Summary

Overall the SM prediction for $\varepsilon_K$ is about 20% lower than the measured value.

New/improved methods necessary!

Hadronic matrix elements (MEs) main theoretical difficulty!

Dominant theory error due to use of LO HQET (static action)

Improved calculation (w/ RHQ) underway (Meinel, Lattice 2013)

The transition from exponential to power law at high pT challenges the theoretical models

Theory issues around interpretation of data

Quantitative calculation still unfeasible

leaves many theorists skeptical

divergent theoretical predictions

Predict more and better!
What are we looking for?

As a particle physicists we want to build "The Theory" such that:

- All observed phenomena are explained
- All predicted particles are discovered
- The resulting theory is mathematical self-consistent

Are we there yet?
→ Based on $SU(3) \times SU(2) \times U(1)$
→ 3 families of quarks and leptons, in $SU(2)$ doublets
→ QCD sector: quarks and gluons only
→ Flavour changing left-handed charged current explained through the Cabbibo-Kobayashi-Maskawa formalism
→ Brout-Englert-Higgs mechanism: spontaneous breaking of the electroweak symmetry

→ Extremely successful!!
An easy 3 generation set-up that seems to **rule**!

The Standard Model rules!

With well-known and well tested **rules**!
SM parameters

3 gauge couplings

2 Higgs parameters

6 quark masses

3 quark mixing angles + 1 phase

3 charged lepton masses

3 neutrino masses

3 neutrino mixing angles + phases

Flavours are the essence of the SM...
Flavoured questions

Many questions:

→ Hierarchy of quark and lepton masses
→ Absence of flavour changing neutral currents
→ Pattern of mixing angles of quarks and leptons
→ Absence of charged lepton flavour violation
→ Origin of the neutrino masses
→ Existence of right-handed/sterile neutrinos
→ Origin of the baryon asymmetry in the Universe
→ ...

Attempts to answer:

→ Continuous flavour symmetries
→ Discrete flavour symmetries
→ Extra-dimensions
→ Compositeness
→ ...

but no definite answer yet...

Description of the quark sector via the CKM formalism
The SM describes the mixing of quarks of different generations through the weak force.

**3 Generations, 1 Phase**: single source of CPV in the quark sector.

Wolfenstein parameterisation: Phase invariant, conserving CKM matrix unitarity at any order in $\lambda$. 

\[ V_{\text{CKM}} = \begin{bmatrix} V_{\text{ud}} & V_{\text{us}} & V_{\text{ub}} \\ V_{\text{cd}} & V_{\text{cs}} & V_{\text{cb}} \\ V_{\text{td}} & V_{\text{ts}} & V_{\text{tb}} \end{bmatrix} \]

\[ R_u = \left| \frac{V_{\text{ud}}V_{\text{ub}}^*}{V_{\text{cd}}V_{\text{cb}}^*} \right| \quad \theta \quad R_s = \left| \frac{V_{\text{ts}}V_{\text{tb}}^*}{V_{\text{cd}}V_{\text{cb}}^*} \right| \]

\[ (0,0) \quad (\rho, \eta) \quad (1,0) \]
CKM and unitarity triangle

\[ \mathbf{V} = \begin{pmatrix}
\alpha & d^{-} & u^{-} \\
\beta & s^{-} & c^{-} \\
\gamma & b^{-} & t^{-}
\end{pmatrix} \]
CKM and unitarity triangle

- Build theory
- Confirm theory
- Disprove theory

- SM – done by Kobayashi & Maskawa
- Large CPV in B system found by Belle & BaBar
- One of the way – check whether all parameters of Unitarity triangle are consistent
Result of 15 years of Belle, BaBar, LHCb operations

\[ \beta \equiv \phi_1 = (21.5^{+0.8}_{-0.7})^\circ \]
\[ \alpha \equiv \phi_2 = (85.4^{+4.0}_{-3.8})^\circ \]
\[ \gamma \equiv \phi_3 = (68.0^{+8.0}_{-8.5})^\circ \]

All triangle parameters are well self-consistent 😞

Don’t give up: we still have a chance to see NP in CKM with x50 more data from Belle II and upgraded LHCb
CKM and unitarity triangle

→ No signs of NP within the CKM global fit paradigm analysis.
All discovered phenomena explained? 😞
Is it really an end of the story?

existence of CPV is one of the requirement for the matter-antimatter asymmetry, which we see in the Universe

- Currently known mechanism of CPV is \(~10\) orders smaller than necessary to explain a large baryon asymmetry in the Universe
- Hardly there is a source of this asymmetry other than CPV
- There must be other sources of CPV
- Q: Where is it ?!
- The answer is unknown, but we can look for/in:
  - new particles in the penguin loops
  - direct CPV in B and D decays
  - leptonic sector
  - strong interaction
New Physics

No evidence for new particles at the LHC...

**Indirect effects in flavour observables?**

→ CP violation?
→ Meson mixings?
→ Rare decays?
→ Neutrino sector?
→ Lepton Flavour Violation?

Most of NP scenarios predict deviations in the flavour sector

And flavour physics observables can probe very large NP scales!
CP Violation in heavy mesons

Penguin Pollution

Issue: Dependence of $\Delta \phi_{\text{pen}}$ on SU(3) breaking

Using full SU(3) analysis: [MJ’12]

- Determines model-independently SU(3) breaking: $\lesssim 20\%$

- Smallness of NP poses new challenges to CPV interpretation
- SU(3) with breaking enables model-independent analyses
- Combined power counting of small effects necessary
- Controlling penguins is necessary for very high precision
**CP Violation in heavy mesons**

\[ \mathcal{B}_d \to J/\psi K, \quad \mathcal{B}_s \to J/\psi \phi \]

*Indirect CP asymmetries*  
*Predictions for \( \mathcal{B}_s \to J/\psi K \)*

*Predictions for unmeasured CP asymmetries*

\[ \mathcal{B} \to DD \text{ decays} \]

Red: expected PC. Blue: enhanced penguins (dark BaBar, light WA)
- Outside red: large penguins or NP. Outside blue: NP.
- Any sizable CPV in \( b \to s \) transitions: NP

**CP violation in charm remains exciting**
Heavy Flavours: Improvements wanted!

- QCD works pretty well!
- Our predictive tools (NLO+PS, FONLL, CEM, CSM, COM...) aren’t perfect
- Our experimental data isn’t fully consistent with them

- Measure more and better!
- Predict more and better!
New Heavy Flavours: Excitement!

**Excitement**

How CERN’s Discovery of Exotic Particles May Affect Astrophysics

Egorychev

Interesting playground for theorists!

Z(4430) - unambiguous four-quark candidate
Minimal Flavour Violation

All results in good agreements with the CKM formalism

Sources of flavour symmetry breaking severely restricted...

Possibility of Minimal Flavour Violation:

all flavour changing phenomena beyond SM in the quark sector dependent on the CKM matrix
New Physics and Meson Mixings

\[ \mathcal{L}_{\text{BSM}} \rightarrow \mathcal{L}_{\nu\text{SM}} + \sum_{i,(d>4)} \frac{Q_{ai}^{(d)}}{\Lambda^{d-4}} \]

Formally, NP flavor cannot be completely trivial

“Minimal Flavor Violation”
NP in $B_d$ mixing: Fit results

\[ M_{12}^{d,s} = (M_{12}^{d,s})_{\text{SM}} \times \left( 1 + h_{d,s} e^{2i\sigma_{d,s}} \right) \]

- at 95% \( NP \leq (\text{many} \times \text{SM}) \implies NP \leq (0.3 \times \text{SM}) \implies NP \leq (0.05 \times \text{SM}) \)

\[ h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left( \frac{4.5 \text{ TeV}}{\Lambda} \right)^2 \]

By Stage II,
\( \Lambda \sim 20 \text{ TeV (tree)} \)
\( \Lambda \sim 2 \text{ TeV (loop)} \)

- Stage II: similar sensitivity to gluino masses explored at LHC 14TeV
What can rare decays then add to this picture?

- Test $\Delta F=1$ processes
- Tests of Minimal Flavour Violation e.g. rate of $b \rightarrow s$ vs $b \rightarrow d$ penguin decays should be related by $|V_{ts}/V_{td}|^2$
- Search for processes that are completely forbidden in the SM
\[ B_s \rightarrow \mu^+ \mu^- \]

Relevant operators:

\[ \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \]

\[ \mathcal{O}_S = \frac{e^2}{16\pi^2} (\bar{s} \gamma^\alpha b_R^\alpha)(\bar{\ell} \gamma^\alpha \ell) \]

\[ \mathcal{O}_P = \frac{e^2}{16\pi^2} (\bar{s} \gamma^\alpha b_R^\alpha)(\bar{\ell} \gamma_5 \gamma^\alpha \ell) \]

\[ \text{BR}(B_s \rightarrow \mu^+ \mu^-) = \frac{G_F^2 \alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_{\mu}^2}{m_{B_s}^2}} \]

\[ \times \left\{ \left( 1 - \frac{4m_{\mu}^2}{m_{B_s}^2} \right) |C_S - C'_S|^2 + \left( C_P - C'_P \right) + 2 \left( C_{10} - C'_{10} \right) \frac{m_{\mu}}{m_{B_s}} \right\} \]

In the MSSM:

\[ C_S \approx -C_P \approx -\mu A_t \frac{\tan^3 \beta}{(1 + \epsilon_b \tan \beta)^2} \frac{m_t^2}{m_{\tilde{t}}^2} \frac{m_b m_{\mu}}{4 \sin^2 \theta_W M_W^2 M_A^2} f(x_{\tilde{t} \mu}) \]
\[ B \rightarrow K^* \mu^+ \mu^- \]

Angular distributions

The full angular distribution of the decay \( \bar{B}^0 \rightarrow \bar{K}^{*0}\ell^+\ell^- (\bar{K}^{*0} \rightarrow K^-\pi^+) \) is completely described by four independent kinematic variables: \( q^2 \) (dilepton invariant mass squared), \( \theta_\ell, \theta_{K^*}, \phi \)

Relevant operators

\[
\begin{align*}
\mathcal{O}_9 &= \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \\
\mathcal{O}_{10} &= \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \gamma_5 \ell), \\
\mathcal{O}_S &= \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\ell), \\
\mathcal{O}_P &= \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)
\end{align*}
\]

Differential decay distribution

\[
\frac{d^4\Gamma}{dq^2 \cos \theta_\ell \cos \theta_{K^*} d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)
\]

\[
J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2) f_i(\theta_\ell, \theta_{K^*}, \phi)
\]

\( J \) angular coefficients \( J_{1-9} \)

\( f \) functions of the spin amplitudes \( A_0, A_\parallel, A_\perp, A_t, \) and \( A_s \)

Spin amplitudes: functions of Wilson coefficients and form factors

Optimised observables: \( P_i, P'_i \) form factor uncertainties cancel at leading order
Range of $B_d^0 \to K^{*0}\mu^+\mu^-$ angular observables in excellent agreement with SM (see talk of M. Tresch)

ATLAS (prelim.) [ATLAS-CONF-2013-038], CMS 5.2 $fb^{-1}$ [PLB 727 (2013) 77], LHCb 1 $fb^{-1}$ [JHEP 08 (2013) 131]

However, 2nd set of LHCb $B_d^0 \to K^{*0}\mu^+\mu^-$ measurements gave a surprise:

New physics or theory issues?
Flavour on the Lattice

Nice interplay between theory and experiment

- First unquenched LQCD calculations of $b \rightarrow s$ form factors
- These reduce uncertainties in f.f., especially at large $q^2$
- $B_{(s)} \rightarrow K^*, \phi$: complement sum rule calculations, many observables, caveat: $K^* \rightarrow K \pi$ threshold effects not included

A lot of progress recently in key decays!
Kaon sector

A NICE INTERPLAY BETWEEN KAONS AND BEES IN THE SM

Kaons are very interesting: CPV, rare decays, ...
Light new particles?

Unsolved problems $\Rightarrow$ new particles should exist

We did not detect them $\Rightarrow$ they are heavy

Or:

We did not detect them $\Rightarrow$ they are heavy light but very weakly interacting

Focus of this proposal:
Feebly coupled particles to be searched at SHIP experiment at CERN (intensity frontier)

New physics at electroweak scale explored at LHC (energy frontier)

Known physics

Unknown physics

Interaction strength

Mass of particles
Neutrinos

Neutrinos are special!

→ Most abundant particles in the Universe, together with photons
→ The lightest particle we know about
→ The weakest interactions we know about

It is necessary to understand neutrinos if we want to understand the Universe!
Neutrinos

- What is the absolute scale of neutrino mass?
- Is the physics behind the masses of neutrinos different from that behind the masses of all other known particles?
  - Are neutrinos their own antiparticles?
- Is the spectrum like □ or □?
- Are there more than 3 mass eigenstates?
  - Are there non-weakly-interacting “sterile” neutrinos?
- Do neutrinos break the rules?
  - Non-Standard-Model interactions?
  - Violation of Lorentz invariance?
  - Violation of CPT invariance?
  - Departures from quantum mechanics?
- Do neutrino interactions violate CP?
  Is \( P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta) \)?
- Is CP violation involving neutrinos the key to understanding the matter–antimatter asymmetry of the universe?
- What can neutrinos and the universe tell us about one another?
Mass of sterile neutrinos is not determined by neutrino oscillations!
Sterile neutrino and cosmology

**Sterile neutrino and 3.5 keV line**

Sterile neutrino DM with such parameters is not completely cold and would leave its imprints in the formations of structures.
Neutrinos and inflation

Inflation and νMSM: dark matter production

DM production (inflaton gives mass)
from inflaton decays in plasma at $T \sim m_\chi$

$$M_{N_i} \bar{N}_i^c N_i \leftrightarrow f_i X \bar{N}_i N_i$$

Can be “naturally” Warm ($250 \text{MeV} < m_\chi < 1.8 \text{GeV}$)

If $\lambda (\sim M_{Pl}) > 0$ & if non-minimally coupled to gravity $H^+ H R$ the SM
Higgs field may serve as the inflaton

Then DM sterile neutrino may be produced via dim-5 operator

$$\mathcal{L} = \frac{\beta}{\Lambda} H^+ H \bar{N}_i^c N_i + \text{h.c.}$$
Lepton Flavour Violation

- Charged Lepton Flavour (practically) conserved in the SM (+ light $\nu$)
  - LFV is clear sign for BSM physics

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{m_W^2} \right|^2 \approx 10^{-56}$$

- Flavour violation in the quark and neutrino sector
  - Strong case to look for CLFV

Generic BSM models at TeV scale with couplings to leptons lead to large CLFV

CLFV can shed light on
  - Grand Unification models
  - Flavour symmetries
  - Origin of flavour
Lepton Flavour Violation

**Quark (suppressed) amplitude**

$$|A_{SM} + \varepsilon_{NP}|^2 \sim |A_{SM}|^2 + 2Re(A_{SM}\varepsilon_{NP}) + |\varepsilon_{N}|^2$$

**Lepton (forbidden) rate**

$$|A_{SM} + \varepsilon_{NP}|^2 \sim |A_{SM}|^2 + 2Re(A_{SM}\varepsilon_{NP}) + |\varepsilon_{N}|^2$$

subject to uncertainty of SM prediction

NP contribution $\sim O(\varepsilon)$

no limitation from uncertainty of SM prediction (can go to higher energy scale)

NP contribution $\sim O(\varepsilon^2)$

CLFV Drawback: Rate $\sim 1/\Lambda^4$, high sensitivity is required.
Lepton Flavour Violation

(Charged) LFV Models

- Models of Neutrino Mass Generation around the TeV scale
  - Seesaw Models
    - I, II, III, Inverse etc.
  - Radiative Mass Models
    - Zee, Babu-Zee, etc.

- Supersymmetry
  - R–Parity Conserving
    - Arbitrary slepton masses or in combination with high-scale Seesaw
  - R–Parity Violating
    - L–violating couplings, Neutrino mass generation

- Extended Higgs/Gauge Sectors
  - Left–Right Symmetry, Little Higgs, Additional Doublets, etc.

- Extra Dimensions
Lepton Flavour Violation

Effective operator approach

\[ \mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O} \left( \frac{1}{\Lambda^3} \right) \]

9 operators remain:

2: (\ell\ell\varphi X)-type operators - modify \( \gamma \ell \ell' \) vertex

LFV related

3: (\ell\ell)(\varphi D\varphi)-type operators - modify \( Z\ell \ell', W\ell'\nu \) vertices

3: 4-lepton contact couplings

1: 2-lepton 2-quark coupling.

Ratios of decay rates – independent of New Physics scale \( \Lambda \)
Leptogenesis

Sakharov’s conditions: (1) B violation (2) C and CP violation (3) departure from thermal equilibrium

(1) and (2) are present in the SM
Electroweak baryogenesis fails in the SM because (3) is not satisfied [also CP violation is too weak] ⇒ need either new physics at \( M_{\text{weak}} \) to modify the dynamics of the EWPT, or generate a (B-L) asymmetry at \( T > T_{\text{EW}} \)

Generate a B-L asymmetry through the out-of-equilibrium decays of the heavy Majorana neutrinos responsible for neutrino mass [Fukugita, Yanagida ‘86]

Leptogenesis is an attractive mechanism for generating the baryon asymmetry of the Universe
Leptogenesis and flavour effects

Flavour effects lead to quantitatively different results from the 1FA

Spectacular enhancement of the final asymmetry in some cases

Scalar triplet leptogenesis

Type II seesaw mechanism

electroweak triplet

Continuous lines indicate the result of the computation involving a $3 \times 3$ density matrix. Dotted lines indicate the result of the single flavour approximation.
Baryogenesis via neutrino oscillations

Baryogenesis via leptogenesis
Fukugita, Yanagida ‘86

Akhmedov, Rubakov, Smirnov ‘98
TA, Shaposhnikov ‘05

Baryogenesis via neutrino osc.
Baryogenesis via neutrino oscillations

Constraints on light RH neutrinos

For normal hierarchy:
- $\tau_N$ vs $M_N$ graph
- $M_N > 163$ MeV
- Cosmology
- Direct search PS191

For inverted hierarchy:
- $\tau_N$ vs $M_N$ graph
- $M_N = 188 - 269$ MeV
- $M_N > 285$ MeV
Many interesting talks
Impressive progress both theoretically and experimentally
Many interesting discussions!

→ Very fruitful conference in an amazing place!

**Personal rec:**

If you want to enjoy the beer in the 12th floor panoramic bar: Don’t accept to give the summary talk!

But if you want to learn a lot in a conference: The best way is to give the summary talk!
Perspectives

- We seem to be left for a long time with:
  1. LHC@14 TeV
  2. Rare Processes: $B, D, K, \mu, \nu, \ldots$

But that means a lot of opportunities!!
And a lot of work for both theorists and experimentalists!!!
Perspectives

Future is bright!

Theorists are hungry for more experimental results!

... and the experimental situation is very promising!

LHC run II
LHC upgrade
Future colliders
Belle II
Neutrino experiments
Other sectors (DM,...)
Perspectives

LHC has already discovered a new fundamental particle

Several small deviations/excesses start to pop up in ATLAS and CMS results

Several anomalies in the LHCb data

Maybe everything will disappear with more data...

Or maybe this is an archeology type of situation!
And finally...

Whatever will be found or will not be found,

Theorists can (try to) explain it!

Whatever will be found or will not be found,

The whole story will be a success story

since we are exploring new territories

And that is all matters!!!
cảm ơn bạn!