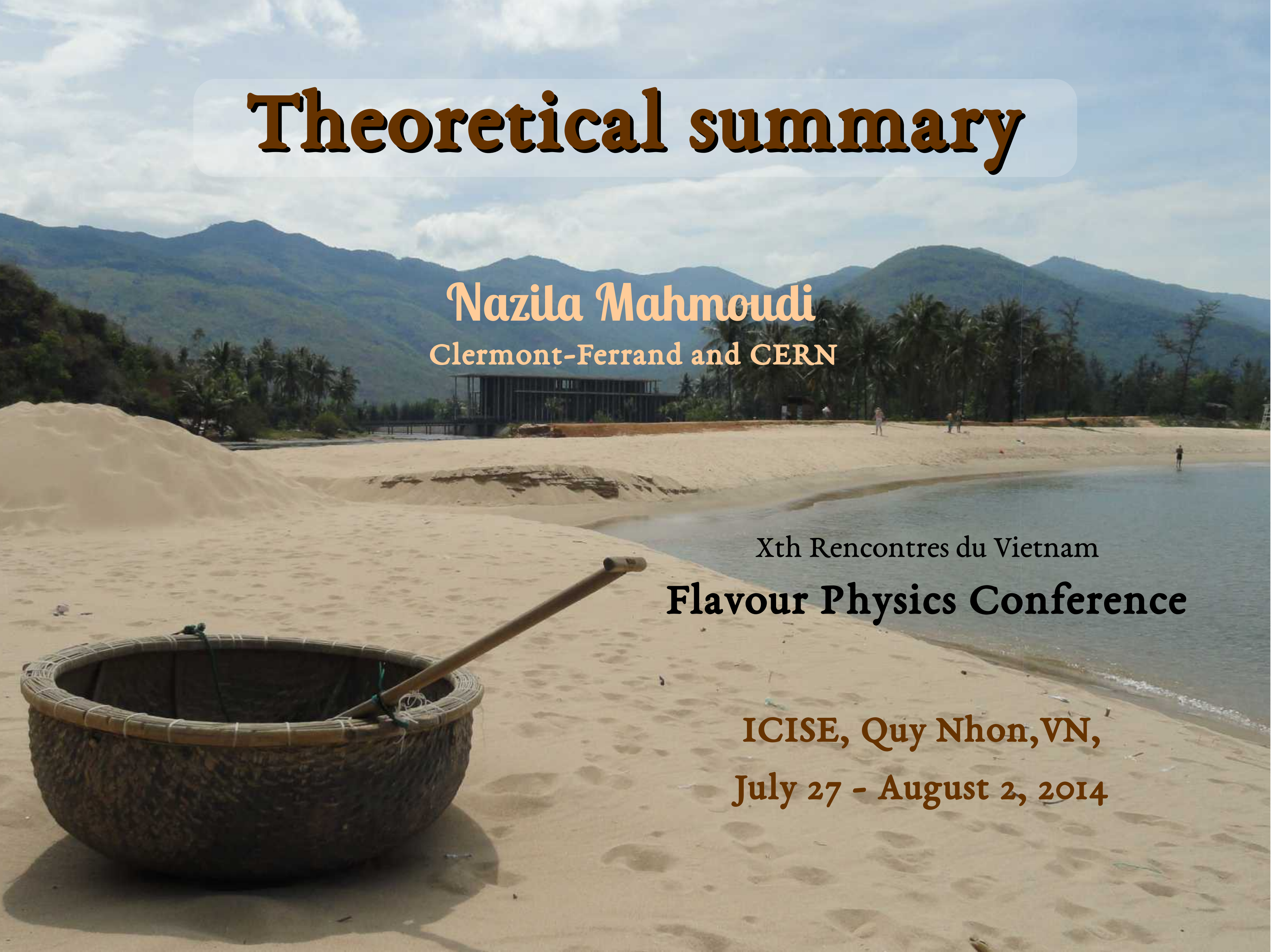


Theoretical summary

Nazila Mahmoudi
Clermont-Ferrand and CERN

Xth Rencontres du Vietnam

Flavour Physics Conference

ICISE, Quy Nhon, VN,
July 27 - August 2, 2014

Summary

Overall the SM prediction for ε_K is about 20% lower than the measured value

New/improved methods necessary!

divergent theoretical predictions

Predict more and better!

Theoretical uncertainties: ~7-30%

Hadronic matrix elements (MEs) main theoretical difficulty!

Theory uncertainties from handling of form factors underestimated,

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

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?

Ruchayskiy

Standard Model

→ Based on SU(3)xSU(2)xU(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

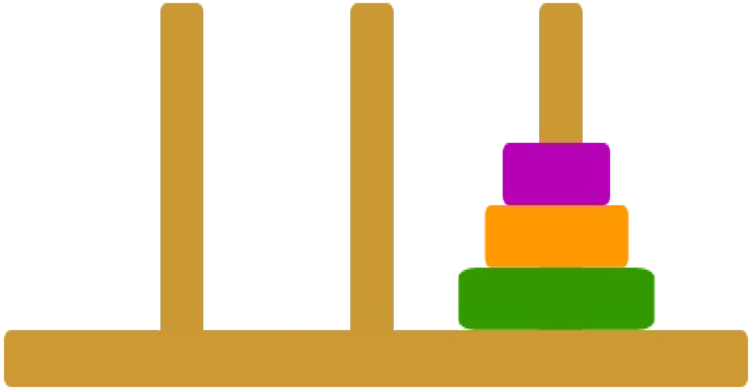
→ Extremely successful!!

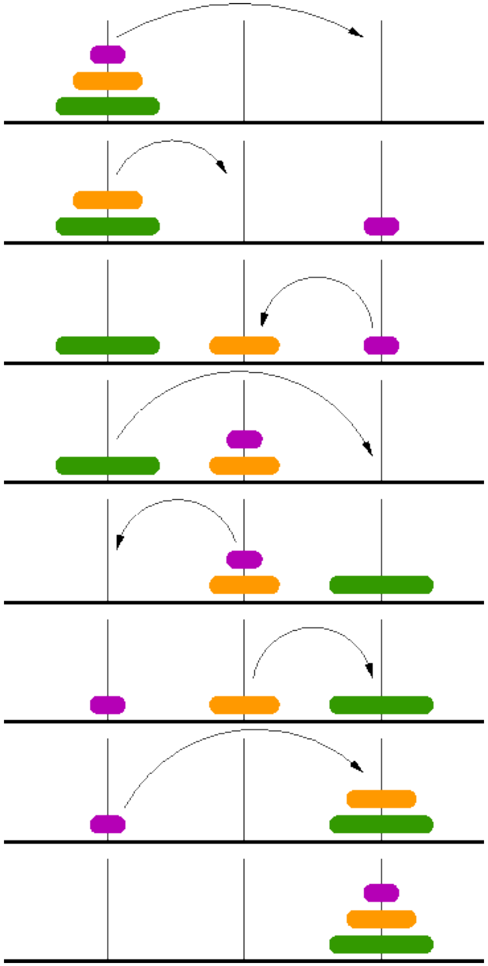
✓ All predicted particles of the Standard Model have been found ☺

The Standard Model rules!

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

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





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

Flavour Parameters

Extended Neutrino Sector

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

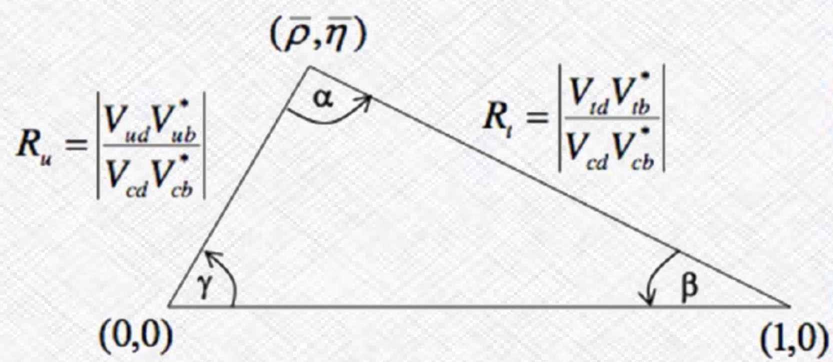
CKM and unitarity triangle

The SM describes the mixing of quarks of different generations through the weak force.

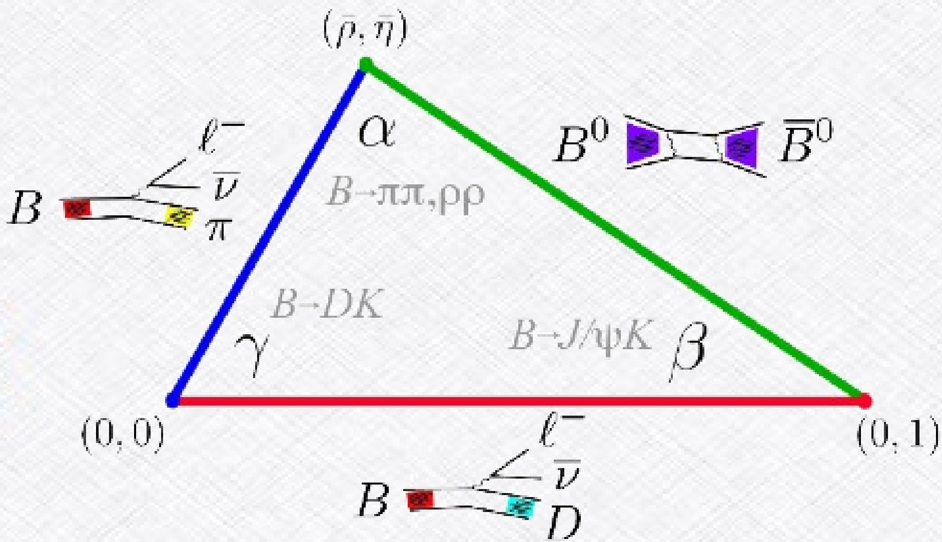
$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

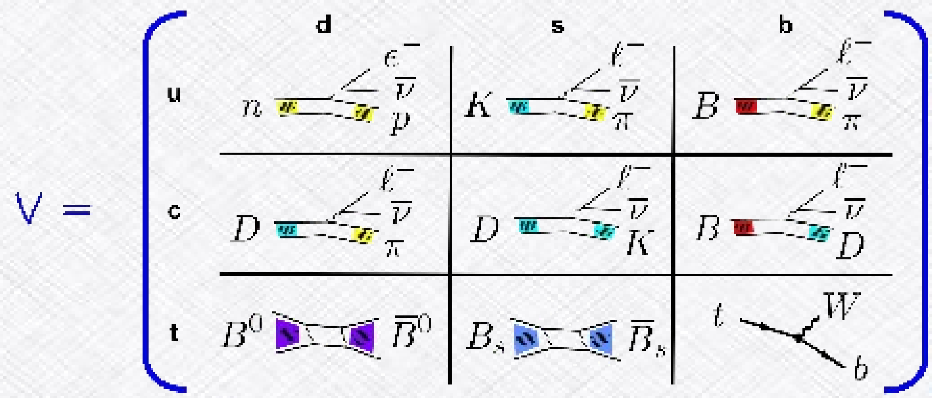
3 Generations, 1 Phase: single source of CPV in the quark sector.

Wolfenstein parameterisation: Phase invariant, conserving CKM matrix unitarity at any order in λ.



CKM and unitarity triangle





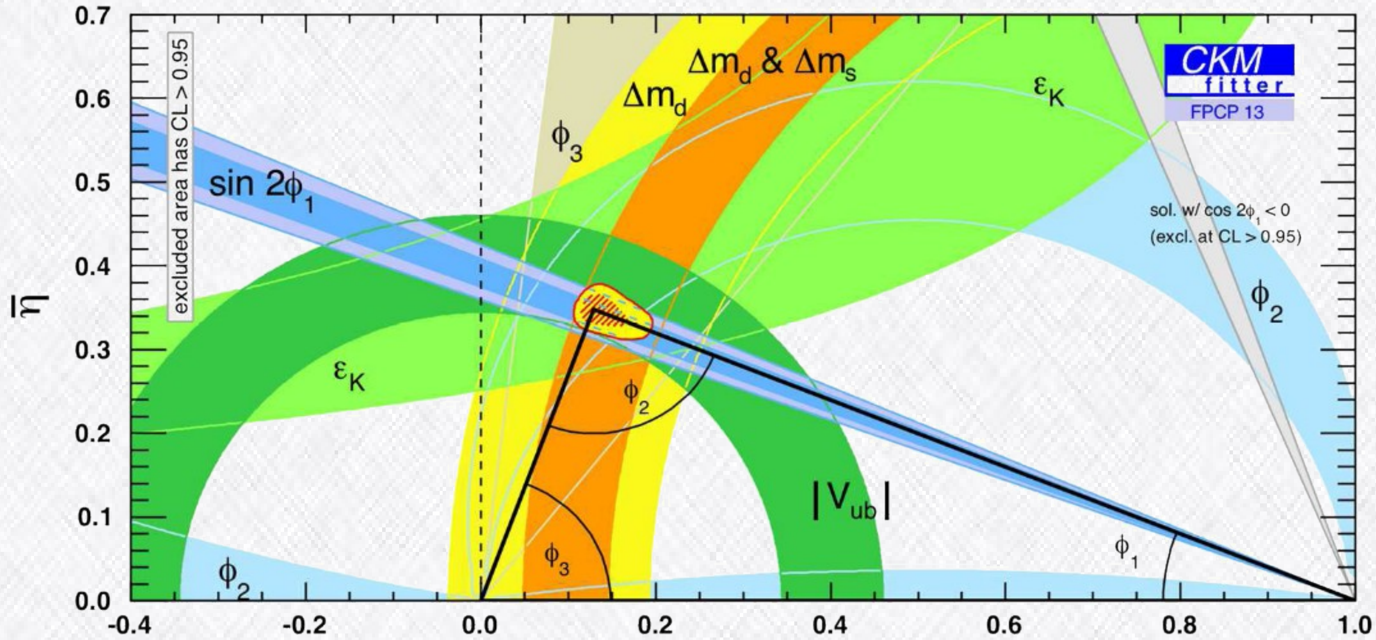
CKM and unitarity triangle

- 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

Aushev

Result of 15 years of Belle, BaBar, LHCb operations



$$\beta \equiv \phi_1 = (21.5^{+0.8}_{-0.7})^\circ$$

$$\alpha \equiv \phi_2 = (85.4^{+4.0}_{-3.8})^\circ$$

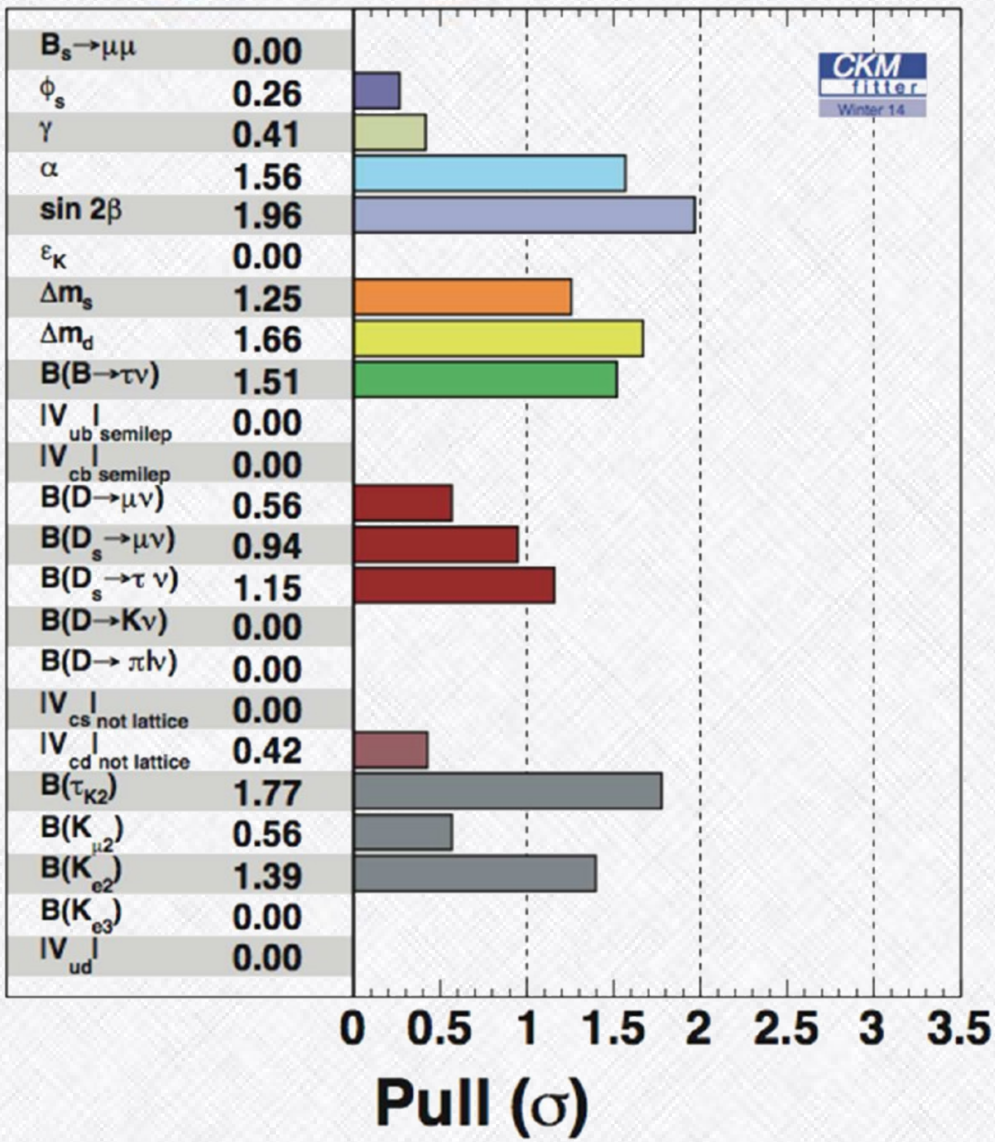
$$\gamma \equiv \phi_3 = (68.0^{+8.0}_{-8.5})^\circ$$

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

Aushev

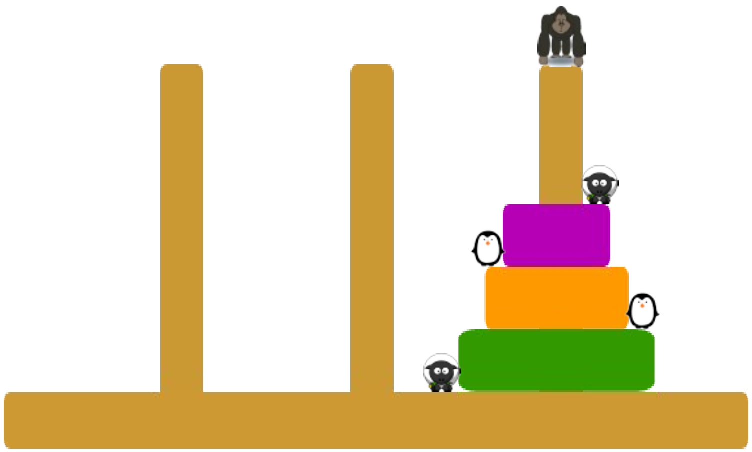
CKM and unitarity triangle



→ **No signs of NP within the CKM global fit paradigm analysis.**

Urquijo

All discovered phenomen 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

Aushev

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 $\Delta\phi_{\rm pen}$ on SU(3) breaking

Using full SU(3) analysis: [MJ'12]

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

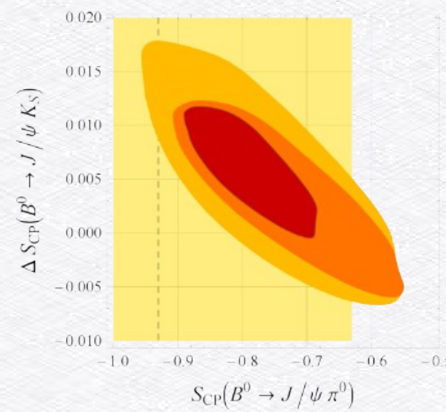
- Smallness of NP poses new challenges to CPV interpretation
- SU(3) with breaking enables model-independent analyses
- Combined power counting of small effects necessary
- Controlling penguins is necessary for very high precision

Jung

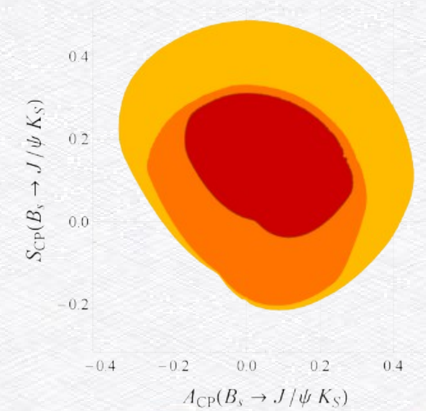
CP Violation in heavy mesons

$B_d \to J/\psi K$, $B_s \to J/\psi \phi$

Indirect CP asymmetries



Predictions for $B_s \to J/\Psi K$

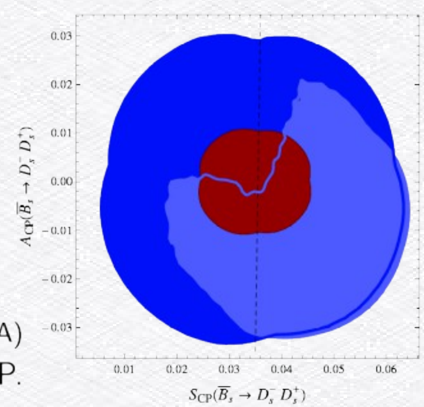


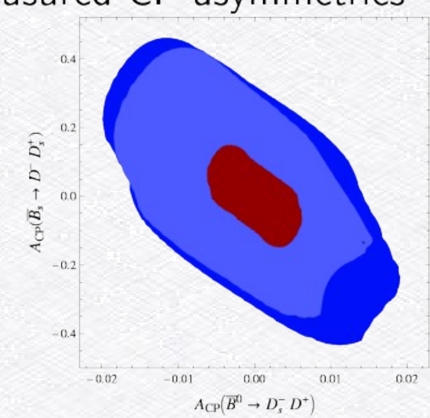
Red/Orange: 68/95% CL, $r_{SU(3)} \leq 40\%$, $r_{\rm pen} \leq 50\%$

Yellow: 95% CL, $r_{SU(3)} \leq 60\%$, $r_{\rm pen} \leq 75\%$

$B \to DD$ decays

Predictions for unmeasured CP asymmetries





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

Jung

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

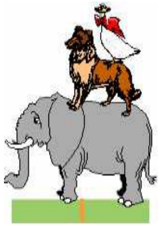
- Measure more and better!
- Predict more and better!

New Heavy Flavours: Excitement!

Z(4430)⁻ unambiguous four-quark candidate

Interesting playground for theorists!

Minimal Flavour Violation



All results in good agreements with the CKM formalism

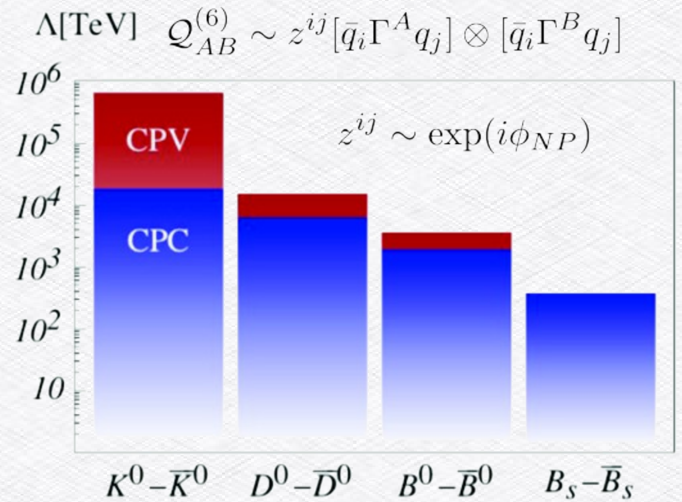
Sources of flavour symmetry breaking severely restricted...

Possibility of Minimal Flavour Violation:

all flavour changing phenomena beyond SM in the quark sector dependent on the CKM matrix

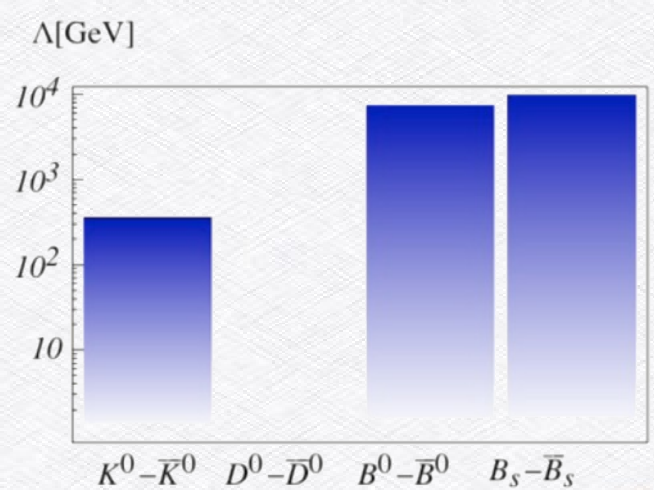
New Physics and Meson Mixings

$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\nu{\rm SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$



Formally, NP flavor cannot be completely trivial

"Minimal Flavor Violation"

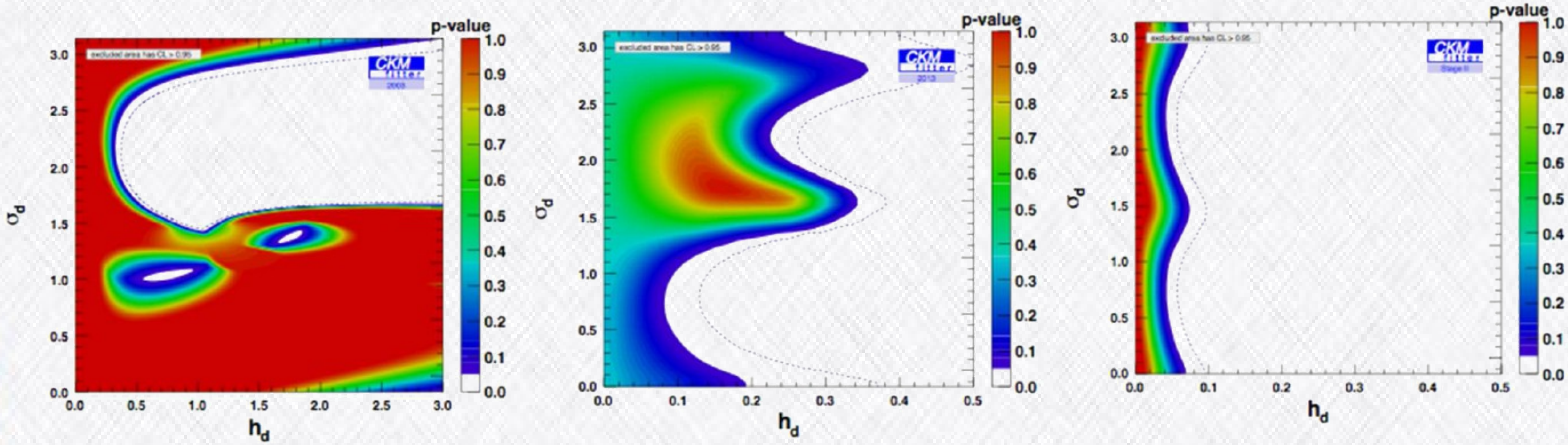


Kamenik

NP in B_d mixing: Fit results

PRD 89, 033016 (2014)

2003 | 2013 | LHCb Upg.+ Belle II



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

- at 95% NP≲(many × SM) $\Longrightarrow$ NP≲(0.3 × SM) $\Longrightarrow$ NP≲(0.05 × SM)

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_{\rm F}\Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\ \mathrm{TeV}}{\Lambda}\right)^2$$

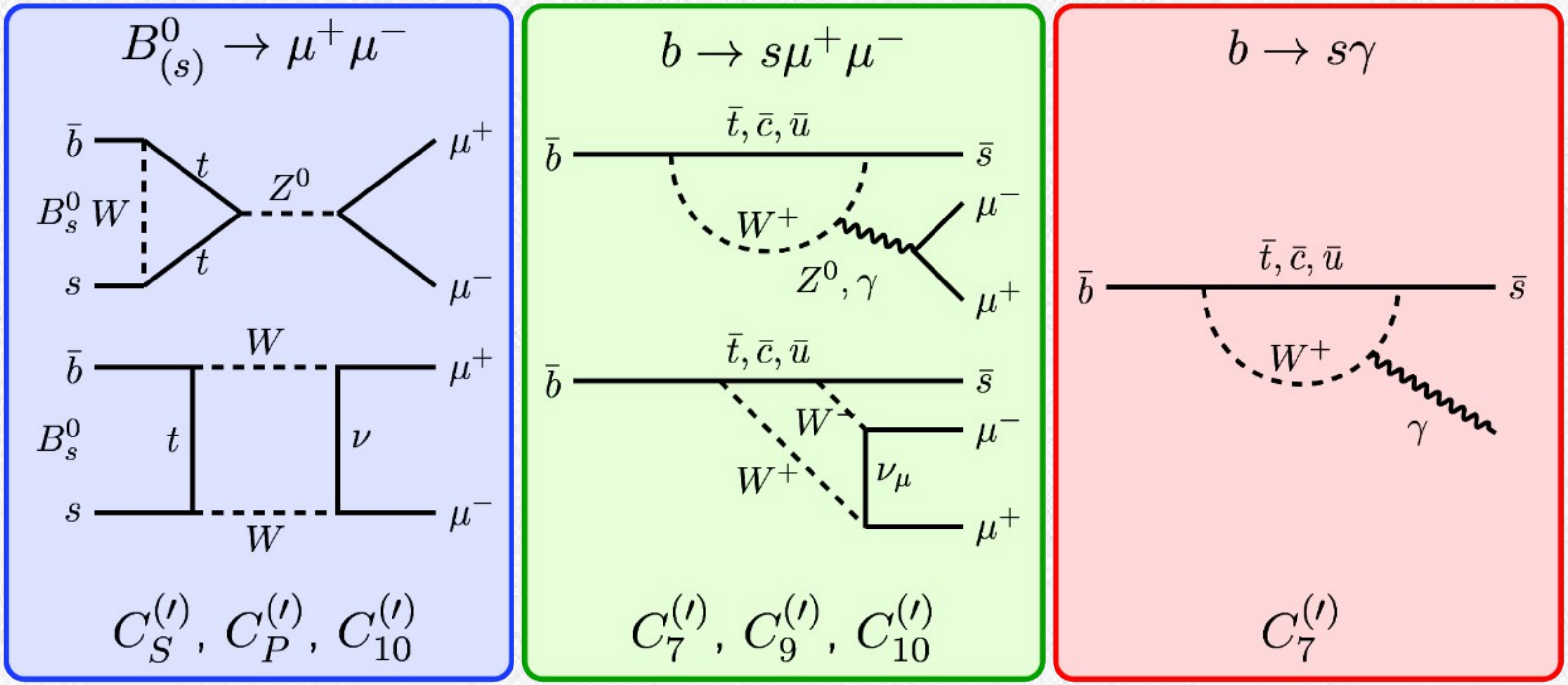
$$\lambda_{ij}^t = V_{ti}^* V_{tj} \qquad \sigma = \arg(C_{ij}\lambda_{ij}^{t*})$$

By Stage II,
Λ ~ 20 TeV (**tree**)
Λ ~ 2 TeV (**loop**)

- Stage II: similar sensitivity to gluino masses explored at LHC 14TeV

Urquijo

Rare decays



What can rare decays then add to this picture?

- Test **ΔF=1** processes
- Tests of Minimal Flavour Violation e.g. rate of b→s vs b→d penguin decays should be related by $|V_{ts}/V_{td}|^2$
- Search for processes that are completely forbidden in the SM

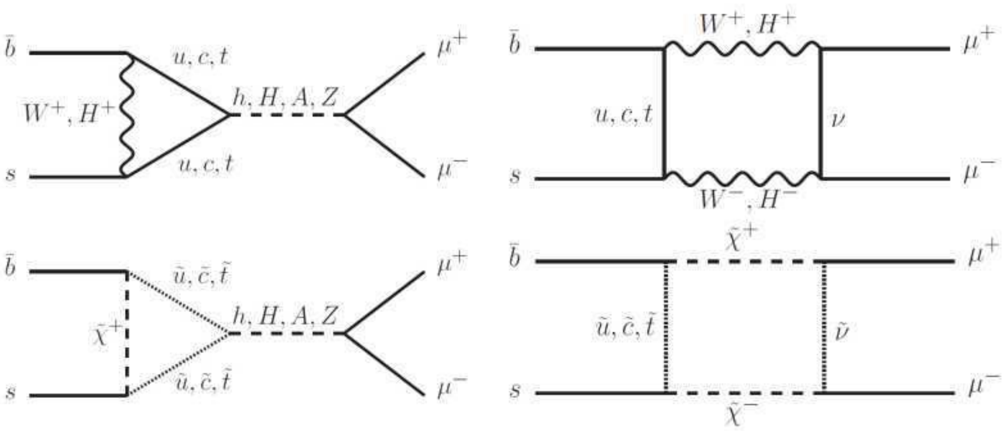
$B_s \to \mu^+\mu^-$

Relevant operators:

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

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell)$$

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



$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) |C_S - C_S'|^2 + \left|(C_P - C_P') + 2\,(C_{10} - C_{10}')\frac{m_\mu}{m_{B_s}}\right|^2 \right\}$$

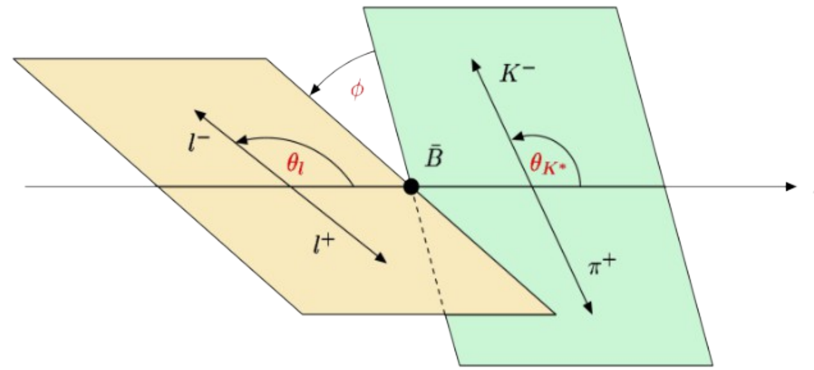
In the MSSM:

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

$B \to K^* \mu^+ \mu^-$

Angular distributions

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



Relevant operators

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)$$

Differential decay distribution

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

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

↘ angular coefficients J_{1-9}

↘ functions of the spin amplitudes A_0, $A_{||}$, $A_\perp$, A_t, and A_S

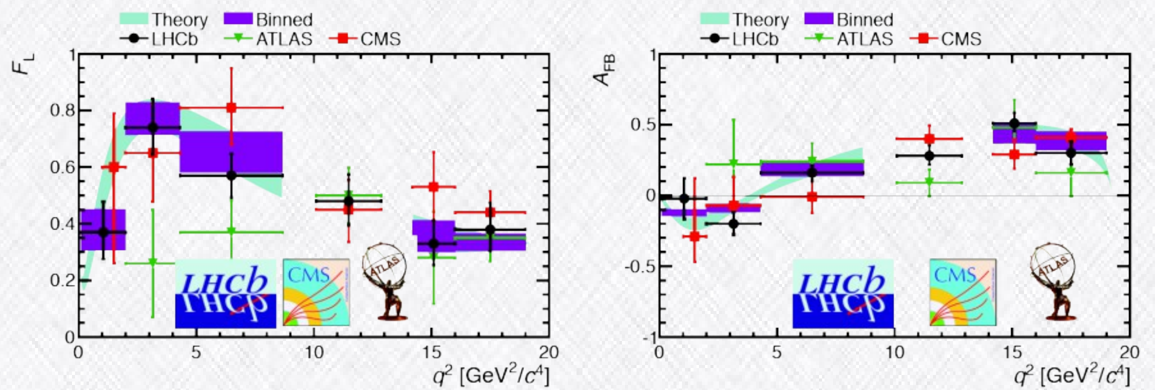
Spin amplitudes: functions of Wilson coefficients and form factors

Optimised observables: P_i, P_i' form factor uncertainties cancel at leading order

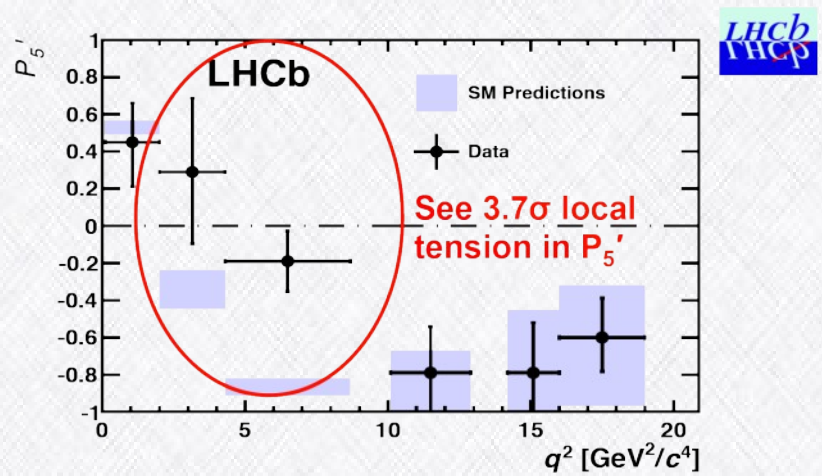
$B \to K^* \mu^+ \mu^-$

- 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:



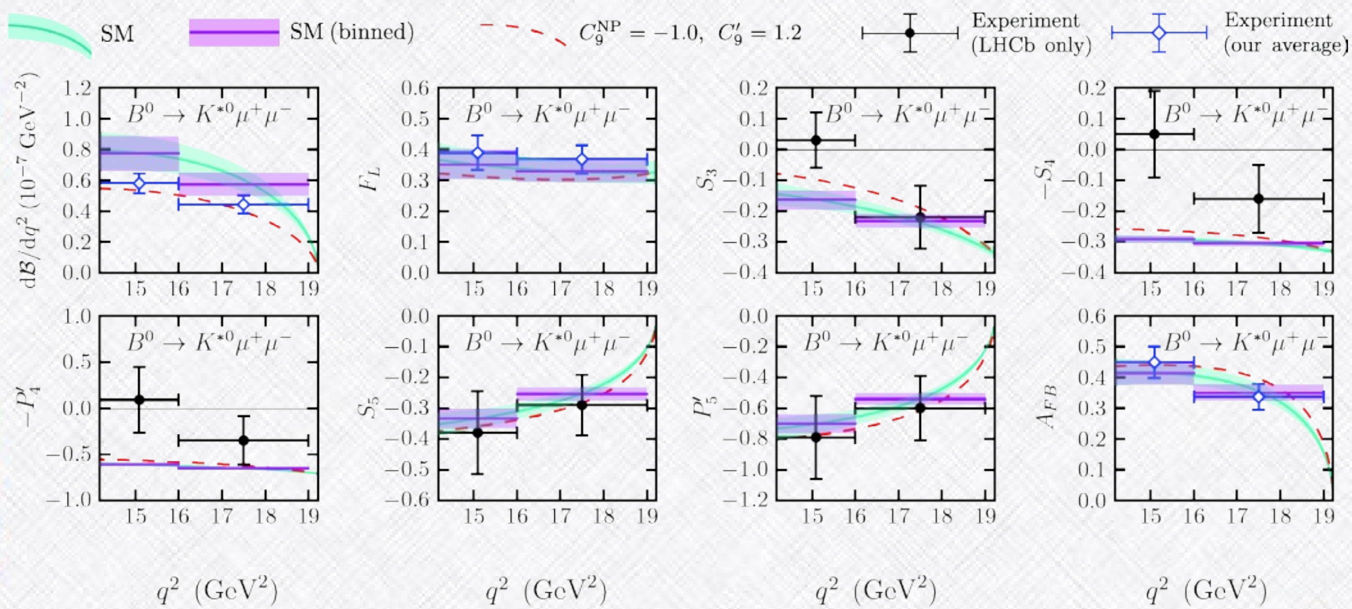
New physics or theory issues?

Flavour on the Lattice

Nice interplay between theory and experiment

Computer-intensive methods

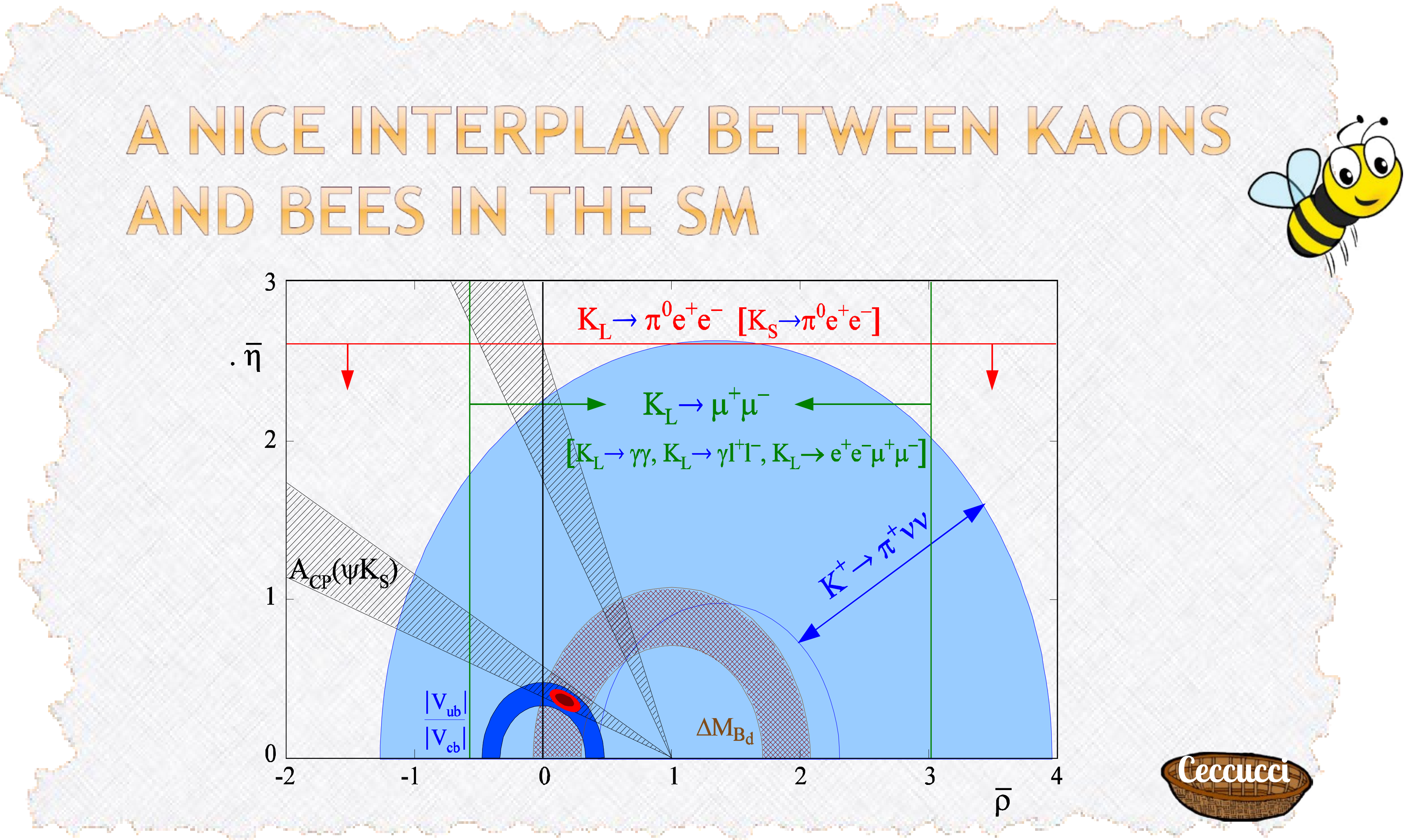
- First unquenched LQCD calculations of $b \to s$ form factors
- These reduce uncertainties in f.f., especially at large q^2
- $B_{(s)} \to K^*, \varphi$: complement sum rule calculations, many observables, caveat: $K^* \to K\pi$ threshold effects not included



Wingate

A lot of progress recently in key decays!

Kaon sector



Kaons are very interesting: CPV, rare decays, ...

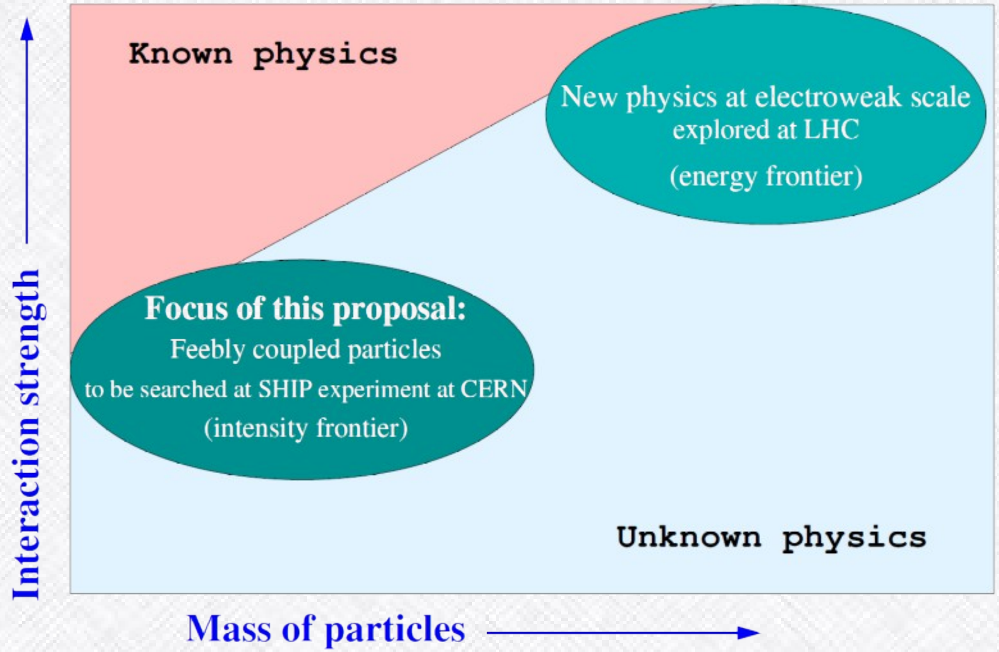
Light new particles?

Unsolved problems ⇒ **new particles should exist**

We did not detect them ⇒ they are **heavy**

Or:

We did not detect them ⇒ they are ~~heavy~~ light but **very weakly interacting**



Ruchayskiy

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?

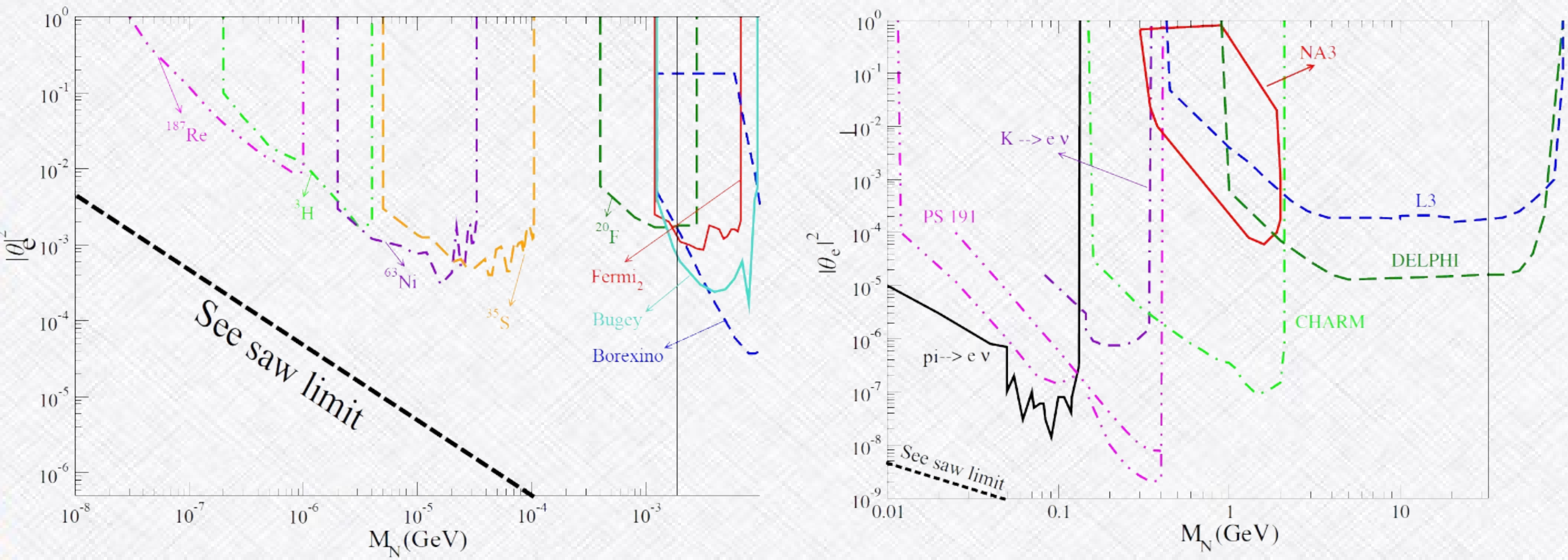
- Do neutrino interactions violate CP?
  Is $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$?

- 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?

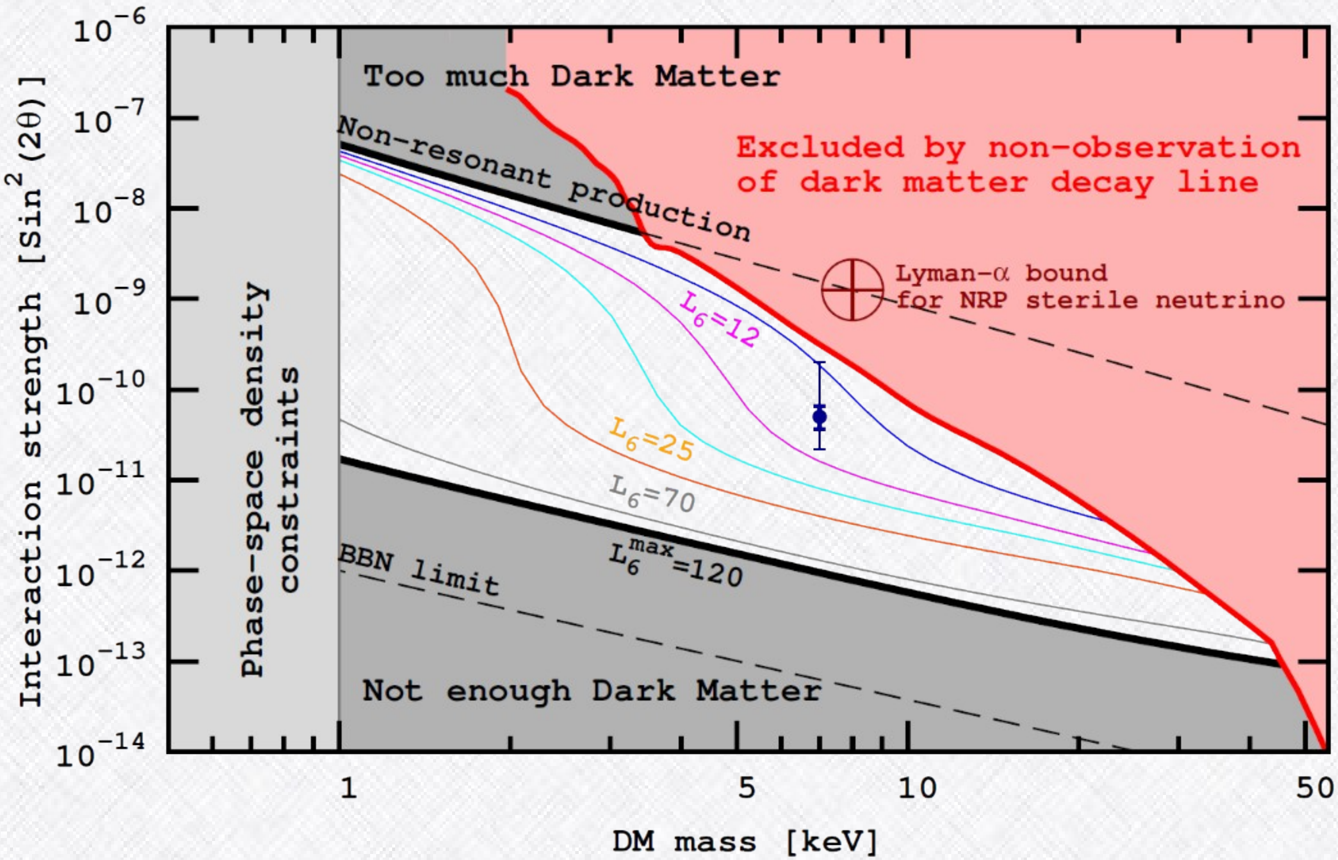
Sterile Neutrinos

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

Ruchayskiy

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 $H^\dagger H R$ the SM Higgs field may serve as the inflaton

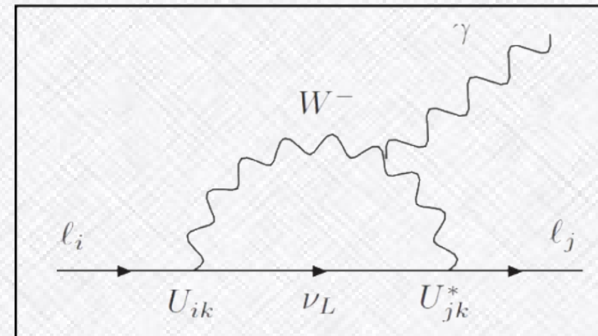
Then DM sterile neutrino may be produced via dim-5 operator

$$\mathscr{L} = \frac{\beta}{\Lambda} H^\dagger H \bar{N}^c N \;+\; \text{h.c.}$$

Lepton Flavour Violation

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

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



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

Generic BSModels at TeV scale with couplings to leptons lead to large CLFV

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

Deppisch

Lepton Flavour Violation

Quark (suppressed) amplitude

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

subject to uncertainty of SM prediction

NP contribution ~ O(ε)

Lepton (forbidden) rate

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

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

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

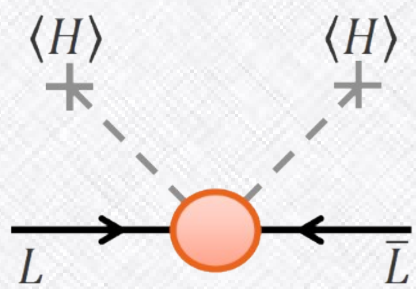
CLFV Drawback : Rate ~ $1/\Lambda^4$, high sensitivity is required.

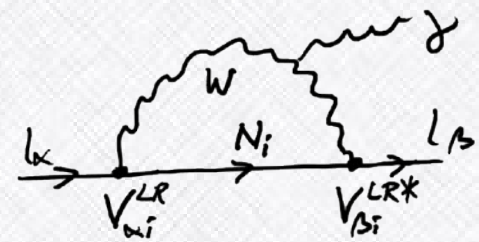
Kuno

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

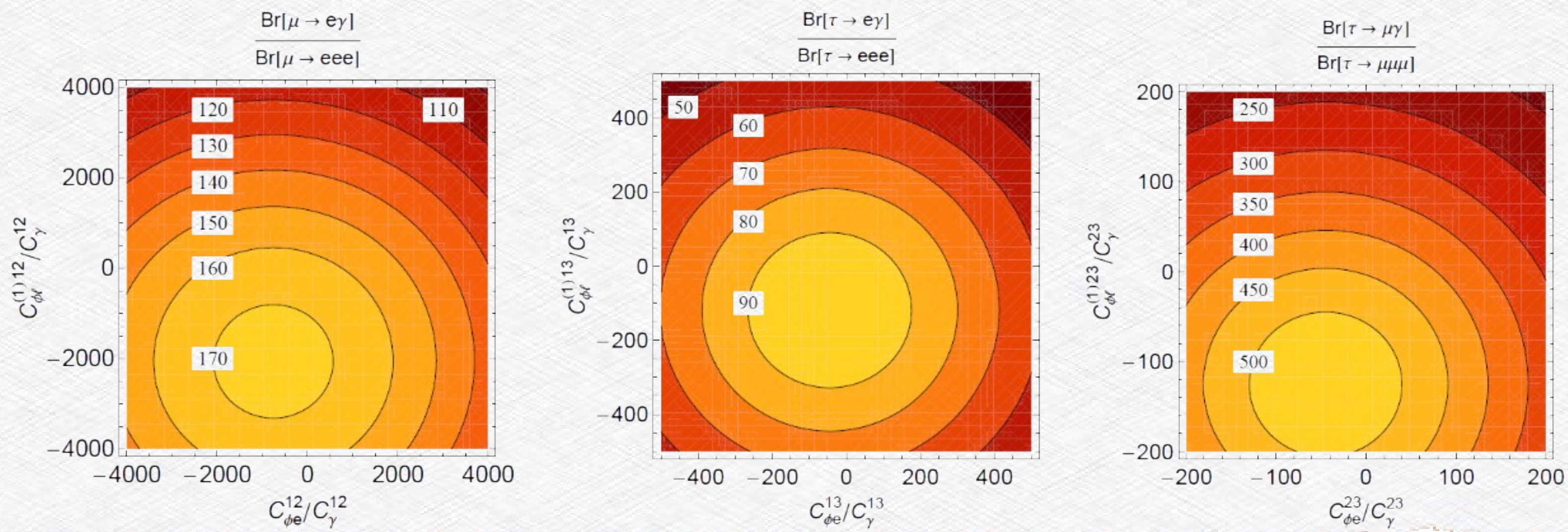
$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

9 operators remain:

LFV related

- 2: $(\ell\ell\varphi X)$-type operators - modify $\gamma l l'$ vertex
- 3: $(\ell\ell)(\varphi D\varphi)$-type operators - modify $Zll', Wl'v$ vertices
- 3: 4-lepton contact couplings
- 1: 2-lepton 2-quark coupling.

Ratios of decay rates – independent of New Physics scale Λ



Rosiek

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_{weak} to modify the dynamics of the EWPT, or generate a (B-L) asymmetry at $T > T_{EW}$

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

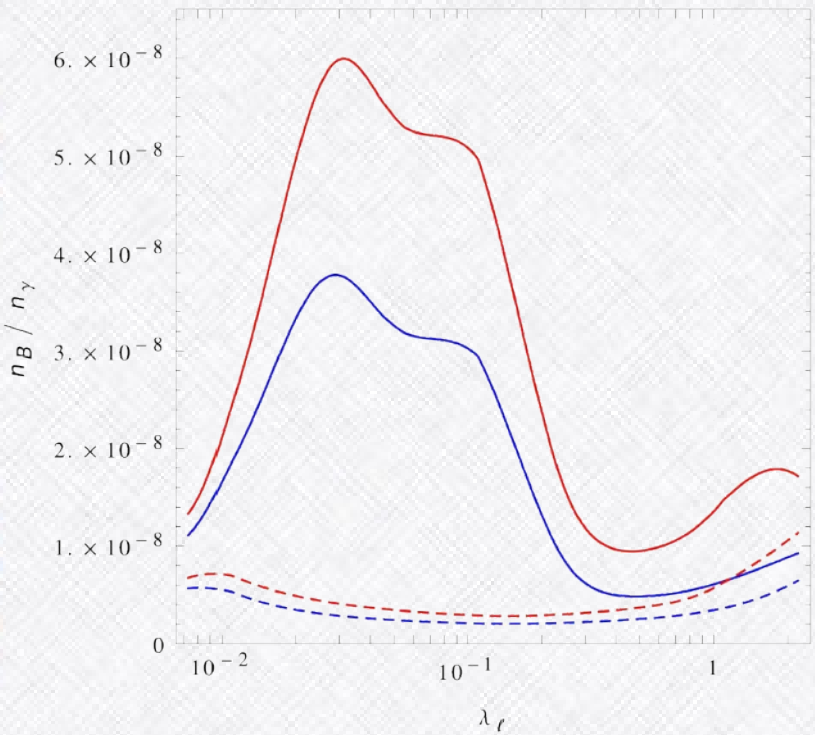
Lavignac

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

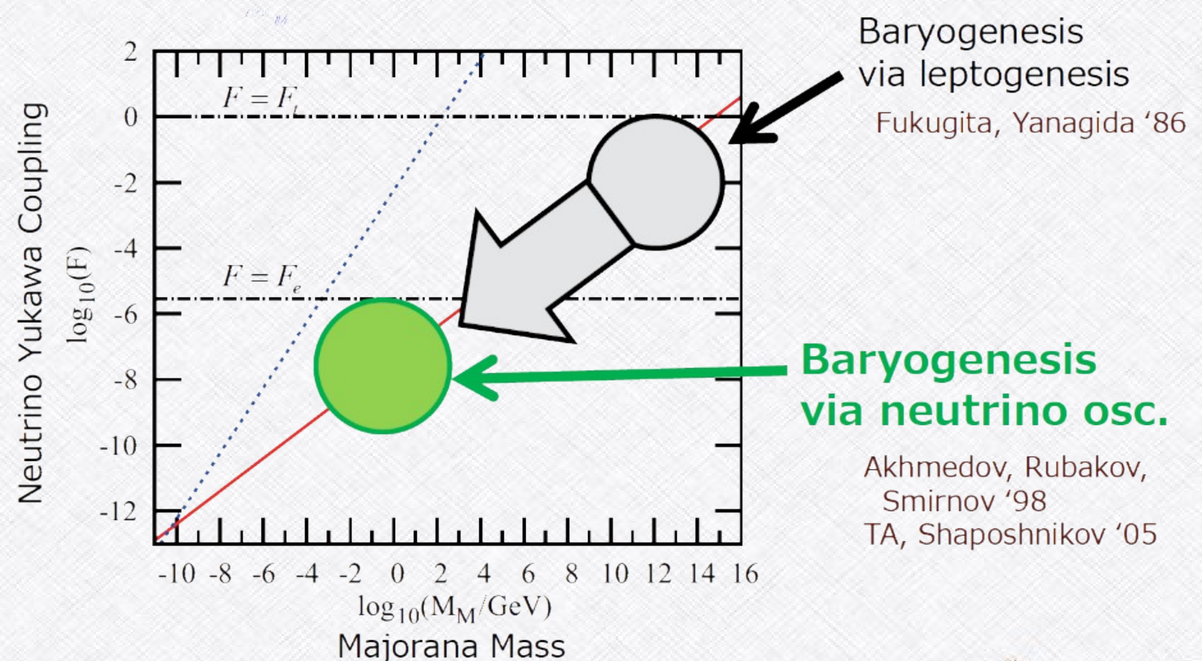
electroweak triplet

continuous lines indicate the result of the computation involving a 3×3 density matrix

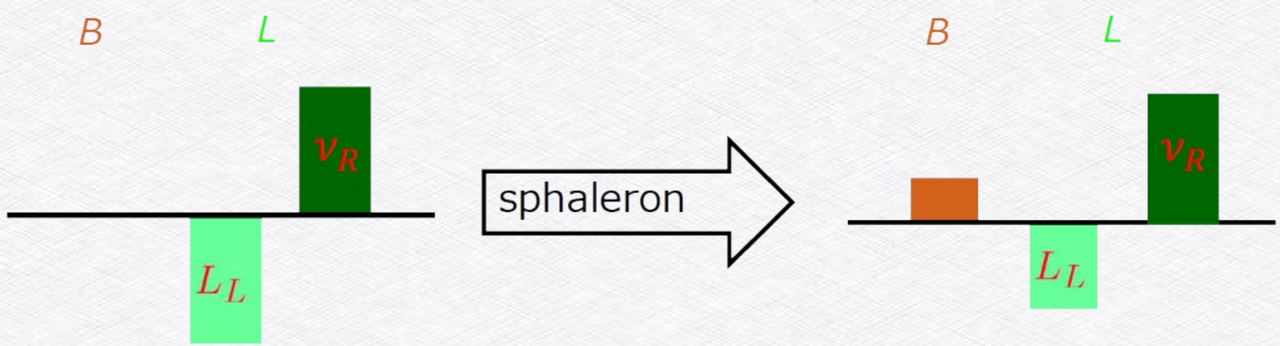
dotted lines indicate the result of the single flavour approximation

Lavignac

Baryogenesis via neutrino oscillations



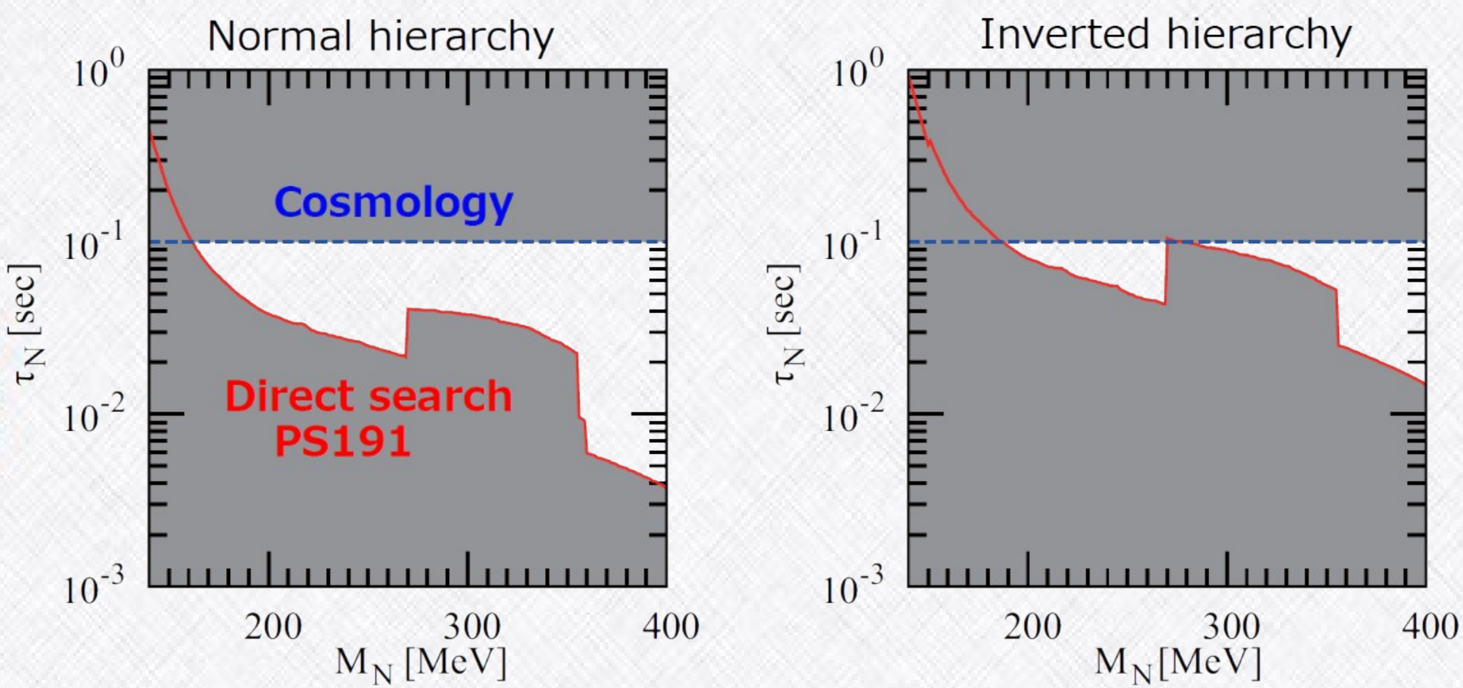
Baryogenesis via neutrino osc.



Asaka

Baryogenesis via neutrino oscillations

Constraints on light RH neutrinos



$M_N > 163$ MeV

$M_N = 188 - 269$ MeV
$M_N > 285$MeV

Asaka

In brief

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

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!