Flavour elements of the HL/HE-LHC workshop

J. Martin Camalich

4th Workshop on LHCb Upgrade II

April 8th 2019

The HL/HE-LHC Workshop

Main Goal

Study the **physics potential** of the High-Luminosity LHC and possible upgrade to the High-Energy LHC

- **HL-LHC:** 14 TeV, 3 ab^{-1} (**LHCb: 300 fb^{-1}**)
- **HE-LHC:** 27 TeV, 15 ab^{-1} (**LHCb: 3 ab^{-1}**)

- **Global effort: Five working groups**
  - **SC:** M. Mangano & G. Salam (**TH**), A. Dainese (**ALICE**), A. Nisati (**ATLAS**), A. Meyer (**CMS**), M. Vesterinen (**LHCb**)
  - **WG1:** Standard Model physics
  - **WG2:** Higgs physics
  - **WG3:** Beyond the Standard Model physics
  - **WG4:** Flavour physics
  - **WG5:** High-density QCD with heavy-ion and proton beams
- **More than one year of work!**

Workshop meetings:

- **Kick-off plenary meeting:** CERN, 3 days on 20, 31 October and 1st November 2017 link
- Joint meeting of WG2, 3 and 4: FNAL April 4-6, 2018, Web page
- **Second plenary meeting:** CERN, 3 days on 18-20 June, 2018 link
- **Final Jamboree:** CERN, March 1 2019 link

CERN-LPCC-2018-06
February 25, 2019

Opportunities in Flavour Physics at the HL-LHC and HE-LHC

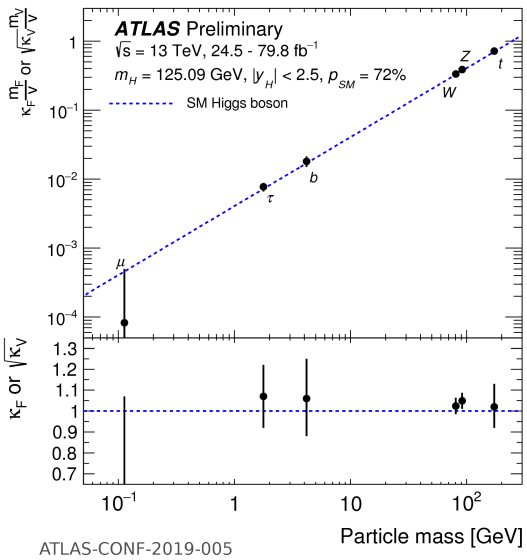
Report from Working Group 4 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

- **arXiv number:** 1812.07638
  - **Cnv's:** A. Cerri (**ATLAS**), S. Malvezzi (**CMS**), V. Gligorov (**LHCb**), JMC & J. Zupan (**TH**)
  - **303 signing authors**
    - 70 **TH** contributors
    - 33 **TH** referees
  - **213 pages** (+78 pages of references)
- Complements "LHCb Upgrade II" document (arXiv:1808.08865) including . . .
  - **Theoretical interpretation of projections**
  - Interplay with **ATLAS** and **CMS**

What have we learned from the LHC so far?

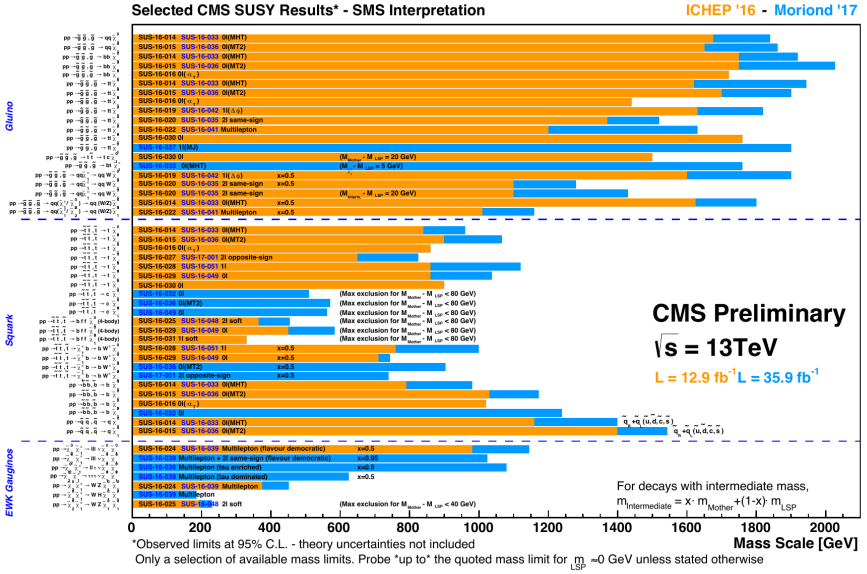
- **Two blunt evidences**

1. **A light SM-like Higgs**



ATLAS-CONF-2019-005

2. **No new particles directly at $\sqrt{s} \sim 1$ TeV**



- **SM becomes a "self-consistent" renormalizable theory up to m_{Planck} ...**
  (Modulo stability of EW vacuum) Buttazzo et *et al.* arXiv: 1307.3636
  - EW hierarchy problem
  - What is the astrophysical/cosmological dark matter
  - ...

Flavor physics was instrumental in **discovering** and **shaping** the SM

- **Nuclear β-decays:** Discovery **weak interactions** and **neutrino**
- **Rare Kaon-decays:** Discovery of the **charm quark**
- **Kaon decays:** Discovery of *CP* **violation** $\Longrightarrow$ Discovery of **3 generations**

- **Expect the unexpected ...**

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

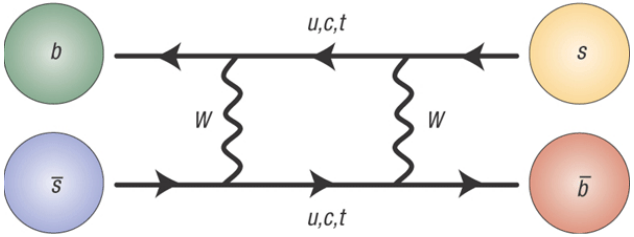
I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$.

Thanks to Zoltan Ligeti for sharing this

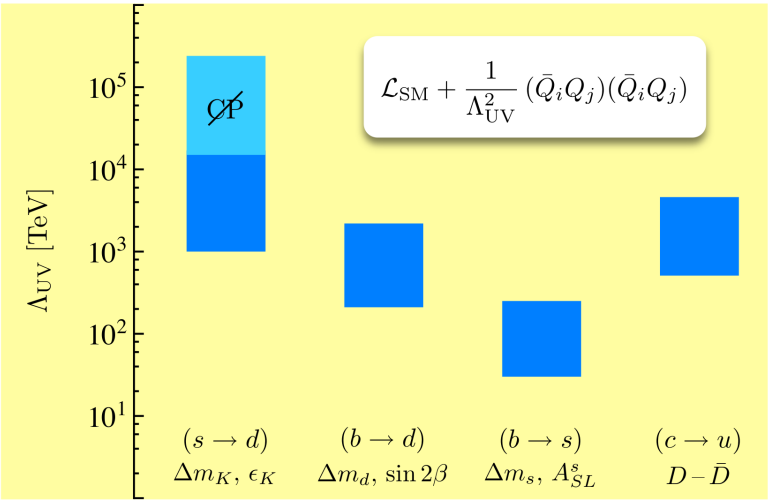
Flavour Physics in the HL-LHC era

- **Prototypical example:** FCNCs



$$\mathcal{M}_{\rm SM} \sim \overbrace{G_F}^{\text{Weak}} \underbrace{\overbrace{\frac{y_t^2}{16\pi^2}}^{\text{Loop}} \overbrace{(V_{ts}^* V_{tb})^2}^{\text{Flavor}}}_{\text{GIM}}$$

- Flavour observables probe (indirectly) very high energy scales!



Generic bounds without a flavor symmetry

M. Neubert at EPS 2011

What is the reach in Λ of flavour physics at HL(HE)-LHC?

CKM metrology in the HL-LHC era: Tree-level inputs

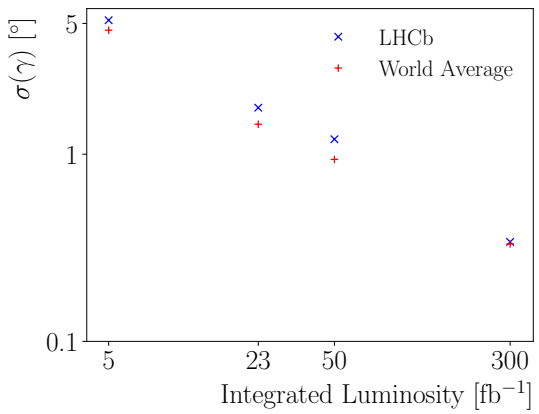
- **Overconstrain CKM: Tree-level inputs (SM) *vs.* loop-level (NP)**
- **LHCb** prospects in tree-level
  - **Measurements of** $|V_{ub}|/|V_{cb}|$

$\Lambda_b \to (p,\ \Lambda_c^+)\mu^-\bar{\nu}$

Current: ± 0.0050
Phase I: ± 0.0025
Phase II: ± 0.0008

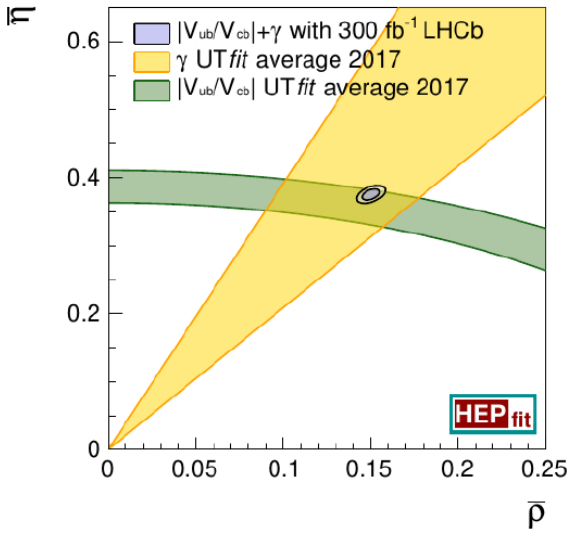
★ **Other:** e.g. $B_c^+ \to D^0\mu^-\bar{\nu}$

  - **Measurements of** γ
    Open competition with **Belle II**



- **Big impact on UT!**

L. Silvestrini, HL/HE-LHC Kick-off

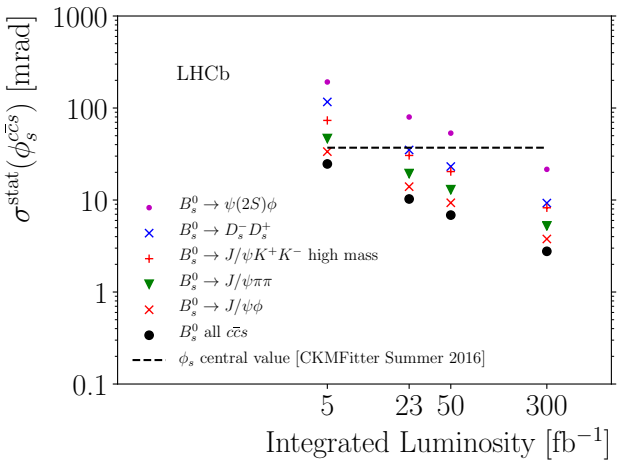


CKM metrology in the HL-LHC era: CPV in the B system

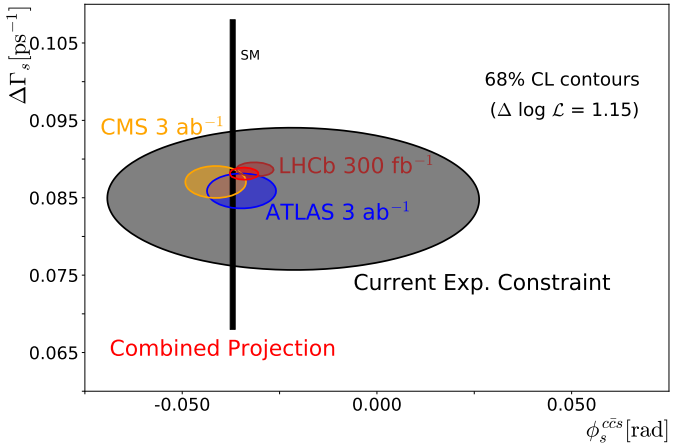
- **Measurements of ϕ_s**

$$\phi_s^{\text{direct}} = -0.21(31)\ \text{mrad}, \quad \phi_s^{\text{SM}} = -0.037(1)\ \text{mrad}$$

  - **Tree-level dominated decays**

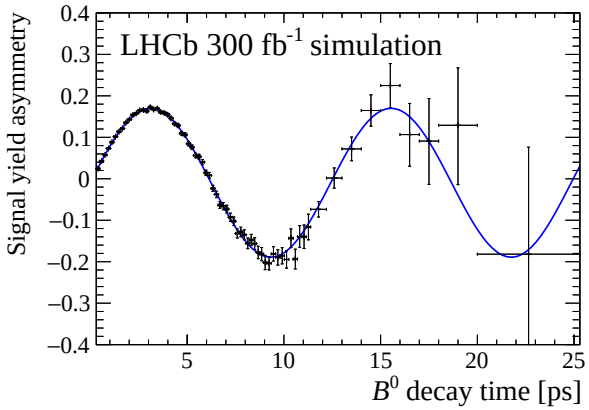


  - **Strong interplay between Expt's**



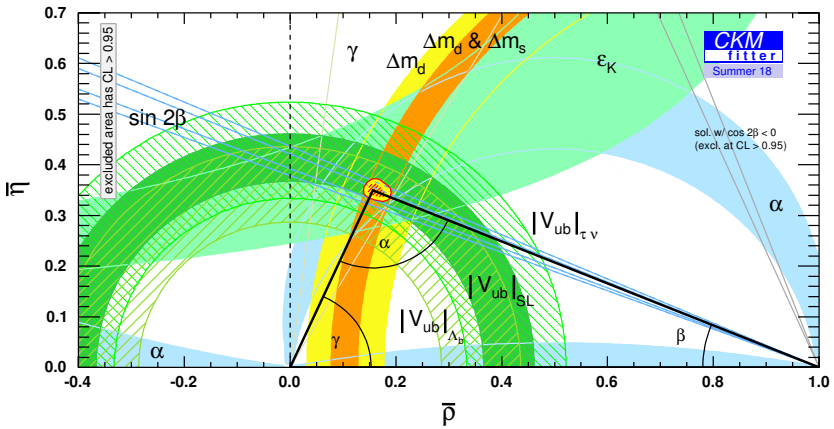
- **Measurement of ϕ_d with $B^0 \to J/\psi K_S^0$**

$\sin\phi_d^{c\bar{c}s}$ (stat.)	
Current:	± 0.029
BELLE II:	± 0.005
LHCb - II:	± 0.003

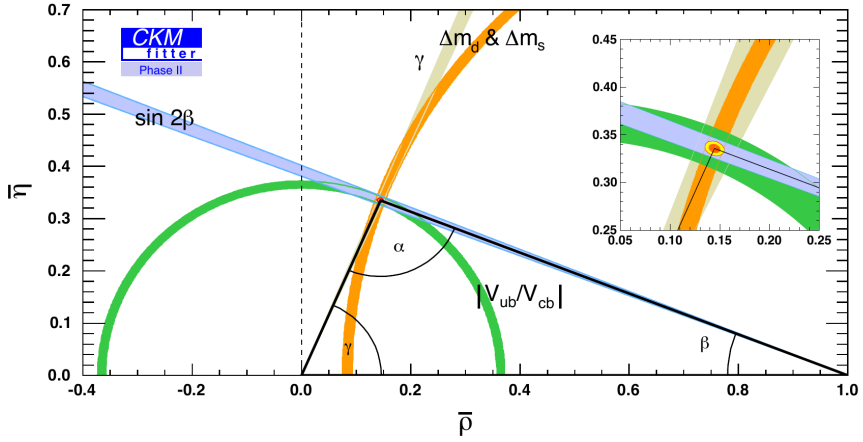


Impact of HL-LHC in Unitarity Triangle

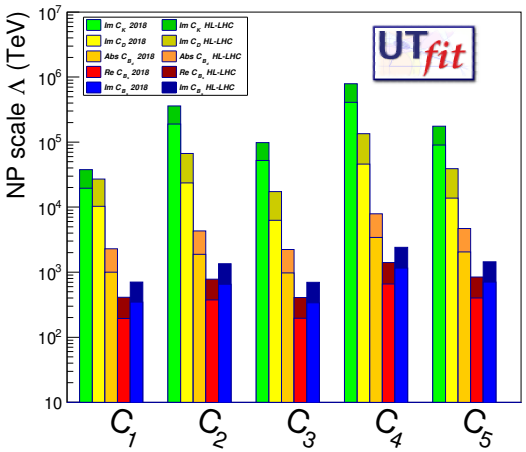
- **Current**



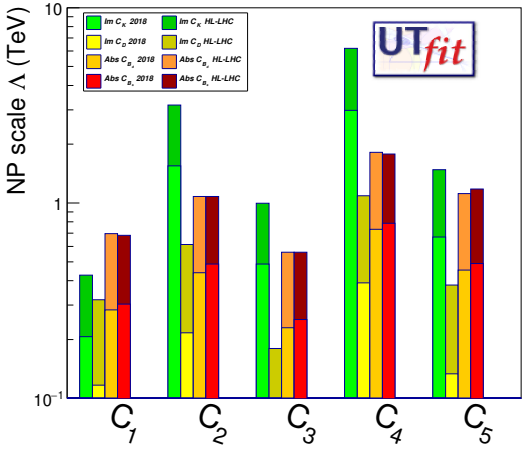
- **Projection HL-LHC only**



- **Projection on bounds on New Physics**
  - **Generic**



  - **MFV and loop**

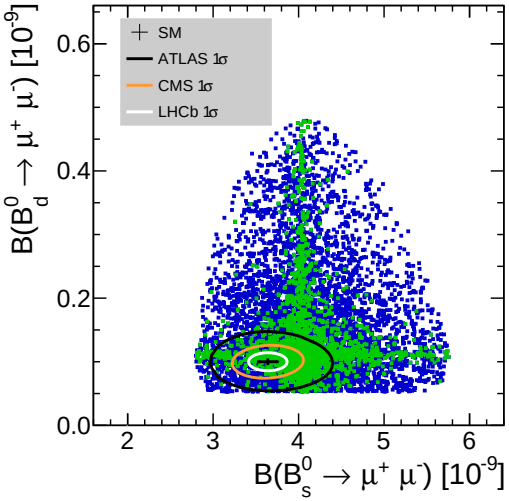


Improvements on Λ by a factor 2-3

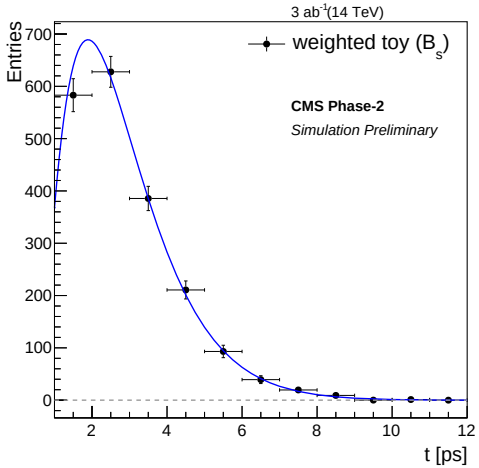
Search of NP in rare B-decays: Rates and angular observables

1 Pure leptonic decay $B_q \to \mu^+\mu^-$

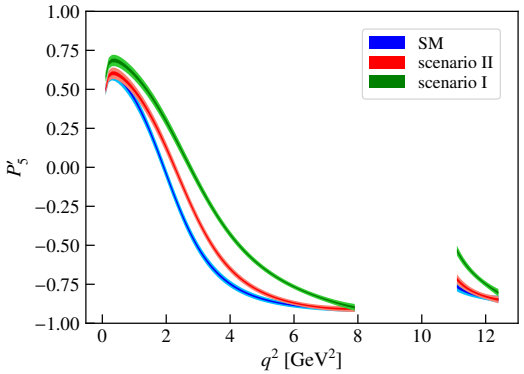
- **Branching fr.** (SM pred. by $|V_{cb}|$)

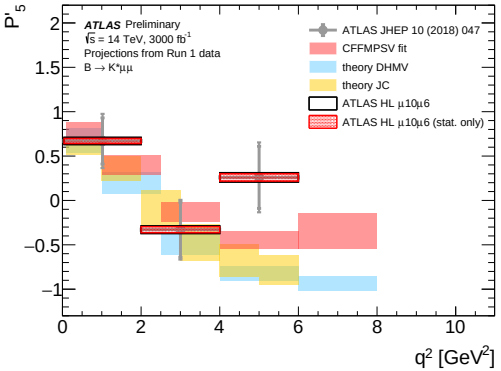


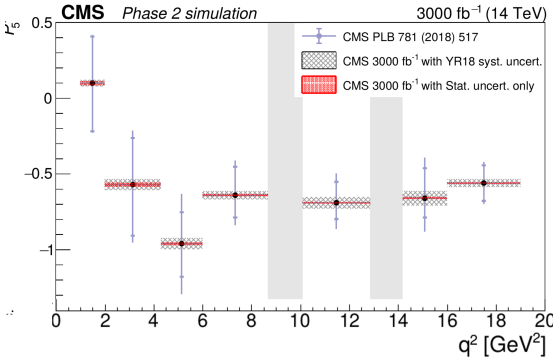
- **Effective lifetime**



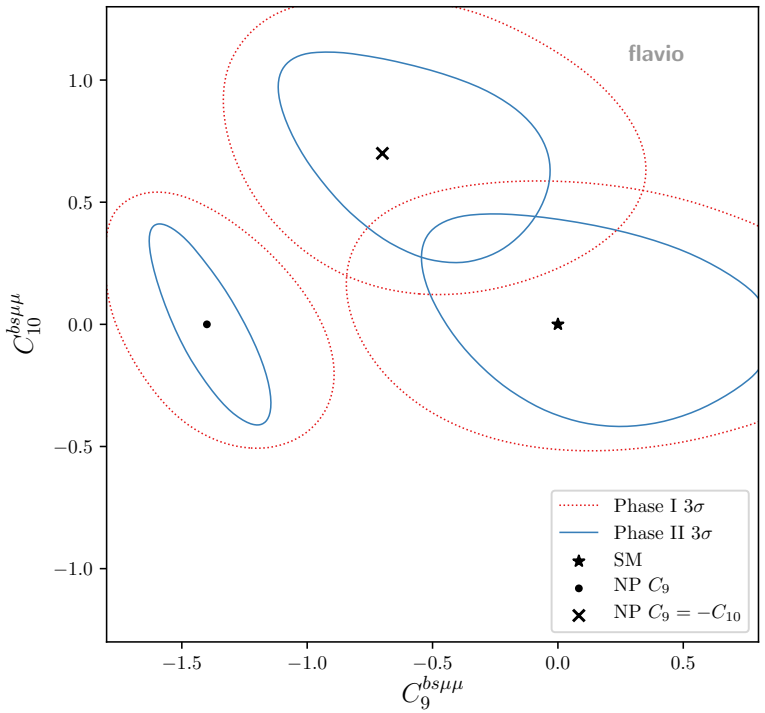
2 Angular analyses $B \to K^*\mu^+\mu^-$





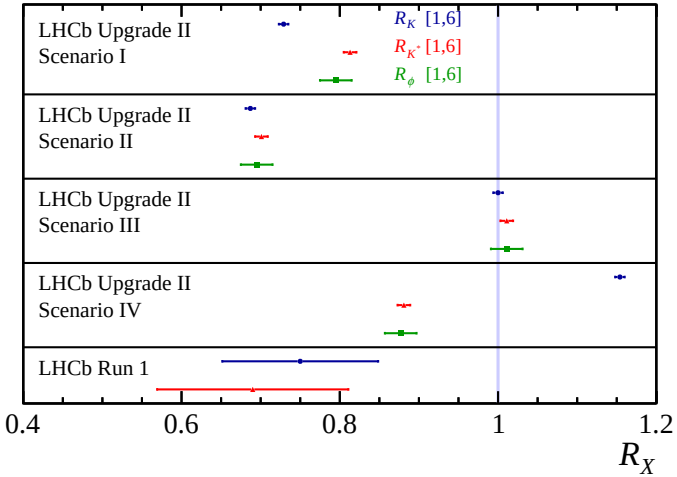


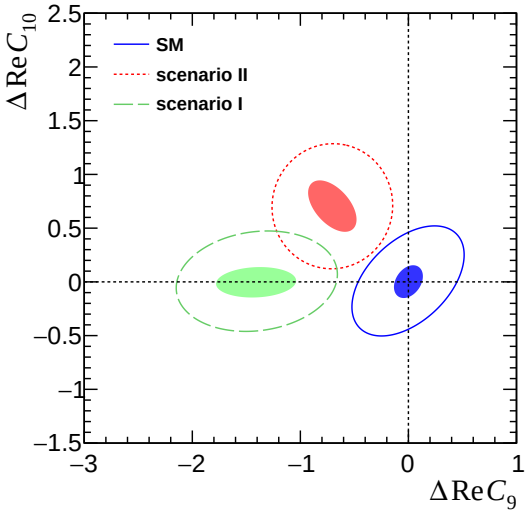
Projection of fits to $B_s \to \mu^+\mu^-$ and angular analyses using ATLAS, CMS and LHCb projections



- Much more explored in the document
  1. **Other decays:** $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, $B_s \to \gamma\mu^+\mu^-$,...
  2. **Radiative decays:** $B_s \to \phi\gamma$, $B \to K^* e^+e^-$, $\Lambda_b \to \Lambda\gamma$,...
  3. $b \to d\mu^+\mu^-$ **transitions:** 17K events of $B \to \pi\mu^+\mu^-$!

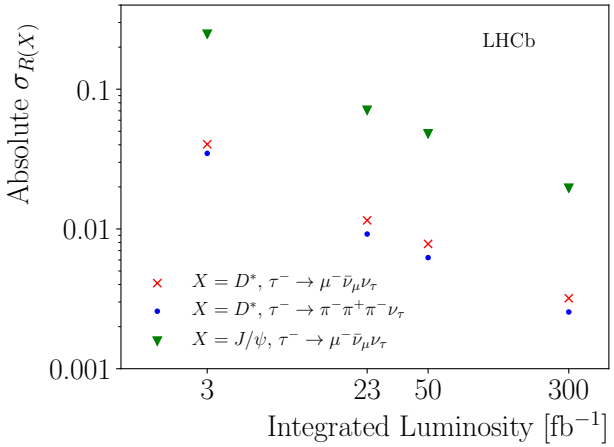
- **LFUV in $b \to s\ell^+\ell^-$**

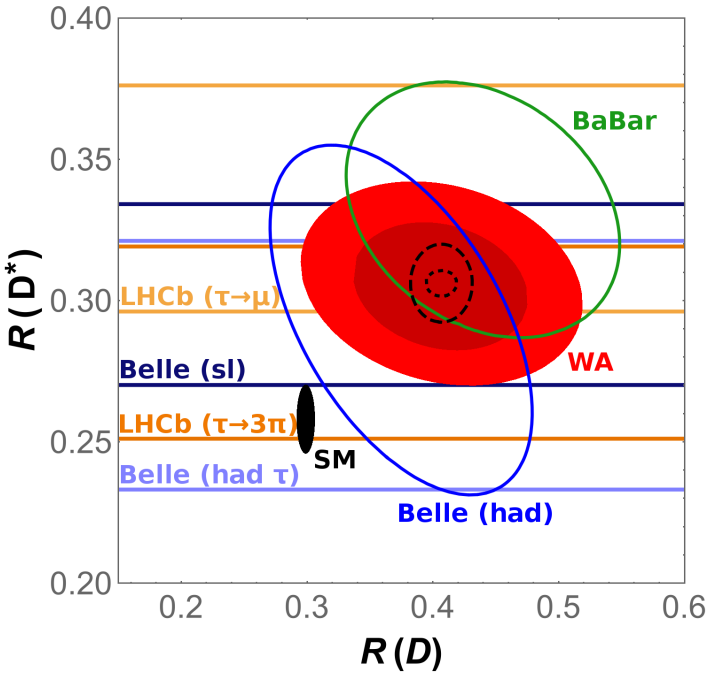




  - **CLFV also generically expected:** e.g. $\mathcal{B}(B^0 \to e^\pm \mu^\mp) \lesssim 2 \times 10^{-10}$ at **LHCb Ph. II**

- **LFUV in $b \to c\tau^-\bar{\nu}$**

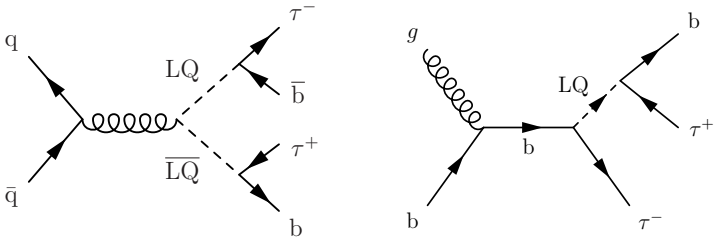




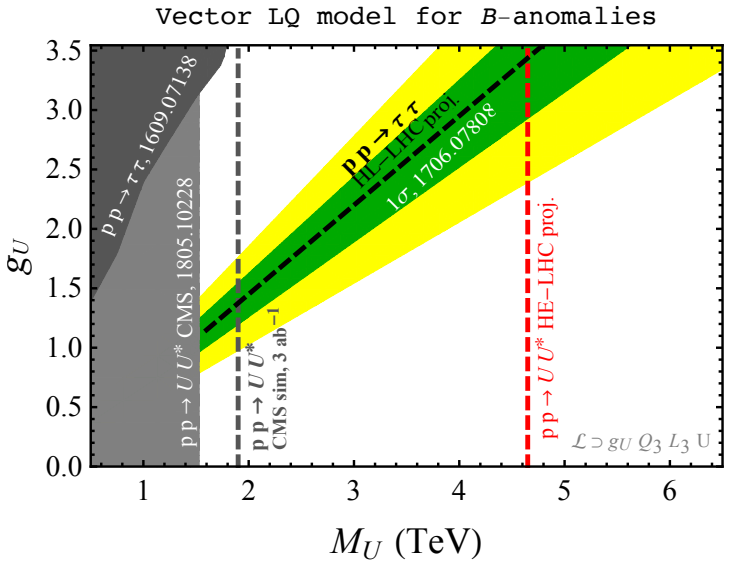
  - **Prospects to measure angular distributions!**

The B-anomalies: Interplay with high p_T searches

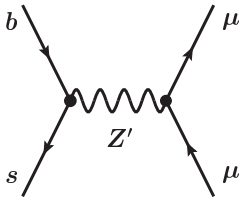
- **The anomalies in CC's:** $\Lambda \sim 1$ TeV
  - **Leptoquarks only survivor**



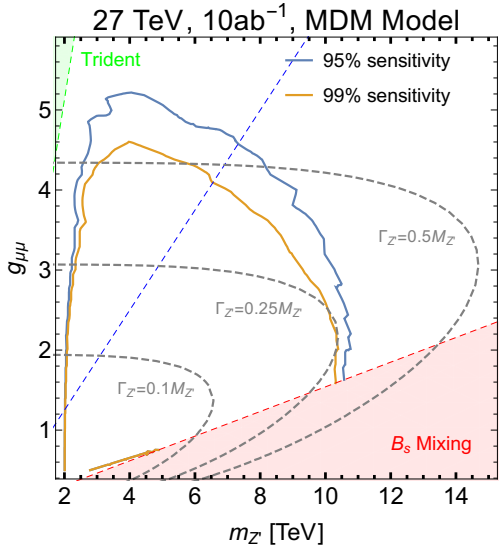
  - Parameter space probed at **HL-LHC** (direct only at **HE-LHC**)



- **The anomalies in FCNC's:** $\Lambda \sim 10$ TeV
  - Z' **or leptoquarks**



  - **@HL-LHC** only if loop-level or combined with CC anomalies



Flavour connection to top-quark and Higgs-boson physics

- **Top-quark flavor transitions**

1. **Top FCNCs**

$\mathcal{B}$ limit at 95%C.L.	3 ab^{-1}, 14 TeV	15ab^{-1}, 27 TeV	Ref.
$t \to gu$	3.8×10^{-6}	5.6×10^{-7}	[1194]
$t \to gc$	32.1×10^{-6}	19.1×10^{-7}	[1194]
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$		[1195]
$t \to \gamma u$	8.6×10^{-6}		[1196]
$t \to \gamma c$	7.4×10^{-5}		[1196]
$t \to Hq$	10^{-4}		[1195]

- Limits relevant for BSM (**Sec.10**)

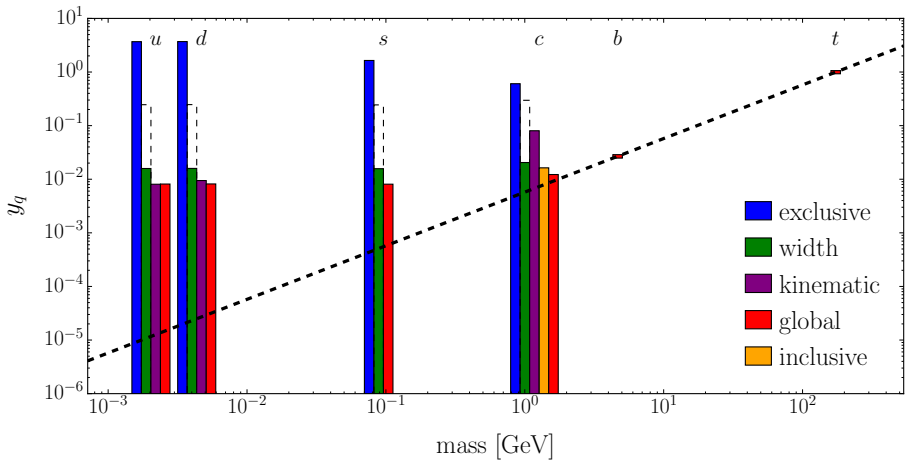
2. **Anomalous *Wtb* couplings**

	Coeff.	c_{tW}	c_{bW}	$c_{\varphi tb}$
Current	Re(...)	$[-0.70, 0.82]$	$[-2.2, 2.2]$	$[-8.9, 10.9]$
	Im(...)	$[-1.5, 2.2]$	$[-2.1, 2.2]$	$[-9.9, 9.9]$
3000 fb^{-1}	Re(...)	$[-0.23, 0.58]$	$[-2.2, 2.0]$	$[-9.3, 10.6]$
	Im(...)	$[-1.2, 1.3]$	$[-2.2, 2.1]$	$[-9.9, 9.9]$

- **Weaker** than $B \to X_s\gamma$: $c_{\varphi tb} \in [-4.6,\ 4.9] \times 10^{-2}$

- **Higgs-flavor physics**

1. **Diagonal yukawas**



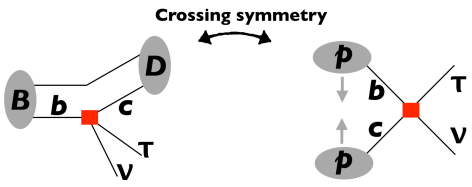
2. **Off-diagonal and CPV yukawas**

- Limits typically weaker than **CLFV** decays ($\mu \to e\gamma$) or **EDM**
- **Exception:** $\tau\mu$-Higgs coupling!
- **Direct limits** on CPV from asymmetries in *ttH* and $h \to \tau\tau$

The tau, kaons and hyperons

- **Flavour physics with the τ-lepton**

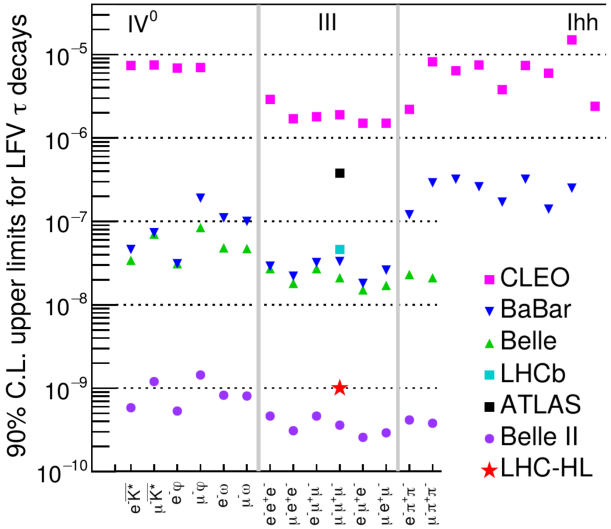
  1. **Collider bounds on high p_T tails**



Greljo *et al.* PRL122, 131803

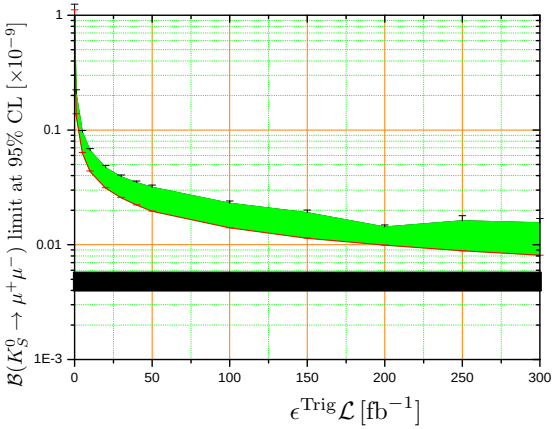
  - Competitive bounds on taus with valence quarks $\Lambda \sim$ **20 TeV!**

  2. **CLFV: $\tau \to 3\mu$**



- **The LHCb strangeness-physics program**

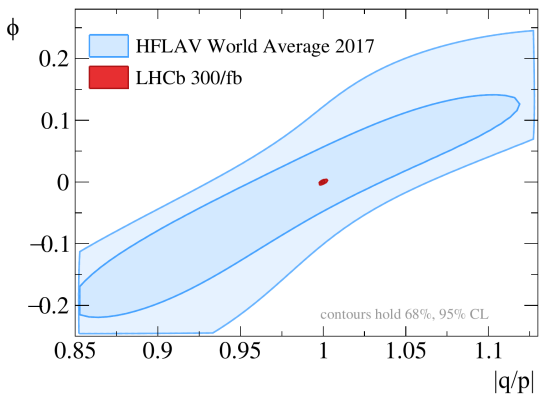
  - **Best bound on $K_S \to \mu^+\mu^-$**



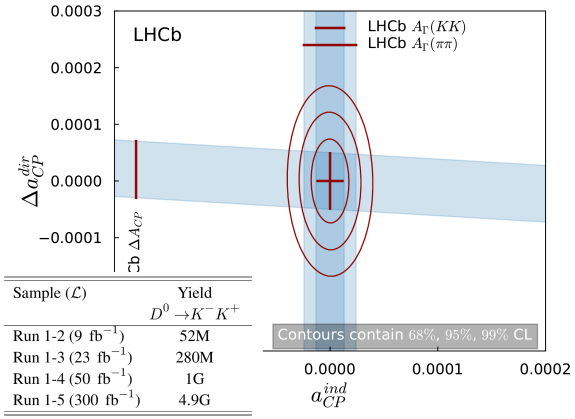
  - **Broad program complementary with "kaon factories"**
    - ★ **LFUV:** e.g. $K^\pm \to \pi^\pm \ell^+ \ell^-$
    - ★ **Hyperon decays:** $\Sigma^+ \to p\mu^+\mu^-$

Charm physics at HL-LHC

- **Probing GIM in up quark system**
  - **Indirect CPV**

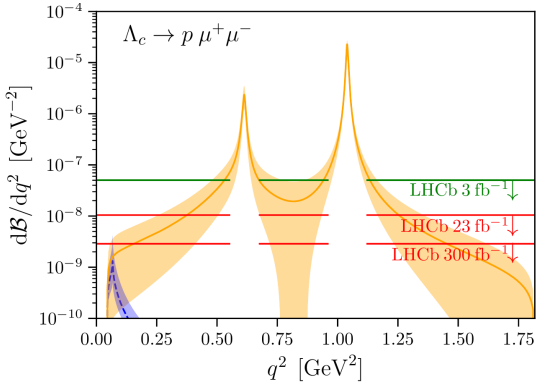


  - **Direct CPV**



Sample ($\mathcal{L}$)	Yield $D^0 \to K^- K^+$
Run 1-2 (9 fb^{-1})	52M
Run 1-3 (23 fb^{-1})	280M
Run 1-4 (50 fb^{-1})	1G
Run 1-5 (300 fb^{-1})	4.9G

- **Rare decays and null-tests of the SM**
  - **Large long-distance cont's**



  - **Null tests and isospin relations**

$D^0 \to \mu^+\mu^-$

Current: 6.2×10^{-9}

LHCb-II: 1.8×10^{-10}

SM: $\lesssim 10^{-10}$

Charm-systems are very challenging for theory

Flavor physics and nonperturbative QCD

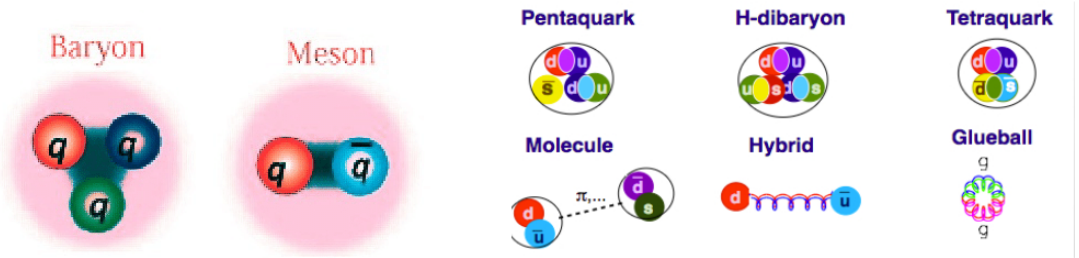
- **Hadronic contributions "plague" interpretation of flavour observables**
  - **Decay constants** and **form factors** in exclusive decays
  - **Long-distance contributions** to rare processes
  - **Penguin pollution** conts. to CPV in B_q^0
  - **QED corrections** to hadron decays
  - ...
- **Progress in QCD crucial for the flavor physics program**
  - Program spearheaded by **lattice QCD** community ... (**Sec. 11**)

Quantity	Published averages	Reference	error (to be published/not in FLAG-2016)	Phase I	Phase II
$f_{K^\pm}$	155.7(7) MeV	$N_f = 2+1$ [66]	0.4%	0.4%	0.4%
$f_{K^\pm}/f_{\pi^\pm}$	1.193(3)	$N_f = 2+1+1$ [66]	0.25%(0.15%, symmet. [822])	0.15%	0.15%
$f_+^{K\to\pi}(0)$	0.9706(27)	$N_f = 2+1+1$ [66]	0.28% (0.20% [1527])	0.12%	0.12%
B_K	0.7625(97)	$N_f = 2+1$ [66]	1.3%	0.7%	0.5%
f_{D_s}	248.83(1.27)	$N_f = 2+1+1$ [66]	0.5%(0.16% [822])	0.16%	0.16%
f_{D_s}/f_{D^+}	1.1716(32)	$N_f = 2+1+1$ [66]	0.27%(0.14% [822])	0.14%	0.14%
f_{B_s}	228.4(3.7)	$N_f = 2+1$ [66]	1.6%(0.56% [822])	0.5%	0.5%
f_{B_s}/f_{B^+}	1.205(7)	$N_f = 2+1+1$ [66]	0.6%(0.4% [822])	0.4%	0.4%
B_{B_s}	1.32(5)/1.35(6)	$N_f = 2/N_f = 2+1$ [66]	$\sim 4\%$	0.8%	0.5%
B_{B_s}/B_{B_d}	1.007(21)/1.032(28)	$N_f = 2/N_f = 2+1$ [66]	2.1%/2.7%	0.5%	0.3%
ξ	1.206(17)	$N_f = 2+1$ [66]	1.4%	0.3%	0.3%
$\overline{m}_c(\overline{m}_c)$	1.275(8) GeV	$N_f = 2+1$ [66]	0.6%	0.4%	0.4%
$B\to\pi$ for $\lvert V_{ub}\rvert_{\rm theor}$		$N_f = 2+1$ [66]	2.9%	1%(1.4%)	1%
$B\to D$ for $\lvert V_{cb}\rvert_{\rm theor}$		$N_f = 2+1$ [66]	1.4%	0.3%(1%)	0.3%
(first param. BCL z-exp.)		$N_f = 2+1$ [66]	1.5%	0.5%(1.1%)	0.5%
$B\to D^*$ for $\lvert V_{cb}\rvert_{\rm theor}$ $h_{A_1}^{B\to D^*}(\omega=1)$		$N_f = 2+1$ [66]	1.4%	0.4%(0.7%)	0.4%
$P_1^{B\to D^*}(\omega=1)$		No LQCD available		1-1.5%	1%
$\Lambda_b\to p(\Lambda_c)$ for $\lvert V_{ub}/V_{cb}\rvert_{\rm theor}$		[71]	4.9%	1.2%(1.6%)	1.2%
$B\to K$ (first param. BCL z-exp.)		$N_f = 2+1$ [66]	2%	0.7%(1.2%)	0.7%
$B_s\to K$ (first param. BCL z-exp.)		$N_f = 2+1$ [66]	4%	1.3%(1.7%)	1.3%

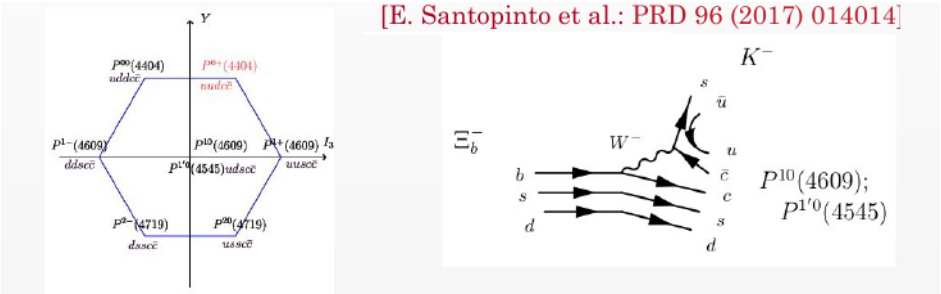
Spectroscopy and QCD exotica

$SU(3)_c$-singlet combinations of q and $\bar{q}$ allowed by QCD dynamics?

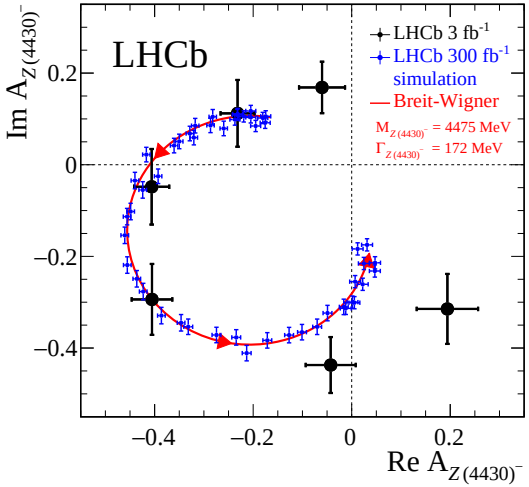
Quark Model VS. QCD *exotica*



- **Experimentally very promising**
  - **Many states to be discovered!** e.g. for the pentaquark ...
  - **HL-LHC:** Argand plot $Z^-(4430)$



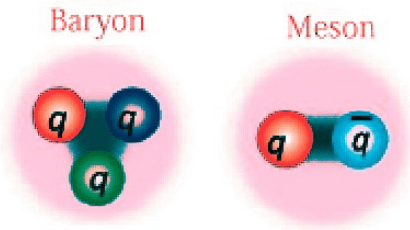
Pappagallo's talk HL/HE-LHC Kick-off

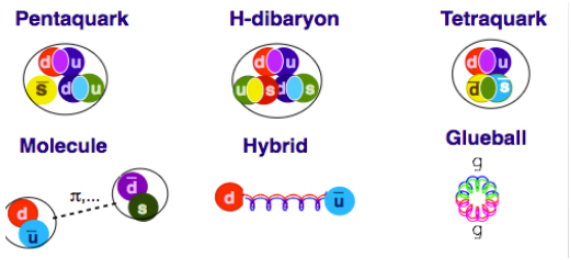


Spectroscopy and QCD exotica

$SU(3)_c$-singlet combinations of q and $\bar{q}$ allowed by QCD dynamics?

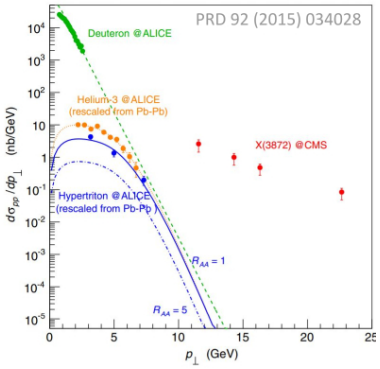
Quark Model VS. QCD *exotica*





- **Theoretically challenging**

- $X(3872)$ **still controversial**
  e.g. prompt production at colliders



Anderlini's talk HL/HE-LHC Kick-off

- **TH's charted interesting states and channels**

Excited single-heavy baryons			A whole SU(3) family; determination of spin and parity
$X(3872)$	$D^0\bar{D}^0\pi^0, D\bar{D}\gamma, J/\psi\pi^+\pi^-, J/\psi 3\pi, J/\psi\gamma, \psi'\gamma$	Line shapes; decay width; production rates	
X_2 (?)	$D\bar{D}, D\bar{D}^* + c.c., J/\psi\omega$		$J^{PC} = 2^{++}$, $M \sim 4$ GeV, $\Gamma \lesssim$ 50 MeV; existence unknown
$\chi_{c1}(2P)$ (?)	$D\bar{D}^* + c.c., J/\psi\omega$		$M \sim 3.9$ GeV, broad; existence unknown
$h_c(2P)$ (?)	$D\bar{D}^* + c.c., J/\psi\eta, \eta_c\omega$		$M \sim 3.9$ GeV, broad; not seen yet
X_b (?)	$\Upsilon\omega, \chi_{bJ}\pi^+\pi^-, B\bar{B}\gamma, \Upsilon\gamma$		Bottom analogue of $X(3872)$; existence unknown
X_{b2} (?)	$B\bar{B}, \Upsilon\omega$		Bottom analogue of X_2; existence unknown
Z_c structures	$(c\bar{c})\pi^\pm, (D^{(*)}\bar{D}^{(*)})^\pm$	Line shapes; production rates; Argand plots	Sensitivity to kinematics

Flavor physics at HL/HE-LHC: Promising program for discoveries!

- **Addresses fundamental questions!**
- **Strong experimental program** extending for the next **two decades**
- **Strong interplay** with Higgs Physics, Collider Physics, Hadron physics, . . .

- **Document will be an important input for European Strategy of HEP**

CERN Council Open Symposium on the Update of

European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain

List of topics

Only contributors to the TH content are listed!

1. Introduction G. Isidori, Z. Ligeti
2. Tests of CKM unitarity J. Charles, M. Ciuchini, O. Deschamps, S. Descotes-Genon, L. Silvestrini, V. Vagnoni
3. Charm-quark probes of NP J. Brod, S. Fajfer, A. Kagan, A. Lenz, L. Silvestrini
4. Strange-quark probes of NP G. D'Ambrosio, D. Guadagnoli, T. Kitahara, D. Martínez-Santos
5. Tau leptons V. Cirigliano, M. González-Alonso, A. Falkowski, E. Passemar
6. Hadron spectroscopy A. Espósito, F-. K. Guo, J. Nieves, A. Pilloni, A. Polosa, S. Prelovsek
7. Bottom-quark probes of NP W. Altmannshofer, D. Straub, J. Virto; M. Freytsis, M. Jung, D. Robinson, S. Schacht
8. Top quark & flavour (WG1) G. Durieux, T. Kitahara, C. Zhang; F. Deliot, W. Dekens; M. Estévez, D. Faroughy, J. Kamenik
9. Higgs boson & flavour (WG2) F. Bishara, R. Harnik, A. Martin, M. Schlafer, Y. Soreq, E. Stamou, F. Yu
10. The high p_T-flavour physics programme (WG3) A. Carmona; S. Banerjee, M. Chala, M. Spannowsky; M. Bauer, M. Carena; T. Han, T. Li, X. Marcano, S. Pascoli, R. Ruiz, C. Weiland; O. Matsedonskyi, G. Servant; A. Celis, A. Greljo, L. Mittnacht, M. Nardecchia, T. You.
11. Lattice QCD in the HL/HE-LHC Era M. Della Morte, E. Gámiz,. Lunghi.

This talk

Glimpse at TH interpretation of Flavour @ HL/HE-LHC!