Flavour lectures

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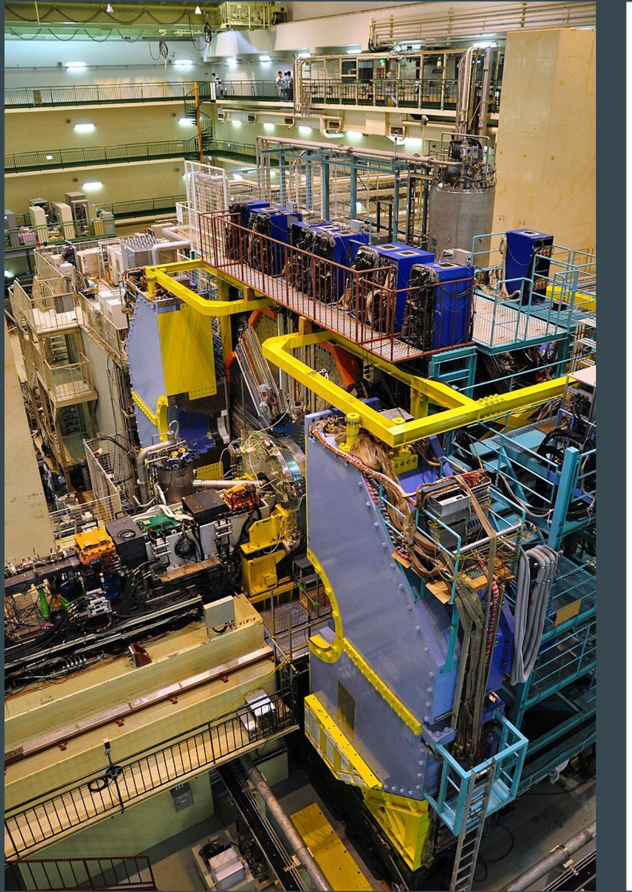
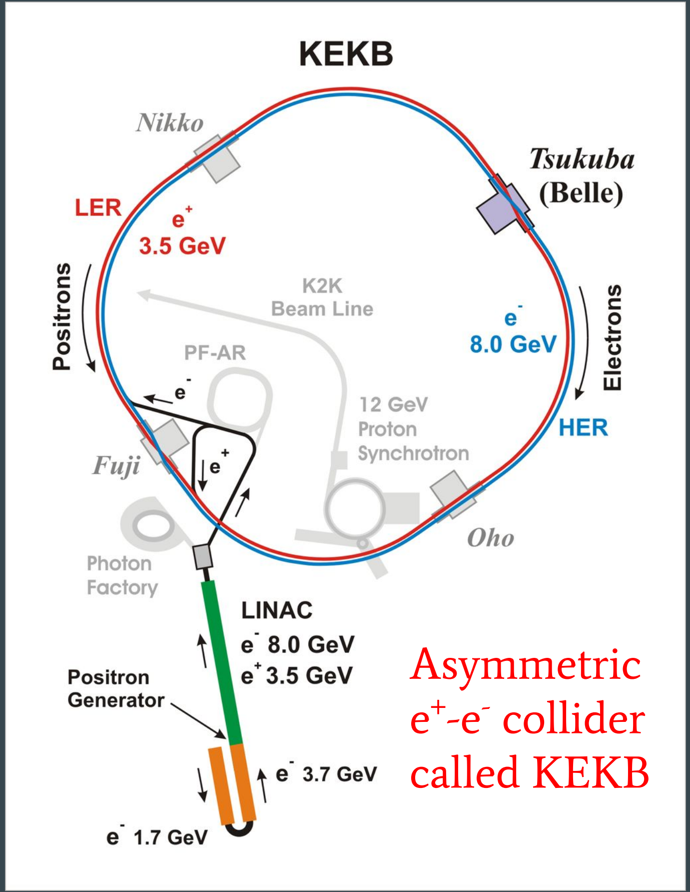
Accompanying slides

Flavour physics experiments - Belle

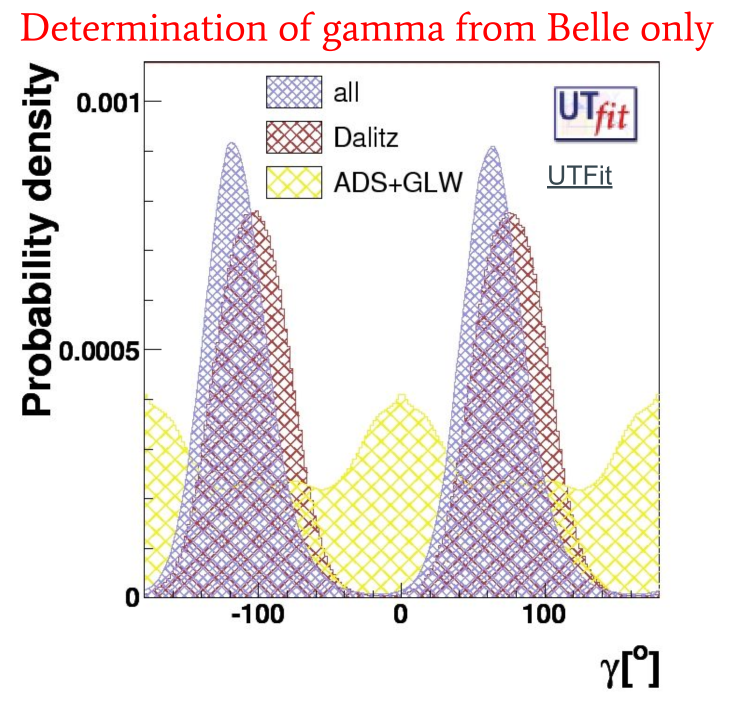


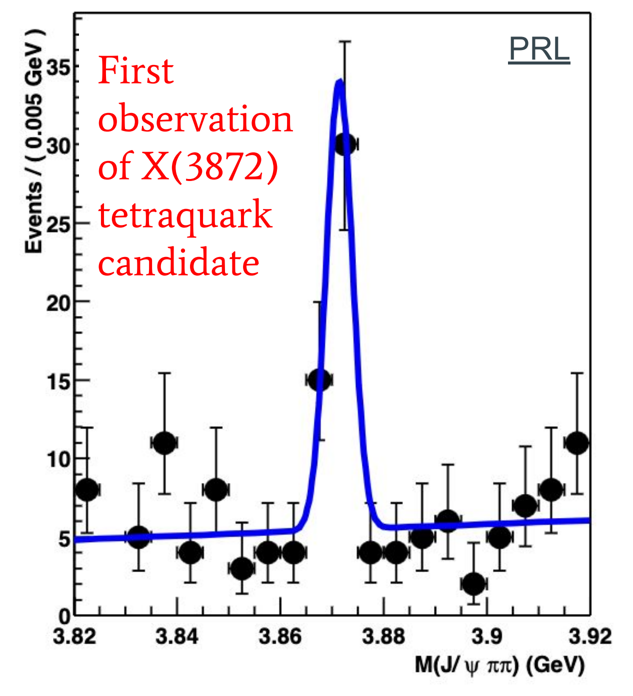


Asymmetric e^+-e^- collider called KEKB

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

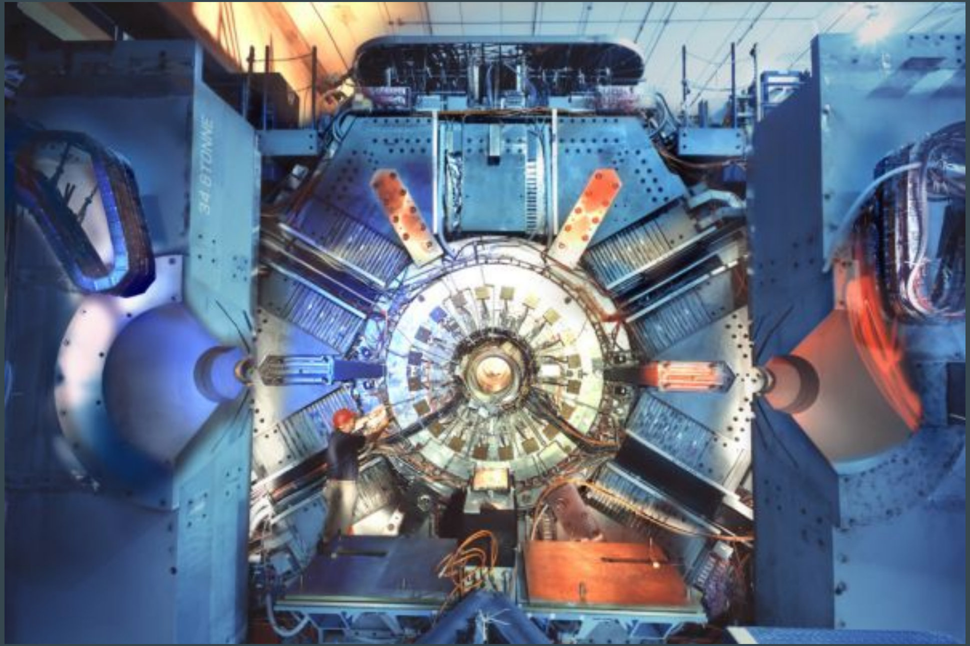
Flavour physics experiments - Belle



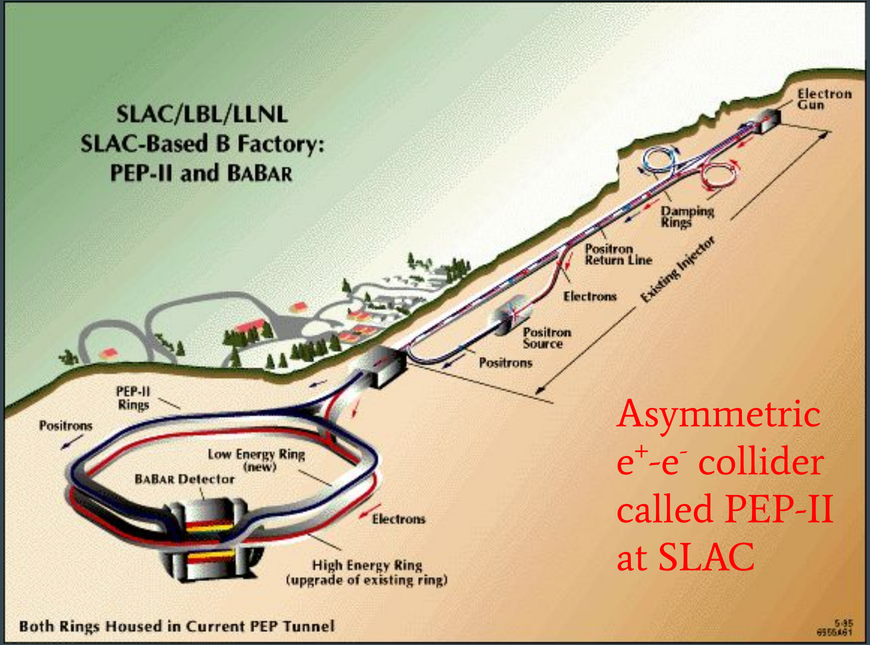


Nature of tetraquark remains unknown : D^0- $\overline{D}^{0*}$ molecule?

Flavour physics experiments - BaBar

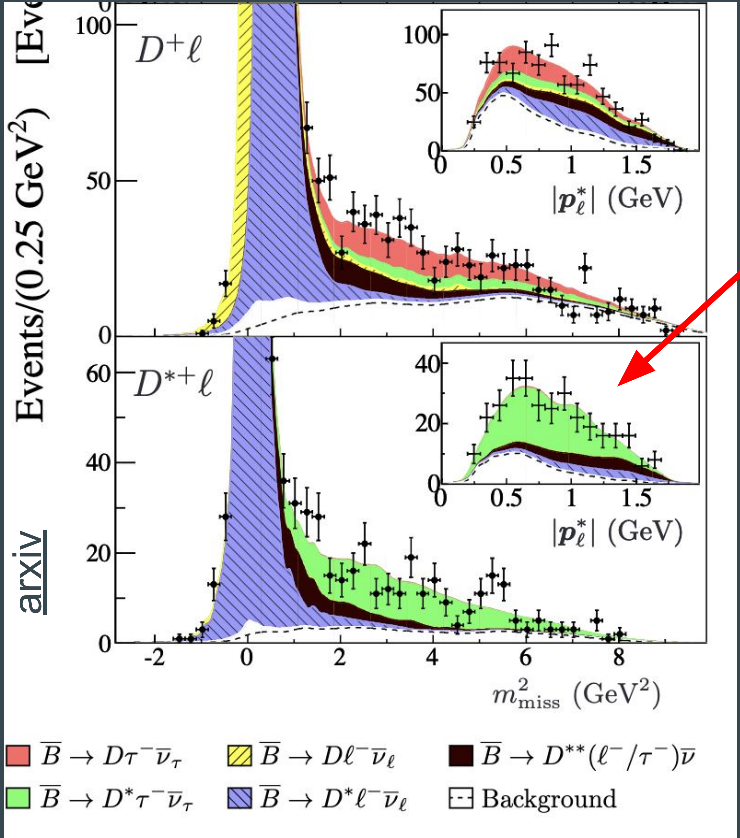


- 1999-2008 (9 yrs)
- Data collected at $\Upsilon(4S)$ => 384M $B\bar{B}$ pairs



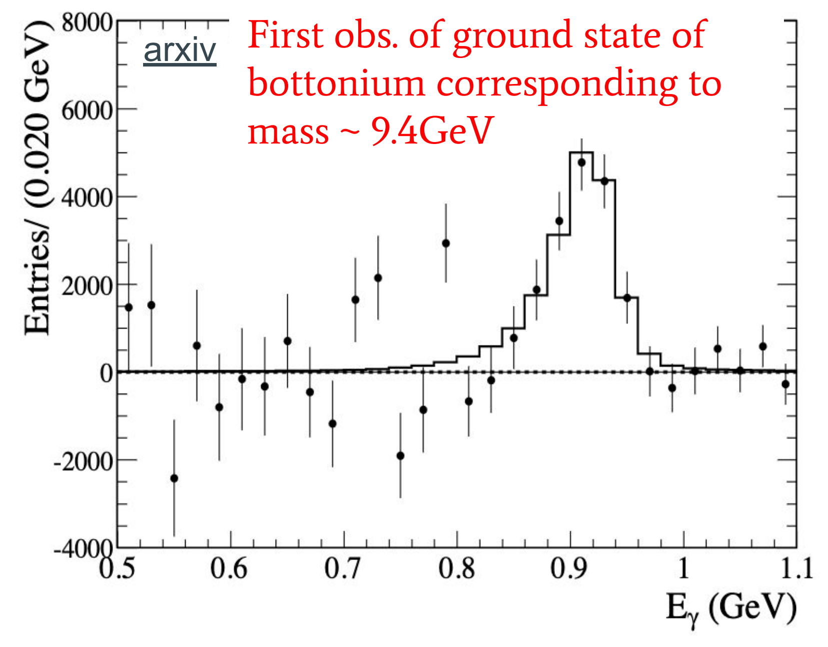
Asymmetric e^+-e^- collider called PEP-II at SLAC

Flavour physics experiments - BaBar



arxiv

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

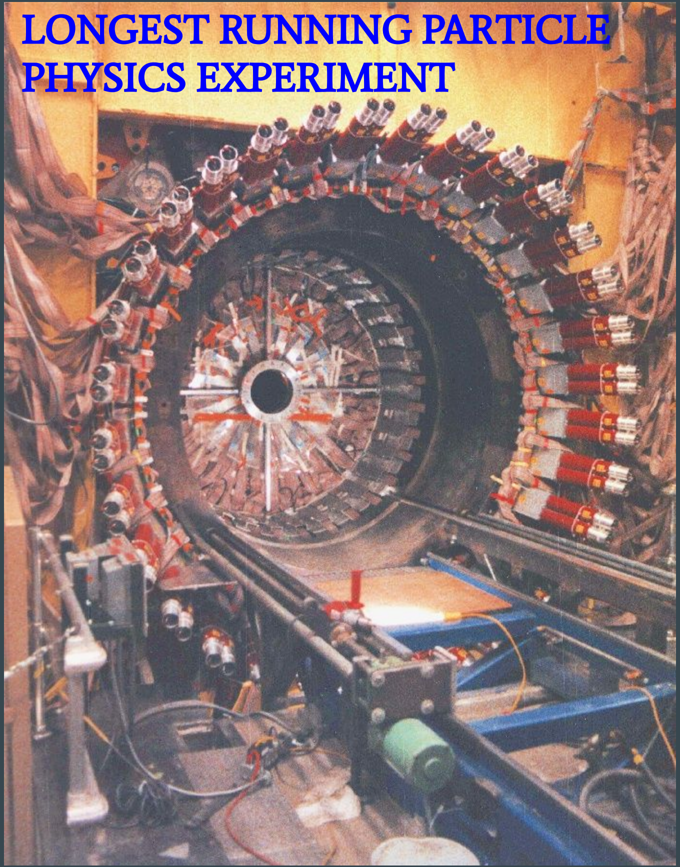


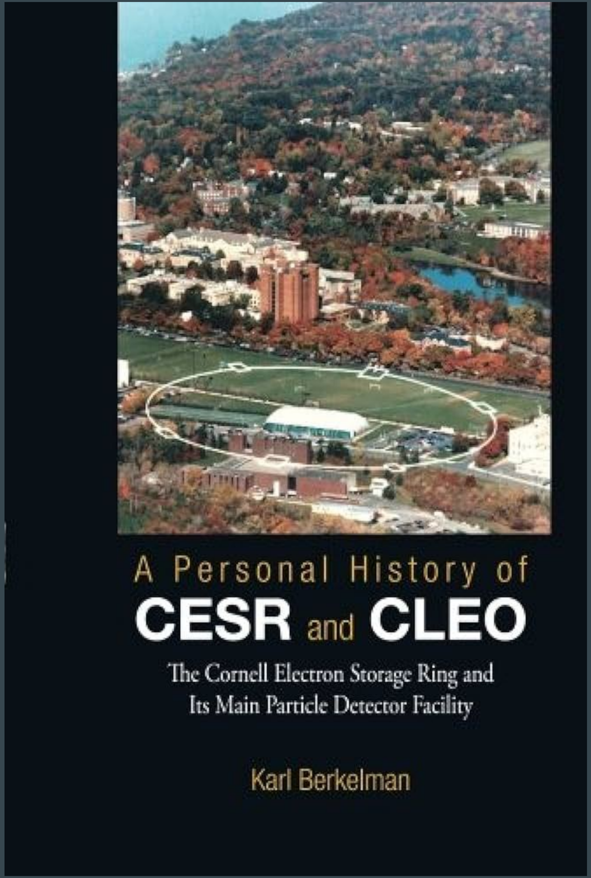
arxiv

First obs. of ground state of bottonium corresponding to mass ~ 9.4GeV

Made in 2012, AFTER datataking

Flavour physics experiments - CLEO(-c)




A Personal History of

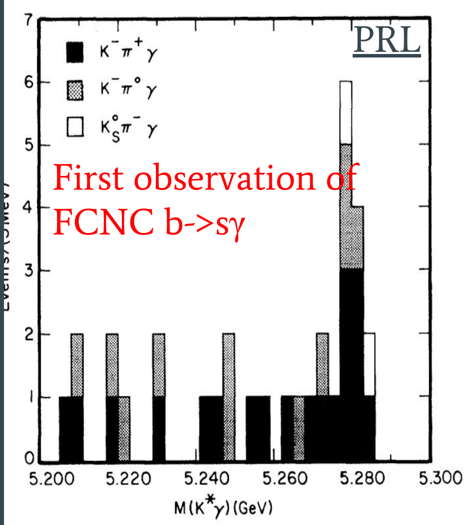
CESR and CLEO

The Cornell Electron Storage Ring and Its Main Particle Detector Facility

Karl Berkelman

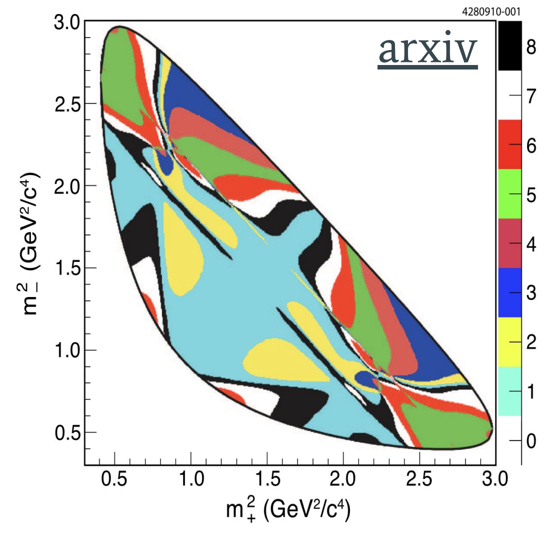
- 1979-2008 (29 yrs)
- Symmetric e^+-e^- collider called CESR at Cornell University
- Collisions at 3.5-12GeV for *b*- and *c*- physics (CLEO-c)

Flavour physics experiments - CLEO(-c)



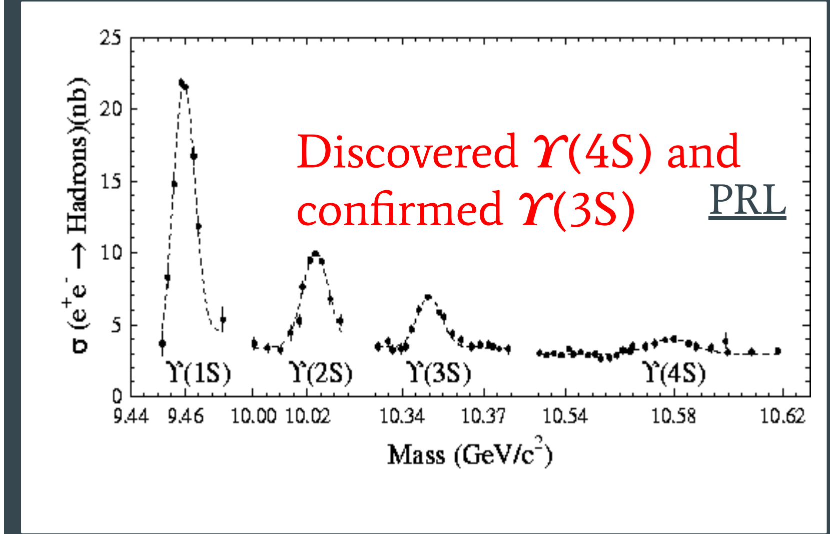
PRL

First observation of FCNC b->sγ



arxiv

Key charm input for CPV measurements



Discovered $\Upsilon(4S)$ and confirmed $\Upsilon(3S)$

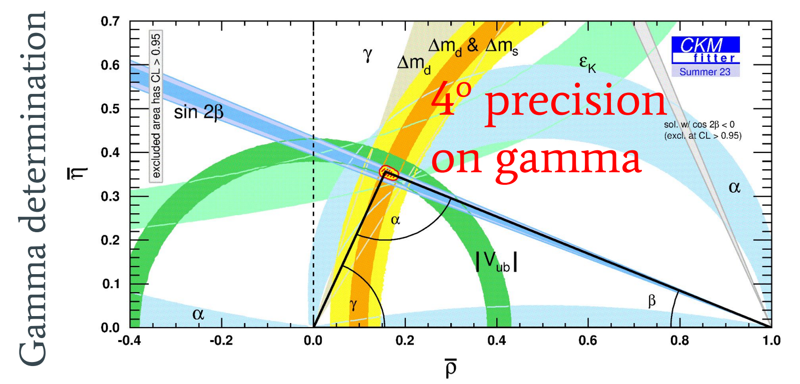
PRL

Discovered 13 new Charm baryons

Flavour physics experiments - LHCb (UO)

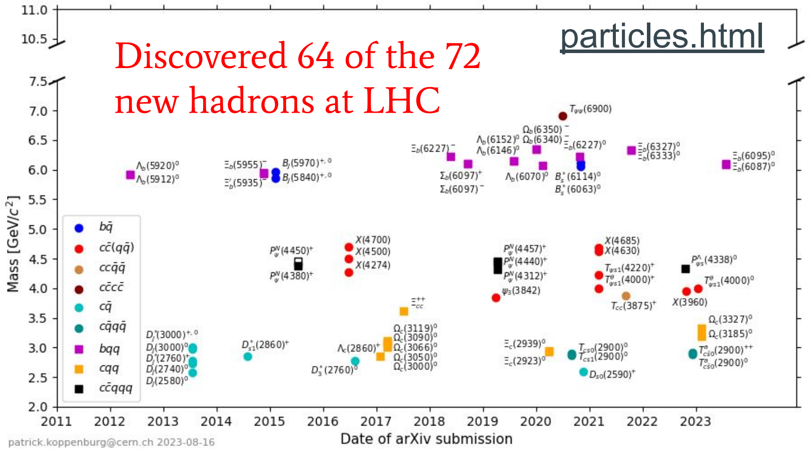
- 2011-2018 (7 yrs)
- Collisions from symmetric p-p collider called LHC
- Collisions at 7-13.6 TeV

Flavour physics experiments - LHCb



Gamma determination

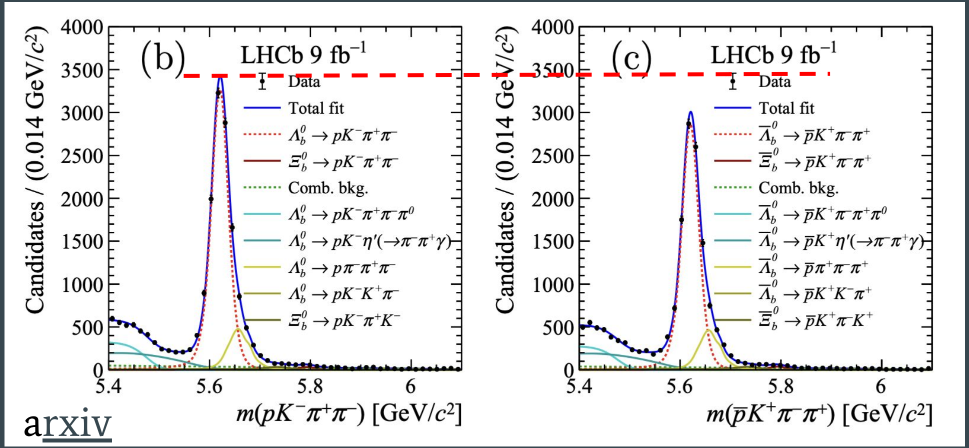
4° precision on gamma



Discovered 64 of the 72 new hadrons at LHC

particles.html

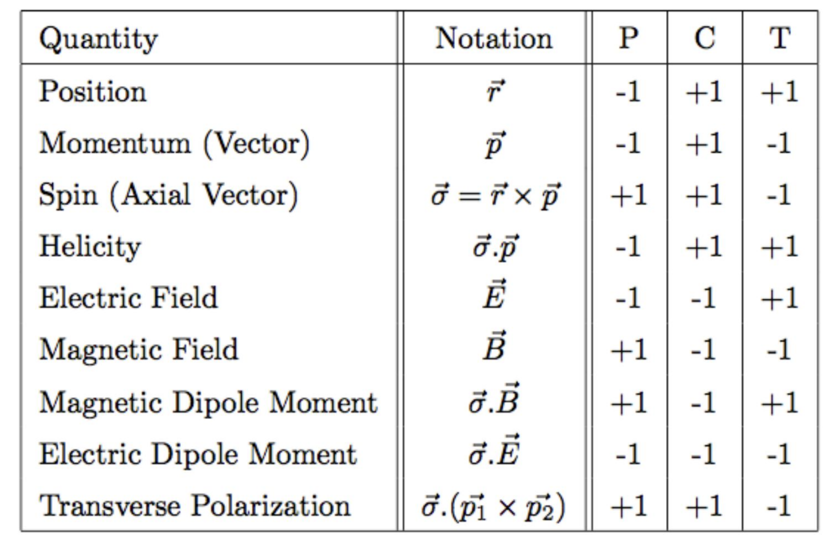
First observation of CPV in Charm mesons and later in baryons



arxiv

6 sigma CPV in pππ 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	$\vec{\sigma}.\vec{p}$	-1	+1	+1
Electric Field	$\vec{E}$	-1	-1	+1
Magnetic Field	$\vec{B}$	+1	-1	-1
Magnetic Dipole Moment	$\vec{\sigma}.\vec{B}$	+1	-1	+1
Electric Dipole Moment	$\vec{\sigma}.\vec{E}$	-1	-1	-1
Transverse Polarization	$\vec{\sigma}.(\vec{p_1} \times \vec{p_2})$	+1	+1	-1

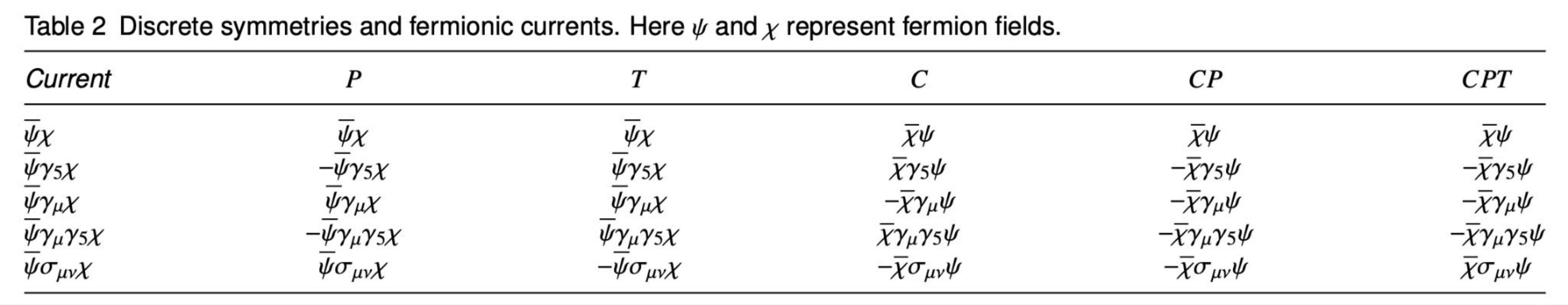
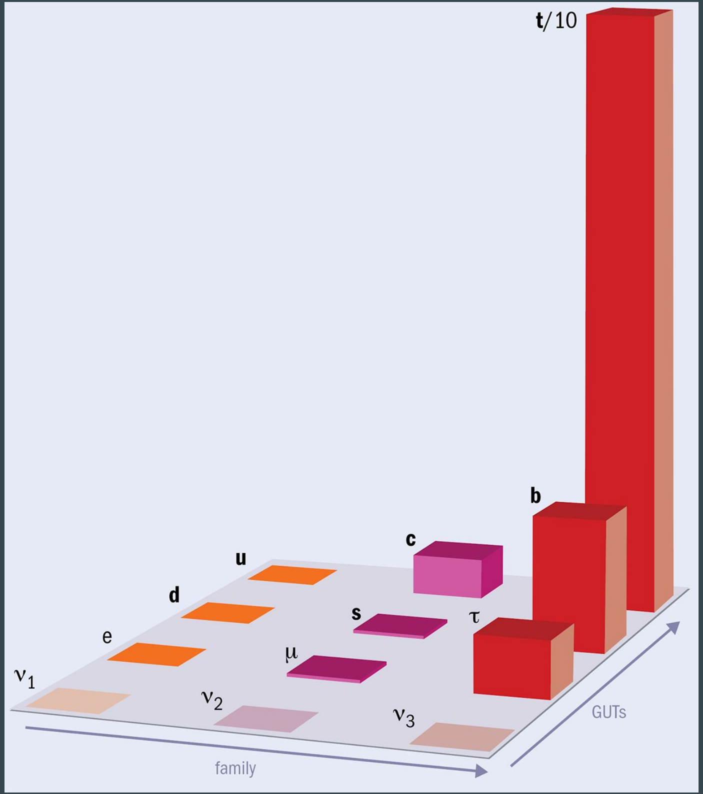


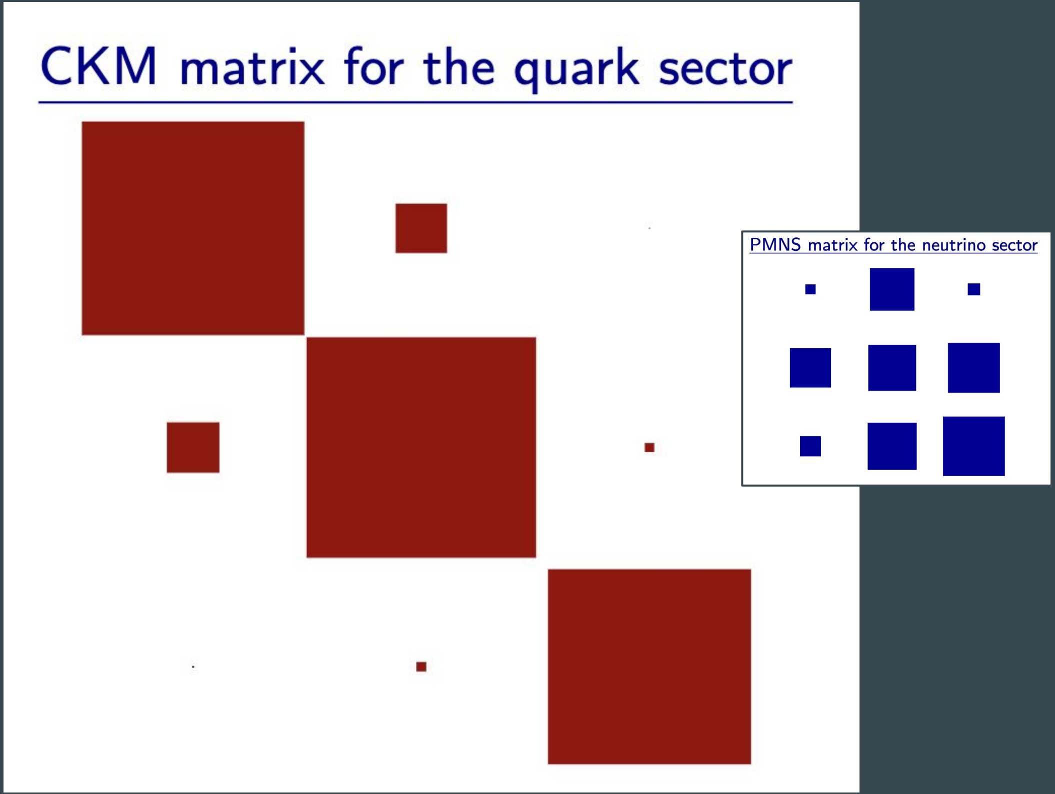
Table 2 Discrete symmetries and fermionic currents. Here ψ and χ represent fermion fields.

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

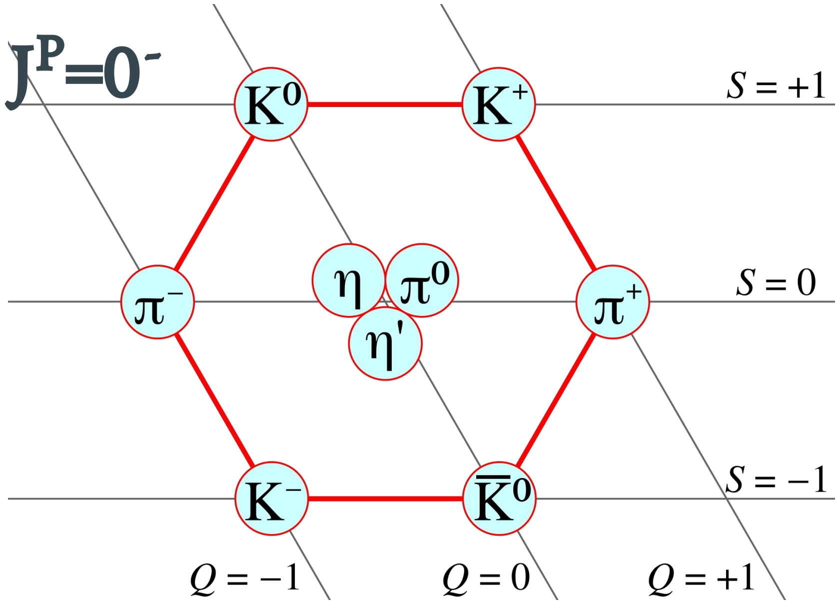
SM puzzles



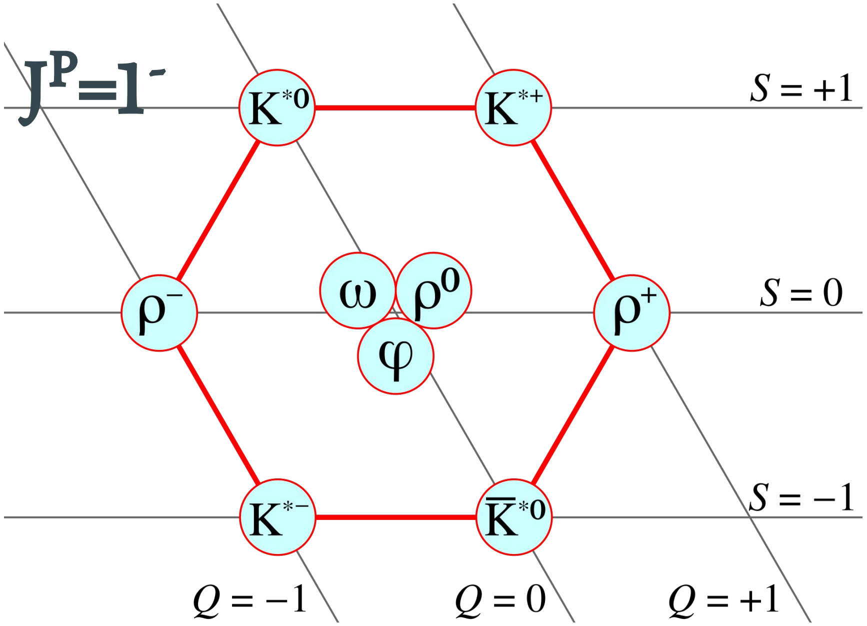
Quark and lepton masses span 12 orders of magnitude



Flavour multiplets - SU(3) mesons

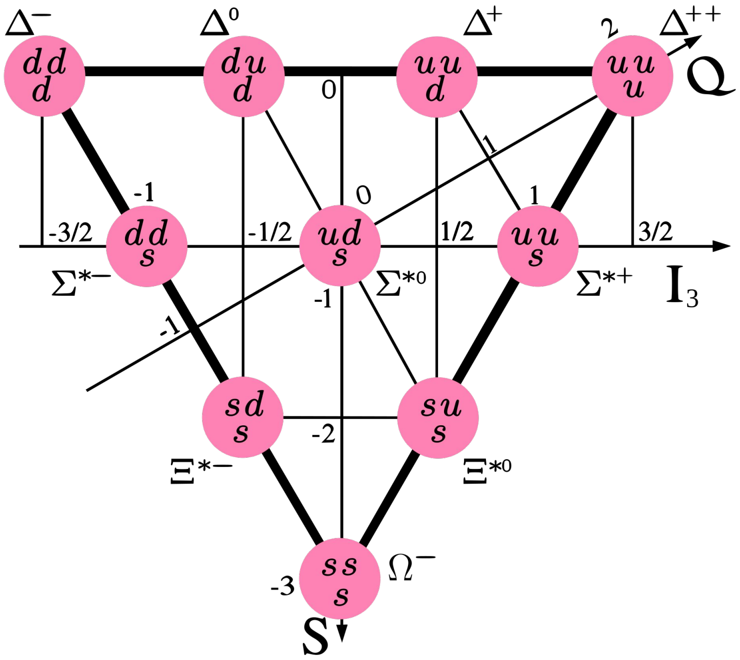


Pseudoscalar mesons of spin-0 form a nonet

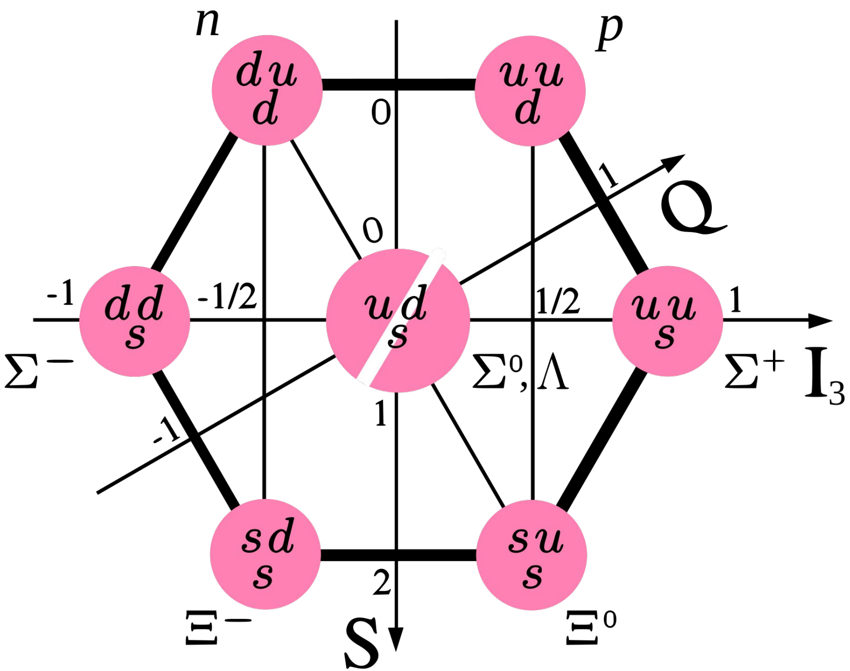


Vector mesons of spin-1 form a nonet

Flavour multiplets - SU(3) baryons



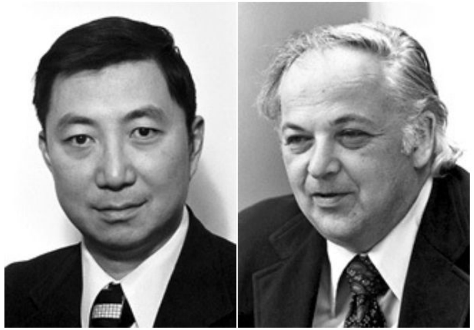
Combinations of three **u, d** or **s** quarks with a spin-3/2 form the *uds baryon decuplet*

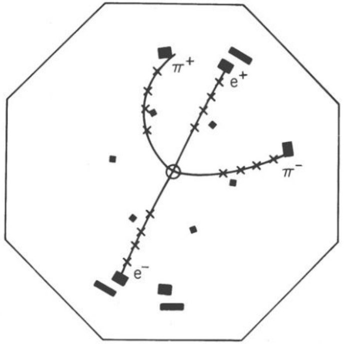


Combinations of three **u, d** or **s** quarks with a spin-1/2 form the *uds baryon octet*

Charm discovery

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





EW LETTERS 2 DECEMBER 197

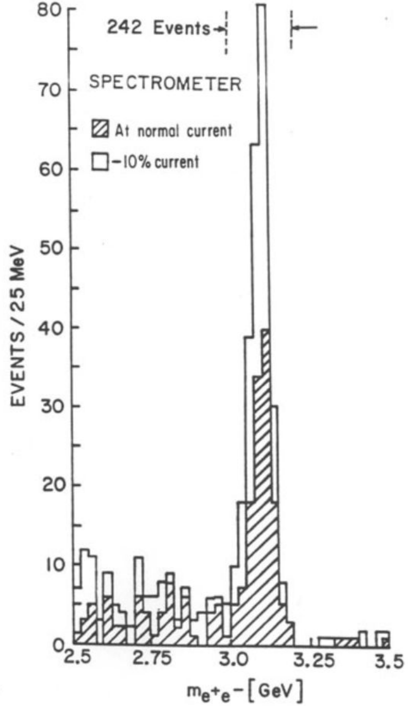
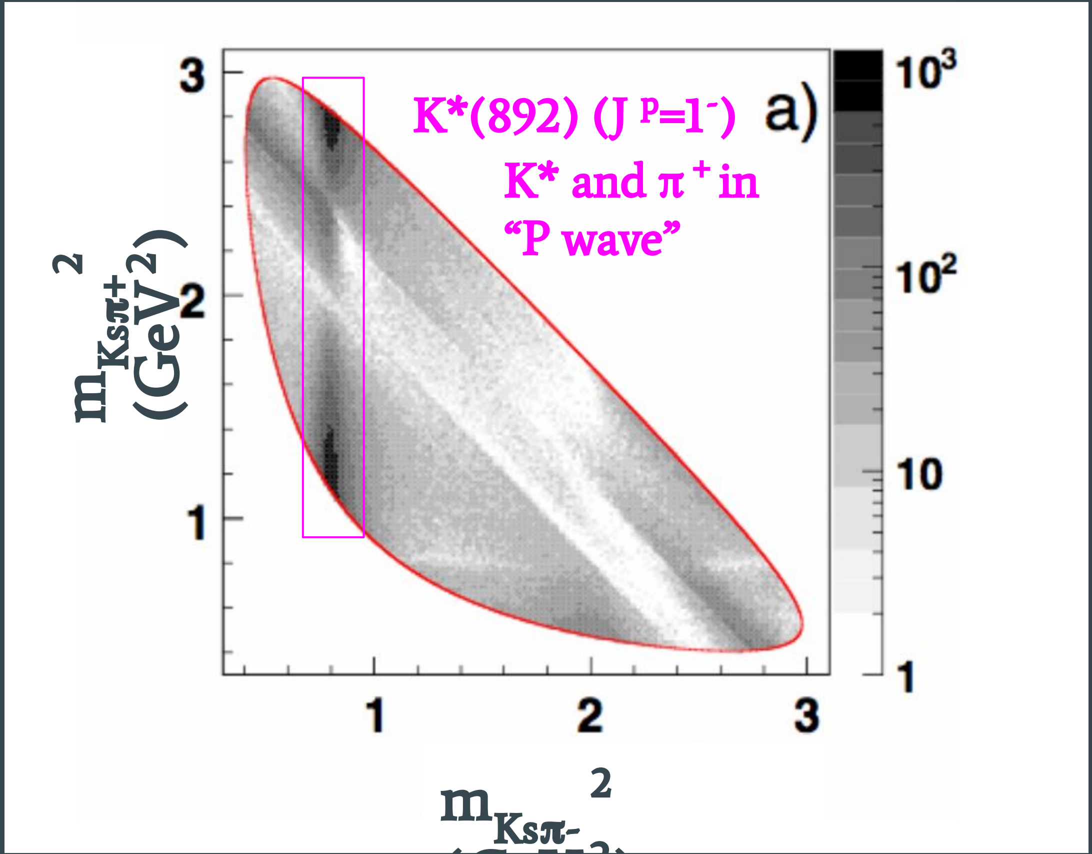


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

Stolen from M. Kenzie

Dalitz plots

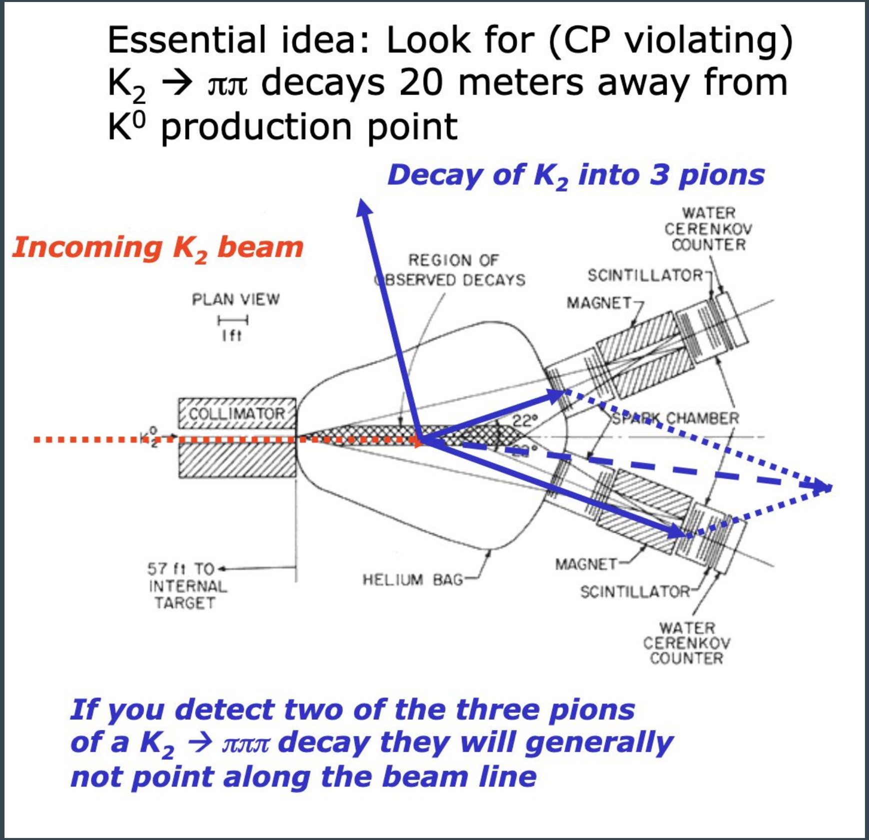


K*(892) ($J^P=1^-$)

K* and π^+ in "P wave"

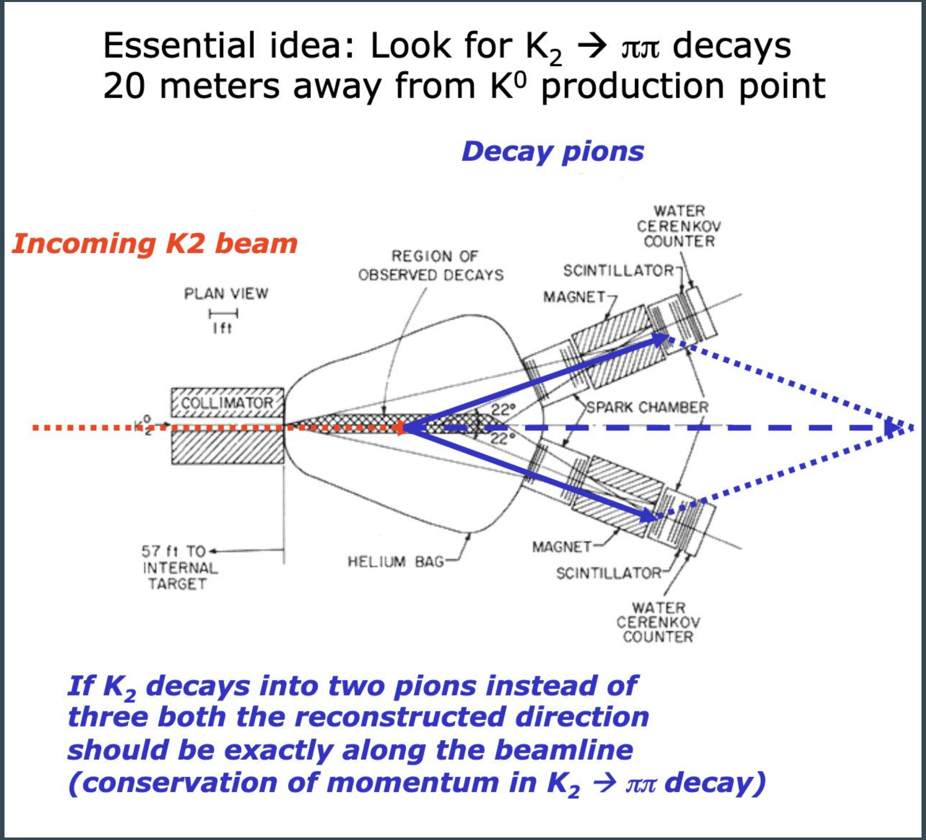
Cronin and Fitch experiment - CPV in Kaons

K_2=K



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

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



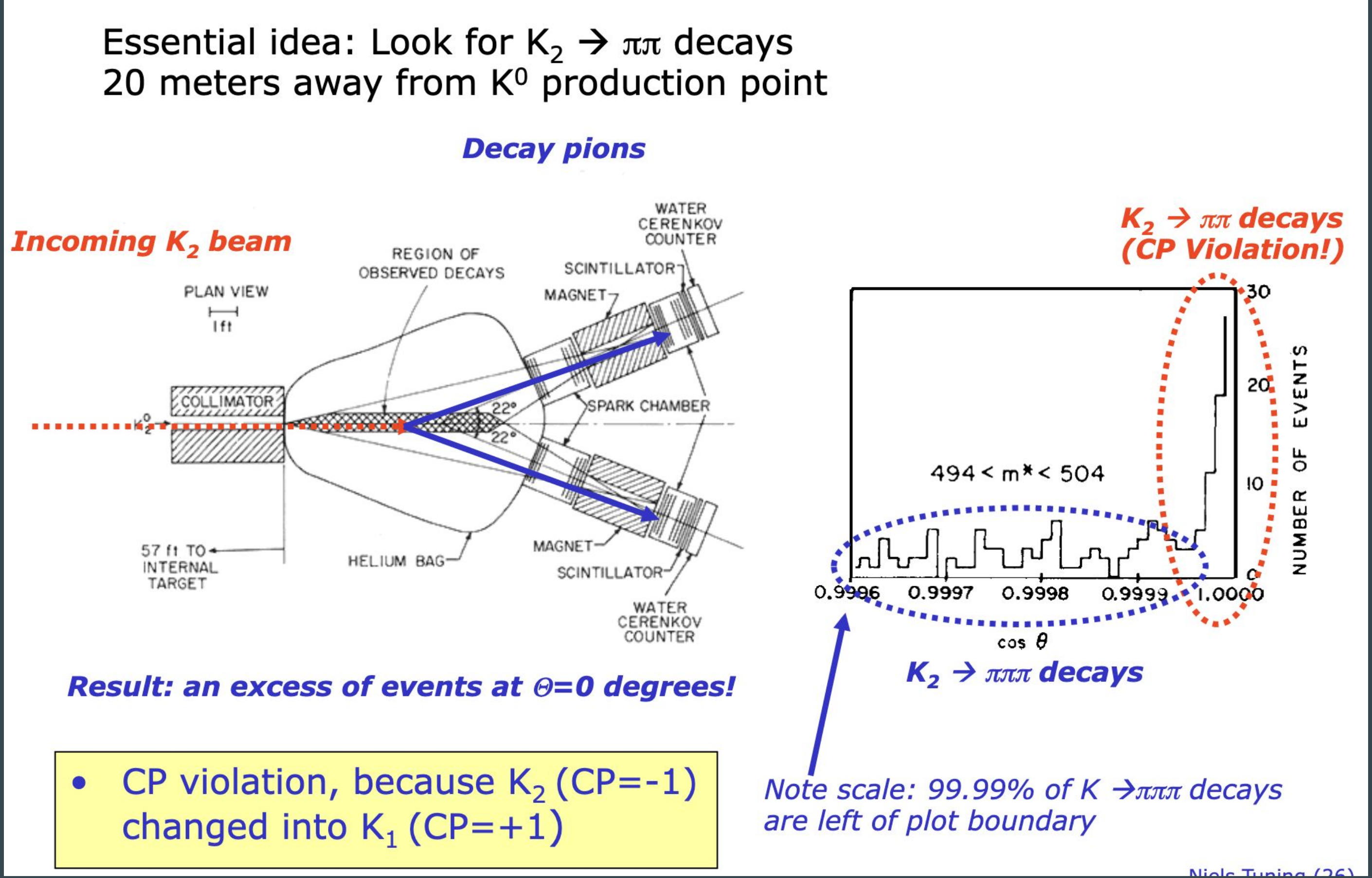
Essential idea: Look for $K_2 \to \pi\pi$ decays 20 meters away from K^0 production point

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

Stolen from N. Tuning

Cronin and Fitch experiment - CPV in Kaons

K_2=K



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

Decay pions

Incoming K_2 beam

Result: an excess of events at Θ=0 degrees!

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

$K_2 \to \pi\pi$ decays (CP Violation!)

$K_2 \to \pi\pi\pi$ decays

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

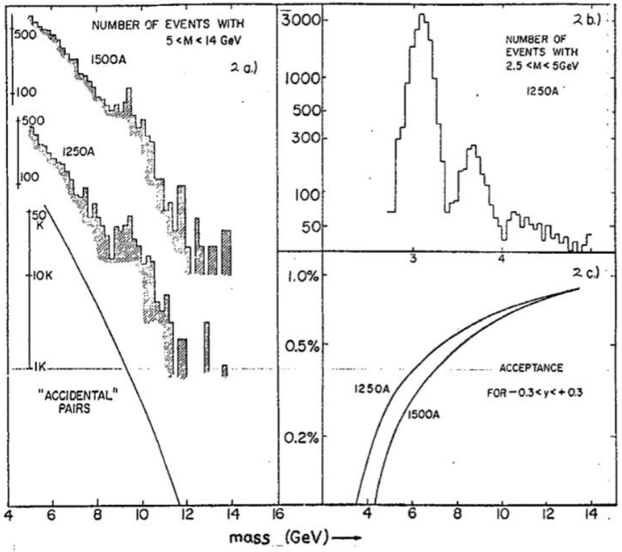
Niels Tuning (26)

Stolen from N. Tuning

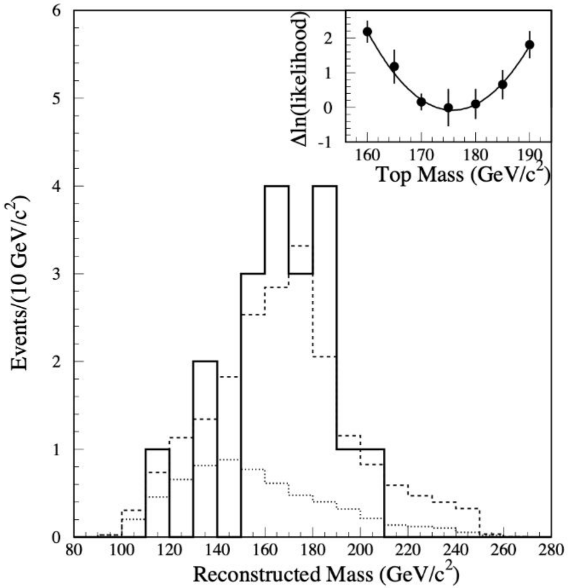
Beauty and Top observation

- 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



Stolen from M. Kenzie

CKM higher orders

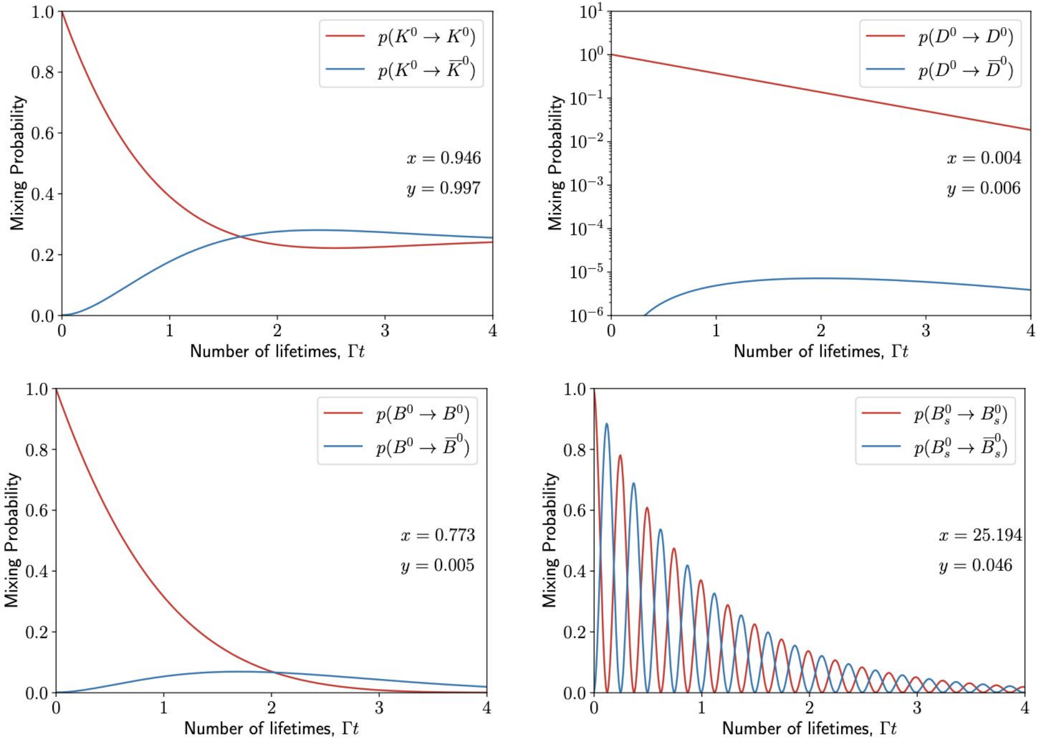
$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

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

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

Neutral meson oscillation

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



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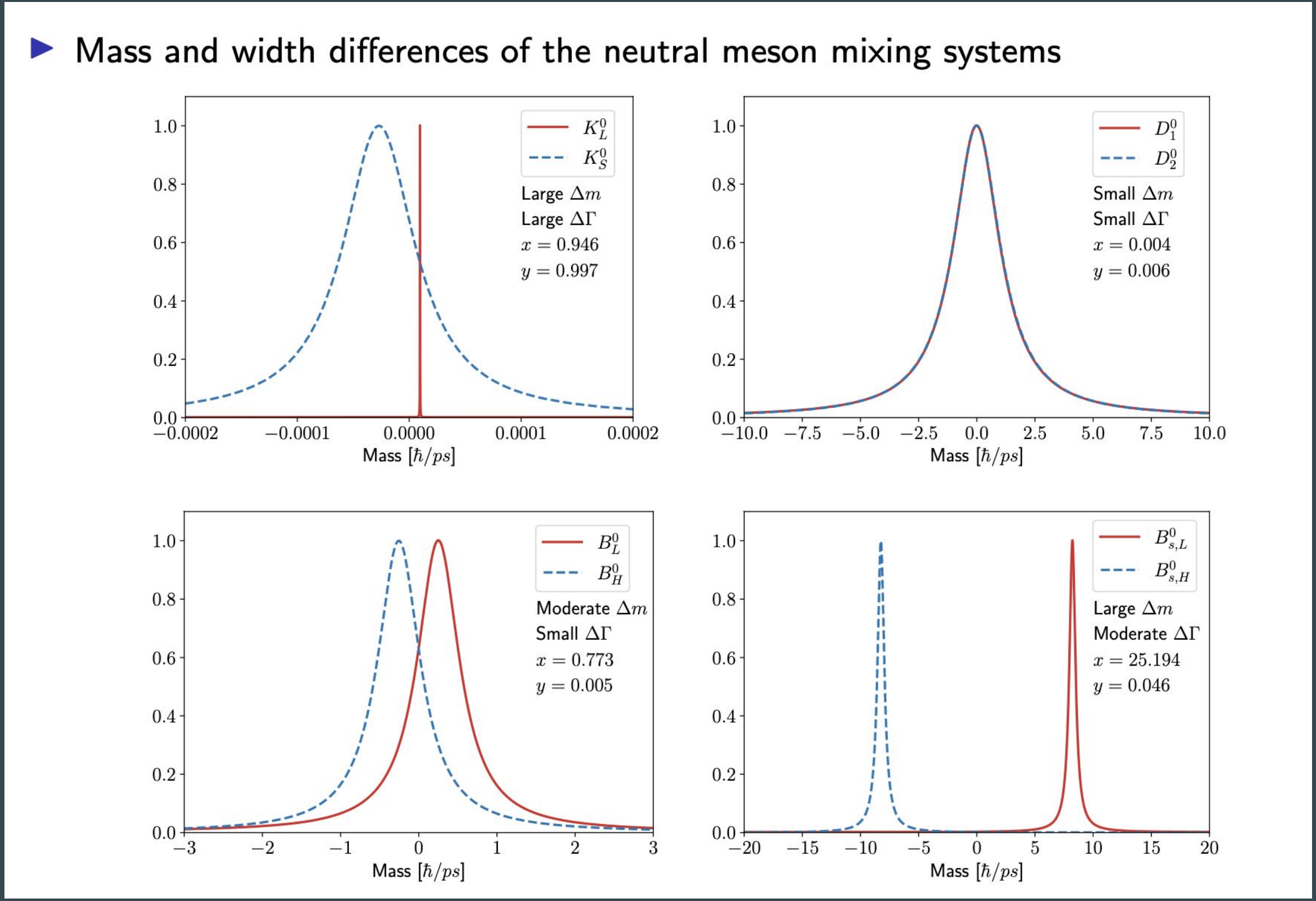
Neutral meson oscillation



- Mass and width differences of the neutral meson mixing systems

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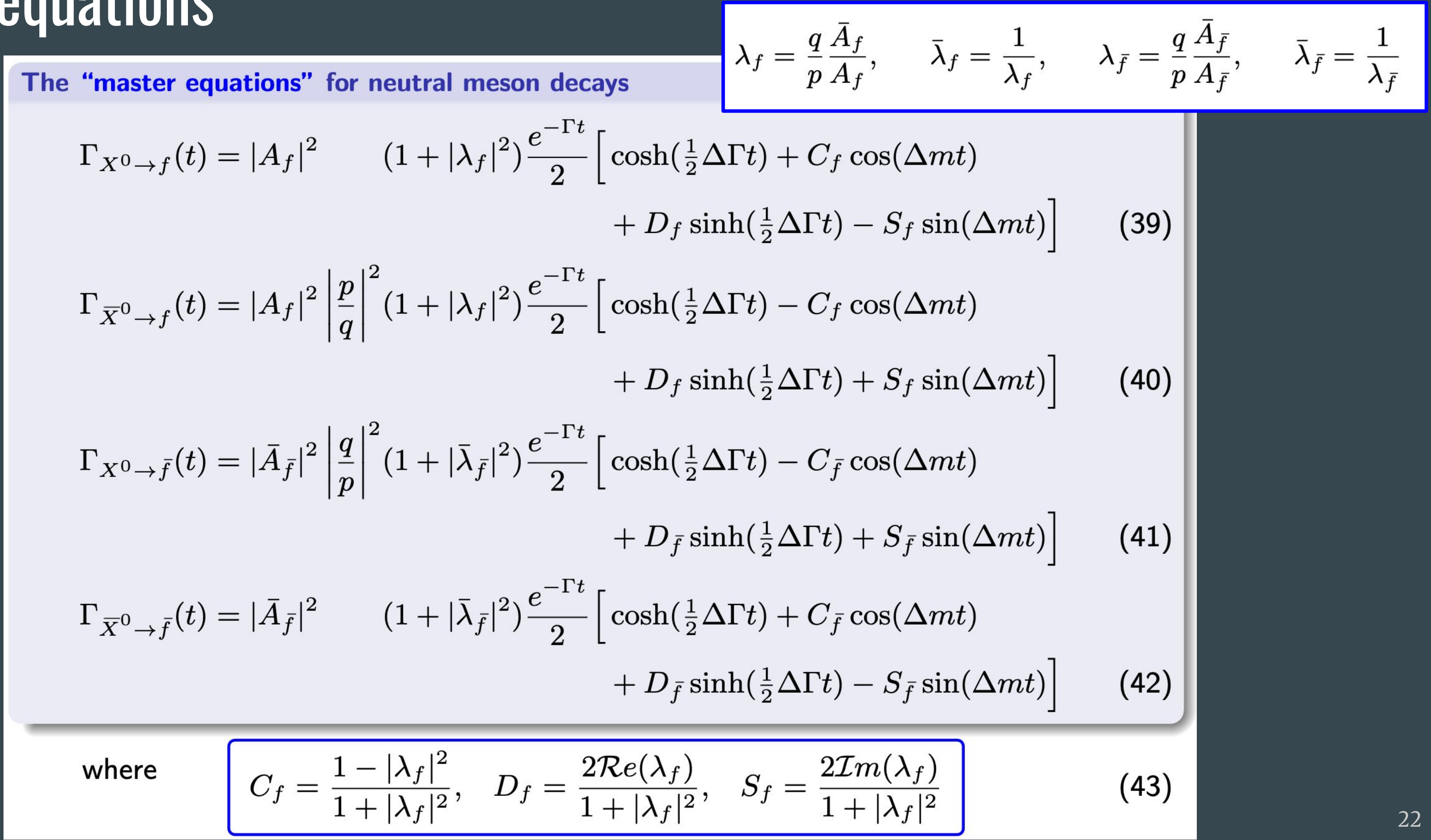
Master equations



$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}, \qquad \bar{\lambda}_f = \frac{1}{\lambda_f}, \qquad \lambda_{\bar{f}} = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}, \qquad \bar{\lambda}_{\bar{f}} = \frac{1}{\lambda_{\bar{f}}}$$

The “master equations” for neutral meson decays

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

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

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

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

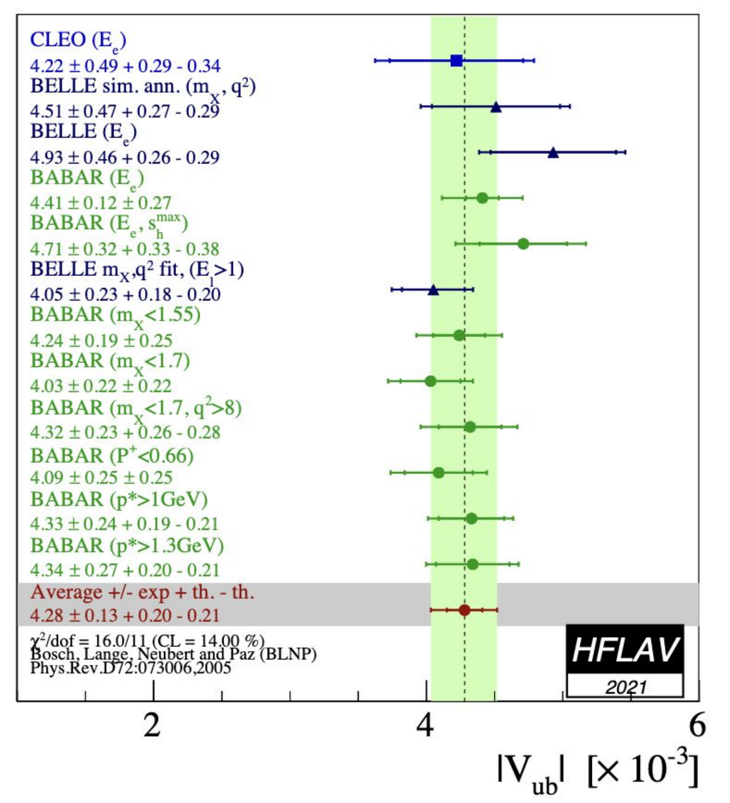
where

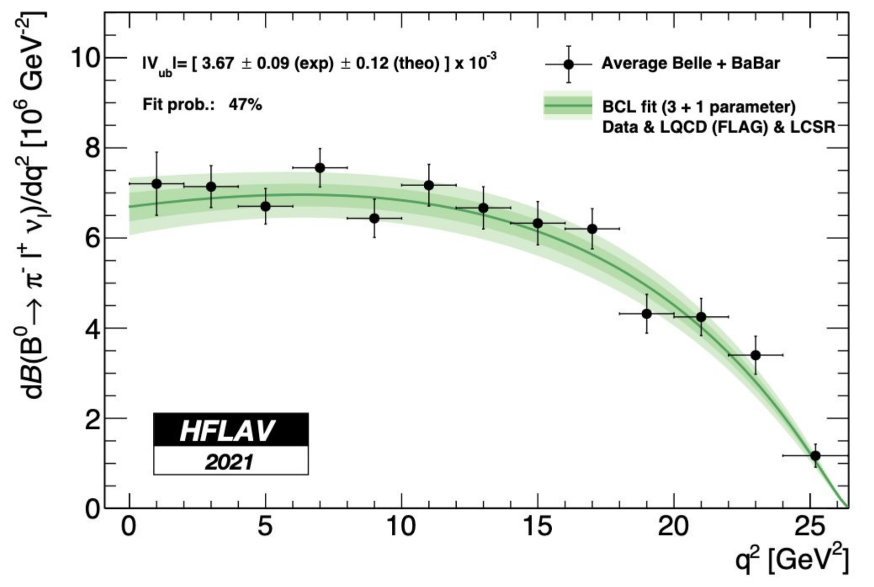
$$\boxed{C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad D_f = \frac{2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2}, \quad S_f = \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}} \quad (43)$$

Stolen from M. Kenzie

Vub measurements

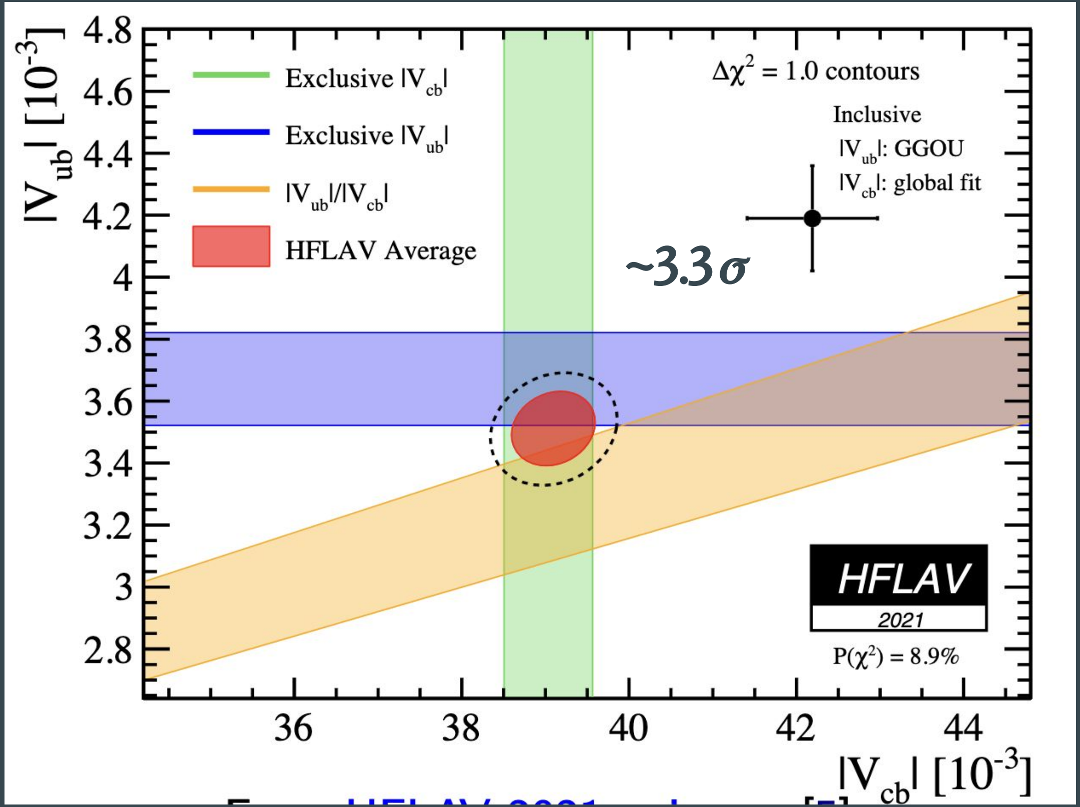
HFLAV





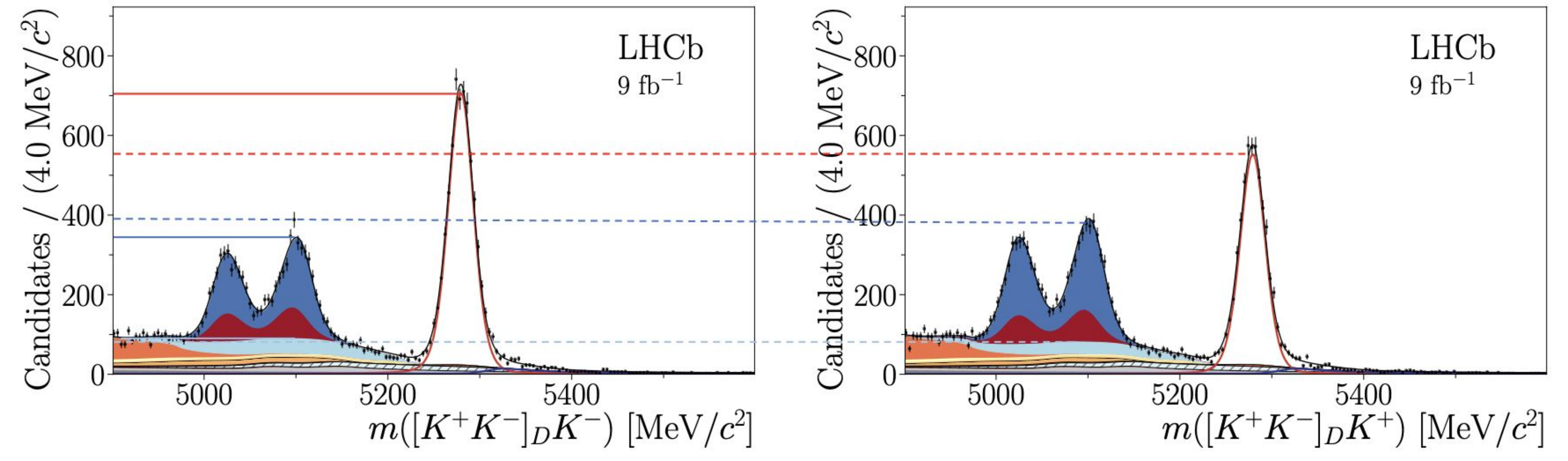
Vub measurements

HFLAV

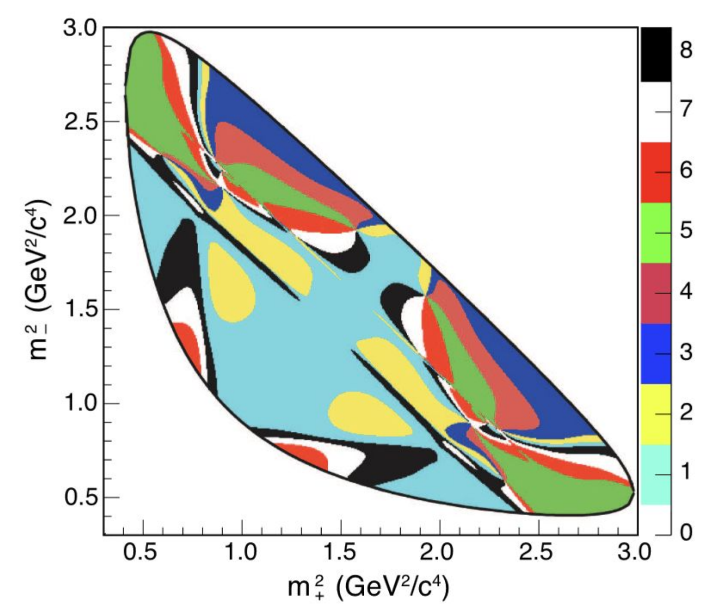


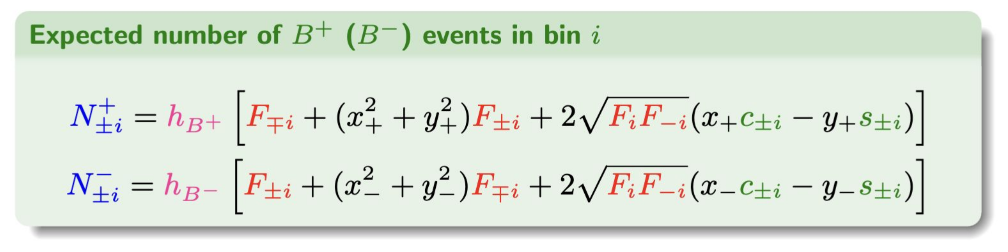
LHCb GLW measurements

arxiv



BPGGSZ method

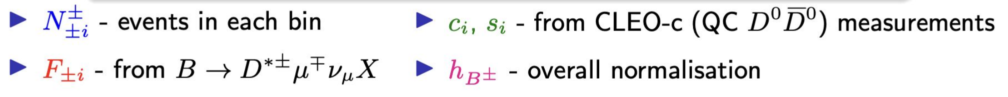




Expected number of B^+ (B^-) events in bin i

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

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

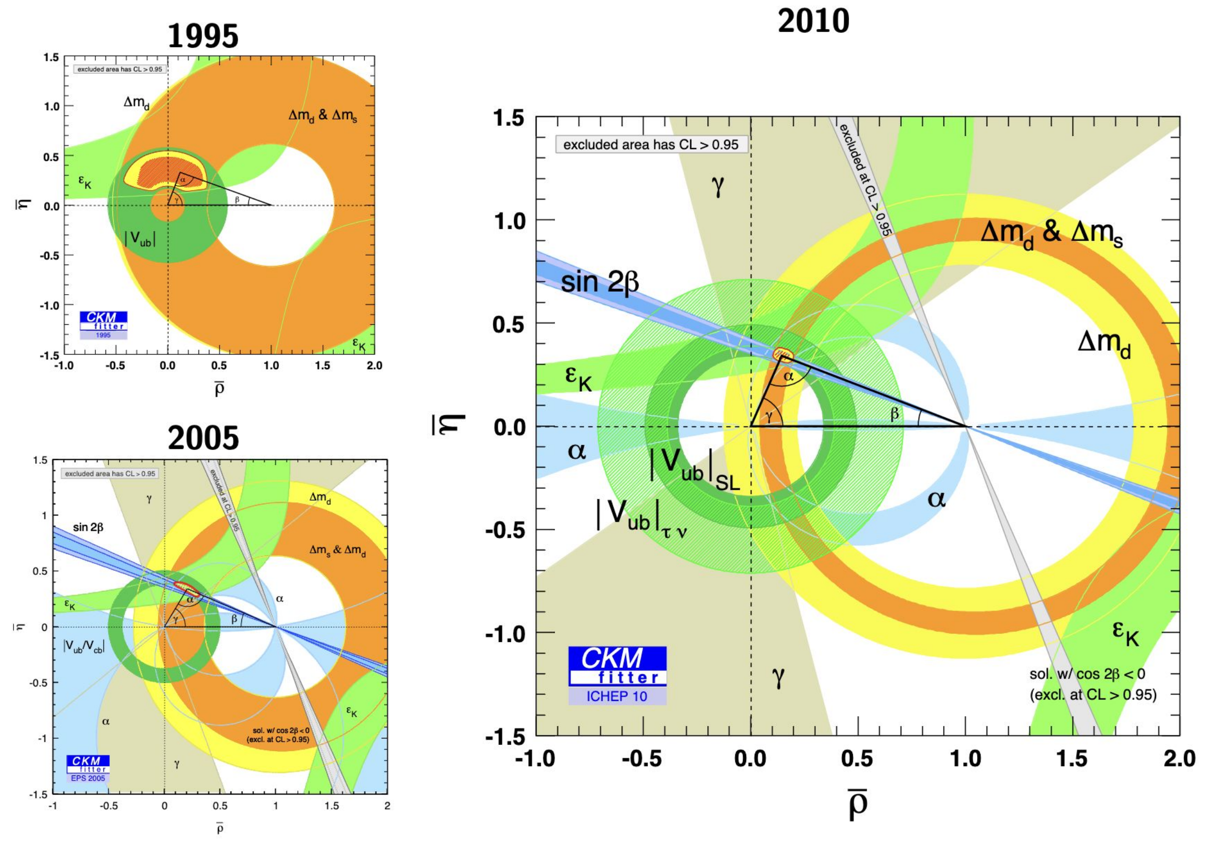


- $N^{\pm}_{\pm i}$ - events in each bin
- $F_{\pm i}$ - from $B \to D^{*\pm}\mu^{\mp}\nu_\mu X$
- c_i, s_i - from CLEO-c (QC $D^0\overline{D}^0$) measurements
- $h_{B\pm}$ - overall normalisation

CKM progress

Before B-factories and LHC

Tevatron and B factories

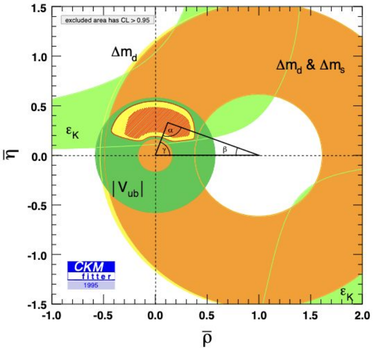


LHC inclusion to 2010

CKM progress

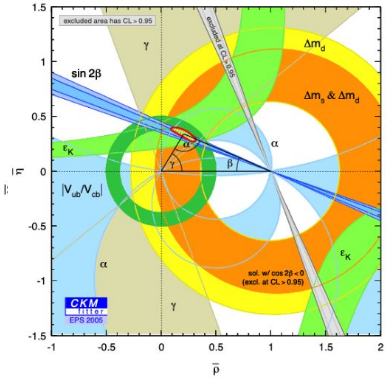
Before B-factories and LHC

1995

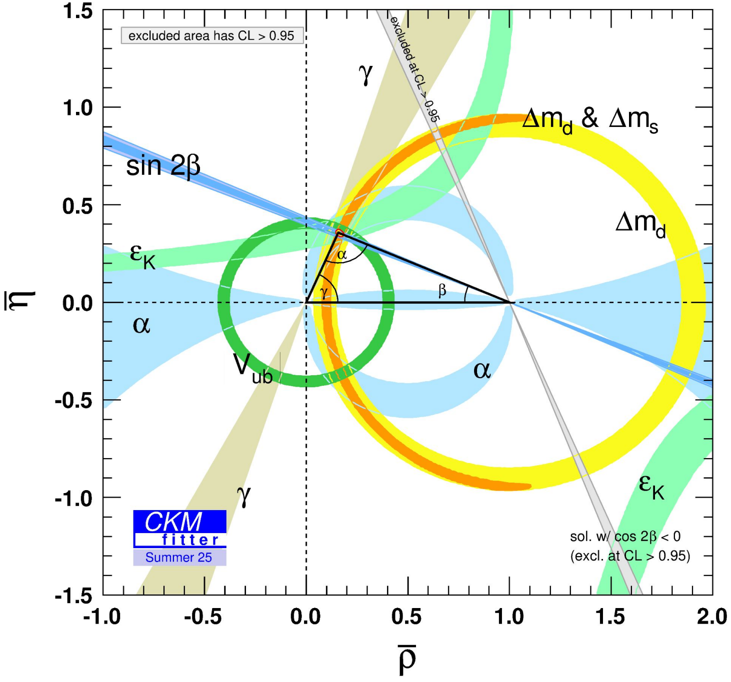


Tevatron and B factories

2005



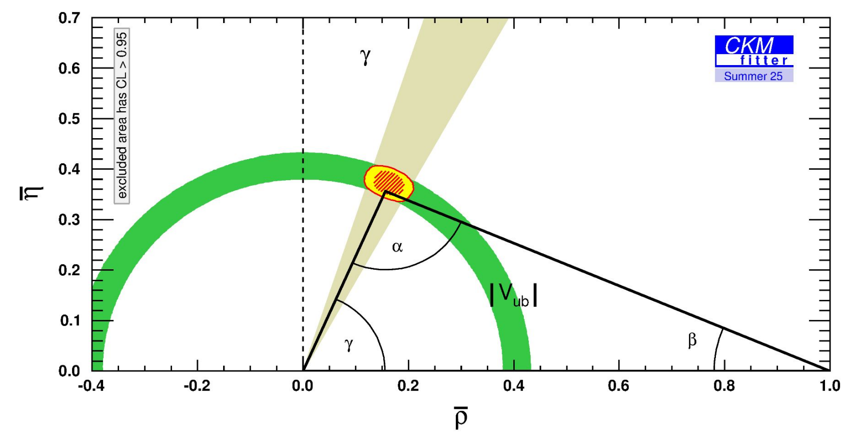
2025

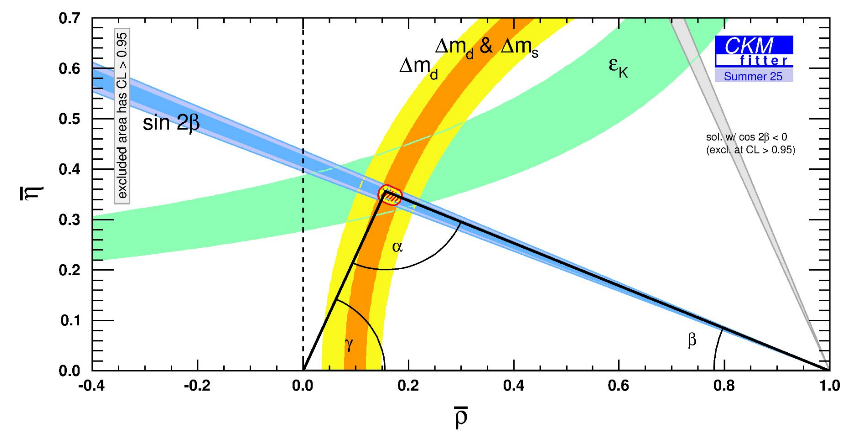


LHC inclusion till now

CKM progress

Comparison between tree-level (**γ**, Vub) and loop-level (α, β, Δm, ε)





Why is this interesting?

EFTs

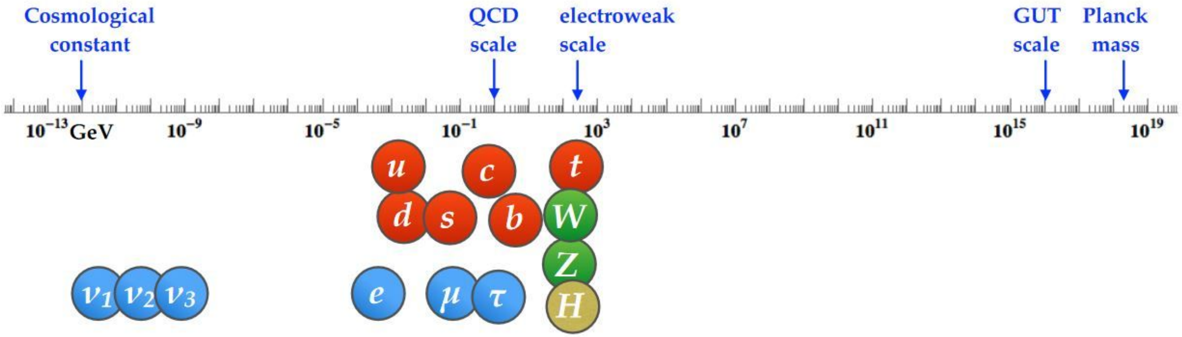
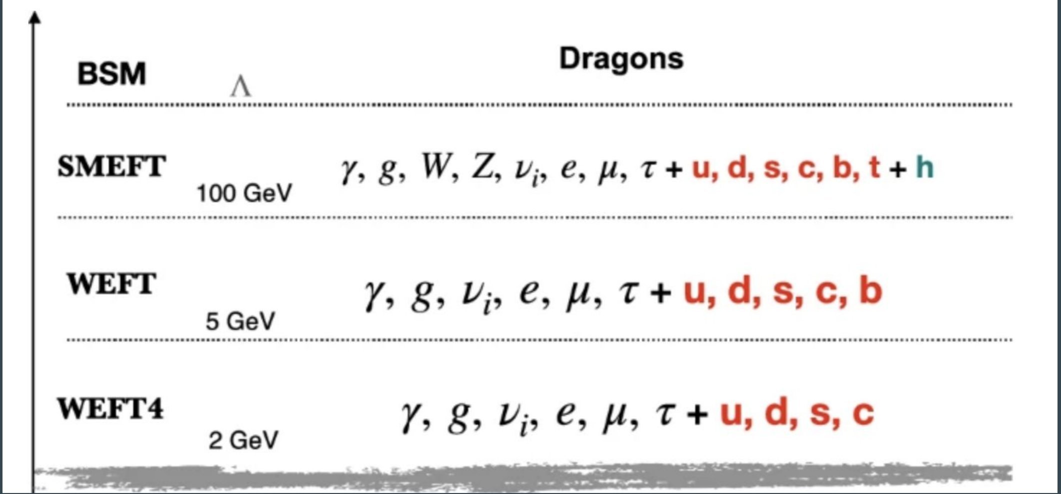
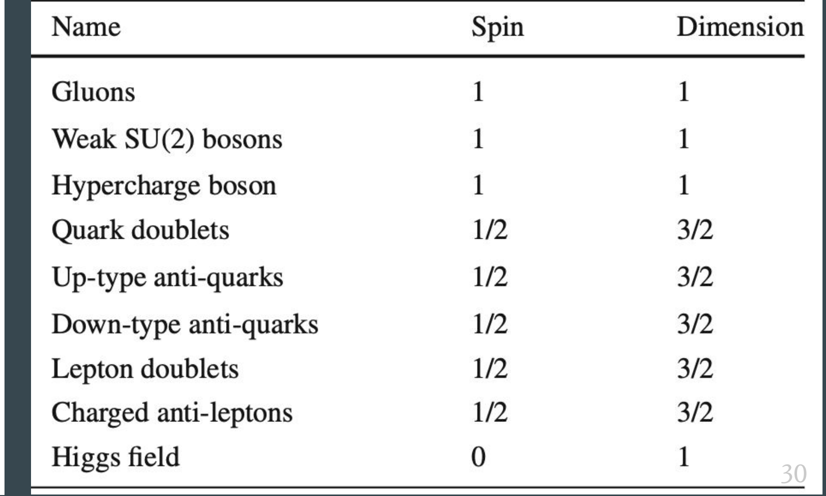


Fig. 1: The distribution of masses of the elementary particles, along with some of the relevant energy scales. The absolute values of neutrino masses are not known - their placement on the graph is indicative of the upper bound.





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

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

Dirac Lagrangian

Dirac Equation

$$\mathcal{L} = \bar{\psi}(i\not\partial - m)\psi$$

$$(i\not\partial - m)\psi = 0$$

Physicist's Notation:

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

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

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

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

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:

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

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

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

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

https://physicstravelguide.com/equations/dirac_equation#tab__concrete

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/eftlectures.pdf