Flavour Physics in 2022 - Opening

Rencontres du Vietnam: Flavour Physics Conference - 14-20 August 2022

Nazila Mahmoudi

Lyon University & CERN

Flavour Physics Conference

This meeting, normally held every three years, is intended to promote fruitful collaboration between experimentalists and theorists, between physicists in the areas of:

- Searches for New Physics including the Dark Sector
- Phenomenology of Physics Beyond the Standard Model
- Beauty and Charm physics
- Kaon physics
- Tau and Muon physics
- Neutrino physics
- CP violation
- Rare decays
- Future facilities

from institutions across the world, by bringing together a limited number of particle physicists in beautiful and inspiring surroundings. A particular emphasis will be made on searches for new physics which complement direct studies at the LHC.

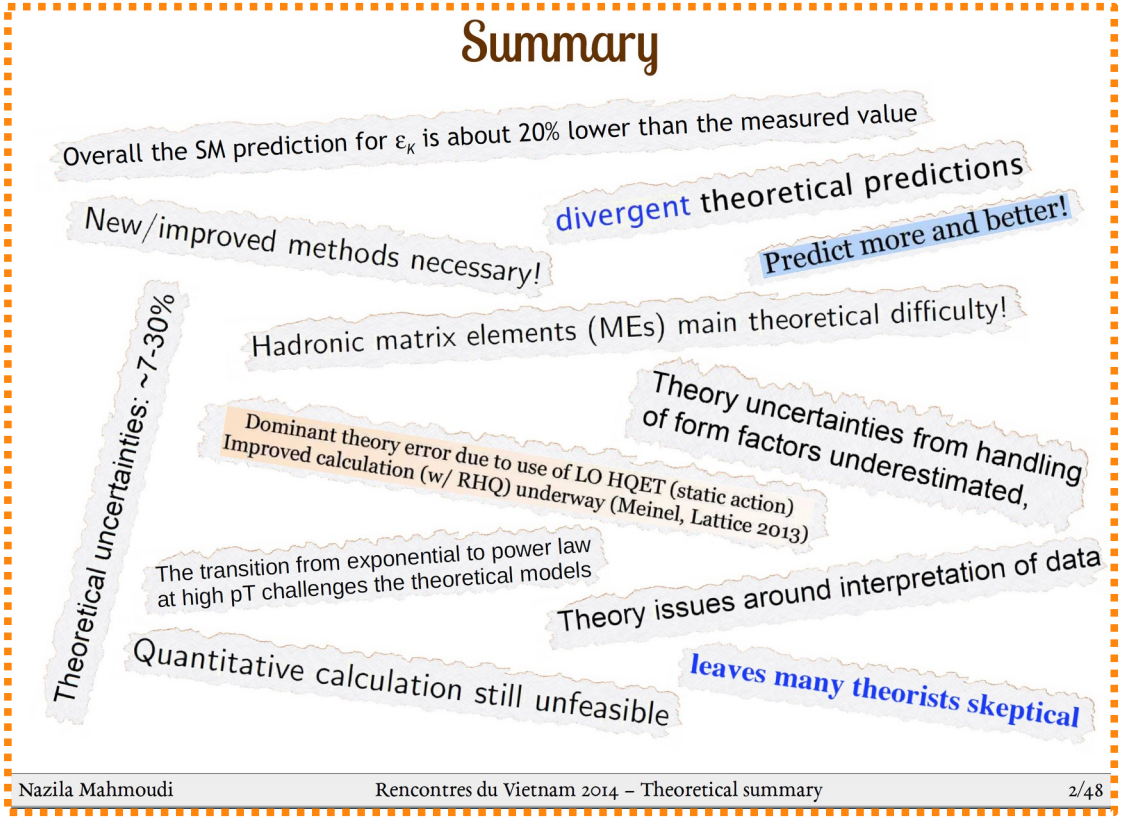
Flavour Physics Conference

- The first Rencontres du Vietnam Flavour Conference was held here in 2014

Perspectives from 2014

- Need for more precise and improve theoretical predictions
- Need for more precise experimental measurements

We have clearly entered the precision era !



SM rules ?

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

Oleg Ruchayskiy

All discovered phenomen explained? 

Particle physics: neutrino oscillations

Cosmology and astrophysics: particle physics (coupled to Einstein gravity) applied to the Universe as a whole faces the challenges of

- dynamics of gravitating objects at scales from galactic to cosmological (**dark matter**?)
- absence of primordial asymmetry of the Universe

CP violation

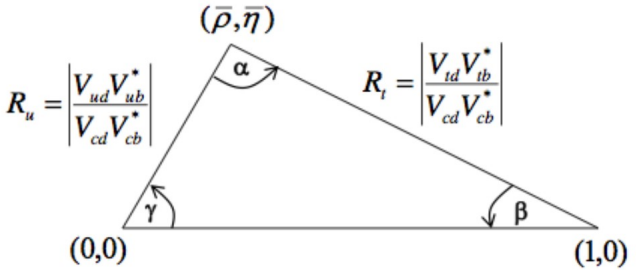
2014 was the 50th anniversary of the discovery of CP violation in Kaon

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.

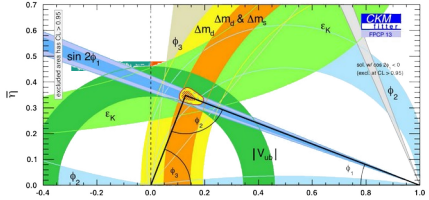
Wolfenstein parameterisation: Phase invariant, conserving CKM matrix unitarity at any order in λ.



Phillip Urquijo

CP violation

Result of 15 years of Belle, BaBar, LHCb operations



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

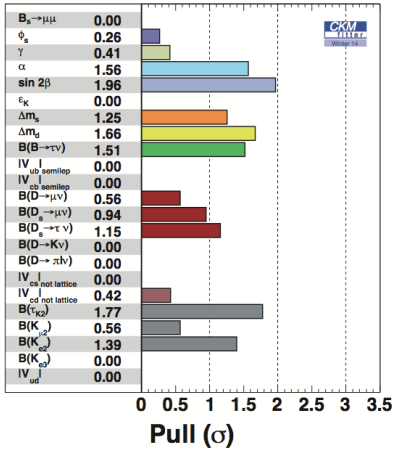
$\alpha \equiv \phi_2 = (85.4^{+4.0}_{-3.8})°$

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

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

Tagir Aushev



Phillip Urquijo

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

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

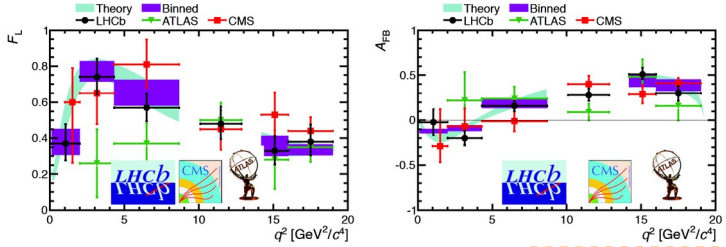
- Currently known mechanism of CPV is ~10 orders smaller than necessary to explain a large baryon asymmetry in the Universe
- Hardly there is a source of this asymmetry other than CPV
- There must be other sources of CPV
- Q: Where is it ?!
- The answer is unknown, but we can look for/in:
  - new particles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

Nazila Mahmoudi Rencontres du Vietnam 2014 – Theoretical summary 14/48

Rare decays

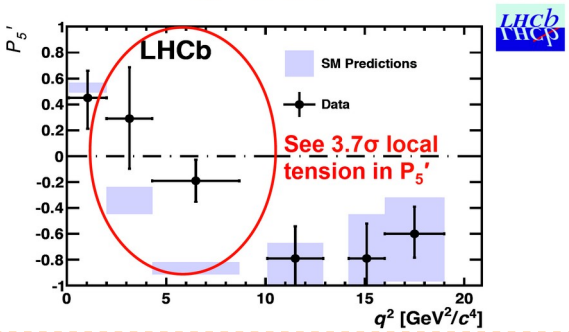
- Range of $B_d^0 \to K^{*0}\mu^+\mu^-$ angular observables in excellent agreement with SM (see talk of M. Tresch)

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



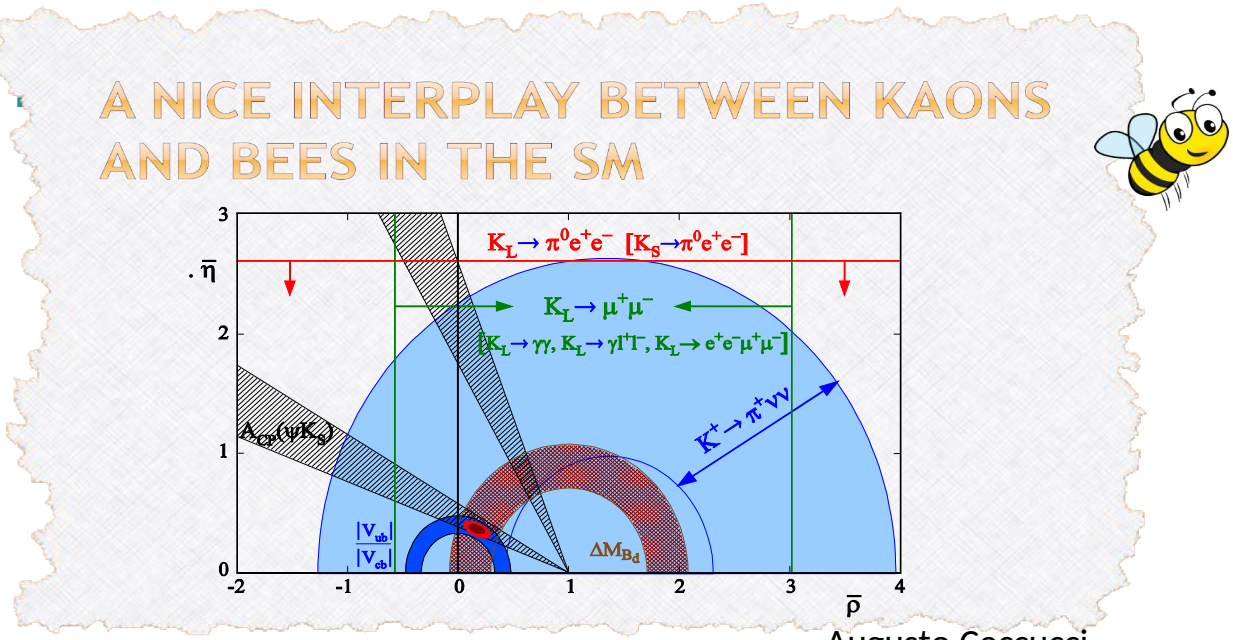
Mitesh Patel

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



New physics or theory issues?

Kaon sector



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

Neutrinos

Neutrinos are special!

→ Most abundant particles in the Universe, together with photons

→ The lightest particles we know about

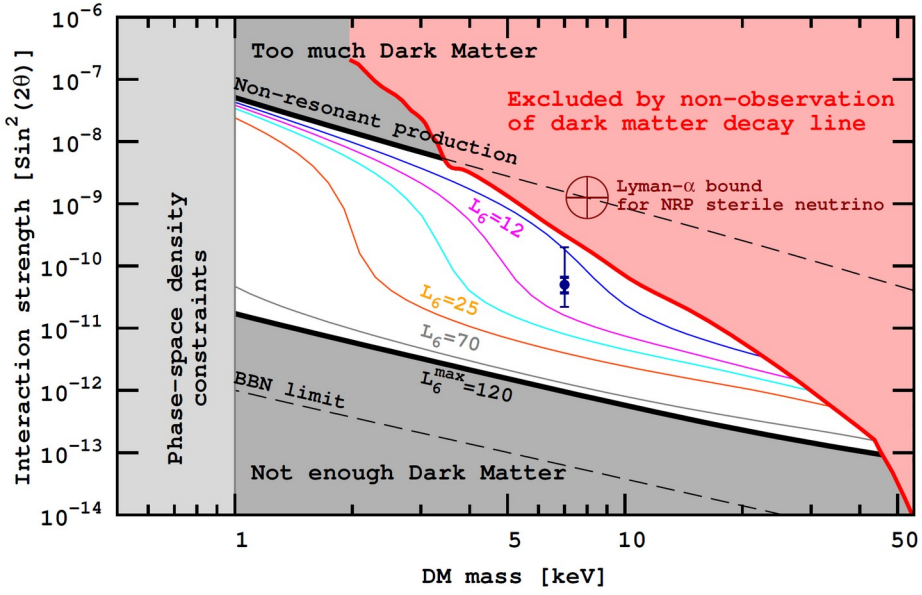
→ The weakest interactions we know about

Neutrinos

Boris Kayser

- 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  ?
- 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?
- 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?

Sterile neutrino and cosmology



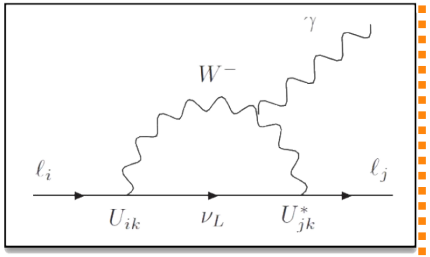
Sterile neutrino DM with such parameters is not completely cold and would leave its imprints in the formations of structures

Oleg Ruchayskiy

Lepton Flavour Violation

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

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



- 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

Frank Deppisch

BSM solutions?

Success of SM in describing flavor-changing processes implies that large new sources of flavor symmetry breaking at TeV scale are mostly excluded.

However, NP at TeV scale need not be flavor trivial!

If (properly aligned) new sources of flavor breaking present

- Precision flavor observables may hide NP signals @10% level in well motivated NP models (natural SUSY)
- can significantly affect & guide NP searches high p_T
- have implications for EW fine-tuning

Jernej F. Kamenik

Perspectives from 2014

- Precision Heavy-Quark Physics at hadron colliders becoming competitive with e^+e^- colliders
- Results of direct searches at the LHC in Run 2 critical
- However, precision flavour measurements are essential either way
- Neutrino physics making very good headway; need to consider impact on, and balance with, the rest of the field—how would further major discoveries affect the plans for colliders?
- Answers to, e.g., *why* we have three families and what lies behind the structure of the mass matrices, are a long-term problem
- Need to look towards the future and explore options, both incremental and transformational—discussions of future facilities

Flavour Physics Conference

- The second Rencontres du Vietnam Flavour Conference was held in 2017

2017 Highlights

Lepton-Number and Lepton-Universality Violation

Contributions to the Session

1. ***Overview of experimental results & searches to come***
   - *Searches for LFV in purely leptonic processes*
     - *Mu2e @ Fermilab – talk by Trần Hoài Nam*
     - *COMET @ JPARC – talk by Yuki Nakai*
     - *LHCb – talk by Gerco Onderwater*
   - *Searches for LFV / LUV in B and D decays*
     - *LFV at LHCb – talk by Gerco*
     - *LUV at LHCb – talk by Julián García Pardiñas*
2. ***Theorists giving their pennyworth***
   - *Flavor anomalies on the eve of the run-2 verdict – talk by DG*
   - *Global fits and impact of hadronic uncertainties – talk by Marco Fedele*

D. Guadagnoli, LNV & LUV Session Summary

Lepton-Number and Lepton-Universality Violation

LNU, LFV (and more) at LHCb, *Gerco Onderwater*

- *Decays involving taus are especially interesting (argument to be given next).*

  But taus are challenging objects, especially in a hadron collider

B factory

- ✘ Babar & Belle ~3×10^9 τ-pairs
- ✓ $e^+e^- \rightarrow \tau^+\tau^-$ extremely clean
- ✓ tag with opposite τ possible

LHC

- ✓ LHCb ~3.5×10^{11} τ's in detector acceptance in 2011 & 2012
- ✘ Nearly no direct τ production, mainly from D_s decay
- ✘ No "production traces" in $D_s \rightarrow \tau\nu_\tau$
- ✘ Charm decay with missing particles similar to τ signature

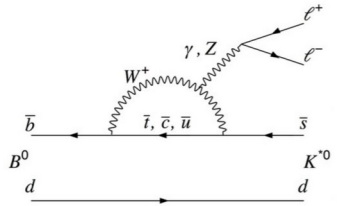
D. Guadagnoli, LNV & LUV Session Summary

Lepton-Number and Lepton-Universality Violation

Lepton Universality Violation at LHCb, *Julián García Pardiñas*

- *Two-front searches (and two-front discrepancies, and from three experiments)*

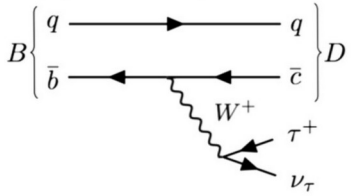
$$R\left(K^{(*)}\right) = \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-) \qquad [b \to sll]$$



- **FCNC process**, rare decay, forbidden at tree level in the SM.
- Very **sensitive to either tree or loop NP** contributions.

$$R\left(D^{(*)}\right) = \mathcal{B}(B \to D^{(*)}\tau^-\bar{\nu}_\tau)/\mathcal{B}(B \to D^{(*)}\mu^-\bar{\nu}_\mu) \qquad [b \to clv]$$

- **Tree level** in the SM.
- Abundant decay.
- Potential NP contributions that couple mainly to the **third family**.



I won't quote the results, you've probably seen them a dozen times

D. Guadagnoli, LNV & LUV Session Summary

Lepton-Number and Lepton-Universality Violation

Summary of take-home messages

- *If R_K & Co. discrepancies are here to stay, then we have BSM LUV*
- *To better understand theoretically what's going on, we will need, first and foremost, further tests of LUV*
- *Aside from them, go for LFV B decays as well (argument given)*
- *BUT, don't forget that searches of purely leptonic LFV decays are not less promising.*

In fact, as a theorist, one has always expected LFV to manifest itself in leptonic decays first

  - *ν oscillations show beyond doubt that lepton flavor is not conserved*
  - *Again because of ν's, leptonic sector more evocative of a NP scale than quark sector*
  - *Looking for more solid theory arguments?*

Hall-Kostelecky, Raby, NPB 1986

Barbieri-Hall, PLB 1994

D. Guadagnoli, LNV & LUV Session Summary

CP violation and rare decays

Ulrich Nierste: *Past, present and future of CP violation*
Sebastian Jäger: *Introduction to rare decays*
Alessio Boletti: *Measurements on rare b-hadron decays by CMS*
Luca Pescatore: *New physics searches via rare decays at LHCb*
Martin Sevior: *Charmless hadronic B decays from Belle*
Giulio Dujany: *Charmless b-hadron decays at LHCb*

CP violating quantities are sensitive to high mass scales and probe physics beyond the Standard Model.

$\Rightarrow$ In K, B, B_s physics
control theory uncertainties of SM predictions,
identify new CP observables with high BSM sensitivity.

In D physics
identify large CP asymmetries to discover charm CP violation,
identify clean observables to probe the SM.

Rare decays

Anomalies

observable	Anomaly?	Dominant theory error	comment
Branching ratios (differential)	Lowish in muonic final states	Form factor values	
Angular (muonic)	P5' off; significance unclear (1-3σ?)	Form factor ratios, long-distance charm	
Angular (electronic)	None (but low statistics)	Similar to muonic	Best theoretical sensitivity to C_7'
Lepton-universality ratios (RK, RK*)	**Each** of 3 bins off by >2σ; 3.7σ combined	no known issue (dominant is QED radiation – tiny)	clean NP discovery with more data Belle2 confirmation?

Possible BSM explanations

to explain all anomalies: require BSM $\bar{s}_L b_L \bar{\mu}_L \mu_L$ coupling

to explain only RK, RK*: BSM $\bar{s}_L b_L \bar{\mu}_L \mu_L$ or various $\bar{s}b\bar{e}e$ possibilities

Eagerly anticipating LHCb updates of RK, RK* with more data; ratios for ϕ l l final state; angular lepton-universality tests

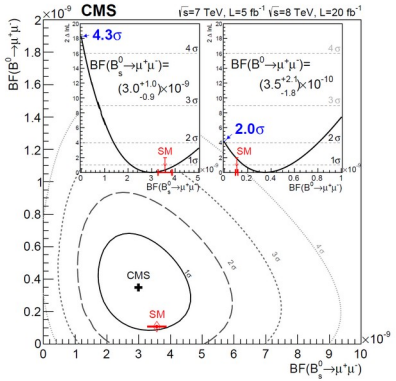
Experimental uncertainties in RK, RK*, … at LHC dominated by electronic modes: Belle2 powerful, with different systematic

17/08/2017 Sebastian Jaeger - Quy Nhon, 17 Aug 2017

Rare decays

Alessio Boletti (CMS): $B^0_{(s)} \to \mu\mu$

- Analysis on Run I dataset ($5 + 20\,\mathrm{fb}^{-1}$)
- Powerful background rejection, thanks to BDT selection
- Combined UML fit to multiple categories, including both B^0_d and B^0_s
- Evidence for $B^0_s \to \mu\mu$ decay (4.3σ) and hint for $B^0_d \to \mu\mu$ decay (2σ)
- Branching fractions compatible with the SM predictions



- Combination with LHCb dataset led to $B^0_s \to \mu\mu$ observation (6.2σ)

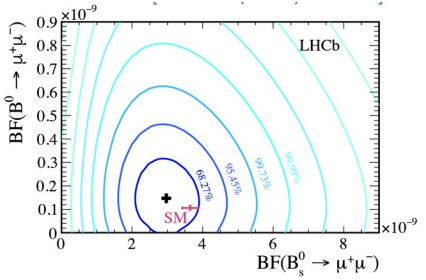
Luca Pescatore (LHCb): leptonic $B_{d,s}$ decays

- Observation of $B(B_s \to \mu^+\mu^-)$ in a single experiment (with 7.8σ):

$$B(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \cdot 10^{-9}$$

95% CL limits:

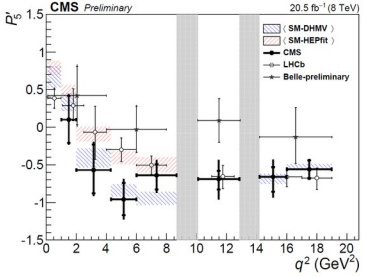
- $B(B_d \to \mu^+\mu^-) < 3.4 \cdot 10^{-10}$
- $B(B_s \to \tau^+\tau^-) < 6.8 \cdot 10^{-3}$
  (SM expectation: $B(B_s \to \tau^+\tau^-) \sim 10^{-7}$.)



Rare decays

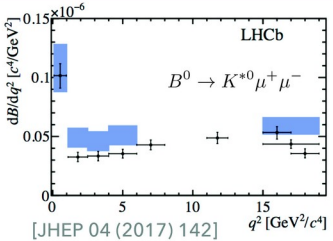
Alessio Boletti (CMS): $B^0 \to K^{*0}\mu\mu$

- Analysis on 2012 dataset (20 fb^{-1}) to measure P_5' and P_1 angular parameters vs. q^2 ($M_{\mu\mu}$)
- Strong event selection against background and resonant decay contamination
- Fit PDF included 3D angular efficiency function and contribution of the S-wave decay

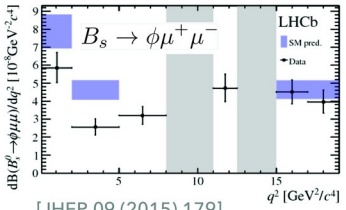


- UML fit to B^0 mass and three angular variables
- Stat uncertainty evaluated with Feldman-Cousins method
- Robust coverage of syst uncertainties
- Results on P_5' and P_1 compatible with SM predictions

Luca Pescatore (LHCb): semileptonic B,B_s decays



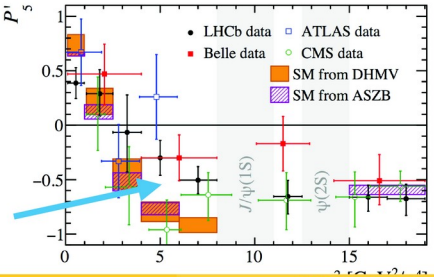
[JHEP 04 (2017) 142]



[JHEP 09 (2015) 179]

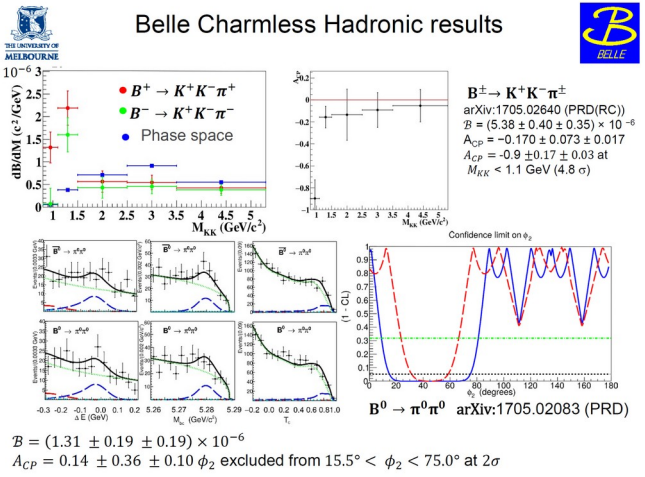
Anomalies in $B \to K^*\mu^+\mu^-$:

- $\frac{dB(B \to K^*\mu^+\mu^-)}{dq^2}$ and $\frac{dB(B_s \to \phi\mu^+\mu^-)}{dq^2}$
- angular observables in $B \to K^*\mu^+\mu^-$: P_5'



CP violation

Martin Sevior (Belle): CP violation in $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ and $B^{0} \to \pi^{0}\pi^{0}$



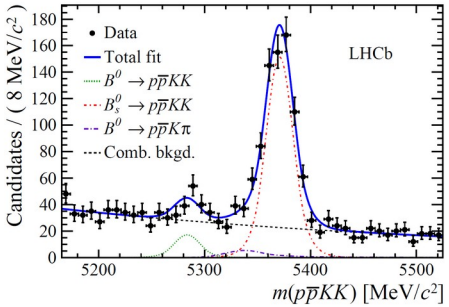
$\mathcal{B} = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$

$A_{CP} = 0.14 \pm 0.36 \pm 0.10$ ϕ_2 excluded from $15.5° < \phi_2 < 75.0°$ at 2σ

Giulio Dujany (LHCb): charmless b-hadron decays

Several new first observations of charmless baryonic decays:

- $B^0_s \to p\bar{\Lambda}K^-$ [PRL 119, 041802 (2017)]
- Three $B^0_{(s)} \to p\bar{p}hh'$ modes [arXiv:1704.08497]
- $B^0 \to p\bar{p}$ (*rarest hadronic B* decay observed so far) [LHCb-PAPER-2017-022]



Updated branching fraction of $B^0 \to K_S hh'$ decays [arXiv:1707.01665]

With more statistics from Run II expect transition from observations to more in-depth studies (CP-violation studies, amplitude analyses, . . .)

CP violation and rare decays

A personal outlook

- CP asymmetries and rare decays probe virtual effects of very heavy new particles. It will not be surprising if new physics will be found here and not in high-p_T experiments.
- The $b \to s\mu^+\mu^-$ puzzle is qualitatively different from the usual "three-sigma hype of the year": Several observables consistently point to $|C_9^{\rm NP}| > |C_9^{\rm SM}|$ and a SM explanation requires at least two effects to conspire; e.g. a wrong form factor calculation and a wrong electron ID.
- At new experiments study new observables, e.g. CP asymmetries in $B_d \to X^-\ell^+\nu$ or $b \to d$ penguin processes.
- Priority in charm physics: discovery of CP violation. There is a long way to precision theory of charm FCNCs.
- Kaon revival: theory breakthrough in ϵ'_K/ϵ_K, upcoming $K \to \pi\nu\overline{\nu}$ measurements, end of MFV paradigm favours Kaon FCNCs over FCNCs in B physics.
- Flavour experiments have something to say about dark matter!

Neutrinos

Ken Long

What we need to know:

- Do neutrino oscillations violate the CP symmetry?

  o Maximal CPiV favoured
  o 2σ w/ reactor
  o Time will tell!

- Ordering of neutrino mass eigenstates and neutrino mass scale

  o Good progress on construction
  o Ambitious energy-resolution specification
  o 4.5σ—5σ sensitivity in 5—6 years

- Empirical relationships between ν-mixing parameters …
  or between ν- and *q*-mixing parameters

- Dirac or Majorana?

  o Building on KL-Zen: 800 kg Xe; Exciting sensitivity

  o Beyond: 10+ years to KL2-Zen: 1000 kg Pressurised Xe

- Anomalies (aka hints for sterile neutrinos):
  statistical fluctuations, systematic effects or indications of new physics?

  5 MeV excess also observed by Daya Bay and Double Chooz

Impact: particle physics, astroparticle physics, cosmology, …

Neutrinos

Ken Long

Pursuing understanding requires:

- Novel, high-resolution detectors
- Novel beams with known flux and energy spectrum

Clearly a vibrant and diverse field that:

- Will complete the "Standard Neutrino Model";
- Is interconnected:
  - o Has impact on astroparticle physics and cosmology;
  - o Is impacted by astroparticle physics and cosmology;
  - o Has synergy with fixed-target/beam dump and collider

Enlightenment? The physics of flavour:

- It seems likely that new techniques … experiment, accelerator and theory … will be required to understand the Standard Neutrino Model:
  - o "Internal relationships"; neutrino-quark relationships
- W/s such as this are an important to create the conditions for the required insights to be articulated

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Perspecyives

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!

Flavour Physics Conference 2022

Rencontres du Vietnam Flavour Physics Conference 2022: Draft Agenda

(version 0810: all titles, times, durations and names subject to change)

Sunday Evening	**Arrival, Registration and Welcome Cocktails at the Seagull Hotel**			
Monday Morning	**Opening Ceremony, Talks and Conference Photograph at the ICISE**			
Monday Morning and Afternoon	*B-Decays and CP-Violation: Introduction*	Roman Zwicky		30+5'
	Rare Decays at the LHC	Alberto Bragagnolo	LHC Experiments	15+5'
	Overview of the Belle II experiment	Kodai Matsuoka	Belle II	15+5'
	Electroweak and radiative penguin decay at Belle and Belle II	Henrikas Svidras	Belle & Belle II	15+5'
	Semileptonic Decays at Belle and Belle II	Peter Lewis	Belle & Belle II	15+5'
	Invisible Decays at BESII	Amit Pathak	BESIII	15+5'
	Mixing and CP Violation at the LHC	Easwar Anand Narayanan	LHC Experiments	15+5'
	QED Effects in Exclusive B Decays	Philipp Böer		15+5'
	Renormalization Group Equations in Generic Effective Field Theories	Mikolaj Misiak		15+5'
	Soft photon QED effects to the ratio of CKM elements	Dayanand Mishra		15+5'
	Study of B → K2(→ Kπ)l+l2− decay*	Juhi Vardani		15+5'
	Discussing several aspects of $\Lambda_b \to \Lambda$ decay	Ria Sain		15+5'
	Discussion and Paper-Writing			
Tuesday Morning and Afternoon	*Lepton Number / Flavour violation : Introduction*	Javier Fuentes-Martin		30+5'
	COMET: Search for mu-e Conversion at J-PARC	Satoshi Mihara	COMET	20+5'
	Searching for Charged Lepton Flavour Violation with the Mu3e Experiment	Ben Gaylher	Mu3E	20+5'
	Lepton universality tests with semileptonic b decays with taus performed by LHCb	Luke Scantlebury-Smead	LHCb	15+5'
	Dark Sector and Tau Physics at Belle and Belle II	Léonard Polat	Belle & Belle II	15+5'
	Search for new physics in b->sll transitions at LHCb	Stefania Ricciardi	LHCb	15+5'
	New physics in b → s μ+ μ−: FCC-hh or a Muon Collider?	Sokratis Trifinopoulos		15+5'
	Fragmentation fractions and b → sll transitions	Greg Landsberg		15+5'
	QED in B→Kll and LFU	Roman Zwicky		15+5'
	Status of the KOTO Experiment: The Search for K_L → π0 νν̄	Joseph Redeker	KOTO	20+5'
	Status and Results from the NA62 Experiment at CERN	Jacopo Pinzino	NA62	20+5'
	Discussion and Paper-Writing			
Wednesday Morning	*Heavy Flavour Physics: Introduction*	Phillip Urquijo		30+5'
	Recent Belle and Belle II Results on Hadronic B decay	Francis Pham	Belle & Belle II	15+5'
	Heavy Flavour Physics at the LHC	Vincenzo Mastrapasqua	LHC Experiments	20+5'
	SM precision measurements in charm decays at BESIII	Christoph Herold	BESIII	15+5'
	Lattice QCD for Quark Flavour Physics	Shoji Hashimoto		30+5'
	Discussion and Paper-Writing			
Wednesday Afternoon	**Excursions**			
Wednesday Evening	**Conference Dinner**			
Thursday Morning and Afternoon	*Neutrinos: Introduction*	Mu-Chun Chen		30+5'
	Three-Flavour neutrino oscillations with NOvA	Ashley Back	NOvA	15+5'
	T2K	Alexander Izmaylov	T2K	15+5'
	MicroBooNE	Melissa Uchida	MicroBooNE	15+5'
	Recent results from the DANSS experiment	Eduard Samigullin	DANSS	20+5'
	Measurements of neutrino mixing with IceCube DeepCore	Juan Pablo Yanez	IceCube	15+5'
	The DUNE Experiment	Pip Hamilton	DUNE	15+5'
	Hyper-K	Stephane Zsoldos	Hyper-K	15+5'
	JUNO: Status and physics prospects	Giuseppe Andronico	JUNO	15+5'
	A new Scattering and Neutrino Detector at the LHC (SND@LHC)	Albert De Roeck	SND@LHC	15+5'
	Absolute neutrino mass scale and dark matter stability from flavour	Ricardo Cepedello		15+5'
	Precision of Model Predictions	Michael Ratz		15+5'
	Discussion and Paper-Writing			
Friday Morning and Afternoon	*BSM and Dark Sector: Introduction*	Stefania Gori		30+5'
	Measuring Muon Moments at J-PARC	Gerco Onderwater	J-PARC Muon g−2	15+5'
	nEDM at PSI	Gilles Ban	nEDM at PSI	20+5'
	Flavor hierarchies and anomalies from a 5D perspective	Javier Fuentes-Martin		15+5'
	Experimental Perspectives	Albert De Roeck		30+5'
	Theoretical Perspectives	Michael Ratz		30+5'
	First Results from LUX-ZEPLIN	Greg Blockinger	LUX/ZEPLIN	30+5'
	Discussion and Paper-Writing			
	Reviews and Closing			

A broad program across flavour physics

→ Hear about good physics together

→ Discuss together (long discussion sessions everyday)

→ Work together (jointly-authored paper)

→ Have fun together 😎