SEARCH FOR NEW SOURCES OF CP VIOLATION IN CHARM BARYONIC DECAYS WITH THE LHCB EXPERIMENT

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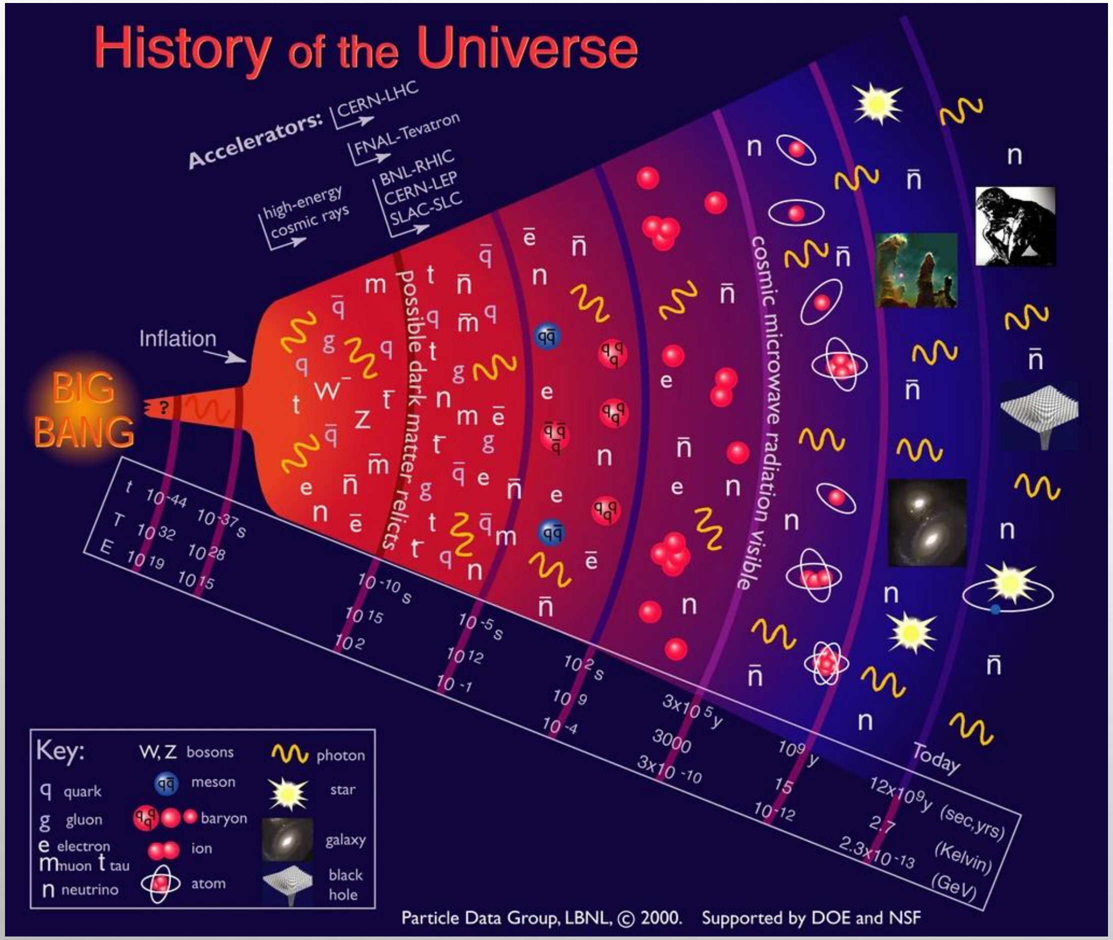
LHCB COLLABORATION

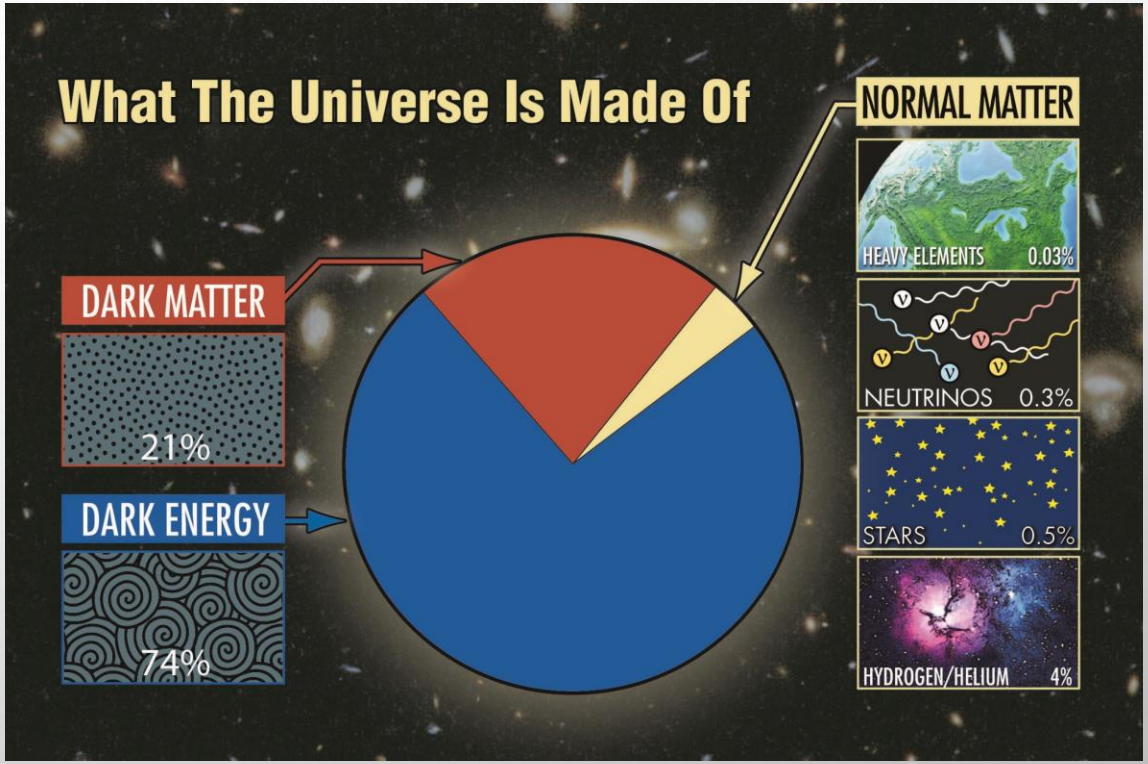
AGH-UST

JAGIELLONIAN UNIVERSITY SEMINAR, 21/06/2021, KRAKÓW

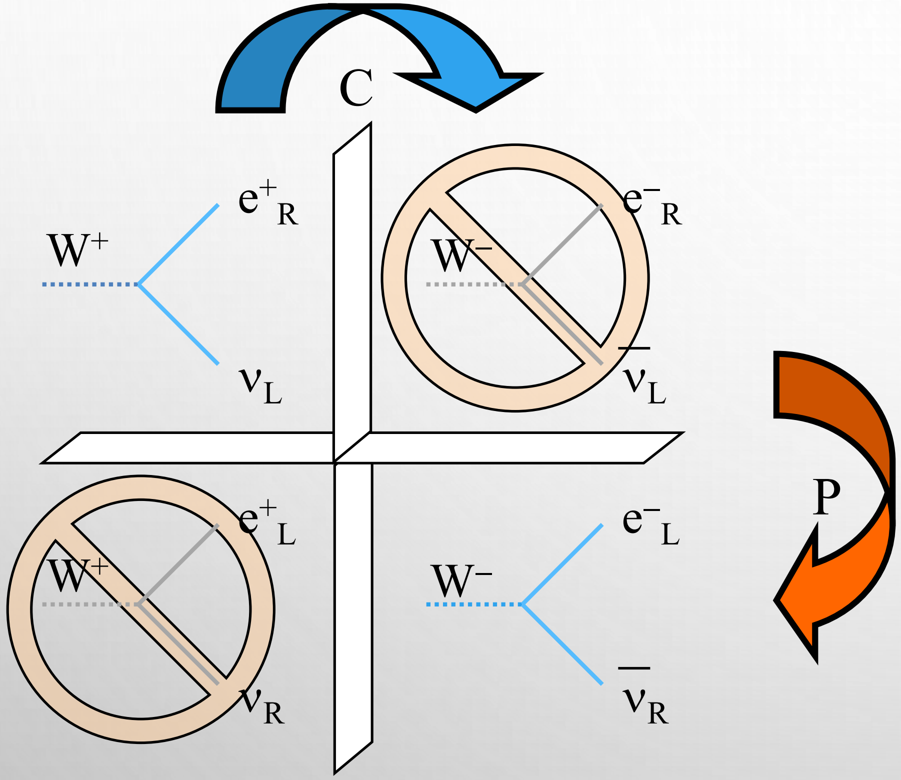
WHY WE ARE HERE AT ALL?



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



WHAT'S THE MATTER WITH ANTI-MATTER…?



WEAK INTERACTIONS VIOLATE MAXIMALLY SPACE PARITY SYMMETRY.

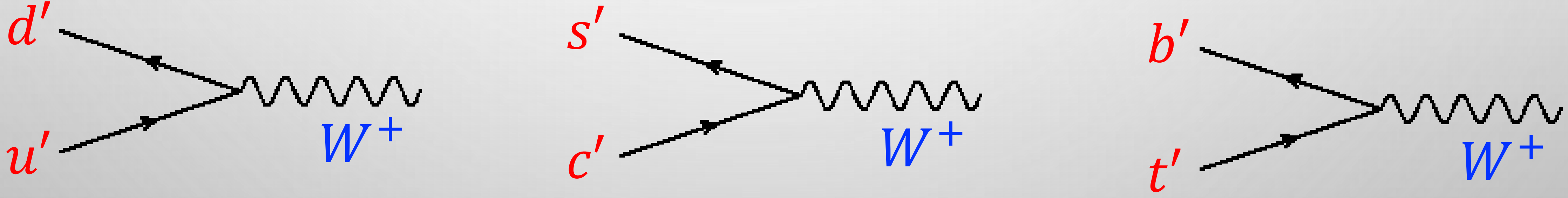
- WOLFGANG PAULI: “*I CANNOT BELIEVE GOD IS A WEAK LEFT-HANDER.*”

- $\boldsymbol{SU_L(2)}$ symmetry for massless quarks

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \, \gamma_\mu \, W^\mu \, d'_L$$

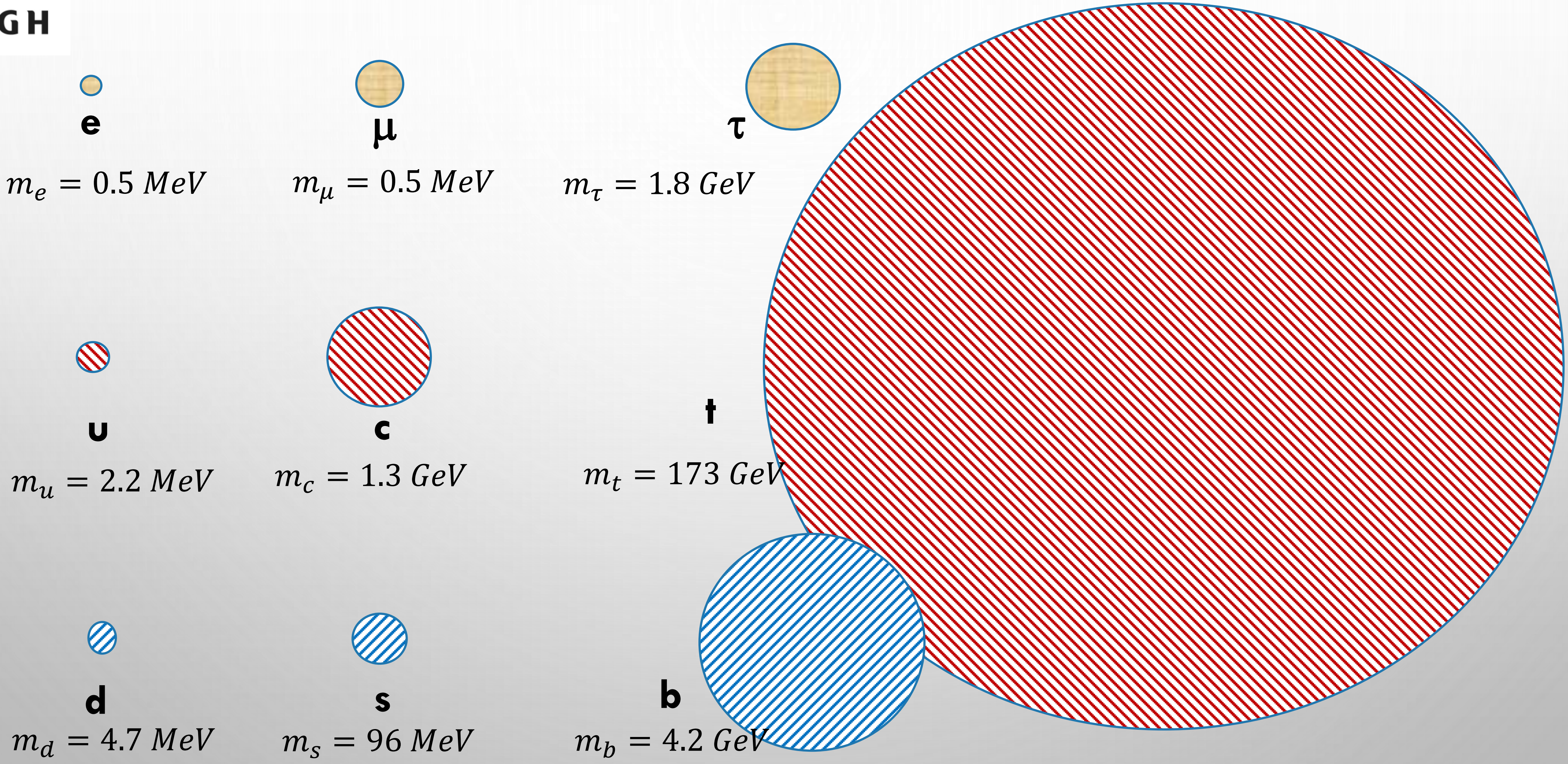
x3 !

- Flavour universality – interactions do not depend on the family.
  - Cannot distinguish d' from s'



- No CP violation possible!!
  - Now we add the mass to the picture!

MASS HIERARCHY PROBLEM…



e

$m_e = 0.5\ MeV$

μ

$m_\mu = 0.5\ MeV$

τ

$m_\tau = 1.8\ GeV$

u

$m_u = 2.2\ MeV$

c

$m_c = 1.3\ GeV$

t

$m_t = 173\ GeV$

d

$m_d = 4.7\ MeV$

s

$m_s = 96\ MeV$

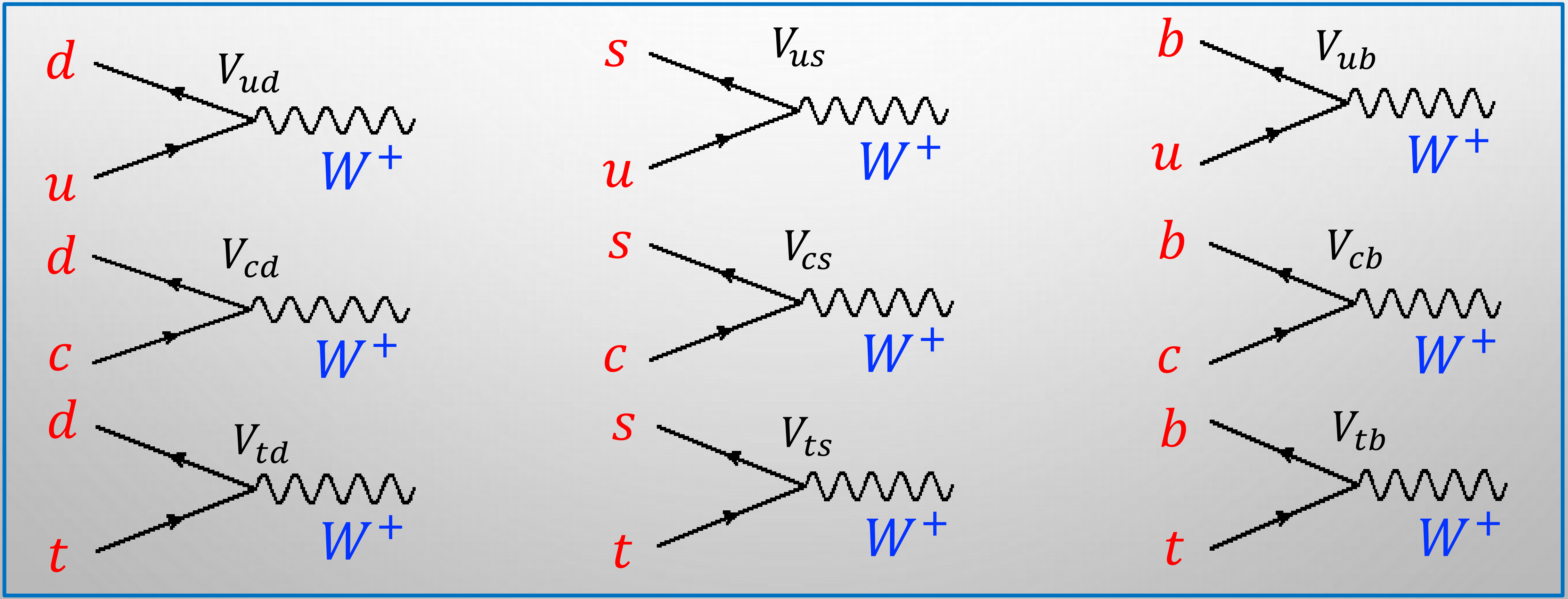
b

$m_b = 4.2\ GeV$

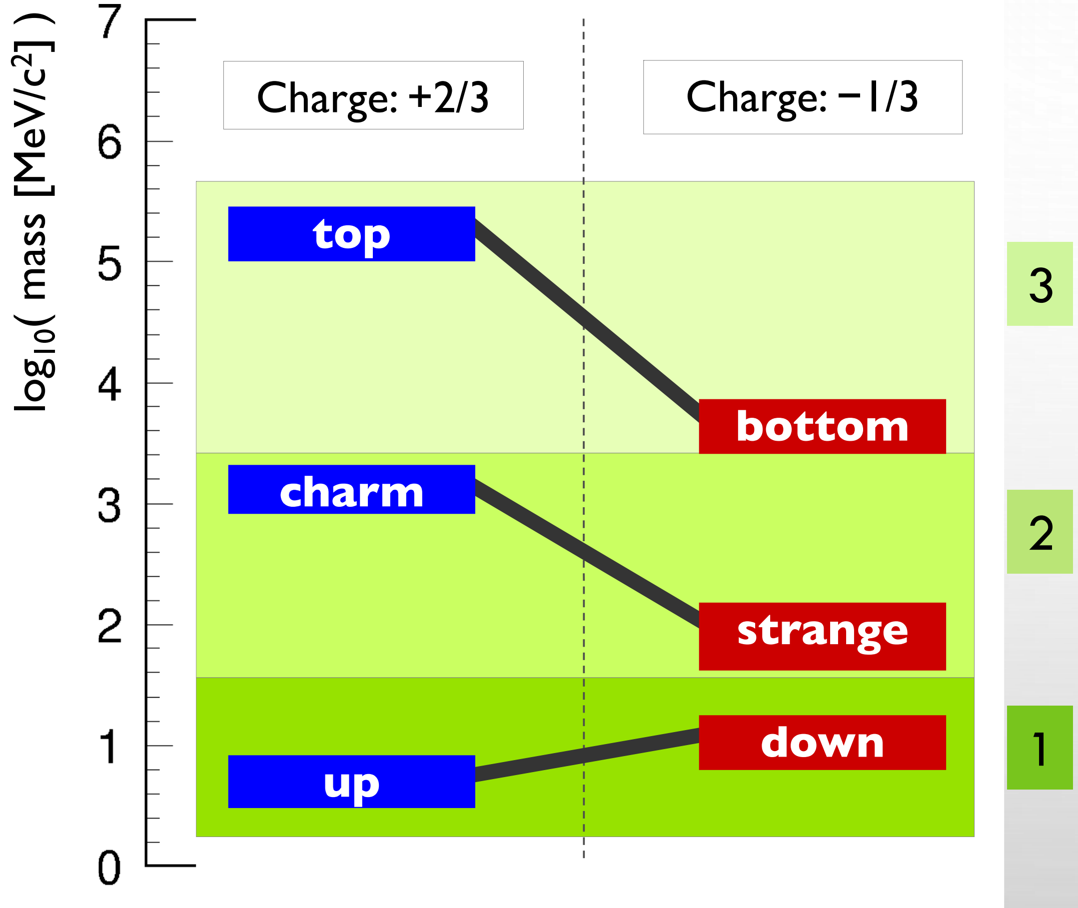
(Interaction base) (Mass base)

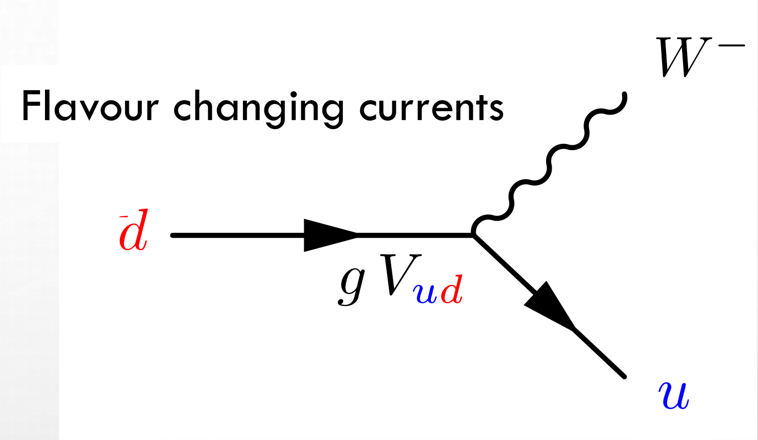
$$\mathcal{L}_W = \frac{g}{\sqrt{2}}\, u'_L\, \gamma_\mu\, W^\mu\, d'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}}\, \boldsymbol{V_{CKM}}\, u_L\, \gamma_\mu\, W^\mu\, d_L$$

Change of base: $u'_i = (V^u)_{ij}\, u_i$ and: $d'_i = (V^d)^\dagger_{ij} d_i$



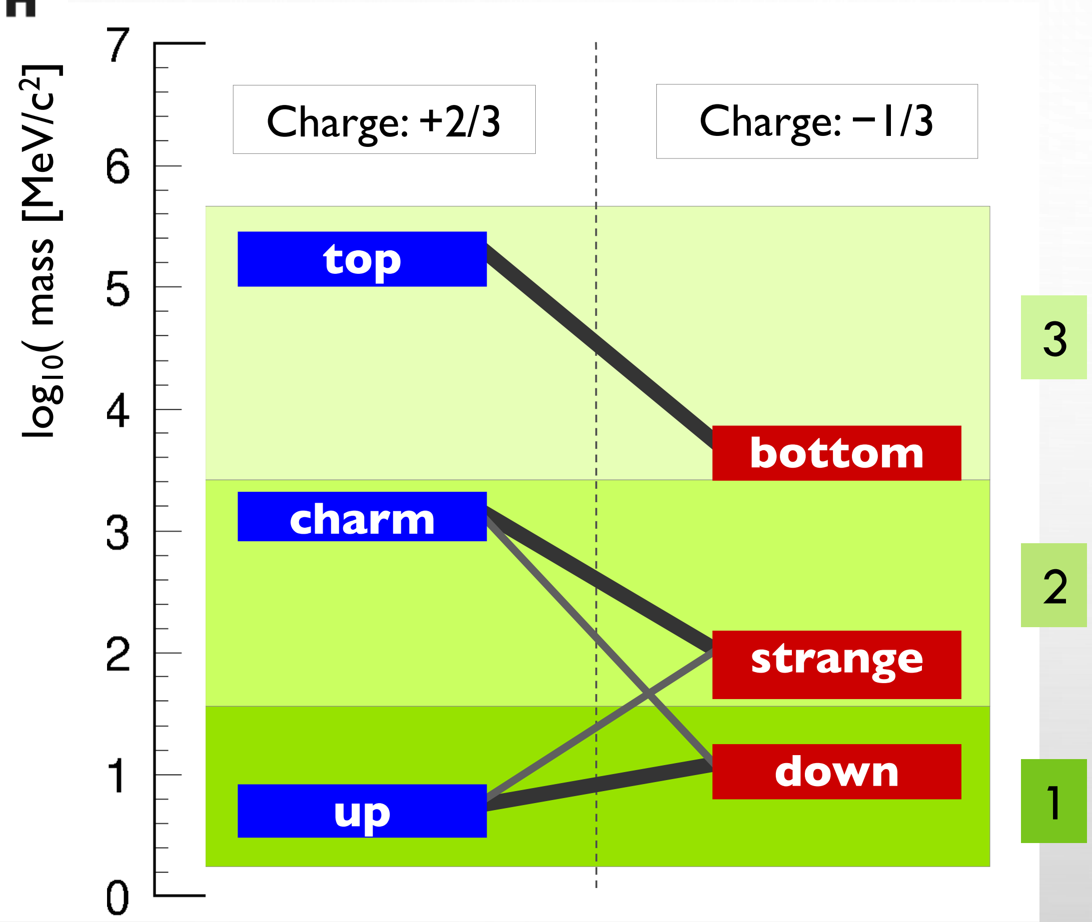
BUILDING CKM MATRIX



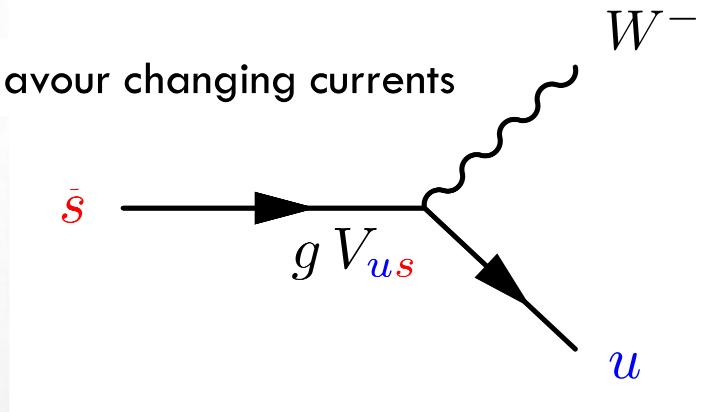

Flavour changing currents

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & & \\ & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

BUILDING CKM MATRIX

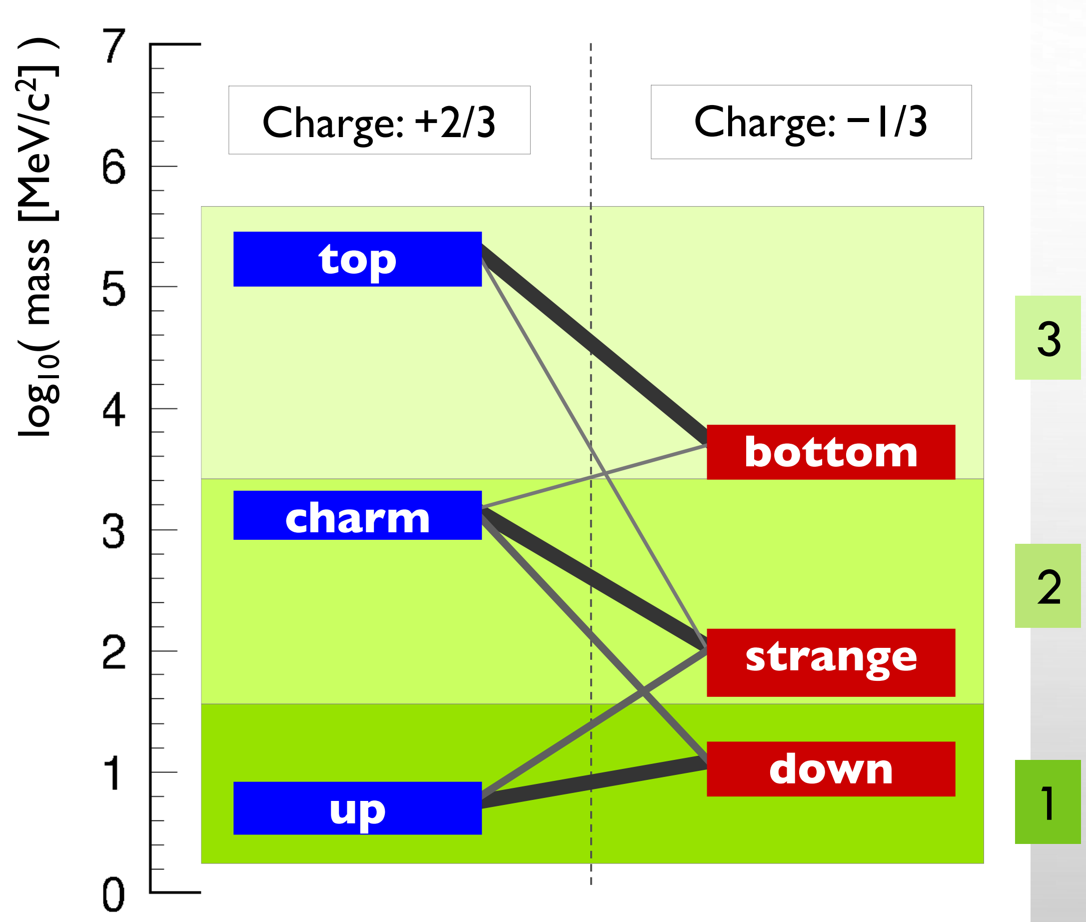


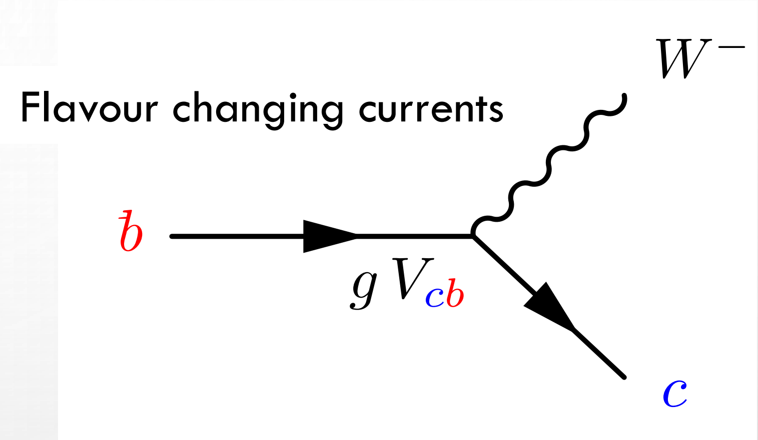
Flavour changing currents



$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

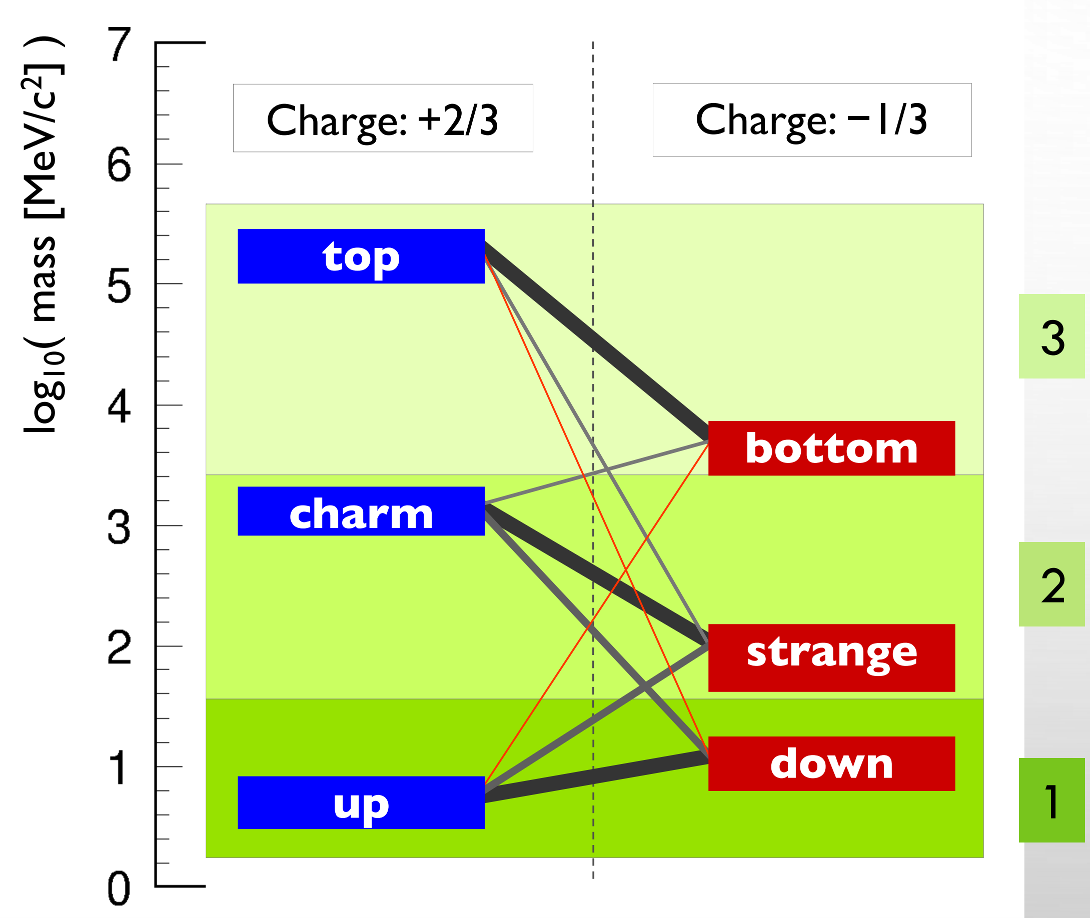
BUILDING CKM MATRIX

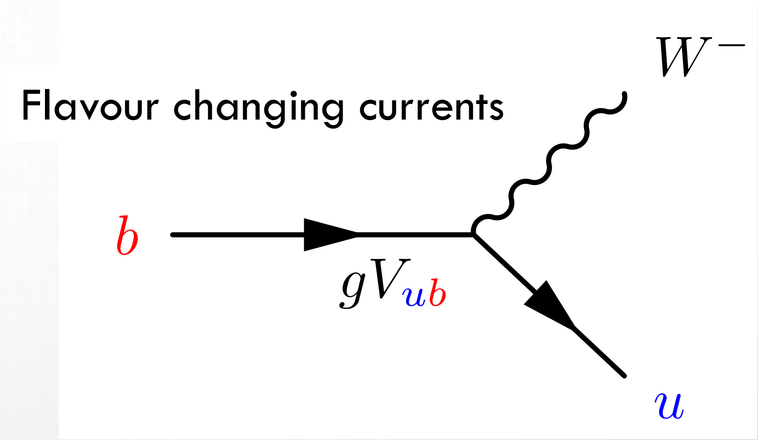




$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & V_{cb} \\ & V_{ts} & V_{tb} \end{pmatrix}$$

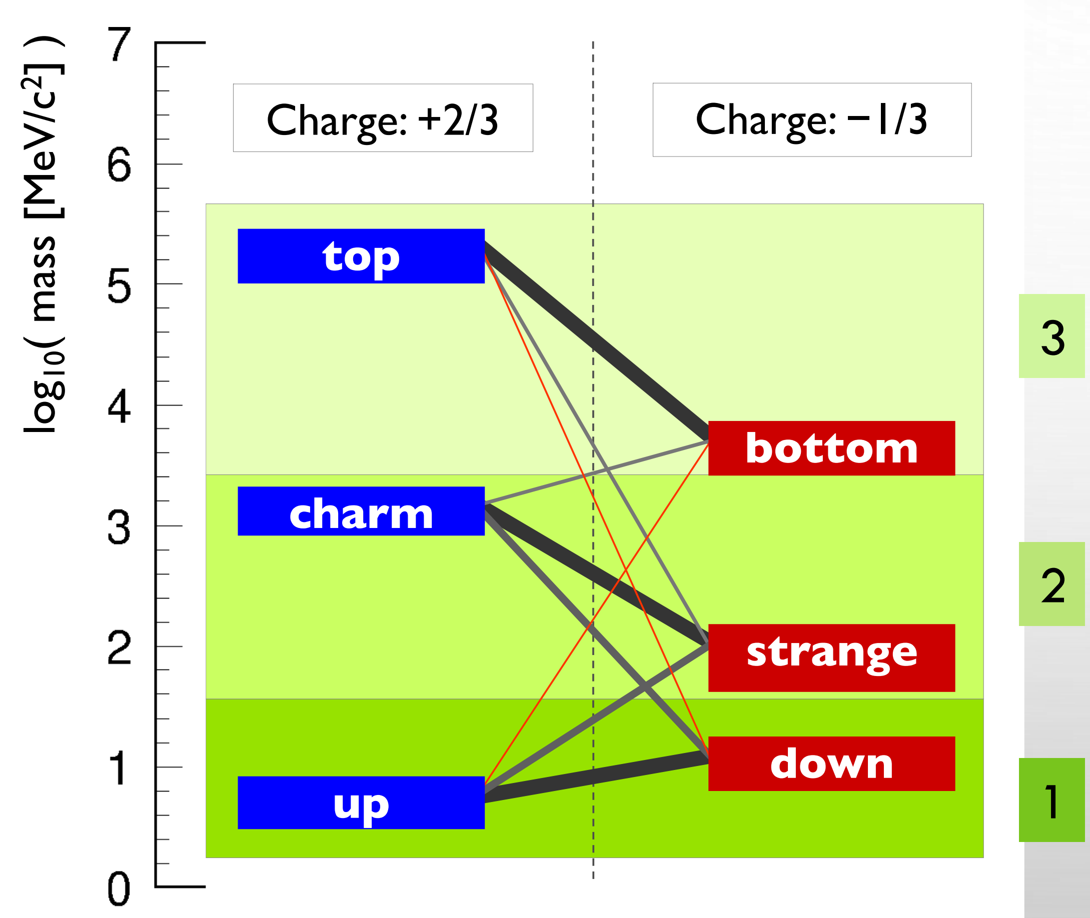
BUILDING CKM MATRIX

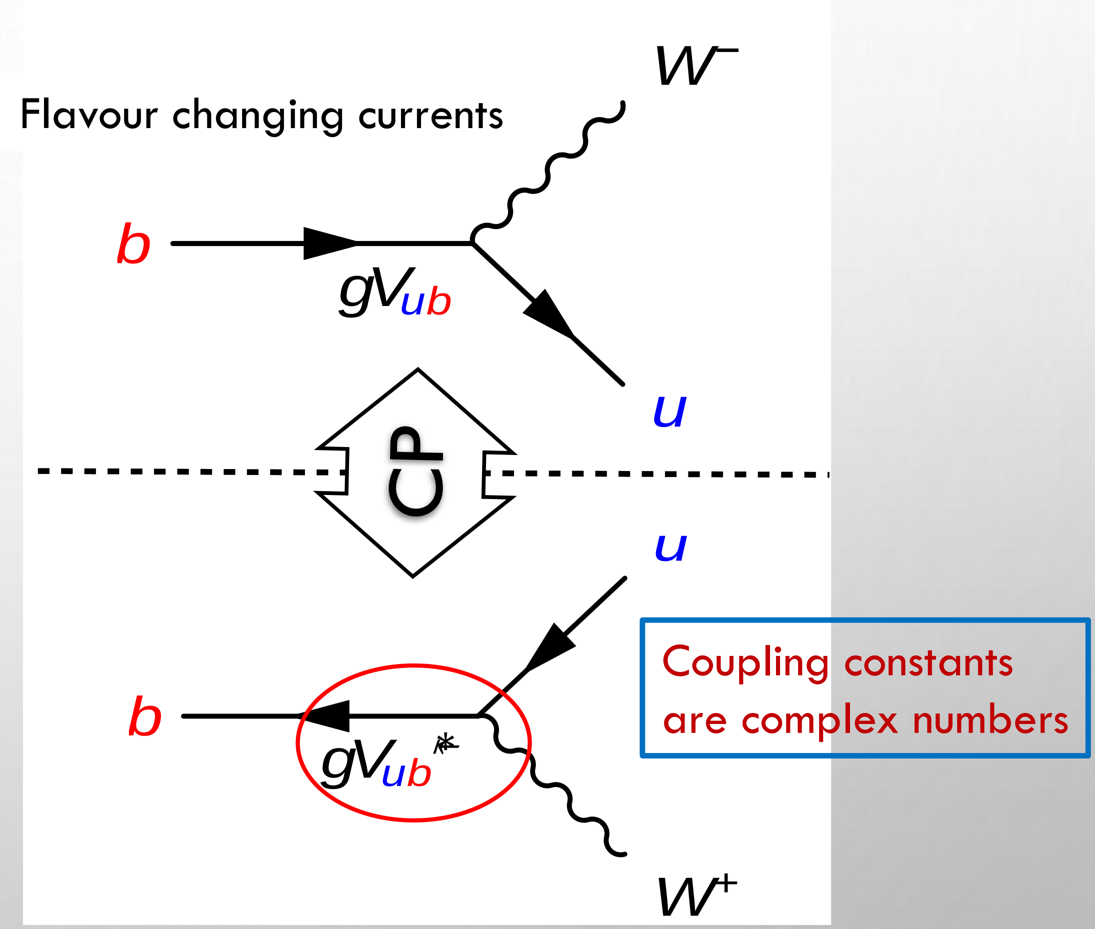




$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

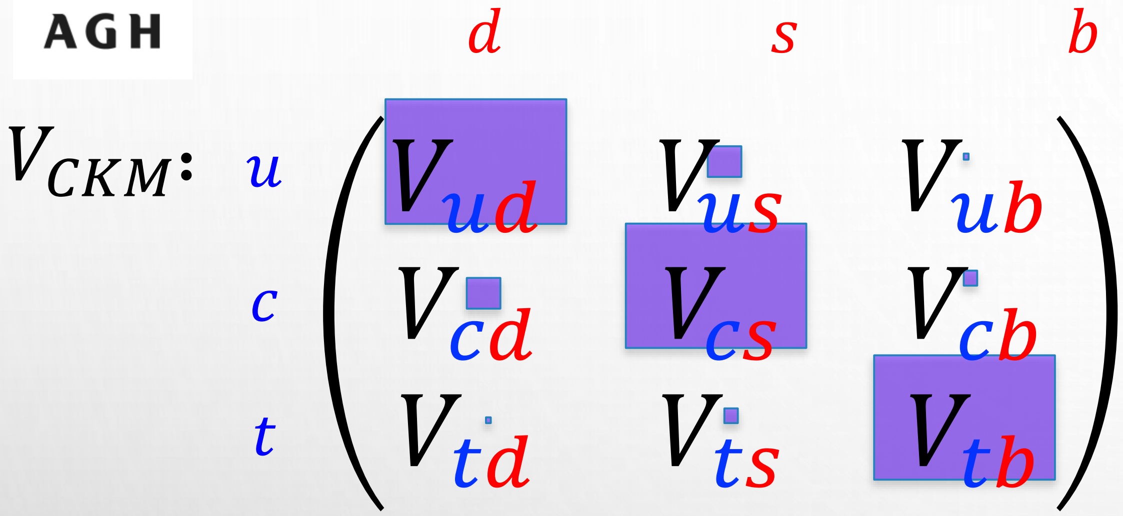
BUILDING CKM MATRIX





Coupling constants are complex numbers

NEED FOR 3 GENERATIONS

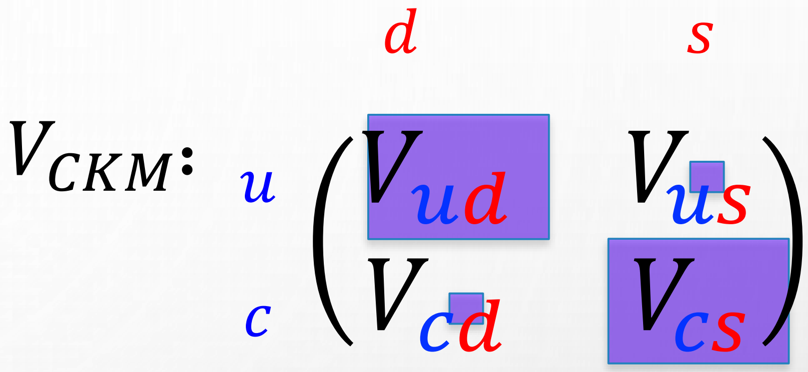


$$V_{CKM}: \begin{array}{cccc} & d & s & b \\ u & V_{ud} & V_{us} & V_{ub} \\ c & V_{cd} & V_{cs} & V_{cb} \\ t & V_{td} & V_{ts} & V_{tb} \end{array}$$

- Wolfenstein parametrisation: $V_{CKM} =$

$$\begin{pmatrix} 1-{}^{1}/_{2}\,\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-{}^{1}/_{2}\,\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

➔ One complex phase



$$V_{CKM}: \begin{array}{ccc} & d & s \\ u & V_{ud} & V_{us} \\ c & V_{cd} & V_{cs} \end{array}$$

$V_{CKM} =$

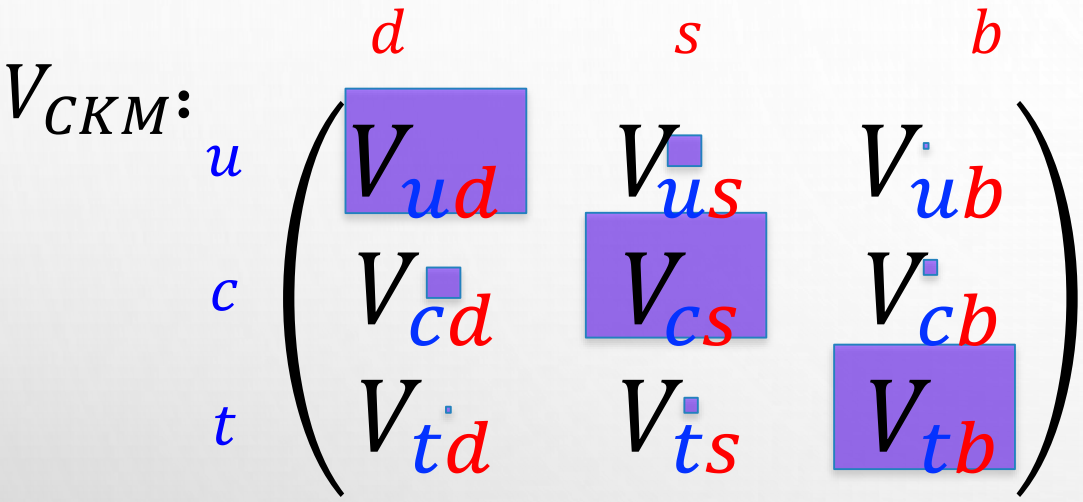
$$\begin{pmatrix} 1-{}^{1}/_{2}\,\lambda^2 & \lambda \\ -\lambda & 1-{}^{1}/_{2}\,\lambda^2 \end{pmatrix}$$

➔ No CP violation

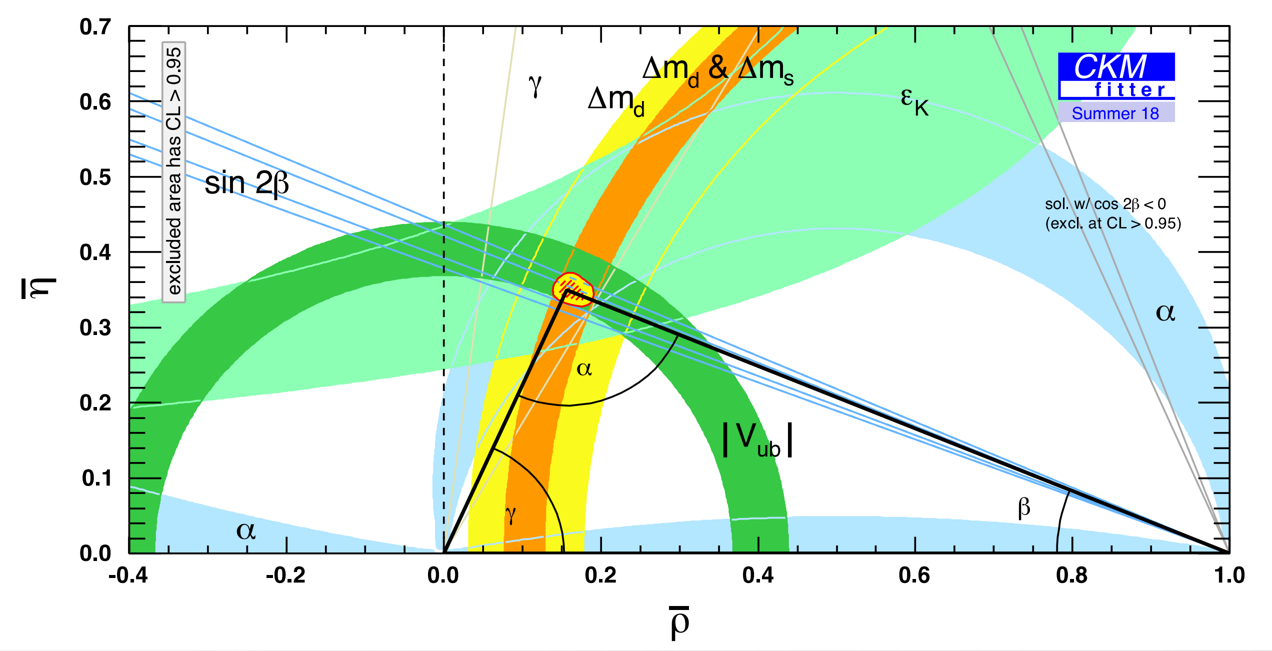
- *3 generations with quark doublets are necessary at the least to broke the CP symmetry*

NEED FOR 3 GENERATIONS

Unitarity: $V_{CKM} V_{CKM}^{\dagger} = 1$



$$V_{CKM}: \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$



- Unitarity triangle view: $V_{CKM} =$

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

CP violation:

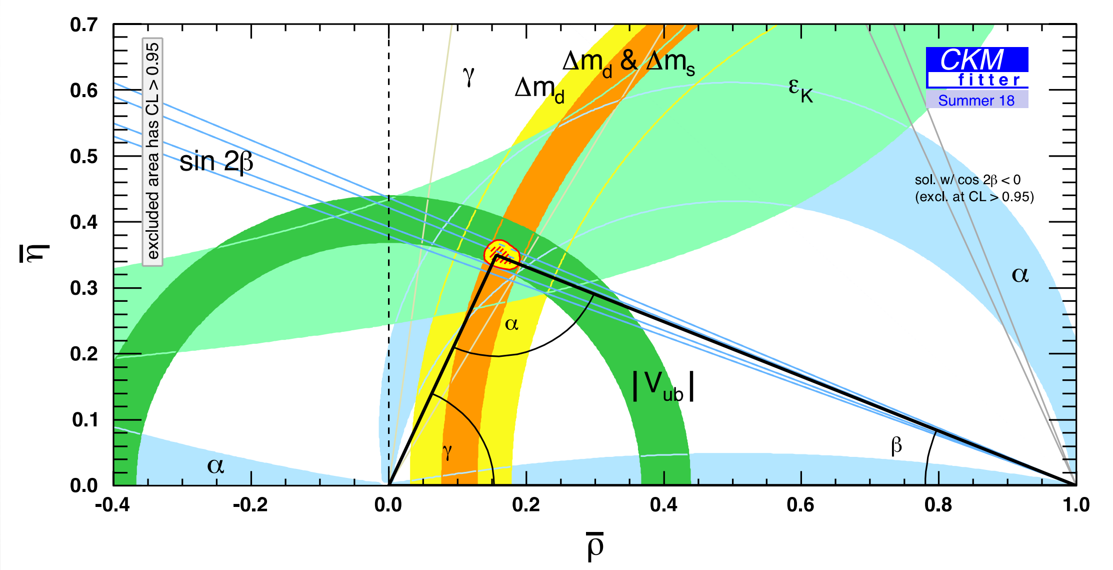
➔ Surface $\neq 0$

➔ Non-zero CP-phases.

CPV IS UNIVERSAL IN THE SM

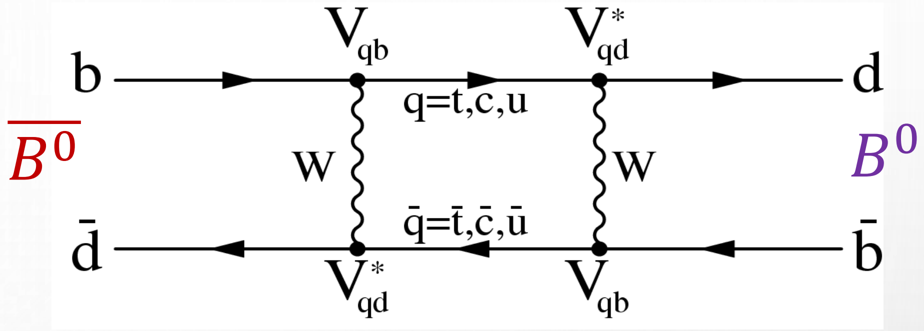
- CPV CANNOT DEPEND ON REPRESENTATION.
  - AREA OF THE UNITARITY TRIANGLE
  - JARLSKOG INVARIANT: $J = 3 \times 10^{-5}$
- 3 quark generations with different masses!!
  - $m_u \neq m_c \quad ; \quad m_c \neq m_t \quad ; \quad m_t \neq m_u$
  - $m_d \neq m_s \quad ; \quad m_s \neq m_b \quad ; \quad m_b \neq m_d$
- Jarlskog (1987) CPV in the SM
  - $\det\left[M_u M_u^\dagger, M_d M_d^\dagger\right] = 2 \cdot J \cdot (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$

$$\boxed{M_{ij} = Y_{ij}\, v/\sqrt{2}}$$



FLAVOUR OSCILLATIONS

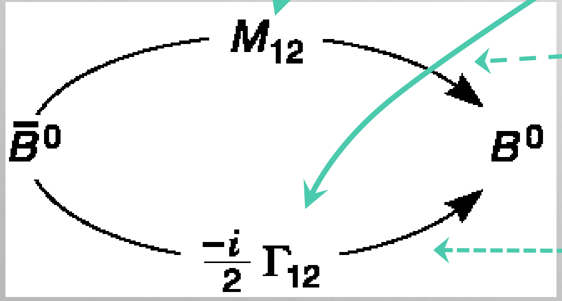
- Quantum interference $\overline{B^0}$ i B^0



- TIME EVOLUTION OF B^0 I $\overline{B^0}$ SYSTEM DESCRIBED BY EFFECTIVE HAMILTONIAN

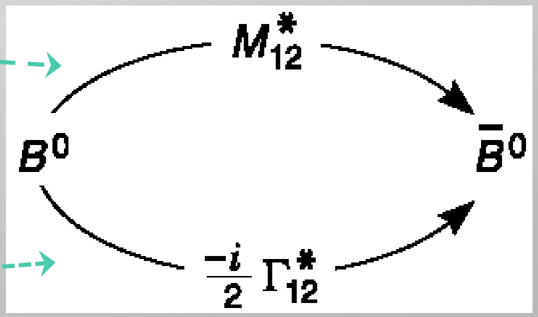
$$i\frac{\partial}{\partial t}\psi = H\psi \qquad \rightarrow \qquad \psi(t) = a(t)|B^0\rangle + b(t)|\overline{B^0}\rangle \quad \equiv \quad \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\textit{Hermitian mass matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\textit{Hermitian decay matrix}}$$



M_{12} $B^0 \leftrightarrow \overline{B^0}$ off-shell particle exchange (short range processes)

Γ_{12} $B^0 \leftrightarrow f \leftrightarrow \overline{B^0}$ on-shell particle exchange (logn range processes) $f = \pi^+\pi^-$



$$i\frac{\partial}{\partial t}\psi(t) = \begin{pmatrix} M-\frac{i}{2}\Gamma & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & M-\frac{i}{2}\Gamma \end{pmatrix}\psi(t)$$

$$\Rightarrow \quad \psi(t) = \alpha|B_H(t)\rangle + \beta|B_L(t)\rangle$$

e-vectors:

$$|B_H(t)\rangle = |B_H\rangle e^{-i\omega_+ t}$$

$$|B_L(t)\rangle = |B_L\rangle e^{-i\omega_- t}$$

B_H , B_L : e-states of mass

$$\omega_\pm = m_\pm - \frac{i}{2}\Gamma_\pm \quad \begin{cases} m_\pm = M \pm \frac{1}{2}\Delta m \\ \Gamma_\pm = \Gamma \pm \frac{1}{2}\Delta\Gamma \end{cases}$$

masses

lifetimes

$$|B_H\rangle = p|B^0\rangle + q|\overline{B^0}\rangle$$

$$|B_L\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$$

B^0 , $\overline{B^0}$: e-states of flavour

$$\Delta m = 2\,\Re\sqrt{\left(M_{12}-\frac{i}{2}\Gamma_{12}\right)\left(M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*}\right)}$$

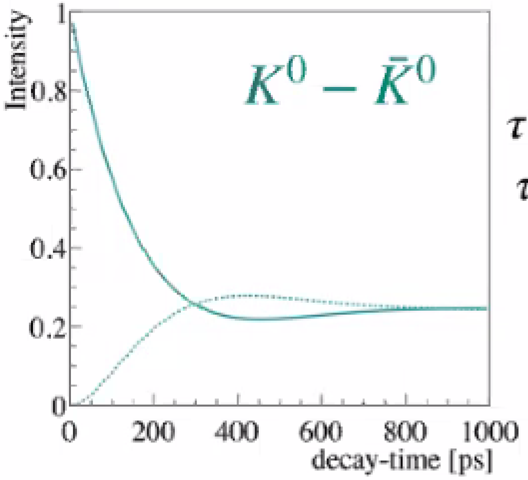
$$\Delta\Gamma = 4\,\Im\sqrt{\left(M_{12}-\frac{i}{2}\Gamma_{12}\right)\left(M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*}\right)}$$

Eigen problem solution:

$$q/p = -\sqrt{\left(M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*}\right)\Big/\left(M_{12}-\frac{i}{2}\Gamma_{12}\right)}$$

B^0 : $\Delta\Gamma \approx 0$, $|q/p| = 1$
B_s^0 : $\Delta\Gamma/\Delta m \ll 1$, $|q/p| = 1$
K^0 : $\Delta\Gamma/\Delta m \simeq 1$, $|q/p| - 1 \simeq 10^{-3}$

THE SAME PHYSICS, DIFFERENT CONSTANTS…

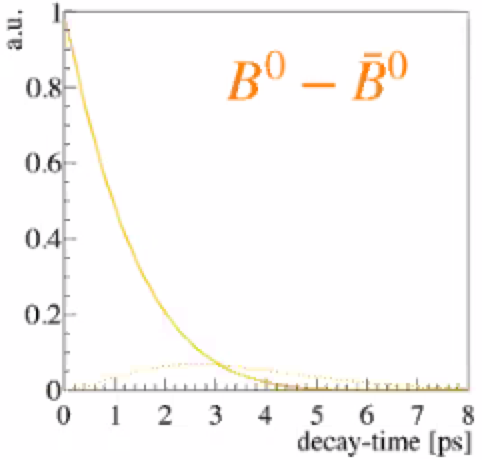


Very different lifetime:

$\tau(K_S^0) \sim 0.9 \times 10^{-10}$

$\tau(K_L^0) \sim 0.5 \times 10^{-7}$

the oscillation period longer than the K_S lifetime, but K_L^0 exceptionally long



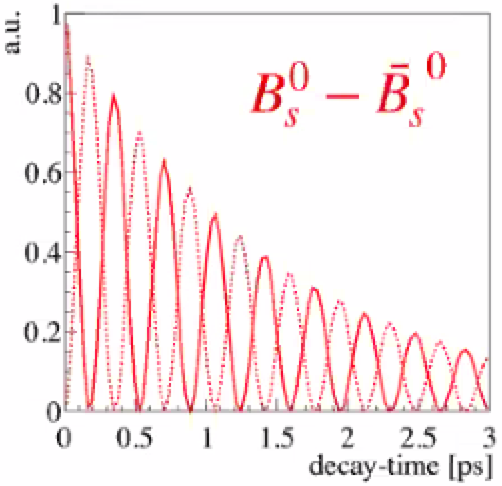
Oscillations

$\Delta m \sim 0.5\ ps^{-1}$

Lifetime

$\tau(B^0) \sim 1.5\ ps$

The same order of magnitudes

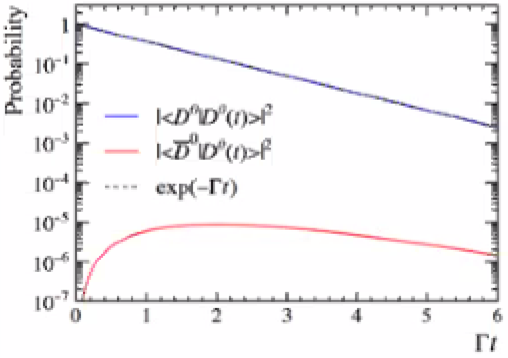


Very fast oscillations

$\Delta m_s > 15\ ps^{-1}$

$\tau(B_s^0) \sim 1.5\ ps$

Non-zero $\Delta\Gamma_s$



$D^0 - \bar{D}^0$

Very slow oscillations

$\Delta m \sim 10^{-3}\ ps^{-1}$

Very short lifetime

$\tau(D^0) \sim 0.4\ ps$

D^0 decays before has a chance to oscillate

MIXING AND CPV - SUMMARY

$$\boldsymbol{x} = \frac{M_H - M_L}{\Gamma} = \frac{\Delta m}{\Gamma} \qquad \boldsymbol{y} = \frac{\Gamma_H - \Gamma_L}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

Δm – determines mixing frequency, if x or y different from zero the mixing can occur

We also define the weak phase or CP violating phase:

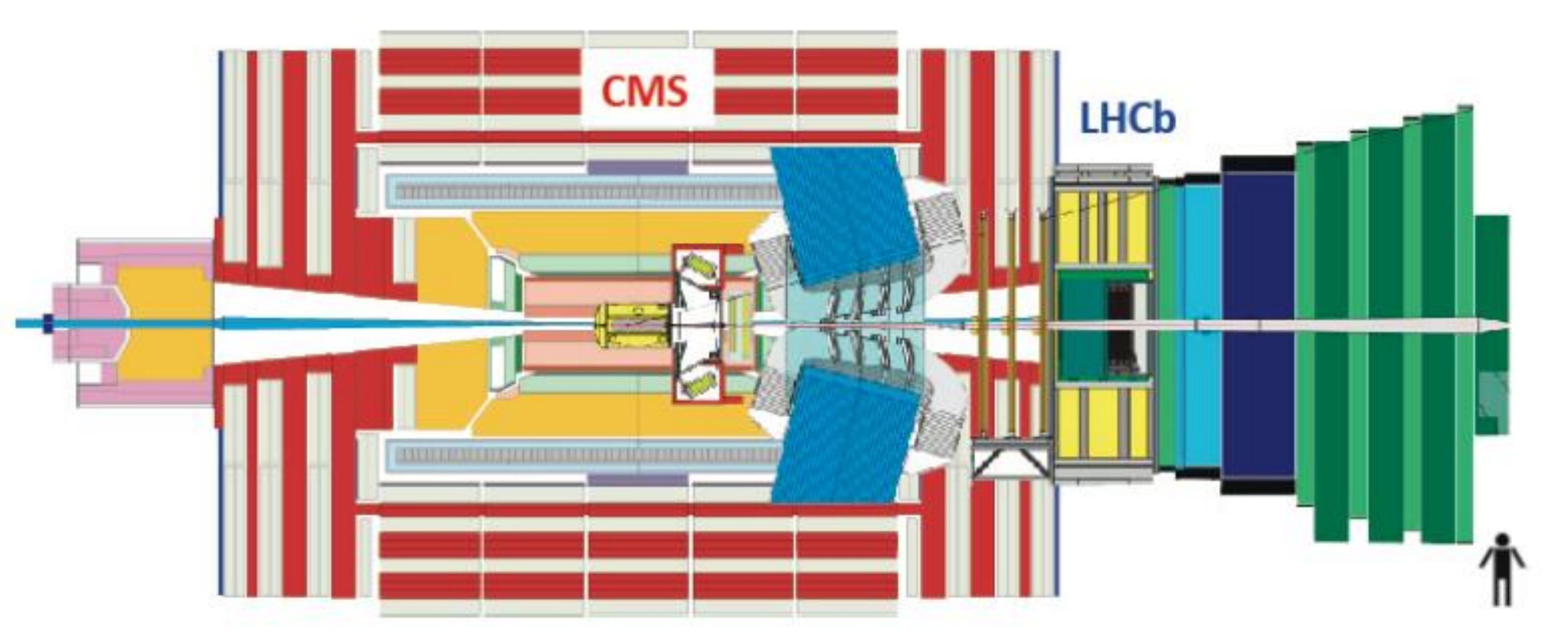
$$\phi = arg(-M_{12} - \Gamma_{12})$$

If ϕ is different from zero and/or $\left|\frac{p}{q}\right| \neq 1$ we also can have CP violation on top of mixing

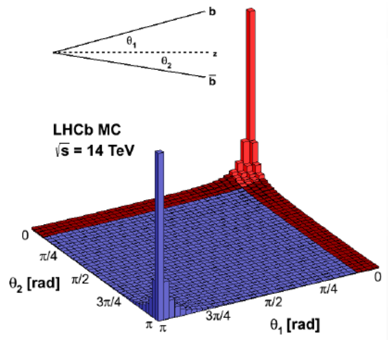
$$\Delta m_q = \frac{G_f^2}{6\pi^2} m_{B_q} M_W^2 f\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD} B_{B_q} f_{B_q}^2 |V_{tb}^* V_{tq}|^2$$

LHCB DETECTOR

- ❑ NON TYPICAL GEOMETRY, BUT A TYPICAL COMPOSITION…



LARGE HADRON COLLIDER **BEAUTY**



- ❑ AFTER RUN 1 AND RUN 2 LHCB PROVED TO BE THE **GENERAL-PURPOSE FORWARD DETECTOR**
  - ❑ A SINGLE ARM SPECTROMETER – NOT YOUR TYPICAL GEOMETRY FOR A COLLIDER BASED EXPERIMENT!
  - ❑ FULLY INSTRUMENTED IN THE PSEUDO-RAPIDITY RANGE OF $(2 < \eta < 5)$
  - ❑ CAN REGISTER UP TO 40% OF ALL HEAVY QUARKS W
    ONLY 4% OF THE SOLID ANGLE COVERAGE!
  - ❑ VERY PRECISE MEASUREMENTS IN BEAUTY AND CHAR
    SECTOR AND NEW PHYSICS SEARCH
  - ❑ EXCELLENT PERFORMANCE IN RUN 1 AND RUN 2:
    - MOMENTUM RESOLUTION $\frac{\Delta p}{p} \sim \mathbf{0.5\%}$ **@20 [GEV]**
    - IMPACT PARAMETER RESOLUTION $\sim \mathbf{15 + \frac{29}{p_T}}$ **[μm]**
    - TIME RESOLUTION $\boldsymbol{\sigma_t} \sim \mathbf{45}$ **[FS]** FOR $B_s \to J/\psi\varphi$
  - ❑ IN TIME, THE PHYSICS PROGRAMME HAS BEEN EXTENDED TO COVER EXCLUSIVE PROCESSES, QCD STUDIES, ELECTRO-WEAK PHYSICS, DIRECT NP SEARCHES AND HEAVY ION PHYSICS

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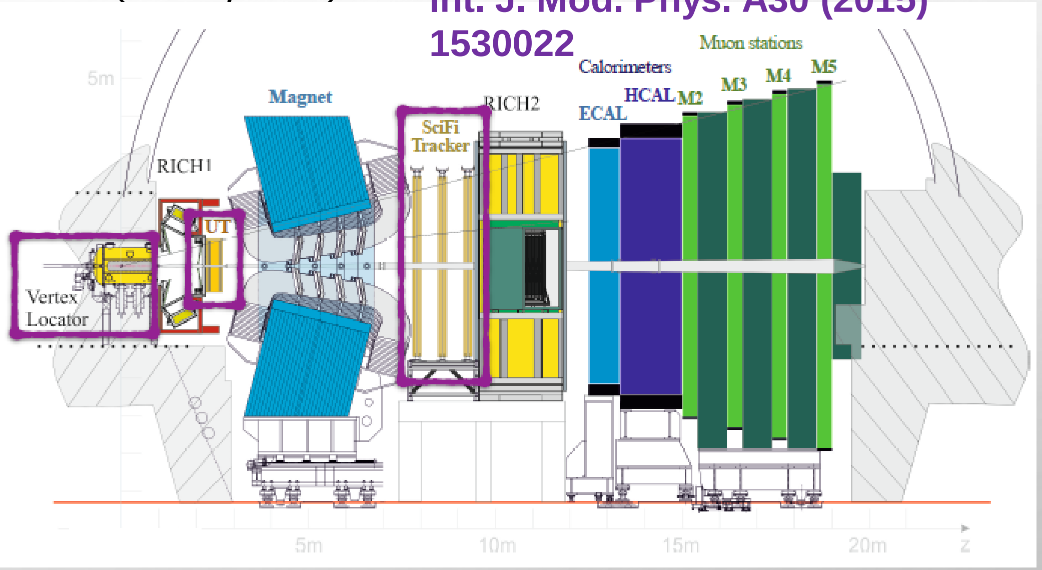
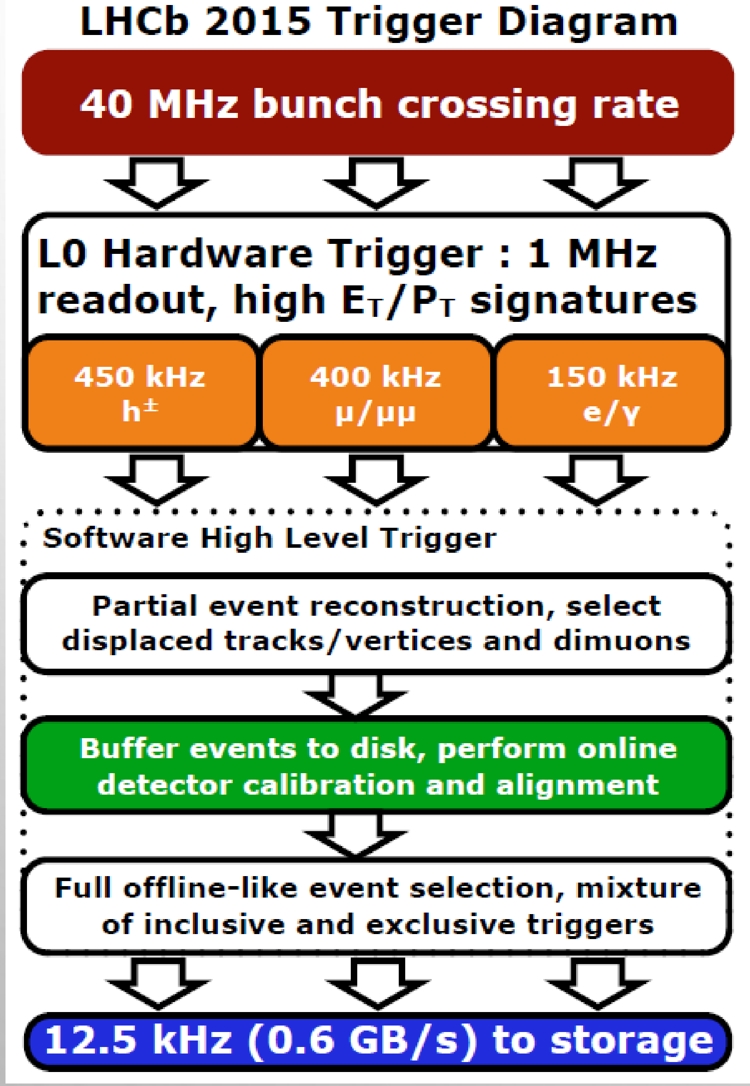


LHCB TRIGGER AND TURBO STREAM



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

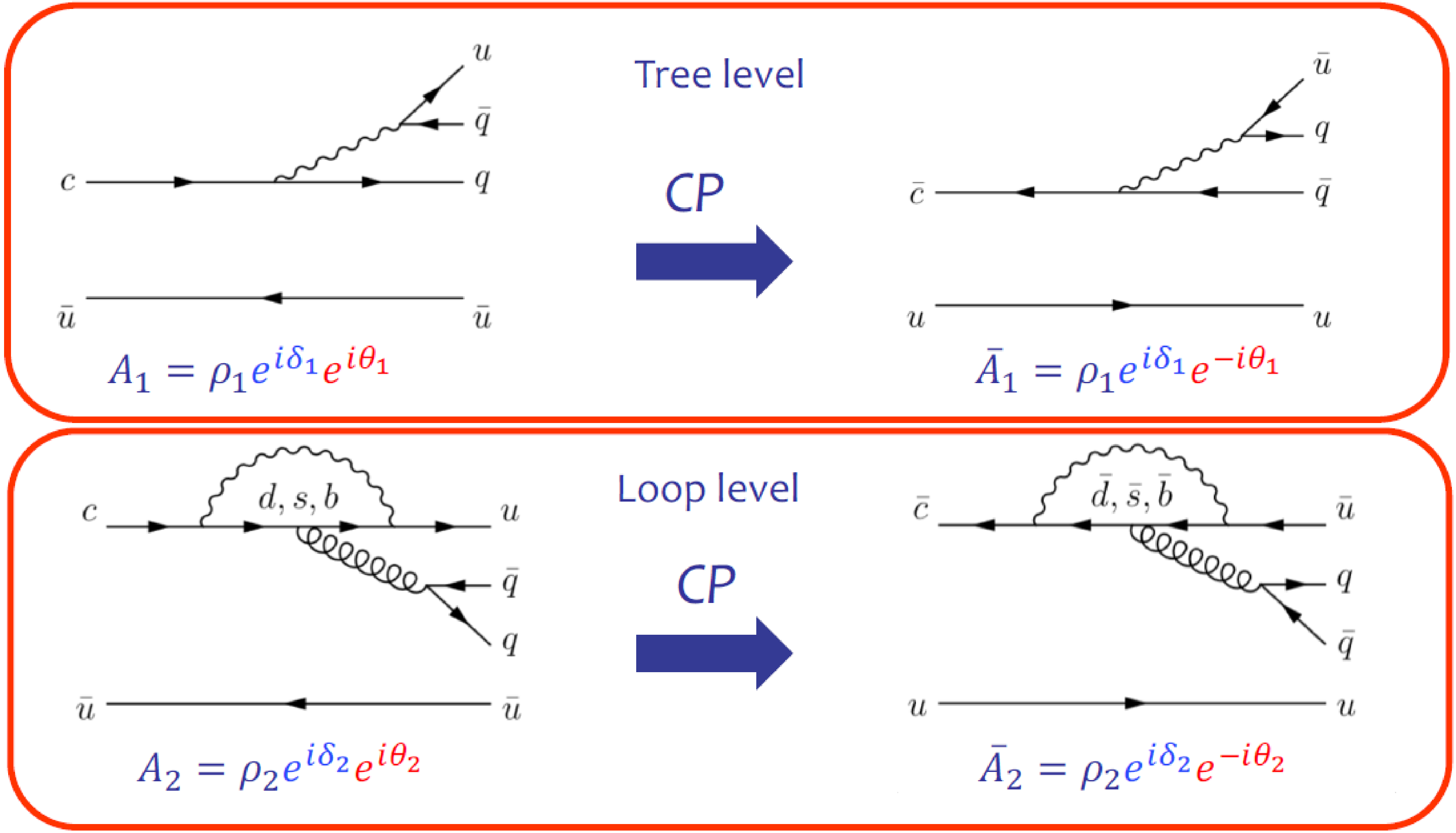
Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

Trigger was continuously improved during Run 1-2 operation

- **Start of operation:** Storage bandwidth 5 kHz wrt 2 kHz in the design (additional b/w for charm)
- **2012:** Deferred trigger. Buffer 20% of bandwidth before HLT to disks (use interfill time)
- **Run 2 (2015-2018):** Split HLT.
  - Buffer all HLT1 output to disk.
  - Run calibration and alignment.
  - Offilne-quality selections at the last stage of HLT.
  - Can run analyses on HLT2 output (Turbo stream)

FIRST CPV OBSERVATION IN CHARM SECTOR



Tree level

CP

$A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1}$

$\bar{A}_1 = \rho_1 e^{i\delta_1} e^{-i\theta_1}$

Loop level

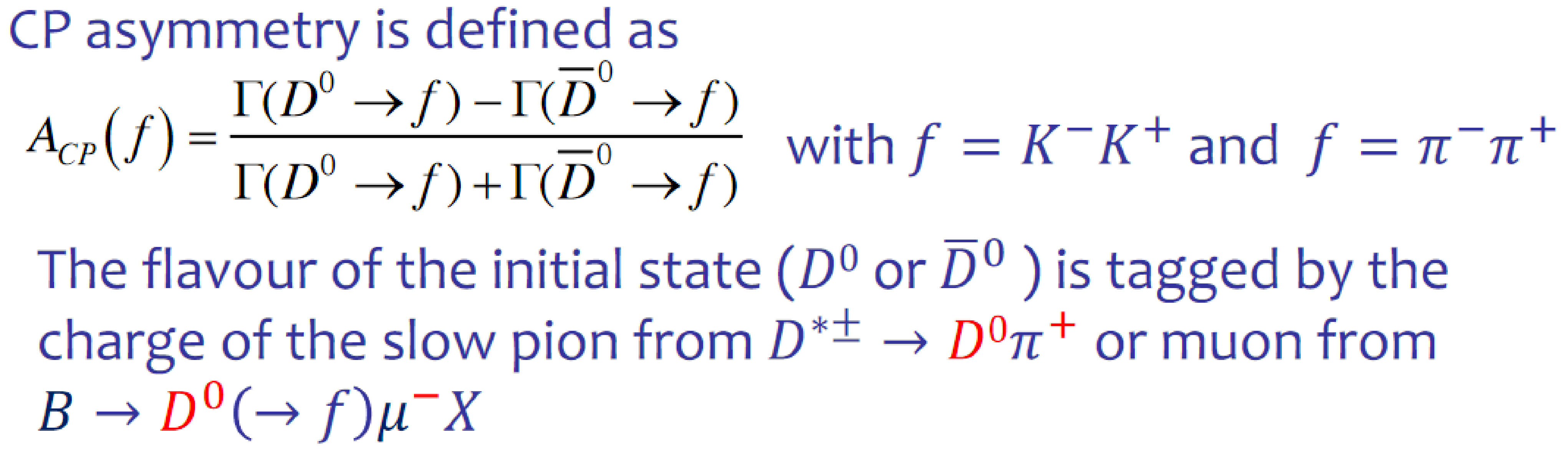
CP

$A_2 = \rho_2 e^{i\delta_2} e^{i\theta_2}$

$\bar{A}_2 = \rho_2 e^{i\delta_2} e^{-i\theta_2}$

$$|\bar{A}_1 + \bar{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2)$$

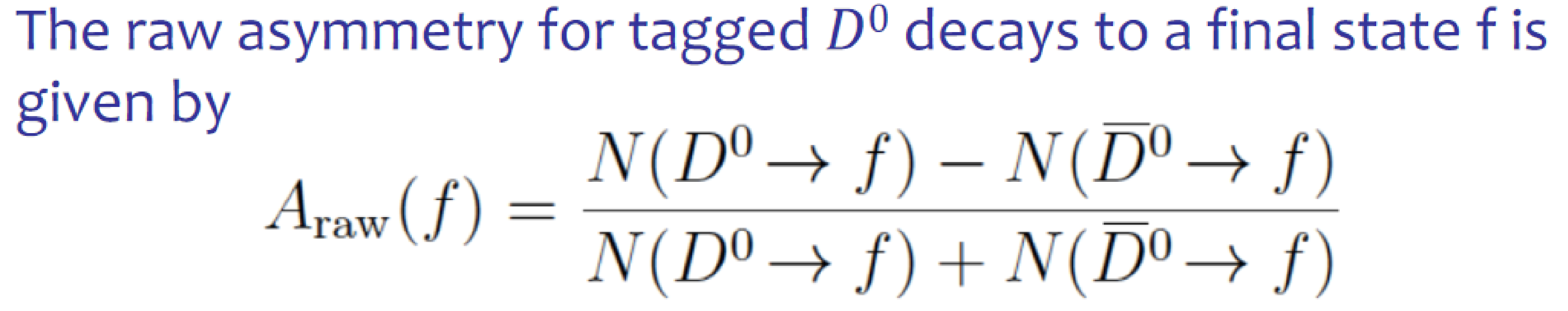
FIRST CPV OBSERVATION IN CHARM SECTOR



CP asymmetry is defined as

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$ with $f = K^-K^+$ and $f = \pi^-\pi^+$

The flavour of the initial state (D^0 or $\overline{D}^0$) is tagged by the charge of the slow pion from $D^{*\pm} \to D^0\pi^+$ or muon from $B \to D^0(\to f)\mu^- X$



The raw asymmetry for tagged D^0 decays to a final state f is given by

$$A_{\mathrm{raw}}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

FIRST CPV OBSERVATION IN CHARM SECTOR

$$\boxed{\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)}$$

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$

5.3 standard deviations from zero

This is the first observation of *CP* violation in the decay of charm hadrons

Charm CPV LHCb Paper (LHCb-2019-006)

DIRECTION BARYONS!!

- So far it seems that mesons are the champions of the CPV searches, but what about baryons? There are a lot of potential there.
- A lot of interest and hope related with Λ_b (Nature Physics 13 (2017) 391), indications for CPV with Run 1 data, but no confirmation with the larger sample
- Large samples of charm baryons collected during Run 2, first attempt to measure the ΔA_{CP}^{Baryon} with Λ_c^+

$$\Delta A_{CP}^{baryon} \equiv A_{CP}(\Lambda_c^+ \to pK^-K^+) - A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61)\%$$

- No luck there…, how about another interesting state… Ξ_c^+?

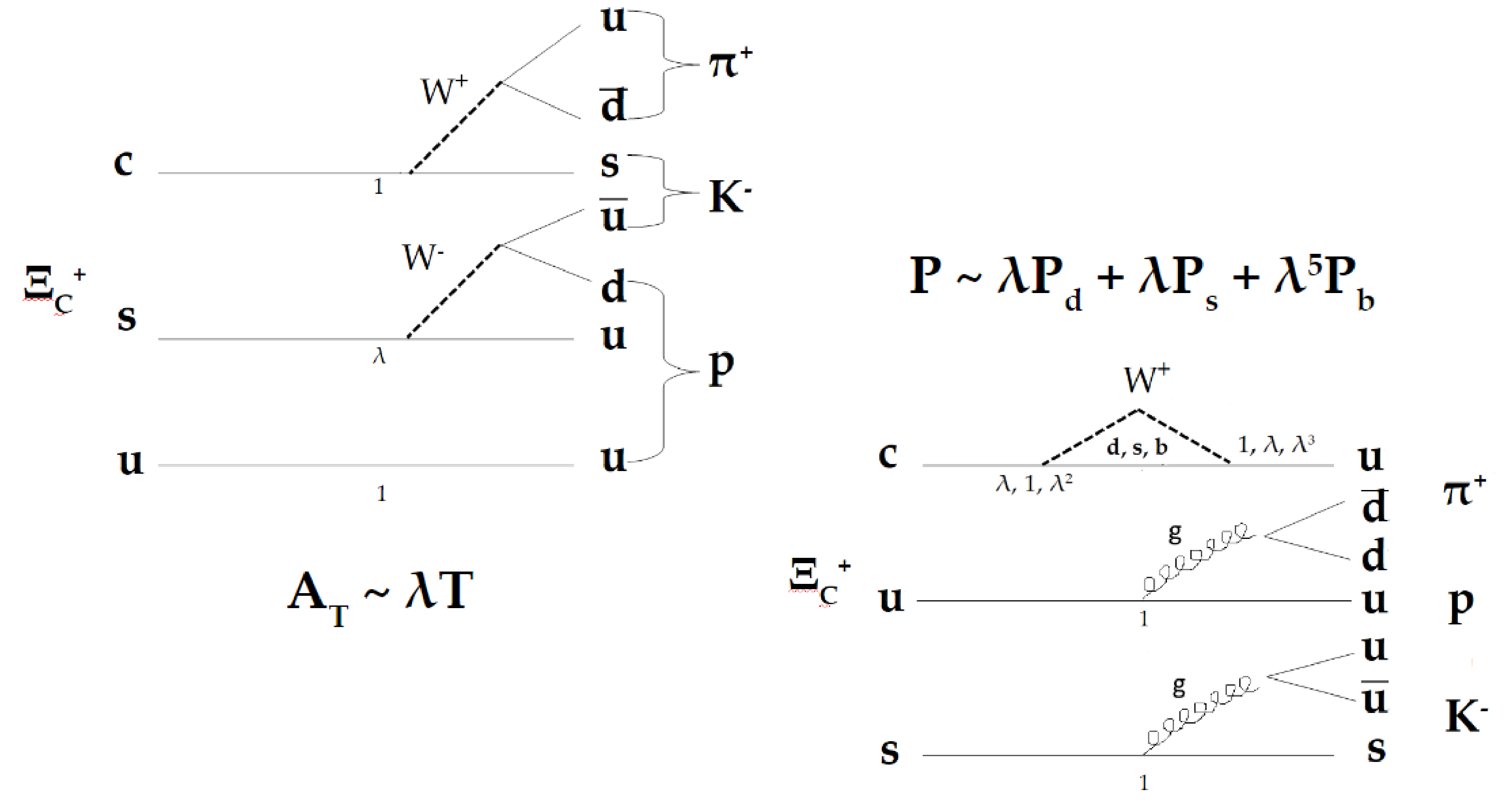
STUDIES OF PROMPT Ξ_c^+ DECAYS

- Run 1 data (2010 – 2012) of prompt $\Xi_c^+ \rightarrow pK^-\pi^+$ decays has been started by the Warsaw group, Krakow joined in 2018
- Two model independent techniques were used S_{CP} and KNN to measure the CP violation
- No luck so far: Paper-2019-026 (The Eur. Phys. Journal C 80, 986 (2020))
- We may face two problems here: either the CPV is very small (for $\Xi_c^+ \rightarrow pK^-\pi^+$ decays we expect the CPV at the level of $10^{-3} - 10^{-4}$), or our methods are not sensitive enough
- In Run 2 analysis we are testing, for the first time, KDE approach to enhance the binned S_{CP} method and to use the energy test also supported by KDE estimator
- Currently involved: Artur Ukleja (Warsaw NCBJ), Jakub Ryżka, TS (AGH)

STUDIES OF PROMPT Ξ_c^+ DECAYS

- ☐ Note! All that follows from this point forth is **LHCb PRELIMINARY**!
- ☐ The work was presented at Charm working group meeting and we are in process of writing the analysis note (which will turn into paper at some point)

STUDIES OF PROMPT Ξ_c^+ DECAYS – DIAGRAMS

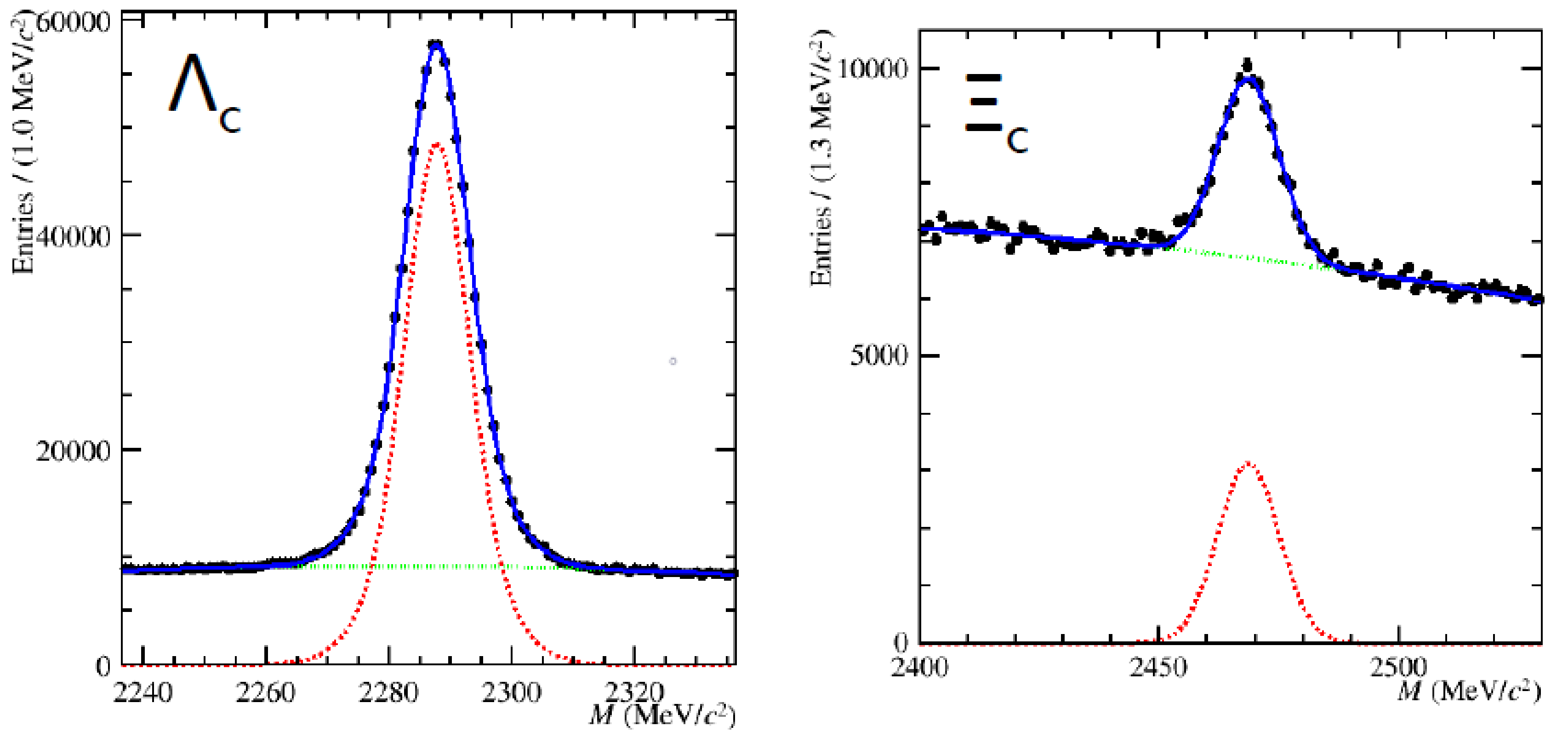


$$A_T \sim \lambda T$$

$$P \sim \lambda P_d + \lambda P_s + \lambda^5 P_b$$

TURBO STREAM

$$FoM = \frac{S}{\sqrt{S+B}}$$



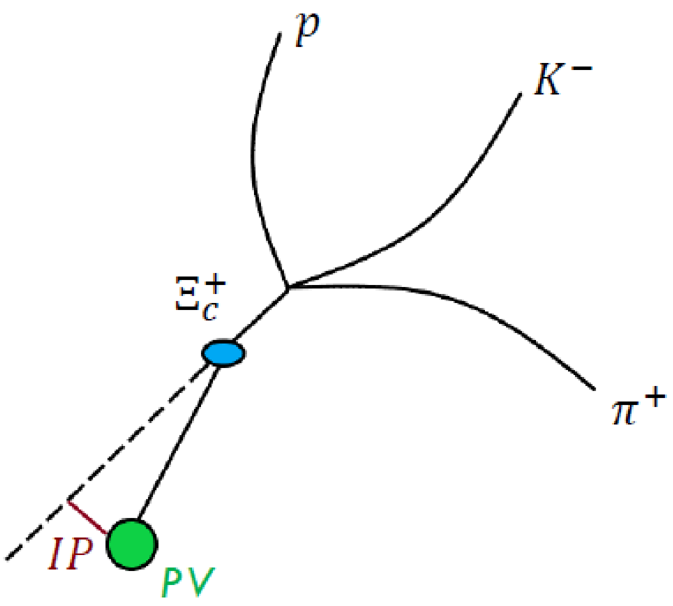
Signal: $f(x) = \text{sig1frac} \cdot G(x, \mu, \sigma_1) + (1 - \text{sig1frac}) \cdot G(x, \mu, \sigma_2)$

Background: $p_0 + p_1 x$

FINAL SELECTION ALGORITHM

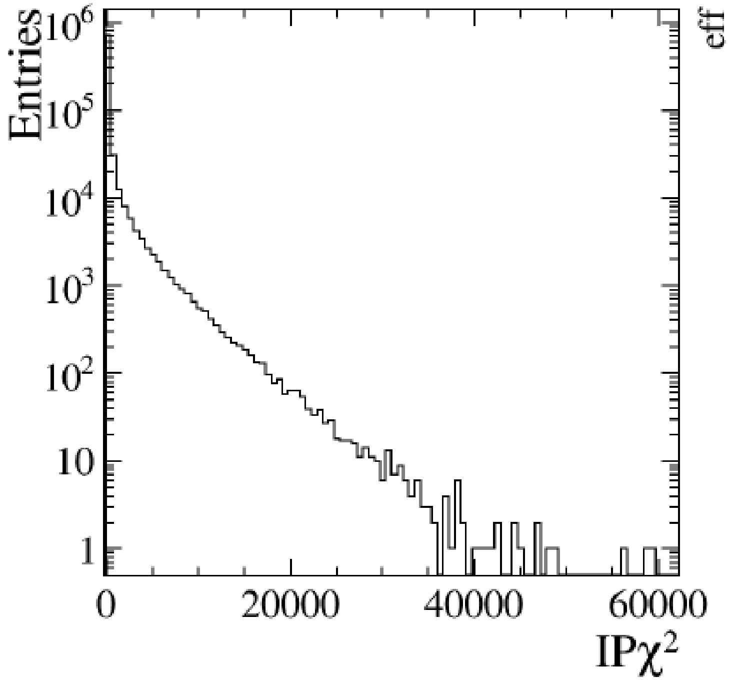
Cut were implemented for the following variables:

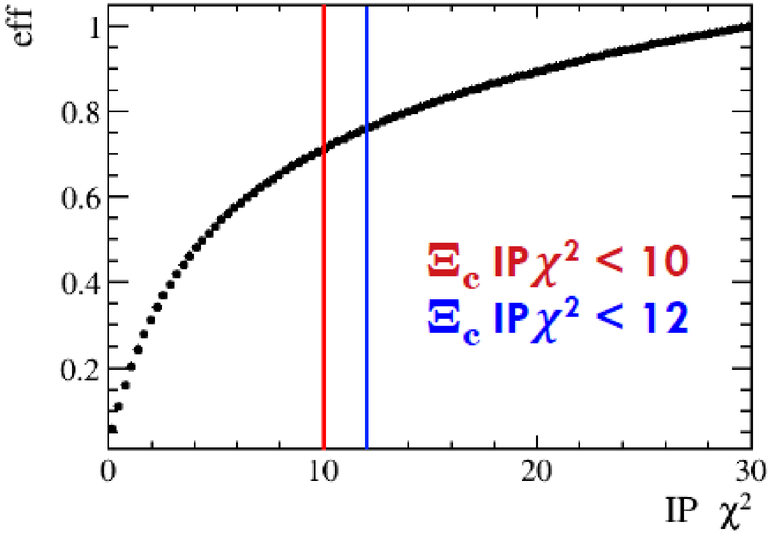
- Proton/Kaon/Pion
  - PID
  - ProbNN
  - IPχ^2
  - TRACK_GhostProb
  - momentum
- Charm baryon
  - Vertex $\chi^2/ndof$
  - IPχ^2
  - Transverse momentum
  - DIRA
  - FDχ^2
  - Pseudorapidity η



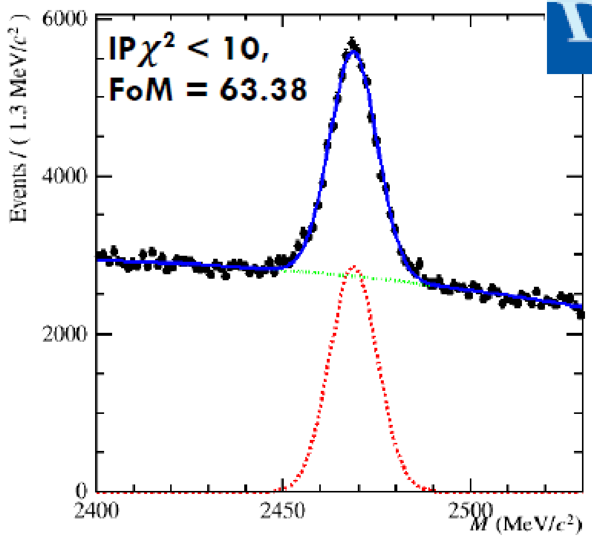
FINAL SELECTION ALGORITHM

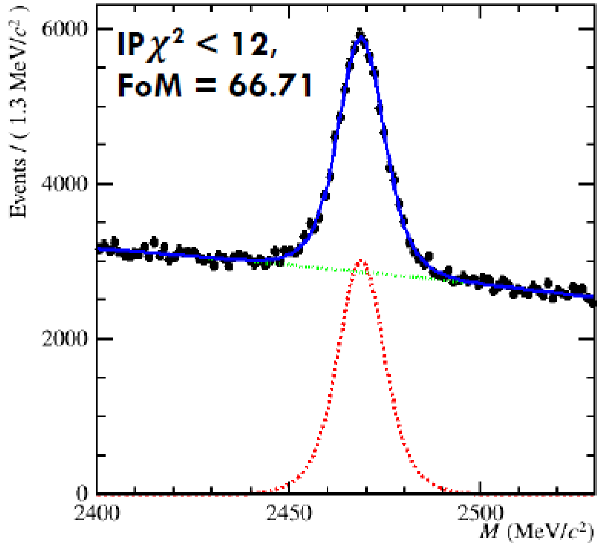
Different cuts are considered: $\mathrm{IP}\chi^2 < 10$, $\mathrm{IP}\chi^2 < 12$



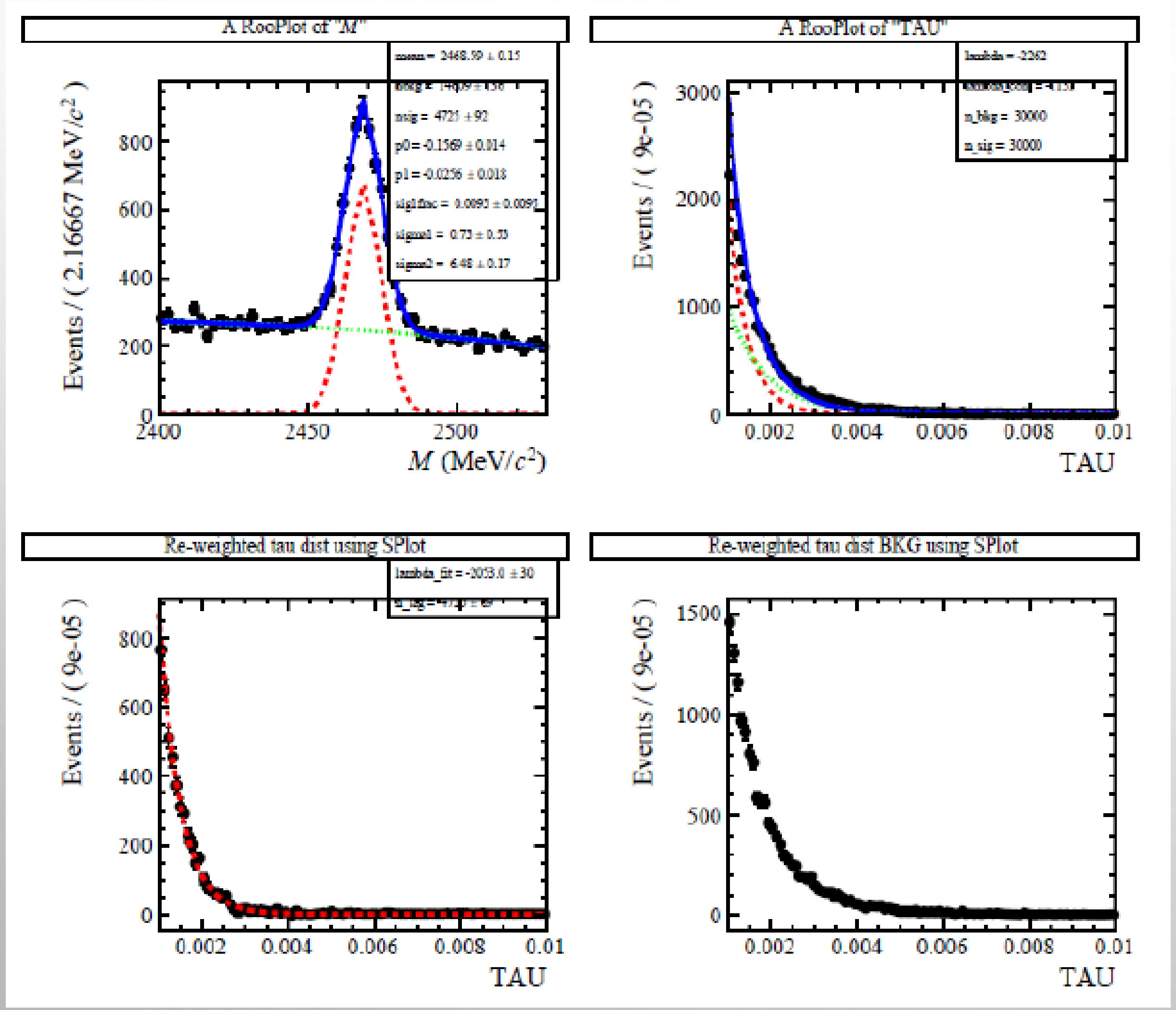


$$Eff = \frac{\#entries\ left\ after\ cut}{\#all\ entries}$$



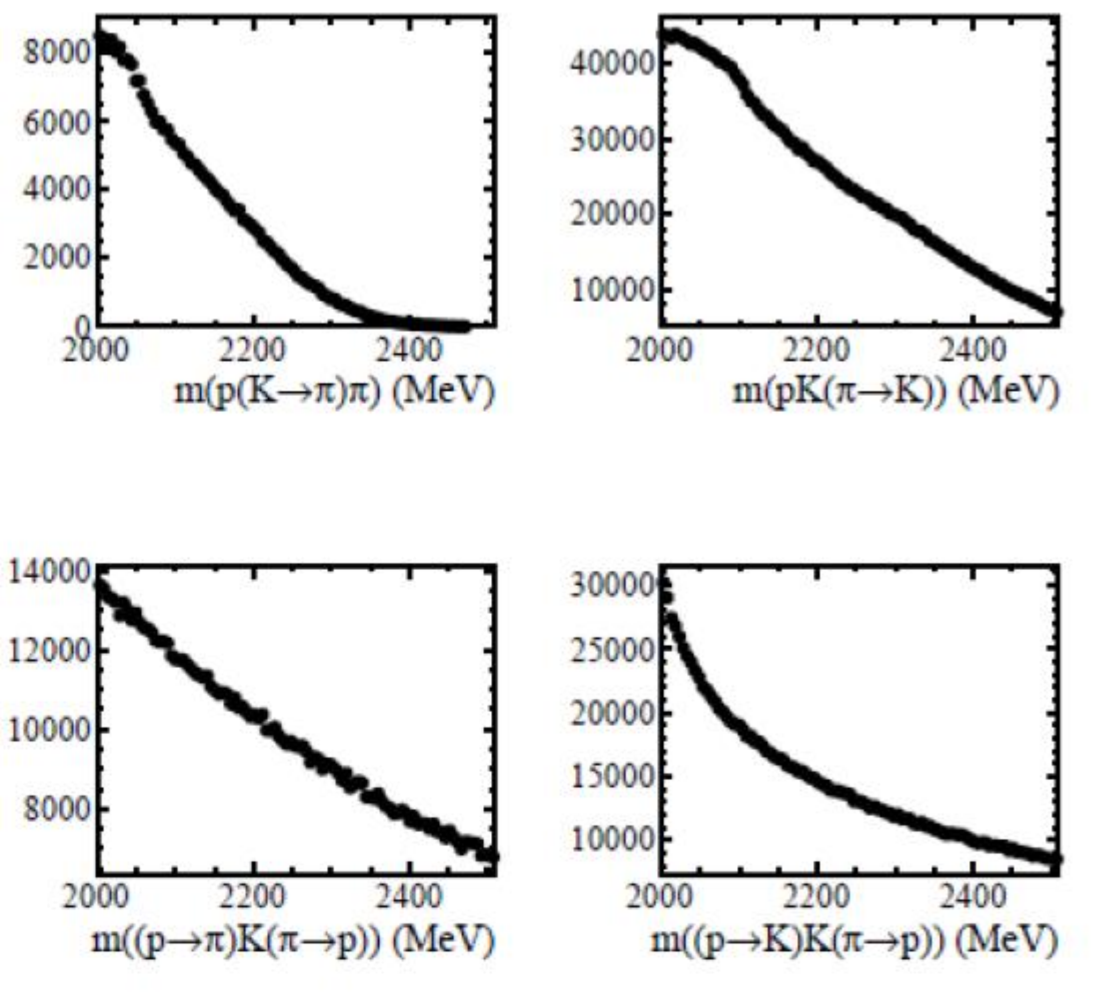


CROSS-CHECKS – LIFETIME



- sPlot technique is also used to determine lifetime of Ξ_c
- $\tau = 0.487 +/- 0.007$ ps
- Contamination from other decays seems to be negligible

CROSS-CHECKS – WRONG MASS HYPO

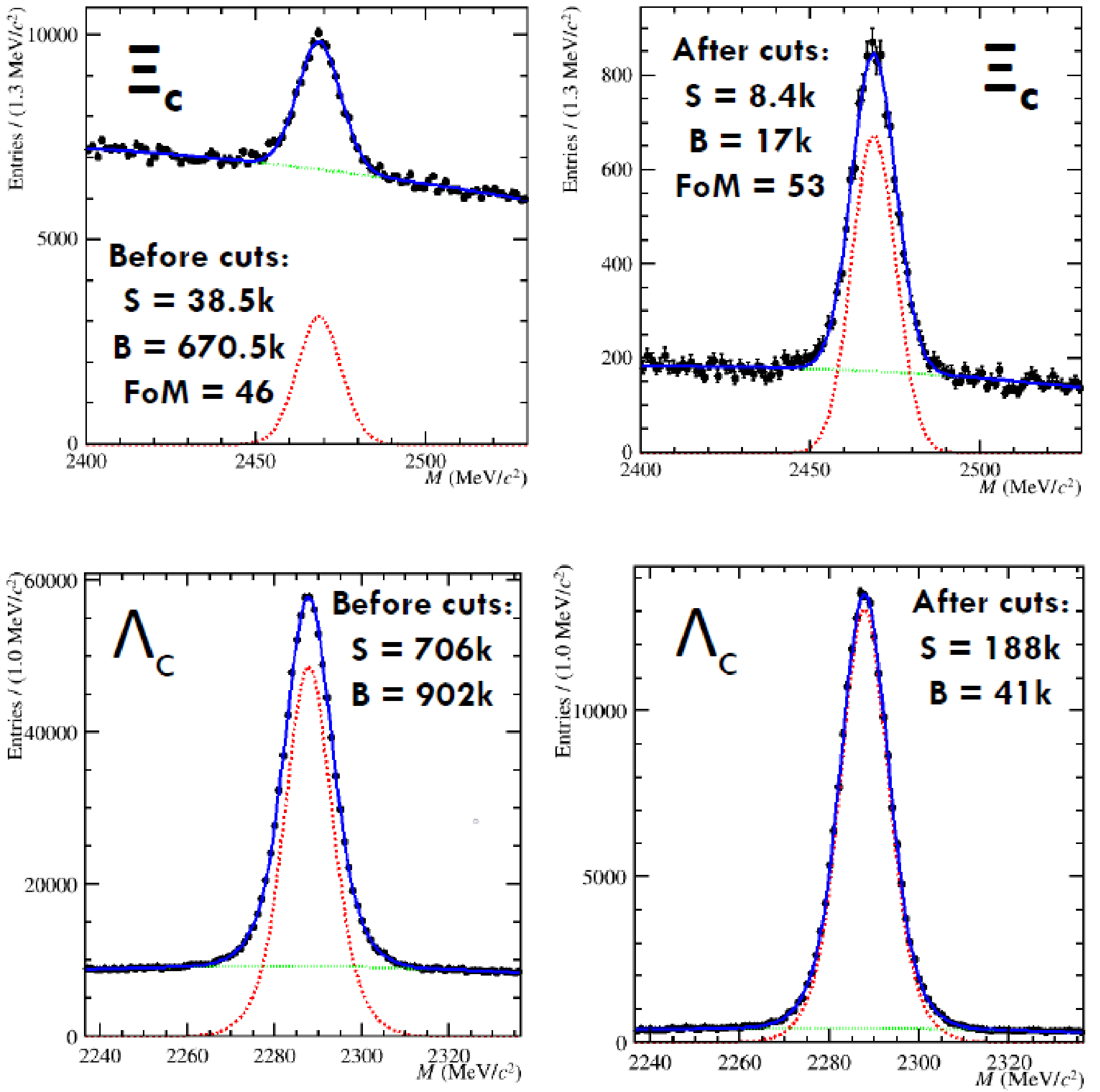


False particle identification is investigated as additional cross-check

- $K \to \pi$
- $\pi \to K$ ...
- 7 combinations
- ~ 1% of data
- 3 mass ranges for better visibility
  - (1200, 1800) MeV
  - (1800, 2000) MeV
  - (2000, 2500) MeV

No mass peaks from the other decays: D, D_s, Λ_b etc.

EVENT YIELDS – FINAL SELECTION



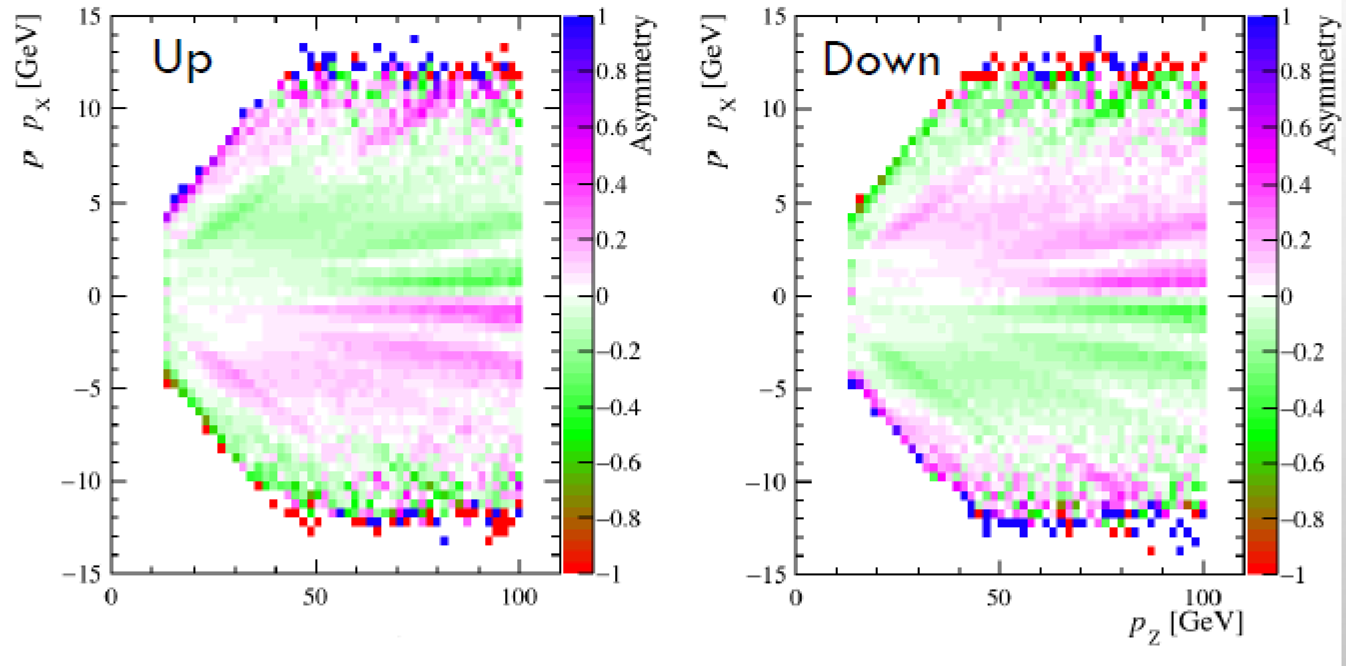
2018	Before offline cuts	After SC (including bkg)
Λ_c	~ 170 mln	~ 20 mln
Ξ_c	~10 mln	~ 4,5 mln

- ☐ Note, this is fully blinded analysis, only ~1% of the data sample used in tests and cut optimisation
- ☐ This is necessary to tune fiducial cuts that take into account the boundary detector effects
- ☐ Close to impossible to get it from MC or the control channel
- ☐ The control channel used for testing the biases in CPV estimation

EVENT YIELDS – FIDUCIAL CUTS

- Geometry of the detector can be not uniform
- Whole data sample
- Detection asymmetries expected in external regions and close to the beam axis
- Asymmetry in PX and PZ

$$Asymmetry = \frac{N_{+} - N_{-}}{N_{+} + N_{-}}$$



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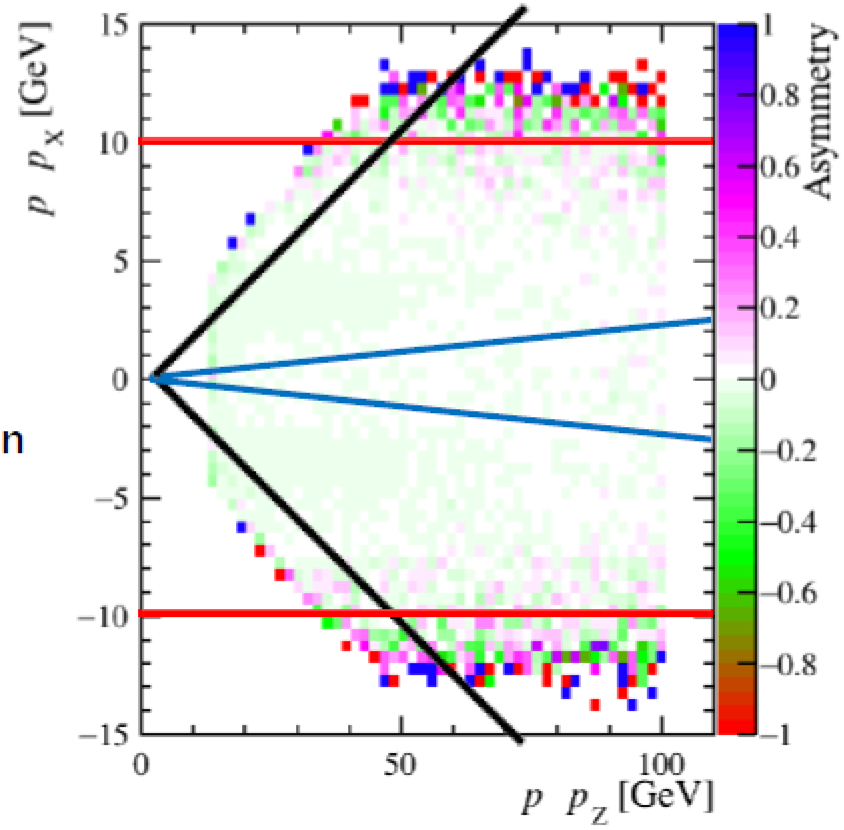
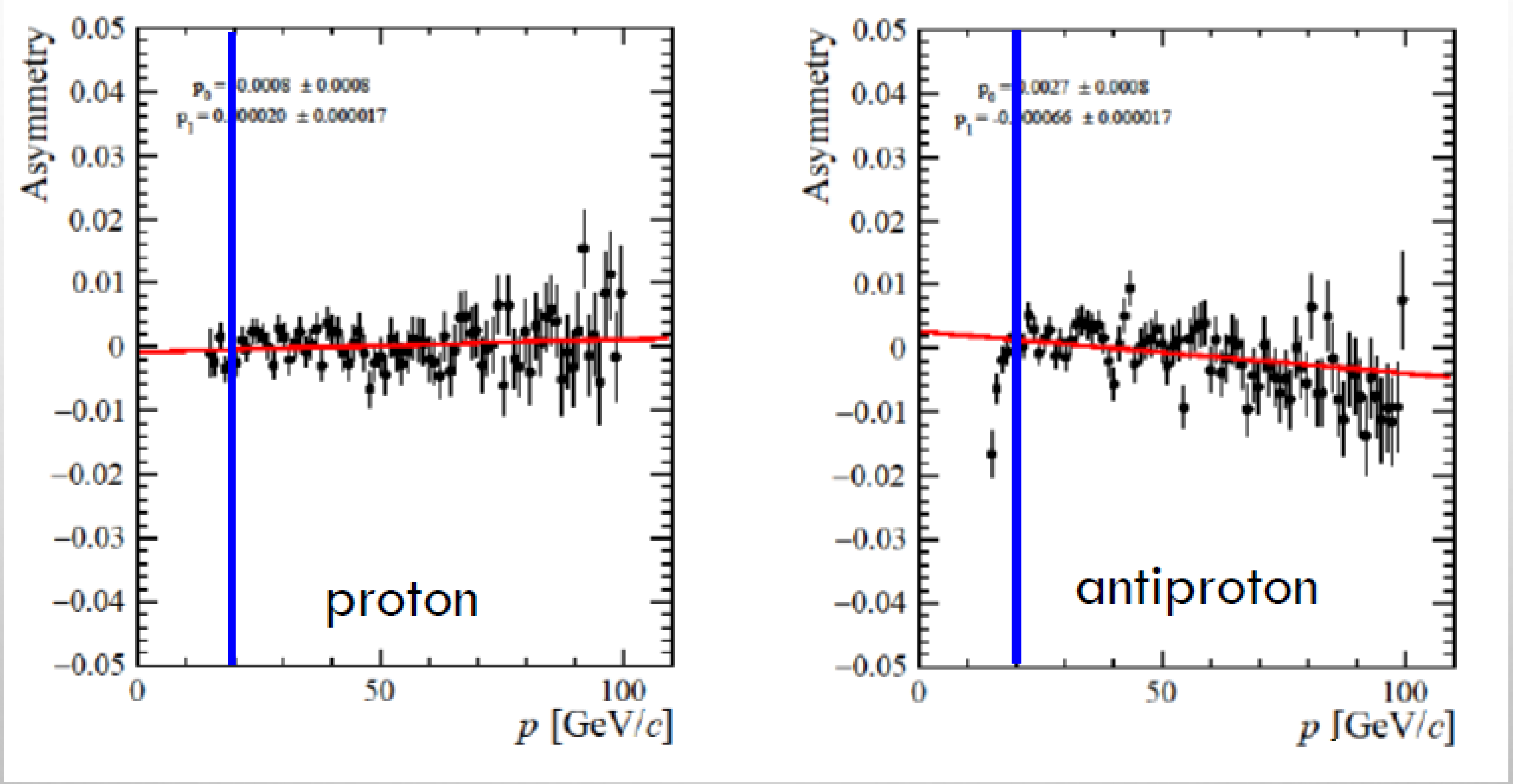
Up
+
Down



p_x vs p_z

Proton

EVENT YIELDS – TRACKING EFFECTS



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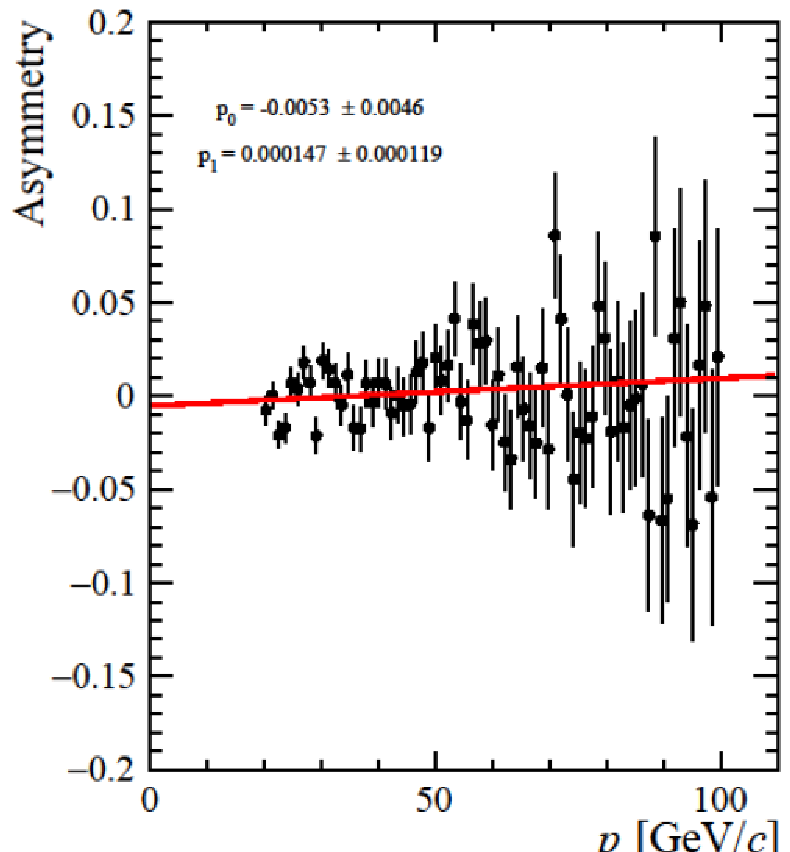
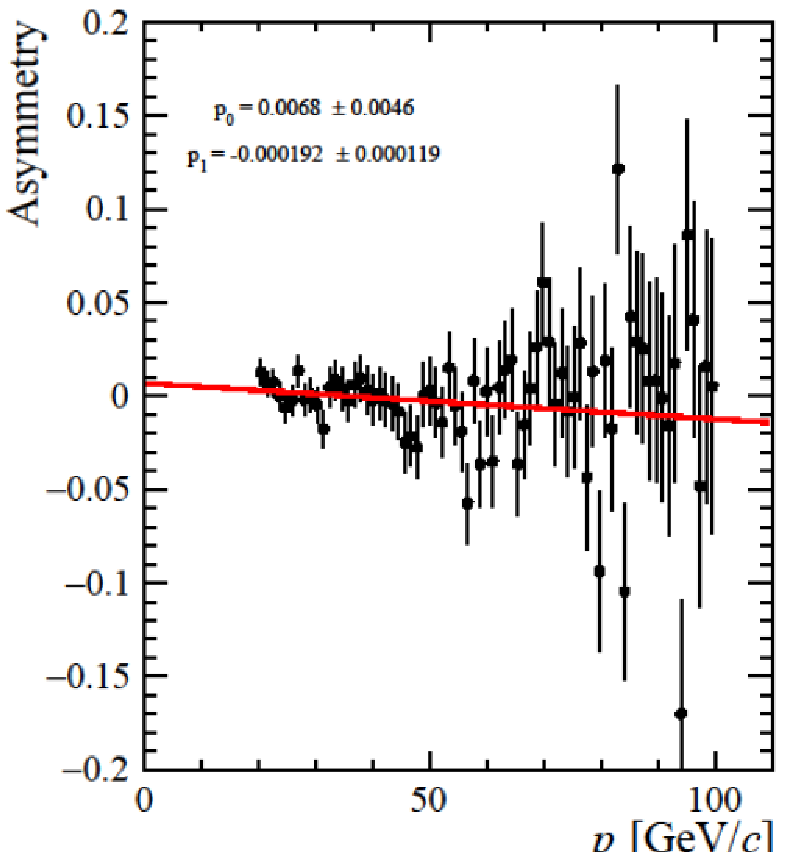


proton



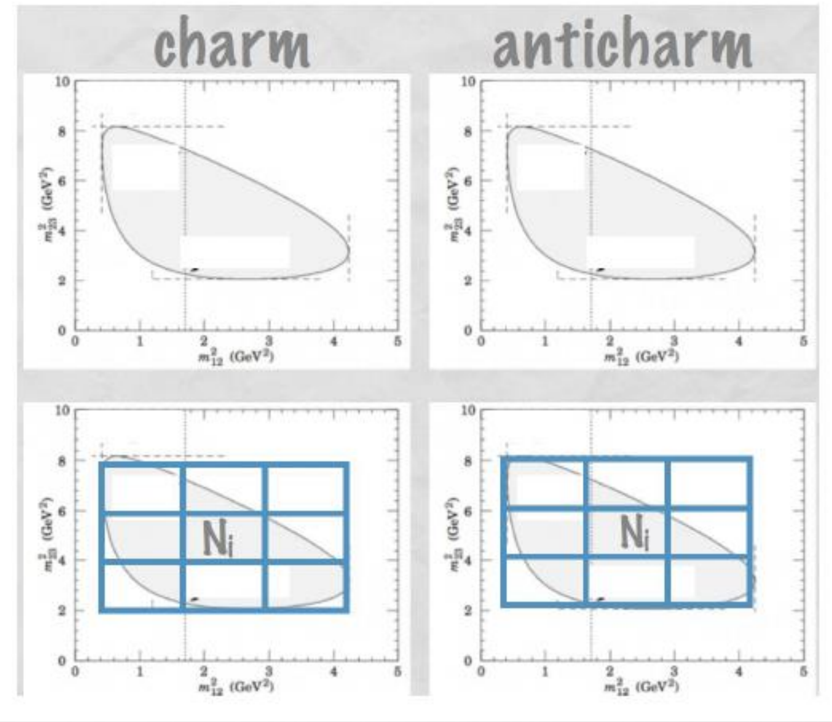
antiproton

CPV WITH S_{CP}

- This method in well-known and commonly used in many analyses:
- The method is based on dividing the phase space into n bins. For each bin, comparison between Dalitz plots for particles and antiparticles is performed.
- Significance of the difference between number of particles (N^+) and antiparticles (N^-) is computed, using the following expression:

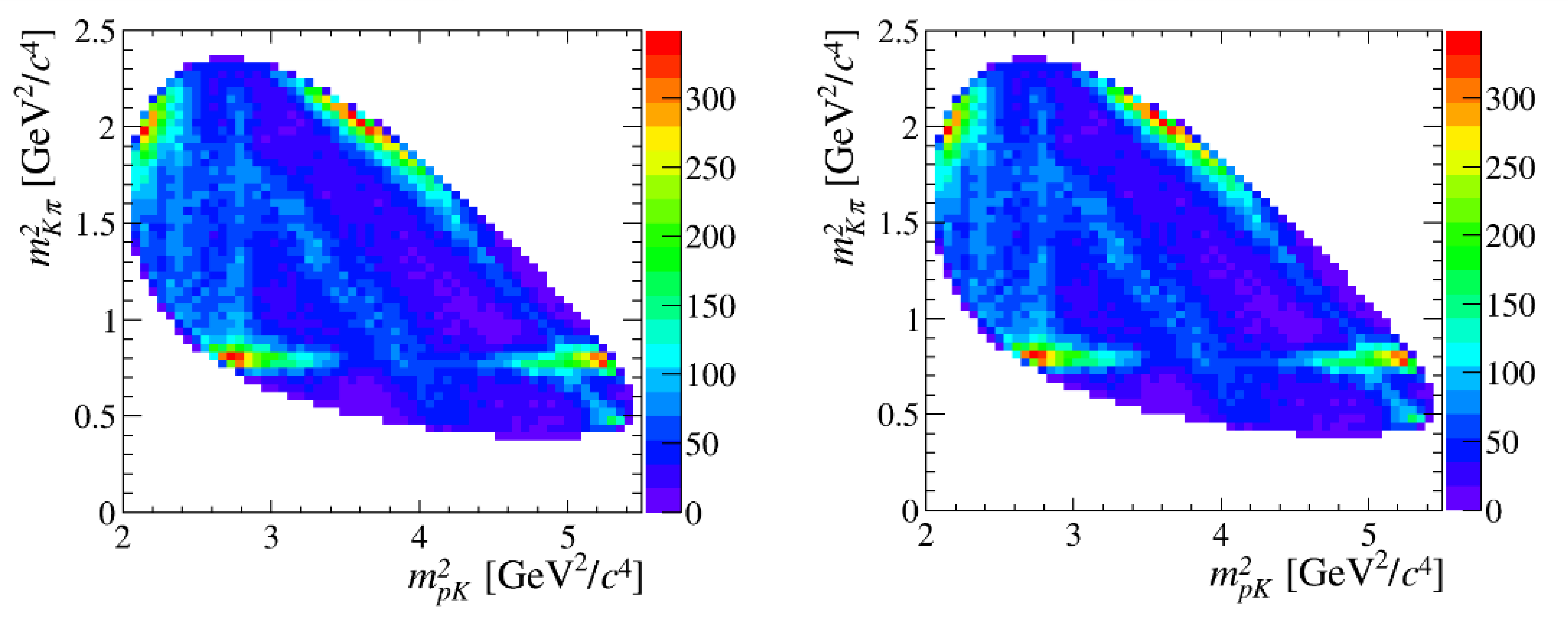
$$S_{CP}^{i} = \frac{N_i^+ - \alpha N_i^-}{\sqrt{\alpha(N_i^+ + N_i^-)}}$$

where **$\alpha = N^+/N^-$** accounts for global asymmetries



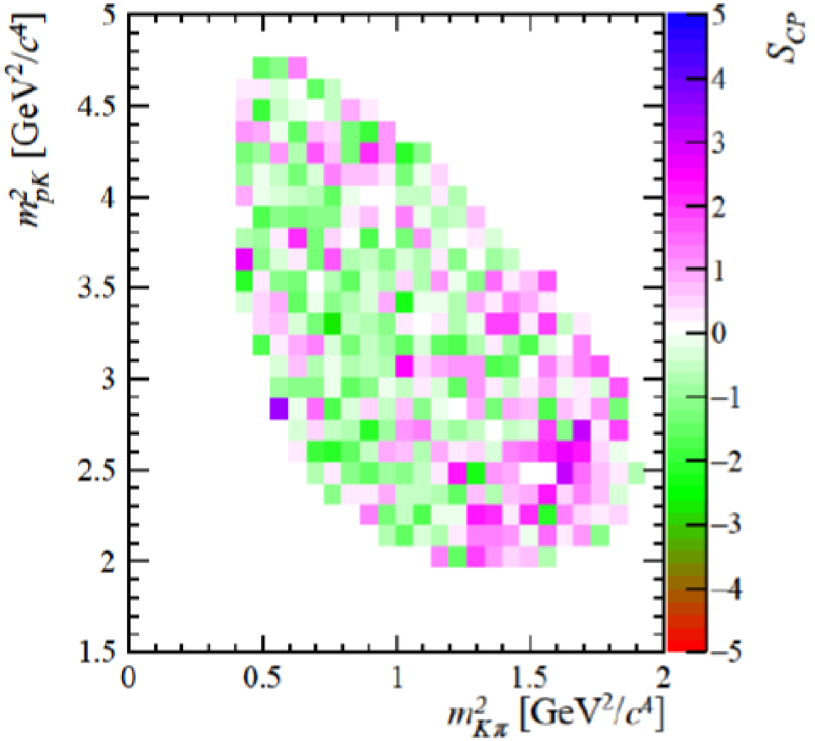
- Without local asymmetries S_{CP} is Gaussian distribution with **$\mu = 0$** and **$\sigma = 1$**.
- Calculating a $\chi^2/_{ndf} = \sum_i (S_{CP}^i)^2 / _{(nbins\,-1)}$
- Measuring ***p-value***
- ***p-value « 1 in case of CPV***

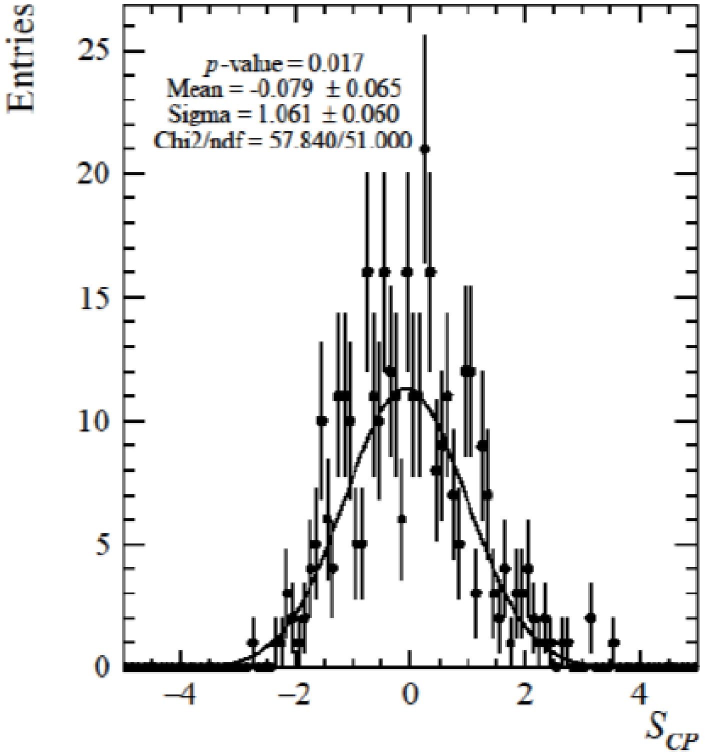
DALITZ PLOTS FOR 2018 (CONTROL CHANNEL)



S_{CP} 2018 (CONTROL CHANNEL)

- Example with 52 bins
- p-value = 1.7%
- If still there are any pollution asymmetry, it is below method sensitivity
- Result is in agreement with no observation of CPV – as expected ☺





KDE APPROACH

- Kernel Density Estimation is a non-parametric way to estimate the probability density function ***f*** of a random variable.

$$f(\hat{x}) = \frac{1}{n}\sum_{i=1}^{n} \omega(x - x_i, h)$$

where:

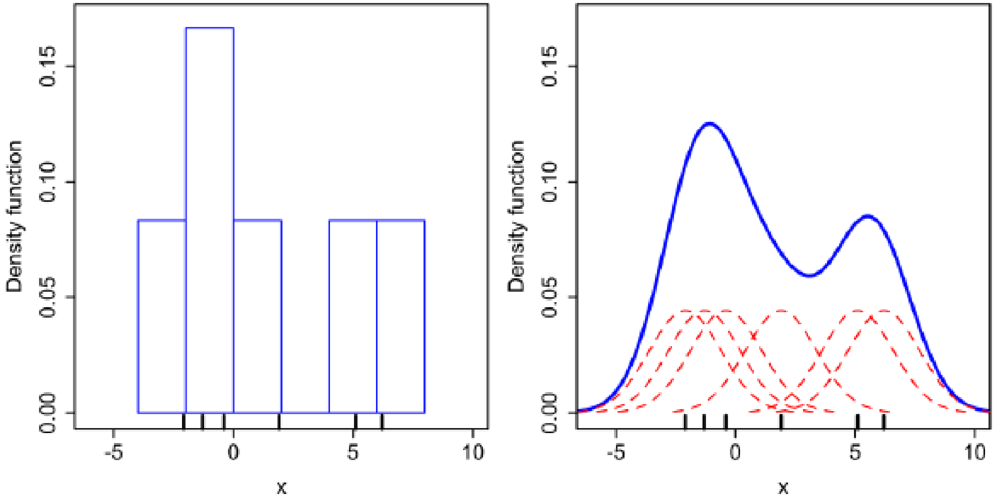
$$\omega(t,h) = \frac{1}{h}K(\frac{t}{h})$$

is weighting function.

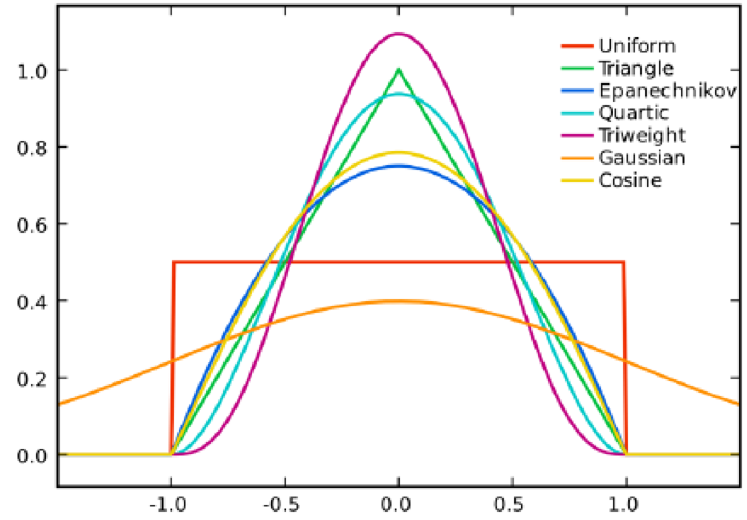
- ***K*** is the kernel, which determines the shape of the weighting function and ***h*** is the smoothing parameter.
- In this analysis I use **triangle kernel**:

$$\omega(t,h) = \begin{cases} \frac{1}{h}\left(1-\frac{|t|}{h}\right) & for\ |t| < h \\ 0 & otherwise \end{cases}$$

KDE method was tested in $K^*\mu\mu$ decays [CERN-THESIS-2010-186]

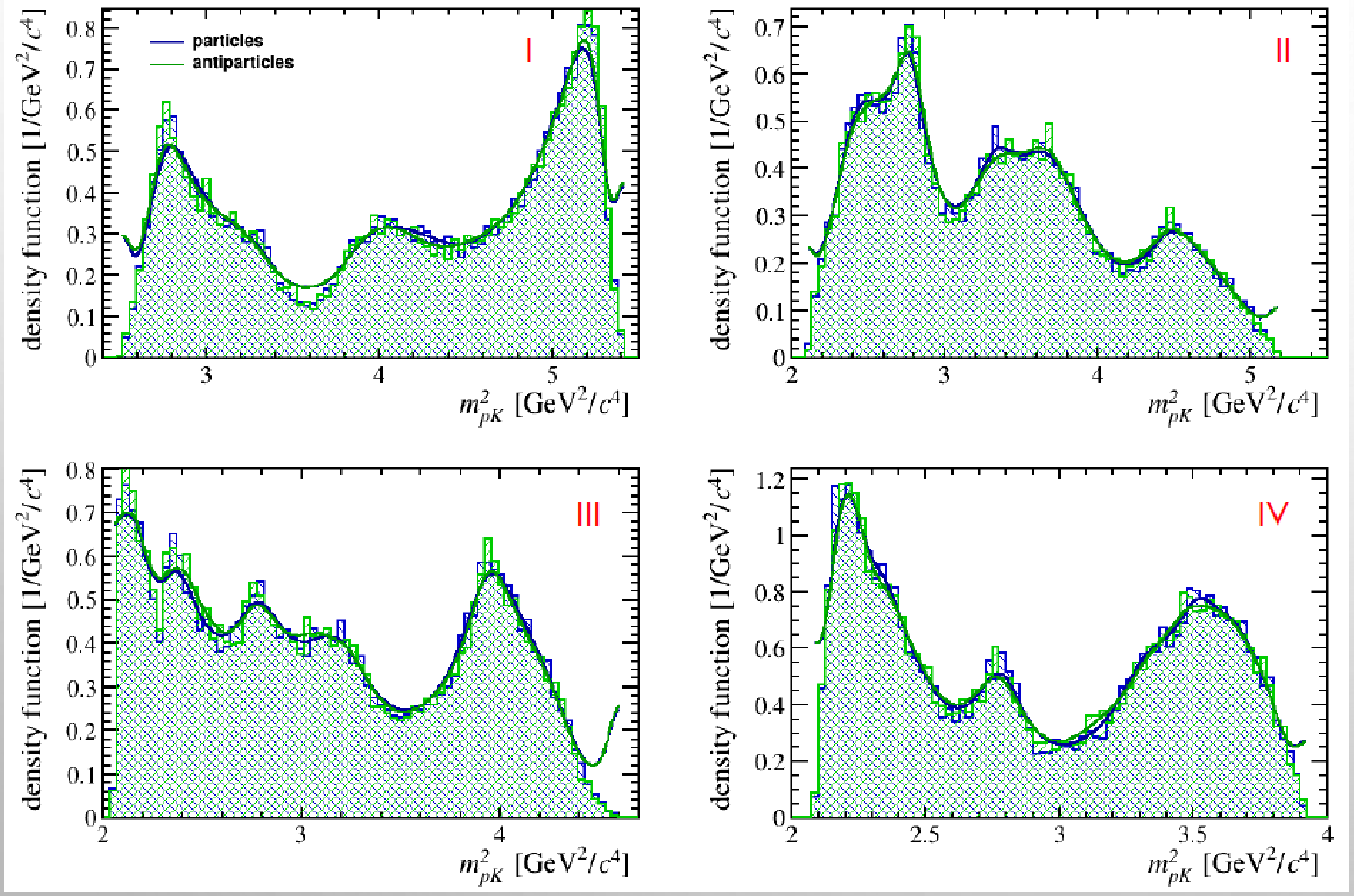


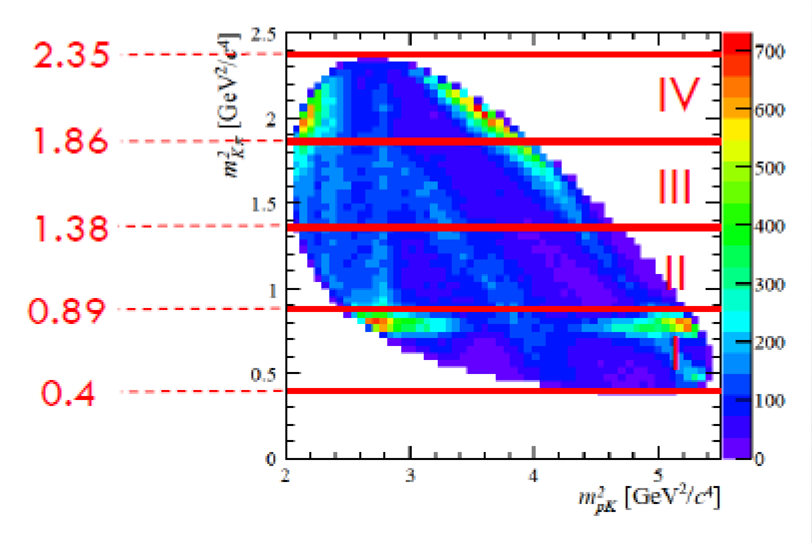
KDE example with Gaussian Kernel



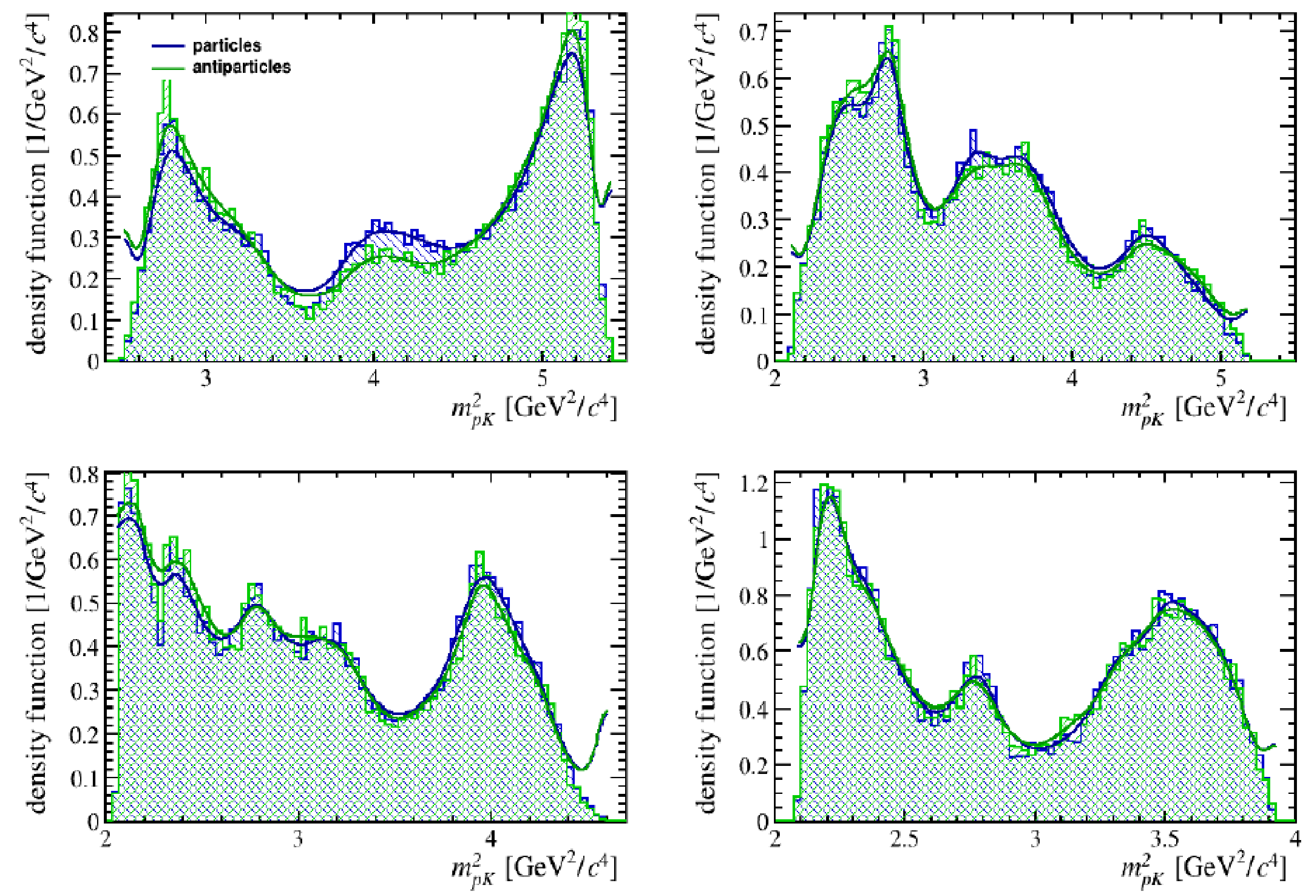
Commonly used kernels

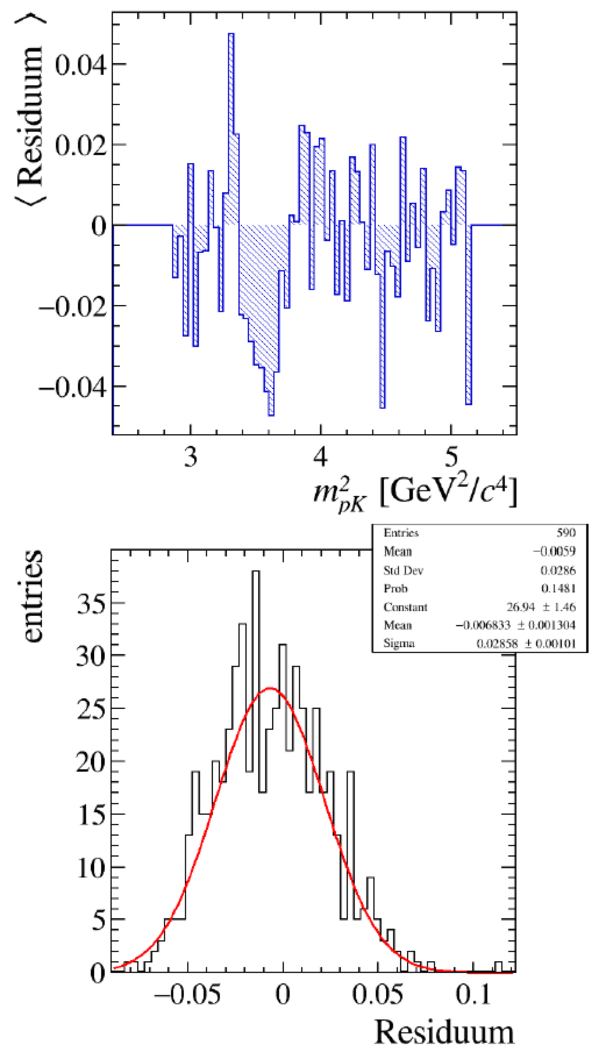
KDE APPROACH – NO CPV SAMPLE





KDE APPROACH – CPV SAMPLE (20%)



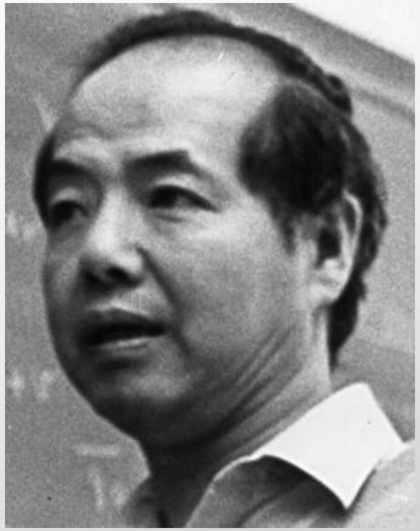



LOST PROPERTY
"Sorry Doc, we had a load of Anti-Matter around 13 billion years ago, but it got lost when we moved"

SPARES

SYMMETRIES…

T.D.Lee:
"The root to all symmetry principles lies in the assumption that it is impossible to observe certain basic quantities; the non-observables"



Four main types:

- Particle permutations:
  Bose-Einstein'a and Fermi-Dirac'a statistics
- Continuous transformations:
  translations, rotations, boosts,…
- Discrete symmetries:
  space parity, time parity, charge parity
- Unitary symmetries: gauge invariance
  U_1(charge), SU_2(isospin), SU_3(color),..

$\Rightarrow$ If we found symmetry that cannot be, even in principle, observed exact symmetry

$\Rightarrow$ Otherwise broken symmetry

Noether's theorem: SYMMETRY $\Longleftrightarrow$ Conservation Law

SHORT HISTORY OF FLAVOUR PHYSICS

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

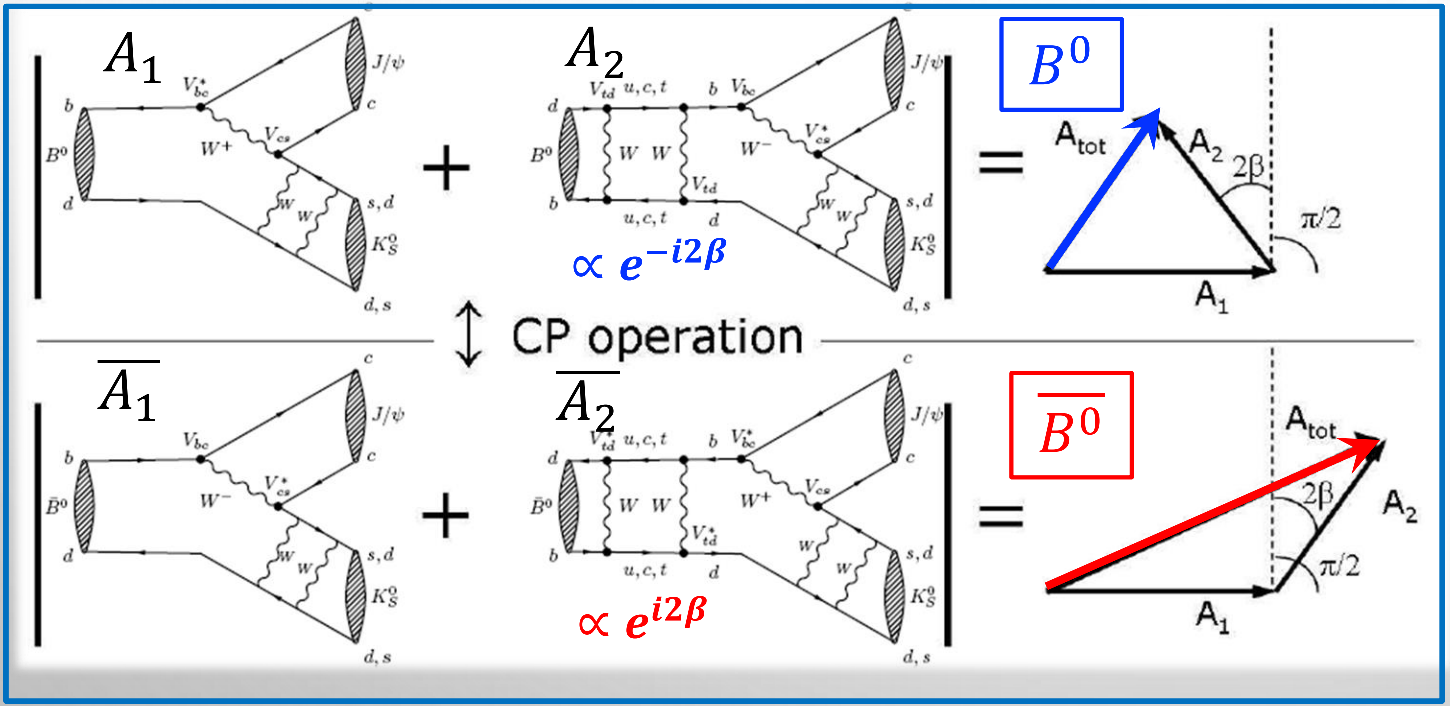
1973
The CKM matrix
M. Kobayashi and
T. Maskawa

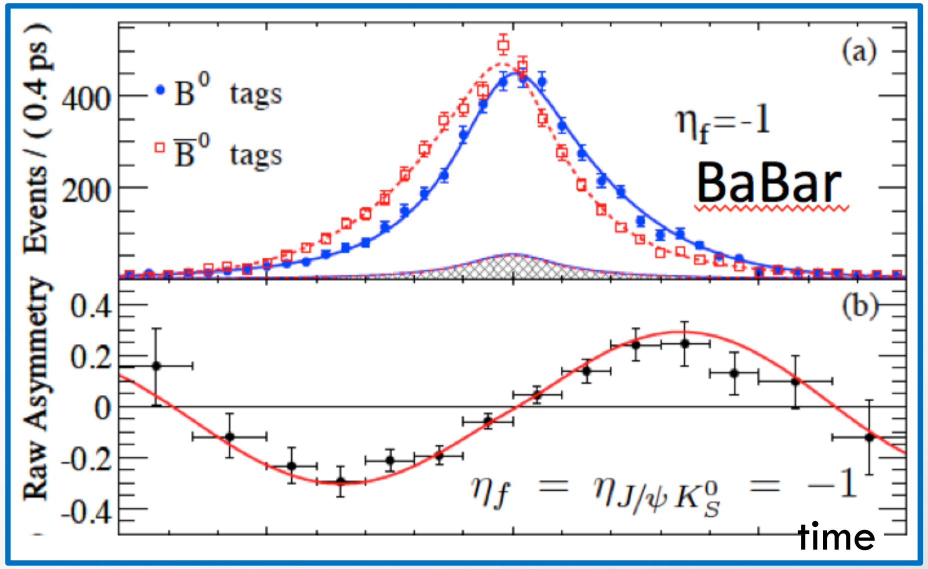
2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

TODAY

- Przejście kwantowe z dwoma amplitudami A_1 i A_2:
  - Eg.: $A_1 = B^0 \to J/\psi\, K_s$ and $A_2 = B^0 \to \overline{B^0} \to J/\psi\, K_s$



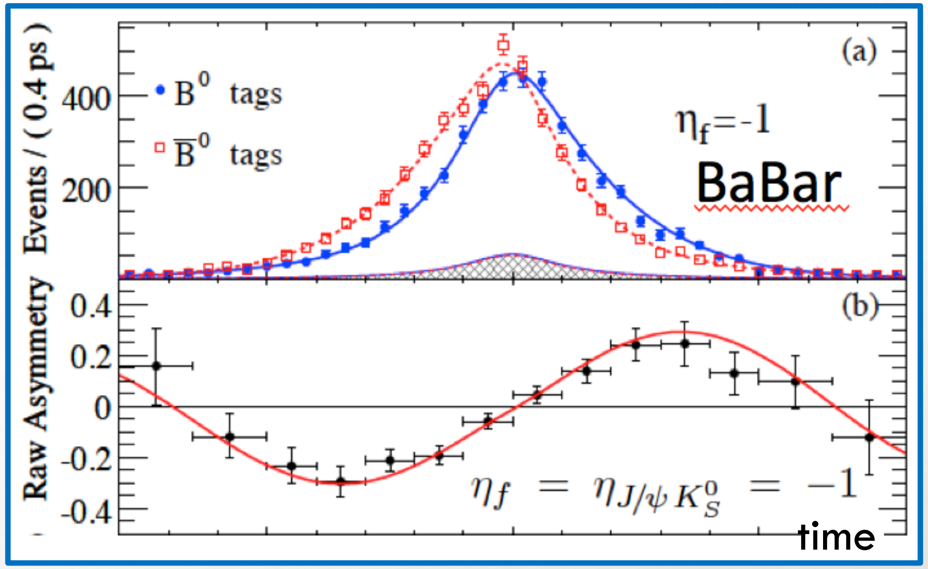


$$|A_1| = |\overline{A_1}|\,,\ |A_2| = |\overline{A_2}|\,,$$

but $|A_1 + A_2| \neq |\overline{A_1 + A_2}|$

ŁAMANIE CP : EKSPERYMENT Z „DWOMA SZCZELINAMI”

- Przejście kwantowe z dwoma amplitudami A_1 i A_2:
    - Eg.: $A_1 = B^0 \to J/\psi\, K_s$ and $A_2 = B^0 \to \overline{B^0} \to J/\psi\, K_s$



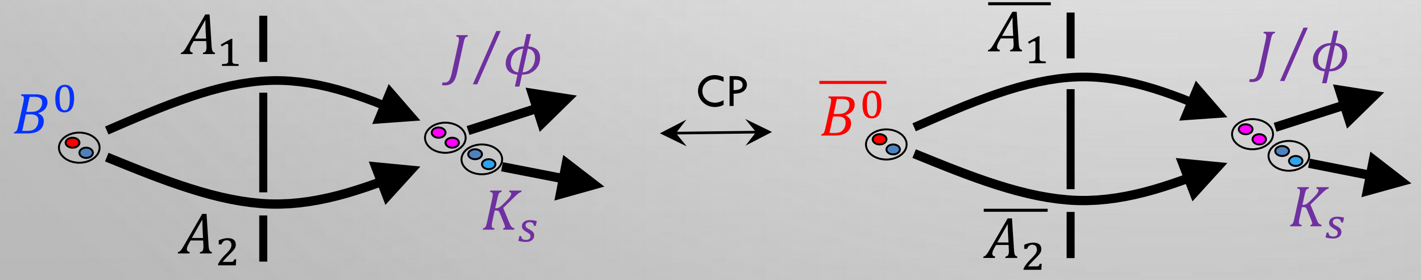
$$A = A_1 + A_2 e^{i\phi} e^{i\delta} \qquad \bar{A} = A_1 + A_2 e^{-i\phi} e^{i\delta}$$

$$|A|^2 = |A_1|^2 + |A_2|^2 + A_1 A_2 \left(e^{i\phi} e^{i\delta} + e^{-i\phi} e^{-i\delta}\right)$$

$$|\bar{A}|^2 = |A_1|^2 + |A_2|^2 + A_1 A_2 \left(e^{-i\phi} e^{i\delta} + e^{i\phi} e^{-i\delta}\right)$$

$$|A - \bar{A}|^2 = 4\, A_1 A_2 \sin\phi \sin\delta$$

$|A_1| = |\overline{A_1}|\,, |A_2| = |\overline{A_2}|\,,$
but $|A_1 + A_2| \neq |\overline{A_1 + A_2}|$



- *Łamanie CP to efektywnie interferencja kwantowo mechaniczna!!*

Pożyczony od M. Merk (LHCb)

Non-observables	Symmetry Transformations	Conservation Laws or Selection Rules
Difference between identical particles	Permutation	B.-E. or F.-D. statistics
Absolute spatial position	Space translation $\vec{r} \to \vec{r} + \vec{\Delta}$	momentum
Absolute time	Time translation $t \to t + \tau$	energy
Absolute spatial direction	Rotation $\hat{r} \to r'$	angular momentum
Absolute velocity	Lorentz transformation	generators of the Lorentz group
Absolute right (or left)	$\vec{r} \to -\vec{r}$	parity
Absolute sign of electric charge	$e \to -e$	charge conjugation
Relative phase between states of different charge Q	$\psi \to e^{iQ\theta}\psi$	charge
Relative phase between states of different baryon number B	$\psi \to e^{iN\theta}\psi$	baryon number
Relative phase between states of different lepton number L	$\psi \to e^{iL\theta}\psi$	lepton number
Difference between different co-herent mixture of p and n states	$\begin{pmatrix} p \\ n \end{pmatrix} \to U \begin{pmatrix} p \\ n \end{pmatrix}$	isospin

The D^0 and $\overline{D}^0$ mesons are produced as flavor eigenstates
They propagate and decay according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Mixing occurs because D^0 and $\overline{D}^0$ are linear combinations of mass eigenstates

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

The mass eigenstates develop in time as follow

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$

$$e_{1,2}(t) \equiv \exp\left[-i\left(M_{1,2} - \frac{i}{2}\Gamma_{1,2}\right)t\right]$$

Two parameters characterize the D^0 and $\overline{D}^0$ mixing

$$x \equiv \frac{\Delta M}{\Gamma},\ \Delta M \equiv M_1 - M_2$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma},\ \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

If either x or y are different from zero, mixing occurs

$$\begin{aligned} |\langle\overline{D}^0|D^0(t)\rangle|^2 &= \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right] \\ |\langle D^0|\overline{D}^0(t)\rangle|^2 &= \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right] \end{aligned}$$