Structure

1. FCNC $\rightarrow$ 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

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

Y: Yukawa matrix, complex, non-diagonal

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

Higgs symmetry breaking

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

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

Skipped

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

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

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

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

insert

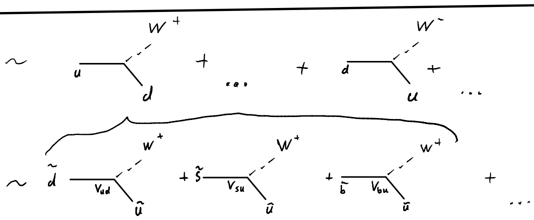
$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} (\bar{u}_{Li} \gamma^\mu W^+_\mu d_{Li} + \bar{d}_{Li} \gamma^\mu W^-_\mu u_{Li})$$

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

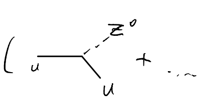
$$\mathcal{L}_{NC} = \frac{g}{c_W} \left\{ \bar{u}_L \gamma^\mu \left(\tfrac{1}{2} - \tfrac{2}{3} s^2_W\right) u_L + \bar{u}_R \gamma^\mu \left(-\tfrac{2}{3} s^2_W\right) u_R + \bar{d}_L \gamma^\mu \left(-\tfrac{1}{2} + \tfrac{1}{3} s^2_W\right) d_L + \bar{d}_R \gamma^\mu \left(\tfrac{1}{3} s^2_W\right)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

$\Rightarrow$ flavour diagonal $\Rightarrow$ no flavour mixing

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



Transition between generations

$\mathcal{L}_{NC} \sim \frac{g}{c_W} ($  $+ \dots)$

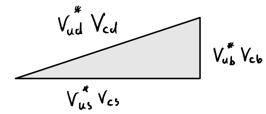
flavour diagonal $\Rightarrow$ no flavour mixing

$V^+ V = \mathbb{1}$

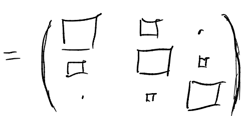
Properties of V_{CKM}:

- Unitary ($V^+ V = V V^+ = \mathbb{1}$)
- 3 real parameters and 1 phase $\rightarrow$ Reason for CPV

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



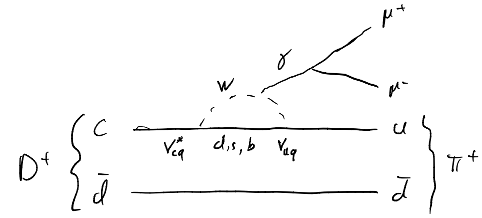
One goal is to overconstrain the unitarity triangle to search for new physics

$|V_{CKM}| =$ 

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]



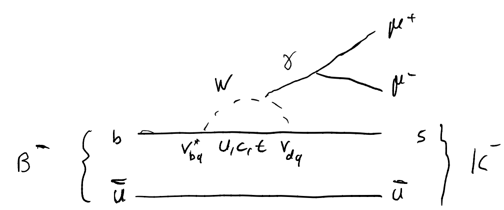
$$A_{SM} \propto \underbrace{V^*_{cd} V_{ud} f\left(\tfrac{m_d^2}{m_W^2}\right)}_{} + V^*_{cs} V_{us} f\left(\tfrac{m_s^2}{m_W^2}\right) + V^*_{cb} V_{ub} f\left(\tfrac{m_b^2}{m_W^2}\right)$$

$\boxed{f\left(\frac{m_q^2}{m_W^2}\right) \sim \frac{1}{16\pi^2} \frac{m_q^2}{m_W^2}}$

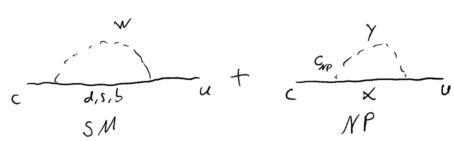
$$= - V^*_{cs} V_{us} f\left(\tfrac{m_d^2}{m_W^2}\right) - V^*_{cb} V_{ub} f\left(\tfrac{m_d^2}{m_W^2}\right)$$

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

"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.

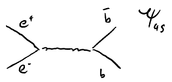
Experiment

Flavour experiment wish list

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

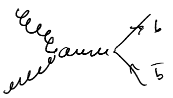
1. Heavy flavour production

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



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

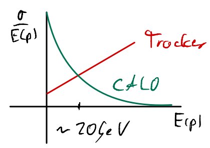
- hadron colliders e.g. LHCb, Atlas, CMS, ...
  CDF, D0



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

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

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

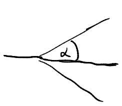
- contains most charged and neutral hadron showers
- layers of scintillators and iron

Muon chambers

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

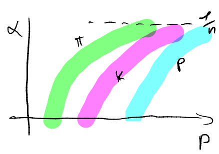
Cherenkov detector

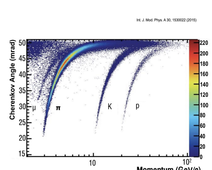
- generell idea: measure $\beta\ (=\frac{v}{c})$ to infer m if p is known
  e.g. @ LHCb Ring Imaging Cherenkov Detector



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

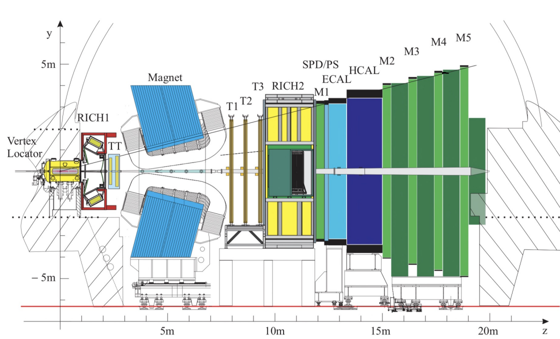
$$\beta = pc/E$$
$$= p/\sqrt{p^2 + m^2c^2}$$





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

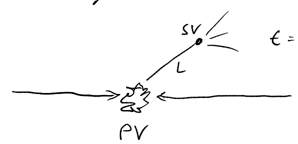
e ~ 90%	$e \to h$ ~ 5%
K ~ 95%	$\pi \to K$ ~ 5%
μ ~ 97%	$\pi \to \mu$ ~ 1-3%



Int. J. Mod. Phys. A 30, 1530022 (2015)

3. Vertex resolution

Tracking stations



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

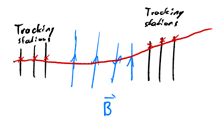
- good vertex resolution $\hat{=}$ good decay time resolution

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

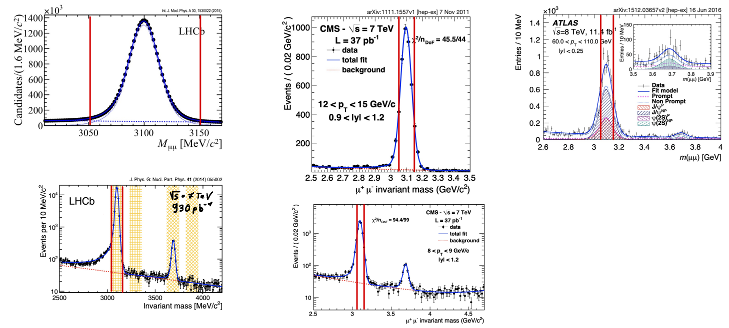
- charged particles are deflected in B-field



@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

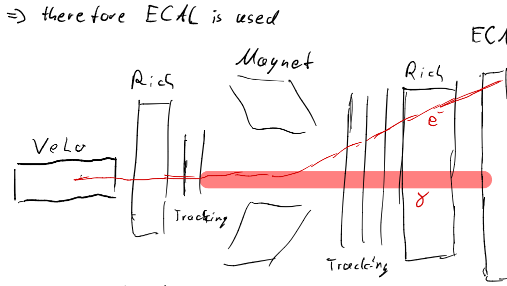
Mass resolution 14,3 ± 0,1 MeV/c²



Electron reconstruction at LHCb

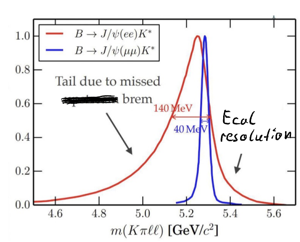
Problem (?): Bremsstrahlung ⟵ electron interacts with detector material

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!!!

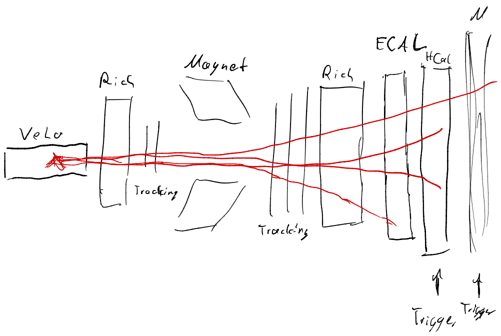


Slides

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

Search for the LFV decay $D^0 \to hh\mu e$

Lepton flavour violation is forbidden in the SM (neutrino oscillations $\sim 10^{-45}$) don't quote me on this this small



What do we want to measure:

"Counting"

You need to understand the detector for this

$$Br(D^0 \to hh\,e\mu) = \frac{N(D^0 \to hh\,e\mu)}{N(D^0 \to K\pi\mu\mu)} \; \frac{\epsilon(D^0 \to K\pi\mu\mu)}{\epsilon(D^0 \to hh\,e\mu)} \; Br(D^0 \to K\pi\mu\mu)$$

External ← Measured relative to $K\pi\pi\pi$

if compatible with 0 a limit will be set.

Current limits and otherwise excluded reach for NP:

$Br(D^0 \to KKe\mu) \lesssim 10^{-9}$

$Br(D^0 \to \pi\pi e\mu) \lesssim 10^{-7}$

BaBar:

$Br(D^0 \to \pi\pi e\mu) \leq 17.1 \times 10^{-7}$

$Br(D^0 \to KKe\mu) \leq 10.0 \times 10^{-7}$

Strategy

1. Candidate reconstruction + background reduction
2. Determine signal yields and significance on a statistical basis
3. Estimate efficiency ratio

Candidate reconstruction

L0 (40 MHz) — Hardware trigger ⇒ HCAL: Hadron; ECAL: electron, photon; Muon: Muon — removed in the future ⇒ μ, hadron

↓ 1 MHz

HLT1 — Software trigger — Partial event reconstruction e.g. Singletrack, Twotrack ⇒ Track + MuonTrack

↓ 110 kHz

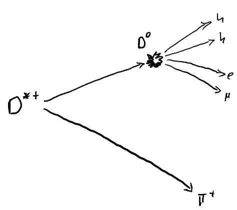
HLT2 — Full event reconstruction based on specific physics cases ⇒ Event is reconstructed starting with daughters

12.5 kHz

⋮

↓

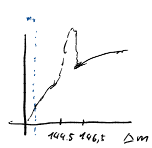
Offline reconstruction (different than HLT2) — Used to create Tuples (.root files) one can work with → Particle are reconstructed under a certain mass hypothesis



$m_{D^0} = 1864$ MeV

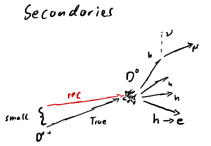
$m_{D^{*+}} = 2010$ MeV

$m_\pi = 139$ MeV



Some "special cases":

Secondaries



→ negligible

MisID

$D^0 \to KK\pi\pi$

$D^0 \to K\pi\pi\pi$

$D^0 \to \pi\pi\pi\pi$

We want to be sensitive to $\sim 10^{-7}$

→ not negligible

strict PID + Fit

Comb.

→ not negligible

BDT

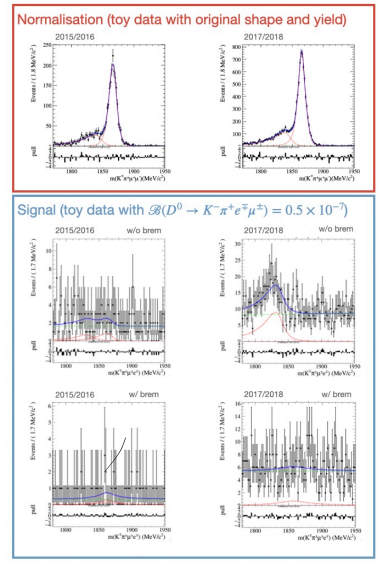
Blind analysis: Strategy is developed on $D^0 \to K\pi\mu\mu$, $D^0 \to K\pi ee$

Determination of signal yield

Last lecture Brem recovery

- $hh\mu e$ Brem
- $hh\mu e$ no Brem
- $K\pi\mu\mu$

→ 15/16, 17/18 are studied separately due to different efficiencies



$$\Longrightarrow \frac{N(D^0 \to hh\mu e)}{N(D^0 \to K\pi\mu\mu)}$$

Efficiency calculation

Different steps in the analysis:

- Acceptance
- Trigger
- Reconstruction → Track
- Preselection
- BDT
- Particle Identification

Acceptance:

$2 < \eta < 5 \sim 20\%$

Trigger:

$B^0 \to K^*(\to K\pi)\, J/\psi(\to \mu\mu)$ (Large statistic) $\longrightarrow f = \frac{\varepsilon_{Trig}(MC)}{\varepsilon_{Trig}(data)}$

$(\to ee)$

Crosschecked

$D^0 \to K\pi ee$ (Lower statistic)

$\mu\mu$

Reconstruction:

Track correction:

K, π systematic, 11% cannot be rec.

14% due to hadronic interactions ⇒ in addition we also have 10% uncertainty on the material budget

$\left.\begin{array}{l}\mu \\ e\end{array}\right\}$ per track correction in kinematic bins (e.g. p, η) using $J/\psi \to \mu\mu$, ee

Preselection & BDT:

Taken from MC (you of course need to check if kinematics match between MC and data this is done with the help of $K\pi ee$ and $K\pi\mu\mu$.)

Particle Identification:

$D^0 \to K\pi$

$J/\psi \to \mu\mu, ee$

$P_{exp}(x \mid p_T, \eta, N_{tr})$ is known (you take the distribution in narrow bins of p_T, η, N_{tr} from the calibration samples)

↑ PID variable

for each event you draw a random PID variable for each variable (particle you want to replace)