Structure

1. FCNC ⟶ no FCNC at tree level
2. How should an flavour experiment look like
3.

Theory that describes fundamental particles and their interactions is the Standard Model (SM)

$$\mathcal{G}_{SM} = \underbrace{SU(3)_c}_{\text{strong}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{electroweak}}$$

flavour conserved global symmetry — symmetry is broken

Focus of this lecture will be on the electroweak sector

Flavour physics: Study difference between the generations such as masses, flavour transitions and CP-violation

$$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix} \quad \left(= \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix} \right)$$ Left handed SU(2) doublets

(i: generation index)

$u_{Ri} = (u_R, c_R, t_R)$ Right handed SU(2) singlets

$d_{Ri} = (d_R, s_R, b_R)$

Yukawa matrix, complex, non-diagonal

$$\mathcal{L}_{Yukawa} = Y^d_{ij}\, \overline{Q}_{Li}\, \phi\, d_{Rj} + Y^u_{ij}\, Q_{Li}\, \tilde{\phi}\, u_{Rj} + h.c.$$

Higgs symmetry breaking

$$= \frac{v}{\sqrt{2}} \left(\bar{d}_{Li} Y^d_{ij} d_{Rj} + \bar{u}_{Li} Y^u_{ij} u_{Rj} \right) + h.c.$$

$$= \bar{d}_{Li} \underbrace{V^+_{Ld} V_{Ld}}_{=1} \underbrace{\frac{v}{\sqrt{2}} Y^d_{ij} \overbrace{V^+_{Rd} V_{Rd}}^{=1}}_{M^d_{ij}} d_{Rj} + \bar{u}_{Li} \overbrace{V^+_{Lu} V_{Lu}}^{=1} \underbrace{\frac{v}{\sqrt{2}} Y^u_{ij} \overbrace{V^+_{Ru} V_{Ru}}^{=1}}_{M^u_{ij}} u_{Rj} + h.c.$$

Skipped

V is defined such that $\frac{v}{\sqrt{2}} V_{Ld} Y^d_{ij} V^+_{Rd} = diag(m_d, m_s, m_b) = M^d$

and $\frac{v}{\sqrt{2}} V_{Lu} Y^u_{ij} V^+_{Ru} = diag(m_u, m_c, m_t) = M^u$

and $\tilde{u}_L = V_{Lu} u_L \quad \tilde{u}_R = V_{Ru} u_R \quad \Rightarrow \quad u_L = V^+_{Lu} \tilde{u}_L \quad u_R = V^+_{Ru} \tilde{u}_R$

$\tilde{d}_L = V_{Ld} d_L \quad \tilde{d}_R = V_{Rd} d_R \quad \quad d_L = V^+_{Ld} d_L \quad d_R = V_{Rd} d_R$

insert

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \left(\bar{u}_{Li} \gamma^\mu W^+_\mu d_{Li} + \bar{d}_{Li} \gamma^\mu W^-_\mu u_{Li} \right)$$

$$= -\frac{g}{\sqrt{2}} \left(\tilde{\bar{u}}_{Li} \gamma^\mu W^+_\mu \underbrace{(V_{Lu} V^+_{Ld})_{ij}}_{V_{CKM}} \tilde{d}_{Lj} + \tilde{\bar{d}}_{Li} \gamma^\mu W^-_\mu \underbrace{(V_{Ld} V^+_{Lu})_{ij}}_{V^+_{CKM}} \tilde{u}_{Lj} \right)$$

$$\mathcal{L}_{NC} = \frac{g}{c_W} \left\{ \bar{u}_L \gamma^\mu \left(\tfrac{1}{2} - \tfrac{2}{3} s^2_W\right) u_L + \bar{u}_R \gamma^\mu \left(-\tfrac{2}{3} s^2_W\right) u_R + \bar{d}_L \gamma^\mu \left(-\tfrac{1}{2} + \tfrac{1}{3} s^2_W\right) d_L + \bar{d}_R \gamma^\mu \left(\tfrac{1}{3} s^2_W\right) d_R \right\} Z^0_\mu$$

⇒ flavour diagonal ⇒ no flavour mixing

$s_W = \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$ electroweak mixing angle

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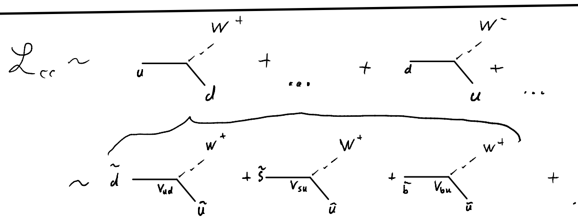
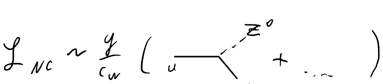


Transition between generations



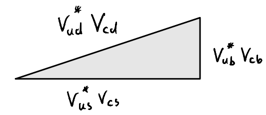
flavour diagonal ⇒ no flavour mixing

$V^+ V = 1$

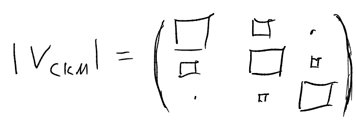
Properties of V_{CKM}:

- Unitary $(V^+ V = V V^+ = 1)$
- 3 real parameters and 1 phase ⟶ Reason for CPV

Remark
First: 18 parameters (9 real + 9 phases)
↓
Unitary: 9 parameters (3 real + 6 phases)
↓
5 phases are absolut quark phases : 4 parameters (3 real + 1 phase)



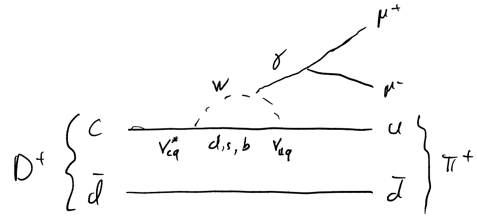
One goal is to overconstrain the unitarity triangle to search for new physics



Magnitude of CKM elements is purely based on measurements

$$V_{CKM} \simeq \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda = |V_{us}| \sim 0{,}22$
[PDG review]

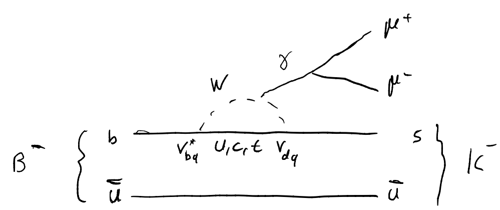


$$A_{SM} \propto \underbrace{V^*_{cd} V_{ud}\, f\!\left(\tfrac{m_d^2}{m_W^2}\right)}_{} + V^*_{cs} V_{us}\, f\!\left(\tfrac{m_s^2}{m_W^2}\right) + V^*_{cb} V_{ub}\, f\!\left(\tfrac{m_b^2}{m_W^2}\right) \qquad \boxed{f\!\left(\tfrac{m_q^2}{m_W^2}\right) \sim \tfrac{1}{100} \tfrac{m_q^2}{m_W^2}}$$

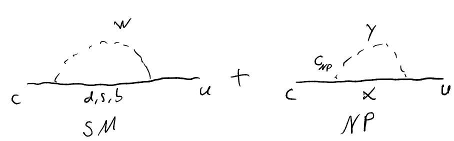
$$= -V^*_{cs} V_{us} f\!\left(\tfrac{m_d^2}{m_W^2}\right) - V^*_{cb} V_{ub} f\!\left(\tfrac{m_d^2}{m_W^2}\right)$$

$$= \underbrace{V^*_{cs} V_{us}}_{\sim\lambda} \underbrace{\left(f\!\left(\tfrac{m_s^2}{m_W^2}\right) - f\!\left(\tfrac{m_d^2}{m_W^2}\right) \right)}_{\text{"GIM suppressed"}} + \underbrace{V^*_{cb} V_{ub}}_{\sim\lambda^5} \left(f\!\left(\tfrac{m_b^2}{m_W^2}\right) - f\!\left(\tfrac{m_d^2}{m_W^2}\right) \right) \approx 10^{-8}$$

"CKM suppressed"



$$A_{SM} \propto \underbrace{V^*_{bt} V_{st}}_{\lambda^2} \underbrace{f\!\left(\tfrac{m_t^2}{m_W^2}\right)}_{O(10^{-2})} \approx 10^{-3}$$



$$\sim A_0 \left(\frac{m_q}{m_W^2} + \frac{c_{NP}}{\Lambda_{NP}} \right)$$

The goal of flavour experiments is often to look at these loop processes to indirectly search for new physics. Even particles to heavy for direct production can contribute and change the final rate.

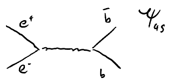
Experiment

Flavour experiment wish list

1. Large amount of data
2. Particle identification
3. Decay-time/Vertex resolution
4. Momentum resolution

1. Heavy flavour production

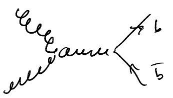
- e^-e^+ collider e.g. Belle II, BES III
  Babar, Belle, Argus



Ψ_{4s}

- low background
- initial state kinematics known
- lower cross section

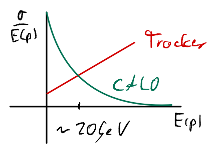
- hadron colliders e.g. LHCb, Atlas, CMS, ...
  CDF, D0



- high cross section
- large background
- Not known initial state kinematics

2. Particle Identification

Main idea is to stop particle with enough mass and measure deposited energy. In an ideal case the energy from the shower is contained inside the calorimeter.



good mass resolution for high energies (e.g. for CMS Calo resolution is better than tracker resolution (momentum))

Electromagnetic Calorimeter ECAL $\quad \frac{\sigma_E}{E} \sim \frac{3\% - 10\%}{\sqrt{E\,[GeV]}}$

- contains complete γ and e^- showers
- 66 layers of 4 mm scintilators between 2 mm thick lead

Hadronic Calorimeter HCAL $\quad \frac{\sigma_E}{E} \sim \frac{50\%}{\sqrt{E\,[GeV]}}$

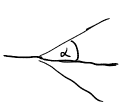
- contains most charged and neutral hadron showers
- layers of scintilators and iron

Muon chambers

- Normaly most distaned detector from interaction point
- defects charged tracks

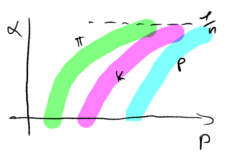
Cherenkov detector

- generell idea: measure $\beta\ (= \frac{v}{c})$ to infer m if p is known
  e.g. @LHCb Ring Imaging Cherenkov Detector

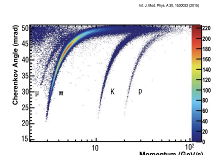


$$\cos(\alpha) = \frac{1}{\beta \cdot n}$$

$$\beta = pc/E$$
$$= p/\sqrt{p^2 + m^2c^2}$$

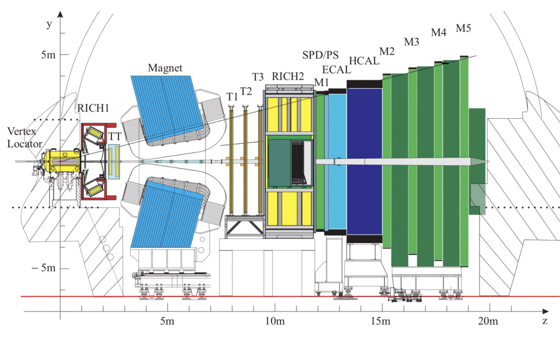


check Martine thesis



At LHCb the information of all subdetector systems is at the end combined

e	~ 90%	e → h	~ 5%
K	~ 95%	π → K	~ 5%
μ	~ 97%	π → μ	~ 1-3%



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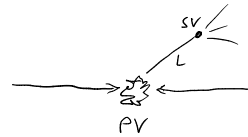
3. Vertex resolution

Tracking stations



$$t = \frac{L \cdot m}{p}$$

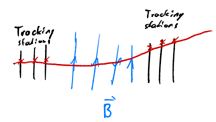
- good vertex resolution $\hat{=}$ good decay time resolution

Difficulties in calculating charm x-section
$\Lambda_{QCD} \sim 300\,MeV$ HQE works sometimes but not always
$m_c \sim 1.2\,GeV$
$m_s \sim 96\,MeV$ ← please don't ask

4. Momentum measurement

Tracking stations + magnet

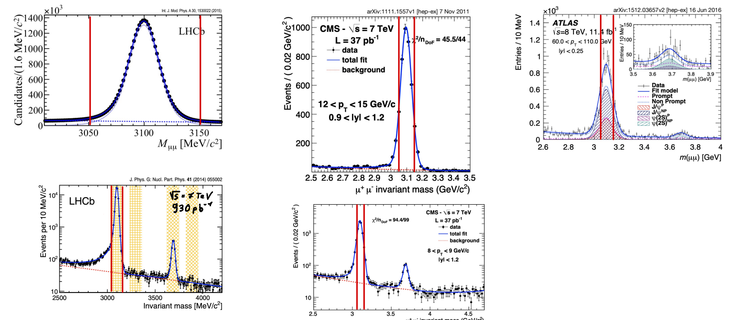
- charged particles are deflected in B-field



@LHCb $\frac{\Delta p}{p} \sim (0.5-1)\%$ ↙ 0,5% at low momentum; 1% at 200 GeV/c

- Long flying distance without material → material reduced as much as possible
- Strong magnet

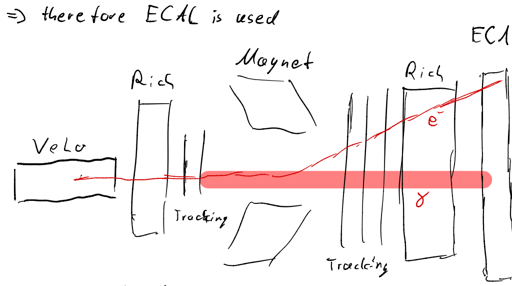
Mass resolution 14,3 ± 0,1 MeV/c^2



Electron reconstruction at LHCb

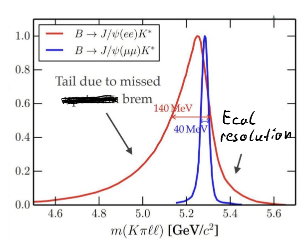
Problem (?): Bremsstrahlung ← electron interacts with detector material

if emitted before the magnet we can't use momentum from magnet
⇒ therefore ECAL is used



The probability to recover bremsstrahlung is around 50%

Advantage: Only electrons emit bremsstrahlung!!!



Slides

Parton – parton interactions producing $b\bar{b}$-quarks at TeV lead to a relatively low mass large boost in forward (and backward direction)

In case of additional time:

L0 — 40 MHz — Hardware trigger
- HCAL — Hadron
- ECAL — electron, photon
- Muon — Muon

removed in the future

↓ 1 MHz

HLT1 — Software trigger — Partial event reconstruction e.g. Singletrack, Twotrack

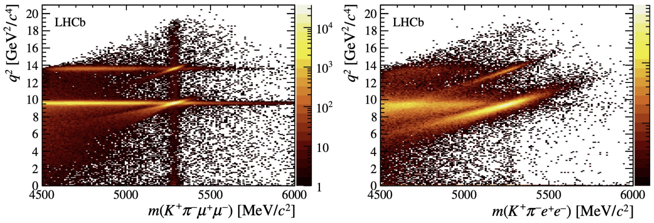
↓ 110 kHz

HLT2 — Full event reconstruction based on specific physics cases

12.5 kHz

$\psi(2S)$ ⟶

J/ψ ⟶



Next:

$D^0 \to hh\mu e$