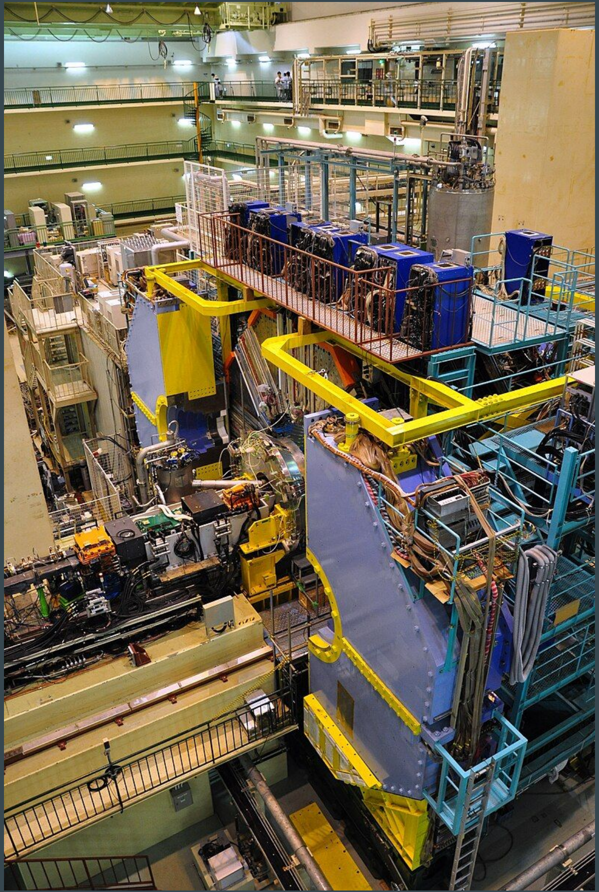
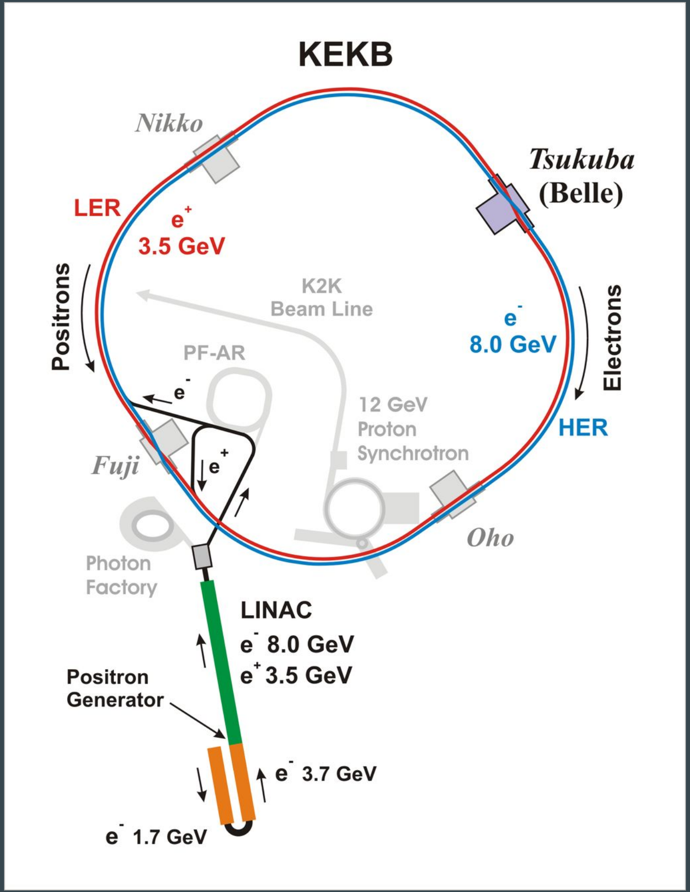
Flavour lectures

Accompanying slides

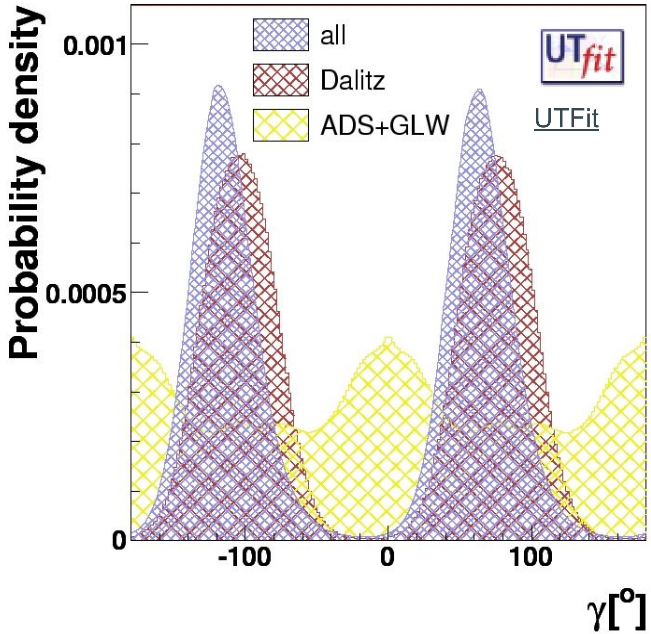
Flavour physics experiments - Belle





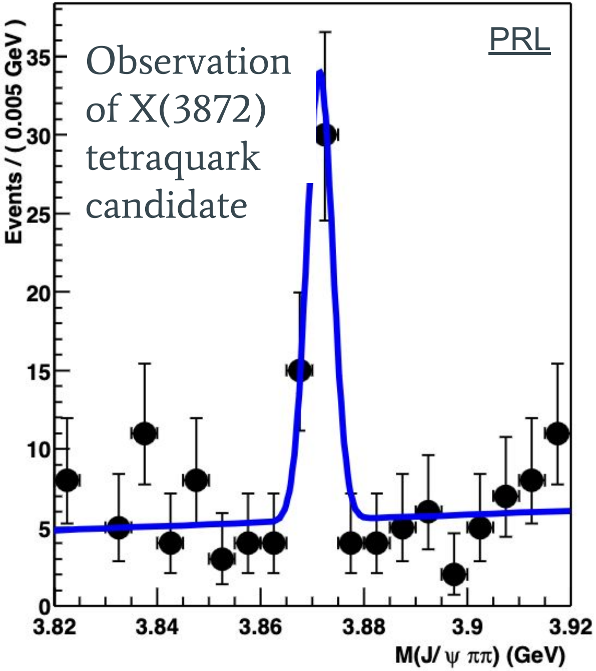
Flavour physics experiments - Belle

Determination of gamma from Belle only

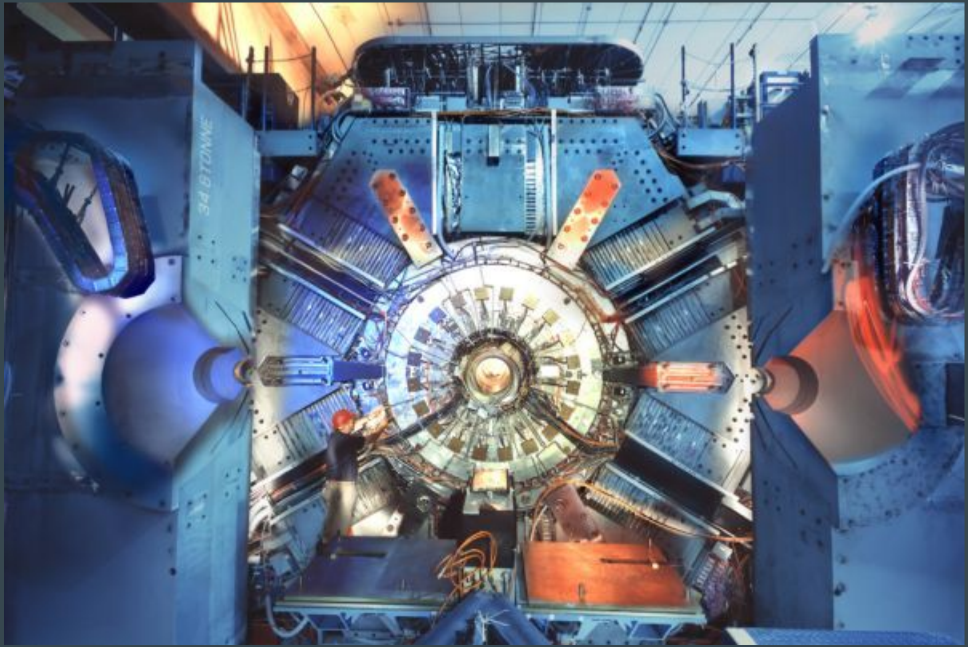


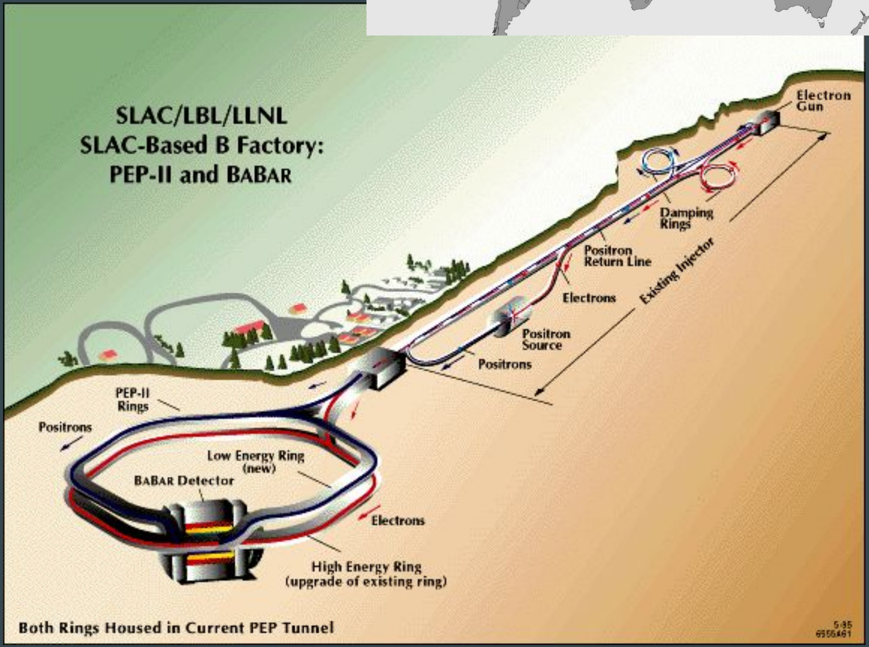
Observation of X(3872) tetraquark candidate

PRL

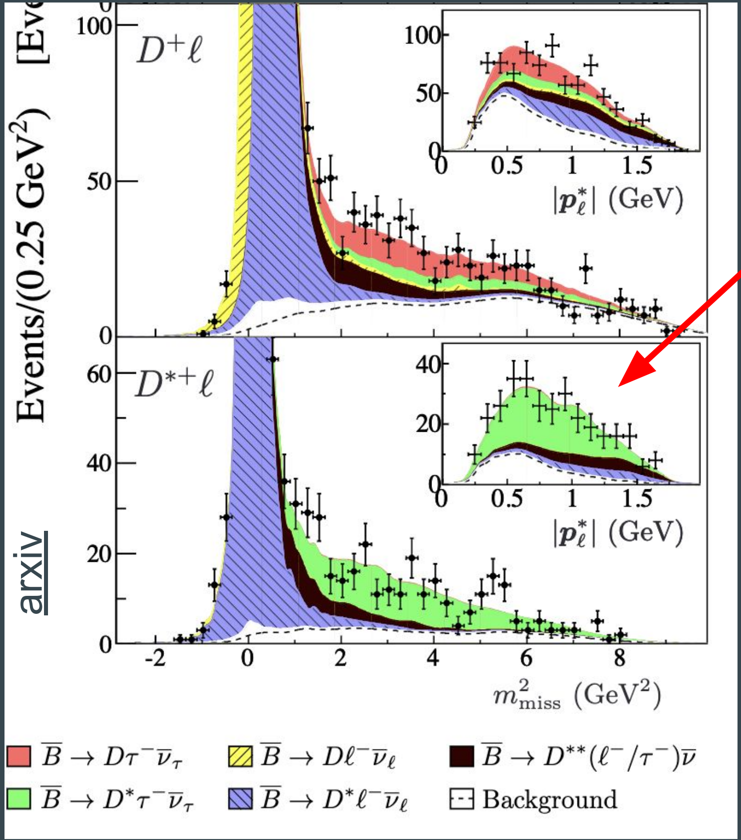


Flavour physics experiments - BaBar

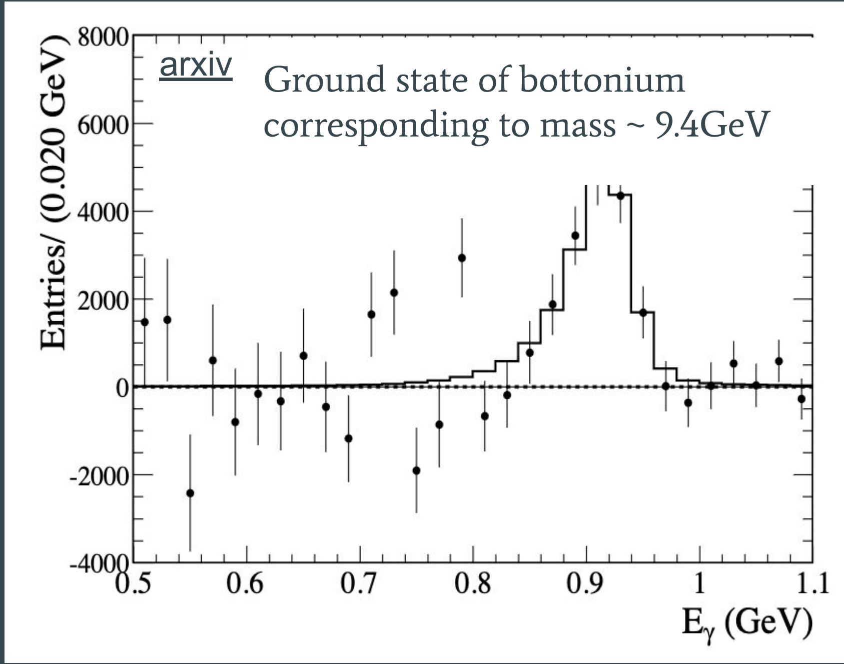




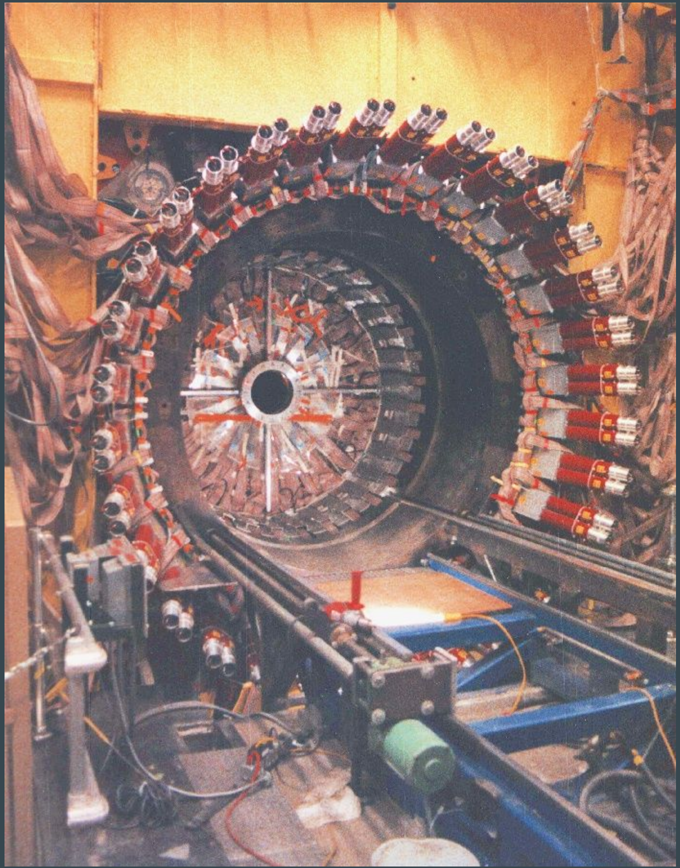
Flavour physics experiments - BaBar

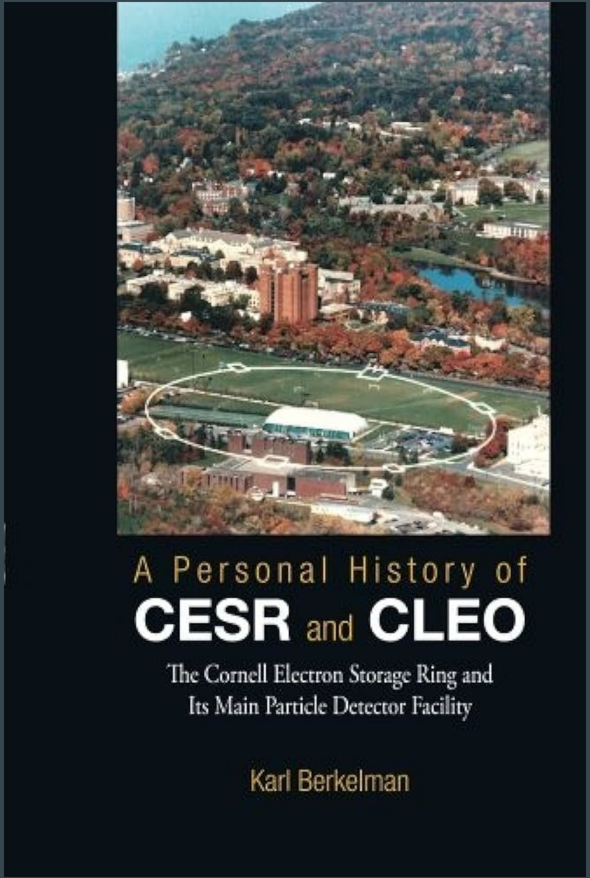


Excess of tauonic SL B decays over e/mu, $R(D^{(*)})$

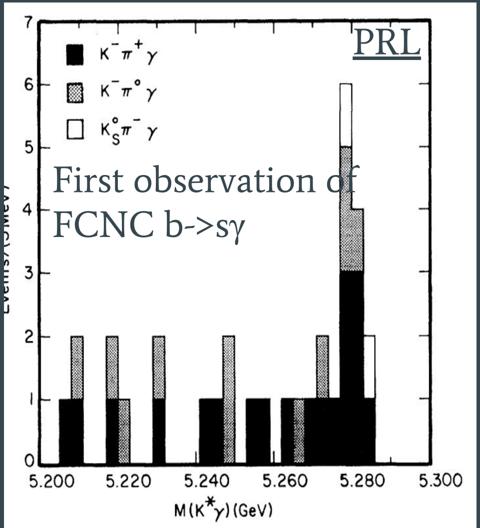


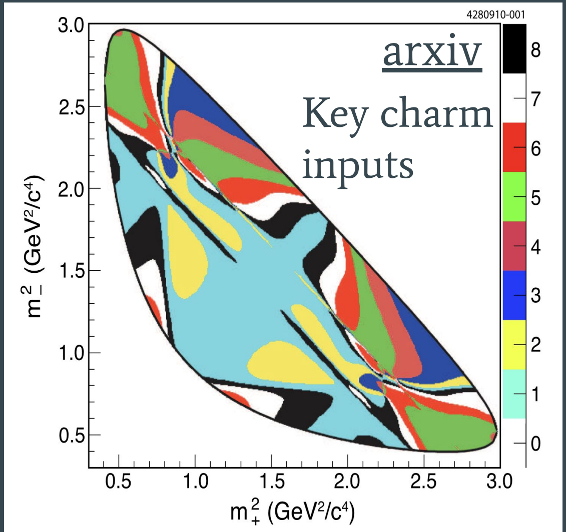
Flavour physics experiments - CLEO(-c)

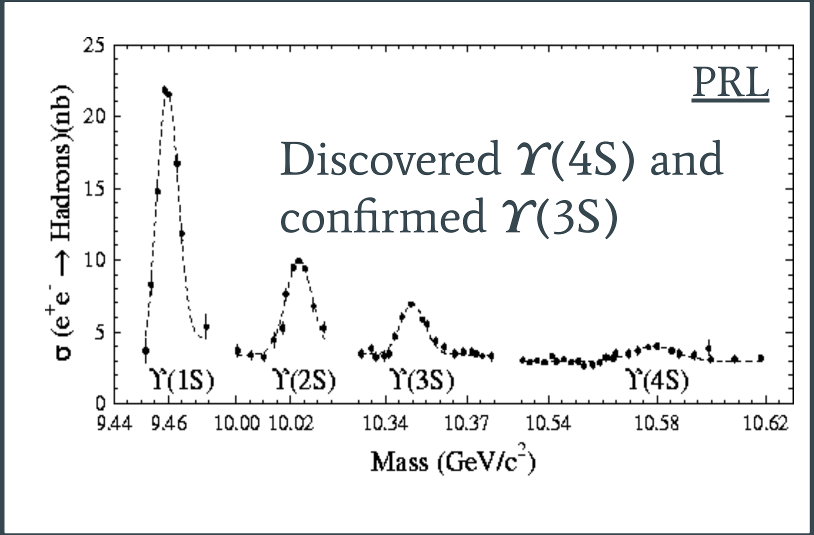




Flavour physics experiments - CLEO(-c)

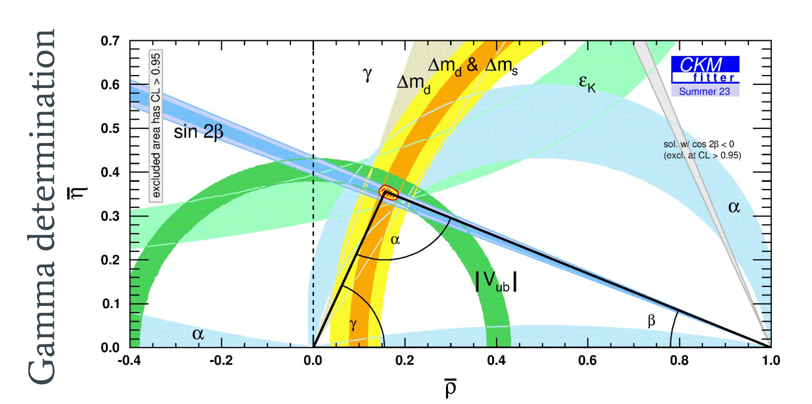


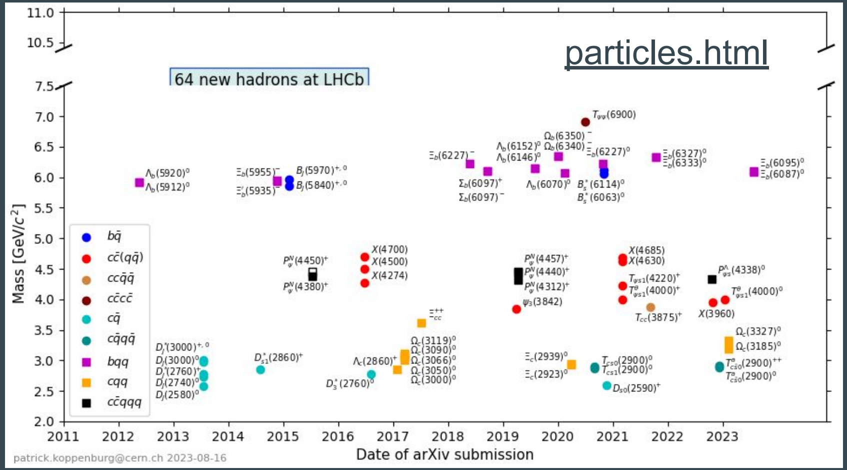


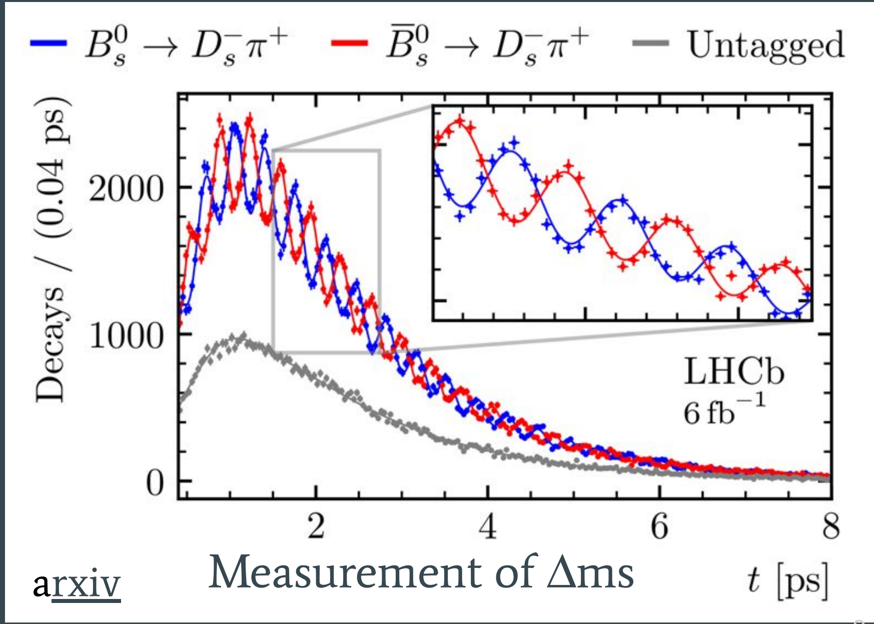


Flavour physics experiments - LHCb

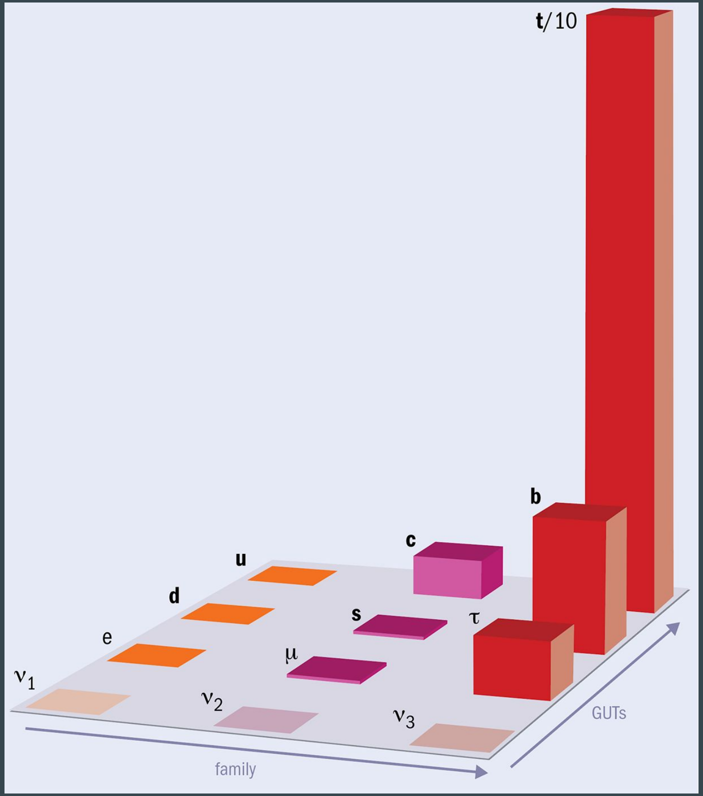
Flavour physics experiments - LHCb



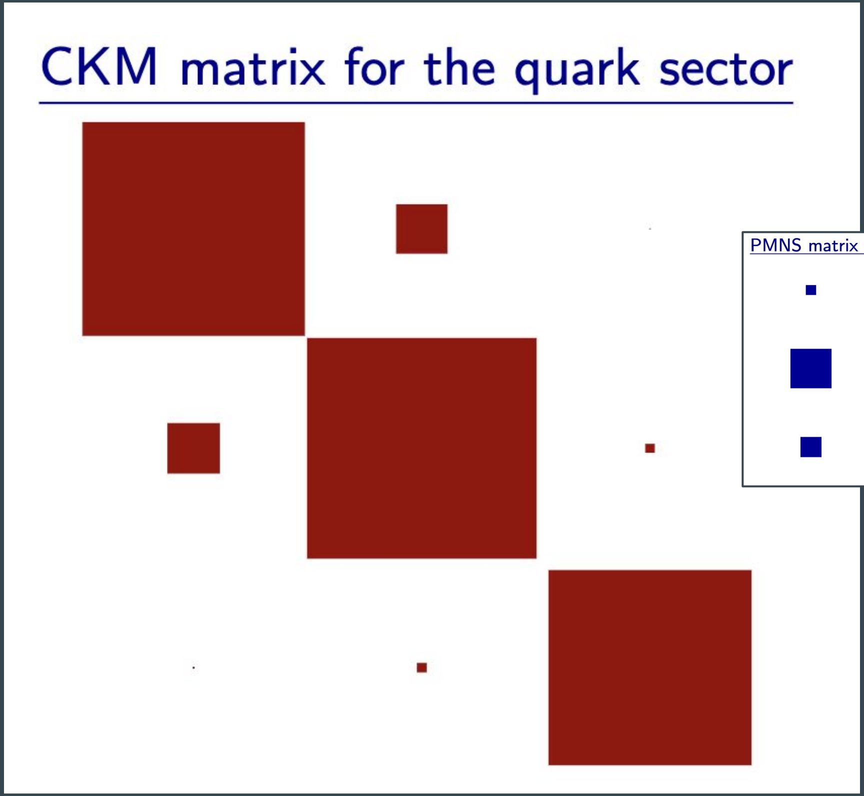


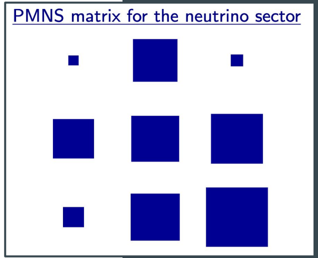


SM puzzles

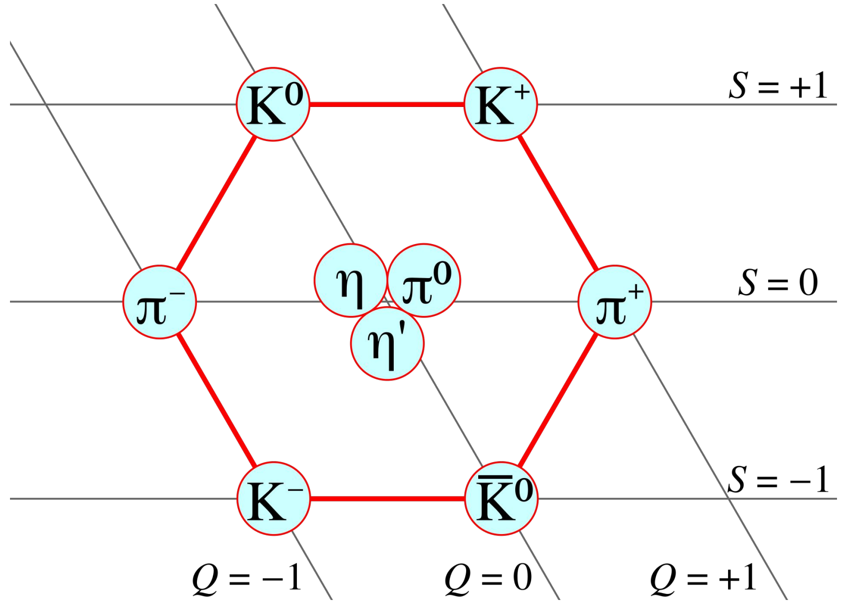


Quark and lepton masses span 12 orders of magnitude

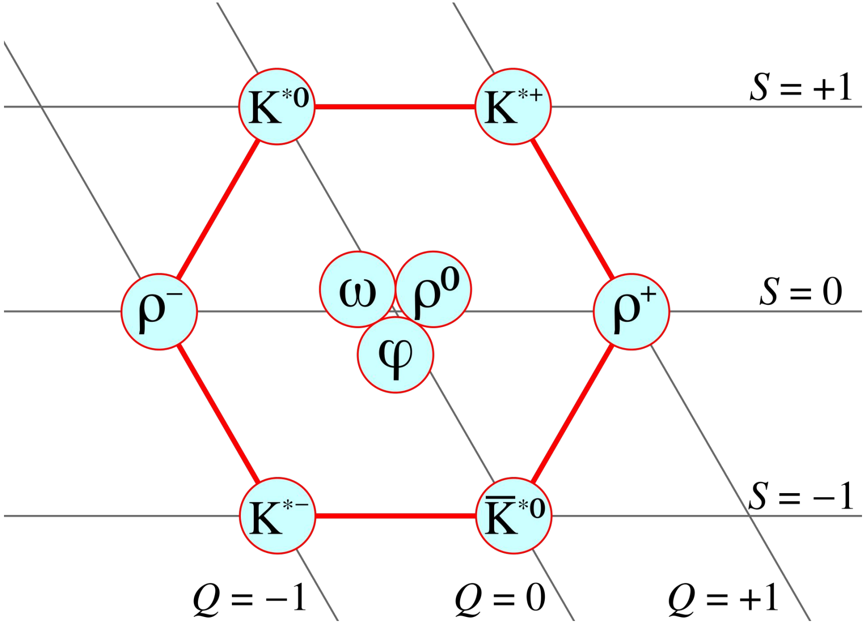




Flavour multiplets

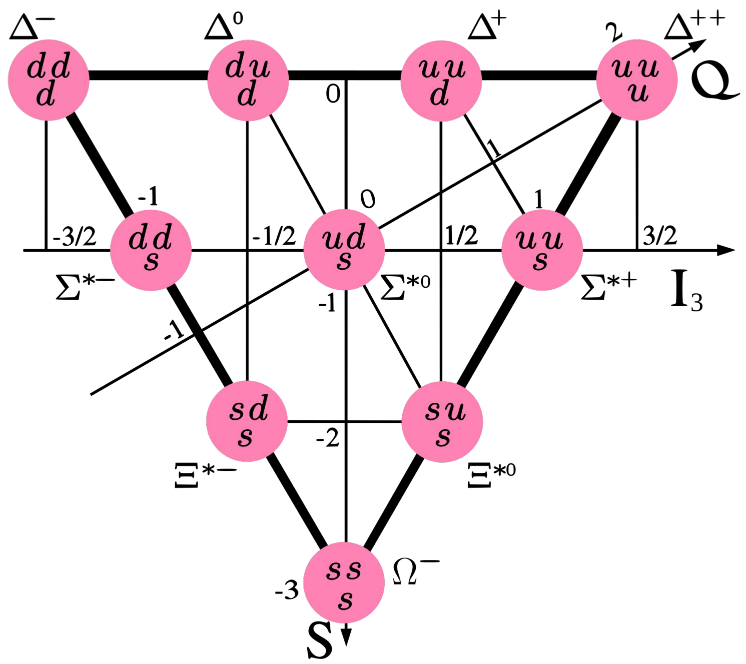


Pseudoscalar mesons of spin-0 form a nonet

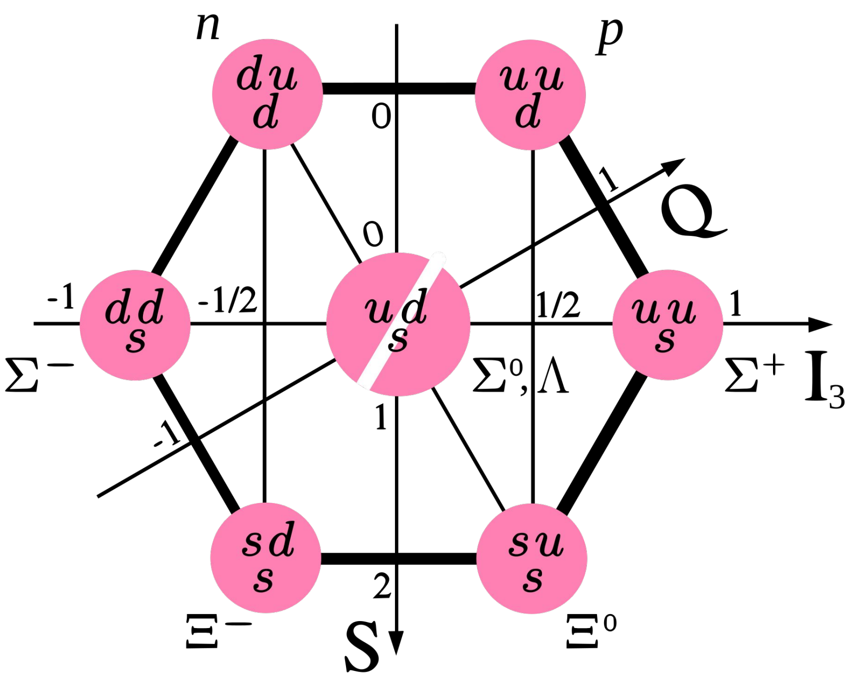


Mesons of spin-1 form a nonet

Flavour multiplets



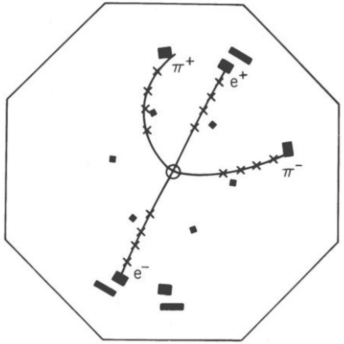
Combinations of three **u, d** or **s** quarks with a spin-3/2 form the *uds baryon decuplet*



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 $p\mathrm{Be} \rightarrow \mathrm{e}^+\mathrm{e}^-\mathrm{X}$
- Discovery of charmonium (ψ) at SLAC in $e^+e^- \rightarrow (\mathrm{hadrons}), \mathrm{e}^+\mathrm{e}^-, \mu^+\mu^-$



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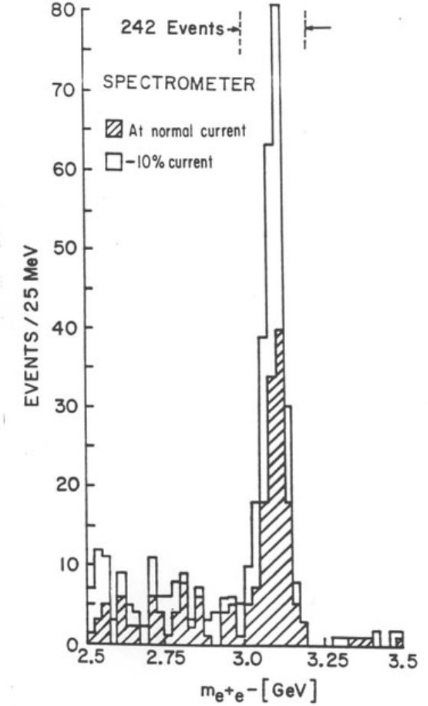
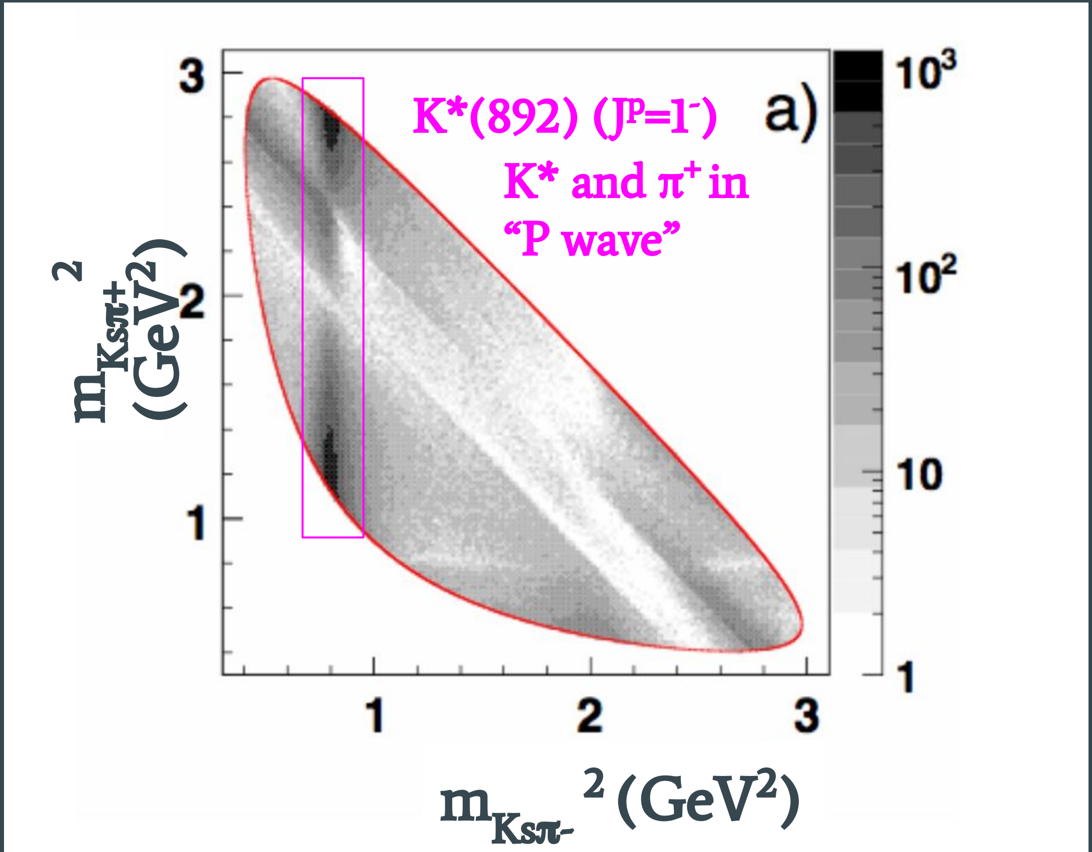


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

Stolen from M. Kenzie

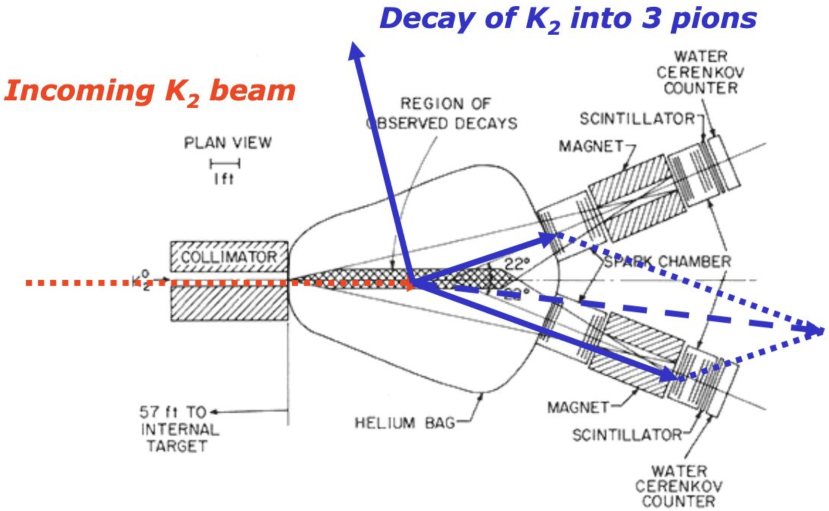
Dalitz plots



Cronin and Fitch experiment - CPV in Kaons

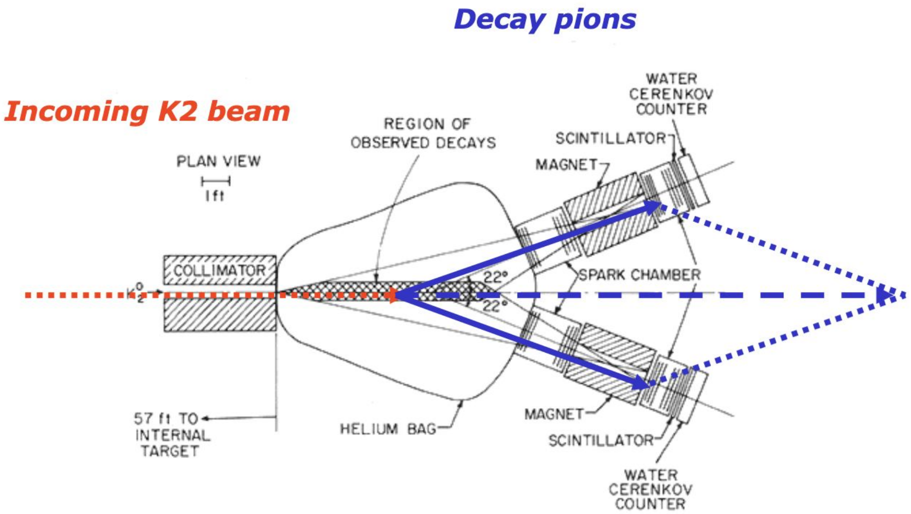
$K_2 = K_L$

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)

Stolen from N. Tuning

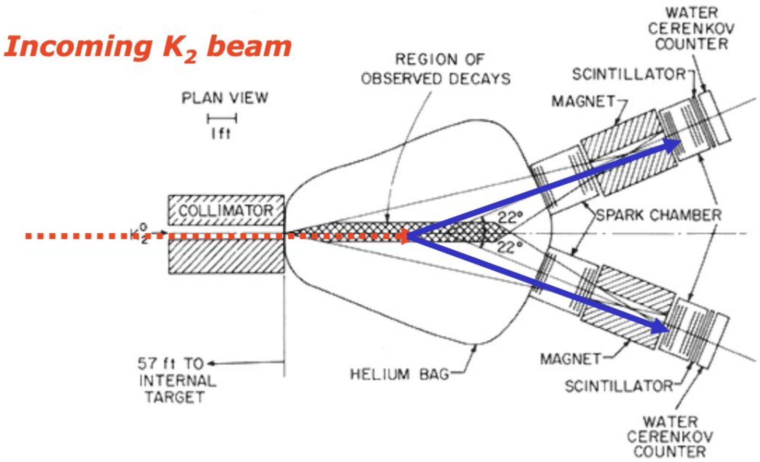
Cronin and Fitch experiment - CPV in Kaons

$K_2 = K_L$

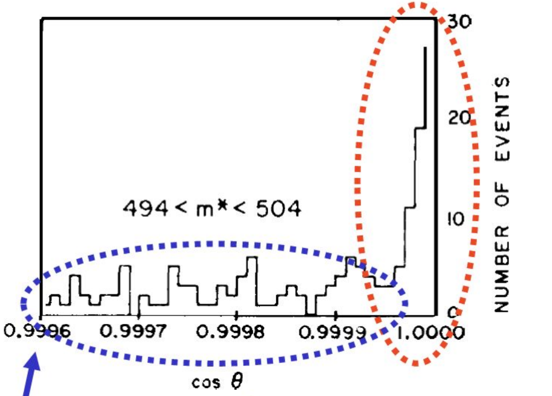
Essential idea: Look for $K_2 \rightarrow \pi\pi$ decays
20 meters away from K^0 production point

Decay pions

Incoming K_2 beam



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



$K_2 \rightarrow \pi\pi\pi$ decays

Result: an excess of events at Θ=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

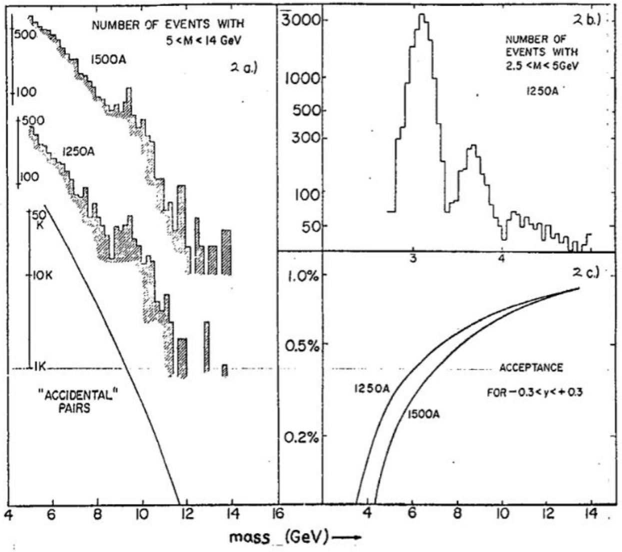
Niels Tuning (26)

Stolen from N. Tuning

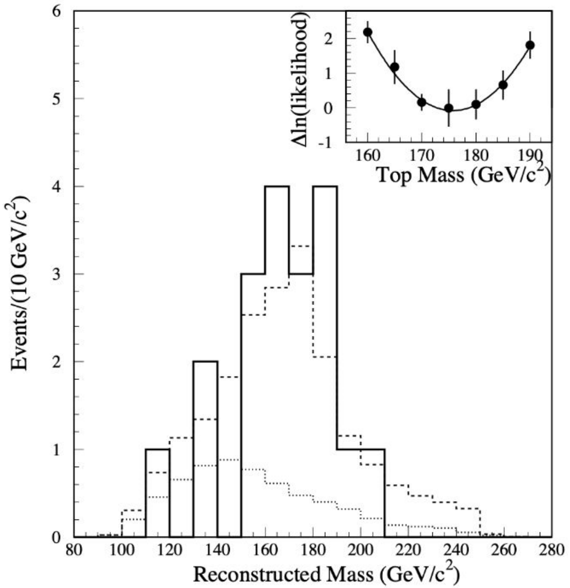
Beauty and Top observation

- 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



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CKM higher orders

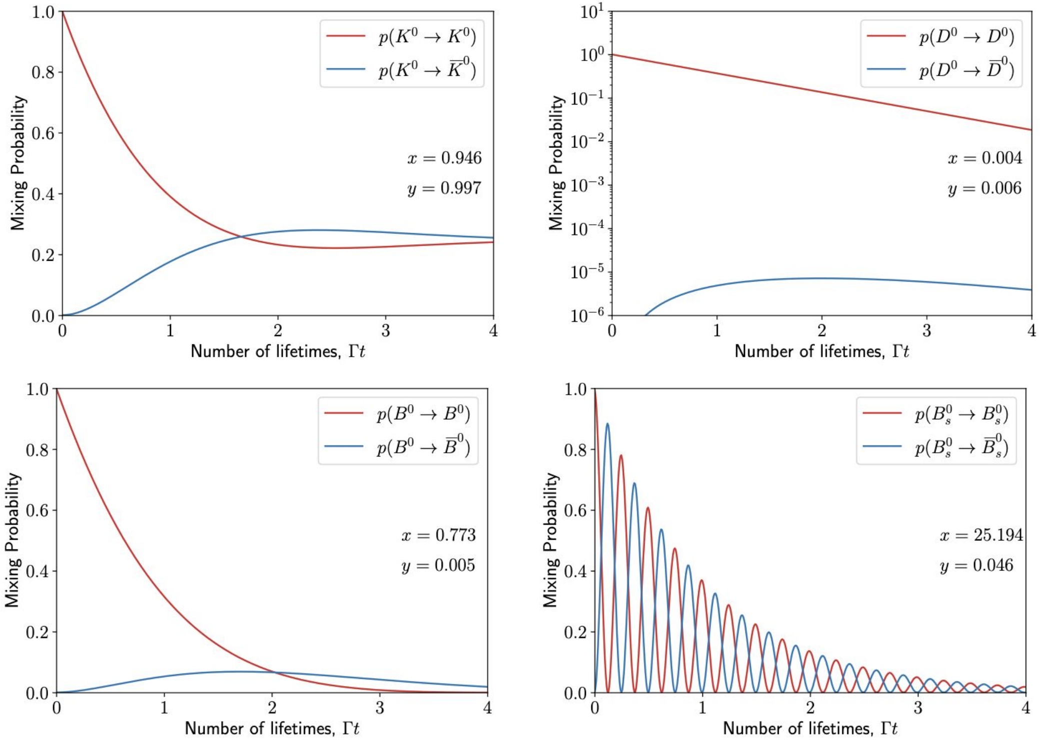
$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

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

- 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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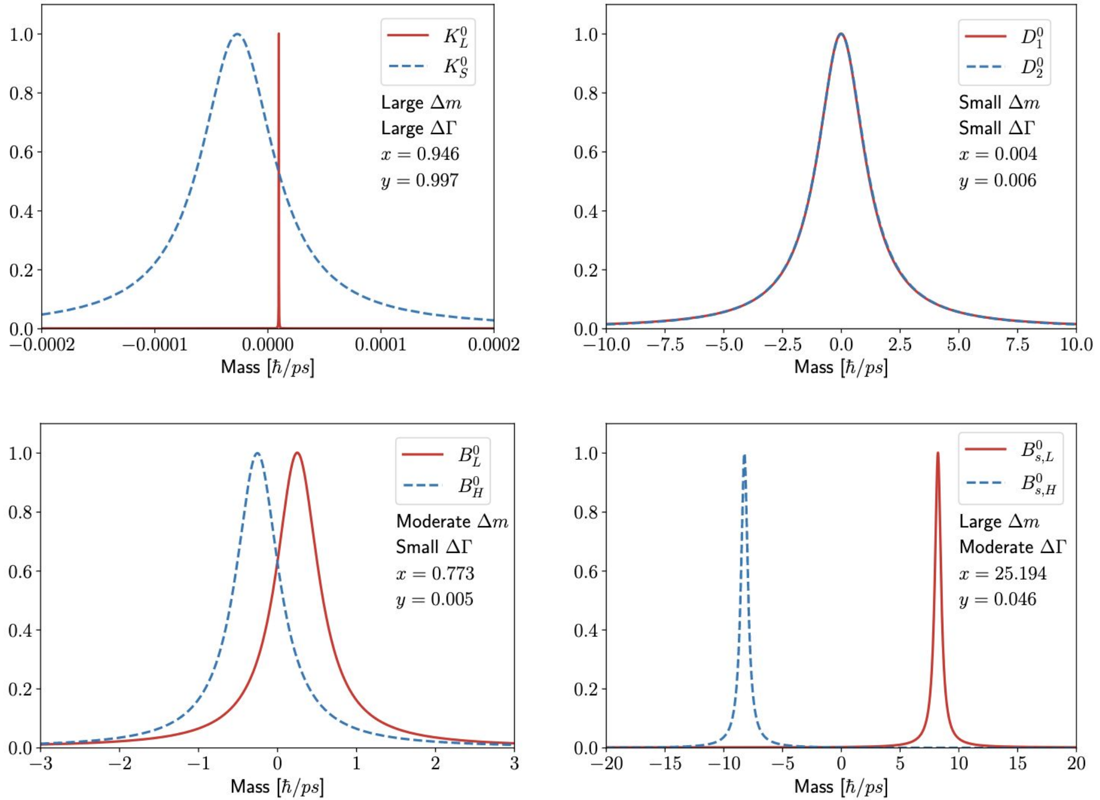
Neutral meson oscillation

- Mass and width differences of the neutral meson mixing systems



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Master equations

The "master equations" for neutral meson decays

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

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

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

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

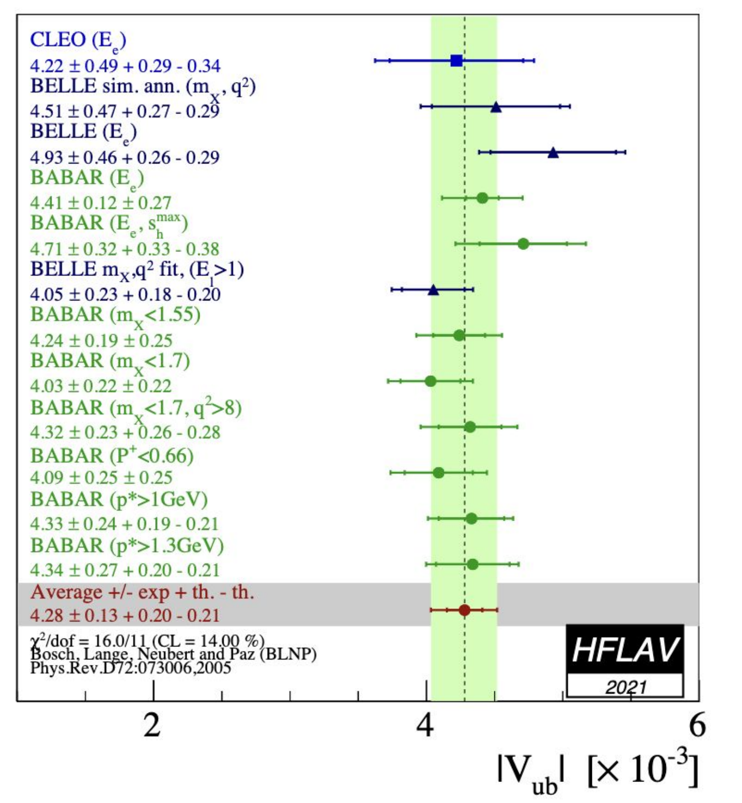
where

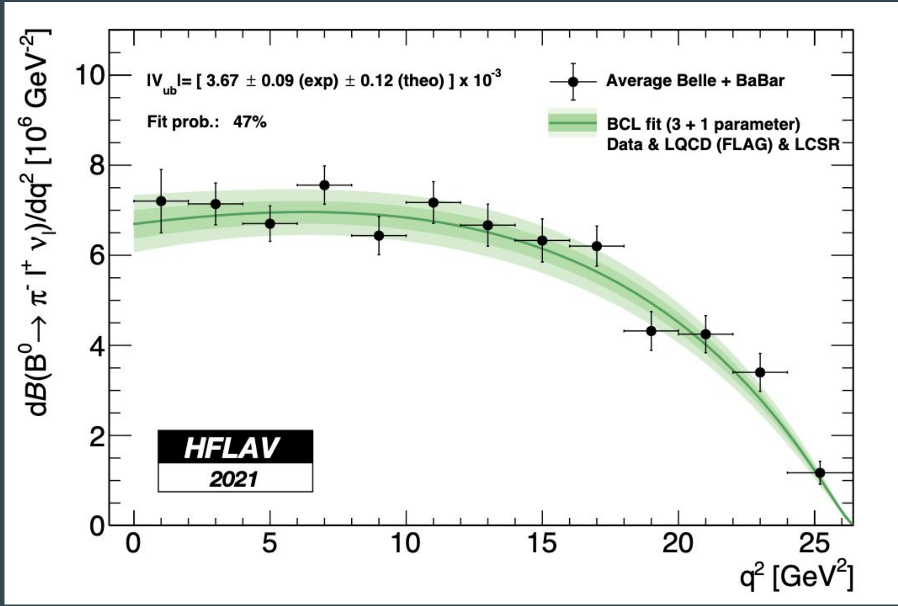
$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad D_f = \frac{2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2}, \quad S_f = \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2} \quad (43)$$

Stolen from M. Kenzie

Vub measurements

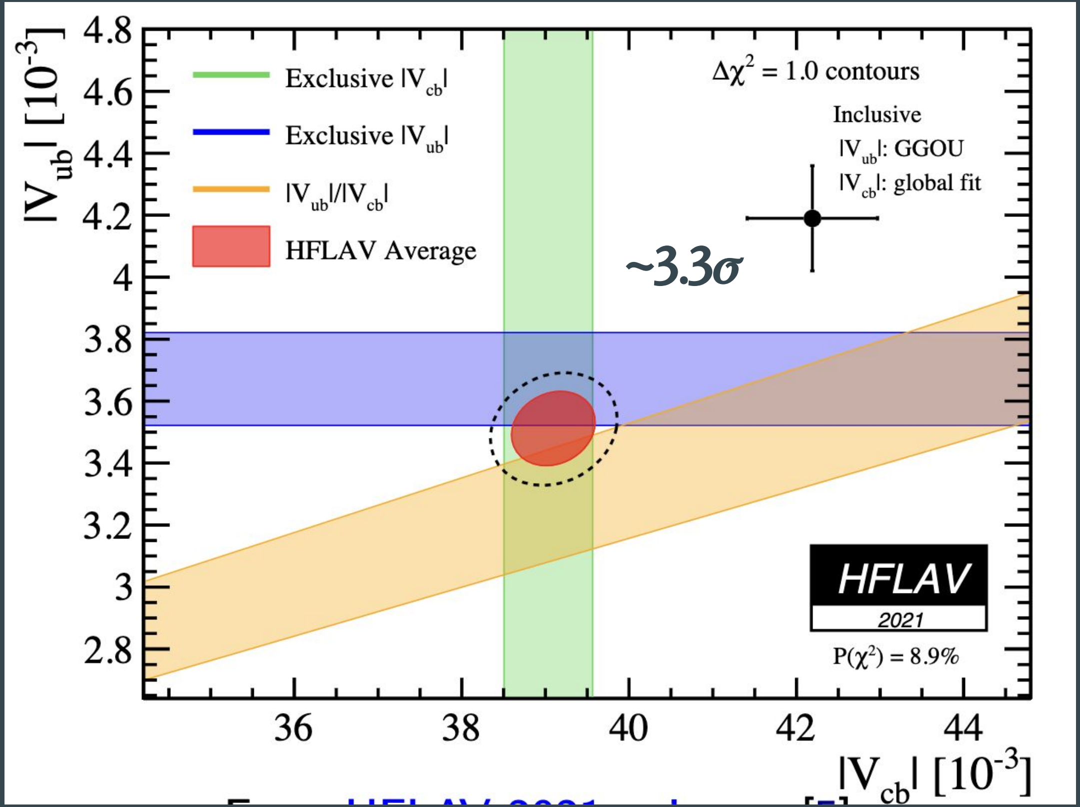
HFLAV





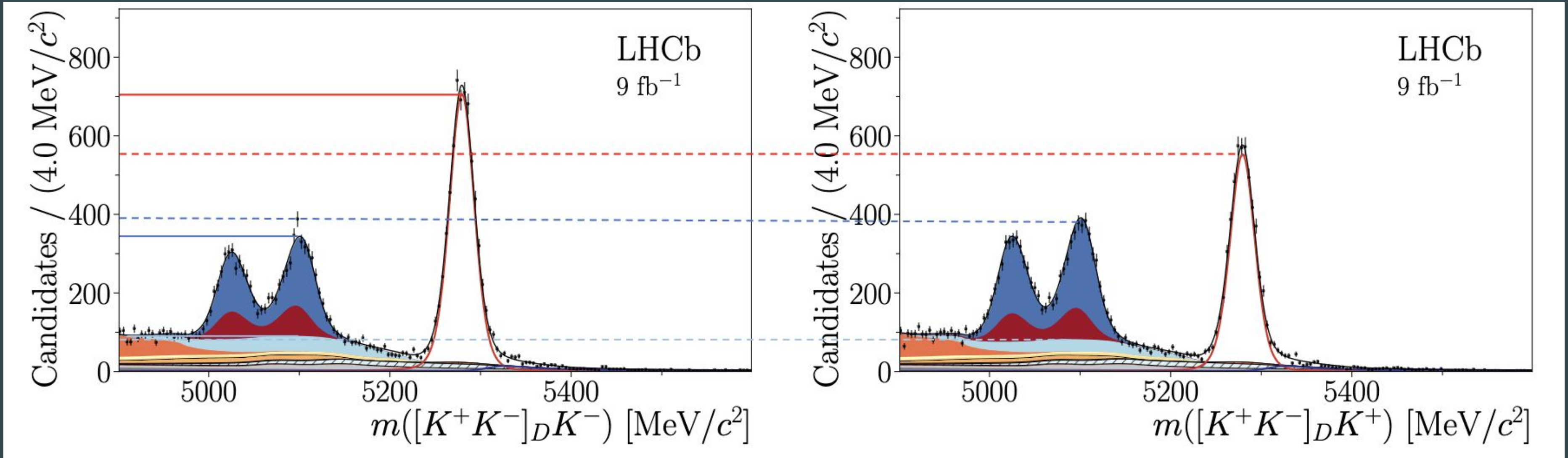
Vub measurements

HFLAV

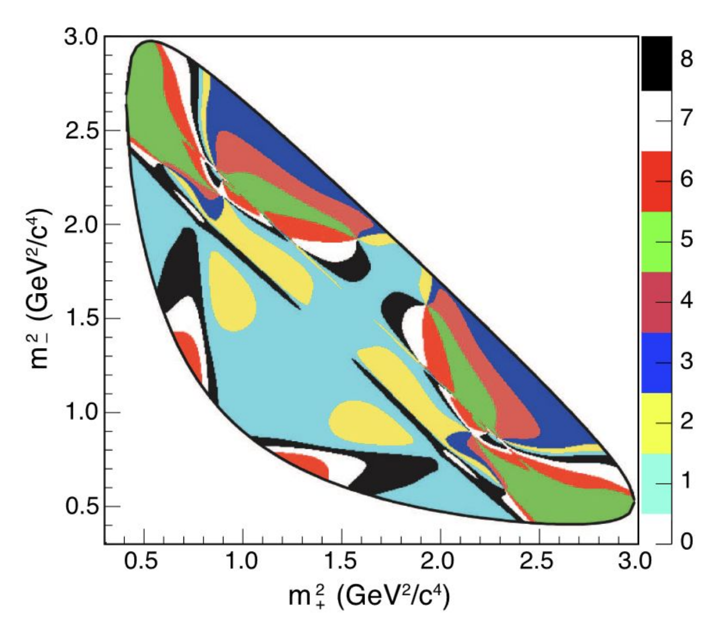


LHCb GLW measurements

arxiv



BPGGSZ method



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

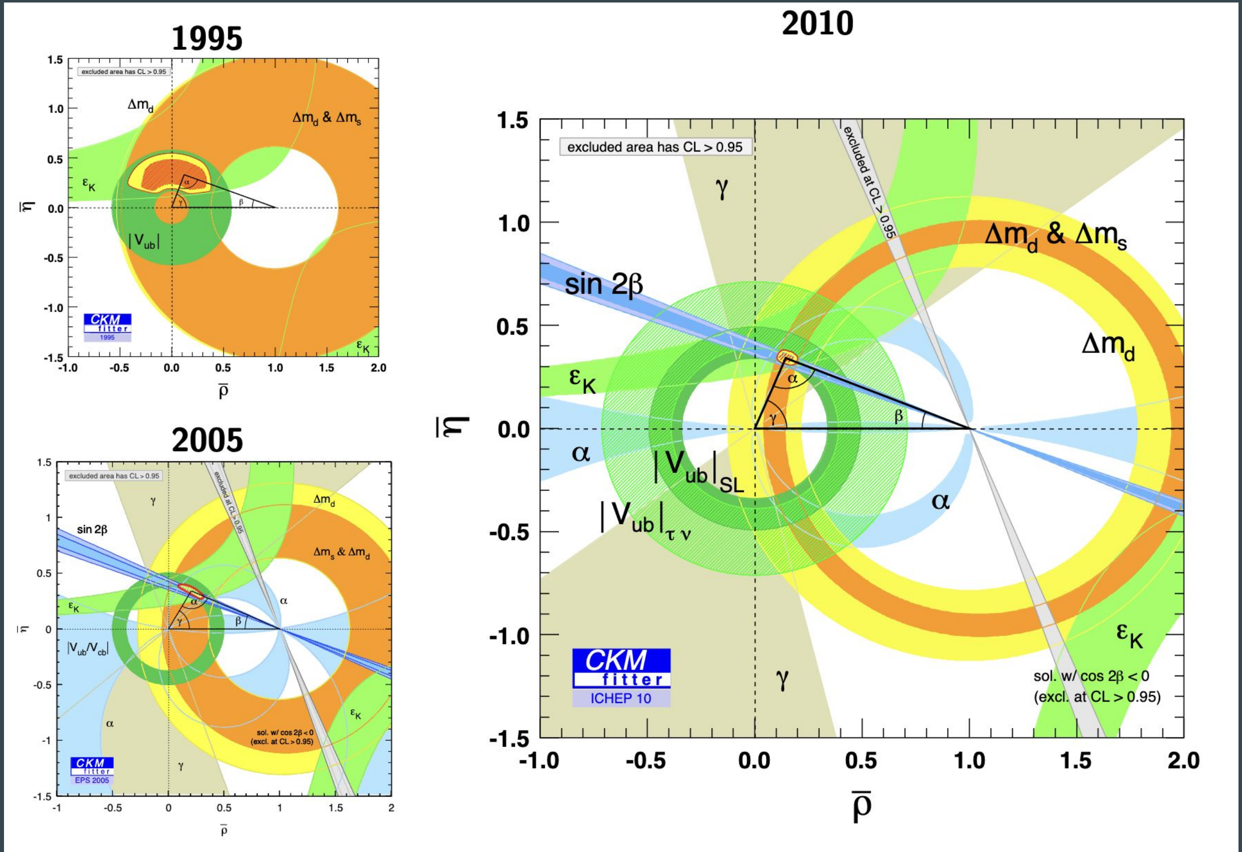
$$N^+_{\pm i} = h_{B+}\left[F_{\mp i} + (x^2_+ + y^2_+)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$

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

CKM progress

Before B-factories and LHC

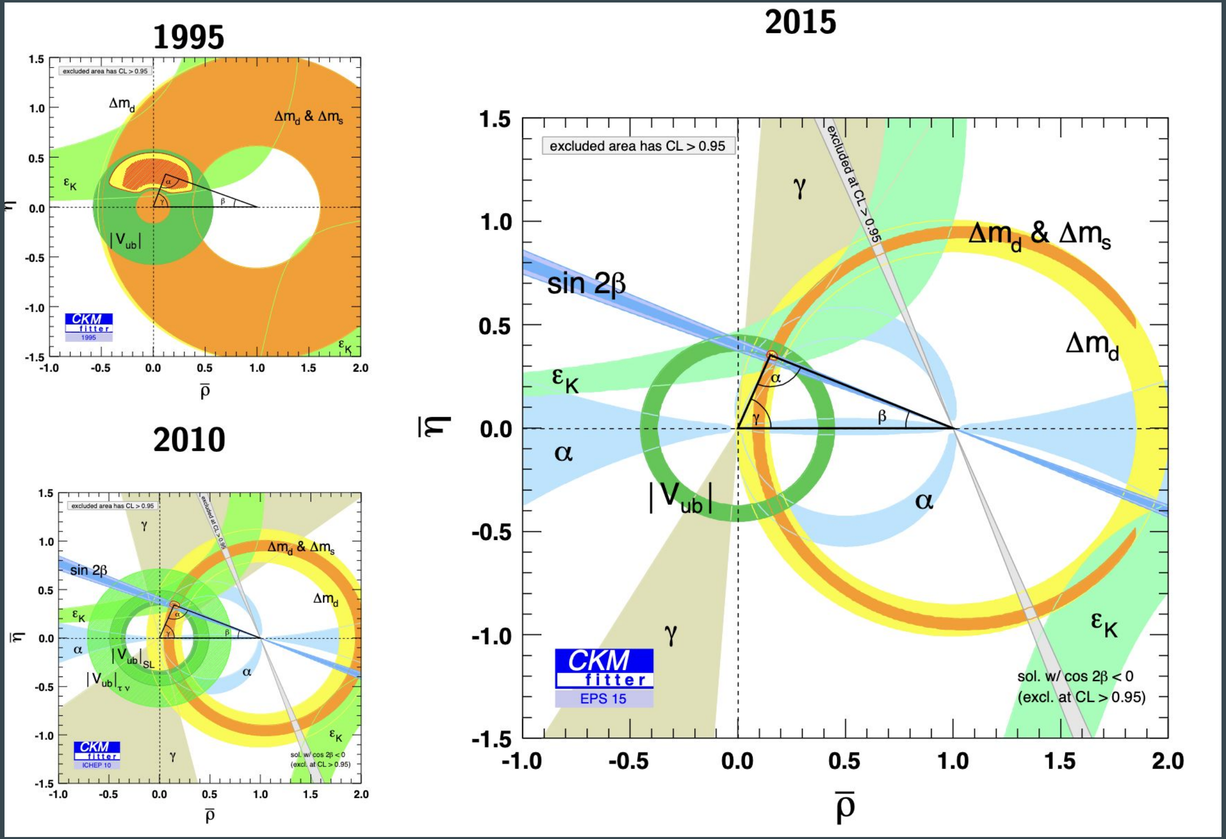
Tevatron and B factories



LHC inclusion

CKM progress

Before B-factories and LHC



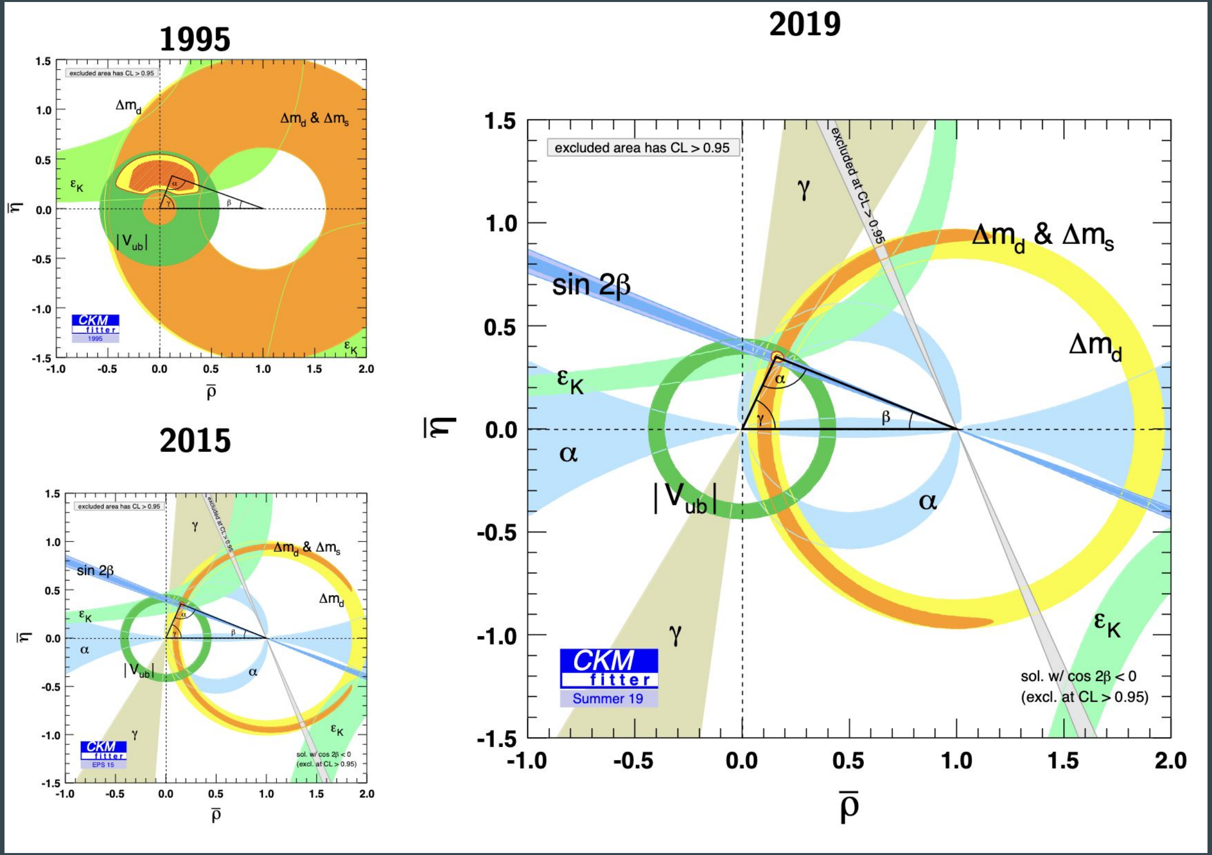
LHC inclusion

LHC inclusion

CKM progress

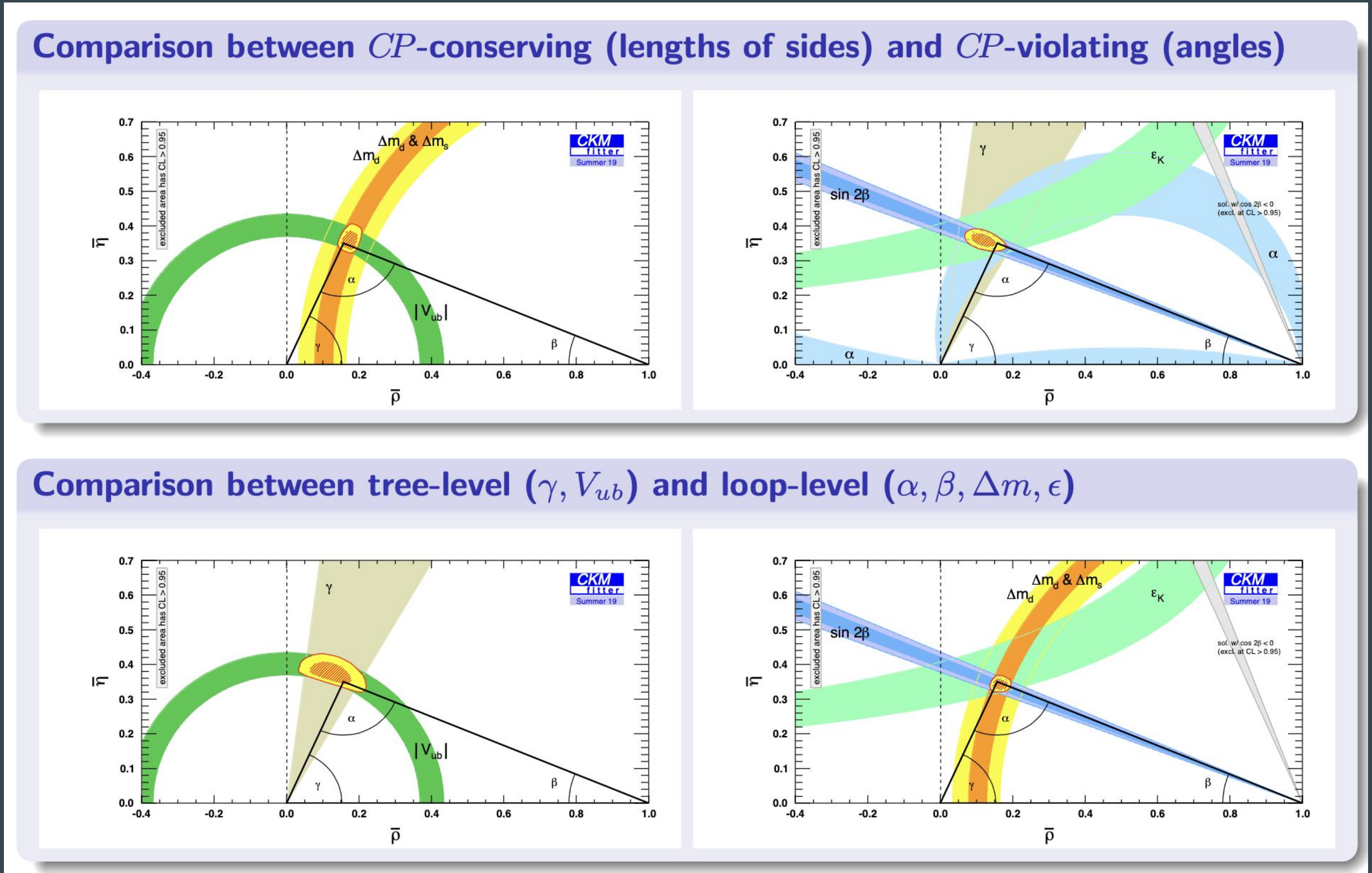
Before B-factories and LHC

LHC inclusion



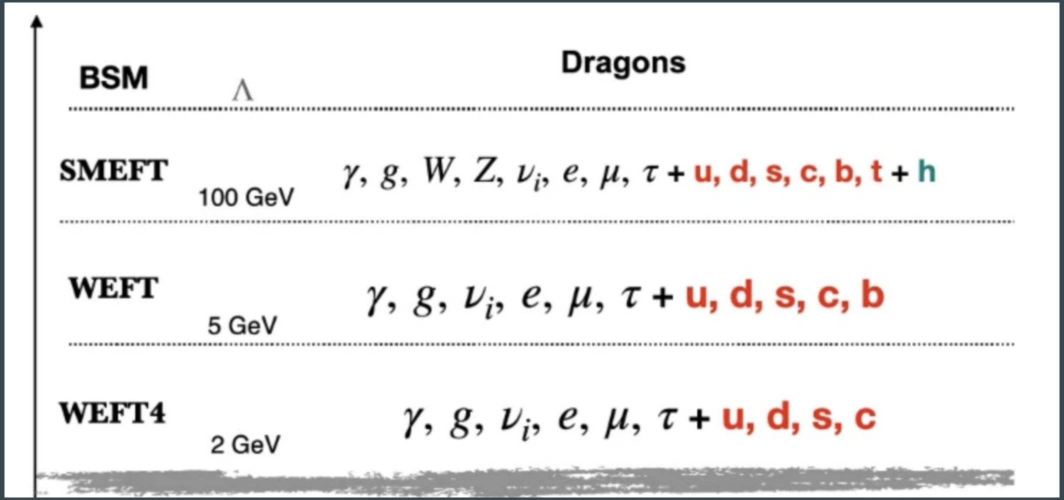
LHC inclusion

CKM progress



←Why is this interesting?

EFTs



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

Resources

Matt Kenzie flavour lectures

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

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