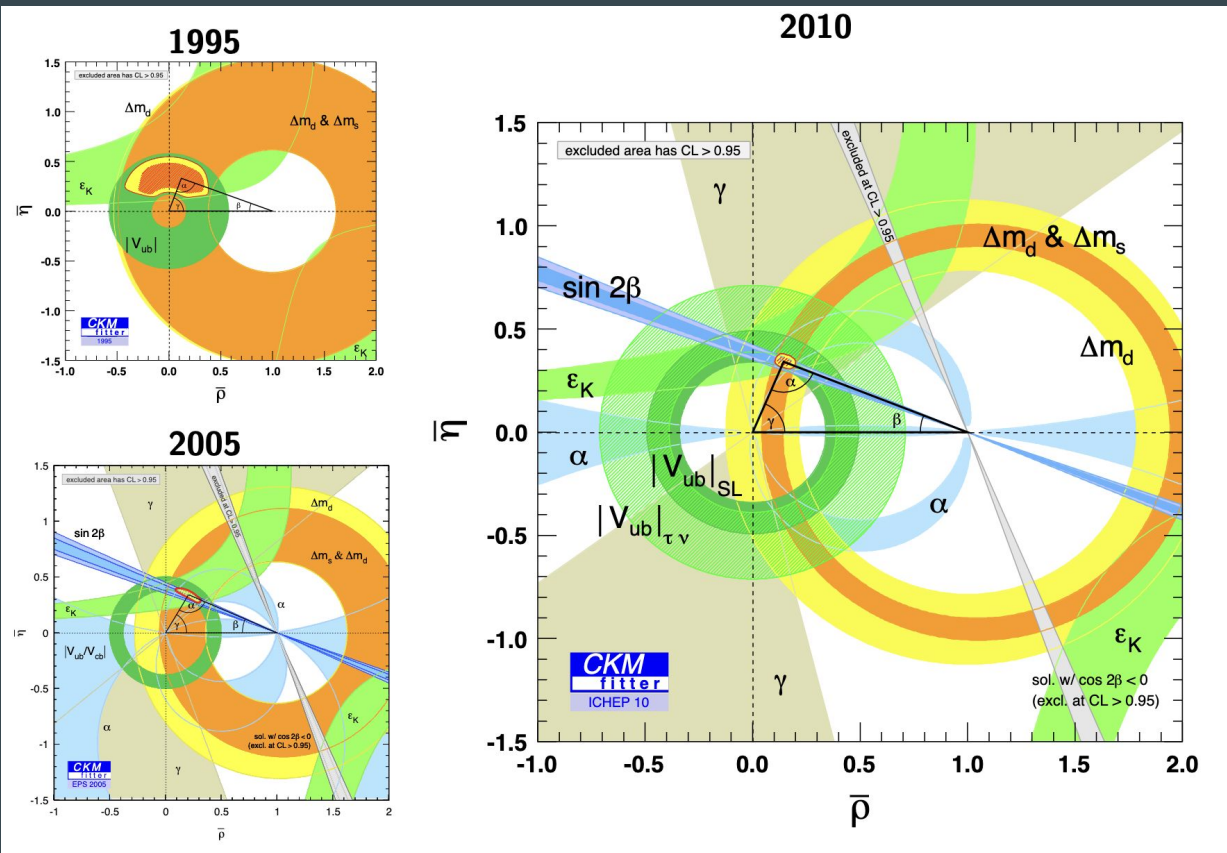
$$N_{\pm i}^+ = h_{B^+} \left[F_{\mp i} + (x_+^2 + y_+^2) F_{\pm i} + 2\sqrt{F_i F_{-i}} (x_+ c_{\pm i} - y_+ s_{\pm i}) \right]$$

$$N_{\pm i}^- = h_{B^-} \left[F_{\pm i} + (x_-^2 + y_-^2) F_{\mp i} + 2\sqrt{F_i F_{-i}} (x_- c_{\pm i} - y_- s_{\pm i}) \right]$$

CKM progress

Before B-factories and LHC

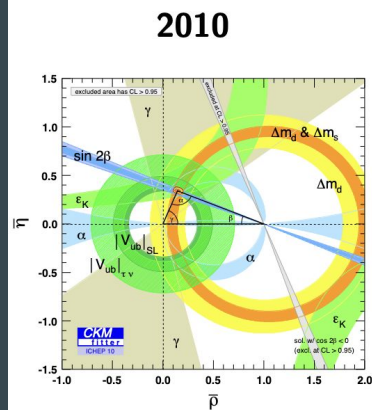
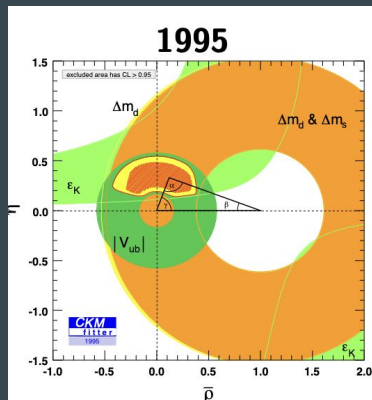
Tevatron and B factories



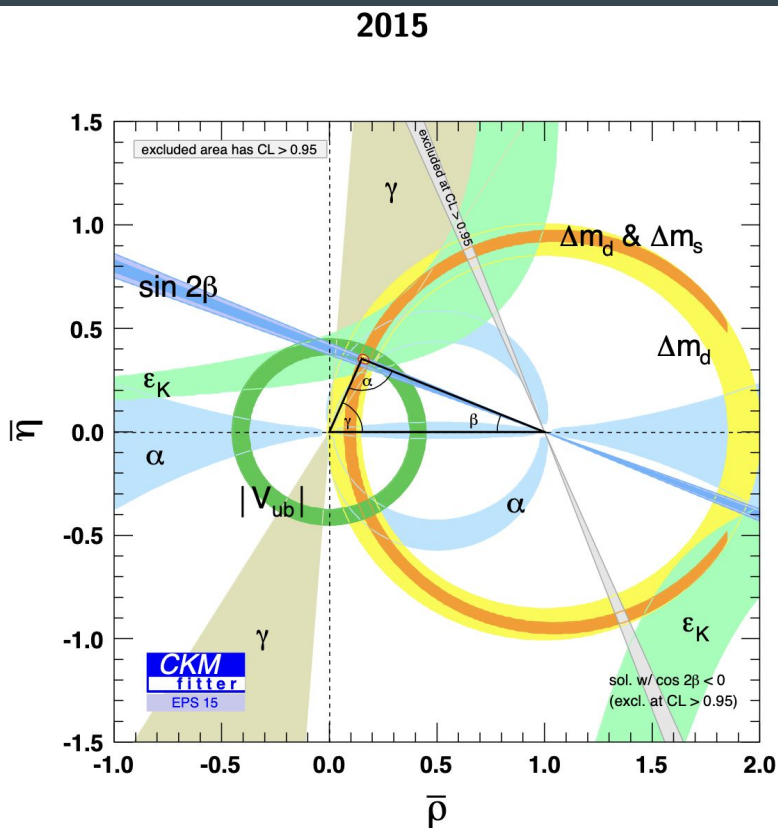
LHC inclusion

CKM progress

Before B-factories and LHC



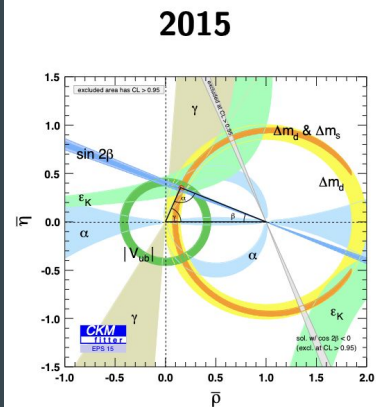
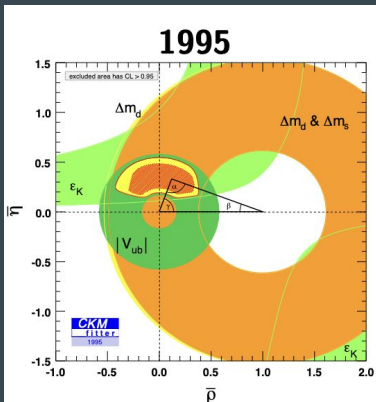
LHC inclusion



LHC inclusion

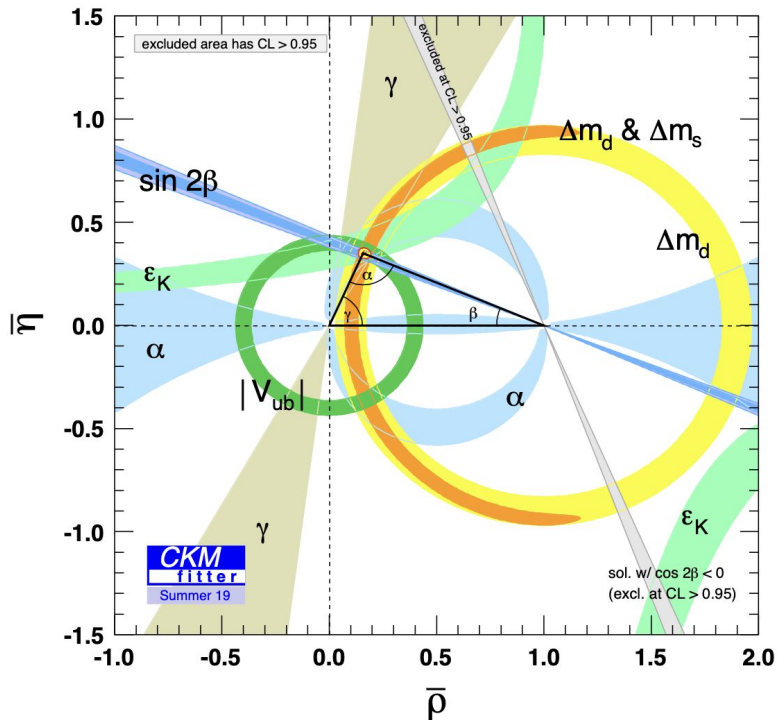
CKM progress

Before B-factories and LHC



LHC inclusion

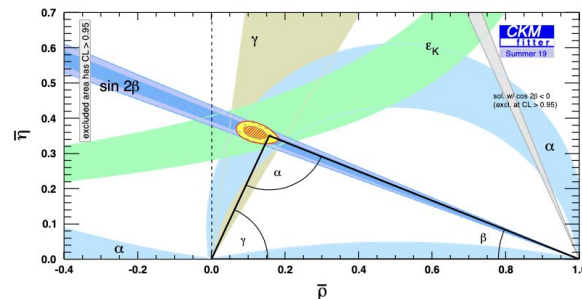
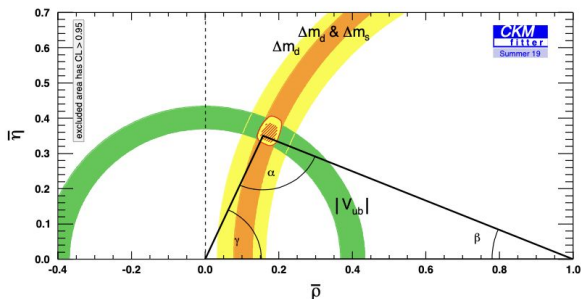
2019



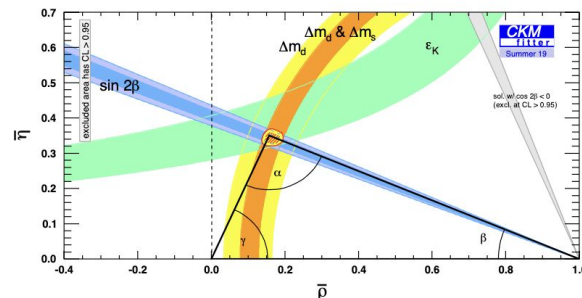
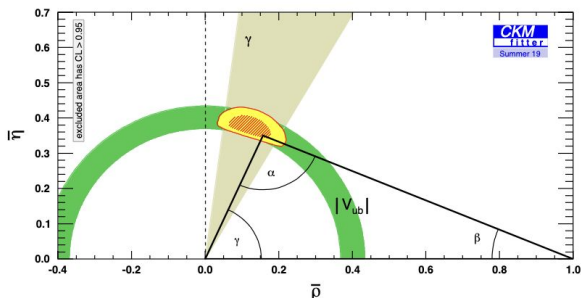
LHC inclusion

CKM progress

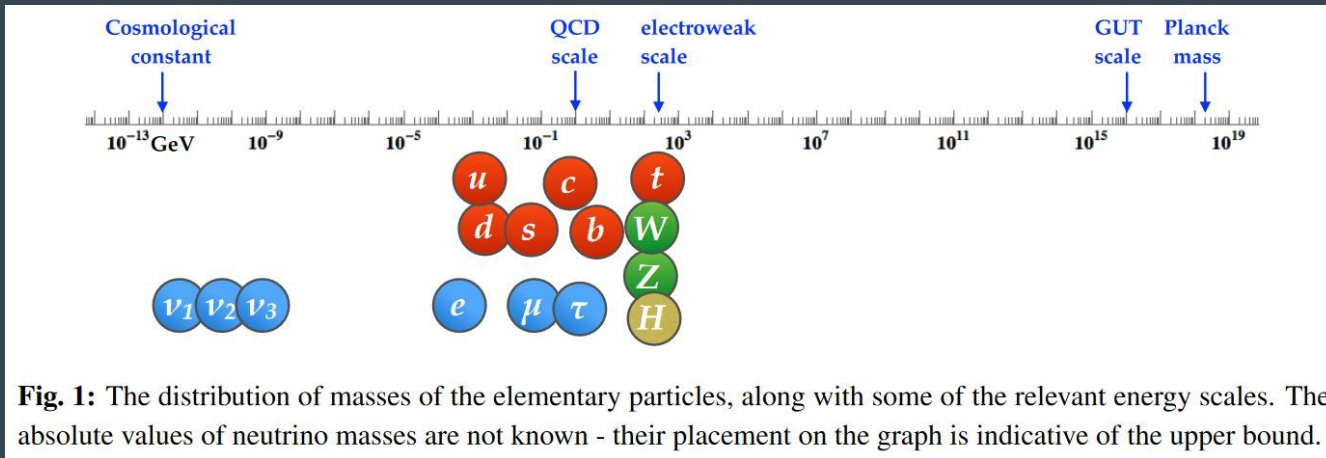
Comparison between CP -conserving (lengths of sides) and CP -violating (angles)



Comparison between tree-level (γ, V_{ub}) and loop-level ($\alpha, \beta, \Delta m, \epsilon$)



← Why is this interesting?



BSM	Λ	Dragons
SMEFT	100 GeV	$\gamma, g, W, Z, \nu_i, e, \mu, \tau + u, d, s, c, b, t + h$
WEFT	5 GeV	$\gamma, g, \nu_i, e, \mu, \tau + u, d, s, c, b$
WEFT4	2 GeV	$\gamma, g, \nu_i, e, \mu, \tau + u, d, s, c$

Name	Spin	Dimension
Gluons	1	1
Weak SU(2) bosons	1	1
Hypercharge boson	1	1
Quark doublets	1/2	3/2
Up-type anti-quarks	1/2	3/2
Down-type anti-quarks	1/2	3/2
Lepton doublets	1/2	3/2
Charged anti-leptons	1/2	3/2
Higgs field	0	1

$$\psi \in \mathbb{C}^4, \text{ Lorentz Rep. } \left(\frac{1}{2}, 0\right) \oplus \left(0, \frac{1}{2}\right)$$

Dirac Lagrangian

Dirac Equation

$$\mathcal{L} = \bar{\psi}(i\partial - m)\psi$$

$$(i\partial - m)\psi = 0$$

Physicist's Notation:

$$\mathcal{L} = \psi^\dagger \gamma^0 (i\gamma^\mu \partial_\mu - m)\psi$$

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

$$\mathcal{L} = i\psi^\dagger \gamma^0 \gamma^\mu \frac{\partial \psi}{\partial x^\mu} - m\psi^\dagger \gamma^0 \psi$$

$$i\gamma^\mu \frac{\partial \psi}{\partial x^\mu} - m\psi = 0$$

Explicit Summation:

$$\mathcal{L} = i \sum_{j=0}^3 \sum_{a=1}^4 \sum_{b=1}^4 \sum_{c=1}^4 \psi_a^* \gamma_{0ab} \gamma_{jbc} \frac{\partial \psi_c}{\partial x_j} - m \sum_{a=1}^4 \sum_{b=1}^4 \psi_a^* \gamma_{0ab} \psi_b$$

$$i \sum_{j=0}^3 \sum_{b=1}^4 \gamma_{jab} \frac{\partial \psi_b}{\partial x_j} - m\psi_a = 0$$

Vector-Matrix Notation:

$$\mathcal{L} = i\psi^\dagger \frac{\partial \psi}{\partial t} + i\psi^\dagger \gamma_0 \gamma_1 \frac{\partial \psi}{\partial x} + i\psi^\dagger \gamma_0 \gamma_2 \frac{\partial \psi}{\partial y} + i\psi^\dagger \gamma_0 \gamma_3 \frac{\partial \psi}{\partial z} - m\psi^\dagger \gamma_0 \psi$$

$$i\gamma_0 \frac{\partial \psi}{\partial t} + i\gamma_1 \frac{\partial \psi}{\partial x} + i\gamma_2 \frac{\partial \psi}{\partial y} + i\gamma_3 \frac{\partial \psi}{\partial z} - m\psi = 0$$

Fully Expanded:

chiral representation:

$$\gamma^0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix},$$

$$\gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}$$

$$\begin{aligned} \mathcal{L} = & i\psi_3^* \frac{\partial \psi_3}{\partial t} + i\psi_3^* \frac{\partial \psi_4}{\partial x} + \psi_3^* \frac{\partial \psi_4}{\partial y} + i\psi_3^* \frac{\partial \psi_3}{\partial z} \\ & + i\psi_4^* \frac{\partial \psi_4}{\partial t} + i\psi_4^* \frac{\partial \psi_3}{\partial x} - \psi_4^* \frac{\partial \psi_3}{\partial y} - i\psi_4^* \frac{\partial \psi_4}{\partial z} \\ & + i\psi_1^* \frac{\partial \psi_1}{\partial t} - i\psi_1^* \frac{\partial \psi_2}{\partial x} - \psi_1^* \frac{\partial \psi_2}{\partial y} - i\psi_1^* \frac{\partial \psi_1}{\partial z} \\ & + i\psi_2^* \frac{\partial \psi_2}{\partial t} - i\psi_2^* \frac{\partial \psi_1}{\partial x} + \psi_2^* \frac{\partial \psi_1}{\partial y} + i\psi_2^* \frac{\partial \psi_2}{\partial z} \\ & - m(\psi_3^* \psi_1 + \psi_4^* \psi_2 + \psi_1^* \psi_3 + \psi_2^* \psi_4) \end{aligned}$$

$$\begin{aligned} i \frac{\partial \psi_3}{\partial t} + i \frac{\partial \psi_4}{\partial x} + \frac{\partial \psi_4}{\partial y} + i \frac{\partial \psi_3}{\partial z} - m\psi_1 &= 0 \\ i \frac{\partial \psi_4}{\partial t} + i \frac{\partial \psi_3}{\partial x} - \frac{\partial \psi_3}{\partial y} - i \frac{\partial \psi_4}{\partial z} - m\psi_2 &= 0 \\ i \frac{\partial \psi_1}{\partial t} - i \frac{\partial \psi_2}{\partial x} - \frac{\partial \psi_2}{\partial y} - i \frac{\partial \psi_1}{\partial z} - m\psi_3 &= 0 \\ i \frac{\partial \psi_2}{\partial t} - i \frac{\partial \psi_1}{\partial x} + \frac{\partial \psi_1}{\partial y} + i \frac{\partial \psi_2}{\partial z} - m\psi_4 &= 0 \end{aligned}$$

Resources

Matt Kenzie flavour lectures and a reading list

<https://www.hep.phy.cam.ac.uk/~mkenzie/teaching/flavour/>

<https://www.hep.phy.cam.ac.uk/~mkenzie/teaching/flavour/reading.pdf>

Niels Tuning flavour lectures

<https://www.nikhef.nl/~h71/Lectures/2020/ppII-cpviolation-14022020.pdf>

Sophie Renner Implications workshop lectures on EFTs

<https://indico.cern.ch/event/1330361/contributions/>

More on SMEFT

<https://link.springer.com/content/pdf/10.1140/epjc/s10052-023-11821-3.pdf>

<https://indico.in2p3.fr/event/22195/contributions/86017/attachments/59873/81148/eflectures.pdf>